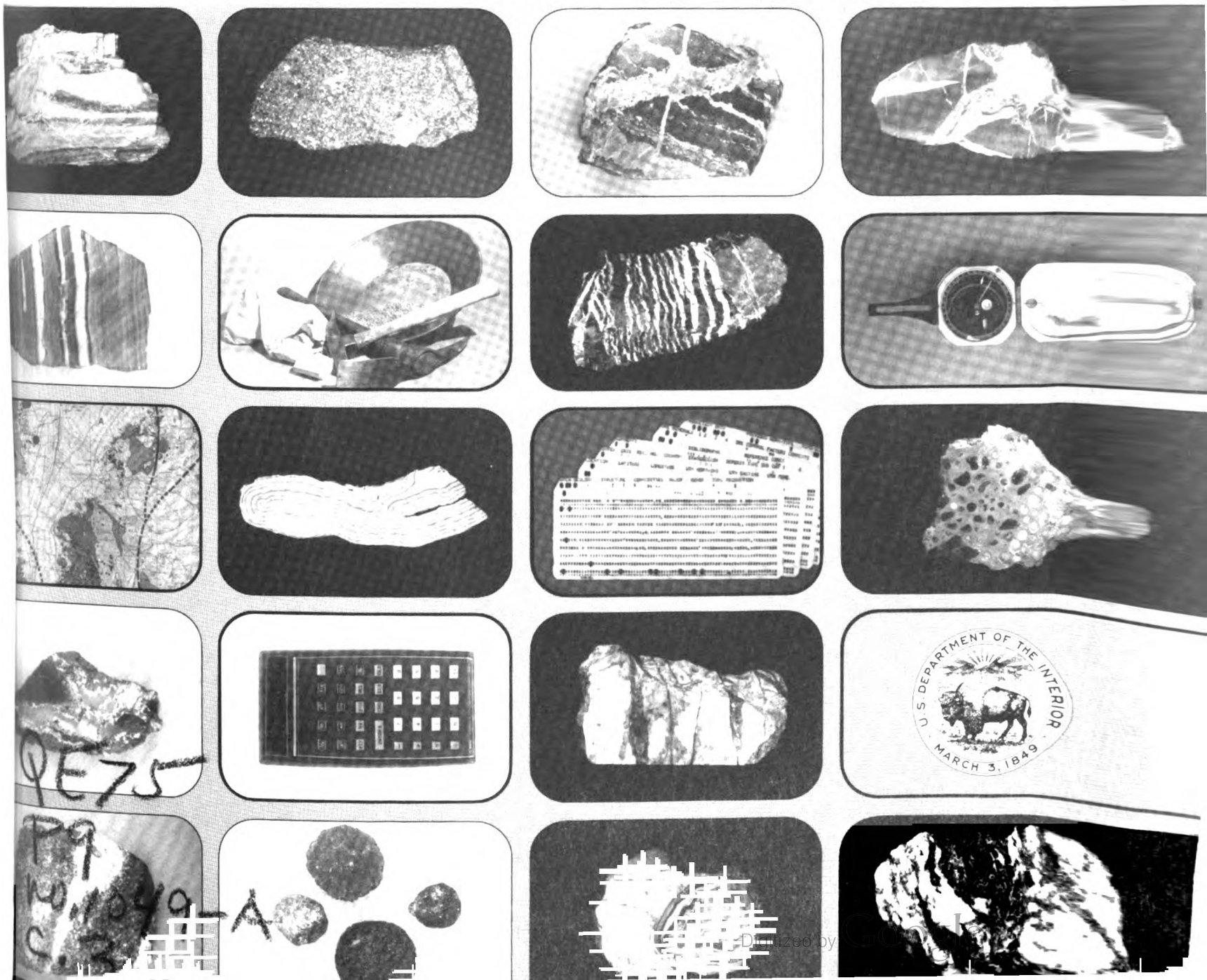
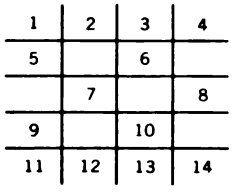
Geology and Mineral Resources of the Lemhi Pass Thorium District, Idaho and Montana

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1049-A



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Geology and Mineral Resources of the Lemhi Pass Thorium District, Idaho and Montana

By MORTIMER H. STAATZ

With a section on DESCRIPTION OF SELECTED THORIUM VEINS
By MORTIMER H. STAATZ, U.S. GEOLOGICAL SURVEY,
and BYRON J. SHARP *and* DONALD L. HETLAND,
U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

GEOLOGY AND RESOURCES OF THORIUM IN THE UNITED STATES
GEOLOGICAL SURVEY PROFESSIONAL PAPER 1049-A

A description of the distribution, geologic setting, mineralogy, and chemistry of the thorium veins in the Lemhi Pass district



UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1979

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UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

H. William Menard, *Director*

Library of Congress Cataloging in Publication Data
Staatz, Mortimer Hay, 1918-
Geology and mineral resources of the Lemhi Pass thorium district, Idaho and Montana.
(Geology and resources of thorium in the United States)
(Geological Survey Professional Paper 1049-A)
Bibliography: p. 83
Includes index.
Supt. of Docs. no.: I 19.16:1049-A
1. Geology—Lemhi Pass region, Idaho and Montana. 2. Thorium ores—Lemhi Pass region, Idaho and Mont.
I. Title. II. Series. III. Series: United States Geological Survey Professional Paper 1049-A.
QE104.L4S7 557.96'78 77-608173

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock Number 024-001-03208-2

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GEOLOGY AND MINERAL RESOURCES OF THE LEMHI PASS THORIUM DISTRICT, IDAHO AND MONTANA

By MORTIMER H. STAATZ

ABSTRACT

The Lemhi Pass thorium district covers approximately 55 square miles in the central part of the Beaverhead Mountains. Approximately 250 veins were mapped in this rectangular district that lies astride the Continental Divide in Idaho and Montana. Thorium veins make up 87 percent of this total. Copper and barren quartz veins each make up 6 percent and iron veins less than 1 percent. Thorium veins range in length from a few feet to at least 4,350 feet and in thickness from thin seams to 40 feet. Fifteen veins are more than 1,000 feet in length. The longest vein, the Last Chance, is also the thickest and ranges from 5 to 40 feet. Much of it is 10-25 feet thick. The veins persist at depth, and the central vein on the Iola property has been traced on the surface for a vertical distance of 560 feet. The veins may strike in almost any direction, but the strikes of more than half of them fall within either the N. 40°-60° W. or N. 70°-80° W. range. Most of them have a steep dip. The thorium veins are generally found along small fractures and shears that are related to faulting of Tertiary age. Movement along these fractures commonly occurred before, during, and after the vein was emplaced. Although 45 minerals have been identified in various thorium veins, only a few are relatively common. Quartz and microcline are the principal gangue minerals. Hematite and limonite (chiefly goethite) commonly vein the earlier minerals and color the veins. Thorite is the most abundant thorium mineral, although monazite is present in many veins. Other thorium or rare-earth minerals found in a few veins are brockite, allanite, xenotime, synchisite, bastnaesite, and doverite. Not all the thorium occurs in discrete thorium minerals; some of it is in limonite. The ThO_2 content of 420 samples from this district ranges from 0.0008 to 9.4 percent. Many of the larger veins have an average ThO_2 content of more than 0.4 percent. The overall total rare-earth oxide content of these veins is about equal to the thoria content, although in various veins the ratio between the two may vary widely. Neodymium is the most abundant rare earth in many of the veins. In addition, europium makes up a greater proportion of the total rare earths in about 70 percent of the Lemhi Pass veins than it does in other reported occurrences. The indicated thorium resources in this district are 176,500 short tons of ThO_2; the inferred resources are 128,900 short tons of ThO_2. The ten largest veins in the district having an average grade of 0.43 percent ThO_2 contain 96 percent of these resources. Rare-earth analyses are available for only 25 veins in the district. These veins contain indicated resources of 186,000 short tons rare-earth oxides and inferred resources of 122,000 short tons total rare-earth oxides. The ratio of total rare-earth oxides to thoria in these 25 veins is four to three. The thorium content of all the veins greatly exceeds the uranium content, and the latter is of little economic significance in this area.

The only other veins of economic importance in the Lemhi Pass thorium district are copper veins. Small amounts of copper ore have been produced from the Copper Queen, Bluebird, and Last Chance properties.

The veins in this district are middle Tertiary or younger in age and were formed after both the Challis Volcanics and the diorite were emplaced. The copper veins are somewhat older than the thorium ones. The latter are believed to have formed from fluids derived from magma that formed buried alkalic rocks. These fluids followed major through-going fractures(faults) but deposited their load along smaller subsidiary breaks. The temperature of formation is probably low, as suggested by the fine grain size of the veins and the distance that some of the fluids apparently traveled.

Precambrian Y sedimentary rocks, which are the host rocks for the thorium veins, are the oldest rocks in the Lemhi Pass district and directly underlie the greater part of the area. The older part of these Precambrian rocks lies below the Peterson Creek thrust fault. This part of the section has been divided by lithology into quartzite and siltite units. Above the thrust fault and in the Ramsey Mountain area the Precambrian Y rocks are divided from oldest to youngest into the Big Creek, Apple Creek, Gunsight, and Swauger Formations.

South of the Peterson Creek thrust fault, the Madison Limestone of Mississippian age is thrust over the Big Creek Formation. Challis Volcanics of Tertiary age once covered the entire area but have been largely removed by erosion. The Challis is now preserved in downfaulted blocks and small erosional remnants. The rocks of the Challis can be divided into two, and possibly three divisions. Rocks of the first division, which contains more than 90 percent of the Challis, consist of a thick basalt-rhyodacite sequence and associated tuffs and conglomerates. Rocks of this division have been divided into the following seven units in ascending order: (1) Basal conglomerate, (2) quartzite-bearing rhyolite tuff, (3) conglomerate of Flume Creek, (4) tuff of Lemhi Pass, (5) basalt-rhyodacite sequence, (6) tuff of Curtis Ranch, and (7) a flow-breccia unit. Rocks of a second division, which are separated from those of the first by an angular unconformity, consist of a younger basalt and a sanidine-quartz welded tuff. Rocks of a third division are light-colored quartz latite flows or intrusives in the northeast part of the district. These are poorly exposed, but the general relations of this rock type to the rest of the Challis Volcanics suggests that it is younger than the bulk of the Challis.

In Tertiary time, after the Challis Volcanics were deposited and uplifted, a sequence of lacustrine tuffaceous sedimentary rocks were formed in the

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large basin occupied by the Lemhi River and in a smaller basin in which Cow and Yearian Creeks now flow. They consist mainly of fine-grained tuffaceous sedimentary rocks with layers or lenses of conglomerate.

Diorite dikes are scattered through the Precambrian Y rocks; these dikes were emplaced in Tertiary time after the Challis Volcanics.

Unconsolidated deposits of Quaternary age are widespread and mask the underlying rocks in about a fifth of the area. Here they have been divided into the following eight units: (1) Older glacial deposits, (2) younger glacial deposits, (3) terrace deposits, (4) alluvial fans, (5) rock glacier, (6) landslide deposits, (7) mud flow, and (8) alluvium.

Faulting is the major structural element, and both thrust faults and steeply dipping faults occur in the Lemhi Pass district. The large Peterson Creek thrust fault in the southeast part of the district separates the area into two geologically distinct areas. Above this thrust, thrusting is the predominant type of faulting; below it, steep faults dominate. The greater number of steep faults strike either northwest or northeast. Although offsets indicate that the faults are of several relative ages, most of them were formed during a period of Tertiary tectonism in which the Challis Volcanics were emplaced. Eight small folds, probably produced by local stresses, are found in this district.

INTRODUCTION

The Lemhi Pass thorium district has the largest known resources of thorium in veins in the United States. The area (fig. 1), which is approximately 13.5 miles north-south by 12 miles east-west, is part of a north-northwest-trending thorium-rich belt at least 85 miles long. This belt extends from southern Ravalli County, Mont. to Bull Canyon, 10 miles southeast of Leadore, Idaho. Rocks or veins that are enriched in thorium but that are not necessarily a high-grade source include carbonatites in the Sheep Creek area of southern Ravalli County and the Mineral Hill area of northern Lemhi County, a granite intrusive near Bull Canyon, and veins in the Lemhi Pass district, the Diamond Creek area 8 miles northwest of Salmon, and along the Salmon River west of North Fork. Although veins occur in three areas, most of them occur in the Lemhi Pass area. Sharp and Hetland's map (1968, pl. 1) shows only six veins in the Diamond Creek area and one along the Salmon River.

LOCATION AND ACCESSIBILITY

The Lemhi Pass thorium district is astride the Beaverhead Mountains (fig. 1), although the greater part of it lies along their west flank. The Continental Divide follows the crest of these mountains and that part of the area which lies to the west is in Lemhi County, Idaho, and that part to the east is in Beaverhead County, Mont. The district, as shown on plate 1, covers 155 square miles. It is bounded on the west by the broad Lemhi Valley. No such definitive boundary occurs to the east, so the eastern boundary arbitrarily has been placed beyond the easternmost known veins. The northern boundary is similarly placed north of most of the known veins. The southern boundary is more definite, ending to the southwest at Lemhi Valley and to the southeast against the Peterson Creek thrust fault. The Lemhi store and post office are in the Lemhi Valley on the southwest corner of the district; the Tendoy store and post office lie on the west edge of the area, 8 miles to the north. State Route 28, which connects these two villages, joins U.S. Route 93 in the town of Salmon 19 miles northeast of Tendoy. The village of Leadore is on State Route 28, 19 miles south of Lemhi. The principal road across the district is a graded dirt one, which in part follows the old Lewis and Clark trail and connects Tendoy with Interstate Route 15 at Clark Canyon Reservoir dam, 28 miles east of the east border of the district. Dillon is the principal nearby town in Montana, 18 miles northeast of the Clark Canyon Reservoir. A poor secondary road extends along the Continental Divide from Lemhi Pass to the northern flank of Goat Mountain. A road branches from this road and follows the ridge on the east side of Bear Creek, and another road leaves the Continental Divide and follows a ridge between the South Fork of Yearian and Reese Creeks. This narrow road is connected with the valley by a series of switchbacks that in part follow the northwest side of Reese Creek. In addition there are other dirt roads along parts of Cow, Yearian, North Frying Pan, South Frying Pan, Bear, Sheser, Reese, and Pattee Creeks, a road up Ramsey Mountain, as well as roads to various springs, propsects, and timbered areas. Travel on some parts of these roads requires a four-wheel-drive vehicle.

PHYSICAL FEATURES

The Beaverhead Mountains are in the southern part of the Bitterroot Range, which forms a great part of the boundary between Idaho and Montana. The name Beaverhead Mountains is applied to the part south of Lost Trail Pass, where U.S. Route 93 crosses the Bitterroots north of North Fork, Idaho. The Lemhi Pass thorium district is in the north-central part of the Beaverhead Mountains. The backbone of the area is the Continental Divide, which rises to peaks almost 11,000 feet above sea level north of the district and from there descends southward to the broad Lemhi Pass at 7,373 feet in the northern part of the district. Southward from the Lemhi Pass the divide gradually rises to about 9,400 feet near the head of Peterson Creek. The highest peak, however, is Goat Mountain, which lies just south of the Continental Divide in the southeast corner of the district. This mountain forms a steep barren pyramid of rock that rises to an elevation of 9,943 feet between Peterson and Little Eightmile Creeks.

The land to the east of the Continental Divide in Montana is higher than that to the west in Idaho. The lowest point to the east of the divide has an elevation of approximately 6,580 feet and is at the east edge of plate 1 on Trail Creek. The lowest elevation to the west of the divide is less than 4,700 feet and it is along the Lemhi River. The difference in elevation can be seen by following the Lemhi Pass road which follows a gentle grade up Trail Creek in Montana to within 300 feet of the pass and then climbs up three gentle switchbacks. On the Idaho side the road pitches steeply

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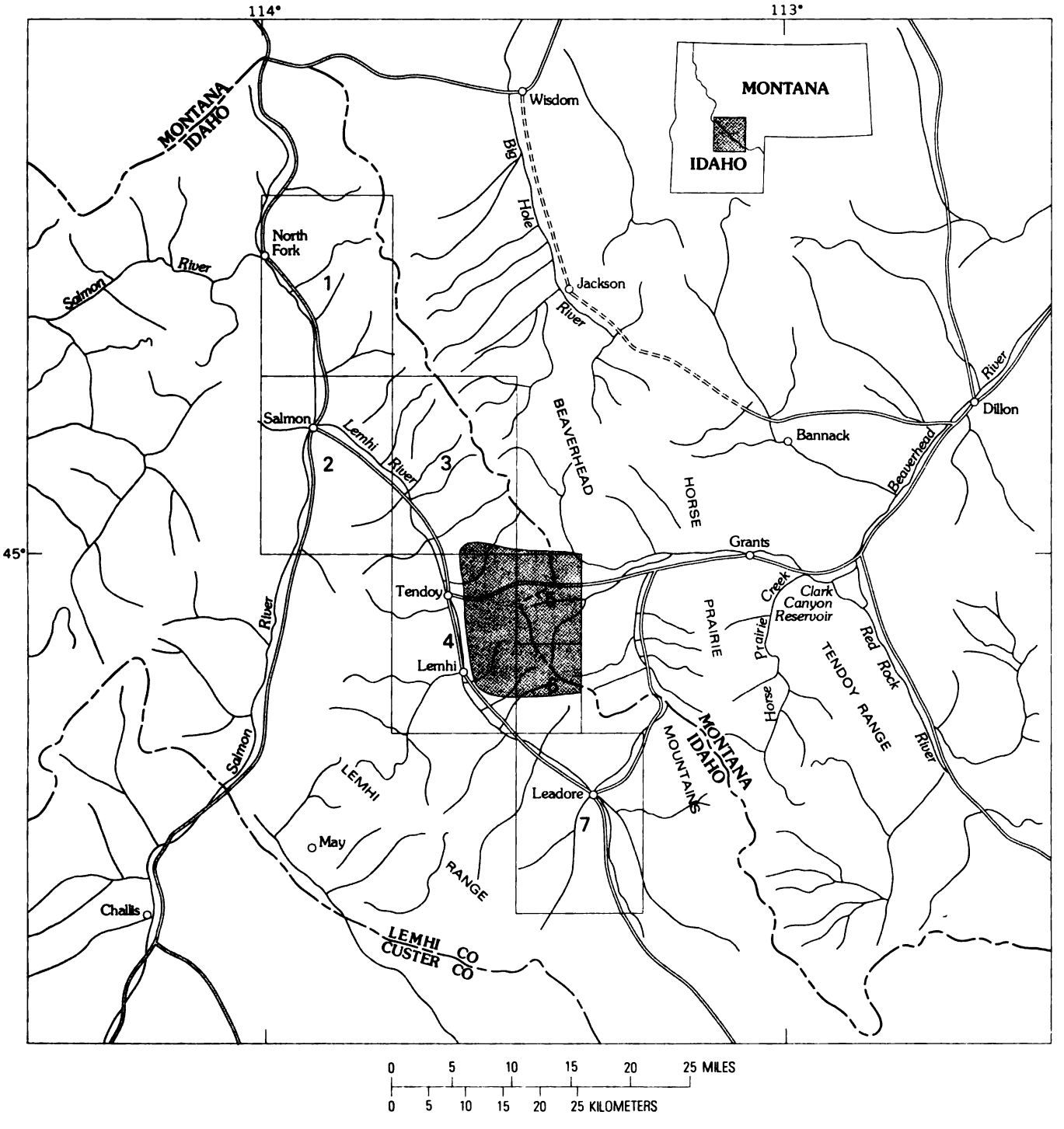


FIGURE 1.—Index map of eastern Idaho and southwestern Montana showing location of the Lemhi Pass thorium district (shaded) and the following quadrangles that are mentioned in the text: 1, North Fork; 2, Salmon; 3, Baker (Goldstone Mountain); 4, Lemhi; 5, Lemhi Pass; 6, Goat Mountain; and 7, Leadore.

downward and in the next 2.4 miles it drops 1,470 feet.

Along the east side of the divide topography becomes quite rugged south of Lemhi Pass, and between North Frying Pan Creek and Bear Creek the east side of the divide is scalloped by steep-walled cirques. The bottoms of these cirques are commonly 1,000 feet below the Continental Divide, and the streams, which head in them, flow eastward down U-shaped valleys.

West of the Continental Divide, although the mountains are steep-sided, they are commonly subdued and

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characterized by rounded ridges that rise steeply from narrow valley floors. South of Agency Creek, the area consists of two mountain masses. The main mountain mass rises to the east to the Continental Divide. Parallel to this mountain mass and along the east side of the Lemhi River is a second mountain mass 7.5 miles long. This separate mountain block is divided from the main part of the range by a broad lowland, whose northern part is occupied by north-flowing Cow Creek, and whose southern part is occupied by south-flowing Yearian Creek. This rugged second mountain mass reaches a maximum elevation of 8,171 feet near its southern end on Ramsey Mountain. To the north the crest is mainly between 7,200 feet and 7,800 feet or 2,500 to 3,000 feet above the floor of the adjacent Lemhi Valley.

The streams in the northern and central part of the area, to the east of the Continental Divide, flow southward or northeastward to Trail Creek; those in the southern part flow eastward down Black Canyon Creek. Both creeks are tributaries of Horse Prairie Creek which flows eastward to Clark Canyon Reservoir (fig. 1). Slopes west of the Continental Divide drain from north to south into Pattee, Agency, Yearian, Reese, Peterson, and Little Eightmile Creeks with the greater part of this area being drained by Agency and Yearian Creeks. All these creeks drain westward into the Lemhi River.

CLIMATE AND VEGETATION

The principal differences in climate in this area are due to differences in elevation. In the lower part of the country, along the Lemhi River and the lower parts of Pattee, Cow, and Yearian Creeks, the climate is semiarid. Here snow rarely falls in significant amounts until December, and then is seldom more than a foot or two in depth. Snow disappears here in early spring. Annual precipitation is only 12 inches a year. In the mountains along the Continental Divide, 2,500-4,000 feet higher, the climate is much cooler, and may even be subalpine. Here snow is common in early autumn, although it does not accumulate in significant amounts until late autumn. It commonly remains on the ground until early summer and scattered drifts occur on the higher ridges as late as July. Summers are generally dry, but regional storms may bring several consecutive days of rainy weather.

Summer temperatures along the Lemhi Valley commonly reach into the nineties, but in the high mountains it is 20-25° F cooler with chilly nights. Winter temperatures are coldest in December and January and average daily temperatures during these two months are 10°-20° F below freezing at lower altitudes. Lowest annual temperature is generally from -20° to -40° F.

The vegetation reflects the differences in altitude, climate, water retention, and rock type. The drier low country is covered with low-growing sage (*Artemisia tridentata*), various grasses, and over 20 species of wild flowers. Along the valleys below 6,600 feet, especially those containing streams, are found western chokecherry (*Prunus virginiana*), dwarf maple (*Acer glabrum*), balsam poplar (*Populus balsamifera*), wild rose (*Rosa woodsii*), red osier dogwood (*Cornus stolonifera*), gooseberry (*Ribes inerme*), mountain alder (*Alnus tenuifolia*), brown birch (*Betula occidentalis*), elderberry (*Sambucus coerulea*), and several kinds of willow. In the drier streambeds rabbit brush (*Chrysothamnus nauseus*) is commonly abundant. Syringa (*Philadelphus lewisii*), ninebark (*Physocarpus capitatus*), and snowberry (*Symphoricarpos occidentalis*) are found in shaded areas along north-facing streams at an elevation of about 6,500 feet. Soil formed on older glacial deposits is richer in nutrients than that on most other rock types, as grass, sage, and flowers growing on the former are bigger and more abundant. Sage, grass, and flowers also clothe most of the mountains at moderate elevations, and evergreens appear on sun-shielded north-facing slopes. The growth of trees on these slopes is not so much a function of elevation and climate as it is of water retention. Winter snows are here protected from the direct rays of the sun and melt and evaporate much more slowly than those on other slopes. Douglas-fir (*Pseudotsuga menziesii*) makes up most of the evergreens to an elevation of about 7,000 feet. Scattered currants (*Ribes viscosissimum*) are commonly found on the same mountain sides. Above this elevation lodgepole pine (*Pinus contorta* var. *latifolia*) is common, and this tree covers most of the forested ridges in the Montana part of the district. Along the tops of ridges, above an elevation of 8,400 feet, limber pine (*Pinus flexilis*) is the common tree, and in places with it is found alpine fir (*Abies lasiocarpa*). Aspen (*Populus tremuloides*) occurs in damp hollows on many mountains of moderate to high elevation. Along the streams above about 6,500 feet elevation are found Engelmann spruce (*Picea engelmanni*), mountain alder (*Alnus tenuifolia*), and several types of willow.

Forested areas in general occur in the higher parts and on north-facing slopes of areas that have a moderate elevation. In those areas that lie close to the normal transition between open and forested country, rock type may be the controlling factor. In such places, trees are more common on Precambrian Y sedimentary rocks than they are on the Challis Volcanics. An excellent example occurs in a roughly triangular patch of volcanic rocks in the northeastern part of the district between South Frying Pan and Bear Creeks. This patch is for the most part unforested, but it is surrounded by forest-covered areas that are underlain by Precambrian rocks or covered with glacial till.

PREVIOUS WORK

The earliest known work in the Lemhi Pass thorium district was a brief description of the Copper Queen mine in 1910 by Umpleby (1913, p. 120-121), as a part of a much larger study on the precious and nonferrous metal mining

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districts of Lemhi County. Thorium discoveries were first reported by Vhay (1951, p. 11-14) in a short paper on a reconnaissance for uranium in Idaho and Montana. Short descriptions of veins on various prospects were given by Anderson (1958, p. 45-74; 1960; 1961a), Jarrard (1957, p. 46-47), Moen (1957, p. 7-23), Schipper (1955), Trites and Tooker (1953, p. 195-208), and Weis, Armstrong, and Rosenblum (1958, p. 36-39). More detailed work was made on a number of individual properties. Armstrong (1956) reported upon the results of a drilling program on the Last Chance property in Montana under a U.S. Defense Minerals Exploration Administration contract, and Shively (1960) described beneficiation tests on ore from the Cago No. 12 vein. The first description of the general geology of the district was by Sharp and Cavender (1962), who compiled a planimetric map from aerial photographs at a scale of 1:24,000. This work was done in 1952 before many of the now known properties had been discovered and covers a little more than half of the present district.

During the early 1960's R. P. Geach made a study of the mining properties of Beaverhead County, Mont. In a special report (1966) on thorium deposits he included mine maps of the two adits on the Last Chance property. Between 1964 and 1966 B. J. Sharp and D. L. Hetland of the U.S. Atomic Energy Commission (now the Department of Energy) studied all the major veins in the Lemhi Pass district. They published a brief summary of the geology of the area (Sharp and Hetland, 1968) which included two reconnaissance maps at a scale of 1:62,500. The maps, which covered an area of approximately 600 square miles, extended from the Mineral Hill mining district, 22 miles northwest of Salmon, Idaho, to Dry Canyon, 11.5 miles southeast of Leadore. Analytical data on samples they collected from many properties were published by Austin (1968). Later, Austin, Hetland, and Sharp (1970) gave a brief description of the mineralogy of some of these deposits. Metallurgical amenability tests on some of the samples collected by Sharp and Hetland were made by the U.S. Bureau of Mines (Ross and George, 1966). In addition to the study of mining properties, a general geologic study of the Lemhi 15-minute quadrangle was made by Anderson (1961b). The report of this area, whose eastern part overlaps about half the Lemhi Pass thorium district (fig. 1), is accompanied by a reconnaissance map at the scale of 1:62,500.

Although considerable work had been done on various thorium veins, with emphasis on their size, shape, and grade, little work had been done on the relation of the veins to the regional geology. Furthermore, owing to the small grain size of most of the minerals in the veins and the masking of various minerals by abundant red and yellow iron oxides, the mineralogy of the veins was poorly known. In order to better understand these veins, I made a detailed study of the Lemhi Pass quadrangle (fig. 1) in 1968 and 1969. The results of this work were reported in three papers: (1) A bulletin describing the geology and thorium-bearing veins of the area (Staatz, 1972), (2) a paper on the occurrence of rare earths in these veins (Staatz and others, 1972), and (3) a paper on geochemical prospecting for thorium using stream-sediment samples (Staatz and others, 1971). Work continued southward during one month in 1970 and all of the summer of 1971 and resulted in a map of the Goat Mountain quadrangle (Staatz, 1973).

PRESENT INVESTIGATIONS AND ACKNOWLEDGMENTS

The present work is a study of the entire Lemhi Pass thorium district. The mapped area (pl. 1) takes in all known veins in this area except at three localities, which are at a distance from other veins. The Daisy Nielsen vein is on the Nielsen Ranch near the headwaters of Sandy Creek about 5 miles north of the area shown on plate 1 and about that far from the nearest other known thorium vein. The Lorado and Ruth veins lie 0.75-1 mile north of McDevitt Creek, approximately 8.3 miles southwest of Tendoy, which is on the west edge of the district. Plate 1 is made up of all or parts of four topographic maps: (1) The entire Lemhi Pass 7½-minute quadrangle, (2) the northern third of the Goat Mountain 7½-minute quadrangle, (3) the northeast part of the Lemhi 15-minute quadrangle, and (4) a few square miles along the southern border of the Goldstone Mountain quadrangle. All mapping was done directly on topographic maps at a scale of 1:24,000 and later reduced to 1:31,680 for the final map. The eastern half of the area, which includes the Lemhi Pass and Goat Mountain quadrangles, was published previously at a scale of 1:24,000 (Staatz, 1972; 1973). Aerial photographs were used to help locate postion, especially in areas of scattered timber. Overburden is thick in many places and outcrops are few; hence, position of contacts between units had to be inferred in many places.

A second part of the work is a detailed study of the veins. All veins were investigated using a scintillation counter, and all those of even moderate radioactivity were sampled for analysis and mineral identification. The individual minerals within the veins were isolated by means of heavy liquids, hand magnet, magnetic separator, and hand picking. Those not readily recognizable were identified by X-ray. B. J. Sharp and D. L. Hetland of the U.S. Atomic Energy Commission mapped and sampled many of the veins in 1965. Some of the workings they mapped have since sloughed in, and the veins in these areas are no longer exposed. In other areas new workings have been opened and other parts of the veins are exposed. To show the greatest amount of data on various veins, many of their maps have been revised to show new workings as of 1973 or 1974. The section entitled "Description of selected thorium veins" was written by Staatz but also includes much data from Sharp and Hetland.

The Lemhi Pass thorium district was mapped between

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1967 and 1974. In 1967 I was assisted in the field by Eric Loeb, in 1968 by Duane R. Packer, in 1969 by Robert A. Langford, and in 1970 by Eric C. Grimm.

I would like to acknowledge help by E. T. Ruppel of the U.S. Geological Survey on the Precambrian Y sedimentary rocks. J. W. Adams aided me with advice on the rare-earth and thorium minerals. M. W. Sullivan and I. K. Brownfield helped with some of the mineral separations.

ROCKS OF THE DISTRICT

Rocks of the Lemhi Pass thorium district are of four principal types: (1) Fine-grained clastic sedimentary rocks of Precambrian Y age, (2) limestone of Mississippian age, (3) volcanic rocks and sedimentary rocks having a volcanic component, of Tertiary age, and (4) unconsolidated deposits of Quaternary age. The Precambrian Y rocks consist principally of micaceous or feldspathic quartzite interbedded in places with siltite. These rocks underlie the entire area but are poorly exposed over about 60 percent of it. Above the Peterson Creek thrust fault and west of the Yearian Creek graben the Precambrian Y rocks resemble those mapped by Ruppel (1968) in the adjoining Leadore quadrangle to the south, and were subdivided similarly. Below the thrust the Precambrian Y rocks are divided on the basis of their lithology. The Mississippian rocks are the Madison Limestone and are principally confined to small areas southeast of the Peterson Creek thrust. The Tertiary rocks consist of the Challis Volcanics and the tuffaceous sedimentary rocks. The former are made up principally of dark flow rocks but also contain some tuff and conglomerate. These rocks were emplaced in the early Tertiary and at one time probably covered the entire area. Directly following this period of volcanism was a major period of diastrophism, which uplifted and downdropped various parts of the Challis Volcanics. Subsequent erosion has stripped away most of these volcanic rocks, and only about 15 percent of the area now is underlain by this rock type, which is found principally in downfaulted blocks (fig. 2). The tuffaceous sedimentary rocks are mainly of lacustrine origin and were deposited in mountain basins during middle Tertiary time. They consist mainly of fine-grained tuffaceous sedimentary rocks containing layers or lenses of conglomerate. These rocks formed after most of the faulting and they are found still in broad topographic lows. Diorite dikes and small intrusives, also of Tertiary age, intrude the Precambrian Y sedimentary rocks. The Quaternary rocks are widespread and entirely mask the underlying rocks in about 20 percent of this district. Eight unconsolidated units have been mapped: (1) Older glacial deposits, (2) younger glacial deposits, (3) terrace deposits, (4) alluvial fans, (5) landslide deposits, (6) a rock glacier, (7) a mudflow, and (8) alluvium. Most of these are limited to local areas in or near valley bottoms. The older glacial deposits at one time, however, covered the entire area, and they still cover broad areas, such as the northeast corner of the district and along the Cow Creek-Yearian Creek trough, where they either have been in part protected from erosion or were originally quite thick.

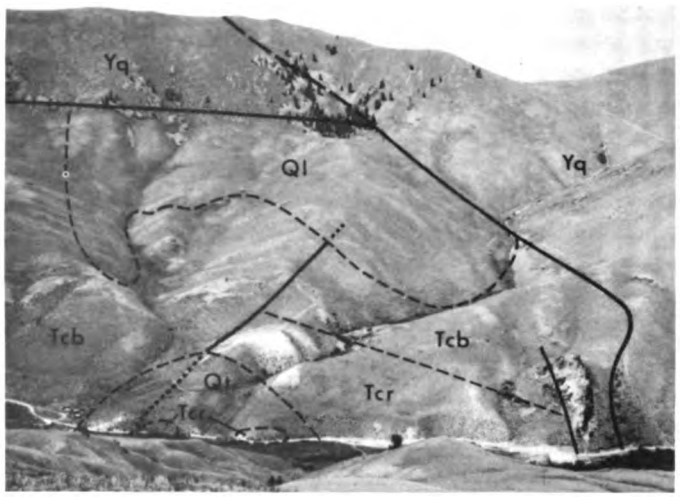


FIGURE 2. Downfaulted block of Challis Volcanics surrounded by Precambrian Y quartzite (Yq) on the north side of Agency Creek opposite the mouth of Sharkey Creek. Units in Challis Volcanics are basalt-rhyodacite sequence (Tcb) and the tuff of Curtis Ranch (Tcr). Landslide deposits shown as Ql and terrace deposits as Qt

PRECAMBRIAN Y SEDIMENTARY ROCKS

The greater part of the Lemhi Pass thorium district is underlain by quartzite and siltite of Precambrian Y age. These rocks underlie much of the Beaverhead Mountains extending at least as far northward as Lost Trail Pass and as far southward as Long Canyon in the southernmost part of this range (Ruppel, 1975, p. 21). They also make up a large part of the Lemhi Range and the Salmon River Mountains (Ruppel, 1968; 1975; Anderson, 1956, p. 16-18; 1957, p. 14-15; 1959, p. 19-25). The Precambrian Y sedimentary rocks form an exceedingly thick section and in the Lemhi Range Ruppel (1975, p. 1) estimates that they are more than 40,000 feet thick. These rocks were first recognized as Precmabrian in this part of Idaho by Umpleby (1913, p. 30-32) who later assigned them to the Belt Series (1917, p. 23).

Although the rocks of Lemhi County can be broadly correlated with the Belt rocks of northern Idaho and western Montana, direct correlation of any particular part appears impractical (Anderson, 1956, p. 18; Ross, 1962, p. 20). Both areas contain thick sections of fine-grained clastic rocks, but in detail they have little in common. The grain size of most of the rocks in western Montana and northern Idaho corresponds to medium silt or finer (Harrison and Campbell, 1963, p. 1415), but that of the greater part of the rocks in the Lemhi area is a fine to medium sand. Limestone and dolomite make up a major part of the Wallace Formation, a

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unit in the central part of the Belt Supergroup, to the north, but are nearly absent to the south. Many shallow-water features such as mud cracks, ripple marks, cut-and-fill structures, and mud-chip breccia are common to the north (Harrison and Campbell, 1963, p. 1415-1416) but are rare to the south. Thus, subdivision of the rocks in east-central Idaho has been largely independent of that of the better known Belt rocks in northern Idaho and western Montana. I have correlated the Precambrian sedimentary rocks in the Lemhi Pass district with the Belt Supergroup in previous reports (Staatz, 1972, 1973), but Ruppel (1975, p. 15-16) has since pointed out that the Precambrian sedimentary rocks in northwestern Montana and east-central Idaho were deposited in different basins and received sedimentation from different sources. He (1975, p. 18) further notes that both were probably deposited during Precambrian Y time, although correlation is based mainly on a few significant events that apparently affected both the Belt Supergroup rocks of northwestern Montana and the Precambrian rocks in the Beaverhead Mountains.

The Precambrian Y sedimentary rocks have been subdivided in various places in east-central Idaho. Ross (1934, p. 16-18) introduced the name Yellowjacket Formation for about 8,500 feet of dark-gray micaceous quartzites near the small mining town of Yellowjacket. He (1947, p. 1096-1099) later named and described two other formations on the west-central flank of the Lemhi Range, the Lemhi and Swauger Quartzites. Anderson studied the Precambrian Y rocks along the west side of the Beaverhead Mountains and the east side of the Lemhi Range when he mapped the Salmon, Baker[1], and Lemhi quadrangles (Anderson, 1956, p. 16-18; 1957, p. 14-15; 1961b, p. 19-25). In the Salmon and Baker quadrangles he did not attempt to subdivide them but in the Lemhi quadrangle he divided them into three formations. He used the names Lemhi and Swauger Quartzites for his uppermost two units and added a new name, the Apple Creek Phyllite, for the lowest unit, which he described as being made up of phyllite and phyllitic quartzite. In the western part of the Lemhi Pass thorium district, which is part of the Lemhi quadrangle, Anderson (1961b, pl. 1) has mapped both Lemhi and Swauger Quartzites. His map shows the two formations commonly separated by low-angle thrust faults, which he infers (1961b, p. 66) from the irregular contact discordances of the northeast and northwest structures and from apparent disappearances of the northeast-trending folds under those of northwest trend. The strike and dip of the quartzite beds show some variance, but no folds were noted in this western part of the district during my mapping, nor are any folds shown on the map of Anderson (1961b, pl. 1). Furthermore, the rocks exposed in areas mapped as Swauger are mostly identical to those in adjacent areas mapped as Lemhi.

[1]On the published topographic sheet, the Baker quadrangle is designated the Goldstone Mountain quadrangle.

Ruppel, working mainly in the Lemhi Range, has mapped the Precambrian Y sedimentary rocks in three 15-minute quadrangles: Leadore (Ruppel, 1968), Gilmore, and Patterson. On the basis of his work in these areas he (1975) has (1) changed the lithologic ending of the Swauger Quartzite to Swauger Formation, (2) changed the stratigraphic rank of the Lemhi Quartzite to Lemhi Group and divided it into five formations, which in ascending order are: Inyo Creek Formation, West Fork Formation, Big Creek Formation, Apple Creek Formation, and Gunsight Formation, and (3) geographically extended the name Yellowjacket Formation into the Lemhi Range and Beaverhead Mountains. The Apple Creek Formation is a modification of the lithologic ending of Apple Creek Phyllite of Anderson (1961b). Ruppel (1975, p. 10) notes that the rocks that overlie the Apple Creek in its type area and which Anderson calls Lemhi Quartzite are a part of the Yellowjacket Formation, and are here thrust over the phyllite, and that the Apple Creek actually occurs near the center of the Lemhi Group. The other formations in Ruppel's Lemhi Group are new. The lowest two formations of the Lemhi Group, the Inyo Creek and the West Fork, are known only in relatively small areas in the southern part of the Patterson quadrangle in the Lemhi Range. The other three formations are much more widespread, occurring in various areas in the Lemhi Range and Beaverhead Mountains. Two of these formations, the Gunsight and Big Creek, consist principally of gray fine-grained feldspathic quartzite and are separated by the Apple Creek, which is principally a siltite. In many areas of isolated outcrop where the Apple Creek is missing the Gunsight cannot be distinguished from the Big Creek.

Exposures over a great deal of the area in the Beaverhead Mountains occupied by the Lemhi Pass thorium district are much fewer than those in the Lemhi Range and farther north in the Beaverhead Mountains. Unlike the other two areas, outcrops are generally widely scattered, and even on steep slopes exposures are commonly poor. In much of the area the topography is also subdued and rounded. Furthermore, many parts of the Lemhi Pass area are partly or completely covered by glacial deposits. Boulders and pebbles in glacial fill in this area consist mainly of fine-grained quartzite from the Precambrian Y rocks. Thus, in many areas it is not possible to determine whether quartzite float was derived from the underlying bedrock or brought in from a distant location. In making the present study I used only bedrock outcrops for determining the position of the Precambrian Y sedimentary rocks.

The area of best exposure is shown in the southeast corner of plate 1 on and adjacent to Goat Mountain. In this area along Peterson Creek and Black Canyon is the large Peterson Creek thrust fault. South of this fault the Precambrian Y sedimentary rocks are different from those to the north. This area is part of the Goat Mountain quadrangle (fig. 1), which has been previously mapped (Staatz, 1973) and adjoins the Leadore quadrangle on the north (Ruppel,

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1968). The Lemhi Group and Swauger Formation as used by Ruppel (1975)[2] have been traced northward into the present map area south of the thrust (pl. 1). Similar rocks have been found on Ramsey Mountain west of the Yearian Creek graben and south of a fault along the south side of Agency Creek. Directly north of the Peterson Creek thrust and east of Ramsey Mountain the quartzite tends to be micaceous instead of feldspathic and may be part of the thick Yellowjacket Formation. Ruppel (1975, p. 21) suggested that the rocks he saw on a visit to Lemhi Pass also resembled those in the Yellowjacket Formation. Many of the Precambrian Y rocks north of the Peterson Creek fault are micaceous quartzite, but not all. In several areas thick siltite units are found. Faulting in the Precambrian Y rocks is not distinguishable unless some marker unit such as a siltite bed is offset or the fault trace can be delineated from where it also offsets younger rocks. The stratigraphy of the Precambrian Y rocks north of the Peterson Creek fault and east of the Yearian Creek graben is further clouded by several thick siltite units. Lithologically the siltites are fairly similar to each other, but the relations to some of the bounding rocks suggest they are different. A thick greenish-gray siltite lies adjacent to and northeast of the Peterson Creek thrust (fig. 3*D*) near the junction of the Left Fork and Right Fork of Peterson Creek. This unit is abruptly overlain by a greenish-gray quartzite, whose green color is due to chlorite. In the northern part of the area, along the north side of the Lemhi Pass fault, a light-gray to black siltite is also overlain by a greenish-gray quartzite. Here the contact is gradational and the green color is due to epidote. In a third area along the Continental Divide about 3 miles due north of the first area, a greenish-gray siltite is underlain by a greenish-gray quartzite. This contact is abrupt and the color of the quartzite is due to chlorite.

The Precambrian Y sedimentary rocks above the Peterson Creek thrust (pl. 1) and on Ramsey Mountain were divided into the Big Creek, Apple Creek, and Gunsight Formations of the Lemhi Group and the Swauger Formation. In the rest of the area, however, the Precambrian Y rocks were simply divided lithologically into either quartzite or siltite.

ROCKS ABOVE THE PETERSON CREEK THRUST FAULT AND ON RAMSEY MOUNTAIN

The Precambrian Y sedimentary rocks in this area are represented by four formations from the upper part of these rocks: The Big Creek, Apple Creek, and Gunsight Formations of the Lemhi Group, and the Swauger Formation. All these units are separated from one another by faults.

BIG CREEK FORMATION

The Big Creek Formation makes up about half of the area south of the Peterson Creek thrust fault including most of the very precipitous Goat Mountain (fig. 3*A*). This quartzite is extremely hard and commonly forms a series of cliffs. In most places it is medium bedded; in a few places it is thick bedded to massive. Shallow-water features are generally absent, although ripple marks are present near the north end of the Goat Mountain ridge. The Big Creek is principally a quartzite, although in some places a few thin siltite beds are present (fig. 3*B*). The quartzite varies in color and may be light gray, gray, tan, brown, greenish gray, or green. Much of the quartzite on Goat Mountain weathers brown. The quartz grains range from angular to rounded, and in most layers they are fairly well sorted. Many of the layers in this rock are made up of fine-grained sand but some have medium-grained sand. In one specimen the grains ranged from 0.0014 to 0.023 in. in diameter. The grains in most of the layers, however, range from about 0.005 to 0.012 in., and, according to Wentworth (1922, p. 381), would be classified from a very fine sand to a medium sand. The greater part of the quartzite is feldspathic and this rock commonly contains 4-12 percent feldspar as small white grains. Plagioclase is the predominant feldspar, although in some specimens microcline is common. Sericite in amounts as much as 10 percent, but generally less, is a common mineral. Some specimens also contain as much as 5 percent of tiny grains of pale-green wispy chlorite. Small grains of chert in amounts as much as several percent occur in most layers. In addition, a few grains of tourmaline and zircon are found in most specimens, and trace amounts of apatite, leucoxene, and hematite occur in some.

APPLE CREEK FORMATION

The Apple Creek Formation is exposed only east of the Lemhi River along the west edge of Ramsey Mountain. It can be traced just east of Lemhi for 5 miles to the north to the mouth of Big Dry Gulch. The base is not exposed and the upper part is separated by a small fault from the overlying Gunsight Formation. The maximum exposed thickness along this outcrop is about 1,400 feet. The Apple Creek is fairly well exposed, forming a series of small rust-stained cliffs along the base of the mountain front. The Apple Creek Formation varies in color from light gray to a pale greenish gray. It is thin bedded and in places also finely laminated. This rock is a fairly well sorted siltite, having an average grain size of about 0.001 in. In a few places there are thin gray layers of fine-grained quartzite. The siltite consists principally of subangular to subrounded grains of quartz. In addition it contains small amounts of biotite, sericite, and feldspar.

GUNSIGHT FORMATION

The Gunsight Formation makes up most of the Ramsey Mountain front along the west margin of the Lemhi Pass thorium district (pl. 1). It is also found in an area between the Peterson Creek thrust fault on the north and a normal fault along the Continental Divide on the south in the southeast part of the district. The Gunsight makes up the greater part

[2]When the Goat Mountain quadrangle report was completed, names had not been given to the various formations in the Lemhi Group, and the upper three formations in the Lemhi Group are identified on this map as units B, C, and D.

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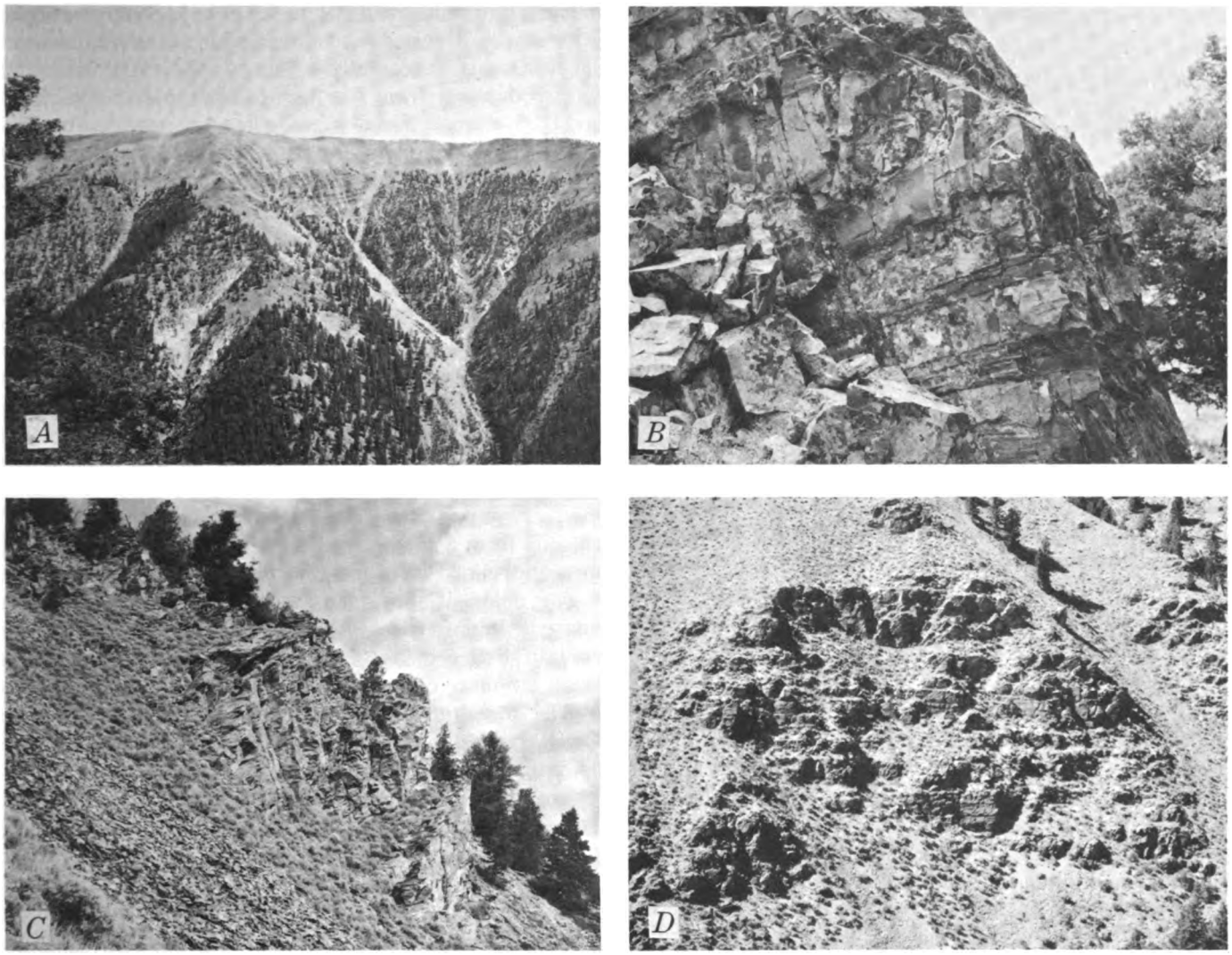


FIGURE 3.—Precambrian Y rocks. *A*, View of Goat Mountain looking southeast across the Right Fork of Peterson Creek. Cliffs of quartzite of the Big Creek Formation. *B*, Big Creek Formation on the southeast side of Little Eightmile Creek showing light-gray quartzite with thin dark-gray siltite interbeds. *C*, Ledges of Swauger Formation along the steep north face of Mollie Gulch about 2 miles south of the Lemhi Pass district. *D*, Siltite exposed along the steep northwest side of the left fork of Peterson Creek.

of the Ramsey Mountain block. The lower part of the Gunsight is separated from the underlying Apple Creek Formation by a small fault, as indicated by divergent strikes and dips in several places. The amount of movement on this fault is small. Ruppel (1975, p. 11) notes that the lower Gunsight contact is gradational through 200-300 feet of interbedded quartzite and siltite beds. Similar interbedding of quartzite and siltite beds is well exposed just above the fault on the ridge north of Little Dry Gulch. The upper part of the Gunsight is cut out by faulting. The greater part of the Gunsight Formation is quartzite, although widely scattered greenish gray siltite beds crop out in a few places, mainly in the lower 1,000 feet of this formation. The quartzite is a gray to light-gray fine- to medium-grained rock, whose individual grains are subangular to subrounded in shape. The quartzite is generally feldspathic, containing as much as 25 percent feldspar. In some beds in the Ramsey Mountain block and along the Continental Divide, the quartzite lacks feldspar; these beds are generally quite resistant and have a greasy luster. The quartzite commonly has sericite. This mineral is most common in those beds having little feldspar. Accessory minerals include tourmaline, zircon, biotite, magnetite, limonite, and hematite. Magnetite is more abundant in the area south of the Peterson Creek thrust. In the Ramsey Mountain area it is commonly scarce, although minute specks of hematite and limonite in some beds may have formerly been magnetite. The Gunsight Formation south of the Peterson Creek thrust is commonly somewhat darker and more commonly banded than is the quartzite in the Ramsey Mountain block.

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SWAUGER FORMATION

The Swauger Formation is found only at the southern boundary of the area adjacent to the east side of the Peterson Creek thrust fault. Not only is this formation on the upper plate of the Peterson thrust, but it is separated from the other rocks in the upper plate by another thrust. Exposures here are generally poor, but this formation is much more extensive and better exposed a few miles to the southeast (Staatz, 1973) (fig. 3C). The part of the Swauger exposed here, whose total thickness is more than 10,000 feet (Ruppel, 1975, p. 12), is not known. The Swauger in this area is generally medium grained, although in places it is fine grained. The individual grains are generally well rounded and the rock commonly has a glassy appearance. This unit is generally white to light gray, although some sericitic quartzite layers are pale green. The quartzite consists mainly of quartz; a few layers may contain a little feldspar. Crossbedding was noted in several places. In comparison to the two quartzites in the Lemhi Group, the Swauger is cleaner, lighter colored, and the grains are somewhat coarser and better rounded.

ROCKS BELOW THE PETERSON CREEK THRUST FAULT AND EAST OF RAMSEY MOUNTAIN

The Precambrian Y rocks below the thrust consist predominantly of fine-grained quartzite. Siltite occurs both as thin beds within the main quartzite sequence and as moderately thick units. Thin siltite layers, which for the most part range from half an inch to 1 foot thick, are found in only certain parts of the quartzite sequences. In many areas siltites are not found. Thick units of siltite (fig. 3*D*) are found widely scattered in this area (pl. 1). They are commonly more than 1,000 feet thick, and may have a few thin quartzite layers but for the most part are of siltite. These thick siltite units are of great aid in determining the position of many faults and are mapped separately (pl. 1).

QUARTZITE

Quartzite in the Lemhi Pass district has a general sameness of appearance, yet there are differences in color, grain size, and mineral content from place to place. Some of these differences occur from layer to layer, but others are found from place to place. The greater part of the rocks north of Agency Creek and in the northeastern part of the district are either light or medium gray; a few are greenish gray or white. In the southeast part of the district north of the Peterson Creek thrust, greenish-gray, green, or olive-green beds are common. These greenish beds generally are interbedded with those of gray or light-gray, although in some places they change color along the same layer. In some areas, such as between Yearian and Peterson Creeks, the green quartzite beds commonly are interbedded with thin greenish-gray siltite units. The quartizite is generally fine grained, although a few layers may be either medium grained or very fine grained (0.001 to 0.020 in.). Sand grains are generally well sorted and subangular to subrounded in shape. Quartzite generally is thin to medium bedded, and most beds range from 3 inches to 2 feet in thickness. Here and there are found a few massive layers as much as about 10 feet thick. Crossbedding occurs in a few places but is most common in the Agency Creek basin between Flume Creek and the Continental Divide.

In much of the northeastern part of the area, the gray quartzite is micaceous rock that contains but little feldspar. For the most part these rocks consist of 60-80 percent quartz, 5-30 percent sericite, 1-10 percent biotite, and less than 1-8 percent plagioclase. In addition some contain as much as 5 percent, but generally about 1 percent, chlorite. Small round grains of hematite or magnetite occur in some specimens. A grain or two of tourmaline was found in almost every thin section, and trace amounts of zircon and apatite are common. The micas, which generally are aligned parallel to their clevage, give the rock its foliation. Sericite, biotite, and chlorite form a mesh around the quartz grains. The three micas appear to be of metamorphic origin.

The color of the green, greenish-gray, or olive-green quartzite in most places is due to chlorite. These rocks may contain 10-25 percent chlorite. They also commonly contain small amounts of biotite. The green of the quartzite that overlies the siltite north of the Lemhi Pass fault in the Flume Creek area is due to epidote. These rocks have 10-20 percent epidote, less than 1-2 percent chlorite, but no biotite or plagioclase. The gray quartzite in this area has about 10 percent plagioclase, and the epidote is probably derived from metamorphism of the original plagioclase in the rock, possibly during movement of the Lemhi Pass fault. This is one of the few areas in which epidote was noted in the quartzite.

Feldspathic quartzite occurs in the Black Canyon and Continental Divide areas in the southeastern part of the district (pl. 1), in the area north of Agency Creek in the northwestern part of the district, and in some other smaller scattered areas. The feldspathic rocks may have 8-35 percent combined plagioclase and orthoclase. The sericite content is commonly low and may drop from the average elsewhere of 15 percent to 5 percent. A few rocks adjacent to the Continental Divide in the headwaters of Black Canyon and Bear Creeks have both a high feldspar and a high sericite content--about 20 percent of each. Much of the sericite in feldspathic rocks occurs as tiny laths on the feldspar, which it partially replaces. Thus, the sericitic quartzite was probably feldspathic when originally deposited, and the potassium feldspar has been converted to sericite during later metamorphism.

SILTITE

Most of the siltite in the Lemhi Pass district is a shade of green--pale green, olive green, or greenish gray. Some, however, is gray or black. Siltite that is interbedded with

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gray to light-gray quartzite is generally gray to light gray, that with greenish-gray quartzite is generally greenish gray or green. The siltite, where it occurs in thick units, is commonly better exposed than the quartzite (fig. 3*D*). In some areas such as along the lower part of Peterson Creek, it forms small cliffs (fig. 3*D*). Siltite generally occurs in thin beds, which, in addition, may be finely laminated. Laminations chiefly vary in being different shades of gray or green, but may also consist of slightly different grain sizes.

The siltite is a dense rock composed of tiny subangular to subrounded grains that are fairly well sorted. Average grain size varies between beds and is from 0.0004 to 0.002 in., the overall average being about 0.0006 in. The siltite beds may include scattered grains as much as 0.008 in. across (very fine sand).

The composition of the siltite is similar to that of the quartzite, although because of the finer grain size, the feldspar grains are generally difficult to distinguish from the quartz grains. The siltites generally contain 50-80 percent quartz, less than 1-2 percent plagioclase, 7-35 percent sericite, 1-3 percent biotite, 1-15 percent chlorite, and a trace to 2 percent magnetite. Trace amounts of tourmaline, zircon, and apatite are present in some specimens. Tourmaline is especially notable, as small amounts are found in almost every sample. Chlorite is responsible for the green color found in some siltites. Gray siltites generally have less than 1-2 percent chlorite, but greenish-gray to green siltites have 7-17 percent chlorite. A dark-gray to black phyllite is found at the Lucky Horseshoe property (loc. 1) just north of the Lemhi Pass fault. The phyllitic character of this rock is apparently due to dynamic metamorphism of siltite during faulting. Away from the fault the beds become lighter gray and finally greenish gray and the character of the rock changes from that of a phyllite to a siltite. Another outcrop of phyllite was noted interbedded with quartzite on a small tributary of Reese Creek adjacent to a fault. A similar change takes place on Apple Creek in the southwest part of the Lemhi quadrangle, the type area of Anderson's Apple creek Phyllite (1961b, p. 19-21). Here Ruppel (1975, p. 10) notes that the phyllitic character of the Apple Creek is due to shearing beneath a thrust fault and in other areas this rock is a siltite.

MISSISSIPPIAN MADISON LIMESTONE

The Madison Limestone occurs only south of the Peterson Creek thrust in the southeast corner of the area (pl. 1). Rocks in the upper plate of this thrust are faulted over each other in a series of lesser thrusts (fig. 12*B*) (Staatz, 1973), and the Madison is thrust over the Big Creek Formation of the Lemhi Group. The Madison Limestone occurs in many places in the Beaverhead Mountains southeast of the Lemhi Pass district (Ruppel, 1968) but is not found to the northwest. Thus, the Madison outcrops, as shown on plate 1, are the northernmost exposures of the formation in this range.

Only part of the Madison Limestone is exposed in the Lemhi Pass thorium district and perhaps 1,000 feet of it are shown on plate 1. In the Leadore quadrangle to the south it is also found in small fault blocks and slices. There Ruppel (1968, p. 3) estimated that its original thickness may have been 2,500 feet. In the Leadore quadrangle and in the southern part of the Goat Mountain quadrangle (Staatz, 1973), it is overlain by the Big Snowy Formation of Late Mississippian age and underlain by the Milligen(?) Formation. Since 1975 the name Milligen has been restricted to the Wood River area of Idaho (Sandberg and others, 1975), and the strata previously called Milligen(?) have been renamed the McGowan Creek Formation of Mississippian age (Sandberg, 1975).

The upper part of the Madison Limestone consists chiefly of thick-bedded to massive light- to medium-gray limestone. This rock is commonly coarse grained, although it may be medium grained. In part it is bioclastic and contains a few horn corals. Some beds contain a little gray or black chert and have a fetid odor. Lithologically this limestone resembles the Mission Canyon Limestone of southeastern Idaho. The lower part of the Madison is made up chiefly of a thin-bedded medium- to dark-gray limestone. It may also be bluish gray and generally weathers to light gray. This limestone is fine grained and commonly contains lenses or nodules of grayish-black or brown chert. The chert lenses are flat and range in thickness from 0.5 to 1.5 inches. In places the limestone contains sparse brown-weathering silt grains. The lower part of the Madison is similar to some of the rocks in the Lodgepole Limestone in southeastern Idaho and southwestern Montana.

Although the massive light-gray limestone is found principally in the upper part and thin-bedded darker gray limestone in the lower part, some thin-bedded limestone occurs in the upper part and some massive limestone in the lower part.

In one small area north of the mouth of Reese Creek in the south-central part of plate 1 the Madison Limestone has been almost entirely silicified. Here the rock consists of black to dark-gray chert breccia made up of angular pieces of chert set in a chert matrix. In one small gully remnants of the original limestone were found. Similar silicified limestone occurs in the southern part of the Goat Mountain quadrangle (Staatz, 1973) and in the adjoining Leadore quadrangle (Ruppel, 1968). In these areas the chert breccia directly overlies thrust faults. The chert breccia is believed to have formed by brecciation of the limestone along the thrust, followed by introduction of silica. The area of silicified Madison Limestone on plate 1 is on strike and a little more than 2 miles northwest of a large thrust fault mapped in the Goat Mountain quadrangle. The thrust, which is not exposed in the intervening covered area, is the probable cause of brecciation of this small area of Madison Limestone.

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TERTIARY CHALLIS VOLCANICS

The Challis Volcanics were first described by Ross in 1927 (p. 7-9) in the Salmon River Mountains, but the name was first used in 1930 in a paper on four small mining districts in Custer and Camas Counties, Idaho (Ross, 1930, p. 1, 10, 23). This formation, which was named after the town of Challis, originally included all of the Tertiary volcanic rocks of central Idaho. Ross (1961) later restricted the Challis to dominantly volcanic strata of early Tertiary age within the part of central Idaho north of the Snake River Plain and south of the westward-flowing segment of the Salmon River. Volcanic rocks are found along the Salmon River northward from the town of Challis past the town of Salmon; they are also found from Salmon to the southeast along the Lemhi River, which joins the Salmon River at Salmon, at least as far as Leadore (Anderson, 1956, pl. 1; Anderson, 1957, pl. 1; Anderson, 1961b, pl. 1; Staatz, 1974; Ruppel, 1968). Thus the Challis Volcanics can be traced fairly continuously from the type locality to the Lemhi Pass area. Although volcanic rocks are found along the valleys of the two rivers just mentioned, the outcrops are not continuous, commonly being in isolated fault blocks. Furthermore, the lithology of the units is somewhat different in the several areas. Ross (1962, p. 75) divided the Challis into a latite-andesite member, basalt and related flows, the Germer Tuffaceous Member, and the Yankee Fork Rhyolite Member near the town of Challis. He noted that Yankee Fork was not strictly uniform either in character or in stratigraphic position. Anderson (1956, p. 18-28), mapping in the Salmon quadrangle, found a lower latite-andesite unit and an upper tuffaceous unit with intercalated latite, rhyolite, and basalt flows. This upper unit he correlated roughly with the Germer Tuffaceous Member. The units are not equally distributed, the latite-andesite unit being present only in the southern part of the Salmon River drainage and the upper tuffaceous unit only in the northern part and in all of the Lemhi River drainage. East of the Salmon quadrangle, in the Baker (Goldstone Mountain) quadrangle, Anderson (1957, p. 16) gives only the briefest description of the Challis Volcanics, but south of this area in the Lemhi quadrangle he (1961b, p. 43-53) divided the Challis Volcanics into a lower unit of latite and andesite, an intermediate unit of pyroclastics, basalt, and basic andesite, and an upper unit of basalt. Farther south in the Lemhi Range, south-southwest of Leadore, Ruppel (1968) divided the Challis into lower basaltic rocks and upper latitic and andesitic rocks. Both units contain interbedded tuffs. Thus the volcanic rocks, preserved in many places along the principal drainages in much of the area from the town of Challis to the Lemhi Pass district are seen to vary in detail from place to place. In other words, although volcanism was common over a wide area in east-central Idaho during early Tertiary time, flows and ash falls commonly were local in extent.

In the Lemhi quadrangle, Anderson (1961b, p. 43-53) proposed that the Challis be raised in rank to the Challis Volcanic Group and that his lower unit be named the Cheney Volcanics, his intermediate unit the Yearian Volcanics, and his upper unit the Kadletz Volcanics.

As has been noted, the lithologic units of the Challis Volcanics are commonly of local extent. For example, the many tuffaceous units that occur with dark-colored flow rock in the northern part of the Lemhi Pass district (pl. 1) pinch out and are not found in the southern part of the district. Thus, volcanic units of considerable importance as marker beds at a particular locality may have little regional significance. I do not feel that the Challis Volcanics should be upgraded to group status because it can be subdivided in a particular place into several divisions of one or more local units. The name Challis Volcanics has, therefore, been retained in this report as a formational name. Furthermore, the descriptions of the new formations—Cheney Volcanics, Yearian Volcanics, and Kadletz Volcanics—given by Anderson (1961b, p. 41-53, pl. 1) do not agree in many places with data I obtained during the present study. As approximately the western half of the Lemhi Pass thorium district lies in the eastern part of the Lemhi quadrangle, which was mapped by Anderson (1961b, pl. 1), direct comparison can be made of these units. Anderson (1961b, p. 44) describes the Cheney Volcanics as an easily recognized unit of relatively light-colored latite and andesite possessing a sparkly appearance on fresh surfaces. The formation contains some andesitic and rhyolitic tuff, rhyolite, and rhyolitic ignimbrite (welded tuff). Most of this formation lies in the western half of the Lemhi quadrangle and was not examined, but several square miles of this formation were mapped in the northeast corner of the Lemhi quadrangle. Here, approximately the eastern half of this formation consists of a thick conglomerate, the western part a white quartzite-bearing rhyolite tuff, and the northern part a drab dark-brown flow rock overlaid in places by a white welded tuff. The dark-colored flow rock is similar to that mapped farther south as Yearian Volcanics, and the white welded tuff is separated by an angular unconformity from the other rocks. Anderson (1961b, p. 48-49) noted that the Yearian Volcanics are "characterized by a general preponderance of pyroclastic materials and, in most places, by only minor intercalations of andesitic and basaltic flows." This is the principal volcanic unit mapped by Anderson in the Lemhi quadrangle and is well represented in the eastern part of the quadrangle. Detailed mapping of these volcanics, however, indicates that more than three-quarters of them are represented by dark flow rocks. Furthermore, one of the larger pyroclastic units in the Yearian Volcanics in this area is a quartzite-bearing rhyolite tuff mapped north of Pattee Creek. This distinctive unit is identical to one mapped between Poison Creek and Agency Creek as part of the Cheney Volcanics. The third formation—the Kadletz Volcanics—occurs only in a small area in the western part of the Lemhi quadrangle, and thus does not occur in the Lemhi Pass thorium area (pl. 1). The

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formations used by Anderson are not used in the present study owing to the lack of correlation between his descriptions and those of the volcanics in the area under study. Instead, the Challis Volcanics are divided informally on the basis of their local lithology.

DISTRIBUTION

The Challis Volcanics are scattered widely over the Lemhi Pass thorium district (pl. 1). The greater part of them, however, are found in two areas: (1) A north-south strip from the Lemhi Pass fault in the north along part of Agency Creek and the Cow Creek and Yearian Creek valleys, and (2) south of the Lemhi Pass fault in Montana in the northeast part of the district. At one time the Challis Volcanics probably covered most of the district. Much of it has since been eroded away, and that part preserved is generally in down-dropped fault blocks (fig. 2). A series of north-, northwest-, and northeast-trending faults bound the Challis Volcanics in the north-south strip south of the Lemhi Pass fault (fig. 13*B*). The volcanics to the south along Yearian Creek lie in a faulted graben (fig. 13*C*). Some of the volcanic rocks in the northeastern part of the district are bounded on the northeast by the large Lemhi Pass fault and on the southwest by the Bull Moose fault. Two other areas of northeast-dipping volcanics a mile south of these outcrops are bounded on the northeast by the Dan Patch fault. Volcanics in the northwest corner of the district are bounded to the east by the Pattee Creek fault.

In a few small areas the Challis Volcanics are preserved in low spots in the prevolcanic topography. One of the largest such areas is in a hollow formed over a pre-Tertiary fault that lies along the Continental Divide near the southeast corner of the Lemhi Pass district. Several volcanic remnants also occur along a main ridgetop at the head of the North Fork of Everson Creek. In a few areas the relation between the Challis Volcanics and the underlying bedrock is not known. One of these areas is in the northeast corner of the district where several units of Challis Volcanics are exposed along the sides of steep draws in an area otherwise blanketed by older glacial deposits. A somewhat similar occurrence is found on the north side of Peterson Creek where exposures of dark flow rock protrude through fan deposits.

ROCK TYPES

The Challis Volcanics can be divided into rocks of two, and possibly three, divisions on the basis of their relative ages. The oldest rocks are in the first division and consist of a thick basalt-rhyodacite sequence and associated tuff and conglomerate. These rocks make up more than 90 percent of the Challis Volcanics and are further subdivided into seven units. A second division contains light-purple, pink, and brown quartz latite flows or intrusive bodies. These rocks substantially differ in appearance from other volcanic rocks in the district. They occur as scattered outcrops in the northeast, extending from near the mouth of Flume Creek to the east edge of the district (pl. 1). Most outcrops are surrounded by glacial deposits, although the contact of the quartz latite body just west of Lemhi Pass with other volcanics is poorly exposed. Distribution of the outcrops of this rock relative to those of the adjacent tuff indicate that the quartz latite most likely intruded the tuff. That these rocks were deposited prior to mid-Tertiary tectonism is indicated by steep dips of some of the quartz latite flows. These rocks may either be a part of the preceding division or they may be part of a distinct division as here discussed. The third division contains younger basalt and a sandine-quartz welded tuff. Both were emplaced after much of the mid-Tertiary tectonism, and overlie rocks of the first division with angular unconformity (fig. 4). Both rock types, in their respective areas, have been cut by the Dan Patch fault, but the welded tuff must also, in part, overlie the fault, as the offset of this rock type is not as great as the older units of the Challis Volcanics. Thus, the welded tuff was laid down after much but not all of the movement occurred along this fault.

The rocks of the oldest division were divided on the basis of their lithology into the following seven units: (1) Basal conglomerate, (2) quartzite-bearing rhyolite tuff, (3) conglomerate of Flume Creek, (4) vitric tuff of Lemhi Pass, (5) basalt-rhyodacite sequence (including rhyolitic tuff beds), (6) tuff of Curtis Ranch, and (7) a flow-breccia unit (fig. 4). Unit 5, the basalt-rhyodacite sequence, is the most common and most widespread unit, and in the southern part of the district it is the only unit exposed. The other units pinch out to the south. The only possible exception is unit 7, the flow-breccia unit, which is similar in places to unit 5. These two units are distinguished by their position below and above unit 6, the tuff of Curtis Ranch. If the tuff is missing, the two units could not be distinguished and whether both units occur in the southern part of the map area, where the tuff is missing, is not known. The rocks of this oldest division apparently correspond to the basaltic rocks mapped by Ruppel (1968) in the lower part of the Challis Volcanics.

Many of the units in the volcanic rocks vary considerably in thickness (fig. 4). The conglomerate of Flume Creek thins from more than 1,000 feet near the mouth of Flume Creek to about 20 feet on Lemhi Pass, 2.8 miles east. The quartzite-bearing rhyolite tuff is at least 1,700 feet thick along the Continental Divide south of Lemhi Pass, but pinches out to the south. The basalt-rhyodacite sequence overlies the first four units in the vicinity of Lemhi Pass but to the south along Trapper Creek, on the Continental Divide north of Goat Mountain, and to the west along Cow Creek, the basalt-rhyodacite sequence directly overlies the Precambrian Y rocks. Thus, some of the rock units here used, although of great aid in unraveling the local structure, are of little significance in regional correlations.

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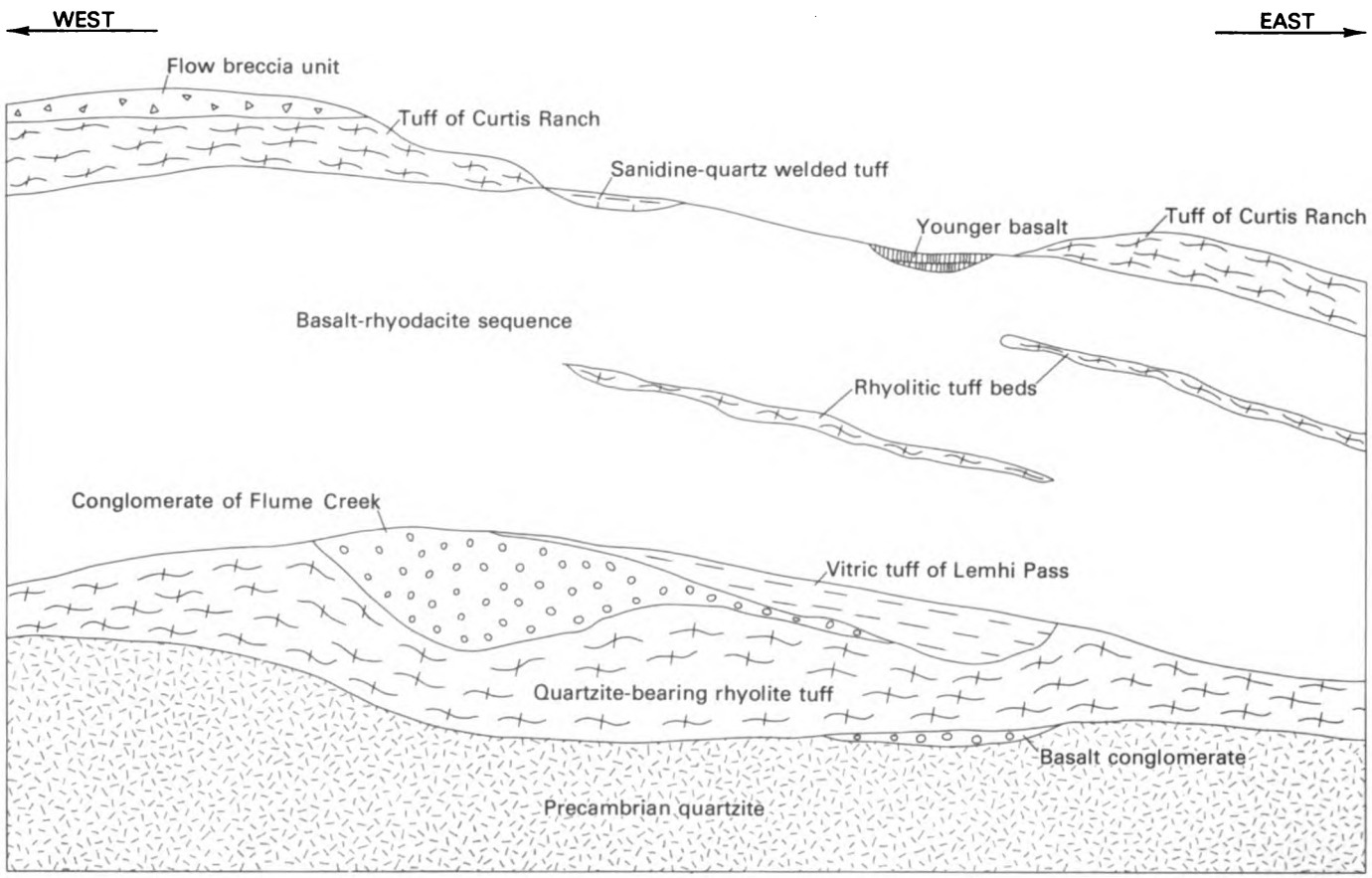


FIGURE 4. - Diagrammatic cross section of the Challis Volcanics across the northern part of the Lemhi Pass thorium district. No scale is implied; directions are general.

BASAL CONGLOMERATE

The basal conglomerate is the oldest unit of the Challis Volcanics and grades upward into the quartzite-bearing rhyolite tuff. This unit is exposed only in one small area, 0.5 mile west to 1 mile southwest of Lemhi Pass, where it lies along the west edge of the Challis outcrop in this area. Here the basal conglomerate is thin and intermittent, never more than 15 feet thick. A conglomerate at or close to the base of the Challis Volcanics is reported by Ross (1962, p. 74) in mappable amounts in many localities. Anderson (1959, p. 21-22) noted a thick conglomerate at the base of the volcanics along the Salmon River south of North Fork, which he called the Kriley Formation.

The basal conglomerate in the Lemhi Pass area is made up of well-rounded pebbles and cobbles set in a white tuffaceous matrix. This matrix may make up less than 5 percent of the rock in the lower part of the unit, but increases in abundance toward the top where it may make up as much as 80 percent of the rock. Micaceous Precambriam Y quartzite makes up most of the pebbles and cobbles. White tuff makes up some of the smaller pebbles, and a gray glassy quartzite, probably from the Ordovician Kinnikinic Quartzite, is the rock type of a few pebbles. Matrix is commonly of ash, although siliceous cement is present in a few places.

QUARTZITE-BEARING RHYOLITE TUFF

The quartzite-bearing rhyolite tuff overlies the basal conglomerate southwest of Lemhi Pass, but in other areas it directly overlies the Precambrian Y rocks. This tuff is overlain by the conglomerate of Flume Creek at Lemhi Pass and about 1 mile east-southeast of the mouth of Flume Creek. South and west both the conglomerate of Flume Creek and the tuff of Lemhi Pass are not present, and in these areas the quartzite-bearing rhyolite tuff is directly overlain by the basalt-rhyodacite sequence (pl. 1; fig. 4). The rhyolite tuff is found across the northern part of the Lemhi Pass thorium district in scattered fault blocks from northwest of Pattee Creek to northeast of Sheser Creek (fig. 5*A*). This unit pinches out southward and is not found in the southern half of the area. The thickness of the quartzite-bearing tuff is variable, and in many places its total thickness is difficult to determine owing to either glacial cover or faults that cut out part of the unit. It is more than 1,000 feet thick northwest of Pattee Creek in sec. 11, T. 19 N.,

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R. 24 E., where its base is removed by a fault; at least 900 feet thick between two faults on the north side of Agency Creek, north of the mouth of White Creek; and at least 1,700 feet thick about 0.5 mile south of Lemhi Pass.

The quartzite-bearing tuff varies in color and may be pinkish brown, pinkish gray, light gray, or white. This tuff has lithic, vitric, and crystal clasts. Generally the latter two are most abundant and the rock may be either a vitric-crystal tuff or a crystal-vitric tuff. Lithic fragments consist mainly of dark-gray quartzite and in places a few siltite clasts. These dark fragments stand out against the light color of the rest of the rock and are its most conspicuous feature (fig. 5*B*). The quartzite fragments are generally subangular to subrounded and from 0.06 to 0.5 inch across, although clasts as large as 1.5 inches across have been noted. The amount of dark quartzite is extremely variable ranging from none to 25 percent of the rock. Vitric fragments are of tuff or glass. As they are commonly small and similar in color and texture to the matrix of tuff, they are rather inconspicuous. In size they are about half that of the quartzite fragments. Vitric clasts make up 2-50 percent of the rock, but generally about 8-25 percent. Crystal fragments are small and angular, either quartz or plagioclase being the most common mineral. Quartz is generally more common in the outcrops in the eastern part of the area and plagioclase in the western part. Quartz crystals make up 7-30 percent of the rock and plagioclase 2-50 percent. Sanidine was not noted in most specimens, but where found, make up 2-15 percent of the tuff. Biotite is common in this rock in many places, but generally is less than 2 percent. It is more abundant in the western than in the eastern part of the district.

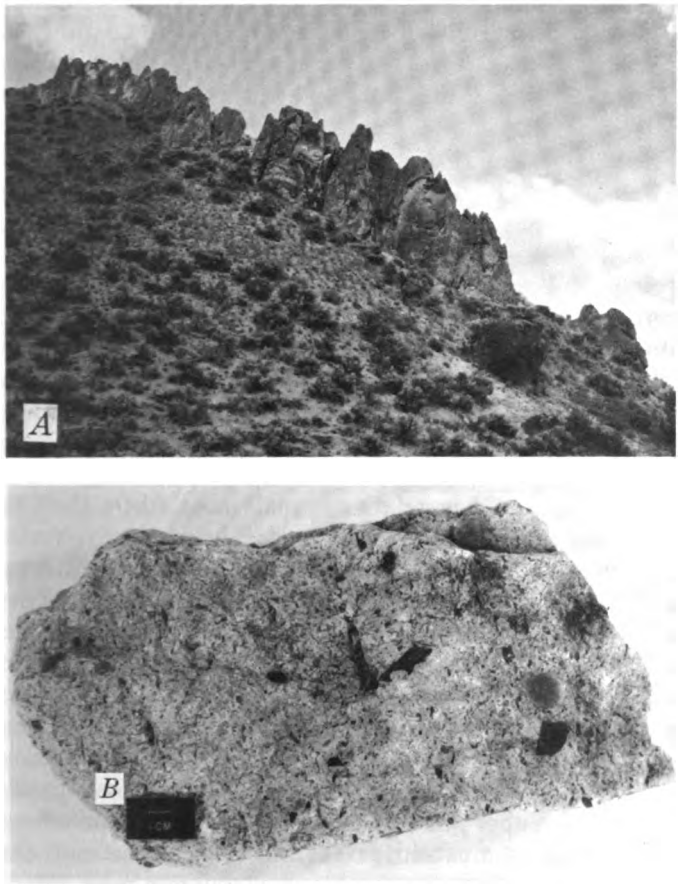


FIGURE 5.—Quartzite-bearing rhyolite tuff. *A*, Prominent outcrop along the north side of Agency Creek opposite the mouth of White Creek. *B*, Dark-gray angular pieces of Precambrian quartzite stand out against the light-gray groundmass consisting of numerous crystal pieces and bleached fragments of volcanic rock in an ash matrix. Photograph by L. S. Hendricks.

The quartzite-bearing rhyolite tuff ranges from a soft rather porous rock to a hard well-compacted rock. Generally it is not welded, but some welded tuff was noted in a few places. One place is near the switchback on the road 1,000 feet southwest of the shaft on the Copper Queen property. Here a purplish-brown tuff consists of vitric fragments firmly cemented by glass. As this rock is surrounded by nonwelded quartzite-bearing rhyolite tuff, it is included in this unit.

Two chemical analyses were made on samples of rhyolite tuff collected 2.3 miles apart. One is from the Continental Divide and the other from along Agency Creek (table 1). These analyses are remarkably similar. The normative composition of both is high in quartz. Part of this is due to presence of quartz fragments, part to quartzite fragments, and part to high silica content of the volcanic ash. The high normative orthoclase composition would not be expected from examining thin sections of these samples, as sanidine was not noted. The high potassium content of this tuff was verified by staining several samples with a sodium cobaltinitrite solution. The potassium content of these samples is mainly within the ash. The rock type of both samples, classified on the basis of their chemical compositions (table 1) according to the nomenclature of Rittmann (1952), is rhyolite.

CONGLOMERATE OF FLUME CREEK

The conglomerate of Flume Creek overlies the quartzite-bearing rhyolite tuff and is overlain by the tuff of Lemhi Pass (fig. 4). This unit is best exposed along the steep sides of Flume Creek near its mouth. This rock type is a local unit and is found only in an area some 3.5 miles long by 1.25 miles wide between Flume Creek and Lemhi Pass. Here it forms a wedge-shaped body that thins to the east. In the vicinity of Flume Creek this conglomerate is bounded by faults, but here it is at least 2,500 feet thick. On Lemhi Pass the total thickness of this unit is only about 20 feet.

The conglomerate of Flume Creek consists of well-rounded pebbles, cobbles, or boulders set in a matrix of ash (fig. 6). The size of the rounded clasts varies from place to place, pebbles being most common in one part of a layer and boulders in another. On the road up Flume Creek boulders as large as 3 feet in diameter are present. Along and west of Flume Creek the conglomerate contains some thin sandstone layers and lenses. The pebbles, cobbles, and boulders of the conglomerate are generally of micaceous

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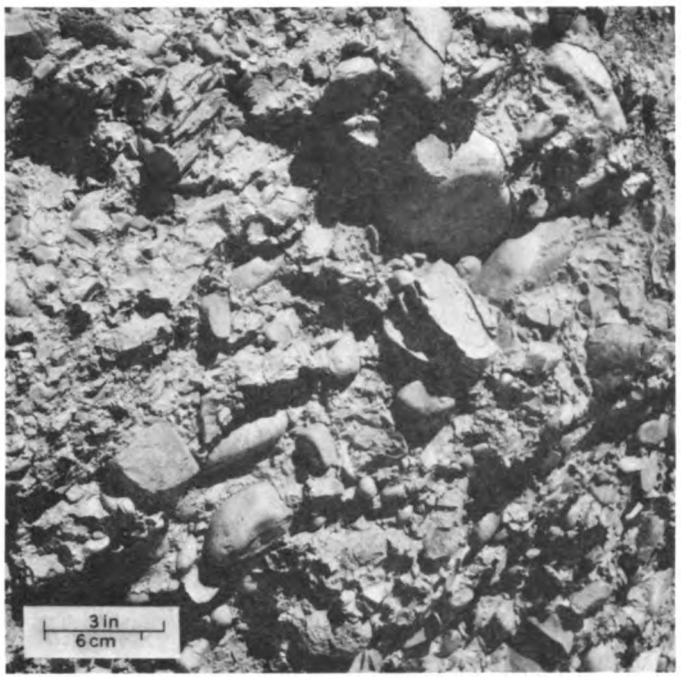


FIGURE 6. Conglomerate of Flume Creek along the north side of Agency Creek west of the mouth of Flume Creek. Well-rounded pebbles and cobbles are mainly of brown volcanic rock.

quartzite, although in some areas purplish-gray and brown plagioclase porphyries are more abundant. A few pebbles are of siltite, white vein quartz, and red quartzite. The matrix is a mixture of white ash and a few sparse crystal fragments. Quartz is the most abundant of these, but they also include biotite, sanidine, and plagioclase. In places the ash matrix is altered to a greenish-white clay.

The sandstone layers within the conglomerate are generally medium grained. The principal clasts are quartz and red or brown aphanitic volcanic rock, but some are of plagioclase, sanidine, siltite, biotite, and augite. The matrix may be of ash or of chalcedonic cement.

The conglomerate of Flume Creek is similar in appearance to the basal conglomerate and to conglomerates found in the younger tuffaceous sedimentary rocks.

VITRIC TUFF OF LEMHI PASS

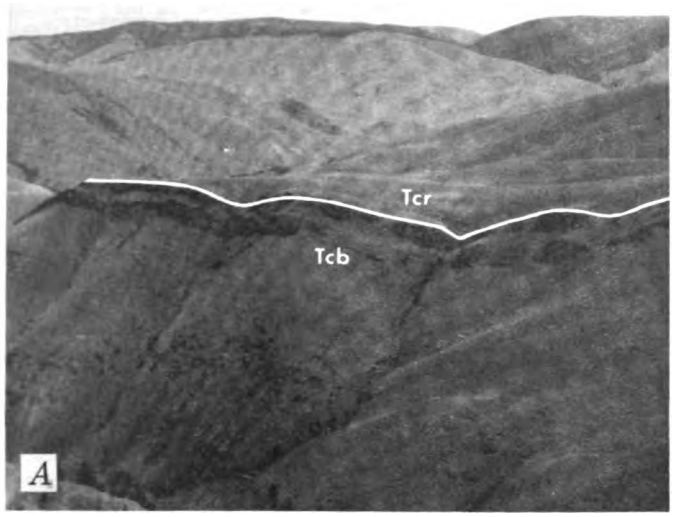
The vitric tuff of Lemhi Pass is rather local in extent and where present lies intercalated with the underlying conglomerate of Flume Creek and the basalt-rhyodacite sequence (fig. 4). It occurs only in the northern part of the Lemhi Pass thorium district from the south side of Lemhi Pass to the northwest for 3.8 miles to a point 0.9 mile northwest of the mouth of Flume Creek, where it is cut off by the Dan Patch fault. This unit thickens along its outcrop trend to the southeast. In the vicinity of Flume Creek it is approximately 380 feet thick but on the east side of Lemhi Pass it has a minimum thickness of 720 feet. The tuff of Lemhi Pass, as well as the underlying conglomerate of Flume Creek, pinches out abruptly to the south, and 1 mile southeast of Lemhi Pass the basalt-rhyodacite sequence lies directly on the quartzite-bearing rhyolite tuff (pl. 1).

The vitric tuff of Lemhi Pass is a white to greenish-white dense rock made up principally of ash and a few rock and crystal fragments. Rock fragments are generally rounded and are 0.06-0.5 inch across. Because they are mainly tuff fragments of the same material as the matrix, they are inconspicuous. A few percent of the rock fragments on the east side of Lemhi Pass consists of granule-size pieces of gray micaceous quartzite. Small sand-size crystal fragments make up a minor part of this rock. They are principally quartz and plagioclase, but biotite is moderately common in the westernmost exposures. The ash consists of numerous glass shards set in a similar appearing clear glass. The vitric tuff contains at least a moderate amount of potassium, which is indicated by the bright yellow color obtained when this rock is stained by sodium cobaltinitrite.

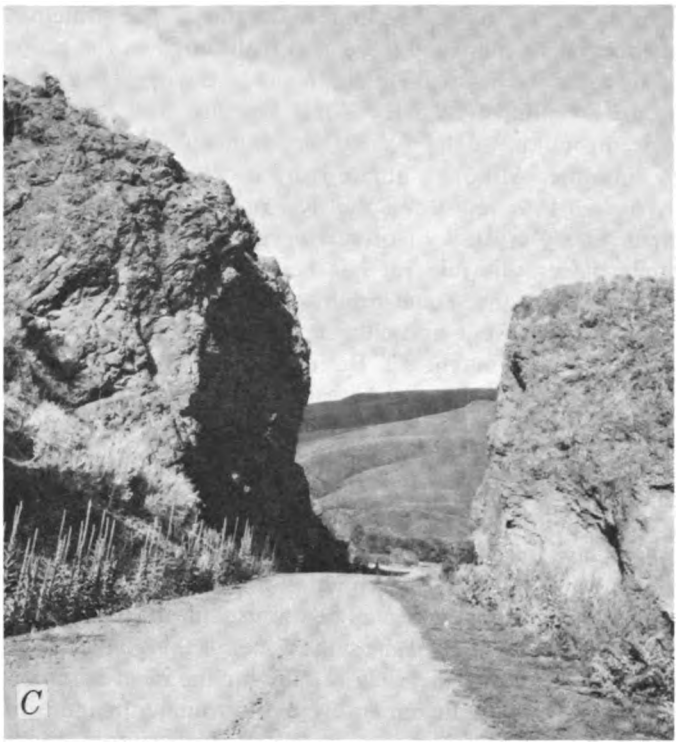
BASALT-RHYODACITE SEQUENCE

The basalt-rhyodacite sequence is the thickest and most widespread unit of the Challis Volcanics in the Lemhi Pass thorium district (pl. 1). This unit near Lemhi Pass is separated from the Precambrian Y sedimentary rocks by the tuff of Lemhi Pass, the conglomerate of Flume Creek, the quartzite-bearing rhyolite tuff, and the basal conglomerate. To the west along Agency and Pattee Creeks these two conglomerates and the tuff of Lemhi Pass have pinched out, and the rhyodacite-basalt sequence overlies the quartzite-bearing rhyolite tuff (fig. 4). To the south the rhyolite tuff also pinches out, and the basalt-rhyodacite sequence directly overlies the Precambrian rocks. The basalt-rhyodacite sequence is overlain by the tuff of Curtis Ranch (fig. 7*A*), and is one of three units in the three divisions of the Challis containing dark-colored volcanic rocks. The other two, the flow-breccia unit and the younger basalt, are found in relatively small areas where they lie above the basalt-rhyodacite sequence. The basalt-rhyodacite sequence makes up more than half of the area underlain by the Challis Volcanics and in most of the southern part of the area it is the only part of the Challis present. Although the basalt-rhyodacite unit is found scattered in many parts of the district (pl. 1), it is most common in three areas: (1) In the eastern part of the district near the junction of Trail, Frying Pan, Trapper, and Bear Creeks; (2) a 4-mile-long northern-trending band from Ghoul Basin across Agency Creek to upper Cow Creek; and (3) a 2.5-mile-long north-trending area astride Yearian Creek in the southern part of the district. The basalt-rhyodacite sequence is generally bounded on one or more side by faults and the entire sequence is only exposed along the southeast side of Trapper Creek. Here these rocks are approximately 3,300 feet thick.

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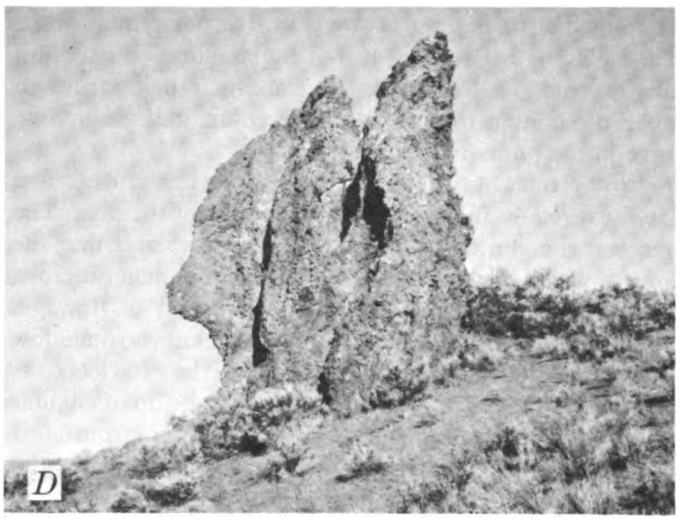


FIGURE 7.--Basalt-rhyodacite sequence. *A*, Dark flows form prominent ledges at top of basalt-rhyodacite sequence (Tcb), which is overlain by tuff of Curtis Ranch (Tcr). Picture taken looking northeastward across Cow Creek. *B*, Massive flow crops out on north side of Agency Creek. *C*, Road along Agency Creek follows stream cut through thick basalt flow. Picture looking northeastward near mouth of Sharkey Creek. *D*, Prominent outcrop of flow breccia on northwest side of Agency Creek 0.75 mile northeast of mouth of White Creek.

The basalt-rhyodacite sequence is made up principally of dark-colored aphanitic flows (fig. 7*B* and *C*) with flow breccias occurring intermittently near the base of individual flows, and thin light-colored rhyolitic tuff units scattered through the sequence. The flow rocks may be black, dark olive green, dark gray, gray, purplish gray, brown, or hematitic red. Many of them weather to a dark russet. The color of these rocks, which range in composition from basalt to rhyodacite, tends to be darker (black or dark olive green) in the more mafic rocks and lighter (gray to hematitic red) in the more silicic rocks. All the rocks are dark colored and fine grained and are not readily separable on the basis of their appearance in hand specimen. In general the most mafic rocks occur in the lower half of the sequence in the eastern part of the area; the flow rocks in the western part of the area are principally quartz latite. The tops of some of the more silicic flows, especially in the eastern part of the area, are oxidized to a hematitic red color. Tops of some flows are also marked by numerous vesicles which range in length from 0.006 to 0.47 in. Some of the vesicles are filled with calcite or chalcedony.

The texture of the flow rocks is highly variable. Some of them have phenocrysts set in a fine-grained matrix, some have phenocrysts set in a glass, a few are fine grained but holocrystalline, and a few consist chiefly of glass containing some microlites. Phenocrysts, where present, make up 1-50

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percent of the rock. Dark-green augite is the principal phenocryst in many of these rocks although in the more mafic rocks the principal mineral may be olivine. The augite occurs in subhedral to euhedral crystals, and in highly altered rock the augite may be pseudomorphically replaced by limonite. Although augite is by far the most common pyroxene, in a few flows the pyroxene is pigeonite. Pale green glassy crystals of olivine occur in many basalts. In other places this mineral has been partly or completely altered to serpentine and bright-orange iddingsite and to a lesser extent to talc and chlorite. Other mafic phenocrysts are biotite and magnetite. Biotite is fairly common in the more siliceous rocks in the western part of the area but is scarcer in the eastern part. Magnetite is common in all rocks but only rarely forms large phenocrysts. Plagioclase is only rarely found as phenocrysts, although the matrix commonly contains either abundant small plagioclase crystals or plagioclase microlites. Some of the plagioclase was determined to be andesine by extinction-angle measurements on albite twins. The matrix may contain small distinct crystals or microlites of many of the same minerals that make up the phenocrysts. Here plagioclase is by far the most common mineral and the mafic minerals are subordinate. In addition a little potassium feldspar in small anhedral crystals occurs in some of these rocks. A pale-brown glass makes up part or all of the matrix in some of the rocks. The potassium content of the glass is roughly measured by staining with sodium cobaltinitrite. The results of this staining, ranging from no apparent staining to a deep-orange color, indicate a wide range in the potassium content.

Flow breccias occur intermittently along the base of some flows, especially in the northeastern part of the area. The breccias are commonly more resistant to weathering than the flows of which they are a part and form prominent outcrops (fig. 7*D*) that locally delineate the direction of flowage. Individual flow-breccia units range in thickness from a few feet to about 50 feet and in length from less than 100 feet to as much as 0.5 mile. The flow breccias are made up of angular to subrounded lava fragments which range in size from 0.062 inch to 3 feet across. The matrix consists of flow material similar in composition to the individual clasts.

Thin tuff layers of various types occur widely scattered throughout this unit. Most of the tuff layers are less resistant than the flows, and in most places they are poorly exposed. They vary in appearance; in color they may be white, gray, tan, pink, or orange, and in type they may be a crystal, crystal-vitric, or vitric tuff. All the tuffs are more silicic than the adjoining flows and most appear to be rhyolitic in composition. A crystal tuff is exposed for about 1 mile in the E½ sec. 18, T. 19 N., R. 25 E., just north of Agency Creek in Idaho. Other good examples occur in the SW½ sec. 22 and along the border between secs. 15 and 16 in T. 10 S., R. 15 W., in Montana. These tuffs contain 35-70 percent crystal fragments in an ash matrix. The crystal clasts in these three tuffs are principally plagioclase, with minor amounts of quartz and biotite. Some tuffs contain about equal amounts of crystal and vitric fragments and some are mainly vitric fragments, although most contain a few percent of crystal clasts. An easily accessible vitric tuff is found just west of the road up Yearian Creek in the SE¼ sec. 25, T. 18 N., R. 24 E., in the southwest part of the area. This rock consists of more than 75 percent rock fragments and as much as 10 percent crystal fragments set in partly devitrified ash. Most of the rock fragments are of volcanic glass, although a few percent of Precambrian Y quartzite or siltite clasts are generally present. Staining with sodium cobaltinitrite indicates that these tuffs have a high potassium content.

Six chemical analyses were made on this widespread unit of the Challis Volcanics (table 1). Considerable variation is found in the amounts of some of the oxides in these rocks—for example, SiO_2, MgO, CaO, and K_2O. The normative compositions (table 1) show equally large variations. Two of the six rocks contain normative, as well as modal, olivine. The largest variation in chemical composition is found in the northeastern part of the area, where the three analyses (table 1, samples 3, 4, and 5) range in rock type from trachybasalt to rhyodacite. Most of the olivine-bearing rocks are found near the base of the flows in this area, and the upper part of the sequence generally contains the highest amount of SiO^2. The silica-rich sample, (table 1, no. 3) is a hematitic red rhyodacitic vesicular glass. As suggested by the color, most of the iron in this sample is in the ferric form. The rocks in the western part of the area are similar to each other in appearance and composition as is indicated by the analyses of three representative samples (table 1, nos. 6, 7, and 8). The anorthite content of the plagioclase, as calculated from normative albite and anorthite, ranges from 30 to 48 percent (andesine). In order to show better the relative abundance of some of the more important oxides in these rocks to one another, two diagrams were constructed. One (fig. 8) has CaO, Na_2O, and K_2O as end members, and the second (fig. 9) has MgO plotted against the total iron oxide content.[3] The plot of the rocks of the basalt-rhyodacite sequence in figure 8 have a linear trend, with the proportion of Na_2O remaining fairly constant. Two analyses of quartzite-bearing rhyolite tuff fall on this same trend, but the analysis of the tuff of Curtis Ranch is not on it. In figure 9 the plot of the rocks of the basalt-rhyodacite sequence shows another linear trend, with these rocks all having a high Σ FeO content and a widely variable MgO content. The plots of the three tuff samples, which have a much lower Σ FeO content, are not on this trend. Analyses of suites of volcanic rocks from a single source in other regions also show a linear arrangement on similar diagrams, according to H. A. Powers (oral commun., 1960), but the lines may be in different position. On the other hand, the analyses of rocks

[3]The ratio of FeO to Fe_2O_3 varies considerably in volcanic rocks owing to inconsistent degree of oxidation. Hence, the Fe_2O_3 is converted to FeO and the total expressed as Σ FeO.

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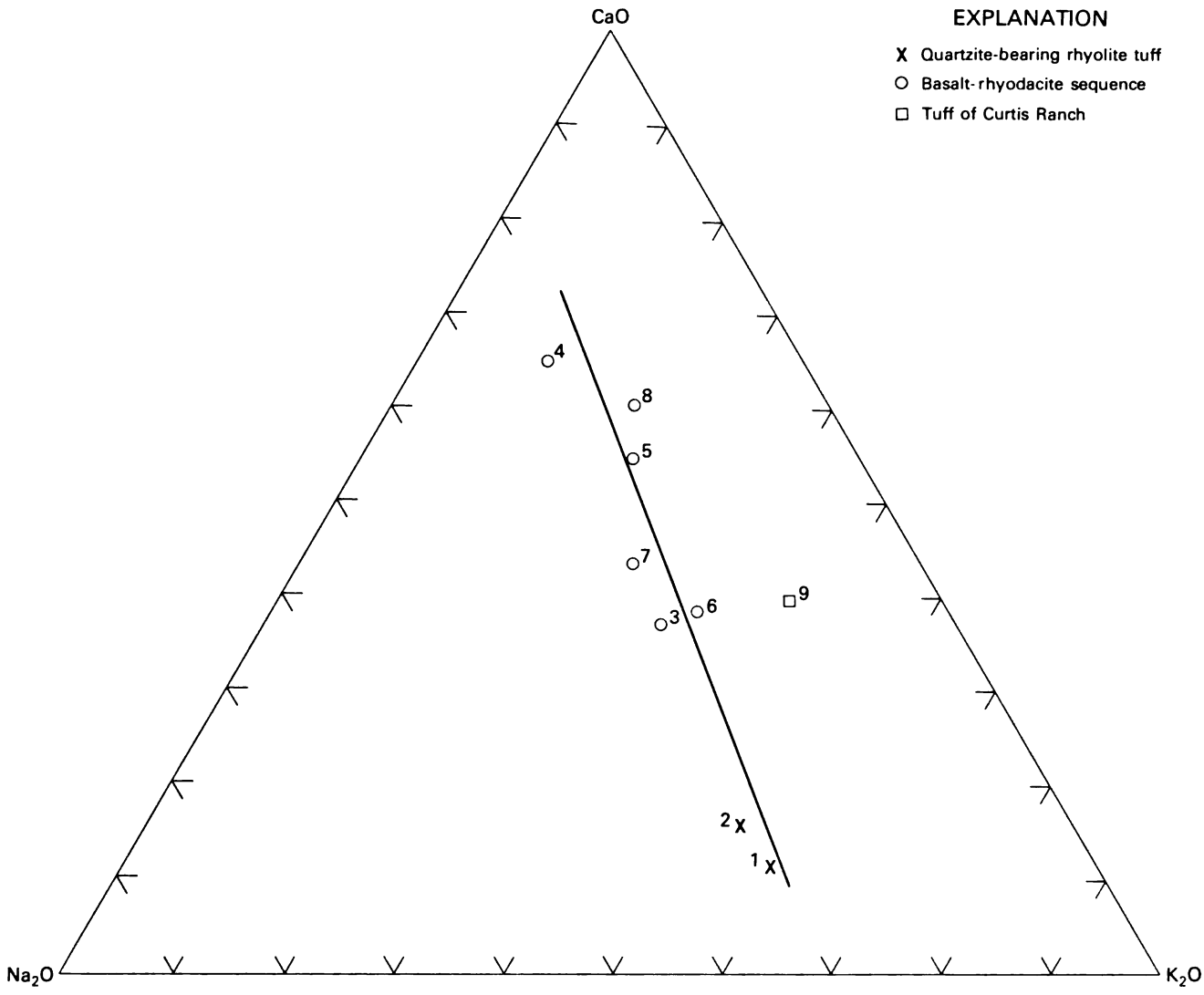


FIGURE 8.—Ternary diagram showing relation of the CaO, Na_2O, and K_2O in rocks from the Challis Volcanics. Sample numbers correspond to those used in table 1. Line shows average linear trend formed by alkalies in Challis Volcanics except the tuff of Curtis Ranch.

of similar composition but from different areas show no such linear arrangement. Thus, the linear relations among the various oxides (figs. 8 and 9) support the thesis that these rocks all came from the same parent magma.

The chemical system used in this paper is from Rittmann (1952). According to his classification, sample 3 would be rhyodacite, sample 4 olivine-andesine trachybasalt, sample 5 olivine latite, and samples 6, 7, and 8 dark quartz latite. As the analyzed rocks are fairly representative of the rocks of the area, they probably come close to covering the extremes of composition expected in this sequence.

TUFF OF CURTIS RANCH

The tuff of Curtis Ranch overlies the basalt-rhyodacite sequence and is overlain by the flow-breccia unit (fig. 4). The tuff occurs in only two outcrop bands: One is 1.5 miles long, south of the Curtis Ranch house near the junction of Frying Pan and Trail Creeks near the east edge of the district, and the other is 2.5 miles long, trending south from Agency Creek to upper Cow Creek, in the north-central part of the district (pl. 1). The northern part of the eastern outcrop band is cut out by a branch of the Lemhi Pass fault, but at least 1,200 feet of tuff is exposed here. In the north-central outcrop band the entire unit is present, but it is somewhat thinner. Here a complete section starting 1,200 feet south of the mouth of Sharkey Creek is 1,200 feet thick. About 1 mile south of this section the tuff has thinned to 400 feet.

The greater part of this unit is made up of light-colored fine-grained crystal-vitric or vitric-crystal tuff. The tuff is generally white or greenish white, although some is a light gray or tan. Rock fragments and crystal fragments are

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TABLE 1.—*Chemical analyses and normative compositions of rocks from the Challis Volcanics*

[n.d., not determined; leaders (...), none]

Constituent or mineral	Samples 1	2	3	4	5	6	7	8	9
Chemical analyses (weight percent)									
SiO_2	74.62	73.1	59.14	48.15	51.38	59.5	58.8	55.5	65.8
Al_2O_3	12.40	13.4	16.66	11.35	10.79	13.4	13.9	14.8	13.5
Fe_2O_3	.77	.88	7.41	2.72	2.15	4.9	6.9	6.8	2.0
FeO	.34	.20	.23	6.21	6.39	2.3	1.2	1.9	.44
MgO	.29	.40	.66	14.46	14.46	3.3	1.9	4.6	1.1
CaO	.84	1.4	4.20	7.38	6.20	4.8	4.9	6.7	2.8
Na_2O	2.30	2.6	3.13	2.63	1.99	2.8	2.9	2.5	.96
K_2O	4.66	4.6	4.07	1.36	2.98	4.7	3.5	3.1	3.3
H_2O+	1.47	1.4	.87	3.12	1.36	1.6	1.8	1.7	6.1
H_2O-	1.76	.90	1.90	.73	.62	1.1	1.8	1.9	4.2
TiO_2	.10	.22	.99	.78	.74	.96	1.0	.75	.27
P_2O_5	.03	.10	.42	.35	.35	.49	.37	.23	.15
MnO	.04	.00	.03	.17	.14	.06	.08	.12	.00
CO_2	.00	.02	.00	.11	.11	.04	.02	.05	.01
Cl	.01	n.d.	.02	.01	.01	n.d.	n.d.	n.d.	n.d.
F	.07	n.d.	.09	.13	.09	n.d.	n.d.	n.d.	n.d.
Subtotal	99.70		99.82	99.66	99.76				
Less O	.03		.04	.05	.04				
Total	99.67	99.1	99.78	99.61	99.72	100.0	99.7	100.7	100.6
Normative compositions (weight percent)									
Quartz	42.84	37.38	17.10			14.04	19.08	11.22	44.58
Orthoclase	28.36	28.36	27.25	8.34	18.35	28.36	21.68	18.90	21.68
Albite	20.44	23.06	25.02	23.58	17.29	24.63	25.15	22.01	8.91
Anorthite	3.89	6.67	18.35	15.85	11.68	10.29	15.57	20.57	14.46
Hypersthene	.70	1.10	1.70	8.78	19.13	4.80	2.50	7.30	3.00
Olivine	.....	.....	.....	21.71	13.98	.....	.....	.....	.....
Diopside	.....	.....	.....	14.79	12.60	7.99	5.40	9.72	.....
Magnetite	.93	.....	.....	4.18	3.25	4.87	1.39	3.94	.70
Hematite	.16	.96	7.68	.....	.....	1.60	6.24	4.32	1.76
Ilmenite	.15	.15	.46	1.52	1.52	1.98	1.98	1.52	.61
Rutile	.....	.16	.80	.....	.....	.....	.....	.....	.....
Corundum	2.24	1.63	.61	.....	.....	.....	.....	.....	3.57
Apatite	.....	.34	1.01	1.01	1.01	1.34	1.01	.34	.34
Calcite	.....	.....	.....	.20	.20	.10	.....	.20	.....
Fluorite	.07	.....	.11	.16	.10	.....	.....	.....	.....
Total	99.78	99.81	100.09	100.12	99.11	100.00	100.00	100.04	99.61

[1]Standard rock analysis by Edythe E. Engelman, U.S. Geological Survey laboratory, Denver, Colo.

[2]Rapid rock analysis by Lowell Artis, U.S. Geological Survey laboratory, Washington, D.C.

Sample descriptions:

1. Quartzite-bearing rhyolite tuff from peak 7,636 on Continental Divide, 1 mile south of Lembi Pass.
2. Quartzite-bearing rhyolite tuff from north side of road along Agency Creek north of mouth of White Creek.
3. Rhyodacite from just east of Trapper Creek in NE¼SE¼ sec. 23, T. 10 S., R. 15 W.
4. Olivine-andesine trachybasalt from low ridge between Trapper and Bear Creeks in SW¼SW¼ sec. 26, T. 10 S., R. 15 W.
5. Olivine latite from knoll just north of Trapper Creek in SE¼NW¼ sec. 34, T. 10 S., R. 15 W.
6. Dark quartz latite from just north of road along Agency Creek, 3,000 feet southwest of mouth of Fluine Creek.
7. Dark latite from just north of road along Agency Creek, 200 feet southwest of mouth of Sharkey Creek.
8. Dark quartz latite adjacent to road along west side of Yearian Creek in SW¼NW¼ sec. 36, T. 18 N., R. 24 E.
9. Crystal tuff from north side of road cut along Agency Creek, 3,700 feet northeast of mouth of Sharkey Creek.

variable in amount and each may range from as little as a few percent to as much as 70 percent. Commonly they each make up 20-50 percent of the tuff. Rock fragments are principally of volcanic material and generally of glass. In the eastern part of the area pumice is the most abundant clast. Other volcanic rock pieces are fine grained; a few have small plagioclase phenocrysts. Crystal fragments are principally quartz and plagioclase, although in some places abundant sanidine is found. Biotite in amounts as much as 2 percent is almost universally present. Minor amounts of hornblende, sphene, zircon, and magnetite are present in some specimens. The matrix is an ash (glass) that commonly contains glass shards and in a few places small microlites. In some places the ash has small vesicles; some of these are filled with tridymite. The tuff is generally fairly compacted and in a few places it is welded. Porcelanite was found in one bed in the eastern outcrop band on the northwest side of Frying Pan Creek.

The upper and lower parts of the tuff of Curtis Ranch differ in the area south of Agency Creek. Here the lower 100 feet of this unit is sorted and consists of layers 0.25-2 inches thick. Some layers may consist mainly of vitric fragments, other of crystal clasts. Grains within the layers are also commonly sorted as to size and the average grain size of one layer may be 0.002 in. and that of an adjacent layer 0.016 in. These tuffaceous rocks are probably water laid. The upper part of the tuff of Curtis Ranch in this same general area consists of a volcanic conglomerate overlain by a volcanic sandstone. The tuffaceous conglomerate is poorly exposed and irregular in thickness; in places it may be as much as 150 feet thick. Near its southern exposure this rock consists of rounded to subrounded pebbles and cobbles of Precambrian quartzite set in a matrix of tuff. Farther north the larger fragments are mainly of medium- to dark-brown aphanitic volcanic rock. In places this rock grades into a breccia. On the south side of Sharkey Creek a volcanic sandstone is found overlying the tuffaceous conglomerate. The sandstone is fairly well sorted and its grains are rounded to subrounded having an average diameter of 0.023 in. They are similar in composition to the clasts found in the tuff, having both large crystal and vitric components. Crystals are chiefly plagioclase, sanidine, and quartz, but minor biotite is conspicuous. Vitric fragments are mainly devitrified glass, including pumice and an aphanitic volcanic rock. A few grains of quartzite are also present. The matrix consists of a minor amount of ash.

A chemical analysis was made of a crystal tuff containing some 30 percent crystal fragments. It was collected on the north side of Agency Creek (table 1, no. 9). If this rock was classified on its chemical composition according to Rittmann (1952), it would be a quartz latite. A comparison of this sample's normative composition with that of the two samples of quartzite-bearing rhyolite tuff (table 1, nos. 1 and 2) shows that the tuff of Curtis Ranch has less orthoclase and albite and more anorthite and hypersthene. A comparison of the alkalies to one another and of MgO to total iron oxide of this rock with other analyzed rocks is shown in figures 8 and 9. Compositionally this rock appears unrelated either to rocks of the basalt-rhyodacite sequence or to those of the quartzite-bearing rhyolite tuff, and was probably derived from another source.

FLOW-BRECCIA UNIT

The flow-breccia unit overlies the tuff of Curtis Ranch (fig. 4) in a relatively small area east of Cow Creek and south of Agency Creek. This unit can be traced in a north-south direction for about 2 miles. The upper part of this unit is cut

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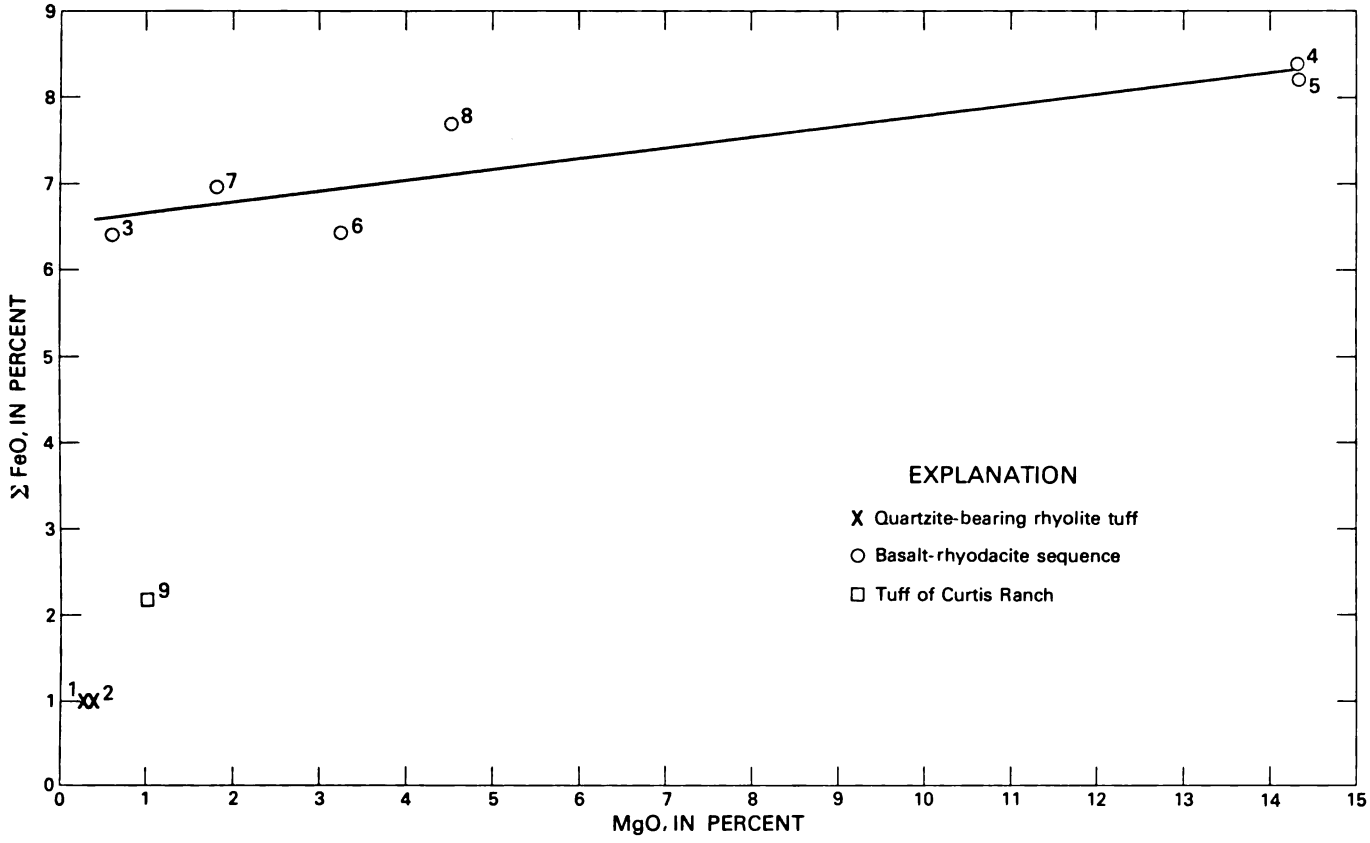


FIGURE 9.—Graph showing relation of MgO to total iron oxide in some rocks from the Challis Volcanics. Sample numbers correspond to those used in table 1. Line shows average linear trend formed by total iron oxide to magnesium oxide ratio in rocks of the basalt-rhyodacite sequence.

out by the fault that bounds the southeast and east sides of the Challis Volcanics. Exposures of this unit are also limited by a cover of older glacial deposits. The flow-breccia unit between White and Sharkey Creeks has a minimum exposed thickness of 580 feet.

The exposed part of this unit consists principally of flow breccia but also includes some dark flow rocks. Flow rocks are probably more common than they appear to be, as they are not as resistant to weathering as the breccias and thus are not as well exposed. Flow breccias are made up of angular to subrounded pieces of flow rocks in a similar matrix. Fragments are 0.06 inch to several feet in diameter of greenish-gray and light- to dark-brown rocks that are commonly weathered limonitic brown. Individual flow-breccia units range from several to about 40 feet thick. Flow breccias are also common in certain parts of the basalt-rhyodacite sequence. The two units are primarily distinguished by the presence of the intervening tuff of Curtis Ranch.

QUARTZ LATITE

Light-colored quartz latite intrusives and flows occur in small areas scattered over the northeast corner of the district. A small pink dike (too small to show on plate 1) cuts the conglomerate of Flume Creek along the north side of the Agency Creek road, 2,500 feet west of the mouth of Flume Creek. The relations of the quartz latite to the volcanic rocks are not exposed in other areas. A circular body of quartz latite that is probably an intrusive occupies a small area about 0.33 mile west of Lemhi Pass. Other outcrops of quartz latite occur near Sheser Creek in the northeast corner of the district. Many of these outcrops have a well-developed flow structure and for the most part are flows. The lack of more definite data precludes determining either the number or the relative ages of most parts of the quartz latite unit.

The quartz latites are generally pink to purplish brown, although some are light gray and brown. They are porphyritic rocks containing 10-20 percent phenocrysts 0.04-0.08 in. in diameter that are set in a matrix of tiny crystals and glass. Their principal phenocrysts are quartz and plagioclase but they also contain small amounts of potassium feldspar and biotite. In the quartz latite west of Lemhi Pass a little altered hornblende was also noted. In the matrix tiny crystals of plagioclase, quartz, potassium feldspar, and biotite are set in a devitrified glass. Staining of several quartz latite specimens with sodium cobaltinitrite

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identified the potassium fledspar among the small crystals as well as indicating that considerable potassium occurred in the glass. These rocks were classified as quartz latite on the basis of their abundant quartz and plagioclase phenocrysts along with positive qualitative tests for potassium.

YOUNGER BASALT

The younger basalt is found in three small areas, none larger than 0.25 square mile in size, in the northeastern part of the district between Trail and Bear Creeks (pl. 1). This rock unconformably overlies rocks of the basalt-rhyodacite sequence in all three areas, and in addition the east edge of the basalt that lies astride of Trail Creek overlaps the tuff of Curtis Ranch. The younger basalt closely resembles some of the flow rocks and flow breccias in the basalt-rhyodacite sequence but is separated from them by an angular unconformity. The younger basalt in the northernmost outcrop area strikes east and dips 15° S., but a flow breccia in the adjoining basalt-rhyodacite sequence strikes north and dips 80° E. The younger basalt in the central area also strikes east, but dips only 5° S.; those in the southernmost area are almost horizontal. Rocks of the basalt-rhyodacite sequence adjacent to these two areas have a northerly strike and dip 30°-55° E.

The younger basalt was once more extensive than at present, and the three outcrop areas represent small remnants of a much larger, thicker unit. The northern two areas are preserved because they are capped by a resistant flow breccia and the southern one because it was deposited in a topographic hollow in the underlying basalt-rhyoacite sequence. The younger basalt ranges in thickness from 50 to 400 feet.

The younger basalt is made up of flows and interlayered flow breccias. The flows are gray or brown aphanitic basalts, and some contain olivine phenocrysts. The fragments in the flow breccias are composed of similar material. These clasts are angular to subrounded and 0.1-8 inches across. The matrix is similar to the fragments. The flow breccia occurs in discontinuous layers that are 20-50 feet thick. Although the breccias are composed of material similar to the flows, they are more resistant to weathering and form prominent outcrops that cap the more poorly exposed flows.

SANIDINE-QUARTZ WELDED TUFF

The sanidine-quartz welded tuff occurs in scattered patches in the central part of the district (pl. 1). Most of it is found in the vicinity of Ghoul Basin, although it occurs as far south as Yearian Creek Valley. This unit is one of the younger units of the Challis Volcanics, and in various places it unconformably overlies rocks of the basalt-rhyodacite sequence and quartzite-bearing rhyolite tuff. It is offset by several large faults, including the Dan Patch and Lemhi Pass faults, but this unit in part overlies some of these faults and is not offset as much as the other units. The smaller amount of movement on the sanidine-quartz welded tuff can be accounted for by this rock being deposited after some but not all the movement had occurred along the faults. The age of this unit relative to the quartz latite or the younger basalt is not known.

The sanidine-quartz welded tuff is a white, tan, or light-brown hard welded tuff containing a few to 20 percent crystal clasts set in a fine-grained dense matrix. Most of the crystal fragments range in size from 0.004 to 0.060 in. although in a few localities in addition to these crystal fragments, smaller ones occur in the matrix. Sanidine and quartz are the principal and in some localities the only crystal fragments noted. Plagioclase was noted in several places, as well as minor amounts of biotite. A few small glass fragments of material similar to the matrix occur locally. The matrix is a partly devitrified glass—an ash—that commonly contains abundant glass shards. Staining indicates that the matrix contains at least moderate amounts of potassium. Compositionally this rock is probably rhyolite.

AGE

The Challis Volcanics are probably mainly of Eocene age, although their range within the Tertiary is not fully known. They generally overlie much older rocks, and are overlain by younger Tertiary rocks. In the Lemhi Pass area the Challis overlies Precambrian Y rocks, but farther south in the Leadore quadrangle it also overlies Kinnikinic Quartzite (Ordovician), Saturday Mountain Formation (Ordovician), and Jefferson Dolomite (Devonian) (Ruppel, 1968). The Challis is overlain by the tuffaceous sedimentary rocks, a sequence of lacustrine volcanic sediments containing plant and vertebrate fossils the ages of which indicate that these tuffaceous rocks were deposited in some part or all of a time between late Eocene and middle Miocene.

The Challis Volcanics have been dated in one place within the Lemhi Pass thorium district. A specimen of crystal tuff was collected along Agency Creek on the north side of the road about 3,500 feet northeast of the mouth of Sharkey Creek in the NW¼SW¼ sec. 19, T. 19 N., R. 25 E. Age determinations by the potassium-argon (K-Ar) method on both biotite and sanidine were made by R. F. Marvin, H. H. Mehnert, and Violet Merritt in the U.S. Geological Survey's age laboratory in Denver, Colo. The determined age of the biotite is 42.3±1.4 million years (m.y.); that of the sanidine is 40.3±1.4 m.y. The average age of the two determinations is 41.3 m.y. The specimen was collected from near the center of the tuff of Curtis Ranch, and is therefore near the top of the Challis Volcanics exposed in the Lemhi Pass thorium area. Ages reported from other areas are older, perhaps because the other samples were taken from lower in the sequence or because the Challis Volcanics were deposited in other areas at a somewhat earlier time. A sample of biotite quartz latite taken from the Germer Tuffaceous Member along U.S.

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Route 93, 4 miles south of Salmon, was dated at 45.5 m.y. by the K-Ar method (Axelrod, 1966, p. 497-498). Five samples collected within 17 miles of the town of Challis from various rock types within the Challis Volcanics had ages that ranged from 43.8 to 49.0 m.y. by the K-Ar method (Armstrong,1974, p. 12). These ages suggest that the Challis was deposited over much of Eocene time. Although data are presently lacking, the Challis may have been deposited as early as Paleocene.

TERTIARY TUFFACEOUS SEDIMENTARY ROCKS

The tuffaceous sedimentary rocks were deposited in topographic basins in mid-Teritary time after the last period of large-scale deformation. These rocks are widespread along the lower flanks of the Lemhi and Salmon Valleys to the north and west of the district and on Horse Prairie (the area between the Beaverhead Mountains and the Tendoy Range to the east). Within the thorium district they also occupy the basin along Cow and Yearian Creeks. They are thickest in the deeper part of the basins, and at the lower end of the Lemhi Valley near the town of Salmon the minimum thickness of these rocks is estimated to be 1,500 feet, and they may be several times as thick. The rocks thin up this valley, and 18 miles southeast, where the valley crosses the northwest corner of the Lemhi Pass thorium district, only a few hundred feet of this unit are found.

The tuffaceous sedimentary rocks, because they had a dominant volcanic component, were of early Tertiary age, and occurred in south-central Idaho, were originally considered to be part of the Challis Volcanics (Ross, 1934, p. 46). The two were separated into two formations by Anderson (1956, p. 31) on the basis of differences in lithology and by the presence of an angular unconformity between them. Ross in 1962 (p. 74-75, 88-91) still believed that little basis existed for separating the tuffaceous sedimentary rocks from the Challis Volcanics. His reasons basically are as follows: (1) Anderson (1956, p. 89) stated in his description of the Salmon quadrangle that the sedimentary rocks contain no products of direct volcanic origin, such as flows, welded tuffs, or tuffs, whereas they obviously do, (2) as most tuffaceous units in the Challis Volcanics are more or less water sorted, they would be difficult to distinguish from sedimentary rocks derived by erosion from volcanic rocks, and (3) Anderson's evidence for unconformities between the two rock types is not convincing. Anderson divided the tuffaceous sedimentary rocks into several units, but large differences occur in his descriptions and in the names he used for the various units (1956, p. 28-31; 1957, p. 16-19; 1959, p. 25-28; 1961b, p. 31-35) in the Salmon, Baker, North Fork, and Lemhi quadrangles. Furthermore, there are major inconsistencies in his mapping both within and between quadrangles. For instance, he traced the tuffaceous sedimentary rocks in the northern part of the Lemhi quadrangle directly into the Challis Volcanics in the southern part of the Baker quadrangle. Although Anderson (1956, p. 89) noted that the sedimentary rocks in the Salmon quadrangle contained no products of direct volcanic origin, in his later studies (1957, p. 16; 1959, p. 26; 1961b, p. 32) he noted the presence of tuff, tuffaceous materials, and even welded tuff in the Baker, North Fork, and Lemhi quadrangles. He (1957, p. 18) also reported widespread occurrence of bentonite, which he presumed was derived from volcanic ash. Ross (1962) noted the difficulty in distinguishing the two water-laid units, yet at only a few places in the Lemhi Pass area, such as the base of the tuff of Curtis Ranch, is there any evidence that any of the tuff in the Challis is water laid. As noted by Ross, inconsistencies of mapping between areas and also within areas are large, but they do not invalidate the observation that the Challis is separated from the tuffaceous sedimentary rocks by an angular unconformity. Anderson (1956, p. 31 and pl. 5-B) even indicates where the unconformity between the two units may be seen. This unconformity is also apparent in several places in the Lemhi Pass thorium district. One example is found in the northwest corner of the district (pl. 1) where the quartzite-bearing rhyolite tuff of the Challis Volcanics strikes N. 25° E. and dips 42° NW. and tuffaceous sedimentary rocks due west strike N. 76° E. and dip 45° SE. Just south of Pattee Creek, conglomerate in the basal part of the tuffaceous sedimentary rocks can be seen irregularly overlying the Challis Volcanics.

As noted above Anderson has divided the tuffaceous sedimentary rocks into several units. In both the Baker and Lemhi quadrangles he has a threefold division (1957, p. 16-19; 1961b, p. 69-71). In the Lemhi quadrangle his three units are called the Kenney, Geertson, and Kirtley Formations. All three are shown on his map in the vicinity of Pattee Creek, and two—the Kenney and the Geertson Formations—are shown in the Cow Creek-Yearian Creek basin. In both areas the contacts separating the units are unrealistic, as in places they cut across the strike of the beds. The units, as mapped, also include flow rocks of the Challis Volcanics and some Precambrian rocks. Exposures in the Cow Creek-Yearian Creek area consist of only a few small widely scattered outcrops in an area noted for its large landslides. Furthermore, neither Anderson's descriptions of the rock units nor the rocks as mapped in the field furnish any evidence for dividing those rocks into three formations. Hence, the general name tuffaceous sedimentary rocks is used in this paper for the relatively thin part of a much thicker and better exposed unit to the northwest.

DESCRIPTION

The tuffaceous sedimentary rocks consist mainly of fine-grained tuffaceous clastic rocks but have some layers and lenses of conglomerate. The finer grained sedimentary rocks range from fine-grained sandstone to shale. In some layers, where the vitric fragments predominate, the rocks are tuff. In places, thin layers of sandstone are interlayered with those of shale, tuff, or silt. These individual layers are thin (fig. 10), the sediment is well sorted, and in a few places

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FIGURE 10.—Thin-bedded tuffaceous sedimentary rocks exposed in low hills northeast of mouth of Agency Creek.

graded bedding is present. The sorting in these rocks indicates that they are water laid. The tuffaceous rocks in this unit differ from those in the Challis Volcanics not only in being better sorted but the grains may be rounded, the layers are commonly fissile, and the many layers of the rocks have a high bentonite content. The bentonite beds can be distinguished on an exposed surface by an intricate pattern of shrinkage cracks around small circular clots of clay or they can readily be distinguished by their stickiness and slipperiness when wet. Most of these beds are white or light gray but some are tan or brown. Beds range from a fraction of an inch to a few feet in thickness (fig. 10), and in some places, such as north of Pattee Creek and in the upper reaches of Cow Creek, they commonly split into paper-thin layers. These sedimentary rocks are made up of detrital material from the surrounding area, principally from the easily eroded Challis Volcanics. These fine-grained rocks weather quickly owing to their friable nature and high clay content, and even in roadcuts, exposures are rare unless they are freshly made. Most exposures occur in areas of active erosion as along streams.

Sandstones and siltstones consist mainly of crystal fragments; they may also have a large component of subrounded to rounded rock fragments. Most also contain a small amount of glass clasts. Crystal fragments are chiefly quartz. Many rocks have a moderate content of sanidine and plagioclase. In places most or some of the feldspar has been altered to sericite. Other minerals noted in minor amounts include biotite, hornblende, chlorite, tourmaline, and zircon. Rock fragments consist of Precambrian Y quartzite or siltite and of light to dark brown aphanitic volcanic rocks.

Tuff layers are fairly common and may be entirely made up of fine particles of ash, or they may have an intermixture of air-laid or water-laid crystal and rock fragments with the ash. Much of the ash has been altered to clay.

Conglomerates are interlayered with the finer grained sedimentary rocks. They are most common in the northwest part of the district on either side of Pattee Creek. Although exposures of conglomerates are spotty, they are much better exposed than the fine-grained rocks. The conglomerate consists of subrounded to rounded pebbles and cobbles set in a sand matrix. Most of the pebbles or cobbles are 0.25-6 in. in diameter, although a layer exposed along a road 0.75 mile east of Yearian Creek has boulders as large as 2 feet across. The clasts may be light- to medium-gray fine-grained quartzite of Precambrian age; they may be red, brown, or black flow rocks of the Challis Volcanics; or they may be, as they commonly are, a mixture of the two principal rock types. Sand grains that fill the interstices and form small lenses or discontinuous layers consist of quartzite and flow-rock clasts plus crystal fragments. The latter are mainly quartz, but sanidine and plagioclase are generally present. Small amounts of vitric fragments may be found in the matrix. These conglomerate layers are similar in appearance to two conglomeratic units in the Challis Volcanics: The basal conglomerate and the conglomerate of Flume Creek. They may also resemble the Beaverhead Formation of Late Cretaceous, Paleocene, and Eocene age.

AGE

The age of the tuffaceous sedimentary rocks in the Lemhi Pass thorium district could range from late Eocene to Pliocene, although the time range of this unit is not fully known. These sediments overlie the Challis Volcanics, from which an age of 41.3 m.y. was determined by the K-Ar method on a tuff near the top of the formation. The sedimentary rocks are overlain by the older glacial deposits of Quaternary age.

Two fossil collections, one of plants and the other of vertebrates, have been made in and near the thorium district. The plant collection was made from two nearby places. One locality is in a roadcut 0.6 mile south of the junction of Cow Creek with a tributary that parallels the road in the NE¼SE¼ sec. 1, T. 18 N., R. 24 E. The other locality is about 800 feet north of the first locality and is on a barren hillside above the road and below a small prospect pit. Abundant plant remains and the tail of a fish were collected here. The following plants were identified by Jack A. Wolfe:

Ginkgo sp.
Metasequoia sp.
Taxodium sp.
Picea sp.
Sassafras hesperia Berry
Mahonia cuprovallis Axel.
"Zelkova" drymeja (Lesq.) R. W. Br.
Quercus sp.
Alnus jarbidgana Axelrod
Crataegus copena (Lesq.) MacG.
Rhus cf. R. obscura (Lesq.) MacG.
Acer mysticum Kirch.
Symphoricarpos salmonensis R. W. Br.

Wolfe (written commun., 1974) notes that the alder, *Alnus*

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jarbidgana, is the most abundant plant in the collections, and that several species, including this one, are present in collections made in tuffaceous sedimentary rocks near Salmon, Idaho. He states that the oldest possible age of these collections is late Eocene, as this is the age of oldest known occurrences of *"Zelkova" drymeja, Almus jarbidgana, Mahonia cuprovallis,* and *Acer mysticum*. The upper limit of this assemblage of plants is not as well known, but it does not extend into the Miocene.

The fish tail was examined by David H. Dunkle (written commun., 1973), who states that the scale characteristics, extended dorsal fin, and caudal fin structure are similar to that of the aberrant sucker, *Amyzon*. This genus has previously been found in sedimentary rocks that range in age from Eocene to middle Miocene.

Several vertebrate collections have been made in a small area about 1.5 miles south of the southeast corner of the area on the east side of Peterson Creek near its mouth (Anderson, 1961b, p. 33-34). Some of the fossils collected by Ralph Nichols and identified by C. L. Gazin are rhinoceros teeth, *Parahippus* sp., *Mylagaulus* sp., and *Merychyus* (Ross, 1962, p. 101). Other specimens collected and identified by J. A. Wilson are *Promerychocherus* sp., *Ticholeptus* sp., *Parahippus* sp., and *Alticamelus* sp. Wilson (1946, p. 1262) considered the fauna to be somewhere between early Miocene and early Pliocene in age. G. E. Lewis, in summarizing previous work in 1961 (written commun.), stated that this vertebrate collection is from a stratigraphic position that is considered to represent either the top of the lower Miocene or the bottom of the middle Miocene in North American continental stratigraphy (Ross, 1962, p. 101). The sedimentary rocks on Cow creek, from which the plants came, are most likely Oligocene; those on Peterson Creek, from which the vertebrates came, are Miocene. The plant-bearing rocks are lacustrine; those containing the vertebrate fossils are continental and may represent a Miocene fan. Sedimentary rocks of this type are fairly common along the Lemhi valley southeast of the area mapped, but are uncommon within the thorium district.

TERTIARY DIORITE

Diorite occurs widely scattered in many thin dikes and several small irregular bodies. Although diorite dikes are found in many parts of the district, most are concentrated in a 9-mile-long northwestward-trending zone some 4 miles broad that extends from the headwaters of Everson Creek on the east margin of the district to the headwaters of Agency Creek. Some diorite bodies occur in adjacent areas. One diorite body is found about a mile south of the Lemhi Pass thorium district on Cedar Gulch in the Goat Mountain quadrangle (Staatz, 1973), and another is found 9 miles north of the area in the Baker quadrangle (Anderson, 1957, pl. 1).

The diorite is generally poorly exposed, and it is principally found on ridges and in prospect pits. Six of the dikes seen in this area are exposed only in trenches or underground workings. Scattered pieces of diorite float on some of the mountainsides indicate that many poorly exposed dikes were not located. Some of the diorite, however, forms prominent outcrops. Two such well-exposed bodies are the long dike that lies east of Bear Creek near the Dan Patch veins (loc. 98) and the irregular body on the east slope of the Cow Creek basin in the SW¼ sec. 32, T. 19 N., R. 25 E. Much of the diorite is partly altered, which may account for the lack of outcrops in many areas.

Most of the diorite bodies are dikes. The dikes have various attitudes, but mainly they have a general westerly strike which ranges from N. 45° W. to S. 45° W. Dips are in any direction, but are generally steep. The attitudes of dikes and thorium veins that are adjacent to one another, such as those on the Brown Bear No. 2 (loc. 78) property, Dan Patch (loc. 98), G&G (loc. 89), and Wonder (loc. 45), are commonly similar, indicating that both probably occupy the same sets of fractures. The presence of diorite dikes in trenches near or adjacent to those containing thorium veins in the northwest end of the zone that contains most of the dikes, originally led to the belief that the two were approximately syngenetic. Further mapping did not support this assumption, and the association of the two is in part because both occur in the same joint sets and in part because trenching has afforded better exposures. In size the dikes range from one with an exposed length of 20 feet and a width of 1 foot to one having a known length of 6,500 feet and a maximum width of 150 feet. The largest dike, which is on the east side of Bear Creek, ranges in thickness from 3 to 150 feet.

In addition to the dikes there are two small irregular diorite intrusives. One, which has a generally triangular shape, occurs on the east side of the Cow Creek drainage in the SW¼ sec. 32, T. 19 N., R. 25 E. This intrusive is 1,150 feet long and has a maximum exposed width of 550 feet. The other intrusive lies on the southwest side of the Bull Moose fault along the east edge of the area. This intrusive is 700 feet long and has a maximum width of 500 feet. From the main part of this intrusive a dike extends southeastward along the fault. The diorite varies in color from medium gray to black; many intrusives are dark gray, greenish gray, drab olive green, or speckled. The diorite tends to be fine to medium grained and locally porphyritic. Equigranular rocks have an average grain size of 0.003 to 0.05 in. Porphyritic rocks have phenocrysts 0.08-0.16 in. across set in a matrix of 0.004 to 0.012 in. grains. In general the larger dikes tend to be coarser grained and are more likely to be porphyritic.

These rocks are made up principally of plagioclase and mafic minerals. They contain 30-75 percent plagioclase and 22-70 percent mafic minerals. All would be classified as diorite according to Grout (1932, p. 50). Plagioclase, which is generally andesine, occurs in anhedral to subhedral crystals that are commonly zoned. Other leucocratic

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minerals include orthoclase and qaurtz. Both are found as small inconspicuous grains interstitial to other minerals. Where present orthoclase makes up less than 1-6 percent of the rock and quartz less than 1-3 percent.

The mineral content of the diorite, especially the mafic minerals, shows considerable variation. The mafic minerals vary not only in amount but also in kind. The principal mafic minerals are augite, hornblende, biotite, and chlorite. Not all of them occur in every specimen of diorite. Augite (3-30 percent) and hornblende (0-30 percent) are generally the most abundant but any one of the four may be most abundant in any particular rock. Biotite, which is the least common of these four minerals, is the principal mafic mineral in a few places. In a dike just north of Pattee Creek in the northwest corner of the area, and in another dike that is adjacent to the north side of the Wonder vein (loc. 45), it makes up 40 and 35 percent, respectively, of the dikes. Augite forms stubby subhedral crystals; hornblende occurs as long dark-brown to green lathlike crystals; biotite forms irregular brown to green plates; and chlorite was found as small pale-green irregular crystals. Chlorite, which is an alteration product of the other three minerals, commonly forms rings around augite phenocrysts in the porphyritic diorite. Accessory mafic minerals include apatite, hematite, and magnetite. In addition, epidote, sericite, and calcite form during the alteration of the other minerals.

The diorite was probably intruded during middle Tertiary time after most of the Challis Volcanics were deposited, but before the emplacement of the veins. Dating these dikes is difficult, as the diorite intrudes only the Precambrian rocks. Diorite does not intrude the Challis Volcanics and might be presumed to be older. The lack of diorite intrusives in the volcanics, however, may be due either to the intrusions being older than the volcanic rocks or to the lack of fractures in the volcanics along which the diorite could be intruded. An answer to this problem can be found near the east edge of the area just north of the North Fork of Everson Creek, where a small diorite intrusion has a dike extending from it along the Bull Moose fault. The dike is thus younger than the fault, and as the fault offsets the Challis Volcanics, it must also be younger than those volcanic rocks. Diorite is older than either the copper or the thorium veins. This relation is best shown in the underground workings of the Copper Queen mine (loc. 43), where both Schipper (1955, p. 29) and Sharp and Cavender (1962, p. 52) noted that a copper-bearing quartz vein cuts across several diorite dikes. The dikes are also highly altered and contain sulfides. Crosscutting relations in this same mine indicate that the thorium veins are younger than the copper veins. In addition, the diorite dike that lies adjacent to the thorium vein on the Wonder property (loc. 45) contains a little pyrite, which was probably introduced when the vein was emplaced. These data limit the age of the diorite and indicate that the intrusives formed after the major faulting that cut the Challis Volcanics, but before the veins were emplaced.

QUATERNARY DEPOSITS

Thick deposits of Quaternary age occur in about one-fifth of the area (pl. 1). These have been divided by composition, form, and origin, into eight unconsolidated units: (1) Older glacial deposits, (2) younger glacial deposits, (3) terrace deposits, (4) alluvial fans, (5) rock glacier, (6) landslide deposits, (7) mudflow, and (8) alluvium. The older glacial deposits are the most widespread and underlie more than half of the area mapped as Quaternary rocks (pl. 1). Actually, they are even more widespread than shown. As the principal interest in this area was in the older consolidated rocks, the glacial deposits are only mapped where the distance between outcrops of the underlying rocks is more than 1,000 feet. The boundaries between the glacial deposits and the consolidated rocks, hence, are approximate. The two types of glacial deposits have different origins: the older glacial deposits are a product of a southward-moving ice lobe, and the younger glacial deposits were formed by small mountain glaciers. The glacial till derived from the two sources is commonly similar, and the two ages of till are separated on the basis of form and occurrence.

OLDER GLACIAL DEPOSITS

Older glacial deposits at one time covered the entire area. Most of these deposits have since been stripped away by erosion, but where protected in topographic lows or where they were originally quite thick, they still mantle the older rocks. These glacial deposits are abundant in three areas: (1) The northeast corner of the district, where they mantle most of the Sheser Creek basin; (2) the northwest corner of the district, where they cover a series of low rounded ridges; and (3) the drainage basins of Cow and Yearian Creeks, where they principally overlie the Challis Volcanics and the tuffaceous sedimentary rocks. Where the till is thick, it fills in the angular irregularities in the pre-Quaternary topography and gives the landscape a more smoothed out and rounded appearance. The topography in the Sheser Creek basin, which is underlain by older glacial deposits, is much gentler than that directly west along the Continental Divide, which is underlain by Precambrian quartzite. Similarly, the head of Yearian Creek basin, which is underlain by glacial deposits, is gently rolling compared to the steep mountains on either side, which are underlain by Precambrian rocks.

The older glacial deposits consist principally of subangular to subrounded blocks, boulders, cobbles, and pebbles set in a matrix of brown sand, silt, clay, and soil. The clasts are mainly fine- to medium-grained Precambrian quartzite. Pieces of quartzite are generally less than 1 foot across, although blocks as much as 10 feet across occur in a few places. In addition to quartzite a few pieces of siltite and, even more rarely, basalt, rhyodacite, or tuff, occur in the till. The volcanic rock fragments are generally not more than several inches across and occur in till that is on or adjacent to volcanic rock outcrops. The volcanic rocks disintegrate

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fairly easily and probably have not been transported more than a mile. In most places the finer material weathers to a rich brown soil, Grass, flowers, and sage, which commonly grow on it, are bigger and more luxuriant than those found on somewhat leaner soils over consolidated materials. The difference in plant size can be used to mark the boundary accurately between the glacial deposits and the adjoining rock type. In places these glacial deposits are hard to identify, as they become mixed with talus, weathered soil formed on the underlying rocks, and landslide deposits.

In additon to till, a small amount of glacial river gravels are included in this unit. These gravels occur as remnants on hilltops and slopes in a few widely scattered localities. The gravel differs from the till in being made up of well-rounded pebbles, boulders, and cobbles. By far the most common gravel is Precambrian quartzite. In addition, however, exotic rocks, which are not found within many miles of the Lemhi Pass district, may be present. A small patch of gravel on hilltop 7,381 on the north side of Frying Pan Creek in the NW¼ sec. 22, T. 10 S., R. 15 W. contains, in addition to Precambrian quartzite, a white quartzite, a coarse-grained quartz monzonite, a coarse-grained quartz diorite, and a biotite-quartz schist. Another patch of gravel at the east end of Ghoul Basin in the E½ sec. 8, T. 19 N., R. 25 E. has, besides the Precambrian quartzite, a few pieces of red quartzite, black chert, and a coarse-grained orbicular biotite granite.

The older glacial deposits were formed under a thick icecap that originated north of this district. Although mountain glaciation has been recognized previously here, regional glaciation has not. Anderson (1961b, p. 36-38) described glacial deposits formed during several periods, but believed them all due to mountain glaciation. In places he has mapped a unit called "ridge gravels," which in the mapped area (pl. 1) corresponds in general to the older glacial deposits. That the older glacial deposits were formed by an icecap is supported by the following lines of evidence: (1) The wide distribution of the deposits across both valleys and mountaintops; (2) the large vertical distribution over which the deposits are found—in this area they are found between elevations of 5,200 and 8,160 feet; (3) the direction of movement of glacial material in some places up drainages, rather than consistently down them; and (4) the general direction of movement of rock fragments from the north. Southward movement of volcanic rock fragments can be demonstrated in glacial deposits that lie southwest of the junction of Frying Pan and Trappers Creeks in the northeast part of the area (pl. 1). These deposits contain a few pieces of tuff and rhyodacite, which are unlike any volcanic rocks south of this area but are similar to rocks that lie 1-1.5 miles northeast.

YOUNGER GLACIAL DEPOSITS

The younger glacial deposits are not as widespread as the older glacial deposits and were formed by mountain glaciers along the bottom of steep-walled valleys that head in large steep-walled cirques. Most occur along the east side of the Continental Divide, although one is found near the mouth of Little Dry Gulch on the east side of the Lemhi River. These glacial deposits are only shown (pl. 1) where they form thick discrete units. Some scattered till is found in several other valleys, such as the valley of North Frying Pan Creek that heads on the east side of the Continental Divide, but the deposit is thin and later erosion has partially removed it and mixed it with more recent sediments.

The younger glacial deposits were formed by valley glaciers moving down the valleys from cirques high on the mountainside. In some areas the glaciers polished the bedrock clear of detrital material, but in other areas it dropped its load. Polished and striated quartzite is exposed in many of the cirques at the head of various tributaries of Bear Creek. Till, however, covers the cirque at the head of the South Fork of Frying Pan Creek.

Glacial till blankets the bottoms and sides of the valleys in fairly even deposits and forms steep-sided moraines. End moraines are not common because in most areas the glacial deposits are confined to narrow valleys and have been subsequently eroded away. The most prominent end moraine occurs at the mouth of Little Dry Gulch, where a pile 400 feet high of poorly sorted quartzite clasts mixed with soil occurs at the edge of the Lemhi Valley. A partial end moraine also is found on the south side of Trapper Creek where several hills as much as 150 feet high stand at the terminus of the glacial deposit. Lateral moraines are more common, and some approximately 50 feet high occur on the northwest side of Bear Creek in the NW¼ sec. 35, T. 10 S., R. 15 W., and on the north side of Trapper Creek in the E½ sec. 33, T. 10 S., R. 15 W. Another forms a prominent ridge on the north side of South Frying Pan Creek in the SW¼ sec. 29, T. 10 S., R. 15 W., and others are found in several places along Bear and South Frying Pan Creeks. A large medial moraine has formed at the junction of the main north-flowing part of Bear Creek with an east-flowing tributary. This northeast-trending moraine forms a low ridge with an irregular rolling surface. It is 3,700 feet long, 1,200 feet wide, and in places is as much as 120 feet high.

The younger glacial deposits consist of angular, subangular, and subrounded clasts of fine-grained quartzite, and in places a little siltite, in a matrix of sand, silt, and clay. Generally the maximum size of the larger boulders does not exceed 4 feet but in one place along Trapper Creek blocks as much as 20 feet across are found. As the younger glacial deposits are similar in composition to the older glacial deposits, they are separated on the basis of form and occurrence.

TERRACE DEPOSITS

Terraces represent the remmants of former alluviated valleys that, owing to erosion, now occur above the present valley bottoms. Terraces occur where the old stream

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gradient flattened. Most were probably formed during the Pleistocene when runoff from melting glaciers furnished abundant soil, gravel, and water. They are common along Agency Creek, Pattee Creek and along the east side of the Lemhi River (pl. 1). They are particularly abundant along Agency Creek, where they are found scattered on either side of the valley from about 0.5 mile below the junction with Cow Creek upstream for 5.25 miles to a point about 0.75 mile above the junction with Flume Creek. Terraces are also found along many of the tributaries of Agency Creek, like Cow, Sharkey, White, and Flume Creeks. They are common along the Lemhi River valley, being especially abundant on both sides of the river southeast of the mapped area. The largest terraces shown on plate 1 lie near the junction of the Lemhi River with Yearian Creek. Terraces occur at several different elevations, and in various places were formed at different times. For example, east of the Lemhi River a terrace on either side of Big Dry Gulch has an average elevation of its upper surface of about 5,400 feet but a terrace about 1.5 miles south, adjacent to the Lemhi River, has an elevation of its top of about 5,080 feet. A terrace deposit on Agency Creek northeast of its junction with White Creek has two separate benches indicating that terraces were formed during at least two periods in the development of the valley.

The upper surface of the terraces, although seemingly flat, slopes in two directions. It has a gentle slope parallel to the stream valley, which represents the old stream gradient. It also slopes up the valley sides, owing to the terrace deposits mingling with slopewash from the adjacent hillside.

The terrace deposits are made up of a mixture of brown soil and pebbles, cobbles, and boulders. Most of the clasts are well rounded, but a few are subangular to angular. They range in size from about 0.25 inch to 2 feet in diameter. Most of the clasts are gray, greenish gray, or brown quartzite. Most of the material that makes up the terrace deposits that formed along such streams as Agency and Pattee Creeks was derived from the mountains only a few miles away. Terrace material along the Lemhi River, however, may have come from many miles away from either the Beaverhead Mountains or the Lemhi Range. In addition to material eroded directly off the mountains, a little of it is from reworked glacial deposits. Pebbles from this source may have come from many miles away, which accounts for the rare pebbles of black chert, red quartzite, and coarse-grained biotite granite noted in a few places. The terrace deposits are similar in composition to alluvium. Along the smaller streams they are rarely cultivated owing to the difficulty of irrigating their elevated surfaces. The larger terraces along the Lemhi River, such as the one south of the village of Lemhi, are used for raising hay.

ALLUVIAL FANS

Pleistocene and Holocene alluvial fans, for the most part, are found along the east side of the Lemhi River valley. They form between the steep mountain slopes and the broad alluviated river valley, and many are found at the mouths of small canyons which contain water only after storms or during the melting of the winter snow. A few fans are also found mantling the area between Reese and Peterson Creeks. Fans along the Lemhi River are being formed at the present time and typically are broad gently sloping surfaces with their apices at the mouths of small canyons. Those in the Reese Creek-Peterson Creek area are somewhat older. Their original smooth surface has been dissected, and both Reese and Peterson Creeks are several hundred feet lower than when most of these fans were formed.

The alluvial fans are made up of subangular to rounded rock fragments mixed with brown sand, silt, and clay. The fragments tend to be angular in the more recent fans and rounded in the older ones. Fragments range in size from 0.25 inch to 3 feet in diameter. Most of the clasts are gray to green fine-grained quartzite. In places a little greenish-gray siltite is present, and in the older fan material between Reese and Peterson Creeks a few small pieces of dark-brown flow rock from the Challis Volcanics are found.

ROCK GLACIER

One rock glacier of Holocene age is found in the Lemhi Pass thorium district (pl. 1). It lies in a valley on the southeast flank of Goat Mountain in the southeast corner of the area. This rock glacier heads in a cirque and extends for 1 mile down the valley. It has an average width of 850 feet and a tonguelike shape. The glacier has a drop in elevation of 1,150 feet from its upper end in the cirque to its lower end in the creek bottom. The lower terminus is quite steep and the rocks here lie at their angle of repose. This rock glacier is entirely made up of subangular pieces of tan, brown, or gray fine-grained, generally feldspathic quartzite of the Big Creek Formation. Clasts range from a fraction of an inch to 15 feet in diameter. Many pieces are several feet across. Curved ridges a few feet to 20 feet high that are convex to its lower end cross its surface. Movement of this rock glacier has now probably either ceased or is very slow, as a small cabin built on it about 50 years ago does not appear to have been shifted.

LANDSLIDE DEPOSITS

Landslide deposits of Holocene age are mapped in 18 widely scattered localities in the Lemhi Pass thorium district (pl. 1). They range in size from one north of Pattee Creek that is 200 by 400 feet to one near the center of Yearian Creek basin that is 7,500 feet long and has an average width of 3,300 feet. The largest landslide, however, is only partly in the area and is shown at the southeast corner of plate 1. This landslide (figs. 11, 12*C*) underlies most of Little Eightmile Creek basin, having a length of about 3 miles and an average width of almost 1 mile. Some of the areas of landslide deposits are the result of more than one landslide. The 7,500-foot-long area of landslide deposit near the center of Yearian Creek basin is the product of at least four separate landslides (fig.

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FIGURE 11.—Large landslide filling headwaters of Little Eightmile Creek basin in southeast corner of Lemhi Pass district.

13*C*). They can be roughly outlined by the various lobes that make up this deposit. They slid south, northwest, east, and west from steep hillsides into the valley of Yearian Creek. The two large landslides southeast of this big landslide deposit each were formed by two coalescing landslides. Another type of multiple landslide is seen along the northwest side of Reese Creek. Here the entire landslide first slid; later a second slide occurred but only the lower part of the old landslide, south of the road, moved. The tops of both movements are marked by prominent scarps. All the landslides are of the slump type. Their upper edges are commonly marked by one or more arcuate scarps. These scarps are particularly well formed on the several landslides that slid off peak 7,073, which lies between Yearian Creek and the South Fork of Yearian Creek. The landslide deposits are all marked by a hummocky surface on which small ponds or springs may be present. Hummocky surfaces are especially well developed on the landslide on the North Fork of Everson Creek near the east edge of the area, the 7,500-foot-long slide near the center of the Yearian Creek basin, and the slide in Little Eightmile Creek basin in the southeast corner of the area (fig. 11). A small pond has formed just below the scarp on the southernmost small landslide on Bear Creek, and several ponds occur scattered in hollows in the large landslide on Little Eightmile Creek. Many of the lakes are ephemeral, but at least in early summer serve as a source of water for cattle. In addition to the small lakes that occur in the irregular poorly drained pockets within the landslides, a small lake was formed on a branch of Yearian Creek owing to damming of a tributary by a landslide.

Most of the landslides overlie or are adjacent to volcanic rocks of various types, either the Challis Volcanics or the tuffaceous sedimentary rocks, and many are adjacent to faults. The volcanic rocks weather much easier than the Precambrian quartzite. Furthermore, the product of weathering of the volcanics is a brown soil which when wet becomes a slippery mud. The tuffaceous sedimentary rocks contain considerable bentonite and make an even more slippery weathering product than the Challis Volcanics. Although the area underlain by the tuffaceous sedimentary rocks is considerably smaller than that underlain by the Challis, some of the larger landslides are found upon it in the Yearian Creek area (fig. 13*C*). The coincidence of landslides and faults in many places suggests that earthquakes that occur during faulting may have been the triggering mechanism for individual landslides (fig. 2).

The landslides are made up of soil plus various types of rock fragments. The most common type of rock fragment in most landslides is a dark flow rock from the Challis Volcanics. In some slides this is mixed with Precambrian quartzite. In one small slide into a north-flowing tributary of Agency Creek, the rock clasts are entirely of quartzite. The large slide in Little Eightmile Creek has Madison Limestone pieces in addition to those of flow rock and quartzite. Although some of the biggest landslides occur in the tuffaceous sedimentary rocks, fragments of this rock type are not seen in the landslide deposits, as they disintegrate quickly by weathering.

MUDFLOW

One Holocene mudflow is found on the south side of Agency Creek about 2,000 feet northeast of White Creek. The head of the mudflow is at an elevation of 6,450 feet in Precambrian quartzite just north of the large fault that separates Challis Volcanics from the quartzite. The mudflow moved northwestward for 4,300 feet to Agency Creek, a drop of 850 feet. It had an average width of 500 feet. The most prominent feature of this mudflow is the somewhat sinuous, bumpy ridges 15-30 feet high that bound the edges of the flow. These ridges were formed by drag along its edges. The top of the flow between the small ridges is fairly smooth. The mudflow is made up of angular pieces, 0.12-5 in. across, of dark-brown flow rock incorporated in a dark-brown soil.

The mudflow is a fairly recent feature, as it cuts through terrace deposits and its features are sharp and have not been greatly changed by erosion. On the other hand, it was not formed in the last few years, as it was examined in 1952 by Sharp and Cavender (1962, p. 20), and its toe along Agency Creek has been eroded.

ALLUVIUM

Alluvium makes up the unconsolidated deposits formed in Holocene time along various streams. It occurs where the stream gradient lessens, allowing the sediment to settle out. In most areas this is where the valley widens. The largest area of alluvium is along the Lemhi River valley (partially shown on pl. 1). Other areas containing alluvium are along Peterson, Yearian, Bear, Frying Pan, Trail, Agency, and Pattee Creeks.

Alluvium consists of brown sand, silt, and clay, mixed with some gravel. Gravels are mainly subrounded to rounded Precambrian quartzite, although in some areas a

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few pebbles of dark flow rock or diorite are found. The various types of sediment are commonly well sorted. For example, near Lemhi in the Lemhi Valley, a 1-foot-thick layer of brown silt overlies a several-foot-thick layer of gravel. The relatively small areas of alluvium are the principal areas under cultivation.

STRUCTURE

The structure of the Lemhi Pass thorium district is moderately complicated, having many faults and folds of diverse trend. Faulting is the major structural element (pl. 1) and both steeply dipping faults and thrust faults are found. Ages of the faults are difficult to estimate unless the faults cut Challis Volcanics or younger rocks and can thus be demonstrated to be of Tertiary or younger age. Some small faults are entirely within rocks of Precambrian age. These faults may also be of Tertiary age, but they could be as old as Precambrian. Much of the faulting, however, is known to have occurred after at least part of the Challis Volcanics of Paleocene(?) and Eocene age were deposited. Little trace of the large faults, which cut Challis Volcanics, was found in the tuffaceous sedimentary rocks within the Yearian Creek graben. Several small north-striking faults offset the tuffaceous sedimentary rocks in the Pattee Creek area, but no large faults were noted. The present position of these rocks also supports the supposition that movement on the major faults was largely complete by the time this rock unit was deposited. The tuffaceous sedimentary rocks are for the most part lake deposits that were formed in basins. These basins originated by faulting during late Challis time and remain essntially unchanged today. One large basin, in which the tuffaceous sedimentary rocks of Pattee Creek are a very small part, lies along the Lemhi and Salmon River valleys. The sediments are much thicker downstream near Salmon and much thinner upstream near Leadore, as they would be if this area had been a lake and received tuffaceous waterborne sediments. As these topographic basins are still intact and show little evidence of later faulting, the major faulting must have been complete by the time the tuffaceous sedimentary rocks were laid down.

Although the attitudes of rocks of different ages indicate that the rocks were deformed during several periods of time, the principal deformation occurred in mid-Tertiary time when the Challis Volcanics were being laid down. The Challis in eastern and central Idaho and its correlative, the Medicine Lodge Volcanics of Scholten and others (1955) of western Montana, were deposited over a large area and mark a time of major tectonism in this part of the country. Tilting of units occurred during the eruption of these volcanic rocks, as can be seen in the northwest part of the area where the gently dipping younger basalt overlies the moderately dipping basalt-rhyodacite sequence, both units of the Challis. Another example is found in the north-central part of the area where gently dipping sanidine-quartz welded tuff overlies more steeply dipping older Challis Volcanics. The greater part of the faulting also probably occurred in mid-Tertiary time.

THRUST FAULTS

Thrust faults are not common in most of this district and are chiefly confined to the southeast part of the area, although one is found in the northeast corner. The most important fault in the Lemhi Pass district is the Peterson Creek thrust fault (fig. 12*A*), which separates two geologically distinct provinces. Northwest of and beneath this fault occur the older Precambrian rocks in this district, where sericite was formed in abundance from most of the feldspar by metamorphism. These older rocks are fractured by steep faults and contain all the thorium veins. Southeast of this thrust the Precambrian quartzite belongs to the Swauger Formation and to the Lemhi Group, which are mainly feldspathic and contain only a small amount of sericite. South of the mapped area (pl. 1) in the Goat Mountain quadrangle, these rocks contain lead-silver veins. Although only three other thrusts are shown southeast of the Peterson Creek thrust on plate 1, many more are found south and east in the Goat Mountain (Staatz, 1973) and Leadore quadrangles (Ruppel, 1968), where thrusts are the principal type of faulting (fig. 12*B*). Paleozoic rocks, chiefly limestones, also occur here; virtually none have been found north and west of the Peterson Creek thrust. These differences in geologic character suggest very large movement along the Peterson Creek thrust, a movement which may well have been several tens of miles. The Peterson Creek thrust can be traced for 5.6 miles across the southeast corner of the district. It has been followed for another 0.5 mile to the southwest in the southern part of the Goat Mountain quadrangle (Staatz, 1973), where it disappears under an alluvial fan. It dips approximately 30° SE. Along most of its trace it separates different Precambrian units. It is most conspicuous southeast of the junction of the Left and Right Forks of Peterson Creek (fig. 12*A*), where a small break in slope along the steep mountainside occurs along the trace of the thrust. Several miles south of the Peterson Creek thrust, the large Goat Mountain fault thrusts Madison Limestone over the Big Creek Formation (fig. 12*C*). The amount of movement is not known but is large, as at least several thousand feet of Precambrian rocks are cut out as well as more than a thousand feet of Paleozoic rocks. The thrust surface of the Goat Mountain fault is undulating and dips 15°-35° S. About 0.5 mile south a somewhat steeper dipping thrust repeats part of the Madison Limestone (fig. 12*C*). This thrust has had much less movement than the Goat Mountain thrust and may be a subsidiary to the latter thrust, as is indicated by its position and steeper dip. Another thrust is found southeast of the Peterson Creek thrust on the east side of Peterson Creek that moves Swauger Formation over the Big Creek Formation. This fault dips approximately 11°W. Another thrust occurs in the northeast corner of the district.

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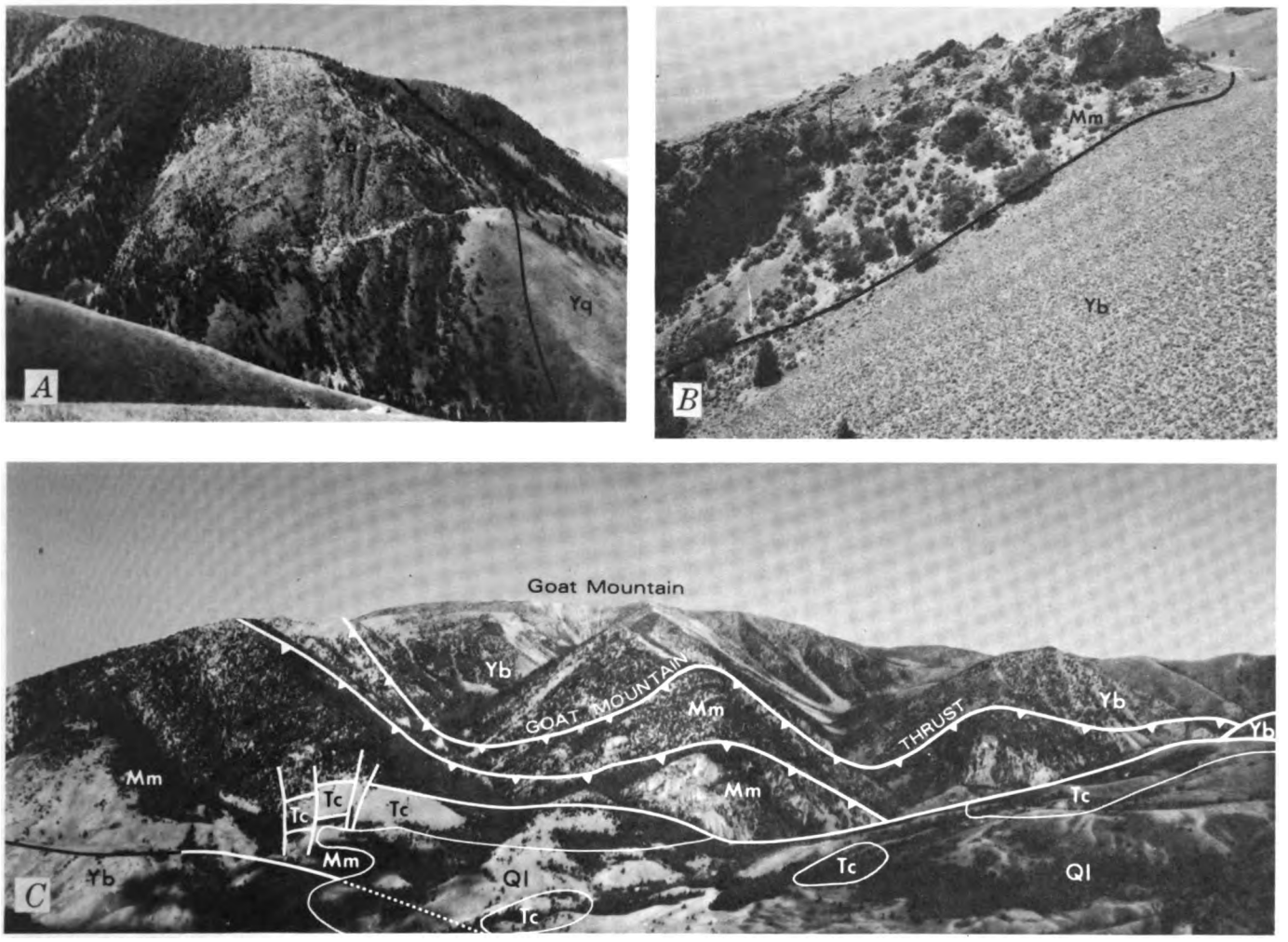


FIGURE 12.—Thrusts. *A*, White scar on mountainside marks trace of Peterson Creek thrust. Rocks of upper plate consist of Big Creek Formation (Yb) in thrust contact with Swauger Formation (Ysw); those of the lower plate consist of Precambrian quartzite (Yq) and siltite (Ys). Picture taken looking south across Right Fork of Peterson Creek. *B*, Light-gray Madison Limestone (Mm) thrust over Big Creek Formation (Yb) 1.5 miles south of the district. *C*, Thrusts (toothed) and steep faults along the southeast side of Goat Mountain in Southeast corner of Lemhi Pass district. Yb, Big Creek Formation; Mm, Madison Limestone; Tc, Challis Volcanics; Ql, landslide deposits.

It lies east of Sheser Creek and is marked by a flat ledge of discontinuous quartzite breccia. The ledge forms prominent outcrops as much as 10 feet thick that overlie highly fractured quartzite. Rocks of the Challis Volcanics occur in the upper plate of this thrust. The fault surface curves from practically horizontal near its easternmost exposure to a gentle westerly dip just east of Sheser Creek.

STEEP FAULTS

Steep faults having diverse trends occur in the district but most strike either northwest or northeast. A few faults have a north to north-northwest trend or a west-northwest to east-northeast trend. Some of them change strike. This is most apparent in some of the longer faults, such as the Lemhi Pass and Dan Patch faults in the northeast part of the district, and the Yearian Creek fault in the central part. A fault that crosses the mouth of Yearian Creek changes trend from N. 84° W. near its west end to N. 64° E. in its eastern part. A fault that passes through Wheat Spring in the northern part of the district has an extremely irregular trend that ranges from N. 67° W. to N. 26° E.

The faults are of several ages; younger faults offset older ones (fig. 13*A*). Some of the northeast-trending faults are older than the northwest-trending faults in some parts of the area, but in other parts the reverse is true. This feature is well illustrated in the Yearian Creek graben, a complexly faulted graben that for the most part occupies the Yearian Creek basin. The northeast-trending fault that bounds the west side of this graben is offset by a series of northwest-trending faults. The northwest-trending faults that bound the east side in places are cut by northeast-trending faults, although in another place a northwest-trending fault terminates an

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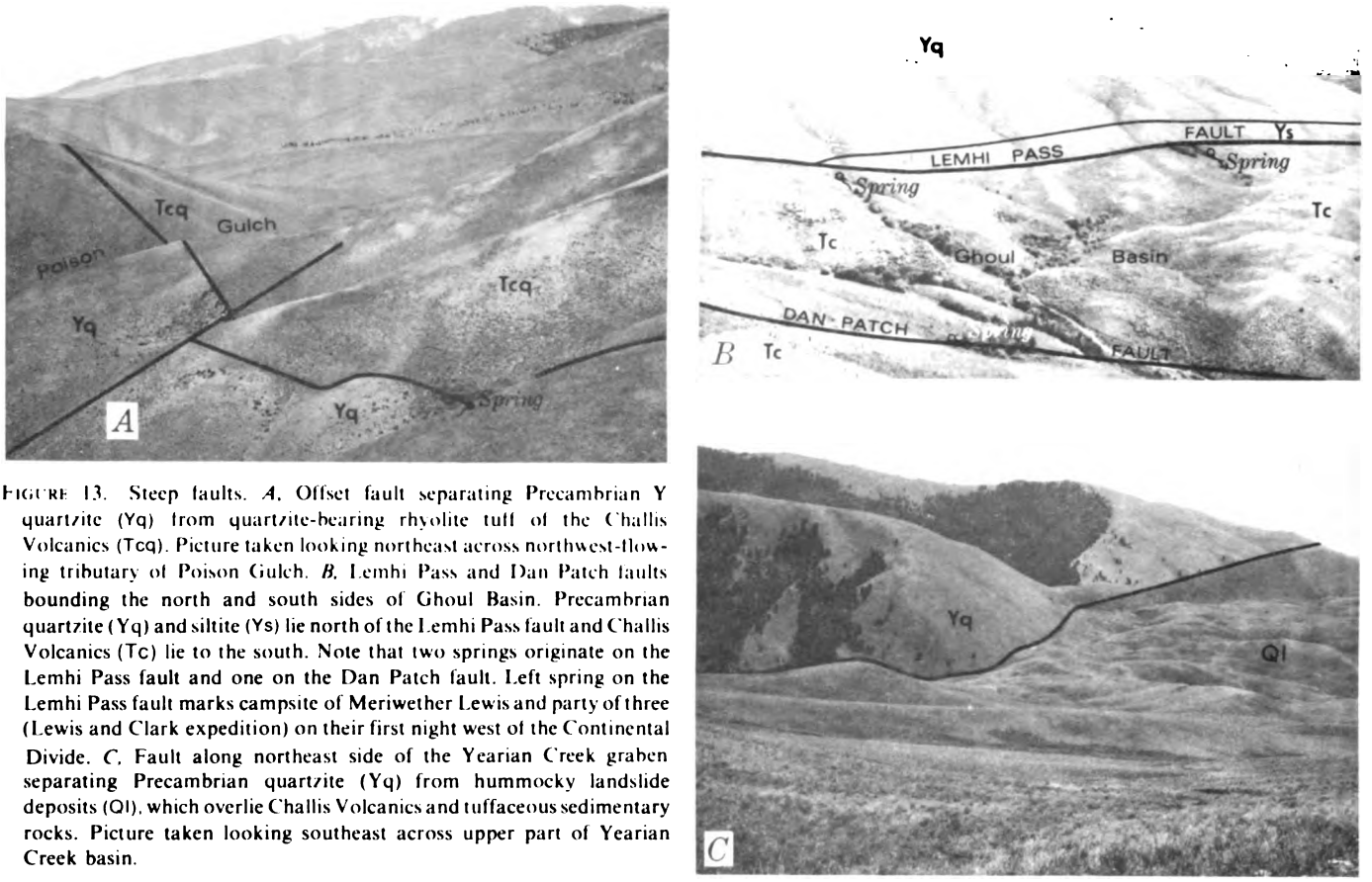


FIGURE 13. Steep faults. *A*, Offset fault separating Precambrian Y quartzite (Yq) from quartzite-bearing rhyolite tuff of the Challis Volcanics (Tcq). Picture taken looking northeast across northwest-flowing tributary of Poison Gulch. *B*, Lemhi Pass and Dan Patch faults bounding the north and south sides of Ghoul Basin. Precambrian quartzite (Yq) and siltite (Ys) lie north of the Lemhi Pass fault and Challis Volcanics (Tc) lie to the south. Note that two springs originate on the Lemhi Pass fault and one on the Dan Patch fault. Left spring on the Lemhi Pass fault marks campsite of Meriwether Lewis and party of three (Lewis and Clark expedition) on their first night west of the Continental Divide. *C*, Fault along northeast side of the Yearian Creek graben separating Precambrian quartzite (Yq) from hummocky landslide deposits (Ql), which overlie Challis Volcanics and tuffaceous sedimentary rocks. Picture taken looking southeast across upper part of Yearian Creek basin.

older northeast-trending fault. Two ages for northwest-trending faults can also be illustrated in the northeastern part of the district where the northwest-striking Dan Patch fault offsets the northwest-trending Bull Moose fault. Thus, there is little correlation between the trend of the faults and their relative age.

Major faults control the position of most of the Challis Volcanics, which are mainly found in down-dropped blocks. In the northeast part of the area three large faults, the Lemhi Pass, Bull Moose, and Dan Patch, bound one or more sides of major outcrop areas of the Challis Volcanics. The Lemhi Pass fault, the northernmost of these, crosses the pass after which it was named by Sharp and Cavender (1962, p. 17). This fault has been traced for 10.6 miles from the eastern to the northern borders of the district. It bounds the north side of Ghoul Basin (fig. 13*B*) and along much of its trace it forms a topographic sag. An old Indian trail, which was used by Meriwether Lewis and William Clark when they first crossed the Continental Divide, follows the hollow that lies along the northwest 5.3 miles of this fault in this district (pl. 1). Ten springs occur along the trace of the fault. The fault develops a zone of brecciated rock in places at least 20 feet wide. The fault has a strike of about N. 70° W. and a steep dip. The north side of the fault was displaced upward relative to the south side a minimum of 2,000 feet, which is the minimum necessary to account for the vertical separation of the quartzite-bearing rhyolite tuff exposed on the south side of the fault near Lemhi Pass and of that exposed on the north side near the east edge of the district. A steeply dipping fault having at least 1,500 feet vertical displacement branches from the Lemhi Pass fault near the east edge of the district.

The Bull Moose fault, which was named after the Bull Moose vein (loc. 76), bounds the southwestern side of a large block of Challis Volcanics. This fault has been traced for 9.6 miles from the east edge of the district to the headwaters of Agency Creek where it is offset about 1 mile to the southeast by the Dan Patch fault and then cut off by the same fault (pl. 1). The strike of the Bull Moose fault varies from N. 29° W. to N. 50° W.; it has a steep dip. The upthrown side is to the southwest.

The Dan Patch fault, which is named after an adjacent vein (loc. 98), has been traced a distance of 12.3 miles from the east edge of the district to a westward-flowing tributary of Pattee Creek, where it is cut off by the Lemhi Pass fault. In its northern part this fault bounds the southern side of Ghoul Basin (fig. 13*B*), and in this area four springs, including the Ghoul Basin Spring, are found along its trace. Its southeastern part is somewhat sinuous, ranging from N. 15° W. to N. 80° W. Its dip ranges from nearly vertical to about 50° SW. Movement along the Dan Patch is large, and the upthrown side is to the northeast.

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In the north-central part of the district the southeast side of the largest block of Challis Volcanics is bounded by the Agency Creek fault. This fault, which was named for the creek that it lies south of and parallels for much of its length, can be traced for 5.4 miles from near the mouth of Flume Creek where it is cut off by the Bull Moose fault to the headwaters of Cow Creek where it terminates on a northwest-trending fault in the Yearian Creek graben. The northeastern part of this fault terminates several north- to north-northwest-trending faults, but its southwestern part is offset in two places by northwest-trending faults. The Agency Creek fault has a general arcuate trend and varies in strike from N. 53° E. to N. 5° E.; it has a nearly vertical dip. Movement along this fault is large, and the upthrown side is to the southeast.

The Pattee Creek fault is a sinuous fracture in the northwest part of the district. This fault, which is named after a major creek it crosses, has been traced for approximately 4.5 miles. The north end of this fault terminates against the Lemhi Pass fault and the south end disappears under alluvium. It separates the rocks of Precambrian age on the east from the Challis Volcanics and tuffaceous sedimentary rocks of Tertiary age that fill the Lemhi Valley on the west. The Pattee Creek fault varies in strike from N. 50° E. to N. 70° E. Movement is large, and the upthrown side is to the southeast.

In the south-central part of the Lemhi Pass district are two long northeast-trending faults, the Yearian Creek and the Reese Creek faults. The northeast ends of both are in the headwaters of Bear Creek. The northernmost one, the Yearian Creek fault, extends from here southwest along the South Fork of Yearian Creek, from which its name is derived. This fault splits near its center. The main fault has an overall length of 5.8 miles and a strike of about N. 65° E. On the Continental Divide this fault dips 68° SE.; to the west it becomes somewhat steeper. Originally this fault (Staatz, 1972, p. 36) was thought to have formed prior to the emplacement of the Challis Volcanics, but further work has shown that it offsets the Challis near its southwest end. The split fault has an approximate length of 2.2 miles and a strike of N. 81° E. Movement along this fault probably occurred several times, not all parts moving at the same time. Movement on the southwest end of the main fault continued after that on the split, as the split is cut off on a northwest-trending fault, but the main part of the Yearian Creek fault offsets this same fault. One to two miles southeast of the Yearian Creek fault is the Reese Creek fault. This fault lies along the northwestern side of the Reese Creek valley, after which it is named. It has a general N. 46° E. strike and a known length of 6.5 miles. Challis Volcanics along its southwest side indicate that this is the downthrown side.

A major geologic structure, the Yearian Creek graben, occupies most of the Yearian Creek basin. This is a complexly faulted wedge-shaped graben (fig. 13*C*), formed during several periods of faulting. The central part of the graben is poorly exposed as much of it is covered with either landslide debris or older glacial deposits. Where the Quaternary sediments are not present, this part of the graben can be seen to be made up principally of Challis Volcanics and tuffaceous sedimentary rocks, the latter being exposed in the central part and the former along the edges. Quartzites of Precambrian age occur in the surrounding uplifted blocks. The west side of the graben is bounded by a northeast-trending fault that is broken into five segments by northwest-trending cross faults. The east side of the graben is bounded by a northwest-trending fault (fig. 13*C*) that is cut into four major segments by northeast-trending faults. A small block of silicified siltite has been faulted up in the center of the graben near the junction of Yearian Creek with the South Fork of Yearian Creek. The amount of movement on the graben is difficult to estimate, but the central part of the graben forms a broad valley whose surface is 1,000-1,700 feet below the Ramsey Mountain ridge to the west and 2,000-3,00 feet below the Continental Divide to the east. These, of course, are minimal figures as the uplands to the west and east have been eroded and the Challis Volcanics stripped off them since the graben was formed.

TILTING AND FOLDING

The rocks in the district also have been tilted and folded. Deformation came at several different times, as angular unconformities occur between the rocks of Precambrian age and the Challis Volcanics, between some of the units within the Challis Volcanics, and between the Challis and the tuffaceous sedimentary rocks. This can be clearly seen north and west of Pattee Creek where the Precambrian quartzites either strike N. 55°-75° W. and dip 25°-45° NE. or strike N. 3°-44° E. and dip 15°-22° SE., as compared to the attitude of the nearby Challis Volcanics, which strike N. 25° W. and dip 42° NW. To the west this Challis is overlain by the tuffaceous sedimentary rocks that strike N. 80° W. to N. 76° E. and dip 22°-70° S. The irregular contact of Challis Volcanics on quartzite can be seen west of the Continental Divide and just southwest of Lemhi Pass. Similarly, irregular contacts and diversely dipping beds can be seen between the Challis Volcanics and the tuffaceous sedimentary rocks in the northwest corner of the area on both sides of Pattee Creek.

In general, the rocks of Precambrian age south of the Peterson Creek thrust fault strike north and dip to the east. They have a similar attitude north of the thrust except in the northernmost part of the district where most beds have an approximately east-west strike and dip to the north. Generally the dips are moderate, although in some places they are steep and in a few places they are overturned. Quartzite beds are commonly massive and the bedding may be indistinct. Crossbedding in certain places aids in determining the top sides of the beds. A well-developed clevage is common in the quartzites in much of the eastern half of the area north of the Peterson Creek thrust (pl. 1). Where

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present, it is commonly much more distinct than the bedding, with which it can be easily confused. Cleavage is controlled by parallel orientation of sericite or chlorite. The relation of the attitude of the cleavage to that of the bedding has proved useful in recognizing overturned beds in the Belt Supergroup in the Coeur d'Alene region (Shenon and McConnel, 1940, p. 440-444). I have also used the cleavage for determining the top sides of the beds, and where checked against crossbeds, they were found to be in agreement.

Most of the Challis Volcanics strike northwest, although some strike northeast and dip 30° to 50° in a northerly direction. In a few places they dip more steeply, and some of the units in the Flume Creek-Agency Creek area are overturned.

The attitudes of the tuffaceous sedimentary rocks may vary from outcrop to outcrop. The strike and dip may be in almost any direction, although the dips are generally 15° to 40°. This widespread variation, although in part due to later deformation, appears in large part to be due to the original dip of the beds, which were laid down on an irregular topography.

Although folding is much less common than faulting, eight relatively small folds occur in the district. Five of the folds are entirely in Precambrian quartzite, two are in the Challis Volcanics, and one in tuffaceous sedimentary rocks. Whether they were all formed in late Tertiary time or whether they formed at several different times is not certain. They range in traceable length from 0.3 to 3.6 miles. The largest fold is a syncline which lies in a horst of quartzite between the Dan Patch and Bull Moose faults in the eastern part of the district. Northeast of it, across the Bull Moose fault, an anticline and a syncline occur in the Challis Volcanics. Although the axes of six of the folds have a northwest strike, they are for the most part not parallel. The folds apparently are produced by local stresses rather than by regional forces, as indicated by their wide areal distribution, relative shortness, and diverse trends.

VEINS

Four kinds of veins are found in the Lemhi Pass thorium district: (1) Thorium veins, (2) copper veins, (3) iron veins, and (4) barren quartz veins. Thorium veins greatly outnumber the other types of veins, making up 87 percent of the 251 veins found in this area. Copper and barren quartz veins each make up 6 percent of the total and iron veins less than 1 percent.

With but one exception, all the veins in the district intrude rocks of Precambrian age. The veins lie north of the Peterson Creek thrust fault, and the country rock is chiefly a fine-grained micaceous quartzite. The 14 veins at localities 1, 14, 135, 149, 182, 183, 188, 190, 191, and 192, however, occur in siltite. As the quartzite is much more widespread than the siltite, either rock type appears equally favorable as a host rock for veins.

THORIUM VEINS

Thorium veins are scattered over a large area in the Lemhi Pass district (pl. 1). The veins are in shear zones, and commonly both parallel and en echelon veins occur in the same zone. Where the vein or veins are exposed only in a series of trenches, the extension of a particular vein and the number of veins present may be difficult to determine. An example of this is at the Shear Zone vein (loc. 75), which consists of a series of veins, lenses, and secondary splits that occur almost continuously for more than 6,000 feet. In some trenches several distinct veins are exposed, but in others there may be only one. Where several closely spaced veins occur in one zone, they may not be shown on plate 1. Each vein locality, however, is given a separate number, and each vein at every locality is noted in table 2. The number of closely spaced veins at any locality ranges from one to six. Thorium veins occur at 173 of the 195 vein localities shown on plate 1. A total of 219 thorium veins are known from these various localities. Generally only one major vein was found at any locality.

Although claim names are known for many veins at various localities, numbers were used instead of claim names for several reason: (1) Names on many claims could not be ascertained owing to loss or destruction of notices, (2) boundary markers commonly have disappeared, and (3) some veins are on several claims. Names, where known, are given in table 2 and throughout the text.

Although the veins are widely scattered, they tend to be concentrated in three more or less distinct areas: (1) A fairly large area in the northeastern part of the district in the headwaters of Agency and North Frying Pan Creeks, (2) the northwestern part of the district along the Pattee Creek drainage, and (3) an area across part of the headwaters of Peterson, Reese, and Yearian Creeks. Scattered veins occur in other areas. Veins in the southwest part of the district, on the mountain block dominated by Ramsey Mountain, tend to be small, scattered, and low grade. In addition to the veins shown on plate 1, a vein is found on the north side of McDevitt Creek, 4 miles west-southwest of Tendoy, and several stringers occur in a shear zone on the Daisy Nielsen ranch near the headwaters of Sandy Creek, 4.3 miles north-northwest of Poison Gulch Spring in the northwest part of the mapped area. None of these veins is large.

Few thorium veins are exposed. Those which crop out generally are those which have a high quartz content and are on a ridge. The veins are primarily made up of quartz, microcline, and various iron oxides. At the surface, the microcline commonly weathers and the iron oxides become soft and pulverulent. Only a vein consisting mostly of quartz will be more resistant than the surrounding country rock and protrude above it. Thorium-bearing minerals tend to be concentratedi in the iron-oxide-rich parts of the vein. Thus, parts of veins that crop out are generally less radioactive than those parts that do not. A glance at the map (pl. 1) will

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show the presence of many veins along ridges. Some veins, such as the Last Chance (loc. 82), Cago No. 12 (loc. 49), Lucky Horseshow (loc. 1), and Silver Queen 52B (loc. 146) were first discovered on ridges and then extended into covered areas by a series of trenches. Many areas that are under thick soil cover have been virtually unexplored. Although a great number of bulldozer trenches are found in parts of this area, most of the exploration has been rather superficial. The principal reasons are that radioactive minerals were of no economic interest until the late 1940's, and there is currently (1976) no open market for thorium. The sudden demand for uranium in the late 1940's led to widespread exploration for radioactive deposits throughout the United States. Radioactive deposits were first discovered in the Lemhi Pass district in the spring of 1949 by Wayne Hinman (Jarrard, 1957, p. 46). The original discovery encouraged a flood of prospectors to come into this area and many additional discoveries were made in the next few years. The original exploration was in the northern part of the district, where most of the prospects are located. Veins were found in the southern part of the area by the 1950's. The lack of a ready market for thorium caused a gradual lessening of prospecting activity. Prospectors having claims either sold their properties or tried to hold on until a market for thorium developed. Some of the prospectors banded together to form small companies in order to better handle the assessment work. From about 1965 through 1974 most of the activity was assessment work and little new prospecting was carried out.

SIZE AND ATTITUDE

The thorium veins are relatively thin tabular bodies having widely varying dimensions (fig. 14*A*, *B*, *C*). They range in length from a few feet to at least 4,350 feet. The known lengths of the various veins in the district are given in table 2. Because of poor exposures (fig. 14*B*), all are minimum lengths. Some veins, such as those at localities 2, 11, 62, 68, 77, 80, 117, 120, and 149, are exposed at only one spot in a trench, and their continuity, if any, is not known. Others can be traced possibly 6 feet across or along a single trench. The vein of longest continuous known length is the Last Chance (loc. 82). The Shear Zone vein, which appears longer, having been traced for 6,000 feet, is actually a shear zone along which several closely spaced branching and en echelon veins are found. Owing to poor exposures of this zone, the exact length of the several veins is poorly known, and the entire zone is treated as a single unit in table 2.







FIGURE 14.—Thorium veins. *A*, South vein (black) of Silver Queen 52B (loc. 146) dipping into wall of cut. *B*, Northwestern end of vein (dark gray) at locality 122 exposed in a bulldozer trench on the Continental Divide. *C*, 1-foot-thick vein, at locality 150 in wall of a cut, is in gouge of the Pattee Creek fault.

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TABLE 2.—*Dimensions and attitude of thorium veins in the Lemhi Pass area*

[n.d., not determined]

Locality No. (pl. 1)	Name of claim or vein, where known	Number of veins	Veins, if more than one or branched	Exposed length (ft)	Thickness (ft)	Strike	Dip
1	Lucky Horseshoe	1		1,400	0.1-20	N.70°W.	50°-75°N.
2	In Trust	1		n.d.	n.d.	n.d.	n.d.
3		(1)		n.d.	n.d.	n.d.	n.d.
4		1		80	.1-1.3	N.70°W.	75°SW.
5		1		100	1.2-1.5	N.50°W.	53°SW.
6		1		6	.5	N.16°E	29°NW.
7	Buffalo (Stenson)[2]	1		100	1.5-2.2	N.75°W.	75°SW.
9	Betty Jo Nos. 1 and 2	1		425	1.0	N.35°E.	20°NW.
10		1		200	n.d.	N.55°E.	n.d.
11		1		n.d.	n.d.	n.d.	n.d.
12		1		n.d.	n.d.	n.d.	n.d.
13		1		n.d.	.3	n.d.	n.d.
14		1		n.d.	.5+	n.d.	n.d.
15	Big Dean No. 1	1		100	.5+	n.d.	n.d.
16		1		150	0.1-0.2	N.40°W.	60°SW.
18	Buffalo	4	Vein in trench a	10	1	N.80°W.	n.d.
			Vein in trench b	20	2	N.80°W.	50°SW.
			Vein in western trenches	430	1.5-2.5	N.70°W.	Steep S.
			Vein in easternmost trench	550	1.0-11	N.5°-27°W	60°SW.
19	Black Bull Fraction No. 4	1		40	10+	n.d.	n.d.
20	Black Bull No. 3	1					
			Northwest-trending branch	130	.5-1.3	N.77°W.	65°-80°NE.
			Northeast-trending branch	5	.2-0.5	N.77°E.	77°NW.
21	Deer Fraction 1A	6	Principal Vein	1,220	1-10	N.87°W.	45°-70°SW.
			First vein south	8	8	n.d.	n.d.
			Second vein south	8	7	n.d.	n.d.
			First vein north	6	1.5	N.87°W.	n.d.
			Second vein north	6	4.0	N.87°W.	n.d.
			Third vein north	6	1.3	N.87°W.	n.d.
22	Deer No. ?	(3)		6	1	N.76°W.	65°SW.
23	Deer No. ?	1		50	n.d.	N.67°W.	n.d.
24	Deer No. ?	1		250	2	N.68°W.	Steep.
29		1		15	.1-.4	n.d.	n.d.
31		(4)		n.d.	n.d.	n.d.	n.d.
33		2	North vein	6	.5-1.2	N.25°W.	84°NE.
			Central vein	6	n.d.	n.d.	n.d.
35		1		80	.7	N.57°W.	63°SW.
37	Black Bear No. 2	2	Northeast vein	135	3-32.5	N. 45°W.	Steep.
			Southwest vein	6	1	N.45°W.	n.d.
38		1		18	1	N.47°W.	n.d.
39	Big Lost Nos. 1 and 2	1		500	n.d.	N.29°W.	n.d.
40	Thorite No. 3	1		350	0.3-0.5	N.86°W.	82°SW.
41	Uranium Queen or Surprise Nos. 5 and 6.	1		50	[2]2-3	N.60°W.	65°SW.
42	Three and one[2]	1		20	[2].5-1	[2]N.30°E.	[2]89°SE.
45	Wonder	1		920	0.7-10	E.-W.	40°-80°S.
47	Badger No. 10	1		20	1.5-7	N.42°W.	Steep.
49	Cago No. 12	1		2,625	.2-16	N.45°-55°W.	45°-55°SW.
50		1		150	.2	N.38°E.	n.d.
51	Cago No. 10	4	Main vein	100	1.3	N.45°W.	Steep.
			Northeast veinlet	6	n.d.	n.d.	90°.
			Middle veinlet	6	n.d.	n.d.	35°N.
			Southwest veinlet	6	n.d.	n.d.	75°S.
52	Contact	1		1,940	.5-10	N.70°E.-N.45°W.	25°-60°S.
53		1		90	2	N.45°W.	n.d.
54		1		20	n.d.	N.75°W.	n.d.
55		2	East vein	60	3+	N.39°W.	Steep SW.
			West vein	50	4.5	N.30°E.	40°NW.
56		1		150	1+	N.85°W.	n.d.
57		1		108	2-5	N.75°E.	n.d.
58		1		45	1-1.5	N.45°W.	n.d.
59		1		400	2-10	N.70°W.	n.d.
60	Benny	1		100	.7	N.80°W.	n.d.
61		1		55	n.d.	n.d.	n.d.
62		1		n.d.	n.d.	N.38°W.	n.d.

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TABLE 2.— *Dimensions and attitude of thorium veins in the Lemhi Pass area*—Continued

Locality No. (pl. 1)	Name of claim or vein, where known	Number of veins	Veins, if more than one or branched	Exposed length (ft)	Thickness (ft)	Strike	Dip
63	.....	1	.....	72	.9	N.75°W.	n.d.
64	Beaverhead (Montana)	1	.....	520	9-25	N.80°W.	50°SW.
65	.....	1	.....	15	n.d.	n.d.	n.d.
66	.....	1	.....	140	3-8	N.77°E.	n.d.
67	Trapper No. 1	1	.....	235	5-11	N.75°-85°W.	45°-60°SW.
68	Lucky R or Little Dandy No. 5.	1	.....	n.d.	n.d.	n.d.	n.d.
69	.....	1	.....	n.d.	n.d.	n.d.	n.d.
70	Wonder No. 18	2	North vein	n.d.	1.0	N.75°W.	n.d.
			Central vein	550	0.7-1.2	N.70°W.	50°-65°SW.
72	Little Dandy No. 1	1	.....	95	1.0-2.5	N.78°W.	90°.
73	Shear Zone	(5)	.....	6,000	.5-2.5	N.55°W.	65°-81°SW.
74	Dictator No. 6	1	.....	n.d.	.1	n.d.	n.d.
75	Black Rock or Radio[2]	2	Northwest-trending vein ...	1,610	1.3-6	N.47°W.	70°-75°SW.
			Northeast-trending vein	135	.7-1	N.75°E.	75°-80°NW.
76	Bull Moose[2]	1	.....	[2]60	[2].1-0.3	N.45°W.	85°SW.
77	Brown Bear No. 3	1	.....	n.d.	n.d.	n.d.	n.d.
78	Brown Bear No. 2	2	North vein	65	1	N.79°W.	n.d.
			South vein	400	.5	N.80°W.	n.d.
79	Skyline No. 1	1	.....	100	.4	N.70°W.	n.d.
80	Brown Bear No. 5	1	.....	n.d.	n.d.	n.d.	n.d.
82	Last Chance	1	.....	4,350	5-40	N.40°-80°W.	40°-70°SW.
83	Big Horn	1	.....	n.d.	.5	n.d.	n.d.
85	Frying Pan and Frying Pan No. 2[2].	3	Western vein	100	3	N.30°W.	54°SW.
			Central vein	10	.7	N.55°W.	n.d.
			Southeast vein	1,100	.5-.7	N.36°-73°W.	72°-78°SW.
86	M-S-D No. 7	1	.....	30	.5+	N.48°W.	n.d.
87	M-S-D No. 1	1	.....	20	2-2.5	N.30°W.	60°SW.
88	Black Widow Nos. 15 and 16.	1	.....	10	n.d.	N.55°W.	n.d.
89	G&G Nos. 6 and 8	1	.....	1,300	1-2	N.48°W.	Steep.
90	G&G Nos. 1, 2, and 5	2	North vein	1,600	.8-2	N.48°W.	58°SW.
			South vein	55	n.d.	N.35°W.	Steep.
91	B. and B. Nos. 1 and 4	1	.....	20	.5	N.74°W.	90°.
92	Atomic Blast Nos. 7 and 8.	1	.....	n.d.	n.d.	n.d.	n.d.
93	Thorite No. 1	1	.....	300	.9	N.45°W.	85°NE.
94	Saddlehorn No. 3	1	.....	300	.2-.5	N.41°W.	n.d.
95	H.R.S. No. 1	1	.....	20	0.9	N.70°E.	45°SE.
96	Lucky Day Nos. 1 and 2 ..	2	West vein	25	.5	N.45°W.	n.d.
			East vein	85	1	N.38°W.	90°.
97	Dan Patch No. 3	1	.....	n.d.	n.d.	n.d.	n.d.
98	Dan Patch Nos. 1 and 2 ...	2	North vein	508	2.0-2.5	N.75°W.	55°-75°SW.
			South vein	105	.5-6	N.40°-77°W.	70°SW-90°.
99	.....	1	.....	225	.5-0.8	N.81°W.	n.d.
100	.....	1	.....	150	5.7	N.82°W.	82°SW.
101	.....	1	.....	100	n.d.	N.80°E.	n.d.
102	Big Thor Nos. 1 and 2	1	.....	125	.3	N.65°W.	Steep.
103	.....	1	.....	50	n.d.	N.36°W.	n.d.
104	Silvertip Nos. 1, 2, and 3 ..	2	North vein	25	1.0	N.50°W.	n.d.
			South vein	50	n.d.	N.35°W.	n.d.
105	Atomic Blast	2	North vein	15	.1-1.3	N.31°W.	20°SE.
			South vein	225	.4	N.65°E.-N.82°W.	n.d.
106	Orpha	1	.....	115	6	N.55°W.	n.d.
107	Reactor Nos. 1, 3, and 5 ...	4	Northeast vein	1,300	.8-5	N.28°-48°W.	70°-85°SW.
			Southwest vein	74	1-3	N.63°W.	55°SW.
			Northwest vein	290	1-3.5	N.23°W.	45°SW.
			Southeast vein	656	.3-.5	N.28°-48°W.	n.d.
108	Elkhorn	1	.....	630	.04-1.5	N.28°-55°W.	90°.
109	Lucky Strike No. 2	1	.....	9+	1.5	N.72°W.	49°NE.
110	.....	1	.....	225	.3-2	N.53°W.	50°SW.-90°.
111	ThO_2 Nos. 5 and 6	2	North vein	20	2	N.86°W.	90°
			South vein	20	3	N.86°W.	90°.
112	Lucky Strike No. 3	1	.....	10	1	E.-W.	80°N.

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TABLE 2. *Dimensions and attitude of thorium veins in the Lemhi Pass area*—Continued

Locality No. (pl. 1)	Name of claim or vein, where known	Number of veins	Veins, if more than one or branched	Exposed length (ft)	Thickness (ft)	Strike	Dip
113	Chief Tendoy Nos. 13 and 14.	1		200	1	N.33°W.	75°SW.
114	Welco No. 10	1		50+	0.4	N.58°W.	n.d.
115	Chief Tendoy No. 6	1		50+	n.d.	N.68°W.	n.d.
116	Chief Tendoy No. 3			50	n.d.	N.47°W.	n.d.
117		1		n.d.	n.d.	n.d.	n.d.
118		1		n.d.	1.3	n.d.	n.d.
119		1		n.d.	.7+	n.d.	n.d.
120		1		n.d.	.5	n.d.	n.d.
121	Chief Tendoy No. 2	3	Vein in west pit	n.d.	n.d.	n.d.	n.d.
			North vein, east pit	3	.5	n.d.	35°NW.
			South vein, east pit	3	n.d.	n.d.	n.d.
122		1		950	.8-1.5	N.32°-45°W.	71°SW.
123	Mining claim No. 7	1		550	.5-2	N.83°E.	n.d.
124	Thorelsen No. 2	1		16	3.5	N.57°W.	78°NE.
125	Welco Nos. 8 and 9	1		15+	3.1	N.70°W.	57°SW.
126		1		90	.7	N.84°E.	70°SE.
127	Ruby Red	3	Northwest vein	12	.02	N.70°W.	50°SW.
			Northeast vein	110	.3-.6	N.86°E.	n.d.
			East vein	10	1.7	N.56°W.	55°SW.
128		3	Northeast vein	n.d.	1.5	n.d.	n.d.
			Central vein	n.d.	.7	n.d.	n.d.
			Southwest vein	n.d.	.5	n.d.	n.d.
129		1		15	.6-1.2	N.55°W.	n.d.
130	Spring Canyon Nos. 1 and 2.	1		10	.7	N.2°E.	n.d.
131	Lookout No. 1	1		50	1.6-1.8	N.17°W.	Steep.
132	Sauser No. 1	1		155	.2-.7	N.34°W.	90°.
133	Welco No. 7	1		27	.08-1.7	N.40°E.	20°SE.
134		1		n.d.	n.d.	n.d.	n.d.
135		3	North vein	6	.2-.3	N.77°W.	n.d.
			Central vein	150	.6	N.77°W.	82°SW.
			South vein	200	1.5	N.57°W.	72°SW.
136	Apex	1		135	1.5-3	N.75°W.	55°-60°NE.
137	Red Hill No. 1	1		n.d.	1-1.8	N.40°W.	19°NE.
138		1		75	.7	N.84°W.	n.d.
139		1		n.d.	n.d.	N.19°E.	n.d.
140		1		60	.2-.4	N.75°E.	55°SE.
141	Silver Queen No. 9	1		n.d.	.2	N.55°W.	31°SW.
142		2	East vein	n.d.	n.d.	n.d.	n.d.
			West vein	75	25	n.d.	n.d.
143	Silver Queen No. 2	1		45	.2-.3	N.55°W.	72°SW.
144		1		n.d.	n.d.	n.d.	n.d.
145	Lone Star No. 2	2	North vein	268	1.5-3	N.75°W.	45°-65°SW.
			South vein	555	10-31.5	N.75°E.-N.75°W.	75°-80°N.
146	Silver Queen 52B	4	South vein	750	.6-3	N.80°W.	34°-55°SW.
			South-central vein	125	.7-2	N.80°W.	55°SW.
			North-central vein	40	.5-2	N.80°W.	n.d.
			North vein	2,080	2-28	N.85°E.	Steep.
147		1		n.d.	n.d.	N.80°E.	n.d.
148	Silver Queen 38A	2	North vein	32	3	N.85°E.	60°NW.
			South vein	210	2-4.5	N.85°E.	60°NW.
149	Idaho No. 3	1		40	.1-.7	N.46°W.	n.d.
150		1		15	1	N.70°W.	40°SW.
151	Iola	1		50	.5-1.2	N.50°W.	50°SW.
152	Iola	3	North vein	500	.7	N.88°E.	60°NW.
			Central vein	2,100	1	N.85°E.	n.d.
			South vein	510	n.d.	N.83°E.	n.d.
153	Nellie B	2	North vein	120	.3-1.5	N.75°W.	70°SW.
			South vein	10	2.5	N.82°W.	n.d.
154	Silver Queen No. 49	1		n.d.	n.d.	n.d.	n.d.
155	Silver Queen No. 49A	1		10	.5	N.50°W.	38°SW.
156	Silver Queen No. 47C	2	Northeast vein	300	n.d.	N.53°W.	n.d.
			Southwest vein	300	n.d.	N.53°W.	n.d.

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TABLE 2.—*Dimensions and attitude of thorium veins in the Lemhi Pass area*—Continued

Locality No (pl. 1)	Name of claim or vein, where known	Number of veins	Veins, if more than one or branched	Exposed length (ft)	Thickness (ft)	Strike	Dip
157		3	Northwest vein	32	.5	N.77°W.	n.d.
			Central vein	50	.8	N.60°W.	n.d.
			Southwest vein	50	.2-.3	N.75°W.	n.d.
158		1		n.d.	.4	n.d.	n.d.
159		1		10	.1-.2	N.70°E.	70°NW.
160		1		25	.5	N.80°W.	n.d.
161	Pine Nos. 1 and 2	1		n.d.	1+	n.d.	n.d.
162		1		12	.9	N.30°W.	n.d.
163	Black Bear No. 1	1		50	3.5	N.72°W.	n.d.
164		2	Northwest-trending vein	20	.7	N.32°W.	62°SW.
			Northeast-trending vein	10	.4	N.84°E.	58°SE.
165	Black Rock	2	Northwest-trending vein	330	1-2.5	N.75°-85°W.	55°-75°SW
			Northeast-trending vein	80	1	N.50°-70°E.	20°NW.
166	Scott	1		600	.2-2	N.68°-85°E.	60°SE.
167		1		7	.2-.3	N.50°W.	40°SW.
168		1		n.d.	n.d.	n.d.	n.d.
169	Katy	1		20	.7	N.35°W.	n.d.
170	Chief Tendoy No. 1	1		110	n.d.	N.16°W.	n.d.
172	Barbara	1		150	1.8-4	N.51°E.	14°NW.
173		1		n.d.	n.d.	n.d.	n.d.
174		1		180	n.d.	N.40°W.	n.d.
175	Ellis	1		n.d.	n.d.	n.d.	n.d.
176		2	Northeast-trending vein	50	n.d.	N.80°E.	n.d.
			Northwest-trending vein	4	.05	N.63°W.	54°SW.
177	Elkhorn No. 5	1		60	.4	N.82°W.	Steep SE.
178	Elkhorn No. 1	1		750	.9-1.5	N.65°W.	78°NE.
179		1		105	1.5+	N.30°E.	35°NW.
180	Viola No. 4	1		50	1.7	N.58°W.	n.d.
181	Viola	1		150	1.1	N.70°W.	56°NE.
185		1		1,550	n.d.	N.38°W.	n.d.
186		1		n.d.	n.d.	n.d.	n.d.
187	Mornell	1		220	.2-9	N.83°W.	68°NE.
188		1		n.d.	n.d.	n.d.	n.d.
189	Thor No. 7	1		n.d.	n.d.	n.d.	n.d.
190	Thor Nos. 1 and 2	2	West vein	150	n.d.	N.-S.	n.d.
			East vein	150	.9	N.55°W.	20°SW.
191		2	West vein	n.d.	n.d.	n.d.	n.d.
			East vein	n.d.	n.d.	n.d.	n.d.
192	ThO_2	2	Main vein	2,860	1-15	N.28°W.	32°NE.-90°
			West vein	740	1-1.3	N.25°W.	Steep.

[1]Irregular veinlets.
[2]Data from Sharp and Cavender, 1962.
[3]Several lenses.
[4]Veinlets in conglomerate.
[5]Several veins; zone treated as a unit.

Fifteen veins are more than 1,000 feet long. These veins are the Shear Zone (loc. 73), Last Chance (loc. 82), main vein at the ThO_2 (loc. 192), Cago No. 12 (loc. 49), central vein at the Iola (loc. 152), north vein of the Silver Queen 52B, Contact (loc. 52), northwest-trending vein on the Black Rock (Montana) property (loc. 75), north vein on the G&G Nos. 1, 2, and 5 claims (loc. 90), Viola (loc. 185), Lucky Horseshoe (loc. 1), vein on G&G Nos. 6 and 8 claims (loc. 89), northeast vein on Reactor (loc. 107), principal vein on Deer Fraction 1A (loc. 21), and southeast vein on the Frying Pan (loc. 85). The first six veins of the above group have been traced for more than 2,000 feet. Further exploration will probably extend the known length of several other veins to more than 1,000 feet.

The thorium veins vary considerably in thickness and range from thin seams to 40 feet thick (table 2). Although some veins pinch and swell abruptly, many are fairly uniform for most of their length, changes in thickness being most common near the ends of the vein. The northwest-trending vein on the Black Rock (Idaho) property (loc. 165) is 1-2.5 feet thick in the 330 feet of its exposed length. The most thorium-rich part of the Cago No. 12 (loc. 49) is about 690 feet long, and the thickness of this part of the bein is 10-16 feet. The northern vein on the Dan Patch Nos. 1 and 2 claims (loc. 98) is 2-2.5 feet thick along its entire known length of 508 feet. The 1,300-foot-long northeast vein on the Reactor property (loc. 107) varies in thickness from 0.8 to 5.0 feet, but the thickness of at least 975 feet of its strike length ranges

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only from 1.5 to 2.0 feet. The maximum thickness of 63 percent of the veins in the district is 1 foot or greater and for 6 percent (16 veins) it is more than 10 feet.

The thorium deposits seem to persist at depth. They are found at elevations ranging from 5,240 to 9,430 feet. The Last Chance vein is exposed on the surface over an elevation difference of about 520 feet. The west adit cuts this vein approximately 160 feet below the surface; the vein is approximately the same thickness in the adit as on the surface. This vein has also been cut in drill holes at least 300 feet below the surface. The northeast vein on the Reactor property (loc. 107) is exposed for 360 feet vertically. Another vein having a large vertical exposure is the central vein on the Iola property (loc. 152), which has been traced intermittently for a vertical distance of about 560 feet.

The attitude of the thorium veins in the 155-square-mile Lemhi Pass district is remarkably similar. A list of all known strikes and dips is compiled in table 2. Most veins have a northwest strike, and the greater part of these strike either N. 40°-60° W. or N. 70°-80° W. (fig. 15). A few, however, show radical departures, and almost every direction, except due north, has been seen. Veins having divergent strike may occupy fractures in the same general area as those having the normal northwest strike. A short vein having a N. 75° E. strike occurs on the Black Rock (Montana) property (loc. 75) adjacent to a much larger vein having a N. 47° W. strike. Similarly, at locality 55 two veins are found: One having a strike of N. 30° E., the other having a strike of N. 39° W. The strike of individual veins commonly varies, as they were intruded along irregular fractures. Five measurements made along the 1,940-foot Contact vein (loc. 52) from east to west show the following variations in strike: (1) N. 70° W., (2) N. 55° W., (3) N. 72° W., (4) east-west, and (5) N. 70° E. Some veins branch, such as the Lucky Horseshoe (loc. 1), the main part of the vein striking N. 70° W. and the largest branch striking about N. 80° E. the Black Bull No. 3 also branches, the main part having a strike of N. 77° W. and the smaller part a strike of N. 77° E.

Most of the veins dip steeply to the south (fig. 15), and 43 percent of them dip between 50° and 80° S. The dips of the rest are scattered over a wide range of values both to the north and to the south. None of the dips, however, were less than 10° and only 15 percent of the veins have dips of less than 40°. South, as noted, is the predominant direction of dip; 73 veins dip to the south (65 percent) and 32 veins dip to the north (28 percent). Eight of the measured veins (7 percent) have a vertical dip. Dips, like strikes, also show considerable variation along the same vein. Dips on the long Last Chance vein range from 40° to 70° S.; four dips measured in the east adit (fig. 30) vary from 43° to 70° S. The Reactor vein (loc. 107), where it is exposed in several places, dips 70°-85° S. The south vein on the Silver Queen 52B property (loc. 146) dips 34°-55° S., and the northwest-trending vein on the Black Rock (Idaho) property (loc. 165) dips 55°-75° SW.

RELATION OF VEINS TO STRUCTURAL FEATURES

Most thorium veins are found along small faults and fractures that are related to faulting of Tertiary age. As previously noted, the veins commonly occur in shear zones which may be as much as 50 feet wide. Rocks in thse zones commonly are thoroughly granulated and are stained with iron oxides. Not only did the movement along these fracture zones start before the veins were introduced, but it also continued during and after the introduction of the veins. A common feature of almost all veins is their brecciated character (fig. 16*A*, *B*, and *C*). The granulation of veins during formation is noted where the first minerals to form generally quartz and microcline—are brecciated, and the fractures are filled by minerals (fig. 16*C*) such as iron oxide minerals, sericite, barite, and thorite, which are in turn brecciated by later movement. Several generations of quartz and feldspar may occur, and at the Last Chance and Chief Tendoy No. 3 and No. 4 claims (locs. 115 and 116) veinlets of later quartz and microcline cut earlier formed microcline and quartz (fig. 16*C*). Quartz, in addition to being granulated, shows stress by the presenc eof strain shadows and sutured borders. Slickensiding is a common feature on the sides of veins and along fractures within many veins. Fracturing is predominantly parallel to the sides of veins.

Although the amount of movement on fractures in which the thorium veins occur is difficult to estimate, most show little measureable movement. In only two places are veins found on faults where substantial offset can be shown. These two places are at localities 149 and 150. At locality 149 a 1-8-inch-thick vein lies in the gouge of the large Lemhi Pass fault zone. At locality 150 a 1-foot-thick vein that can be traced for 15 feet occurs in the gouge of the Pattee Creek fault zone (fig. 14*C*).

Although most of the vein-bearing fractures show little movement, these fractures are related to the major faulting. The greater part of the veins in the Lemhi Pass district are less than 1 mile from either one of the large faults or from smaller cross faults (pl. 1). The greatest concentration of veins is in the northeastern part of the district, where the large Lemhi Pass, Bull Moose, and Dan Patch faults either intersect or approach one another. A second group of veins, in the northern part of the area, occurs near Pattee Creek, where most are either close to the Pattee Creek fault or close to one of several smaller faults. Several veins lie adjacent to cross faults that offset the east side of the Yearian Creek graben. These include the Mornell vein (loc. 187), which is adjacent to a fault along the upper part of Yearian Creek, and seven veins, including the ThO_2 vein, at localities 110, 190, 191, and 192, which are adjacent to a fault 3 miles farther south. Most of the veins that are not close to faults are short and thin.

The strike of the veins in the northeast part of the district may be parallel, at a fairly acute angle, or at a more obtuse angle to the long Tertiary faults; the strike of veins in other

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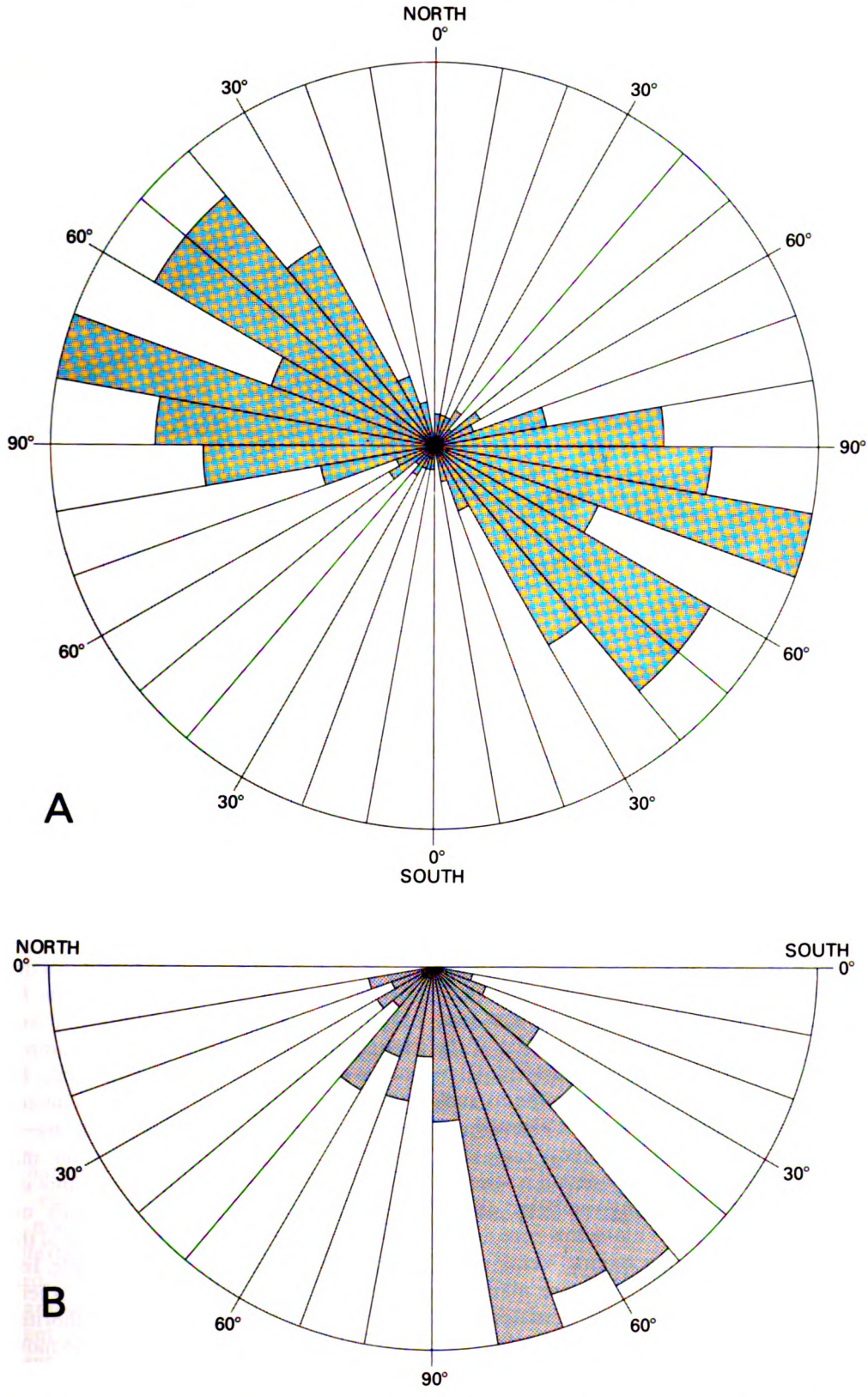


FIGURE 15.—Attitudes of thorium veins in the Lemhi Pass district. *A*, Strike diagram of 182 veins. *B*, Dip diagram of 113 veins.

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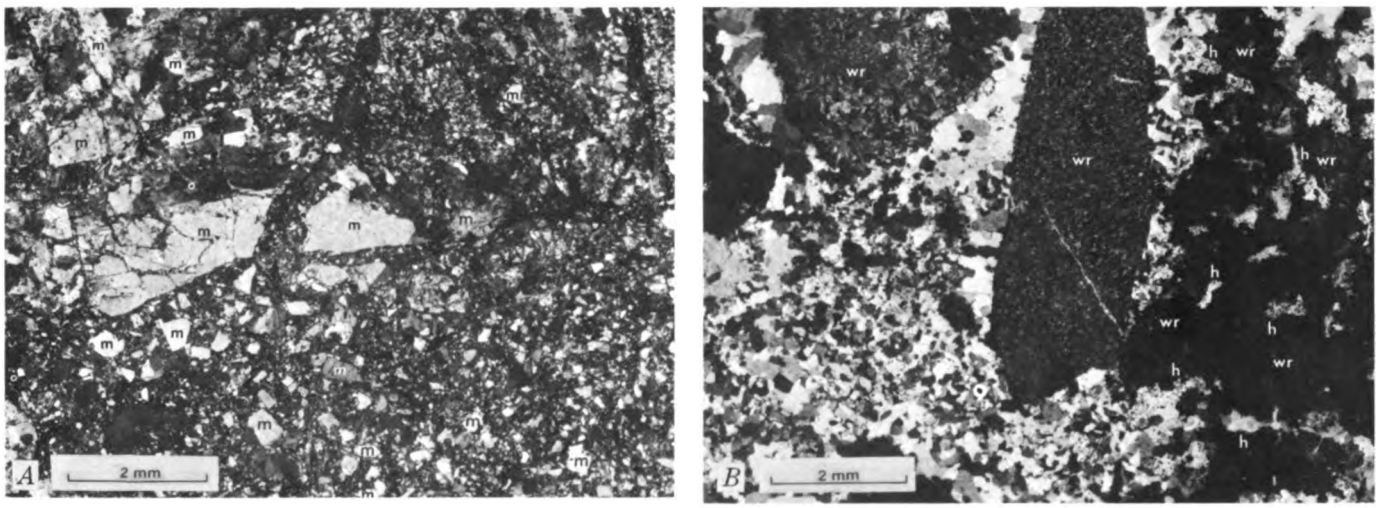


FIGURE 16.—Brecciated and granulated vein material shown under crossed nicols. Photographs by L. S. Hendricks. *A*, Last Chance vein (loc. 82). Fine granulated quartz and microcline with large pieces of microcline (m). Black veinlets are of limonite. *B*, Angular fragments of quartzite wall rock (wr) surrounded by partly granulated quartz in a vein from the Chief Tendoy No. 3 property (loc. 116). Hematite (h) rims small pieces of quartzite on right side of picture. *C*, Large crystals of microcline (m) and limonite (black) cut by later veinlets of feldspar and quartz showing two periods of mineralization in the Last Chance vein (loc. 82).

areas is generally at an obtuse angle to the neighboring faults. Veins parallel to the large faults, as the Lucky Horseshoe (loc. 1) is parallel to the Lemhi Pass fault, and the Black Rock (loc. 25), Bull Moose (loc. 76), Frying Pan (loc. 85), G&G Nos. 6 and 8 (loc. 89), G&G Nos. 1, 2, and 5 (loc. 90), and Reactor (loc. 107) veins are parallel to either the Bull Moose or Dan Patch faults, are probably formed on small subsidiary breaks. Veins formed in fractures at small angles to the faults are mainly formed in tight shears. These veins tend to be thin and commonly are multiple. The largest shear zone occupied by veins contains 22 vein localities and extends for 2.7 miles from the ridge top northwest of the Cago No. 12 (loc. 49) to South Frying Pan Creek (pl. 1). In addition to the Cago No. 12, this zone also contains such well-known localities as the Contact (loc. 52), Beaverhead (loc. 64), Trapper No. 1 (loc. 67), and the Shear Zone (loc. 73). The Shear Zone vein is in turn not one but a series of closely spaced en echelon and branching veins that can be traced for about 6,000 feet. The rocks along this zone are all highly sheared and stained with iron oxides. Veins which form at a more obtuse angle to the faults are mainly in tension fractures formed by shear movement along the faults. These veins occur in fairly open fractures and tend to be thick. Veins of this type in the northeast part of the district include the Wonder (loc. 45), H.R.S. No. 1 (loc. 95), and the Dan Patch Nos. 1 and 2 (loc. 98). Veins of this type in other parts of the area include localities 135 and 138, Elkhorn (loc. 108), Thor Nos. 1 and 2 (loc. 190), and ThO_2 (loc. 192).

MINERALOGY

Forty-five minerals were found in a detailed examination of 160 samples from the veins in the Lemhi Pass district. Many of these minerals are rare, and only 14 minerals were found in at least 10 percent of the samples (table 3). In spite of the bewildering number of minerals, the basic mineralogy of the veins is fairly simple. The veins consist primarily of a quartz of microcline gangue cut by numerous irregular limonite or hematite veinlets and masses that contain thorium minerals and small amounts of various accessory minerals. Although many minerals occur repeatedly in various parts of the veins, only a few of the minerals make up as much as 10 percent of any sample. In addition to quartz, microcline, hematite, and limonite, other minerals that make up this amount of any sample are thorite, barite, calcite, and siderite. Thorite and barite make up more than 10 percent of the Shear Zone vein (loc. 73) in a few places. Calcite is the chief gangue mineral in seven veins, including the Black Bull No. 3 (loc. 20) and the Wonder (loc. 45) veins. Siderite occurs in substantial amounts in parts of the Wonder vein, one of only two veins in which it was recognized in the district.

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TABLE 3.—*Occurrence of minerals in 160 samples from 92 different thorium veins in the Lemhi Pass district*

Minerals	Samples in which mineral was observed	
	Number	Percent
Principal gangue minerals:		
Quartz	160	100
Microcline	126	78.8
Other gangue minerals:		
Barite	64	40.0
Calcite	39	24.4
Siderite	4	2.5
Iron oxide minerals:		
Limonite	136	85.0
Goethite	55	34.4
Lepidocrocite	2	1.3
Specularite	133	83.1
Red granular hematite	45	28.1
Magnetite	147	91.9
Thorium and rare-earth minerals:		
Thorite	110	68.8
Monazite	37	23.1
Brockite	11	6.9
Allanite	4	2.5
Xenotime	4	2.5
Synchisite	3	1.9
Bastnaesite	1	.6
Doverite	1	.6
Accessory minerals:		
Rutile	94	58.7
Pyrite	42	26.3
Muscovite	42	26.3
Apatite	31	19.4
Biotite	10	6.3
Chlorite	4	2.5
Manganese oxide	20	12.5
Psilomelane	2	1.3
Pyrolusite	2	1.3
Chalcopyrite	10	6.3
Malachite	9	5.6
Galena	2	1.3
Pyromorphite	4	2.5
Wulfenite	3	1.9
Molybdenite	2	1.3
Sphalerite	1	.6
Pyrrhotite	1	.6
Fluorite	7	4.4
Brookite	2	1.3
Anatase	1	.6
Jarosite	4	2.5
Dolomite	4	2.5
Diopside	1	.6
Plagioclase	1	.6
Tourmaline	1	.6
Garnet	1	.6
Staurolite	1	.6
Covellite	1	.6
Azurite	1	.6

Thorite, calcite, and barite, where they occur in other places, generally make up only minor amounts of the veins. Minerals such as magnetite, rutile, pyrite, monazite, muscovite, and apatite (table 3) are found fairly frequently in the samples examined but occur in only minor amounts in each sample. For example, magnetite is found in 92 percent and rutile in 59 percent of the samples, yet neither make up as much as 0.5 percent of any sample.

The color of the veins is due principally to limonite and hematite. Most are medium brown, but they may be reddish brown or even black depending on the amounts and type of iron oxide present. Iron oxides not only form discrete veinlets and masses but also stain and permeate many other minerals making them difficult to identify in hand specimen. The larger crystals are generally of quartz and feldspar, and they rarely exceed one-tenth of an inch in size. The original size of the other minerals is much smaller, and many thorite crystals are only 0.001-0.004 in. across. Every vein has been granulated, and bigger fragments are commonly set in a matrix of more minute material. Small pockets of granulated material are common in many veins. The result of the staining by iron oxides, the small original grain size, and the granulation makes the identification of most minerals extremely difficult. Hence, only quartz, feldspar, hematite, limonite, manganese oxide minerals, and malachite are readily identifiable in hand specimen.

A study of the vein mineralogy was carried out using routine heavy-liquid and magnetic-separation procedures. Any mineral not readily identifiable under a binocular microscope was identified by its X-ray diffraction pattern. In a few instances spectographic analyses were used as an aid in seeking the mineral's identity.

PRINCIPAL GANGUE MINERALS

Many veins contain both quartz and microcline in abundance. A few veins, such as the Black Bull No. 2 (loc. 37) and the Pine Nos. 1 and 2 (loc. 161), are made up of more than 95 percent feldspar. Although quartz-rich and microcline-rich veins commonly occur in the same areas, a group of veins (locs. 113, 115-123) along the Continental Divide between the headwaters of Reese and Peterson Creeks are all rich in microcline. Quartz is more easily recognizable than microcline in hand specimen, as it is not as easily stained by iron oxides as the microcline, much of which is stained brown. Microcline in the veins differs somewhat in physical features from that commonly seen in igneous rocks. Under the microscope, the microcline from veins commonly is filled with fine dust-size particles probably of iron oxides. Under crossed nicols the microcline has an irregular patchy appearance. Generally it is not twinned, although a few grains showed crosshatch twinning typical of microcline. Most of the feldspar occurs in aggregates of small grains that appear in hand specimen to be large single grains. Although this mineral has a well-developed cleavage, the cleavage is not readily visible in the fine-grained aggregates.

OTHER GANGUE MINERALS

Calcite is the principal gangue mineral in only seven veins. All of these veins are small with the exception of the Wonder vein (loc. 45), which is 920 feet long. In most other veins calcite is absent or present only in trace amounts. Siderite was noted in only two veins. Carbonates, especially calcite, are common in veins in the Hall Mountain area, Idaho; Mountain Pass region, Calif.; and the Powderhorn and Wet

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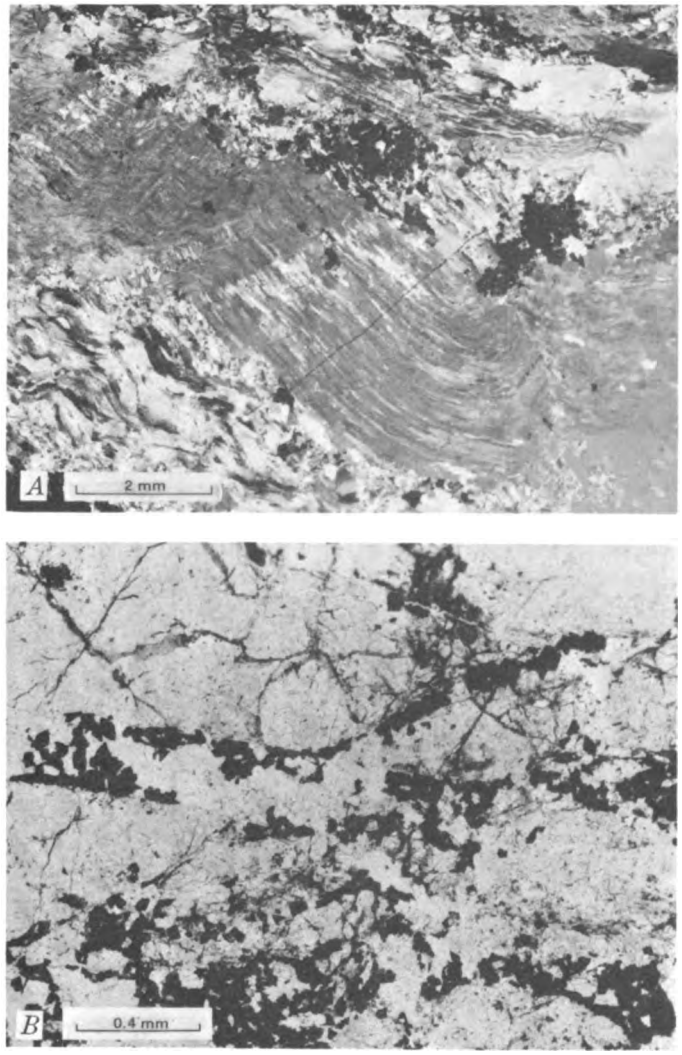


FIGURE 17. Photomicrographs of thorium vein material. *A*, Swirled light-gray barite bounded by crushed layers of quartz and barite, from the Black Rock vein (loc. 75). Black material is goethite. Picture taken using crossed nicols. *B*, Small black thorite crystals along fractures in microcline, from the Uranium Queen vein (loc. 41). Note diamond-shaped cross sections of many of the thorite crystals. Photographs by L. S. Hendricks.

Mountain districts, Colorado (Staatz, 1974, p. 499). Barite was found in 40 percent of the samples examined (table 3, fig. 17*A*). It has an erratic distribution within the veins, being fairly abundant in some parts of a vein and absent in others. In two samples taken 18 feet apart in the adit on the Shear Zone vein (loc. 73) the barite content in one is about 40 percent and in the other less than 1 percent. Barite is a common mineral in most thorium veins in the United States. This mineral is more plentiful in the thorium veins in the Wet Mountains and Powderhorn areas of Colorado and the Mountain Pass district of California than in the Lemhi Pass district.

IRON OXIDE MINERALS

Iron oxides are ubiquitous in the thorium veins; limonite and hematite make up substantial parts of many veins. The limonite varies in color and form, commonly in the same deposit. It may be dark brown, medium brown, tan, or ocherous yellow in color, have a dull to shiny surface, and a dense, granular, or vuggy texture. Limonite was visually identified in 85 percent of the samples, but in only 36 percent (57 samples) was the particular limonite mineral identified by X-ray. In most samples (55) the limonite was goethite, although in two it was identified as lepidocrocite. The lepidocrocite could not be separated from the goethite on the basis of its physical appearance. The limonite minerals commonly are associated with thorium minerals. Not only do discrete thorium minerals commonly occur in the limonitic parts of the veins, but some of the thorium apparently occurs within the limonite itself. Autoradiographs of limonite-rich parts of several veins show a bright haze of tiny gray spots over all the limonitic parts, indicating that some of the thorium occurs in this mineral either in its lattice or adsorbed on the limonite as minute crystals of some thorium mineral (Staatz, 1972, p. 65-67).

Hematite occurs with limonite in many veins, although in some it is found without limonite. Hematite occurs in two principal forms, black platy specularite and dark-red granular hematite. The former is most abundant, and tiny shiny tabular plates of this mineral a hundredth of an inch long are found in most veins. Red granular hematite is commonly associated with the specularite. It generally occurs in irregular earthy masses. Its dark-cherry-red color makes it readily identifiable in most places. Hematite is also commonly associated with thorium minerals, which it surrounds or is adjacent to in many places. Magnetite is the most common but least abundant of all the iron oxide minerals. It is found in 92 percent of the samples, but rarely does it make up more than a few tenths of 1 percent of the rocks. Magnetite is found in minute black grains, some of which are small octahedrons.

THORIUM AND RARE-EARTH MINERALS

Thorite is the predominant thorium mineral in the veins. It occurs in dark-red to reddish-brown shiny enameloid crystals that in places show conchoidal fracture. Thorite is tetragonal, and it forms crystals which have a diamond-shaped cross section (fig. 17*B*). In thin section thorite is light yellow to deep orange; it may be virtually isotropic or have appreciable birefringence. Thorite may occur by itself as tiny crystals along fractures in quartz or feldspar (fig. 17*B*), but commonly it is surrounded by limonite or hematite. In some places, as in the Last Chance vein (loc. 82), it is intergrown with monazite. Although thorite can generally be recognized under the microscope, it can also be identified by its X-ray diffraction pattern. The thorite is partly metamict, as indicated by broad, poorly defined peaks on the X-ray diffraction pattern. The major diffraction peaks of thorite, when it is heated in air for 1 hour at 1,000°C, become sharp and well defined; in addition,

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some minor peaks appear that were not present in the pattern of the unheated material. The composition of thorite is commonly expressed as $ThSiO_4$, but thorium may be replaced by appreciable amounts of rare earths and the SiO_4 by PO_4. For example, in seven veins in which analyses indicate a high rare-earth content, thorite was the only thorium or rare-earth mineral identified. Rare earths have been found to make up as much as 20 percent of thorite in material collected from the Seerie pegmatite near Pine, Colo. (Staatz and others, 1976, p. 577), and in the seven above-mentioned samples from the Lemhi Pass district it appears to be the most likely host for these elements. Phosphorus content of several grains from three different veins was determined by G. A. Desborough using the electron microprobe (Staatz, 1972, p. 70). It varied from 0 to 10 percent and showed variation from vein to vein, grain to grain, and even within the same grain.

Monazite is the next most common thorium and rare-earth mineral, occuring in 23 percent of the samples. Although it is generally not as abundant as thorite, in seven localities (nos. 52, 61, 85, 96, 104, 126, and 169) it is considerably more abundant. In one locality (no. 86) it occurs with brockite, and in three localities (nos. 63, 106, and 113) it is the only throium mineral noted. At the Black Rock property (loc. 75) monazite occurs in clear shiny yellow euhedral crystals, but mainly it occurs in opaque anhedral to subhedral crystals that in color may be cream, tan, brown, orange, or yellow. Monazite is easily stained by iron oxides and some of the difference in color is due to admixtures with these minerals, but some is probably due to differences in primary composition. Differences in composition of monazite in different veins is also indicated in the X-ray diffraction pattern by shifts in position of various peaks and by differences in the relative heights of the peaks.

Brockite, a calcium thorium phosphate, is found in nine veins in the Lemhi Pass district. All are in Montana in the northeast corner of the mapped area. At four of these localities (nos. 59, 86, 89, and 90) it is the principal thorium mineral. This mineral is generally fine grained and occurs in tan, yellow, or orange anhedral crystals. Viewed through the binocular microscope, it is commonly indistinquishable from monazite or apatite. Brockite contains abnormal amounts of gadolinium, and analyses of four brockite-bearing samples showed that they were rich in this element (Staatz and others, 1972, p. 78).

Other thorium and rare-earth minerals occur in only a few veins. Allanite, which is a fairly common mineral in silicic igneous rocks, is found in only three veins. Only in parts of the Lucky Horseshoe (loc. 1) is it found in more than trace amounts. Synchisite ($CeFCO_3.CaCO_3$) and its yttrium analog doverite ($YFCO_3.CaCO_3$) are found in only three veins (locs. 136, 137, and 138); all occur in the northernmost part of the district. In two of the veins (locs. 136 and 138) synchisite is the principal rare-earth- or thorium-bearing mineral. Xenotime and bastnaesite are found in only trace amounts in four veins and one vein, respectively.

ACCESSORY MINERALS

Although 28 accessory minerals have been identified in the veins, only five accessory minerals occur in as many as 10 percent of the samples. With the exception of fluorite in one vein, and the manganese oxide minerals, all occur in only trace amounts. Rutile is the most common, being present in over half the samples examined (table 3). This mineral is found as tiny anhedral crystals having a greasy luster. It varies in color and may be black, dark brown, tan, light orange, or olive green. At a few localities, rutile of two different colors is present. Brookite and anatase, polymorphs of rutile, were identified in two samples and in one sample, respectively.

A few grains of pyrite are found in a little over a quarter of the samples in the Lemhi Pass district. This mineral does not make up as much as 1 percent of any sample. In many samples, however, brown cubes of limonite, a pseudomorphous replacement of the pyrite, indicate that pyrite was once much more abundant.

Muscovite also occurs in a little over a quarter of the samples. In many it is only found as a few scattered flakes, and in none is it even moderately abundant. Muscovite may also occur as small aggregates of tiny pale-green plates.

Apatite is present in sparse amounts in about a fifth of the samples. In a few veins, such as the Black Rock (loc. 75) and Atomic Blast (loc. 105), it forms discrete white to pink acicular crystals as much as 0.12 in. long. In most veins, however, it occurs in tiny white, yellow, or pink grains intergrown with other minerals. Apatite commonly occurs in the same veins with the other phosphate minerals, monazite and brockite. Small amounts of apatite are common in thorium veins in other districts and it has been reported in veins in the Hall Mountain district, Idaho, Wet Mountains and Powderhorn districts, Colorado, Laughlin Peak area, New Mexico, and Mountain Pass district, California (Staatz, 1974, p. 498).

Black amorphous manganese oxide minerals, where present, are fairly abundant. They may be intergrown with iron oxide minerals, whose color they commonly mask. They account for the black color of much of the Wonder vein (loc. 45), the main thorium vein on the Wonder No. 18 property (loc. 70), and both veins on the Black Rock property (loc. 75). The manganese oxide minerals are black to steely gray in color and are extremely fine grained. X-ray diffraction patterns of most specimens were commonly so diffuse that a particular manganese mineral could not be determined. Psilomelane was identified in two samples from the Last Chance vein (loc. 82) and pyrolusite was identified in samples from the Last Chance and from the Black Bear No. 2 (loc. 37) properties.

None of the other 22 accessory minerals were found in more than 6 percent of the veins, of which 18 occur in only a

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few samples. The presence of minerals containing copper, zinc, lead, and molybdenum are of special interest. Nonthorium-bearing copper veins occur in the area, and small amounts of malachite can be easily recognized in a number of thorium veins. The amount of copper minerals in various thorium veins, with the exception of the Wonder (loc. 45), is scant, and even these scant amounts are generally confined to a small part of the vein. At the Wonder vein copper minerals can be found throughout much of the vein, chalcopyrite predominating. Covellite is found in the matrix of the vein intermixed with quartz, chalcopyrite, hematite, thorite, and sphalerite (Sharp and Cavender, 1962, p. 46). Malachite and azurite coat some fracture surfaces. This vein lies only 0.75 mile south of the copper-quartz veins of the old Copper Queen mine. Sphalerite, the only zinc mineral recognized, occurs principally as transparent "grass-green" crystals in the western part of the Wonder vein.. The dark-brown iron-rich variety of sphalerite, marmatite, also was reported from this part of the vein (Sharp and Cavender, 1962, p. 46). Three lead minerals, galena, pyromorphite, and wulfenite, occur in sparse amounts in a few veins. Their presence testifies to small amounts of lead in the vein fluids, but their sparsity gives little hope of finding economically important amounts of these minerals. Molybdenum minerals are even scarcer than those of lead, and trace amounts of molybdenite were found in veins at the Daisy Nielsen ranch and at the Barbara (loc. 172), and yellow platy wulfenite at the Black Bear No. 2 (loc. 37). The source of the small amounts of these minerals need not have been the original magma from which the vein fluids were derived, but could well have been the sedimentary rocks of Precambrian age through which the vein fluids passed.

CHEMICAL COMPOSITION

The thoria content of various parts of the thorium veins in the Lemhi Pass district is known from about 420 samples. More than 350 samples have been reported on previously by Trites and Tooker (1953, p. 194, 195, 198, 201, 205), Sharp and Cavender (1962, p. 62-67), Austin (1968, p. 6-12), and Staatz (1972, table 5). Sixty-seven new thoria analyses are listed in this report. Those analyses which come from properties described in detail in the last section of this report will be found in the description of that property; those which come from properties that are not described will be found in table 4. The samples in this district ranged in thoria content from 0.0008 to 9.4 percent. The high value was determined by wet chemical analysis from an 0.8-foot sample collected from a vein in the Shear Zone vein (loc. 73) (Austin, 1968, p. 6).

The thorium analyses given in this report were in part done in the U.S. Geological Survey laboratories and in part done for the U.S. Atomic Energy Commission by Lucius Pitkin, Inc. Those done in the Geological Survey laboratories include all samples with MHS numbers in this report as well as all samples done for a previous report by Staatz (1972). These analyses were done by C. A. Bunker and C. M. Bush using a gamma-ray spectrometer. The accuracy of this method is ±3 percent. Those done by Lucius Pitkin were done by standard wet chemical methods. Earlier analyses, such as many of those used by Trites and Tooker (1953, p. 195, 198, 201, and 205) and Sharp and Cavender (1962, p. 62-67), were done by the following three steps: (1) A measurement of total radiation, given as equivalent uranium; (2) a chemical analysis for uranium; and (3) calculation of thorium needed to account for the radiation present after subtracting radiation due to the small amount of uranium present. Although this method is based on the assumptions that the uranium present has no significant daughter products and that thorium is in equilibrium with itself, the results check well with those done by other methods, because the amount of uranium and its daughter products is so small that any disequilibrium between the two would not significantly change the overall radioactivity, and the half-life of thorium daughter products is so short that in most deposits thorium and its daughter products are in equilibrium.

The samples represent a wide variety of vein materials. A few represent thin seams in a quartzite country rock but most are entirely of vein material. The material ranges from almost barren quartz vein to thorium- and iron oxide-rich parts of veins. Variations in grade may take place both across and along a vein. The hanging wall or footwall part of a vein may contain severalfold more ThO_2 than the rest of the vein. A striking example of this relationship occurs in the south vein on the Lone Star No. 2 property (loc. 145), where a 1-foot-thick hanging wall, a dark-brown limonitic part of the vein, overlies a much thicker (9-30 feet thick), light-gray, quartz-rich part. In one prospect, two samples were cut across this vein; the hanging wall part contained 0.32 percent ThO_2 and the footwall part 0.004 percent ThO_2. Variations in grade are equally common along the veins. A somewhat extreme example occurs in a small adit near the south end of the Shear Zone vein where two channel samples cut across the entire vein some 20 feet apart contained 0.0081 and 2.49 percent ThO_2.

Although the thoria content of individual parts of different veins may vary widely, the grade of large sections of a particular vein may be fairly constant. Seven samples along 300 feet of vein exposed in the main workings of the Lucky Horseshoe vein (loc. 1, fig. 18) range from 0.52 to 1.00 percent ThO_2 (table 6). Five samples along 520 feet of the principal vein on the Deer Fraction 1A (loc. 21, fig. 21) have values ranging from 0.18 to 0.59 percent ThO_2 (table 8). Seven samples along 595 feet of the northwest-trending vein on the Black Rock (Montana) property (loc. 75, fig. 29) have a thoria content between 0.63 and 3.10 percent (table 15). Five samples along 420 feet of the northwest-trending vein on the Black Rock (Idaho) property (loc. 165, fig. 40) range from 0.16 to 0.62 percent ThO_2 (table 23). Overall thoria

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TABLE 4.—*Analyses of samples from the Lemhi Pass thorium district, Idaho and Montana*

[C, chip sample; CH, channel sample; G, grab sample; leaders(.....) not determined; NA, not applicable]

Locality No. (pl. 1)	Name of claim, where known, and vein, if more than one	Sample No. (MHS-)	Vein thickness (ft.) and type	Description of locality	Percent composition									
					[1]ThO_2	[1,2]ReU_3O_8	[1]K_2O	[1,4]ΣRE_2O_3	[4]Cu	[4]Pb	[4]Zn	[4]Ba	[4]Sr	[4]Nb
106	Orpha	33-70	4.4 C	Center of west trench	0.055	...	5.54							
109	Lucky Strike No. 2	22-70	1.5 CH	Center of east trench	.024	...	1.89							
112	Lucky Strike No. 3	25-71	.67 C	Southwest trench in center of ridge	.088	0.0005	4.13							
113	Chief Tendoy Nos. 13 and 14	30-70	1.0 CH	Northwest trench	.60									
114	Welco No. 10	2-70	NA G	Trench adjacent to road	.77									
115	Chief Tendoy No. 6	28-70	8.0 C	South wall of trench	.63									
121	Chief Tendoy No. 2	34-70	.5 CH	Side of southeast trench	.076	...	10.0							
122		10-70	1.5 C	Back of secondmost eastward trench	.93									
122		31-70	.9 CH	West branch of vein at west end of northwest trench	.045	.0004	10.01							
126		32-70	3.0 C	Between the two trenches	.19	...	3.25							
132	Sauser No. 1	35-70	.4 CH	Near center of trench	.28									
133	Welco No. 7	6-70	1.4 CH	Pit above road	.034	.0003	2.02							
135	South vein	47-70	.6 CH	Back of trench	.098	...	1.32							
137	Red Hill No. 1	56-72	.9 CH	Back of trench	.19	...	6.42	0.67	0.0070	0.015	<0.030	0.70	0.070	0.015
138		81-72	.67 C	East end of trench	.19	...	...	.76	<.0002	<.0010	<.030	1.50	.050	.015
143		77-72	.2 C	Center long trench	.52									
149	Idaho No. 3	28-72	.67 C	Center of vein	.032	.0012	7.73	.051	.0003	.0030	<.030	.070	.015	.030
150		83-72	1.0 C	High on south side of trench	.029	.0015	3.68							
151	Iola	73-72	1.2 C	Side of trench	.36	.0014	8.90							
152	Iola	72-72	.67 C	Pit just below road	.39	...	2.51	.61	.007	.015	.20	1.50	.70	.15
157	Silver Queen No. (?)													
	Northeast vein	53-72	.5 C	Northwest side of pit	.19	.0078	3.93							
	Central vein	54-72	.37 C	Northwest side of pit	.13	.0034	7.16							
160		46-72	.5 C	Bottom of trench	.23	...	55							
161	Pine Nos. 1 and 2	9-72	NA G	Center of lower trench	.19	.041	11.6							
162	Lucky Boy	6-72	1.0 C	South side near lower end of trench	.10	.054	11.9							
163	Black Bear No. 1	7-72	NA G	South side of trench	.11	..	4.93							
166	Scott	93-72	NA G	Second trench from west	.079	.014	5.07							
167		74-72	.2 CH	Back of cut	.90	...	2.07							
169	Katy No. 1	17-72	.67 C	Bottom of trench	.16	...	6.23							
172	Barbara	75-72	1.8 CH	Southwest side of long trench	.32	.0035	4.14	1.92	.0015	.015	.050	>2.00	.70	.30
178	Elkhorn No. 1	44-73	2.0 C	Second trench from west	.014	.0003	.60							
180	Viola No. 4	33-71	1.7 C	Center of trench complex	.77	.0084	8.50	.81	.015	.010	<.030	.15	.030	.030
181	Viola	34-71	1.1 C	East trench	.034	.0004	3.22							
187	Mornell	3-73	NA G	Second pit from top	.11	.0006	8.06							
190	Thor Nos. 1 and 2													
	East vein	65-73	.8 C	East pit, adjacent to road	.16	.0006	4.70							
	West vein	66-73	1.5 C	West pit, south of road	.037	.0007	6.26							
....	Daisy Nielsen Ranch													
	West vein	77-73	.75 CH	West side of north trench	1.14									
	Middle vein	78-73	.1 CH	Middle of south trench	.75	..	7.35							
....	McDevitt Creek area	17-71	1.3 C	Lower trench	.037	.0003	1.24							

[1]Analyzed by gamma-ray spectrometer by C. M. Bunker and C. A. Bush, U.S. Geological Survey.
[2]Equivalent U_3O_8 content as determined from radium daughter product.
[3]Total rare-earth oxides.
[4]Analyzed by semiquantitative six-step spectrographic method by N. M. Conklin, U.S. Geological Survey.

content may also vary in different segments of veins. Thus, five samples on a 410-foot segment of the southeastern part of the northeast vein on the Reactor property (loc. 107, fig. 32) range from 0.14 to 1.32 percent ThO_2, but two samples along a 320-foot segment of the northwestern part of this same vein range from 0.006 to 0.07 percent ThO_2 (table 18). Four samples across the main pit, 200 feet across, on the ThO_2 property (loc. 192, fig. 41) have 0.51-2.39 percent ThO_2, but one sample taken 735 feet farther northwest has only 0.033 percent ThO_2 (table 24). Most of the better explored veins have an average ThO_2 content of 0.30 percent or greater. Some veins are much higher grade than others, and at least one vein on each of the following properties has an average grade in excess of 1.0 percent: Black Rock (Montana) (loc. 75), Elkhorn (loc. 108), Silver Queen 52B (loc. 146), ThO_2 (loc. 192), and Shear Zone (loc. 73).

The total overall rare-earth oxide content of these veins is somewhat greater than the thoria content. As the atomic radius of thorium is similar to that of the various rare-earth elements, many primarily rare-earth minerals contain thorium, and vice versa. Thus, it would appear that samples rich in thorium would be rich in rare earths. This is not necessarily the case. Samples having similar concentrations of thoria and of the rare-earth oxides include six samples from the Last Chance (loc. 82) which contain 0.20, 0.18, 1.34, 0.28, 0.61, and 0.28 percent total rare-earth oxides and 0.36, 0.26, 1.45, 0.30, 0.61, and 0.28 percent thoria, respectively. Similarly, a sample from the Viola No. 4 (loc. 180) contains 0.81 percent total rare-earth oxides and 0.77 percent thoria; a sample from M.S.D. No. 1 (loc. 86) has 0.26 percent total rare-earth oxides and 0.22 percent thoria; and a sample from the Thorite No. 3 (loc. 40) has 0.37 percent total rare-earth

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oxides and 0.38 percent thoria. On the other hand, other samples show little agreement between the amounts of rare earths and thorium. Three samples from the Apex (loc. 136) contain 1.67, 1.11, and 1.05 percent total rare-earth oxides and 0.32, 0.24, and 0.17 percent thoria, respecitvely. Similar wide variations occur on the Barbara property (loc. 172), where a vein has 1.92 percent total rare-earth oxides and 0.32 percent thoria; on the Black Rock (Montana) property (loc. 75), where the northwest vein has 0.11 percent total rare-earth oxides and 2.19 percent thoria; and on the Frying Pan property (loc. 85), where a vein contains 0.16 percent total rare-earth oxides and 1.35 percent thoria.

The rare earths consist of 16 elements having similar chemical properties. Fifteen of the elements - lanthanum (La), cerium (Ce), praeseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu) occur sequentially in the periodic table, elements 59 through 71. This group is called the lanthanides. One of these, promethium, is almost unknown in nature. Yttrium, not one of the lanthanides, but chemically similar to them, is also classed as a rare earth. All rare earths have a 3^+ valence and similar atomic radii; hence, they can easily substitute for one another, and they are always found together.

In the normal distribution of the lanthanides in the earth's crust, and in most minerals, the ones having the even atomic numbers are more abundant than the adjacent odd-numbered ones, and the even- or odd-numbered lanthanides having a lower atomic number are more abundant than those having a higher atomic number. Generally, therefore, cerium is the most abundant lanthanide and lutetium the least. Although this distribution pattern of the lanthanides occurs in many minerals, it may be markedly different in a few, owing to partial separating out (fractionation) of the rare earths. In rocks in which the rare earths are not fractionated, cerium is the most common lanthanide having an even atomic number and lanthanum is the most common lanthanide having an odd atomic number. In the Lemhi Pass thorium district the rare-earth content of many veins has been fractionated, and the proportions of the rare-earth elements commonly vary in different veins. Complete rare-earth analyses were made of 31 samples from 21 veins and are reported by Staatz, Shaw, and Wahlberg (1972). These data show that cerium, expected to be the principal even-numbered lanthanide, was most abundant in only six samples. In 17 samples neodymium is the most abundant lanthanide; in three, gadolinium; in two, dysprosium; and in three samples two lanthanides are equally abundant. The larger amount of neodymium than cerium in most of these samples may not be due to its enrichment but rather to depletion of the cerium. In some environments cerium can be oxidized from Ce^{+3} to Ce^{+4} (Adams, 1969, p. C42) and may then be largely excluded from minerals containing the other rare earths. The mineral content of the samples, except for those rich in gadolinium, could not be directly correlated to lanthanide distribution. The three gadolinium-rich samples contained abundant brockite.

Generally, lanthanum is the most abundant lanthanide of odd atomic number in the thorium veins, but europium was the most common odd-numbered lanthanide in about one-third of the samples. Furthermore, in another 40 percent of the samples europium is enriched as compared with its neighboring odd-numbered elements (Staatz and others, 1972, p. 76-77). This enrichment of europium occurs in more than 70 percent of the samples and, hence, is an extremely common feature of the thorium veins.

The rare-earth content of these veins was more commercially valuable in 1975, even though not producible economically, than the thorium content. The veins may be of particular value in the future for uses requiring neodymium or europium.

The uranium content of these deposits is small. When a sample has a Th:U ratio greater than about 40, the radiation due to thorium commonly interferes with the uranium measurement. This is especially true if the sample also has a high potassium content. At only one place did the amount of uranium exceed that of thorium. Veinlets at this locality (No. 31) occur in a different environment, replacing the basal conglomerate of the Challis Volcanics rather than, as normally, the Precambrian quartzite. These veinlets contain 0.014 percent U_3O_8 but only 0.0012 percent ThO_2. At all other localities the thorium greatly exceeds the uranium content. The U_3O_8 content of 19 samples, as shown in table 4, ranges from 0.0003 to 0.054 percent. The ratio of ThO_2 to U_3O_8 in these samples ranges from 1.9 to 385, but most fall in the range of 20 to 180. Thus, uranium is not only of little economic importance, but the radiation due to uranium in most thorium veins is minor.

Copper, lead, zinc, molybdenum, gold, and silver have been detected in some of the thorium veins, but in most they occur in only minor amounts. Analyses of some of the veins in the Lemhi Pass quadrangle are given by Staatz (1972, table 5). Other analyses are given in tables 4, 10, 15, 19, and 21. Copper is by far the most widespread of these metals, and scant amounts of malachite are seen in many veins. Thirty-one copper analyses were made on 17 veins, all of which, in at least one place, have visible copper minerals. The copper content of these samples ranged from less than 0.0002-2.80 percent, but samples from only two properties, the Wonder (loc. 45) and the Black Rock (Montana) (loc. 75), exceeded 0.06 percent copper. Ten samples from the Wonder vein (table 10) yielded 0.15-2.80 percent copper, and one sample from the Black Rock had 0.15 percent. The Wonder vein was first prospected for its copper content, and small amounts of copper-bearing on were shipped to the Copper Queen mill (Sharp and Cavender, 1962, p. 44).

Lead is considerably less common than copper. Lead

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minerals were not noted in the field, and only scant amounts of galena are present in heavy separates from two veins, pyromorphite from three, and wulfenite from one. Twenty-three analyses were made for lead on samples from 17 veins (tables 4, 10, 19, 21, and 23; Staatz, 1972, table 5). The lead content of these analyses ranged from less than 0.001-0.23 percent. High values came from a sample taken on the Silvertip property (loc. 104), which contained pyromorphite.

Zinc, when present, is found in minor amounts. Zinc minerals have only been identified from the Wonder vein. In 31 analyses from 17 properties the zinc content ranged from 0.0025 to 3.46 percent, but at only two properties, the Wonder and the Black Rock (Montana), is it in excess of 0.20 percent. In 10 samples from the Wonder, the zinc content ranged from 0.08 to 3.70 percent (table 10), and if this property is mined for thorium, zinc could be an important byproduct. One sample from the northwest-trending vein on the Black Rock property had 1.10 percent zinc (Staatz, 1972, table 5), and this property could possibly also be of economic importance.

Molybdenum is uncommon in the veins of this district. The only molybdenum minerals noted were a few rare pieces of molybdenite in heavy-mineral separates from veins on the Barbara property (loc. 172) and the Daisy Nielsen Ranch and a little yellow wulfenite from the Black Bear No. 2 property (loc. 37). Molybdenum minerals are most abundant in the vein on the Black Bear property, and a sample of the vein material in which the wulfenite was found contained 0.024 percent molybdenum (Staatz, 1972, table 5).

Little gold is present in the thorium veins. Only 7 of 39 samples contained more than 0.0015 ounces per short ton. The sample which had the most gold came from the Wonder vein (loc. 45); it yielded 0.020 ounce per short ton (table 10).

Silver is not common in the thorium veins, although moderate amounts have been found in a few veins. Two samples from the Wonder had 0.99 and 0.52 ounce per short ton, respectively (table 10). Significant amounts of silver also occur in samples from the Black Rock (Montana) (loc. 75; MHS-63-68), east vein of the Buffalo (loc. 18; MHS-142-68), and Last Chance (loc. 2; MHS-147-68) properties. Those samples contained 0.23; 0.38, and 0.20 ounce per short ton of silver, respectively (Staatz, 1972, table 5). None of the other 31 samples yielded as much as 0.10 ounce per short ton of silver.

Microcline, as noted in the previous section, is one of the principal gangue minerals of the thorium veins. As other potassium-bearing minerals occur in such small amounts, more than 95 percent of the potassium in the veins is due to microcline. Thus, the potassium content of the veins can be used to estimate their microcline content. The potassium content of 82 samples from thorium veins was measured; the results of some of the samples are given in table 4. The potassium content of the samples ranged from 0.46 to 12.4 percent. This correlates roughly with 3.3 to 88 percent microcline. Seven samples from the Black Bear No. 2 (loc. 37), Chief Tendoy No. 2 (loc. 121), locality 122, Pine Nos. 1 and 2 (loc. 161), Lucky Boy (loc. 162), and the ThO_2 (loc. 192) contained 10 or more percent potassium (71 or more percent microcline).

The barium content of 15 samples from the Lemhi Pass district varied from 0.007 to less than 2 percent; most contained 0.03-1.5 percent barium. The strontium content of 15 samples ranged from 0.002 to 0.70 percent. No strontium minerals have been identified in the veins. Strontium is highest in those veins that contain the most barium, and lowest in those veins that contain the least barium. As both barium and strontium have two valences and their atomic radii are similar in size, the strontium most likely substitutes for barium in barite. The niobium content of 15 samples ranged from 0.002 to 0.30 percent. In samples that contain as much as 0.1 percent niobium, this element could become an important byproduct.

RESOURCES

The Lemhi Pass district has important resources of both thorium and rare earths. Of the total resources, only reserves are reported here; no attempt was made to estimate the hypothetical undiscovered resources. A total of 219 thorium veins were identified in the district. These range in size from thin veinlets that coat the surface of shears to the Last Chance (loc. 82) that ranges in thickness from 5 to 40 feet. In this study of reserves only veins that were at least 0.2 foot thick were considered. A total of 110 veins were at least that thick and were used in reserve calculations. Data used in calculating the reserves of veins came mainly from surface exposures. Only two veins, the Last Chance (loc. 82) and the Wonder (loc. 45), have their downward extension in part blocked out by both drill holes and underground workings. Part of the reserve figures from these two properties could be considered as measured. Reserve figures from all other properties are considered as either indicated or inferred. As the amount of measured reserves is small, they are included in this study with the indicated reserves. Indicated reserves in the veins in this district are those found in a block consisting of the traceable length of the vein times the average thickness times the depth, which is assumed to equal the length. Inferred reserves in the veins are those found in a block that surrounds the indicated reserves. Length of this block is half the indicated length or a quarter of the indicated length in each direction. This is shortened where geologic evidence indicated the vein had terminated, or lengthened where anomalous radioactivity was detected through the overburden. Thickness was the same as that used in calculating the indicated reserves. Depth of this block is 1½ times the trace of the vein or one half the indicated length below the block of indicated reserves. The inferred length of the vein, although hypothetical, is probably a conservative estimate. For the most part outcrops in this district are widely

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scattered, and veins are outlined along the ridges in trenches where the overburden is thin. The inferred lengths of some veins have been greatly extended by later work. The Last Chance vein is described by Sharp and Cavender (1962, p. 29) in 1952 as being exposed for about 1,200 feet. Since then, additional trenches have increased its known length to 4,350 feet. Many veins have been found in only one trench and other trenches either were not put in or failed to cut through the overburden. The thickness used in most veins, as previously stated, was the average thickness. In a few veins, however, different parts of the vein have radically different thicknesses. Here the average thickness was calculated for each part of the vein, and the reserves for each part of the vein were calculated separately. An example is the Cago No. 12 vein (loc. 49), where much of the eastern part of the vein averages 16.0 feet thick, but the western part and the east end are 4.3 and 5.5 feet thick, respectively. The depth of the veins, although definite data are lacking, appears to be of the same order of magnitude as the length. There are no apparent geologic restrictions on depth, as the Precambrian quartzite and siltite host rock are exposed over wide areas, and faults associated with the veins can be traced for many miles. Furthermore, veins have been found at all elevations where the Precambrian host rock is exposed from 9,430 feet on the Continental Divide to 5,240 feet on Pattee Creek, a vertical distance of 4,160 feet. Difference in surface elevation of individual veins is as much as 560 feet.

The strike length and depth used in calculating indicated reserves for those veins that are exposed in only one place is 50 feet. A tonnage factor of 12 cubic feet per short ton is used in converting vein volume to vein weight.

THORIUM

The amount of ThO_2 in each vein is a product of the average grade and the tonnage. The average grade was obtained by weighing the analyses according to the length of each chip or channel sample. Thus, a sample 6 feet long carried twice as much weight in the overall average as a sample that was only 3 feet long. The few grab samples taken are assumed in these calculations to have come from where the vein is of average thickness. The grade of some veins is represented by only one sample; other veins are an average of as many as 17 samples.

Indicated ThO_2 reserves of the Lemhi Pass thorium district are 176,500 short tons. Inferred ThO_2 reserves of this district are 128,900 short tons. Total indicated and inferred ThO_2 reserves are 305,400 short tons. The veins that contain these reserves vary in grade, but 99 percent of these reserves are in veins that contain at least 0.1 percent ThO_2. As in most mining districts, the greater part of the reserves occur in a few veins. In the Lemhi Pass thorium district 96 percent of the total reserves are in the 10 largest veins. These veins are the Last Chance (loc. 82), Shear Zone (loc. 73), ThO_2 (loc. 192), Black Rock (loc. 75), Contact (loc. 52), Cago No. 12 (loc. 49), G&G Nos. 6 and 8 (loc. 89), G&G Nos. 1, 2, and 5 (loc. 90), Lucky Horseshoe (loc. 1), and Beaverhead (loc. 64). These 10 veins have an overall average grade of 0.43 percent ThO_2.

RARE EARTHS

The amount of rare earths in any vein, like that of thorium, is a product of the average grade and the tonnage. Data on grade of the rare earths in these veins are much more meager than those on thorium. Accurate rare-earth analyses are both difficult to make and costly to obtain. For these two reasons only 41 reasonably accurate analyses are available of 25 veins. For many of these 25 veins only one rare-earth analysis was made, although on the large Last Chance vein nine samples were analyzed for rare earths. Most of these analyses (39) were done in two stages. First, a chemical concentrate was made that contained all the rare earths and thorium, and then the individual rare earths in this separate were determined by X-ray fluorescence. Thirty-one of the 39 samples were analyzed in the laboratories of the U.S. Geological Survey in Denver, Colo.; the other eight samples were done in the laboratories of the U.S. Bureau of Mines in Salt Lake City, Utah. The detailed results of these analyses have been previously published by Staatz and others (1972, p. 76-77) and by Austin (1968), respectively. The other two samples were analyzed by a quantitative spectrographic method in the U.S. Geological Survey laboratories in Denver.

The 25 veins for which some analytical data on rare earths is available are: (1) Lucky Horseshoe (loc. 1), (2) vein at locality 4, (3) vein at locality 5, (4) principal vein on Buffalo property (loc. 18), (5) Black Bull Fraction No. 4, (6) vein at locality 35, (7) Thorite No. 3 (loc. 40), (8) Contact (loc. 52), (9) Shear Zone (loc. 73), (10) northwest-trending vein on Black Rock (Montana) property (loc. 75), (11) Last Chance (loc. 82), (12) central vein on Frying Pan property (loc. 85), (13) southeast vein on Frying Pan property (loc. 85), (14) M-S-D No. 7 (loc. 86), (15) G&G Nos. 6 and 8 (loc. 89), (16) G&G Nos. 1, 2, and 5 (loc. 90), (17) Thorite No. 1 (loc. 93), (18) Saddlehorn No. 3 (loc. 94), (19) H.R.S. No. 1 (loc. 95), (20) north vein on Dan Patch property (loc. 98), (21) south vein on Dan Patch property (loc. 98), (22) Atomic Blast (loc. 105), (23) Apex (loc. 136), (24) south vein on Silver Queen 38A (loc. 148), and (25) northwest-trending vein on Black Rock (Idaho) property (loc. 165). Indicated reserves of rare-earth oxides in these 25 veins total 186,000 short tons, and inferred reserves of rare-earth oxides total 122,000 short tons.

A ratio of the rare-earth oxide reserves to the thoria reserves of these 25 veins is 1.33 or four parts rare-earth oxides to three parts thoria. An estimate can be made of the total rare-earth oxide reserves of the entire district by assuming that the relation between these two compounds in the 25 veins is the same as that for the district. Using this assumption, the total indicated and inferred reserves of

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rare-earth oxides for the Lemhi Pass district is 406,000 short tons.

OTHER VEINS

In addition to thorium veins, 15 copper veins, 15 barren quartz veins, and 2 iron veins occur in the Lemhi Pass district. The most economically important of these are the copper veins. In this report the term copper veins is reserved for any vein that contains copper minerals but does not contain thorium. This division is used because some thorium veins contain a little copper, and the thorium veins can be shown to be younger than those copper veins that do not contain thorium. With two exceptions, the copper veins occur either in the northeast part of the area or on the east side of the Lemhi River just north of the mouth of Little Dry Gulch. Veins at three localities, Copper Queen (loc. 43), Bluebird (loc. 30), and Last Chance (loc. 184), have produced small amounts of copper ore. The value of production at the Copper Queen from its discovery in 1893 until 1910 was approximately $100,000 (Umpleby, 1913, p. 120). Since that time the mine has been operated sporadically, but production appears to have been small (Schipper, 1955, p. 7-10). A minor part of the total receipts at this property was due to gold. The Bluebird has a recorded production of 8 short tons of ore containing 1,432 pounds of copper, 3.6 counces of gold, and 68 ounces of silver (Weed, 1926, p. 788). The Last Chance (loc. 184) reportedly produced about 40 short tons of copper ore (Pete Mahaffey, oral commun., 1973). Other veins are generally both smaller and much leaner. At two localities (Nos. 8 and 36) the copper minerals are in seams or they coat fractures in shear zones. At other localities the copper minerals occur in quartz veins that range in thickness from 0.5 inch to 9 feet. The Copper Queen vein ranges in thickness from a few inches to 9 feet and has an average thickness of about 3.5 feet (Schipper, 1955, p. 27). The Last Chance vein (loc. 184) was also about 3.5 feet thick. The exposed length of the copper veins ranges from 5 to 1,300 feet. The four longest veins are the main vein on the Copper Queen (loc. 43), the Rufus (loc. 25), the southern or Lupine vein on the Copper Queen property, and the large vein on the Bluebird property (loc. 30), which have been traced 1,300, 850, 500, and 450 feet, respectively.

Strikes of the copper veins range from almost due north (N. 3° W°), to almost east-west (N. 85° W.). Unlike the thorium veins, more than half of the copper veins (8 of the 13 measured) have a northeast strike. Dips are moderate to steep and may be variable. The north vein on the Copper Queen follows a curved fault, and above the 150-foot level this vein dips 40°-70° NW., but below this level the dip reverses so that on the 250-foot level the vein dips steeply southeast (Schipper, 1955, p. 27). The copper veins were deposited along shears, fractures, and small faults. Shears can be seen along one or both sides of the vein on the Idaho Pride property (loc. 28), the two veins on the Copper Queen property (loc. 43), and the vein on the Last Chance (loc. 184). The fractures containing these veins are all related to major faulting, most of them to faulting of Tertiary age. Twelve of the 13 copper veins or shear zones in the northeast part of the area lie within 1 mile, and 9 of the veins are within 0.25 mile of one of three big Teritary faults in this part of the area. The other vein (loc. 36) lies directly beneath a thrust fault of uncertain age. Ten of these veins occur in an area where three large Tertiary faults either intersect or approach each other. The three copper veins which lie just to the east of the Lemhi River are within 300 feet of a northward-trending fault that separates Precambrian quartzite and siltite. The strike of the copper veins is at an acute angle to that of the neighboring faults (pl. 1), although the strike of the Last Chance (loc. 184) vein is nearly at right angles to that of the adjacent fault. The fractures that most of the thicker veins fill were probably formed by tension, and some of the larger veins, such as the Rufus (loc. 25), the two veins on the Copper Queen property (loc. 43), the vein at locality 182, and the Last Chance (loc. 184), resemble gash veins.

The copper veins consist primarily of a white quartz gangue and primary and secondary copper minerals and secondary iron minerals. On the surface, malachite, chrysocolla, and azurite may be the only copper minerals seen. At depth, bornite and chalcopyrite are commonly present. Bornite is the principal ore mineral at the Copper Queen and has also been reported at the Idaho Pride (loc. 28) and No Pay (loc. 8) properties (Sharp and Cavender, 1962, p. 53 and 54). Chalcopyrite is present at the Copper Queen, Idaho Pride, and Last Chance properties. A little covellite and black copper oxides have been found on some of these properties. Specularite and limonite are commonly present in parts of these veins but are much less common than in the thorium veins. Other minerals include gold, calcite, pyrite, and molybdenite at the Copper Queen, and barite at the Bluebird (loc. 30). The Copper Queen mine is described by Schipper (1955) and Sharp and Cavender (1962, p. 51-52).

Barren quartz veins, like copper veins, are most common in the northeast part of the area (pl. 1), where 12 of the 15 veins are found. These veins tend to be small and range in length from 6 to 310 feet. The longest vein is adjacent to a thorium vein on the Wonder No. 18 property (loc. 70). Eight of the veins have been traced for less than 50 feet. Vein thickness varies from 0.2 to 25 feet. Individual veins may pinch and swell; for instance, the vein on the Blue Boar (loc. 32) ranges from 0.2 to 1 foot in thickness. Most of the quartz veins have an easterly trend, individual strikes ranging from N. 40° W. through east-west to N. 55° E. Overall, the strike of these veins is similar to that of the thorium veins, but where adjacent to a thorium vein the strike of the two differ. For example, at locality 16 the quartz vein strikes east-west and the thorium vein N. 40° W. At the Wonder No. 18 property (loc. 70), the large quartz vein strikes N. 70° E. toward an adjacent thorium vein that strikes N. 70° W. (fig. 27). The quartz veins dip steeply either north or south.

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The quartz veins, like the thorium and copper veins, were deposited along shears, fractures, and small faults. Movement along at least some of the veins continued after the veins were emplaced, as both the Blue Boar (loc. 32) and the Blue Ridge (loc. 48) are in part brecciated. Most of the barren quartz veins were intruded along fractures within a short distance of the large Tertiary faults in the northeastern part of the area. Their distribution is similar to that of the copper veins which, except for the lack of copper minerals, they closely resemble. The barren quartz veins consist principally of white to gray opaque quartz with minor amounts of limonite and hematite. In one vein (loc. 27) a small amount of chlorite was found and in two others (locs. 32 and 48) Sharp and Cavender (1962, p. 56) reported a little chalcedony, montmorillonite, rutile, and pyrite. A vein in the southern part of the area (loc. 193) is somewhat different from the other quartz veins in containing much more limonite and hematite than the other veins. This vein also contains some calcite, clay minerals, white platy barite, and a little spinel. Although these veins were examined both mineralogically and radiometrically, I did not find any recognizable minerals that contained any valuable metals.

Two iron veins occur in sec. 6, T. 17 N., R. 25 E., in the south-central part of the area on the north side of Reese Creek (pl. 1). The smaller vein (loc. 194) is exposed for 150 feet and has an average thickness of 8 feet; the larger vein (loc. 195) is exposed for 450 feet and is 10-40 feet thick. The length of the latter vein cannot appreciably be extended, because to the northwest it abruptly pinches out and to the southeast a large Tertiary fault cuts it off. The larger vein is on the Hematite claim which was located in May 1957 by Carroll Wells and associates (Anderson, 1961b, p. 103-104). The edges of this vein are not sharply defined, as irregular masses and veinlets extend outward into the country rock. The vein is massive in its central and northwestern parts, but in its southeasternmost exposure, it is brecciated. This vein is composed chiefly of specularite with some associated martite (Anderson, 1961b, p. 104). Little quartz is found in most of this vein. The vein at locality 194, on the other hand, contains more quartz and is a mixture of specularite and quartz. These two iron veins are too small to be of economic importance.

ORIGIN

Although all the veins in the Lemhi Pass thorium district intrude Precambrian siltite and quartzite, they are post-Challis Volcanics and postdiorite in age. The post-Challis age for these veins is suggested by two lines of evidence: (1) The shears and fractures along which the veins are deposited are related for the most part to large faults of Tertiary age. The greatest concentration of veins is found in the northeast part of the area, where most of the veins are within 1 mile of three large converging Tertiary faults. (2) Three small thorium veins lie along major faults that offset the Challis Volcanics. Two small veins at localities 4 and 149 occur in the fault zone of the Lemhi Pass fault, and another vein is found at locality 150 on the Pattee Creek fault. The postdiorite age is indicated in the workings of the Copper Queen mine (loc. 43), where Schipper (1955, p. 21) reported four diorite dikes mineralized by copper veins. The copper veins are somewhat older than the thorium veins, as indicated by a thorium vein found along a small fault that offsets a copper vein a few feet about 350 feet from the portal of the lowest adit of the north vein of the Copper Queen mine (Schipper, 1955, p. 30, pl. 13). The veins are, thus, middle Tertiary or later in age. As previously noted, although the Tertiary faulting is later than most of the Challis Volcanics, it isn't much later. The two were probably generated during the same period of tectonism. The veins may also have been deposited during the latter part of this period. As the volcanics make up the greater part of the igneous rocks in this area, it is possible that the veins are a late-stage derivative of the magma from which the volcanics were derived. If this is so, then the Challis might be expected to contain abnormal amounts of thorium. To check this hypothesis several tuffs and flow rocks were analyzed for thorium and uranium (table 5). The average thorium content of three dark flow rocks is 10.8 parts per million (ppm) and for three rhyolitic tuffs is 14.0 ppm; the average uranium content of the flow rocks is 2.24 ppm and of the tuffs 2.93 ppm. The more silicic rhyolite tuffs have a slightly higher thorium and uranium content, as would be expected, than the flows, which appear in hand specimen to be andesitic or rhyodacitic in composition.

The thorium and uranium contents of volcanic rocks vary considerably, and depend in part on the alkalic and silicic contents of the rocks. For comparison, the thorium and uranium contents of volcanic rocks having a similar composition, from two other areas, are reported below. Four samples of volcanic rocks, ranging from andesite to rhyodacite in composition, from the Valles Mountains, N. Mex., contained 5.2-15.3 ppm thorium and 1.6-3.7 ppm uranium (Larsen and Gottfried, 1960, p. 165). Four other samples of rhyolite from this area yielded 12-46 ppm thorium and 4.0-18 ppm uranium. Three samples of andesite

TABLE 5. *Thorium and uranium content of rocks from the Challis Volcanics*

[Analyses by gamma-ray spectrometer by C. M. Bunker and C. A. Bush]

Sample No.	Unit	Description	Th (ppm)	U (ppm)	Th/U
MHS-72-73	Basalt-rhyodacite sequence.	Greenish-black aphanitic flow rock.	14.3	2.38	6.0
MHS-73-73	.....do.....	Dark-brown aphanitic flow rock.	8.52	2.01	4.2
MHS-79-73	.....do.....	.....do.....	9.72	2.34	4.2
MHS-74-73	Tuff of Curtis Ranch.	Greenish-white crystal tuff having abundant quartz and sanidine fragments.	19.5	3.62	5.4
MHS-75-73	Quartzite-bearing rhyolite tuff.	Quartzite fragments in crystal tuff with abundant clear quartz fragments.	12.8	2.98	4.3
MHS-80-73	.....do.....	.....do.....	9.83	2.18	4.5

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and dacite from the Modoc area of California yielded 3.9-10.8 ppm thorium and three samples of rhyolitic rocks had 14.1-15.5 ppm thorium. The uranium content of five samples of andesite and dacite from the Modoc area was 1.4-4.4 ppm and that of eight samples of rhyolitic rocks was 4.4-5.6 ppm (Z. E. Peterman, written commun., 1963). The thorium and uranium contents of these three suites of volcanic rocks from three different regions have similar ranges except that the rhyolitic rocks from the Valles area contain almost twice as much thorium and uranium as do the rocks of the Lemhi Pass district. Thus, the overall thorium and uranium contents of the Lemhi Pass rocks are not anomalously high compared to other areas. Furthermore, although thorium is greatly in excess of uranium in the veins, the thorium-to-uranium ration of the Challis Volcanics is similar to that found in rocks in unmineralized areas. The thorium-to-uranium ratios of the six analyzed samples from the Challis range from 4.2 to 6.0 (table 5). Graphs of the thorium-uranium ratios compiled by Clark, Peterman, and Heier (1966, p. 536-537) for mafic, intermediate, and granitic rocks show some scatter but have average values of 4.0, which is slightly but not significantly less than the ratios obtained from the Challis Volcanics.

Thorium veins are not unique to the Lemhi Pass district. They have been described in 13 separate areas in the United States (Staatz, 1974). The most important geologic relation in many of these districts is the association of the thorium veins with alkalic rocks and carbonatites. Although alkalic rocks and carbonatites are sparse in the United States, one or both are found in 8 of the 13 areas. Although no alkalic intrusives have been found in the Lemhi Pass area, a small carbonatite dike is exposed in a small pit on the Continental Divide adjacent to locality 77. This rock forms a small gray dike only a few feet long, which consists principally of calcite with rosettes of iron oxide-stained apatite crystals and masses of green chlorite and black magnetite. In addition, this rock contains minor amounts of specularite, goethite, chalcopyrite, malachite, and monazite. The presence of the carbonatite in this district, as well as the association of thorium veins with alkalic rocks in other districts (Staatz, 1974), suggests that alkalic rocks are present at depth.

The thorium veins probably were precipitated from fluids derived from a magma that formed buried alkalic rocks. These fluids followed major through-going fractures, but the veins generally were deposited in subsidiary breaks. The large area over which the veins are spread, as well as tight shears that some of the fluids migrated along, indicates that the vein fluids were of low viscosity. The length of time needed to form these veins probably varied, but for many this period was long enough for vein material to be deposited, to be fractured by later movement, and then for new vein material to fill the fractures. That the temperature of vein formation was probably low is suggested both by the fine grain size of the veins and the distance that some of the fluids apparently traveled.

DESCRIPTION OF SELECTED THORIUM VEINS

By Mortimer H. Staatz, U.S. Geological Survey,
and Byron J. Sharp and Donald L. Hetland,
U.S. Energy Research and Development Administration

We do not attempt to describe all the veins in the district, as little data are available on many. Some veins are known only from one spot in the bottom of one trench. Other veins have been uncovered in several trenches, but sloughing of the sides commonly has left poor exposures. Some of the veins that were exposed in the workings prior to 1953 are described by Trites and Tooker (1953, p. 193-195) and Sharp and Cavender (1962, p. 29-50). These include the following claims: Wonder, Buffalo No. 1 and No. 2, Wonder No. 18, Lucky Strike No. 1 and No. 2, Trapper No. 1 and No. 4, Brown Bear, Last Chance, Shady Tree, Radio (Black Rock), Bull Moose, Black Bull No. 2 and No. 3, Uranium Queen, and Three-and-One. We have described selected veins from the 23 localities from which we have the best data. In general, they include the larger veins in the district. The descriptions do not include all the largest veins, for instance, the Iola and the Shear zone, each of which is more than 2,000 feet long. We have included some veins previously described by Sharp and Cavender (1962) and Trites and Tooker (1953), such as the Last Chance and the Buffalo, where subsequent development work and mineralogic studies have substantially added to the knowledge of the veins at these localities.

The following properties are described in detail: Lucky Horseshoe (loc. 1), Buffalo (loc. 18), Black Bull No. 2 (loc. 20), Deer Fraction 1A (loc. 21), Black Bear No. 2 (loc 37), Wonder (loc. 45), Cago No. 12 (loc. 49), Contact (loc. 52), Beaverhead (Montana) (loc. 64), Wonder No. 18 (loc. 70), Little Dandy (loc. 72), Black Rock (Montana) (loc. 75), Last Chance (loc. 82), Dan Patch (loc. 98), Reactor (loc. 107), Elkhorn (loc. 108), Apex (loc. 136), Lone Star No. 2 (loc. 145), Silver Queen 52B (loc. 146), Silver Queen 38A (loc. 148), Nellie B (loc. 153), Black Rock (Idaho) (loc. 165), and ThO_2 (loc. 192).

LUCKY HORSESHOE

The Lucky Horseshoe (loc. 1) vein crosses Flume Creek about 1 mile northeast of its junction with Agency Creek. It lies on the lower frontal slope of the mountain where Flume Creek emerges from a deep rocky canyon and enters a broad basin. The principal workings lie on the nose of a ridge on the west side of the creek in the NW¼SE¼ sec. 9, T. 19 N., R. 25 E., Boise meridian, Idaho. It is most easily reached by following a secondary road up Flume Creek which leaves the Lemhi Pass road about 0.25 mile east of Flume Creek.

A group of 12 claims makes up the Lucky Horseshoe group and the principal workings are on the Lucky Horseshoe No. 1. This claim was located on May 31, 1954, by Tony N. Nardello, Ernest A. Woodman, and Clyde Goodwin. In 1957 the property was leased to Fred Gunderjohn who subsequently developed the property by means of

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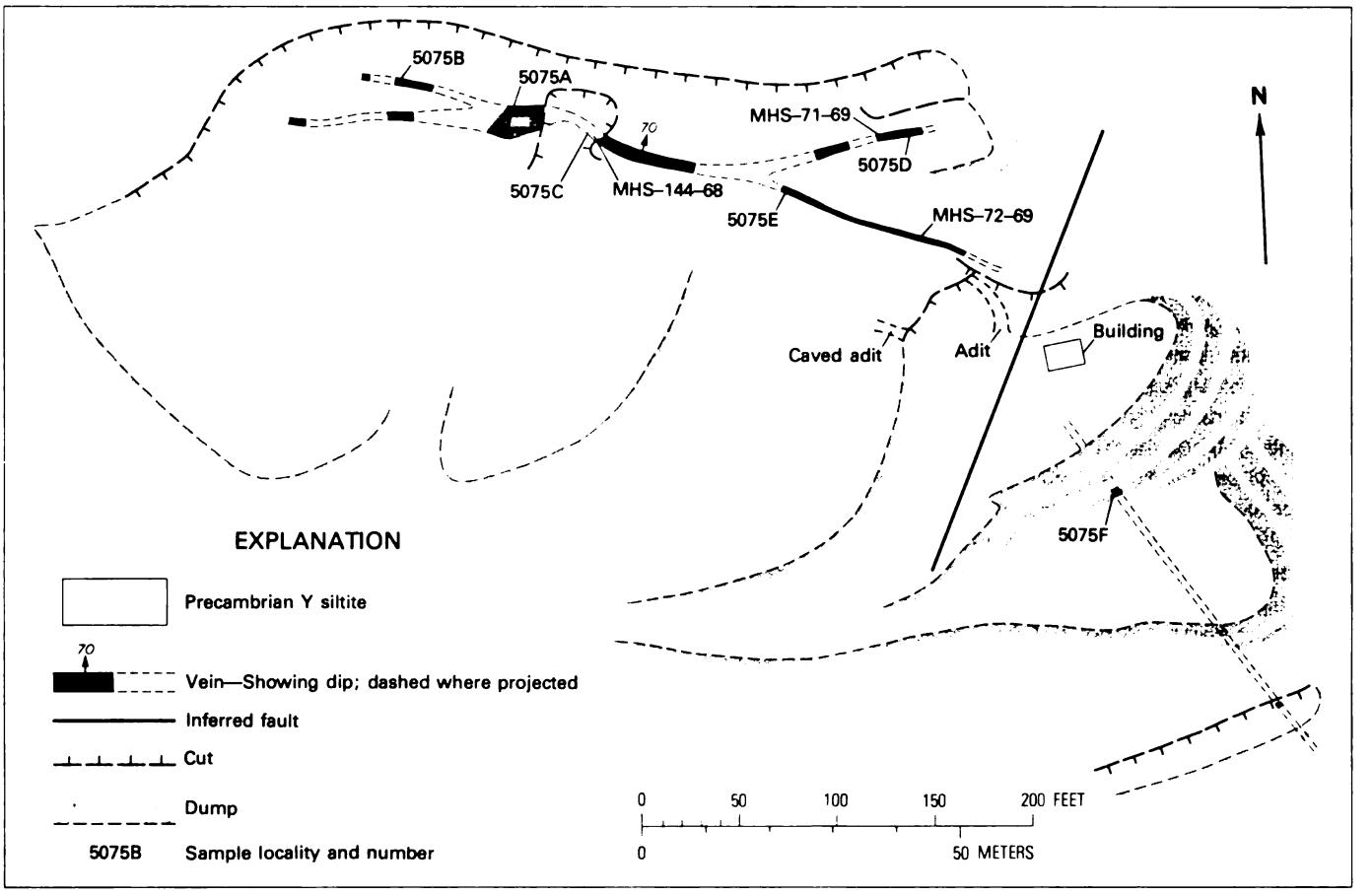


FIGURE 18.—Geologic map of the west end of the Lucky Horseshoe vein (loc. 1). Mapped by B. J. Sharp and D. L. Hetland, 1965; revised by M. H. Staatz, 1973.

extensive bulldozer trenches. Later, Harvey V. Bell became a part owner of this property and in 1972 the assessment work was done by Bell and Goodwin. The principal workings consist of several large cuts and two short adits (fig. 18). The largest cut, where the vein is best exposed, is 440 feet long. East of the cuts shown in figure 18, four trenches cut the vein on the steep west side of Flume Creek. East of Flume Creek, on the Lucky Horseshoe No. 10 claim, a trench in a broad bulldozed area exposes the extension of the main vein.

The Lucky Horseshow vein lies approximately parallel to and 700 to 1,000 feet north of the Lemhi Pass fault. The main workings expose highly sheared rocks that have a general east-west strike and dip 45° south. The rocks east of Flume Creek are also sheared and the beds in several pits are highly contorted. One or more subsidiary faults of the main Lemhi Pass fault probably pass through the mine workings. The country rock is greenish-gray siltite of Precambrian Y age. The greenish color is due to epidote. Adjacent to the vein, however, the siltite is dark gray or black. This vein is one of the few in the area in which siltite is the host rock. The siltite near the vein strikes N. 70° W. to N. 60° E. and in general dips gently to the north.

The vein has several branches (fig. 18). The principal vein has an overall strike of N. 70° W. The smaller branches strike from N. 80° W. to N. 80° E. Dip is 50°-75° N. Exposed length is 1,400 feet. The vein thickness ranges from less than an inch to 20 feet. Unlike most veins in this district whose fluids were confined to a fracture or replaced granulated material along fractures, the vein material at the Lucky Horseshoe also erratically replaced parts of certain beds adjacent to the fractures. The thickness of the vein, therefore, can change radically within a few feet. The vein is thickest in the principal workings, but consists only of a few small seams in the easternmost workings. The vein is brecciated, black to gray, and commonly contains augen of light-colored unfractured feldspar and quartz surrounded by a granulated dark-gray matrix. Shearing of vein material gives it a marked foliation, and the vein commonly resembles a banded gneiss. In some places there are augen-shaped bodies of unreplaced siltite. The principal gangue mineral is microcline; quartz is also common. The black color is due chiefly to abundant black shiny plates of specularite and biotite. A little magnetite is also present. Allanite is the most common thorium-bearing mineral. This is the only vein in

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TABLE 6.—*Analyses of samples from the Lucky Horseshoe vein, Idaho*

[C, chip sample; Ch, channel sample; n.d., no data]

Sample No.	Sample length and type (ft)	ThO_2 (percent)	Total rare-earth oxides (percent)
5075B	1.5 C	[1]1.00	[2]10.95
5075A	8.0 C	[1].52	[2]3.16
5075C	6.0 C	[1].47	N.d.
MHS-144-68	.8 C	[3].89	[4].35
MHS-71-69	1.5 C	[3].80	n.d.
5075D	6.0 C	[1].62	n.d.
5075E	4.0 C	[1].71	n.d.
MHS-72-69	2.8 Ch	[3].047	n.d.
5075F	2.0 C	[1].72	[2]4.29

[1]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.
[2]X-ray fluorescence spectrographic analysis by the U.S. Bureau of Mines, Salt Lake City, Utah.
[3]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.
[4]X-ray fluorescence spectrographic analysis by J. S. Wahlberg and V. S. Shaw, U.S. Geological Survey, Denver, Colo.

the district in which this mineral is abundant. Other thorium-bearing minerals are dark-red thorite and dark-brown monazite. Other minerals identified in this vein are muscovite, barite, plagioclase, calcite, apatite, rutile, chalcopyrite, and fluorite. The latter three minerals are very rare. Nine samples were taken from the various branches of this vein in the main workings (fig. 18). These samples ranged from 0.047 to 1.00 percent ThO_2 (table 6). The total rare-earth oxide content obtained from four of these samples ranged from 0.35 to 10.95 percent. The unusually high rare-earth content of this vein could be expected from its high allanite content.

BUFFALO

A series of workings (loc. 18) collectively known as the Buffalo mine lies on a gently sloping ridge on the north side of and 300 feet above Agency Creek, about 0.75 mile north of the Copper Queen mine in the NW¼ sec. 15, T. 19 N., R. 25 E. The property is reached by a secondary road up the Flume Creek basin that leaves the Lemhi Pass road about 0.25 mile east of where the latter road crosses Flume Creek.

This property was originally prospected for copper and gold, and 100 short tons of copper ore was reported to have been mined from a shaft that now lies under a mine dump near the location of sample MHS-74-69 (fig. 19) (Trites and Tooker, 1953, p. 195). In the early 1950's these claims were relocated for thorium by G. E. Shoup and Earl Pyeatt of Salmon, Idaho. In 1953 ownership was transferred to Irwin C. Porter and Frank Hussey of Salmon. In 1958 the claims were leased by Empire Explorations, Inc., of New Jersey, who made many bulldozer trenches and did some drilling. Lawrence Gini did the assessment work on this property in August 1973.

Early work consisted merely of a deep shaft and several adits. Later work consisted primarily of bulldozer trenches. The later trenching has obliterated the shaft and covered the adits in the northwestern and southern workings shown in figure 19. The adit shown on the eastern edge of the map follows a thorium vein for 90 feet. Bulldozing has made new trenches and changed old ones since the early 1950's. Figure 19 shows the workings as of September 1973. These workings lie on the Buffalo No. 2 and Buffalo No. 4 claims.

Country rock is a gray fine-grained micaceous quartzite that is shattered and brecciated. The property lies about 1,000 feet south of the Lemhi Pass fault and just east of a fault that brings the Challis Volcanics in contact with the Precambrian Y quartzite (pl. 1). Four, possibly five, veins were exposed in the workings in 1973. The principal vein lies in the eastern workings and has the adit driven along it (fig. 19). This vein has a north to northwest strike. At the mouth of the adit it strikes N. 5° W. and dips 60° SW. It can be traced in almost continuous outcrop for 280 feet. Two exposures in the southernmost working (fig. 19) may be a branch of this vein or may be a separate vein. If they belong to the principal vein, then they extend the known length to 550 feet. The principal vein ranges from 1.0 to 11.0 feet thick, being thickest near the portal of the adit.

The vein is medium brown to dark brown and is brecciated. Gangue minerals consist of abundant quartz, much of which is stained brown by limonite, and a little microcline. Specularite in flat shiny black plates is the principal iron oxide mineral. Limonite is common and in places occurs as tiny dark-brown cubes, a pseudomorphous replacement of pyrite. Some magnetite is also present. The chief thorium mineral is reddish-brown shiny thorite, although sparse crusts of clear-yellow monazite occur. In addition, minor brassy pyrite cubes and dark-brown to amber rutile were noted. Three samples were taken near the portal of the adit (fig. 19, table 7). One of these samples (MHS-141-68), taken at the widest spot, 11 feet, yielded 0.098 percent ThO_2. A second sample (MHS-142-68), consisting of the most radioactive 1.5 feet of the first sample, yielded 0.48 percent ThO_2. The total rare-earth oxide content of the entire 11 feet was 0.12 percent, but that of the most radioactive part was only 0.073 percent (Staatz, 1972, table 5). The third sample (5080C), taken about 10 feet away where the vein had thinned to 20 feet, yielded 1.05 percent

TABLE 7.—*Analyses of samples from the Buffalo property, Idaho*

[C, chip sample; G, grab sample; n.d., no data]

Vein	Sample No.	Sample Length and type (ft)	ThO_2 (percent)	Total rare-earth oxides (percent)
Principal	MHS-141-68	11 C	[1]0.098	[2]0.12
	MHS-142-68	1.5 C	[1].48	[2].073
	5080C	2.0 C	[3]1.05	[4].46
West	MHS-74-69	2.0 C	[1].37	N.d.
	5080B	G	[3].13	n.d.
	5080A	2.0 C	[3].61	n.d.

[1]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.
[2]X-ray fluorescence spectrographic analysis by J. S. Wahlberg and V. S. Shaw, U.S. Geological Survey, Denver, Colo.
[3]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.
[4]X-ray fluorescence spectrographic analysis by the U.S. Bureau of Mines, Salt Lake City, Utah.

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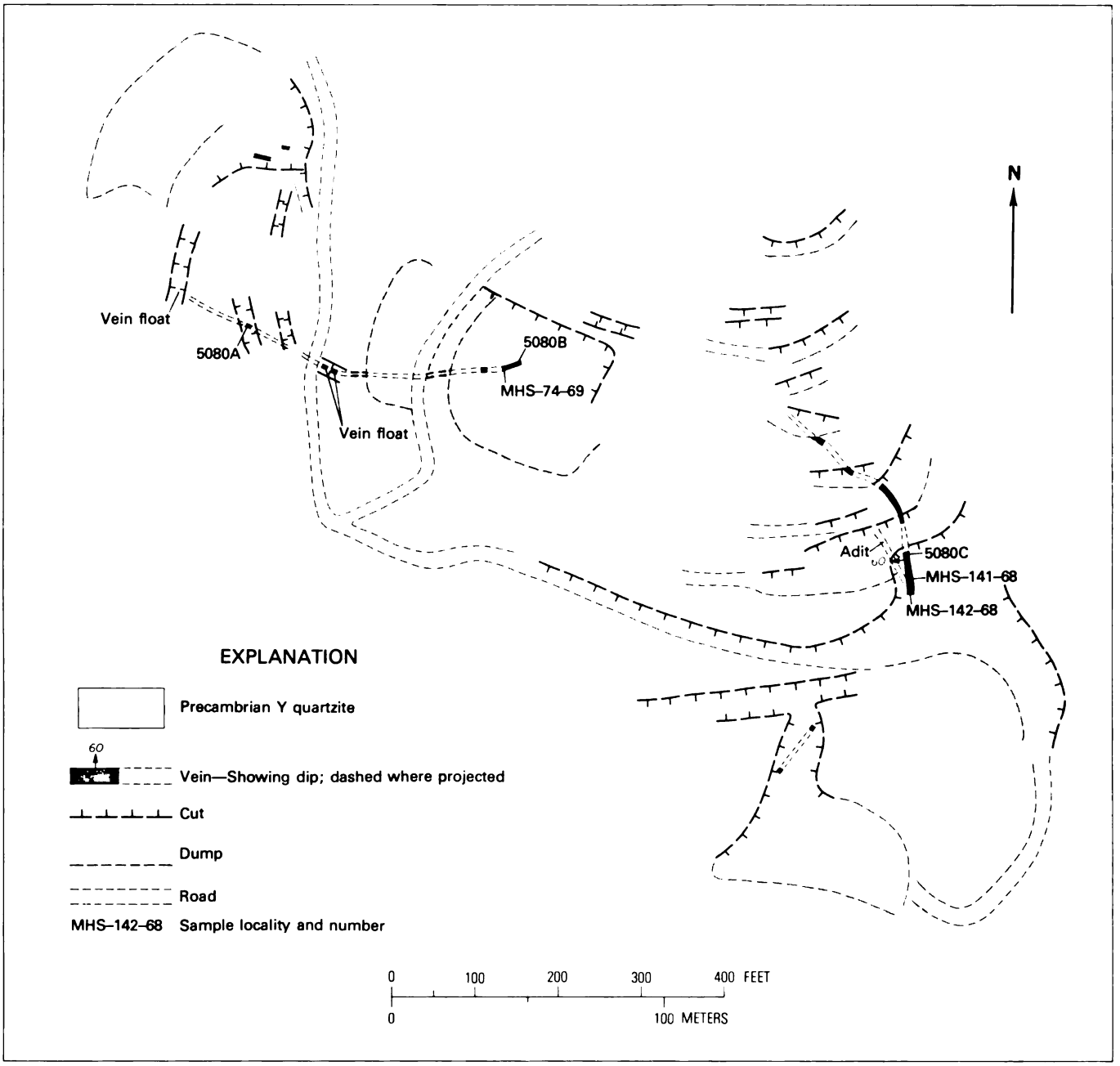


FIGURE 19.—Geologic map of the Buffalo property (loc. 18). Mapped by M. H. Staatz, 1973.

ThO_2 and 0.46 percent total rare-earth oxides (Austin, 1968, p. 3).

West of the main vein is a second vein which strikes from about S. 80° W. to N. 70° W. and appears to dip steeply to the south. Much of the vein material in the western four trenches is float, but some of it appears to be essentially in place. The length of the vein as mapped is 430 feet. The thickness at the eastern end is 1.5-2.5 feet. This vein is also dark brown and its principal gangue mineral is quartz. Some microcline is present as well as minor calcite. Black shiny plates of specularite are the common iron oxide. Magnetite and limonite are less common. Thorite was the only thorium mineral recognized. Other minerals include rutile and pyrite. Three samples taken from this vein range from 0.13 to 0.61 percent ThO_2 (fig. 19, table 7).

Two other thorium-bearing veins are exposed in the northwestern most group of trenches (fig. 19). These veins strike about N. 80° W. The southern one dips 50° SW., is exposed for approximately 20 feet, and is 2 feet thick. The northern one is exposed for about 10 feet and is about 1 foot thick. Both are dark brown and consist essentially of quartz and iron oxides.

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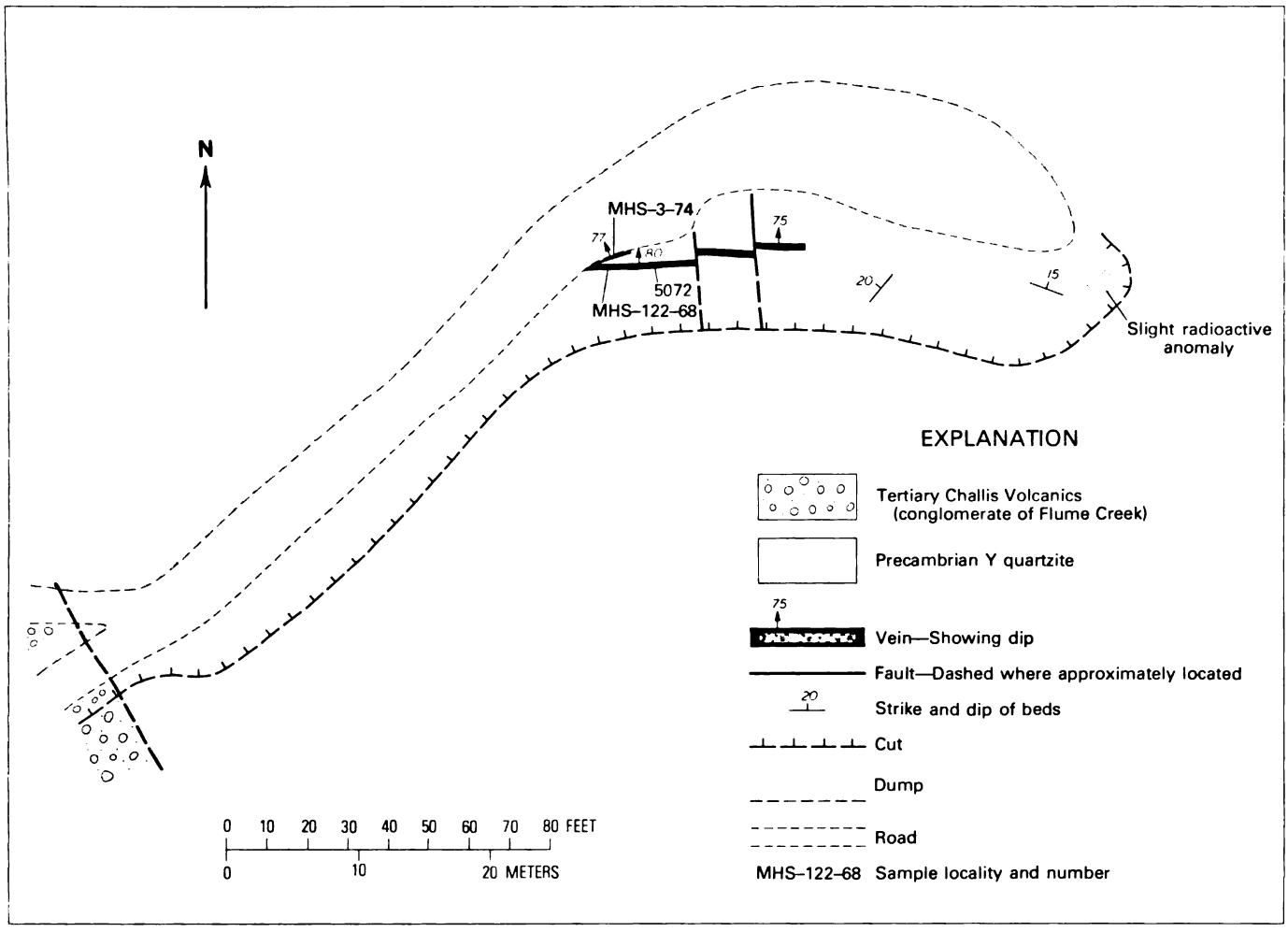


FIGURE 20.—Geologic map of the Black Bull No. 3 property (loc. 20). Mapped by B. J. Sharp and D. L. Hetland, 1965; revised by M. H. Staatz, 1973.

BLACK BULL NO. 3

The Black Bull No. 3 claim (loc. 20) lies on the south side of Agency Creek just west of the road leading south to the Copper Queen Mine. The vein is only about 30 feet above Agency Creek in the SW¼ sec. 15, T. 19 N., R. 25 E. The property was located by E. P. Peron in 1952 (Sharp and Cavender, 1962, p. 42). In August 1972 the property was owned by Nuclear Fuels and Rare Metals Corp. The country rock is an iron-oxide-stained micaceous quartzite of Precambrian Y age. This red-stained quartzite is part of a zone a hundred to several hundred feet wide that can be traced for more than a mile along the east side of the Dan Patch fault. The workings on this property consist of a cut more than 290 feet long that has a wall as much as 20 feet high. A branching vein is exposed along the wall of the cut (fig. 20), where it is offset by two small faults. The main part of this vein is well exposed for 60 feet, and a radioactive spot near the east end of the cut indicates that it probably continues for at least 70 more feet. The possible extension of this vein is limited by two large faults, the Dan Patch fault 150 feet to the west (fig. 20), and the Bull Moose fault, approximately 200 feet to the east. This vein varies in thickness from 0.5 to 1.3 feet. It strikes N. 77° W. and dips 75°-80° NE. The vein bifurcates near its west end (fig. 20), and the smaller branch strikes N. 77° E. and dips 77° NW. This thinner branch is 2-6 inches thick and is exposed for only 5 feet.

Unlike most of the veins in this district, calcite is the principal gangue mineral; some white quartz is also present. Black shiny specularite is the principal iron oxide mineral, although hematite also occurs in a dark cherry-red granular form. Brown limonite is abundant, and black granular magnetite occurs in scant amounts. Radioactivity is due to dark-red thorite. Other minerals include white platy barite and cubes and pyritohedrons of brassy pyrite.

Two samples cut across the main part of the vein, one (MHS-122-68) 0.7 foot long and the other (5072) 1.25 feet

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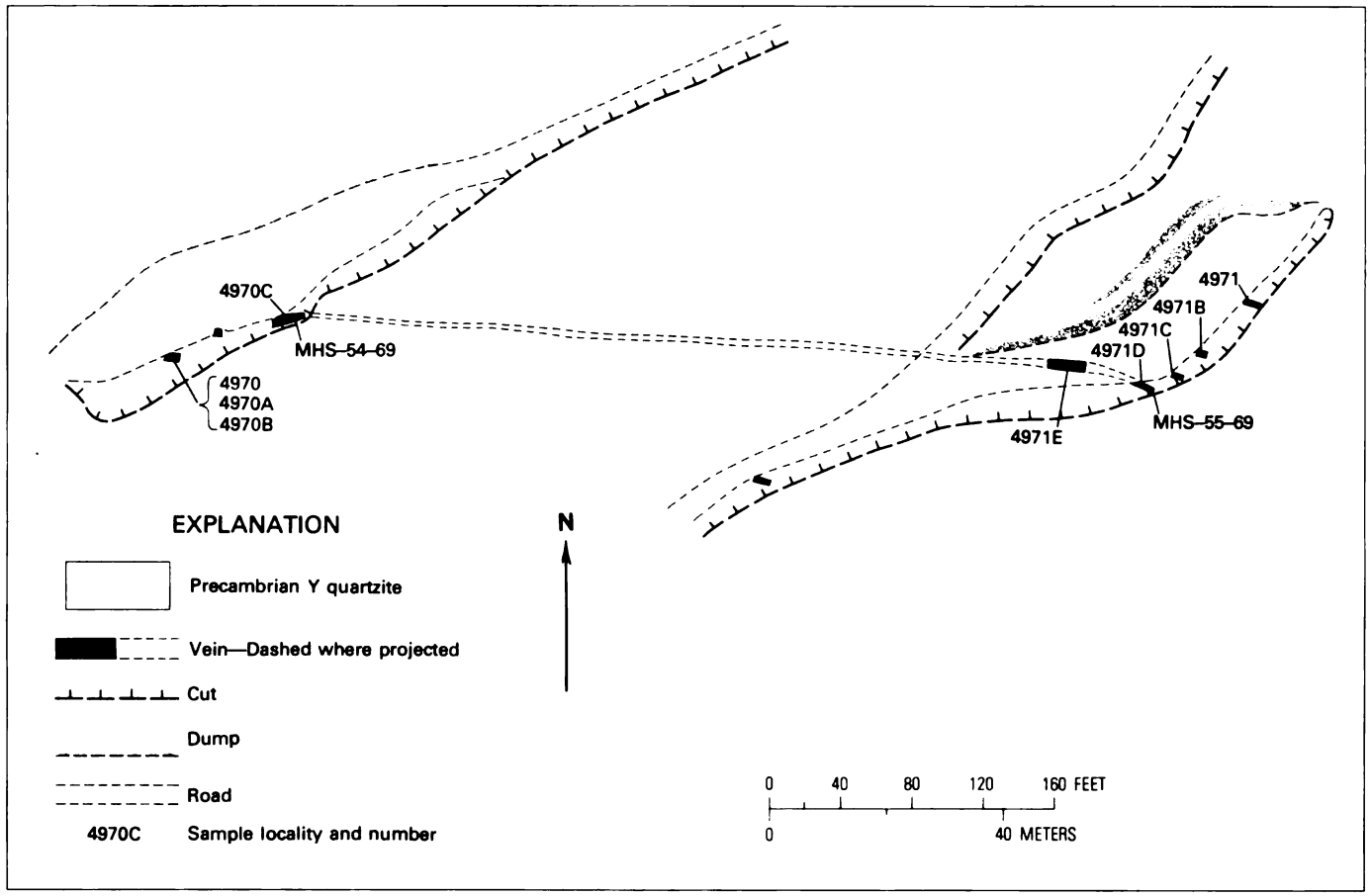


FIGURE 21.—Geologic map of the Deer Fraction IA veins (loc. 21). Mapped by B. J. Sharp and D. L. Hetland, 1965; revised by M. H. Staatz, 1973.

long (fig. 20), yielded 0.80 and 0.72 percent ThO_2, respectively. A third sample (MHS-3-74) from the thinner branch vein, 0.5 foot long, contained 0.24 percent ThO_2.

DEER FRACTION IA

A number of veins have been exposed on the eight Deer claims that lie along the south side of Agency Creek north of the Copper Queen mine. The largest of these lies on the Deer Fraction 1A claim (loc. 21), which is in the NW¼SE¼ sec. 15, T. 19 N., R. 25 E., Boise meridian, Idaho. This claim is on a steeply dipping, north-facing, heavily vegetated slope, and the only exposures are found in deep cuts. The property was located May 15, 1955, by Jacob Schenk for Nuclear Fuels and Rare Metals Corp., who still owned it in the summer of 1972. This claim was explored by several long inclined roads. In the two areas where radioactivity was found, cuts deep enough to expose the veins were made. The westernmost cut (fig. 21) is about 300 feet long and has a back of as much as 20 feet; the easternmost one is about 350 feet long and has a back of as much as 12 feet. The country rock of Precambrian Y age is gray micaceous quartzite that contains some greenish siltite beds. The westernmost cut exposes three veins and the easternmost one five (fig. 21). Veins appear to occupy a broad shear zone and some appear to be lenticular. In the westernmost cut the principal vein thins from 10 feet thick near the base of the cut to 2.5 feet at the top of the cut. This vein (fig. 21) has an overall strike of about N. 87° W. and dips 45°-70° SW. Its length between the two cuts is 520 feet. Along strike east of this claim radioactive vein material occurs in the rubble of another cut. If this is an extension of this vein, as seems probable, then this vein can be extended another 700 feet. The thickness of this vein is about 1-10 feet and averages about 3 feet. In addition two other veins were exposed in the floor of the westernmost cut in 1965 but were later covered. Where exposed they were approximately 8 and 7 feet thick. They appear, however, to be short lenses along the main shear zone, as they are not exposed to the east in the back of the cut. In the easternmost cut three veins, 1.5, 4.0, and 1.3 feet thick, lie north of the principal vein. In addition, a poorly exposed rather weakly radioactive vein lies about 80 feet south of the principal vein. Veins are brown to black and are made up principally of quartz and various iron oxides. Where the veins are brown, goethite is the chief iron oxide, and where they are black, specularite. In addition, all contain a minor amount of magnetite. Thorite

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TABLE 8.—*Thorium analyses of chip samples from the Deer 1A claim, Idaho*

Vein	Sample No.	Sample length (ft)	ThO_2 (percent)
Principal	4970C	4.0	[1]0.18
	MHS-54-69	3.0	[2].19
	4971D	6.0	[1].25
	4971E	7.0	[1].34
	MHS-55-69	.4	[2].59
Subsidiary	4970	2.4	[1].35
	4970A	2.0	[1].83
	4970B	2.4	[1].73
	4971C	1.5	[1].38
	4971B	4.0	[1].08
	4971	1.3	[1]2.00

[1]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.
[2]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.

was the only thorium mineral noted. In addition, there are minor amounts of calcite, rutile, feldspar, barite, and pyrite. The ThO_2 content of five samples from the principal vein ranged from 0.18 to 0.59 percent (fig. 21; table 8). Six other samples, taken from the other veins, are shown in figure 21 and table 8. They ranged from 0.08 to 2.0 percent ThO_2.

BLACK BEAR NO. 2

This property (loc. 37) covers the nose of a small northward-trending ridge 6,000 feet south of the junction of Flume and Agency Creeks. It is about halfway between Agency Creek and the Continental Divide on a Douglas-fir-clad northward-facing slope in the E½NW¼ sec. 21, T. 19 N., R. 25 E., Boise meridian, Idaho. The property is reached by a steep narrow road that meets the Agency Creek road about 0.25 mile east of the Flume Creek junction and ends at the property about 1 mile to the south. The Black Bear No. 2 was located by Earl Pyeatt and G. E. Shoup on May 14, 1954. This property was controlled by Nuclear Fuels and Rare Metals Corp. in 1961. Assessment work was done on it in 1971 by Nuclear Fuels and Golden Pleasures Mining Co. The Black Bear No. 2 was developed by a bulldozer cut 100 feet long having a 15-foot back, a small pit, and a branching road (fig. 22).

The country rock is a gray fine-grained micaceous quartzite (Precambrian Y). The workings on this property expose an undulating vein that strikes N. 45° W. The dip is steep but is difficult to determine because the vein changes shape in the large cut. The vein has an exposed length of 135 feet. Thickness ranges from about 3 to 32.5 feet. In the back of the large cut the thickness ranges from 13 to 32.5 feet, and at the southeastern exposure of the vein (fig. 22) it ranges from 3 to 4 feet. In this same exposure a second vein was uncovered 2 feet to the west. This vein is 1 foot thick. Although from the one exposure it appears to be a separate vein or lens, it might be a branch of the main vein.

The principal vein is made up mainly of pink to white microcline. Quartz is only a minor accessory mineral. Most of the vein has thin irregular layers and patches of black shiny specularite. Some limonite is present, especially in the southeast part of the vein. In part, this mineral occurs as dark brown cubes, a pseudomorphous replacement of pyrite. The only other iron oxide mineral noted was magnetite, which occurs as small black granular crystals. Reddish-brown shiny thorite was the only thorium mineral noted. Barite is found as both white platy and clear pink crystals. In addition, this vein contains minor amounts of black shiny rutile, greasy greenish-white pyromorphite, and bright-yellow wulfenite. This was only one of three veins in this district in which molybdenum minerals were found, the others being the Barbara (loc. 172) and the Daisy Nielsen.

Six samples were taken from this vein and they contained from 0.02 to 0.26 percent ThO_2 (fig. 22; table 9). In the thick northwest end of the vein the thorium is concentrated in the outer 3-4 feet of both the hanging and footwall sides. As both lead and molybdenum minerals were noted in several samples, one sample (MHS-133-68) was also analyzed for these elements and other base and precious metals. This sample had 0.024 percent molybdenum, 0.050 percent lead, 0.080 percent zinc, 0.0053 percent copper, 0.090 ounce per short ton of silver, and less than 0.0006 ounce per short ton of gold. This vein is noted for its very high microcline content and a sample (MHS-47-73) analyzed by gamma-ray spectrometer yielded 12.4 percent potassium. As microcline was the only potassium mineral noted, this amount of potassium would be equivalent to about 88 percent microcline.

WONDER

The Wonder vein (loc. 45) lies astride Camp Creek, 1.1 miles south-southeast of this creek's junction with Agency Creek, in the SE¼ sec. 22, T. 19 N., R. 25 E., Boise meridian, Idaho. The property is 0.75 mile south of the Copper Queen mine, and the road to the Copper Queen mine from the Agency Creek road continues up Camp Creek to the Wonder property. The original location was made on five claims, then called the Wonder Lode and the Buckhorn mining claims, in about 1923 by James Quinn (Sharp and Cavender, 1962, p. 44). Later the five claims were relocated as the Wonder Lodes Nos. 1-5 by Ray and Claire Pierce of Salmon, Idaho.

The vein is zoned, the west part containing copper, zinc,

TABLE 9.—*Thorium analyses of chip samples from the Black Bear No. 2 claim, Idaho*

Sample No.	Sample length (ft)	ThO_2 (percent)
4998D	3.5	[1]0.20
4998C	25.0	[1].04
4998B	4.0	[1].26
MHS-133-68	19.0	[2].082
4998A	3.0	[1].19
MHS-47-73	3.0	[2].02

[1]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.
[2]Gamma-ray spectrometric analysis by C.M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.

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and a little thorium, and the central and eastern parts containing more thorium and a little copper and zinc. Early workings, which consisted of several pits and eight short adits, some not more than 20 feet long, were made on a small ridge west of Camp Creek and immediately adjacent to the east side of the creek. A little ore containing copper and zinc was shipped to the mill on the Copper Queen property (Sharp and Cavender, 1962, p. 44). In 1950, when interest shifted to thorium, the property was owned by G. E. Shoup of Salmon, Idaho (Trites and Tooker, 1953, p. 193). At this time six of the small adits were caved; the other two were 50 and 75 feet long. The property was leased to Frank Eichelberger and associates of Spokane, Wash., in October 1951, who turned all their rights over to Defense Metals, Inc. of Kellogg, Idaho (Sharp and Cavender, 1962, p. 44). In August 1952, the U.S. Defense Minerals Exploration Administration granted an exploration loan to Defense Metals, Inc., to aid in exploring for thorium. During this contract, which lasted until December 1954, 13 trenches, 2 adits, and 3 diamond-drill holes were made. The trenches form a zigzag pattern up 680 feet of the steep east face of Camp Creek canyon (pl. 2*A*). There are two adits, the lower one, 40 feet above the creek level on the east side of Camp Creek, which has 487 feet of workings, and the upper one, 120 feet above the first adit on the same side of the creek, which has 336 feet of workings. Three diamond-drill holes totaling 941 feet in length were drilled. In one hole the vein was not found, apparently cut out by a large fault. The other two cut the vein approximately 150 feet below the level of Camp Creek. Little work has been done since this contract terminated, and the tunnels have caved near their mouths and many of the trenches show considerable sloughing. From at least 1966 to 1972, this property was owned by Nuclear Fuels and Rare Metals Co.

Most of this property is underlain by a Precambrian Y dark-gray fine-grained micaceous quartzite. These rocks

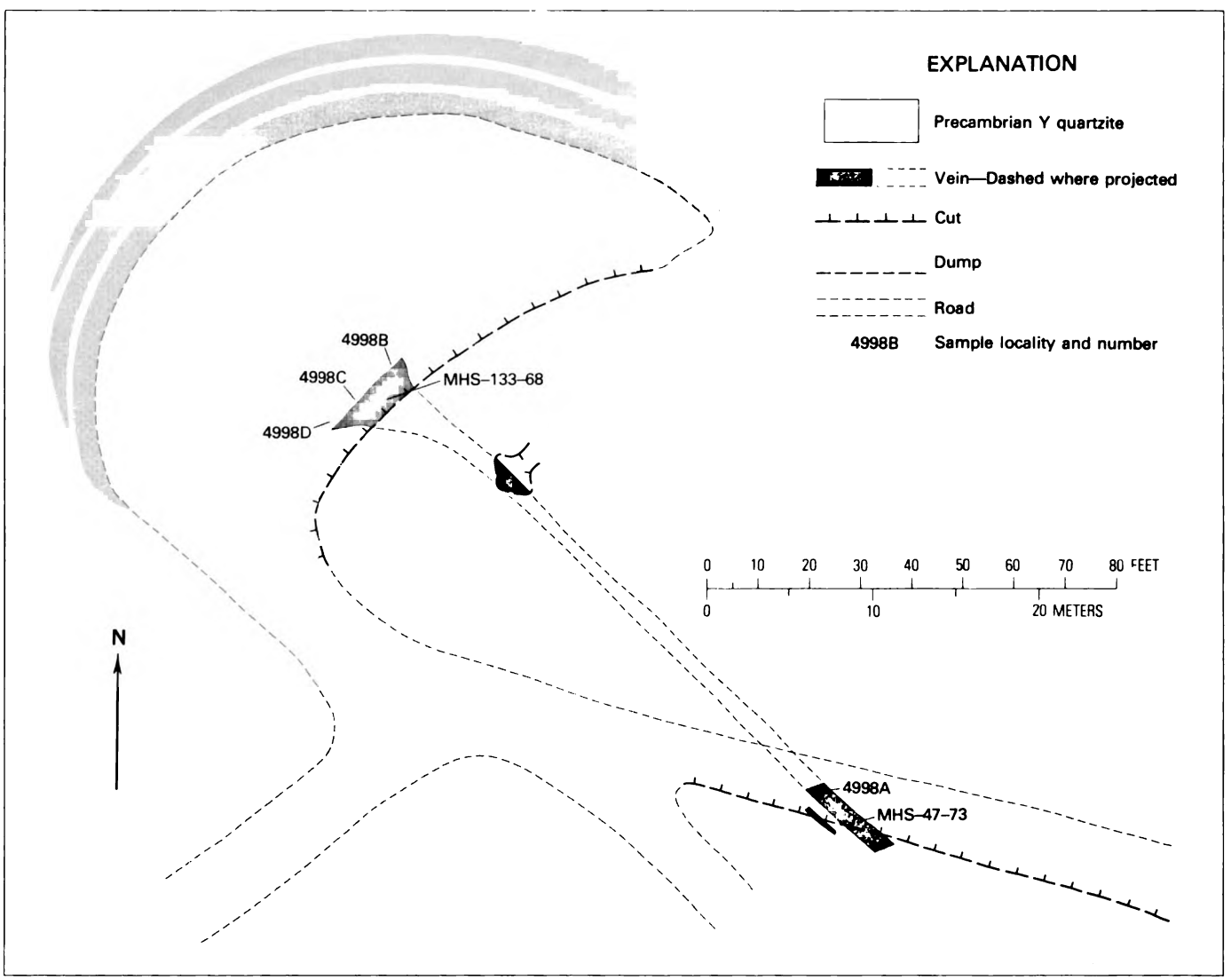


FIGURE 22.—Geologic map of the Black Bear No. 2 property (loc. 37). Mapped by B. J. Sharp and D. L. Hetland, 1965; revised by M. H. Staatz, 1973.

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have varying attitudes, striking from N. 30° W. to N. 70° E. and dipping 10°-40° N.; most, however, strike N. 50°-70° E. and dip 25°-35° NW. An east-west-trending shear zone cuts these quartzites and contains two Tertiary diorite dikes in addition to the thorium veins. One diorite dike lies 40-80 feet north of the principal vein, which it tends to parallel (pl. 2*A*). This dike has been traced for about 970 feet and is 5-20 feet thick. Its dip is nearly vertical near the east end and 58° S. near the west end (Weis and others, 1958, p. 38). The second dike lies approximately 410 feet south of the east end of the main vein, which it parallels, and is exposed for 560 feet (pl. 2*A*). This dike is about 10 feet thick. Both dikes weather easily to a soft olive-green material and are exposed only in the deeper cuts. The diorite dikes vary somewhat in composition from place to place but in general contain about equal amounts of mafic minerals and plagioclase. The principal mafic minerals are generally either hornblende or augite, although in some places these have been largely altered to biotite. Minor amounts of epidote, chlorite, magnetite, quartz, clinozoisite, pyrite, and hematite are also present.

The thorium mineralization, for the most part, is localized in one large generally eastward-trending vein that dips 40°-80° S. The vein ranges in thickness from 0.7 to 10 feet and has an average thickness of a little less than 3 feet. Near the eastern end of the main vein a number of smaller veins or lenses, 0.5 inch to 2.0 feet thick, trend parallel to, or fan away from, its southern side (pl. 2*A*). The main vein can be traced for approximately 920 feet. To the west along a small gulch 235 feet west of Camp Creek, it ends abruptly on the large Dan Patch fault. Eastward it apparently ends against a small cross fault, although east of the fault it may be represented by one of several small veins. The main vein is exposed on the steep side of Camp Creek canyon through a vertical distance of 350 feet. Drilling extended its known vertical distance another 150 feet. As has been noted previously, the thorium veins, as well as the diorite dikes, occupy a wide shear zone. Shearing along this zone not only preceded the intorduction of the vein filling, but continued during and after its deposition. In many places early vein material was brecciated and a second generation of minerals was introduced along the fractures, followed by further fracturing. Not only was there fracturing along the shear zones, but several cross faults were noted that cut both the main vein and the northern diorite dike (pl. 2*A*). These faults have a northerly strike and a steep (63°-90°) dip. Horizontal offset ranges from 8 to 25 feet. The country-rock quartzite is stained hematitic red adjacent to the veins and along some of the fractures in the shear zone. Locally the iron oxide-stained rock extends as much as several feet from the vein but in most places is only a few inches thick. The veins are generally brown and amorphous in appearance, containing irregular black layers and areas. For the most part, the veins are soft and friable. The mineralogy of the main vein varies from place to place. West of Camp Creek the chief gangue minerals are quartz and calcite; sphalerite and copper minerals are relatively abunant. This is the part of the vein developed in the early days for copper. East of the creek, especially high on the slope, calcite and siderite are the most abundant gangue minerals and barite is fairly common. Sphalerite is present but less common than to the west. Reddish-brown thorite is more abundant on the east side of the valley. Limonite and black manganese oxide minerals are ubiquitous, generally occupying fractures cutting the earlier formed minerals. Specularite and magnetite are less common. Chalcopyrite is the chief copper mineral, but minor chrysocolla, malachite, and azurite are found coating fractures. Other sulfides identified are pyrite and pyrrhotite. Minor amounts of microcline, apatite, and rutile also occur in this vein.

TABLE 10.—*Analyses of surface samples from the Wonder property, Idaho*

[C, chip sample; Ch, channel sample; n.d., no data]

Sample No.	Length of samples and type (ft)		ThO_2 (percent)	Copper (percent)	Zinc (percent)
MHS-19-69[1]	2.0	Ch	[2]0.066	[3]0.42	[3]3.70
TEH-1	1.5	C	[4].19	[5].35	[5].28
TEH-2	1.5	C	[4]1.10	[5].15	[5].21
TEH-3	1.5	C	[4]1.00	[5]2.80	[5]1.56
TEH-5	2.5	C	[4].30	[5].45	[5]3.46
TEH-4	2.0	C	[4].26	[5]1.05	[5]3.40
TEH-6	2.5	C	[4]2.5	[5].15	[5].29
MHS-60-69[6]	9.8	C	[7].34	[3].44	[3].40
5069B	6.0	C	[7].34	N.d.	N.d.
TEH-7	2.5	C	[4].50	[5].65	[5].26
5069A	3.0	C	[7].54	n.d.	n.d.
5069C	2.0	C	[7].15	n.d.	n.d.
5069D	2.0	C	[7]2.14	n.d.	n.d.
TEH-8	2.0	C	[4].07	[5].20	[5].08
5069E	1.0	C	[7]1.47	n.d.	n.d.
MHS-59-69	0.7	C	[3].34	n.d.	n.d.

[1]This sample also contains 0.012 percent lead, 0.99 ounce ton silver, and 0.0058 ounce ton gold. Atomic absorption analysis, U. S. Geological Survey, Denver, Colo.

[2]Gamma-ray spectrometer analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.

[3]Atomic absorption analysis, U.S. Geological Survey, Denver, Colo.

[4]$eThO_2$ calculated from eU and U analyses by the U.S. Geol. Survey and U.S. Bureau of Mines, respectively.

[5]Analyses by U.S. Bureau of Mines, Albany, Oreg.

[6]This sample also contains 0.013 percent lead, 0.52 ounce ton silver, and 0.020 ounce ton gold. Atomic absorption analysis, U. S. Geological Survey, Denver, Colo.

[7]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.

The veins on the Wonder property have been sampled many times. Sixteen samples collected by Sharp and Cavender (1962, p. 62, pl. 5) and by Trites and Tooker (1953, p. 195) contained 0.02-3.2 percent ThO_2. The location of 16 other surface samples is shown on figure 23. These samples contained 0.066-2.5 percent ThO_2 (table 10). Although the two long adits (pl. 2*A*) financed by the U.S. Defense Minerals Exploration Administration loan were sampled, data on individual samples is not available. A summary of these data, however, is given by Weis, Armstrong, and Rosenblum (1958, p. 38) who state: "The upper working exposes brecciated vein material for more than 100 feet averaging 2.5 feet in thickness and containing about 0.75 percent thorium oxide. In the lower working, vein material exposed for 150 feet averages 1.75 feet in thickness and contains about 0.30 percent thorium oxide." Ten copper and

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zinc analyses were made of the main vein (table 10). The copper content ranged from 0.15 to 2.80 percent; the zinc content, which ranged from 0.08 to 3.70 percent, is highest in the western and central parts of the vein. Two samples analyzed for silver contained 0.52 and 0.99 ounce per short ton, suggesting that this element could be an important economic consistuent of this vein. Only minor amounts of lead and gold are present in the two samples analyzed for this element (table 10).

CAGO NO. 12

This property (loc. 49) lies 0.3 mile north of the Continental Divide on a steep north-facing Douglas-fir-covered slope in the NE¼ sec. 28 and NW¼ sec. 27, T. 19 N., R. 25 E., Boise meridian, Idaho. It is reached from the Agency Creek road by following a twisty secondary road that connects the mouth of Camp Creek to the Continental Divide. A second road leads west from this road at a point 3.2 miles from Agency Creek, for 0.8 mile to the property. The original locators are not known, but in 1957 this property was owned by the Salmon Uranium and Thorium Co. (Anderson, 1958, p. 73). Since then it has been controlled by the Rare Metals Corp. (a subsidiary of El Paso Natural Gas Co.) in 1961; the Agency Creek Thorium and Rare Metals Co. of Salmon, Idaho, in 1966; and the Nuclear Fuels and Rare Metals Corp. of Salmon in 1972.

Workings consist of a series of interconnecting bulldozer cuts and trenches that blanket the hillside for a distance of 2,700 feet, and one 120-foot-long adit (pl. 2*E*). These workings are cut in a Precambrian Y gray fine-grained micaceous quartzite. The vein on the Cago No. 12 is the westernmost known vein of many that lie along a northwest-trending shear zone. This shear zone can be traced for 2.5 miles across the Continental Divide to the Dan Patch fault. Other veins in this same shear zone include the Contact vein, Beaverhead vein, Trapper No. 1 vein, and Shear Zone vein.

The vein on the Cago No. 12 property strikes N. 45°-55° W. and dips 45°-55° SW. It has been traced for 2,625 feet and is 0.2-25 feet thick. The thickest and also most radioactive part of the vein is about 690 feet long. This part, which is 10-16 feet thick, extends from 270 feet southeast of the adit to 420 feet northwest of it. The northwestern part of this vein varies from 0.2 to 10 feet in thickness. The vein varies both in color and in mineralogy. In the thicker part near the adit it is yellowish brown and appears to be mainly brown jasper. Actually, the color and texture are produced by the intermixing of fine-grained quartz with tiny particles of limonite. In some places farther northwest, the vein is white and made up mainly of quartz; in other places it is reddish brown due to a high content of hematite. In the thickest part, tan microcline is also an important gangue mineral. At least part of the limonite is goethite, and some of the goethite occurs as small dark-brown cubes, a pseudomorphous replacement of pyrite. Other iron oxide minerals are specularite, which is common in many samples, and minor amounts of black magnetite. The chief thorium mineral is reddish-brown shiny thorite; minor amounts of monazite and allanite are present. In addition, tan to pale-orange rutile, white apatite, clear to pale-orange barite, and a few crystals of pyrite, galena, and chalcopyrite were also noted. Eight samples were taken along this vein by the U.S. Atomic Energy Commission and the U.S. Geological Survey (pl. 2E). These range in ThO_2 content from 0.02 to 0.29 percent (table 11).

TABLE 11.—*Thorium analyses of chip samples from the Cago No. 12 vein, Idaho*

Sample No.	Sample length (ft)	ThO_2 (percent)
MHS-30-69	1.0	[1]0.12
4976C	2.0	[2].03
4976A	2.5	[2].11
4976B	2.0	[2].02
4976D	8.0	[2].05
4976E	4.0	[2].16
MHS-28-69	13.0	[1].085
MHS-29-69	12.0	[1].29

[1]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.
[2]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.

CONTACT

The Contact (loc. 52) is a name applied to one major vein having several branches, or to several veins, that lie along the Continental Divide on the north side of North Frying Pan Creek (pl. 2*C*). The ridge here has a N. 75° W. trend, and the principal vein lies more or less parallel to the ridge and just on the Idaho side, although one branch and nearby parallel veins lie on the Montana side. These veins are in sec. 27, T. 19 N., R. 25 E., Boise meridian, and secs. 19 and 20, T. 10 S., R. 15 W., Montana Principal Meridian. The property can be reached from Lemhi Pass by following the road south along the Continental Divide for 3.2 miles. The principal workings are on the Contact Nos. 1 and 2 claims, which in the early 1960's were part of the Nuclear Fuels and Rare Metals Corp. holdings. In 1972 the assessment work on these two claims was done by the Jan Corp. On the east end of the vein in Idaho is the Beaverhead claim, which was held in 1972 by Nuclear Fuels and Rare Metals Corp. The western end of this vein system, which was discovered much later than the rest of the vein, is covered by the Jan claims which were located in May 1967 by D. L. Davidson and Jacob Schenk. The Jan Corp. also did the assessment work on these in 1972. On the Montana side of the divide, the area is covered principally by the Ragand Nos. 8 and 10 claims. These claims were located in July 1957 by R. A., Ned, Billy, and Dave Wellborn. In 1973 they were part of the holdings of Sawyer-Adecor International, Inc. The veins in this area are

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explored by a series of bulldozer trenches (pl. 2*C*). On the Idaho side, most are relatively short trenches as much as 10 feet deep, and on the Montana side many are long, relatively shallow trenches.

The country rock consists principally of gray fine-grained micaceous quartzite and some interbeds of gray siltite (Precambrian Y). The Contact and adjacent veins (pl. 2*C*) are along a well-developed shear zone trending N. 70° W. that contains many large and small veins, including the Cago No. 12, Beaverhead, Trapper No. 1, and Shear Zone veins. The main Contact vein follows an undulating fracture system. Strike of the vein measured at various places ranges from N. 45° W. to N. 70° E. and its dip from 25°-60° S. Near the east-central part, the vein apparently splits, and has one branch on each side of the Continental Divide fence. In places as near as the west end of the vein, several parallel veins are exposed in the trenches, and some of the projections shown on the map (pl. 2*C*) may actually connect two parallel veins. Small cross faults may also account for some of the offset of alinement between various segments of the main vein. The overall length of the principal vein is 1,940 feet. Measured thicknesses of the main vein varied from 0.5 to 10 feet.

Vein material varies from brown to black. Quartz is the principal gangue mineral except near the eastern end where pink microcline is the most abundant mineral. Hematite, which occurs both as black shiny plates of specularite and as granular grains, is common in much of this vein. The other principal iron oxide is brown goethite that commonly fills irregular fractures cutting earlier formed minerals. In some places the goethite occurs in pyritohedrons as a pseudomorphous replacement after pyrite. A few grains of black magnetite may be present. Brownish-orange to tan granular monazite is the principal thorium mineral; red shiny thorite also occurs in most specimens. In addition, most parts of this vein generally contain a little brown shiny rutile and a few brassy pyritohedrons of pyrite. Eight samples were taken along the main vein and they ranged from 0.029 to 1.40 percent ThO_2 (pl. 2*C*; table 12). In addition, a sample (MHS-23-69) taken of a vein adjacent to the west end of the main vein yielded 0.046 percent ThO_2, and another sample (5061A) taken from a vein about 350 feet south of the main vein contained 0.20 percent ThO_2.

TABLE 12.—*Thorium analyses of samples from the Contact and adjacent veins, Idaho and Montana*

[C, chip sample; G, grab sample; N.d. not determined]

Sample No.	Sample length and type (ft)	ThO_2 (percent)
MHS-23-69	2.0 C	[1]0.046
5061E	3.5 C	[2].38
MHS-20-69	1.3 C	[1].12
MHS-17-69	16.0 C	[1].17
5061F	4.0 C	[2].23
MHS-21-69	N.d. G	[1].029
AO-440	6.0 C	[2]1.39
MHS-16-69	2.5 C	[1].86
5061G	2.5 C	[2]1.40
5061A	3.0 C	[2].20

[1]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.
[2]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.

BEAVERHEAD, MONTANA

The Beaverhead vein (loc. 64) lies about halfway up the north slope of North Frying Pan Creek valley in the SW¼ sec. 20, T. 10 S., R. 15 W., Montana Principal Meridian. It is about 0.5 mile north of the Last Chance vein, a few hundred feet northwest of the Trappers No. 1 vein, and 0.1 mile south of the Continental Divide. A road to this property splits off the Continental Divide road 0.25 mile east of this vein and rejoins it 0.5 mile northwest of it. The original claim on this vein was the Lucky Strike No. 1, which was located by R. G. Denny of Salmon, Idaho, in about 1950 (Trites and Tooker, 1953, p. 196). The vein was relocated in 1954 as the Montana Beaverhead by R. G. and Everett Denny, and from at least 1965-1972 this property has been owned by Nuclear Fuels and Rare Metals Corp. In 1973 assessment work on this property was done by Charles B. Kane. Workings consist of a road along the southern part of the vein, a broad area above this road some 280 by 40 feet where the vein has been scraped free of overburden, and a cut, 630 feet long, 55 feet above the road (fig. 23). Country rock is a Precambrian Y gray fine-grained sericitic quartzite.

The Beaverhead is one of many veins that lie along a N. 66° W.-trending shear zone that can be traced for 2.6 miles westward from the Dan Patch fault. This shear zone is fairly broad, and some veins are en echelon. Other well-known veins in this zone are the Cago No. 12, Contact, Trapper No. 1, and Shear Zone veins. Because many veins are found on this hillside and the extent of the Montana Beaverhead claim is poorly known, the following discussion is confined to the principal vein on this property. The Beaverhead vein strikes about N. 80° W. and dips 50° SW. Near its southeast end the vein terminates on a fault that strikes N. 87° W. and dips 46° SW. Although slickensides on the vein indicate postvein movement, the abrupt thickening of the vein adjacent to the fault points to the fault acting as a dam to the vein fluids. This vein can be traced in almost unbroken outcrop for 520 feet. The vein is 9 feet thick at its northwestern exposure, but adjacent to the fault it abruptly thickens to about 25 feet.

The Beaverhead is a tan to medium-brown limonitic vein having quartz as its principal gangue mineral. Tan microcline is moderately abundant and these minerals are veined and crisscrossed by iron oxides, chiefly goethite and specularite. Some red granular hematite and a trace of magnetite also are found. Reddish-brown shiny thorite is the principal thorium mineral. Some thorium occurs in orangish-brown granular monazite. Other minerals noted are light-brown shiny rutile, brassy pyrite, muscovite,

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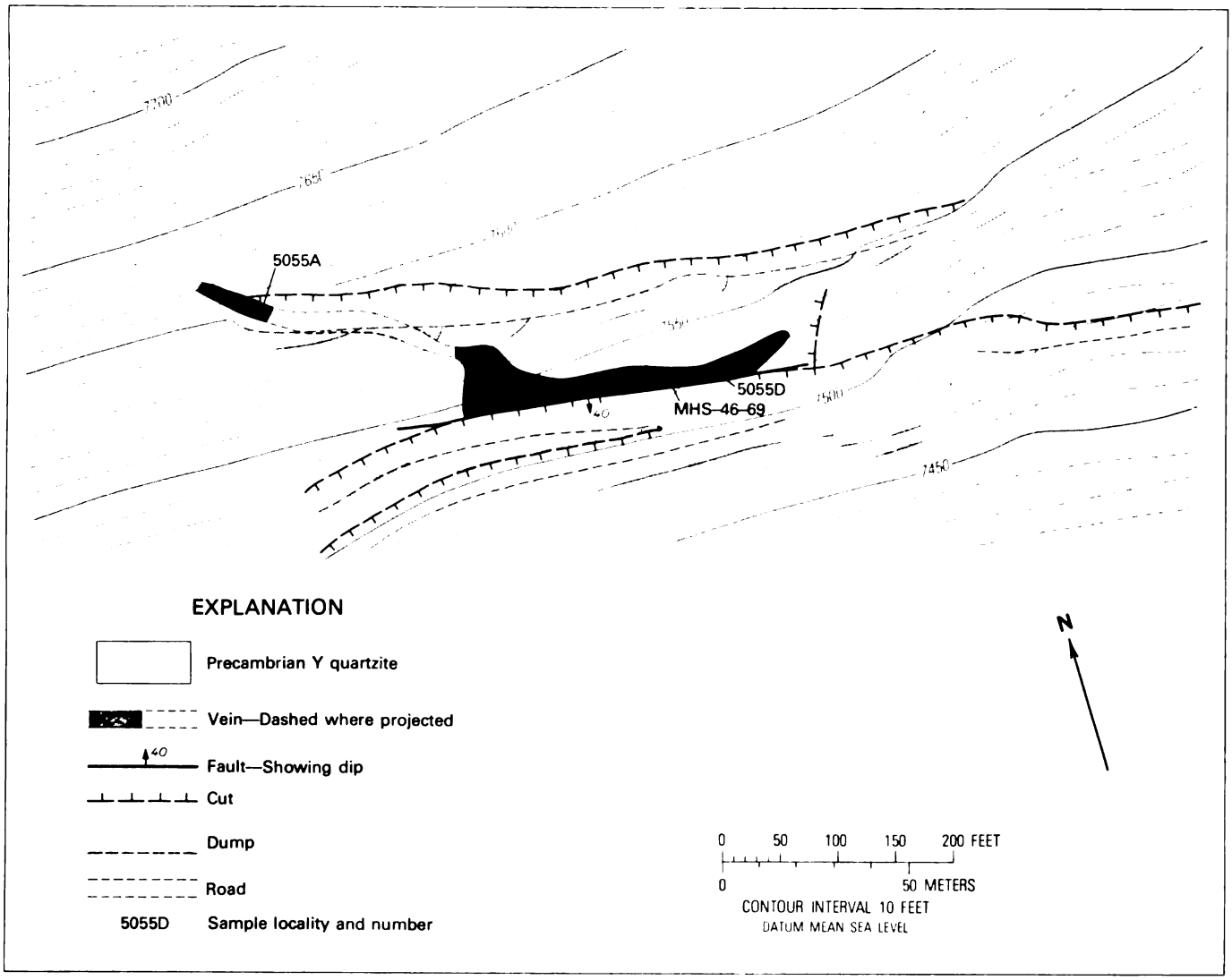


FIGURE 23.—Geologic map of the Beaverhead, Mont., vein (loc. 64). Mapped by B. J. Sharp and D. L. Hetland, 1965; revised by M. H. Staatz, 1974.

apatite, and barite. Three samples from this vein yielded 0.24-0.53 percent ThO_2 (fig. 23; table 13). In addition, one sample (MHS-46-69) was analyzed for precious metals; it contained 0.020 ounce of silver per short ton and no detectable gold (less than 0.0006 ounce per short ton).

WONDER NO. 18

The Wonder No. 18 property (loc. 70) is on the Idaho side of the Continental Divide in the NW¼NW¼ sec. 26, T. 19 N., R. 25 E. It lies along the top of a northwest-trending ridge near the junction of the ridge with the divide. Two thorium-bearing veins and one barren quartz vein are exposed on this property. These veins are within several hundred feet of the large northeast-trending Dan Patch fault. This property was controlled by Nuclear Fuels and Rare Metals Corp. in August 1972. The three veins are exposed by more than a dozen bulldozer trenches (fig. 24). Country rock is a Precambrian Y gray sericitic quartzite. The two thorium-bearing veins have a northwesterly strike and are generally parallel to the Dan Patch fault; the quartz vein, on the other hand, has a northeasterly strike.

The best exposed thorium-bearing vein can be traced for about 550 feet. Near its southeast end it splits into two veins that diverge at an acute angle. This vein ranges in thickness from 0.7 to 1.2 feet in the northwestern group of trenches and from 1.5 to 2.0 feet in the southeast group before the split. The two bifurcated veins are each about 1 foot in thickness. The strike of this vein varies somewhat along its length, but its overall strike is N. 70° W. Dip also varies, but ranges from about 50°-65° SW. This vein consists chiefly of black granulated quartz and hematite. The black color is due to

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TABLE 13.—*Analyses of samples from the Beaverhead, Mont. vein*

[C, chip sample; G, grab sample; NA, not applicable]

Sample No.	Sample length and type (ft)	ThO_2 (percent)
5055A	NA G	[1]0.24
MHS-46-69	6.0 C	[2].48
5055D	NA G	[1].53

[1]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.
[2]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.

hematite, which occurs here only as specularite. Red enameloid thorite is the principal thorium-bearing mineral. A little tan granular monazite also occurs. Minor amounts of the following minerals are present: magnetite, muscovite, rutile, barite, pyrite, and apatite. Four samples taken along this vein yielded 0.21-1.21 percent ThO_2 (fig. 24; table 14).

The second thorium-bearing vein is exposed only in the bottom of one trench 220 feet north of the vein just discussed (fig. 24). This vein is approximately 1 foot thick and its strike across the trench is N. 75° W. Vein material is dark brown and the principal gangue mineral is quartz. Radioactivity of this vein was measured at approximately 400,000 counts per minute with a Geiger counter.

The nonradioactive quartz vein lies south of the two thorium-bearing veins and crops out at the top of the hill (fig. 24). This vein has an overall strike of N. 70° E. and a dip of 78° SE. It parallels another nonradioactive quartz vein which lies about 400 feet to the south, on the Montana side of the Continental Divide (pl. 1). The quartz vein on the Wonder No. 18 claim can be traced for 285 feet and is 7-10 feet thick. The vein is white to purple and consists mainly of quartz, with hematite scattered along shear planes in the quartz.

LITTLE DANDY

The Little Dandy claim (loc. 72) is on the Idaho side of the Continental Divide in the NW¼NW¼ sec. 26, T. 19 N., R. 25 E. The workings lie adjacent to the road along the divide, and although not exposed on the Montana side, the vein is exposed within 25 feet of the boundary. The Little Dandy vein is about 650 feet southwest of the principal thorium-bearing vein on the Wonder No. 18 property and about 100 feet southwest of the Dan Patch fault. The claim was located June 9, 1955, by James Thompson, Carroll Wells, and Jacob Schenk. In August 1972, it was owned by the Nuclear Fuels and Rare Metals Corp. Workings made over a period of years consist of six intersecting trenches (fig. 25) as much as 90 feet long. The trenches cut Precambrian Y gray sericitic quartzite.

TABLE 14.—*Analyses of samples from the Wonder No. 18 claim, Idaho*

[C, chip sample; G, grab sample; NA, not applicable]

Sample No.	Sample length and type (ft)	ThO_2 (percent)
MHS-10-69	1.0 C	[1]0.22
MHS-9-69	NA G	[2].33
649	2.0 C	[1]1.21
650	1.5 C	[1].21

[1]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.
[2]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.

One vein, which has an overall strike of N. 78° W. and a nearly vertical dip, is exposed in these trenches. The vein can be traced for 95 feet and has a thickness of 1.0-2.5 feet. It occupies a shear zone and is brecciated. The vein is dark brown and consists chiefly of iron oxide-stained microcline intermixed with goethite. Other iron oxides include minor specularite, magnetite, and reddish-brown hematite. Thorite was the only thorium mineral identified. Minor amounts of muscovite, pyrite, and fluorite also were noted. A 2.5-foot chip sample (MHS-8-69) taken across the east end of the vein (fig. 25) contained 0.047 percent ThO_2.

BLACK ROCK, MONTANA

The Black Rock property (loc. 75) is in Montana in the E½ sec. 21, T. 10 S., R. 15 W. This property lies along the north side of North Frying Pan Creek near its junction with South Frying Pan Creek. Access to the workings is along a southeast-trending road which branches from the Continental Divide road. The property is about 0.5 mile from the Continental Divide. Two veins, a long northwest-trending one and a short northeast-trending one, are found on this property. Part of the northwest-trending vein cropped out on the surface, and the first prospect was dug on it near the turn of the century. The principal vein was located for thorium as the Radio claim in 1949 by R. A. Wellborn of Armstead, Mont., and Frank Stocker of Medicine Lodge, Mont. (Sharp and Cavender, 1962, p. 39-40). The veins are on Montana State land and in the 1960's were leased to Harry Katseanes of Blackford, Idaho, and called the Black Rock. On the shorter vein, at the southeast end of the area, two claims were filed in June 1973. They are the K. and G. No. 1 and K. and G. No. 2, staked by Harry Katseanes and A. E. Granger of Salt Lake City, Utah. By 1952 Wellborn and Stocker had exposed the longer vein in two shallow bulldozer trenches about 200 feet apart. By 1965 a complex group of interconnecting bulldozer trenches exposed about 420 feet of the central part of the northwest-trending vein and a 210-foot trench exposed 120 feet of the northeast-trending vein (pl. 2*G*). The country rock is gray fine-grained sericitic quartzite (Precambrian Y) which, for the most part, strikes west to northwest and dips 20°-50° N. and NE.

The larger vein has an overall strike of No. 47° W. and dip of 70°-75° SW. This vein has been traced in workings and by anomalous soil radioactivity for 1,610 feet on the north side

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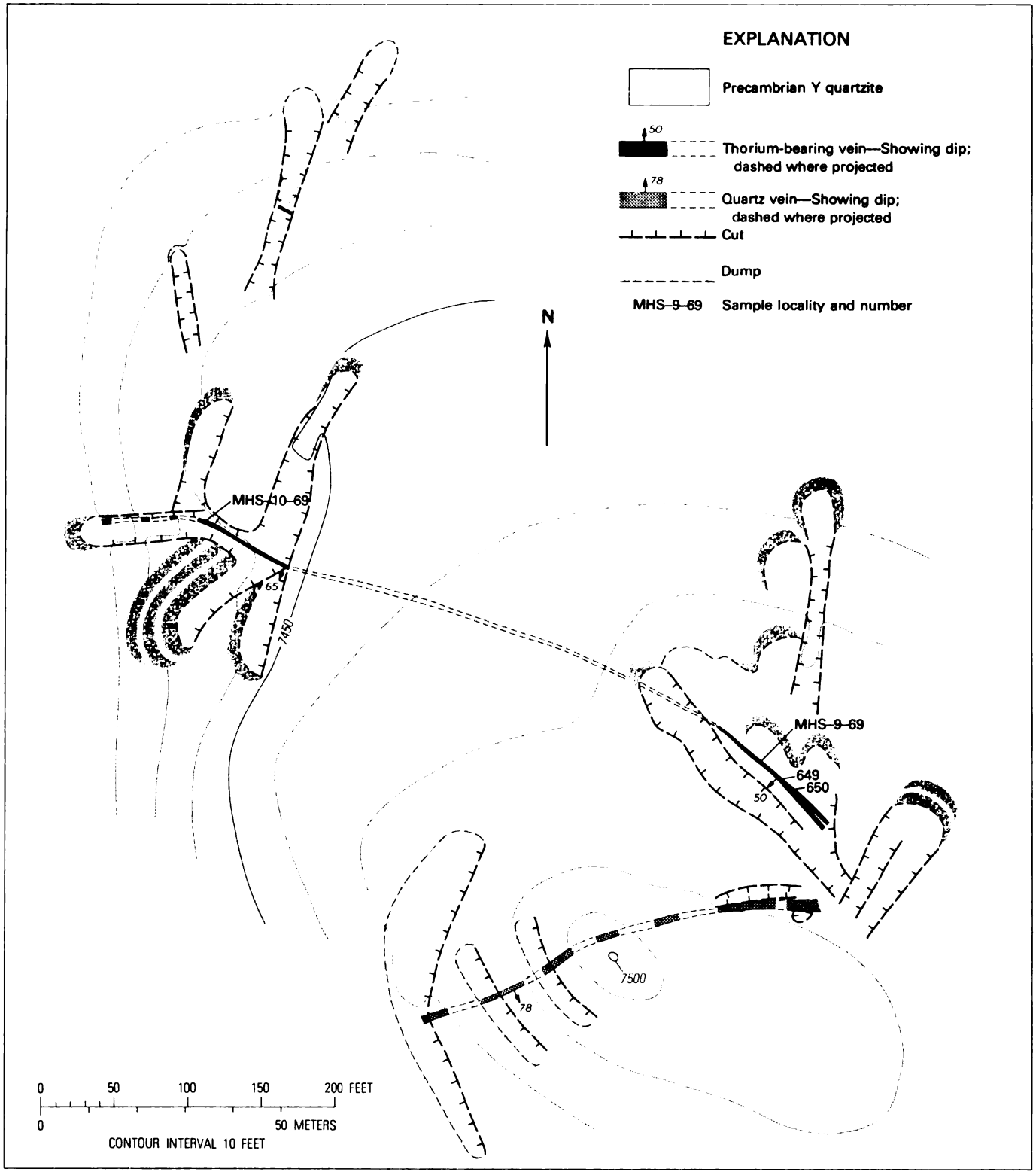


FIGURE 24.—Geologic map of the Wonder No. 18 property (loc. 70). Mapped by B. J. Sharp and D. L. Hetland, 1965, revised by M. H. Staatz, 1973.

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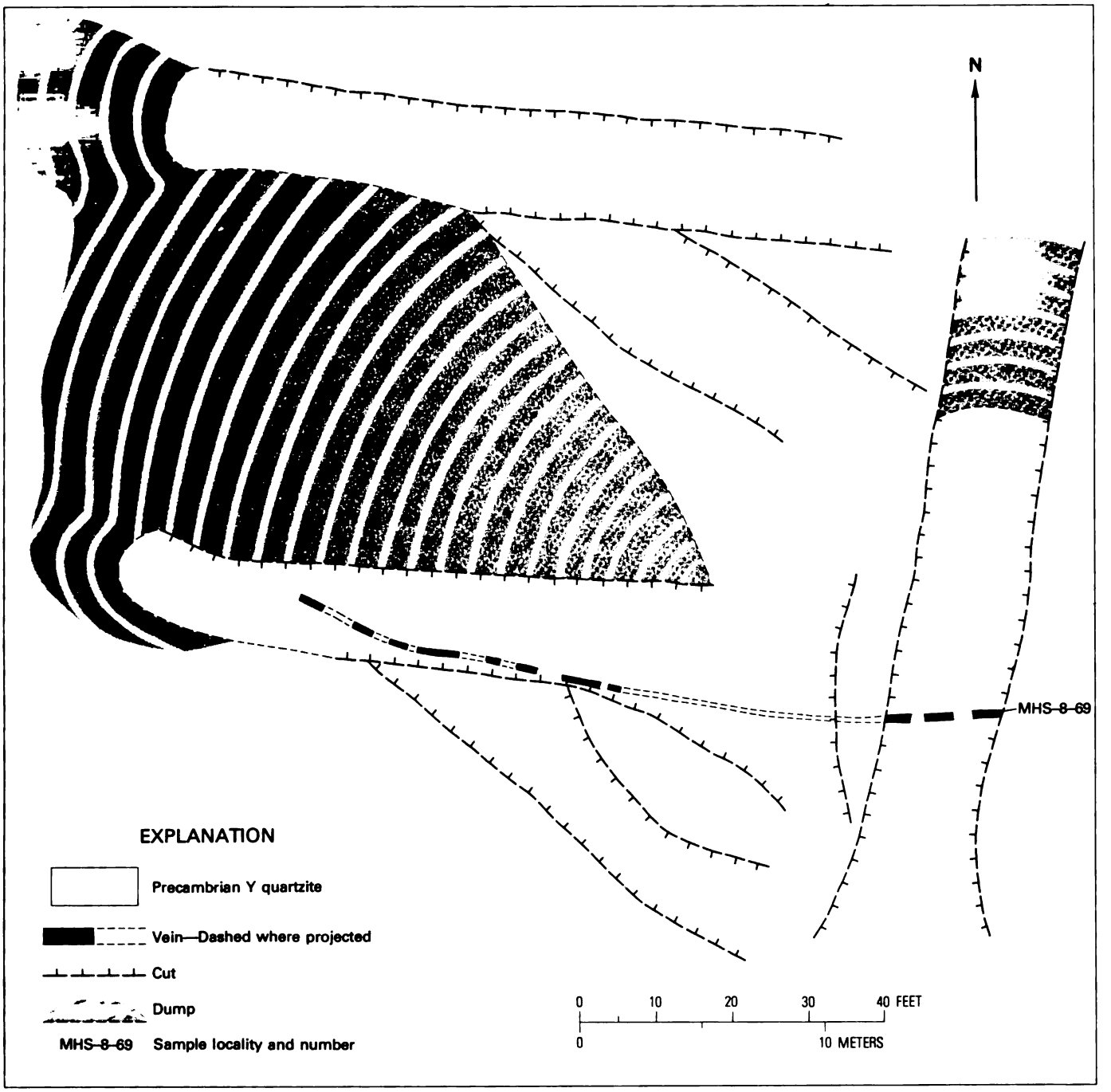


FIGURE 25.—Geologic map of the Little Dandy Vein (loc. 72). Mapped by B. J. Sharp and D. L. Hetland, 1965; revised by M. H. Staatz, 1973.

of North Frying Pan Creek (pl. 2*G*). Along the strike of this vein, on the ridge on the southeast side of Frying Pan Creek, is a vein on the Bull Moose claim (loc. 76, pl. 1). If the Bull Moose is a continuation of the long Black Rock vein, as seems likely, then it extends another 1,600 feet. In the principal workings the northwest-trending vein ranges from 1.3 to 6 feet in thickness. The vein on the Bull Moose property is only 0.1-0.3 feet thick. The large northwest-trending vein is sheared, but not as intensely as most veins in this area. Furthermore, limonite, although present, is not as

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TABLE 15.—*Thorium analyses of samples from the Black Rock, Mont. property*

[C, chip sample; G, grab sample; CH, channel sample; NA, not applicable]

Vein	Sample No.	Sample length and type (ft)	ThO_2 (percent)
Northwest-trending.....	644	6.0 C	[1]0.82
	645	4.0 C	[1].70
	5064A	3.5 C	[1].63
	5070A	NA G	[1].69
	5070B	4.0 C	[2]3.10
	5070C	3.0 C	[1].68
	MHS-63-68	1.3 C	[2]2.19
Northeast-trending.....	4972A	1.0 C	[1].44
	4972B	1.0 C	[1].38
	4972C	1.0 C	[1].44
	MHS-62-68	.7 CH	[2]1.70

[1]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.
[2]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.

common as in most veins and does not mask most of the minerals in the vein. The vein is irregularly banded, having layers of white coarsely crystalline quartz interspersed with layers of dark-brown limonite and black manganese oxides. Other minerals recognizable in hand specimens include a little microcline, barite, apatite, thorite, monazite, and chrysocolla. Although monazine occurs in many veins in this district, this vein was the only one in which monazite was noted in hand specimen. Other minerals, identified in mineral separates, are brockite, rutile, magnetite, and specularite. In addition, a little malachite was also identified by Sharp and Cavender (1962, p. 40). The ThO_2 content of seven samples (pl. 2*G*; table 15) ranged from 0.63 to 3.10 percent. One sample (MHS-63-68) contained 0.23 ounce per short ton of silver, 0.15 percent copper, 0.023 percent lead, and 1.10 percent zinc. Compositionally this vein is similar to the Wonder, as both are rich in manganese oxides and in addition contain silver, zinc, copper, and lead.

The shorter vein, which apparently splits off the larger vein, has a strike of N. 75° E. and a dip of 75°-80° NW. This vein can be traced 135 feet northeastward from the larger vein. It is 0.7-1.0 foot thick and is brown to black in color. The predominant gangue mineral in this vein, unlike the northwest-trending vein, is pink to tan microcline. Quartz, however, is also common. The color of the vein is due to limonite and a black manganese oxide mineral. Other minerals identified are thorite, brockite, apatite, magnetite, specularite, and calcite. Four samples taken across this vein (pl. 2*G*; table 15) contained 0.38-1.70 percent ThO_2.

LAST CHANCE

The Last Chance property (loc. 82), which is on one of the longer veins in the Lemhi Pass district, lies just east of the Continental Divide in sec. 29, T. 10 S., R. 15 W., Montana principal meridian. The northwesternmost exposures of this vein are on the south side of North Frying Pan Creek, and it can be traced from there southeastward over the divide and across South Frying Pan Creek. Several roads reach various parts of this vein, but from Lemhi Pass there are two principal routes: (1) Drive 2.4 miles eastward on the road that crosses the pass, then southward on a dirt road along the north side of Frying Pan and South Frying Pan Creeks for 4.8 miles to the property; (2) drive south from Lemhi Pass along the Continental Divide for 2.0 miles, then turn southeast off the divide and follow another road for 1.3 miles across North Frying Pan Creek to this road's intersection with the first route. This junction is 1.2 miles from the property. The Last Chance vein is principally on the Last Chance, Shady Tree, and Last Chance 30 claims. The first discovery was made on the Last Chance, which was located by R. A., Ned, Billy, and Dave Wellborn, on July 15, 1949. In 1950 the property was optioned to the Elkhorn Mining Co. who, using a U.S. Defense Minerals Exploration Administration loan, exposed the vein in several places by means of bulldozer trenches and cut the vein 240 and 290 feet below the surface in two diamond-drill holes. The Elkhorn Mining Co. allowed their option to lapse, and the Wellborns later sold this property to the Sawyer Petroleum Co. In the mid-1960's Sawyer Petroleum Co. went into a partnership with Union Pacific Railroad Co. who did the assessment work. By 1970 Union Pacific Railroad Co. was no longer involved in this property. Sawyer Petroleum Co., whose name was changed to Sawyer-Adecor International, Inc., did the assessment work on this property in October 1973.

On the surface the vein has been exposed by many bulldozer trenches (pl. 2*D*), including several large longitudinal cuts that completely expose the vein for 900 feet at its northwest end. The vein also has been explored by two adits and a shaft. The west adit consists of a crosscut 630 feet long that intersects the vein 500 feet from the portal. From this intersection a drift 35 feet long extends to the west, and one 220 feet long extends to the southeast. The vein, where it is cut by the crosscut, is about 160 feet below the surface. The east adit consists of a 452-foot slightly curved drift to the northwest that follows the vein for 355 feet. Between these two adits is an 80-foot-deep vertical shaft, sunk along the footwall of the vein. A short crosscut driven west from the bottom of the shaft is about 22 feet long and cuts the vein, which is here 14 feet thick (Geach, 1966, p. 15). In addition, Union Pacific Railroad Co. drilled several diamond-drill holes.

One main vein, which intrudes gray fine-grained micaceous quartzite of Precambrian Y age, is found on this property. This vein has an overall strike of about N. 55° W., but as it follows a somewhat irregular fracture zone, it varies from about N. 40°-80° W. in different parts of the vein. Its dip also varies from about 40°-70° SW. The vein has a known length of 4,350 feet (pl. 2*D*). A short distance northwest of the last exposure, the vein has been reported to end against a fault. Southeast of the last known exposure, thick cover on a heavily wooded slope makes the vein

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difficult to trace. The vein thickens and thins along strike and measured thicknesses range from 5 to 40 feet. In the east adit the vein varies from 8 to 13 feet thick, and in the crosscut of the west adit the vein is 30 feet thick.

The Last Chance vein is exposed on the surface on the east side of the ridge that separates South from North Frying Pan Creeks. These exposures are quartz rich; those parts of the vein that are rich in iron oxides are more easily weathered and are not exposed. The vein varies from white containing black streaks to deep brown. Quartz is the principal gangue mineral, although in some places yellow-stained pale-pink microcline is a common mineral. White platy barite, although not abundant, is found in most samples. Specularite is the most abundant iron oxide. In some places red granular hematite also occurs. Dark-brown goethite is also abundant and commonly colors the entire rock. Magnetite is found in most places, but is sparse. The iron oxides commonly vein the earlier formed minerals. Goethite may occur as a pseudomorphous replacement of pyrite cubes. Dark-reddish-brown shiny thorite is the most abundant thorium mineral, although yellow-brown monazite is found in minor amounts in most samples. Brockite was noted in one sample. Minor amounts of many minerals were found in this vein. The most common of these were pyrite, rutile, and black manganese oxide minerals. Other minerals noted in scant amounts in a few samples are: calcite, muscovite, biotite, apatite, malachite, jarosite, and anatase.

The analytical results of 17 samples taken by us (pl. 2*D*) from the surface workings and in the west and east adits are given in table 16. They contained 0.017-1.45 percent ThO_2.

TABLE 16.—*Analyses of samples from the Last Chance vein, Mont.*

[C, chip sample; Ch, channel sample; n.d., no data]

Sample No. (MHS-)	Location	Sample length and type (ft)	[1]ThO_2 (percent)	[2]Total rare-earth oxides (percent)
12-74	Surface, west end.....	10 C	0.74	N.d.
13-74	.....do.....	7.0 C	.34	n.d.
11-74	Surface, 120 ft. west of ridge crest.	6.6 C	.25	n.d.
63-69	Surface at ridge crest....	6.8 C	.54	n.d.
155-67	Surface cut, 150 ft. NW of shaft.	2.2 Ch	.30	0.94
156-67	.....do.....	3.2 Ch	.43	2.04
157-67	.....do.....	5.7 Ch	.61	1.00
158-67	.....do.....	5.2 Ch	.15	1.38
159-67	.....do.....	2.0 Ch	.017	n.d.
15-74	Surface, 150 ft. SE of shaft.	12 C	.43	n.d.
81-73	Surface, near SE end of vein.	6.0 C	.038	n.d.
149-68	West adit	12.5 C	.36	.20
150-68	.....do.....	10.0 C	.26	.18
148-68	.....do.....	6.9 C	1.45	1.34
151-68	East adit	10.0 C	.16	.19
152-68	.....do.....	14.0 C	.20	.28
153-68	.....do.....	14.8 C	.074	n.d.

[1]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.

[2]X-ray fluorescence spectrographic analysis by J. S. Wahlberg and V. S. Shaw, U.S. Geological Survey, Denver, Colo.

The vein varies in ThO_2 content in different parts, and the southeastern end is noticeably leaner than the northwestern end. The southeasternmost sample, plus three samples taken from the east adit, ranged from 0.038 to 0.20 percent ThO_2; the three samples from the west adit, on the other hand, contained 0.26-1.45 percent ThO_2. In addition, 16 other surface samples have been reported on by Sharp and Cavender 1962, p. 62-63). These samples, which were collected along the vein from the divide between North and South Frying Pan Creeks for 950 feet to the east, ranged from 0.05 to 2.1 percent ThO_2. The rare-earth oxide content of this vein appears to be somewhat greater than the ThO_2 content. The total rare-earth oxide content of nine of the samples ranged from 0.18 to 2.04 percent. The amounts of the individual rare earths in these samples have been previously published (Staatz and others, 1972, p. 76-77). Neodymium is the principal rare earth, and europium occurs in above-average amounts.

DAN PATCH

The Dan Patch (loc. 98) is on the top of a ridge 1.5 miles east of Bear Creek and between that creek and Bear Gulch. This property, which is near the eastern edge of the district, lies southwest of the Dan Patch fault (pl. 1). The property may be reached by steep secondary roads from either the east or the west. Two veins are exposed in the workings of the Dan Patch 1 and 2, which were located on July 1, 1956, by R. A., Ned, Grace, and Hattie Wellborn, and Edward McCande. Assessment work on these claims was done in July 1974 by Ned Wellborn. The two veins on these two claims were developed by 15 bulldozer trenches and four smaller trenches dug within the larger bulldozer trenches (fig. 26). The veins were intruded into a Precambrian Y gray fine-grained micaceous quartzite. The larger, or northern, vein has a general strike of N. 75° W., and dips 55°-75° SW. This vein ranges in thickness from 2 to 2.5 feet. It can be traced across nine bulldozer trenches for 508 feet. A possible continuation of this vein, although not exactly on line with its extension, is found in a trench 420 feet to the northwest. To the southeast, extension of this vein is limited by basalt, which is exposed some 50 feet from the last trench exposure, and by the Dan Patch fault. The smaller vein, to the south, has been exposed only in two trenches (fig. 26). The strike of this vein changes, being N. 77° W. in the northwestern of the two trenches and N. 40° W. in the other trench. Dip is from about 75° SW to vertical. This vein is exposed for only 105 feet and is 0.5-6 feet thick.

Both veins consist principally of quartz, some pink microcline, and goethite, which colors the veins brown. Other iron oxides are hematite and magnetite. Hematite occurs chiefly as black shiny plates of specularite, although some dark-red granular material was found. Magnetite is a very minor constituent. Dark red shiny thorite was the only thorium mineral noted. Other minerals include a little white

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platy barite and minor shiny dark-brown rutile.

Three samples taken from the north vein yielded 0.36-0.71 percent ThO_2 (fig. 26; table 17). One of these samples (MHS-126-68) was also analyzed for total rare-earth oxides; it contained 0.083 percent.

Three samples from the smaller south vein yielded 0.22 to 0.47 percent ThO_2. One of these samples (MHS-127-68) was also analyzed for total rare-earth oxides, and it contained 0.22 percent.

REACTOR

The Reactor property (loc. 107) lies on a steep subsidiary ridge on the east side of Bear Creek (pl. 1) near its headwaters. It is in the eastern part of the district approximately 1.5 miles southwest of the Dan Patch property. The eastern edge of this property is reached by a four-wheel-drive vehicle road along a broad ridge that trends northward from the Continental Divide and that, at the Reactor property, separates Bear Creek from the North Fork of Everson Creek. The Reactor property consists of the Reactor Nos. 1 to 6 claims and was located by Carroll Wells and Miley Evans on September 15, 1959. This property subsequently became part of the ThO_2 and Rare Metals Exploration, Inc., portfolio. The president of this company is Carroll Wells, and assessment work was done by him on this property in September 1973. Development work consists of a dozen trenches down a steep rocky ridge (pl. 2*F*) and several long trenches on the covered slope to the northeast. The difference in elevation between the uppermost and lowermost trenches is approximately 700 feet. The country rock is the Precambrian Y gray fine-grained micaceous quartzite, which in places is banded and has thin interbeds of siltite.

Veins on the Reactor property follow a steeply-dipping northwest-trending shear zone. This zone is well exposed in trenches in the southeast part of the property, and is here approximately 50 feet wide. The largest vein is exposed in the easternmost working and can be traced for 1,300 feet to the

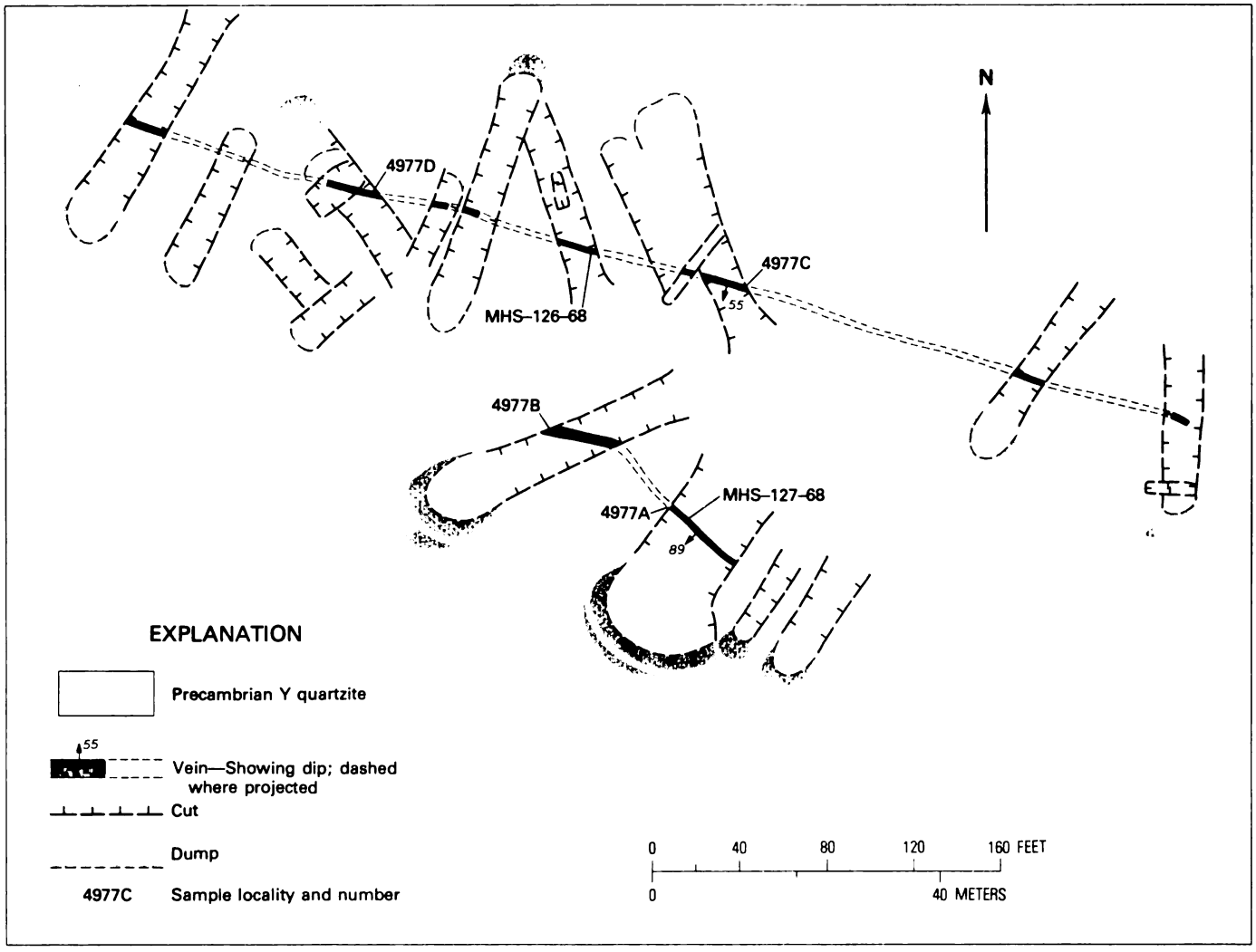


FIGURE 26.—Geologic map of the Dan Patch property (loc. 98). Mapped by B. J. Sharp and D. L. Hetland, 1965; revised by M. H. Staatz, 1974.

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TABLE 17.—*Analyses of samples from the Dan Patch property, Mont.*

[C, chip sample; G, grab sample; n.d., no data; NA, not applicable]

Vein	Sample No.	Sample length and type (ft)	ThO_2 (percent)	Total rare-earth oxides (percent)
North vein	4977D	2.0 C	[1]0.71	N.d.
	MHS-126-68	NA G	[2].41	[3]0.083
	4977C	2.5 C	[1].36	n.d.
South vein	4977B	6.0 C	[1].26	n.d.
	4977A	3.0 C	[1].22	n.d.
	MHS-127-68	1.0 C	[2].47	[3].22

[1]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.
[2]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.
[3]X-ray fluorescence spectrographic analysis by J. S. Wahlberg and V. S. Shaw, U.S. Geological Survey, Denver, Colo.

northwest (pl. 2*F*). This vein ranges in thickness from 0.8-5.0 feet. It has an overall strike of N. 38° W., but ranges from about N. 28° W. to N. 48° W. Dip varies from about 70° to 85° SW. Some 15-20 feet south of this vein and more or less parallel to it is a smaller vein some 4-6 inches thick. This vein is only exposed in three trenches, and if continuous, would be at least 656 feet long. The long vein dies out to the northwest, but two other veins are found in this area. A northwest vein having a N. 23° W. trend is exposed in four places. This vein, which dips about 45° SW., can be traced for 290 feet. It is 1-3.5 feet thick. The other vein lies southwest of the northwest vein, and is exposed in the two lowest (westernmost) trenches on the ridge (pl. 2*F*). This vein strikes N. 63° W. and dips about 55° SW. It has been traced for 74 feet, and is 1-3 feet thick.

These veins are cherry red to yellow brown in color and their principal gangue mineral is pale-pink microcline. White quartz is also moderately abundant. Hematite is by far the most abundant iron oxide mineral. It generally occurs as small black shiny plates of specularite, although in places it occurs as red granular hematite. Dark-brown limonite is fairly common, and black magnetite is rare. Reddish-orange thorite was the only thorium mineral identified. In addition, a little pyrite and clear plates of barite occur in some places.

Three of the four veins were sampled. Seven samples were taken along the long east vein. They contained from 0.007 to 1.32 percent ThO_2 (pl. 2*F*; table 18). A sample from near the center of the northwest vein yielded 1.79 percent ThO_2, and one from the short southwest vein had 0.69 percent ThO_2.

TABLE 18.—*Analyses of chip samples from the Reactor property, Mont.*

Vein	Sample No.	Sample length (ft)	ThO_2 (percent)
Northeast vein	MHS-25-69	1.0	[1]0.15
	4974B	2.0	[2]1.23
	4974C	2.0	[2].14
	4974A	2.0	[2]1.10
	MHS-26-69	1.3	[1]1.32
	MHS-2-74	1.5	[1].007
	4974D	5.0	[2].07
Northwest vein	4974F	3.5	[2]1.79
Southwest vein	4974E	3.0	[2].69

[1]Gamma-ray spectrometric analyses by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.
[2]Wet chemical analyses by Lucius Pitkin, Inc., Grand Junction, Colo.

Only the narrow vein south of the long east vein was not sampled. This vein is five times less radioactive than the larger vein it parallels.

ELKHORN

The Elkhorn (loc. 108) is on the northwest side of the prominent ridge that separates Reese Creek from Yearian Creek in the NW¼NE¼ sec. 28, T. 18 N., R. 25 E., Boise meridian, Idaho. It is about 0.5 mile northeast of the ThO_2 property and is reached from the road that passes the ThO_2 and connects the Lemhi Valley with the Continental Divide. This property is on the Elkhorn No. 1 and No. 2 claims, which were located by Carroll Wells and Ross Murray on July 6, 1960. It was owned in July 1973 by Ross Murray. Development work consists of six bulldozer trenches, 60-155 feet long (fig. 27). The country rock is a Precambrian Y gray micaceous quartzite that strikes N. 12° E. and dips 35°-45° SE.

A curved vein is exposed in the workings, which near the center of the area of figure 27 has a strike of N. 28° W., but in the southeasternmost part has a strike of N. 55° W. Dip appears to be nearly vertical. The vein has been traced for 630 feet. In the next to the southeasternmost trench the vein has split into four veinlets, and in the southeasternmost trench only a soil anomaly was noted. Thus the vein appears to be pinching out in this direction. In the northwesternmost trench a soil anomaly was also noted but this downhill locality is heavily forested and the overburden is thick. Hence, the soil anomaly may represent the top of a vein under a thick cover of overburden, or radioactive debris carried downhill from the vein. The vein ranges in thickness from 0.5 inch near the southeast end to 1.5 feet near the center. Most of it appears to be between 0.5 and 0.7 foot thick. The vein is limonitic brown and has some black streaks. It consists principally of granular limonite-stained microcline, although in places quartz is also common. Dark-brown granular goethite is the most abundant iron oxide mineral. Some black shiny plates of specularite and minor black magnetite are the other iron oxides. Thorite was the only thorium mineral noted, and in the trenches near the center of the area of figure 27 it is abundant enough to be observed in hand specimens. Minor amounts of muscovite, biotite, rutile, and apatite are also present. Two samples were taken from the central part of this vein (fig. 27). One (651) contained 1.63 percent ThO_2; the other (MHS-82-69) yielded 4.16 percent ThO_2.

APEX

The Apex vein (loc. 136) is on a high ridge on the west side of Flume Creek in the NW¼NW¼ sec. 4, T. 19 N., R. 25 E. The vein lies about 1 mile north-northeast of the Lemhi Pass fault and is one of the few known veins north of this fault. This property is at the north end of the district (pl. 1) in the

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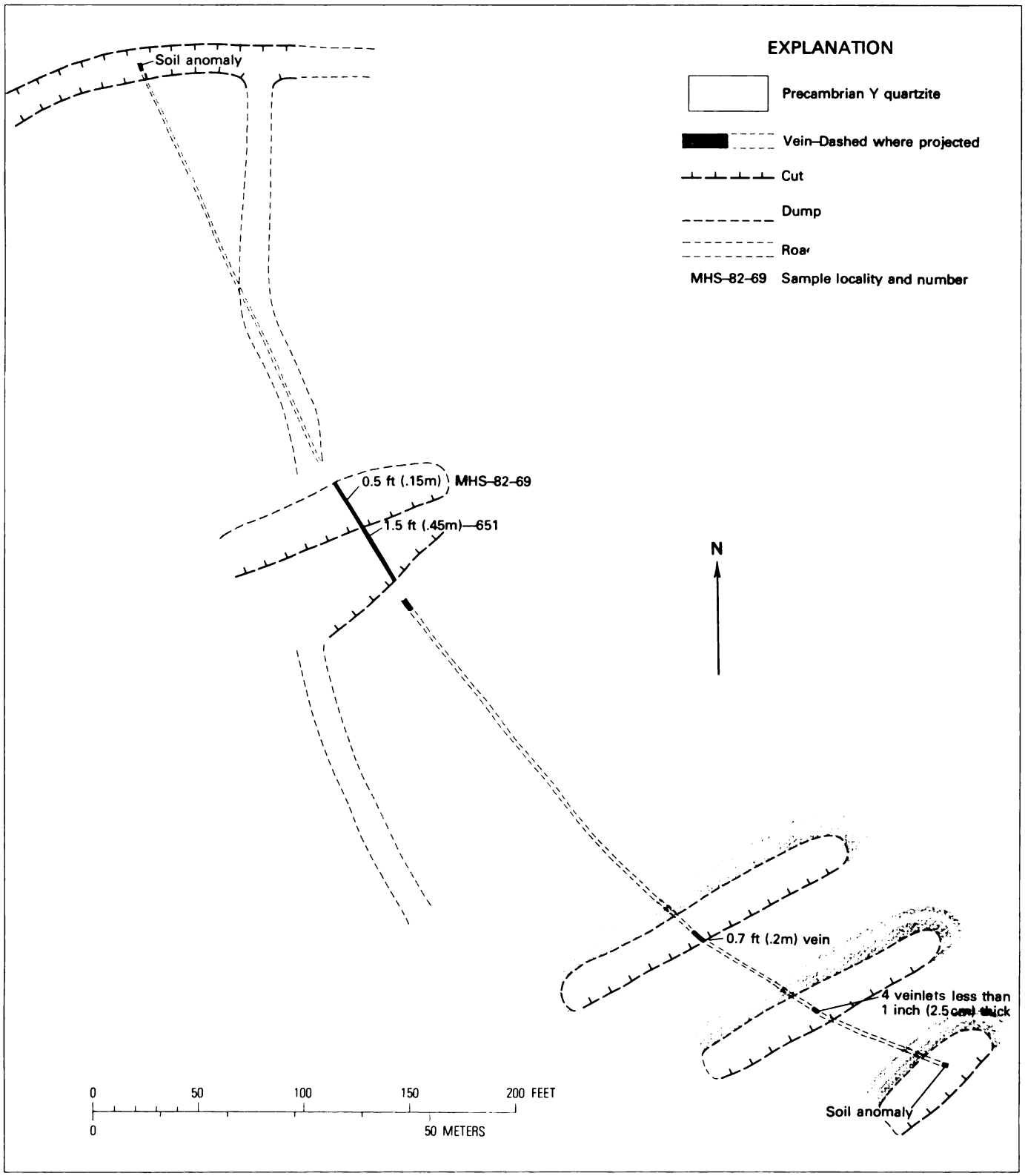


FIGURE 27.– Geologic map of the Elkhorn property (loc. 108). Mapped by B. J. Sharp and D. L. Hetland, 1965; revised by M. H. Staatz, 1973.

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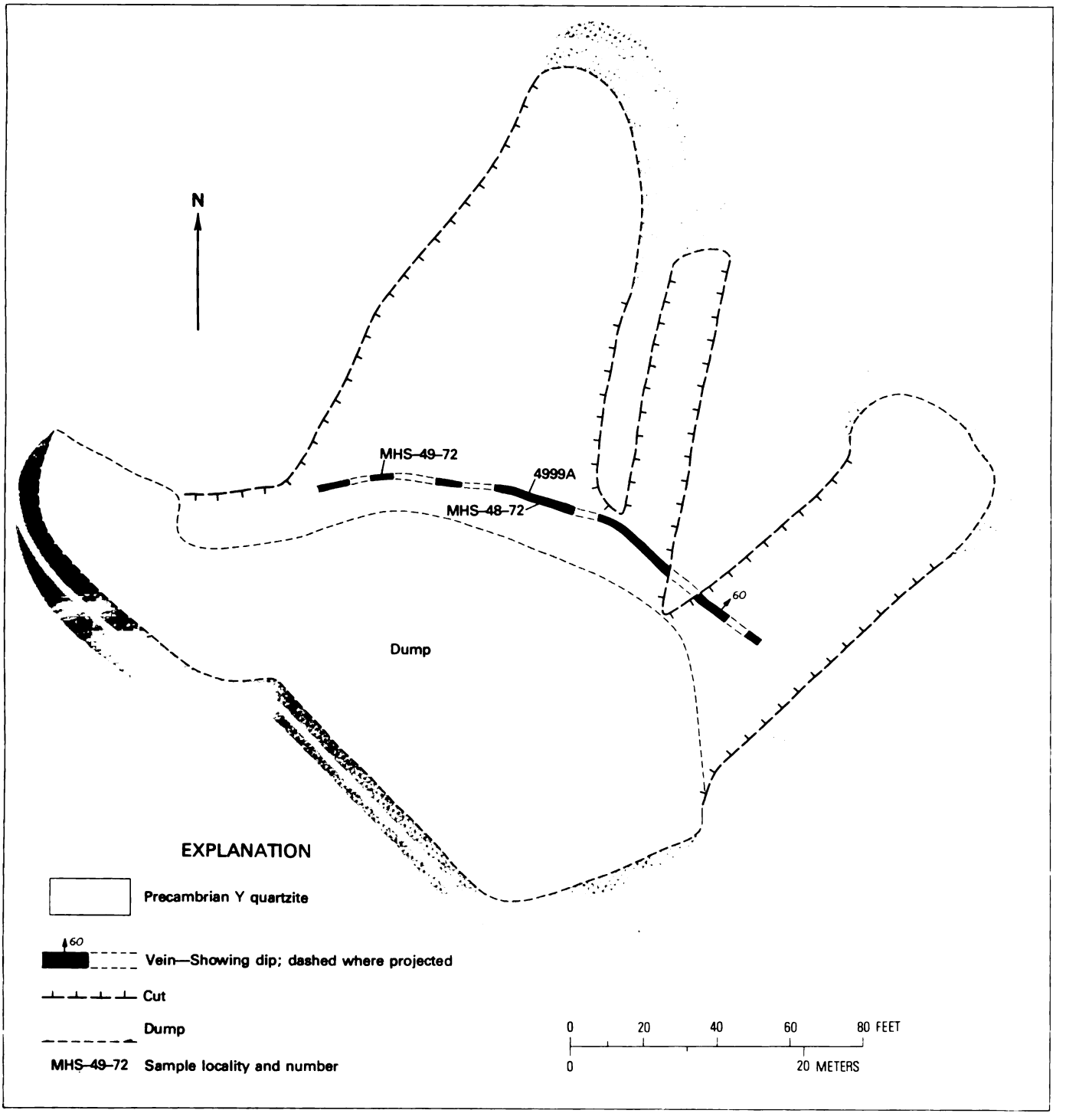


FIGURE 28.—Geologic map of the Apex vein (loc. 136). Mapped by B. J. Sharp and D. L. Hetland, 1965; revised by M. H. Staatz, 1973.

Salmon National Forest, and is reached by about 2 miles of steep secondary road from the headwaters of Poison Creek. This property has been controlled in the past by the Lemhi Pass Thorium Corp. Workings on the property consist of at least three interconnected trenches covering an area of 275 by 240 feet (fig. 28). Bedrock consists of dark gray fine-grained quartzite of Precambrian Y age.

The workings expose a curved vein having a general strike

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TABLE 19.- *Analyses of samples from the Apex property, Idaho*

[C, chip sample; G, grab sample; N.d., no data; NA, not applicable; <, less than]

Sample No.	Sample length and type (ft)	ThO_2 (percent)	Total rare-earth oxides (percent)	Copper[1] (percent)	Lead[1] (percent)	Zinc[1] (percent)	Silver[2] (ounces per short ton)	Gold[3] (ounces per short ton)
MHS-48-72	NA G	[4]0.32	[5]1.67	0.002	0.004	0.013	<0.6	0.0015
MHS-49-72	1.5 C	[4].24	[5]1.11	.003	.004	.038	<.6	<.0015
4999A	3.0 C	[6].17	[7]1.05	N.d.	N.d.	N.d.	N.D.	N.D.

[1]Atomic-absorption analysis by J. A. Thomas, U.S. Geological Survey, Denver, Colo.
[2]Fire assay by J. A. Thomas and W. D. Goss, U.S. Geological Survey, Denver, Colo.
[3]Fire assay and atomic-absorption analysis by W. D. Goss, A. W. Haubert, and J. A. Thomas, U.S. Geological Survey, Denver, Colo.
[4]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.
[5]Quantitative spectrographic analysis by N. M. Conklin, U.S. Geological Survey, Denver, Colo.
[6]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.
[7]X-ray florescence spectrographic analysis by the U.S. Bureau of Mines, Salt Lake City, Utah.

of N. 75° W. and dipping 55°-60° NE. It has an exposed length of 135 feet and ranges in thickness from 1.5 to 3.0 feet. Much of the vein is dark brown due to limonite staining but in some places it has dark-purple spots due to fluorite. This is the only vein in the district in which fluorite is readily visible in hand specimens and the only one that has more than a fraction of a percent of this mineral. Distribution of the fluorite is erratic, as it may be a major gangue mineral at one place and absent in another place. The principal gangue mineral throughout the vein is quartz. Other gangue minerals include small amounts of pink microcline and tan calcite. Iron oxides are common, especially specularite, but the vein also has limonite and magnetite. The rare-earth and thorium minerals are shiny yellowish-orange synchisite, $CeFCO_3 \cdot CaCO_3$, and red porcelaneous thorite. Synchisite is by far the most common. The small amount of thorite identified in the analyzed samples is not nearly enough to account for their thorium content, and much of the rest may be in synchisite, where thorium may proxy for the rare earths. Minor amounts of barite, rutile, an unidentified manganese oxide mineral, and apatite are also present. Three samples were taken from this vein. They contained 0.17-0.32 percent ThO_2 (fig. 28; table 19). As might be expected, their total rare-earth oxide content was high and ranged from 1.05 to 1.67 percent. Two of the samples were also analyzed for base and precious metals. They contained only minor amounts of base metals, silver was not detected, and gold was found in only one sample in a barely detectable amount (table 19).

LONE STAR NO. 2

This claim (loc. 145) is on the nose of a small ridge on the southeast side of Pattee Creek just south of the mouth of Poison Creek in the SE¼SE¼ sec. 11, T. 19 N., R. 24 E., Boise meridian, Idaho. It lies just above the creek bottom and is reached by the road up Pattee Creek. The property was originally located by J. A. Rucker. It has had several owners, being controlled by Idaho Thorium Co. in 1957 (Anderson, 1958, p. 58), Nuclear Fuels and Rare Metals Corp. in 1965, and Joyce Corp. in 1970. Workings consist of a principal cut approximately 200 feet long about 30 feet above the valley bottom, and several branching and interconnected roads on the steep slope above (fig. 29). Workings are cut in a Precambiran Y gray to greenish-gray banded fine-grained micaceous quartzite that strikes N. 50° E. and dips 15° SE.

Two veins are exposed on this property. The northernmost one is exposed in the principal cut. It strikes N. 75° W. and dips 45°-65° SW. This vein can be traced for 268 feet between cuts and is 1.5-3.0 feet thick. In the main cut near its west end it is offset about 7 feet by a shallowly dipping fault that strikes N. 30° E. and dips 15° SE. This vein is mainly black, and consists principally of white quartz and of pink microcline impregnated with black shiny specularite. Red porcelaneous thorite was the only thorium mineral noted. A little brown limonite, yellow resinous rutile, black biotite, white barite, and white apatite are also present. Five samples were analyzed for ThO_2 from this vein, and they contained 0.41-1.75 percent (fig. 29; table 20).

About 200 feet south of this vein in the principal cut another vein is exposed. The second vein has two parts: a narrow (0.7-1.5-foot-thick) iron oxide-rich hanging wall and a thick (9-30-foot-thick) quartz-rich footwall containing hematite. The iron-rich part is only exposed in the main cut and on the road above the cut. The quartz-rich part not only is exposed in the cuts, but in places forms prominent outcrops on the hillside. The strike of this vein ranges from N. 75° W. near its western end to N. 75° E. and it dips 75°-80° N. The thick footwall part of the vein is similar in appearance and thickness to a quartz-hematite vein on the Silver Queen 52B property, less than 0.5 mile east. As the two are on strike with one another and as there are several scattered outcrops of similar vein material in between, it is probable that this is one long continuous vein more than 0.5 mile long. On the Lone Star No. 2 property the vein has been traced for 555 feet (fig. 29), and is 10-31.5 feet thick. It is thickest in the cut at its southwesternmost exposure and thins to the northeast. The footwall part of the vein varies in color from light gray to dark purplish gray and consists mainly of quartz intermixed with specularite. Radioactivity here is highly variable, much of the vein containing little in the way of thorium minerals. An 8.0-foot sample from this part of the vein contained only 0.004 percent ThO_2. Thorite

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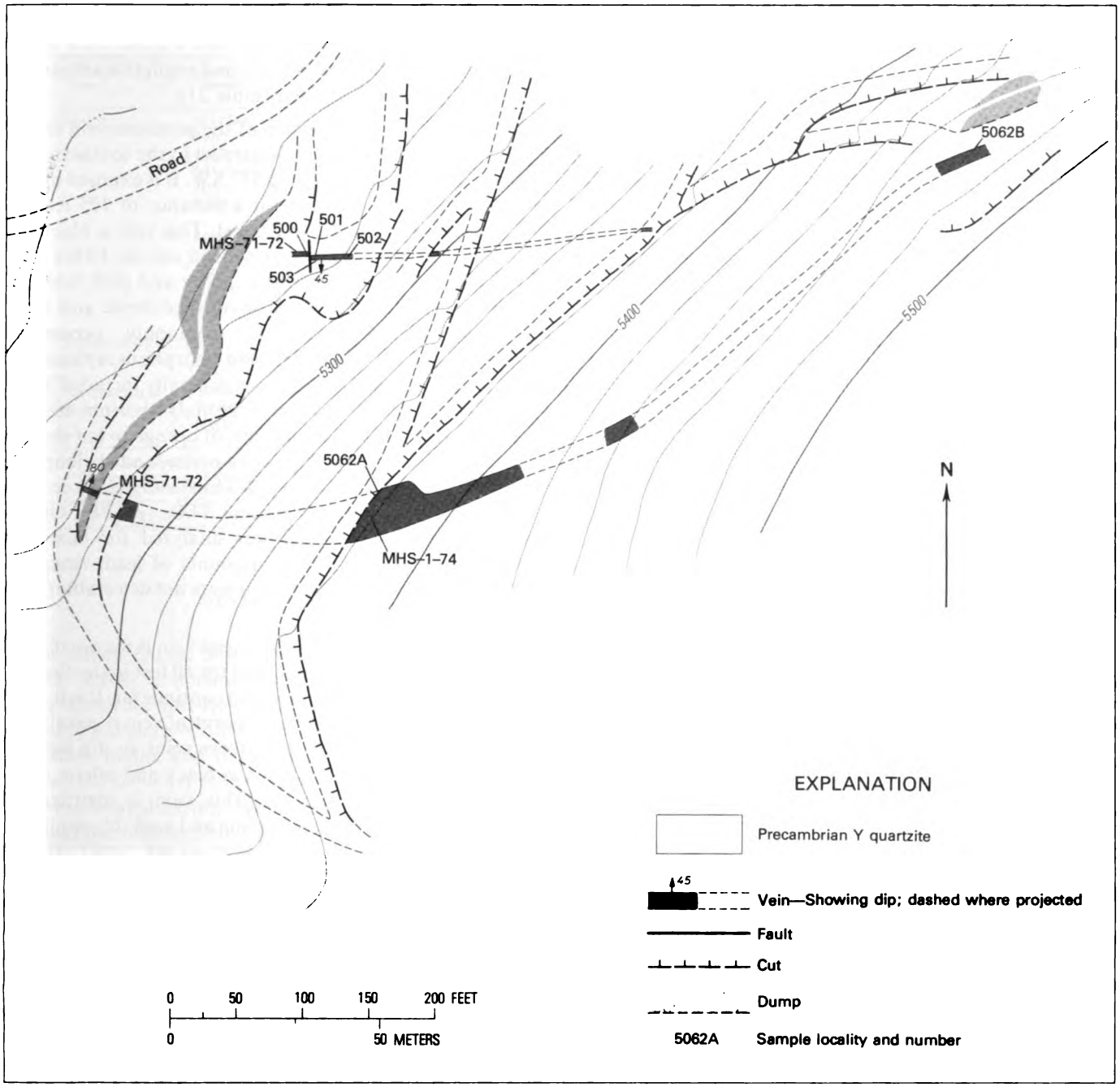


FIGURE 29.—Geologic map of the Lone Star No. 2 property (loc. 145). Mapped by B. J. Sharp and D. L. Hetland, 1965; revised by M. H. Staatz, 1973.

is most commonly found concentrated in the hanging-wall part of this vein. Three samples from this part of the vein yielded 0.32-1.75 percent ThO_2 (fig. 29; table 20).

The chief gangue mineral of the dark-brown hanging-wall part of the vein is quartz, but it also contains abundant microcline and black shiny specularite. In addition, some of the feldspar is coated with limonite, and a small amount of magnetite is present. Red porcelaneous thorite is the principal thorium mineral. Barite was the only other mineral noted.

SILVER QUEEN 52B

This property (loc. 146) lies across a small gulch about 250 feet above the valley bottom in the S½ sec. 12, T. 19. N., R. 24 E., Boise meridian, Idaho. It is about 0.5 mile up the valley from its mouth on Pattee Creek, and it is reached by the road up Pattee Creek. The Silver Queen 52B was located in 1955 by J. A. Rucker. This property was owned in 1957 by the Idaho Thorium Co. (Anderson, 1958, p. 50), in 1965 by the Nuclear Fuels and Rare Metals Corp. and in 1970 by the

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TABLE 20.—*Thorium analyses of chip samples from the Lone Star No. 2 property, Idaho*

Vein	Sample no.	Sample length (ft)	ThO_2 (percent)
North	503	1.5	[1]0.52
	500	3.0	[1].45
	MHS-71-72	1.5	[2].41
	501	2.0	[1].50
	502	2.0	[1].75
South	MHS-70-72	.7	[2].39
	5062A	2.5	[1].32
	5062B	2.0	[1].75
	MHS-1-74	8.0	[2].004

[1]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.
[2]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.

Joyce Corp. On the west side of the small gulch, workings consist of one large cut 640 feet long having a back as much as 55 feet high, and several interconnected roads, and on the east side of the gulch by three levels of roads (pl. 2*B*). Bedrock on this property is gray to greenish-gray fine-grained feldspathic quartzite and minor interbedded greenish-gray siltite of Precambrian Y age.

Four veins are exposed in and adjacent to the main cut. The northernmost vein is a massive quartz-hematite vein of erratic but generally low thorium content. This vein probably extends westward for 0.5 mile to the Lone Star No. 2 property. The other three are calcite-rich veins. The big cut was excavated mainly to expose the southern or largest of these three veins. The other two calcite-rich veins are only exposed in the central part of the floor of the main cut. A small northwest-trending fault down the small gulch east of the main cut offsets the quartz-hematite vein and largest calcite-rich vein about 140 feet to the northwest (pl. 2*B*). The largest calcite-hematite vein (southernmost vein) strikes N. 80° W. and dips 34°-55° SW. It has been traced for 750 feet and ranges in thickness from 0.6 to 3.0 feet. This vein varies in color from brown to black and consists principally of limonite-stained calcite and lesser amounts of quartz and microcline. East of the gulch, microcline becomes the most abundant gangue mineral. Goethite is the chief iron oxide in most places. This mineral occurs not only in veinlets but also forms dark-brown cubes and pyritohedrons—a pseudomorphous replacement of pyrite. Black shiny specularite is common and east of the gulch is more abundant than limonite. All samples contain minor amounts of magnetite, some of which is included in specularite. Part of the coloration is due to a black manganese oxide mineral. Brick-red thorite was the only thorium mineral noted. In addition, minor amounts of rutile, barite, apatite, jarosite, muscovite, fluorite, pyrite, and chalcopyrite were identified in some samples. The vein is highly brecciated and has at least two generations of minerals; the second set of minerals follows a set of fractures in early minerals and is in turn fractured. Eleven samples were taken from this vein, and they range from 0.12 to 2.91 percent ThO_2 (pl. 2*B*; table 21). Two of these samples (MHS-65-72 and MHS-67-72) were also analyzed for base and precious metals; only minor amounts of lead, zinc, and copper, and negligible amounts of gold and silver were detected (table 21).

Approximately 15 feet north of the southern vein lies the south-central vein. This vein is parallel to the southern vein, striking N. 80° W. and dipping 55° SW. It is exposed only in the bottom of the main cut for a distance of 125 feet. Its thickness ranges from 0.7 to 2.0 feet. This vein is black and consists principally of limonite-stained calcite. Other common gangue minerals are white quartz and pink feldspar. The vein is colored by black shiny specularite and black manganese oxides. Limonite commonly occurs as dark-brown pyritohedrons, a pseudomorphous replacement of pyrite. Magnetite occurs but is generally included in the specularite. Red shiny thorite, the only thorium mineral noted, is common. Minor amounts of orange to tan striated rutile, white frosted apatite, brassy pyrite, and chalcopyrite were the other minerals identified. Three samples taken from this vein yielded 0.79-1.07 percent ThO_2 (pl. 2*B*). One of these samples (MHS-66-72) was analyzed for base and precious metals. Only minor amounts of lead, zinc, and copper were noted; gold and silver were not detectable (table 21).

Eight feet north of the south-central vein is the north-central vein. This vein is only exposed for 40 feet in the floor of the main cut and probably does not continue far. It is 0.5-2.0 feet thick. The strike of the north-central vein is parallel to that of the south-central and southern veins; its dip was not observed. The north-central vein is black and calcite is the predominant gangue mineral. This vein is identical in appearance to the south-central vein and probably similar in composition. The one sample taken of this vein had 3.83 percent ThO_2 (pl. 2*B*; table 21).

The northern vein differs from the other three veins in being mainly quartz and specularite. It is thus more resistant and forms massive outcrops both east and west of the small gulch. A major part of the vein on this property lies under the dump of the main cut. On the Silver Queen 52B property this vein strikes approximately N. 85° E. and dips steeply. It can be traced on the property for 810 feet but probably connects with a similar vein on the Lone Star No. 2 property on strike with it 0.5 mile to the west. This vein shows considerable thickening and thinning and ranges in thickness from 2.0 to 28 feet. The northern vein varies from white to dark purplish gray in color and is brecciated. In places white quartz is fractured and filled with later dark-purplish-gray vein material of quartz and specularite. In addition, in places this vein contains limonite and thorite. Thorium content, as indicated by its radioactivity, is erratic, much of the vein having only a minor amount of thorium but parts of the vein being fairly rich in thorium. Two samples were taken on abnormally highly radioactive parts of the vein (pl. 2*B*). They yielded 0.27 and 0.77 percent ThO_2 (table 21).

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TABLE 21.—*Analyses of samples from the Silver Queen 52B property, Idaho*

[C, chip sample; Ch, channel sample; n.d., no data; <, less than]

Vein	Sample No.	Sample Length and type (ft)	ThO_2 (percent)	Copper[1] (percent)	Lead[1] (percent)	Zinc[1] (percent)	Silver[2] (ounces per short ton)	Gold[3] (ounces per short ton)
South	MHS-67-72	0.6 Ch	[4]1.63	0.001	0.024	0.022	<0.6	0.0020
	4967	1.2 C	[5].12	N.d.	N.d.	N.d.	N.d.	N.d.
	4967A	1.5 C	[5]2.22	n.d.	n.d.	n.d.	n.d.	n.d.
	MHS-65-72	2.0 C	[4].87	.007	.016	.011	<.6	.0015
	5067C	2.0 C	[5]2.22	n.d.	n.d.	n.d.	n.d.	n.d.
	4969A	1.8 C	[5]1.20	n.d.	n.d.	n.d.	n.d.	n.d.
	4969	1.0 C	[5].35	n.d.	n.d.	n.d.	n.d.	n.d.
	5067B	2.0 C	[5]2.91	n.d.	n.d.	n.d.	n.d.	n.d.
	5067A	2.0 C	[5]1.03	n.d.	n.d.	n.d.	n.d.	n.d.
	5063B	3.0 C	[5].90	n.d.	n.d.	n.d.	n.d.	n.d.
	MHS-68-72	3.0 C	[4].24	n.d.	n.d.	n.d.	n.d.	n.d.
Southcentral	4968	1.5 C	[5].79	n.d.	n.d.	n.d.	n.d.	n.d.
	MHS-66-72	1.9 Ch	[4]1.04	.001	.010	.004	<.6	<.0015
	5067E	1.0 C	[5]1.07	n.d.	n.d.	n.d.	n.d.	n.d.
Northcentral	5067D	2.0 C	[5]3.83	n.d.	n.d.	n.d.	n.d.	n.d.
North	5063D	3.0 C	[5].77	n.d.	n.d.	n.d.	n.d.	n.d.
	5063C	3.0 C	[5].27	n.d.	n.d.	n.d.	n.d.	n.d.

[1]Atomic-absorption analysis by J. A. Thomas, U.S. Geological Survey, Denver, Colo.
[2]Fire assay by J. A. Thomas and W. D. Goss, U.S. Geological Survey, Denver, Colo.
[3]Fire assay and atomic-absorption analysis by W. D. Goss, A. W. Haubert, and J. A. Thomas, U.S. Geological Survey, Denver, Colo.
[4]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.
[5]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.

SILVER QUEEN 38A

The Silver Queen 38A claim (loc. 148) lies near Wheat Spring across a northwest-trending tributary of Poison Creek which is a west-flowing tributary of Pattee Creek. This property is in the SW¼SW¼ sec. 17, T. 19 N., R. 28 E., Boise meridian, Idaho, and is reached by a secondary road that follows the tirbutary from Poison Creek. The Silver Queen 38A was located during the summer of 1954 by J. A. Rucker, and was one of more than 100 Silver Queen claims located by him in the mid-1950's in the Pattee Creek drainage. The property was owned in the mid 1960's by the Nuclear Fuels and Rare Metals Corp. By 1969 ownership had passed to the Joyce Corp. Workings consist of several interconnected bulldozer cuts on either side of the small tributary (fig. 30). Workings are cut in a tan fine-grained micaceous quartzite of the Precambrian Y age.

Two parallel veins are exposed on this property, but only one was noted on the west side of the tributary. Where both veins are exposed on the east side of the tributary the intervening quartzite is silicified. The large south vein can be traced for 210 feet across the creek, and is 2.0-4.5 feet thick. This vein has a N. 85° E. strike and dips 60° NW. The north vein has been traced only for 32 feet and is as much as 3.0 feet thick. The veins lie in a horst and are bounded both to the east and west by downdropped blocks of Challis Volcanics. A third fault, a northeast-trending cross fault that offset the horst faults, lies 700 feet to the northwest of the larger vein (pl. 1). If the veins extend far from the vicinity of the workings, then these faults might well limit their extent. The veins are generally black with some dark-brown spots and the gangue is chiefly quartz, although pink microcline is also abundant. The black color is due to numerous finely disseminated black shiny plates of specularite. Other iron oxide minerals include brown limonite, cherry-red hematite, and a little black magnetite. Reddish-brown shiny thorite is the only thorium mineral noted. The only other mineral identified was a minor amount of brown shiny rutile. Four samples were cut of the longer vein and one each of the shorter vein and of the intervening silicified country rock. The ThO_2 content of the south vein ranged from 0.16 to 2.40 percent, that of the north vein and silicified country rock 0.22 and 0.05 percent, respectively (fig. 30; table 22). The total rare-earth content of one sample from the longer vein (sample 4911D), as determined by X-ray fluorescence by the U.S. Bureau of Mines at Salt Lake City, Utah, was 1.60 percent.

NELLIE B

This property (loc. 153) lies on the divide between Pattee and Agency Creeks in the NW¼NW¼ sec. 24, T. 19 N., R. 24 E., Boise meridian, Idaho. It is about 1.5 miles north-northeast of the junction of Agency and Cow Creeks. Several Nellie B claims lie in this general region, and the claim number of this particular property is not known. It was located by Nuclear Fuels and Rare Metals Corp. in 1956 and was controlled by the same company in the summer of 1972. Workings consist of three 4-foot-deep bulldozer trenches 60-200 feet long (fig. 31). The country rock is a Precambiran Y gray fine-grained brecciated micaceous quartzite.

Two veins are exposed in the workings. The northern one has a general strike of N. 75° W. and dips 70° SW. This vein can be traced for about 120 feet. It probably does not continue much farther to the east, as no trace of it was found

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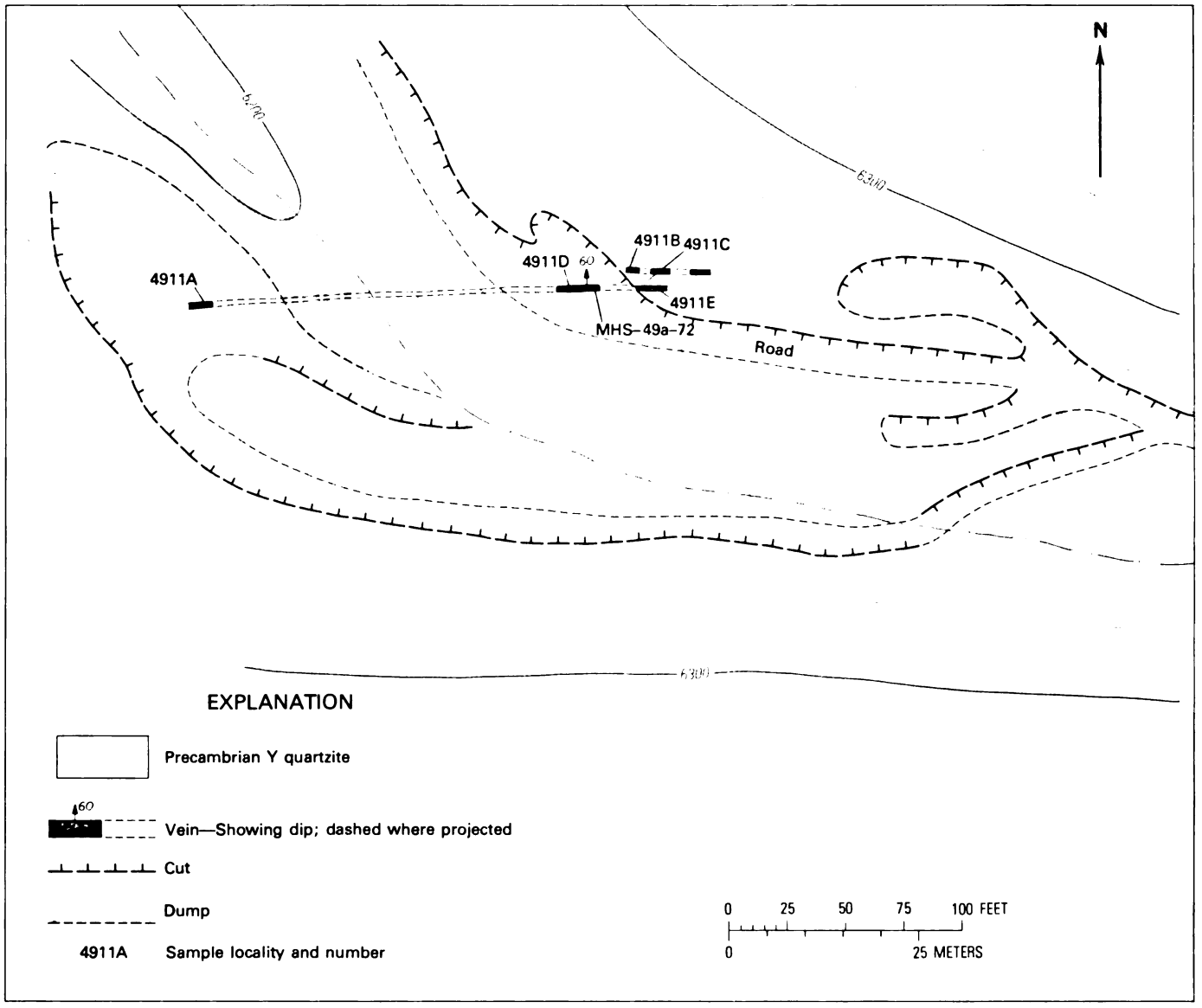


FIGURE 30.—Geologic map of the Silver Queen 38A property (loc. 148). Mapped by B. J. Sharp and D. L. Hetland, 1965; revised by M. H. Staatz, 1973.

TABLE 22.—*Analyses of chip samples from the Silver Queen 38A claim, Idaho*

Vein or silicified rock	Sample No.	Sample length (ft)	ThO_2 (percent)
South vein	4911A	3.2	[1]0.27
	4911D	1.7	[1]2.40
	MHS-49a-72	4.2	[2].16
	4911E	2.0	[1].20
North vein	4911B	3.0	[1].22
Silicified quartzite.	4911C	9.5	[1].05

[1]Wet chemical analyses by Lucius Pitkin, Inc., Grand Junction, Colo.
[2]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.

in the long northeast-trending trench (fig. 31). This vein is 0.3-1.5 feet thick. A sample (4985A) cut in the middle trench contained 0.30 percent ThO_2 and 0.45 percent total rare-earth oxides (Austin, 1968, p. 10).

The second vein is only exposed in the western trench. It has a strike of N. 82° W. and may be a branch of the northern vein. It is 2.5 feet thick. A sample (4995B) of this vein yielded 0.17 percent ThO_2. Both veins are dark brown and composed chiefly of limonite-stained quartz mixed with hematite.

BLACK ROCK, IDAHO

The Black Rock property (loc. 165) is on the steep north side of Agency Creek about 0.3 mile northwest of the mouth of Cow Creek in the NW¼NW¼ sec. 26, T. 19 N., R. 24 E., Boise meridian, Idaho. It is on the west side of a small gulch,

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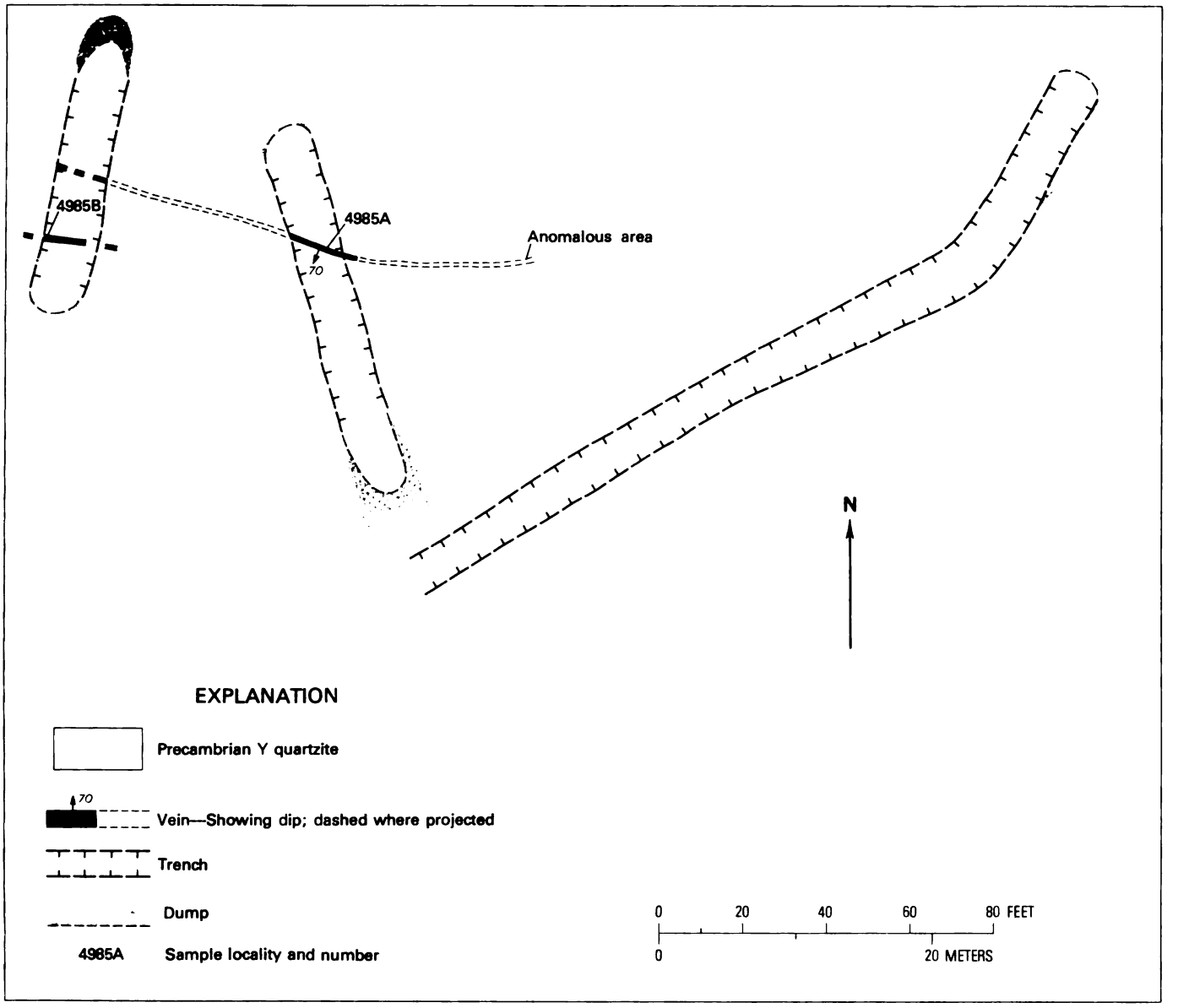


FIGURE 31.—Geologic map of the Nellie B property (loc. 153). Mapped by B. J. Sharp and D. L. Hetland, 1965; revised by M. H. Staatz, 1973.

500-850 feet above Agency Creek, and at the end of a poor, narrow, unused road. The Black Rock claim was located by John W., Arthur M., and Donald L. Gage on April 1, 1955. Assessment work on this property was done in 1971 by Arthur Gage.

Two veins, a long northwest-trending one (fig. 32) and a short northeast-trending one, are exposed on this property. The northeast-trending vein is only exposed in the uppermost trench. Previous to 1957 two adits about 90 feet apart vertically, and a small cut midway between them, were made on the northwest-trending vein. The adits are small, the lower one being only 8 feet long and the upper one 15 feet long. The property was further developed by five bulldozer cuts 265-485 feet long interconnected by roads (fig. 33). Country rock is gray micaceous quartzite of Precambrian Y age. The main northwest-trending vein follows a shear zone in the quartzite. The vein is 1.0-2.5 feet thick, but silicification of the country rock extends beyond the vein. Silicified quartzite forms a prominent outcrop about 10 feet thick. Most of the radioactivity is confined to the vein proper. The vein, from the lowest to the highest trench, has been traced vertically for 330 feet. Along the east side of the gulch east of the area of figure 33 is the Scott lode, which has a somewhat thinner vein having a similar strike. This vein is offset at least several hundred feet from the projected trace of the Black Rock vein. A fault is exposed near the bottom of the east side of the gully (fig. 33) along which the vein could be offset. If the Scott lode is a continuation of the Black Rock vein, then

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FIGURE 32.—Northwest-trending vein on the Black Rock, Mont., property (loc. 75) exposed by a series of bulldozer trenches.

the total exposed length would be 1,600 feet.

On the Black Rock property the northwest-trending vein strikes N. 75°-85° W. and dips 55°-75° SW. This vein is commonly brecciated and is medium to dark brown in color. It consists principally of quartz and microcline veined and cut be goethite. Other iron oxides include some black shiny plates of specularite and minor tiny grains of magnetite. This is one of the few veins which contains siderite. The only radioactive mineral noted was a little thorite. The amount of thorite noted was too minor to account for the measured thorium content, and probably some of the thorium occurs within the goethite. Other minerals identified in this vein include pyrite, chalcopyrite, malachite, barite, rutile, and apatite. Pyrite is visible in tiny cubes both in the vein and in the adjoining silicified quartzite. Five samples taken from this vein yielded from 0.16-0.62 percent ThO_2 (fig. 33; table 23). One of these samples (5074A) contained 0.27 percent total rare-earth oxides. Two of the samples (MHS-94-72, MHS-95-72) were analyzed for base and precious metals. They contained small amounts of copper, lead, and zinc, but did not yield any detectable gold or silver (table 23).

The northeast-trending vein is exposed for 80 feet in the highest trench. This vein is about 1 foot thick. It strikes N. 50°-70° E. and dips 20° NW. It is a medium-brown color and consists chiefly of quartz mixed with medium- to dark-brown goethite. Minor magnetite is included in some of the goethite. No thorium minerals were noted in the specimen (MHS-24-73) examined and the thorium most likely occurs within the goethite. Other minerals noted are minor amounts of barite, rutile, and fluorite. A sample from this vein had 0.21 percent ThO_2 (fig. 33; table 23).

THO_2

The main workings on the principal vein of the ThO_2 property (loc. 192) lie at an elevation of approximately 7,850 feet in a small densely wooded northwest-trending valley of a tributary of the South Fork of Yearian Creek. This property, which is near the top and on the northwest side of the main ridge separating the Yearian Creek from the Reese Creek drainages, is in the W½ sec. 28, T. 18 N., R. 25 E., Boise meridian, Idaho. A steep secondary road connecting the Lemhi Valley with the Continental Divide passes through the property. The mine road branches off a good gravel county road 4 miles southeast of where the latter joins Idaho Route 28 at Lemhi (pl. 1). A group of 16 ThO_2 claims were located by Carroll Wells and Ann Lundin (Anderson, 1961b,

TABLE 23.—*Analyses of chip samples from the Black Rock property, Idaho*

[n.d., no data; <, less than]

Vein	Sample No.	Sample length (ft)	ThO_2 (percent)	Total rare earths[1] (percent)	Copper[2] (percent)	Lead[2] (percent)	Zinc[2] (percent)	Silver[3] (ounces per short ton)	Gold[4] (ounces per short ton)
Northwest-trending.	MHS-94-72	1.8	[5]0.62	N.d.	0.002	0.012	0.043	<0.6	<0.0015
	643	2.5	[6].20	n.d.	N.d.	N.d.	N.d.	N.d.	N.d.
	5074A	2.5	[6].16	0.27	n.d.	n.d.	n.d.	n.d.	n.d.
	MHS-95-72	1.9	[5].40	n.d.	.03	.007	.005	<.6	<.0015
	5074B	2.0	[6].43	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Northeast-trending.	MHS-24-73	1.0	[5].25	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

[1]X-ray fluorescence spectrographic analysis by the U.S. Bureau of Mines, Salt Lake City, Utah.
[2]Atomic-absorption analysis by J. A. Thomas, U.S. Geological Survey, Denver, Colo.
[3]Fire assay by J. A. Thomas and W. D. Goss, U.S. Geological Survey, Denver, Colo.
[4]Fire assay and atomic-absorption analysis by W. D. Goss, A. W. Haubert, and S.A. Thomas, U.S. Geological Survey, Denver, Colo.
[5]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.
[6]Wet chemical analysis by Lucius Pitkin, Inc., Grand Junction, Colo.

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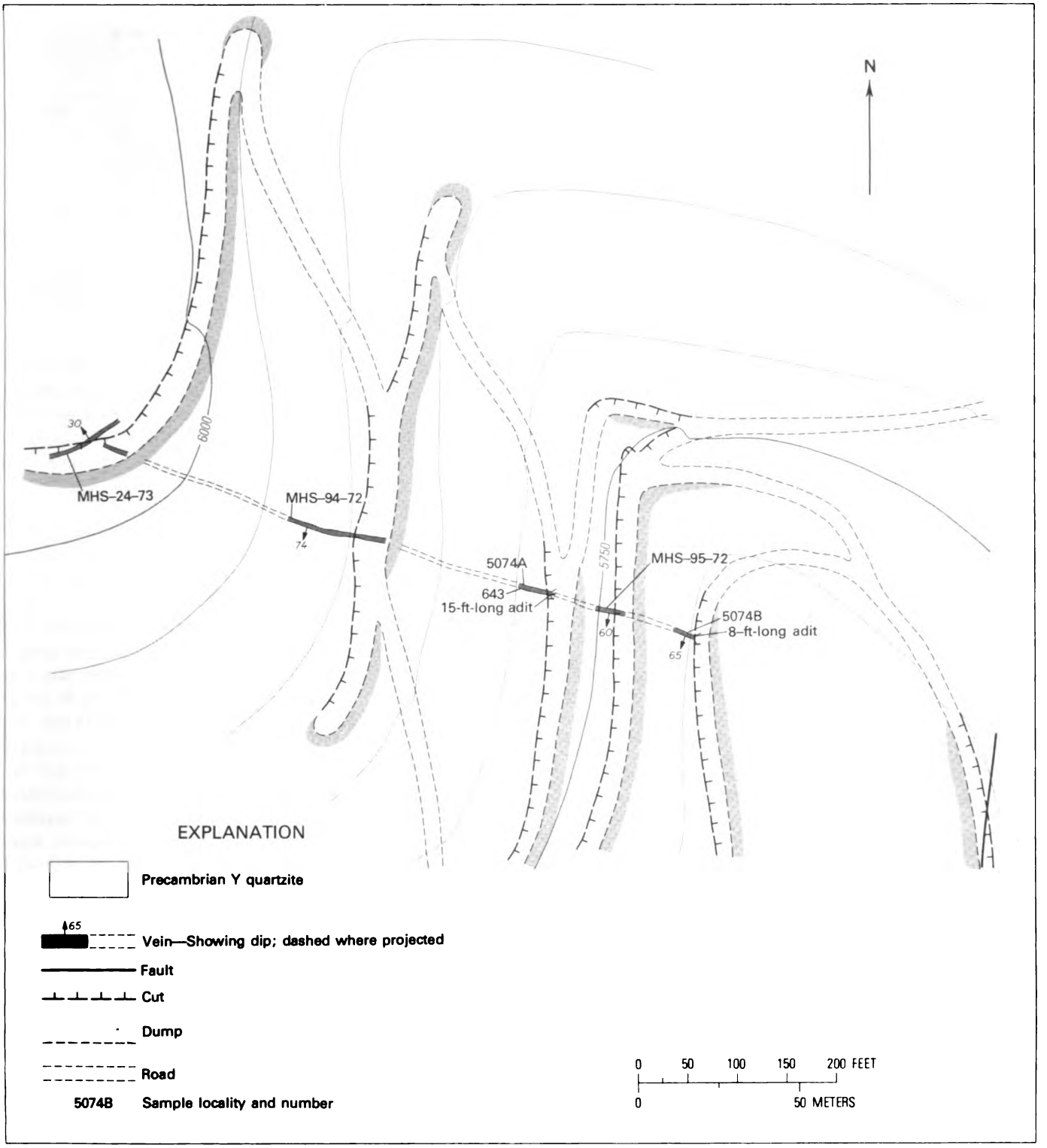


FIGURE 33.—Geologic map of the Black Rock, Idaho, property (loc. 165). Mapped by B. J. Sharp and D. L. Hetland, 1965; revised by M. H. Staatz, 1973.

p. 96), the first (the ThO_2) being located June 1, 1960, and the others later during the same summer. Ownership was later transferred to the ThO_2 and Rare Metals Exploration, Inc., of which Mr. Wells is president. In the 1960's the property was leased to the Dow Chemical Co. who made many bulldozer cuts and did some diamond drilling. In the late

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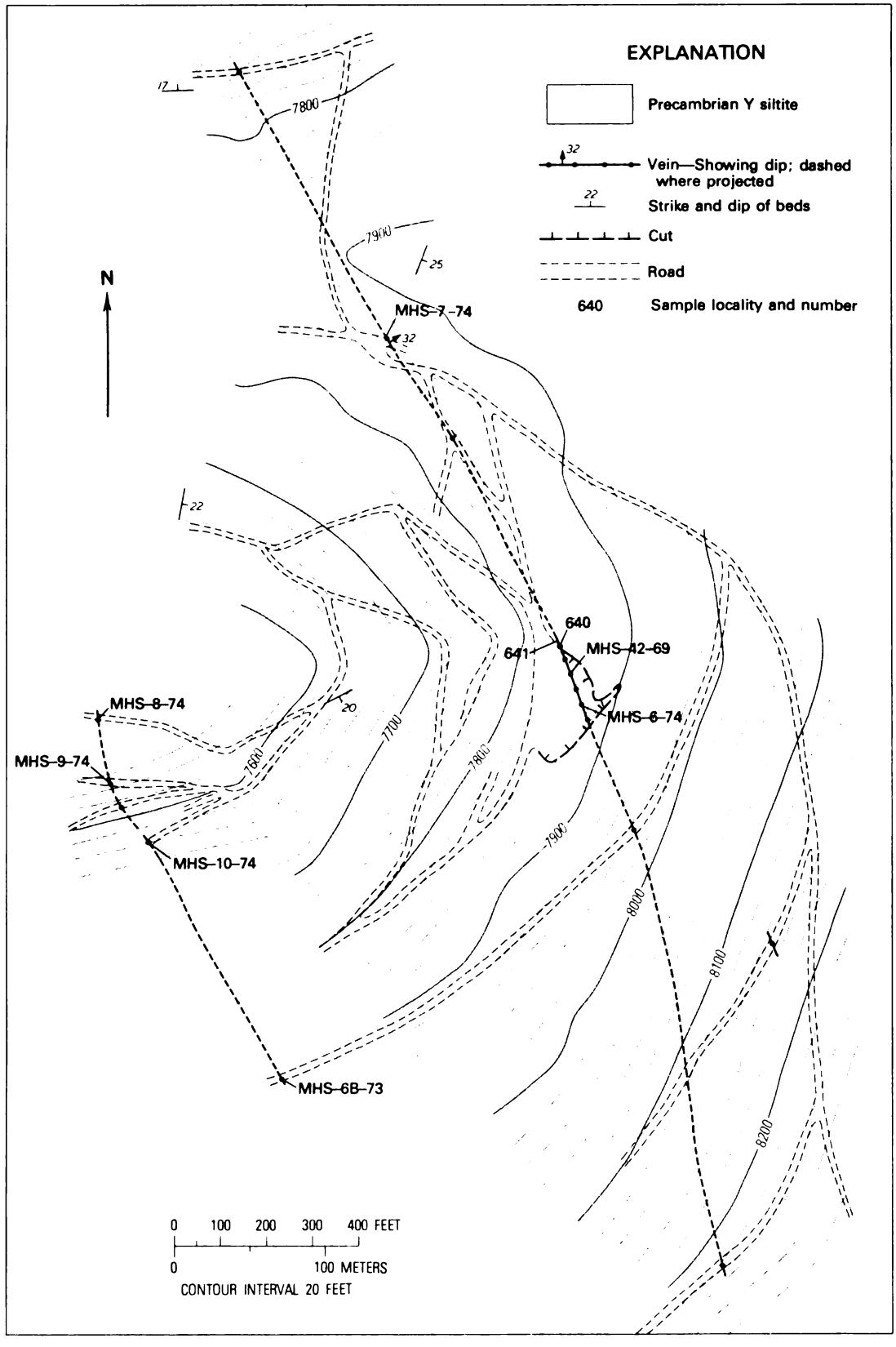


FIGURE 34.—Geologic map of the ThO_2 property (loc. 192). Mapped by B. J. Sharp and D. L. Hetland, 1965; revised by M. H. Staatz, 1973.

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TABLE 24.—*Thorium analyses of samples from the ThO_2 property, Idaho*

[C, chip sample; G, grab sample; NA, not applicable]

Vein	Sample No.	Sample length and type (ft)	ThO_2 (percent)
Main vein	MHS-7-74	0.7 C	[1]0.032
	640	4.0 C	[2]2.30
	641	3.0 C	[2].84
	MHS-42-69	NA G	[1]2.39
	MHS-6-74	.9 C	[1].51
West vein	MHS-8-74	1.0 C	[1].007
	MHS-9-74	.9 C	[1].21
	MHS-10-74	.7 C	[1].11
	MHS-68-73	1.3 C	[1].61

[1]Gamma-ray spectrometric analysis by C. M. Bunker and C. A. Bush, U.S. Geological Survey, Denver, Colo.
[2]Wet chemical analysis by Lucius Pitkin, Inc., Gran Junction, Colo.

1960's, Dow Chemical Co. sold its lease to the Kough Mining and Manufacturing Co. of California. One long vein and several smaller veins are found on this property. As the area has a thick soil cover, the vein exposures are restricted to various cuts. The workings consist of one large bulldozed area some 250 feet long near the center of the principal vein, and more than 13,000 feet of roads (fig. 34). The country rock is greenish-gray siltite of Precambrian Y age. The ThO_2 property is on the east side of the Yearian Creek graben and the veins on this property lie adjacent to a northeast-trending fault that cuts the graben.

A number of veins occur on the ThO_2 claims, but most appear to be small. Figure 34 shows the extent of the largest vein and parts of two others. The largest vein has an overall strike of N. 28° W. Near its northern end the vein dips 32° NE, but along most of its length the dip is much steeper and in places is nearly vertical. This vein has been traced for 2,860 feet (fig. 34). Its thickness varies, and it apparently is thickest in the main cut, where it ranges from about 1 to 15 feet. Eight hundred feet northwest of the main cut the vein is 10 inches thick, and on the road 300 feet southeast of the cut it is about 1 foot thick. The vein is brecciated, and in places dark-red vein material surrounds white quartz augen. In some areas the entire vein is rusty brown. The principal gangue minerals are white quartz and pink feldspar. The principal iron oxide is black shiny specularite. Minor goethite and black granular magnetite are also present. Reddish-brown thorite, the principal thorium mineral, is common. Minor monazite has also been noted (Anderson, 1961b, p. 97). Other minerals include muscovite, rutile, a black manganese oxide mineral, barite, apatite, and rare pale-pink xenotime. Five samples collected from this vein (table 24; fig. 34) yielded 0.032-2.39 percent ThO_2. Some of the most radioactive samples in this district have come from the main working on this vein.

Another fairly continuous vein is exposed in a series of cuts 1,040 feet west of the main pit (fig. 34). This vein has a strike of about N. 25° W. and a steep dip. It extends for 320 feet between four closely spaced roads. A vein outcrop on a road farther southeast indicates that it extends at least another 600 feet. This vein is poorly exposed, but where visible has a thickness of 1.0-1.3 feet. The vein is yellowish brown and is brecciated. The principal gangue mineral is pink microcline; a little quartz is also present. Dark-brown goethite, black shiny specularite, and dark-red granular hematite vein and stain the feldspar. Magnetite is present in minor amounts. Reddish-brown thorite was the only thorium mineral noted. Small amounts of muscovite and rutile were also seen. Four samples from this vein (table 24; fig. 34) ranged from 0.007 to 0.61 percent ThO_2.

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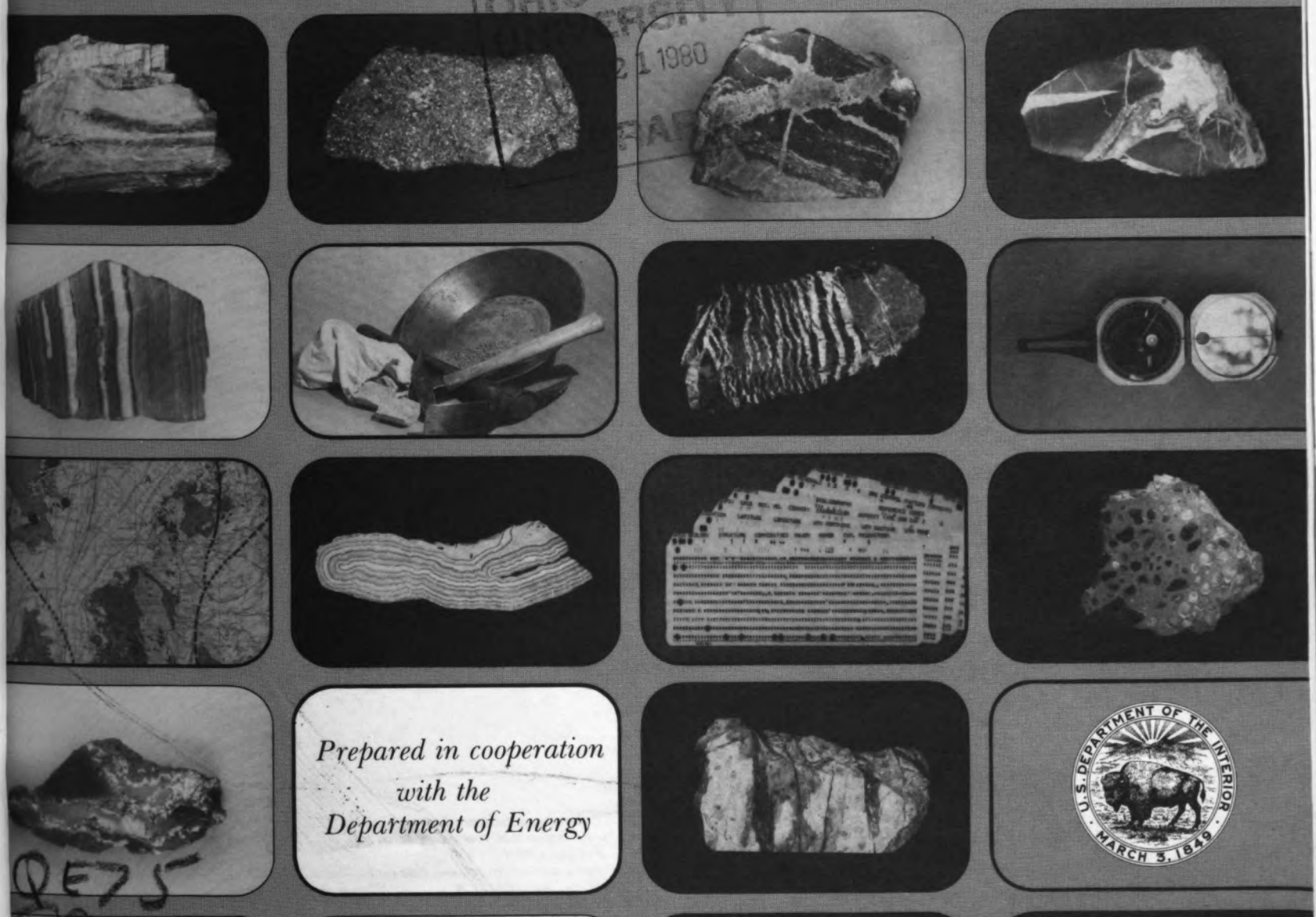
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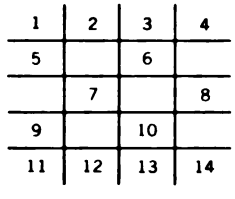
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Abundance and Distribution of Thorium in the Carbonatite Stock at Iron Hill, Powderhorn District, Gunnison County, Colorado

By THEODORE J. ARMBRUSTMACHER

GEOLOGY AND RESOURCES OF THORIUM IN THE UNITED STATES

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1049-B

Prepared in cooperation with the Department of Energy

An evaluation of the thorium resources of the carbonatite stock at Iron Hill



UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1980

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UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

H. William Menard, *Director*

Library of Congress Cataloging in Publication Data

Armbrustmacher, Theodore J. 1946-
Abundance and distribution of thorium in the carbonatite stock at Iron Hill, Powderhorn District, Gunnison County, Colorado.

(Geology and resources of thorium in the United States) (Geological Survey professional paper ; 1049-B)
Bibliography: p. B11.
Supt. of Docs. no.: I 19.16:1049-B
1. Thorium. 2. Carbonatites–Colorado–Gunnison Co. I. United States. Dept. of Energy. II. Title. III. Series. IV. Series: United States. Geological Survey. Professional paper ; 1049-B.
QE516.T5A74 553.4'94 79-607145

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

Stock number 024-001-03296-1

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ABUNDANCE AND DISTRIBUTION OF THORIUM IN THE CARBONATITE STOCK AT IRON HILL, POWDERHORN DISTRICT, GUNNISON COUNTY, COLORADO

By THEODORE J. ARMBRUSTMACHER

ABSTRACT

The carbonatite stock at Iron Hill is part of an alkalic complex of Cambrian or latest Precambrian age containing pyroxenite, uncompahgrite, ijolite, nepheline syenite, and related rocks characterized by their subsilicic composition and by their lack of calcic plagioclase. Thorium averages 36.2 parts per million (ppm) Th (0.0041 percent ThO_2) in the carbonatite, which also contains considerably more Ba, Ce, Nd, La, Nb, P, Mn, Mo, Sr, U, and rare-earth elements than average igneous rocks. Thorium content of the carbonatite ranges from 6 ppm Th (0.0007 percent ThO_2) to 150 ppm Th (0.017 percent ThO_2), and several areas of anomalous concentration are apparent. The distribution of thorium is not the same as the distribution of niobium and rare-earth elements. Thorium abundances of the level found in the carbonatite at Iron Hill are of little economic interest unless considered as a byproduct of potential niobium, rare-earth, and uranium exploitation.

INTRODUCTION

The alkalic rocks and especially the carbonatite stock at Iron Hill, near Powderhorn, Colo., have been intensely studied since 1912 (Larsen, 1942) not only because of their unusual lithologies but also because of the economically significant mineral concentrations. Economic minerals associated spatially and genetically with these rocks include vermiculite and minerals that contain thorium, iron, titanium, niobium, and rare-earth elements. Several reports by government agencies and mining company representatives have discussed various aspects of the economic geology of the complex of alkalic rocks, but the abundance and distribution of thorium in the carbonatite stock have not been investigated in detail. The interest in the thorium content of the stock results mainly from the fact that thorium is a potential byproduct of possible future niobium and rare-earth exploitation.

This study was conducted in order to provide resource data on one of the principal thorium deposits in the United States (Staatz and others, 1979) for a Department of Energy contract with the U.S. Geological Survey.

ACKNOWLEDGMENTS

Robert R. Norman of Buttes Gas and Oil Co. arranged for permission to investigate the thorium resource potential of their land holdings at Iron Hill. James V. Thompson of Kaiser Engineers, consultant to Buttes, visited us in the field and discussed the geology of the area. Jerry C. Olson of the U.S. Geological Survey provided unpublished data and also discussed various aspects of the geology of the area. Semiquantitative spectrographic analyses were performed by L. A. Bradley, and laboratory gamma-ray spectrometer analyses were performed by C. M. Bunker and C. A. Bush, all of the U.S. Geological Survey. The cost analyses of mine and mill models were provided by J. F. Lemons, Jr., L. V. Coppa, and B. V. Clingan of the U.S. Bureau of Mines. Mineral separations and other supporting laboratory work were conducted by Isabelle K. Brownfield and William F. Robinson IV. Brownfield also constructed the cross sections across the Iron Hill carbonatite stock and determined the volume of carbonatite used in the resource calculations. Michael B. Sawyer calculated the correlation coefficients used to test the strength of association of various element pairs.

GEOLOGIC SETTING

The carbonatite stock (fig. 1) is part of the complex of alkalic rocks at Iron Hill originally described by Larsen (1942). The complex, which occupies an area of about 30 km^2, consists chiefly of pyroxenite, magnetite-ilmenite-perovskite segregations, uncompahgrite, ijolite, hybrid pyroxenite-syenite rocks, nepheline syenite, and carbonatite, listed oldest to youngest (Hedlund and Olson, 1961). Rocks of the complex were emplaced about 570 million years ago (Olson and others, 1977) into Precambrian X Powderhorn Granite and metamorphic rocks, which are locally

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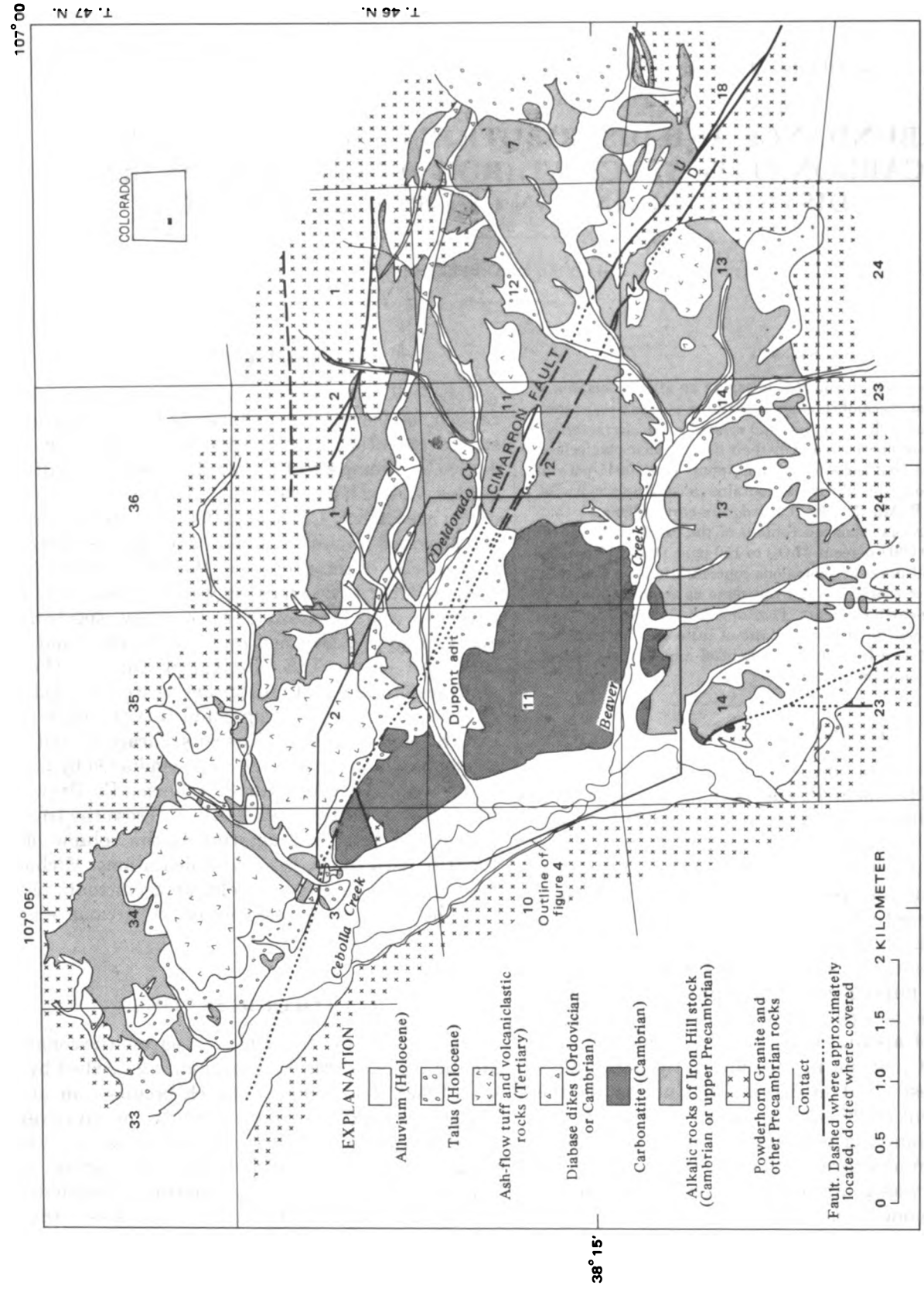


FIGURE 1.—Geologic map of the alkalic complex at Iron Hill, Gunnison County, Colo. Modified from Hedlund and Olson (1975) and Olson (1974).

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fenitized adjacent to the complex. Parts of the complex are covered by ash-flow tuffs, welded tuffs, and colluvium mainly of Oligocene age and by colluvium and alluvium of Quaternary age, mainly along the drainages of Cebolla, Deldorado, and Beaver Creeks.

The complex is bisected by the Cimarron fault. Hedlund and Olson (1975) indicate that relative movement on the fault is such that a deeper level of the alkalic complex is exposed on the northeast side of the fault. The structural interpretation of Temple and Grogan (1965), however, suggests that a deeper level is exposed on the southwest side of the fault. Regardless of the interpretation, nearly all of the uncompahgrite, most of the ijolite, and the carbonatite stock are found southwest of the fault; the magnetite-ilmenite-perovskite segregations and the nepheline syenite seem to be restricted to the northeast side of the fault. Diabase dikes of Ordovician or Cambrian age mainly intrude rocks of the complex on the northeast side of the Cimarron fault, although one diabase dike does cut fenitized Powderhorn Granite just southwest of the fault (Olson, 1974).

Carbonatite dikes, probably similar in age to the carbonatite stock, intrude all rocks of the complex except the carbonatite stock and the Precambrian host rocks, especially those within the fenitized aureole. Martite-fluorapatite veins and jasper-rich veins, the latter probably representing silicified fracture zones, are found intersecting the carbonatite stock. Rocks of the complex and the surrounding area have been mapped in detail by Hedlund and Olson (1968, 1975) and Olson (1974).

Many aspects of the alkalic complex at Iron Hill suggest that it is a representative of the Ijolite Series as defined by Bailey (1974). Rocks of this series are characteristically undersaturated with respect to silica and contain fairly abundant alkalies. The complex at Iron Hill is also representative of the carbonatitic type of alkalic complex as defined by Rock (1976). These complexes are characterized by the occurrence of intrusive rocks such as carbonatite, ijolite, pyroxenite, melilitic rocks, and nepheline syenite, all lacking calcic plagioclase, and are also found occupying the root zones of nephelinitic volcanoes. King (1965) suggested that rocks of this type formed by differentiation from an immediate parental nephelinite-melteigite magma, which maintained silica undersaturation with a trend toward enrichment of lime, alkalies, and volatiles. With increasing concentration of these components, a point was reached whereupon a highly mobile fraction of alkali and calcium carbonates separated from the crystallizing silicate phase, forming a carbonatite melt. Initially the melt contained abundant alkali carbonates, which allowed the carbonatite to remain as a liquid at low temperatures and pressures, according to King. The presence of fenitized country rocks reflects the alkali content of the melt and shows that alkalies were removed from the melt through reaction with the host. The final product was a carbonatite probably not unlike that found at Iron Hill.

Potentially economic deposits of a number of mineral commodities are known to be associated spatially and genetically with the alkalic complex at Iron Hill. Olson and Wallace (1956) discuss the occurrence of thorium and rare-earth minerals, the thorium mainly concentrated in veins and shear zones outside of the complex, the rare earths mainly in carbonatite dikes and in the Iron Hill carbonatite stock. Hedlund and Olson (1961) identify four environments containing thorium, niobium, and rare-earth minerals in the Powderhorn district: (a) carbonatite, (b) magnetite-ilmenite-perovskite bodies, (c) thorite veins, and (d) trachyte porphyry dikes. The magnetite-ilmenite-perovskite segregations were discussed as early as 1912 (Singewald, 1912) as a source of iron and titanium. Rose and Shannon (1960) reported an average grade of 6.5 percent titania and 11.7 percent iron and a possible tonnage in excess of 100 million tons in pyroxenites containing the segregations. In the February 25, 1976, issue of the Denver Post newspaper, Buttes Gas and Oil Co. announced results of a study that indicated 419 million tons of reserves averaging about 12 percent TiO_2 occurred at Powderhorn. Earlier studies of the carbonatite stock by E. I. DuPont de Nemours and Company (Temple and Grogan, 1965) indicated a niobium reserve of over 100,000 tons of Nb_2O_5 in rocks averaging at least 0.25 percent Nb_2O_5. Vermiculite deposits are found in altered pyroxenite, but data on reserves are not available.

THE CARBONATITE STOCK AT IRON HILL

Various modes of origin have been proposed for the carbonatite stock at Iron Hill, the largest exposed massive carbonatite in the United States. Larsen (1942) considered the "marble" of Iron Hill to be the oldest rock of the alkalic complex. He felt that there were no data that suggested an igneous origin for the carbonate rocks and preferred a hydrothermal origin with deposition occurring in a volcanic throat and later modification due to subsequent intrusion of other rocks of the complex. The first application of the term "carbonatite" to the Iron Hill carbonate rocks appears to have been by Wallace and Olson (1956); the term "stock" for the form of the massive carbonatite, implying an igneous intrusive origin, was first used by Hedlund and Olson (1961). Temple and Grogan (1965) ascribed a mode of origin based on metasomatic modification of country

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rock by a CO_2-rich phase associated at depth with volcanic activity. Carbon isotopic data from the Iron Hill carbonatite (Taylor and others, 1967) are similar to values found in diamond, indicating that the CO_2 in the carbonatite had a deep-seated igneous source. The carbon isotopic data and oxygen isotopic data from the Iron Hill carbonatite both fall within the field of primary igneous carbonatite defined by Taylor and others (1967). Strontium isotopic data from various lithologies within the alkalic complex, including carbonatite (Powell and others, 1966), indicate that the rocks within the complex are comagmatic. Strontium isotopic values also suggest that carbonatite-alkalic rock associations, such as that observed at Iron Hill, are mantle derived. Analyses of calcite-dolomite and pyrite-pyrrhotite mineral pairs by Nash (1972) indicate crystallization temperatures between 435°C and 290°C for late-stage carbonatites. Samoylov (1975) determined formation temperatures of Iron Hill carbonatite at 600°C using biotite-pyroxene geothermometry and at 400°C using amphibole-pyroxene geothermometry.

METHODS OF STUDY

Distribution of thorium in the Iron Hill carbonatite stock was determined by field measurements of thorium abundances at 173 stations within or immediately adjacent to the carbonatite. Measurements were made with a Geometrics[1] model DISA–400A portable differential four-channel gamma-ray spectrometer. This instrument uses a 7.6-cm-diameter by 7.6-cm-thick sodium iodide crystal as a detector. Counting times at each station were 2 minutes duration. The instrument was calibrated using an external ^{137}Cs source, and the detector was held 0.5 m above the ground surface.

In order to relate the instrument count rate on the thorium channel of the spectrometer to thorium abundance, the following formula was used:

$$eTh = 0.094\ (C_{Th} - b_{Th}),$$

where C_{Th} represents counts per minute on the thorium channel and b_{Th} represents counts per minute (cpm) background. The b_{Th} was measured over standing water and mainly represents cosmic-ray counts, which for this study is taken as 40 cpm. The value 0.094 is a sensitivity constant derived from a least-squares fitting procedure of measurements made over an area of known thorium abundance by J. S. Duval (written commun., 1976). Drift was checked by periodically returning to a base station and repeating the counting operation at a fixed location. Precision was determined by repeated measurements, after correction for drift, at the base station during the course of the field study. A total of 84 measurements, each of 2 minutes duration, averaged 769±67 counts. An attempt was made to evaluate accuracy by analyzing samples of carbonatite from 28 stations by laboratory gamma-ray spectrometric techniques. The laboratory analyses averaged 47 ppm Th, whereas field measurements at the same localities yielded analyses averaging 38 ppm Th. According to Hansen (1975), the gamma-ray spectrum observed in the laboratory is different from that observed in the field, the latter being strongly influenced by the interaction of gamma rays emitted within the rocks. Inconsistencies also result from the differences in the geometry of the field and laboratory environments. A much greater volume of rock is scanned in the field than in the laboratory. Thus, the accuracy of the field method is difficult to evaluate by comparison with laboratory data.

In addition to being analyzed for potassium, thorium, and uranium by laboratory gamma-ray spectrometric techniques, the samples of carbonatite collected from 28 localities were also analyzed for 61 elements by semiquantitative spectrographic techniques. Splits of the same samples were processed by routine heavy-liquid and magnetic-separation methods, and the component minerals were identified either by physical characteristics or by X-ray powder diffraction methods. Thin sections of the rocks were also studied by routine petrographic techniques.

MINERALOGY AND GEOCHEMISTRY OF CARBONATITE

The mineralogy of the samples collected from the carbonatite stock during this study is not complex. The variety of minerals is somewhat less than that found in the neighboring carbonatite dikes. X-ray and optical studies show the presence of the following minerals, listed approximately in the order of their frequency of occurrence: dolomite, barite, goethite, hematite, calcite, quartz, fluorapatite, pyrochlore, pyrite, magnetite, biotite, rutile, fluorite, bastnaesite, aegirine, anatase, sphalerite, synchisite, zircon, magnesite(?), and manganese oxide minerals. The dolomite occurs as clear, colorless to milky-white grains and as brown, ferric oxide-rich grains often described as ankeritic or sideritic by Temple and Grogan (1965), Hedlund and Olson (1975), and Olson (1974). Neither ankerite nor siderite was identified in the current study, although siderite occurs in carbonatite dikes adjacent to Iron Hill. Barite occurs as disseminated colorless grains

[1]Use of a brand name in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

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scattered throughout the dolomite matrix in highly variable amounts. Goethite most commonly occurs as shiny, dark-reddish-brown, conchoidally fractured grains entirely or partly replacing pyrite and forming pseudomorphs after pyrite. Hematite may be associated with goethite but also appears to form pseudomorphs after magnetite. This pattern of occurrence is especially apparent in the martite-fluorapatite veins that cut the carbonatite stock. Calcite is found in the carbonatite, but its paragenesis is difficult to determine because of its similar appearance to dolomite. Small rounded quartz grains are seen within some dolomite grains. Fluorapatite occurs as clear, colorless grains in widely variable amounts. Although chemical analyses are not available, the fluorapatite is suspected to contain abundant rare-earth elements. Pyrochlore occurs in a variety of colors including light gray, purplish gray, pink, and pale lemon yellow to greenish yellow. Pyrochlores analyzed by Nash (1972) contain up to several percent ThO_2. However, alpha counter measurements of pyrochlore separates show that not all are radioactive and that there is no correlation between color and radiation. Additional studies of pyrochlore are in progress. Pyrite is a common constituent but is frequently at least partly replaced by goethite. Biotite occurs in streaks at places within the carbonatite, helping to define a foliated variety, and magnetite occurs disseminated throughout the carbonatite. The remainder of the minerals listed earlier are sparse and are seldom seen either in thin sections or in mineral separates. The minerals that have been found in each sample are listed in Armbrustmacher and Brownfield (1979).

The abundance of a variety of elements in 28 samples of Iron Hill carbonatite, the average element content of igneous rocks of the upper continental crust (Wedepohl, 1971, table 7.3), and the average composition of carbonatites (Gold, 1963) are given in table 1. Histograms showing the frequency distributions of elements are presented in figure 2. In comparison with average igeneous rocks, the Iron Hill carbonatite contains greater than 20 times more Ba, Ce, and Nd, 15–20 times more La, Nb, P, and ΣREE, and nearly 10 or more times Mn, Mo, and Sr. There is 4.2 times more Th and 3.1 times more RaeU. According to Heinrich (1966, p. 222) characteristic elements found in carbonatites and associated alkalic rocks in general include Ti, Nb, Zr, rare earths of the Ce subgroup (La, Ce, Nd, Pr, Sm, and Eu), P, F, Ba, Sr, and Th. All these elements except Ti and Zr occur in large average concentrations in the Iron Hill carbonatite relative to average igneous rocks. However, abundant Ti occurs in the magnetite-ilmenite-perovskite segregations that are found in the pyroxenite. The Iron Hill rocks were not analyzed for fluorine, but fluorite grains appear in a few mineral separates.

Table 1.--Abundance of elements in the carbonatite at Iron Hill, the igneous rocks of the upper continental crust, and the average carbonatite

[Values are in percent. Dashes signify that data are not available]

Element	Average Iron Hill carbonatite	Average igneous rocks of upper continental crust (Wedepohl, 1971)	Average chemical composition of carbonatites (Gold, 1963)
Fe.....	5.4	3.54	5.12
Mg.....	4.3	1.39	3.40
Ca.....	10.	2.87	25.10
Ti.....	.3	.47	.48
Mn.....	.58	.069	.47
Ba.....	1.56	.059	.23
Be.....	.0007	.0002	--
Co.....	.0018	.0012	.0017
Cr.....	.0065	.007	.0048
Cu.....	.0050	.003	.00025
La.....	.085	.0044	.0516
Mo.....	.0013	.0001	.0042
Nb.....	.040	.002	.1951
Ni.....	.0053	.0044	.0008
Pb.....	.0018	.0015	--
Sc.....	.0015	.0014	.001
Sr.....	.27	.029	.34
V.....	.0050	.0095	--
Y.....	.0037	.0034	.0096
Zr.....	.0064	.016	.112
Si.....	4.4	30.54	5.66
Al.....	.60	7.83	1.88
Na.....	.23	2.45	.31
K.....	1.2	2.82	1.24
P.....	1.2	.081	.90
Ce.....	.17	.0075	.15
Ga.....	.0004	.0017	.0001
Yb.....	.00014	.00034	--
Nd.....	.067	.003	--
Th.....	.0047	.0011	--
RaeU[1].....	.0011	.00035	--
ΣREE[2].....	.34	.0225	--

[1]Radium-equivalent uranium.
[2]Total rare-earth elements.

In comparison with the average composition of carbonatites in general (Gold, 1963), the Iron Hill carbonatite contains at least four times more Ba, Cu, Ni, and Ga. It also contains at least three times less Mo, Nb, Y, Zr, and Al. The remaining elements occur in amounts similar to Gold's averages. The analytical data for each sample are given in Armbrustmacher and Brownfield (1979).

ABUNDANCE AND DISTRIBUTION OF THORIUM

Although many carbonatite occurrences around the world are anomalously radioactive, available data

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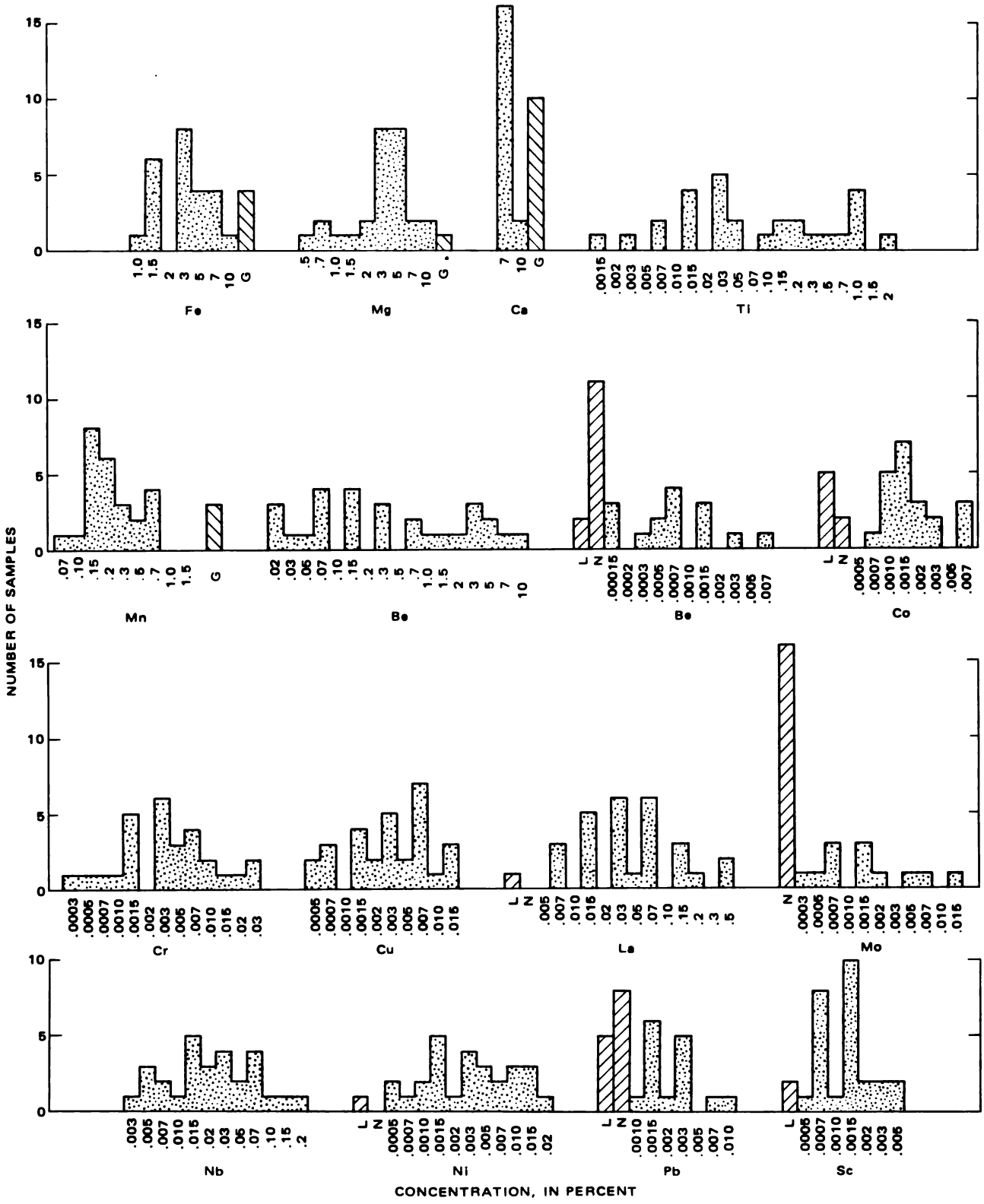


FIGURE 2.—Histograms showing frequency distribution of elements in 28 samples of carbonatite at Iron Hill.

suggest that the overall abundance of thorium in carbonatites is not great and that there are probably few carbonatite bodies in which thorium would be of principal economic interest. Thorium, however, could be an important byproduct in those carbonatites being exploited chiefly for niobium or rare-earth elements.

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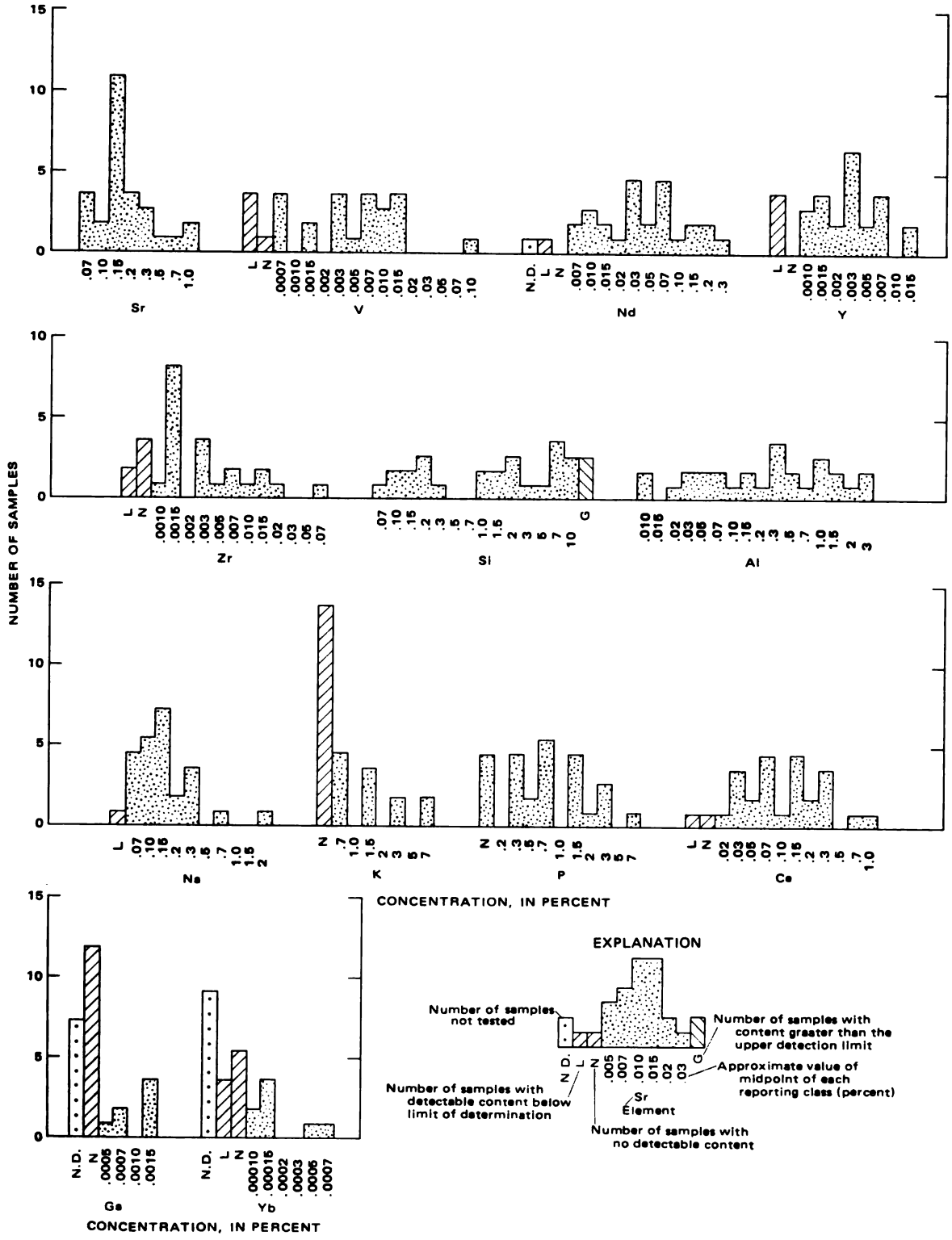


FIGURE 2.—Continued.

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Thorium appears to have a wide variation in carbonatites in general. Gerasimovskiy (1973) reports 1.8 ppm Th (0.0002 percent ThO_2) for the Kerimasi carbonatite and 46.8 ppm Th (0.0053 percent ThO_2) for the Fort Portal carbonatite; these values represent average compositions for East Africa rift-zone carbonatites. That part of the carbonatite at Palabora, Transvaal, that constitutes the copper ore body contains about 0.033 percent Th (0.038 percent ThO_2) (Hanekom and others, 1965). The Sulfide Queen carbonatite at Mountain Pass, California, contains an average grade of 0.026 percent ThO_2 (Shawe, 1953). Primary magmatic carbonatite dikes in the Wet Mountains area, Colorado, average 0.18 percent Th (0.20 percent ThO_2) (Armbrustmacher, 1979). The thorium content of carbonatite at Magnet Cove, Arkansas, appears to be very low (Erickson and Blade, 1963) and does not exceed about 35 ppm Th (0.004 percent ThO_2) in any rock within the entire alkalic complex. Data on several other carbonatite localities are given by Olson and Overstreet (1964).

Occurrences of anomalous amounts of thorium in rocks of the Powderhorn district have been known since 1949 (Olson and Wallace, 1956). Wallace and Olson (1956) point out the presence of at least one locality within the Iron Hill carbonatite stock characterized by anomalous radioactivity, and Hedlund and Olson (1961) indicate that the carbonatite stock has a maximum radioactivity five times greater than background. Temple and Grogan (1965) indicate that "typical foliated carbonatite" in the carbonatite stock averages 0.01–0.02 percent Th (0.011–0.023 percent ThO_2).

Data gathered in the current study are summarized in figure 3. This histogram shows the variation in 173 thorium analyses of carbonatite in the Iron Hill stock. The average thorium value is 36.2 ppm Th (0.0041 percent ThO_2); the median value is 31 ppm Th (0.0035 percent ThO_2); the minimum value is 6 ppm (0.0007 percent ThO_2); and the maximum value is 150 ppm (0.017 percent ThO_2).

The distribution and variation of thorium in the Iron Hill stock is portrayed by the contour map in figure 4. Using a contour interval of 10 ppm Th, several areas of stronger concentration of Th are outlined. Especially noteworthy are the areas just west of the summit of Iron Hill and at the southwest corner of the stock.

The areas containing stronger concentrations of thorium do not correspond to areas known to contain more abundant niobium, such as the area around the DuPont adit and the area immediately north of Beaver Creek (James V. Thompson, oral commun., 1977). Temple and Grogan (1965, p. 680) also point out the lack of general correlation between radioactivity and niobium occurrence. Using analyses of the 28 samples

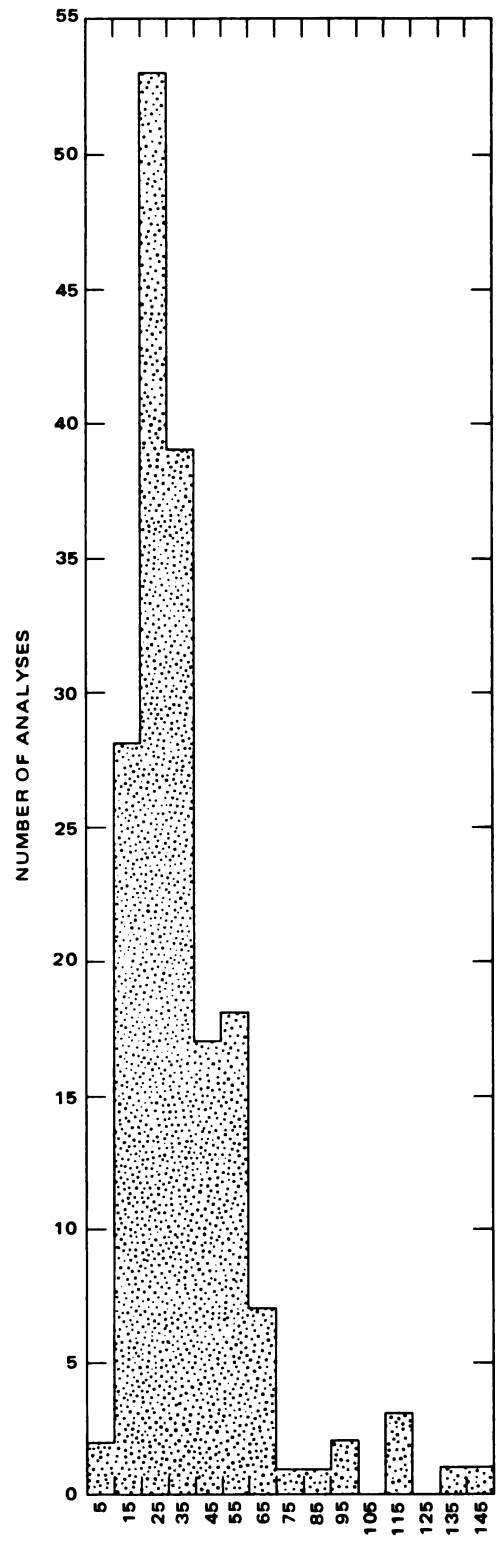


FIGURE 3.—Histogram showing frequency distribution of 173 thorium values, in parts per million, determined by field gamma-ray spectrometry from the Iron Hill carbonatite. Thorium concentration values, on the abscissa, represent the midpoints of intervals 10 ppm wide.

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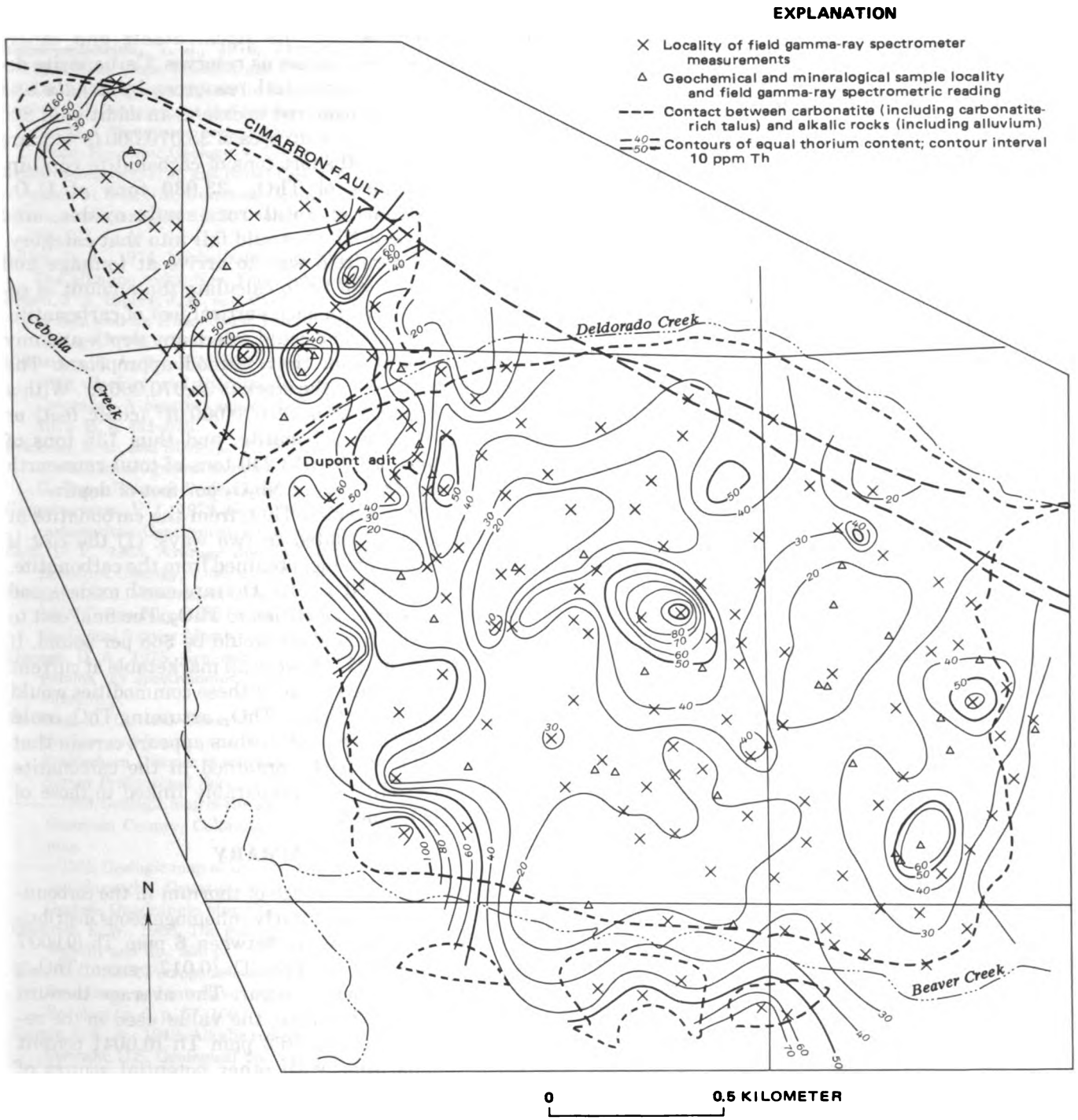


FIGURE 4.—Contour map of thorium distribution in the carbonatite at Iron Hill. See figure 1 for location of this area.

of carbonatite, correlation coefficients were calculated in order to test the strength of associations among thorium, niobium, total rare earths, and uranium. A perfect correlation would be 1.0, a perfectly random association would be 0.0. Results give Nb-REE, 0.41; Nb-U, 0.18; Nb-Th, 0.10; U-Th, 0.59; REE-Th, 0.50; and REE-U, 0.19. Although based on data insufficient to support generalizations, it is interesting to note that the niobium-thorium association shows the weakest correlation. Alpha-counter measurements of mineral separates show moderate amounts of radioactivity, 5–10 counts per minute above background, in some of the pyrochlore concentrates. None of the other minerals in the carbonatite appears to be radioactive.

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RESOURCE ASSESSMENT

As part of a program to assess the thorium reserves of the United States, funded by the U.S. Department of Energy, the Minerals Availability Field Office of the U.S. Bureau of Mines was requested to design cost analyses of mine and mill models for the recovery of thorium from massive carbonatite deposits. The details of the procedures, which are only outlined here, can be found in Staatz and others (1979).

The cost analyses provide for an open-pit mining procedure with recovery of thorium based on flotation of pyrochlore, followed by chlorination, acid leach, and a solvent extraction procedure. Byproducts of the procedure are uranium, niobium, and rare-earth elements. It is assumed that thorium, uranium, niobium, and rare-earth elements occur together in the pyrochlore. Mining costs are subdivided into capital costs, which include mine development, mine structures, and mine equipment; and operating costs, which include materials, utilities, labor, and maintenance, as well as taxes and insurance. Milling costs are also subdivided into capital costs and operating costs. These four items are represented by curves that fit a range of 1,000–10,000 tons per day mining capacity with the maximum value of 10,000 tons per day used in the cost calculations. A maximum mill life or mine life of 15 years is assumed, and so the maximum tonnage that can be handled is 52,500,000 tons (10,000 tons per day times 350 days per year times 15 years).

Various methods can be used to determine the amount of carbonatite at Iron Hill that might be potentially economically important. The method used by Staatz and others (1979) is presented here.

Staatz and others (1979) determined the amount of carbonatite that projects above the surrounding land surface. Seven evenly spaced cross sections were constructed across the carbonatite stock, the area was measured in each cross section, and the average area in each pair of sections was multiplied by the distance between them. Using this method, Iron Hill was found to contain 722,700,000 short tons of carbonatite.[2] Based on the field gamma-ray spectrometric readings, the average thorium concentration is 0.0041 percent ThO_2, which yields 29,775 tons of ThO_2 in the carbonatite. Assuming the abundance of elements in the 28 analyzed samples to be representative of the entire carbonatite stock, the stock would contain 9,180 tons of U_3O_8 (avg. 0.00127 percent), 2,865,500 tons total rare-earth oxides (avg. 0.3965 percent), and 412,000 tons Nb_2O_5 (avg. 0.057 percent). Higher grades of thorium and the coproduct elements could be obtained by selective mining because the distribution of each element is not consistent within the stock. Staatz and others (1979) define these values as reserves. Carbonatite defined as probable potential resources by Staatz and others (1979) is considered to extend an additional 800 feet in depth. With a map area of 38,070,000 ft^2 (square feet), 2,672,000,000 short tons of carbonatite containing 110,090 tons of ThO_2, 33,930 tons of U_3O_8, 10,590,000 tons of total rare-earth oxides, and 1,523,000 tons of Nb_2O_5 would fall into that category.

A more generalized way to arrive at tonnage and grade figures would be to calculate the amount of coproducts contained in each vertical foot of carbonatite. With those values one could select any depth and any mining configuration that seemed appropriate. The map area covered by the stock is 38,070,000 ft^2. With a depth of 1 ft, there is 38,070,000 ft^3 (cubic feet) or 3,339,470 tons of carbonatite, and thus 138 tons of ThO_2, 42 tons of U_3O_8, 13,240 tons of total rare-earth oxides, and 1,900 tons of Nb_2O_5 per foot of depth.

The cost of producing ThO_2 from the carbonatite at Iron Hill was estimated in two ways: (1) the cost if ThO_2 is the only product obtained from the carbonatite, and (2) the cost if Nb_2O_5, RE_2O_3 (rare-earth oxides), and U_3O_8 are products in addition to ThO_2. The final cost to mine and mill ThO_2 alone would be $68 per pound. If Nb_2O_5, RE_2O_3, and U_3O_8 were all marketable at current prices, the combined value of these commodities would be more than twice that of ThO_2, assuming ThO_2 could be sold for $50 per pound. It thus appears certain that the economics of ThO_2 contained in the carbonatite stock at Iron Hill are inseparably linked to those of Nb_2O_5, RE_2O_3, and U_3O_8.

SUMMARY

Studies of the occurrence of thorium in the carbonatite at Iron Hill show a fairly inhomogeneous distribution with values ranging between 6 ppm Th (0.0007 percent ThO_2) and 150 ppm Th (0.017 percent ThO_2); several local anomalies occur. The average thorium content of the carbonatite, the value used in the resource calculations, is 36.2 ppm Th (0.0041 percent ThO_2). Comparisons with other potential sources of thorium, such as the vein deposits in the Lemhi Pass district, Idaho and Montana (Staatz, 1972), and in the Wet Mountains, Colo. (Armbrustmacher, 1976; Christman and others, 1959), and the disseminated deposits at Hicks Dome, Ill. (Brown and others, 1954), and Bear Lodge Mountains, Wyo. (M. H. Staatz, written commun., 1978), show that the carbonatite at Iron Hill contains considerably less total reserves (Staatz and others, 1979, table 1). Therefore, the economic future of thorium at Iron Hill appears to be closely tied to the economics of niobium and rare earths.

[2]All calculations were made in U.S. customary units as required by the U.S. Department of Energy contract.

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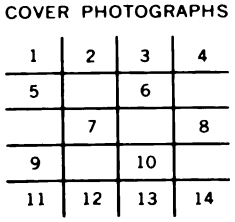
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2. Lead ore, Balmat mine, N. Y.
3. Chromite, chromium ore, Washington
4. Zinc ore, Friedensville, Pa.
5. Banded iron-formation, Palmer, Mich.
6. Ribbon asbestos ore, Quebec, Canada
7. Manganese ore, banded rhodochrosite
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11. Zinc ore, Edwards, N. Y.
12. Manganese nodules, ocean floor
13. Botryoidal fluorite ore, Poncha Springs, Colo.
14. Tungsten ore, North Carolina

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Alkalic Rocks and Resources of Thorium and Associated Elements in the Powderhorn District, Gunnison County, Colorado

By JERRY C. OLSON *and* DAVID C. HEDLUND

GEOLOGY AND MINERAL RESOURCES OF THORIUM IN THE UNITED STATES

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1049-C

An evaluation of thorium resources, their distribution, and geologic relationships



UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1981

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Library of Congress Cataloging in Publication Data
Olson, Jerry Chipman, 1917-
Alkalic rocks and resources of thorium and associated elements in the Powderhorn district, Gunnison County, Colorado.
(Geology and resources of thorium in the United States)
(Geological Survey Professional Paper 1049-C)
Bibliography: p. 33
Supt. of Docs. no.: I 19.16:1049-C
1. Alkalic igneous rocks. 2. Intrusions (Geology)—Colorado—Gunnison Co. 3. Thorium ores—Colorado—Gunnison Co.
I. Hedlund, David Carl, 1924- joint author. II. Title. III. Series. IV. Series: United States Geological Survey Professional Paper 1049-C.
QE462.A4044 552'.1 80-607811

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ALKALIC ROCKS AND RESOURCES OF THORIUM AND ASSOCIATED ELEMENTS IN THE POWDERHORN DISTRICT, GUNNISON COUNTY, COLORADO

By JERRY C. OLSON and DAVID C. HEDLUND

ABSTRACT

Alkalic igneous rocks and related concentrations of thorium, niobium, rare-earth elements, titanium, and other elements have long been known in the Powderhorn mining district and have been explored intermittently for several decades. The deposits formed chiefly about 570 m.y. (million years) ago in latest Precambrian or Early Cambrian time. They were emplaced in lower Proterozoic (Proterozoic X) metasedimentary, metavolcanic, and plutonic rocks.

The complex of alkalic rocks of Iron Hill occupies 31 km² (square kilometers) and is composed of pyroxenite, uncompahgrite, ijolite, nepheline syenite, and carbonatite, in order of generally decreasing age. Fenite occurs in a zone, in places more than 0.6 km (kilometer) wide, around a large part of the margin of the complex and adjacent to alkalic dikes intruding Precambrian host rock. The alkalic rocks have a radioactivity, chiefly due to thorium, greater than that of the surrounding Powderhorn Granite (Proterozoic X) and metamorphic rocks. The pyroxenite, uncompahgrite, ijolite, and nepheline syenite, which form more than 80 percent of the complex, have fairly uniform radioactivity. Radioactivity in the carbonatite stock, carbonatite dikes, and the carbonatite-pyroxenite mixed rock zone, however, generally exceeds that in the other rocks of the complex.

The thorium concentrations in the Powderhorn district occur in six types of deposits: thorite veins, a large massive carbonatite body, carbonatite dikes, trachyte dikes, magnetite-ilmenite-perovskite dikes or segregations, and disseminations in small, anomalously radioactive plutons chiefly of granite or quartz syenite that are older than rocks of the alkalic complex.

The highest grade thorium concentrations in the district are in veins that commonly occur in steeply dipping, crosscutting shear or breccia zones in the Precambrian rocks. They range in thickness from a centimeter or less to 5 m (meters) and are as much as 1 km long. The thorite veins are composed chiefly of potassic feldspar, white to smoky quartz, calcite, barite, goethite, and hematite, and also contain thorite, jasper, magnetite, pyrite, galena, chalcopyrite, sphalerite, synchysite, apatite, fluorite, biotite, sodic amphibole, rutile, monazite, bastnaesite, and vanadinite. The ThO_2 content of the thorite veins ranges from less than 0.01 percent to as much as 4.9 percent in high-grade samples. The ThO_2 content is generally less than 1 percent, however, and is only 0.05 to 0.1 percent in many of the veins examined in the district.

Samples of the dolomitic carbonatite of Iron Hill mostly range from 3 to 145 ppm (parts per million) thorium. Thirty samples of the carbonatite dikes, the most radioactive rocks within the complex of Iron Hill, contain about 30 to 3,200 ppm thorium and a trace to about 1.5 percent rare-earth oxides.

The magnetite-ilmenite-perovskite rocks have a radioactivity of 2 to 12 times the background of Precambrian granite that is attributable chiefly to thorium substitution for calcium in the perovskite. In two analyses the perovskite contains 0.12 and 0.15 percent ThO_2.

Trachyte dikes as much as 25 m thick cut the Precambrian rocks; their radioactivity is generally about two to four times the background of typical Precambrian granite, is locally higher, but is low relative to other types of thorium concentrations. A fine-grained granite that is anomalously radioactive occurs in thick, dikelike plutons as much as 1.2 km wide, or more. The thorium content varies widely within the granite bodies. Eight samples of the granite contain 32 to 281 ppm thorium (averaging 115 ppm).

The economic potential of thorium in the Powderhorn district is related in part to other elements such as niobium, titanium, iron, and rare earths. The proportions of niobium and rare earths to thorium vary in different parts of the district. Within the carbonatite body of Iron Hill, the Nb_2O_5 content greatly exceeds ThO_2, but the ThO_2-Nb_2O_5 ratio increases markedly northwestward to as high as 10.7 in vein deposits near the northwest end of the district.

The ratio of cerium-group rare-earth oxides to ThO_2 to yttrium-group rare-earth oxides in the district is roughly 3.6 to 1 to 0.5, but this ratio varies considerably in different parts of the district. For example, the proportion of the cerium group is greatest in and near the complex of Iron Hill, and is least in an area of thorite veins about 6 km to the north. The proportion of the yttrium group in these two areas varies approximately inversely to that of the cerium group.

Thorium deposits shown on the geologic quadrangle maps of the Powderhorn district number at least 261. Most are small or low in grade, hence only a minority contribute significantly to total resources. Indicated and inferred reserves of ThO_2 total about 10,000 short tons in rock greater than 0.1 percent ThO_2 in grade. This estimated tonnage is in 15 deposits including 13 veins and two carbonatite dikes. Larger amounts of thorium are present in lower grade materials. Additional quantities are probably present in deposits as yet undiscovered, which could add significantly to the total resources.

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INTRODUCTION

The Powderhorn district is a 650 km² area in Gunnison County, Colo., that has long been known for its occurrences of alkalic igneous rocks and related concentrations of thorium, niobium, rare-earth elements, titanium, and other metals. This mapping and geologic study of the district was undertaken primarily to learn more about the geologic occurrence and origin of the mineral deposits listed above and to evaluate their economic potential and resources.

Mining activity in the district began in 1872 and has continued intermittently to the present. The early mining was chiefly for gold, silver, copper, lead, zinc, and arsenic from veins and volcanogenic massive sulfide deposits. In more recent years mining and prospecting has been aimed toward thorium, rare-earth elements, niobium, and titanium as well. Various attempts have been made to mine and process vermiculite, particularly about 1935–45, by the Black Mica Mining Co., Allied Minerals Co., and the Alexite Co.

Thorium veins were discovered in the Powderhorn district in 1949, and about 250 veins were prospected for thorium during 1949–56. In order to assess niobium resources, the pyrochlore-bearing carbonatite and related rocks of the complex of Iron Hill were drilled and an adit was driven by the DuPont Co. in 1957–58. Titaniferous iron ores in the complex have been prospected at various times since their discovery in the 1880's. The Humphreys Gold Corp. explored the titanium deposits by digging test pits in the early fifties, and in 1957 the complex was investigated by the U.S. Bureau of Mines by drilling and surface sampling. In the mid-1970's the titanium deposits were being explored by Buttes Gas and Oil Co.

GENERAL GEOLOGY

The area is underlain largely by metasedimentary and metavolcanic rocks intruded by Precambrian granitic and other igneous rocks. In late Precambrian or Cambrian time, about 570 m.y. ago, the Precambrian rocks were intruded by alkalic igneous rocks of Iron Hill and by slightly younger tholeiitic diabase dikes (Olson and others, 1977). Mesozoic sedimentary rocks and Tertiary volcanic rocks originally covered much of the area and now remain as scattered mesas and ridges where they cover the older rocks.

The geology of the complex of Iron Hill has been described by Larsen (1942), Temple and Grogan (1965), Rose and Shannon (1960), and Nash (1972). The thorium deposits in the Powderhorn district have been described by Burbank and Pierson (1953), Hedlund and Olson (1961), and by Olson and Wallace (1956), who included a detailed map and description of one of the largest thorium deposits, the Little Johnnie vein. The thorium content of the Iron Hill carbonatite stock has been studied by Armbrustmacher (1980). The geology of the district and location of thorium deposits are shown on geologic quadrangle maps by Hedlund and Olson (1973, 1975), Olson and Hedlund (1973), and Olson (1974).

PURPOSE AND SCOPE OF REPORT

This report focuses primarily on the distribution of thorium and associated elements in various rock types, the evaluation of resources of thorium in different areas and types of deposits, and the relation of the mineral deposits to geologic history and structural features. We have tried to avoid excessive duplication of data already published in the extensive literature on the district, listed in references at the end of the report. Accordingly, the reader is referred to these reports for additional information on rock descriptions, mineralogy, geologic maps, analyses of rocks and minerals, descriptions of selected deposits, and other geologic features not specifically treated herein.

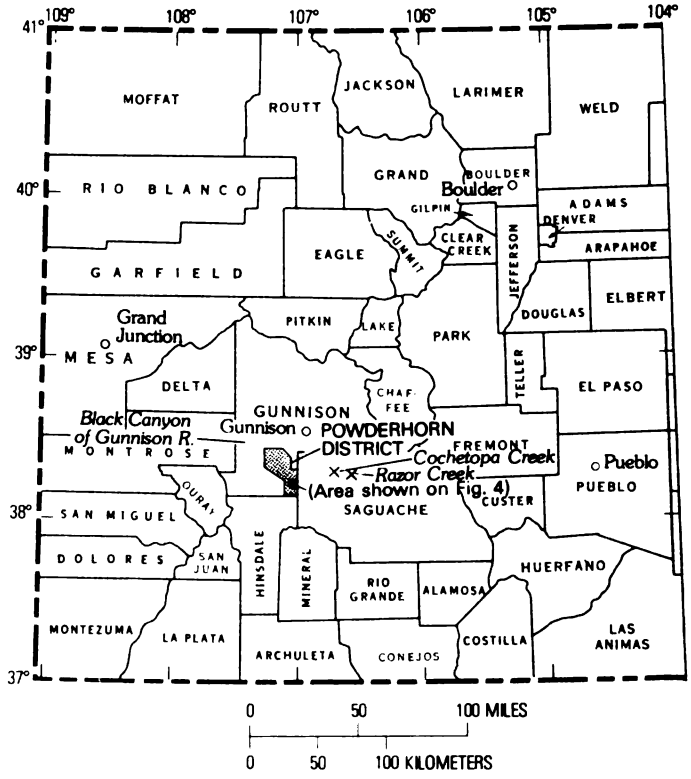


FIGURE 1.—Index map of Colorado showing location of Powderhorn district, Gunnison County.

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FIELDWORK AND ACKNOWLEDGMENTS

This report is based chiefly on the geologic mapping of the Powderhorn, Rudolph Hill, Gateview, Carpenter Ridge, and Big Mesa 7½ minute quadrangles by J. C. Olson and D. C. Hedlund during 1956–63. During the mapping, 261 thorium deposits and numerous other mines and prospects were examined briefly with a scintillation counter, and some resources were estimated. In 1976 and 1977, Olson reexamined 67 of the deposits with the aid of a portable four-channel gamma-ray spectrometer and collected additional samples. These 101 samples were analyzed in the laboratory by C. M. Bunker and C. A. Bush by gamma-ray spectrometry to provide an approximate calibration of thorium content and the field readings.

Laboratory work has included petrographic study of many thin sections, chemical and spectrographic analyses of rock samples, and mineralogical studies. The analytical work is summarized briefly in this report, but the 178 analyses of rock and thorium vein samples are available in Hedlund and Olson (1980).

Mineral exploration companies and prospectors in the district gave friendly cooperation during the work. R. M. Grogan and A. K. Temple of the DuPont Co. provided information on drilling and access to drill-core samples. S. S. Shannon of the U.S. Bureau of Mines made available thin sections and drill-core data from various parts of the pyroxenite of the complex of Iron Hill. T. J. Armbrustmacher provided radiometric and mineralogic information on the carbonatite body. M. H. Staatz identified minerals in 23 samples of thorium veins. I. K. Brownfield made heavy-liquid separations and X-ray diffractograms of mineral concentrates from some of the thorium-bearing rocks and veins.

The estimation of costs to produce thorium from various types of deposits used a method of cost analysis designed by Lemons and Coppa (1979).

PRECAMBRIAN ROCKS

The oldest rocks in the Powderhorn district are metasedimentary and metavolcanic rocks that were deposited to great thickness largely in a trough beneath the sea. These rocks were metamorphosed, mostly to amphibolite facies, about 1.7 billion years ago, probably shortly after their deposition. This regional metamorphism has not been dated in the Powderhorn area but is probably part of the widespread metamorphism known in many places in Colorado to be of about this age. The grade of metamorphism increases generally northwestward in the district to as high as the sillimanite subfacies. Migmatite and small dikes and lenses of pegmatite were formed locally in the northwestern part of the district. The metamorphic rocks throughout the district were intruded by plutons of granitic to quartz dioritic composition and by small, more mafic intrusive bodies. None of the concentrations of thorium and related minor elements appear to be related in origin to this older, 1.7–1.8 billion-year chapter of Precambrian history.

VOLCANOGENIC MINERAL DEPOSITS

Massive sulfide deposits and veins containing gold, silver, copper, lead, zinc, and locally telluride minerals occur in the metavolcanic rocks of the Dubois Greenstone of Proterozoic X age in an east to northeast-trending zone termed the Gunnison gold belt. These volcanogenic copper- and gold-bearing deposits differ markedly from the quartz-orthoclase-carbonate-barite-thorite veins. The Gunnison gold belt deposits, which show no anomalous radioactivity, commonly strike northeast to east, generally parallel with the overall trend of the metavolcanic and metasedimentary formations, whereas the thorite veins are in younger fractures that cut discordantly across the country rocks. In the volcanogenic deposits pyrite is the principal sulfide, with local concentrations of chalcopyrite, arsenopyrite, sphalerite, galena, or native gold. The quartz of these veins differs from that of the thorite veins, being generally finer grained and chloritic. Spatial relations to the sequence of metavolcanic rocks indicate that the massive sulfide deposits of the Gunnison gold belt were formed at least 1,700 m.y. ago at about the time the enclosing volcanic and sedimentary rocks were deposited. The gold-bearing quartz-chlorite veins were formed slightly later, as they are discordant to their host rocks, but are also Precambrian in age.

SYENITES AND RELATED ROCKS

The older Precambrian rocks were intruded by small plutons of leucosyenite and melasyenite about 1,400 m.y. ago (Olson and others, 1977). About 20 of these small stocks or plugs, the largest about 0.6 by 1.3 km, and numerous smaller dikes, occur in the district. They are mostly in the north half of the Gateview and Powderhorn quadrangles and the southeastern part of the Carpenter Ridge quadrangle (Hedlund and Olson, 1973). The individual plutons are generally composite, consisting of several textural and compositional varieties of leucosyenite and melasyenite. Typical augite syenite, shown in figure 2, contains augite and

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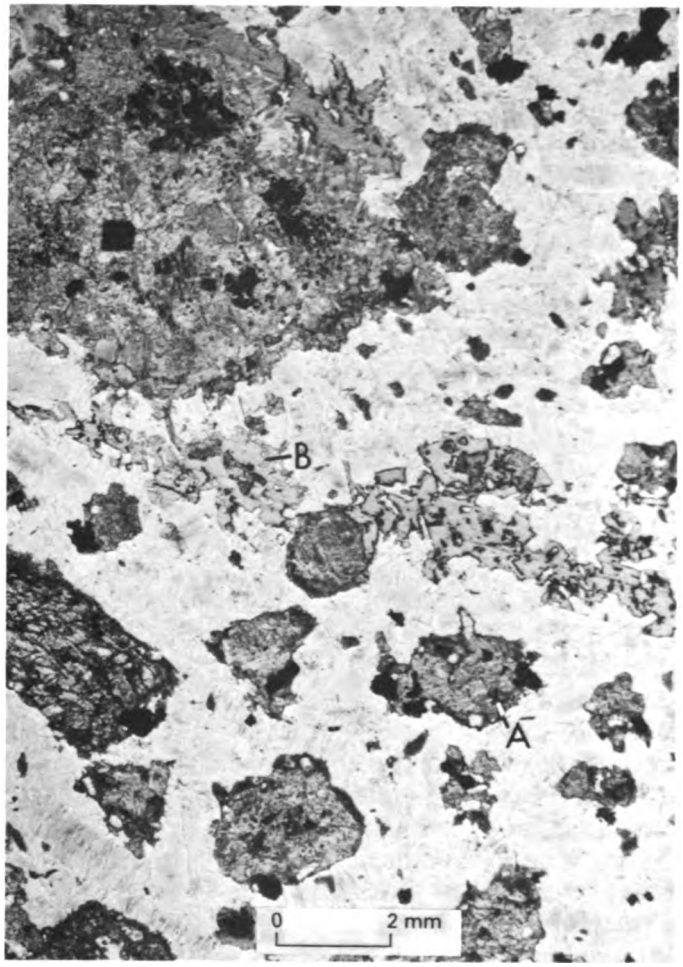


FIGURE 2.—Augite syenite from intrusive body near Spencer, Powderhorn quadrangle. Augite (A) and biotite (B) phenocrysts are set in a fine-grained groundmass consisting chiefly of microcline laths.

biotite phenocrysts in a fine-grained groundmass consisting chiefly of microcline laths. The biotite phenocrysts are highly poikilitic and locally segmented. The augite phenocrysts show various stages of alteration to uralitic hornblende, chlorite, ferric oxides, and biotite. About 65 chemical, spectrographic, and modal analyses have been given by Hedlund and Olson (1980).

The 1,400-m.y.-old (Olson and others, 1977) syenitic rocks contain thorium in amounts above the crustal average of about 11 ppm but not in exceptionally high amounts for syenitic rocks. Five samples of biotite melasyenite and one of leucosyenite had eU of 0.003–0.004 percent and uranium contents of less than 0.001 percent, suggesting thorium as the principal radioactive element. Three other samples were analyzed by gamma-ray spectrometry and found to contain 19.78, 14.5, and 18.3 ppm thorium, respectively. The thorium content of the syenites and their proximity to some thorium veins suggest a possible relationship of some thorium veins to the syenites. A relationship of thorium veins to the 570-m.y.-old rocks of the complex of Iron Hill, however, is more likely and is discussed in connection with those rocks.

Three pluglike bodies of intrusive breccia, discovered during mapping of the Carpenter Ridge quadrangle (Hedlund and Olson, 1973), are spatially and perhaps genetically related to the 1,400-m.y.-old mafic syenites. The largest body of intrusive breccia is elliptical in general plan and is about 900 m long and 240 m wide. The intrusive breccia consists of angular fragments of diverse Precambrian rocks set in a light-gray or pale-green groundmass of comminuted rock fragments, ankerite or dolomite, and opaque minerals. Parts of these bodies of intrusive breccia have radioactivities of two to three times the background of the surrounding quartz-mica schist, and the one sample analyzed by gamma ray spectrometry contains 38 ppm thorium. Three semiquantitative spectrographic analyses showed (in percent) barium and strontium generally about 0.15, zirconium 0.03–0.07, cerium 0.03, lanthanum 0.015, neodymium 0.015–0.03, yttrium 0.003–0.015, niobium 0.007, and vanadium 0.015–0.03 (Hedlund and Olson, 1980, table 1). These concentrations are several times the crustal averages for these elements.

UPPER PROTEROZOIC OR LOWER PALEOZOIC IGNEOUS ROCKS

Rocks of Late Proterozoic or Cambrian age comprise the complex of Iron Hill; related outlying dikes of trachyte, carbonatite, nepheline syenite, pyroxenite, melasyenite, and lamprophyre; thorium-bearing veins; and diabase dikes. The alkalic rocks of Iron Hill have been dated at about 570 m.y. and the diabase dikes are somewhat younger, probably about 510 m.y. old (Olson and others, 1977).

The thorium concentrations in the district are probably all related to this episode of igneous activity. These concentrations include thorite veins, the Iron Hill carbonatite body, carbonatite dikes, trachyte dikes, magnetite-ilmenite-perovskite segregations, and the disseminated thorium-bearing minerals in small, anomalously radioactive plutons chiefly of granite or quartz syenite. The latter plutons are of uncertain age and may be older than the other deposits listed. The genetic relation of the thorium deposits to the 570-m.y.-old igneous activity is suggested by the suite of minor elements such as thorium, rare-earth

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TABLE 1.—*Chemical analyses of Powderhorn Granite and fenite*

	Powderhorn Granite			Fenite	
Sample No.--	G2300a	G4500	P9820a	U1206a	IH-71
SiO_2	76.3	73.1	73.15	65.1	62.55
Al_2O_3	13.8	13.2	13.45	16.6	15.07
Fe_2O_3	.8	1.2	1.25	2.0	2.42
FeO	.27	.96	1.19	1.1	2.03
MgO	.14	.45	.57	.2	1.33
CaO	.36	1.2	1.86	1.5	4.09
Na_2O	3.3	3.5	3.73	7.3	5.80
K_2O	4.8	4.7	3.43	5.1	5.68
TiO_2	.12	.22	.16	.2	.15
P_2O_5	0.00	.10	.10	.0	.14
MnO	.02	.04	.07	.1	.29
H_2O+	.48	.56	.50	.3	.13
H_2O-	.06	.11	.3	.05	
CO_2	.07	.14	.21	.0	.03
Sum	100.46	99	99.89	99.8	99.8

Sample descriptions

G2300a. Powderhorn Granite, medium grained, light pink. NE1/4 sec 3, T. 47 N., R. 3 W, at 8,680 ft elevation, east side of gully, 110 m northwest of road fork marked 8694. Analysis by P. L. D. Elmore and S. D. Botts.

G4500. Powderhorn Granite. NE1/4 sec. 8, T. 47 N., R. 3 W. Above road on east side of Lake Fork of Gunnison River. Analysis by N. G. Skinner.

P9820a. Powderhorn Granite, coarse grained, biotitic, pink perthitic microcline phenocrysts 2.5 cm across. SW1/4 sec. 36, T. 47 N., R. 2 W. At 9,320 ft elevation, north side of Huntsman Gulch, in tributary gully northeast of spring. Analysis by E. L. Munson.

U1206a. Soda syenite (Larsen, 1942, p. 26), considered to be fenite. SW1/4 sec. 7, T. 46 N., R. 1 W. South of gully, near northwest base of hill above 9,000 ft contour. Analysis by George Steiger.

IH-71. Fenite, gray, gneissic, medium grained, composed chiefly of microcline perthite and elongate, alined aggregates of aegirine-augite grains. NE1/4 sec. 12, T. 46 N., R. 1 1/2 W. Analysis by E. L. Munson.

elements, niobium, titanium, barium, and strontium characteristic of the rocks and deposits; the alkali metasomatism (fenitization) of the wall rocks adjacent to the thorium-bearing veins and the alkalic rock complex; and the fact that veins as well as alkalic rocks are cut by diabase dikes. Furthermore, the veins and the trachyte dikes are characterized by a fetid odor that is also found in places in the fenite surrounding the alkalic complex. Such a fetid odor has been described in other areas where thorium concentrations are related to alkalic rocks (e.g. Olson and others, 1954; Heinrich and Anderson, 1965).

Although the alkalic rock complex occupies 31 km², thorium-bearing veins are present in at least a 650-km² area (fig. 1). They have been found from the Black Canyon of the Gunnison River southeastward to Cochetopa Creek and Razor Creek.

ALKALIC ROCK COMPLEX OF IRON HILL

The complex of Iron Hill is the best example of the carbonatite-alkalic rock association in the United States and is one of the outstanding occurrences in the world, comparable to many of the classic areas in Africa and other continents. This heterogeneous assemblage of alkalic igneous rocks was intruded, probably from a source in the mantle, about 570 m.y. ago. The complex of Iron Hill lacks a clearly defined ring or cone sheet structure typical of some of the African complexes, but it has a radial carbonatite dike system that partly surrounds an eccentrically placed carbonatite stock. This stock was emplaced as a carbonatitic magma, and it is suggested that forcible emplacement was accompanied by radial fracturing of the surrounding pyroxenite. The depth of the complex below the surface at the time of intrusion is not known. Possibly the complex breached the surface, but erosion during long periods of Paleozoic, Mesozoic, and Cenozoic time has removed the upper part.

The alkalic rock complex of Iron Hill occupies an elliptical area (fig. 3) of about 31 km² along the east side of Cebolla Creek. The complex is about 10 km long, has a maximum width of about 5 km, and the long axis strikes N 55°-60°W. The dolomitic carbonatite (rauhaugite) stock that forms Iron Hill is also elliptical in outcrop, the long axis striking northwest.

The alkaline complex forms a distinctive topography that is largely controlled by lithology and climate. In this semiarid region the carbonatite of Iron Hill is

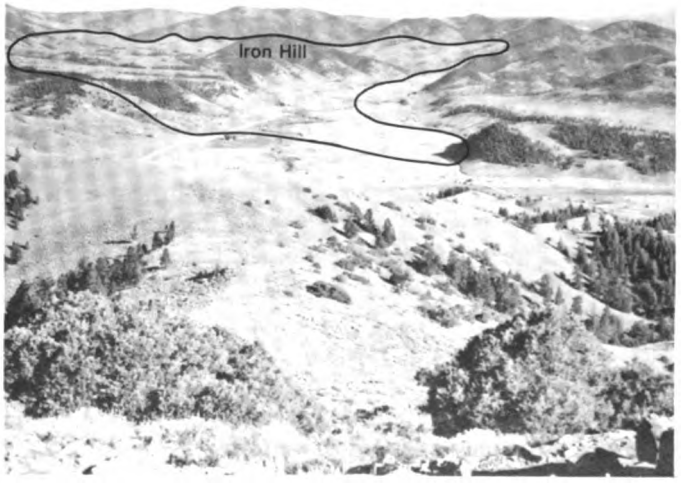


FIGURE 3.—View southeastward of Cebolla Creek valley and Iron Hill. Approximate outline of the complex of Iron Hill is indicated by the line.

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more resistant to weathering than the surrounding basic alkaline rocks; hence the carbonatite forms a hill surrounded by a horseshoe-shaped depression of low relief. Older Precambrian granite forms an outer, arcuate ridge about the inner outcrop belt of basic alkalic rocks.

The rocks in the complex (fig. 4) from oldest to youngest are pyroxenite, uncompahgrite, ijolite, nepheline syenite, and carbonatite; the last two rock types locally show overlapping age relations. Magnetite-ilmenite-perovskite dikes and segregations are chiefly confined to the pyroxenite. Fenite occurs commonly at the borders of the complex. Carbonatite dikes radiate outward from the dolomitic carbonatite stock and cut all the other rock types of the complex.

The distribution of radioactivity in the alkalic rocks of Iron Hill was studied by taking 1,258 random scintillation-counter readings distributed among the various rock types approximately in proportion to their area. These readings, which were made on the outcrop with a scintillation counter, are given in the description of the various rock types that follow. The total radioactivity of the alkalic rocks is well above that of the surrounding Powderhorn Granite and metamorphic rocks that commonly show a background count of 0.02–0.025 mr/hr (milliroentgens per hour). The radioactivity of pyroxenite, uncompahgrite, ijolite, and nepheline syenite, which, combined make up more than 80 percent of the complex, is fairly uniformly distributed among the rock types and averages about 0.035 mr/hr or about 1½ times that of the surrounding granite.

Within the complex, carbonatite is the most radioactive rock. The carbonatite stock averages 0.055 mr/hr for 226 readings, or more than twice the background of typical Powderhorn Granite. Carbonatite dikes vary considerably in their radioactivity from one dike to another and within individual dikes, hence a representative average figure was difficult to obtain. On the average, however, they are somewhat more radioactive than the carbonatite stock. Furthermore, the radioactivity of pyroxenite increases markedly in those areas where the pyroxenite is permeated by many small dikes and seams of carbonatite, including the mixed rock zone near the carbonatite stock.

FENITE

Fenite occurs in a zone, in places more than 0.6 km wide, around a large part of the margin of the complex. It is a syenitic rock formed from various country rocks, chiefly granite and felsite, by metasomatic alteration associated with the intrusion of alkalic or carbonatitic magmatic fluids. The fenite zone is generally wider along the south margin of the complex and is present but narrower along the north side. Although the fenite may not have all formed at one time, it is cut by and apparently predates some dikes and apophyses of the pyroxenite. In places the fenite is intruded by dikes of nepheline syenite, carbonatite, and by diabase. The fenite is essentially the same as the "soda syenite" described by Larsen (1942, p. 25–26).

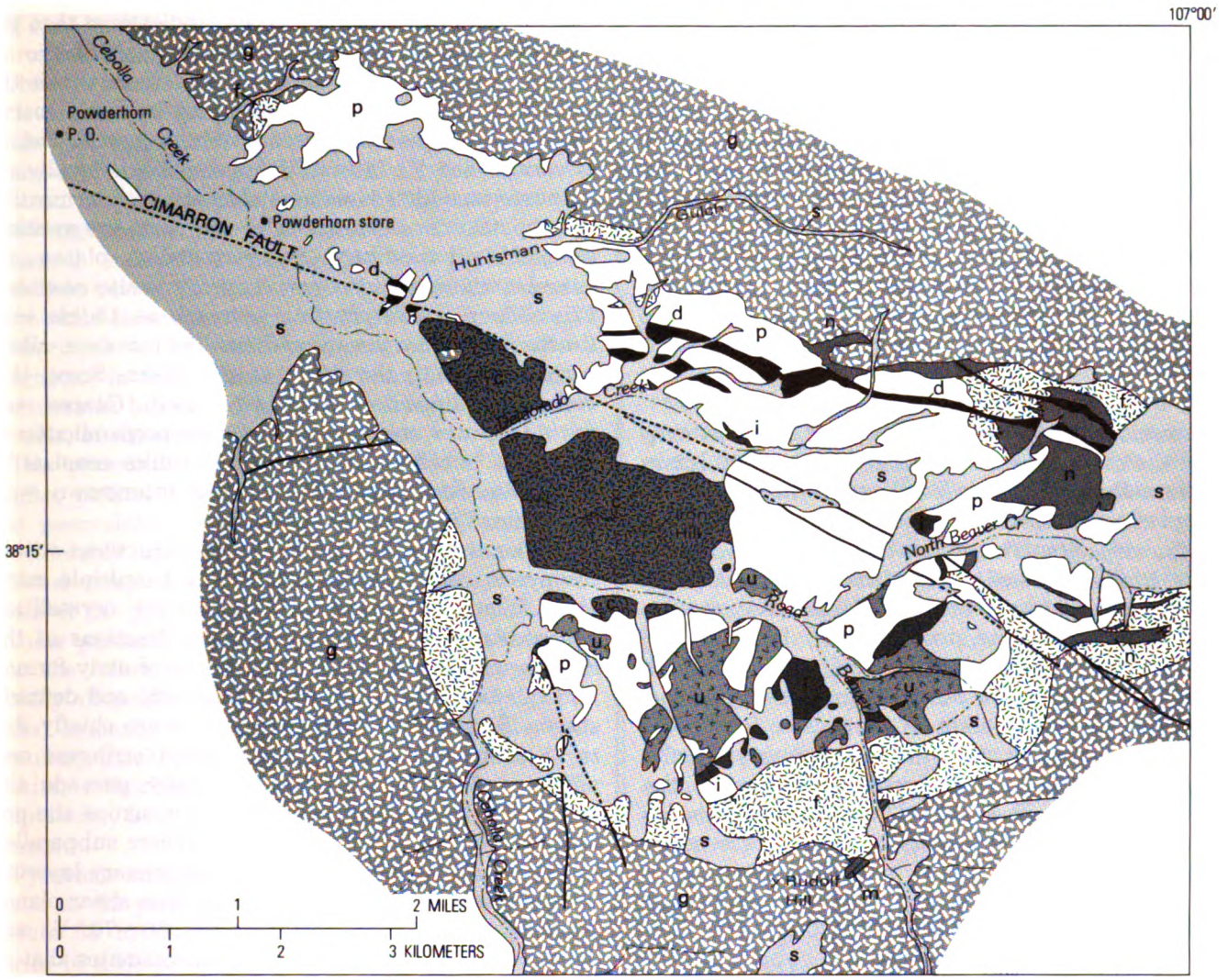
The most abundant fenite in the Powderhorn area is gray, is medium to coarse grained, and contains lenticular aggregates of aegirine-augite that impart a schlieric texture to the fenite (fig. 5). The highly perthitic microcline grains are anhedral to euhedral and commonly have dusty inclusions of ferric oxides and thin, marginal selvages of fine-grained albite. Accessory minerals include calcite, muscovite, apatite, and sphene.

The gradation from granite country rock to fenite is characterized by the following changes: the microcline phenocrysts become grayer rather than red, more perthitic, less euhedral, and the porphyritic texture of the granite becomes less conspicuous. The quartz content diminishes, aegirine-augite replaces the biotite, and a gneissic or schlieric texture may develop or intensify. In advanced stages the fenite probably became rheomorphic locally, as suggested by the schlieric texture. Fracture fillings of blue-green sodic amphiboles, such as riebeckite(?) and richterite, and sodic pyroxenes are common in granite or felsite in places in the fenite zone. These represent a less intense form of fenitization and may be found as much as several kilometers from the complex. Some veinlets of sodic amphibole have slightly anomalous radioactivity due to thorium.

Fenite varies with the type of original country rock. Fenite derived from hornblende gneiss is likely to be rich in sodic pyroxene. Generally the felsitic rocks northwest of the complex, which are siliceous metavolcanic rocks such as metarhyolite, show less conspicious fenitization than other rocks close to margins. Fenite is present, however, in felsite at the northwest end of the complex, for example at a point 1 km north of the Powderhorn store. Here the schistose felsite near the contact with pyroxenite has been albitized, and the normally gray, fine-grained felsite grades into white, medium-grained, equigranular, albite-rich rock containing sparse wispy clots of biotite. The microcline has been albitized, and vein, patch, and string perthite is abundant.

Table 1 illustrates the chemical changes that occur as granite is altered to fenite near the alkalic complex. Two analyses of Powderhorn Granite from the Gateview quadrangle and one from about 1.1 km north of

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EXPLANATION

s	Surficial deposits and volcanic rocks		QUATERNARY AND TERTIARY
d	Diabase and gabbro dikes		ORDOVICIAN OR CAMBRIAN
	Carbonatite	Nepheline syenite	Complex of alkalic rocks of Iron Hill: CAMBRIAN OR UPPER PROTEROZOIC
	Ijolite		
	Uncompahgrite	Melasyenite	
p	Pyroxenite		
f	Fenite		
g	Granite and metamorphic rocks		PROTEROZOIC

Contact, dotted where concealed

Fault, dotted where concealed

FIGURE 4.—Generalized geologic map of the complex of alkalic rocks at Iron Hill, Powderhorn district.

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the pyroxenite contact are representative of the Powderhorn Granite. Development of fenite from the granite involves a loss of silica and a gain of alkalies, iron, and alumina.

Fenite was developed near several of the rock types of the complex and probably formed at different times in several places. It was formed, for example, extensively near pyroxenite and uncompahgrite of the complex, near isolated bodies of carbonatite outside the complex, and near the nepheline syenite stock and dikes at the east end of the complex.

PYROXENITE

Pyroxenite underlies about 70 percent of the outcrop area in the complex of Iron Hill and is about 10 km in maximum dimension. It is locally capped by remnants of Oligocene ash-flow tuffs and Quaternary and Tertiary fan deposits. The pyroxenite weathers readily, forming a terrane of low relief between the surrounding hills of Precambrian granite and felsite and the resistant Iron Hill carbonatite stock.

The pyroxenite has steep, sharp, discordant contacts with the surrounding Precambrian granite and felsite. A few apophyses and dikes of pyroxenite locally extend into the country rocks. Most of the pyroxenite is medium grained and equigranular. Generally the pyroxenite lacks a fine-grained, chilled border facies and shows medium- to coarse-grained texture near the contact with the country rocks, indicating that the wall-rock temperature was close to that of the intrusive magma. Primary internal structures within the pyroxenite consist locally of a strong layering, coarse-grained pyroxene-rich layers alternating with biotite- or vermiculite-rich layers. The pyroxenite is locally cut by numerous dikes and veins consisting of vermiculite and apatite or of magnetite. In some pegmatitic, vermiculite-rich dikes the vermiculite plates are coarsest where the intergrown pyroxene also coarsens. Prismatic diopside crystals as much as 15 cm (centimeters) long in the dikes have their c axes alined perpendicular to the walls of the dikes. Some thin vermiculite-diopside dikes are zoned. Coarse vermiculite plates are near and roughly perpendicular to the walls, whereas the core of the dike consists of decussate, fine-grained vermiculite intergrown with fine-grained diopside and magnetite.

The heterogeneity of the internal structures within the pyroxenite suggests that it was a multiple intrusion. Dilatant fractures in the earlier crystallized pyroxenite were filled with younger fractions of the magma, and considerable replacement of early formed minerals occurred in the later magmatic and deuteric stages. Secondary internal structures are chiefly due to shearing. Light gray, fine grained stringers and veinlets of calcite and biotite locally pervade the pyroxenite along shear zones and cut across the primary structures of the pyroxenite. Where subparallel, the micaceous shear planes resemble primary layering in the pyroxenite (fig. 6). The micaceous shear planes generally strike N. 60°–70° E. and N. 60°–70° W. and dip 70°–80° N. This orientation approximates that of the carbonatite dikes in the complex; hence the shear-

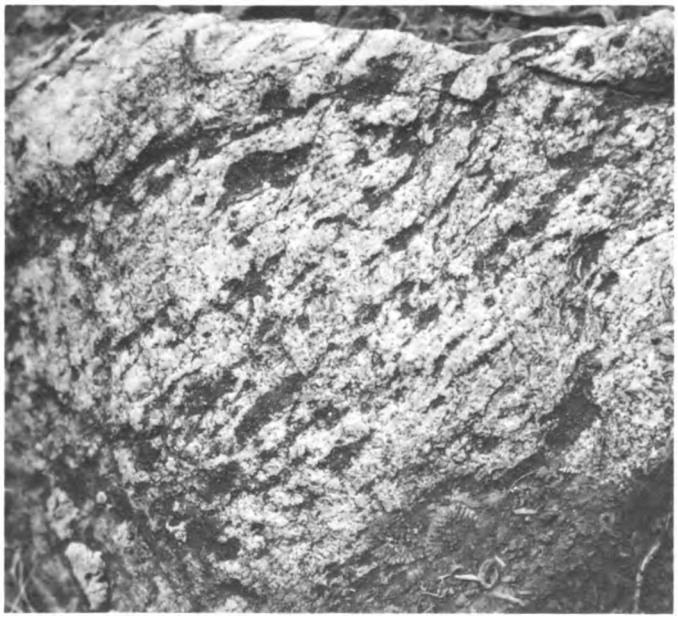


FIGURE 5.—Fenitized granite, with schlieric texture; northeast margin of the complex of Iron Hill. Lenticular clots of aegirine augite are dark. Microcline perthite is the dominant leucocratic mineral. Width of rock shown is about 1 m.



FIGURE 6.—Series of parallel micaceous shear planes in pyroxenite. Many of the micaceous shears follow joints and cut pre-existing structures in the pyroxenite.

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ing may have been related to the period of carbonatite intrusion. This relation also is suggested by the high carbonate content in the shear planes.

Several textural varieties occur in pyroxenite and include (1) pegmatitic, typically developed in coarse-grained clinopyroxene-biotite rock; (2) fine-to coarse-grained hypidiomorphic, shown by pyroxenite that contains euhedral pyroxene, sphene, and melanite with anhedral interstitial magnetite and ilmenite; (3) poikilitic, shown by inclusions of sphene in melanite, perovskite in magnetite, and diopside in melilite; (4) schlieric, shown by lenticular aggregates of melanite or magnetite in the pyroxenite; (5) brecciated, shown by fractures in brecciated pyroxenite filled by nepheline syenite, at the east end of the complex.

The pyroxenite is composed chiefly of diopsidic augite, biotite, magnetite, melanite, sphene, apatite, and perovskite. Proportions of these minerals vary considerably, making it difficult to assess the average mineral composition. About 94 modal analyses were made of the pyroxenite. These values were plotted on volume percent-frequency curves (fig. 7). In thin section the following minerals were observed: pyroxene (chiefly diopsidic augite), magnetite, ilmenite, perovskite, leucoxene, melanite, sphene, phlogopite, vermiculite, biotite, apatite, pyrite, chalcopyrite, pyrrhotite, orthoclase, brown amphibole, chlorite, sodic amphibole, idocrase, calcite, sericite, quartz, and hematite.

Pyroxene and its alteration products make up as much as 92 percent of the rock but commonly constitute 55 to 70 percent by volume. The pyroxene varies in different rocks of the complex; it is mostly augite but includes also diopside, aegirine-augite, and aegirine (Larsen, 1942, p. 47). The pyroxene shows a wide range in crystal size from very fine grained augite to grains of diopside as much as 15 cm long. Much of the augite of the pyroxenite has moderate pleochroism: green to yellowish green; Z to c, 40°–45°; 2 V, 60°–70°; Nx, 1.68–1.72, Ny, 1.69–1.73, Nz, 1.71–1.75. Some grains are replaced along their margins by brown amphibole, biotite (fig. 8*A*), magnetite, chlorite, sodic amphibole, and calcite; such replacement is sporadic and is most intense near carbonatite bodies or dikes. Spectrographic analyses of two diopside samples are shown in table 2.

Amphiboles are present in amounts of as much as 5 percent. The amphibole is quite variable in composition (Larsen, 1942, p. 48–52) but commonly is dark brown to black and has moderate pleochroism light brown to greenish brown. The common variety in the pyroxenite was considered to be hastingsite by Larsen (1942, p. 52). It commonly mantles or replaces the pyroxene.

Melanite is present in many of the thin sections of pyroxenite to a maximum of about 25 percent by volume. The melanite is isotropic and is zoned; lighter brown zones alternate with darker brown. The melanite is anhedral to euhedral and is commonly poikilitic; inclusions of sphene (fig. 8*H*) and perovskite (fig. 8*D*) are common. Some melanite forms thin mantles about pyroxene and magnetite-ilmenite grains. The index of refraction ranges from 1.85 to 1.98 and is commonly about 1.88. The specific gravity is 3.71 ± 0.05. The unit cell is 12.051 ± 0.002 angstroms. Spectrographic analysis of one melanite sample is shown in table 2.

Magnetite and ilmenite are ubiquitous in the pyroxenite as dikes, veins, and segregations, and as discrete grains intergrown with melanite and other silicates. Discrete grains of magnetite and ilmenite constitute as much as 40 percent of the pyroxenite but commonly range from 10 to 15 percent by volume. They are commonly intergrown with each other and with perovskite to form composite grains. Some of the ilmenite forms bladed, exsolution-type intergrowths along the (111) direction in the magnetite. Spectrographic analysis of one magnetite sample from pyroxenite is shown in table 2.

Perovskite is present in about 53 percent of the thin sections of pyroxenite, making up as much as 20 percent by volume. The amounts of perovskite and magnetite tend to correlate with one another and are comparable in most rocks. Larsen (1942, p. 36) estimated the perovskite to make up about 7 percent of the pyroxenite and 6 percent of the entire complex, and magnetite 11 percent of the pyroxenite and 10 percent of the entire complex. The perovskite commonly occurs as euhedral crystals intergrown with magnetite and ilmenite but also occurs as discrete grains. The perovskite is dusky purple, slightly anisotropic, and has complex penetration twinning. Semiquantitative spectrographic analyses of two perovskite samples are shown in table 2.

Leucoxene is present in 28 percent of the thin sections, as an alteration product of perovskite, and composes as much as 18 percent by volume of the pyroxenite.

Sphene is present in about 34 percent of the thin sections of pyroxenite and constitutes a maximum of about 19 percent by volume of the rock. The sphene commonly occurs as relatively coarse, dark, honey-colored euhedral crystals with excellent twinning. The sphene occurs as inclusions in melanite (fig. 8*H*), as discrete grains intergrown with silicates, and as aggregated crystals associated with magnetite. Sphene-bearing pyroxenite is most common on the ridge in the NE¼ sec. 2, T. 46 N., R. 2 W.

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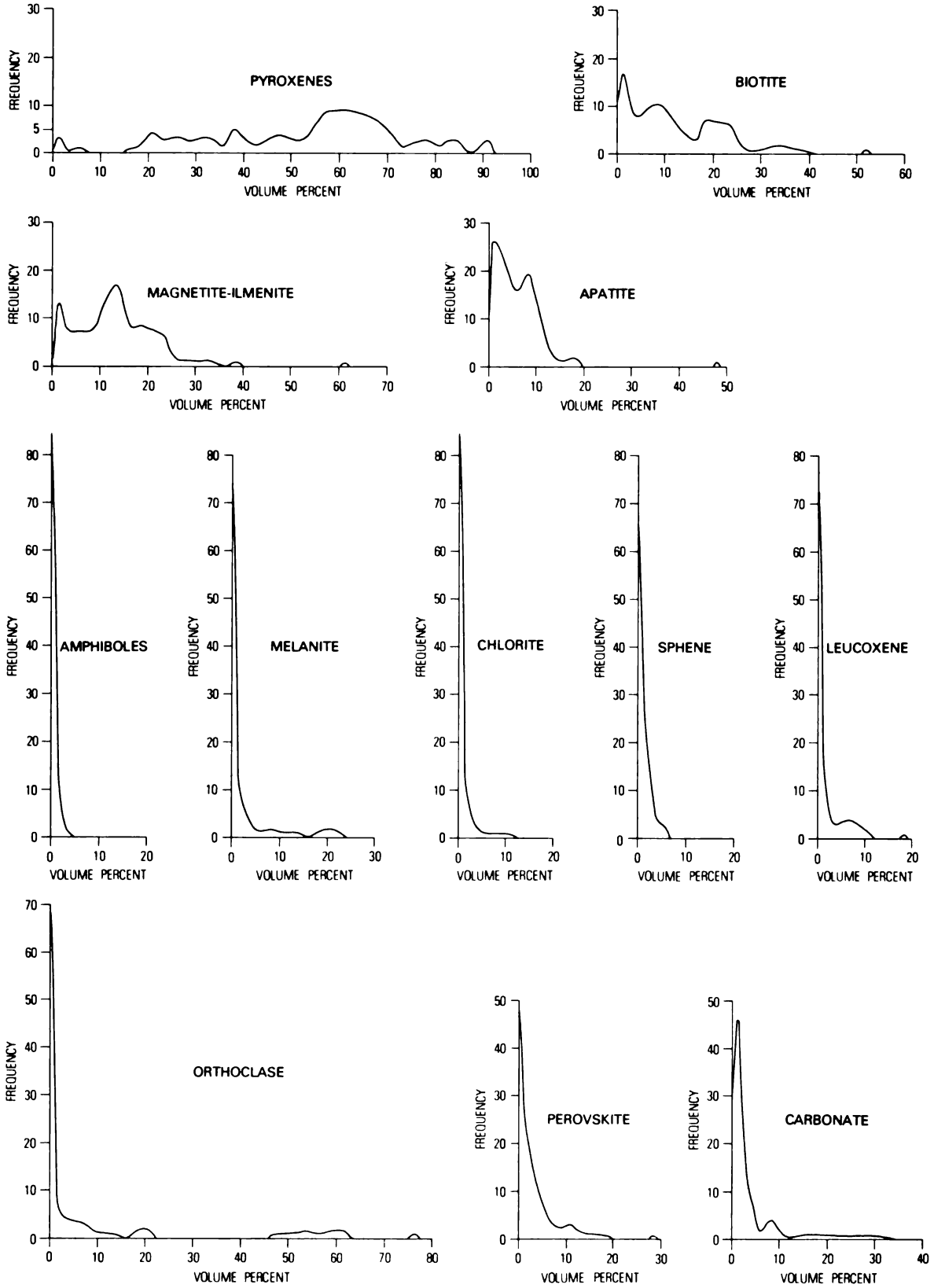


FIGURE 7.—Graphs showing percentages of principal minerals in 94 modal analyses of altered pyroxenite. Frequency is the percentage of thin sections that have the determined volume percent of a mineral. Low values for pyroxenes in some thin sections indicate degree of alteration or presence of variants related to the pyroxenite body but not strictly classifiable as pyroxenite. Minor accessory minerals include pyrite, chalcopyrite, pyrrhotite, sericite, quartz, zoisite, limonite, barite, and idocrase.

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TABLE 2.—*Semiquantitative spectrographic analyses of melanite, diopside, perovskite, and magnetite from pyroxenite, complex of Iron Hill*

[Analysts: J. C. Hamilton, and R. G. Havens. >, greater than; <, less than; leaders (—), analyses did not show any elements in these concentrations]

Sample No.--	P8085a	P301	P8811	P8326	P8326a	P8922
Amount (percent)	Melanite	Diopside	Diopside	Perovskite	Perovskite	Magnetite
>10	Si, Fe, Ca	Si, Fe, Ca	Si, Fe, Mg, Ca	Ca, Ti	Ca, Ti	Fe, Ti
7	---	Mg	---	---	---	---
5	---	---	---	---	---	Mg
3	---	Na	---	Fe, Mg	Fe	---
2	---	---	---	---	---	Ca
1.5	Al	---	---	Ce	Mg, Ce	Al
1	Ti	---	---	---	---	K
.7	Mn	---	Al, Na, Ti	La, Nd	La, Nd	---
.5	---	Mn	---	---	---	---
.3	Mg	Al	---	Si, Al, Nb, Sr	Si, Al, Nb, Sr	Si, Mn
.2	V	---	Mn	---	---	---
.15	Na	---	---	Mn, Pr	Mn, Pr	Zn
.1	Ba, Sr	Ti, Ba	Sr	---	---	Na, V
.07	Y, Zr, Nd	Sr, V	---	Sm	Sm	---
.05	---	---	V	---	---	Ce
.03	---	---	---	V, Y, Zr	V, Y, Zr	La, Nd
.02	La	---	---	---	---	Co
.015	---	---	Zr	Ba	Ba	---
.01	---	Zr	---	---	---	Ba, Nb, Sr
.007	---	Cu	Cu	Cu	Cu	Ni, Zr
.005	---	Co	Ba	---	---	Cu
.003	---	La	Co	Pb	Pb	---
.002	---	---	Pb, Sc	---	---	Mo
.0015	Cr	Sc, Y	Y	Yb	Yb	---
.001	Sc	---	Cr	---	---	---
.0007	Cu	Ni	---	---	---	Cr
.0003	---	Be	---	---	---	---
<.05	Ce	Ce	Ce	---	---	---
<.005	---	---	---	Co, Dy, Er, Eu, Gd	Co, Dy, Er, Eu, Gd	---
<.002	Ga	Ga	Ga	---	---	---

Apatite is ubiquitous in pyroxenite and makes up as much as 48 percent by volume of the rock but is most commonly 5 to 10 percent. The apatite occurs as colorless to pale green prismatic grains, rarely as much as 5 cm long and 7 mm (millimeters) thick, commonly associated with magnetite (fig. 8*B*, *C*), phlogopite, biotite (fig. 8*B*, *C*, *D*), and vermiculite. Apatite inclusions occur in melanite (fig. 8*C*, *D*), orthoclase, pyroxene, and other minerals. The apatite is generally a fluorapatite with N_o 1.63–1.64. Some grains of apatite enclose minute rutile(?) prisms alined along the c axes of the apatite. The P_2O_5 content of the pyroxenite averages 1.3 percent in seven analyses weighted according to the proportions of the types present in the total pyroxenite mass (Larsen, 1942, p. 20).

Biotite ranges from 0 to 52 percent by volume of the pyroxenite and averages about 10 percent. The biotite is fine to coarse grained and is closely associated with magnetite (fig. 8*A*, *B*) in the more homogeneous varieties of pyroxenite. It is moderately to strongly pleochroic, dusky dark brown to pale yellowish brown, Nz 1.63. Vermiculite, a near-surface weathering product of biotite and phlogopite, is sporadically distributed in altered pyroxenite as segregations and in dikelike bodies (fig. 9). The vermiculite occurs in plates as much as 10 cm across and is commonly associated with coarse-grained diopside, apatite, and magnetite. Chlorite is present but not abundant in about 17 percent of the thin sections of pyroxenite, in amounts as much as 12 percent. It commonly replaces biotite or pyroxene and is most abundant where the pyroxenite has been altered adjacent to carbonatite dikes and veinlets.

Orthoclase and microcline are sporadically distributed but uncommon in the pyroxenite. Potassic feldspar is present in about 30 percent of the thin sections from the pyroxenite body, and the maximum amount is about 77 percent. The orthoclase is a late stage mineral that generally forms veins in the pyroxenite. It poikilitically encloses some pyroxene and apatite grains, and it shows varying degrees of alteration to sericite.

Calcite and dolomite generally average 2 to 5 percent by volume of the pyroxenite but may constitute as much as 35 percent. Some of the carbonate minerals that are considered primary are generally coarse grained and occur interstitially between grains of pyroxene, melanite, and magnetite, which show little or no alteration. Ocellar textures were not observed. Secondary carbonate minerals that are probably hydrothermal are generally associated with anastomosing carbonate veins or are adjacent to carbonatite dikes that cut the pyroxenite.

A melanite-orthoclase-apatite rock, characterized by abundant, euhedral melanite crystals, occurs in the pyroxenite in one place at the head of the north fork of Huntsman Gulch (NE¼SW¼, sec. 35, T. 47 N., R. 2 W.). The melanite-orthoclase-apatite rock ranges from coarse to fine grained; in places the dark-brown, zoned melanite crystals are as much as 2 cm across and compose 75 percent of the rock. Between the melanite crystals, interstitial orthoclase makes up about 18 percent of the rock. Pale-green fluorapatite, composing about 5 percent of the rock, is intergrown with orthoclase and fills fractures in the melanite and orthoclase. Pyroxene in amounts of generally 1 percent or less occurs as inclusions in orthoclase and melanite and as clustered aggregates about the melanite grains. The accessory minerals include sphene and magnetite.

Pyroxenite is generally more radioactive than the surrounding Precambrian rocks because of its higher thorium content. It also is more radioactive than the mafic rocks of some other alkalic complexes, such as the mafic-ultramafic rocks in the northeastern part of the Middle Cambrian McClure Mountain Complex in the Wet Mountains. The pyroxenite of the complex of Iron Hill ranges from 0.01 to 0.08 mr/hr for 596 random readings with a scintillation counter, averaging 0.035 or about 1½ times the background of surrounding

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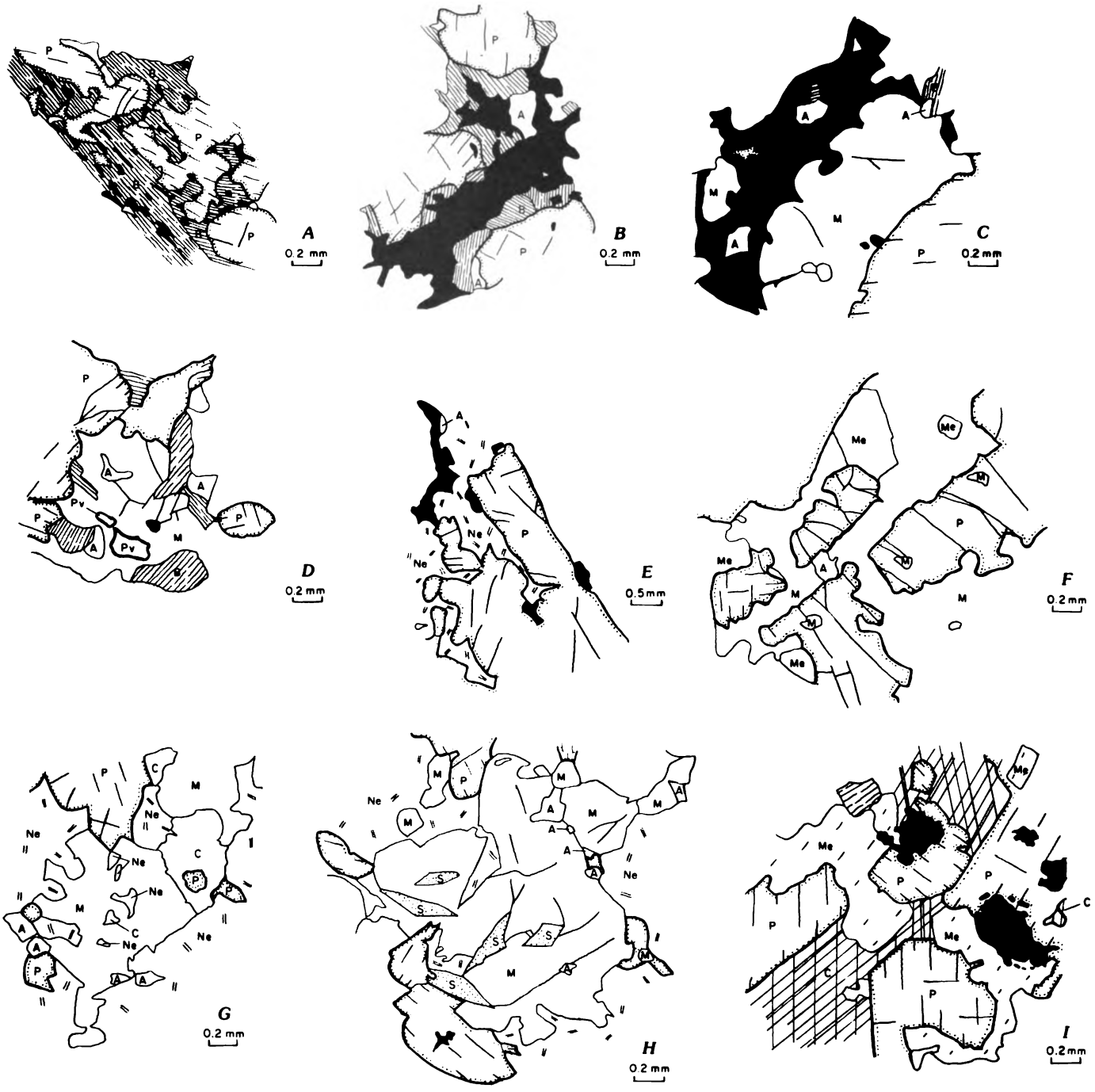


FIGURE 8.—Sketches of textures indicative of paragenetic sequence in pyroxenite, uncompahgrite, and ijolite. Minerals are A, apatite; B, biotite; C, calcite; M, melanite; Me, melilite; Ne, nepheline; P, pyroxene; Pv, perovskite; S, sphene; black areas, magnetite-ilmenite. *A*, pyroxenite; biotite replacing diopside (P); abundant magnetite associated with the biotite. *B*, pyroxenite; biotite reaction rims around magnetite-ilmenite grains. *C*, pyroxenite; cusp-cary textures and veinlets of magnetite-ilmenite in apparently older melanite. *D*, pyroxenite; melanite interstitial and younger than pyroxene. *E*, ijolite; nepheline interstitial to and replacing pyroxene. *F*, uncompahgrite; melanite along intergrain boundaries of pyroxenes; melilite inclusion in melanite. *G*, ijolite; caries of nepheline in melanite; calcite replaces nepheline and pyroxene. *H*, ijolite; nepheline interstitial to melanite; sphene and apatite intergrown with and included in melanite. *I*, uncompahgrite; strongly twinned, primary calcite interstitial to pyroxene and melilite; melilite interstitial to pyroxene.

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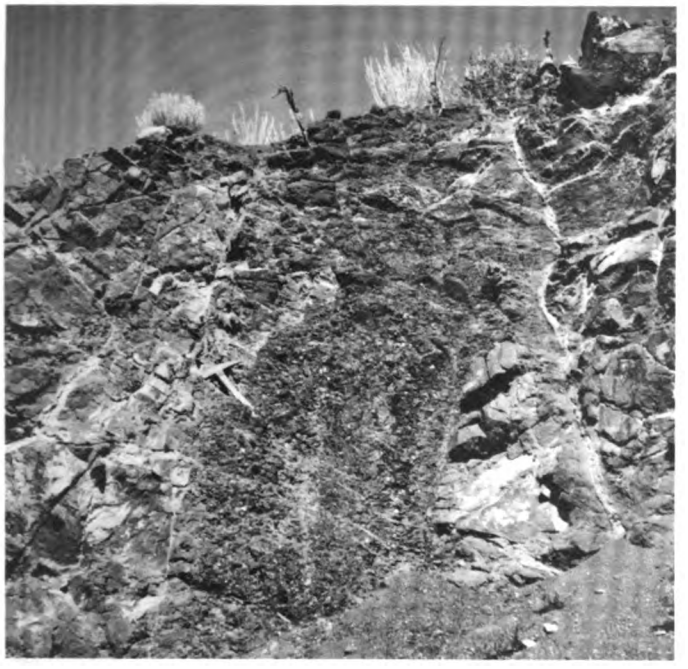


FIGURE 9.—Vermiculite-rich lens or dike in pyroxenite of the complex of Iron Hill. Coarse vermiculite plates are intergrown with sparse amounts of coarse diopside, magnetite, and green apatite.

Precambrian granite. Where carbonatite pervades the pyroxenite as small dikes, seams, and veinlets, the pyroxenite has a higher level of radioactivity. When such areas are added to the previous readings, the combined total of 775 random scintillation-counter readings averages 0.045 mr/hr or about twice the Precambrian granite background.

MAGNETITE-ILMENITE-PEROVSKITE ROCK

Dikelike bodies (fig. 10) and segregations of magnetite-ilmenite-perovskite rock constitute a small part of the complex of Iron Hill; they are most abundant in pyroxenite along a west-northwest-striking belt north of Deldorado Creek and at the northwest end of the complex. Most of the dikes are less than 60 cm thick and are traceable for less than 30 m, but some are 25 to 45 m thick. One of the larger magnetite-ilmenite-perovskite bodies, about 45 m thick, occurs about 300 m southeast of the Powderhorn store and strikes about N 15° E. Its south end is covered by the alluvium of Cebolla Creek valley, and to the north it extends a short distance beneath the overlying Oligocene Sapinero Mesa Tuff.

The magnetite-ilmenite-perovskite rock commonly contains apatite and sparse biotite or phlogopite, augite, and idocrase. The magnetite and ilmenite occur in a granular intergrowth, as seen in polished sections, and some of the magnetite grains contain exsolution blades of ilmenite along (111) directions of the magnetite. The perovskite is very fine grained, generally less than 1 mm across, and occurs in variable amounts in the magnetite-ilmenite-pervoskite rock, locally constituting as much as 50 percent of the rock. The perovskite is commonly present as octahedra and less commonly as anhedral grains, and shows varying degrees of alteration to leucoxene. The perovskite is dusky purple, has complex penetration twinning, is weakly anisotropic, and has a low reflectivity and index of refraction of 2.34. Augite and phlogopite or biotite locally are present in isolated pods in the magnetite-ilmenite-perovskite rock.

A spectrographic analysis by J. C. Hamilton of magnetite from a magnetite-ilmenite-perovskite dike indicated iron as a major constituent, and amounts, in percent, of 3 calcium and titanium (3.9 percent TiO_2 by chemical analysis), 1.5 silicon and aluminum, 1 magnesium and potassium, 0.5 manganese, 0.3 sodium, 0.15 zinc and vanadium (0.14 percent V_2O_5 by chemical analysis), and, in parts per million, 500 strontium, 200



FIGURE 10.—Two subparallel dikes of magnetite-ilmenite-perovskite rock cutting pyroxenite.

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cerium, 150 lanthanum, barium, and neodymium, 100 niobium, 70 copper and cobalt, 50 nickel and zirconium, 30 molybdenum, and 15 chromium.

The radioactivity of the magnetite-ilmenite-perovskite rocks at 128 localities ranges from 0.05 to 0.25 mr/hr, or two to 12 times the background of typical Powderhorn Granite, and is attributable chiefly to thorium substitution for calcium in the perovskite. In two radiochemical analyses the perovskite contains 0.12 and 0.15 percent ThO_2. In addition to thorium, rare earths are present in the perovskite, and niobium is present in amounts of 0.17, 0.2, and 0.7 percent in three semiquantitative spectrographic analyses of perovskite concentrates by E. L. Hufschmidt. Rare earths, like thorium, probably substitute for calcium in the perovskite and apatite, whereas niobium probably substitutes for titanium in the perovskite lattice. Because of the radioactivity of the perovskite and its common association with magnetite and ilmenite, radioactivity and magnetic surveys can give an approximate indication of perovskite concentration in the pyroxenite areas. Ground magnetic traverses show magnetic highs associated with many small magnetite concentrations in the pyroxenite, and belts of magnetic anomalies can be distinguished. The weathering of the magnetite-ilmenite-perovskite rocks and the pyroxenite, uncompahgrite, and ijolite has left numerous residual accumulations of granular magnetite.

Some of the magnetite and perovskite that is disseminated in the pyroxenite evidently coprecipitated with the silicate phases of the pyroxenite. The magnetite-ilmenite-perovskite dikes and segregations, however, formed chiefly after or during the late stages of pyroxenite crystallization from iron-and titanium-enriched fluid. They are cut by nepheline syenite dikes, and at least one carbonatite dike about 12 cm thick cuts the magnetite-ilmenite-perovskite rock, which is reddened adjacent to the dike. Veins of phlogopite, chlorite, and carbonate mineral also cut the magnetite-ilmenite-perovskite rocks in places.

UNCOMPAHGRITE

Uncompahgrite forms irregular bodies and apophyses in the pyroxenite, chiefly south of Road Beaver Creek. The uncompahgrite is a light-gray, white-weathering, medium- to very coarse grained rock (fig. 11) composed of melilite and its alteration products, variable amounts of diopside (about 15 percent), and small amounts of magnetite, apatite, phlogopite, melanite, biotite, calcite, and perovskite. Texturally the uncompahgrite varies from poikilitic to hypidiomorphic granular. The melilite occurs both interstitially between diopside grains (fig. 8*I*) and poikilitically enclosing diopside, magnetite, and apatite. Where the rock is pegmatitic the lustrous, smoky-gray melilite crystals are rarely as large as 50 cm in diameter. In thin section the fresh melilite commonly has a mosaic pattern with subindividuals of different optical orientation. The melilite is commonly uniaxial negative, N_o, 1.63 and N_e, 1.62. The cell dimensions of the tetragonal melilite are: a, 7.796 A; and c, 5.038 A±0.004 A with c/a, 0.646. Using the reference lattice spacings for the synthetic akermanite-gehlenite solid-solution series (Ervin and Osborn, 1949), the melilite contains about 70 percent akermanite. According to Nash (1972, p. 1368–1369), microprobe analyses of several melilite samples indicate they consist of roughly 50 percent sodium melilite and 50 percent akermanite.



FIGURE 11.—Outcrop of uncompahgrite, composed chiefly of melilite and its alteration products (light colored); dark minerals are magnetite, pyroxene, and melanite.

In thin section, myrmekitic intergrowths of melanite and melilite are present but rare. Melanite also forms thin marginal selvages about diopside (fig. 12) in some varieties of the uncompahgrite. Biotite commonly mantles the magnetite.

The radioactivity of the uncompahgrite is generally high. Random readings with scintillation counter at 93 places showed a range of 0.01–0.1 mr/hr, averaging 0.033 or about 1½ times the background of surrounding Precambrian granite.

IJOLITE

Several small bodies of ijolite in the pyroxenite and uncompahgrite form an arcuate zone suggestive of a ring dike. Contacts of ijolite with pyroxenite are commonly gradational. The ijolite is a mafic nepheline-pyroxene rock (fig. 8*E*, *G*, *H*) consisting of nepheline,

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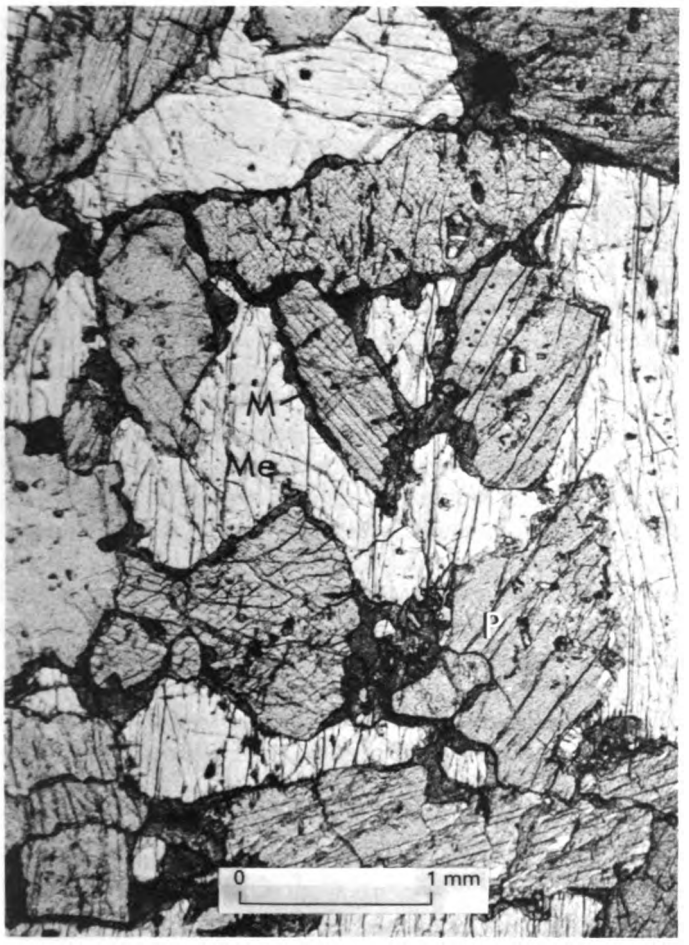


FIGURE 12.—Uncompahgrite, complex of Iron Hill. Melanite (M) rims on diopside (P) with interstitial melilite (Me).

aegirine-augite, melanite, and accessory calcite, apatite, magnetite, ilmenite, and sphene. The nepheline content varies, and locally the ijolite grades into urtite containing about 80 percent nepheline. In most of the rock the nepheline is altered to very fine-grained sericite, cancrinite, natrolite, and analcite, chiefly along fractures and grain boundaries of the nepheline. The ijolite is fine to coarse grained and hypidiomorphic granular in texture. Locally, small pyroxene-rich layers 2 to 5 cm thick alternate with nepheline-rich layers. This layering is discontinuous and does not appear to reflect the shape of the intrusion.

The radioactivity readings at 25 points in ijolite range from 0.01 to 0.06 mr/hr, averaging 0.033 or nearly the same as pyroxenite, uncompahgrite, and nepheline syenite. High radioactivity was found on the hill of ijolite just north of North Beaver Creek, 2.3 km east of Iron Hill, but is associated mainly with small carbonatite dikes that cut ijolite and pyroxenite near their contact.

NEPHELINE SYENITE

Nepheline syenite intricately intrudes granite, fenite, and pyroxenite near the eastern end of the complex of Iron Hill. In the vicinity of the nepheline syenite stock and dikes, the fenite aureole is more extensively developed than at other places along the north side of the complex. Immediately south of the nepheline syenite stock, the pyroxenite is brecciated and veined by nepheline syenite to form a mixed pyroxenite-syenite rock. The nepheline syenite is cut by carbonatite and diabase dikes.

The nepheline syenite is light gray, weathers pinkish gray, and is medium to coarse grained. Orthoclase microperthite laths compose about 75 percent of the nepheline syenite and locally impart a strong trachytic texture to the rock (fig. 13). Aegirine-augite, melanite, nepheline, and the alteration products of nepheline



FIGURE 13.—Nepheline syenite, complex of Iron Hill, composed chiefly of lath-shaped microcline perthite (white). Melanite (black), aegirine-augite, and altered nepheline occur interstitially to the microcline laths.

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make up much of the remainder of the rock. Accessory minerals include magnetite, sphene, apatite, muscovite, calcite, and an unidentified zeolite. The orthoclase microperthite is Carlsbad twinned and shows string and patch perthite. The aegirine-augite, composing about 5 percent of the rock, is deep bluish green and weakly pleochroic; Z c, 14° and Nz, 1.76; Nx, 1.73; 2V is large. In some of the nepheline syenite dikes, aegirine-augite crystals are oriented perpendicular to the walls of the dike. Nepheline is largely altered to a mixture of muscovite, calcite, natrolite, and cancrinite. The nepheline and its alteration products are interstitial to the orthoclase and make up about 10 percent of the rock. The brown melanite is weakly zoned and commonly has inclusions of aegirine-augite, sphene, and apatite.

The nepheline syenite has a radioactivity that averages about 1½ times the background reading of the Precambrian granite surrounding the complex. A range of 0.02-0.08 mr/hr, averaging 0.035, was obtained in 39 random readings in nepheline syenite with a scintillation counter.

At the east end of the complex, near the head of North Beaver Creek in sections 7 and 12, the pyroxenite is brecciated and cut by thin fracture fillings and small dikelike bodies of nepheline syenite (fig. 14) to form a mixed rock. Nepheline syenite forms a small, irregular stock north of this area of mixed rock and was probably forcibly intruded into the pyroxenite to cause brecciation and some mixing. The pyroxenite part of the mixed rock consists chiefly of anhedral pyroxene, zoned melanite, sphene, apatite, and sparse amounts of altered melilite. The nepheline syenite is leucocratic and consists chiefly of Carlsbad-twinned orthoclase and minor amounts of melanite, aegirine-augite, and altered nepheline.

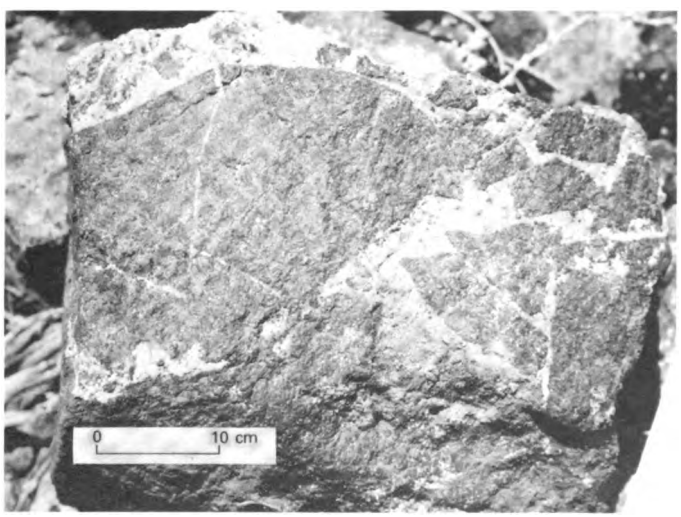


FIGURE 14.—Mixed pyroxenite-syenite rock from the complex of Iron Hill. The pyroxenite is brecciated, and syenite fills the fractures and locally replaces pyroxenite.

CARBONATITE OF IRON HILL

Dolomitic carbonatite (rauhaugite) is the youngest member in the intrusive series of the alkalic complex of Iron Hill. It occurs as a stock or plug and as numerous dikes both within and outside the complex. The carbonatite stock is roughly elliptical in outcrop, the long axis striking N. 35° W., and its 4-km² area is about 12 percent of the outcrop area of the entire complex.

Carbonatite resists weathering more than the surrounding alkalic rocks of the complex, and Iron Hill rises about 300 m above the floor of the valley of Cebolla Creek or Road Beaver Creek (fig. 15) and above the adjacent pyroxenite. The resistance of the carbonatite to weathering is attributable to the semiarid climate; the jaspery, ferruginous capping or mantle that formed locally on the dolomite by weathering processes; and the cementation of fractures and other zones of weakness in the carbonatite by secondary quartz, carbonates, and iron and manganese oxides.

The carbonatite is generally well exposed except for the more highly timbered east- and north-facing slopes where talus has been stabilized and has accumulated to thicknesses of 6 m or more. Contacts of the carbonatite stock with the Precambrian country rocks and the alkalic intrusives of the complex are poorly exposed. The best exposures of the contact are near the north end of the stock, along the south side of Huntsman Gulch and along the east side of the valley of Cebolla Creek about midway between Deldorado Creek and Huntsman Gulch. The felsite and granite at these localities are generally sheared, reddened, and fenitized, and the contacts are sharp and discordant. South of Road Beaver Creek the carbonatite-pyroxenite contact is partly concealed by alluvium. Locally along the southern margin of the carbonatite stock there are



FIGURE 15.—Iron Hill from the southeast.

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phlogopite-rich zones in the carbonatite that may represent xenoliths of pyroxenite that have been partly replaced by carbonate minerals and phlogopite owing to reaction with the carbonatitic fluid. Near the carbonatite, the pyroxenite is highly veined by carbonates, and the pyroxene is highly altered to biotite, chlorite, or sodic amphiboles in a mixed zone abont 100–300 m thick of thin carbonatite and pyroxenite layers (Temple and Grogan, 1965, p. 681–682).

The west margin of the complex is largely buried by the alluvium of Cebolla Creek, but at one place on the hillside east of Cebolla Creek the contact is with sheared granite and felsite, indicating that the carbonatite stock of Iron Hill was emplaced between pyroxenite on the northeast and southeast and sheared granite and felsite on the southwest. Numerous radial dikes of carbonatite, which cut all the other rock types of the complex, are lithologically similar to the carbonatite stock of Iron Hill and increase in number toward the stock, indicating a genetic relationship.

The carbonatite stock is complex in its internal structures and textural features. These structures and textures include grain sizes ranging from fine to pegmatitic; varying degrees of development of foliation, drag folds, and shear zones; and the presence of partially replaced xenoliths of other rocks near the margins of the body. Most of the internal structures are considered primary, formed during or shortly after intrusion; examples are the foliation surfaces or shear planes along which apatite, phlogopite, or barite have been deposited. Iron or manganese oxides and jasper deposited along joints or other structural features, however, are considered secondary.

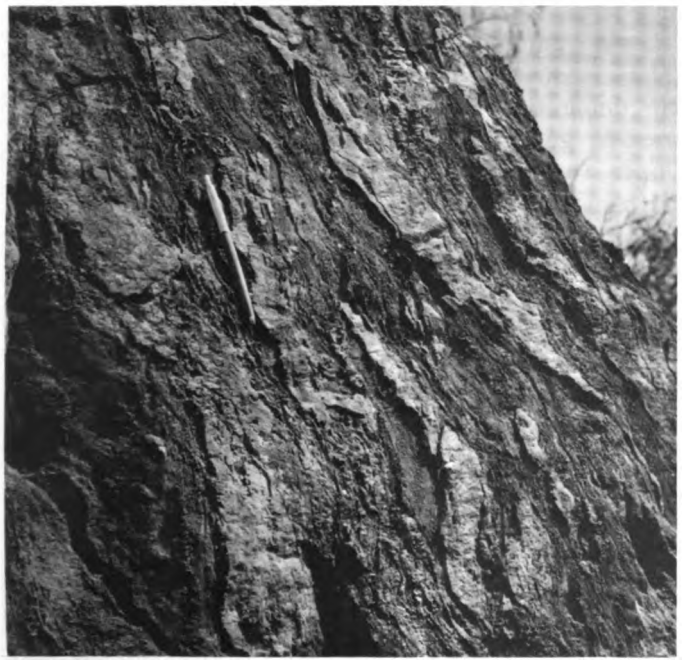


FIGURE 16.—Strongly foliated carbonatite from Iron Hill. Phlogopite and apatite-rich lenticles are locally jasperized and are etched into relief by weathering.

The foliation in the carbonatite is well developed, and dips are generally steep to vertical. The foliation is commonly imparted by the presence of apatite-rich seams or segregations, phlogopite-biotite seams, or by strained and deformed carbonate crystals (fig. 16). Between Road Beaver and Deldorado Creeks the foliation surfaces strike dominantly northeast, but a few strike north-northwest along the western margin of the carbonatite. North of Deldorado Creek the strike of the foliation is dominantly northwest but is locally northeast. The pattern of foliation is generally arcuate and convex to the northeast. At the south end of the carbonatite stock the foliation is discordant to the inferred contact of the carbonatite.

Folds within the carbonatite are not common. At one place along Deldorado Creek, a well-exposed 8-cm layer of coarsely crystalline carbonatite is folded into a small drag fold, indicating some deformation after emplacement.

Texturally the carbonatite is heterogeneous; coarse-grained and pegmatitic varieties are in sharp contact with finer grained carbonatite. In some places this sharp change in texture can be attributed to dikes of coarsely crystalline carbonatite cutting finer textured carbonatite. Generally the coarse-grained carbonatite contains less silicate minerals, sulfides, apatite, and pyrochlore than the finer textured varieties.

Mineralogically, the carbonatite stock consists chiefly of ankeritic dolomite and minor amounts of apatite, phlogopite, biotite, barite, pyrite, calcite, magnetite, ilmenite, pyrochlore, and sodic amphiboles. Hematite, manganese oxide, and reddish-brown chalcedonic jasper or quartz occur as secondary minerals. Goethite and hematite pseudomorphs after pyrite and magnetite are common. Pyrolusite forms coatings on joints or vugs in the carbonatite. Apatite, which makes up a few percent to locally 10 percent or more of the carbonatite, is generally a colorless or pale green fluorapatite with N_o, 1.63–1.64. The apatite varies from stubby prisms to strongly oriented prismatic aggregates that tend to be localized along foliation surfaces. Much of the apatite appears to be late, as veins of apatite cut the carbonatite or are localized along intergranular or cleavage surfaces of the dolomite crystals. Eight chemical analyses of carbonatite showed a P_2O_5 content from 0.13 to 4.34 percent (Hedlund and Olson, 1980, table 8A). Spectrographic analyses of two apatite concentrates from carbonatite are shown in table 3.

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TABLE 3.—*Semiquantitative spectographic, X-ray fluorescent, fluorometric, and radiochemical analyses of pyrochlore and apatite from carbonatite, Iron Hill*

[Analysts: J. C. Hamilton, N. M. Conklin, E. J. Fennelly, and A. P. Marranzino. >, greater than; <, less than; leaders (—), analyses did not show any elements in these concentrations]

Sample No.-----	IH469	PH-c-1v	PH-c-v
Amount (percent)	Pyrochlore	Apatite	Apatite
>10	Nb(33)[1]	Ca, P	Ca, P
7	Ca	---	---
3	---	Mg	Nb
2	Ce	---	---
1.5	[2]Th(1.32), Fe, Ti	---	Si, Mg
1	Na, Ba, Sr	---	---
.7	---	Si, Fe, Ce, Nb	Fe, Na, Ce, Sr
.5	Fe, Zr	---	---
.3	Si, La, Nd	Na, Ti, Sr, Nd	Ti, La, Nd
.15	Pr, Sm	Al, Mn, La	Mn
.07	Mg, Pb, [1]Ta(0.085)	---	---
.05	Mn, [3]U(0.055)	---	---
.03	Eu	Ba	Ba, Y
.015	---	Zr, Eu, Dy, Gd, Y	Zr, Eu, Dy, Gd
.007	---	Er	Er
.005	Ag	---	---
<.005	---	V	V
.003	---	Cu, Ho	Pb, Cu, Ho, Sn
.0015	---	Cr, Ni, Sn, Yb	Ni, Yb
.0007	Be	Co	Cr, Co

[1]By X-ray fluorescent analysis.
[2]By radiochemical analysis.
[3]By fluorometric analysis.

Pyrite occurs widely in the carbonatite as disseminated cubes as much as 1.2 cm across, rare pyritohedrons, and as vein fillings. Some of the pyrite grains are poikilitic, containing inclusions of apatite. Other pyrite grains are fractured and veined by secondary quartz.

Barite is disseminated in minor amounts throughout the carbonatite stock and more abundantly in the carbonatite dikes. The barite grains are commonly interstitial to the dolomite, but some barite occurs as veinlets, generally having formed later than the dolomite. In nine analyses of carbonatite the barium content ranges from 0.037 to 4.9 percent; the strontium content ranges from 0.007 to 0.02 percent (Hedlund and Olson, 1980, table 8B).

Phlogopite and sparse amounts of bluish-green hydrobiotite(?) are disseminated sporadically within the carbonatite and also occur as lenticular aggregates. Along the south edge of the carbonatite the phlogopite and associated carbonates locally appear to replace a pyroxenite xenolith. Much of the phlogopite shows strong reverse pleochroism, one or two outer zones showing reversed positions for the pleochroic colors from that of the cores. Generally the cores of the phlogopite plates have a stronger birefringence than the margins. Around individual dolomite inclusions in the phlogopite there is a similar zone of reversed pleochroism. The N_z value of the cores is 1.613, whereas that of the marginal resorption zones is 1.614 (Larsen, 1942, p. 53). Such reversed pleochroism has been noted in the dark mica of other alkalic rock complexes and was first described at Iron Hill by Larsen (1942, p. 53). The reversed pleochroism of the dark mica was discussed by Nash (1972, p. 1365), who found that the significant chemical change between the two types of micas is the decrease of aluminum in the margin with a concomitant increase of iron.

Magnetite is present in small amounts in the carbonatite stock and is partly replaced by hematite to form martite. In one place at the southwest margin of the stock, 2- to 5-cm layers of carbonatite containing abundant magnetite octahedra alternate with biotitic carbonatite in an outcrop area of only a few square meters. The magnetite grains are as much as 1 cm across and are intergrown with ilmenite.

A computation of the normative carbonate minerals from five analyses (Hedlund and Olson, 1980, table 8A) of carbonatite from the Iron Hill stock indicates that the $CaCO_3/MgCO_3$ ratio is 1.32 whereas the ratio for pure dolomite is 1.185. This difference is thought to reflect the substitution of $FeCO_3$ and $MnCO_3$ for $MgCO_3$ in the dolomite lattice, which is also indicated by the presence of ferric and manganese oxides along the margins and cleavage surfaces of individual dolomite grains in the weathered carbonatite. About 30 X-ray diffraction patterns of carbonatite material from the Iron Hill stock showed predominantly dolomite with very little calcite or other carbonates.

Green, pink, purple, lemon-yellow, and gray pyrochlore is disseminated in minor amounts throughout the dolomitic stock and dikes as tiny octahedral crystals generally less than 3 mm across (fig. 17). Under the microscope the pyrochlore shows faint anisotropism, and the crystals are weakly zoned. Numerous opaque inclusions related to certain zones are present in some of the grains. The unit cell of the pyrochlore is 10.435 ± 0.002 A. The pyrochlore is radioactive but not metamict. The radioactivity varies considerably. In one analyzed sample the pyrochlore contains 0.055 percent uranium, 1.32 percent thorium, 33 percent niobium, and only 0.085 percent tantalum (table 3). Microprobe analyses of two pyrochlore samples by Nash (1972, p. 1369) indicate 62.5 and 65.4 percent Nb_2O_5, 2.36 and 0.31 percent ThO_2, and negligible UO_2.

The dolomitic carbonatite (rauhaugite) stock of Iron Hill is generally more radioactive than other igneous rocks of the complex but is less radioactive than the carbonatite dikes. Field readings of radioactivity in places exceed 0.1 mr/hr or five times the background of nearby Powderhorn Granite, and samples mostly range from 3 to 63 ppm thorium. An average of 173 gamma ray spectrometric measurements made by

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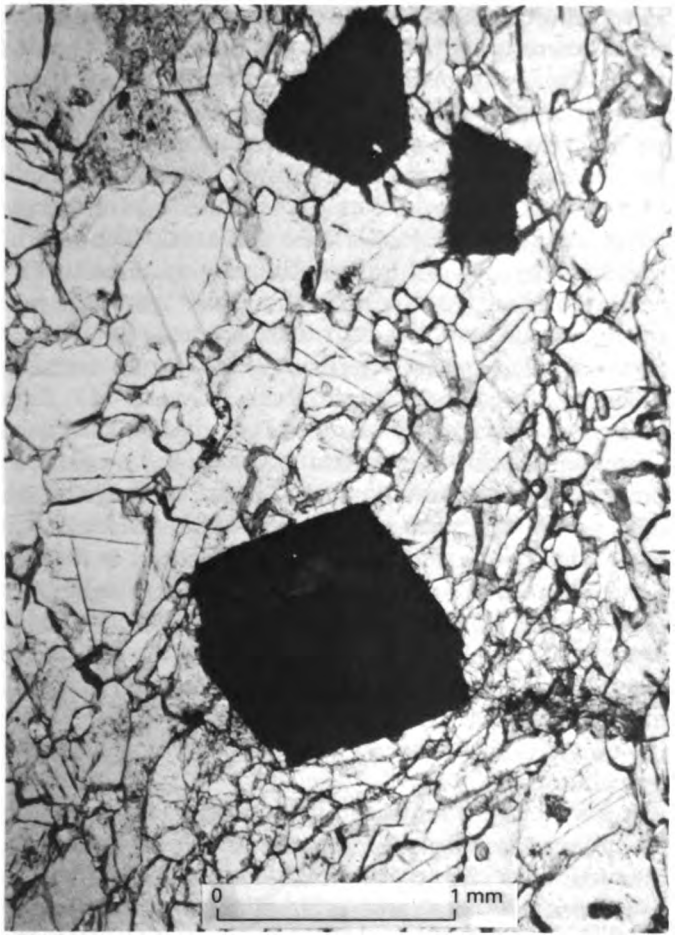


FIGURE 17.—Pyrochlore and apatite in carbonatite, Iron Hill. Euhedral to subhedral pyrochlore (black) in dolomitic carbonatite containing abundant small, rounded grains (high relief) of accessory apatite.

Armbrustmacher (1980; Armbrustmacher and Brownfield, 1979) was 41 ppm ThO_2. The radioactivity of the carbonatite stock is probably due chiefly to thorium-bearing pyrochlore (table 3), although other thorium-bearing minerals may also be present.

CARBONATITE DIKES

Several hundred carbonatite dikes were mapped in pyroxenite and other rocks in and just outside of the complex. They are distributed radially about the carbonatite stock of Iron Hill although there is a great preponderance of N. 45°–85° W. strikes parallel to the long dimension of the complex. Dikes and plugs of carbonatite cut all other alkalic rocks of the complex and also less commonly cut the surrounding Precambrian rocks. The dike orientations show a similarity to the directions of strong jointing in the adjacent alkalic rocks. This similarity suggests that fractures that developed in the complex prior to or during the intrusion of the Iron Hill carbonatite stock influenced the orientation of the dikes.

The carbonatite dikes commonly have sharp contacts with the wall rocks. Many are about 1 to 1.5 m thick, but some are as much as 45 m thick. Most are fairly homogeneous, but layered and brecciated dikes are also present. The layering parallels the walls of some dikes and is commonly due to the alternation of sideritic layers with calcitic or dolomitic layers or to the alternation of silicated carbonatite layers with nonsilicated carbonatite. The siderite-rich layers commonly weather dark gray or black, which sharply contrasts with the light brown color of the weathered dolomite. The silicated carbonatite commonly contains abundant phlogopite and biotite, and some of the micas are altered to a bluish-green hydrobiotite(?). The brecciated texture of some carbonatite dikes is probably related to the forcible injection of carbonatitic fluids. Some fragments consist of partially replaced pyroxenite inclusions characterized by carbonate pseudomorphs after pyroxene and thin selvages of phlogopite about the margins of the former pyroxene crystal.

Carbonatite dikes also cut the Precambrian rocks outside the complex of Iron Hill. At one locality, about 0.5 km N. 46° W. from the Powderhorn Post Office, there are inclusions of felsite within a carbonatite dike. Foliation or flow structure within the carbonatite wraps about the largest inclusion (figs. 18 and 19), which suggests flowage about the inclusion after the carbonatite was largely crystallized.

Most carbonatite dikes in Precambrian wall rocks are within 1.2 km of the margin of the pyroxenite of the

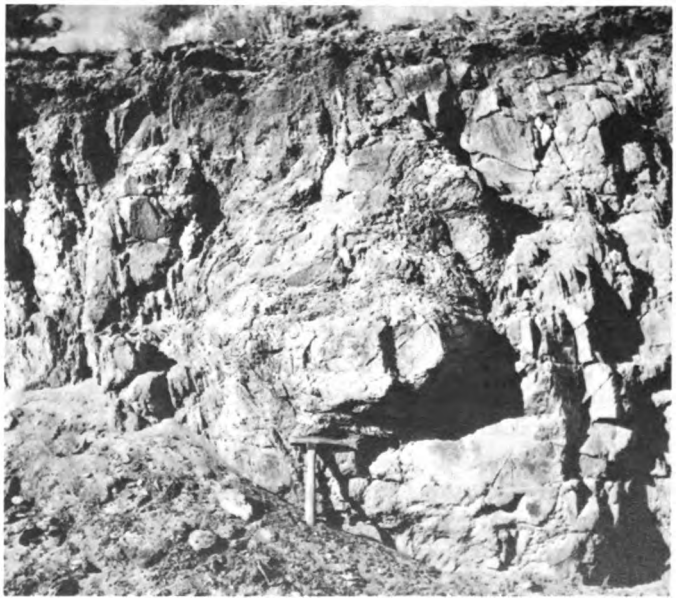


FIGURE 18.—Inclusion of felsite in carbonatite dike. Position of inclusion and foliation in carbonatite are shown in figure 19.

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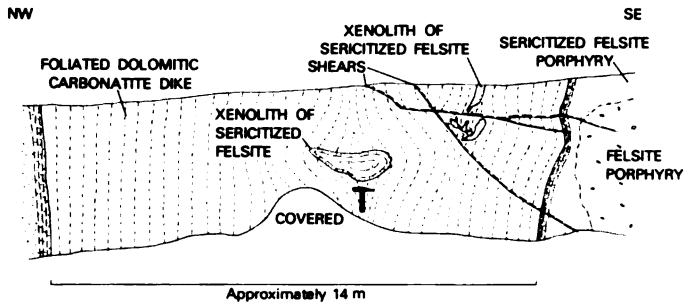


FIGURE 19.—Sketch of felsite xenoliths in carbonatite dike (fig. 18), 0.5 km west-northwest of Powderhorn Post Office. Foliae within the carbonatite wrap about the xenoliths.

complex of Iron Hill. In the Gateview quadrangle, only two small carbonatite dikes were found, 0.3 and 1.2 m thick. Of these the most distant carbonatite dike from the complex of Iron Hill was noted on the east side of Goose Creek near the old Dubois mine. It is calcitic and coarse grained, contains accessory orthoclase and pyrite, and is slightly radioactive. A semiquantitative spectrographic analysis of the carbonatite (Hedlund and Olson, 1980, table 3, G2630) shows a suite of elements similar to dikes in or near the complex.

In decreasing order of abundance, the minerals in the carbonatite dikes are dolomite, calcite, siderite, biotite, phlogopite, pyrite, barite, apatite, orthoclase, pyrochlore, monazite, chalcopyrite, sphalerite, galena, fluorite, synchysite, and parisite. The siderite occurs in a few dikes as distinct layers or segregations. The micas are disseminated and also form lenticular aggregates. The sulfide grains, especially pyrite, tend to be in clusters and are most abundant in the sideritic carbonatite dikes. Pyrite is the most common sulfide and is in cubes that show varying degrees of oxidation to goethite or hematite. The sphalerite contains exsolution blebs of chalcopyrite, and a few chalcopyrite grains occur outside the sphalerite host. Galena is present in very minor amounts associated with the sphalerite.

Eight partial chemical and 14 spectrographic analyses of carbonatite samples from various occurrences, tabulated by Hedlund and Olson (1980, table 8A–8B), show a $CaCO_3/MgCO_3$ ratio ranging from 1.79 to 5.18. These include samples from eight localities in the carbonatite stock of Iron Hill, three from carbonatite dikes, and one from a small pluglike body. The three carbonatite dike samples are atypical variants of carbonatite containing calcite, siderite, and $FeCO_3$-rich dolomite. They differ considerably in composition from the other samples, having higher $FeCO_3$ content and lower $MgCO_3$ content, and this difference probably indicates fractionation of the carbonatitic fluids.

The carbonatite dikes are the most radioactive rocks in the alkalic complex of Iron Hill. Of 214 dikes in the Powderhorn quadrangle, for example, 132 have radioactivities ranging from 0.05 to 0.79 mr/hr or two to 35 times the background of typical Powderhorn Granite. Thirty samples of the dikes contain about 30 to 3,200 ppm thorium. The more radioactive dikes commonly have a crudely layered structure, weather chocolate brown, and contain dolomite, siderite, calcite, barite, pyrite, apatite, hydrobiotite(?), and small amounts of monazite, pyrochlore, bastnaesite, and synchysite. The weakly radioactive carbonatite dikes are relatively homogeneous, weather buff or rusty yellow, and contain dolomite, calcite, apatite, pyrite, hydrobiotite(?), and sparse barite.

No mineral in which thorium is a major constituent is known in the carbonatite dikes. Some thorium is present in the sparse monazite, which contains about 0.15 percent thorium, and in pyrochlore. Monazite is more common in the carbonatite dikes than in the carbonatite stock. The monazite is very fine grained, reddish brown, resinous, and where identified is mostly associated with barite. Rare earths in the carbonatites range from a trace to about 1.5 percent and occur in monazite, in the fluocarbonates synchysite and bastnaesite, and also substitute for calcium in apatite and pyrochlore.

A few localities for uncommon minerals identified by X-ray are: bastnaesite and synchysite in a carbonatite dike just east of Iron Hill in SE¼, sec. 12, T. 46 N., R. 2 W.; monazite in a carbonatite dike from N½, sec. 11, T. 46 N., R. 1½ W., and rutile from one in SE¼, sec. 12, T. 46 N., R. 1½ W.; galena in a carbonatite dike in N½, sec. 11, T. 46 N., R. 1½ W., and sphalerite in a carbonatite dike in SE¼, sec. 12, T. 46 N., R. 2 W.

IGNEOUS ROCKS AND VEINS OUTSIDE THE COMPLEX OF IRON HILL

TRACHYTE PORPHYRY DIKES

Pink or red, porphyritic to aphanitic trachyte dikes occur chiefly in the Powderhorn and Rudolph Hill quadrangles. They cut most Precambrian rocks but do not cut any alkalic rocks, diabase, or rocks younger than the Precambrian. The trachyte dikes are commonly 1.5 to 3 m thick but may be as much as 25 m thick. The dikes show some branching and sharp changes in strike, follow the local joint pattern, and are clearly structurally controlled. Many have low dips toward the complex of Iron Hill.

The trachyte is composed of scattered, alined, stubby to lath-shaped red orthoclase phenocrysts commonly 3 to 5 mm long set in a trachytic, aphanitic groundmass consisting of alined orthoclase microlites. The orthoclase contains abundant dusty ferric oxide inclusions. Some of the trachyte dikes are autobrec-

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ciated, as angular fragments of coarsely textured trachyte occur in a fine-grained trachytic groundmass. The fragments generally consist of anhedral aggregates of coarse-grained orthoclase. Granite fragments have been observed as rare inclusions in some of the trachyte. Mafic minerals are rare in the trachyte and are chiefly interstitial iron oxides.

Some of the trachyte dikes are radioactive, generally about four times that (0.02 mr/hr) of nearby felsic metavolcanics; readings of 0.04 to 0.08 mr/hr are common. Most trachyte dikes are relatively low grade; hence, their contribution to ThO_2 resources (table 5) is small. The trachyte dikes resemble some of the thorite veins in that they contain abundant red orthoclase, but the igneous origin of the dikes is indicated by the porphyritic texture. Locally the wall rocks are replaced by orthoclase in a thin zone resembling fenite along the margins of some of the trachyte dikes. Freshly broken trachyte dike rock commonly has a fetid odor resembling garlic that also characterizes the thorium veins and some fenite.

FINE-GRAINED GRANITE

Fine-grained granite of uncertain age occurs within 2 km south and west of the complex of Iron Hill and is anomalously radioactive. The granite occurs in numerous dikelike bodies, irregular small plutons about 150–750 m wide, and two larger bodies 3–4 km by 600–1,200 m. The granite is mostly fine grained, some is medium grained, and locally it is porphyritic. It is composed of microcline microperthite, quartz, plagioclase, and biotite. Associated with the granite near Road Beaver Creek are two bodies of melasyenite 60–120 m wide.

The fine-grained granite was considered by Hunter (1925) to be a variety of the Powderhorn Granite of Precambrian age. On the geologic maps of the Rudolph Hill (Olson, 1974) and Powderhorn (Hedlund and Olson, 1975) quadrangles, however, it is shown as a separate Precambrian(?) unit. It appears relatively little deformed in comparison with adjoining gneissic coarse-grained Powderhorn Granite. The granite is fenitized in places, as shown by feldspathization and blue-green amphibole veinlets, and it is cut by carbonatite, lamprophyre, and thorium veins that are probably related to the complex of Iron Hill. Some of the fine-grained granite occurs in crudely arcuate plutons around the southern part of the complex of Iron Hill. These forms, which are suggestive of ring dikes, together with the locally high radioactivity, may indicate a genetic link between fine-grained granite bodies and the complex.

The fine-grained body west of Cebolla Creek near the north edge of the Rudolph Hill quadrangle (Olson, 1974) is at least 4 km long but is covered by Tertiary welded tuff at the south end. This granite is cut by many thorium-bearing veins but is not in itself highly radioactive where studied. Another granite pluton that crosses Cebolla Creek 5 km south of Powderhorn is about 3.3 km long and 1.2 km wide. It is strongly fenitized near the complex of Iron Hill. The radioactivity has been measured in only a few places. In the roadcut at the south end of the valley of Cebolla Creek, measurements with a gamma-ray spectrometer in slightly fenitized granite suggest a possible range of 40 to nearly 300 ppm ThO_2. This thorium-beering part of the granite, which may average on the order of 100 ppm ThO_2, appears at least 120 m wide, but it has not been delineated and may be only a minor part of the entire granite body.

The fine-grained granite bodies on the canyon sides of Road Beaver Creek, 0.5 to 2 km south of the margin of the complex of Iron Hill, have been explored by numerous bulldozer trenches. These granites are in secs. 24 and 25, T. 46 N., R. 1½ W., and are shown on the map of the Rudolph Hill quadrangle (Olson, 1974). In this area five granite bodies are 300 to 1,000 m in exposed length and 100 to 500 m wide. Within the plutons the radioactivity of the fine-grained granite varies considerably. Samples from some of the more radioactive, small, local concentrations exceed 1,000 ppm in thorium. Considerable parts of the granites, however, have thorium contents on the order of 100 to 225 ppm, as judged by eight samples and hundreds of field gamma-ray spectrometer readings. The eight samples of the granite analyzed in the laboratory range from 32 to 281 ppm thorium and average 115.1 ppm (131 ppm ThO_2). Areas that have the most radioactivity are typically characterized by red and yellow-brown limonitic staining and by narrow, black, siliceous, rusty-weathering veinlets along joint or shear planes, suggesting transport and deposition of thorium by iron-bearing solutions.

A spectrographic analysis of a sample of the granite containing abundant limonite veinlets showed, in weight percent, 0.7 phosphorus, manganese, barium, cerium, and lanthanum; 0.3 neodymium and strontium; 0.07 titanium and praseodymium; 0.03 gadolinium, samarium, and yttrium; 0.015 niobium, lead, and vanadium; and 0.007 dysprosium and zirconium. Thorium was determined radiochemically to be 0.08 percent in this sample. The rare earths are unusually abundant, particularly the light or cerium group of rare earths; the niobium content is also anomalous relative to other granites in the area but is not as high as in some of the alkalic rocks.

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THORITE VEINS

About 250 thorium veins are shown on geologic quadrangle maps of the Powderhorn district and are illustrated on figure 20. Of these about 200 are in the Gateview (Olson and Hedlund, 1973) and Powderhorn (Hedlund and Olson, 1975) quadrangles and the remainder in the Rudolph Hill (Olson, 1974) and Carpenter Ridge (Hedlund and Olson, 1973) quadrangles.

The thorite veins contain the highest grade thorium concentrations in the district. The ThO_2 content of the thorite veins ranges from less than 0.01 percent to as much as 4.9 percent in high-grade samples. The ThO_2 content is generally less than 1 percent, however, and is only 0.05 to 0.1 percent in many of the veins examined in the district. The veins are as much as 1 km in length, but most cannot be traced for more than 100 m. They range in thickness from 1 cm or less to 5 m but most are less than 0.6 m thick. They commonly occur in steeply dipping shear or breccia zones within the Precambrian rocks. In one of the principal areas, near the north end of Huntsman Mesa, 3 to 8 km north of the complex of Iron Hill, most of the veins strike slightly north of east. In the Sapinero Mesa-Goose Creek area, in the northwestern part of the district, however, the veins generally strike northwest. The veins are generally discordant to the foliation of hornblende schist, felsite, quartz-biotite schist, granite, syenite, and other rocks, the type of host rock apparently having little effect on the localization of the veins.

The thorium veins are composed of thorite, white to smoky quartz, jasper, pink potassic feldspar, calcite, specular and earthy hematite, goethite, magnetite, barite, and pyrite, and sporadic galena, chalcopyrite, sphalerite, synchysite, apatite, fluorite, biotite, sodic amphibole, rutile, monazite, vanadinite, and bastnaesite.

Pink to red, poorly twinned orthoclase is common in the veins as large laths or as clustered subhedral to anhedral grains. Minor amounts of microcline are present in some veins. Adjacent to most veins the wall rocks have been partly replaced by pink to red orthoclase, and this fenitelike replacement is conspicuous where hornblende schist wall rocks are reddened and altered to biotitic and chloritic rocks alongside the veins. Some breccia fragments of feldspathized wall rocks have been incorporated in the veins. Thin feldspathic fracture fillings 1 to 3 cm thick in Precambrian melasyenite or other rocks are locally radioactive, giving readings of as much as 0.06 mr/hr or three times background.

The chief thorium mineral is thorite, much of which is partly metamict but shows an X-ray pattern for thorite (or thorogummite). The thorite is very fine grained and is intergrown with ferric oxides. A thorium-bearing phosphate with rhabdophanelike structure has been found locally in the district (Dooley and Hathaway, 1961, p. 340). Monazite has been found in several veins.

Pink to white barite is present in small amounts in many of the thorium veins and is a major constituent in a few of them. At one locality on the ridge west of Goose Creek a discontinuous vein of massive, light pink barite 60 cm thick cuts the hornblende schist. Barite occurs in at least two generations in relation to orthoclase. Some early formed barite is intergrown with quartz. Other grains occur as inclusions in orthoclase and are partly replaced by orthoclase. Most barite appears later than the potassium feldspar, however, and veinlets of barite in orthoclase are common, especially along cleavage surfaces in the feldspar. The pink to red color of some barite may to be due to minute inclusions of ferric oxide observed in thin section.

Orthoclase and quartz formed early as primary minerals in the veins. Quartz occurs in at least two generations. The early quartz, some of which is smoky, occurs as anhedral and euhedral grains intergrown with orthoclase or barite. The later generation of quartz is commonly chalcedonic quartz that occurs as pseudomorphs after orthoclase or other silicates and as vug fillings. Much of this secondary quartz is associated with ferric oxides.

Carbonate minerals, chiefly calcite or ankeritic dolomite, are present in many of the thorite veins. They commonly appear to replace silicates, quartz, and barite, and are typically associated with ferric oxides. In some veins the carbonate minerals are present as pseudomorphs after prismatic silicate minerals. Coarsely crystalline calcite fills vugs in some veins. Some rare carbonate veinlets have been observed to cut the jasper and are believed to have formed at the time of Oligocene volcanism, unlike the bulk of the carbonate, which is of probable Cambrian or late Precambrian age.

Apatite and fluorite are present as rare constituents in a few veins. Apatite was noted as minute inclusions in orthoclase.

Specular hematite is not abundant but is conspicuous in some veins. It forms veinlets that cut early formed orthoclase, barite, and quartz. Earthy hematite and goethite are weathering products of iron-bearing minerals such as pyrite and specular hematite. In some small areas, numerous dispersed, thin, red hematitic or limonitic feldspathized veinlets and seams occur, locally causing a radioactivity of two to three times background. Red staining due to hematite accompanies some thorium mineralization and has encouraged some exploration of red rocks, but hematitic veinlets are also abundant in some places that are low in radioactivity.

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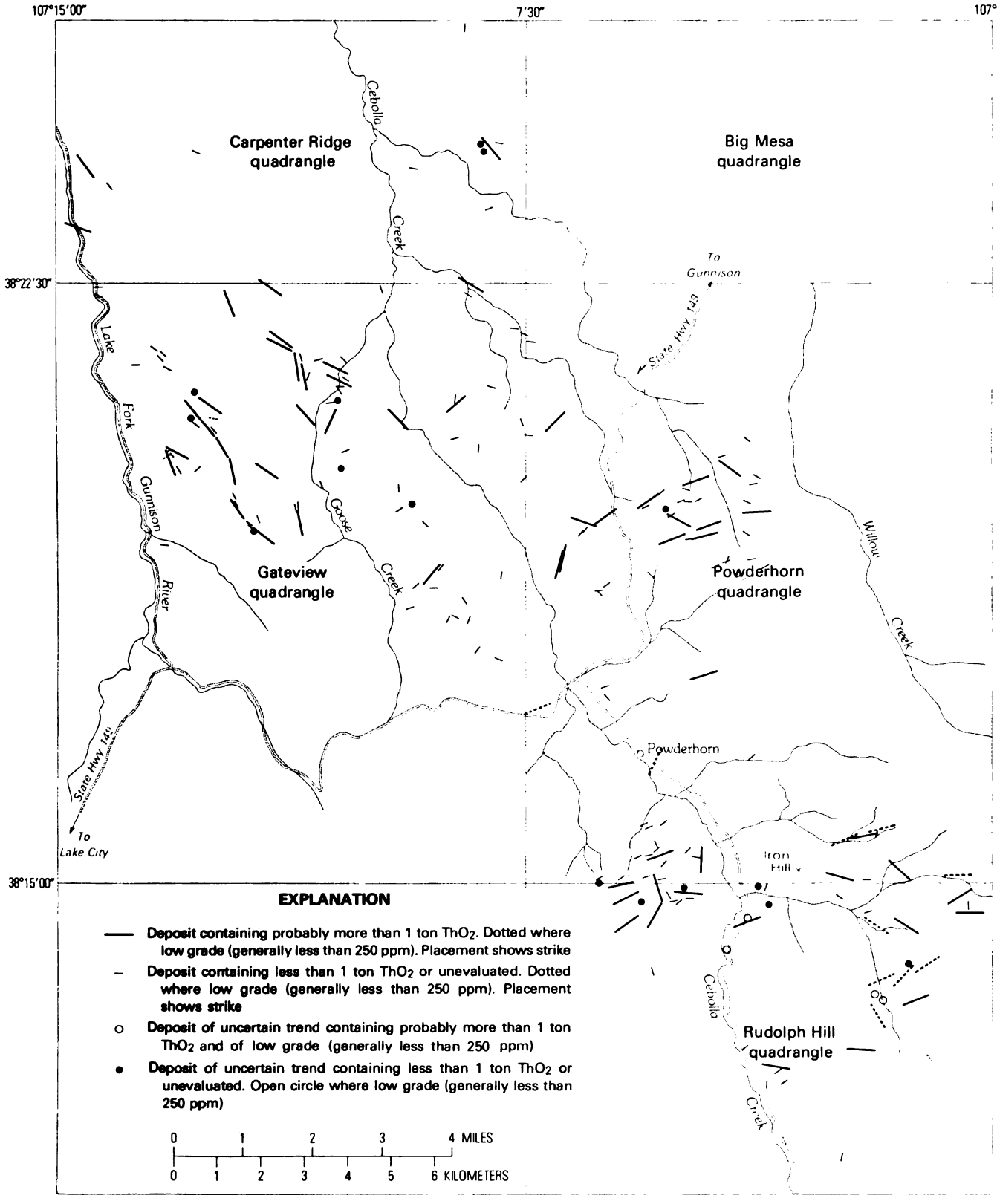


FIGURE 20.—Map showing distribution and trend of thorium deposits, Powderhorn district.

The thorite is so fine grained and sparsely distributed that its place in the paragenetic sequence is difficult to establish. Because thorite is commonly associated with earthy hematite and goethite, it may

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be about the same age as the specular hematite and formed fairly late in the paragenetic sequence.

Biotite and sodic amphiboles are sparsely distributed in many thorite veins. Some of the biotite represents detached parts of biotitic wall rocks or formed by replacement of hornblendic wall-rock fragments. The sodic amphiboles, which have nearly parallel extinction and high birefringence, occur as radiating clusters or as aggregates of prisms in the veins.

Pyrite, chalcopyrite, galena, and minor sphalerite are present but not generally abundant in the thorite veins. The sulfide minerals are generally later and occur as veinlets filling fractures in orthoclase and barite and occupying interstices between barite grains. The chalcopyrite forms exsolution blebs in sphalerite and also occurs as separate grains. Galena is intergrown with sphalerite.

Varicolored jasper, mostly yellowish to reddish brown, has generally replaced the carbonate gangue of the veins on Sapinero Mesa and similar areas where the veins were near the surface that was covered by volcanic rocks in Oligocene time. The jasper is found to at least 30 m below the mesa level, and oxidation extends locally to at least 60-m depth. Within the deep canyons of the Lake Fork of the Gunnison River and Cebolla Creek, however, jasperization and oxidation have been less intense, and unaltered sulfide minerals persist in a few of the veins.

The veins have been altered and leached during several cycles. An earlier one is related to the surface on which the Junction Creek Sandstone of Jurassic age was deposited and may have resulted in some shallow jasperization of carbonate mineral in the vein. Later periods of oxidation and leaching are related to the Oligocene surface, on which the volcanic rocks were deposited, and also to the present cycle of weathering. Most of the silicification is probably a hydrothermal replacement localized near the ancient Oligocene surface just beneath the base of the flows.

The effects of oxidation, leaching, and jasperization of the veins on the original thorium content are not clearly known because few workings have penetrated more than 10 m in depth. Jasperized veins on the mesa surfaces show radioactivity in both jasper and carbonate gangue. Locally the jasper forms pseudomorphic replacements of the carbonate and has apparently retained some dispersed thorium. Oxidation, leaching, and jasperization might result in some enrichment or diminution in grade of near-surface vein material, but without sufficient subsurface data on possible changes in grade, the surface exposures are assumed to be reasonably representative of the grade of vein material at depth.

The following minerals probably occur in numerous other veins, but a few localities are listed. Bastnaesite and synchysite, for instance, have been identified by X-ray analysis from a vein in SE¼ sec. 2, T. 47 N., R. 3 W. Bastnaesite occurs in a vein near Razor Creek in NW¼ sec. 27, T. 47 N., R. 3 E. and synchysite in a vein in NE¼ sec. 20, T. 47 N., R. 2 W. Monazite and vanadinite were identified in a vein in NW¼ sec. 2, T. 47 N., R. 3 W., and rutile in veins in SE¼ sec. 2, T. 47 N., R. 3 W., and NW¼ sec. 8, T. 47 N., R. 2 W. Galena and cerussite were found in a vein in NE¼ sec. 20, T. 47 N., R. 2 W., and galena in veins in NW¼ and SE¼ sec. 2, T. 47 N., R. 3 W.

DIABASE AND GABBRO DIKES

Several northwest-trending gabbro and diabase dikes occur in a narrow zone that cuts across the alkalic-rock complex. Similar dikes also occur in Precambrian rock elsewhere in the district. The gabbro and diabase dikes have the lowest radioactivity of the major rock types in the immediate area. They are as much as 150 m thick and 6.7 km in length. They are predominantly tholeiitic, but within the complex, one nepheline-bearing gabbro also occurs (Larsen, 1942, p. 28–29).

Most of the dikes have a diabasic texture and are referred to as diabase in this discussion. The diabase dikes are black, commonly weather rusty brown, locally show spheroidal weathering, and are medium grained with an intergranular hypidiomorphic to subophitic texture. Augite grains partly mantle the labradorite (An_{52-55}) laths and partly occupy interstices between labradorite grains. The labradorite laths show oscillatory-normal zoning. The augite commonly is very pale purple and has only faint pleochroism; Z c, 47°; Nz, 1.715; Nx, 1.690; $2V = 65° \pm 5°$. Augite constitutes about 25 percent by volume of the diabase; some augite grains show incipient alteration to chlorite and biotite. Magnetite and ilmenite(?) occur as aggregated granules and skeletal crystals that may be as much as 25 percent of the diabase.

Three diabase dikes crop out in the complex of Iron Hill and are clearly younger than the rocks of the complex. These dikes resemble in mineralogy, texture, and attitude the other, genetically related, west-northwest-striking diabase dikes of the region, but they are generally thicker, coarser grained, and locally have a strong trachytic texture. The dikes cut pyroxenite, nepheline syenite, and fenite of the complex but were not observed to cut the carbonatite stock. Carbonatite dikes and veins do not cut the diabase.

The diabase is generally coarse grained, ophitic, and locally trachytic in the thicker parts of the dikes.

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Where the dikes are thinner the texture changes to fine to medium grained and a hypidiomorphic-granular texture is common. Marginal chill zones, present along some of the diabase dikes, are porphyritic with phenocrysts of labradorite and augite. The groundmass makes up about 80 percent of the rock and consists of plagioclase microlites, minute grains of augite, and magnetite. Some of the augite phenocrysts have mantles of a later generation of pyroxene.

FAULTS

The Powderhorn district is on the south side of the Gunnison uplift, a northwest-trending block roughly 30 by 100 km in size, composed of Precambrian rocks overlain by Mesozoic sediments, which was elevated in Laramide time. Within the district, Precambrian metamorphic foliation and elongate metamorphic and igneous bodies trend mostly northeast to east. This older trend is cut by many younger Precambrian faults, shear zones, and Cambrian or Ordovician diabase dikes that strike predominantly northwest (Olson and others, 1977). Many of the thorium veins are in northwest-trending faults and shear zones, although trends vary in different parts of the district.

The Gunnison uplift is bounded on the south by the northwest-trending Cimarron fault, which passes near Powderhorn (fig. 4). The concealed Cimarron fault is indicated by a series of six springs and travertine spring deposits that strike approximately N. 70 W. along the southwest side of Cebolla Creek at Powderhorn. Six travertine spring deposits can be mapped, although they coalesce in places. Movement on the Cimarron fault took place in Laramide time, although earlier movement may have occurred in late Precambrian time (Olson and others, 1977). Northwest of Powderhorn, the position of the fault at the beginning of Oligocene volcanism was marked by a long, southward-facing scarp, against which the early, intermediate-composition flows and volcanic breccias accumulated. Diabase dikes of Cambrian or Ordovician age parallel the Cimarron fault zone and are thus related to it in trend, but considerable postdike fault movement has occurred as some dikes are cut by the fault.

The Cimarron fault cuts the complex of Iron Hill and can be traced northwestward along strike at least 65 km. Southeast of the complex the fault is buried by Oligocene volcanic rocks. For most of its length, the fault shows a displacement, northeast side upthrown, of 1,000 m or more. Much of this movement occurred after the Mancos Shale of Cretaceous age was deposited. A fault block of Junction Creek Sandstone of Jurassic age crops out along the east side of Powderhorn Creek about 500 m south of the old Powderhorn Post Office. This sandstone block is slightly tilted and the base is at an elevation of about 2,470 m. This elevation represents a difference of about 520 m from the elevation of the Junction Creek Sandstone outcrop on Huntsman Mesa to the northeast and 400 m difference from the outcrop of sandstone on Tolvar Peak. The different levels are accounted for by fault displacement, but the fault or faults are concealed.

Where the fault cuts the eastern part of the complex of Iron Hill, the displacement, as shown by offset of the Junction Creek Sandstone of Jurassic age, is very small and is probably no more than 50–120 m, with the south side upthrown. Post-Jurassic movement was greater, however, on a different but probably related east-trending fault that crosses the south end of Huntsman Mesa and cuts granite just north of the complex, because the Junction Creek Sandstone is displaced about 250 to 300 m in this area, south side upthrown. These displacements of south side up relative to north differ from the relative displacements of north side upthrown, shown along the Cimarron fault from Powderhorn northwestward. They are, however, compatible with the sense of displacement interpreted to have occurred between the two sides of the fault within the complex of Iron Hill. The varying amounts of displacement at different points along the Cimarron fault are taken up in part by northeast- to east-trending cross faults that divide the major blocks into smaller ones of varying throw.

Erosion since the fault movement has exposed two different levels in the alkalic stock. Whereas pyroxenite and ijolite are found on both sides of the fault, the block southwest of the fault contains the Iron Hill carbonatite body, a greater number of thin carbonatite dikes, and abundant uncompahgrite; it also has a generally wider fenite zone. The block northeast of the fault contains an abundance of nepheline syenite and magnetite-ilmenite-perovskite dikes, far more than found in the southwest block. The carbonatite and uncompahgrite southwest of the fault may well represent the deeper seated rocks, as interpreted by Temple and Grogan (1965, p. 689), in which case the fault movement at this point was the reverse of that farther northwest.

To account for the great difference between rocks of the complex of Iron Hill on the two sides of the fault, more displacement would seem to be required than is shown by the offset of Mesozoic sediments. Some pre-Jurassic movement is therefore inferred. The Cimarron fault was apparently active over a long period of time and may also have been active in late Precambrian time and even have been a factor in the localization

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of the complex of Iron Hill (Olson and others, 1977, p. 686).

RESOURCES[1] OF THORIUM AND ASSOCIATED ELEMENTS

THORIUM

Thorium exploration has been aimed at finding thorium concentrations of several tenths of a percent ThO_2 or more, such as are found in the thorite veins, in a few of the carbonatite dikes, and in some trachyte. Lower grade material, containing 0.02 to 0.1 percent ThO_2, adds significantly to total thorium resources in the district (Olson and Overstreet, 1964, p. 23) and includes, in addition to the thorite veins, concentrations in carbonatite, magnetite-ilmenite-perovskite bodies, trachyte porphyry dikes, and small plutons of granite.

Thorium deposits shown on maps in the Powderhorn district number at least 261, which are concentrated in the Gateview and Powderhorn quadrangles. The majority of the deposits are small or low in grade; hence, it is only a minority that contribute significantly to total resources. Sixty-seven localities, including most of the richer deposits, were examined with the aid of a portable four-channel gamma-ray spectrometer, and 66 samples were collected. An additional 35 samples were collected from outside the Powderhorn district to provide additional data for calibration purposes. The samples were analyzed by C. M. Bunker and C. A. Bush for thorium, RaeU, and potassium by laboratory gamma-ray spectrometry. The field gamma-ray spectrometer readings were calibrated with the sample analyses from the same stations by a linear regression analysis to provide a rough guide to approximate thorium content for field readings on unsampled veins.

The gamma-ray spectrometer readings, coupled with sample analytical data, provide a reasonable approximation of the thorium content of the surficial part of the deposit. Projecting these readings to infer reserves at depth requires consideration of the amount of cover that might locally obscure the vein; the dispersal of radioactive elements by slope wash, soil creep, or leaching; the possible enrichment of surficial material by selective removal of constituents other than thorium; as well as the known variability of thorium mineralization from place to place, particularly in the thorite veins. Generally, the surficial thorium content was assumed to be fairly representative of that at depth except where radioactivity may be obscured by ground cover.

[1]The mining industry presently uses the inch-pound system of measurements.

For indicated ore, a depth was assumed of from one-third to one times the surface length of the vein, to a maximum of 1,000 feet; for inferred ore a maximum depth of 1½ to two times the surface length was used, to a maximum of 3,000 feet.

Resource estimates of thorium veins in the Powderhorn district, compiled as cumulative totals, according to average grade of deposit, are shown in table 4, and the minimum amount of ThO_2 estimated to be present at various grades is shown graphically on figure 21. As the curve is for minimum amounts, the actual amount of ThO_2 present is somewhere to the right of the curve shown, perhaps two or three times as much.

In order to relate the reserves to the cost of producing the thorium, a method of cost analysis was designed by the U.S. Bureau of Mines for mine and mill costs to recover thorium from thorite vein deposits (Lemons and Coppa, 1979). The cost analyses were made on the veins that contain more than 35,000 short tons of indicated and inferred reserves. In testing the Powderhorn veins by cost analysis, it was found that ThO_2 might be obtained for less than $30 per lb (pound) in those having a grade of at least 0.15 percent ThO_2 (1,500 ppm). Very few, if any, veins averaging less than 700 ppm ThO_2 could be expected to produce ThO_2 at a

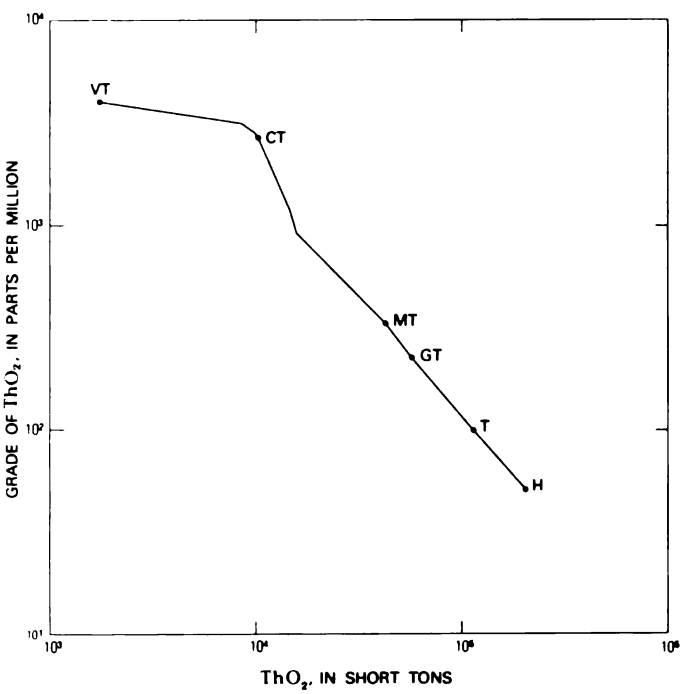


FIGURE 21.—Curve showing cumulative total of ThO_2 resources at various grades. Thorite veins (tonnages at several grades of ThO_2 are plotted along VT; minimum of 100 ppm plotted at T). Carbonatite dikes (several grades along CT); magnetite-perovskite rock (MT); thorium-rich granite (GT); carbonatite stock of Iron Hill (H).

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TABLE 4.—*ThO_2 resources in the Powderhorn district*

[Values in short tons. Figures for carbonatite dikes are for only 10 dikes that have been estimated. The total, including other carbonatite dikes, is probably at least several times these amounts. Undiscovered resources in all categories are not included, but they would probably at least double the resource estimates for veins, carbonatite dikes, and granite. The total number of veins estimated is 56, and the number of carbonatite dikes is actually 10. These numbers are less than the total shown because several deposits are repeated by dividing them into more than one grade category. >, greater than]

	Grade range (ppm)	Reserves				Cumulative totals			
		No. of deposits	Indicated	Inferred	Total	No. of deposits	Indicated	Inferred	Total
Veins.....	>1,000	13	1,800	7,900	9,700	13	1,800	7,900	9,700
Carbonatite dikes..	>1,000	2	100	200	300	15	1,900	8,100	10,000
Veins.....	500-1,000	15	200	600	800	30	2,100	8,700	10,800
Carbonatite dikes..	500-1,000	1	500	1,000	1,500	31	2,600	9,700	12,300
Veins.....	100-500	38	1,400	3,800	5,200	69	4,000	13,500	17,500
Carbonatite dikes..	100-500	9	700	1,000	1,700	78	4,700	14,500	19,200
Magnetite-perovskite rock.....	±250	1?	None	25,000	25,000	79	4,700	39,500	44,200
Granite.....	>100	5	5,000	9,000	14,000	84	9,700	48,500	58,200
Carbonatite stock..	41	1	30,000	110,000	140,000	85	39,700	158,500	198,200

cost of less than $50 per lb. The approximate cost categories of the reserves (in veins only) are shown in table 5.

Indicated and inferred reserves in veins exceeding 500 ppm ThO_2 in average grade amount to 10,400 short tons, as shown in the two columns on the left side of the table. Of this total, 95 percent is estimated to be in only seven deposits. The other four categories on the right side of the table are made up of veins having more than 700 ppm ThO_2.

The larger and higher grade veins, which contain a large proportion of the resources estimated in veins exceeding 500 ppm ThO_2 (table 4), are found in secs. 14, 15, 16, and 20, T. 47 N., R. 2 W.; secs. 1, 2, 4, 9, 10, 15, and 24, T. 47 N., R. 3 W.; sec. 34, T. 48 N., R. 3 W.; sec. 10, T. 47 N., R. 2 W.; and secs. 23 and 24, T. 46 N., R. 1½ W. These areas are shown on figure 22 along with the areas of thorium-bearing magnetite-perovskite rock, carbonatite, and thorium-bearing granite.

Five deposits account for the 9,300 tons of reserves estimated, from the U.S. Bureau of Mines cost analysis, to be producible at less than $30 per lb. The $30–50 per lb category is made up of ore in seven deposits.

Analysis of production costs likely for low-grade disseminated deposits minable by open-cut methods suggests that some of the lower grade thorium resources in the fine-grained granite plutons near Powderhorn may be minable by open-cut methods at a cost on the order of $50–100 per lb ThO_2 (Staatz and others, 1979). Parts of the granites of four small areas in the Road Beaver Creek drainage and one near Cebolla Creek, judging from gamma-ray spectrometer measurements and eight sample analyses, range mostly from 100 to 200 ppm ThO_2 in average grade, probably averaging a little more than 100 ppm ThO_2. Parts of the granite contain 200 ppm or more, and the highest sample analysis of 1,600 ppm ThO_2 was from part of the granite that contains abundant limonitic material as small veins. The granites of the five areas are estimated to have a combined tonnage of about 125 million tons of rock. At an assumed overall average grade of 112 ppm ThO_2, this amount of granite is inferred to contain at least 14,000 tons ThO_2 (at least 5,000 tons indicated and 9,000 tons inferred), and additional low-grade resources probably exist in other parts of the granite bodies not estimated.

Thorium oxide content of the carbonatite stock of Iron Hill has been estimated by Armbrustmacher (1980) to average 41 ppm; thus, to a depth of 245 m the 3.4 billion tons of carbonatite would contain about 140,000 tons ThO_2. Other elements in the same amount of rock were estimated (Armbrustmacher, 1980) as 1,900,000 tons Nb_2O_5 (570 ppm); 13,500,000 tons combined rare-earth oxides (3,970 ppm), and 43,000 tons U_3O_8 (12.7 ppm). Inasmuch as the content of thorium and the other elements is not uniform, some large parts

TABLE 5.—*Indicated and inferred reserves of ThO_2 in veins of more than 500 ppm ThO_2 average grade in the Powderhorn district*

[Values are in short tons]

Total indicated	Total inferred	Producible at less than $30/lb		Producible at between $30 and $50/lb	
		Indicated	Inferred	Indicated	Inferred
1,900	8,500	1,600	7,700	200	700

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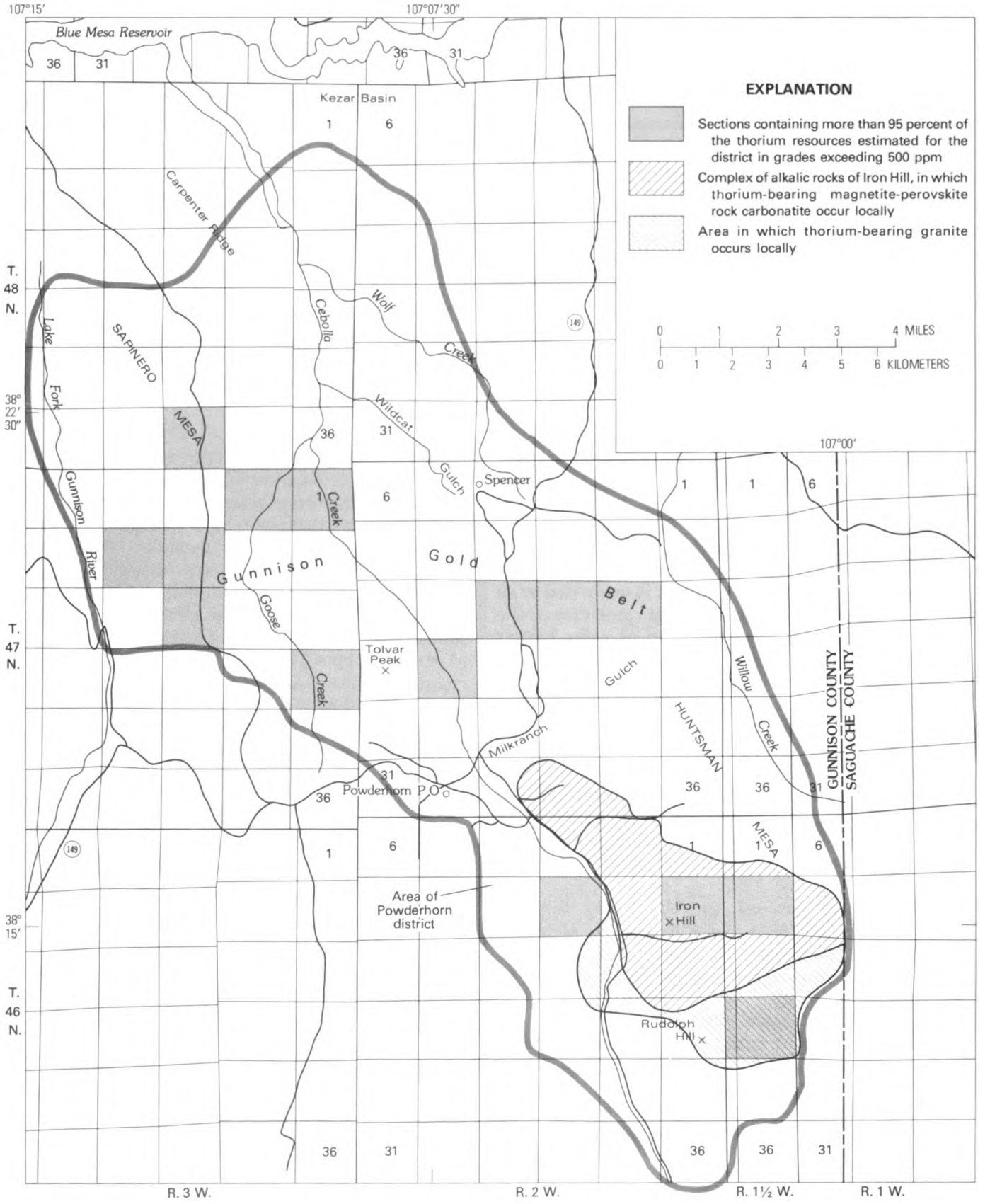


FIGURE 22.—Map showing areas of principal thorium resources estimated in veins, magnetite-perovskite rock, carbonatite, and thorium-bearing granite.

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of the carbonatite are higher or lower than the average grade. For example, Temple and Grogan (1965, p. 673) estimated a reserve of more than 100,000 tons of Nb_2O_5 in rock averaging at least 0.25 percent Nb_2O_5; some parts of this tonnage, large enough for open-pit mining, were 0.35 percent Nb_2O_5. Similarly, higher ThO_2 concentrations of 60 to 100 ppm probably occur locally in parts of the carbonatite body large enough to be quarried.

The ThO_2 content of the magnetite-ilmenite-perovskite rock has been approximated from only a few available analyses, which are summarized in table 6.

These data suggest a ThO_2 content in the magnetite-ilmenite-perovskite rock of perhaps 200–500 ppm; the radiochemical analyses, compared with TiO_2 in the same samples, suggest an approximate TiO_2/ThO_2 ratio of about 380. The grade of TiO_2 in this rock is discussed in the section on "Titanium." From these approximate figures, 100 million tons of such rock, if mined and processed for titanium at 12 percent TiO_2 grade, might be expected to contain on the order of 25,000-50,000 tons ThO_2; the actual tonnage available may be several times this amount.

ASSOCIATED ELEMENTS

The economic potential of thorium in the Powderhorn district is related in part to other elements and potential mineral commodities that have been prospected in the area. The complex of Iron Hill contains a minor-element assemblage characteristic of many alkalic rocks, including iron, titanium, phosphorus, strontium, barium, niobium, thorium, rare earths, and vanadium. Potential economic products include niobium, titanium, iron, and rare-earth elements.

TABLE 6.—*ThO_2 content of magnetite-ilmenite-perovskite rock, complex of Iron Hill*

[>, greater than; leaders (—), not analyzed for]

Material	Content in percent			
	ThO_2 or eThO_2	TiO_2	Nb	Rare earths
Magnetite-ilmenite-perovskite rock NJX-1, spectrographic analysis	0.025	>10	0.07	0.772
Two radiochemical analyses of perovskite	.12-.15	51	.34	---
Magnetite-ilmenite-perovskite rock	.01	---	---	.003
Magnetite-ilmenite-perovskite rock Temple and Grogan, 1965, p. 688).	.05	---	---	---
Magnetite-ilmenite-perovskite rock (0.05-0.25 mr/hr field readings, approximate)	.0076-.0680	---	---	---

TABLE 7.—*ThO_2 and Nb_2O_5 ratios in veins in the Powderhorn district*

Quadrangle	No. of analyses	$ThO_2:Nb_2O_5$
Rudolph Hill	6	2.55
Powderhorn	16	5.50
Gateview	18	15.81
Carpenter Ridge	6	19.70
Total and average	46	6.79

NIOBIUM

Niobium occurs in pyrochlore disseminated throughout much of the dolomitic carbonatite stock. Drilling by the DuPont Co. in 1957 and 1958 indicated a reserve of more than 100,000 tons of Nb_2O_5 in carbonatite averaging at least 0.25 percent Nb_2O_5, a substantial amount of which averaged 0.35 percent. This reserve estimate was subsequently increased by underground work and additional drilling (Temple and Grogan, 1965, p. 673).

The pyrochlore is most abundant in the finer textured dolomitic carbonatite and also associated with fluorapatite along shear planes in the carbonatite. Small amounts of niobium also occur in several other minerals in the complex of Iron Hill. Semiquantitative spectrographic analyses of three perovskite concentrates from the magnetite-ilmenite-perovskite rock show niobium values of 0.17, 0.2, and 0.7 percent. Niobium is also present in trace amounts in the ilmenite, sphene, magnetite, and melanite.

The thorite veins commonly contain anomalous amounts of niobium; some of it is in columbite, which has been identified in a black siliceous vein in the Road Beaver Creek area (Temple and Grogan, 1965, p. 684). Rough calculations from semiquantitative spectrographic analyses of 46 thorite vein samples show niobium in amounts generally from 30 to 1,500 ppm, averaging 172 ppm (246 ppm Nb_2O_5). This amount may be compared to an average of 1,669 ppm for ThO_2 in the same samples, a ThO_2-Nb_2O_5 ratio of 6.79. The ThO_2-Nb_2O_5 ratio varies in veins in different parts of the districts, however, as shown in table 7. The ThO_2-Nb_2O_5 ratio in the thorite veins thus increases, from southeast to northwest, with increasing distance from the complex of Iron Hill. Within the carbonatite body of the complex of Iron Hill, the Nb_2O_5 content greatly exceeds ThO_2.

TITANIUM

Titanium-bearing minerals are abundant in the pyroxenite of the complex of Iron Hill. These include perovskite, ilmenite, leucoxene, sphene, melanite garnet, and titaniferous magnetite; minor amounts are present in diopside (0.1–0.7 percent) and biotite. The

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magnetite, ilmenite, and perovskite are commonly intergrown in a titanium-rich rock that forms segregations and dikes, and they also are disseminated as discrete grains in the pyroxenite. The perovskite is partly replaced by leucoxene, but the other titanium-bearing minerals show this alteration less commonly. Sphene and melanite are commonly intergrown with the silicates of the pyroxenite and occur less commonly as granular aggregates. The TiO_2 content of perovskite concentrates is about 51 percent, of the magnetite-ilmenite composite grains about 6 to 19 percent, and of melanite concentrates about 5 percent. Some titanium is in solid solution in the magnetite, and the TiO_2 content of two samples of magnetite is 3.90 and 15.0 percent.

Modal analyses of 102 thin sections of pyroxenite indicate an average weight percentage of the following minerals in the pyroxenite: magnetite-ilmenite, 18.4; perovskite, 2.4; leucoxene, 1.1; melanite, 3.3; sphene, 0.5 percent.

According to Larsen (1942, p. 57), the TiO_2 content averages 7.4 percent in the pyroxenite and is more than 35 percent in some of the magnetite-ilmenite-perovskite bodies. Partial chemical analyses of pyroxenite drill-core samples have been published by Rose and Shannon (1960). Their data from 441 analyses, derived from three drill cores totaling 569.5 m of mostly pyroxenite, indicate that within the pyroxenite the TiO_2 content ranges from 0.3 to 11.9 percent and the total iron content from 7.0 to 22.5 percent. Rose and Shannon (1960, p. 19) estimated from surface- and core-sample data that the average grade of the pyroxenite is 11.7 percent iron and 6.5 percent titanium, and that the deposit may contain more than 100 million tons. The same figures are given by Berkenkotter and Hazen (1963), who made statistical studies of the drill-core sample data supplied by Rose and Shannon. As the titanium content is highest in the magnetite-ilmenite-perovskite dikes and segregations, the parts of the pyroxenite containing large amounts of such rocks exceed the average titanium content and offer the most promise for titanium exploration.

The pyroxenite has been explored for titanium during the mid 1970's by Buttes Gas and Oil Co. A newspaper account (Denver Post, February 25, 1976, p. 31) reported company officials as saying that studies had indicated 419 million tons of reserves of rock averaging about 12 percent TiO_2.

IRON

Iron deposits were discovered in the Powderhorn district before 1880. The iron content of the material mined has not been sufficient to attract mining for iron alone, and the total production has been less than 4,000 tons (Harrer and Tesch, 1959, p. 33). The iron occurs chiefly as magnetite-ilmenite-perovskite concentrations in pyroxenite. Thirteen samples of the titaniferous magnetite rock range from 8.6 to 30.8 percent iron and 3.8 to 32.7 percent TiO_2 (Harrer and Tesch, 1959, p. 34). An average of 11.7 percent iron for more than 100 million tons of magnetite-bearing pyroxenite was given by Rose and Shannon (1960, p. 19). Small iron deposits in the carbonatite of Iron Hill have also been prospected; these consist of small martite-apatite veins and small bodies of cellular and siliceous limonite and hematite.

VANADIUM

Vanadium is present in the iron- and titanium-bearing minerals of the complex. Magnetite in one sample of uncompahgrite contains 0.21 percent V_2O_5, and a magnetite sample from a magnetite-ilmenite-perovskite dike contains 0.14 percent V_2O_5. Other mineral samples with the greatest concentration are melanite garnet, which contains 0.2 percent V_2O_5; perovskite 0.06 percent V_2O_5; and diopside, 0.05–0.07 percent V_2O_5.

Vanadium is commonly reported in spectrographic analyses of thorite veins. Vanadinite was identified in a sample from the Sand Rock No. 5 Lode 1 km northwest of the old Dubois mine by M. H. Staatz. In 45 semiquantitative spectrographic analyses (Hedlund and Olson, 1980) of vein samples, vanadium ranges from 0 to 1.5 percent, averaging 0.069 percent. This is a higher concentration than is found in most of the alkalic igneous rocks in the district. Probably the highest concentration is in the titaniferous magnetite-ilmenite-perovskite rocks, containing on the order of 0.1 percent V_2O_5. Fischer (1975, p. 5) has estimated that about 50,000 tons of vanadium may occur in 100 million tons of magnetite-ilmenite-perovskite rock in the complex of Iron Hill.

RARE-EARTH ELEMENTS

All the various types of thorium deposits in the district contain an appreciable amount of rare-earth elements, generally considerably in excess of the thorium. In the thorite veins the ratio of total rare-earth oxides to ThO_2 averages about 2.4. The rare earths occur at least partly in such minerals as monazite, thorite, rhabdophane, synchysite, and bastnaesite. Rough calculations based on semiquantitative spectrographic analyses, mostly of veins but including other rock types as well, indicate that in the entire district the ratio of light (cerium-group) rare-earth oxides to tho-

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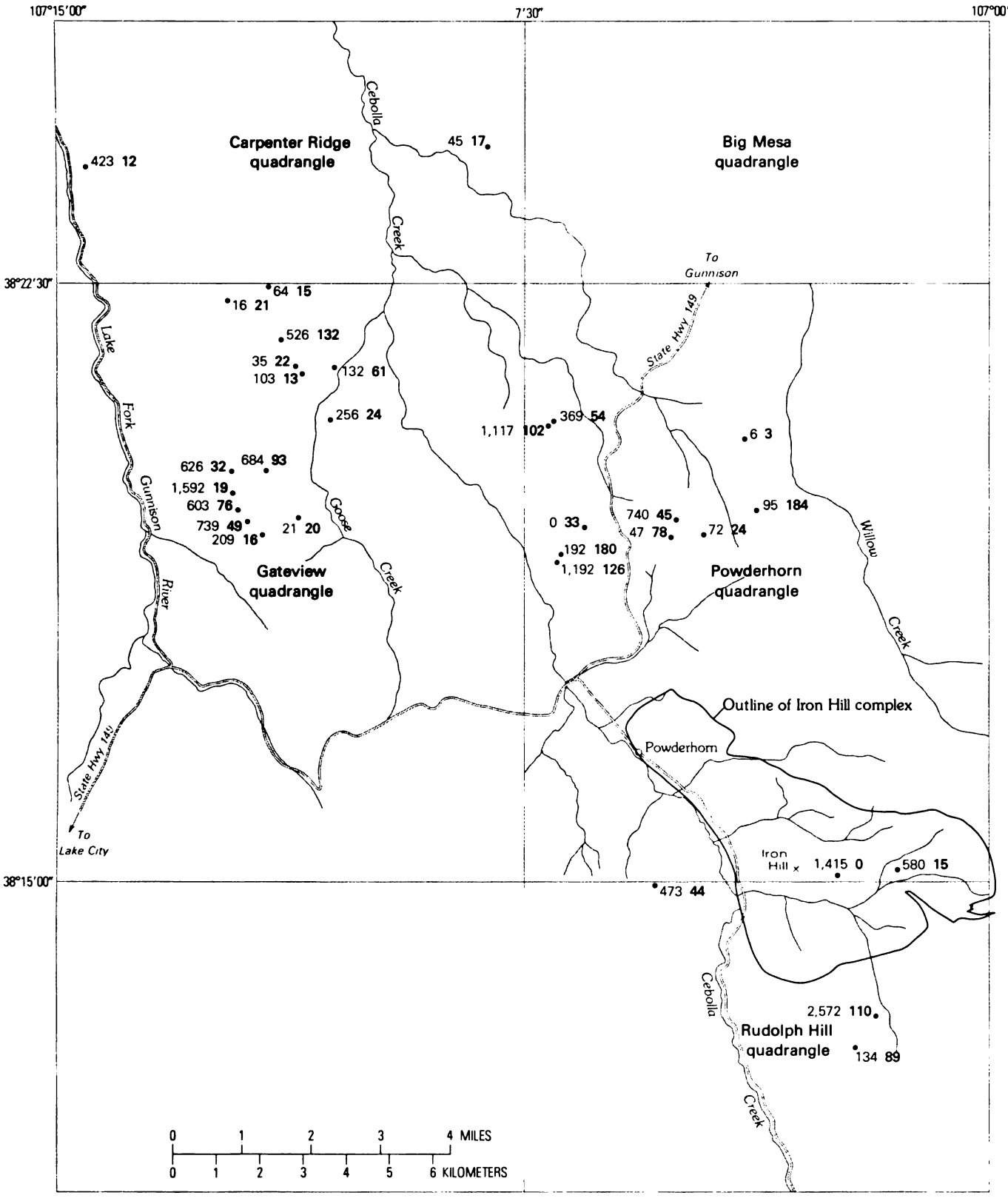


FIGURE 23.—Map showing proportions of cerium-group rare-earth oxides, yttrium-group rare-earth oxides, and thorium oxide in samples from 31 thorium deposits. Numbers show ratios of cerium-group rare-earth oxides (light type) and yttrium-group rare-earth oxides (bold type) to thorium oxide taken as 100. Amounts are approximate only, as they are based upon semiquantitative spectrographic analyses.

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TABLE 8.—*Ratio of cerium-group rare-earth oxides to ThO_2 to yttrium-group rare-earth oxides in various thorium deposits*

Area	Cerium-group rare-earth oxides:ThO_2: yttrium-group rare earth oxides
1. Thorite veins in Gateview and Carpenter Ridge quadrangles	1.8:1:0.4
2. Thorite veins in Powderhorn quadrangle excluding vicinity of complex of Iron Hill	0.6:1:0.78
3. Thorite veins near south and west sides of complex of Iron Hill	4.6:1:0.45
4. Carbonatite, magnetite-perovskite rock, granite, and thorite veins of no. 3, in or near complex of Iron Hill	6.0:1:0.31

rium oxide to heavy (yttrium-group) rare-earth oxides is about 3.6 to 1 to 0.5. Restricting the ratios to thorite veins containing more than 100 ppm ThO_2 only, these ratios are about 1.75 to 1 to 0.65. Like the niobium-thorium oxide ratios, the proportions of these three groups of constituents vary considerably in different parts of the district (fig. 23). These variations are summarized in table 8. Individual deposits differ greatly in rare-earth-thorium ratios from nearby deposits, suggesting that fractionation of rare-earth metals and thorium—and probably niobium as well—has taken place on a local as well as a district-wide scale. The variation in proportions of rare-earth metals, thorium, and niobium may be due partly to fractionation associated with changes in the composition of the fluids with distance from the source. In part the variations correlate very roughly with carbonate mineral content, for the deposits richer in carbonate minerals, as near the complex of Iron Hill, generally have a higher proportion of cerium in relation to the other elements.

The relation of cerium- and yttrium-group metals to ThO_2 content in 59 samples of thorium deposits is illustrated in figures 24 and 25.

URANIUM

The ratio of thorium to uranium was determined for 74 samples of thorite veins. Uranium content is generally quite low and exceeds 10 ppm in only three of the samples, in which it consists of 11.78, 20, and 41 ppm. Of the 74 samples, the thorium-uranium ratio ranged from 1 to 10 in six, 10 to 30 in eight, 30 to 70 in 20, 70

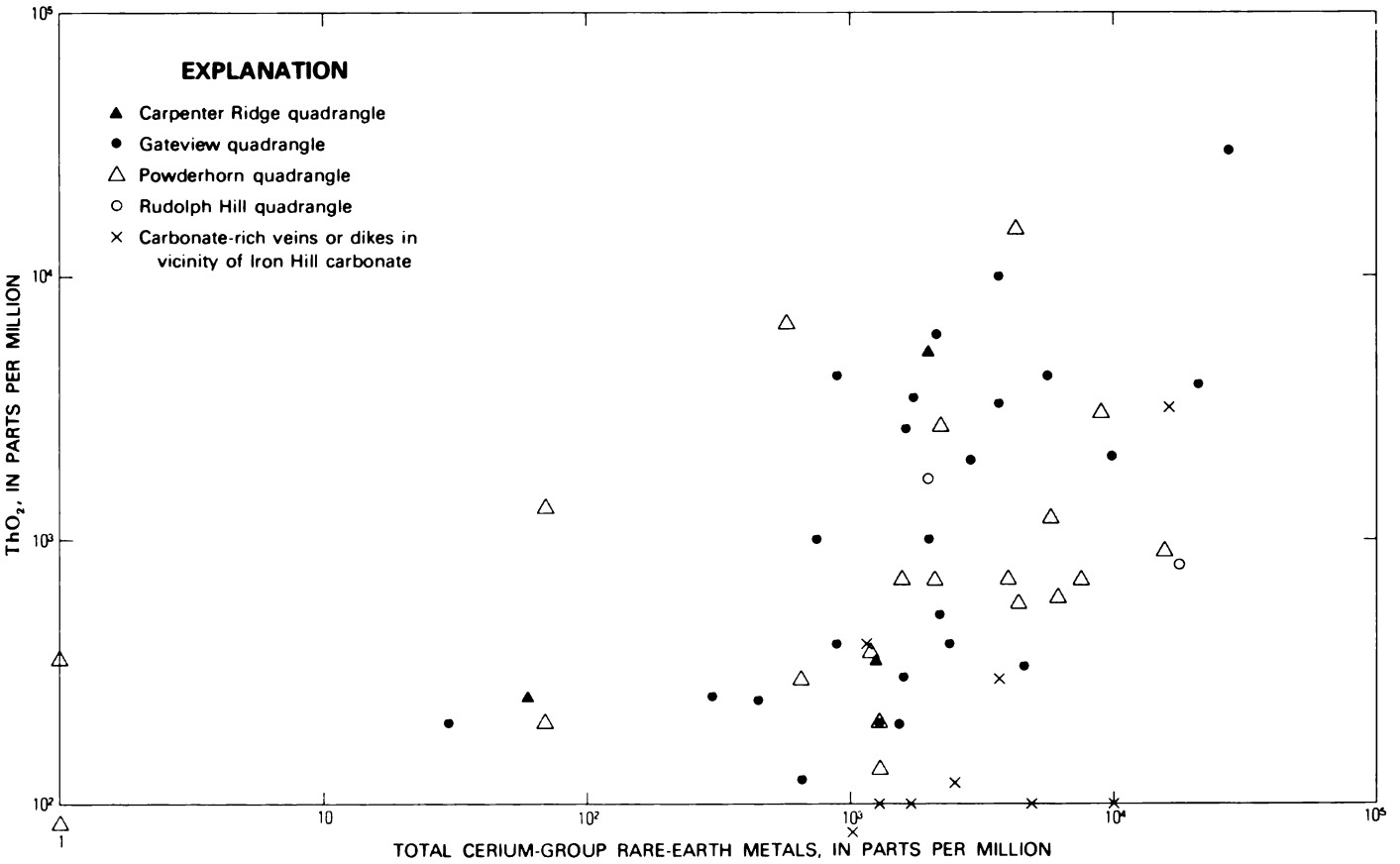


FIGURE 24.—Graph showing relation of total cerium-group rare-earth metals to ThO_2 content in 59 samples of thorium deposits.

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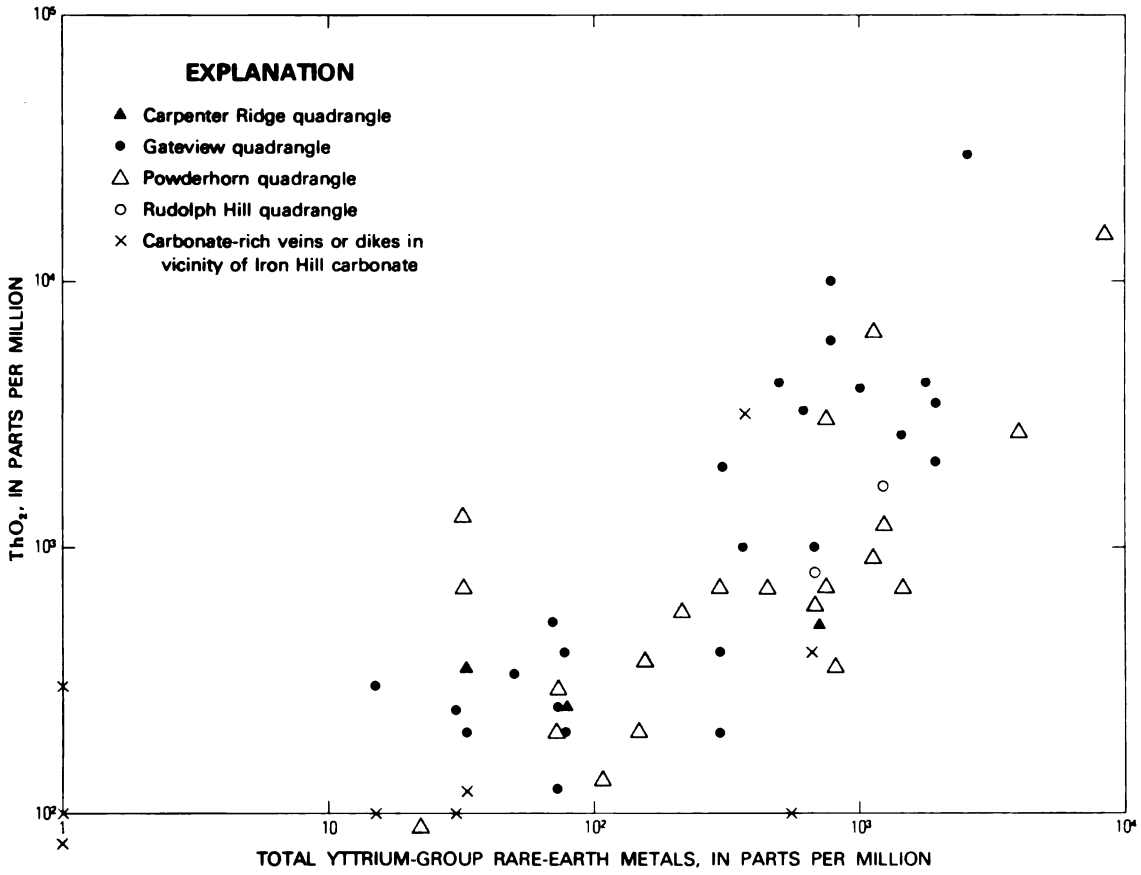


FIGURE 25.—Relation of total yttrium-group rare-earth metals to ThO_2 content in 59 samples of thorium deposits. Rare-earth values approximated from semiquantitative spectrographic analyses.

to 130 in 10, 130 to 1,000 or more in 14, and in 16 of the samples the thorium-uranium ratio is probably high but the uranium content is very low or not determined. The ratio of thorium to uranium is also generally high in rocks other than the thorite veins, such as carbonatite dikes and thorium-bearing granite. In 23 samples of carbonatite or alkalic rocks, uranium exceeds 10 ppm in only one, a carbonatite dike sample in which it is 93.4 ppm, exceeding thorium. Significant uranium resources therefore seem unlikely to be associated with the thorium deposits and alkalic igneous rocks in the district.

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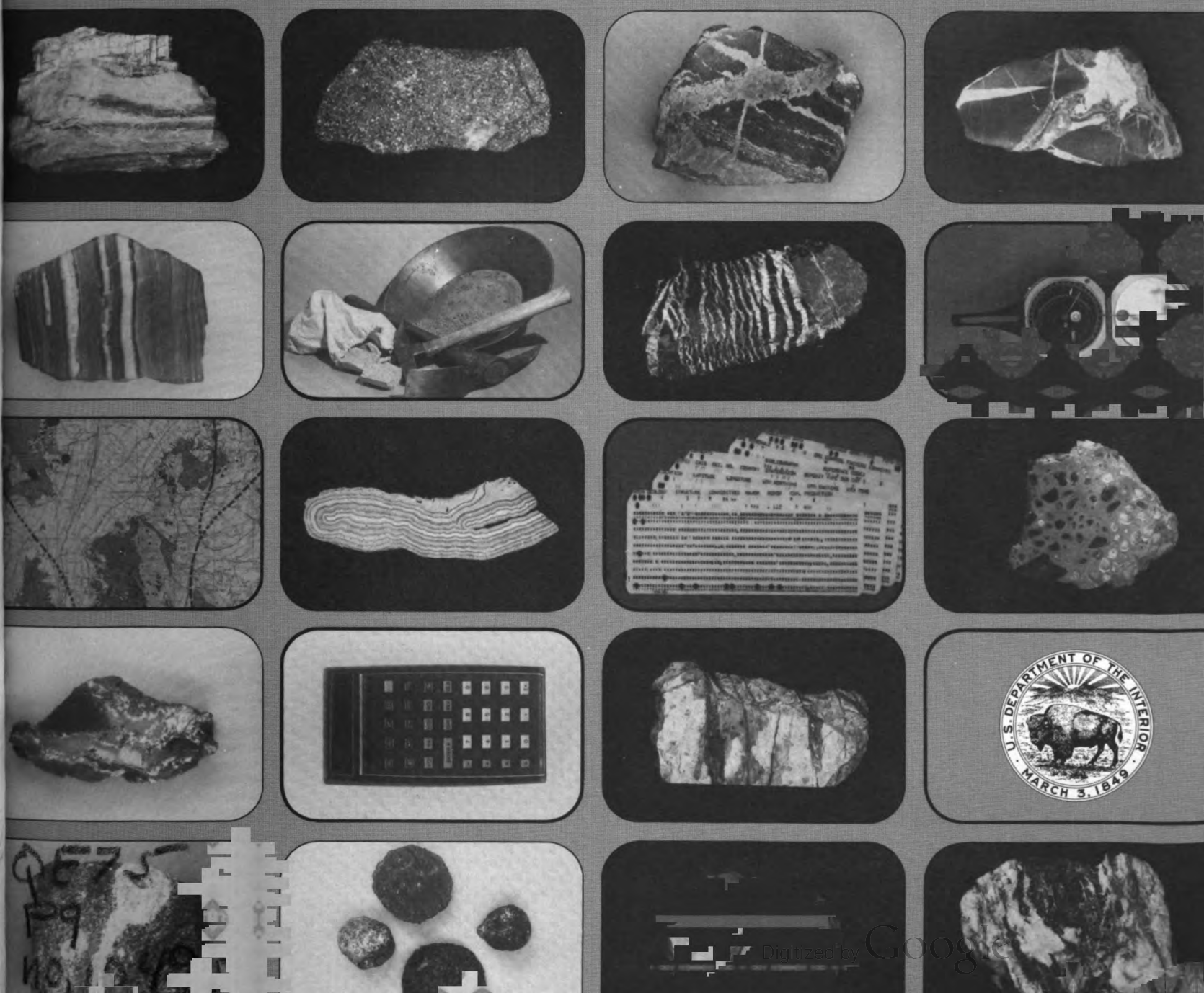
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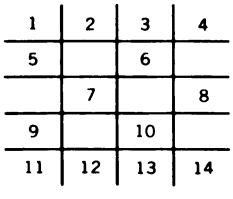
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Geology and Description of Thorium and Rare-Earth Deposits in the Southern Bear Lodge Mountains, Northeastern Wyoming

By MORTIMER H. STAATZ

GEOLOGY AND RESOURCES OF THORIUM IN THE UNITED STATES

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1049-D

A description of the size, mineralogy, chemical composition, economic geology, and geologic setting of the thorium and rare-earth veins and newly discovered large disseminated deposits



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UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, ***Secretary***

GEOLOGICAL SURVEY

Dallas L. Peck, ***Director***

Library of Congress Cataloging in Publication Data
Staatz, Mortimer Hay, 1918–
Geology and description of thorium and rare-earth deposits in the southern Bear Lodge Mountains, northeastern Wyoming
(Geological Survey Professional Paper 1049–D)
Bibliography: 52 p.
Supt. of Docs. No.: I 19.16:1049–D
1. Thorium ores—Wyoming—Bear Lodge Mountains. 2. Earth, Rare—Wyoming—Bear Lodge Mountains.
I. Title. II. Series. III. Series: Geological Survey Professional Paper 1049–D
QE390.2.T45S73 553.4'93 81–607092 AACR2

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GEOLOGY AND DESCRIPTION OF THORIUM AND RARE-EARTH DEPOSITS IN THE SOUTHERN BEAR LODGE MOUNTAINS, NORTHEASTERN WYOMING

By MORTIMER H. STAATZ

ABSTRACT

The Bear Lodge Mountains are a small northerly trending range approximately 16 km northwest of the Black Hills in the northeast corner of Wyoming. Thorium and rare-earth deposits occur over an area of 16 km² in the southern part of these mountains. These deposits occur in the core of the Bear Lodge dome in a large multiple intrusive body made up principally of trachyte and phonolite. Two types of deposits are recognized: disseminated deposits and veins. The disseminated deposits are made up of altered igneous rocks cut by numerous crisscrossing veinlets.

The disseminated deposits contain thorium and rare-earth minerals in a matrix consisting principally of potassium feldspar, quartz, and iron and manganese oxides. Total rare-earth content of these deposits is about 27 times that of the thorium content.

The general size and shape of the disseminated deposits were outlined by making a radiometric map using a scintillation counter of the entire Bear Lodge core, an area of approximately 30 km². The most favorable part of this area, which was outlined by the 40 count/s (count-per-second) isograd on the radiometric map, was sampled in detail. A total of 341 samples were taken over an area of 10.6 km² and analyzed for as many as 60 elements. Rare earths and thorium are the principal commodities of interest in these deposits. Total rare-earth content of these samples ranged from 47 to 27,145 ppm (parts per million), and the thorium content from 9.3 to 990 ppm. The amount of total rare earths of individual samples shows little correlation with that of thorium. Contour maps were constructed using the analytical data for total rare earths, thorium, uranium, and potassium. The total rare-earth and thorium maps can be used to define the size of the deposits based on what cut-off grade may be needed during mining. The size is large as the 2,000 ppm total rare-earth isograd encloses several areas that total 3.22 km² in size, and the 200 ppm thorium isograd encloses several areas that total 1.69 km². These deposits could be mined by open pit. The Bear Lodge disseminated deposits have one of the largest resources of both total rare earths and thorium in the United States, and although the grade of both commodities is lower than some other deposits, their large size and relative cheapness of mining make them an important future resource.

Vein deposits in the Bear Lodge Mountains include all tabular bodies at least 5 cm thick. Twenty-six veins were noted in this area. These veins are thin and short; the longest vein was traced for only 137 m. Minerals vary greatly in the amount present. Gangue minerals are commonly potassium feldspar, quartz, or cristobalite intermixed with varying amounts of limonite, hematite, and various manganese oxides. Rare earths and thorium occur in the minerals monazite, brockite, and bastnaesite. Thorium content of 35 samples ranged from 0.01 to 1.2 percent, and the total rare-earth content of 21 samples from 0.23 to 9.8 percent. Indicated reserves were calculated to a depth of one-third the exposed length of the vein. Inferred reserves lie in a block surrounding indicated reserves. Indicated reserves of all veins are only 50 t of ThO_2 and 1,360 t of total rare-earth oxides; inferred reserves are 250 t of ThO_2 and 6,810 t of total rare-earth oxides.

The Bear Lodge dome, which underlies the greater part of this area, is formed by multiple intrusive bodies of Tertiary age that dome up the surrounding sedimentary rocks. In the southern part of the core, the younger intrusive bodies surround and partly replace a granite of Precambrian age. This granite is approximately 2.6 b.y. old. The sedimentary rocks around the core are (from oldest to youngest): Deadwood Formation of Late Cambrian and Early Ordovician age, Whitewood Limestone of Late Ordovician age, Pahasapa Limestone of Early Mississippian age, Minnelusa Sandstone of Pennsylvanian and Early Permian age, Opeche Formation of Permian age, Minnekahta Limestone of Permian age, Spearfish Formation of Permian and Triassic age, Sundance Formation of Middle and Late Jurassic age, Morrison Formation of Late Jurassic age, and the lower part of the Lakota Formation of Early Cretaceous age. In places, especially around the north half of the dome, the intrusive rock replaces one or more of these formations. Generally only the most resistant quartzite layers of the Deadwood Formation are not replaced. The best exposed section of the Deadwood occurs along the east flank of the area where a separate intrusive plug has pushed up a circular block of sedimentary rocks. Here, although not a complete section, 270 m of Deadwood Formation was measured, one of the thickest known sections of this formation.

The Tertiary intrusive bodies not only form the center of the Bear Lodge dome but also form many smaller plugs, dikes, and sills along its flanks. The intrusives all have a relatively high potassium and a low silica content. These rocks represent a complex sequence of alkalic rocks that were intruded into the older sedimentary rocks at shallow depth over a considerable period of time. In a few places the magma reached the surface, forming flows and pyroclastic deposits. Six age determinations have been made on intrusive bodies from this area, including four that are first reported here. They indicate that the intrusives formed over a minimum time span of 12.2 m.y. (million years) (38.3 to 50.5 m.y. ago). During waning stages of the Tertiary intrusion, many of the intrusive bodies were fractured and altered by

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hydrothermal solutions. This alteration is most intense in the central part of the Bear Lodge dome, and here the various rock types are difficult to separate. Many of the outlying intrusives show little alteration, and the various rock types are more easily mapped. The greater part of the intrusive rocks are trachyte and phonolite. In addition, however, there are other intrusives of latite, syenite, and nepheline syenite. Irregular areas of intrusive breccia indicate the force of intrusion in some areas, and patches of tuff are still preserved in a few places. Dikes and (or) sills of lamprophyre, pseudoleucite porphyry, carbonatite, and younger trachyte and syenite are present. Carbonatites form numerous dikes at depth near the headwaters of Whitelaw Creek. These interesting rocks are commonly rich in rare earths and strontium. Rare earths occur in bastnaesite and ancylite; strontium occurs in ancylite and strontianite.

Along the flanks of the Bear Lodge dome, the Tertiary intrusive rocks and older sedimentary rocks are overlain by sedimentary rocks of Tertiary and Quaternary ages. The Tertiary rocks consist of loosely consolidated sandstones and conglomerates of the White River and Ogallala Formations. Those rocks formed on the flanks of a rising upland whose center is now located near Warren Peaks. The Quaternary rocks are landslide deposits and alluvium.

Although the central structure is the large Bear Lodge dome, another dome, folds, and small faults also occur here. The Hershey Creek dome, underlying 3 km², is in the northwestern part of the area. Anticlines, synclines, and 10 short faults are found on the flanks of the Bear Lodge dome. All the domes, folds, and faults have been formed by the force of intrusion of one or more intrusives. The most striking example of the relationship between faulting and intrusion is on Sheep Mountain, where several curved faults outline the approximate shape of the underlying plug, which has pushed the overlying rocks up like a cork in a bottle.

INTRODUCTION

Thorium and rare-earth deposits have been known in the Bear Lodge Mountains since 1949 (Wilmarth and Johnson, 1953, p. 5). Their discovery brought about a flurry of prospecting accompanied by location of more than 100 claims and the digging of several hundred bulldozer trenches. The lack of a readily available thorium and rare-earth market in the 1950's caused active exploration for these ores to cease. The largest and potentially most economic deposits occur in large disseminated deposits consisting of numerous crisscrossing veinlets in altered intrusive rocks. These deposits, which are first described here, are similar in occurrence to copper and molybdenum porphyry-type deposits. Thorium and rare earths occur in disseminated deposits and veins over an area of about 16 km² and represent a sizable future resource of these elements. The deposits occur in and are related to a large multiple alkalic intrusion, made up mainly of trachyte and phonolite. These intrusive bodies, which underlie an area of approximately 31 km², dome up the surrounding rocks to form the Bear Lodge dome and expose sedimentary rocks as old as Cambrian in age. The present study describes the geology and mineralogy of the thorium and rare-earth deposits, the petrology of both the principal and adjacent outlying intrusives, and the geologic setting of the surrounding rocks.

LOCATION AND ACCESSIBILITY

Thorium- and rare-earth-bearing veins and disseminated deposits occur near the middle of an oval-shaped body of intrusive rock in Crook County, Wyo. This area makes up the higher part of the southern Bear Lodge Mountains and includes the Warren Peaks, Smith Ridge, and Bull Hill (pl. 1). The size of the region covered by this report is approximately 112 km² (pl. 1). This area occupies most of the southern Bear Lodge Mountains (fig. 1), and the greater part of it is within the boundaries of the Black Hills National Forest. The area mapped is roughly rectangular in shape, and is approximately bounded by lats 44° 25′ 15″ and 44° 32′ 50″ N., longs 104° 22′ 25″ and 104° 30′ W. The town of Sundance, Wyo., is 1.5 km south of this area's southeast corner and the town of Hulett, Wyo., lies 16 km northwest of its northwest corner.

The principal road through the study area is a north-south-trending all-weather road that divides the area roughly in half. Its southern terminus is on U.S. Highway 14 about 2.8 km west of Sundance. Other improved U.S. Forest Service roads follow Beaver Creek, Whitelaw Creek, Ogden Creek, Lytle Creek, Togus Creek, and Blacktail Creek. The road down Blacktail Creek connects the area with the town of Hulett. In addition numerous secondary roads have been added to aid in lumbering operations. Some of the older roads became abandoned and overgrown, and newer roads have been added in the same region with the start of new lumbering operations. The only habitations are two farm houses in and adjacent to Krusee Canyon in the southwest corner of the region (pl. 1).

GEOGRAPHY

The Bear Lodge Mountains are a low, northerly trending range 43 km long by 13 to 20 km wide. This range lies approximately 16 km northwest of the northwest end of the Black Hills (fig. 1). The two are separated by a broad, undulating depression called the Red Valley (Darton, 1909, p. 27), which is underlain for the most part by the Spearfish Formation and extends continuously around the Black Hills. The Bear Lodge Mountains have a relief of about 869 m and vary in elevation from about 1,160 m at the north end of the range to 2,029 m on the northernmost of the Warren Peaks in the

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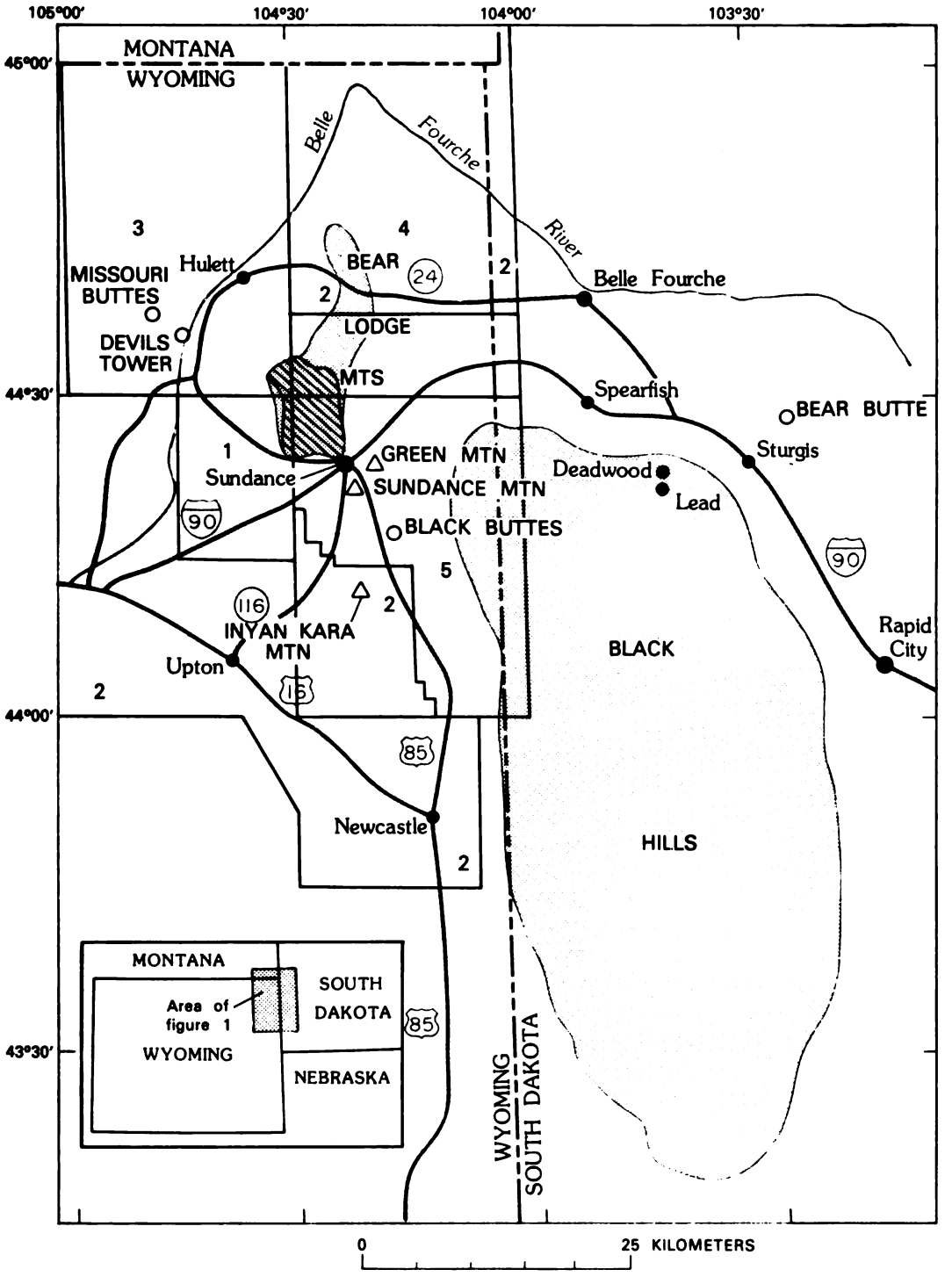


FIGURE 1.—Index map of northeastern Wyoming and northwestern South Dakota showing the location of the area mapped (diagonal-line pattern) in relation to the Bear Lodge Mountains and the Black Hills. Adjacent mapped areas mentioned in text are 1, Nefsy Divide quadrangle (Pillmore and Mapel, 1963, pl. 1); 2, northern and western flanks of the Black Hills uplift (Robinson and others, 1964, pl. 1); 3, Devils Tower quadrangle (Darton and O'Harra, 1907); 4, Aladdin quadrangle (Darton and O'Harra, 1909); 5, Sundance quadrangle (Darton, 1905).

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southern part of the range. Difference in elevation in the area mapped is about 555 m. The Warren Peaks occur near the center of an intrusion that domes up the southern part of the Bear Lodge Mountains. Here the mountain tops are rounded, and the drainage pattern radiates off this uplifted highland. Although the streams flow off these highlands in all directions, they all, either directly or via other streams, flow into the Belle Fourche River, which flows along the west and northeast sides of the Bear Lodge Mountains (fig. 1). The longest stream in the Bear Lodge Mountains is Beaver Creek, which heads on the northeast side of Warren Peaks and then follows a meandering northward course along much of the length of the Bear Lodge Mountains for 50 km to the Belle Fourche River. Some streams near the center of the domed-up area form broad, shallow valleys, like Whitelaw Creek and the upper parts of Lytle and Beaver Creeks. Other creeks, generally on the flanks of the dome, form steep, V-shaped valleys, like Reuter, Tent, and Ogden Creeks. These steep-walled valleys, however, rarely have more than 125 m of relief. The shape of the valleys is also, in part, determined by the rock type. The broad, gently sloping valleys of the upper part of Beaver and Winchester Creeks change to steep narrow rock-bound gorges where they flow through the resistant Minnelusa Sandstone (pl. 1).

The Bear Lodge Mountains are covered with western yellow pine, which in parts of these mountains is the only tree found. Other trees include aspen, white birch, hawthorn, and burr oak. These small trees are most common along valley bottoms and on north-facing slopes. In the northern part of the mapped area, the smaller trees form dense thickets in some places; but in the central and southern parts, they are rare. The western yellow pine has supported a small lumbering industry for many years. Logs from this area are hauled to sawmills in Hulett.

PREVIOUS WORK

One of the first to mention the rocks in the vicinity of the Bear Lodge area was Lieutenant G. K. Warren, who led an expedition from Fort Laramie to Inyan Kara Mountain in 1857 (Warren, 1859, p. 60). Warren Peaks, the highest peaks in the Bear Lodge Mountains, were named after this explorer. Early geologists were attracted not only to mineral deposits of this region, but also to the prominent small- to medium-sized intrusives that occur in an east-west-trending belt from Bear Butte on the northeast side of the Black Hills to Missouri Buttes, 25 km to the west of the Bear Lodge Mountains (fig. 1). Newton and Jenney (1880, p. 199–200, 283–289) briefly described the geology and early gold prospecting activity in the vicinity of Warren Peaks; their report contains the first published description of one of the veins that contains thorium and rare earths (p. 199–200). The petrography of some of the trachytic rocks collected by Newton and Jenney is described in detail by Caswell (1880, p. 517–523). Russell (1896, p. 390–410) and Jaggar (1901, p. 251) briefly studied the intrusive rocks near Warren Peaks. In the early 1900's, N. H. Darton and C. C. O'Harra mapped the Sundance, Devils Tower, and Aladdin 30-minute quadrangles at a scale of 1:125,000 (Darton, 1905; Darton and O'Harra, 1907; 1909) (fig. 1). These three quadrangles cover the greater part of the present study area. The geology of these quadrangles and of the adjoining northern part of the Black Hills was summarized by Darton (1909). In the 1950's Brown in a thesis study made a reconnaissance map and described the main intrusive body in the Bear Lodge Mountains (Brown, 1952; Brown and Lugn, 1952). Another result of this study was the dating of some of the sedimentary rocks of Tertiary age (Lugn and Brown, 1952). In another thesis, Chenoweth (1955) described the rocks of the southeastern part of the Bear Lodge Mountains. Also during the 1950's, the U.S. Geological Survey investigated the uranium deposits that occur in the Lakota and Fall River Formations along the western flanks of the Bear Lodge Mountains and the Black Hills. One of the results of this work was the mapping of the Nefsy Divide quadrangle (Pillmore and Mapel, 1963), the northeast corner of which overlaps a small part of the present study area (fig. 1). The stratigraphy and structure of the northern and western flanks of the Black Hills uplift which included the Nefsy Divide and Devils Tower quadrangles were correlated over an area of about 13,000 km^2 (Robinson and others, 1964) (fig. 1). The sedimentary section in this study area is chiefly the Sundance and younger formations, because outcrops of the older units are sparse where present at all.

Brief studies of the mineral resources of the Bear Lodge Mountains have been made previously by the U.S. Bureau of Mines and the U.S. Geological Survey. The Bureau of Mines trenched and sampled some fluorspar deposits on the east side of the main intrusive body to the north and east of Peterson Spring in 1944 (Dunham, 1946), and they drilled and sampled a few of the rare-earth deposits in 1951 (E. D. Everett, written commun., 1951). Later, Wilmarth and Johnson (1953) of the U.S. Geological Survey studied and sampled some of the thorium- and rare-earth-bearing veins.

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PRESENT WORK AND ACKNOWLEDGMENTS

Little previous work has been done on the thorium and rare-earth deposits of the Bear Lodge Mountains, and what has been done was either confined to a few small areas or has been reconnaissance in nature. The mineralogy of these deposits is poorly known, owing primarily to the small grain size and to the masking of minerals and their relation to one another by considerable pulverulent black manganese oxides and red and yellow iron oxides. The radioactivity of individual deposits has been noted, but few data are available on the widespread anomalous radioactivity in the central part of the district.

The present work in the Bear Lodge Mountains was originated to study the thorium and rare-earth deposits and their geologic setting. This investigation includes a detailed study of the mineralogy of many of the thorium and rare-earth deposits, which was carried out by separating the individual minerals by means of heavy liquids, a magnetic separator, and hand picking. All visually unrecognized minerals were then identified by their X-ray diffraction patterns. The radioactivity of both the deposits and adjoining intrusive rocks was measured with a scintillation counter, and a total count radiometric map was constructed. The results of this work indicated that the thorium and rare-earth disseminated deposits, which underlie an area of approximately 10.6 km^2, needed further study. Hence, during the summer of 1979, a detailed radiometric study using a portable gamma-ray spectrometer and a sampling program was carried out in and adjacent to the disseminated deposits. In this study some 318 new samples were taken and analyzed for thorium, uranium, and potassium on a quantitative gamma-ray spectrometer by C. M. Bunker and C. A. Bush. In addition, semiquantitative spectrographic analyses were made on 192 samples, primarily to determine their rare-earth content, by N. M. Conklin. These detailed analytical data are available in Staatz and others (1980).

The geology of the area was mapped in detail on a scale of 1:24,000 (pl. 1). Mapping was done directly on a composite topographic base, which was compiled from parts of four 15-minute quadrangles: Sundance (1958), Alva (1958), Nefsy Divide (1957), and Devils Tower (1955). Exposures are poor in many of the thickly wooded parts in the central and northern parts of the area, and the positions of contacts were inferred in many places. Furthermore, the entire central part of the intrusive body has been altered, and the various igneous rock types are not everywhere recognizable. Hence, although the intrusive rocks are separated where they are less altered near the margins of the area, they are lumped as one complex unit in the central part of the region.

The fieldwork was done during the summers of 1975, 1976, and 1979 and the spring of 1977. I was assisted by T. M. Staatz during 1975, by A. J. Staatz during 1975 and 1976, by L. F. Osmonson during the spring of 1977, by D. F. Piske, Jr., for 1 week in June 1979, by T. E. Mower for 2 weeks in July 1979, and by R. F. Dubiel for 1 week in September 1979. Isabelle Brownfield did sample preparation, ran X-ray diffraction patterns, and did mineral identification.

During the first 3 years, Duval Corporation was carrying out an exploration program in the northern part of this area. I am indebted to geologists of this company, particularly John L. McGillis, Fred Reisbick, and Richard K. Larsen, for definite information on geology of the area. I am also indebted to the U.S. Department of Energy, which furnished funds for resource studies in 1978.

ROCK UNITS

Four general groups of rocks occur in the southern Bear Lodge Mountains. They are: (1) intrusive rocks of Precambrian age, (2) sedimentary rocks of Paleozoic and Mesozoic age (fig. 2), (3) intrusive rocks of Tertiary age, and (4) consolidated and unconsolidated rocks of Tertiary and Quaternary age. The only Precambrian rocks exposed in the area are remnants of a granitic body that have been intruded and in part replaced by later intrusive bodies of Tertiary age. Biotite-bearing schists probably occur at depth, inasmuch as inclusions of schist are found in the Tertiary intrusive rock near Warren Peaks. Sedimentary rocks of Paleozoic and Mesozoic ages have a total thickness of approximately 1,070 m in the southern Bear Lodge Mountains (fig. 2). Paleozoic rocks account for about two-thirds of this section. The rocks of Paleozoic age are mainly limestone with some sandstone, quartzite, shale, and siltstone. These are divided into: (1) the Deadwood Formation of Late Cambrian and Early Ordovician age, (2) the Whitewood Limestone of Late Ordovician age, (3) the Pahasapa Limestone of Early Mississippian age, (4) the Minnelusa Sandstone of Pennsylvanian and Early Permian age, (5) the Opeche Formation of Permian age, (6) the Minnekahta Limestone of Permian age, and (7) the lower part of the Spearfish Formation of Permian age. Mesozoic rocks are principally siltstones and shales but include some minor sandstones. These rocks make up: (1) the upper part of the Spearfish Formation, which is

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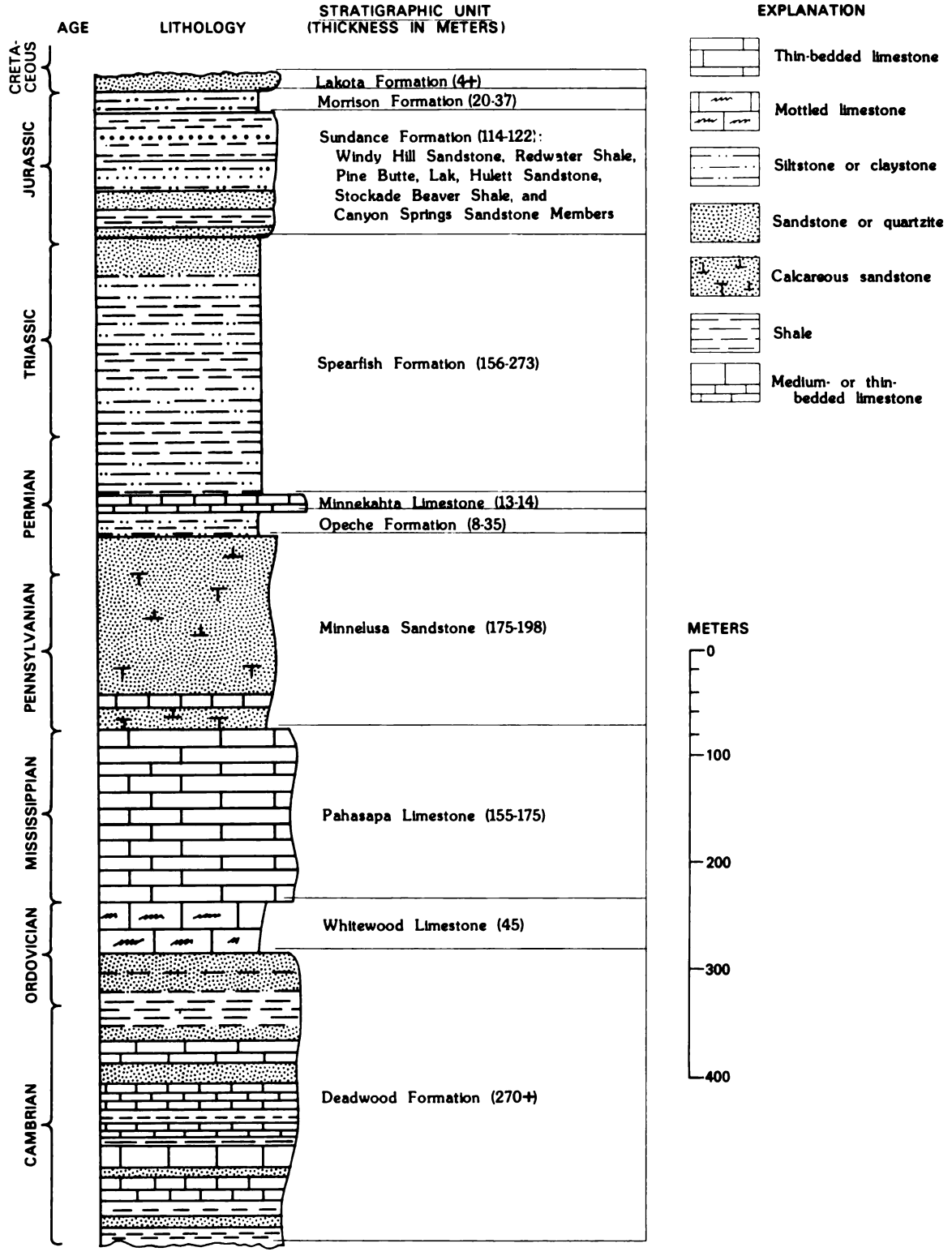


FIGURE 2.—Generalized columnar section of the Paleozoic and Mesozoic rocks in the southern Bear Lodge Mountains, Wyo. (pl. 1).

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of Triassic age, (2) the Sundance Formation of Middle and Late Jurassic age, (3) the Morrison Formation of Late Jurassic age, and (4) the lowest part of the Lakota Formation of Early Cretaceous age. A generalized column of these rocks is shown in figure 2.

Multiple intrusive bodies of early Tertiary age domed up and replaced older rocks in the central part of this district. Smaller intrusives cut the Paleozoic and Mesozoic rocks that lie on the flanks of the principal intrusive. All these intrusives are alkalic and deficient in silica. The principal rock types are trachyte and phonolite, but minor amounts of latite, syenite, nepheline syenite, pseudoleucite porphyry, lamprophyre, pyroclastic rocks, intrusive breccia, and carbonatite occur.

The sedimentary rocks of Tertiary and Quaternary ages unconformably overlie the older rocks and are made up of material derived at the most from a few kilometers away. The Tertiary rocks are the White River and Ogallala Formations, consisting of loosely consolidated clastics, mainly siltstones, sandstones, and conglomerates that formed on the flanks of an eroded and beveled upland whose center is now represented by Warren Peaks. Alluvium and landslide deposits make up the Quaternary rocks.

GRANITE (PRECAMBRIAN)

The granitic rocks in the Bear Lodge Mountains are confined to the south half of the core of the Bear Lodge dome (pl. 1), where they occur as isolated bodies surrounded by intrusive rocks of Tertiary age. Dikes of the intrusive rocks cut the granite at many places. Granite is also found as clasts in a trachytic-flow breccia exposed on Smith Ridge. The largest granite body (fig. 3), which is irregularly lenticular, is approximately 3.4 km long and has a maximum width of 600 m. This granite body lies along the northeast side of the core of the Bear Lodge dome. One of the lower quartzite beds in the Deadwood Formation lies adjacent to the northeast side of this granite body and at one place on Smith Ridge overlies the older granite. The contact between the two rock types is not exposed. The next largest granite body is T-shaped and underlies Warren Peaks. The various granite bodies, as a whole, have a discontinuous ring-shaped form within the south half of the main Tertiary intrusive (pl. 1). The semicircular outcrop pattern of the granite (pl. 1) resembles a ring dike, but the granite is the older rock rather than the reverse. One explanation for this ring-like shape is that the separate granite bodies may be at the periphery of a Precambrian mountain whose center was replaced by the intrusive. North



FIGURE 3.—Granite along southeast side of Ogden Creek showing typical massive outcrop.

of this outcrop ring, granite may be absent, as it is neither exposed on the surface nor encountered in a 900-m-deep drill hole located 2.3 km north of the edge of the granite on Warren Peaks.

The granite for the most part is a medium-grained holocrystalline leucocratic igneous rock. This rock is generally fairly homogeneous, and its grain size at most places is about 1 to 3 mm. The rock has a porphyritic texture in a few areas, feldspar phenocrysts being two or three times as large as surrounding grains. The rock is uniformly light colored with the actual color ranging from light gray to tan; however, at many places the weathered rock is a light brown because of limonite stain along numerous fractures.

The common minerals are quartz, albite, and microcline. This rock is everywhere silica rich, having a quartz content that ranges from about 20 to 35 percent. Normative quartz in three chemically analyzed samples is approximately 35 percent (table 1). Albite is generally the most common feldspar, and the albite to microcline ratio varies from about 3:1 to 7:10. Albite is, in general, poorly twinned and contains many dust-like inclusions. The lack of good twinning makes measurement of maximum extinction angles of limited use in determining the type of plagioclase. The sodium:calcium ratio of the plagioclase was obtained from the normative minerals (table 1). The anorthite content of the three analyzed specimens ranged from An_2 to An_7, so all three are

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TABLE 1.—*Chemical analyses and normative compositions in weight percent of Precambrian granite*

[Analyst, Lowell Artis, U.S. Geological Survey. Leaders (--), none]

Constituent or mineral	Sample No. 1	2	3
Chemical analyses			
SiO_2	75.1	75.5	75.2
Al_2O_3	13.8	13.8	15.1
Fe_2O_3	.61	.48	.66
FeO	.08	.04	.08
MgO	.07	.00	.10
CaO	.17	.12	.80
Na_2O	2.8	2.3	4.9
K_2O	6.2	6.9	2.8
H_2O+	.39	.61	.51
H_2O-	.10	.15	.10
TiO_2	.08	.05	.11
P_2O_5	.04	.03	.05
MnO	.02	.03	.01
CO_2	.08	.05	.03
Total---	99.54	100.06	100.45
Normative compositions			
Quartz	35.2	36.2	34.7
Orthoclase	37.3	40.6	16.7
Albite	23.6	19.4	41.4
Anorthite	.56	.56	2.8
Hypersthene	.20	--	.30
Corundum	2.4	2.5	3.0
Hematite	.64	.70	.64
Ilmenite	.15	.15	.15
Apatite	--	--	.34
Calcite	.20	.10	.10
Total---	100.25	100.21	100.13

SAMPLE LOCALITY DESCRIPTIONS

1. Ridge top south of Tent Canyon, NE1/4 NE1/4 sec. 33, T. 52 N., R. 63 W.
2. Roadcut just south of U.S. Forest Service lookout tower on Warren Peaks, SE1/4 SE1/4 sec. 20, T. 52 N., R. 63 W.
3. End of ridge top just north of the mouth of Richardson Creek, SE1/4 NW1/4 Sec. 27, T 52 N., R. 63 W.

albite. The potassium feldspar is probably chiefly microcline, as well-defined cross-hatch twinning is found in some thin sections. In other thin sections the potassium feldspar is untwinned and might be either untwinned microcline or orthoclase. The discrimination of untwinned potassium feldspar from untwinned plagioclase was made by staining the potassium feldspar yellow with sodium cobaltinitrite. Accessory minerals are biotite, magnetite, apatite, zircon, monazite, hornblende, anatase, rutile, galena, pyrite, and fluorite. Black biotite is the most common accessory mineral, generally making up 1-3 volume percent of the rock. Tiny black octahedra of magnetite constitute less than 1 percent of some granite specimens; in others magnetite has been altered to limonite. White apatite, pale-gray zircon, and yellowish-orange monazite make up trace amounts of the granite in many places. The granite was fractured and underwent minor alteration when it was metamorphosed by the surrounding Tertiary intrusive bodies. During this period a little pyrite was formed in the granite; later weathering converted the striated cubes of pyrite to goethite. Small flakes of sericite, which make up from a trace to 5 percent of the rock, formed on the potassium feldspar. A little hematite is present locally.

Granite samples from three widely separated areas were chemically analyzed in the U.S. Geological Survey's rapid rock-analysis laboratory (table 1). All three are typical of granite in the area from which they came and are similar in appearance. The oxide contents of samples 1 and 2 are also quite similar (table 1), but that of sample 3 differs principally in having almost twice as much Na_2O and less than half as much K_2O. These differences are best shown in the normative feldspar content, where the orthoclase content of samples 1 and 2 is 37 and 41 percent by weight, that of sample 3 is 17 percent; the albite content of samples 1 and 2 is 24 and 19 percent, respectively, and that of sample 3 is 41 percent. The maximum normative anorthite is 2.8 percent, indicating that the plagioclase is unusually rich in albite.

Dating the granite is uncertain, because all of its outcrops are within a relatively short distance of and may be affected by a much larger intrusive body of Tertiary age. The age of the granite was determined by lead-uranium ratios in zircon, because lead-uranium isotopic ratios are not as easily affected by heat as the isotopic ratios of other elements used in some other methods. The zircon crystals have a clear, pale-purple central part that is mantled by a thick, opaque, pale-gray rind. These rinds are the direct result of radiation damage. K. R.

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Ludwig of the U.S. Geological Survey (oral commun., 1976) stated that only zircons of Precambrian age exhibit the extreme radiation damage found in zircons from the granite of the southern Bear Lodge Mountains. Zircons from a sample of granite collected on Houston Ridge in the NE¼SE¼ sec. 33, T. 52 N., R. 63 W. were dated by the uranium-lead isotope method by Ludwig. The results are as follows:

Uranium (ppm)	Lead (ppm)	$\frac{^{206}Pb}{^{238}U}$ age	$\frac{^{207}Pb}{^{235}U}$ age	$\frac{^{207}Pb}{^{206}Pb}$ age
1863	129.9	389 m.y.	939 m.y.	2628 m.y.

The extreme discordance between the ages is at least in part due to the heating of the zircons by the Tertiary intrusive. The heating of the granite tends to drive off lead from the zircons and makes the ages obtained appear to be too young. Thus, although a definite age cannot be determined, the above data do give a minimum age of about 2,600 m.y. Samples from two other areas in the Black Hills have similar ages. An age of approximately 2,500 m.y. has been reported both from the Little Elk Granite on Little Elk Creek in the northeastern part of the Black Hills (Zartman and Stern, 1967) and from a gneissic granite in the Bear Mountain dome on the west side of the central Black Hills (Ratté and Zartman, 1970).

DEADWOOD FORMATION (LATE CAMBRIAN AND EARLY ORDOVICIAN)

The Deadwood Formation, a unit made up principally of quartzite and shaly limestone, is the oldest sedimentary unit in the Bear Lodge Mountains. This formation is exposed in three areas: (1) in and around the edge of the igneous core of the Bear Lodge dome, (2) on Sheep Mountain, and (3) along the north edge of the intrusive core of Hershey Creek dome (pl. 1). Around the edge of the Bear Lodge dome, the intrusive bodies have replaced much of the Deadwood and the lower part is not present. Around the northern part of this dome, the entire Deadwood has been replaced and in places the main intrusive body extends out into the Minnelusa Formation. As many as four layers of the Deadwood separated by intrusive rock are present in the southern part of this dome. These layers are principally quartzite; the intrusive preferentially replaced the intervening limestone parts of the Deadwood. At some places the quartzite layers are completely replaced by the intrusive, and in other places the quartzite remains to form prominent ledges that protrude as much as 4 m above the surrounding terrain. Small areas of unreplaced limestone were noted in several places, notably on the ridge at the north end of Ragged Top in the SE¼ sec. 32, T. 52 N., R. 63 W., and on top of a narrow ridge north of Ogden Creek in the NE¼NE¼ sec. 27, T. 52 N., R. 63 W.

The thickest and most complete exposure of the Deadwood Formation is on Sheep Mountain on the east edge of the area shown on plate 1 and on figure 12. Here a thick sequence of shaly limestone interbedded with some quartzite is found in an uplifted block that overlies a partly concealed intrusive plug. The lower part of the Deadwood is cut off by faulting. The northernmost exposure of Deadwood is on the north side of the Hershey Creek dome, where small areas of quartzite and thin-bedded limestone are exposed.

The Deadwood Formation in the Bear Lodge and Hershey Creek domes differs from that in the Black Hills in being metamorphosed and having many of the calcareous layers replaced by the Tertiary intrusive. A section measured on Sheep Mountain indicates that the greater part of the Deadwood in the Bear Lodge Mountains was originally thin bedded shaly limestone; yet the remanent layers of Deadwood around the Bear Lodge dome are mainly quartzite.

The most continuous and in some places the only part of the Deadwood present is an upper quartzite unit. This is a massive layer of hard, white, medium-grained quartzite, 6–9 m thick, that at many places has acted as a dam to the outward penetration of intrusive magma. Around much of the south end of the Bear Lodge dome and around part of the north end of the Hershey Creek dome, this resistant layer of quartzite marks the edge of the intrusive rock. Farther north in the Bear Lodge dome, where intrusive rock extends out into the younger rocks, remnants of this layer commonly form isolated islands in the intrusive rock. Between this quartzite and the overlying Whitewood Limestone is approximately 15 m of shale, which is rarely exposed. Directly below the massive quartzite unit is found approximately 15 m of thin-bedded, medium-grained, brown to red quartzite. Beds are from about 0.5–30 cm thick, and worm burrows are locally present. This unit is not nearly as well exposed as the massive quartzite. In some places a little limestone is present below the thin-bedded quartzite. The limestone is fine grained and pinkish gray, pink, or red, containing greenish-gray silty partings that commonly exhibit worm trails. Below these rocks occur three similar-appearing quartzite layers, which generally consist of hard, white,

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medium-grained quartzite made up of well-rounded quartz grains. In places these quartzites are cross-bedded, contain some small pebbles up to about 0.3 cm in diameter, and have thin shale or slate layers.

The Deadwood Formation is exposed on Sheep Mountain in a thick unbroken section (Section 1), but faulting has cut out some of the lower quartzite units around the south side of the Bear Lodge dome (pl. 1).

The Deadwood Formation near the town of Deadwood was reported to be 116–122 m thick (Darton, 1909, p. 12). From there it tends to thin to the south and thicken to the northwest. On Elk Creek, 14.3 km southwest of Deadwood, it has thinned to 61 m thick (Darton, 1909, p. 12), and in the southern Black Hills it is as little as 1.2 m thick (Gries, 1952, p. 70). Although the Deadwood is present in the subsurface northwest of the Black Hills, only a few drill holes in the vicinity of the Bear Lodge Mountains extended into it. One hole, C. H. Jackson's R-1-Fredricks in the NE¼NE¼ sec. 28, T. 57 N., R. 61 W., although not drilled completely through the Deadwood, did cut 176.5 m of the formation. On Sheep Mountain 270.3 m of Deadwood is exposed in the partial section given previously. To the northwest of the Bear Lodge Mountains, in the northwestern part of the Powder River Basin, more than 335 m of Cambrian rocks are shown on an isopach map by McCoy (1958a, p. 22).

SECTION 1.—*Deadwood Formation*

[Measured on the south side of Sheep Mountain in the SW¼NW¼ sec. 13, T. 52 N., R. 63 W.]

	Meters
Top of ridge.	
Whitewood Limestone (part):	
20. Limestone, massive; light gray with pink mottling	6.0
Partial thickness of Whitewood Limestone	6.0
Deadwood Formation:	
19. Covered	50.0
18. Covered; white quartzite float	14.9
17. Shale, greenish-gray	1.2
16. Quartzite, red, hard	0.5
15. Quartzite, massive, white, medium-grained	5.5
14. Quartzite, brown, medium-bedded; beds 0.3–0.9 m thick; worm trails along bedding planes	7.4
13. Quartzite, brown, calcareous, medium- to thick-bedded; beds 0.9–2.4 m thick	7.6
12. Limestone, thin-bedded, red-stained gray; shale partings; contains several thin intraformational limestone conglomerates	18.0
11. Covered	10.5
10. Quartzite, medium-bedded, medium-grained, brown, calcareous; beds 0.10–0.45 m thick; contains greenish-gray shale interbeds	6.1
9. Limestone, thin-bedded, gray to brown, locally sandy; beds 0.6–10 cm thick; contains greenish-gray shale interbeds. Sparse worm trails in partings near top	46.7
8. Covered	22.3
7. Limestone, thin-bedded; beds 0.3–5 cm thick, like unit 12, but worm trails are common along shale partings	47.0
6. Covered	6.0
5. Limestone, like unit 7	4.7
4. Quartzite; reddish brown with darker reddish brown mottles, feldspathic	0.4
3. Limestone, like unit 7	6.9
2. Limestone, thin-bedded, gray; interbedded with thin layers of gray shale	0.6
1. Covered	14.0
Partial thickness of Deadwood Formation	270.3
Fault.	

The Deadwood Formation as mapped by Darton (1909, p. 12–18) in the northern Black Hills is a clastic sequence containing sandstone, shale, conglomerate, and silty limestone that lies below the Whitewood Limestone and above metamorphosed Precambrian rocks. Fossils collected by Darton in the lower part of the Deadwood and identified by C. D. Walcott (Darton, 1909, p. 18), were originally thought to represent a Middle Cambrian fauna. Darton and Paige (1925, p. 5–7, 24–25) later changed the age of the Deadwood to Late Cambrian. In 1936, fossils of Ordovician age were described from the upper part of the type section of the Deadwood (Furnish and others, 1936). Fossils are scarce in the southern Bear Lodge Mountains because the intrusive rocks cut out most of the fossiliferous limestone beds. A small collection was made from the first limestone below the upper massive quartzite bed on a saddle on a ridge in the SE¼SE¼ sec. 32, T. 52 N., R. 63 W. This collection contained several kinds of trilobites, one indeterminant conodont fragment, and some fish remains. The trilobites were examined by Michael E. Taylor, who identified the following fossils:

Ellipsocephaloides sp.
Ptychaspis striata Whitfield 1878
? *Ptychaspis tuberosa* Feniak 1952
Linguloid brachiopods

Taylor noted that these fossils are Late Cambrian in age and probably came from more than 30 m below the Cambrian-Ordovician boundary.

The fish remains were identified as *Anatolepis*, cf. *A. heintzi* Bockelie and Fortney by Repetski (1978, p. 529). *Anatolepis* is the earliest vertebrate genus known. Four small phosphatic plates and about two dozen individual tubercles of this fossil were originally found in the collection reported above. A later collection made of the same rock contained several thousand fragments consisting mostly of inclined bony scales of the same genus. *Anatolepis* is assigned by Bockelie and Fortey (1976) to the heterostracan fishes. This collection is important, as the rocks from which it came are among the oldest in

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which fishes have yet been found. These fish fossils from the Bear Lodge Mountains are approximately 510 m.y. old, or about 40 m.y. older than any previously collected vertebrate fossils.

Although the upper part of the Deadwood is in general similar to the lower part, McCoy (1952) revised the upper boundary because he felt that the name Deadwood should not be applied to the part of the formation of Ordovician age. He divided the Ordovician part of the section into three thin formations. In ascending order these are: Aladdin Sandstone, 3.7–7.6 m thick; Ice Box Shale, 10.6–12.2 m thick; and Roughlock Siltstone, 7.6–9.1 m thick.

Later study showed additional rocks of Ordovician age in rocks below the Roughlock (McCoy, 1958b, p. 28). In the Bear Lodge Mountains the Ordovician clastic rocks are difficult to differentiate separately due to their thinness, their poor exposure, and their partial replacement by the later intrusive bodies. Hence, boundaries of the Deadwood Formation used here are the same as those used by Darton (1909, p. 12–17), and include all the sedimentary rocks below the Whitewood Limestone. Their age is Late Cambrian and Early Ordovician.

WHITEWOOD LIMESTONE (LATE ORDOVICIAN)

The Whitewood Limestone is a thin, inconspicuous, and poorly exposed unit in the Bear Lodge Mountains (pl. 1). It forms a U-shaped outcrop pattern around the south half of the Bear Lodge dome. The outcrop is not continuous, however, as in places, like along Houston Ridge and on Ragged Top, the Whitewood is cut out by Tertiary intrusive rocks. The Whitewood is also exposed on the northeast side of the Hershey Creek dome and on Sheep Mountain. The best exposures of the Whitewood are found on Sheep Mountain, where the formation makes cliffs as much as 19 m high at the top of this prominent mountain.

The Whitewood Limestone at most places in the Bear Lodge Mountains is light-gray, fine-grained limestone with irregular pink mottles as much as 4 cm across. Beds are generally massive but range from thin bedded to massive.

The lower contact of the Whitewood Limestone is generally not well exposed, because the upper part of the underlying Deadwood Formation rarely crops out. The base of the Whitewood is placed below the lowest exposure of light-gray limestone.

The thickness of the Whitewood Limestone in the mapped area is probably close to 45 m. At its type section in Whitewood Canyon just north of Deadwood, S. Dak., McCoy (1958b, p. 25) reported the formation to be 15.2 m thick. The Whitewood in general thickens to the northwest, and in Mobil Producing Company's Helmer No. F-13-21P well, which is approximately 56 km northwest of the type section and 29 km northeast of Sheep Mountain, it is 68.3 m thick (McCoy, 1958b, p. 26). Farther northwest in Sinclair Oil Company's No. 1 McCanns well, 27.4 km north-northwest of Sheep Mountain, the Whitewood is 158 m thick.

No fossils were found in the Whitewood Limestone in the Bear Lodge Mountains, but Darton (1909, p. 19–20) reported numerous large invertebrates in the northern Black Hills. This fauna is Late Ordovician in age.

PAHASAPA LIMESTONE (EARLY MISSISSIPPIAN)

The Pahasapa is the only thick gray limestone found in the Bear Lodge Mountains. This formation extends around the Bear Lodge dome (pl. 1). Exposures are best around the southern part of the dome, and excellent ones are found in Cole, Ogden, and Tent Canyons. Around the northern part of the dome, the Tertiary intrusive rocks locally have replaced part or all of the Pahasapa. The Pahasapa Limestone also crops out around most of the Hershey Creek dome in the northwestern part of the area, and on Sheep Mountain on the area's eastern margin (pl. 1).

The Pahasapa Limestone, for the most part, is a massive, hard, gray, fine-grained limestone that commonly weathers bluish gray. It is resistant and generally forms prominent hills and low cliffs. The contact of the Pahasapa Limestone and the overlying Minnelusa Sandstone is marked in many places by an abrupt topographic steepening of the slopes underlain by the Pahasapa. Although much of the Pahasapa is massively bedded, the lower part of the formation is partly medium bedded and a few layers are thin bedded. A few light-tan beds were noted, some of which contain a small amount of quartz sand. The lower contact of the Pahasapa is generally not well exposed, and it is placed at the base of the first thick-bedded medium-gray limestone that lies above the pink-mottled, light-gray Whitewood Limestone.

The thickness of the Pahasapa Limestone was not measured in this region, but the formation has been measured in several drill holes both to the north and south of the mapped area. The Pahasapa is 154.2 m thick in Jay Huisman's No. 1 Shelldorf well that lies 10.5 km south of the area. It is 184.1 m thick in Sinclair Oil Company's No. 1 Lawrence well that is 18.2 km northwest of the area, and it is 193.6 m thick in Mobil Producing Company's No. F-13-21P Helmer well that

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is 30.1 km northeast of the present study area. Thus, the Pahasapa is probably between 155 and 175 m thick within the southern Bear Lodge Mountains. The Pahasapa varies considerably in thickness regionally, and Darton (1909, p. 21) noted that it ranged from 30.5 to 213 m thick in the northern Black Hills.

Although fossils in the Pahasapa are scarce in the Bear Lodge Mountains, they are plentiful in other areas. Numerous brachiopods and corals collected by Darton (1909, p. 21–22) in the Black Hills date this formation as Early Mississippian. The fauna and stratigraphy of the Pahasapa Limestone, as a whole, are similar to those of the Lodgepole Member of the Madison Limestone of western Wyoming.

MINNELUSA SANDSTONE (PENNSYLVANIAN AND EARLY PERMIAN)

The Minnelusa is a tan to light-brown, friable sandstone that underlies the lower slopes of the Bear Lodge dome. The Minnelusa Sandstone almost continuously rings the dome, except around the dome's northern part, where the sandstone has been replaced locally by Tertiary intrusive rocks (pl. 1). The Minnelusa also is exposed on the flanks of the Hershey Creek dome. Good exposures are found along the south and east sides of the Bear Lodge dome, but the best ones occur on the east side of the map area (pl. 1) south of Cole Canyon, where the forest has been removed by a fire and considerable topsoil has been stripped by later erosion. Most outcrops consist of gently to moderately dipping sandstone ledges a few meters high, but in the lower part of Winchester Creek and along Beaver Creek east of Ladogar Flats, this formation forms cliffs as much as 20 m high that bound steep gorges.

The greater part of the Minnelusa is fine-grained calcareous sandstone. Color of the sandstone, although predominantly tan, locally varies from white to brown. The sand grains are generally subangular and well sorted, and the sand in some layers is medium grained. Calcareous layers are interspersed with noncalcareous ones. Most of the Minnelusa Sandstone is either thin or medium bedded, and at places the unit has well-developed crossbedding. The base of the Minnelusa is placed below the lowest sandstone and above the massive gray Pahasapa Limestone. Some gray to tan limestone beds occur within the Minnelusa. A conspicuous medium-bedded, gray limestone bed approximately 4 m thick that resembles limestone in the Pahasapa occurs about 10 m above the base of the Minnelusa. Thinner beds of sandy tan limestone are found in the middle part of the formation. A bed of red siltstone less than a meter thick is exposed in a few places in the upper part of this formation. The uppermost member of the Minnelusa is a massive, coarse-grained, cliff-forming sandstone.

The thickness of the Minnelusa Sandstone in northeast Wyoming has been compiled from drill-hole measurements by Foster (1958). His maps show the Minnelusa to be 175–198 m thick in the southern Bear Lodge Mountains. The Minnelusa has the following variation in thickness in the drill holes closest to the map area: (1) 233 m thick in a hole 10.6 km south of the study area, Jay Huisman's No. 1 Shelldorf; (2) 199 m thick in a hole 4.2 km west of the area, Murphy Corporation's Snook No. 1 well; (3) 166 m thick in a hole 9.7 km north of the area, Sinclair Oil Company's No. 1 Mahoney; and (4) 160 m thick in a hole 15.3 km east-northeast of the area, Investor Drilling Company's No. 1 Simons.

No fossils were noted in the mapped area nor were any found by Darton (1909, p. 25) in the northern Black Hills. Fossils, however, have been found along Redwater Creek about 15 km east of the mapped area, where Brady (1958, p. 47) identified 40 species in limestone and dolomite of a local evaporite section. The age of these species ranges from Pennsylvanian to Early Permian.

OPECHE FORMATION (PERMIAN)

The Opeche Formation is a thin, distinctive red clastic unit that separates calcareous tan sandstone of the Minnelusa from the light-gray limestone of the Minnekahta. The Opeche Formation occurs along the lower flanks of the Bear Lodge dome. It is found also along the eastern and northern flanks of the Hershey Creek dome. Although nowhere well exposed, the best exposures are found along the southern and southeastern flanks of the Bear Lodge dome where the Opeche lies directly below gently sloping crests formed by the more resistant overlying Minnekahta Limestone (fig. 4). The Opeche Formation consists of fine-grained, reddish-brown siltstone and some shale. Purplish-red shales crop out at the top of the formation beneath the Minnekahta Limestone. Siltstones commonly are calcareous; calcite makes up the matrix between the quartz grains. The lower boundary is placed at the base of the lowest hematitic, reddish-brown siltstone, and it is an unconformity. The Opeche, being quite friable, is rarely exposed; and this formation is generally marked by scattered patches of reddish-brown soil identical to that of the Spearfish Formation from which it is separated by the intervening Minnekahta Limestone.

The thickness of the Opeche Formation was measured at two places in the study area: (1) northeastern part of the area in a roadcut on the southeast side of Beaver

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FIGURE 4.—Opeche Formation (Po) lies between ledges of the more resistant overlying Minnekahta Limestone (Pm) and the underlying Minnelusa Sandstone (PPm).

Creek in the NE¼SW¼ sec. 3, T. 52 N., R. 63 W., and (2) southeastern part of the area on a small ridge in the NW¼NW¼ sec. 10, T. 51 N., R. 63 W. At the first locality, the Opeche is 20.6 m thick and at the second, 26.1 m thick. The thickness of the Opeche varies considerably in short distances because of its unconformable relation with the underlying Minnelusa Sandstone (Privrasky and others, 1958, p. 50). The Opeche ranges irregularly from 7.6 to 36.3 m in thickness in 60 drill holes that lie within a distance of 36 km of the north, west, and south sides of the study area.

No fossils were noted in the Opeche Formation in the study area, nor have any been reported from the Black Hills. Its age assignment of Permian is based on its stratigraphic position between formations that contain fossils of Permian age.

MINNEKAHTA LIMESTONE (PERMIAN)

The Minnekahta Limestone is a thin gray limestone unit that forms a prominent marker in the Bear Lodge Mountains and the northern Black Hills (Darton, 1909, p. 26). The hardness of this unit combined with the softness of the overlying Spearfish Formation gives rise to broad gentle dip slopes made up entirely of the Minnekahta. The Minnekahta encircles the outermost part of the Bear Lodge dome except in the northeastern part of the area, where it has been replaced by the Tertiary intrusive rocks. Where it laps up on the dome, the limestone commonly forms a low scalloped ridge.

The Minnekahta is for the most part light-gray, thin-bedded, fine-grained limestone. At places the limestone is pinkish gray or is mottled pink and gray. Tan blotches of fine sandy limestone occur in places in the upper and middle parts of this unit. From a distance the Minnekahta appears fairly massive because it commonly forms a low unbroken cliff where it caps ridges. The beds, however, are generally 2.5–8 cm thick, although some are as thick as 75 cm. Some of the beds are finely laminated. The base of the Minnekahta is distinct and is placed at the contact between the uppermost reddish brown, friable siltstone in the Opeche with the lowermost light gray limestone in the Minnekahta.

The thickness of the Minnekahta Limestone was not measured in the study area, but the formation has been measured in four drill holes 4.4–8.9 km west of the area. Its thickness in the Amerada Petroleum Company's Garman No. 1, Nicholson No. 1, and Rathbun No. 1, and the Murphy Corporation's Snook No. 1 holes ranged from 12.8 to 14.0 m. The Minnekahta was also measured 11.0 km south of the mapped area in Jay Huisman's Shelldorf No. 1 hole, where it is 14.3 m thick.

Fossils were not noted in the Bear Lodge Mountains and are rare in other areas. A meager fossil collection made by Darton (1909, p. 26) from the east side of the Black Hills is assigned a Permian age. The Minnekahta Limestone probably correlates with the lower part of the Goose Egg Formation in southeastern Wyoming.

SPEARFISH FORMATION (PERMIAN AND TRIASSIC)

The Spearfish Formation is a thick sequence of reddish-brown shale, siltstone, and fine-grained sandstone that discontinuously encircles the Bear Lodge dome. It is friable and easily eroded, and forms part of the valley bottoms along Togus, Blacktail, Lytle, and Miller Creeks, and Krusee Canyon. The Spearfish forms the center of a syncline between the Bear Lodge and the Hershey Creek domes. It also underlies broad, rolling range land both south and east of the Bear Lodge Mountains.

The lower part of the Spearfish Formation consists of reddish-brown siltstone, shale, and irregular thin interbeds and lenses of white gypsum. The gypsum is more resistant to erosion than the friable clastic rocks and commonly forms the capping on small hills. The upper part of the Spearfish is made up principally of reddish-brown siltstone and fine-grained sandstone. Outcrops are few, and areas underlain by Spearfish are characterized by broad, low areas covered with red soil. The most resistant bed is a thin-bedded, reddish-brown siltstone that is discontinuously exposed about 6 m below the top of the formation. The Spearfish rests with a sharp contact on the underlying Minnekahta Limestone.

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The thickness of the Spearfish Formation was not measured within the study area, but in logs of 64 wells drilled within a distance of 35 km of its north, west, and southwest sides, its thickness ranges from 155.7 to 273.1 m. The Spearfish is 248.7 m thick in the well nearest the map area, the Murphy Corporation's Snook No. 1, which lies 4.0 km west of the southwest corner of the area in the NE¼SW¼ sec. 33, T. 52 N., R. 64 W. Only 6.0 km to the northwest of this hole, the Spearfish thins to 193.0 m in Amerada Petroleum Company's Garman No. 1 hole in the NE¼NE¼ sec. 26, T. 52 N., R. 65 W.

Fossils have not been reported from the Spearfish Formation. The age of this formation is based in part on its position above the Minnekahta Limestone of Permian age and below the Sundance Formation of Jurassic age and in part on the ages of other formations with which it can be correlated. Burk and Thomas (1956) and Privrasky and others (1958, p. 49–50) included the lower gypsum-bearing part of the Spearfish along with the Minnekahta Limestone and Opeche Formation in the Goose Egg Formation of "Permo-Triassic" age in southwestern Wyoming. The upper part of the Spearfish has the same lithology and position as the Red Peak Member of the Chugwater Formation of Triassic age (Robinson and others, 1964, p. 9).

SUNDANCE FORMATION (MIDDLE AND LATE JURASSIC)

The Sundance Formation consists mainly of sandstone and shale. It crops out along the western and northern borders of the mapped area (pl. 1), and it underlies much of the region from the Bear Lodge Mountains westward and northwestward to the Belle Fourche River (Robinson and others, 1964, pl. 1). The Sundance was divided by Imlay (1947, p. 246) into five members, which from oldest to youngest are: Canyon Springs Sandstone, Stockade Beaver Shale, Hulett Sandstone, Lak Shale, and Redwater Shale Members. Subsequently, the Redwater Shale Member of Imlay (1947) was subdivided by Pipiringos (1968, p. D12) into the Pine Butte Member of the Sundance overlain by the Redwater Shale (redefined) and Windy Hill Sandstone Members, giving a total of seven members.

The Canyon Springs Sandstone Member ranges from about 1 to 7.5 m thick and is generally found near the base of a ridge, where the more resistant sandstone units of the Sundance overlie the friable, valley-forming Spearfish Formation. The Canyon Springs is a medium-bedded, light-yellowish-brown, fine-grained, calcareous sandstone that closely resembles the Hulett Sandstone Member in appearance. The base of the Sundance is placed at the base of the first yellowish-brown sandstone above the red soils formed on the Spearfish Formation. Farther west the Sundance overlies the Gypsum Springs Formation (Robinson and others, 1964, p. 10–11), but in the southern Bear Lodge Mountains, the Sundance directly overlies the Spearfish.

The Stockade Beaver Shale Member in two sections measured in the Nefsy Divide quadrangle was 15.2 and 27.4 m thick (Pillmore and Mapel, 1963, p. E12). The Stockade Beaver is for the most part a soft, green, calcareous shale, but it has some thin siltstone and sandstone units in its upper part. This member is generally poorly exposed; its best exposures in this area are found above the road down Lytle Creek in the NE¼NE¼ sec. 3, T. 52 N., R. 64 W. The Stockade Beaver Shale and the Canyon Springs Sandstone Members are mapped as a single unit on plate 1.

The Hulett Sandstone Member is the most topographically prominent unit in the Sundance Formation and generally crops out as a cliff (fig. 8*A*) that can be followed continuously for several kilometers. The member is generally from 20 to 25 m thick. It is well exposed in the map area on the east side of lower Beaver Creek, the north side of Blacktail Creek, on lower Lytle Creek, and along Miller Creek. The Hulett is a yellowish-brown to tan, thin-bedded, well-sorted, calcareous, fine-grained sandstone and siltstone. Ripple marks were noted locally. The lower 1–3 m have some green shale partings.

The Lak Member is 38–57 m thick (Pillmore and Mapel, 1963, p. E12). This unit is made up of yellowish-brown to tan poorly sorted siltstone and fine-grained sandstone. The Lak has few outcrops in the map area. It differs from the underlying Hulett Sandstone Member in being more massively bedded and in being less firmly cemented.

The Pine Butte, Redwater Shale, and Windy Hill Members taken together are approximately 52 m thick, and for the most part they underlie rolling, heavily forested ridges. The Pine Butte Member at the base is made up principally of interbedded calcareous, greenish-white sandstone and interbedded siltstone and greenish-gray shale. The overlying Redwater Shale Member is greenish-gray shale with interbeds of gray to tan calcareous siltstone and subordinate fine-grained sandstone. Glauconite is present in most of the sandstone layers in both the Pine Butte and Redwater Shale Members. Just west of the map area in the Redwater Shale Member on lower Hershey Creek is a bed of brownish-gray, fragmented limestone, 0.2 m thick, that contains numerous shell fragments. The Windy Hill

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Member, at the top of the Sundance, is yellowish-gray, fine-grained, calcareous sandstone.

The entire Sundance Formation is about 114 m thick along Miller and Houston Creeks in the northwestern part of the Nefsy quadrangle (Pillmore and Mapel, 1963, p. E8). The formation does not vary much in thickness along the western flanks of the Bear Lodge Mountains and the Black Hills, where Robinson, Mapel, and Bergendahl (1964, p. 14) noted that in most places it is between 114 and 122 m thick.

Fossils have been found in all but the Lak Member of the Sundance Formation; they include ammonites, pelecypods, brachiopods, foraminifera, and ostracodes (Pillmore and Mapel, 1963, p. E8). The age of the Lak and lower members was considered by Imlay (1947, p. 230–231) to be Callovian (Late Jurassic) and the Redwater Shale Member as defined by him to be Oxfordian (Middle Jurassic). The lower four members of the Sundance are correlated by Peterson (1954, p. 484) to the Rierdon Formation of Montana and the upper part of the Twin Creek Formation of western Wyoming and southeastern Idaho; the upper three members (the Pine Butte, Redwater Shale, and Windy Hill Sandstone) are correlated by Peterson (1954, p. 491, 494) to the Swift Formation of Montana and the Stump Sandstone of western Wyoming and southeastern Idaho.

MORRISON FORMATION (LATE JURASSIC)

The Morrison Formation, consisting chiefly of crumbly claystone, is not exposed in the mapped area. It is exposed along the lower slopes of low ridges to the west and north of the mapped area (Robinson and others, 1964, pl. 1), but in the mapped area (pl. 1) it occurs in only two small wooded areas along the west edge, where it underlies the Lakota Formation. As it is exposed in neither area, the description of the Morrison comes from outcrops to the west of the map area (Pillmore and Mapel, 1963, p. E14–E16; Robinson and others, 1964, p. 19–22).

The Morrison Formation is made up mainly of greenish-gray claystone, although in the uppermost beds it is dark gray to dark brownish gray in color. The Morrison can be divided into two parts: the upper 0 to about 15 m being noncalcareous claystone, and the lower part being mostly calcareous claystone. The lower 7 m of the formation is commonly sandy and contains one or more 0.3- to 1.2-m-thick beds of cross-laminated, fine-grained, calcareous sandstone and light-gray limestone. The Morrison grades downward into the Sundance Formation, and the base of the Morrison is placed on the top of a persistent bed of yellow-weathering sandstone in the Windy Hill Member of the Sundance. In some areas, such as the thickly wooded hills along the western margin of the map area, the position of this contact is not easily located.

In 17 measured sections in the Nefsy Divide quadrangle (fig. 1) Pillmore and Mapel (1963, p. E14, pl. 2) found that the Morrison Formation ranged in thickness from about 19.8 to 36.6 m. Locally, however, it may be much thinner, and 3 km north of the northwest corner of the map area in sec. 22, T. 53 N., R. 64 W., it is only 6.1 m thick (Robinson and others, 1964, p. 19).

Fossils are locally abundant in the lower calcareous part of the Morrison Formation and include ostracodes, charophytes, dinosaur bones, a few pelecypods, and silicified wood (Pillmore and Mapel, 1963, p. E16). Their age is considered to be Late Jurassic (Reeside, 1952; Sohn, 1958, p. 124; and Peck, 1957, p. 8).

LAKOTA FORMATION (EARLY CRETACEOUS)

The Lakota Formation is the uppermost unit of Mesozoic age exposed in this region. This formation is widespread just west of the Bear Lodge Mountains and is well exposed on Sherrard Hill adjacent to the northwest corner of the map area (pl. 1). In the mapped area, however, it underlies only two small areas along the west edge (pl. 1).

Only the lowermost part of the Lakota Formation is present in the study area. It is mainly a medium-grained, light-gray to white, medium-bedded to massive sandstone. Sand grains are well rounded and fairly well sorted, and almost all are quartz. Rounded chert and quartzite pebbles are scattered through the rock in some places. Some beds are conspicuously crossbedded. The lower contact is placed at the base of the first sandstone along a covered slope formed on the much less resistant Morrison Formation.

Only the lower 3–4 m of the Lakota Formation are present in this area. Pillmore and Mapel (1963, p. E17) reported the Lakota Formation to range in thickness from 30.5 to 36.6 m in the neighboring Nefsy Divide quadrangle (fig. 1), and it thickens northward to about 90 m in the northern part of the Bear Lodge Mountains (Robinson and others, 1964, p. 23).

The Lakota Formation is considered to be Early Cretaceous in age on the basis of fossil ferns, cycads, conifers, ostracodes, and charophytes (Robinson and others, 1964, p. 26). The Lakota has been correlated with the lower part of the Cloverly Formation of central and western Wyoming (Cobban and Reeside, 1952, chart 10b).

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TERTIARY INTRUSIVE AND VOLCANIC ROCKS

INTRODUCTION

The Tertiary intrusive rocks in the southern Bear Lodge Mountains are a group of interrelated alkalic rocks that have a relatively high potassium content and a low silica content. These rocks form a central mass 8.4 km long by about 3.4 km wide that underlies the central part of the area. Other smaller intrusive bodies are intruded into both the sedimentary rocks surrounding the main mass and into older intrusive rocks (fig. 5*A*). They are especially numerous northwest of the main mass along Lytle and Hershey Creeks, where more than 30 separate intrusive bodies have been recognized (pl. 1). The intrusive rocks form dikes, sills, irregular bodies, and possibly laccoliths. These bodies cut older rocks ranging from Precambrian to Jurassic in age. A similar intrusive cuts rocks of Early Cretaceous age 1.6 km west of the area (Pillmore and Mapel, 1963, pl. 1). The intrusive rocks are overlain within the area by both the White River and Ogallala Formations. Both of these formations contain subangular clasts of Tertiary intrusive rocks.

The Tertiary igneous rocks that are now exposed represent, for the most part, a composite sequence of alkalic rocks that were intruded into the older rocks at a fairly shallow depth. These rocks tend to be porphyries, as they were emplaced close to the surface and cooling rate was rapid. Flow banding is common in many of the intrusives (fig. 5*B*), although in the more altered rocks it may be difficult to discern. Flows and pyroclastic deposits were formed in a few places where the magma reached the surface. A vesicular flow top was noted on the ridge at the head of Whitelaw Creek in the SE¼SE¼ sec. 7, T. 52 N., R. 63 W. Tops of flows are commonly difficult to determine, as not all vesicular rocks are extruded on the surface. Pyroclastic deposits, on the other hand, are easier to identify and give proof of surface breaching. They are not common and occur as a few, small, widely scattered erosional remnants in the northwestern part of the area. Small bodies of fine-grained syenite or nepheline syenite are found in a few places, where cooling was slower. Syenite and nepheline syenite were also encountered in several deep holes drilled near the headwaters of Whitelaw Creek, where they make up the bulk of the rock.

The greater volume of intrusive rocks is either trachyte or phonolite. Distinction between these two rock types is commonly based on the recognition or lack of recognition of some feldspathoid. In addition to

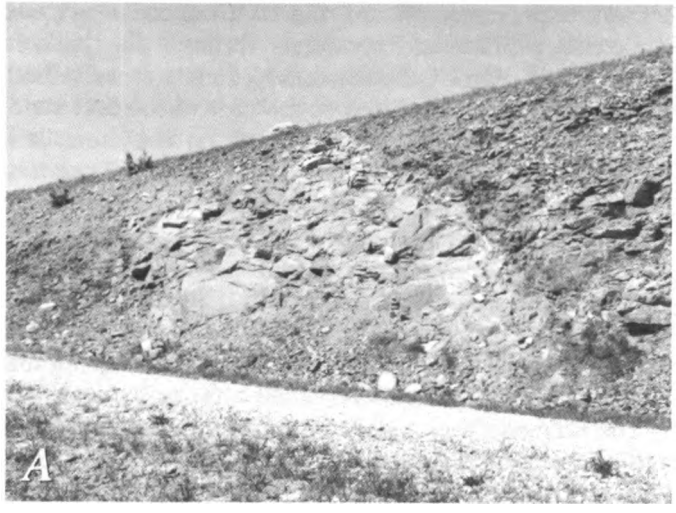






FIGURE 5.—Trachyte intrusives. *A*, One of the younger trachyte dikes (light gray) cuts an older trachyte body (dark gray) along the road to the Forest Service lookout. *B*, Well-developed flow structure in an outcrop of trachyte exposed along the west side of Lytle Creek. *C*, Cliffs of an unaltered trachyte intrusive along the northeast side of Lytle Creek.

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trachyte and phonolite, lesser amounts of latite and minor amounts of syenite, nepheline syenite, lamprophyre, pseudoleucite porphyry, carbonatite, and intrusive breccia were noted within the main mass or in outlying intrusives.

The distinguishing of various rock types from one another or of bodies of the same rock type formed at different times is difficult for two reasons: (1) a single intrusive unit is commonly not homogeneous, and (2) most of the intrusive rock has been hydrothermally altered after formation. The phenocrysts in the different porphyritic rocks are commonly used to distinguish between the various rock types. Phenocrysts are an unreliable guide to rock type in the Tertiary intrusive rocks of the Bear Lodge Mountains; in part this is because not all rocks of the same composition have phenocrysts. For example, one intrusive rock may have well-developed rectangular phenocrysts of sanidine as long as 2 cm, whereas another may have few or no visible phenocrysts. Yet in places rocks with 15 percent of large sanidine phenocrysts can be traced a few meters laterally into a nonporphyritic rock. Phenocrysts are an unreliable guide in this study area, because minor changes in composition in the same dike may result in different suites of minerals. For example, in the southern part of a dike that crosses Lytle Creek in the S½ sec. 12, T. 52 N., R. 64 W., phenocrysts consisted of 24 percent hornblende, 6 percent magnetite, and 5 percent biotite. Phenocrysts from near the north end of this same dike, however, consisted of 20 percent sanidine, 8 percent hornblende, 4 percent magnetite, and less than 1 percent biotite.

During the waning stages of Tertiary intrusion, many of the intrusive rocks were fractured and altered by hydrothermal solutions. This alteration is most intense in the intrusives in the central part of the Bear Lodge dome, although most of the rocks show some sign of alteration. In many places most of the mafic minerals have been partly or entirely destroyed. In some places only crystal molds filled or partly filled with iron oxides indicate the former presence of mafic minerals. Nepheline is also easily altered to a mixture of compound feldspar and clay, which occur in hexagonal holes. Less altered rocks are most commonly found in some of the smaller intrusives peripheral to the major igneous mass. Thus, many of the outlying rock types are more easily identified than those in the main body, and here I have separated syenite, lamprophyre, pseudoleucite porphyry, and latite from trachyte and phonolite. In the central mass of Tertiary intrusion, these rocks were not mapped separately, but an intrusive breccia body, a carbonatite, and several younger dikes were readily distinguishable. The younger dikes were intruded into the central body of the intrusion during the waning stages of Tertiary magmatism after most of the hydrothermal alteration was completed. These unaltered dikes with their greenish-gray matrices stand out from the surrounding bleached, light-gray to white older rocks. These latter dikes, although not all of the same composition, have also been mapped separately (pl. 1). A large, poorly exposed, intrusive breccia body in the northern part of the central mass was crudely outlined. Many carbonatite dikes were intercepted during drilling in secs. 17 and 18, T. 52 N., R. 63 W., but only one such dike in the SE corner sec. 7, T. 52 N., R. 63 W. is exposed and mapped on the surface (pl. 1).

PHONOLITE AND TRACHYTE

These two rock types make up the bulk of the Tertiary intrusive rocks exposed in the southern Bear Lodge Mountains. They not only make up the greater part of the core of the Bear Lodge dome, but they also make up most of the smaller separate intrusions that occur on the flanks of this dome (pl. 1; fig. 5*C*).

Phonolite and trachyte are discussed together in this report because of the difficulty in separating these two rock types in the field or laboratory. Separation of these two rock types is based on silica content. A rock is considered a trachyte when sufficient silica is present to form feldspar from all the alkalies; the rock is a phonolite when it contains insufficient silica to form feldspars from all the alkalies. Thus, the presence of a feldspathoid, such as nepheline, denotes a silica deficiency. Feldspathoids generally form small inconspicuous crystals that in many places are not readily identifiable in hand specimens. Nepheline may occur only in the matrix and its presence may be determinable only by chemical analysis. For example, nepheline was not identified in thin sections of samples collected from an intrusive body just east of Jim Wayne Canyon. The composition of this sample (table 2, No. 10), however, indicated a deficiency of silica (3.4 percent nepheline) (table 2, No. 10). Thus, these two rock types are in many places not readily separable in the field. Phonolite and trachyte may be light gray, dark gray, or greenish gray, although where stained by iron oxides they are commonly shades of brown. They are commonly porphyritic with most having 20–35 percent phenocrysts, although some have as little as 2 percent and others as much as 95 percent. The most common phenocrysts are distinctive white tabular crystals of sanidine, which range in size from about 1 to 35 mm. Dull-white hexagonal phenocrysts of nepheline (1–6 mm in diameter) in amounts up to 25 percent are visible in some of the phonolite. Small trapezohedrons of pseudoleucite were noted in a few places. Plagioclase phenocrysts were also noted in a few

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TABLE 2.—*Chemical analyses and normative compositions in weight percent of Tertiary intrusive rocks*

[Sample Nos. 1-10, analysts, Hezekiah Smith and Lowell Artis; sample No. 11 collected by N. H. Darton; analyst, George Steiger (Darton, 1965, p. 6); sample No. 12, analysts, K. F. Coates and Hezekiah Smith. Leaders (–), none]

Constituent or mineral	Sample No. 1	2	3	4	5	6	7	8	9	10	11	12
Chemical analyses												
SiO_2	52.3	54.3	58.7	58.9	56.7	55.4	56.4	57.0	58.1	59.2	55.14	60.1
Al_2O_3	15.0	16.4	17.1	16.8	17.4	19.2	20.5	17.7	21.8	17.2	18.98	16.9
Fe_2O_3	6.1	5.0	5.5	5.7	3.4	2.3	1.8	2.4	1.5	2.6	2.60	3.5
FeO	2.5	1.7	.76	.80	1.8	1.5	.40	1.5	.48	1.3	1.62	1.4
MgO	3.2	1.3	1.7	1.5	1.4	.77	.23	1.2	.54	1.1	.32	1.4
CaO	5.9	3.5	3.8	3.4	4.1	3.3	.90	3.5	1.1	2.8	3.96	3.5
Na_2O	2.8	4.8	5.0	4.9	4.9	5.5	8.3	5.2	6.4	5.5	5.38	5.1
K_2O	6.5	6.4	3.7	3.9	5.2	7.0	6.4	6.2	6.7	6.5	6.64	5.8
H_2O+	1.9	2.7	.83	.84	1.1	2.8	2.9	2.3	2.9	1.9	3.70	.91
H_2O-	1.1	1.4	.76	.53	.54	.52	.34	.56	.47	.42	.63	.52
TiO_2	1.4	1.1	.84	.80	.68	.52	.18	.54	.16	.59	.50	.82
P_2O_5	.57	.19	.46	.43	.31	.13	.04	.14	.04	.13	.17	.22
MnO	.14	.15	.14	.10	.10	.12	.14	.12	.10	.12	Trace	.11
CO_2	.12	.01	.03	.08	1.0	.07	.07	.36	.05	.01	.00	.24
	99.53	98.95	99.32	98.68	98.63	99.13	98.60	98.72	100.34	99.37	99.64	100.52
Normative compositions												
Quartz	--	--	7.08	7.74	1.38	--	--	5.04	--	--	--	3.24
Orthoclase	39.48	40.03	22.24	23.91	31.69	43.37	39.48	26.69	40.59	39.48	41.14	35.03
Albite	23.06	31.44	42.97	42.44	42.97	26.72	34.06	40.87	39.82	41.39	29.87	39.82
Anorthite	10.29	4.45	13.90	12.79	10.01	7.51	.56	15.29	5.56	3.34	8.62	8.06
Nepheline	--	6.25	--	--	--	11.36	20.73	--	8.52	3.41	9.37	--
Hypersthene	1.80	--	3.70	3.40	2.70	--	--	2.10	--	--	--	.40
Diopside	12.74	7.34	1.51	1.36	2.45	4.81	1.30	2.16	--	6.05	1.94	6.70
Wollastonite	--	1.86	--	--	--	1.51	1.04	--	--	1.39	3.60	--
Olivine	.84	--	--	--	--	--	--	--	1.96	--	--	--
Corundum	--	--	--	--	--	--	--	--	2.24	--	--	--
Magnetite	4.41	2.78	.46	.46	4.18	3.48	1.16	3.71	1.39	2.55	3.71	2.32
Hematite	3.20	3.19	5.28	5.60	.64	--	1.12	--	.64	.96	.16	1.92
Ilmenite	2.89	2.28	1.67	1.52	1.37	1.06	.46	1.06	.30	1.22	.91	1.52
Apatite	1.34	--	1.34	1.01	.67	--	--	--	--	--	.34	.34
Calcite	--	--	--	.20	2.40	--	--	--	--	--	--	--
Na_2O_3	.32	--	--	--	--	.21	.21	.95	--	--	--	.64
TOTAL--	100.37	99.62	100.15	100.23	100.46	100.03	100.12	97.87	101.02	99.79	99.66	99.99

SAMPLE DESCRIPTIONS

1. Lamprophyre collected on ridge top on west side of the North Fork of Miller Creek, NE1/4 NE1/4 sec. 23, T. 52 N., R. 64 W.
2. Pseudoleucite porphyry from east side of road that follows a tributary of Lytle Creek, SE1/4 SE1/4 sec. 11, T. 52 N., R. 64 W.
3. Latite from ridge top about 400 m east of paved road, SE1/4 SW1/4 sec. 28,T. 52 N., R. 63 W.
4. Latite from roadcut SW1/4 SW1/4 sec. 28, T. 52 N., R. 63 W.
5. Latite from roadcut near headwaters of Ogden Creek, SW1/4 NW1/4 sec. 28, T. 52 N., R. 63 W.
6. Phonolite from dike on lookout tower road, SE1/4 SE1/4 sec. 20, T. 52 N., R. 63 W.
7. Phonolite from small intrusive body on ridge, SW1/4 NW1/4 sec. 3, T. 51 N., R. 63 W.
8. Trachyte from Bock Mine to west of lookout tower, SW1/4 SE1/4 sec. 20, T. 52 N., R. 63 W.
9. Phonolite from intrusive body in southeast corner of area, NE1/4 SE1/4 sec. 3, T. 51 N., R. 63 W.
10. Trachyte from intrusive body on ridge to east of Jim Wayne Canyon, NW1/4 SW1/4 sec. 30, T. 52 N., R. 63 W.
11. Phonolite from Warren Peaks (Darton, 1905, p. 6).
12. Trachyte from intrusive body that crosses Lytle Creek, SE1/4 sec. 2, T. 52 N., R. 64 W.

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samples. The principal mafic mineral is aegirine-augite, which may make up as much as 20 percent of the rock but is generally less than half this amount. This mineral occurs in small, greenish-black, prismatic crystals. Tiny black magnetite grains commonly make up a few percent of the rock. Sphene, apatite, and biotite are other common accessories that generally make up less than 1 percent of the rock. Other phenocrysts noted in a few samples are hornblende and the black garnet, melanite. The phenocrysts are set in a brown matrix, which contains numerous feldspar and, in some places, mafic microlites. Staining tests with sodium cobaltinitrite indicate that much of the feldspar in the matrix is potassium rich.

Chemical analyses on six samples of phonolite and trachyte are reported in table 2 (Nos. 7–12). These samples are noted for their low silica content, and four of the six contain nepheline in the norm. They also have relatively high potassia and soda content. The high alkali content and low silica content of these rocks are also apparent in the norms, which have high orthoclase and albite contents, as well as containing nepheline. The relations between CaO, Na_2O, and K_2O are shown in figure 6 along with that of various average rock types

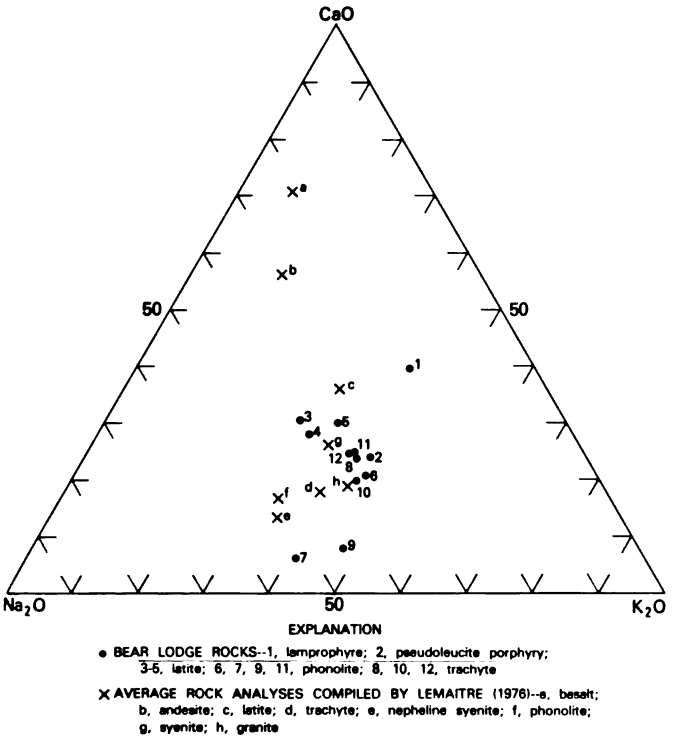


FIGURE 6.—Relations of K_2O, Na_2O, and CaO in the Tertiary intrusive rocks of the southern Bear Lodge Mountains compared to average rock analyses by LeMaitre (1976). Numbers on Bear Lodge rocks correspond to those used in table 2.

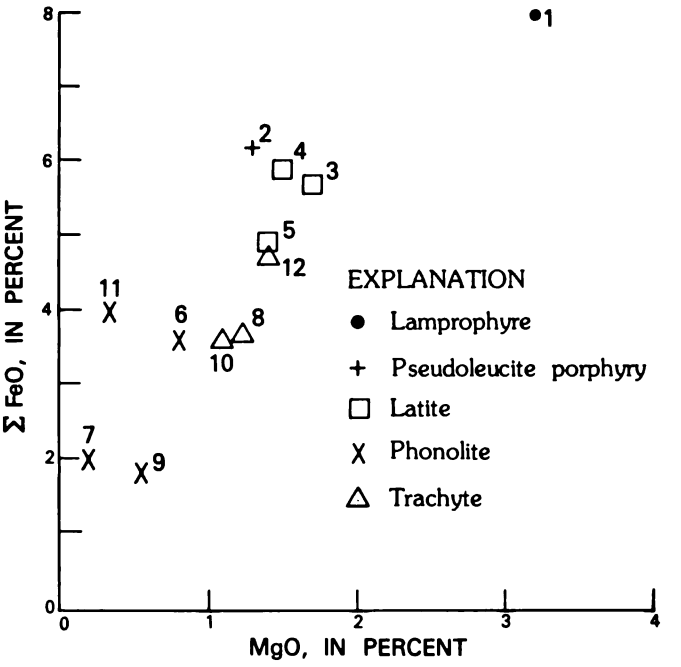


FIGURE 7.—Relation of MgO to total iron oxide in the Tertiary intrusive rocks of the southern Bear Lodge Mountains. Numbers used correspond to those used in table 2.

compiled by LeMaitre (1976). The Bear Lodge rocks with the exception of the lamprophyre contain about equal amounts of Na_2O and K_2O. The CaO contents of the trachyte and phonolite show considerable spread; most samples are somewhat richer in CaO than LeMaitre's average trachyte or phonolite. The magnesia and total iron contents are similar in the trachyte and phonolite (table 2). The MgO content does not exceed 1.5 percent, and the total iron oxide content ranges from about 2 to 4 percent. Plotting the MgO content against the total iron content for all the analyses of Tertiary intrusive rocks of the southern Bear Lodge Mountains shows that in general the MgO content increases proportionally as the total iron oxide content increases (fig. 7).

LATITE

Fine-grained latite is found principally in the core of the Hershey Creek dome and in places in the southeastern part of the main intrusive complex. Latite makes up all the Tertiary rocks in the Hershey Creek dome except for two trachyte dikes and a small patch of pyroclastic rocks. In the southeastern part of the main complex, scattered latite intrusives occur south of Richardson Creek. The latite in Hershey Creek dome is unal-

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tered and the phenocrysts are readily recognizable. Here it is mapped separately. The latite in the southeastern part of the main Tertiary igneous mass is partly altered, fine grained, and difficult to distinguish from the other Tertiary igneous rock types without the aid of a microscope. These rocks were included in my mapping with the other Tertiary intrusive rocks of the central complex. Most of the latite forms irregular masses presenting indistinct contacts with other Tertiary intrusive rocks. A 3- to 5-m-thick north-trending latite dike that cuts trachyte is well exposed in a roadcut in the headwaters of Ogden Creek. Not all the latite is younger than all the trachyte, as several dikes of trachyte cut latite in the Hershey Creek dome. In some places, the latite has flow banding. This can be seen on the ridge east of the main road and southwest of the headwaters of Ogden Creek where weathering along flow banding has developed into irregular platy layers, 1–5 cm thick. These layers dip 25°–40° N. (pl. 1).

Latite is a light-gray porphyritic rock, generally with 30–35 percent small phenocrysts, although as much as 65 percent phenocrysts have been noted. Most phenocrysts are 0.5–1.2 mm long; a few as long as 3 mm occur in some places. White, elongate plagioclase (8–50 percent), which is either oligoclase or andesine, is commonly the most abundant phenocryst. Black, prismatic hornblende (<1–15 percent) is generally the most abundant mafic mineral, although aegirine-augite (trace to 6 percent) may be locally more common. Other minerals identified are biotite (0–2 percent), augite (0–2 percent), magnetite (1–4 percent), apatite (trace to <1 percent), sphene (0–<1 percent), and zircon (0 to trace). The matrix is aphanitic and consists principally of tiny plagioclase microlites with some black mafic minerals and some indeterminate leucocratic minerals. Staining of all thin sections with sodium cobaltinitrite indicates potassium in the matrix.

Three samples of latite from sec. 28, T. 52 N., R. 63 W. in the southeastern part of the area were chemically analyzed (table 2, Nos. 3, 4, and 5). These rocks contain the least amount of K_2O of any rocks analyzed. They also differ from the trachytes and phonolites with which they are generally associated by having more total iron oxides, MgO, TiO_2, and P_2O_5, and less Na_2O and total water. The normative mineral compositions of the three latites all have quartz, more than 40 percent albite, and a substantial amount of orthoclase. Each sample has similar proportions of alkalies (fig. 6). The CaO content, however, is somewhat lower that that of the average latite given by LeMaitre (1976) and shown on figure 6. All three of these samples would also be classified as latites according to the system of Rittmann (1952).

SYENITE AND NEPHELINE SYENITE

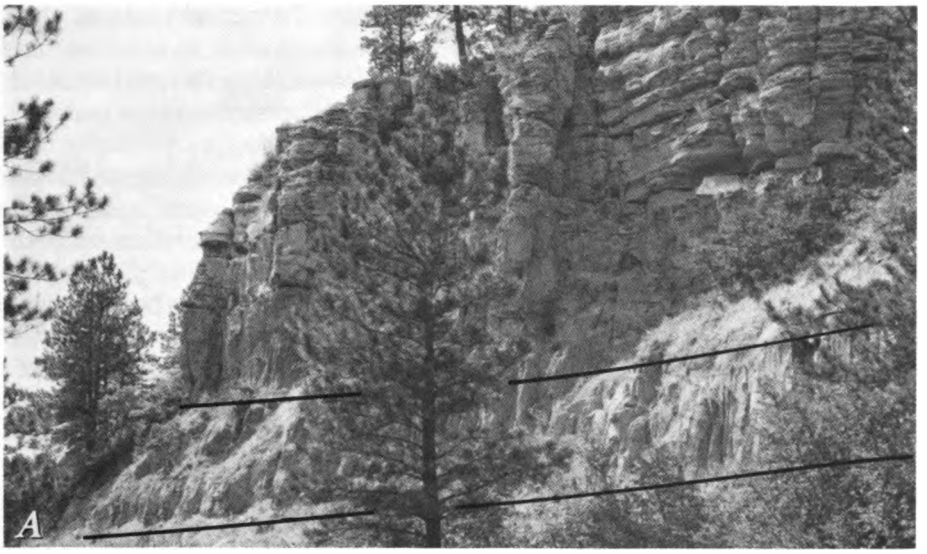
These two rock types are the holocrystalline phase of trachyte and phonolite. They are sparse at the surface in the study area. Syenite and nepheline syenite were mapped in three areas: (1) a dike approximately 190 m in length cuts the Minnelusa Sandstone near the east edge of the area 300 m north of Ogden Creek; (2) several outcrops occur along one of the tributaries to Winchester Creek in the central part of sec. 6, T. 52 N., R. 63 W.; and (3) several small bodies intrude trachyte and phonolite 1,800 m east of Fort Ranch in the northwestern part of the study area. In addition, syenite and nepheline syenite are common at depth in several drill holes located near the headwaters of Whitelaw Creek. Most of the larger bodies of trachyte and phonolite probably grade downward into syenite and nepheline syenite where the cooling of this alkali magma was slower.

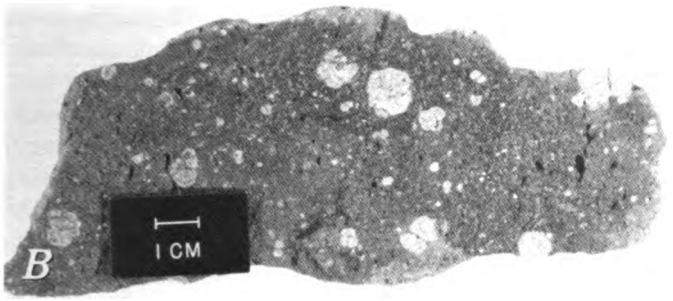
Average grain size of various samples of syenite or nepheline syenite ranges from about 0.1 to 3 mm or from fine to medium grained. Most of the small bodies of this rock exposed at the surface are syenite, although an intrusive on the nose of the mountain 1,800 m east of Fort Ranch is nepheline syenite. The syenite consists of 60–80 percent potassium feldspar, a little plagioclase, and 20–35 percent aegirine-augite or augite. Small black crystals of magnetite make up 1–8 percent of the rock, and apatite, sphene, and hornblende range from a trace to 1 percent of the rock. The nepheline syenite east of Fort Ranch is in general similar but contains less potassium feldspar and 22 percent nepheline. Samples from drill holes from near the headwaters of Whitelaw Creek have as much as 20 percent biotite, but only a little pyroxene. The black garnet, melanite, also makes up several percent of some of these rocks.

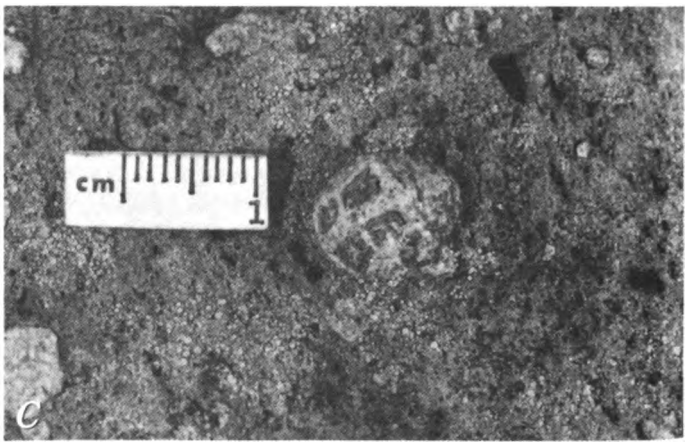
LAMPROPHYRE

Lamprophyre is the term applied to those porphyritic igneous rocks whose phenocrysts consist almost entirely of mafic minerals and whose groundmass consists of the same mafic minerals and leucocratic minerals. Five lamprophyre dikes and sills have been noted in the southern Bear Lodge Mountains. The largest is a sill (fig. 8*A*) along the western margin of the area that crosses the North Fork of Miller Creek. The sinuous outcrop pattern of this sill has been traced for 4.5 km and it is approximately 4–12 m thick. Two other lamprophyre sills are exposed within 150 m of each other 700 m southeast of Fort Ranch in the northwest corner of the area. These two sills are approximately 45 m vertically

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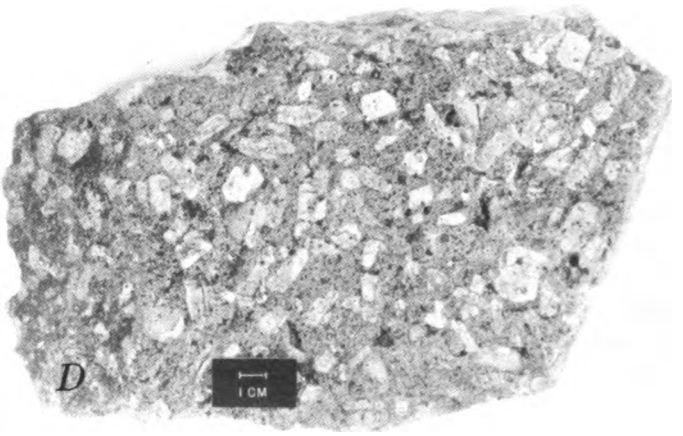


FIGURE 8.—Tertiary intrusive rocks. Photographs *B*, *C*, and *D* by L. S. Hedricks, U.S. Geological Survey. *A*, Lamprophyre sill (between lines) intruded into the Sundance Formation along the north side of Miller Creek. The flaggy sandstone above the lamprophyre belongs to the Hulett Sandstone Member. *B*, Pseudoleucite porphyry. Large white pseudoleucite and small white sanidine phenocrysts set in a dark-gray aphanitic matrix. *C*, Close-up of pseudoleucite phenocryst showing pattern formed by white, potassium feldspar rims around gray central part consisting of nepheline and clay. *D*, Trachyte consisting of large white sanidine and small black aegerine-augite phenocrysts set in a gray aphanitic matrix.

apart with one being intruded into the upper part of the Spearfish Formation and the other into the lower part of the Sundance Formation. Two lamprophyre dikes too small to show on plate 1 were noted in the central part of the intrusive complex. One is a small dike exposed on the southeast side of Bear Den Creek, 1,000 m southwest of the U.S. Forest Service Lookout tower; the other crosses a pit on Smith Ridge 1,330 m south of Davis Spring.

The lamprophyres vary somewhat in mineralogy, with augite being the most abundant phenocryst in the large sill that crosses Miller Creek, biotite in the two sills south of Fort Ranch, and hornblende on the exposure on Smith Ridge. The sill on Miller Creek is made

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up of small phenocrysts up to about 1 mm in length that consist of 18–25 percent augite, 2–5 percent magnetite, and less than 1 percent apatite and biotite set in a matrix containing many small mafic and plagioclase microlites. The sill is freshest on the ridge south of Miller Creek; it is commonly altered along Miller Creek, and in specimens collected here just above the road, most of the pyroxene has been altered to limonite. This sill contains oval amygdules 3–20 mm long, filled with calcite and feldspar. The only visible phenocryst in the sills south of Fort Ranch is biotite, which makes up 10–20 percent of the rock. These sills also have small, white, oval amygdules. The small lamprophyre dike on Bear Den Creek consists of 60 percent mafic phenocrysts (30 percent augite, 15 percent biotite, 10 percent magnetite, 4 percent hornblende, and 1 percent apatite) and 5 percent plagioclase phenocrysts set in a gray aphanitic matrix. The fine-grained lamprophyre exposed on Smith Ridge consists of 85 percent mafic minerals (40 percent hornblende, 15 percent chlorite, 10 percent epidote, 10 percent biotite, and 10 percent sphene) set in a light-gray matrix made up mainly of plagioclase.

A chemical analysis of the lamprophyre that crosses the North Fork of Miller Creek is given in table 2 (No. 1). This analysis compared to those of phonolite and trachyte is low in SiO_2, Al_2O_3, and Na_2O, but high in Fe_2O_3, FeO, MgO, CaO, TiO_2, and P_2O_5. The high mafic-mineral content in the mode is reflected in the 27 percent mafic minerals in the normative compositions, which includes 12.7 percent diopside and 4.4 percent magnetite (table 2). The rocks of the southern Bear Lodge Mountains are noted for their high K_2O content, and this lamprophyre in spite of its high content of mafic minerals is no exception, having 6.4 percent K_2O.

PSEUDOLEUCITE PORPHYRY

The pseudoleucite porphyry is a type of phonolite, but the presence of large pseudoleucite crystals makes it distinctive from all the other intrusives in the area (figs. 8*B*, 8*C*). The pseudoleucite porphyry occurs principally in the northwestern part of the area, where it forms one long intrusive and several smaller ones. The large intrusive is principally a sill in the middle of the Sundance Formation, but in places it has cross-cutting relations. The sill-like body is the westernmost intrusive in the study area and occurs about 3 km south of Fort Ranch. It has an irregular, sinuous form and a length of approximately 2,600 m. Thickness is difficult to measure because at many places it caps a ridge, but it is approximately 6 m thick. Five other small pseudoleucite sills and dikes were mapped in the same area. Two small lens-like bodies occur in the middle of the Sundance Formation north of the big body, two dikes cut the Morrison Formation south of it, and an intrusive body occurs along the road to its southeast. The longest dimension on any of these bodies is 140 m.

The pseudoleucite porphyry is a medium-gray porphyritic rock containing 5–20 percent white pseudoleucite and 3–10 percent sanidine set in an aphanitic matrix that has microlites of both feldspar and mafic minerals. The sanidine phenocrysts are inconspicuous, as they are generally less than 1 mm in length. The pseudoleucite crystals, on the other hand, range from 1 to 38 mm in diameter, with most of them between 5 and 10 mm. The pseudoleucite crystals are round to octagonal, and some crystals show the outline of several intergrown minerals (fig. 8*C*). The pseudoleucite crystals are made up of intergrowths of potassium feldspar, nepheline, and clay. Generally the potassium feldspar forms a narrow white rind around the exterior of the crystal (fig. 8*C*), although in some places this rind is pink. Potassium feldspar also forms narrow septa cutting across the interior of the crystal. The feldspar can be distinguished from the other minerals on a weathered surface, because it stands out in relief.

Pseudoleucite porphyry, like most of the other rocks in this area, has a high potassium content. The presence of abundant potassium was noted both from staining this rock with sodium cobaltinitrite solution and by chemical analysis of one sample (table 2, No. 2). This sample contained 6.4 percent K_2O, which is similar to the amount found in trachyte and phonolite in the southern Bear Lodge Mountains. This sample was also deficient in silica, containing less SiO_2 than all the other rocks analyzed except the lamprophyre. Classified on the basis of its chemical composition according to the system used by Rittmann (1952), this rock would be a dark leucite phonolite.

PYROCLASTIC DEPOSITS

Pyroclastic deposits are rare in the southern Bear Lodge Mountains, but they are geologically important because they indicate that the Tertiary igneous rocks breached the surface in a few places. These deposits occur in two areas: (1) two separate patches of pyroclastics are found on the northeast side of Lytle Creek near the eastern border of sec. 13, T. 52 N., R. 64 W., and (2) a small area of pyroclastics is found on a small ridge in the center of the Hershey Creek dome (pl. 1). The position of most of the pyroclastics along the valley walls on the steep northeast side of Lytle Creek and part way up the south side of Hershey Creek suggest that they were preserved principally along Tertiary valleys. The pyroclastic deposits, which were at one time more widespread, have been largely removed by erosion. Those

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patches preserved are where the pyroclastics were thicker and somewhat protected in the valleys.

The pyroclastic deposits range from volcanic breccia to tuff. The volcanic breccia is medium gray to light brown and made up of subangular to subrounded fragments, a few to 40 mm across, set in a glassy matrix. Fragments are chiefly porphyritic volcanic rock containing small sanidine phenocrysts. A few of the lithic fragments in the Hershey Creek dome locality are of syenite and fine-grained quartzite. The tuff is light brown to white in color. Fragments are principally lithic, although this rock can contain as much as 10 percent crystal fragments. The lithic fragments are chiefly volcanic glass, aphanitic volcanic rock full of microlites, and porphyritic volcanic rock. Minor syenite and quartzite fragments also occur in the tuff. Crystal fragments include sanidine, magnetite, plagioclase, and apatite. The matrix, which in thin section is a devitrified glass, was an ash. Both volcanic breccia and tuff commonly contain small (as much as 1 mm long) vesicles filled with opal and (or) chalcedony. Staining tests using sodium cobaltinitrite indicated abundant potassium minerals in both the volcanic fragments and the ash.

CARBONATITE

Carbonatite exposures are rare in the Bear Lodge Mountains, and only one known carbonatite dike was found at the surface. This dike occurs in two bulldozer trenches on a ridge in the southeast corner of sec. 7, T. 52 N., R. 63 W. It strikes N. 36° W., and dips 62° SW. It has been traced for 26 m and is approximately 4.6 m thick. Carbonatite dikes have also been cut in seven drill holes in the NE¼ sec. 18 and NW¼ sec. 17, T. 52 N., R. 63 W. More than 20 carbonatite dikes were cut in one 435-m-deep hole. These dikes range from thin stringers to 3.5 m in thickness. All dip steeply.

The weathered carbonatite dike exposed at the surface is a brown to yellowish-brown mottled rock in contrast to unweathered carbonatites from the drill holes, which are principally white or light-gray rocks banded or streaked with pink, green, white, or purple accessory minerals. All the carbonatites consist principally of calcite. Other minerals vary in kind and amount from place to place. Rare-earth minerals are plentiful in many samples. The commonest rare-earth minerals are pink ancylite [$(Ce,La)(Sr,Ca)(CO_3)_2(OH)\cdot H_2O$] and brown bastnaesite [$(Ce,La)FCO_3$]. Although those two minerals occur together in a few samples, only one or the other is found in most samples. Ancylite was not found in the dike exposed on the surface. Strontianite fluorite, and the sulfides, pyrite, pyrrhotite, sphalerite, and galena, occur in most samples, although the quantity of each may be highly variable with one or more being common in some places and absent in others. Acmite and actinolite are locally abundant. Other minerals found in minor amounts in some samples are magnetite, marcasite, muscovite, barite, biotite, quartz, siderite, potassium feldspar, and rutile.

The mineralogy of carbonatite samples obtained from the dike on the surface varies somewhat from that found in the drill cores. At the surface bastnaesite intergrown with minor synchysite [(Ce, La) Ca $(CO_3)_2F$] is the principal rare-earth mineral. A small amount of xenotime (YPO_4) was noted in one sample. Ancylite and strontianite are absent, as are the sulfides. Hematite and goethite are fairly abundant. Bastnaesite obtained at the surface is a friable, yellowish-brown, powdery material unlike that of primary bastnaesite seen in other areas such as Mountain Pass, Calif., and Gallinas Mountains, N. Mex. The general shape of the bastnaesite patches in surface samples is similar to that of ancylite from the drill core. Bastnaesite in the carbonatites of the southern Bear Lodge Mountains, because of its apparent relationship to the land surface and its association with limonite, is probably formed by weatherings of ancylite. Adams and Young (1961, p. C293) also have noted secondary bastnaesite in the Pikes Peak Granite in southern Jefferson County, Colo., which they believed to have formed from allanite by reaction with late-stage magmatic solutions.

The thorium and uranium contents of 12 samples of carbonatite were determined by gamma-ray spectrometer (table 3); the thorium content ranges from 54 to 1,510 ppm and uranium ranges from 10 to 340 ppm.

TABLE 3.—*Gamma-ray spectrometric analyses of carbonatites in the southern Bear Lodge Mountains in parts per million*

[Analysts, C. M. Bunker and C. A. Bush]

Sample No.	MHS-1-77	MHS-2-77	MHS-3-77	MHS-4-77	MHS-7-77	MHS-10-77	MHS-11-77	MHS-13-77	MHS-15-77	MHS-20-77	MHS-22-77	MHS-25-77
Thorium	68.	115.	149.	54.	155.	225.	860.	445.	110.	182.	1,510.	204.
Uranium	11.	27.	17.	16.	10.	29.	82.	19.	45.	16.	340.	26.
Thorium:uranium	6.2	4.3	8.8	3.4	15.5	7.8	10.5	23.4	2.4	11.4	4.4	7.8

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up of small phenocrysts up to about 1 mm in length that consist of 18–25 percent augite, 2–5 percent magnetite, and less than 1 percent apatite and biotite set in a matrix containing many small mafic and plagioclase microlites. The sill is freshest on the ridge south of Miller Creek; it is commonly altered along Miller Creek, and in specimens collected here just above the road, most of the pyroxene has been altered to limonite. This sill contains oval amygdules 3–20 mm long, filled with calcite and feldspar. The only visible phenocryst in the sills south of Fort Ranch is biotite, which makes up 10–20 percent of the rock. These sills also have small, white, oval amygdules. The small lamprophyre dike on Bear Den Creek consists of 60 percent mafic phenocrysts (30 percent augite, 15 percent biotite, 10 percent magnetite, 4 percent hornblende, and 1 percent apatite) and 5 percent plagioclase phenocrysts set in a gray aphanitic matrix. The fine-grained lamprophyre exposed on Smith Ridge consists of 85 percent mafic minerals (40 percent hornblende, 15 percent chlorite, 10 percent epidote, 10 percent biotite, and 10 percent sphene) set in a light-gray matrix made up mainly of plagioclase.

A chemical analysis of the lamprophyre that crosses the North Fork of Miller Creek is given in table 2 (No. 1). This analysis compared to those of phonolite and trachyte is low in SiO_2, Al_2O_3, and Na_2O, but high in Fe_2O_3, FeO, MgO, CaO, TiO_2, and P_2O_5. The high mafic-mineral content in the mode is reflected in the 27 percent mafic minerals in the normative compositions, which includes 12.7 percent diopside and 4.4 percent magnetite (table 2). The rocks of the southern Bear Lodge Mountains are noted for their high K_2O content, and this lamprophyre in spite of its high content of mafic minerals is no exception, having 6.4 percent K_2O.

PSEUDOLEUCITE PORPHYRY

The pseudoleucite porphyry is a type of phonolite, but the presence of large pseudoleucite crystals makes it distinctive from all the other intrusives in the area (figs. 8*B*, 8*C*). The pseudoleucite porphyry occurs principally in the northwestern part of the area, where it forms one long intrusive and several smaller ones. The large intrusive is principally a sill in the middle of the Sundance Formation, but in places it has cross-cutting relations. The sill-like body is the westernmost intrusive in the study area and occurs about 3 km south of Fort Ranch. It has an irregular, sinuous form and a length of approximately 2,600 m. Thickness is difficult to measure because at many places it caps a ridge, but it is approximately 6 m thick. Five other small pseudoleucite sills and dikes were mapped in the same area. Two small lens-like bodies occur in the middle of the Sundance Formation north of the big body, two dikes cut the Morrison Formation south of it, and an intrusive body occurs along the road to its southeast. The longest dimension on any of these bodies is 140 m.

The pseudoleucite porphyry is a medium-gray porphyritic rock containing 5–20 percent white pseudoleucite and 3–10 percent sanidine set in an aphanitic matrix that has microlites of both feldspar and mafic minerals. The sanidine phenocrysts are inconspicuous, as they are generally less than 1 mm in length. The pseudoleucite crystals, on the other hand, range from 1 to 38 mm in diameter, with most of them between 5 and 10 mm. The pseudoleucite crystals are round to octagonal, and some crystals show the outline of several intergrown minerals (fig. 8*C*). The pseudoleucite crystals are made up of intergrowths of potassium feldspar, nepheline, and clay. Generally the potassium feldspar forms a narrow white rind around the exterior of the crystal (fig. 8*C*), although in some places this rind is pink. Potassium feldspar also forms narrow septa cutting across the interior of the crystal. The feldspar can be distinguished from the other minerals on a weathered surface, because it stands out in relief.

Pseudoleucite porphyry, like most of the other [illegible] in this area, has a high potassium content. The presence of abundant potassium was noted both from [illegible] this rock with sodium cobaltinitrite solution [illegible] chemical analysis of one sample (table 2, [illegible] sample contained 6.4 percent K_2O, which [illegible] the amount found in trachyte and [illegible] southern Bear Lodge Mountains. This [illegible] deficient in silica, containing less SiO_2 [illegible] rocks analyzed except the lamprophyre. [illegible] the basis of its chemical composition [illegible] system used by Rittmann (1952) [illegible] dark leucite phonolite.

PYROCLAS[illegible]

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a similar-appearing dike, 3.3 km northwest
st dike. This dike is exposed in a small hand-
on a ridge in the northeast corner of sec. 18,
N., R. 63 W. A third sample (MHS–256–79) came
a fairly fresh exposure of trachyte near the north
of the core. This sample was collected from a
quarry used as a source of local road metal that lies
near the northern boundary of the central part of
sec. 8, T. 52 N., R. 63 W. A fourth sample of sanidine
(MHS–71–76) was obtained from a fresh-appearing
phonolite porphyry that is part of a satellitic intrusion
on the western flank of the central intrusive core. This
sample was taken along the north side of Bear Den
Creek in the SE¼SW¼ sec. 30, T. 52 N., R. 63 W. The

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These carbonatites have greater thorium concentrations than any other type of Tertiary intrusive rock, although the concentration is lower than in veins. The thorium-to-uranium ratio varies from 2.4 to 23 (table 3). In addition semiquantitative spectrographic analyses of 17 samples (table 4) show that these carbonatites compared to most other rocks contain abnormal amounts of rare earths, strontium, and barium. The Bear Lodge carbonatites contain abundant rare earths, as do carbonatites occurring at Mountain Pass, Calif., and in the Bear Paw Mountains, Mont. Total rare-earth content of the samples analyzed from the Bear Lodge Mountains ranges from 0.58 to 64 percent (table 4). Although other samples are undoubtedly lower grade, the grade of the analyzed samples is similar to that of many of the carbonatite dikes in the Mountain Pass area (Olson and others, 1954, p. 68). The rare earths in the Bear Lodge samples are also similar to those in the Mountain Pass area in being predominantly of the light rare earths. In the 17 analyzed samples the lighter elements make up more than 95 percent of the rare-earth group.

The strontium content of the Bear Lodge carbonatites is unusually high compared with most other carbonatites, and several samples contain in excess of 10 percent. Regions containing strontium-rich carbonatites are not common, but strontium-rich carbonatites include the dolomite-barite-monazite carbonatites at Gem Park in the Wet Mountains of Colorado (Parker and Sharp, 1970, p. 19–20), niobium-bearing carbonatites of Ravalli County, Mont. (Heinrich and Levinson, 1961, p. 1442), and the massive carbonatites of Kangakunde Hill, Malawi (Holt, 1965, p. 14–15).

The barium content of the Bear Lodge carbonatites ranges from 0.10 to 3.0 percent (table 4). Barium in this range is a common constituent of many carbonatites in the United States and other countries.

Considerable niobium and phosphorus are found in many carbonatites, such as in the massive carbonatite at Iron Hill in the Powderhorn district of central Colorado and at Oka in Quebec, Canada. The niobium content of the Bear Lodge carbonatites is relatively low, ranging from less than 10 to 50 ppm. The phosphorus of these samples is also low, and although not shown in table 4, was less than the limit of detection (3,000 ppm) in all samples.

INTRUSIVE BRECCIA

Intrusive breccia bodies of several ages are found in the central part of the Bear Lodge dome. Most of these breccia bodies form small dikes that cut Precambrian granite and older Tertiary intrusives. An irregular breccia body having a length of 1,470 m and a maximum width of 700 m is found just north of the headwaters of Whitelaw Creek in the northern part of the central core (pl. 1). The breccia is poorly exposed and its presence is generally noted either from exposures in trenches or

TABLE 4.—*Semiquantitative spectrographic analyses of samples of carbonatites in the southern Bear Lodge Mountains in parts per million*

[Analyst, N. M. Conklin, U.S. Geological Survey; <, less than value indicated; >, greater than value indicated]

Sample No.	BL-1-76	BL-2-76	BL-3-76	BL-7-76	BL-14-76	BL-16-76	BL-17-76	BL-18-76	MHS-25-77	MHS-1-77	MHS-2-77	MHS-3-77	MHS-4-77	MHS-7-77	MHS-10-77	MHS-13-77	HS-20-77
Lanthanum	10,000	15,000	7,000	15,000	10,000	15,000	10,000	15,000	10,000	15,000	30,000	3,000	10,000	1,500	15,000	15,000	1,500
Cerium	15,000	15,000	10,000	20,000	10,000	15,000	15,000	15,000	15,000	30,000	30,000	7,000	15,000	3,000	15,000	30,000	7,000
Praesodymium	1,500	2,000	1,500	3,000	1,500	1,000	3,000	2,000	2,000	1,500	3,000	700	1,000	200	1,500	3,000	300
Neodymium	3,000	5,000	3,000	7,000	3,000	15,000	5,000	5,000	7,000	3,000	3,000	1,500	2,000	1,000	3,000	7,000	1,000
Samarium	<100	<100	<100	1,000	<100	3,000	<100	500	300	300	300	150	300	<200	300	700	<200
Europium	<100	<100	<100	<100	<100	500	<100	<100	<100	<100	<100	<100	<100	<100	100	150	<100
Gadolinium	<50	<50	<50	<50	<50	1,000	<50	<50	300	<200	<200	<200	<200	<200	<200	<200	<200
Terbium	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300
Dysprosium	<50	<50	<50	<50	<50	<50	<50	<50	<500	<200	<200	<200	<200	<200	<200	<200	<200
Holmium	<20	<20	<20	<20	<20	50	<20	<20	30	<50	<50	<50	<50	<50	<50	<50	<50
Erbium	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50
Thulium	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Ytterbium	7	7	10	20	5	100	3	7	30	<10	<10	<10	<10	3	7	7	7
Lutetium	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
Yttrium	200	200	200	200	150	1,000	100	150	500	70	50	70	100	70	150	100	150
Total rare earths	29,707	37,207	21,710	46,220	24,155	51,650	33,103	37,657	35,160	49,870	66,380	12,420	28,400	5,773	35,057	55,957	9,957
Barium	2,000	2,000	5,000	15,000	1,500	30,000	1,000	2,000	1,000	2,000	3,000	700	1,500	700	3,000	20,000	300
Beryllium	1.5	<1.5	7	7	<1.5	20	<1.5	<1.5	3	<1.5	<1.5	<1.5	<1.5	<1.5	<1.5	7	<1.5
Bismuth	30	30	100	100	<30	<50	<30	<50	30	30	<15	70	<15	30	15	100	30
Copper	15	10	<1	1,000	100	20	30	150	30	30	15	200	50	50	10	200	100
Lead	300	700	1,500	2,000	1,500	1,500	1,500	1,000	1,000	700	200	2,000	200	500	200	2,000	500
Manganese	3,000	2,000	5,000	10,000	5,000	10,000	5,000	5,000	10,000	1,500	1,500	1,500	5,000	3,000	3,000	10,000	2,000
Molybdenum	20	15	10	300	70	1,500	15	70	200	30	70	70	30	15	70	150	100
Niobium	30	20	30	50	15	15	<10	10	10	<10	<100	<10	<100	<10	<100	<100	<10
Strontium	>100,000	>100,000	>100,000	>100,000	>100,000	70,000	30,000	30,000	7,000	>100,000	>100,000	70,000	20,000	>100,000	>100,000	>100,000	30,000
Tin	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Vanadium	150	50	300	1,500	500	700	30	150	150	70	200	70	100	30	150	700	70
Zinc	500	1,500	2,000	2,000	2,000	<300	500	2,000	700	1,500	<300	2,000	<300	300	<300	1,500	300
Zirconium	<10	<10	30	150	<10	30	<10	<10	70	150	150	<10	<10	30	150	300	200

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from widely scattered pieces of float. Crosscutting relations indicate breccias of several ages in a few places in this large body. Intrusive breccia dikes are common in and adjacent to the large Precambrian granite body east of Richardson Creek. In addition, intrusive breccia has been noted both east and west of Warren Peaks. Most of these areas of outcrop are small, and only the large body north of Whitelaw Creek is shown on plate 1.

The intrusive breccia consists of angular to rounded fragments of rock, a few millimeters to 10 cm across, set in a fine-grained igneous matrix. Most of the fragments are of bleached, light-gray volcanic rock with small sanidine phenocrysts. A few fragments are of coarser grained syenite. The breccia that is adjacent to and cuts the granite commonly contains granitic fragments, which were also noted by W. S. Tangier Smith (Darton and O'Harra, 1905, p. 5). Sparse quartzite fragments from the Deadwood Formation are found in these same breccias. The matrix is aphanitic to fine grained and in places has sanidine phenocrysts a few millimeters across. It is commonly weathered and has minute cavities due to the leaching of minerals, especially the mafic ones. Near the surface, the matrix is commonly colored by red or yellow iron oxides. In drill cores the intrusive breccia is gray.

YOUNGER TRACHYTE AND PHONOLITE DIKES

The younger dikes are those intrusives that intruded trachytes and phonolites that have been hydrothermally altered. Thus, the younger dikes have unaltered white sanidine phenocrysts that stand out sharply against the gray matrix (fig. 8*D*). Any crosscutting intrusives that formed prior to the hydrothermal alteration commonly are bleached and resemble the rocks that they intrude. The dikes discussed here are only those unaltered ones that intrude older igneous rocks. Similar-appearing dikes that intrude the sedimentary rocks are not included because away from the core of the Bear Lodge dome where the rocks show little alteration, these younger dikes cannot be distinguished from older ones.

The younger dikes discussed here represent the waning stages of intrusion. Seven of the 10 dikes are in the central intrusive complex; one is in a subsidiary intrusive just north of the main intrusive body; and two are in the core of the Hershey Creek dome. Others undoubtedly occur in this study area because the dikes are generally small and exposures are poor. The dikes range from about a meter to 12 m in thickness, and have been traced 30–300 m. The dikes are intruded into randomly oriented, steeply dipping fractures and do not have a preferred direction of strike. A 6-m-thick dike is well exposed in the cut of the road that leads to the lookout tower on Warren Peaks (fig. 5*A*).

The younger dikes are all porphyritic, having white, rectangular phenocrysts of sanidine that range from 1 to 25 mm long set in a dark-gray to greenish-gray matrix (fig. 8*D*). In some samples, small mafic phenocrysts are noted. The phenocryst content is highly variable, ranging from about 2 to 75 percent. Sanidine (2–50 percent) is the principal mineral. Aegirine-augite is the chief mafic mineral in most dikes, although in a dike near Corral Springs, augite was the chief mafic mineral and aegirine-augite was absent. Accessory are apatite, magnetite, sphene, and black garnet (melanite). About half the dikes contain 10–15 percent nepheline. Thus, some of the dikes are trachyte and some are phonolite.

A chemical analysis was made of the dike exposed on the road to the lookout tower in the Warren Peaks (table 2, No. 6). A comparison of this analysis with that of the older trachyte and phonolites (table 2, Nos. 7–11) does not indicate any major differences. Thus, the magma that formed this younger dike probably is derived from the same source as that which formed the older trachyte and phonolite intrusives.

AGE

The ages of four samples were determined on sanidine from four localities. Three of these localities are from intrusives in the core of the Bear Lodge dome; one is from a separate intrusive. Field relations indicate that the igneous rocks that form the core of the Bear Lodge dome consist of at least several sets of intrusive bodies, although north of Warren Peaks later alteration has made it difficult to distinguish among them. A few dikes that postdate this alteration cut the older altered intrusives. One such dike about 6.6 m thick is exposed on the road to the U.S. Forest Service lookout tower on the centralmost of the Warren Peaks (fig. 5*A*). Sanidine, which occurs as large phenocrysts, was separated from this rock for age dating (sample No. MHS–64–76). Another sample (MHS–294–79) was taken from a similar-appearing dike, 3.3 km northwest of the first dike. This dike is exposed in a small hand-dug pit on a ridge in the northeast corner of sec. 18, T. 52 N., R. 63 W. A third sample (MHS–256–79) came from a fairly fresh exposure of trachyte near the north end of the core. This sample was collected from a quarry used as a source of local road metal that lies near the northern boundary of the central part of sec. 8, T. 52 N., R. 63 W. A fourth sample of sanidine (MHS–71–76) was obtained from a fresh-appearing phonolite porphyry that is part of a satellitic intrusion on the western flank of the central intrusive core. This sample was taken along the north side of Bear Den Creek in the SE¼SW¼ sec. 30, T. 52 N., R. 63 W. The

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sanidine from two samples (MHS-64-76 and MHS-71-76) was analyzed for potassium and argon by R. F. Marvin, H. H. Mehnert, and Violet Merritt, U.S. Geological Survey. The other two samples were analyzed by the same three people and J. J. Kenney. The results are as follows:

Field No. MHS-	K_2O (percent; average)	^{40}Ar 10^{-10} moles/g	^{40}Ar (percent)	$^{40}Ar/^{40}K$	Age (m.y. $\pm 2\sigma$)
64-76	11.23	8.275	96	0.00298	50.5±0.8
71-76	12.28	6.833	84	.00225	38.3±0.6
294-79	13.87	10.21	60	.00297	50.5±1.2
256-79	6.12	4.360	87	.00288	48.8±1.7

Two other ages have also been determined by the potassium-argon method on samples from the Bear Lodge Mountains (McDowell, 1971, p. 14). Both samples were collected from rocks in the central intrusive core. One sample came from a little south of the Forest Service lookout tower and the other about 2 km south of this tower. The age of the northernmost sample, which was measured on hornblende and aegirine, is 38.8±2.1 m.y.; that of the southernmost sample, which was measured on augite and hornblende, is 48.9± 1.6 m.y. The age spread among these six samples is 12.2 m.y., which represents a minimum age spread, as these samples may represent neither the youngest nor the oldest rocks in this intrusive complex.

The Bear Lodge intrusive bodies, as previously noted, are but a few of many alkalic intrusives occurring in an east-west belt from the east edge of the northern Black Hills through the Bear Lodge Mountains to the Missouri Buttes. Ages of these similar rocks have been determined on 11 minerals from nine other plutons (McDowell, 1971, p. 13-15; Hill and others, 1975). They range in age from 49.4 to 58.9 m.y. Thus, the Bear Lodge intrusives are some of the latest to be intruded in this belt.

WHITE RIVER FORMATION (OLIGOCENE)

The White River Formation consists principally of a poorly bedded, friable, tan siltstone. This formation at one time probably overlay the greater part of this region, but most of it has been stripped off the older rocks by erosion during late Tertiary time. The White River Formation is found in the northwestern part of the mapped area along the sides of flat-topped ridges, where it overlies the Spearfish Formation, Minnelusa Sandstone, Sundance Formation, and Tertiary intrusives. The White River Formation is everywhere unconformably overlain by the Ogallala Formation. In most places the White River is covered by float from the overlying Ogallala. The best exposure of the White River is in landslide scarps of two small adjoining hills on the northeast side of Lytle Creek in the SW¼SW¼ sec. 1, T. 52 N., R. 64 W. This exposure is also one of the best exposures in northeastern Wyoming, and three sections measured at this locality have been described by Brown (1952, p. 16-19) and Robinson, Mapel, and Bergendahl (1964, p. 105).

The White River Formation is mainly tan, but in places it is gray. Although most of the grains are silt sized, the grain size of much of this rock varies from that of a fine sand to a clay. The siltstone is generally noncalcareous, but within it are thin layers and irregular lenses of tan, calcareous siltstone. This calcareous siltstone is somewhat more resistant to weathering, and small ledges of this rock project out from the noncalcareous siltstone. Several layers of gravel 0.15 to 1.0 m thick are interbedded with the siltstone. The gravel was derived principally from the Tertiary intrusives.

The thickest section of the White River Formation, measured by Robinson, Mapel, and Bergendahl (1964, p. 105) on the northeast side of Lytle Creek, is 42.1 m thick; the section measured by Brown (1952, p. 19) at the same locality is 35 m thick. In other parts of the area, the White River is much thinner, and it is missing in Cole Canyon in the eastern part of the area (pl. 1).

Several different fossils were collected by Brown (1952, p. 18-19, 51) from the measured section on the northeast side of Lytle Creek. These are: (1) fossil hackberry seeds from approximately 5.5 m below the top of the White River, (2) the gastropod *Helix* sp. from 14.6 m below the top, and (3) the left maxilla from the oreodont genus *Merycoidodon* from 16.8 m below the top. The oreodont jaw, which was identified by C. B. Schultz, University of Nebraska, dates these beds as middle or late Oligocene in age. The gastropod *Helix* is similar to gastropods found in upper Oligocene beds. Brown (1952, p. 51-52) assigned the upper part of these rocks to the Brule Formation. Lower gravel-bearing units in this same section, because of lithologic similarities, were assigned to the Chadron Formation (Lugn and Brown, 1952). These two formations make up the White River Group. I have used the name White River Formation in preference to the Brule and Chadron Formations as these rocks generally are called White River in northeastern Wyoming, and they are so identified by Robinson, Mapel, and Bergendahl (1964, pl. 1) in their map of the northern and western flanks of the Black Hills uplift.

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OGALLALA FORMATION (LATE MIOCENE AND PLIOCENE)

The Ogallala Formation in the southern Bear Lodge Mountains consists mainly of gravels and coarse conglomerate that lap up on the periphery of the Bear Lodge dome. This formation underlies broad, flat-topped ridges on the west, north, and northeast sides of this dome (pl. 1). The tops of these ridges, where not steepened by later erosion, dip gently away from the center of the dome at angles of from 1° to 4°. The upper surface weathers to form about a half-meter of soil that generally supports a thick growth of pine, although some of the ridges in the northern part of the area are covered by grass. The Ogallala is generally poorly exposed due to ease of weathering and the lack of topographic relief. The best exposures occur in recent landslide scarps like those found just north of Cole Canyon and along the northeast side of Lytle Creek.

The Ogallala Formation consists of poorly sorted conglomerate interbedded with thin irregular layers of sandstone or siltstone (fig. 9). The conglomerate clasts (pebbles to boulders) may range from 0.4 to 45 cm across, although in some layers the clasts are more evenly sized. The clasts are subangular to subrounded in shape and consist principally of trachyte and phonolite. In addition, minor amounts of granite, quartzite from the Deadwood Formation, Minnelusa Sandstone, and Pahasapa Limestone are present in some places. These clasts are set in a white, calcareous sandstone matrix. The interbedded sandstone thickens and thins along strike (fig. 9) and in some places pinches out. This rock is friable, and generally calcareous, and ranges from white to tan in color. In places it contains scattered rounded pebbles of trachyte or phonolite. In one place along a narrow ridge top on the north side of Cole Canyon, a 0.3 to 0.6-m-thick gray limestone bed containing fragments of intrusive rock was noted. The Ogallala Formation is much coarser in the southern Bear Lodge Mountains than in many other areas where it is mostly sandstone, algal limestone, siltstone, and claystone (Denson, 1969, p. C27). The rocks here represent the part of the Ogallala closest to the mountains, with the source material being at most only a few kilometers away.

The Ogallala Formation in the northwestern part of the area overlies an irregular erosion surface cut on the White River Formation. Farther east, where the White River is missing, the Ogallala is separated by an angular unconformity from sedimentary rocks ranging from Cambrian to Jurassic in age. Two partial sections measured along the edge of canyons north of Cole Canyon are as follows:

SECTION 2.—*Ogallala Formation (part) measured on steep south-facing slope in the NW¼NW¼ sec. 14, T. 52 N., R. 63 W. (fig. 9)*

	Thickness (meters)
Top of ridge.	
Ogallala Formation:	
6. Conglomerate, poorly sorted; consists of subangular to subrounded clasts, 0.3–5 cm in diameter, made up principally of trachyte or phonolite clasts, but some clasts are of quartz monzonite and quartzite of the Deadwood Formation; matrix a white calcareous sandstone	4.0
5. Sandstone, fine-grained, tan, calcareous	1.4
4. Conglomerate, like unit 6	3.4
3. Sandstone, like unit 5	1.1
2. Conglomerate, like unit 6	5.5
1. Sandstone, like unit 5	1.1
Partial thickness of Ogallala Formation	16.5
Top of landslide deposit.	

SECTION 3.—*Ogallala Formation (part) measured on steep south-facing slope in the NE¼SW¼ sec. 11, T. 52 N., R. 63 W.*

	Thickness (meters)
Top of ridge.	
Ogallala Formation:	
5. Conglomerate, poorly sorted; consists of subangular to subrounded clasts, 0.3–30 cm in diameter, made up principally of trachyte and phonolite clasts, but some clasts are of quartz monzonite, quartzite of the Deadwood Formation, and limestone; matrix a white calcareous sandstone	0.6
4. Siltstone, white, calcareous	0.9
3. Conglomerate, like unit 5	3.6
2. Sandstone, white, calcareous, with about 5 percent subangular 0.3–30 cm clasts of trachyte and phonolite	1.5
1. Conglomerate, like unit 5	5.1
Partial thickness of Ogallala Formation	11.7
Top of landslide deposit.	

The Ogallala Formation varies in thickness, tending to be quite thin toward the center of the area and thickening towards its outer edge. Original total thickness of this formation is difficult to ascertain as its upper boundary is an erosion surface and the lower contact is commonly hidden under talus and slope wash. In the two measured sections described above, 16.5 and 11.7 m of the Ogallala were measured. In a section on the northeast side of Lytle Creek in the SW¼SW¼ sec. 1, T. 52 N., R. 64 W., Brown (1952, p. 18) measured 4.9 m. In several bulldozer trenches on the flats north of Peterson Spring it is less than a meter thick.

Fossil seeds were collected by Lugn and Brown (1952) from the Ogallala Formation along the northeast side of Lytle Creek in the SW¼SW¼ sec. 1, T. 52 N., R. 64 W.

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FIGURE 9.—Ogallala Formation exposed in back of landslide scarp along west side of Cole Canyon. Dark-gray resistant layers are of conglomerate. Light-gray layers are of sandstone and siltstone.

They were identified as *Stipidium commune* and *Biorbia fossila*. The former is an index fossil in the lower part of the Ogallala occurring from late Miocene to early Pliocene time (Elias, 1942, p. 115, pl. 17). The latter is an index fossil in the middle and upper parts of the Ogallala; this plant lived in middle and late Pliocene time (Elias, 1942, pl. 17).

LANDSLIDE DEPOSITS

Eighteen landslides were mapped in the southern Bear Lodge Mountains (pl. 1). The greatest concentration of landslides occurs in the northwest corner of the region where 10 landslides underlie approximately a quarter of this study area. The landslides range in size from a small slide northwest of Lytle Creek that is only 120 × 200 m in extent to a slide south of Togus Creek that is 850 × 1,680 m. The upper end of most of the landslides is marked by one or more steep arcuate scarps (fig. 10). Other scarps may be found within the landslide deposit itself, and mark where multiple slippage took place. The most distinct feature of these landslides is their hummocky surface. Some of the landslides like the one south of the mouth of Togus Creek and the one southwest of Fort Ranch in the northwest corner of the area contain jumbled blocks of sandstone. Landslides in this area are found where a resistant rock layer caps a soft friable unit. The erosion of the underlying softer rock along a canyon side causes slope steepening and eventually forms an unstable slope that leads to slippage. Most landslides in this area form either where the soft Spearfish Formation is overlain by a hard layer of Ogallala conglomerate or where the soft Stockade Beaver Shale Member of the Sundance Formation is overlain by the resistant Hulett Sandstone Member. Landslides of the former type are found west of Sheep Mountain, east of Beaver Creek, and along Lytle Creek in secs. 1, 2, 11, and 12, T. 52 N., R. 65 W. Those of the latter type occur south of the mouth of Togus Creek and along the lower part of Lytle Creek.

ALLUVIUM

Alluvium is made up of the modern sediments found along stream valleys. In the southern Bear Lodge Mountains, it consists of soil intermixed with sand and some gravel. All the gravels are locally derived from rocks in the uplifted Bear Lodge dome or reworked from the Ogallala Formation. They consist mainly of intrusive rocks and, depending on the source area, some quartzite, sandstone, and limestone. The alluvium occurs mainly along valleys on the outer edges of the area, as along Cow Creek and the lower parts of Togus, Lytle, and Reuter Canyons. The largest area of alluvium is in the southwest corner of the area near the junction of Krusee Canyon with Lost Houston Creek. Here the alluvium, which underlies broad valleys as wide as 460 m, supports a yearly hay crop.



FIGURE 10.—Moat formed along upper edge of landslide as it slid downhill; just southeast of Fort Ranch in the northwest corner of the mapped area. Landslide is to left.

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STRUCTURE AND ITS RELATION TO IGNEOUS BODIES

The Bear Lodge dome is the dominant structure of the southern Bear Lodge Mountains. This dome, which underlies the greater part of the mapped area (pl. 1), is formed by the pushing up of the Paleozoic and Mesozoic sedimentary rocks by intrusives that form the core of the dome. Some of the subsidiary intrusives on the flanks of the main dome have formed smaller folds. Small faults found on the flanks of the Bear Lodge dome are apparently related to it as rocks farther from it are unfaulted.

The central intrusive mass in the Bear Lodge dome has pushed up and exposed formations that generally lie much deeper. These beds dip away from the center of the dome and dip most steeply near its center: some of the innermost beds dip at angles of 40°–50°. Farther away from the center the beds flatten out, and dips along the western, northern, and southern margins of the mapped area are only 10°–20° (pl. 1).

A smaller dome, the Hershey Creek dome, underlies an area of a little more than 3.1 km² in the northwest part of the area (pl. 1). This dome has a latite core and exposes sedimentary rocks as deep as the Deadwood Formation along the north side of that core. Other sedimentary units exposed in this dome are the Whitewood Limestone, Pahasapa Limestone, Minnelusa Sandstone, Opeche Formation, and Minnekahta Limestone. These rocks are not exposed along the dome's west side, where they are hidden under landslides or cut out by other intrusives. A shallow syncline lies between this dome and the larger Bear Lodge dome to the southeast.

Smaller folds occur at several other places along the flanks of the Bear Lodge dome. A parallel northwest-trending anticline and syncline are found in the southeast corner of the area east of Reuter Creek. These two structures, which are each approximately 1,850 m long, are formed in the Pahasapa Limestone and Minnelusa Sandstone (pl. 1). Two intrusives are exposed on the surface at the southeast end and the southwest flank of this anticline. These intrusives are probably only the surface exposure of a larger intrusive body that lies beneath the center of the anticline.

Another fold with a north-northeast trend occurs in the southwest corner of the mapped area along the east side of Krusee Canyon (pl. 1). This fold is approximately 2,750 m long, and at the surface involves the Minnelusa Sandstone, Opeche Formation, Minnekahta Limestone, and Spearfish Formation. The greater part of the surface exposure of this fold is underlain by a dip slope of the Minnekahta Limestone. Although this fold is not pierced by any intrusive bodies, it was probably bowed up by a hidden Tertiary intrusive.

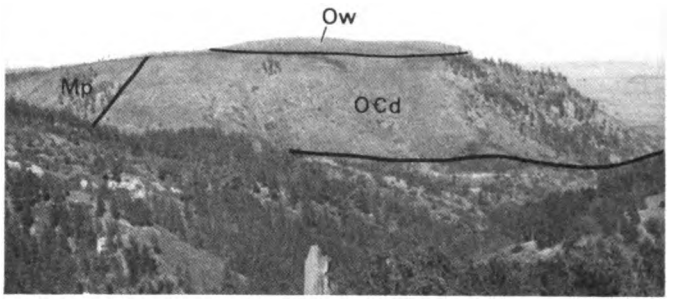


FIGURE 11.—Sheep Mountain on the eastern flank of the Bear Lodge Mountains exposes Deadwood Formation (O€d) overlain by Whitewood Limestone (Ow). A straight fault near the left side of the photograph separates the Deadwood Formation from the Pahasapa Limestone (Mp). A curved fault near the base of the mountain separates these formations from younger Paleozoic rocks in the foreground.

Paleozoic sedimentary rocks are domed up on Sheep Mountain along the east side of the area (fig. 11). In addition to being bowed up over the intrusive, these rocks have been faulted near the intrusive's margins (fig. 12). Several curving faults outline the approximate oval shape of the underlying plug which has pushed the overlying sedimentary rocks up like a cork coming out of a bottle. Rocks exposed in the central part of this uplifted plug are as old as Cambrian (the lower part of the Deadwood Formation). Rocks exposed around the margins of this plug are from Pennsylvanian to Triassic in age (Minnelusa to Spearfish Formations). The fault that bounds the west and south sides offsets the sedimentary rocks approximately 710 m. The fault along the east and north sides offsets the sedimentary rocks 410 m. Differences in offset between the two boundary faults are taken up on several steeply dipping faults that are within the circular plug (fig. 12). The intrusive plug itself is only exposed in a small area on the steep south side of Sheep Mountain.

In addition to the faults associated with the Sheep Mountain uplift, six others were mapped on the western and southern flanks of the Bear Creek dome. These faults do not have a common trend, although all have a general northwest or northeast strike. All have steep dips. Horizontal offset, where measurable, is between

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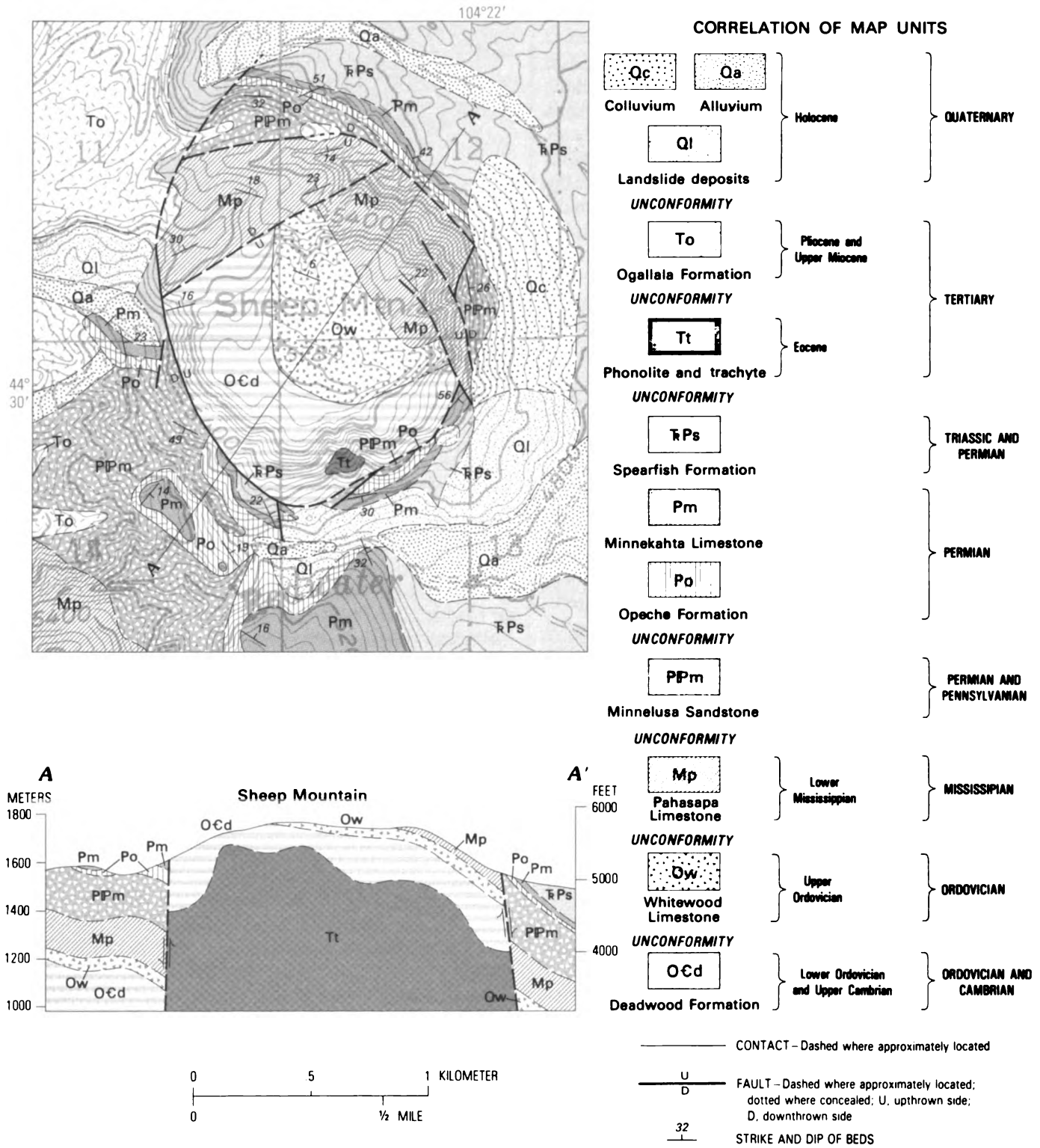


FIGURE 12.—Geologic map and section of Sheep Mountain. Geology by M. H. Staatz, assisted by L. M. Osmonson, June 1977. Base from U.S. Geological Survey 1:62,500 Sundance and Alva (1958). Contour interval 40 ft (1 ft=0.3048 m); datum is mean sea level.

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300 and 700 m. Only one fault, which crosses the upper part of Reuter Canyon, cuts the main Tertiary intrusive body. This fault formed after this part of the intrusive had solidified. Two other faults in the southwestern part of the area, however, have Tertiary rocks intruded along them and are therefore older than these intrusives (pl. 1). The Tertiary alkalic rocks were formed over a time span of at least 12 m.y. Thus, some of these rocks may be older and some younger than any particular fault.

The greater part of the doming, folding, and faulting in the southern Bear Lodge Mountains was caused by the force of multiple intrusion during Tertiary time. The size and type of structure depend on the amount of igneous material and how it was injected. Small amounts of magma may be injected along fractures to form dikes. Narrow dikes cut the Pahasapa Limestone and the Minnelusa and Spearfish Formations in the west and northwestern parts of the area (pl. 1). The attitudes of the adjacent sedimentary rocks show little change. In some places access is easier between the beds, and here sills were formed. Two of the larger ones are the lamprophyre that intrudes the Sundance Formation where this rock crosses the North Fork of Miller Creek along the west edge of the area (fig. 8*A*) and the large pseudoleucite porphyry body that also intrudes the Sundance 2.3 km to the northwest. Several sills intruding the Minnelusa Formation are well exposed in roadcuts along Beaver Creek in the eastern part of the area. In some places the sedimentary rocks capping the sill were stripped off, leaving a broad area of sill top exposed. One such sill with an area of about 975 × 610 m occupies most of the SW¼ sec. 2, T. 52 N., R. 64 W. on the southwest side of Lytle Creek. These sills make room for themselves by lifting the overlying strata, but as the thickness of the sills here is generally not more than 15 m and as the movement is mostly at right angles to the bedding, little change is noted in the attitude of the overlying beds.

Much of the magma, however, forms larger intrusive bodies. It may be forced up through sedimentary rocks along a narrow conduit, spread out between the upper layers of rock, and dome up the top to form a laccolith. It may also be intruded or shoulder its way upward over a broad area. This type of igneous body, whose base is essentially the original magma chamber, is called a plug, stock, or batholith, depending on the area it underlies. Sedimentary rocks that overlie a plug, stock, or batholith are also domed up by the force of intrusion. Thus, the rocks overlying both floored and unfloored intrusives may be domed up. The distinction between laccoliths and other massive intrusives depends mainly on one's being able to show that the former are floored. The principal Bear Lodge intrusives, which are generally described as the intrusive underlying Warren Peaks, have been interpreted as a laccolith in several papers (Russell, 1896, p. 39; Jaggar, 1901, p. 251–252; Darton, 1905, p. 8; Darton and O'Harra, 1907, p. 6; Darton, 1909, p. 67–68; and Brown, 1952, p. 48–49).

Laccoliths were first described by G. K. Gilbert in the Henry Mountains of Utah. In subsequent years geologists in various parts of the United States considered many igneous bodies to be laccoliths. In the Black Hills region, Russell (1896, p. 23–24) examined a number of the intrusive bodies. He noted that "they differ from the laccolites of G. K. Gilbert, in the fact that the molten rock did not spread out horizontally among the stratified beds so as to form 'stone cisterns'." Russell (1896, p. 39) did not visit the Bear Lodge Mountains, but in discussing Newton's description of the rocks underlying the Warren Peaks (Newton and Jenny, 1880, p. 199–200) he stated, "Its broad extent and the manner in which the surrounding stratified rocks dip away from it in all directions, seem to indicate that it is a true laccolite, very similar to those of the Henry Mountains." Jaggar (1901) considered the Bear Lodge Mountains to be an elongate laccolithic uplift extending some 32 km in a northwest direction with a porphyry core exposed for 12.8 km. Most of Jaggar's evidence that a particular igneous body is a laccolith was based on the doming of the overlying sedimentary rocks. In some places, he interpreted as laccoliths with even less evidence such obvious plug-like igneous bodies as Devils Tower. In a few places, as on Deadman Mountain, 4.8 km southwest of Sturgis in the northern Black Hills, Jaggar (1901, p. 218–220) could clearly demonstrate both a roof and a floor to a laccolith. Later writers following Jaggar's lead have described the principal intrusive or intrusives of the Bear Lodge Mountains as one or more laccoliths. None have demonstrated that those major intrusions are floored. Doming of the overlying sedimentary rocks could be formed by either a laccolith or a stock. This central intrusive core, however, is not a single intrusive but consists of a number of igneous bodies intruded over a period of at least 12 m.y. Furthermore, a floor, if present, is not a single planar surface. Granite of Precambrian age forms isolated knobs in the central part of the intrusive of Tertiary age south of Warren Peaks (pl. 1). Precambrian rocks are not exposed in the intrusion north of Warren Peaks, nor were any encountered in drilling in this area, although the deepest hole reached a depth of 850 m below the elevation of most of the granite outcrops in the southern part of the area. I believe that the main intrusive is probably a complex stock formed by multiple intrusions.

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THORIUM AND RARE-EARTH DEPOSITS

Thorium and rare earths are found in the southern Bear Lodge Mountains in veins and disseminated deposits. The latter type of deposit is somewhat analogous to copper porphyries. Thorium and rare-earth-bearing disseminated deposits have not previously been described in the literature. They represent a large low-grade source of these elements.

Thorium and rare-earth deposits occur principally in the central part of the main intrusive mass. Most are found between Whitelaw Creek on the north and the U.S. Forest Service lookout on Warren Peaks to the south. The favorable area is marked by high radioactivity and is shown on plate 2*A*. Exploration for thorium and rare earths in the Bear Lodge Mountains began in the early 1950's, and high-grade veins were the target. A number of small- to moderate-sized veins were found in this area, but the greater part of the thorium and rare earths occurs in disseminated deposits, which consist of intrusive rock cut by numerous thin, crisscrossing, steeply dipping veinlets. Both types of deposit commonly occur together, although veins are scattered over a much larger area. The veins and the disseminated deposits will be discussed separately because they vary in size, shape, grade, and method of mining.

VEINS

LOCATION AND DESCRIPTION

The veins are distinct, tabular bodies with an average thickness of at least 5 cm. Their separation from smaller veins and veinlets is somewhat arbitrary and assumes that veins thinner than 5 cm would probably be included with the disseminated deposits in any mining operation.

Twenty-six veins were noted at 24 localities (pl. 1). Exposures are generally poor, and most of the veins are seen only in one or more old trenches or pits. Present or past names of the claim or claims on which these veins lie are difficult to ascertain for several reasons. Most of the thorium and rare-earth exploration occurred in the early 1950's, and none of the claim locations made at this time remain. The land in the vicinity of the old radar site on the northernmost of the Warren Peaks has been removed from mineral entry. Many of the claims in sections 17 and 18, T. 52 N., R. 63 W. have been relocated by Duval Corporation. As their discovery locations are based on drill holes, it is commonly difficult to determine which claim or claims a particular vein may now be on. Hence, in order to clarify the discussion of various veins, I have given each locality a number starting with 1 in the north and numbering consecutively to the south. Number 1 is on the ridge northwest of the headwater of Whitelaw Creek and number 24 is on the northeast side of Richardson Creek.

The exposed length of the 26 veins is relatively short with the longest one being traced for only 137 m. Nine of the veins, listed in table 5 as 0.5 m long, are only exposed in one place in a trench or pit. The two longest veins are parallel and lie about 50 m apart on the north slope of the hill to the south of Bull Hill. The lack of traceable length is in places due to the lack of outcrops or workings along the strike. In other areas, as at locality 18, other workings indicate the maximum extent of a particular vein.

The thickness of the veins ranges from 5 to 250 cm (figs. 13*A*, *B*). The maximum thickness is reached in the northwest-trending vein at locality 22 on the east edge of the main intrusive mass. Sixteen of the 26 veins are at least in part more than 30 cm thick. Thickening and thinning are common; the larger vein at locality 22 ranges from 60 to 250 cm in thickness. A tenfold change in thickness occurs at locality 12, south of Bull Hill, where a long vein varies from 15 to 152 cm.

The veins of the southern Bear Lodge Mountains have no common direction of strike (table 5). The strikes of the two longest veins, which are on the hill south of Bull Hill (locs. 11, 12), are parallel, but strikes of other

TABLE 5.—*Dimensions and attitude of the veins in the southern Bear Lodge Mountains*

[N. D., no data]

Location No.	Vein if more than one	Exposed length (m)	Thickness (cm)	Strike	Dip
1	----------	0.5	10.2	N.D.	N.D.
2	----------	.5	25	N.D.	N.D.
3	----------	6.5	92	N. 45° E.	N.D.
4	North vein	4.6	6-10	N. 67° W.	45° NE.
	South vein	16.8	33	N. 56° W.	N.D.
5	----------	90	2.5-45	N. 20° W.	85° NE.
6	----------	.5	5	N.D.	N.D.
7	----------	40	25-40	N. 84° E.	Steep
8	----------	.5	7.5	N. 1° E.	90°
9	----------	12	155	N. 50° W.	Steep
10	----------	23	9-100	N. 44° E.	58° SE.
11	----------	137	15-40	N. 3° W.	Steep
12	----------	135	15-152	N. 2° W.	65° SW.
13	----------	50	150-185	N. 80° E.	59° NW.
14	----------	.5	20+	N.D.	N.D.
15	----------	13.7	108	N. 5° E.	25° SE.
16	----------	.5	30+	N.D.	N.D.
17	----------	7.5	46	N. 23° W.	55° NE.
18	----------	.5	20	N.D.	N.D.
19	----------	6	2.5-10	N. 78° W.	30° NE.
20	----------	.5	5	N.D.	N.D.
21	----------	45	50	N. 15° E.	N.D.
22	NE.-trending	8	20-76	N. 20° E.	80° NW.
	NW.-trending	38	60-250	N. 32° W.	40° SW.
					80° NE.
23	----------	.5	35	N. 40° W.	N.D.
24	----------	21	10.2	N. 32° E.	82° SE.

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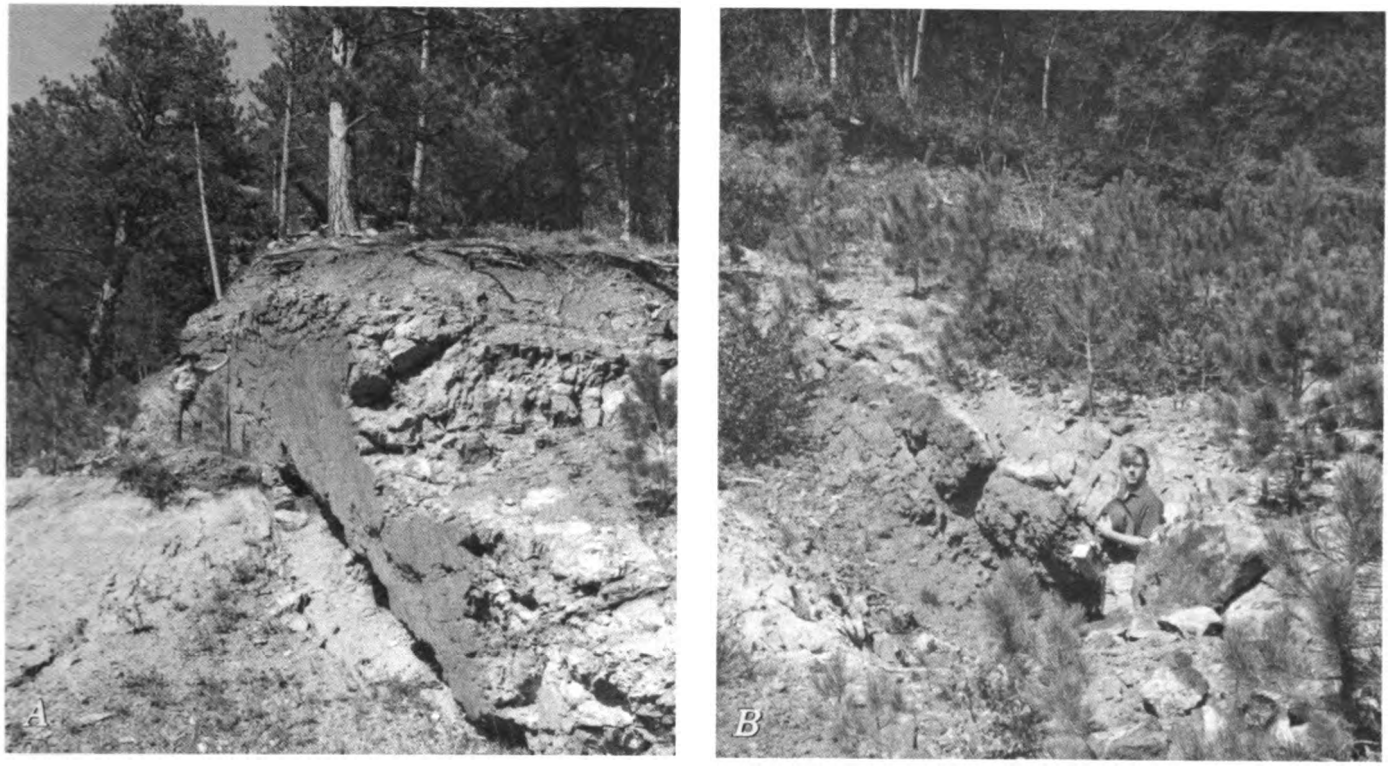


FIGURE 13.—Veins. *A*, Steeply dipping vein (locality No. 24) exposed in cut on northeast side of Richardson Creek. Man's hand is on hanging wall side of vein. Vein is light-colored material lying to viewer's left of this plane. It is about 10 cm thick. *B*, Black manganese-oxide-bearing vein (locality 13) is exposed in a partly overgrown cut. Vein is about 180 cm thick.

adjacent veins may be at considerable angles to one another. For example, the two veins that lie in the same broad bulldozer trench at locality 22 have strikes of N. 20° E. and N. 32° W. The strikes of the veins given in table 5 are the average strike of each vein, and the strike of the veins at any one place may vary somewhat from this average. For example, the vein at locality 18 is fairly sinuous.

Dips are more difficult to determine than strikes because of poor third-dimension exposure of many of the veins. Dips of only 12 of the 26 veins were determined (table 5). These data, however, indicate that the dip also is highly variable. Measurements range from 25° to 90°. Dip in a single vein might also vary, and measurements made on the northwest-trending vein at locality 22 varied from 40° southwest to 80° northeast. In general, however, most of the veins dip at angles greater than 50° (fig. 13*A*).

All the veins except the one at locality 21 lie along irregular fractures in the central Tertiary intrusive complex. This body of rock, as previously noted, has had a complex history of intrusion, and veins that formed along these fractures are divergent in strike and dip, are commonly sinuous, and thicken and thin along strike.

MINERALOGY

A total of 27 minerals have been identified in the samples from the Bear Lodge veins. Some of these minerals are sparse and were found in only one or two places. About a third of the minerals occur in half of the samples. Amounts of various minerals present also vary greatly, and this is particularly noticeable in principal gangue, manganese oxide, and iron oxide minerals. The gangue minerals are commonly intermixed with various amounts of finely granular manganese oxides, iron oxides, or both. The color of the veins chiefly reflects the kind and amount of iron or manganese oxides present. Manganese oxides give the vein a black color (fig. 13*B*); limonite, a tan to dark-brown color; hematite, a black to dark-cherry-red color. At a few localities where the content of iron and manganese oxides is low, the colors of some other minerals may be apparent. For example, at locality 10, which has only 0.1 percent manganese and 5 percent iron, the vein is colered pistachio green by the presence of abundant monazite. Color banding occurs in some veins. The minerals in the various veins are all fine grained, and in a few veins the grain size is submicroscopic. The result of abundant iron and manganese ox-

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ides, as well as fine grain size, makes identification of most minerals difficult. Hence, in only a few veins are any minerals other than quartz, manganese oxides, and iron oxides identifiable in hand specimens.

A study of the vein mineralogy was carried out using routine heavy-liquid and magnetic separation procedures. Any mineral not readily identifiable under the binocular microscope was identified by its X-ray diffraction pattern. The minerals identified in samples from all 26 veins are given in table 6. Other minerals undoubtedly occur but are not identified for two reasons. First, the minerals are commonly erratically distributed along a vein, and a particular mineral that occurs in a vein may not be present where the sample was taken. Second, when abundant manganese oxides, or to a lesser extent, iron oxides are present, they commonly coat or surround another mineral so much that it is unrecognizable. This is particularly obvious among the rare-earth minerals. A sample from locality 7 had 5.3 percent total rare earths, yet the presence of any rare-earth minerals was masked by about 5 percent manganese oxide minerals. Conversely, rare-earth minerals were found in samples from localities 21 and 22, that contained only 0.23 and 0.45 percent total rare earths, respectively. These samples, however, have a maximum of 0.02 percent manganese.

The principal gangue minerals are generally potassium feldspar, quartz, cristobalite, or at locality 21, where the country rock is limestone, calcite. Potassium feldspar is the most common gangue mineral in 18 of the 26 samples. Because this mineral is easily stained with iron and manganese oxides, it is rarely conspicuous. Quartz and cristobalite are important in some of the veins; the latter mineral occurs only in the veins in the north half of section 20 just south of Bull Hill. Another gangue mineral that occurs in lesser amounts in some samples is barite. This mineral occurs in over two-thirds of the samples but is generally fairly erratic in distribution. Barite is also a common mineral in the thorium veins of the Lemhi Pass, Wet Mountains, Powderhorn, and Mountain Pass districts (Staatz, 1974, p. 498).

Iron oxide minerals are common in many of these veins, with limonite and hematite making up substantial parts of many veins. Limonite varies in color, from ocherous yellow to dark brown, and may have a dense, granular, or vuggy texture. The term limonite is applied to all the brown, hydrous iron oxides in the sample, but the name of the particular limonite mineral is only used in table 6 if it has been identified by its X-ray diffraction pattern. The variety of limonite present was identified in about half of the samples; it is generally goethite. One sample, however, had some lepidocrocite in addition to goethite. Black to reddish-gray, granular hematite is an important mineral in the veins at localities 1, 11, 13, 15, and 16. This mineral is rarely associated with manganese oxide minerals, although in other veins the manganese minerals are commonly associated with limonite. Magnetite is the most common but least abundant of all the iron oxides. It was noted in all but one of the veins, but rarely does it make up more than a few tenths of one percent. Magnetite occurs in tiny, black crystals, which are commonly intermixed with other iron oxide minerals.

Manganese oxide minerals are black to dark gray in color and, in places, they have a botryoidal structure. The specific manganese oxide mineral was not identified in most samples, but cryptomelane was identified in a sample from locality 5; pyrolusite, in a sample from locality 22; and both these minerals in a sample from locality 24 (table 6). Other manganese oxide minerals may also be present.

Although analytical data indicate abnormal amounts of rare earths compared to unmineralized intrusive rock in all the samples analyzed (table 7), rare-earth minerals were found in only 11 of the 26 samples (table 7). The three rare-earth minerals found are brockite, bastnaesite, and monazite. None were found in the same samples. Brockite [$(Ca,Th,Ce)PO_4 \cdot H_2O$] was noted in five samples. It commonly occurs in hematite-rich samples. Brockite varies in color and appearance in the five samples, although some of the difference in color may be due to hematite or limonite stain. The following colors of brockite occur in various samples: white, light yellow, tan, yellowish brown, brown, and reddish brown. Its surface may be dull, opaque, greasy, or resinous. Brockite-bearing samples were generally those with a higher thorium content. Although brockite is a little-known mineral, it is fairly common in thorium-bearing veins. It has also been identified in some veins from the following districts: Wet Mountains, Colo. (Fisher and Meyrowitz, 1962); Lemhi Pass, Mont. and Idaho (Staatz, 1972, p. 62–64); Laughlin Peak, N. Mex.; Monroe Canyon, Utah (Staatz, 1974, p. 500); and Rawhide Mountains, Ariz. Bastnaesite, ranging from white to yellow in color, was found in three samples. It is the source of most of the rare earths being mined at Mountain Pass, Calif. (Olson and others, 1954, p. 34–35). Monazite was found at three localities, and at two of these (10 and 19) it is clearly visible in hand specimens.

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TABLE 6.—*Mineralogy of the thorium and rare-earth-bearing veins in the southern Bear Lodge Mountains*

[Minerals listed in italics were identified by their X-ray diffraction pattern]

Location No.	Vein if more than one	Minerals--relative amounts			
		Large	Moderate	Small	Rare
1	---------	Hematite-------	Limonite, sanidine, fluorite.	Barite--------	Magnetite, calcite, brookite.
2	---------	Sanidine-------	Goethite---------	Magnetite, quartz, chlorite.	Anatase (?).
3	---------	Sanidine-------	Montmorillonite, goethite, manganese oxide mineral.	Hematite, calcite, barite, brockite.	Magnetite, rutile.
4	North vein.	Sanidine-------	Manganese oxide mineral.	Limonite, hematite, chlorite, barite.	Magnetite.
4	South vein.	Limonite-------	Sanidine, manganese oxide mineral.	Magnetite, hematite, quartz.	Calcite, fluorite.
5	---------	Sanidine, limonite.	Cryptomelane.	Bastnaesite, hematite, barite.	Magnetite, rutile, brookite.
6	---------	Manganese oxide mineral, sanidine.	Goethite---------	Quartz, fluorite.	Magnetite, zircon.
7	---------	Sanidine-------	Goethite, manganese oxide mineral.	Barite--------	Magnetite, calcite.
8	-------	Sanidine-------	Fluorite, limonite, manganese oxide mineral.	Hematite, barite, rutile.	Calcite, magnetite, zircon, sphalerite.
9	---------	Sanidine, quartz, limonite.	Barite----------	Manganese oxide mineral.	Magnetite, calcite, rutile.
10	---------	Quartz, monazite.	Rutile----------	Hematite, barite.	Magnetite, calcite, brookite.
11	---------	Sanidine, beta-cristobalite, hematite.	Kaolinite, quartz, goethite, barite.	Lepidocrocite, rutile, anatase, brookite.	Magnetite, calcite.
12	---------	Goethite, sanidine.	Manganese oxide mineral, kaolinite, montmorillonite.	Quartz, cristobalite, barite, brookite.	Magnetite, calcite, biotite, rutile.
13	---------	Sanidine, limonite.	Quartz, hematite, barite.	Rutile--------	Magnetite, brookite.

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TABLE 6.—*Mineralogy of the thorium and rare-earth-bearing veins in the southern Bear Lodge Mountains*—Continued

Location No.	Vein if more than one	Minerals--relative amounts			
		Large	Moderate	Small	Rare
14	---------	Sanidine-------	Quartz, limonite.	Magnetite, rutile, plagioclase.	Zircon, fluorite.
15	---------	Sanidine, hematite, cristobalite.	Limonite, barite, bastnaesite.	Brookite------	Magnetite, rutile, calcite.
16	---------	Hematite, goethite.	Sanidine, cristobalite, barite.	Rutile--------	Calcite, magnetite.
17	---------	Sanidine, goethite.	Monazite---------	Rutile, brookite, barite.	Magnetite.
18	---------	Sanidine-------	Goethite, quartz.	Rutile, barite, brookite.	Do.
19	---------	Cristobalite, goethite.	Quartz, monazite.	Brookite, barite, hematite.	Calcite, magnetite.
20	---------	Cristobalite	Sanidine, manganese oxide mineral, goethite.	Quartz, rutile, brookite, bastnaesite.	Magnetite, calcite.
21	---------	Calcite, sanidine.	Goethite, plagioclase.	Quartz, hematite, dolomite, brockite.	Ilmenite.
22	Northeast-trending vein.	Sanidine-------	Pyrolusite-------	Quartz, limonite, fluorite, brockite, anatase.	Magnetite, biotite.
22	Northwest-trending vein.	Sanidine-------	Goethite, brockite.	Manganese oxide mineral, plagioclase.	Magnetite, hematite, fluorite, anatase, aegirine(?).
23	----------	Sanidine-------	Manganese oxide mineral.	Quartz, plagioclase, limonite, barite.	Calcite, magnetite.
24	----------	Quartz---------	Pyrolusite, cryptomelane.	Limonite, barite.	Magnetite, hematite, anatase, zircon, brookite.

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TABLE 7.—*Chemical analyses of samples from veins in the southern Bear Lodge Mountains*

[N.D., not determined; <, less than value indicated; >, greater than value indicated]

Locality No.	1	2	3	4	4	5	5	6	7	8
Vein if more than one	---	---	---	North vein	South vein	---	---	---	---	---
Sample No.	MHS-87-75	MHS-99-75	MHS-82-75	MHS-79-75	MHS-80-75	MHS-98-75	MHS-55-77	MHS-56-75	MHS-83-75	MHS-54-75
	In parts per million									
Thorium[1]	390	1,320	6,750	3,550	2,300	745	391	2,575	3,725	12,000
Uranium[1]	250	45	220	235	80	96	106	40	60	N.D.
Lanthanum[2]	30,000	N.D.	20,000	15,000	5,000	15,000	N.D.	2,000	10,000	3,000
Cerium[2]	30,000	N.D.	20,000	15,000	10,000	15,000	N.D.	5,000	15,000	5,000
Praesodymium[2]	3,000	N.D.	7,000	3,000	1,500	3,000	N.D.	1,000	3,000	1,000
Neodymium[2]	7,000	N.D.	30,000	15,000	7,000	10,000	N.D.	5,000	10,000	5,000
Samarium[2]	700	N.D.	7,000	3,000	1,000	1,000	N.D.	700	3,000	2,000
Europium[2]	<100	N.D.	1,500	700	<100	<100	N.D.	300	1,000	700
Gadolinium[2]	300	N.D.	5,000	3,000	1,000	200	N.D.	700	3,000	5,000
Terbium[2]	<300	N.D.	<300	<300	<300	<300	N.D.	<300	<300	<300
Dysprosium[2]	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Holmium[2]	<20	N.D.	300	70	<20	<20	N.D.	70	500	200
Erbium[2]	<50	N.D.	100	<50	<50	<50	N.D.	<50	300	150
Thulium[2]	<20	N.D.	<20	<20	<20	<20	N.D.	<20	<20	<20
Ytterbium[2]	30	N.D.	200	50	70	15	N.D.	70	500	300
Lutetium[2]	<30	N.D.	<30	<30	<30	<30	N.D.	<30	<30	<30
Yttrium[2]	500	N.D.	7,000	2,000	700	150	N.D.	3,000	7,000	7,000
Total rare earths	71,530	N.D.	98,100	56,820	26,270	44,365	N.D.	17,840	53,300	29,350
Barium[2]	20,000	N.D.	30,000	15,000	7,000	1,500	N.D.	20,000	30,000	15,000
Beryllium[2]	10	N.D.	30	7	3	15	N.D.	15	20	10
Bismuth[2]	50	N.D.	300	<50	700	300	N.D.	<50	<50	<50
Copper[2]	200	N.D.	300	300	20	1,500	N.D.	150	70	1,000
Lead[2]	1,000	N.D.	3,000	500	2,000	5,000	N.D.	700	1,500	1,000
Manganese	[2]>100,000	N.D.	[3]70,500	[2]>100,000	[3]93,400	[3]37,800	N.D.	[3]224,000	[3]45,900	[3]23,600
Molybdenum[2]	700	N.D.	300	200	300	700	N.D.	1,000	150	300
Niobium[2]	50	N.D.	500	150	200	150	N.D.	100	500	1,000
Strontium[2]	1,000	N.D.	1,500	2,000	150	1,000	N.D.	1,500	3,000	2,000
Tin[2]	<10	N.D.	70	<10	<10	<10	N.D.	<10	<10	50
Vanadium[2]	500	N.D.	700	150	150	30	N.D.	300	300	1,500
Zinc[2]	3,000	N.D.	7,000	10,000	7,000	500	N.D.	1,500	1,500	<300
Zirconium[2]	<50	N.D.	<50	<10	<10	200	N.D.	<10	<50	<50
	In percent									
Calcium[2]	2	N.D.	1.	0.3	0.1	2	N.D.	>10	>10	0.7
Iron	[2]>10	N.D.	[3]17.20	[2]>10	[3]41.40	[3]34.80	N.D.	[3]7.2	[3]9.5	[3]11.04
Magnesium[2]	.03	N.D.	1.5	.15	.07	.3	N.D.	.15	.15	.3
Phosphorus[2]	<.2	N.D.	<.2	<.2	<.2	<.2	N.D.	<.2	10	1
Potassium[1]	N.D.	9	N.D.	N.D.	N.D.	2	2	N.D.	N.D.	N.D.
Sodium[2]	.15	N.D.	<.3	1.5	.7	.15	N.D.	.3	.7	.7
Titanium[2]	.3	N.D.	.7	.3	.7	.7	N.D.	.07	.7	.7

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TABLE 7.—*Chemical analyses of samples from veins in the southern Bear Lodge Mountains*—Continued

Locality No.	9	10	11	12	12	13	14	15	16	17
Vein if more than one---	---	---	---	---	---	---	---	---	---	---
Sample No.---	MHS-49-75	BL-5-74	MHS-44-75	BL-8-74	BL-9-74	MHS-45-75	M 43-75	MHS-48-75	MHS-47-75	BL-14-74
	In parts per million									
Thorium[1]-----	1,950	700	1,120	1,020	395	1,850	890	5,100	560	720
Uranium[1]-----	75	255	110	107	150	90	33	60	175	76
Lanthanum[2]---	N.D.	30,000	N.D.	15,000	1,500	5,000	500	30,000	15,000	N.D.
Cerium[2]------	N.D.	30,000	N.D.	15,000	3,000	7,000	1,000	20,000	15,000	N.D.
Praesodymium[2]	N.D.	7,000	N.D.	7,000	700	1,000	200	5,000	5,000	N.D.
Neodymium[2]---	N.D.	20,000	N.D.	15,000	1,500	7,000	1,500	15,000	15,000	N.D.
Samarium[2]----	N.D.	2,000	N.D.	3,000	700	1,500	300	3,000	2,000	N.D.
Europium[2]----	N.D.	500	N.D.	700	<100	300	<100	300	300	N.D.
Gadolinium[2]--	N.D.	1,000	N.D.	3,000	300	1,500	300	1,000	700	N.D.
Terbium[2]-----	N.D.	<300	N.D.	<300	<300	<300	<300	<300	<300	N.D.
Dysprosium[2]--	N.D.	200	N.D.	300	<200	N.D.	N.D.	N.D.	N.D.	N.D.
Holmium[2]-----	N.D.	30	N.D.	70	<20	50	50	30	30	N.D.
Erbium[2]------	N.D.	<50	N.D.	<50	<50	<50	<50	<50	<50	N.D.
Thulium[2]-----	N.D.	<20	N.D.	<20	<20	<20	<20	<20	<20	N.D.
Ytterbium[2]---	N.D.	70	N.D.	70	15	100	50	30	70	N.D.
Lutetium[2]----	N.D.	<30	N.D.	<100	<100	<30	<30	<30	<30	N.D.
Yttrium[2]-----	N.D.	1,500	N.D.	3,000	300	1,500	1,500	700	700	N.D.
Total rare earths---	N.D.	92,300	N.D.	62,140	8,015	24,950	5,400	75,060	53,800	N.D.
Barium[2]------	N.D.	20,000	N.D.	20,000	10,000	30,000	5,000	70,000	50,000	N.D.
Beryllium[2]---	N.D.	20	N.D.	15	3	10	3	7	15	N.D.
Bismuth[2]-----	N.D.	300	N.D.	70	30	200	<30	200	500	N.D.
Copper[2]------	N.D.	50	N.D.	300	200	300	200	200	300	N.D.
Lead[2]--------	N.D.	3,000	N.D.	3,000	1,500	1,500	150	5,000	5,000	N.D.
Manganese----	N.D.	[2]1,000	N.D.	[2]>100,000	[2]100,000	[2]1,500	[2]70,000	[2]300	[2]150	N.D.
Molybdenum[2]--	N.D.	70	N.D.	300	300	500	700	500	300	N.D.
Niobium[2]-----	N.D.	2,000	N.D.	150	100	150	150	700	1,000	N.D.
Strontium[2]---	N.D.	1,500	N.D.	1,500	1,000	200	1,000	500	500	N.D.
Tin[2]---------	N.D.	<10	N.D.	<10	<10	<10	<10	15	50	N.D.
Vanadium[2]----	N.D.	300	N.D.	200	300	500	30	300	700	N.D.
Zinc[2]--------	N.D.	<300	N.D.	7,000	7,000	3,000	500	500	<300	N.D.
Zirconium[2]---	N.D.	50	N.D.	<100	<100	<10	200	30	30	N.D.
	In percent									
Calcium[2]-----	N.D.	0.5	N.D.	3	0.15	0.3	2	0.3	0.5	N.D.
Iron---------	N.D.	[2]5	N.D.	>10	>10	[2]>10	[2]10	[2]>10	[2]>10	N.D.
Magnesium[2]---	N.D.	.1	N.D.	1	.07	.15	.3	.03	.007	N.D.
Phosphorus[2]--	N.D.	1.5	N.D.	1.5	<.2	<.2	<.2	<.2	1	N.D.
Potassium[1]---	2.4	1.6	5	2.2	.74	N.D.	10	N.D.	2	8.8
Sodium[2]------	N.D.	.1	N.D.	.15	.07	<.05	.7	.3	.3	N.D.
Titanium[2]----	N.D.	2	N.D.	.5	.15	.15	.7	.7	1.5	N.D.

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TABLE 7.—*Chemical analyses of samples from veins in the southern Bear Lodge Mountains*—Continued

Locality No.	18	19	20	21	21	22	22	23	24
Vein if more than one---	---	---	---	---	---	Northeast trending	Northwest trending	---	---
Sample No.---	MHS-40-75	BL-2-74	MHS-42-75	MHS-96-75	MHS-97-75	BL-12-74	MHS-73-75	MHS-76-75	MHS-60-75
				In parts per million					
Thorium[1]-----	112	1,220	1,020	4,100	917	4,125	2,250	1,600	850
Uranium[1]-----	21	150	77	N.D.	5	270	25	30	30
Lanthanum[2]---	N.D.	15,000	10,000	70	N.D.	150	300	N.D.	300
Cerium[2]------	N.D.	20,000	15,000	<200	N.D.	300	300	N.D.	700
Praesodymium[2]	N.D.	5,000	3,000	<100	N.D.	<100	<100	N.D.	100
Neodymium[2]---	N.D.	15,000	7,000	<70	N.D.	<70	300	N.D.	700
Samarium[2]----	N.D.	2,000	3,000	<100	N.D.	<100	<100	N.D.	200
Europium[2]----	N.D.	500	300	<100	N.D.	<100	<100	N.D.	<100
Gadolinium[2]--	N.D.	1,000	700	N.D.	N.D.	2,000	200	N.D.	150
Terbium[2]-----	N.D.	<300	<300	<300	N.D.	<300	<300	N.D.	<300
Dysprosium[2]--	N.D.	500	N.D.	150	N.D.	1,000	<50	N.D.	<50
Holmium[2]-----	N.D.	30	30	70	N.D.	200	70	N.D.	<20
Erbium[2]------	N.D.	500	<50	300	N.D.	500	150	N.D.	<50
Thulium[2]-----	N.D.	<20	<20	<20	N.D.	70	<20	N.D.	<20
Ytterbium[2]---	N.D.	20	30	200	N.D.	1,000	200	N.D.	7
Lutetium[2]----	N.D.	<30	<30	<30	N.D.	<30	<30	N.D.	<30
Yttrium[2]-----	N.D.	1,000	500	1,500	N.D.	1,000	3,000	N.D.	200
Total rare earths---	N.D.	60,550	39,560	2,290	N.D.	15,220	4,520	N.D.	2,357
Barium[2]------	N.D.	20,000	7,000	3,000	N.D.	3,000	1,000	N.D.	3,000
Beryllium[2]---	N.D.	7	20	20	N.D.	<1.5	20	N.D.	70
Bismuth[2]-----	N.D.	200	50	<30	N.D.	<10	<50	N.D.	70
Copper[2]------	N.D.	300	1,500	70	N.D.	30	50	N.D.	1,000
Lead[2]--------	N.D.	3,000	2,000	70	N.D.	70	70	N.D.	700
Manganese----	N.D.	[2]300	[3]32,300	[3]1,880	N.D.	[2]3,000	[2]700	N.D.	[2]3,000
Molybdenum[2]--	N.D.	700	70	<3	N.D.	<3	<3	N.D.	70
Niobium[2]-----	N.D.	150	200	50	N.D.	3,000	150	N.D.	30
Strontium[2]---	N.D.	1,000	700	700	N.D.	3,000	1,500	N.D.	150
Tin[2]---------	N.D.	<10	50	<10	N.D.	50	15	N.D.	<10
Vanadium[2]----	N.D.	700	700	500	N.D.	7,000	7,000	N.D.	30
Zinc[2]--------	N.D.	<300	1,500	<300	N.D.	<300	<300	N.D.	<300
Zirconium[2]---	N.D.	70	70	1,500	N.D.	500	700	N.D.	150
				In percent					
Calcium[2]-----	N.D.	0.2	1.5	>10	N.D.	1	0.3	N.D.	2
Iron---------	N.D.	[2]>10	[3]11.40	[3]2.91	N.D.	[2]1	[2]7	N.D.	[2]3
Magnesium[2]---	N.D.	.05	1.5	7	N.D.	.3	.15	N.D.	.07
Phosphorus[2]--	N.D.	.7	1.5	<.2	N.D.	.5	<.2	N.D.	<.2
Potassium[1]---	9.8	4.6	2.4	N.D.	0.4	7.9	7	7	3
Sodium[2]------	N.D.	.2	.7	1	N.D.	.5	1.5	N.D.	.5
Titanium[2]----	N.D.	.07	.7	.3	N.D.	3	.7	N.D.	.07

[1]Analyzed by gamma-ray spectrometer by C. M. Bunker and C. A. Bush
[2]Analyzed by semiquantitative six-step spectrographic method by N. M. Conklin
[3]Analyzed by atomic absorption method by C. A. Gent

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Here it is a fine-grained, pale-green to light-tan, opaque mineral. Monazite is visible in hand specimens at these localities because the monazite content is high and the manganese oxide content is low. This mineral is also visible in several smaller veinlets in the same area.

Ten other accessory minerals occur in some of these samples. Rutile is the most common, occurring in a little over half the samples. This mineral, found in tiny, black, shiny, granular crystals, reflects the presence of small amounts of titanium (table 7). Titanium also occurs in the minerals brookite, anatase, and ilmenite. Some samples contain more than one titanium mineral, and rutile and brookite occur together in eight samples. Fluorite is another fairly common accessory in the Bear Lodge veins. It varies in color from clear to pale purple to dark purple. The other five accessories are zircon, biotite, chlorite, sphalerite, and dolomite.

CHEMICAL COMPOSITION

The thorium content of 35 vein samples ranges from 112 to 13,000 ppm, and 20 of these samples contain at least 1,000 ppm. Twenty-nine of these samples are reported in table 7, and the other six were reported by Wilmarth and Johnson (1953, p. 21 and table 4). Most of the 29 samples reported in table 7 are chip samples, although a few are grab samples. All were collected to represent the entire thickness of the vein. Thorium analyses on these samples (table 7) were made by C. M. Bunker and C. A. Bush, U.S. Geological Survey, on a gamma-ray spectrometer. This method has an accuracy of ±3 percent. The highest thorium content was obtained from a vein at locality 8, which is only 7.5 cm thick and is exposed in only one pit. The thorium content of a sample from the longest vein (loc. 11) contained 1,120 ppm; that of two samples from the next longest vein (loc. 12) had 1,020 and 395 ppm.

The analyses used for rare earths in this report were done by the semiquantitative spectrographic method. Results are identified within brackets whose boundaries are 1.2, 0.83, 0.56, 0.38, 0.26, 0.18, 0.12, and so forth, but are reported as midpoints between these brackets. Thus, the numbers reported would be 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, and so forth. The precision of a reported value is approximately plus or minus one bracket. The total rare-earth content of the 21 samples analyzed for these elements varies from 3,290 to 98,100 ppm (table 7), and the average is 40,200 ppm.

The rare earths are generally much more abundant than thorium in the Bear Lodge veins. Only one of our samples (table 7) contained more thorium than total rare earths. This sample, which came from the only vein cutting a limestone (loc. 21), contained 4,100 ppm thorium to 2,290 ppm total rare earths. The total rare-earth-to-thorium ratios in the other 20 samples for which I have chemical data range from 2.0 to 184, but 14 of the samples contain 10 times more rare earths than thorium. Although rare earths and thorium commonly occur in the same minerals, little correlation exists between the amounts of rare earths and thorium that occur in these veins. The lack of correlation between the amounts of total rare earths and thorium has also been noted in other areas, such as the Lemhi Pass district, Idaho and Montana (Staatz and others, 1972, p. 75–77), the Hall Mountain district, Idaho (Staatz and others, 1974, p. 680), and in the Wet Mountains, Colo. (Christman and others, 1959, p. 522, 524, and 530). This lack of correlation may be due in part to the separation of rare earths and thorium at depth, and in part to slight differences in chemical and physical conditions at the vein site. Differing conditions would tend to favor the formation of different proportions of rare-earth and thorium minerals at different places.

The rare earths consist of 16 elements with similar chemical properties. Fifteen of the elements—lanthanum (La), cerium (Ce), praesodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu)—occur sequentially in the periodic table, elements 59 through 71. This group is called the lanthanides. One of these, promethium, is almost unknown in nature. Yttrium (Y), not one of the lanthanides but chemically similar to them, is also classed as a rare earth. All rare earths have a +3 valence and similar atomic radii; hence, they can easily substitute for one another, and they are always found together.

In the normal distribution of the lanthanides in the Earth's crust, and in most minerals, the ones with the even atomic numbers are more abundant than the adjacent odd-numbered ones. The average crustal abundance of either even- or odd-atomic numbered lanthanides decreases with an increase in atomic number. Generally, therefore, cerium is the most abundant lanthanide and lutetium the least. This distribution pattern of the lanthanides occurs in many minerals, but may be markedly different in a few, owing to the partial separating out (fractionation) of various rare earths. Thus, in rocks that are not fractionated, cerium is the most abundant lanthanide with an even atomic number, and lanthanum is the most abundant lanthanide with an odd atomic number.

Three principal types of lanthanide distribution are seen in the Bear Lodge veins. In one common type, cerium and lanthanum are the most common even-atomic-

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numbered and odd-atomic-numbered lanthanides, respectively. This type, which is exemplified by samples from locality numbers 1, 12, 19, and 20, is similar to that of the Earth's crust. A second common distribution type is similar to the first except that the cerium content is much lower, so that the neodymium content of the sample either equals or exceeds that of the cerium. Samples from locality numbers 3, 14, and 16 in the Bear Lodge Mountains are of this type. This type of fractionation is fairly common in thorium veins and was the most common type found in those at Lemhi Pass (Staatz and others, 1972, p. 78). A probable explanation of this type of fractionation is as follows: All lanthanides have a +3 valence, but cerium is the only one that also has a +4 valence. Thus, if cerium is oxidized from Ce^{+3} to Ce^{+4}, the resulting decrease in ionic radius and increase in charge would exclude this element from structural sites in the rare-earth mineral molecule that was normally available to it in the trivalent form. The third principal type of lanthanide distribution involves an abrupt increase in the heavier lanthanides. In two samples, BL-12-74 at locality 22 and MHS-96-75 at locality 21, gadolinium and erbium, respectively, are the principal lanthanides. The possible cause of this type of distribution is not known, but fractionation probably took place prior to vein emplacement.

Mineral content of thorium veins is generally difficult to correlate with lanthanide distribution. Some minerals, such as bastnaesite and monazite, are made up principally of the lighter lanthanides (those with an atomic number less than 63); others, such as xenotime and brockite, are made up principally of the heavier lanthanides (those with an atomic number greater than 63). The structure of a few minerals, such as thorite, is not markedly selective in its acceptance of various lanthanide elements, and proportions of the various rare earths in these minerals closely reflect the lanthanide content of the vein-forming fluids (Staatz and others, 1974, p. 682). In thorium veins in other districts the abundance of thorite, a nonselective mineral, masks any correlation between lanthanide distribution and mineral content. In the thorite-rich Lemhi Pass district, the only correlation between mineral content and lanthanide abundance is found in three brockite-bearing samples, in which gadolinium and other heavy lanthanides are relatively common (Staatz, 1972, p. 77). Brockite is also a marker of high gadolinium and other heavy lanthanides in the Bear Lodge Mountains, where samples containing brockite at localities 21 and 22 have a relatively high proportion of heavy lanthanides (tables 6 and 7). Similarly, in mineral samples where monazite is common (locs. 10, 17, and 19) or bastnaesite is found (locs. 5, 15, and 20), the light lanthanides, cerium and lanthanum, make up the greater part of the total lanthanides. As thorite has not been found in the veins of the Bear Lodge Mountains, the rare-earth minerals might be useful in identifying the major type of lanthanide distribution. Unfortunately, the masking effect of the abundant manganese and iron oxides conceals the presence of most of the rare-earth minerals in many samples, limiting the use of these minerals in determining the lanthanide distribution.

The uranium content of these deposits is less than that of thorium. The uranium content of 27 vein samples ranges from 5 to 270 ppm (table 7). The Th:U ratios of these samples range from 1.6 to 183, but most fall between 3 and 65. The Th:U ratios of these samples are for the most part lower than those of the Lemhi Pass district, which generally range from 20 to 180 (Staatz, 1979, p. A48).

Iron, manganese, calcium, and potassium contents of the 26 veins vary considerably. They are found in amounts exceeding 7 percent in some samples but are scarce in others. Iron makes up 7 or more percent of 17 of the 21 samples analyzed for this element, yet it makes up only 1 percent of the samples from the northeast-trending vein at locality 22 (table 7). Similarly, manganese makes up 7 or more percent of 8 of the 21 samples analyzed for this element but makes up 0.3 percent or less in 9 samples and in 1, only 0.015 percent. The calcium content in these veins is generally between 0.1 and 2 percent, yet, in three samples it exceeds 10 percent. In addition, the potassium content varies from 0.4 to 10 percent in 19 samples, which is approximately a 25-fold change. Eleven of the samples were analyzed by the semiquantitative spectrographic method, which has an upper detection limit of 10 percent Fe. The other eight samples were analyzed by the more accurate atomic absorption method (table 7). Two of these latter samples yielded 34.8 and 41.4 percent iron, which is equivalent to 49.8 and 59.2 percent Fe_2O_3. Thus, ferric oxide is the principal oxide in some of these veins. Black manganese minerals appear to be fairly common in many of these veins. A sample from one of them (table 7, loc. 6) contains 22.4 percent manganese, but in most samples manganese is much less abundant. Manganese appears in hand specimen to make up considerably more of the vein than it does when analyzed. In part this is due to black manganese oxide staining other minerals so that they appear to be mainly manganese oxide, and in part it is due in some veins to the presence of abundant fine-grained black hematite, which is easily confused with the manganese oxide minerals. The potassium content of the greater part of the samples falls into one of two groups: (1) those that contain 1.5-2.5 percent potassium, and (2) those that

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contain 7–10 percent. Potassium occurs almost entirely in potassium feldspar, which in many places may be the principal gangue mineral. The potassium content of these veins is roughly equivalent to 3–70 percent potassium feldspar. Although the iron, manganese, calcium, and potassium contents of these veins vary radically, this variation seems to have little effect on the amount of thorium or rare earths present. Small amounts of lead, zinc, molybdenum, copper, and bismuth occur in some of these veins. Lead and zinc are the commonest metals in this group and make up from 70 to 5,000 ppm and from <300 to 10,000 ppm, respectively, of various samples (table 7). Copper and molybdenum are anomalous but much less so than the lead and zinc. Only 4 of 21 samples contained as much as 1,000 ppm copper, and only one contained 1,000 ppm molybdenum. Bismuth, although below the limit of detection in eight samples, made up 30–700 ppm of the remaining analyzed samples. Bismuth commonly occurs in lead minerals (Hasler and others, 1973, p. 95), and in the Bear Lodge samples all of the higher bismuth values came from samples that are high in lead.

Barium, strontium, and niobium are commonly found in thorium-bearing veins. Barium content of 21 samples from the Bear Lodge veins varies from 1,000 to 70,000 ppm; 13 of the samples contain at least 10,000 ppm. Barium generally occurs in barite, which was identified in 13 samples. Strontium content of these samples ranges from 150 to 3,000 ppm. No strontium minerals were identified in these veins, but some strontium commonly substitutes for barium in barite. In most samples, where the barium content is 10 or more times larger than the strontium content, all the strontium is probably proxying for barium in barite. In two samples from locality 22, however, the strontium content either equals or exceeds the barium content (table 7). Strontium here is probably in another mineral.

The niobium content of the vein samples ranges from 30 to 3,000 ppm. This is approximately the same range of niobium values found in vein samples from the Lemhi Pass district (Staatz, 1979, p. A49).

ECONOMIC GEOLOGY

The veins of the Bear Lodge Mountains have received more attention than the disseminated deposits because they have distinct boundaries, have the most radioactivity, contain higher grades of rare earths and thorium, and have been explored in the past for these elements. The veins in this district, however, are smaller and less continuous than thorium- and rare-earth-bearing veins found in the Lemhi Pass district of Idaho and Montana, Wet Mountains and Powderhorn districts of Colorado, Diamond Creek and Hall Mountain districts of Idaho, and the Mountain Pass district of California (Staatz, 1974). The resources of the Bear Lodge veins were calculated on 26 veins, or all known veins over 5 cm thick. These veins are exposed along strike for about a meter to 137 m, and are as much as 2.5 m thick. All the data used in calculating resource data come from surface exposures. Lacking any data on the downward extension of these veins, none of the resources can be considered measured reserves. Resources are divided into indicated and inferred reserves. Indicated reserves in each vein are those found in a block consisting of the traceable length of the vein multiplied by the average thickness multiplied by a depth equal to one-third the length of the vein. Inferred reserves are extensions of the indicated reserves both laterally and at depth. For inferred reserves, the vein was extended on the surface a quarter of the known length in each direction. This distance was shortened where the vein could not be extended through areas of outcrop. Thickness was the same as that used in calculating indicated reserves. Depth of this block is one and a half times the trace of the vein. All veins regardless of length are included in these reserves. If the vein is exposed in only one place, it is assumed to have a length of 7.6 m. A tonnage factor of 2.38 m^3/t is used in converting vein volume to vein weight. The average grade of all veins ranges from 0.011 to 0.68 percent ThO_2 and from 0.23 to 9.81 percent total rare-earth oxides. Indicated reserves of all 26 veins are 50 t of ThO_2 and 1,360 t of total rare-earth oxides. Inferred reserves amount to 250 t of ThO_2 and 6,810 t of total rare-earth oxides. Reserves of most veins are small, and those of 17 of the 26 veins do not exceed 10 t of ThO_2. Most veins in this district are too small to support a viable mining operation. The ThO_2 content is lower, although the total rare-earth content is higher, than most other thorium- or rare-earth-containing veins in other districts. A discussion of the necessary size and grade of thorium veins in various districts to support a viable mining industry has been presented by Staatz and others (1979). They concluded that in a modern mining operation, a vein should contain a minimum of 32,000 t of mineable rock. Only two of the veins in the Bear Lodge Mountains have this much in total reserves. These two veins have indicated reserves of only 20 t of ThO_2 and 545 t of total rare-earth oxides. They also have inferred reserves of 125 t of ThO_2 and 3,140 t of total rare-earth oxides.

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DISSEMINATED DEPOSITS

PHYSICAL AND RADIOMETRIC DESCRIPTION

The disseminated deposits occur entirely within the fractured Tertiary intrusive rocks that form the core of the Bear Lodge dome. Much of the intrusive rock in the core has been fractured and altered, but the greatest concentration of fracturing and the most mineralization occur in the central part of the core. Boundaries of disseminated deposits may be either gradational or sharp, and they commonly are erratic. The deposits can be roughly outlined by radioactivity that is concentrated in veinlets within the altered rock.

The radioactivity, however, of all the Tertiary intrusives is above that of the adjacent sedimentary rocks. These igneous rocks range from 120 to 3,500 counts/s on a model SC-1314 Mount Sopris scintillation counter.[1] The least altered parts of the main intrusive, the south and north ends, and the little-altered small intrusives that surround the main intrusive have the least radioactivity. The intrusive rocks in these areas commonly yield only 150 to 300 counts/s. The radioactivity of the surrounding sedimentary rocks is typically between 60 and 80 counts/s. Radioactivity is greatest near Bull Hill in the hydrothermally altered central part of the area that is seamed by many thin veinlets. As the central part of the intrusive body has been erratically mineralized and altered, measurements taken a meter apart may show considerable differences.

The size and extent of the disseminated deposits are not readily determinable by visual examination, and this must depend on either radiometric or chemical measurements. As a first step in determining the extent of mineralization, radiometric readings were taken over the entire central core of the Bear Lodge dome, an area of approximately 30 km^2, with a Mount Sopris scintillation counter. Plate 2*A* is a radiometric map made from measurements taken at 537 different localities. The contours on this map represent a generalized position of points of equal radiation.

The scintillation counter measures both gamma and high-energy beta-rays. These come from three sources, (1) thorium, (2) uranium, and (3) potassium, all three of which may have an appreciable effect on the total radioactivity. The radiation from potassium comes from the isotope ^{40}K, which only makes up 0.0119 percent of the total potassium. Hence, in high-grade thorium veins, the radioactivity due to potassium is insignificant when compared to the total radioactivity. In disseminated deposits, however, where the thorium content is relatively low and potassium content fairly high, radiation due to potassium makes up a much larger proportion of the total radiation. The potassium content of 354 samples was measured on a quantitative gamma-ray spectrometer (Staatz and others, 1980, table 1). An overall average of these samples is close to 9.1 percent potassium. The amount of radioactivity from a rock containing this amount of potassium is equal to that produced by 260 ppm thorium (John Stuckless, oral commun., 1978). The potassium occurs mainly in feldspar, both as an essential mineral in the igneous rocks and as a gangue mineral in the veinlets. Potassium is an important source of radioactivity in these rocks, and in some areas it may be the principal source of radioactivity. The radioactivity due to potassium changes much more gradually than that due to thorium or uranium, as it takes a major change in the amount of potassium to make an abrupt change in radioactivity. Thus, the effect of potassium is to give a generally high background radioactivity over all the Tertiary intrusive rocks. Abrupt changes in potassium content are most commonly due to changes in country rock.

The radioactivity in the Bear Lodge deposits due to uranium is greater than in most other thorium districts. The uranium content of 354 samples of rock from the Tertiary intrusive ranges from 2 to 346 ppm; most, however, contain less than 15 ppm. The radioactivity due to uranium is approximately 5.7 times that created by an equal amount of thorium. Thus, the radiation due to uranium would about equal that due to approximately six times as much thorium. Although the amount of uranium exceeds thorium in only 3 of the 354 samples, the amount of radioactivity due to uranium is greater than that due to thorium in a number of others.

Thorium is the principal source of radiation in most samples. In the other samples, uranium is the principal source. Potassium contributes a significant amount of radiation to all samples. The following questions need answering: Is the radioactivity due to thorium masked by radiation from uranium and potassium in many places? Can the overall pattern of thorium radioactivity be discerned on a radiation map (pl. 2*A*) made with a scintillation counter? The problem is twofold with part of the variation due to the presence of uranium and potassium and part due to differences between measurements made by the scintillation counter and data obtained from analyses. To separate the two problems, the proportionate amount of radiation obtained from

[1]Brand or manufacturers' names used in this report are for descriptive purposes and do not constitute endorsement by the U.S. Geological Survey.

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thorium, uranium, and potassium in each sample was calculated from analyses. This was done by arbitrarily equating the radioactivity due to 1 ppm thorium to 1 count/s. Then, the radioactivity due to 1 ppm of uranium is 5.7 counts per second and that of 1 percent potassium is 28.5 counts/s. The thorium content of the samples is plotted against their calculated total count (fig. 14*A*)[2]. The well-defined linear trend formed by these points indicates that the thorium content is for the most part proportional to the total count. The one point to the far right that does not fit the general pattern contained 346 ppm uranium. The radioactivity due to uranium in this sample is about 15 times that due to thorium.

The difference obtained between the actual radiation measured by a scintillation counter and the thorium content of the sample from that locality is shown in figure 14*B*. The linear trend is still quite apparent for the samples with a low thorium content. The two graphs show that higher radioactivity, no matter what the source, indicates a greater thorium content. Furthermore, the total thorium content is roughly proportional to the radioactivity.

Although the contour map shown on plate 2*A* in general outlines the principal radiometric areas, it is of too small scale to define the size and grade of the disseminated deposits. In 1979 a more detailed radiometric measuring and sampling program was started. This program covered an area of about 10.6 km² of the most radioactive part of the igneous core. At each sample site a chip sample was collected and analyzed for thorium, uranium, and potassium on a quantitative gamma-ray spectrometer in the U.S. Geological Survey's Denver laboratory (Staatz and others, 1980). In addition semiquantitative spectrographic analyses were performed on a little over half of these samples. Radiometric measuring and sampling were made only on soil-free areas. Many of the sites were in pits, trenches, or on dumps, but some were of roadcuts and of outcrops along ridges. Samples and radiometric readings were taken so as to be as representative as possible; none contained material from any of the larger veins described in the previous section. These data were used to construct five contour maps: (1) a detailed total-count radiometric map, (2) a thorium map, (3) a uranium map, (4) a potassium map, and (5) a total rare-earths map.

The detailed radiometric contour map (pl. 2*B*) gives a more detailed picture of a smaller area than that shown on plate 2*A*. Differences between these two maps can largely be accounted for by having many more points on view *B*. The areas of greatest radioactivity on view *B* are concentrated in section 17 and adjacent parts of sections 18 and 20.

A thorium map (pl. 2*C*), which is based on thorium analyses of samples taken at 354 localities, fairly closely resembles the total count map. Differences are due to the fact that view *C* represents only the thorium content of the rock and that the two sets of measurements, although taken at the same locality, were not exactly the same sample. View *C* can be used to define the edge of the disseminated deposit as a thorium resource.

A thorium aeroradioactivity map or thorium gamma-ray intensity map of the same area at a scale of 1:62,500 was published in 1979 (Geometrics, 1979). This map and plate 2*C*, except for their difference in scales, are remarkably similar in the area of principal thorium concentration in sections 17, 18, and the north half of section 20. Away from the principal thorium concentration, the two show many differences. These differences are due to both the size of the samples and the difference in material measured. Plate 2*C* is a spot map, and each sample represents a small specific area of bedrock. The aeroradiometric measurements were made at an average elevation of 122 m at a flight speed of 112 km/hr, and each 1-second measurement corresponds to an oval area 213 m long by 183 m wide (Geometrics, v. 1, p. 47). The material measured includes both alluvial cover and bedrock, and most measurements represent more of the former.

The uranium contour map (pl. 2*D*) shows little resemblance to the thorium map (pl. 2*C*). A comparison of the two maps indicates that the few concentrations of uranium present are not closely associated with those of thorium. The uranium values of more than 60 ppm appear to represent scattered individual samples rather than part of a general increase in uranium in that area. Furthermore, except for the few scattered samples, the uranium tenor is fairly low and rarely exceeds 40 ppm. The uranium contour map shows little resemblance to a previously published aeroradiometric uranium gamma-ray contour map (Geometrics, 1979). The aeroradiometric contour map over the area of thorium concentration resembles the thorium contour map. The values used in constructing the aeroradiometric uranium map are corrected readings of gamma-ray spectrometer measurements. Correcting is done by using a complicated formula to remove excess radiation due to thorium or potassium in the uranium channel. The formulas for the instrument used by Geometrics were calculated from measurements made on the U.S. Department of Energy's sample areas in Grand Junction, Colo., which have known thorium, uranium, and potassium contents. These formulas, however, are apparently

[2]The analyses used in these graphs were those from samples collected between 1975 and 1977 and do not include those collected in 1979.

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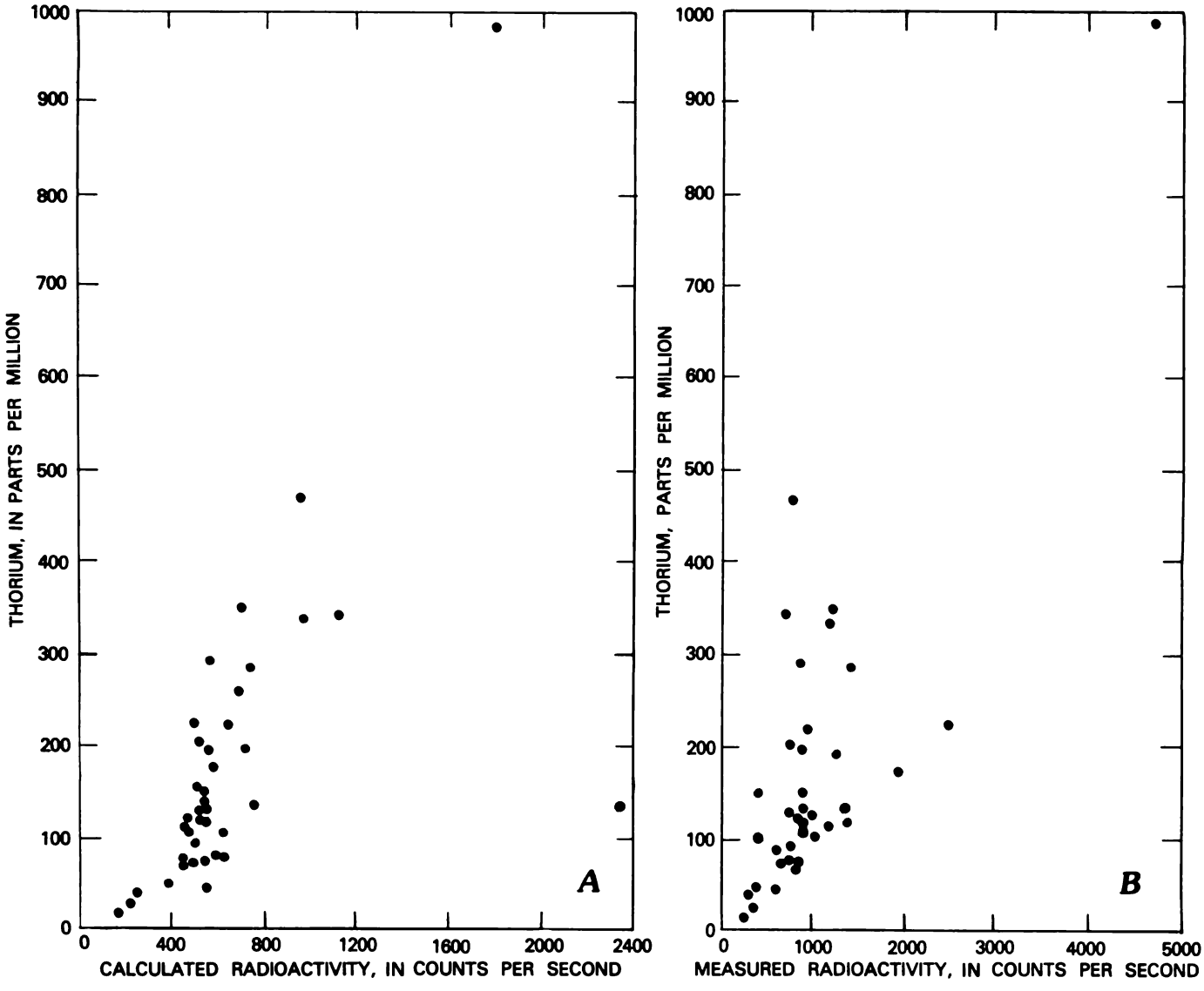


FIGURE 14.—Relation of thorium content to radioactivity in the core of the Bear Lodge dome. *A*, Radioactivity calculated from analyses. *B*, Radioactivity measured with scintillation counter at sample site.

not satisfactory for areas that have a high thorium content, as considerable thorium is apparently interpreted as uranium. I have also measured the thorium, uranium, and potassium content of the trachyte core with a portable gamma-ray spectrometer. My instrument was also calibrated on the U.S. Department of Energy's sample areas in Grand Junction, Colo. Results obtained were not satisfactory, and a uranium contour map constructed from this data also resembled that of thorium.

The potassium contour map (pl. 2*E*) shows little resemblance to the total count, thorium, rare-earth or uranium maps. Potassium is principally in the feldspar of the host rock, and changes in potassium content reflect changes in the amount of potassium-bearing feldspar. In some places, a change indicates different rock types, but in other places it is due to later alteration that has resulted in leaching of some of the original potassium from the rock.

The rare-earth contour map (pl. 2*F*) shows little resemblance to the other contour maps. The area in which the greater part of the rare earths occurs is the same general area in which the thorium is concentrated. In detail the major rare-earth concentrations are found in different places than those of thorium. The reason that rare earths and thorium are found in the same general area is that both occur in the veinlets that make

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up the disseminated deposits. Furthermore, both rare earths and thorium commonly occur in the same minerals. The amounts of rare earths in various minerals, however, show little correlation with the amount of thorium. Hence, although the amounts of rare earths may not correlate with those of thorium, those areas lacking veinlets will lack both rare earths and thorium.

MINERALOGY

The study of the mineralogy of the disseminated deposits was carried out in the same manner as that of the veins. The minerals identified in samples from 36 locations are given in table 8. Twenty-nine minerals have been identified. Although the altered trachytic rock and phonolitic country rock make up the bulk of the samples, most of the identified minerals were derived from the veins. Minerals from the country rock are now largely shown in table 8 as groundmass, which means very fine grained or aphanitic pieces in which individual minerals are not distinguishable under the binocular microscope. Minerals from the country rock also make up part of the feldspar and iron oxides. Thus, the gross mineralogy, as shown in table 8, is mainly derived from the veins, but the concentration of the various vein minerals has been diluted by the addition of the country-rock fraction.

The mineralogy of the disseminated deposits includes both that of the altered and fractured trachytic and phonolitic host rock, and that of the included tiny veinlets. The mineralogy of the veinlets is similar to and shows the same kind of variations as that of the previously described veins (p. D33–D34). The trachyte and phonolite consist principally of larger sanidine and smaller nepheline and mafic phenocrysts set in a fine-grained to aphanitic groundmass. The mafic minerals are commonly aegirine-augite but locally may be hornblende or biotite. Accessory minerals include sphene, rutile, apatite, zircon, and fluorite. The country rock, however, was altered during or preceding the mineralization. Nepheline and the mafic minerals have for the most part been completely altered, and the former sites of these minerals are now occupied by fine intergrowths of feldspar, clay, and iron and manganese oxides.

Feldspar is the principal mineral in the rocks containing disseminated deposits. As previously noted it is derived both from the country rock and from the veins. In unaltered trachyte or phonolite, sanidine is the principal feldspar. Fine-grained feldspar is abundant in most of the veinlets. The X-ray diffraction method of Bowen and Tuttle (1950, p. 493) was used to compare the variation in the angular separation between the (201) plane in feldspar and the (1010) plane in a quartz standard to that of known feldspars to determine relative amounts of potassium feldspar versus plagioclase. These data indicate that the six samples are made up of from 99 to 100 percent potassium feldspar. The relative amounts of potassium feldspar versus plagioclase were also obtained by using optical data on several samples. Although the feldspar in many samples was too microcrystalline to be analyzed by this method, E. J. Young was able to determine the β index of refraction of several samples. This index, which is 1.522, was compared by Young with the potassium feldspar content of this value on a diagram compiled by Tuttle (1952, p. 559). Potassium feldspar makes up approximately 100 percent of the total feldspar, where the β index is 1.522. These data corroborate those obtained by the X-ray diffraction method.

Iron oxide minerals are derived from the alteration of both iron-bearing veins and country-rock minerals. Goethite and hematite make up the greater part of the heavy minerals recovered in many samples. Goethite most commonly occurs in these rocks as a dark-brown, granular mineral. It may vary in color from nearly black to a light brownish yellow. In addition to granular the texture can be smooth or vesicular, and the luster may be either dull or shiny. Several different types may occur in a single hand specimen. The various types may reflect different modes of origin. Some of the goethite occurs as dark-brown striated cubes and is formed by pseudomorphous replacement of pyrite cubes. Other goethite occurs in small veinlets that crosscut earlier minerals, where the iron oxide has been transported at least a short distance before it was redeposited. Goethite was identified by its X-ray diffraction pattern in mineral separates from about half the samples. Although goethite was the only variety of limonite identified in the disseminated deposits, lepidocrocite probably also occurs in minor amounts, as small amounts of this mineral have been found in the veins. Hematite is generally a dark-reddish-gray, granular mineral commonly found in association with goethite. Magnetite is present in most samples, but in no place does it make up more than a few tenths of one percent of any sample. This mineral occurs in tiny crystals that are commonly intergrown with the other iron oxides.

Manganese oxide minerals were found in about two-thirds of the samples examined. The manganese oxide minerals range from dark gray to black, and their surfaces may be either dull or shiny. Most manganese oxide minerals are similar in appearance but can be identified by their X-ray diffraction pattern. Six of the

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TABLE 8.—*Mineralogy of the disseminated deposits in the southern Bear Lodge Mountains*

[Minerals listed in italics were identified by their X-ray diffraction pattern]

Locality No.	Rock or minerals--relative amounts			
	Large	Medium	Small	Rare
27	Groundmass------	Feldspar, goethite.	Hematite, manganese oxide mineral.	Quartz, anatase.
28	Groundmass, sanidine.	Goethite---------	Magnetite, pyrolusite, rutile.	Fluorite.
29	Sanidine, groundmass.	---do----------	Brookite----------	Magnetite, rutile, barite.
30	Sanidine, groundmass.	Goethite, hematite.		Magnetite, zircon.
31	Groundmass, sanidine.	Goethite, cryptomelane.	Hematite, sphene.	Magnetite.
32	Groundmass------	Feldspar, hematite.	Biotite, goethite.	Chalcedony, fluorite, barite.
33	Groundmass, feldspar.	Goethite---------	Hematite, magnetite, rutile, manganese oxide mineral.	Brookite, barite.
34	Groundmass------	---do----------	Rutile, hematite, magnetite, manganese oxide mineral.	Calcite.
35	Groundmass, sanidine.	Goethite---------	Hematite, rutile.	Barite.
37	---do----------	Goethite---------	Hematite, cryptomelane.	Magnetite, barite, rutile.
38	Sanidine, groundmass.	Goethite---------	Biotite, magnetite.	Barite.
39	---do----------	Goethite---------	Pyrite, rutile, magnetite, manganese oxide mineral.	Calcite.
40	Groundmass, manganese oxide mineral.	Feldspar, goethite.	Hematite, bastnaesite.	Magnetite, barite.
42	Groundmass, sanidine.	Hematite, cryptomelane.	Goethite----------	Magnetite, barite.
43	---do----------	Goethite, manganese oxide mineral.	Magnetite, sphalerite, brockite, uraninite, rutile.	Barite.
44	---do----------	Goethite---------	Hematite, magnetite, biotite, manganese oxide mineral, jarosite, apatite, sphene.	Fluorite.
45	Sanidine, groundmass.	Goethite, manganese oxide mineral.	Hematite, barite.	Magnetite, rutile.
46	Sanidine, groundmass.	Goethite---------	Pyrolusite, brookite, rutile.	Magnetite, pyrite, calcite.
47	Groundmass------	Sanidine, hematite, barite.	Goethite.	
48	Sanidine, groundmass.	Pyrolusite, goethite.	Quartz, barite.	Magnetite, calcite.

TABLE 8.—*Mineralogy of the disseminated deposits in the southern Bear Lodge Mountains*—Continued

Locality No.	Rock or minerals--relative amounts			
	Large	Medium	Small	Rare
49	Groundmass------	Sanidine, goethite.	Hematite, cryptomelane, brookite.	Magnetite, rutile.
53	Groundmass, sanidine.	Goethite hematite.	Rutile----------	Barite.
54	---do----------	Goethite---------	Hematite, biotite, cryptomelane, barite, rutile.	Magnetite.
55	Sanidine, groundmass.	Hematite, goethite.	Rutile, barite.	Magnetite, brookite.
56	Groundmass, sanidine.	Chalcedony, goethite, hematite.	Rhabdophane, rutile, brookite, barite.	
57	---do----------	Quartz, goethite.	Hematite, barite, sphalerite.	Magnetite, rutile.
58	Groundmass, sanidine.	Goethite---------	Quartz, manganese oxide mineral, hematite, monazite, kasolite.	Barite, zircon, magnetite.
59	Groundmass, sanidine.	Hematite, goethite.	Cryptomelane, barite.	
109	Groundmass------	Sanidine, goethite, hematite, brockite.	Barite, manganese oxide mineral, rutile.	Biotite.
113	---do----------	Sanidine, hematite.	Goethite, barite.	Magnetite, rutile.
133	Groundmass, sanidine.	Goethite---------	Magnetite, hematite, manganese oxide mineral, barite, brockite, rutile, bastnaesite.	
134	Groundmass------	Sanidine, goethite, hematite, manganese oxide mineral.	Barite----------	Uraninite.
141	---do----------	Sanidine---------	Manganese-oxide mineral, barite, rutile, brockite, weinschenkite(?).	
142	---do----------	Sanidine, goethite.	Hematite, magnetite, pyrolusite, rutile monazite barite.	Apatite.
144	---do----------	---do----------	Magnetite, hematite, pyrolusite, rutile, barite.	Brookite.
252	---do----------	Sanidine, goethite.	Barite, cerussite, sphene, bastnaesite, brockite.	Hematite, magnetite, rutile.

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manganese oxides gave a cryptomelane pattern, and five had a pyrolusite one.

In only 7 of the 36 samples are thorium minerals recognized. Brockite was identified at five localities and monazite at two. Rare earths also occur in these minerals and in several other minerals. Bastnaesite was found at localities 40, 133, and 144; rhabdophane at locality 56; and weinschenkite at locality 142 (table 8). The relatively high contents of rare earths and thorium found by the chemical analysis of those same samples indicate that minerals of these elements should occur in most of these samples, but iron and manganese oxides tend to mask them. Two uranium minerals, uraninite and kasolite, were identified in two samples and one sample respectively. Neither occurs in the most uranium rich samples. Uranium minerals in other samples are probably also masked with iron and manganese oxides. Although uraninite is a primary mineral, kasolite, $PBO_3UO_3 \cdot SiO_2 \cdot H_2O$, is a secondary one, and it probably formed along fractures during weathering from uraninite.

Other minerals that are fairly common in small amounts in these samples include barite, rutile, brookite, fluorite, biotite, and calcite. All of these minerals occur in the larger veins.

CHEMICAL COMPOSITION

The shape of the disseminated deposits, as stated previously, is determined by the grade of the rock. The shape and the grade of the disseminated deposits are generally not known until after analyses have been made. A total of 341 samples were taken in outlining the disseminated deposits (Staatz and others, 1980, fig. 1). These samples contain from 9.3 to 990 ppm thorium. Two hundred sixty-five samples of this group fell inside the 50 ppm contour (pl. 2*C*) and they contain from 51.1 to 990 ppm thorium. Although trachyte and phonolite of Tertiary age made up the bulk of the country rock sampled, granite of Precambrian age was also included along the edge of the disseminated deposits in the vicinity of Warren Peak and Smith Ridge. The granite in many places is cut by thin dikes of trachyte or phonolite, and some samples in these areas include both rocks. Nine samples that were made up of both granite and trachyte contain from 22.7 to 158 ppm thorium; nine samples made up only of granite contain from 9.3 to 87.4 ppm thorium. All but one of the samples made up entirely of granite had less than 50 ppm thorium. Granite does not appear to be a favorable host rock, although some abnormally high thorium values occur where cut by or immediately adjacent to trachyte or phonolite dikes.

In addition to the samples taken in and around the disseminated deposits, another 10 samples were collected in trachytic and phonolitic rocks that were not in or adjacent to the disseminated deposits. Three of these samples were taken in the southern part of the core of the Bear Lodge dome; the others came from separate intrusives that are bodies satellitic to the core. These 10 samples, which represent nonmineralized alkalic rocks, contain from 15.4 to 55 ppm Th.

The total rare-earth content of the disseminated deposits varies in 192 samples from 47 to 27,145 ppm (Staatz and others, 1980). One hundred seventy-one of these samples contain at least 500 ppm, 103 samples contain at least 1,000 ppm, and 54 samples contain in excess of 5,000 ppm. The distribution of the rare earths in the disseminated deposits is shown by contours on plate 2*F*. The overall amount of total rare earths in the 192 analyzed samples is 26.6 times greater than that of thorium. A plot of the amounts of rare earths and thorium found in various samples indicates no correlation between the amounts of one with those of the other. Total rare-earth content does correlate with that of uranium. A plot of uranium, excluding two values over 140 ppm, with total rare earths shows a general increase in one with that of the other (fig. 15). The amounts of most other elements that occur in anomalous amounts in this area show little correlation with the amounts of rare earths. These other elements include: niobium, barium, strontium, potassium, manganese, iron, copper, lead, zinc, and molybdenum.

The lanthanide distribution of the samples analyzed for rare earths is remarkably similar. The amounts of light rare earths greatly exceed those of the heavy rare earths. The principal rare earth in all samples containing as much as 5,000 ppm total rare earths is cerium or cerium with neodymium and (or) lanthanum. Yttrium, the principal heavy rare earth, makes up from 0.8 to 17.5 percent of the total rare earths in these same samples. In 52 of the 54 samples that contain as much as 5,000 ppm total rare earths, however, yttrium makes up only 0.8 to 8.6 percent of the total rare earths. The average yttrium content of the total rare earths in the 54 higher grade samples is only 3.2 percent.

The uranium content of the disseminated deposits ranges in 341 samples from 1.8 to 346 ppm (Staatz and others, 1980). The average uranium content of all samples is 16.5 ppm. Twenty-seven samples contained 40 or more ppm uranium, but only five samples contain as much as 80 ppm. Granite within the area of disseminated deposits contains only minor amounts of uranium, and nine samples taken of this granite yield from 1.8 to 7.0 ppm uranium. For comparison 10 samples of trachyte and phonolite were collected either in the Bear Lodge core away from the disseminated deposits or in

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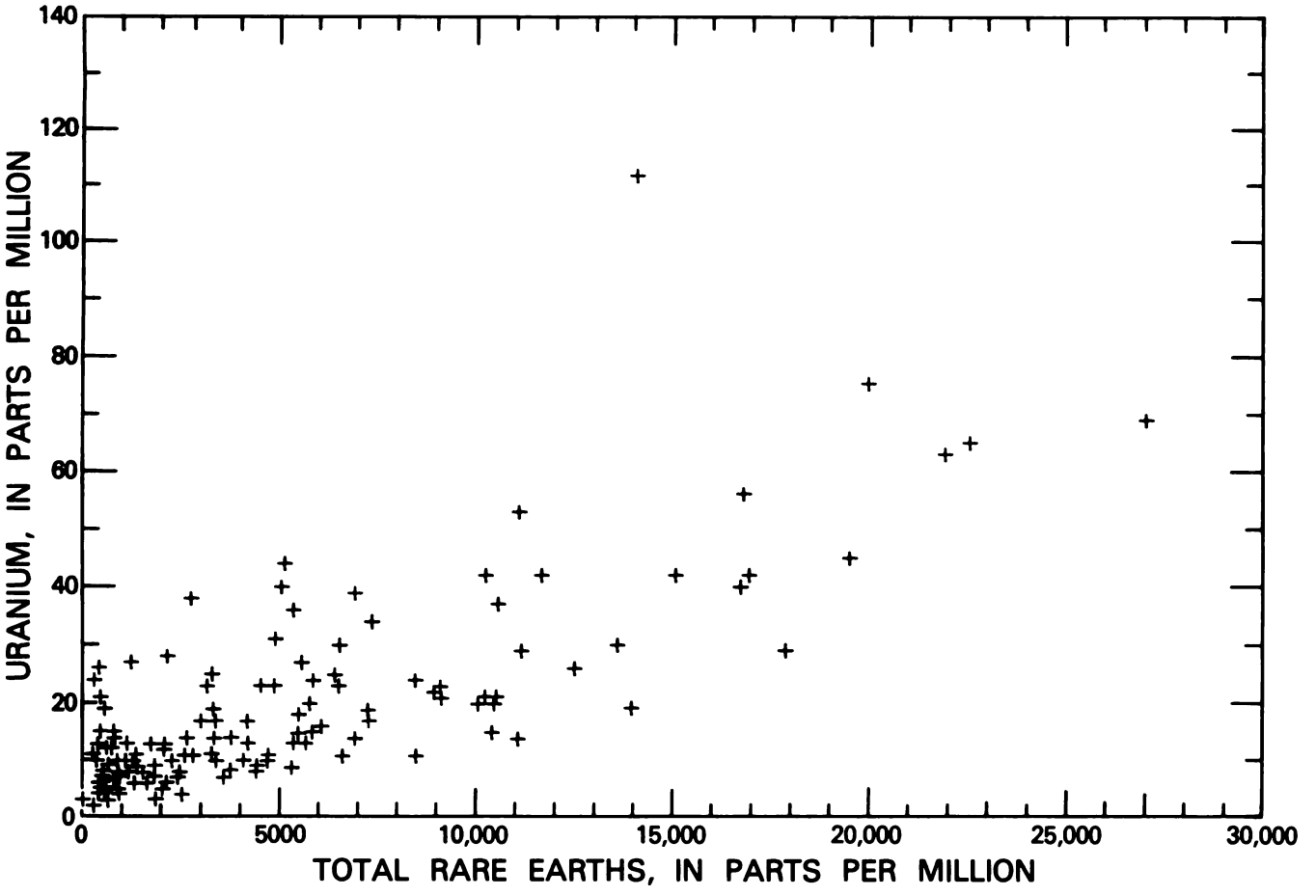


FIGURE 15.—Relation of uranium to total rare earths in samples from the disseminated deposits.

separate peripheral bodies. These nonmineralized rocks contain from 8.0 to 19.8 ppm uranium. Thorium to uranium ratios of samples taken in the disseminated deposits are highly erratic; they vary from 0.4 to 136. Most of this variation is due to later mineralization, as the thorium to uranium ratios of the 10 samples of trachyte and phonolite that were collected away from the sites of mineralization vary only from 2.1 to 3.4. The amount of uranium present at any place within the disseminated deposits has no relation to the amount of thorium. This can best be seen by comparing the contour map showing the distribution of uranium with that showing the distribution of thorium (pls. 2*D*, 2*C*).

The potassium content of trachyte and phonolite, the host rocks for the disseminated deposits, is generally high. In addition some potassium also occurs in the gangue minerals in the veinlets. Potassium content varies from 3.1 to 12.4 percent of the 354 samples. Three hundred and one of these samples, however, have more than 7 percent potassium. On the average, potassium content of all samples was 9.1 percent. This amount of potassium is equivalent to the rock's being made up of 65 percent sanidine. As the greater part of the potassium in disseminated deposits comes from the host rock, potassium content of various samples shows little relation to the metal content of various other anomalous elements.

Barium and strontium are also present in the disseminated deposits. Barium content ranges from 500 to 15,000 ppm and the strontium content from 150 to 7,000 ppm. Barium occurs in barite, which is a common mineral in some of the veinlets. Rare earths are also common in the veinlets. Most samples containing 5,000 ppm or more of barium are high in rare earths and many contain in excess of 1 percent total rare earths, although there is no direct correlation between the amount of barium and that of rare earths in the samples. A part of the strontium probably substitutes for barium in the barite. The amount of strontium, however, is unrelated to the amount of barium, and a plot of strontium and barium from the same samples shows no overall trend. Although a few samples that contain

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5,000 ppm or more strontium also contain 5,000 ppm or more barium, most samples with a high strontium content contain 3,000 ppm or less barium. Strontium-high samples also generally have a fairly low rare-earth content. Most samples that have a strontium content of 5,000 ppm or more come from localities scattered along the periphery of the disseminated deposits. No mineral in which strontium is an essential component has been identified. Furthermore, strontium analyses of the light and heavy fractions of several samples separated in methylene iodide indicate that most of the strontium occurs in the light fraction. Hence, this element most likely proxies for one of the alkalies in feldspar.

Niobium makes up from less than 10 to 2,000 ppm of the disseminated deposits. Most samples contained from 30 to 70 ppm niobium, and only 15 samples had 200 or more ppm. The amount of niobium present in any sample shows little relation to the amounts of the following elements: thorium, rare earths, uranium, potassium, strontium, copper, molybdenum, lead.

Copper, molybdenum, lead, and zinc are anomalously high in many samples (Staatz and others, 1980, table 1). Copper content of 193 samples ranges from 3 to 10,000 ppm. The two samples that contained more than 500 ppm were taken from dumps of old copper prospects and contained green secondary copper minerals. Sixty-two samples, however, contain from 150 to 300 ppm copper. Molybdenum content of the samples ranges from less than 2 to 700 ppm, and 40 samples contain at least 100 ppm molybdenum. Lead content varies from 15 to 5,000 ppm, and 24 samples contain at least 700 ppm lead. Zinc content ranges from less than 200 to 2,000 ppm, and 17 samples contain at least 700 ppm zinc. The amounts of copper, molybdenum, lead, and zinc present in various samples in these rocks have neither a positive nor a negative correlation with the amounts of thorium, total rare earths, or uranium. Furthermore, the amounts of these four base metals show little correlation with one another. The samples are all taken from the surface where the rocks are oxidized. Few sulfides remain, and it is doubtful that the grade at the surface is representative of these metals at depth.

ECONOMIC GEOLOGY

The disseminated deposits, although lower grade than the veins previously discussed, are large and contain the bulk of the thorium and rare earths in this district. The entire central part of the Bear Lodge dome, which is anomalously radioactive, contains numerous crisscrossing veinlets over an area of approximately 10.6 km² as outlined by a scintillation counter (pl. 2*A*). As previously noted, the area of thorium and rare-earth mineralization has been further defined by a more detailed sampling program (pls. 2*C*, 2*F*). Although sampling has shown that in places grade boundaries are erratic, in many places, as shown by the maps of plate 2*C* and plate 2*F*, they are also gradational. These maps allow choosing an area with a specific grade. As ore is defined as a metal-bearing deposit that can be mined at a profit, the size and shape of any future mineable part of the disseminated deposits depend on the economic conditions at the time of mining. These conditions include whether thorium, rare earths, or both are being sought, the cost of mining at the time, and the price obtained for the commodities, as well as such nonmineral related problems as land ownership, environmental considerations, and mining company policies. Thus, the size and shape of the ore body in the disseminated deposits at any particular time can be defined by whichever grade contour fits the economic conditions of that time.

The bulk of the thorium and rare earths occur in sec. 17, the E½ sec. 18, and the N½ sec. 20 (pls. 2*C*, 2*F*). The most thorium rich parts of this area generally do not coincide with those richest in rare earths. A thorium content of 200 ppm was chosen as a likely lower limit of rock that would be mineable in the foreseeable future. The 200 ppm contour encloses several areas that total 1.69 km². The thorium content of these areas ranges from 200 to 990 ppm. Higher grade localities tend to be small and local and are scattered through the areas enclosed by the 200 ppm contour. Areas falling within the 500 ppm contours encompass only 0.09 km².

Rare earths are much more abundant than thorium in this region, and the greater part of the higher rare earth concentrations lie within a contour representing 2,000 ppm total rare earths (pl. 2*F*). This contour encloses one large area and a couple of small ones, which have a total area of 3.22 km². The grade of the total rare earths falling within this contour ranges from 2,000 to 27,145 ppm. Seven smaller areas containing 1 percent (10,000 ppm) or more of total rare earths fall within the 2,000 ppm contour. Total size of these smaller areas is 0.84 km². More than half of the area containing this higher grade rock occurs at one place along the west side of sec. 20 (pl. 2*F*). Two other areas that contain most of the rest of the higher grade rock lie along the northwest side of Bull Hill and astride the road along Taylor Divide in the northern part of sec. 20. Few data are available on the thorium and rare-earth content of these rocks at depth. Anomalous amounts of thorium or rare earths, however, are exposed at the surface over a difference of elevation of approximately 260 m. In addition, sparse drilling data from the W½ sec. 17 and the E½ sec. 18 indicate that the rock is mineralized in places at least 370 m below the surface.

Large low-grade deposits, like the disseminated

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deposits, which occur near the surface, can be mined by the open-pit method (Staatz and others, 1979, p. 20–21). Overburden covers much of the area, but is thin; it generally ranges from less than 1 to 5 m in thickness. Although the open-pit method is fairly cheap, not all the resources would be recovered. The walls of an open pit must be terraced with an overall slope of 45° or less. Furthermore, if the thorium and rare-earth resource continued to a depth greater than about 460 m, the deeper resources would have to be recovered by some other method. The Bear Lodge disseminated deposits have one of the largest resources of both thorium and rare earths in the United States. Although neither the thorium nor the rare earths are producible under 1980 market conditions and the grade of both commodities is lower than that of some other deposits in the United States, the disseminated deposits' large size and their cheap cost of mining makes them an important future economic resource.

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Geology and Description of the Thorium and Rare-Earth Veins in the Laughlin Peak Area, Colfax County, New Mexico

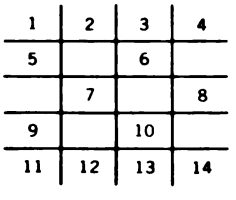
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GEOLOGICAL SURVEY PROFESSIONAL PAPER 1049–E



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COVER PHOTOGRAPHS



1. Asbestos ore
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Geology and Description of the Thorium and Rare-Earth Veins in the Laughlin Peak Area, Colfax County, New Mexico

By MORTIMER H. STAATZ

GEOLOGY AND MINERAL RESOURCES OF THORIUM IN THE UNITED STATES

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1049–E

Geologic setting and size, shape, mineralogy, and chemistry of veins that contain thorium and rare-earth elements northeastern New Mexico



UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1985

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UNITED STATES DEPARTMENT OF THE INTERIOR

Donald Paul Hodel, ***Secretary***

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, ***Director***

Library of Congress Cataloging in Publication Data
Staatz, Mortimer Hay, 1918–
Geology and description of the thorium and rare-earth veins in the Laughlin Peak area, Colfax County, New Mexico
(Geology and resources of thorium in the United States)
(Geological Survey Professional Paper ; 1049–E)
Bibliography: p. 31
Supt. of Docs. No.: I 19.16:1049–E
1. Geology—New Mexico—Colfax County. 2. Thorium ores—New Mexico—Colfax County. 3. Earths, Rare—New Mexico—Colfax County.
I. Title. II. Series. III. Series: Geological Survey professional paper ; 1049–E
QE144.C6S73 1984 553.4'94'0978922 84–600153

For sale by the Superintendent of Documents
U. S. Government Printing Office
Washington, D. C. 20402

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GEOLOGY AND DESCRIPTION OF THORIUM AND RARE-EARTH VEINS IN THE LAUGHLIN PEAK AREA, COLFAX COUNTY, NEW MEXICO

By MORTIMER H. STAATZ

ABSTRACT

This study concerns the geologic setting of 29 veins that contain thorium and rare earths. The study area comprises about 40 km^2 near Laughlin Peak, about 38 km southeast of Raton in northeastern New Mexico. The veins range in length from 0.5 to 550 m and in thickness from 0.2 to 70 cm. The thorium- and rare-earth-bearing minerals are brockite, xenotime, and crandallite. Gangue minerals are potassium feldspar, quartz, or calcite. Other common minerals include goethite, magnetite, barite, zircon, rutile, and a manganese oxide mineral. Brockite and xenotime consist principally of yttrium-group rare earths, and crandallite of cerium-group rare earths. Thorium content of 30 samples ranges from 30 to 24,200 ppm (parts per million), and the total rare-earth content from 147 to 19,030 ppm. Most of the veins are richer in yttrium-group than in cerium-group rare earths. Veins that have a high yttrium-group rare-earth content tend to have high thorium content. Uranium content of these veins is generally low, and in most samples the ratio of thorium to uranium ranges between 18 and 860. The veins were probably formed in late Tertiary by fluids derived from a thorium- and rare-earth-rich phonolitic magma.

The Dakota Sandstone of Early and Late Cretaceous age is the oldest rock exposed in this area. Exposures of this unit are widespread, especially in the western part of the area. The Dakota is overlain in ascending order by the Graneros Shale, Greenhorn Formation, Carlile Shale, and Niobrara Formation—all of Late Cretaceous age. The middle three units are principally shales but have some sandstone and limestone interbeds. The five formations total about 170 m in thickness. Seven kinds of igneous rocks were intruded into and extruded upon the sedimentary rocks in late Tertiary time. Olivine basalt flows blanket the southeastern part of the area. Five different types of alkalic rocks occur within the area: trachyte, trachyandesite, phonolite, rhyodacite, and lamprophyre. Trachyte forms two massive sills, underlying areas of 2.5 and 3.3 km^2, and numerous narrow dikes. Phonolite forms one thick sill that forms a prominent scarp for 3.3 km, as well as several small dikes and sills. Trachyandesite, which generally is altered, occurs principally as poorly exposed sills. Rhyodacite is found in several forms: Rhyodacitic vitrophyre flows, and some breccias, make up the large volcano of Laughlin Peak; porphyritic rhyodacite forms a plug that makes up Raspberry Mountain; and a white ashy rhyodacitic tuff is found low on the south flank of Laughlin Peak. The content of thorium and uranium in all these igneous rocks increases as the total alkali content ($Na_2O + K_2O$) of the rocks increases. Lamprophyre, of several types, makes up a few small dikes. In addition, intrusive breccia occurs as cross-cutting dikes and pipes. These rocks are made up of fragments of volcanic, sedimentary, and plutonic rocks set in a matrix of crystal fragments and finely granulated material. Intrusive breccia in some areas contains granite fragments that are derived from a concealed underlying pluton.

Rocks of Quaternary age commonly cover the flanks of the principal mountains, as well as some of the flatter areas. The Quaternary rock types are terrace gravels, landslide deposits, colluvium, and alluvium.

The structure of the Laughlin Peak area is marked by gently dipping sedimentary rocks and small crisscrossing faults. A broad east-west-trending anticline is the only major fold in the area.

INTRODUCTION

The thorium- and rare-earth-bearing veins of the Laughlin Peak area are similar to the thorium- and rare-earth-bearing veins in other districts. Common features are their association with alkalic igneous rocks, their steep dip, and their fractured and brecciated character. Thorium- and rare-earth-bearing veins that have similar features are found in the following districts: Wet Mountains, Colorado (Olson and others, 1977); Powderhorn area, Colorado (Olson and Hedlund, 1981); Mountain Pass district, California (Olson and others, 1954); Bear Lodge Mountains, Wyoming (Staatz, 1983); and Wausau district, Wisconsin (Vickers, 1956). The principal difference between veins in the Laughlin Peak area and these other areas is in the thorium and rare-earth minerals, which in the Laughlin Peak area are brockite and crandallite, rather than the more commonly found thorite and monazite. Geology of this district is complex; it has seven different varieties of igneous rock, which occur as sills, dikes, plugs, and flows. The present report describes the shape, mineralogy, and chemical composition of the thorium and rare-earth deposits and describes the petrology and geologic setting of the igneous and sedimentary rocks.

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LOCATION AND ACCESSIBILITY

The Laughlin Peak thorium and rare-earth area lies along the southwest flank of Laughlin Peak in east-central Colfax County, N. Mex. As shown in figure 1, its northeast corner is near the top of Laughlin Peak. Its dimensions are 5.6 km in an east-west direction and 6.9 km in a north-south direction. This area lies approximately 38 km southeast of the town of Raton and 31 km east-northeast of the village of Maxwell. A county dirt road, A–8, follows Tinaja Creek across this area from its northwest corner to the central part of its east edge (fig. 1). Ranch roads branching off the county road lead to within 1 km of most parts of the area. The best maintained route from Raton follows U.S. Highways 64 and 87 east for 19.0 km to State Highway 193. This State road is followed south and southeast for 19.5 km to county road A–8. The distance along county dirt road A–8 from its junction with Highway 193 to the east edge of the Laughlin Peak area is approximately 8.5 km. The distance from the northwest corner of the area along county road A–8 to Maxwell is 31 km.

GEOGRAPHY

The Laughlin Peak area is in the northwest part of the Pine Buttes quadrangle, which is mainly in the eastern part of the Piñon Hills. These hills cover about 62 km^2, most of which lies to the west in the adjoining Tres Hermanos Peak quadrangle. The Piñon Hills are oval-shaped and are cut by numerous canyons that radiate out from their center. The canyons drain either northward into Tinaja Creek or southward into Rio del Plano. Most of the hills rise from 60 to 120 m above the adjacent canyons, although Turkey Mountain, just west of the mapped area (pl. 1) rises 210 m above the headwaters of the Rio del Plano on the west edge of the map area, and Raspberry Mountain at the southeast corner of the Piñon Hills towers 220 m above the plains to the south. The Piñon Hills differ from the surrounding country in that, as their name suggests, they are covered with trees. The trees that cover the Piñon Hills, in addition to the New Mexico piñon pine (*Pinus edulis*), include Rocky Mountain juniper (*Juniperus scopulorum*), western yellow pine (*Pinus ponderosa*), limber pine (*Pinus flexilis*), birch-leaf mountain mahogany (*Cercocarpus montanus*), and Emory oak (*Quercus emoryi*). The surrounding area is devoid of trees and is covered with grasses and wild flowers.

Northeast of the Piñon Hills is Laughlin Peak. This extinct volcano underlies an area of approximately 28 km^2. Its peak, which has an elevation of 2,688 m, is one of the tallest volcanoes in northeastern New Mexico. The mapped area covers only the southwest part of this mountain. The remaining part of the mapped area, south of Laughlin Peak and east of the Piñon Hills, is a gently sloping open area underlain by basalt flows. These flows originated from The Crater, which lies just east of the southeast corner of the mapped area (fig. 1).

PREVIOUS INVESTIGATIONS

The region surrounding Laughlin Peak has been included in several reconnaissance studies. The volcanic rocks of northeastern New Mexico were investigated by R. F. Collins in 1925, 1926, and 1930. The petrology of these same rocks was studied by H. R. Stobbe, who visited this area in 1940 and 1948. The results of these two investigations were published in companion articles (Collins, 1949; Stobbe, 1949). A reconnaissance map of eastern Colfax County, which includes the Laughlin Peak area, was made by Woods, Northrop, and Griggs (1953); this map, which covers some 4,860 km^2, was made as part of an oil and gas investigation.

Prospecting for radioactive materials began in the Laughlin Peak area in the early 1950's. Some of these prospects were visited by Charles Tschanz of the U.S. Geological Survey in 1954 who called my attention to the area (written commun., 1955). I visited the area for 2 days in 1964 and collected samples from several of the veins. Mineralogic and chemical data on these veins was later published as part of an overall study of thorium veins in the United States (Staatz, 1974).

PRESENT INVESTIGATIONS AND ACKNOWLEDGMENTS

The present work in the Laughlin Peak area was undertaken in 1980 to describe the thorium and rare-earth veins and their geologic setting. The study covers an area of about 40 km^2 that contains most of the known thorium and rare-earth veins. The area underlain by veins is not well defined, as it was poorly explored, and some of the veins were first reported by me. Mapping was done on the northwest part of the Pine Buttes 7½-minute topographic quadrangle that was enlarged

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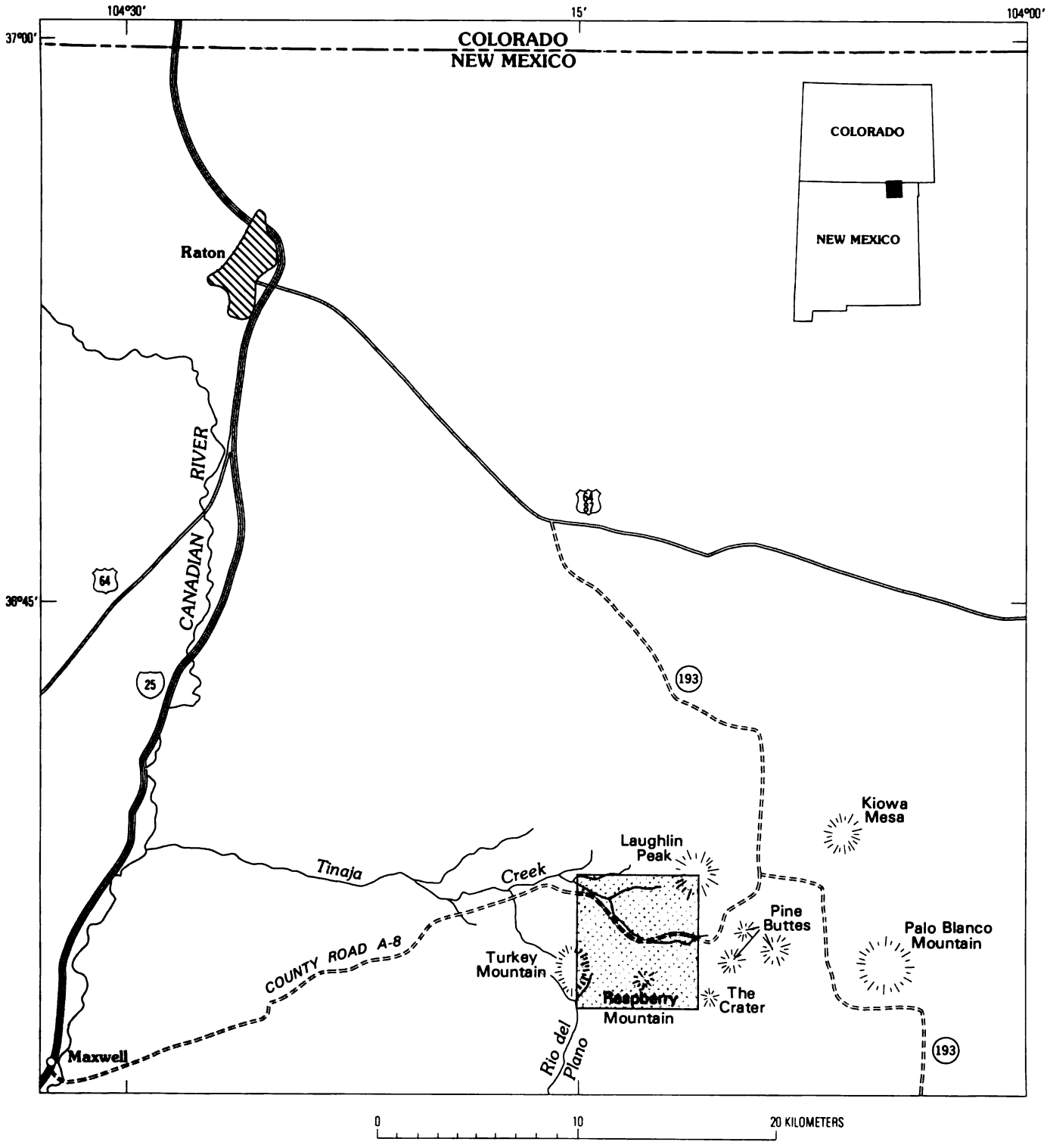


FIGURE 1.—Index map showing the location of the Laughlin Peak area of northeastern New Mexico, and adjacent landmarks.

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to a scale of 1:12,000. Aerial photographs proved especially useful in tracing faults through the wooded hills. This area was mapped during the summer of 1980. I was assisted at various times during the summer by William F. Robinson IV, Frank T. Perniciaro, and Daniel S. Morris.

A second part of the work was a detailed study of veins. Samples were taken of various radioactive deposits and both their mineralogic and chemical composition studied. Minerals were determined by separating them from each other by means of heavy liquids, a magnetic separator, and handpicking. All visually unrecognized minerals were identified by means of their X-ray diffraction patterns. I was assisted in this work by Isabelle Brownfield, William F. Robinson IV, Timothy E. Mower, and Daniel S. Morris. Thorium, uranium, and potassium were analyzed with a quantitative gamma-ray spectrometer by Carl M. Bunker and Charles A. Bush. Other elements were determined by semiquantitative spectrographic analysis by Nancy M. Conklin. In addition, the major elements in 13 samples of various igneous rocks were determined by H. G. Neiman, J. S. Wahlberg, J. E. Taggart, Jr., and J. W. Baker.

The Kiowa Land and Cattle Co. and the Hennigan ranch own both the land and most of the mineral rights of the Laughlin Peak area. I want to thank James Hennigan, principal owner of both these properties, for permission to work in this area and for the many discussions about this land. I would also like to acknowledge fruitful discussions on the general geology of the region with Glenn R. Scott of the U.S. Geological Survey.

ROCK TYPES

Three major groups of rocks are exposed in the Laughlin Peak area: (1) clastic sedimentary rocks of Cretaceous age, (2) igneous rocks of Tertiary or Quaternary ages, and (3) unconsolidated deposits of Quaternary age. The sedimentary rocks of Cretaceous age are approximately 170 m thick and consist principally of gently dipping sandstones and shales. Most of the sandstones occur in the Dakota Sandstone at the base of the exposed section of Cretaceous rocks. Outcrops of Dakota underlie much of the west half of the mapped area. The rocks overlying the Dakota Sandstone are mostly shales with some interbedded limestone. These rocks are the Graneros Shale, the Greenhorn Formation, the Carlile Shale, and the Niobrara Formation.

The sedimentary rocks were cut and overlain by a variety of fine-grained igneous rocks ranging from phonolite to basalt in composition. Basalt flows cover the southeast part of the area and are part of extensive late Tertiary and Quaternary flows in northeast New Mexico. Glassy rhyodacite flows have been piled up to form the 435-m-high Laughlin Peak in the northeast part of the mapped area. A separate rhyodacite intrusive forms Raspberry Mountain in the southern part of the area. Trachyte forms two massive sills and numerous small dikes that intrude and cut the sedimentary rocks of Cretaceous age. Phonolite, as one thick sill intruded mainly into the Carlile Shale, forms the upper edge of several flat-topped hills along the southwest flank of Laughlin Peak. Phonolite also occurs in several dikes. Trachyandesite intrusives underlie both the trachyte and the phonolite at various locations along the drainage of Tinaja Creek. A few small lamprophyre dikes intruded the trachyte and Dakota Sandstone. Intrusive breccia dikes and pipes were emplaced within the drainage basin of Tinaja Creek during late Tertiary time. A medium-grained gray granite also occurs in this area, although it is not exposed at the surface. This rock has been found in fragments in several intrusive breccia bodies and as inclusions in the basalt and in a rhyodacite flow, all in the north half of the area. Thus, granite underlies a part of the Laughlin Peak area, and at one time may have been exposed at the surface.

Unconsolidated deposits conceal the underlying rocks in about 20 percent of the area; they are especially abundant in the northeastern part, where they cover about 75 percent of the outcrops. These deposits have been divided into (1) terrace gravels, (2) landslide deposits, (3) colluvium, and (4) alluvium. Colluvium, which includes talus and slope wash, covers the flanks of Laughlin Peak and Raspberry Mountain. Landslide deposits are numerous below the massive phonolite sill and cover much of the shaly underlying Carlile and Greenhorn Formations.

SEDIMENTARY ROCKS (CRETACEOUS)

DAKOTA SANDSTONE (LOWER AND UPPER CRETACEOUS)

The Dakota Sandstone is made up principally of sandstone with some shale interbeds. It probably underlies the entire area. It is exposed mainly in the western part of the area south of Tinaja Creek. The Dakota Sandstone is the best exposed sedimentary unit; it forms prominent cliffs along the sides of many canyons (fig. 2*A*) and commonly caps broad flat-topped ridges. The Dakota in this area is made up of three principal members. The upper and lower members are mainly sandstone with some thin shale interbeds; the middle member is mainly shale and siltstone with some sandstone beds. Dakota Sandstone, as mapped here, would also include rocks described elsewhere as Lower Cretaceous Purgatoire Formation (Baltz, 1965, p. 2061).

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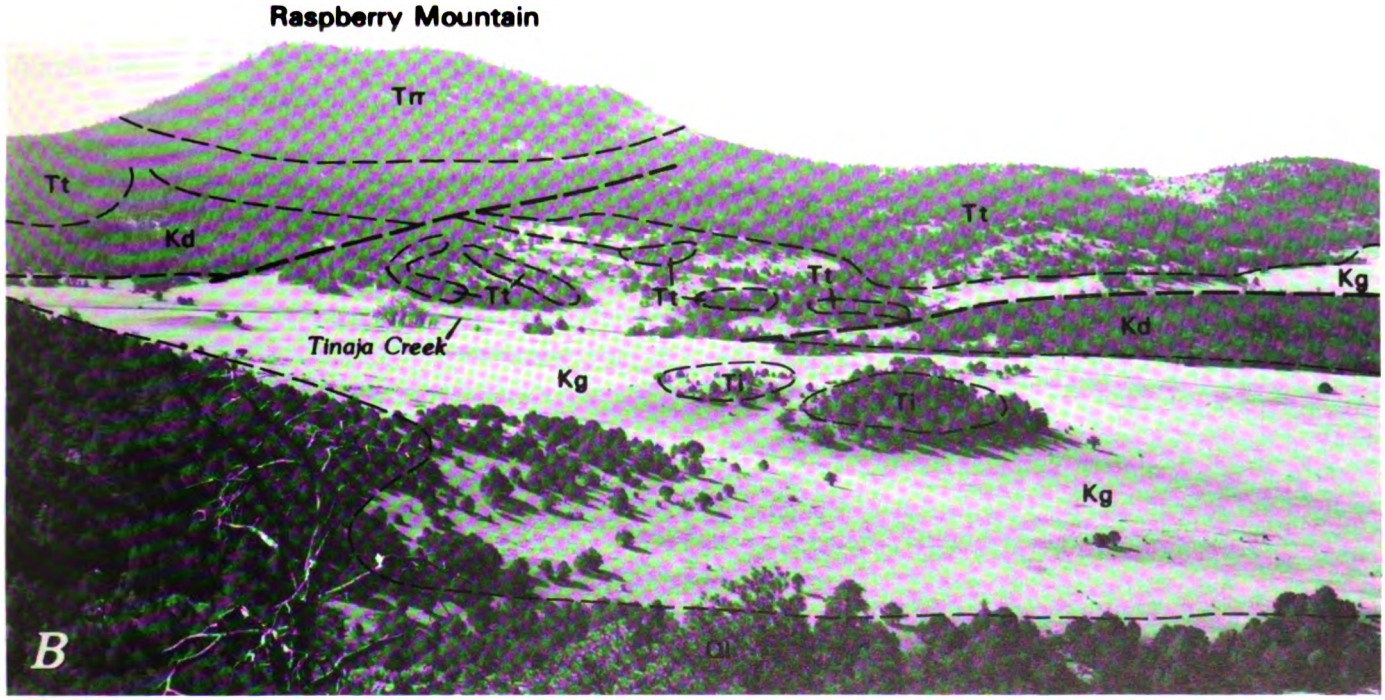


FIGURE 2.—Sedimentary rocks of Cretaceous age. *A*, Dakota Sandstone forming prominent ledge along the north side of Tinaja Creek in the SW¼SW¼ sec. 6, T. 27 N., R. 26 E. *B*, Graneros Shale (Kg) underlies open meadows along Tinaja Creek. Kd, Dakota Sandstone; Tt, trachyte; Ti, intrusive breccia; Trr, rhyodacite of Raspberry Mountain; and Ql, landslide deposits.

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The sandstone is light brown, fine to medium grained, and is made up principally of well-rounded quartz grains. A few beds contain some interstitial detrital feldspar. The sandstone is commonly crossbedded, and ripple marks occur in a few places. Sandstone is generally thick bedded to massive.

The middle part of the Dakota is principally shale and siltstone that are poorly exposed. A good exposure of this central part of the Dakota, 5.4 m thick, is exposed along Jimmy Spring Creek 185 m northeast of its junction with Tinaja Creek. Here, thin layers of dark-gray carbonaceous siltstone and brown fine-grained sandstone are interbedded with a black flaky noncalcareous shale.

The base of the Dakota is not exposed in this area. The top of the Dakota is exposed along a branch of Tinaja Creek in the northeast corner of sec. 1, T. 27 N., R. 25 E. The upper meter of Dakota is a dark carbonaceous sandstone. A complete section of the Dakota Sandstone is not exposed here but was calculated to be at least 55 m thick. No fossils were found in the Dakota.

GRANEROS SHALE
(UPPER CRETACEOUS)

The Graneros Shale is mainly black shale. It is poorly exposed throughout the area (fig. 2*B*) and is represented in most places by smooth covered slopes that lie above the Dakota Sandstone and below the first dark-gray limestones of the Greenhorn Formation. Exposures of the Graneros are most commonly found scattered along steep-sided canyons where recent erosion has cut into the banks, as in the northwest part of the mapped area (pl. 1). The best exposure of the Graneros is along a branch of Tinaja Creek in the northeast corner of sec. 1, T. 27 N., R. 25 E. Here the lowermost part of the Graneros Shale and the underlying top of the Dakota Sandstone are exposed.

The Graneros Shale is mainly a fissile, dark-gray to black noncalcareous shale. A bed of brown-weathering gray limestone (Thatcher Limestone Member) is exposed at one place in the central part of this unit. The base of the Graneros is placed at the top of the last massive brown sandstone of the Dakota. The Graneros Shale was not measured in the field, but a measurement from the map (pl. 1) indicates it is approximately 30 m thick. No fossils were found in the Graneros.

GREENHORN FORMATION
(UPPER CRETACEOUS)

The Greenhorn Formation consists of thin-bedded limestones interbedded with shale. This formation has been divided elsewhere into three members, which are from bottom to top: the Lincoln Limestone Member, the Hartland Shale Member, and the Bridge Creek Limestone Member (Hook and Cobban, 1980, p. 43). Because exposures of the Greenhorn in the Laughlin Peak area are both widely scattered and few, this formation was not divided here. The Greenhorn crops out in the northern part of the area, notably along the upper slopes of Tinaja Creek. The best outcrops are found in the NW¼ sec. 36, adjacent to Jimmy Springs Creek (pl. 1).

The Greenhorn Formation consists of light-gray to black, thin-bedded limestones interbedded with black calcareous shales. Most of the outcrops are limestone; the shales rarely are exposed. Limestone beds are most abundant in the lower and upper part of the formation. The base of the formation is placed at the base of the first limestone above a thick shale section. The lower part of the Greenhorn contains several dark-gray to sooty-black, fine-grained limestones. These beds are generally 2–15 cm thick. In the upper part the limestone is a light gray to bluish gray and fine grained; beds are 4–30 cm thick. Limestone beds also occur scattered through the central part of the formation. Many of the limestones contain fossil trash.

The thickness of the Greenhorn Formation in this area is approximately 25 m. The Greenhorn thickens somewhat to the west, and measurements made on the Greenhorn along the Canadian River near Springer, 19 km south of Maxwell by Hook and Cobban (1980, p. 43) and along Gold Creek, 64 km west-northwest of Raton by Pillmore and Eicher (1976, p. 173) indicate that it is 40 m thick at these two localities. No identifiable fossils were found in the mapped area.

CARLILE SHALE
(UPPER CRETACEOUS)

The Carlile Shale consists principally of shale interbedded with some thin limestone units. The Carlile occurs only north of Tinaja Creek on the lower slopes of Laughlin Peak. It is found below the thick phonolite sill that forms the massive rimrock 75–120 m above the valley bottom. This area is, for the most part, covered by landslide. Small, widely scattered outcrops of Carlile occur only where erosion has stripped off the overlying cover. The best exposures of the Carlile occur in the NW¼ sec. 31, adjacent to Jimmy Springs Creek (pl. 1). This formation has been divided elsewhere into four or five members (Pillmore and Eicher, 1976, p. 172–173; Hook and Cobban, 1980, p. 43). Individual members can not be adequately mapped in this area because of the lack of sufficient outcrops.

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The Carlile Shale consists mostly of black shale. At the base are black to dark-gray, thin-bedded, argillaceous limestones. These are overlain by black shale with widely scattered thin, gray to brown, limestone beds. A light-gray blocky limestone bed, 3–6 m thick, occurs in the central part of the formation. In places the central part of the Carlile contains a few widely scattered gray septarian limestone concretions. Pelecypods were found at two localities and were identified by William A. Cobban of the U.S. Geological Survey. One collection, which came from within 5 m of the base of the formation at a tributary stream junction of Jimmy Spring Creek in NW¼ sec. 31, was in a thin-bedded dark-gray argillaceous limestone. It contained large flat pelecypods, as much as 15 cm across, which were identified as *Mytiloides hercynius* (Petraschek). Cobban (oral commun., 1980) noted that this fossil is indicative of the Fairport Member (the lowest unit) of the Carlile. The other collection came from about 50 m above the base of the Carlile on a branch of Jimmy Spring Creek just below the thick phonolite sill in the central part of sec. 31. This shale contains *Inoceramus perplexus* Whitfield. Cobban noted that this fossil occurs in the middle part of the Carlile. The Carlile was not measured in this area, but it has been measured along the Canadian River near Springer, 19 km south of Maxwell, by Hook and Cobban (1980, p. 43) and along Gold Creek 64 km west-northwest of Raton by Pillmore and Eicher (1976, p. 172). At these two localities it is 50 and 76.8 m thick, respectively.

NIOBRARA FORMATION
(UPPER CRETACEOUS)

The Niobrara Formation is the youngest Cretaceous formation exposed in the Laughlin Peak area. Where exposed elsewhere in Colfax County it is about 290 m thick and is divided into two members. The lower or Fort Hays Limestone Member is made up of 4.6–6.0 m of limestone, and the upper or Smoky Hill Member of some 285 m of calcareous shales (Griggs, 1948, p. 30–33). Only part of the Fort Hays Limestone Member is exposed in this area in three small outcrops. These outcrops are found above the Carlile Shale in the northwest corner of sec. 31, just below the phonolite sill in the NE¼ sec. 6, and just above the phonolite in the NE¼ sec. 5.

The Fort Hays Limestone Member of the Niobrara Formation consists of limestone beds, 30–75 cm thick, separated by thin interbeds of gray shale. The limestone, which is light gray on a weathered surface and medium gray on a fresh surface, is a very fine grained rock. It fractures into blocky pieces. A maximum of only about 2.5 m of this member is exposed in this area.

IGNEOUS ROCKS
(TERTIARY)

Igneous rocks of at least seven distinct compositions occur in the small Laughlin Peak area. These are fine-grained rocks, which were either extruded on the surface or intruded fairly close to the surface. The emplacement of these rocks occurred during the last half of the Tertiary. The various rock types are (1) trachyte, (2) trachyandesite, (3) phonolite, (4) intrusive breccia, (5) lamprophyre, (6) rhyodacite, and (7) basalt. At least one sizeable body of all but the lamprophyre and intrusive breccia is found within this area, and standard chemical analyses of them are given in table 1. The intrusive breccia can not be compared with the other igneous rocks on the basis of its composition, as its composition varies considerably depending on the country rock types incorporated into it. The five principal rock types represent at least two and possibly three chemical or magmatic lineages. These lineages can be shown on two simple chemical variation diagrams (fig. 3). In figure 3*A* CaO is plotted against the alkalies, and in figure 3*B* MgO is plotted opposite total iron oxides. In both diagrams the points representing phonolite, trachyte, and trachyandesite lie along one trend, but those points representing the five rhyodacite samples lie along a separate trend. Rocks along each of these two linear trends could form by fractionation from a common magma. The separate trends, however, indicate the rhyodacitic rocks that form one of these trends were probably derived from a separate magma then the alkalic rocks which lie along the other trend. The chemical composition of the basalt (sample No. 13) is quite different from the compositions of the other rocks, as can be seen in figure 3 where the points representing basalt are widely separated from those of the other rocks. The basalt is obviously not on the trend formed by the rhyodacites. It might possibly be on the trend of the alkalic rocks, although not sufficient number of chemical analyses are available to verify the continuation of this trend. Although not apparent in the mapped area (pl. 1), basalts are much more widespread in this part of New Mexico than all the other rock types combined. Olivine basalt similar in composition to that exposed in the southeastern part of the mapped area cover broad areas in Colfax and Union Counties (Lee, 1922, p. 9–12; Collins, 1949, p. 1026–1031; Stobbe, 1949, p. 1049–1066). These rocks were extruded at various times in the late Tertiary and Quaternary (Stormer, 1972, p. 2445).

The minor-element contents of these igneous rocks show some significant differences. Table 2 summarizes data of 13 samples from the five principal rock types. The rock types are arranged from left to right in order

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TABLE 1.—*Chemical analyses and normative compositions, in weight percent, of igneous rocks in the Laughlin Peak and adjacent area*

[FeO by volumetric titration, CO_2 by coulometric titration, H_2O+ by the Penfield method, and H_2O- by difference after heating to 105°C for 2 hours—all analyses done by H. G. Neiman; other oxides by X-ray spectroscopy done by J. S. Wahlberg, J. E. Taggart, Jr., and J. W. Baker; N.D., not determined]

Constituent or mineral	Sample Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Chemical Analyses													
SiO_2	54.8	53.9	61.5	62.6	68.0	70.9	69.0	67.8	68.1	51.9	57.6	55.0	45.6
Al_2O_3	21.0	21.3	18.1	18.3	15.1	15.6	16.0	15.1	15.7	14.6	18.6	16.1	15.1
Fe_2O_3	2.94	2.86	3.25	3.18	2.34	1.44	1.55	2.36	2.21	5.35	4.69	5.81	7.0
FeO	.20	.36	.73	.35	.39	.36	.43	.20	.88	2.97	1.44	2.89	5.20
MgO	.2	.2	.66	.3	1.1	.1	.3	1.2	1.3	2.6	1.5	2.8	6.86
CaO	.42	.60	1.97	1.21	3.20	1.90	2.47	3.09	3.34	5.57	3.39	3.68	11.4
Na_2O	9.6	10.3	7.1	6.5	4.0	4.0	3.7	3.6	4.0	4.3	5.6	4.4	3.1
K_2O	4.96	4.14	3.78	4.65	2.94	2.64	2.83	3.01	2.68	3.73	3.56	4.20	1.06
TiO_2	.30	.30	.46	.36	.33	.21	.22	.32	.38	1.06	.80	1.02	1.45
H_2O+	4.90	4.70	.98	1.14	1.36	1.06	2.28	2.23	1.25	N.D.	N.D.	N.D.	1.79
H_2O-	0.25	.65	.20	.13	.23	.22	.55	.45	.28	N.D.	N.D.	N.D.	.20
P_2O_5	<.1	<.1	.2	.2	.2	<.2	<.1	.2	.2	.4	.5	.55	1.1
MnO	.20	.22	.15	.11	.05	<.02	<.02	.04	.05	.13	.12	.16	.18
CO_2	.08	.10	1.14	.60	.11	<.01	.02	.09	.08	N.D.	N.D.	N.D.	.12
Total	99.85	99.63	100.22	99.64	99.35	98.43	99.35	99.69	100.45	92.78	97.80	96.61	100.16
Normative Compositions													
Quartz	--	--	3.72	6.42	26.22	34.38	32.04	28.44	26.22	1.26	3.96	3.12	--
Orthoclase	31.14	26.13	22.80	27.80	17.79	16.12	17.24	18.35	16.12	23.91	21.13	26.13	6.67
Albite	38.25	39.82	60.78	55.54	34.58	34.58	32.49	31.44	34.06	39.30	48.21	38.77	25.68
Anorthite	--	.28	1.95	1.39	14.73	9.73	12.79	14.18	15.57	10.01	13.62	11.95	24.46
Nepheline	25.28	27.83	--	--	--	--	--	--	--	--	--	--	.57
Hypersthene	--	--	1.70	.80	2.80	.30	.80	3.10	3.40	0.90	3.80	6.10	--
Diopside	1.08	1.08	--	--	--	--	--	--	--	13.18	--	2.59	19.44
Wollastonite	.35	.70	--	--	--	--	--	--	--	--	--	--	--
Olivine	--	--	--	--	--	--	--	--	--	--	--	--	7.23
Corundum	--	--	1.53	2.14	.10	2.86	2.45	.61	.61	--	.71	--	--
Magnetite	.46	1.16	1.39	.23	.46	.46	.93	--	1.86	7.89	2.55	6.96	10.21
Hematite	2.72	2.24	2.40	3.04	2.08	1.12	.96	2.40	.96	.32	3.04	1.28	--
Ilmenite	.61	.61	.91	.76	.61	.46	.46	.46	.76	2.13	1.52	2.13	2.89
Apatite	--	--	.34	.34	.34	--	--	.34	.34	1.01	1.34	1.34	2.69
Calcite	--	--	2.60	1.40	.20	--	--	.20	.20	--	--	--	.30
Sphene	--	--	--	--	--	--	--	.20	--	--	--	--	--
Na_2CO_3	.21	.21	--	--	--	--	--	--	--	--	--	--	--
Total	100.10	100.06	100.12	99.86	99.91	100.01	100.16	99.72	100.10	99.91	99.88	100.37	100.14

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TABLE 1.—*Chemical analyses and normative compositions, in weight percent, of igneous rocks in and near the Laughlin Peak area*—Continued

SAMPLE DESCRIPTIONS

1. Phonolite from top of massive sill, 1,340 m south of Jimmy Spring near the northern border of sec. 6, T. 27 N., R. 26 E.
2. Phonolite from just west of road, 980 m south of Jimmy Spring in the south-central part of sec. 31, T. 28 N., R. 26 E.
3. Trachyte from southwest end of sill, just north of Jimmy Spring Creek in the NE1/4 sec. 36, T. 28 N., R. 25 E.
4. Trachyte from north end of dike adjacent to large sill just south of county road A-8 in the SW1/4 sec. 36, T. 28 N., R. 25 E.
5. Rhyodacite from steep northeast flank of Raspberry Mountain.
6. Rhyodacite from peak 8632 on southwest flank of Laughlin Peak in the NE1/4 sec. 32, T. 28 N., R. 26 E.
7. Rhyodacite tuff from north side of county road A-8, 290 m northeast of ranch house in the SE1/4 sec. 5, T. 27 N., R. 26 E.
8. Rhyodacite from southeast flank of easternmost of the Pine Buttes in the SE1/4 SE1/4 sec. 11, T. 27 N., R. 26 E., east of mapped area.
9. Rhyodacite from lower south flank of Palo Blanco Mountain in the SW1/4 SE1/4 sec. 17, T. 27 N., R. 27 E., east of mapped area.
10. Trachyandesite from 570 m south of county road A-8 and 115 m east of the west border of the mapped area in SW1/4 SE1/4 sec. 35, T. 28 N., R. 25 E.
11. Trachyandesite from small knoll, 230 m northeast of county road A-8 in the SE1/4 SW1/4 sec. 6, T. 27 N., R. 26 E.
12. Trachyandesite from low hill, 380 m north of county road A-8 in the SW1/4 SE1/4 sec. 6, T. 27 N., R. 26 E.
13. Basalt from 100 m north of county road A-8, between two drainages of Tinaja Creek in the NW1/4 SE1/4 sec. 5, T. 27 N., R. 26 E.

of their decreasing alkali content, which is the same as increasing mafic content. As might be expected, as the mafic content increases in the rocks, so does the content of chromium, cobalt, copper, nickel, and scandium. Other elements, such as gallium, lead, niobium, and zirconium, tend to correlate with the alkali content. The phonolite has a deviant minor-element content. Phonolite contains more rare earths, beryllium, gallium, lead, niobium, and strontium than any other rock type. Beryllium, niobium, and zirconium are especially concentrated in the phonolite, and this rock may contain as much as 10 times that found in the other rock types. Phonolite contains less chromium, cobalt, nickel, and scandium than the other rock types. Two elements common in the thorium- and rare-earth-bearing veins, barium and strontium, occur in phonolite in amounts only one-third to one-fifth that of other rocks.

The thorium and uranium contents of various igneous rock types are shown in table 2. The lowest thorium contents are found in the five samples with rhyodacitic composition. Trachyandesite contains a little more thorium, and, surprisingly, the basalt has about the same amount. Trachyte in general is higher in thorium than the trachyandesite. The thorium content of phonolite is much higher than that of any of the other rock types. The least uranium occurs in the five samples of rhyodacite and the one of basalt. Uranium content generally follows that of thorium, and phonolite contains six to seven times as much uranium as trachyte, which has the next highest content of uranium. The rocks with the higher alkali content tend to have a higher content of thorium and uranium. This can be seen graphically in figure 4 where thorium and uranium are plotted against the $Na_2O + K_2O$ content of each rock. The two curves are similar and show a gradual increase in thorium and uranium content as the alkali increases from basalt to trachyte. A large increase in the amounts of thorium and uranium occurs as the

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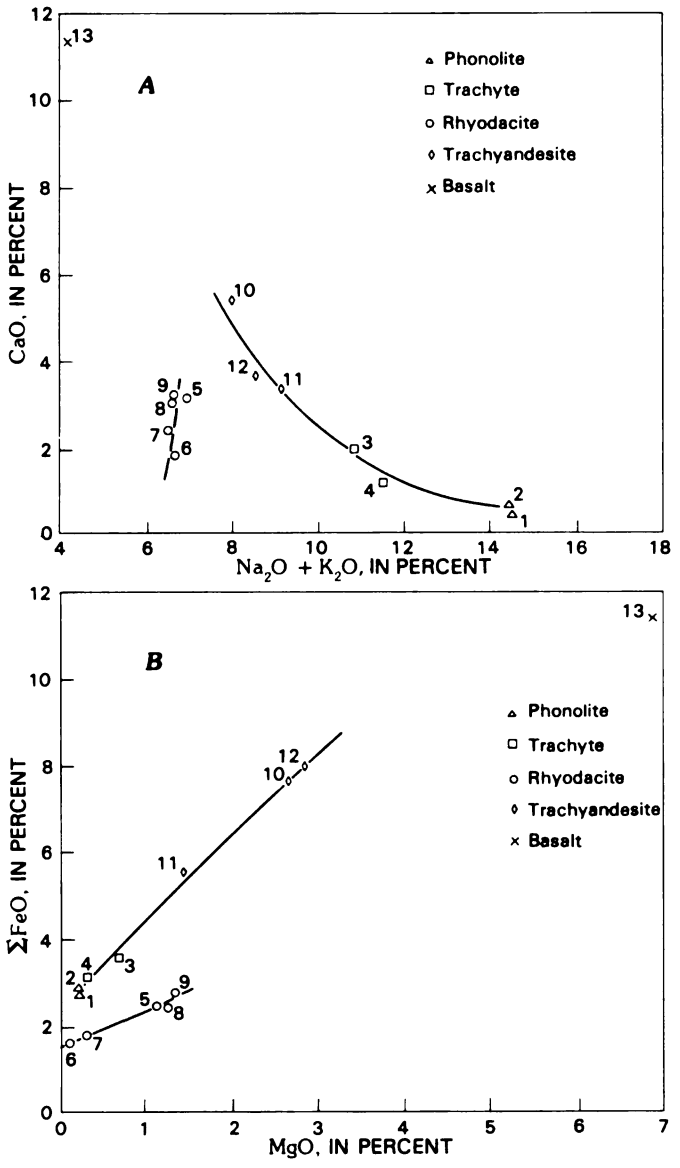


FIGURE 3.—Graphs showing chemical relations in rocks in and near the Laughlin Peak area. Sample numbers correspond to those used in table 1. *A*, CaO to the alkalies ($Na_2O + K_2O$). *B*, MgO to total iron oxides.

$Na_2O + K_2O$ content increases from about 11 to 14 percent.

The increase in thorium and uranium contents can also be noted by the increase in radioactivity measured with a scintillometer, although an increase in radioactivity also reflects an increase in potassium. The radiation due to K^{40} is generally small, but the amounts of potassium in an igneous rock compared with the amounts of thorium and uranium are large. The

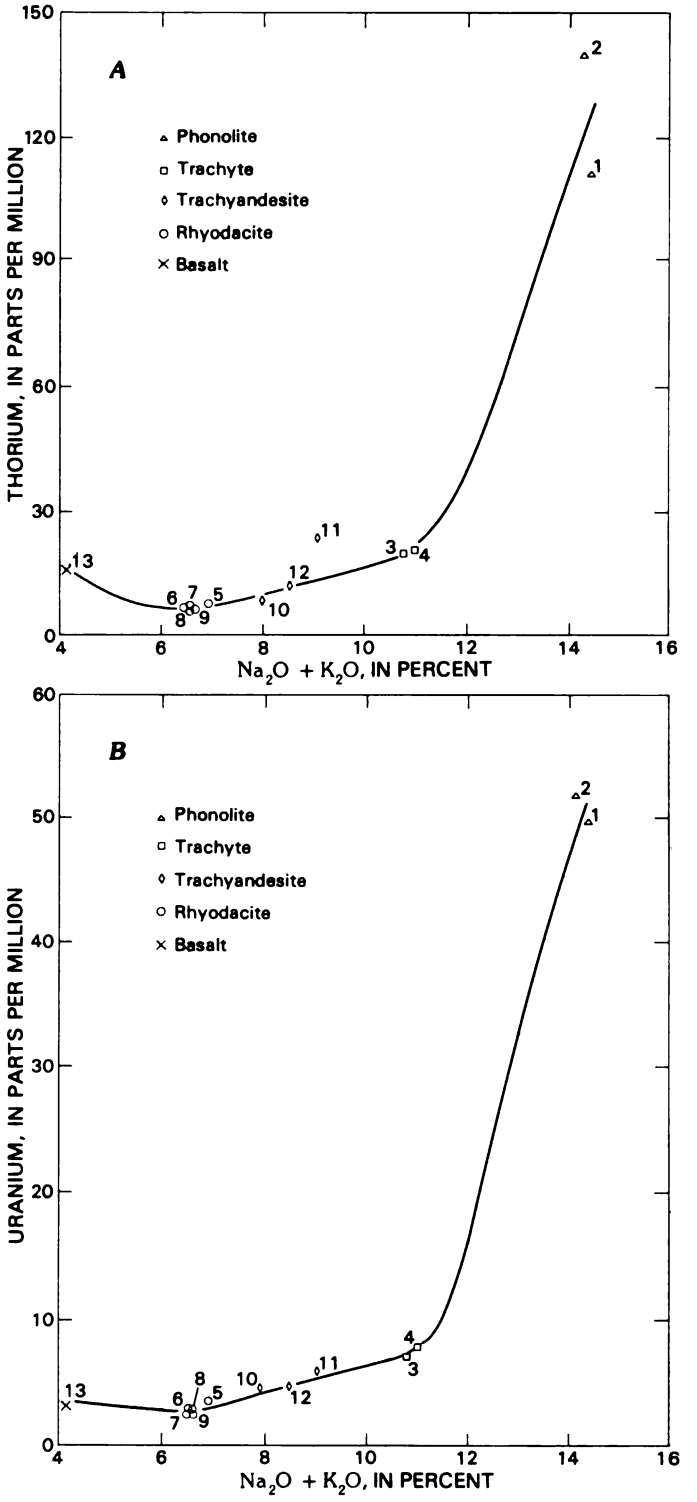


FIGURE 4.—Graphs showing relation between thorium and uranium and the alkalies ($Na_2O + K_2O$) of various rock types. *A*, Thorium; *B*, uranium.

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TABLE 2.—*Chemical analyses of minor elements of igneous rocks in and near the Laughlin Peak area*

[Thorium and uranium analyses were done done on a gamma-ray spectrometer by C. M. Bunker and C. A. Bush. All other elements, including 24 elements looked for but not detected, were determined by semiquantitative spectrographic analysis by N. M. Conklin; <, less than value indicated; N.D., not determined; elements looked for but not detected: Ag, As, Au, B, Bi, Cd, Eu, Ge, Hf, In, Li, Mo, Pd, Pr, Pt, Re, Sb, Sm, Sn, Ta, Te, Tl, W, and Zn]

Rock Type.....	Phonolite		Trachyte		Rhyodacite					Trachyandesite			Basalt
Sample No.....	1	2	3	4	5	6	7	8	9	10	11	12	13
Element													
Lanthanum.....	300	150	150	150	30	N.D.	N.D.	N.D.	N.D.	70	150	70	150
Cerium.....	300	150	200	150	<150	N.D.	N.D.	N.D.	N.D.	<150	200	150	<150
Neodymium.....	150	70	150	100	<70	N.D.	N.D.	N.D.	N.D.	70	150	100	70
Ytterbium.....	7	5	7	3	1	N.D.	N.D.	N.D.	N.D.	3	3	3	2
Yttrium.....	50	30	70	30	10	N.D.	N.D.	N.D.	N.D.	30	30	30	20
Total rare earths..	807	405	577	433	41	N.D.	N.D.	N.D.	N.D.	173	533	353	242
Barium.....	150	300	1500	1500	1500	N.D.	N.D.	N.D.	N.D.	1500	1500	3000	1500
Beryllium.....	10	15	1.5	1	<1	N.D.	N.D.	N.D.	N.D.	<1	1	1	<1
Chromium.....	3	<1	3	3	15	N.D.	N.D.	N.D.	N.D.	50	30	150	200
Cobalt.....	<5	<5	7	7	7	N.D.	N.D.	N.D.	N.D.	20	15	30	30
Copper.....	7	1.5	30	30	30	N.D.	N.D.	N.D.	N.D.	70	15	70	150
Gallium.....	70	70	30	30	30	N.D.	N.D.	N.D.	N.D.	20	30	30	15
Lead.....	70	70	30	30	15	N.D.	N.D.	N.D.	N.D.	10	15	15	15
Manganese.....	1500	1500	1500	1000	700	N.D.	N.D.	N.D.	N.D.	1000	700	1500	1500
Nickel.....	2	<2	3	2	7	N.D.	N.D.	N.D.	N.D.	15	15	30	150
Niobium.....	150	70	30	30	<10	N.D.	N.D.	N.D.	N.D.	15	30	15	20
Scandium.....	<5	<5	7	7	7	N.D.	N.D.	N.D.	N.D.	15	15	15	15
Strontium.....	300	300	1500	1500	1000	N.D.	N.D.	N.D.	N.D.	700	3000	2000	1500
Vanadium.....	70	50	150	70	50	N.D.	N.D.	N.D.	N.D.	300	150	300	150
Zirconium.....	1000	700	300	200	70	N.D.	N.D.	N.D.	N.D.	150	150	150	70
Thorium.....	111	139	21	22	8.1	6.5	6.6	6.7	7.3	8.7	23	11	16
Uranium.....	50	52	7	8	3.6	3.2	2.6	2.8	3.2	4.4	6.2	3.8	3.5

percentage of radioactivity due to potassium was calculated for the igneous rocks of the Laughlin Peak area. Potassium accounts for 54–58 percent of the radiation in two samples of trachyte. It makes up 59–72 percent of the radiation in three samples of trachyandesite, 71–78 percent in five samples of rhyodacite, and 42 percent in a sample of basalt. Only in the phonolite, where it accounts for only 10–21 percent of the total radiation in two samples, is the radiation principally due to uranium and thorium. In the phonolite the uranium accounts for 56–57 percent of the total radiation and thorium 22–26 percent. Phonolite can be easily identified in the field by its high radioactivity. It is about 3.5 times more radioactive than trachyte, the next most radioactive igneous rock. It also has approximately 4 times the radioactivity of trachyandesite, 5.5 times as much as rhyodacite, and 8.5 times as much as the basalt.

TRACHYTE (OLIGOCENE)

Trachyte is the most widespread igneous rock in Laughlin Peak area (pl. 1). It occurs principally in dikes and sills from the northernmost to the southernmost part of the area. The bulk of the trachyte occurs in two massive sills. One is in the northwest part of the area just south of Tinaja Creek where a sill at least 45 m thick underlies an area of approximately 2.5 km^2

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(fig. 5). The other surrounds Raspberry Mountain. (See sec. *B–B'*, pl. 1.) There, a sill at least 30 m thick underlies an area of about 3.2 km^2. Trachyte outcrops have been seen to the west in the central and western part of the Piñon Hills and southward down into the Chico Hills.

Dikes, smaller sills, and small irregular-shaped intrusions occur in many parts of this area. Dikes are steeply dipping and trend in many directions. Along the northern border near Jimmy Spring Canyon, most of the dikes have a northeasterly strike, and adjacent to the Slagle Canyon, in the southwest corner of the area, most dikes have a east-northeast strike. Dikes range in length from a few meters to at least 860 m. The longest dike and several other long dikes occur in the southwest corner of the area. Dikes range in thickness from a few tenths of a meter to about 10 m. In the northwest corner of sec. 6, northeast of county road A–8, a dike can be traced up a mountain to where it merges with a sill.

The trachyte is the oldest Tertiary igneous rock in the area. Lamprophyre, trachyandesite, and phonolite dikes, and intrusive breccia bodies cut the trachyte, and, in places, inclusions of trachyte are found in intrusive breccia bodies and lamprophyre. Its relations with the rhyodacites and the basalt are not well exposed, although basalt flows appear to lap onto trachyte along the south and east flanks of Raspberry Mountain. Trachyte from widely scattered outcrops is generally altered. The only other igneous rock that is commonly altered is trachyandesite. The trachyte and trachyandesite were altered before the other rocks were emplaced. As previously noted, the trachyte forms many dikes and sills, which were not all emplaced at the same time. Field relations, such as alteration, however, indicate that the trachyte bodies are older than most other igneous rocks of the region. A potassium-argon determination was made on hornblende separated from the large sill in the northwest part of the area. Specifically this sample was collected on a ridge in the SE¼NE¼ sec. 2, T. 27 N., R. 25 E. The analysis, which was made by R. F. Marvin, H. H. Mehnert, and E. L. Brandt of the U.S. Geological Survey, yielded an Oligocene age of 36.7 ± 1.3 m.y. (million years).

Altered trachyte is a tan to light-tan porphyritic rock. Phenocrysts consist principally of chalky white, partly altered plagioclase. In addition, goethite-filled, elongate-shaped crystal molds indicate the former presence of mafic minerals. Where unaltered, trachyte is light gray. Trachyte contains hornblende and augite phenocrysts, and the feldspar phenocrysts are unaltered. Most fresh trachyte contains 10–20 percent phenocrysts, although their total range is from about 4 to 100 percent. The most common phenocrysts are white tabular crystals of plagioclase about 1–3 mm long. Much of the plagioclase is oligoclase to andesine in composition. A few of the feldspar phenocrysts are potassium feldspar. The principal mafic mineral is brown hornblende that makes up about 1–15 percent of the rock; it is pleochroic from light brown to olive green and occurs as elongate crystals as much as 4 mm long. Minor amounts of pyroxene, from less than 1 to 3 percent, are commonly present. Optically, the pyroxene is clear to pale green, nonpleochroic, and occurs as subhedral crystals. The optical properties of this mineral most closely fit those of diopside. The matrix of the trachyte can be either glassy or finely crystalline. Where holocrystalline it is made up principally of feldspars. Studies of all rock specimens stained with sodium cobaltinitrite indicate that the matrix has a high content of potassium feldspar. Twinned plagioclase is also present in the matrix. A little quartz (as much as several percent) occurs interstitially between the feldspar grains in some rocks. Small black grains of magnetite also are common in the matrix. Other accessory minerals that occur in some samples are brown biotite, apatite, and, more rarely, zircon.

Chemical analyses of two samples of trachyte are reported in table 1 (Nos. 3 and 4). Compared with most igneous rocks these samples have a relatively low silica and CaO content and a high K_2O and Na_2O content. These relations can also be seen by the relatively low quartz and anorthite contents and the high orthoclase and albite content of the norms. The relations between the CaO and $Na_2O + K_2O$ and between MgO and total iron oxides in samples of trachyte and various other types of igneous rocks in the Laughlin Peak area are shown in figure 3. Classified on the basis of their chemical composition according to the systems of Rittmann (1952) or De la Roche, Letterrier, Grandclaude, and Marchal (1980), both these samples are trachytes.

TRACHYANDESITE (OLIGOCENE)

Trachyandesite is a rather inconspicuous rock type; it forms subdued outcrops on gently sloping hillsides and on low hills. Most of the trachyandesite occurs in what appear to be sills in three areas. The easternmost of these is a little over 200 m north of county road A–8 near the east edge of the Laughlin Peak area, in sec. 5, where trachyandesite is intruded into the Carlile Shale and lies directly below the phonolite. These outcrops, which are exposed over an area of 650 by 230 m, may represent an irregular intrusive because, although its top underlies the phonolite sill, its base appears to crosscut the Carlile in the one outcrop where the base is exposed. The second major area of the

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FIGURE 5.—Trachyte and phonolite sills. *A*, North end of large trachyte sill exposed just south of county road A–8. *B*, Phonolite sill forms skyline of ridge 1 km north of Jimmy Spring Creek.

trachyandesite lies approximately 230 m north of county road A–8, in sec. 6, about 640 m west of the first one. This body is intruded principally into the Graneros Shale. Its top, however, is in the Greenhorn Formation and everywhere lies below the Bridge Creek Limestone Member. The trachyandesite is exposed over an area of 740 by 750 m. The third principal area of trachyandesite occurs south of county road A–8 on the west edge of the area. It underlies the western part of the large trachyte sill and extends westward into the adjoining Tres Hermanos Peak quadrangle. The upper part of this trachyandesite body is in part directly below the trachyte and in part separated from the trachyte by part of the Greenhorn Formation. Its lower part is in the Graneros Shale. In addition to the three principal areas, several small sills and dikes of

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trachyandesite have been mapped. These small intrusives range in length from 12 to 170 m. The largest has a thickness that ranges from 10 to 60 cm.

A similar rock was reported by Stobbe (1949, p. 1071) on the southwest flank of Turkey Mountain (fig. 1). She called this rock a hornblende andesite, but her nomenclature was based chiefly on the phenocryst content of the rock.

Trachyandesite is for the most part intruded into the Graneros Shale and the Greenhorn Formation. In two of the areas, dikes of trachyandesite cut the older trachyte. Trachyandesite lies below the large phonolite sill, but the contact between these two rock types is poorly exposed. Trachyandesite does not come in contact in this area with basalt, rhyodacite, or lamprophyre, and their relationship to trachyandesite is not known. Trachyandesite and trachyte are the only two igneous rocks that are commonly altered. Thus, the trachyandesite probably was emplaced and altered before the unaltered basalt, rhyodacite, and phonolite were emplaced. Although most of the trachyandesite is altered, fresh porphyritic trachyandesite occurs on a small knoll 230 m northeast of county road A–8 in the SE¼SW¼ sec. 6, T. 27 N., R. 26 E. A potassium-argon age determination was made on hornblende from a sample of this rock by R. F. Marvin, H. H. Mehnert, and E. L. Brandt of the U.S. Geological Survey. They obtained an Oligocene age of 32.3 ± 1.5 m.y. A chemical analysis of this sample is also given in table 1 (No. 11).

Trachyandesite ranges in color from dark gray, where fresh, to olive green and brown, where altered or partly altered. This rock is porphyritic, having 10–30 percent phenocrysts that range in length from 0.2 to 5 mm. Phenocrysts are 8–26 percent greenish-brown euhedral crystals of hornblende, 0–15 percent small laths of plagioclase, 0–3 percent augite, less than 1 to 2 percent magnetite, and trace amounts of apatite, biotite, and sphene. The matrix ranges from entirely crystalline to a glass. Where crystalline it consists of numerous crisscrossing plagioclase microlites with a few percent magnetite and hornblende crystals. This is intermixed with colorless anhedral crystals, which under the microscope have a light-gray birefringence. Yellow coloring as a result of staining of the rock with sodium cobaltinitrite indicates that the matrix contains considerable potassium feldspar. Less than 1 percent of tiny anhedral grains of quartz were noted in one thin section. Fresh trachyandesite, like that described above, is not common. The mafic phenocrysts of many samples have been completely altered to limonite, hematite, magnetite, chlorite, or calcite. Plagioclase phenocrysts are generally altered to clay. All the small dikes and sills are altered, as are much of the larger masses of trachyandesite.

Chemical analyses of three samples of trachyandesite are reported in table 1 (Nos. 10–12). These samples, when compared with those of the other igneous rocks, have a low silica content, having only 1.3–4 percent quartz in the norm. They also have a high potassium content, containing 21–26 percent orthoclase in the norm. The relations between CaO to $Na_2O + K_2O$ and MgO to total iron oxides in these three samples of trachyandesite and other igneous rocks from the Laughlin Peak area are shown in figure 3. The relation between both the alkalic (fig. 3*A*) and mafic elements (fig. 3*B*) in trachyandesite to other rocks suggest that they are related chemically to the trachyte and phonolite, rather than the rhyodacites. Although the dark-colored trachyandesite looks somewhat like the basalt in hand specimen, there is no similarity between their alkali content.

Classified on the basis of its chemical composition according to the system of De la Roche, Letterrier, Grandclaude, and Marchal (1980), this rock could be called either a trachyandesite or a trachyte. I prefer the name trachyandesite, as the composition is considerably different than the trachyte previously described. The trachyandesite has less SiO_2 and Na_2O and has more MgO, Fe_2O_3, and FeO than the trachyte. It is a much more mafic rock and is darker in color than the trachyte.

PHONOLITE (OLIGOCENE)

Phonolite is one of the most distinctive rocks in the Laughlin Peak area. It consists of large white tabular feldspar and small rounded white ocellar masses of feldspathoids set in a greenish-gray matrix. It is resistant to weathering and commonly forms prominent cliffs (fig. 5*B*). The greater part of the phonolite is in one thick sill on the southwest flank of Laughlin Peak and is exposed over a distance of approximately 3.3 km between Jimmy Spring Canyon and the eastern border of the area. Both ends and part of its upper surface are buried by colluvium derived from Laughlin Peak. The same phonolite sill is also exposed about 1 km north of the mapped area in the adjoining Mesa Larga quadrangle (fig. 5*B*). A much smaller sill, about 320 m long, is exposed 15 m below the larger sill in a canyon along the northern border of the NE¼ sec. 6. Several widely scattered dikes occur in the northwestern part of the area. The largest of these forms a protruding outcrop along the crest of a hill, about 460 m long, north of Jimmy Spring Canyon in the N½ sec. 36. Phonolites are widespread in the Tres Hermanos Peak quadrangle to the west, and in the southern part of the Chico Hills, which lie 5 km to the southeast of the Laughlin Peak area.

The large sill that makes up the bulk of the phonolite is intruded into Cretaceous sedimentary rocks; this sill is 18–25 m thick. Collins (1949, p. 1034–1035) thought

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this phonolite was a flow, but the presence of sedimentary rocks both above and below the phonolite, the general shape of the unit, and the presence of a smaller sill directly below the larger sill suggest to me that this phonolite body is a sill.

Phonolite is younger than trachyte, as it cuts a trachyte sill in the SE¼ sec. 2. Contacts between phonolite and the other igneous rocks are not exposed. Although phonolite has not been dated within the area of study, an age was reported from a large phonolite sill at the Dorsey Mansion State Monument, which is 10.5 km south-southeast of Raspberry Mountain in the NW¼SE ¼ sec. 17, T. 26 N., R. 26 E. (Scott, Wilcox, and Mehnert, written commun., 1983). This phonolite, which was dated by the K-Ar method on potassium feldspar, had a Oligocene age of 25.80 ± 0.88 m.y.

Although most phonolite is greenish gray, the color of this rock varies from a dark gray through greenish gray to bluish gray. The rock is porphyritic and contains both white rectangular feldspar phenocrysts and white, round to oval-shaped ocellar masses (aggregates of feldspathoids) set in a greenish-gray aphanitic matrix. These white crystals or aggregates constitute about 5–30 percent of the rock. The feldspar is orthoclase and forms elongate tabular crystals as much as 3.8 cm long, although most crystals are in the 0.6–1.0 cm range. The orthoclase may be in part replaced by small laths of plagioclase. Flow structure in the phonolite is brought out by the alinement of these tabular crystals of feldspar. The white ocellar masses are made up of intergrown crystals of nepheline—and lesser amounts of plagioclase. Nepheline is marked by hexagonal and rectangular crystal outlines and has both low relief and low birefringence. The nepheline in some samples has been altered to natrolite or analcime. In some places, small (1–2 mm long) bright green acicular aegirine crystals are present. The groundmass consists chiefly of 10–20 percent aegirine, 1–10 percent plagioclase, and most of the rest intergrown nepheline and orthoclase. In addition, some samples contain less than 1 percent of apatite, light-brown biotite, and magnetite. The aegirine is a distinctive mineral in this rock, occurring as bright-green acicular crystals. These crystals commonly occur in clots, which in some places form rosettes. Nepheline and orthoclase are commonly difficult to distinguish visually under the microscope as both are colorless and have low relief and low birefringence, but the hexagonal or rectangular form of nepheline is diagnostic, and orthoclase is distinguished by sodium cobaltinitrite staining.

Chemical analyses of two samples of phonolite collected from the large sill are reported in table 1 (Nos. 1 and 2). These samples have low silica content and both samples contain more than 25 percent nepheline in the norm. They also have low CaO content, as neither sample exceeds 0.6 percent. The anorthite content of the norm ranges from 0 to 0.2 percent with most of what little CaO there is going into diopside in the norm. The phonolite samples have the highest Na_2O content and one of the highest K_2O content of all the rocks in the region. This is expressed by the high albite, nepheline, and orthoclase contents of the norm. The relations between the CaO to $Na_2O + K_2O$ and MgO to total iron oxides of phonolite to that of the other rocks are seen in figure 3. Phonolite has more alkalies than any other rock in the area. It forms the alkali-rich end of a linear sequence that shows an increase in alkali as the CaO content decreases. Phonolite also has less total iron oxide and MgO than the other rocks and forms part of another linear sequence with the same rock types (fig. 3*B*). Rhyodacite samples lie on separate linear trends in both these graphs and do not appear to have formed from the same source as the phonolite. The two analyzed samples are classified as phonolite on the basis of their chemical composition by the systems of Rittmann (1952), or De la Roche, Leterrier, Grandclaude, and Marchal (1980).

INTRUSIVE BRECCIA (OLIGOCENE)

Intrusive breccia occurs in cross-cutting bodies in the central part of the area. Some of these bodies are dikes (fig. 6) that are as much as 170 m long and range in thickness from about 0.5 to 6 m. These bodies may strike in any direction, but a group of intrusive breccia dikes just south of Tinaja Creek in the northern part of sec. 7 have a west-northwest trend. These bodies occur along fractures, some of which show displacement of a few meters. An intrusive breccia body just south of county road A–8 down Tinaja Creek lies along a small fault that separates the Graneros Shale from the Dakota Sandstone. Intrusive breccia bodies form irregular pipes in two areas. The largest occurs on a hill in the western part of secs. 1 and 12. This intrusive breccia body is roughly 300 by 180 m, although its size and form are not well known because outcrops are scarce. Two smaller pipelike bodies occur on the low hill on the north side of Tinaja Creek in the SW¼ sec. 6. Within the mapped area the intrusive breccia is emplaced into Dakota Sandstone, Graneros Shale, Greenhorn Formation, Carlile Shale, and trachyte. It is, therefore, younger than these rocks. It is also noted cutting phonolite some 6.5 km south of this area in the Chico Hills.

The composition of the intrusive breccia varies, but generally it consists of fine- to pebble-size fragments of sedimentary, volcanic, and plutonic rocks in a matrix of crystal fragments and finely granulated material. Composition of the rock fragments varies from body to body. Some are mainly sedimentary rocks, others mainly trachyte, and some contain a mixture of various

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FIGURE 6.—An intrusive breccia dike protrudes out of a plain underlain by Graneros shale south of Tinaja Creek near the northern border of the NW¼ sec. 7, T. 27 N., R. 26 E.

rock types. Fragments were derived from underlying rock types and hence vary as these rock types change. Sedimentary rock fragments include shale, limestone, and sandstone. These may be bleached and recemented so that the original formation is not recognizable. Trachyte fragments are abundant in some intrusive breccias. Three intrusive breccias contain fragments of granite as large as 0.5 m across. Granite is not exposed at the surface in this area. Granite along with black shale, trachyte, and Dakota Sandstone fragments occurs in the intrusive breccia dike south of Tinaja Creek near the northern border of sec. 7. Abundant granite fragments are also found in the westernmost of two small pipes on a low hill about 0.8 km north of this locality. An adjacent pipe to the east of this one contains principally sedimentary rock fragments.

Rock fragments in the intrusive breccia range from angular to subrounded in shape and from a few millimeters to 0.6 m across. Most, however, are from 1 to 5 cm across. The matrix may be a white or tan, or it may be stained brown or black with limonite or manganese oxide minerals. The matrix contains small mineral fragments, mainly quartz and feldspar. These are probably, in turn, derived from disintegration of the rock fragments. The rest of the matrix is extremely finely granulated material, which is too fine to identify even with the aid of petrographic microscope.

LAMPROPHYRE DIKES (OLIGOCENE)

Five small lamprophyre dikes were found during mapping in the Laughlin Peak area. This rock type is generally poorly exposed and most of its exposures are along ridges or in pits. The dikes have been traced from 3 to 18 m and range in thickness from 0.3 to 2 m. They all have a general northwest strike.

The lamprophyres are found in two general areas: (1) in and adjacent to the large trachyte sill in the northwest corner of the area, and (2) near Slagle Canyon in the southwest part of the area. In the northwest part of the area two dikes are exposed along ridge tops where they cut the trachyte sill, and one is exposed in a small working in the Graneros Shale along the east side of the trachyte sill. At the latter locality the lamprophyre contains small inclusions of Graneros Shale. In the southwest part of the area two dikes cut Dakota Sandstone. At one locality the lamprophyre also cuts a trachyte dike, and 3 km southeast of the area along Joe Cabin Arroyo several lamprophyres are found cutting phonolite.

The lamprophyres are black to dark gray, and the individual crystals are not readily apparent. These dikes vary somewhat in mineralogy. Augite is the most abundant mineral in two dikes in the southwest part

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of the area and in one dike in the northwest part of the area, olivine predominates in the dike in the Graneros Shale, and hornblende is most abundant in the other dike. The two dikes in the southwest part of the area are quite similar in composition and contain 70–75 percent augite, 7–15 percent olivine, 6–8 percent magnetite, 1–5 percent biotite, and 2–5 percent feldspar. These two dikes are holocrystalline. One of the two dikes that intrudes the trachyte in the northwest part of the area contains 45 percent augite, 20 percent pale-brown hornblende, and 5 percent magnetite. The other dike that intrudes the trachyte has 55 percent hornblende, 8 percent magnetite, 5 percent biotite, and 3 percent augite. The dike that intrudes the Graneros Shale is made up of 50 percent olivine, 35 percent augite, 5 percent biotite, and 2 percent magnetite. The remainder of these three dikes consists of a glass.

RHYODACITE (MIOCENE)

Rhyodacite makes up several volcanic cones and intrusions in and around Laughlin Peak (fig. 7). Rocks of rhyodacite composition form the flows on Laughlin Peak, the intrusive that makes up Raspberry Mountain, and a small patch of tuff on the lower part of the southern flank of Laughlin Peak. Rhyodacites also are found in the surrounding area, and occur on Palo Blanco Mountain and the southern two Pine Buttes (fig. 1). Samples taken from these six areas were classified as rhyodacites on the basis of their chemical composition according to the system of either Rittmann (1952) or De la Roche, Leterrier, Grandclaude, and Marchal (1980). Rhyodacites were identified in two other adjacent areas from their chemical analyses according to the same systems. One is the intrusion on Red Mountain some 30 km north of Laughlin Peak (Lee, 1922, p. 11) and the other is from Cunningham Butte some 21.5 km northwest of Laughlin Peak (Stobbe, 1949, p. 1067). These rocks are called the Red Mountain Dacites by Stobbe (1949, p. 1066–1071), who studied the petrography of these rocks in some detail. Her basis for this nomenclature is evidently petrographic as she had few chemical analyses to aid her. A large part of these rocks is either made up of a glassy or a very fine grained matrix. Hence, in these types of rocks a nomenclature based on chemical composition is greatly preferred, and these rocks have been renamed rhyodacite.

The three rhyodacites that are found in the Laughlin Peak area will be discussed separately, as they occur in separate parts of the area and differ from each other in color, texture, and degree of crystallinity.

RHYODACITE OF RASPBERRY MOUNTAIN

The rhyodacite which makes up the central mass of Raspberry Mountain (fig. 7*A*), has an oval-shaped outcrop pattern (pl. 1). In addition, this rock body is steep sided and of fairly uniform composition. Collins (1949, p. 1033) believed Raspberry Mountain to be a small eroded cone. He noted that no crater exists. The shape and uniformity of this rock body, however, indicate that this rhyodacite probably formed as a plug intruded into the largely shaly Graneros, Greenhorn, and Carlile Formations, which have since been eroded away. This plug is approximately 1,200 m in an east-west direction, 900 m in a north-south direction, and protrudes some 220 m above the surrounding countryside. The contact of this rhyodacite with the adjacent trachyte and basalt are everywhere hidden by talus (colluvium) derived from the rhyodacite plug. An age determination made on this rhyodacite indicates it is younger than the trachyte and older than the basalt. This determination was made on hornblende using the K-Ar method by R. F. Marvin, H. H. Mehnert, and E. L. Brandt of the U.S. Geological Survey from a sample collected on the northeast part of Raspberry Mountain. This rock was intruded in Miocene time and has an age of 8.1 ± 0.6 m.y.

The rhyodacite of Raspberry Mountain is a light-brownish-gray, fine-grained, porphyritic rock. Small phenocrysts, 0.05–2 mm long, make up 20–30 percent of the rock. Plagioclase is the most abundant phenocryst; it makes up 15–20 percent of the rock. Other phenocrysts are oxyhornblende, which make up 5–10 percent of the rock, and magnetite, which accounts for less than 1 percent. The plagioclase occurs as subhedral to euhedral crystals that are commonly zoned. The centers of many of these crystals have been partly destroyed. The plagioclase is both oligoclase and andesine. Oxyhornblende ranges in color in thin section from a distinctive dark reddish brown to a greenish brown. These crystals are subhedral and a little smaller than those of plagioclase. The groundmass is made up partly of recognizable small grains intermixed with those of low birefringence and little crystal form; some glass is also present in some samples. The recognizable grains consist of a few percent each of magnetite and reddish-brown oxyhornblende. Much of the rest is small plagioclase laths. Groundmass minerals with low birefringence may be potassium feldspar—as this part of the rock takes on a yellow sodium cobaltinitrite stain.

A chemical analysis of a sample of rhyodacite collected from the steep northeast flank of Raspberry Mountain is given in table 1 (No. 5). All five analyses of rhyodacite from Laughlin Peak and surrounding

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A



B

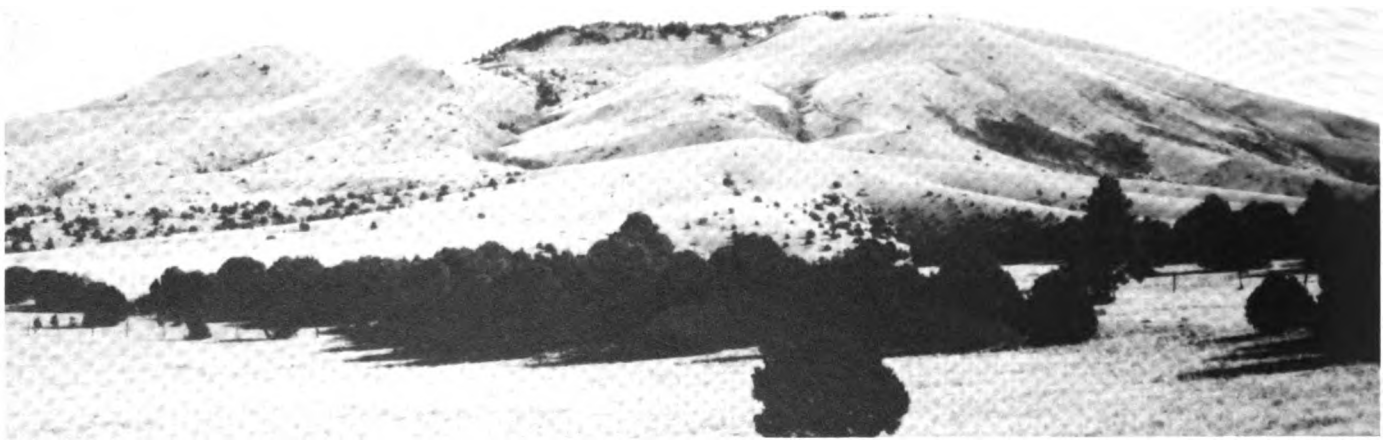


FIGURE 7.—Rhyodacites. *A*, Raspberry Mountain, a plug of rhyodacite, rises some 200 m above the surrounding countryside. *B*, Laughlin Peak, a volcano made up principally of glassy rhyodacite flows; view from the southwest.

areas are generally similar but differ from other rock types in the Laughlin Peak area (fig. 3). The rhyodacites are the most siliceous rock type in this area, and the rhyodacite from Raspberry Mountain has 26 percent quartz in the norm. This rhyodacite has a fairly low MgO content (1.1 percent). The chemical composition of the rhyodacite sample from Raspberry Mountain is quite similar to that of the samples from Palo Blanco Mountain and Pine Buttes (table 1; fig. 3). The amount of difference in the composition of the three samples is no more than one would expect to find between three samples taken from the same intrusive.

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RHYODACITE OF LAUGHLIN PEAK

Rhyodacite makes up the entire upper part of Laughlin Peak (fig. 7*B*). Most of it occurs as gray or red flows, but a little is in the form of volcanic breccia. Less than a quarter of the rhyodacite of Laughlin Peak is shown on plate 1. The top of Laughlin Peak lies only 45 m north of the northeast corner of this map area. Two breached craters also lie just north of the mapped area. Rhyodacite is exposed only on the upper one-third of the mountain; the lower two-thirds is covered by colluvium made up of a thick blanket of rhyodacite debris. Near the top of Laughlin Peak is a large block, about 380 m long, of sedimentary rocks. These rocks consist of Dakota Sandstone and Graneros Shale that were carried upward by the rhyodacite magma. This block of sedimentary rocks is now about 400 m above the Dakota-Graneros contact along Tinaja Creek.

An age determination of the rhyodacite was made on a lahar block from the north flank of Laughlin Peak (Scott, Wilcox, and Mehnert, written commun., 1983). The age, which was determined on oxyhornblende by the K-Ar method, is 6.9 ± 0.6 m.y. (Miocene).

The rhyodacite of Laughlin Peak is principally a light-gray or brownish-red vitrophyre, which in places is made up of red and gray bands. This rock consists of 1–5 percent small phenocrysts, which range in length from 0.4 to 2 mm, set in a fine-grained to glassy matrix. Tiny vesicles, 0.5–4 mm across, generally make up 1–10 percent of the rock. The phenocrysts are principally plagioclase and oxyhornblende. The plagioclase—which may be either andesine or labradorite—occurs as euhedral crystals that commonly exhibit zoning. Oxyhornblende occurs in several colors and may be brown or green. A little biotite was noted in one sample. The matrix is made up of 10–25 percent plagioclase microlites, a few percent magnetite, some light-gray anhedral birefringent material, and the rest, glass. Some of the glassy parts of the rock contain potassium, as is indicated by a yellow color brought out by staining the rock with sodium cobaltinitrite.

A chemical analysis of a sample of rhyodacite of Laughlin Peak is given in table 1 (No. 6). This rock is the most siliceous of all the rocks analyzed, and although it contains no visible quartz, it contains 34 percent quartz in the norm. It also has one of the lowest contents of Fe_2O_3, FeO, and MgO (fig. 3*B*), which is reflected in the small amounts of iron oxide and ferromagnesium minerals in the norm.

RHYODACITIC TUFF

Rhyodacitic tuff is exposed on the south flank of Laughlin Peak. Here it is found on the north side of county road A–8 near the east edge of the area. Similar tuff has been observed by Glenn Scott (oral commun., 1981) to be fairly extensive on the northern flank of Laughlin Peak.

The tuff is a white, thin-bedded, noncalcareous stratified rock. Beds are 2.5–10 cm thick, and the bedding is horizontal. The tuff consists of 15–40 percent fragments of volcanic glass set in fine-grained white ash. The glass fragments are subangular to subrounded, white to light gray in color, and range in size from less than 1 mm to 2 cm. A few oxyhornblende fragments are also found in this rock.

A chemical analysis of a sample of the rhyodacitic tuff is reported in table 1 (No. 7). The composition of the tuff resembles that of the other rhyodacites given in this table (Nos. 5, 6, 8, and 9), in particular, the rhyodacite from Laughlin Peak (No. 6). The normative corundum contents of the rhyodacitic tuff and the rhyodacite of Laughlin Peak are noticably higher than that of the other rhyodacites (table 1), and the anorthite and hypersthene contents are lower.

BASALT (PLIOCENE)

Basalt blankets the southeastern part of the Laughlin Peak area. The basalt, which covers trachyte and the sedimentary rocks of Cretaceous age, originated from The Crater, a small double cratered cone just east of the southeast corner of the area (fig. 1). Close to the cone the basalt has piled up into small ridges (fig. 8). Farther from the source the basalt has spread out forming a flat-topped unit that slopes gently away from its source at The Crater. The basalt in this area is younger than the sedimentary rocks of Cretaceous age and the trachyte, which it partially covers. A sample was taken for age determination by Scott (written commun., 1983) near the southern distal edge of this flow, some 6.5 km south of the mapped area in the SW¼NW¼ sec. 13, T. 26 N., R. 25 E. A Pliocene age of 3.3 ± 0.15 m.y. was determined on a whole-rock sample by the K-Ar method.

Basalts are common in Colfax and Union Counties in northeastern New Mexico, and Collins (1949, p. 1023) estimated that in this area more than 1,800 km^2 is overlain by basalt flows. The basalts originated from many different sources over a period of about 7 million years. The youngest flows are the basalt flows from Capulin Mountain, 25 km northeast of the northeast corner of the area. Carbon isotopic dating has established that these flows were erupted between 8,000 and 2,500 years before present (B.P.) (Baldwin and Muehlberger, 1959, p. 156). Stormer (1972, p. 2445) dated five other basalts from Colfax and Union Counties by the K-Ar method. His dates indicated at least four other periods of extrusion ranging from 1.8 to 7.2 million years B. P.

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FIGURE 8.—Piles of basalt form a small ridge west of The Crater in the southeast corner of the area.

The basalt is a black vesicular rock. Vesicles make up as much as one-third of the rock. They are round to oval, and the oval ones are generally alined parallel to the direction of flow. They range in size from less than a millimeter to several centimeters. Some of the vesicles are filled or partially filled with chalcedony and calcite. Small pheonocrysts—a millimeter or less in size—make up 5–25 percent of the rock. They consist chiefly of pale-brown glassy olivine and in some places a few percent of smaller subhedral augite crystals. The olivine has numerous conchoidal fractures, and it commonly alters along these fractures and along grain boundaries to bright-orange iddingsite. The matrix is generally fine grained and consists of 40–60 percent plagioclase, 15–35 percent augite, 5–15 percent magnetite, and 4–10 percent of olivine or iddingsite. Plagioclase in the groundmass occurs as rectangular-shaped microlites and interstitial patches. Augite occurs as pale-green faintly pleochroic prismatic crystals that are found in between the plagioclase laths. Olivine may be partly or completely altered to iddingsite.

A chemical analysis of a sample of basalt collected on the lower south flank of Laughlin Peak at the northernmost exposure shown on plate 1 is given in table 1 (No. 13). The basalt contains less SiO_2, Na_2O, and K_2O and more CaO, MgO, and FeO than any other rocks in the Laughlin Peak area. The very low silica content is also shown by the presence of olivine and a small amount of nepheline in the norm. This analysis is similar to that of several basalts reported near Raton (Lee, 1922, p. 11).

UNCONSOLIDATED DEPOSITS (QUATERNARY)

TERRACE GRAVELS

Terrace gravels are found only in the northwest corner of the mapped area (pl. 1). The terrace gravels form smooth high level benches and consist of well-rounded pebbles and cobbles mixed with sand and soil. The pebbles are principally gray-and-red rhyodacite from Laughlin Peak and olive-green phonolite. A few are also of tan trachyte and of dark-gray limestone from the Greenhorn Formation. Although the terrace gravels in this area lie astride Tinaja Creek, these gravels were not derived from the headwaters of this valley. Most of the gravels came from the northwest flank of Laughlin Peak and were brought down the drainage shown on plate 1 just below the northern border of the map. This subsidiary stream to present day Tinaja Creek was once a much larger stream, judging from the amount and size of the debris.

LANDSLIDE DEPOSITS

Landslides are fairly common in the Laughlin Peak area. They are formed where thick units of resistant rock overlie a soft shaly unit. These conditions occur north and northeast of Tinaja Creek, where a thick layer of phonolite that forms a prominent ledge overlies the soft incompetent shale of the Carlile Shale; along the headwaters of Tinaja Creek, where massive basalt

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flows overlie the incompetent Graneros Shale; and in the southwest part of the area, where the upper massive sandstone layer of the Dakota Sandstone overlies shale in the central part of the Dakota. Landslide deposits form a continuous belt below the phonolite ledge from near the east edge of the area to Jimmy Spring Creek, a distance of 5 km. These deposits may be as much as 640 m broad. Landslides below the basalt and the Dakota Sandstone are smaller. The maximum breadth of the former is only about 140 m and that of the latter about 370 m. All the landslides are marked by a hummocky surface, and little hillocks containing jumbled pieces of the competent rock type are common. Landslide deposits in the upper part of Jimmy Spring Canyon form chaotic topography consisting of broken ledges of phonolite. The upper ends of some of the landslides are marked by arcuate scarps. One of the best examples is in the basalt along Tinaja Creek at the east edge of the area, where an arcuate scarp is outlined by the topography (pl. 1). This small landslide, which is only 150 m wide, has dropped only about 12 m.

COLLUVIUM

Colluvium, as used here (pl. 1), consists of several types of unconsolidated sediments that cover the sides and flanks of various mountains. Mainly it is a mixture of talus and sediments deposited by sheet wash. It was mapped in three areas: south and west flanks of Laughlin Peak, around Raspberry Mountain, and near the head of Slagle Canyon on the lower slopes of Raspberry Mountain. The area on the south and west flanks of Laughlin Peak is part of a much larger area that completely surrounds this peak. Within the mapped area it ranges in width from 980 to 1,980 m, but on the north side of Laughlin Peak it extends down the mountain for at least 3,200 m. All the material here has been derived from the rhyodacite on Laughlin Peak and consists of soil intermixed with subrounded to subangular clasts of gray-and-red aphanitic rhyodacite. Some of the clasts may be as much as 1 m across. Much of the material was derived high on Laughlin Peak, has been carried many meters down the mountain, and now covers other sedimentary and igneous rocks. Water courses cutting into it on the lower slopes of Laughlin Peak indicate that some of it is at least 12 m thick.

The colluvium at the head of Slagle Canyon is derived by slope wash from the hills on the southwest flank of Raspberry Mountain. Clasts are all derived from the light-tan trachyte that makes up the adjacent hills. Subangular to subrounded trachyte pieces, of all sizes up to 0.5 m across, are found here intermixed with soil.

The colluvium surrounding Raspberry Mountain is a fairly narrow band, 50–300 m wide, consisting of talus derived from the rhyodacite on Raspberry Mountain. This material is mainly a jumble of angular pieces as much as several meter across, but the colluvium contains some soil.

ALLUVIUM

Alluvium includes various unconsolidated sediments formed in Holocene time along stream valleys. It occurs where the stream gradient lessens, thereby allowing the sediment to settle out. Areas of alluvium occur along the valleys of Tinaja Creek, Rio del Plano, and that of an upland drainage 1 km northeast of Tinaja Creek. In the Laughlin Peak area alluvium consists of a mixture of soil with sand, gravel, and boulders. Boulders along Tinaja Creek are subrounded to subangular and consist principally of olive-green phonolite, red or gray rhyodacite of Laughlin Peak, and brown Dakota Sandstone. Near the western border of the area brown trachyte boulders are also found. Boulders along Rio del Plano are mainly of Dakota Sandstone. Coarser material most commonly is found along the present stream drainage. These sediments, which are formed during short periods of stream runoffs, are generally poorly sorted.

STRUCTURE

The structure of the Laughlin Peak area is marked by gently dipping sedimentary rocks, and small crisscrossing faults. The attitude of the sedimentary rocks was modified in local areas by the intrusion of numerous bodies of igneous rocks. This is best illustrated in sec. 36, in the northwest corner of the mapped area, where trachyte dikes and sills have distorted the predominately shaly Graneros, Greenhorn, and Carlile Formations so that their beds strike in almost every direction. The more competent Dakota Sandstone does not appear to be as affected by the intrusions, but the presence of crossbedding in many layers commonly makes accurate measurement of bedding attitudes difficult. The Dakota is, however, by far the best exposed sedimentary unit in the area, and the overall structure can be best seen in the outcrop of this formation.

A broad east-west-trending anticline (pl. 1) is the only major fold in this area. In the western part of the area, the top of a broad ridge lies about 0.5 km south of the crest of this anticline. From here the Dakota Sandstone can be traced down dip to the north for about 2 km to Tinaja Creek and to the south for about 1.7 km to Slagle Canyon. To the east the fold is hidden by a trachyte sill, but near the west edge of Raspberry Mountain the fold is offset by a steep-dipping north-northeast-trending fault. The anticline is offset approximately 1.3 km to the northeast, where

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it lies along the hillside on the south side of Tinaja Creek.

Faults were mapped principally in the west-central part of the area. They strike in most directions; the area is too small to determine if there is any overall significance to the pattern of faulting. Dip exposures on the faults are rare, but the trace of the faults suggest that most are steeply dipping. Horizontal offset along them ranges from about 12 m to 1.3 km. Vertical offset is generally not large and in many is from 30 to 75 m. The faults cut and are, therefore, younger than the Dakota, Graneros, and Greenhorn Formations, and the trachyte and trachyandesite igneous units. They do not offset either the basalt or phonolite. The faults probably formed in the late Tertiary and may have been a result of adjustment during volcanism. Not all the faults formed at exactly the same time, as is evidenced by a long northeast-trending fault that offsets a northwest-trending fault approximately 140 m near the west edge of sec. 12 (pl. 1).

THORIUM- AND RARE-EARTH-BEARING VEINS

Known thorium- and rare-earth-bearing veins are scattered over an area of approximately 12 km^2. Many occur either in or adjacent to the large trachyte sill on Raspberry Mountain; a few occur in or adjacent to the trachyte sill that lies along the western border of the area, south of Tinaja Creek (pl. 1). The veins lie along fracture zones and consist of either one large vein or a series of parallel smaller veins lying in the same fracture zone. Veins were noted at 29 localities (pl. 1). The veins were given numbers for the purpose of identification. Number 1 is the northwestmost vein and 29 the southernmost vein.

Where present, exploration generally consists of a few small pits. The most development work has been on vein No. 27, which has six pits along it. The next most developed vein, No. 4, was exposed by a shallow shaft (now filled with silt) and some drilling, where it crossed Tinaja Creek, and by another small shaft near its east end. Some veins, such as Nos. 2, 5, 8, 9, 10, 11, 13, 14, 15, 18, and 20, have not been explored. These veins, which commonly are covered by a thin soil cover, were found with a scintillation counter.

Veins cut trachyte, Dakota Sandstone, intrusive breccia, and trachyandesite. Most are in trachyte and Dakota Sandstone (table 3). None have been found in the Graneros Shale. Vein No. 4, however, cuts a shale unit in the Dakota Sandstone, and the apparent lack of veins in the Graneros may be due to the paucity of outcrops rather than a lack of veins. The occurrence of veins in intrusive breccia is of particular interest as this rock type makes up only a small percentage of the total exposed rocks. Veining here is generally confined to one or more fractures within the intrusive breccia body. The overall radioactivity of some intrusive breccia bodies is slightly greater than that of the surrounding country rock. Other intrusive breccia bodies, however, are not anomalous.

The known length of the 29 veins ranges from 0.5 to 550 m. More than half of them are 30 m or less in length (table 3). Although some of these veins are undoubtedly quite short, others could be longer. Vein No. 4 is exposed at several places over a strike length of 550 m. Exposures on this vein occur at the east and west ends and near the center.

The thickness of the veins ranges from 0.2 to 70 cm (table 3). The thickness of vein No. 27 is best known, as it is cut by six trenches. This vein varies from 20 to 48 cm in thickness. The thicknesses of about half the veins are poorly known, because their presence is traced only by radioactive zones in the soil.

The attitude of the individual veins considerably, but three-fourths of the veins strike between N. 30° W. and N. 85° W. The most common strike direction of the veins is parallel to that of some of the early faults in this area. Northeast-trending veins are most common where the host rock is intrusive breccia. The veins in intrusive breccias commonly cut across the trend of the intrusive breccia body.

TABLE 3.—*Host rock, dimensions, and attitudes of the veins in the Laughlin Peak area*

[N. D., not determined]

Location No.	Vein type	Host rock	Exposed length (m)	Thickness (cm)	Strike	Dip
1	Single--	Trachyte--------	180	20	N. 50° W.	90°
2	--do---	-------do-------	9	N.D.	N. 65° W.	N.D.
3	Multiple	Dakota Sandstone	15	0.2-0.4	N. 58° W.	73° SW.
4	Single--	-------do-------	550	15-40	N. 85° W.	77° SW.-90°
5	--do----	Trachyte--------	6	N.D.	N. 85° W.	Steep
6	Multiple	Dakota Sandstone	3	N.D.	N. 60° W.	86° NE.
7	Single--	Intrusive breccia	38	15	N. 7° E.	Steep
8	--do----	Dakota Sandstone	9	N.D.	N. 72° W.	78° NE.
9	--do----	-------do-------	9	15	N. 74° W.	N.D.
10	--do----	Trachyandesite--	30	20	N. 55° W.	N.D.
11	--do----	-------do-------	27	N.D.	N. 52° W.	N.D.
12	--do----	Intrusive breccia	46	3	N. 30° W.	84° SW.
13	--do----	Trachyte--------	12	N.D.	N. 30° W.	N.D.
14	--do----	Intrusive breccia	3	N.D.	N. 66° E.	N.D.
15	Multiple	Trachyte--------	215	1-70	N. 75° W.	N.D.
16	Single--	-------do-------	60	30	N. 72° W.	80° NE.
17	--do----	-------do-------	15	15	N. 50° W.	90°
18	--do----	-------do-------	45	N.D.	N. 82° E.	N.D.
19	--do----	Intrusive breccia	9	30	N. 60° E.	N.D.
20	--do----	Dakota Sandstone	45	N.D.	N. 33° W.	N.D.
21	--do----	-------do-------	.5	N.D.	N.D.	N.D.
22	--do----	-------do-------	3	2.5	N. 76° W.	N.D.
23	--do----	Trachyte--------	45	N.D.	N. 78° W.	N.D.
24	--do----	-------do-------	6	N.D.	N. 35° W.	N.D.
25	--do----	-------do-------	9	45	N. 54° W.	83° SW.
26	--do----	-------do-------	36	15	N. 28° E.	Steep
27	--do----	-------do-------	165	20-48	N. 70° W.	64° NE.-90°
28	--do----	-------do-------	3	N.D.	N. 70° W.	N.D.
29	--do----	Dakota Sandstone	11	N.D.	N. 68° E.	N.D.

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The dip of many of the veins could not be determined owing to poor exposures. Those that were exposed dip steeply from 64° to 90°. Dips show some variation along the same vein; in the best exposed vein (No. 27), dips range from 64° to 90°.

MINERALOGY

Twenty-nine minerals were found in a detailed examination of 26 samples (table 4). Some of them occur in minor quantities in only a few samples. Mineral abundance varies considerably from sample to sample, notably in the principal gangue minerals—potassium feldspar, quartz, and calcite. Only 12 minerals occur in more than one-fourth of the samples: the three principal gangue minerals plus goethite, magnetite, a manganese oxide mineral, barite, brockite, crandallite, xenotime, zircon, and rutile. Other minerals may occur in some veins but were either not present in the samples taken or were too fine grained to be separately discerned under the binocular microscope. The various minerals are commonly fine grained and in places stained with iron oxides. Few minerals are identifiable in hand specimens. In order to identify the minerals, they were separated from each other by routine heavy-liquid and magnetic-separation procedures. They were then examined under a binocular microscope, and any mineral not readily identifiable by this method was picked out and identified by X-ray diffraction pattern.

The veins occur in brecciated country rock and commonly contain inclusions of it. Some of the minerals in the veins are probably derived from the country rock. Thus, the small amounts of amphibole, pyroxene, and micas found in a few of the samples probably were derived from this source. Other minerals, such as potassium feldspar and quartz, occur both in the country rocks and as a part of the vein filling.

The suite of thorium and rare-earth minerals in these veins is unusual when compared with that of veins in other thorium and rare-earth districts. In the Laughlin Peak area this suite is made up of brockite ($(Ca,Th,Ce)PO_4 \cdot H_2O$), crandallite ($(Ca,Sr,Ce)Al_3(PO_4)_2(OH)_6$), and xenotime ($YPO_4$). In most other thorium-vein districts in the United States, such as the Lemhi Pass district of Idaho and Montana (Staatz, 1979, p. A44–A45), Hall Mountain, Idaho (Staatz, 1972, p. 246), Wet Mountains, Colorado (Staatz, 1974, p. 498), and Powderhorn district, Colorado (Olson and Hedlund, 1981, p. 22), thorite is the principal thorium-bearing mineral and monazite is commonly abundant. Brockite has been found in some veins in these districts, but it is not common in any district. In the Laughlin Peak district neither thorite nor monazite have been identified.

Brockite is the most common thorium or rare-earth mineral in the Laughlin Peak area. It has been identified in six of the veins (Nos. 4, 7, 11, 12, 27, and 28). Here it is a white, fine-grained, opaque mineral. In many places it may be tan or light orange owing to iron oxide staining. In some veins it is intergrown with xenotime. Brockite-bearing veins here all have more yttrium-group rare earths than cerium-group rare earths. This has also been found true in brockite-bearing veins in the Lemhi Pass district, Idaho–Montana (Staatz, 1979, p. A45) and the Bear Lodge Mountains, Wyo. (Staatz, 1983, p. D41). Although brockite is not a common mineral, it is most common in thorium-bearing veins and has been found in veins in the following areas: Wet Mountains, Colo. (Fisher and Meyrowitz, 1962); Lemhi Pass, Idaho and Montana (Staatz, 1979, p. A44); Bear Lodge Mountains, Wyoming (Staatz, 1983, p. D34–D36); Diamond Creek district, Idaho (Staatz, 1974, p. 498); Monroe Canyon, Utah (Staatz, 1974, p. 498); Hicks Dome, Ill.; and the Rawhide Mountains, Ariz.

Crandallite has been identified in four veins (Nos. 1, 4, 16, and 27), and in three of these veins (Nos. 1, 4, and 16) it is the principal thorium and rare-earth mineral. In general, it is not found with either brockite or xenotime. Crandallite forms aggregates of white to cream-colored rhombic crystals, although it may be stained yellow or brown by goethite. Crandallite is a member of the crandallite group of isostructural hydrous aluminum phosphate minerals that have an ideal chemical formula of $XAl_3(PO_4)_2(OH)_6$ (Lefebvre and Gasparrini, 1980, p. 301), where X is predominantly calcium in crandallite, strontium in goyazite, rare earths in florencite, barium in gorceixite, and lead in plumbogummite. Being isostructural, all have similar X-ray diffraction patterns. In the Laughlin Peak area this mineral was determined to be a member of the crandallite group by its X-ray pattern. The composition of this phosphate mineral separated from vein No. 4 was obtained by semiquantative spectrographic analysis (table 5). This mineral contained 100,000 parts per million (ppm) strontium, 70,000 ppm calcium, 38,900 ppm total rare earths, 3,000 ppm barium, and 300 ppm lead. In addition, it also contained 20,000 ppm thorium, which probably proxies for the rare earths. The molecular amount of each end member in this mineral is approximately as follows: 53 percent of the calcium member, crandallite; 34 percent of the strontium member, goyazite; 12 percent of the rare earth and thorium member, florencite; 0.7 percent of the barium member, gorceixite; and 0.04 percent of the lead member, plumbogummite. In the florencite molecule there are about four parts total rare earths to one part thorium. The mineral is called crandallite after its principal constituent. The

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TABLE 4.—*Mineralogy of the veins in the Laughlin Peak area*

[Minerals underlined were identified by their X-ray diffraction pattern]

Loc. No.	Number of samples examined	Minerals -- relative amounts			
		Large	Moderate	Small	Rare
1	1	Potassium feldspar--	Goethite--	Hematite, manganese oxide mineral, calcite, jarosite, barite, crandallite.	Nacrite.
4	5	Quartz------	Potassium feldspar, goethite, crandallite.	Jarosite, calcite, barite, brockite.	Magnetite, lepidocrocite, zircon, fluorite, rutile, clay, biotite, hematite, manganese oxide mineral.
6	1	Quartz-----	Goethite---	Magnetite---	Zircon, manganese oxide mineral, pyroxene.
7	1	Potassium feldspar, quartz.	Goethite---	Pyrite, brockite, barite.	Magnetite, rutile?, zircon.
10	1	Calcite, quartz.	Manganese oxide mineral, goethite, barite.		Magnetite, xenotine(?).
11	1	Potassium feldspar	Brockite, xenotime.	Quartz, barite, goethite.	Magnetite, biotite, amphibole, pyrite.
12	3	Potassium feldspar	Quartz, goethite, xenotime.	Barite, brockite	Magnetite, zircon, rutile, thorite, plagioclase, mucovite, pyrite, anatase, amphibole.
16	1	Calcite----	Goethite, potassium feldspar, barite, quartz(?).	Crandallite--	Magnetite.
19	1	Quartz-----	Nacrite, goethite	Calcite, rutile, xenotime(?), anatase, barite.	Magnetite, zircon.
22	1	Quartz-----	Barite, goethite	Amphibole, zircon	Magnetite, rutile, spinel, pyroxene, mica, epidote.
25	1	Potassium feldspar	Goethite, cryptomelane, xenotime, barite.	Quartz-----	Magnetite.
26	1	Potassium feldspar	Goethite-----	Magnetite, manganese oxide mineral.	Amphibole, zircon.
27	6	Potassium feldspar	Quartz, goethite, brockite, xenotime.	Manganese oxide mineral, plagioclase.	Magnetite, hematite, apatite, zircon, biotite, anatase, fluorite, crandallite, thorianite-uraninite.
28	2	Potassium feldspar	Quartz-----	Manganese oxide mineral, brockite, goethite.	Magnetite, zircon, fluorite.

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TABLE 5.—*Semiquantitative spectrographic analysis of crandallite from vein No. 4*

[Analyst: N. M. Conklin; <, less than value indicated; >, greater than value indicated. Other elements looked for but below the limits of measurement are As, Au, B, Bi, Cd, Co, Ge, Hf, In, Li, Mo, Ni, Pd, Pt, Re, Sb, Sc, Ta, Te, U, W, and Zn]

	In percent		
Aluminum	>10	Potassium	<2
Calcium	7.0	Silicon	0.3
Iron	0.7	Sodium	0.1
Magnesium	0.05	Titanium	0.15
Phosphorus	>10		

	In parts per million		
Barium	3,000	Lanthanum	7,000
Beryllium	300	Cerium	15,000
Chromium	70	Praesodymium	3,000
Copper	150	Neodymium	7,000
		Samarium	1,500
Gallium	30		
Lead	300	Europium	150
Niobium	500	Gadolinium	700
Strontium	100,000	Terbium	<200
		Dysprosium	700
Thorium	20,000	Holmium	150
Tin	30		
Vanadium	150	Erbium	300
Zirconium	300	Thulium	70
Total rare earths	38,900	Ytterbium	300
		Lutetium	30
		Yttrium	3,000

rare earths in the crandallite are principally the cerium group (light rare earths), comprising 87 percent of the total rare earths. The distribution of the lanthanides in the Laughlin Peak crandallite is shown in figure 9. This distribution pattern might be called the normal distribution pattern as it is quite similar to that found in crustal abundance (Staatz and others, 1976, p. 580). Crandallite is a rare mineral in the thorium veins in the United States. Only at Hicks Dome in Illinois has another member of the crandallite group been reported; a veined breccia exposed in a small trench contained florencite (Trace, 1960, p. B63).

Worldwide, xenotime is by far the most abundant mineral made up principally of the yttrium group of rare-earths minerals. In the Laughlin Peak area, xenotime occurs in six veins (Nos. 10, 11, 12, 19, 25, and 27). The xenotime here is a white to tan, very fine grained opaque mineral that resembles brockite. Although in the Laughlin Peak area xenotime commonly occurs with brockite, it is rarely associated with crandallite. The xenotime is probably associated with brockite because the rare earths in both these minerals belong principally to the yttrium group; whereas, the rare earths in crandallite belong principally to the cerium group.

The iron oxide minerals, goethite and hematite, are relatively rare in the Laughlin Peak area; hematite is but a minor constituent and goethite, although present, rarely makes up more than a few percent of any sample. These two minerals, however, make up a major part of many thorium veins in the Lemhi Pass district, Idaho and Montana; Wet Mountains, Colo.; Powderhorn district, Colorado; Bear Lodge Mountains, Wyo.; and Rawhide Mountains, Ariz. Goethite in the Laughlin Peak area comes in several color and textural varieties. In most places it is dark brown and granular, but even in the same sample some may have a brown shiny or a light-yellowish-brown vesicular appearance. This mineral commonly coats the surface of other minerals imparting a brown to yellow color. Black manganese oxide minerals occur here in about a third of the samples; in none of them is it abundant. Most of the manganese oxide minerals formed late as evidenced by their coating fractures within the veins. These minerals form thin dull-black crusts, some of which are botryoidal. X-ray diffraction patterns of the manganese oxides were commonly diffuse, and in most patterns the particular manganese oxide could not be identified. Only one X-ray pattern was sufficiently distinct to identify the particular manganese oxide mineral as cryptomelane.

Barite, found in half the samples, is common in most thorium vein districts. The barite content of the Laughlin Peak samples does not exceed 1 percent, and in some samples barite is quite rare. Barite generally occurs as clear platy crystals. In vein No. 4 it is also found as small, white, opaque nodules.

Rutile is found in minor amounts in about a third of the samples, either as dull black granular aggregates or as small black shiny crystals. Zircon occurs as tiny

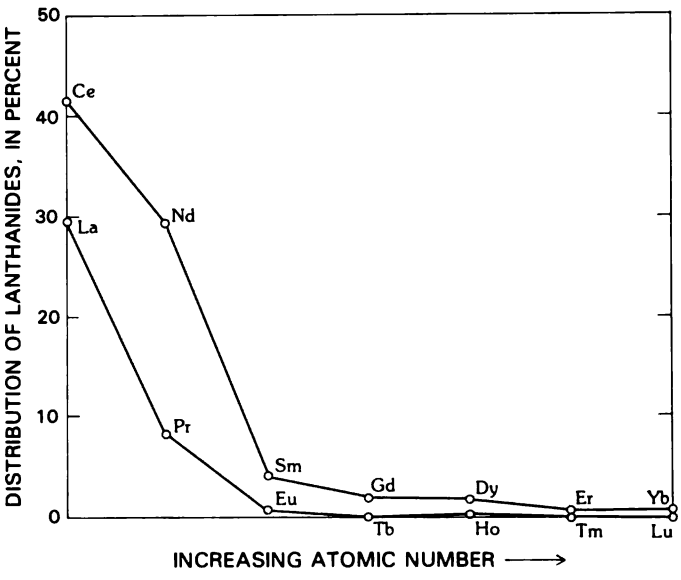


FIGURE 9.—Graph showing distribution of lanthanides in crandallite from vein No. 27 in the Laughlin Peak area. Upper line, even atomic-numbered lanthanides; lower line, odd atomic-numbered lanthanides. The elements are so arranged that pairs of lanthanides that are adjacent in the periodic table fall on the same ordinate.

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TABLE 6.—*Chemical analyses of samples from veins in the Laughlin Peak area*

[Symbols: N.D., not determined, <, less than the value indicated]

Vein No.--	1			4			6	7		10	11		12		16
Sample No.--	MHS-27-80	CH-9-64	CH-10-64	Ch-7-73	CH-8-73	MHS-4-80	MHS-8-80	CH-12-64	CH-6-73	MHS-63-80	MHS-65-80	CH-11-64	CH-3-73	MHS-16-80	MHS-23-80
Element	In parts per million														
Thorium	a181	b500	b5,000	a30	a2,905	a5,140	a620	b3,600	a1,885	a3,870	a14,000	b1,200	a7,000	a8,330	a1,890
Uranium	a10	b<10	b50	a8	a50	a37	N.D.	b10	a8	N.D.	N.D.	b10	a40	a46	a44
Lanthanum	c70	d220	d1,100	N.D.	c700	c1,500	N.D.	d90	N.D.	c1,500	c150	d140	c150	c300	c7,000
Cerium	c<150	c500	d2,400	N.D.	c1,500	c1,500	N.D.	c<200	N.D.	c2,000	c300	c200	c500	c300	c7,000
Praesodymium	c<100	c<100	c<100	N.D.	c200	c200	N.D.	c<100	N.D.	c200	c<100	c<100	c<100	c<100	c700
Neodymium	c<70	c150	d1,100	N.D.	c700	c1,000	N.D.	c50	N.D.	c700	c150	c100	c200	c300	c3,000
Samarium	c<100	c<100	c300	N.D.	c150	c300	N.D.	c<100	N.D.	c150	c<100	c<100	c<100	c150	c300
Europium	c<70	c<100	c<100	N.D.	c<70	c70	N.D.	c<100	N.D.	c<70	c<70	c<100	c<70	c<70	c70
Gadolinium	c<50	c<100	c150	N.D.	c70	c150	N.D.	c200	N.D.	c<100	c500	c<100	700	c500	c100
Terbium	c<300	c<300	c<300	N.D.	c<300	c<300	N.D.	c<300	N.D.	c<300	c150	c<300	c150	c<300	c<300
Dysprosium	c<50	c<40	c200	N.D.	c100	c300	N.D.	c700	N.D.	c150	c1,500	c150	c1,500	c1,500	c70
Holmium	c<20	c<70	c100	N.D.	c30	c100	N.D.	c300	N.D.	c<50	c500	c<70	c500	c700	c<50
Erbium	c<50	c<40	c200	N.D.	c70	c200	N.D.	c500	N.D.	c<50	c1,500	c70	c1,000	c1,500	c<50
Thulium	c<20	c<100	c<100	N.D.	c<20	c70	N.D.	d300	N.D.	c<20	c150	c<100	c150	c200	c<20
Ytterbium	c7	d31	d220	N.D.	c100	c200	N.D.	d520	N.D.	c70	c1,000	d62	c1,000	c1,000	c70
Lutetium	c<30	c<100	c100	N.D.	c<30	c30	N.D.	c150	N.D.	c<30	c300	c<100	c150	c100	c20
Yttrium	c70	d190	d940	N.D.	c1,000	c2,000	N.D.	d3,100	N.D.	c700	c7,000	d520	c10,000	c10,000	c700
Total rare earths	147	1,091	6,810	N.D.	4,620	7,620	N.D.	5,910	N.D.	5,470	13,200	1,242	16,000	16,550	19,030
Barium	c1,000	d430	d420	N.D.	c500	c5,000	N.D.	d8,700	N.D.	c3,000	c3,000	d1,200	c3,000	c1,500	c30,000
Beryllium	c1.5	c15	c50	N.D.	c30	c7	N.D.	c3	N.D.	c3	c3	c5	c7	c3	c20
Copper	c15	c7	c30	N.D.	c20	c20	N.D.	c15	N.D.	c70	c30	c10	c15	c15	c150
Lead	c15	c10	c150	N.D.	c100	c70	N.D.	c50	N.D.	c100	c30	c50	c70	c70	c150
Manganese	c2,000	c70	c70	N.D.	c50	c150	N.D.	c70	N.D.	c7,000	c70	c50	c100	c150	c70
Molybdenum	c<3	c7	c7	N.D.	c20	c<3	N.D.	c5	N.D.	c7	c<3	c10	c15	c15	c<3
Niobium	c30	d180	d1,200	N.D.	c500	c300	N.D.	d360	N.D.	c150	c700	d490	c500	c300	c300
Strontium	c700	d860	d9,700	N.D.	c15,000	c3,000	N.D.	d88	N.D.	c7,000	c1,500	d1,000	c3,000	c3,000	c7,000
Zinc	c<200	c<300	c<300	N.D.	c<300	c<300	N.D.	c<300	N.D.	c<200	c<200	c<300	c<300	c<300	c<200
Zirconium	c150	c300	c300	N.D.	c500	c300	N.D.	c300	N.D.	c150	c1,500	c200	c1,500	c700	c150
	In percent														
Iron	c3	c.7	c1.5	N.D.	c1.0	c1.5	N.D.	c1.0	N.D.	c3	c1.5	c1.5	c1.5	c2.0	c7.0
Magnesium	c.07	c.02	c.3	N.D.	c.15	c.03	N.D.	c.05	N.D.	c.15	c.07	c.05	c.05	c.03	c.07
Phosphorus	c<.2	c.5	c3.0	N.D.	c1.5	c1.5	N.D.	c.5	N.D.	c1.5	c.7	c<.2	c.7	c.5	c1.5
Potassium	a2.2	c<.7	c2.0	N.D.	a1.9	N.D.	N.D.	c1.5	N.D.	N.D.	c3.0	c7.0	a5.0	c5.0	c3.0
Sodium	c.3	c<.05	c.7	N.D.	c.2	c.05	N.D.	c<.05	N.D.	c.07	c<.1	c0.7	c.5	c.3	c<.05

bipyramidal crystals in almost half the samples. These crystals may be pale purple, pale pink, white, or amber.

In addition, some 17 other minerals occur in a few veins in minor amounts (table 4). Some of these minerals, such as hematite, lepidocrocite, pyrite, muscovite, apatite, and fluorite, are commonly found in veins in other thorium districts, where, except for hematite, they occur only in minor amounts. The nacrite that occurs in some of these samples is probably an alteration product of feldspathoids from inclusions of country rock.

CHEMICAL COMPOSITION

The thorium content of 30 vein samples ranges from 30 to 24,200 ppm and in 18 samples exceeded 2,000 ppm (table 6). All analyses are from chip samples that were cut across the entire thickness of the vein. Thorium analyses were made by C. M. Bunker and C. A. Bush on a quantitative gamma-ray spectrometer. This method has an accuracy of ±3 percent. The highest thorium content comes from vein No. 27. The thorium content of eight samples taken along 165 m of this vein ranges from 1,800 to 24,200 ppm. Five samples were

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TABLE 6.—*Chemical analyses of samples from veins in the Laughlin Peak area*—Continued

Vein No.	19	22	25		26					27					28
Sample No.	MHS-52-80	MHS-55-80	CH-8-64	MHS-13-80	CH-7-64	MHS-12-80	CH-2-64	Ch-3-64	CH-4-64	CH-5-64	CH-9-73	CH-10-73	MHS-9-80	MHS-10-80	CH-11-73
Element	In parts per million														
Thorium	[a]114	[a]5,100	[b]2,200	[a]2,270	[b]500	[a]178	[b]8,600	[b]3,400	[b]2,900	[b]1,800	[a]2,970	[a]12,000	[a]24,200	[a]5,725	[a]1,790
Uranium	[a]60	[a]230	[b]<10	N.D.	[b]<10	[a]6.5	[b]10	[b]<10	[b]10	[b]10	[a]6	N.D.	N.D.	N.D.	[a]4.6
Lanthanum	[c]150	[c]300	[d]110	[c]150	[d]80	[c]150	[d]270	[d]220	[d]300	[d]130	[c]150	[c]300	[c]300	[c]150	N.D.
Cerium	[c]150	[c]700	[c]150	[c]200	[c]200	[c]200	[c]300	[c]300	[c]200	[c]200	[c]<150	[c]300	[c]300	[c]150	N.D.
Praesodymium	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	N.D.
Neodymium	[c]70	[c]500	[c]50	[c]150	[c]50	[c]70	[c]300	[c]150	[c]150	[c]70	[c]150	[c]300	[c]300	[c]150	N.D.
Samarium	[c]<100	[c]150	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	[c]<100	N.D.
Europium	[c]<70	[c]<70	[c]<100	[c]<70	[c]<100	[c]<70	[c]<100	[c]<100	[c]<100	[c]<100	[c]<70	[c]<70	[c]<70	[c]<70	N.D.
Gadolinium	[c]<50	[c]150	[c]100	[c]70	[c]<70	[c]<50	[c]70	[c]70	[c]<70	[c]<70	[c]<50	[c]150	[c]150	[c]<50	N.D.
Terbium	[c]<300	[c]<300	[c]<300	[c]<300	[c]<300	[c]<300	[c]<300	[c]<300	[c]<300	[c]<300	[c]<300	[c]<300	[c]<300	[c]<300	N.D.
Dysprosium	[c]<50	[c]200	[c]200	[c]300	[c]<50	[c]<50	[c]300	[c]150	[c]100	[c]50	[c]70	[c]300	[c]700	[c]150	N.D.
Holmium	[c]<20	[c]70	[c]100	[c]70	[c]<70	[c]<20	[c]150	[c]70	[c]70	[c]<70	[c]30	[c]150	[c]300	[c]70	N.D.
Erbium	[c]<50	[c]150	[c]150	[c]150	[c]<50	[c]<50	[c]300	[c]150	[c]100	[c]<100	[c]70	[c]300	[c]700	[c]150	N.D.
Thulium	[c]<20	[c]20	[c]<100	[c]30	[c]<100	[c]<20	[c]150	[c]<100	[c]<100	[c]<100	[c]<20	[c]70	[c]150	[c]30	N.D.
Ytterbium	[c]5	[c]150	[d]160	[c]200	[d]8	[c]15	[d]360	[d]110	[d]110	[d]78	[c]100	[c]700	[c]700	[c]150	N.D.
Lutetium	[c]<30	[c]20	[c]<100	[c]30	[c]<100	[c]<30	[c]100	[c]<100	[c]<100	[c]<100	[c]<30	[c]100	[c]70	[c]30	N.D.
Yttrium	[c]50	[c]1,500	[d]920	[c]2,000	[d]71	[c]150	[d]1,400	[d]800	[d]560	[d]460	[c]1,000	[c]5,000	[c]7,000	[c]1,500	N.D.
Total rare earths	425	3,910	1,940	3,350	409	585	3,700	2,020	1,590	988	1,570	7,670	10,670	2,530	N.D.
Barium	[c]1,500	[c]70,000	[d]2,300	[c]5,000	[d]540	[c]700	[d]900	[d]520	[d]710	[d]590	[c]700	[c]1,500	[c]1,500	[c]700	N.D.
Beryllium	[c]1.5	[c]3	[c]3	[c]2	[c]3	[c]1	[c]3	[c]2	[c]5	[c]2	[c]1.5	[c]3	[c]1.5	[c]1.5	N.D.
Copper	[c]30	[c]30	[c]5	[c]10	[c]3	[c]3	[c]15	[c]7	[c]7	[c]3	[c]5	[c]7	[c]15	[c]3	N.D.
Lead	[c]30	[c]1,500	[c]100	[c]150	[c]30	[c]30	[c]50	[c]50	[c]50	[c]50	[c]70	[c]70	[c]70	[c]30	N.D.
Manganese	[c]700	[c]70	[c]200	[c]1,500	[c]1,000	[c]700	[c]300	[c]100	[c]1,000	[c]1,000	[c]200	[c]150	[c]300	[c]1,500	N.D.
Molybdenum	[c]7	[c]70	[c]7	[c]5	[c]7	[c]<3	[c]10	[c]5	[c]5	[c]10	[c]7	[c]5	[c]<3	[c]7	N.D.
Niobium	[c]150	[c]150	[d]270	[c]70	[d]140	[c]70	[d]260	[d]330	[d]320	[d]180	[c]150	[c]150	[c]200	[c]150	N.D.
Strontium	[c]300	[c]1,500	[d]330	[c]700	[d]250	[c]700	[d]880	[d]380	[d]1,400	[d]280	[c]700	[c]3,000	[c]1,500	[c]700	N.D.
Zinc	[c]<200	[c]<200	[c]<300	[c]<300	[c]<300	[c]<300	[c]<300	[c]<300	[c]<300	[c]<300	[c]<200	[c]<200	[b]<300	[c]<300	N.D.
Zirconium	[c]700	[c]3,000	[c]200	[c]300	[c]500	[c]300	[c]300	[c]300	[c]300	[c]300	[c]300	[c]700	[c]700	[c]500	N.D.
	In percent														
Iron	[c]3.0	[c]1.5	[c]1.5	[c]3.0	[c]1.5	[c]1.5	[c]2.0	[c]1.5	[c]2.0	[c]2.0	[c]1	[c]1.5	[c]1.5	[c]1.5	N.D.
Magnesium	[c].03	[c].03	[c].07	[c].15	[c].07	[c].07	[c].15	[c].2	[c].3	[c].07	[c].1	[c].3	[c].15	[c].07	N.D.
Phosphorus	[c]<.2	[c].3	[c]<.2	[c]<.2	[c]<.2	[c]<.2	[c]<.2	[c]<.2	[c]<.2	[c]<.2	[c]<.2	[c].3	[c].5	[c]<.2	N.D.
Potassium	[a].25	[c]7.0	[c]5.0	[c]7.0	[c]5.0	[a]5.5	[c]5.0	[c]5.0	[c]5.0	[c]5.0	[a]5.0	[c]5.0	[c]3.0	[c]7.0	N.D.
Sodium	[c].05	[c].1	[c]0.7	[c]0.7	[c]5.0	[c]7.0	[c]3.0	[c]3.0	[c]3.0	[c]5.0	[c]3	[c]3	[c]3	[c]5	N.D.

[a]Analyzed by gamma-ray spectrometry by C. M. Bunker and C. A. Bush.

[b]Uranium analyzed chemically; thorium calculated from the chemical uranium and an eU value determined by beta-gamma scaler. Analysts: Lorraine Lee and G. T. Burrow.

[c]Analyzed by semiquantitative six-step spectrographic method by N. M. Conklin.

[d]Analyzed by quantitative spectrographic method by N. M. Conklin.

taken from the longest vein (No. 4), whose thorium content ranges from 30 to 5,140 ppm.

Rare-earth elements were determined by a semiquantitative spectrographic method. Results are identified within brackets whose boundaries are 1.2, 0.83, 0.56, 0.38, 0.26, 0.18, 0.12, and so forth, but are reported as midpoints between these brackets. Thus, the numbers reported would be 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, and so forth. The precision of a reported value is approximately plus or minus one bracket. The total rare-earth content of the 26 samples from 12 veins ranges from 147 to 19,030 ppm (table 6). Large differences in rare-earth content exist between veins, and the rare-earth content of individual veins also varies considerably. For example, the rare-earth content of eight samples taken from vein No. 27 ranges from 988 to 10,670 ppm.

The ratio of total rare earths to thorium in the

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Laughlin Peak veins ranges from 0.44 to 10. The total ratio of rare earth to thorium in 24 of the 25 samples measured has a much narrower range and is only from 0.44 to 3.26. These ratios tend to be fairly similar in the same vein, and the ratios of eight samples from vein No. 27 range only from 0.44 to 0.76.

The rare-earth metals comprise the 15 elements having atomic numbers 57 to 71, including lanthanum, cerium, praesodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. Yttrium, with atomic number 39, is also classed with the rare earths because of its chemical similarities and geochemical affinities. The first seven elements just listed (lanthanum through europium) are called the cerium-group rare earths, after their most common member. The remaining elements (gadolinium through lutetium) together with yttrium are called the yttrium-group rare earths. The two groups are also referred to respectively as the "light" and "heavy" rare earths. The cerium-group rare earths are by far the most common rare earths both in the Earth's crust (Taylor, 1964, p. 1281) and in most thorium- and rare-earth-bearing veins. In the Laughlin Peak area, however, yttrium-group rare earths are generally the most abundant (fig. 10). Seventeen of twenty-six samples have more yttrium-group than cerium-group rare earths. Yttrium-group rare earths are more abundant in some veins and cerium group in others. The ratio of yttrium-group rare earths to total rare earths in the 26 samples ranges from 0.05 to 0.98 The range in individual veins is much smaller: for example, eight samples from vein No. 27 have a range of from 0.59 to 0.92.

The relation between the cerium-group rare earths, yttrium-group rare earths, and thorium is shown in a triangular diagram (fig. 10). This plot shows that, although the amount of cerium-group to yttrium-group rare earths varies considerably between the samples taken, the majority of the samples are much richer in the yttrium-group rare earths. This diagram also shows that the thorium content tends to increase as the yttrium-group rare-earth content increases. Multiple samples from the same vein have generally similar compositions (fig. 10). Most analyses fall in a triangular area having vertices Ce_{100}, $Th_{80}Y_{20}$, $Th_{30}Y_{70}$—that is, thorium- and yttrium-group elements are closely associated, whereas cerium-group elements show a wide range including two or three that are cerium-rich.

The distribution of individual lanthanides in the veins can be shown using a plot originated by Semenov and Barinskii (1958, p. 416). In these graphs, one line connects the values of elements of even atomic number and the other line connects those of elements of odd atomic number. The elements are so arranged that pairs of the lanthanides that are adjacent in the periodic table fall on the same ordinate line. The ordinate represents the percent of each individual rare earth to the total lanthanides. Thus, the relative importance of various rare earths to one another is shown. Graphs were originally made from the analytical data (table 6) of all 26 samples. Four of these graphs showing typical distribution of the lanthanides in the veins of the Laughlin Peak area are shown in figure 11. Figure 11*A* shows the pattern of one of several samples from vein No. 4 and is typical of veins rich in cerium-group rare earths. Here, the cerium-group rare earths make up more than 80 percent of the total lanthanides. Other samples from this vein and samples from veins Nos. 10, 16, 19, 22, and 26 have similar patterns. Lanthanide patterns of samples in which the yttrium-group lanthanides are predominant are more diverse (figs. 11*B*–11*D*). In these samples the yttrium-group rare earths make up more than 50 percent of the total lanthanides. The most abundant lanthanide is generally dysprosium, but in some samples it is erbium or ytterbium. Yttrium, which is not shown on these graphs, is the most common yttrium-group rare earth, and in the 15 samples in which this group is dominant, yttrium makes up from 35 to 66 percent of the total rare earths.

In many districts it is difficult to correlate the rare-earth distribution with the mineralogy, because thorite and (or) monazite are abundant and are the principal sources of rare earths in the the veins. These minerals are not markedly selective in their acceptance of various rare-earth elements, and the proportions of the various rare earths in these minerals may vary considerably (Staatz and others, 1972, p. 75–77, 1976, p. 450; Staatz, 1983, p. D40–D41). The rare-earth minerals that occur in the Laughlin Peak district (xenotime, brockite, and crandallite), however, are fairly selective in the type of rare earths retained. Samples in which xenotime or brockite are common predominate in yttrium-group rare earths. On the other hand, samples in which crandallite is common predominate in cerium-group rare earths.

The uranium content of these radioactive veins is, in general, low; and in 23 samples where measurements were obtained, uranium ranges from 4.6 to 230 ppm (table 6). Fifteen of these samples contain 10 ppm or less of uranium, and only one sample has more than 60 ppm. The Th/U ratios of these samples range from 1.9 to 860. The two lowest Th/U ratios reflect low thorium contents, and the range in Th/U ratios, excluding the two samples that have less than 150 ppm Th, is from 18 to 860. The overall Th/U ratios for veins in this district is higher than that for veins found in the Lemhi Pass district, Idaho–Montana; Hall Mountain district, Idaho; Diamond Creek area, Idaho; Bear

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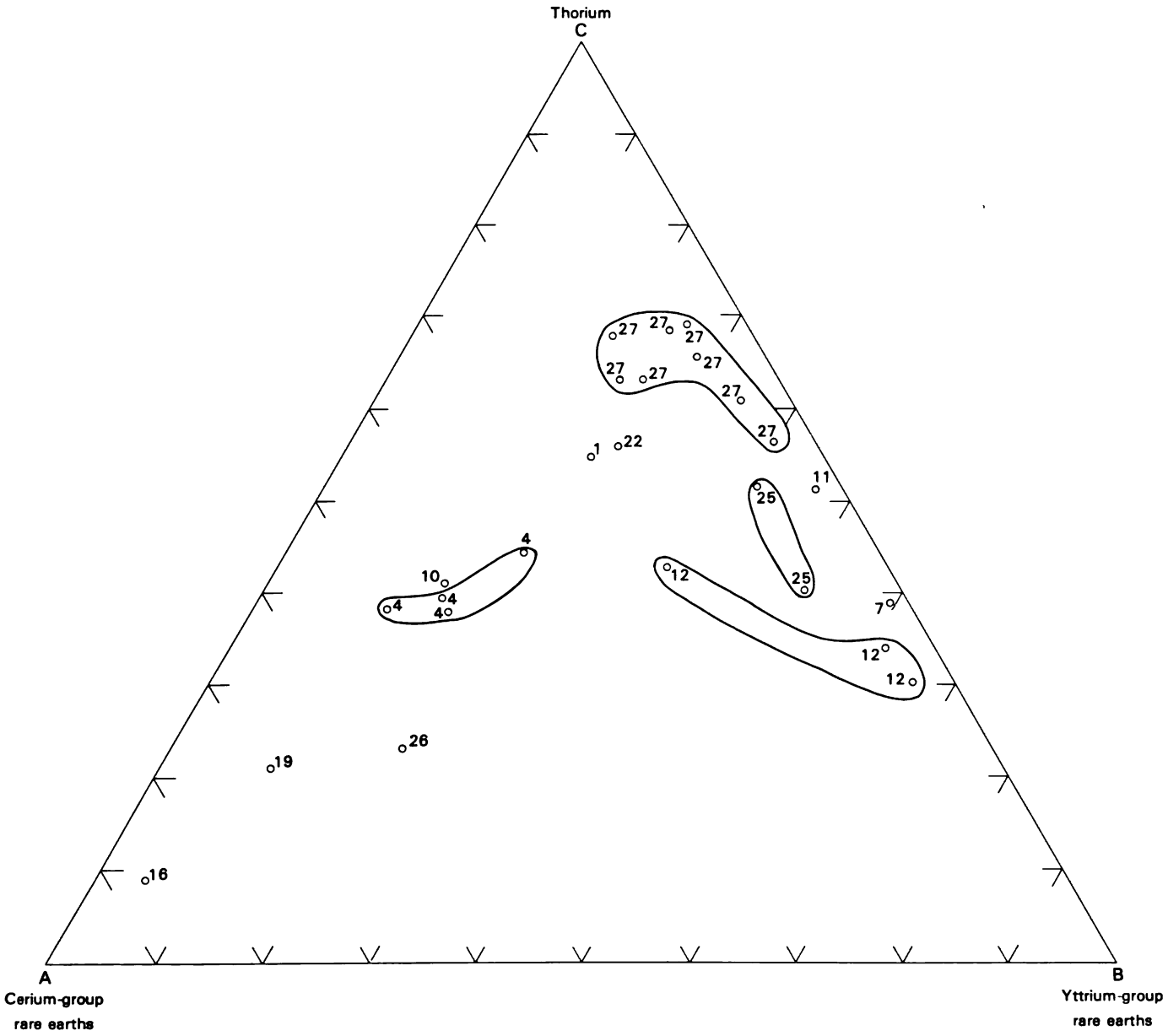


FIGURE 10.—Ternary diagram showing relation of thorium, cerium group of rare earths, and yttrium group of rare earths in veins from the Laughlin Peak area. Number on diagram indicates vein from which each sample came. Lines enclose all samples from the same vein.

Lodge district, Wyoming; Wet Mountains, Colo.; Mountain Pass district, California; or the Bokan Mountain area, Alaska.

Barium content of the 26 samples (table 6) ranges from 420 to 70,000 ppm. Its abundance is erratic among veins, and the greatest amounts of barium occur in veins Nos. 22 and 16. Barium occurs principally in the mineral barite. The amounts of barium in these veins are about the same as those found in the Bear Lodge Mountains, Wyo. (Staatz, 1983, p. D42), somewhat more than found in those of the Lemhi Pass district, Idaho and Montana (Staatz, 1979, p. A49), and considerably less than found in the veins of the Wet Mountains, Colo., where barite has been mined in the past (Christman and others, 1959, p. 527). The strontium content of the veins varies from 88 to 15,000 ppm. The most strontium occurs in samples from veins Nos. 4, 10, and 16. Strontium occurs principally in the mineral, crandallite, one sample of which contains 10 percent strontium (table 5). The veins of the Laughlin Peak area have one of the highest strontium contents of thorium-bearing veins in the United States. The

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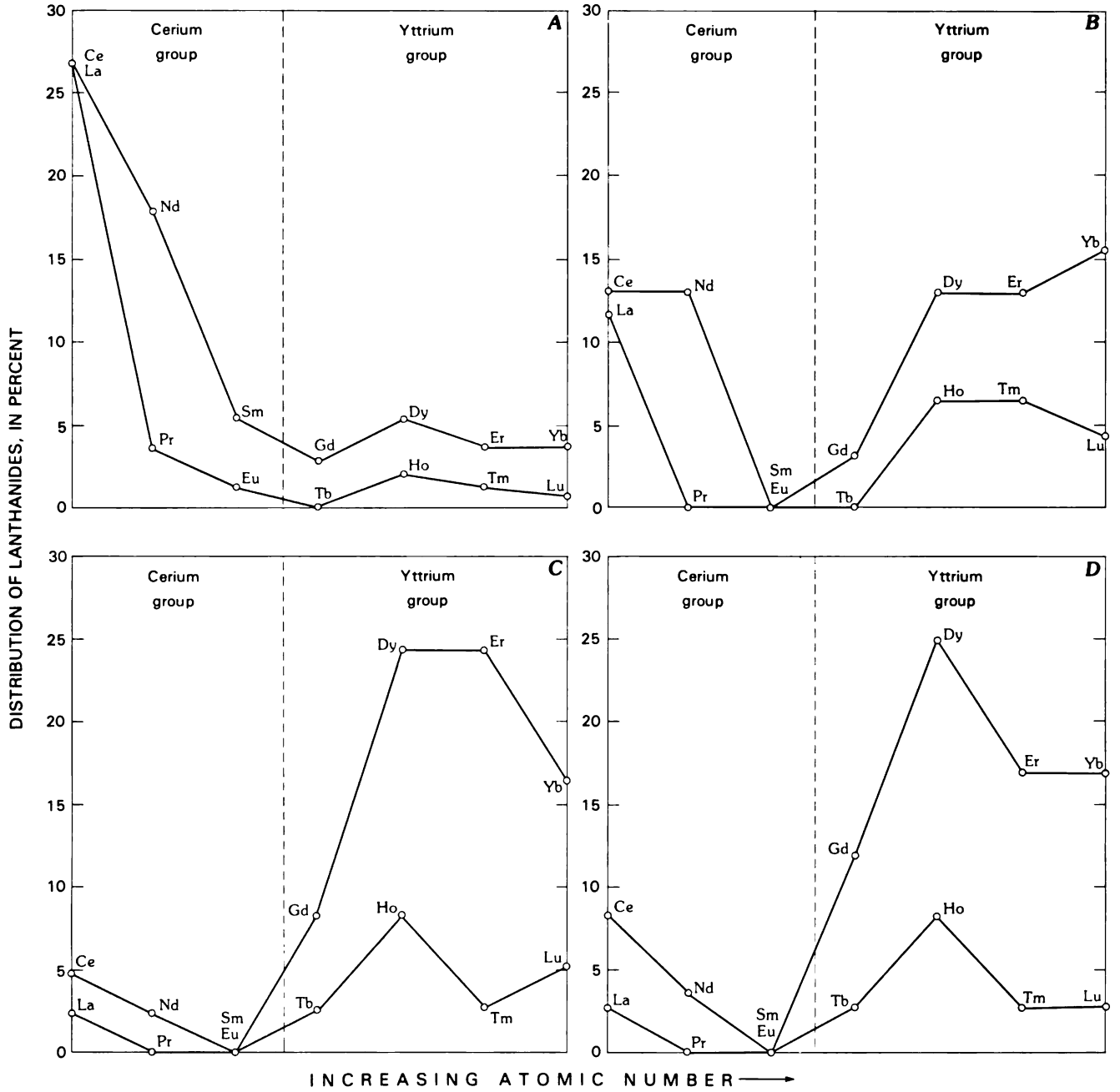


FIGURE 11.—Distribution of lanthanides in four samples from veins in the Laughlin Peak area. Upper line, even atomic-numbered lanthanides; lower line, odd atomic-numbered lanthanides.

A, Sample MHS–4–80 from vein No. 4.
B, Sample CH–2–64 from vein No. 27.
C, Sample MHS–65–80 from vein No. 11.
D, Sample CH–3–73 from vein No. 12.

niobium content of the samples ranges from 30 to 1,200 ppm. No niobium minerals have been found in any of the samples, so the niobium is probably in the titanium minerals—rutile or anatase. This range in niobium values is about half that found in the Lemhi Pass district (Staatz, 1979, p. A49) and the Bear Lodge district (Staatz, 1983, p. D42).

Iron and (or) manganese minerals are a major part of many thorium veins in other districts. The Laughlin Peak area differs from those other districts in low iron and manganese contents. Iron content of 26 samples (table 6) ranges from 0.7 to 7 percent. Iron content of 24 of the 26 samples, however, is in the range of from 1.0 to 3.0 percent. Thus, although the samples

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commonly are yellowish brown due to the presence of disseminated goethite, iron makes up only a minor amount of the total vein material. Manganese is even less abundant and ranges from 0.005 to 0.7 percent. Most of the manganese appears to be a late addition, as it most commonly occurs as black manganese oxides coating fracture surfaces.

Copper, lead, zinc, and molybdenum commonly occur in minor amounts in thorium veins in other districts. The veins in the Laughlin Peak area contain only scant amounts of these elements, and considerably less than found in veins of most other districts. Lead is the most common of these elements in the Laughlin Peak area and is found in amounts ranging from 10 to 1,500 ppm (table 6). All but one sample, however, contain 150 ppm or less of lead. Copper and molybdenum are less abundant; copper in most samples is in the 10–30 ppm range, and molybdenum in about three-quarters of the samples is 7 ppm or less. The limit of detection for zinc by semiquantitative spectrographic analysis varied from 200 to 300 ppm over the years the analyses were made. None of our samples contain this much zinc. No lead, copper, molybdenum, or zinc minerals have been identified in any of the samples.

ORIGIN

Thorium- and rare-earth-bearing veins are associated with alkalic rocks and carbonatites in many districts in the United States. Alkalic rocks are common in the Laughlin Peak area, and one small carbonatite dike has been found associated with alkalic rocks 2.7 km south of the mapped area in the western part of Joe Cabin Arroyo. In other areas in the United States the thorium veins are believed to have formed from fluids derived from a late-stage, volatile phase of the alkalic magma that formed the alkalic rocks (Staatz, 1974, p. 506).

The veins in the Laughlin Peak area cut the Dakota Sandstone and Graneros Shale of Cretaceous age and the trachyte, trachyandesite, and intrusive breccia of late Tertiary age. These rocks are all older than the faulting (pl. 1). Veins are not found cutting phonolite, rhyodacite, or basalt. Thus, it is likely that the veins were formed along fractures during volcanism after the trachyte and trachyandesite were intruded, but before the phonolite, rhyodacite, and basalt were emplaced. A logical source for the thorium and rare earths found in the veins is from the magma that formed the phonolite. Two samples of phonolite contained 139 and 111 ppm thorium (table 2), or at least five times the amount of thorium found in any other rock type. Rare earths also are concentrated here, and the same two samples contained 807 and 405 ppm total rare earths. Another line of evidence supporting the phonolitic magma as a source for the veins is that both were formed at approximately the same time.

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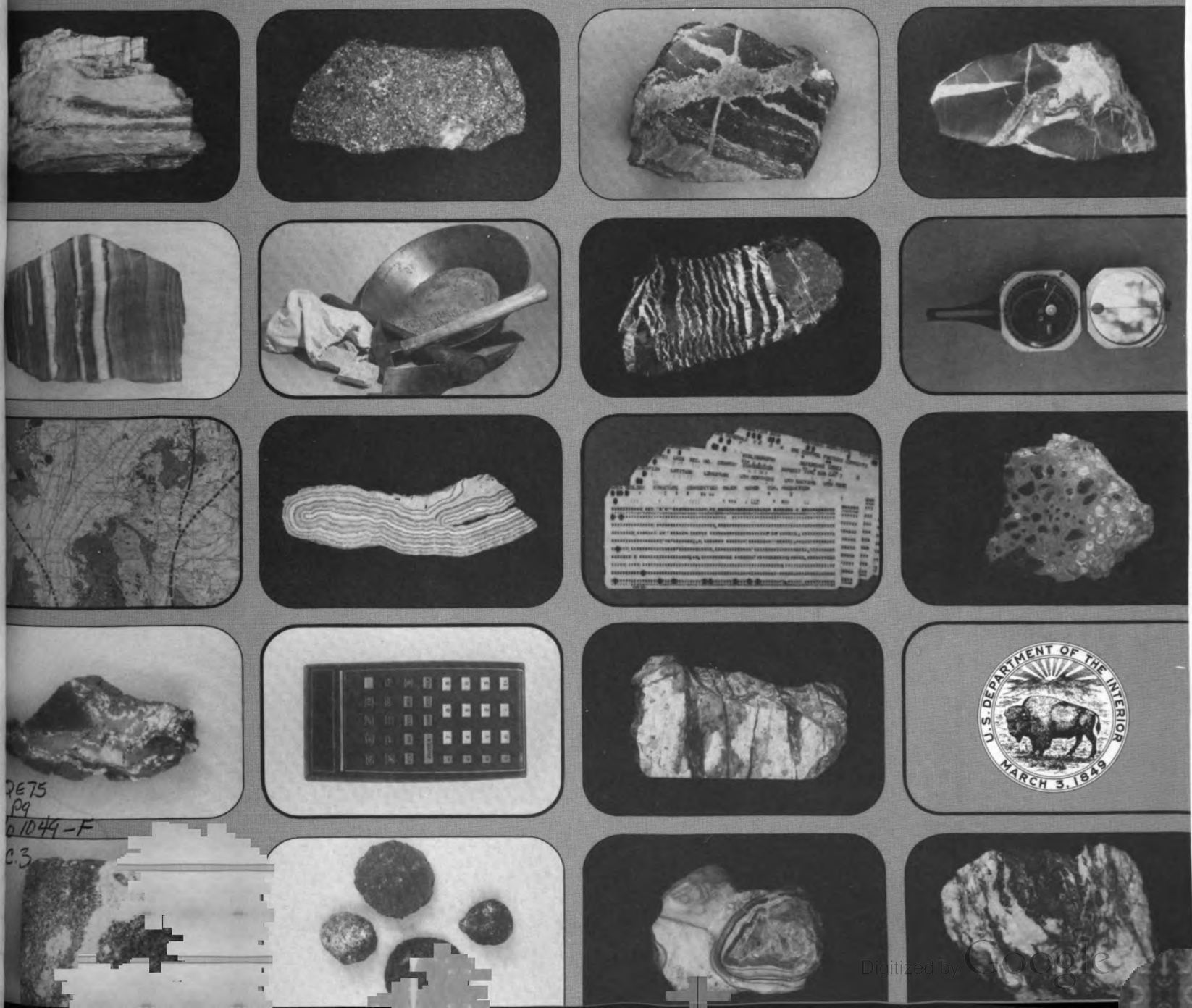
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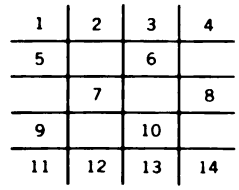
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4. Zinc ore, Friedensville, Pa.
5. Banded iron-formation, Palmer, Mich.
6. Ribbon asbestos ore, Quebec, Canada
7. Manganese ore, banded rhodochrosite
8. Aluminum ore, bauxite, Georgia
9. Native copper ore, Keweenawan Peninsula, Mich.
10. Porphyry molybdenum ore, Colorado
11. Zinc ore, Edwards, N. Y.
12. Manganese nodules, ocean floor
13. Botryoidal fluorite ore, Poncha Springs, Colo.
14. Tungsten ore, North Carolina

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By THEODORE J. ARMBRUSTMACHER

GEOLOGY AND RESOURCES OF THORIUM IN THE UNITED STATES

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1049-F

A description of the geologic setting, mineralogy, geochemistry, and size of thorium and rare-earth deposits, including calculations of reserves and potential economic resources



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Library of Congress Cataloging-in-Publication Data

Armbrustmacher, Theodore J., 1946-
Geology and resources of thorium and associated elements in the Wet Mountains area, Fremont and Custer Counties, Colorado.

(Geology and resources of thorium in the United States) (U.S. Geological Survey professional paper ; 1049-F)
Bibliography: p.
Supt. of Docs. no.: I 19.16:1049-F
1. Thorium ores—Colorado—Wet Mountains Region. 2. Earths, Rare—Colorado—Wet Mountains Region. 3. Geology—Colorado—Wet Mountains Region. 4. Mines and mineral resources—Colorado—Wet Mountains Region. I. Title. II. Series. III. Series: Geological Survey professional paper ; 1049-F.
QE390.2.T45A76 1988 553.4'93 87-600023

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GEOLOGY AND RESOURCES OF THORIUM AND ASSOCIATED ELEMENTS IN THE WET MOUNTAINS AREA, FREMONT AND CUSTER COUNTIES, COLORADO

By THEODORE J. ARMBRUSTMACHER

ABSTRACT

Thorium in potentially economic amounts occurs in three types of deposits in the Wet Mountains area of Colorado: (1) quartz-barite-thorite veins and fracture zones, (2) carbonatite dikes, and (3) red syenite dikes. The quartz-barite-thorite veins and fracture zones contain the largest resources of thorium; they cut all Precambrian and Paleozoic rock types in the area and tend to strike normal to the foliation in the Proterozoic metasedimentary and metavolcanic rocks. The veins and fracture zones are end products of the episode of Cambrian alkaline magmatism that also produced rocks of the McClure Mountain Complex, the Gem Park Complex, the complex at Democrat Creek, and associated dikes of carbonatite, lamprophyre, and red syenite. The veins and fracture zones contain an average of 0.46 percent ThO_2, 0.21 percent ΣLREE (total light rare-earth elements), 0.14 percent ΣHREE (total heavy rare-earth elements), and 0.012 percent Nb_2O_5. They contain reserves of 64,200 tons ThO_2, 29,300 tons ΣLREE, 19,540 tons ΣHREE, 1,675 tons Nb_2O_5; they contain probable potential resources of 160,500 tons ThO_2, 73,270 tons ΣLREE, 48,850 tons ΣHREE, and 4,185 tons Nb_2O_5.

The carbonatite dikes form two distinct groups: replacement carbonatites and primary magmatic carbonatites. The latter group appears to be the better source of potentially economic commodities. The primary magmatic carbonatites contain an average of 0.17 percent ThO_2, 0.0097 percent Nb_2O_5, 0.0031 percent U_3O_8, and 2.15 percent total rare-earth oxides. The seven largest dikes contain reserves of 131 tons ThO_2, 40 tons Nb_2O_5, 17 tons U_3O_8, and 2,500 tons ΣRE_2O_3 (total rare-earth oxides), and probable potential resources of 753 tons ThO_2, 228 tons Nb_2O_5, 105 tons U_3O_8, and 14,300 tons ΣRE_2O_3.

The red syenite dikes contain anomalous amounts of thorium, uranium, niobium, and rare-earth elements. Although reserves and probable potential resources have not been calculated, they are likely to be small.

INTRODUCTION

This paper discusses the mineralogy, geochemistry, and resources of the thorium and rare-earth deposits in the Wet Mountains area of south-central Colorado (fig. 1). Anomalous amounts of thorium and related elements are found in three types of deposits: quartz-barite-thorite veins and fracture zones, carbonatite dikes, and red syenite dikes. These deposits are genetically and spatially related to three alkaline intrusive complexes of early Paleozoic age that intrude the Middle Proterozoic igneous and metasedimentary host rock. After discovery of these radioactive deposits in the late 1940's, a flurry of prospecting took place in the mid-1950's; minor amounts of hand-cobbed ore from several veins were shipped to several small mills, mainly for testing. Because of the lack of a thorium market, only minor exploration has been done in recent years. However, interest in the economic potential of rare-earth elements and niobium in the carbonatite dikes continues to the present.

LOCATION AND ACCESS

Thorium deposits occur in an area bounded roughly by the Arkansas River on the north, the Custer-Huerfano County line on the south, the Texas Creek-Westcliffe fault on the west, and the Ilse fault on the east (pl. 1). The area containing the thorium deposits is referred to as the Wet Mountains in earlier literature. Many of the deposits are actually found in an area referred to as the DeWeese Plateau by Scott and Taylor (1975, p. 2); the actual Wet Mountains are east of the Ilse fault (pl. 1). The area is located about 65 km west of Pueblo, Colo., in Fremont and Custer Counties. The communities of Westcliffe and Silver Cliff are near the west-central edge of the area. The magnificent Sangre de Cristo Range is immediately west of the Wet Mountain Valley to the west and provides a scenic backdrop for studies in the area.

U.S. Highway 50 follows the Arkansas River along the northern edge of the area. State Highway 69 follows the western edge of the area south from Texas Creek at U.S. 50 through Westcliffe. State Highway 96 transects the area in an east-west direction from Westcliffe and Silver Cliff east to McKenzie Junction and past the intersection with Highway 165, to Wetmore and Pueblo.

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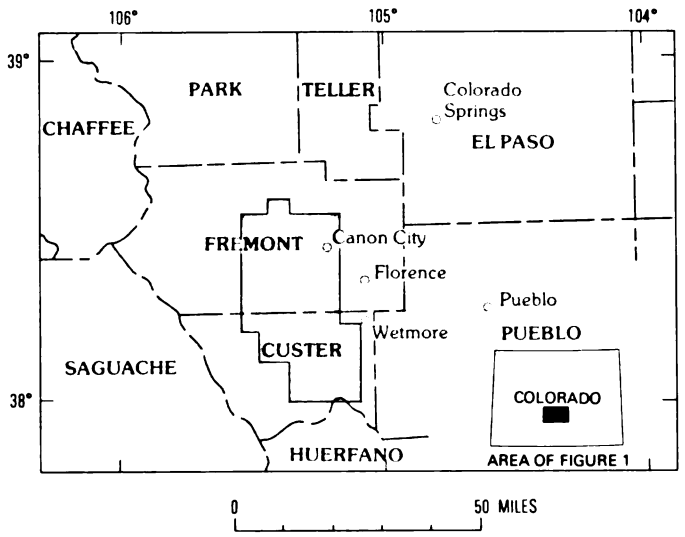


FIGURE 1.—Index map showing location of area in plate 1 (patterned area).

Numerous county roads connect the defunct mining communities of Ilse, Querida, and Rosita with the State highways. Land development in recent years has also provided additional roads throughout the area so that access for the most part is excellent.

Grape Creek, which heads in the Sangre de Cristo Range and flows into DeWeese Reservoir, has cut a canyon diagonally across the DeWeese Plateau that causes some access problems. From DeWeese Reservoir northeastward toward Temple Canyon, vehicles can ford Grape Creek only at Bear Gulch and then only at times of low water.

PREVIOUS WORK AND PROSPECTING HISTORY

Although the geology and mineral deposits of the Wet Mountains area have been known since 1896 (Cross, 1896; Emmons, 1896), thorium deposits were probably first mentioned in 1951 by Dellwig. G.B. Gott and L.F. Dellwig of the U.S. Geological Survey discovered radioactive shear zones at the Haputa Ranch in 1950 using a car-mounted geiger counter while en route to investigate the source of radioactive samples submitted to the Survey by Lawrence C. Knobbe of Silver Cliff (Christman and others, 1953).

Knobbe's interest in radioactive deposits dates from the mid-1940's, and his recollection of events leading to the discovery of thorium in the Wet Mountains area is interesting. During the mid- to late-1940's, various truck crops, particularly potatoes, were grown in the Wet Mountains area. Upon harvesting, the potatoes were sold to wholesalers in nearby Westcliffe and trucked to various markets by Lee Jones, a local rancher. One sack of potatoes found its way to Knobbe's home in Spearville, Kans., where it was stored in his basement near some rock samples that he had collected. In checking his rock samples for radioactivity, Knobbe discovered that the potatoes were radioactive. Knobbe traced the radioactivity to the bright-red dirt in the eyes of the potatoes, reconstructed the route traveled by the potatoes, and moved to the Wet Mountains area in order to prospect for the radioactive material, which he assumed to be uranium. After submitting samples from the Haputa Ranch, Lee Jones Ranch, and Anna Lee prospect to the Atomic Energy Commission for analysis in 1946-47, Knobbe learned that the radioactivity was due to thorium rather than uranium.

In response to Knobbe's discoveries, the U.S. Bureau of Mines drilled the veins and fracture zones at the Haputa Ranch in 1951-52 (Christman and others, 1953). The U.S. Geological Survey mapped various prospects and the surrounding Precambrian rocks in the vicinity of McKinley Mountain (Christman and others, 1954; Singewald and others, 1955; Singewald and Brock, 1956; and Christman and others, 1959).

Parker and Hildebrand (1963) first reported on the alkaline rock complexes in the Wet Mountains and their associated thorium, niobium, and rare-earth elements. Detailed studies of the alkaline complexes have been made by Shawe and Parker (1967), Parker and Sharp (1970), Armbrustmacher, Hedge, and Parker (1979), and Armbrustmacher and Hedge (1982). Various aspects of the geology of the alkaline rocks have also been studied by Armbrustmacher (1984), Heinrich (1965, 1977), Heinrich and Anderson (1965), Heinrich and Dahlem (1966, 1969), Heinrich and Moore (1970), Heinrich and Quon (1963), and Heinrich and Shappirio (1966).

The study of the thorium deposits has benefited from the areal geologic mapping previously done in the area by the U.S. Geological Survey, especially in the Mount Tyndall 7½-minute quadrangle (Brock and Singewald, 1968), the Cotopaxi and Royal Gorge 15-minute quadrangles (Taylor and others, 1975a, b), the Deer Peak-Hardscrabble Mountain quadrangle (Taylor, R. B., 1974), and the Pueblo 1°×2° quadrangle (Scott and others, 1976).

PRESENT INVESTIGATION

This study of thorium deposits in the Wet Mountains area systematically examines their mineralogy and geochemistry. Grab samples weighing about 1,000 grams were collected and ground to -20 mesh. Approximately 250 grams were split from the sample and reground to -100 mesh to prepare them for 6-step

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semiquantitative spectrographic analyses for 61 elements. The remainder of the -20 mesh fraction was analyzed for radium-equivalent uranium, thorium, and potassium by gamma-ray spectrometer. After analysis, this same fraction was subjected to routine heavy-liquid and isodynamic magnetic separation and the resulting mineral separates were identified optically or by standard X-ray powder diffraction methods. Many of the samples were also examined petrographically.

In the field, detailed sketch maps were prepared of some of the larger deposits. Radiometric surveys with a hand-held gamma-ray spectrometer and scintillation counter were also used to delineate zones of high radioactivity.

Light stable-isotope studies of carbonatites and veins aided in delineating the physical-chemical conditions of formation of these rocks. R.O. Rye determined $\delta^{18}O$ and $\delta^{13}C$ contents; this allowed unique solutions to problems of origin of various carbonatites. Determination by Rye of $\delta^{18}O$ and $\delta^{34}S$ values in quartz and coexisting barite and galena, respectively, also placed constraints on the characteristics of the hydrothermal fluids that deposited the vein materials. Rubidium and strontium isotopic analyses of some of the alkaline rocks indicate a relationship between the intrusions and associated carbonatites and red syenite dikes, and suggest a possible origin of these rocks.

Calculations of thorium, rare-earth elements, niobium, and uranium resources reported in Staatz and others (1979) and in Staatz and others (1980) are summarized.

ACKNOWLEDGMENTS

U.S. Geological Survey colleagues with previous experience in the Wet Mountains area have freely discussed various aspects of the geology and, in some instances, have contributed unpublished data. Especially helpful to this project were M.H. Staatz, M.R. Brock, W.N. Sharp, and R.L. Parker. R.O. Rye and J.F. Whalen contributed to an understanding of mineralization by supplying light stable-isotope data. C.E. Hedge analyzed various rocks of the alkaline complexes for rubidium and strontium isotopes. The semiquantitative spectrographic analyses were performed by L.A. Bradley, H.G. Neiman, and N.M. Conklin; the gamma-ray spectrometric analyses were performed by C.M. Bunker and C.A. Bush. I.K. Brownfield provided the mineral separates and the X-ray diffraction data. L.M. Osmonson helped with fieldwork.

Local prospectors and ranchers gladly shared information concerning the history, location, and details of various claims. I am especially indebted to Lawrence C. Knobbe, Earnest Sparling, Robert H. Bliss, Joe Tomsick, Dennis Shaydak, Ed Lepley, Eugene Griffin, and Allan Ellison. Also, Dolf Fieldman of Congdon and Carey Company freely shared information and diamond drill core from the Gem Park area.

GEOLOGIC SETTING

The terrane occupied by the Wet Mountains thorium deposits consists of a variety of Proterozoic metamorphic and intrusive igneous rocks that have been intruded by a series of alkaline intrusive rocks and associated dikes and veins of early Paleozoic age (pl. 1). The alkaline intrusive rocks comprise three complexes: the McClure Mountain Complex, the Gem Park Complex, and the complex at Democrat Creek. Fenite is found adjacent to the complexes and the thorium deposits. The alkaline intrusive rocks are partly covered by a variety of Tertiary volcanogenic rocks and Quaternary sediments.

PROTEROZOIC METAMORPHIC ROCKS

Host rocks for the Wet Mountains thorium deposits consist chiefly of Proterozoic metasedimentary and metavolcanic rocks, especially in the area south of the alkaline complexes. The rocks are chiefly migmatitic gneisses that contain quartz, biotite, microcline, and plagioclase interlayered with hornblende gneiss, biotite gneiss, calc-silicate gneiss, and garnet- and sillimanite-bearing gneisses. Brock and Singewald (1968) have further subdivided the various gneisses on the basis of variation in the proportions of the major minerals in the rocks. They included in their Proterozoic gabbroic gneiss and metamorphosed ultramafic rocks unit some Paleozoic ultramafic rocks. As pointed out by Heinrich and Dahlem (1966), some of these rocks are part of the complex at Democrat Creek and are discussed in this report with the alkaline rocks. Some of the ultramafic rocks, such as those in the roadcut of Highway 96 about 11 km east of Silver Cliff, are not typical of alkaline rocks but appear to be cumulates with tholeiitic affinities. One specimen from the roadcut contained oikocrysts of hypersthene 5 cm across, green spinel, apatite, olivine, magnetite, and green amphibole. Although contact relationships with the enclosing rocks are not always clear, some of these ultramafic rocks, such as those in the roadcut, most likely are Proterozoic in age rather than early Paleozoic, and they do not show obvious evidence of metamorphism.

EARLY AND MIDDLE PROTEROZOIC GRANITIC ROCKS

Early Proterozoic quartz diorite and granodiorite are fairly common in the northern part of the Royal Gorge and Cotopaxi quadrangles (Taylor and others, 1975a,

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b). These rocks have been dated at 1.72 b.y. (billion years), and belong to the Routt Plutonic Suite (Tweto, 1987), which includes the Boulder Creek Granodiorite. Granitic rocks in the Cotopaxi quadrangle have been dated at 1.45 b.y., belong to the Berthoud Plutonic Suite (Tweto, 1987) and thus correlate with Silver Plume Quartz Monzonite (Taylor and others, 1975a). Scott and others (1976) renamed the "r" granite of Brock and Singewald (1968) in the Mount Tyndall quadrangle the San Isabel Granite (Boyer, 1962), which also correlates with the Silver Plume Quartz Monzonite. Rocks mapped as San Isabel Granite become more abundant toward the southeastern part of the area (Taylor, 1974; Scott and others, 1976).

The "r" granite of Brock and Singewald (1968) was reported by them to possess relatively high radioactivity on a scintillation counter—1.5–2.5 times that of other granitic rocks. Five samples of this granitic rock were collected during this study and found to contain 1.78–2.39 ppm (parts per million) RaeU (radium-equivalent uranium), and averaging 2.09 ppm RaeU; they also contain 10.29–28.48 ppm thorium, averaging 18.81 ppm thorium (table 1). Wedepohl's (1971) average igneous rocks of the upper continental crust contain 3.5 ppm uranium and 11 ppm thorium. Thus, the higher radioactivity in the "r" granite appears to be due to thorium. The "r" granite also contains more abundant barium, lanthanum, cerium, and neodymium than the average igneous rocks (table 1). Petrographic and heavy mineral studies of the same five samples indicate that sphene and apatite are the most likely sources of uranium, thorium, and rare-earth elements.

CAMBRIAN ALKALINE INTRUSIVE COMPLEXES

Alkaline rocks in the Wet Mountains area occur in three distinct intrusive complexes: the McClure Mountain Complex, the Gem Park Complex, and the complex at Democrat Creek (Armbrustmacher, Brownfield, and Osmonson, 1979; Armbrustmacher and Hedge, 1982; Armbrustmacher, 1984). Additional alkaline intrusive rocks, comprising lamprophyre, carbonatite, and red syenite, are found as dikes that appear to be spatially and genetically related to the intrusive complexes. The quartz-barite-thorite veins also appear to be related to this episode of alkaline magmatism.

The McClure Mountain Complex contains nepheline syenite, hornblende-biotite syenite, mafic nepheline-clinopyroxene rocks, and mafic-ultramafic cumulate rocks (Shawe and Parker, 1967). The Gem Park Complex contains mafic-ultramafic cumulate rocks nearly identical to those in the McClure Mountain Complex, and a single exposure of nepheline syenite pegmatite (Parker and Sharp, 1970, p. 6). The complex at Democrat Creek is different: it contains quartz syenite, breccia, and mafic-ultramafic rocks. The latter were mapped by Brock and Singewald (1968) as Precambrian gabbroic gneisses and metamorphosed ultramafic rocks but were thought by Heinrich and Dahlem (1966) to be similar to the gabbros and pyroxenites of the Gem Park and McClure Mountain Complexes. The intrusive rocks at Democrat Creek are less notable for their similarities to the rocks of the other two complexes than for their differences.

The intrusive complexes and associated dikes are 520 m.y. (million years) old, according to Olson and others (1977, p. 683). Their dating of leucocratic rocks from the McClure Mountain Complex and the complex at Democrat Creek by fission-track, potassium-argon, and rubidium-strontium techniques could not resolve the differences in the ages of the various complexes or in the ages of different syenites at McClure Mountain. However, subsequent rubidium and strontium isotopic determinations by C.E. Hedge (Armbrustmacher and Hedge, 1982), yielded ages of 535 ± 5 m.y. for syenites at McClure Mountain and 511 ± 8 m.y. for syenites at Democrat Creek.

The petrology of the Wet Mountains alkaline rocks, as outlined by major- and minor-element contents, suggests the presence of several different rock series (Armbrustmacher, 1984). Data on rubidium, strontium, rare-earth elements, and strontium isotopes show that rocks of the complexes did not form through fractionation of a single magma but formed instead as end products of several magmas generated from different source materials (Armbrustmacher and Hedge, 1982).

FENITE

Alkali metasomatism has formed fenite in the rocks adjacent to the alkaline intrusive rocks, carbonatite dikes, and quartz-barite-thorite veins in the Wet Mountains area. Fenite forms when sodium and(or) potassium and ferric iron oxides are added to host rocks and silica is removed. Host rocks with original granitic compositions typically show progressively greater alteration toward nepheline syenite compositions nearer the alkaline intrusives. Original mafic minerals in the granitic rocks are replaced by sodic pyroxenes and amphiboles; original potassic and sodic feldspars are replaced by another potassic or sodic feldspar that contains abundant ferric iron oxide so that the entire rock takes on a pink color; original quartz is removed. Fenite adjacent to thorite-bearing veins emits a fetid odor when struck with a hammer. This same odor can be obtained from the vein material. Lawrence Knobbe (oral

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TABLE 1.—*Chemical analyses of "r" granite from the Wet Mountains area, Colorado*

[Semiquantitative spectrographic analyses by H.G. Neiman; gamma-ray spectrometric analyses by C.A. Bunker and C.A. Bush. Abundance of elements in igneous rocks of upper continental crust given for comparison; data from Wedepohl (1971, p. 65)]

Element	Sample No. 192	193	194	195	196	Average	Average of Igneous Rocks in Upper Crust
Semiquantitative spectrographic analyses, in percent							
Fe.....	5.	3.	3.	3.	5.	3.8	3.54
Mg.....	.7	.5	.5	.5	.5	.54	1.39
Ca.....	1.	3.	.7	.7	.7	1.22	2.87
Ti.....	.5	.5	.3	.3	.5	.42	.47
Mn.....	.1	.07	.05	.05	.07	.068	.069
Ba.....	.2	.2	.15	.2	.15	.18	.059
Be.....	.0003	.0002	.0002	.0002	.0003	.00024	.0002
Co.....	.0005	.0005	.0005	.0005	.0005	.0005	.0012
Cr.....	.0005	.0003	.00015	.0002	.0003	.0003	.007
Cu.....	.002	.0015	.0007	.001	.0015	.0013	.003
La.....	.01	.03	.015	.015	.02	.018	.0044
Nb.....	.003	.005	.002	.003	.005	.0036	.002
Pb.....	.003	.003	.005	.003	.003	.0034	.0015
Sc.....	.001	.001	.0007	.0007	.0007	.0008	.0014
Sr.....	.05	.05	.03	.03	.02	.036	.029
V.....	.007	.005	.003	.003	.01	.0056	.0095
Y.....	.01	.01	.005	.007	.01	.0084	.0034
Zr.....	.03	.03	.05	.07	.05	.046	.016
Si.....	>10.	>10.	>10.	>10.	>10.	>10.	>10.
Al.....	7.	10.	10.	7.	7.	8.2	7.83
Na.....	3.	3.	3.	3.	3.	3.	2.45
Ce.....	.03	.03	.03	.03	.05	.034	.0075
Ga.....	.003	.003	.002	.003	.002	.0026	.0017
Yb.....	.001	.001	.0005	.0007	.001	.0008	.00034
Nd.....	.015	.02	.015	.015	.02	.017	.003
Gamma-ray spectrometric analyses, in parts per million							
Rae U..	2.21	2.26	1.79	1.78	2.39	2.09	3.5
Th.....	14.62	10.29	21.18	19.49	28.48	18.81	11.
K.....	4.64	4.83	4.89	4.71	4.62	4.74	2.82

commun., 1976) said that when a dynamite blast opened a section of thorite-bearing vein, the odor from the associated fenite was strong enough to give the prospectors headaches if they entered the newly created hole too soon. This characteristic odor has been discussed by Heinrich and Anderson (1965), Christman and others (1953), Singewald and Brock (1956), and Christman and others (1959). It has also been noted in other thorium districts.

The odor-producing gas contains a variety of hydrocarbon compounds as well as sulfur-bearing compounds (Heinrich and Anderson, 1965, and G.E. Claypool, oral commun., 1978). The odoriferous material may be the fugitive constituents of complexing agents

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that combined with thorium to produce a highly mobile species capable of being transported under pressure-temperature conditions that existed in the hydrothermal solutions. The complexing of thorium in low-temperature environments is discussed by Langmuir and Herman (1980).

Response of mafic rocks, alkaline and tholeiitic, to fenitizing solutions is considerably different than granitic rocks. The end product of fenitization of mafic rocks is usually a rock containing abundant vermiculite. Mafic-ultramafic rocks near the center of the Gem Park Complex have been vermiculitized and that material was exploited at one time at the Vermiculite mine. Parker and Sharp (1970) suggested that the vermiculitized area occurs over a central core of carbonatite. However, holes drilled in this area passed through vermiculitized rock into relatively fresh mafic-ultramafic rocks. Vermiculite zones also occur at the Niles mine, in Gem Park, where carbonatite dikes intersect mafic-ultramafic rocks of the Gem Park Complex. The mafic-ultramafic rocks at the contact are strongly vermiculitized for a width of about 1 m.

TERTIARY VOLCANOGENIC ROCKS AND QUATERNARY SEDIMENTS

Tertiary and Quaternary rocks postdate the thorium deposits in the Wet Mountains area. Scott and Taylor (1975) and Sharp (1978) described these rocks in detail. Because these rocks are considerably younger than the thorium deposits and have no relationship to thorium deposit genesis, they will not be discussed.

THORIUM DEPOSITS

Thorium in the Wet Mountains area is found in three kinds of deposits: carbonatites, red syenite dikes, and quartz-barite-thorite veins and fracture zones (Armbrustmacher, 1976). Some exploration has been done in carbonatites, especially those in and around the Gem Park Complex, principally in search of economic deposits of niobium and rare-earth elements. Most of the exploration for thorium, however, has been directed toward locating the quartz-barite-thorite veins and fracture zones, where higher concentrations of thorium have been found.

CARBONATITES

Carbonatite dikes and irregularly shaped intrusions in and near the McClure Mountain and Gem Park Complexes form two distinct groups, replacement and primary magmatic, as determined chiefly by differences in petrography (Armbrustmacher, 1979; Armbrustmacher and Brownfield, 1978). Replacement carbonatites show textures indicating pseudomorphous replacement of an originally porphyritic or hypidiomorphic-granular rock by carbonate mineral. They contain an element suite characteristic of carbonatites as well as a trace-element signature indicative of a mafic-silicate precursor. Primary magmatic carbonatites, which are typically equigranular and lack obvious replacement textures, are also enriched in elements characteristic of carbonatites but contain average amounts of these elements greater than replacement carbonatites. The carbonatites found in and around the Gem Park Complex appear to form a subgroup within the primary magmatic group because of differences in mineralogy and geochemistry.

REPLACEMENT CARBONATITES

Replacement carbonatites occur chiefly as dikes. The rocks are dark green, dark greenish brown, dark reddish brown, purple, or maroon on weathered surfaces; fresh rock surfaces of individual dikes have similar colors, but the color of the weathered and fresh surfaces is not necessarily the same. Radioactivity of the dikes does not exceed about 5–8 times background with stronger radioactivity typically occurring along contacts, especially if they are sheared. The host rock is invariably fenitized to varying degrees, seldom extending more than several centimeters from the contact, and the fenite may also be anomalously radioactive.

Carbonate minerals in replacement carbonatites are fine to medium grained and replace preexisting minerals as aggregated pseudomorphs so that the original texture is retained. The porphyritic rocks most likely to have been replaced appear to be lamprophyres similar to those found throughout the area. Partial replacement of phenocrysts in the lamprophyres by carbonate and other minerals is often observed, suggesting the possibility that a continuous series may exist between fresh, unaltered lamprophyre and replacement carbonatite. Partial replacement of potassic feldspar by carbonate minerals in various red syenite dikes and the presence of feldspar remnants in some of the replacement carbonatites suggests that the syenite dikes were parent rocks of some of the carbonatites.

The replacement carbonatites occur chiefly southeast of the McClure Mountain Complex as shown on plate 1. The only replacement carbonatites found thus far north of the complex occur along the Ilse fault and near the contact of the complex with the country rock. Lamprophyres and red syenites, which may be the original

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material of some of the replacement carbonatites, are abundant throughout the area (Heinrich and Dahlem, 1966, 1969).

MINERALOGY

The replacement carbonatites contain a fairly large variety of minerals, although not as many as the primary magmatic carbonatites (table 2), based on Armbrustmacher (1979) and Armbrustmacher and Brownfield (1978). Calcite/dolomite ratios are variable although calcite is usually more abundant. Magnesite was also identified in a few samples. Barite is a common constituent but has a highly variable distribution along strike. Ferric oxide minerals are fairly abundant and occur as primary specular hematite, as goethite replacing pyrite in pseudomorphs, and as secondary hematitic and amorphous intergranular stain. Quartz, microcline, albite, acmite, and biotite occur in at least minor amounts, but microcline can be present in major amounts. Accessory minerals that are probably responsible for the rare-earth and thorium content include fluorapatite, sphene, and zircon, and sparse bastnaesite, monazite, and xenotime. Magnetite, spinel, and rutile are also common accessory minerals. Alpha-counter measurements of handpicked concentrates of iron oxide minerals sometimes show anomalous radioactivity that may be due to minor amounts of metamict thorite or monazite associated with the iron oxides.

GEOCHEMISTRY

The replacement carbonatites in the Wet Mountains contain at least twice the average amount of calcium, barium, lanthanum, niobium, strontium, yttrium, and cerium as the average igneous rocks of the upper continental crust, as reported by Wedepohl (1971) (table 3). High values for these elements are characteristic of carbonatites (Heinrich, 1966, p. 222; Gold, 1963). The carbonatites also contain more abundant manganese, cobalt, chromium, scandium, and nickel than crustal averages (table 3). This group of elements is typically more abundant in mafic and ultramafic igneous rocks (Goles, 1967) and also apparently is abundant in lamprophyres (Armbrustmacher, 1979) relative to crustal igneous rocks. The major elements silicon, aluminum, sodium, potassium, iron, magnesium, and titanium are more abundant in replacement carbonatites than in primary carbonatites and, with the exception of magnesium, in carbonatites found at Gem Park (table 3). This reflects the abundance of rock-forming silicates, especially potassic feldspars, sodic amphiboles, and sodic pyroxenes, in replacement carbonatites relative to primary magmatic carbonatites and Gem Park carbonatites. The major- and trace-element abundances in replacement carbonatites seem compatible with the suggestion that the rocks were originally either lamprophyres or red syenites.

PRIMARY MAGMATIC CARBONATITES

Primary magmatic carbonatites occur chiefly in dikes ranging in thickness from a few centimeters to about 3 m—a typical thickness is 1 m. However, southeast of Gem Park, primary magmatic carbonatite occurs in a plug-shaped mass about 30 m in diameter (Parker and Sharp, 1970, p. 9). Primary magmatic carbonatite weathers to a dark reddish brown to dark brown color. On fresh surfaces this rock is commonly white, although in some places, it is similar in color to replacement carbonatites; it is brown, greenish brown, or (rarely) bluish gray on fresh surfaces. Primary magmatic carbonatites typically contain 10 times as much radioactivity as adjacent host rocks and have been of economic interest because of local concentrations of thorium as well as rare-earth elements and niobium.

At the outcrop these rocks tend to be quite coarse grained—carbonate grains 4 cm across are common. Carbonatite near the contact with host rocks tends to form a fine-grained chill zone, but the maximum grain size is usually attained within a few centimeters of the contact.

Lamprophyre dikes are sometimes found in close proximity with primary magmatic carbonatite dikes. According to Heinrich and Dahlem (1966), the carbonatite is typically younger than the associated lamprophyre. However, the sequence of intrusion of various members of the alkaline sequence may be more complicated than they indicate: at one locality near the southeast side of the McClure Mountain Complex, a primary magmatic carbonatite is intruded by a lamprophyre dike (Armbrustmacher and others, 1979). Hence, rather than sharing a direct genetic relationship, the carbonatites and lamprophyres may only occupy the same zones of structural weakness within the host rock.

All the primary magmatic carbonatites thus far examined occur within one of the three alkaline intrusive complexes, or at a distance less than 6.5 km from the complexes. The carbonatites are especially numerous west of the McClure Mountain Complex, east of the McClure Mountain Complex along Bear Creek, and in and adjacent to the Gem Park Complex.

MINERALOGY

There is a greater variety of minerals, especially rare-earth minerals, in the primary magmatic carbonatites

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TABLE 2.—*Mineralogy of carbonatites from the Wet Mountains area, Colorado*

[C, common, present in greater than 50 percent of the samples. M, moderately common, present in 20-50 percent of the samples. R, rare, present in 5-20 percent of the samples. VR, very rare, present in less than 5 percent of the samples. Leaders (---), not identified. Taken from Armbrustmacher, 1979, p. 892]

Mineral	Formula	Abundance in Carbonatites		Mineral	Formula	Abundance in Carbonatites	
		Primary	Replacement			Primary	Replacement
Acmite.....	$NaFe^{+3}Si_2O_6$	R	M	Magnesite.....	$MgCO_3$	---	R
Actinolite.....	$Ca_2(Mg,Fe^{+2})_5Si_8O_{22}(OH)_2$	---	VR	Magnetite.....	$Fe^{+2}Fe_2^{+3}O_4$	R	M
Anatase.....	TiO_2	R	---	Microcline....	$KAlSi_3O_8$	M	C
Ancylite.....	$SrCe(CO_3)_2(OH)\cdot H_2O$	R	---	Monazite.....	$(Ce,La,Nd,Th)PO_4$	R	R
Ankerite.....	$Ca(Fe^{+2},Mg,Mn)(CO_3)_2$	R	---	Muscovite.....	$KAl_2(Si_3Al)O_{10}(OH,F)_2$	VR	---
Barite.....	$BaSO_4$	C	M	Phlogopite....	$KMg_3Si_3AlO_{10}(F,OH)_2$	R	M
Bastnaesite....	$(Ce,La)(CO_3)F$	M	VR	Plagioclase...	$(Na,Ca)Al(Al,Si)Si_2O_8$	VR	R
Biotite.....	$K(Mg,Fe^{+2})_3(Al,Fe^{+3})Si_3O_{10}(OH,F)_2$	R	M	Pyrite.....	FeS_2	M	R
Calcite.....	$CaCO_3$	C	C	Pyrochlore....	$(Na,Ca)_2Nb_2O_6(OH,F)$	R	---
Cancrinite.....	$Na_6Ca_2Al_6Si_6O_{24}(CO_3)_2$	VR	---	Quartz.....	SiO_2	C	C
Cerussite.....	$PbCO_3$	VR	---	Rutile.....	TiO_2	M	M
Chalcopyrite...	$CuFeS_2$	---	R	Siderite.....	$FeCO_3$	VR	---
Chlorite.....	$(Mg,Al,Fe)_{12}(Si,Al)_8O_{20}(OH)_{16}$	R	---	Sphalerite....	(Zn, Fe)S	VR	---
Chromite.....	$Fe^{+2}Cr_2O_4$	---	VR	Sphene.....	$CaTiSiO_5$	R	VR
Crocidolite....	$Na_2(Fe^{+2},Mg)_3Fe_2^{+3}Si_8O_{22}(OH)_2$	VR	VR	Spinel.....	$MgAl_2O_4$	VR	R
Diopside.....	$CaMgSi_2O_6$	---	VR	Strontianite..	$SrCO_3$	R	---
Dolomite.....	$CaMg(CO_3)_2$	C	M	Synchysite....	$(Ce,La)Ca(CO_3)_2F$	M	---
Epidote.....	$Ca_2(Al,Fe^{+3})_3(SiO_4)_3(OH)$	R	VR	Thorite.....	$ThSiO_4$	VR	---
Fluorapatite...	$Ca_5(PO_4)_3F$	M	R	Vermiculite...	$(Mg,Fe^{+2},Al)_3(Al,Si)_4O_{10}(OH)_2\cdot 4H_2O$	R	R
Fluorite.....	CaF_2	R	---	Xenotime.....	YPO_4	VR	R
Galena.....	PbS	VR	---	Zircon.....	$ZrSiO_4$	VR	VR
Goethite.....	α-$Fe^{+3}O(OH)$	M	M				
Hematite.....	α-Fe_2O_3	C	C				
Ilmenite.....	$Fe^{+2}TiO_3$	VR	---				
Lepidocrocite..	γ-$Fe^{+3}O(OH)$	R	---				

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TABLE 3.—*Arithmetic means and ranges of elements in carbonatites from the Wet Mountains area, Colorado, and other comparative rocks*

[Data in percent. Leaders (---), no analyses. Mean values of elements in other rock series have been included for comparative purposes]

	1. Replacement carbonatite		2. Primary magmatic carbonatite		3. Carbonatites from Gem Park		4. Average carbonatite (Mean)	5. Average igneous rocks	6. Average sedimentary carbonate rocks	7. Lamprophyre (Mean)
Element	Mean	Range	Mean	Range	Mean	Range				
Fe.....	6.0	2.-10.	5.4	0.5->10.	3.6	1.5->10.	5.1	3.54	0.42	>10.
Mg.....	3.3	.1->7.	1.9	.02->7.	6.6	.15->10.	3.4	1.39	4.8	1.5
Ca.....	>10.	1.5->10.	>10.	.5->10.	>10.	7.0->10.	>10.	2.87	>10.	.6
Ti.....	.61	.003-2.	.24	<0.0002-1.	.07	<0.0002-1.5	.5	.47	.03	1.2
Mn.....	.23	.05-2.	.66	.02-3.	.6	.1-1.	.5	.069	.05	.2
Ba.....	.53	.015-10.	1.5	.0015->10.	.7	.007-10.	.23	.059	.015	.3
Be.....	.0007	<0.0001-0.002	.0008	<0.0001-0.01	---	---	---	.0002	.0001	.004
Co.....	.0033	<0.0003-0.03	.0016	<0.0005-0.03	.0014	.0003-0.003	.0017	.0012	.0004	.007
Cr.....	.047	.0015-0.2	.011	<0.0001-0.07	.005	<0.0001-0.07	.0048	.007	.0009	.07
Cu.....	.0039	.0002-0.02	.0043	<0.0001-0.02	.0029	<0.0001-0.07	.0002	.003	.0014	.006
La.....	.023	<0.005-0.5	.65	<0.002->3.	.54	<0.005-3.	.052	.0044	.0014	.01
Mo.....	.0004	<0.0003-0.003	.0009	<0.0003-0.007	<0.0003	<0.0003-0.0015	.0042	.0001	.0001	.0002
Nb.....	.014	<0.001-0.2	.0068	<0.001-0.03	.07	<0.001-0.7	.2	.002	---	.03
Ni.....	.020	<0.0005-0.1	.0051	<0.0005-0.03	.0013	<0.0005-0.03	.0008	.0044	.0012	.07
Pb.....	.0084	<0.001-0.1	.018	<0.001-0.5	.0083	<0.001-0.02	---	.0015	.0008	.0045
Sc.....	.0025	.0007-0.015	.0025	<0.0005-0.05	.0018	<0.0005-0.007	.001	.0014	.00003	.005
Sr.....	.088	.015-0.2	.32	.007-5.	1.8	.07-7.	.34	.029	.047	.02
V.....	.024	.003-0.05	.012	<0.0007-0.1	.0034	<0.0007-0.03	---	.0095	.0015	.03
Y.....	.015	.0015-0.15	.049	.002-0.7	.013	.001-0.05	.01	.0034	.0013	.01
Zr.....	.015	<0.001-0.07	.013	<0.001-0.2	.0031	<0.001-0.03	.11	.016	.0017	.01
Si.....	>10.	2.0->10.	6.8	.1->10.	1.1	.01-7.	5.7	30.54	2.4	>10.
Al.....	4.3	.3->10.	2.3	.02->10.	.2	.03-2.	1.9	7.83	.43	5.
Na.....	3.3	<0.05-10.	1.3	<0.05-10.	.4	<0.05-0.7	.3	2.45	.04	1.1
K.....	4.8	<0.7-<10.	2.6	<0.7-10.	<0.7	<0.7-2.	1.2	2.82	.27	7.
P.....	<0.2	<0.2-1.5	.6	<0.2-10.	1.4	<0.2-10.	.85	.081	.02	.1
Ce.....	.038	<0.01-1.	.61	<0.01-2.	.64	.01-3.	.15	.0075	---	.02
Ga.....	.0013	<0.0005-0.003	.0007	<0.0005-0.003	<0.0005	<0.0005-0.002	.0001	.0017	.0002	.001
Yb.....	.0011	<0.0001-0.007	.0075	<0.0001-0.3	.0006	<0.0001-0.005	---	.00034	---	.001
Pr.....	<0.01	<0.01-<0.01	.16	<0.01-0.7	.23	<0.01-1.5	---	.00076	---	<0.01
Nd.....	.025	<0.007-0.7	.30	<0.007-2.	.28	<0.007-3.	---	.003	---	.01
Sm.....	<0.01	<0.01-<0.01	.055	<0.01-0.3	.036	<0.01-0.3	---	.00066	---	<0.01
Eu.....	<0.007	<0.007-0.01	.0083	<0.007-0.03	<0.007	<0.007-0.015	---	.00014	---	<0.007
[1]ΣLREE..	.084	---	1.55	---	1.6	---	---	.016	---	.04
[2]ΣHREE..	.018	---	.087	---	.019	---	---	.0059	---	.015
Th.....	.013	.0004-.06	.15	.0013-1.8	---	---	---	.0011	.0002	.012
[3]RaeU...	.0005	.00002-0.0036	.0026	.00002-0.012	---	---	---	.00035	.0002	.0004

[1] [2]Total light rare-earth elements, La+Ce+Pr+Nd+Sm+Eu.
[3]Total heavy rare-earth elements, Y+Gd+Tb+Dy+Ho+Er+Tm+Lu+Yb.
Radium-equivalent uranium.

SAMPLES AND METHODS OF ANALYSIS

1. Replacement carbonatite, Wet Mountains area. Based on 6-step semiquantitative spectrographic and gamma ray spectrometric (RaeU and Th) analyses (Armbrustmacher and Brownfield, 1978). Number of samples = 8.
2. Primary magmatic carbonatite, Wet Mountains area. Based on 6-step semiquantitative spectrographic analyses (Armbrustmacher and Brownfield, 1978). Number of samples = 52.
3. Carbonatites from Gem Park, Wet Mountains area. Means and ranges calculated from data in Parker and Sharp (1970, table 11). Number of samples = 39.
4. Average carbonatite; partly recalculated from Gold (1963, p. 989, col. III).
5. Abundance of elements in the igneous rocks of the upper continental crust (Wedepohl, 1971, table 7.3, p. 65).
6. Average concentrations in sedimentary carbonate rocks; minor elements from Graf (1960a, p. 71), major elements from Graf (1960b, p. 24, col. 6).
7. Average of lamprophyre samples 407 and 410 from Wet Mountains area. Both are altered and may be somewhat mineralized.

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than in the replacement carbonatites (table 2). White calcite is typically the major constituent. Bastnaesite is a fairly common constituent, having been identified in nearly 50 percent of the samples. Usually the bastnaesite is associated with synchysite and, rarely, with ancylite and strontianite. Other rare-earth-bearing minerals include monazite, xenotime, and fluorapatite. Dolomite is common, and strontianite and ankerite are rare. Quartz, hematite, and barite are common and present in variable amounts; microcline is also quite common. Of the sulfides, pyrite is more common than sphalerite or galena; pyrite is also more common than the alteration product of galena—cerussite. Thorite, fluorite, and pyrochlore were also identified in a limited number of samples. Most of the minerals found in replacement carbonatites are also found in the primary magmatic carbonatites.

GEOCHEMISTRY

The primary magmatic carbonatite contains at least twice, and as much as 21 times, as much sodium, potassium, barium, chromium, copper, lanthanum, nickel, scandium, yttrium, cerium, and gallium as the "average carbonatite" of Gold (1963), based on the mean values in 52 samples (table 3). On the other hand, titanium, molybdenum, niobium, and zirconium are depleted. Compared with average crustal igneous rocks, as reported by Wedepohl (1971), primary magmatic carbonatites contain 6–132 times as much manganese, barium, strontium, niobium, lanthanum, cerium, yttrium, and thorium. Relative to replacement carbonatites, primary magmatic carbonatites contain at least twice as much manganese, barium, lanthanum, lead, strontium, yttrium, ytterbium, cerium, ΣLREE (total light rare-earth elements), and ΣHREE (total heavy rare-earth elements). The rock-forming minerals—reflected by the abundances of silicon, aluminum, sodium, potassium, iron, and titanium—appear to be greater in the subgroup of primary magmatic carbonatites of Gem Park than in primary magmatic carbonatites (table 3).

SELECTED CARBONATITE OCCURRENCES

Several individual carbonatite intrusions or groups of intrusions have been selected for further discussion because of their unusual mineralogy or relative economic importance. Most are primary magmatic carbonatites.

GOLDIE CARBONATITE

The aluminofluoride mineral assemblage in the Goldie carbonatite (near lat 38°22′ N., long 105°32′ W.) reported by Heinrich and Anderson (1965), Heinrich and Quon (1963), and Heinrich (1965, 1977) has not been observed in other carbonatites in the Wet Mountains area. The carbonatite consists of coarse-grained calcite with intergranular patches of finer grained carbonate, albite, barite, and unusually large amounts of fluorite. Late replacement nodules contain cryolite, pachnolite, ralstonite, weberite, prosopite, fluorite, and sericite (Heinrich, 1977). Semiquantitative spectrographic analysis of several carbonatite samples shows that they contain more iron, magnesium, manganese, and barium than the average primary magmatic carbonatite (table 3; Armbrustmacher and Brownfield, 1978). They also contain more of the other typical carbonatite elements, such as rare-earth elements, strontium, niobium, and thorium, than are found in igneous rocks of the upper continental crust (Wedepohl, 1971; table 3), but less than are found in primary magmatic carbonatites (table 3).

AMETHYST CARBONATITE

Amethyst forms veins within a rock (near lat 38°31′30″ N., long 105°25′30″ W.) described as silico-carbonatite by Heinrich and Shappirio (1966). This is the only known occurrence of amethyst in a carbonatite within the Wet Mountains area. The silico-carbonatite dikes and associated fenite occur along the Ilse fault more than 16 km north of the McClure Mountain Complex (pl. 1); these dikes are found farther from the alkaline intrusive complexes than any other carbonatite. Examination of thin sections of the silico-carbonatite shows it to be intensely brecciated with small remanent grains and grain clusters of quartz, microcline, and barite. The interstitial material appears to be very fine grained, poorly sorted fragments of the same minerals. Calcite veins cut across the rock and partly replace some parts of it. Heavy mineral separates of the same rocks yielded hematite, goethite, and barite but no rare-earth or thorium-bearing minerals. Semiquantitative spectrographic analysis of the same rocks shows variable barium (0.01–7.0 percent), variable strontium (0.0005–0.2 percent), and low total rare-earth content (0–0.18 percent). Other elements characteristic of carbonatites are present in low concentrations (Armbrustmacher and Brownfield, 1978). Gamma-ray spectrometric analysis yields 145–1,180 ppm thorium and 0.5–408 ppm uranium. The mineral content, rock texture, and element content show almost no similarities to primary magmatic carbonatites that occur farther south. Because of the replacement textures, these rocks appear to be replacement carbonatites.

MCCLURE GULCH CARBONATITE

The multiple carbonatite (near lat 38°20′ N., long 105°27′ W.) that intrudes the McClure Mountain

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Complex at McClure Gulch (pl. 1) appears to have several unique aspects (Armbrustmacher, Brownfield, and Osmonson, 1979). This primary magmatic carbonatite dike shows two separate and distinct kinds of carbonatite that persist side-by-side in a discontinuous manner with a consistent thickness along the entire length of the dike. A sulfide-bearing phase contains unusually large amounts of pyrite and sparse disseminated sphalerite (table 4). Strontianite and ancylite, which have not been identified at other carbonatite localities other than Gem Park, are closely associated with bastnaesite and synchysite. A coarse-grained phase, adjacent to but older than the sulfide-bearing phase, does not contain sulfide- or strontium-bearing minerals but does contain pyrochlore, which has also been found only at Gem Park. This is also the only known locality where a lamprophyre dike intrudes carbonatite.

TABLE 4.—*Mineralogy of carbonatites from McClure Gulch, Wet Mountains area, Colorado*

[C, common constituent; M, moderately common; R, rare; query (?), data insufficient for positive identification; leaders (---), not identified. Identifications are based on data obtained by X-ray diffraction and microscopic examination. Taken from Armbrustmacher, Brownfield, and Osmonson, 1979, p. 41]

Mineral	Formula	Abundance of Carbonatites	
		Coarse-grained	Sulfide-bearing
Ancylite.....	$SrCe(CO_3)_2(OH)\cdot H_2O$.....	?	M
Ankerite.....	$Ca(Fe^{+2},Mg,Mn)(CO_3)_2$.....	---	R
Barite.....	$BaSO_4$.....	M	M
Bastnaesite.....	$(Ce,La)(CO_3)F$.....	?	M
Biotite.....	$K(Mg,Fe^{+2})_3(Al,Fe^{+3})Si_3O_{10}(OH,F)_2$...	R	---
Calcite.....	$CaCO_3$.....	C	C
Dolomite.....	$CaMg(CO_3)_2$.....	?	C
Fluorapatite....	$Ca_5(PO_4)_3F$.....	M	M
Goethite.....	α-$Fe^{+3}O(OH)$.....	M	M
Hematite.....	α-Fe_2O_3.....	M	M
Lepidocrocite...	γ-$Fe^{+3}O(OH)$.....	?	R
Magnetite.....	$Fe^{+2}Fe_2^{+3}O_4$.....	?	R
Pyrite.....	FeS_2.....	---	M
Pyrochlore.....	$(Na,Ca)_2Nb_2O_6(OH,F)$.....	R	---
Quartz.....	SiO_2.....	---	R
Rutile.....	TiO_2.....	R	---
Sphalerite.....	$(Zn,Fe)S$.....	---	R
Strontianite....	$SrCO_3$.....	R	M
Synchysite.....	$(Ce,La)Ca(CO_3)_2F$.....	---	M

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Analyses of the sulfide-bearing and coarse-grained phases show that the sulfide-bearing carbonatite contains at least twice the average amount of iron, magnesium, manganese, barium, chromium, lanthanum, lead, strontium, vanadium, yttrium, cerium, ΣREE, thorium, and uranium than the coarse-grained carbonatite (table 5). Primary magmatic carbonatites as a group (table 3) contain more abundant magnesium, titanium, manganese, barium, chromium, lanthanum, niobium, nickel, vanadium, zirconium, silicon, aluminum, sodium, potassium, phosphorus, thorium, and uranium than both the sulfide-bearing and coarse-grained carbonatites, due chiefly to the common occurrence of silicate minerals in primary magmatic carbonatites. Both sulfide-bearing and coarse-grained carbonatites contain more abundant strontium than average primary magmatic carbonatites, and this is reflected by the presence of ancylite and strontianite.

GEM PARK CARBONATITES

The primary magmatic carbonatites at Gem Park, which occur at various localities, surface and subsurface, within that complex, have been studied by Parker and Sharp (1970) and by Papson (1981). They contain minerals that have not been found in primary magmatic carbonatites elsewhere in the Wet Mountains area. These include columbite, natrolite, pyrrhotite, and thorianite (Parker and Sharp, 1970, p. 12). Minerals found in primary magmatic carbonatites away from Gem Park but not reported from Gem Park include chlorite, epidote, fluorapatite, goethite, hematite, lepidocrocite, microcline, rutile, siderite, synchysite, and thorite. The most important workings in and around Gem Park include the Gem mine, the Niles mine, the Vermiculite mine, and the carbonatite plug at Pine Gulch, 1.3 km east of the south end of the Gem Park Complex (pl. 1).

The carbonatite dike at the Gem mine intrudes rocks of the Gem Park Complex and also Proterozoic granitic gneiss north of the complex. The silicate-bearing carbonatite contains quartz, barite, iron oxide rich carbonate as well as patches of clearer carbonate, ancylite, phlogopite, pyrite, and monazite(?). Eckel (1961) reported the occurrence of niccolite, annabergite, and native silver in ore mined in the late 1900's, presumably from this carbonatite, but none of these minerals was identified in this study. The thorium and rare earth abundances are relatively low (Armbrustmacher and Brownfield, 1978, table 1).

The carbonatite dike at the Niles mine has fenitized the ultramafic rocks that it intrudes to vermiculite-rich rock for a distance of about 1 m away from the contact. The carbonatite consists of calcite, dolomite, goethite, hematite, magnetite, ilmenite(?), phlogopite, bastnaesite, minor quartz, rutile, and monazite. The bastnaesite and monazite do not appear to coexist in the same hand specimen but their paragenesis is not known. These moderately coarse-grained rocks contain fairly abundant total rare earths (2.8 percent), about 350 ppm thorium, and low concentrations of niobium (less than 30 ppm).

The Vermiculite mine occupies an area of strongly altered ultramafic rocks and only a few small carbonatites occur in the workings. According to Parker and Sharp (1970, p. 22) the vermiculitized rocks may represent the surface expression of an alteration halo around a buried carbonatite stock. However, according to Dolf Fieldman (oral commun., 1978), drill core from the immediate vicinity shows that alteration of the ultramafic rocks ceases at depth without encountering a carbonatite stock.

The carbonatite plug at Pine Gulch is about 30 m in diameter and has abundant blue crocidolite. The rock consists predominantly of calcite and dolomite with interstitial and crosscutting fibrous crocidolite. Also present are magnetite, hematite, goethite, microcline, monazite, and perhaps quartz. The carbonatite contains about 26 ppm thorium, 200 ppm niobium, and 1.2 percent ΣREE.

Parker and Sharp (1970, table 11) reported the analyses of 30 samples of carbonatite at Gem Park. Some differences in the average abundance of elements are noted between these samples and the primary magmatic carbonatites (Armbrustmacher, 1979). The Gem Park carbonatites contain an average of 10 times more niobium, 6 times more strontium, and considerably less silicon, aluminum, sodium, potassium, iron, and titanium (table 3). This is due to lower abundances of rock-forming minerals. The ΣHREE are also somewhat depleted in Gem Park carbonatites.

In a study supported by the U.S. Geological Survey, Papson (1981) investigated the carbonatite at Gem Park from several diamond drill cores of Congdon and Carey Company of Denver, Colo. The list of minerals that he found in the cores is given in table 6. Modal analyses of the carbonatites are given in table 7, and partial chemical analyses are given in table 8.

The results of Papson's (1981) studies show that the Gem Park Complex has at least three types of carbonatite. The oldest type consists of dolomite, fluorapatite, magnetite, and phlogopite with accessory pyrochlore and zircon. It is characterized by low-grade niobium (mean=584 ppm) and rare-earth elements (mean=3,713 ppm). Niobium and the ΣREE occur chiefly in pyrochlore. The presence of uranium (high value=131 ppm) in core samples of carbonatite is

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TABLE 5.—*Chemical analyses of carbonatites from McClure Gulch, Wet Mountains area, Colorado*

[From Armbrustmacher, Brownfield, and Osmonson (1979, p. 44). N.D., no data. Average primary carbonatites based on 52 analyses from Armbrustmacher and Brownfield (1978). Semiquantitative spectrographic analyses by L.A. Bradley; looked for but not found: Ag, As, Au, Be, Bi, Cd, Pd, Pt, Sb, Sn, Te, W, Zn, Ga, Ge, Hf, In, Li, Re, Ta, Tl, Pr, Tm, Lu. Gamma-ray spectrometric analyses by C.M. Bunker and C.A. Bush]

Sample No.	Coarse-grained carbonatite		Sulfide-bearing carbonatite				Average primary carbonatite
	453	455B	419	454	455A	456	
	Semiquantitative spectrographic analyses (in percent)						
Fe.....	1.5	1.5	3.	7.	3.	7.	5.2
Mg.....	.2	.2	.5	.15	.15	1.	2.0
Ca.....	>10.	>10.	>10.	>10.	>10.	>10.	>10.
Ti.....	.002	.001	<0.0002	.01	.003	<0.0002	.22
Mn.....	.7	.7	.2	.5	.3	.5	.6
Ba.....	.07	.1	.15	.5	.5	.2	1.5
Co.....	<0.0005	<0.0005	.003	.001	.001	.003	.0016
Cr.....	.0002	.0002	.0003	.0007	.0005	.0007	.014
Cu.....	.003	.0007	.007	.0015	.0015	.0015	.0047
La.....	.05	.07	.15	.2	.2	.3	.56
Mo.....	<0.0003	.0005	.0007	<0.0003	.0005	.0007	.007
Nb.....	.001	.005	<0.001	.005	<0.001	.0015	.007
Ni.....	<0.0005	.0015	.001	<0.0005	<0.0005	.0007	.0055
Pb.....	.002	.003	.01	.01	.015	.015	.002
Sc.....	<0.0005	.001	.0015	.0015	.0015	.0015	.0026
Sr.....	1.	1.5	2.	.5	.7	5.	.28
V.....	.0007	.001	.0015	.005	.0015	.015	.012
Y.....	.02	.02	.07	.07	.07	.15	.046
Zr.....	<0.001	<0.001	.0015	.005	<0.001	<0.001	.013
Si.....	.15	.3	.15	.5	.5	.2	6.8
Al.....	.3	.07	.07	.3	.1	.1	2.3
Na.....	.15	.3	.2	.15	.15	.15	1.3
K.....	<0.7	<0.7	<0.7	<0.7	<0.7	<0.7	2.6
P.....	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	.6
Ce.....	.05	.15	.3	.5	.5	.7	.53
Yb.....	.0015	.002	.003	.003	.005	.007	.0075
Nd.....	.03	.03	.15	.2	.2	.3	.3
Sm.....	<0.01	<0.01	.03	.07	.07	.07	.05
Eu.....	<0.01	<0.01	.01	<0.01	<0.01	.015	.055
Gd.....	<0.005	<0.005	<0.005	.015	.02	.03	N.D.
Tb.....	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	N.D.
Dy.....	<0.005	<0.005	.015	.015	.015	.02	N.D.
Ho.....	<0.002	<0.002	.005	<0.002	<0.002	.007	N.D.
Er.....	<0.005	<0.005	.007	<0.005	.007	.015	N.D
ΣLREE[1]..	.13	.25	.643	.97	.97	1.385	1.53
ΣHREE[2]..	.0215	.022	.1	.103	.117	.229	.085
	Gamma ray spectrometric analyses (in parts per million)						
RaeU[3]..	0.4	0.6	6.69	1.2	4.5	2.7	26.
Th.....	14.	23.2	245.	224.	247.	250.	1500.

[1]ΣLREE--total light rare-earth and related elements: La+Ce+Nd+Sm+Eu.
[2]ΣHREE--total heavy rare-earth elements: Y+Yb+Gd+Tb+Dy+Ho+Er.
[3]RaeU--radium-equivalent uranium.

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TABLE 6.—*Mineralogy of carbonatites in diamond drill core from Gem Park, Wet Mountains area, Colorado*

[From Papson (1981, p. 18). C, common; M, moderately common; R, rare; VR, very rare]

Mineral	Formula	Abundance
Albite (low)..	$NaAlSi_3O_8$.....	R
Ancylite.....	$SrCe(CO_3)_2(OH)\cdot H_2O$.....	VR
Ankerite.....	$Ca(Fe^{+2},Mg,Mn)(CO_3)_2$.....	R
Barite.....	$BaSO_4$.....	R
Bastnaesite...	$(Ce,La)(CO_3)F$.....	R
Bornite.....	Cu_5FeS_4.....	VR
Calcite.....	$CaCO_3$.....	M
Celestite.....	$SrSO_4$.....	R
Chalcopyrite..	$CuFeS_2$.....	M
Dolomite.....	$CaMg(CO_3)_2$.....	C
Edenite.....	$NaCa_2(Mg,Fe^{+2})_5Si_7AlO_{22})(OH)_2$...	C
Fluorapatite..	$Ca_5(PO_4)_3F$.....	C
Fluorite.....	CaF_2.....	R
Hematite.....	α-Fe_2O_3.....	M
Lamprophyllite	$Na_2(Sr,Ba)_2Ti_3(SiO_4)_4(OH,F)_2$....	R
Magnetite.....	$Fe^{+2}Fe_2^{+3}O_4$	C
Marcasite.....	FeS_2.....	VR
Monazite.....	$(Ce,La,Nd,Th)PO_4$.....	R
Phlogopite....	$KMg_3Si_3AlO_{10}(F,OH)_2$.....	C
Pyrochlore....	$(Na,Ca)_2Nb_2O_6(OH,F)$.....	C
Pyrite.....	FeS_2.....	C
Pyrrhotite....	$Fe_{1-x}S$	R
Quartz.....	SiO_2.....	VR
Siderite.....	$FeCO_3$.....	VR
Sphalerite....	ZnS.....	VR
Strontianite..	$SrCO_3$.....	R
Zircon.....	$ZrSiO_4$.....	C

significant since no such concentrations have been reported in previous studies of the Gem Park Complex. Anomalous values of copper (mean=49 ppm) are also found. The intermediate carbonatite type is characterized by the presence of calcite, monazite, hematite, pyrite, bastnaesite, and low albite. This type has much more rare earths (mean >3.35 percent) than the oldest type, and three times as much niobium (mean=1,754 ppm). Copper values are about the same as the oldest type, but the uranium content is substantially less (highest value=3 ppm). Although of higher grade for niobium and rare-earth elements, this type occurs principally in small dikes. Larger masses of this carbonatite may occur elsewhere within the complex and could prove a potential source for these elements. The youngest carbonatite type occurs in dikes containing calcite, barite, and strontianite with accessory celestite, ancylite, and rhabdophane. It shows further enrichment in the rare-earth elements (mean >5.23 percent ΣREE) but much less niobium (mean=190 ppm). Copper is about the same as the two older types, but uranium is negligible. Addition of sulfate in this youngest type is indicated by barite and celestite in the carbonatites and a gypsum stockwork within the host gabbro.

ISOTOPIC RATIOS

Primary magmatic and replacement carbonatites in the Wet Mountains area form two distinct petrographic groups that also differ in their mineralogical and geochemical characteristics. These differences suggest the possibility of different origins for the two groups—perhaps the replacement carbonatites are hydrothermal, and the fluids transporting the carbonate and other components were derived from a source completely unlike that of the primary magmatic carbonatites. With this possibility in mind, several samples of primary magmatic and replacement carbonatites were analyzed for their oxygen and carbon isotopic contents by R.O. Rye (written commun., 1977) and by Irving Friedman (written commun., 1965), both of the U.S. Geological Survey. The results appear in table 9.

According to Deines and Gold (1973), the average $\delta^{13}C$ value for a large number of carbonatites is -5.1 per mil ($s=\pm 1.4$ per mil). This value is indistinguishable from values found in carbonates of kimberlite pipes and in diamond, indicating a deep-seated origin. The value for marine carbonates is near 0 per mil (Rye and Ohmoto, 1974). The $\delta^{13}C$ values for Wet Mountains primary magmatic and replacement carbonatites are nearly identical to one another and also indicate that the carbon had a deep-seated origin. If the replacement carbonatites have a hydrothermal origin, exchange of isotopes with other carbon reservoirs has not occurred to any great extent and changes in $\delta^{13}C$ due to variations in f_{O_2}, temperature, and other factors as shown by hydrothermal systems (Rye and Ohmoto, 1974) also have not occurred.

Primary unaltered igneous rocks typically have $\delta^{18}O$ values between +5.5 and +10.0 per mil (H. P. Taylor, Jr., 1974, p. 859) and $\delta^{18}O$ for Wet Mountains carbonatites fall in that range (table 9). Interaction with meteoric ground water ($\delta^{18}O$ for temperate fresh

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TABLE 7.—*Modal analyses, in volume percent, of 29 carbonatites in diamond drill cores from Gem Park, Wet Mountains area, Colorado*

[From Papson (1981, p. 19). Leaders (---), no analyses. X, present in amounts less than 1 percent]

	Sample Numbers														
Mineral	17.77.5	17.222.4	17.276.1	17.280.5	17-296.5	17.350.5	17.353.4	17.355.8	17-366	17-376.5	17-406.3	17-411.3	17-425.4	17-434.5	17-450
Dolomite.....	51.2	31.4	51.2	21.5	27.5	51.5	23.3	59.4	39.2	85.7	60.8	23.7	79.9	80.4	26.4
Apatite.....	33.7	39.6	19.4	54.5	32.8	39.2	41.0	20.3	39.8	5.9	8.3	42.0	4.4	0.2	44.5
Fluorite.....	---	8.4	0.7	---	---	---	---	20.3	7.3	---	---	---	0.3	0.2	0.8
Phlogopite (fresh).....	---	15.3	---	6.8	4.6	2.0	---	---	8.1	---	5.3	---	---	---	24.2
Phlogopite (altered)....	---	---	2.8	3.2	15.4	9.3	---	---	---	5.8	20.1	---	11.8	11.7	---
Pyrochlore.....	---	2.1	---	0.4	1.6	0.3	1.7	---	0.5	0.4	---	---	---	0.4	---
Zircon.....	---	3.1	---	---	---	---	---	---	X	---	---	---	---	---	---
Pyrite.....	1.3	X	12.7	0.4	X	X	4.0	---	---	---	12.3	0.8	X	1.0	---
Magnetite.....	---	X	6.5	8.6	16.9	0.1	20.5	---	3.3	1.8	6.8	0.7	2.4	0.5	2.3
Hematite.....	8.1	---	---	4.6	0.2	---	---	---	---	---	X	10.5	---	---	X
Chalcopyrite...	---	X	---	---	---	---	---	---	---	---	---	---	---	---	---
Calcite.....	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Bastnaesite....	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Monazite.....	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Albite (low)...	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Strontianite...	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Ancylite.....	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Others.....	5.7	0.1	6.7	---	1.0	6.9	0.2	---	1.8	0.4	6.5	2.2	1.2	5.6	1.8
Points counted	1230	1854	1466	1508	1336	1404	1419	1340	1931	1522	1464	1462	1485	1725	1449

	Sample Numbers														
Mineral	17-499	17-504.3	17-515.9	17-537.5	17-541.2A	17-541.2B	17-570.5	39-7	39-80	39-88	39-102	39-117	35-544.7	35-618	35-783.4
Dolomite.....	79.0	74.3	39.8	22.0	38.1	28.1	54.2	22.1	40.9	70.7	76.6	26.6	5.4	39.2	10.3
Apatite.....	1.1	7.6	10.3	36.9	25.0	50.0	10.1	---	29.3	---	---	27.1	13.6	9.9	---
Fluorite.....	0.1	3.7	X	---	0.6	---	3.1	---	---	---	---	---	---	---	---
Phlogopite (fresh).....	---	0.2	X	3.2	5.4	8.8	25.0	---	---	---	---	---	39.8	---	---
Phlogopite (altered).....	4.9	7.1	2.2	---	---	---	---	---	---	---	---	1.2	---	---	---
Pyrochlore.....	0.8	0.3	0.3	1.8	1.4	2.8	1.9	---	---	3.4	---	---	---	---	---
Zircon.....	---	0.1	0.4	0.3	1.0	---	---	---	---	---	---	---	---	---	---
Pyrite.....	X	---	---	12.5	6.5	---	---	---	---	---	---	---	---	---	---
Magnetite.....	6.6	3.9	43.7	11.9	8.0	1.2	0.1	---	---	---	---	---	---	---	---
Hematite.....	X	---	---	---	X	---	---	---	---	4.8	3.2	---	---	---	---
Chalcopyrite...	---	---	---	---	X	0.1	---	---	---	---	---	---	---	---	---
Calcite.....	---	---	---	---	---	---	---	59.3	---	---	---	41.8	---	32.7	25.1
Bastnaesite....	---	---	---	---	---	---	---	---	7.0	5.4	2.6	1.2	---	---	6.2
Monazite.....	---	---	---	---	---	---	---	13.8	---	1.4	4.6	2.1	12.1	10.1	0.3
Albite (low)...	---	---	---	---	---	---	---	4.1	19.7	14.3	11.9	---	---	---	---
Strontianite...	---	---	---	---	---	---	---	---	---	---	---	---	29.1	---	28.4
Ancylite.....	---	---	---	---	---	---	---	---	---	---	---	---	---	---	29.7
Others.....	7.5	2.9	3.6	23.8	8.7	1.5	5.6	0.7	3.1	---	1.1	---	---	8.1	---
Points counted	1436	1303	1959	1641	1977	2000	1350	1450	1461	1176	1512	1455	1079	1213	1300

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TABLE 8.—*Summary of geochemical data from carbonatites in diamond drill core from Gem Park, Wet Mountains area, Colorado*

[Data are in percent. ΣREE, total rare-earth elements; N.D., no data. Data and drill-hole locations from Papson (1981)]

Element	Average of 29 Gem Park samples	Drill Hole No. GP-17 (21 samples)	Drill Hole No. GP-35 (3 samples)	Drill Hole No. GP-39 (5 samples)	Average composition of carbonatites (Gold, 1963)
Fe.....	5.89	>6.52	2.667	5.2	5.12
Mg.....	4.95	5.48	2.833	4.0	3.40
Ca.....	>10.0	>10.0	>10.0	>10.0	25.10
Ti.....	0.083	0.078	0.008	0.148	0.48
Mn.....	0.314	0.281	0.3	0.46	0.47
Ba.....	0.328	0.0128	2.833	0.15	0.23
Co.....	0.0038	0.0035	0.002	0.0061	0.0017
Cr.....	0.0015	0.001	0.004	0.0021	0.0048
Cu.....	0.005	0.0049	0.006	0.0046	0.00025
La.....	>0.519	0.0888	>2.0	>1.44	0.0516
Nb.....	0.074	0.0584	0.019	0.1754	0.1951
Ni.....	0.0014	0.0011	N.D.	0.0032	0.0008
Pb.....	0.0014	0.0005	0.007	0.0016	N.D.
Sc.....	0.0021	0.0025	N.D.	0.0016	0.001
Sr.....	>2.31	1.619	>10.0	0.59	0.34
V.....	0.0088	0.0087	N.D.	0.0144	N.D.
Y.....	0.015	0.0164	0.0133	0.013	0.0096
Zr.....	0.0425	0.058	0.0007	0.0036	0.112
Si.....	0.731	0.764	0.35	0.82	5.66
Al.....	0.179	0.111	0.25	0.41	1.88
Na.....	0.384	0.302	0.667	0.56	0.31
K.....	0.576	0.262	1.67	1.24	1.24
P.....	2.84	3.476	1.5	1.0	0.90
Ce.....	>0.522	0.14	2.0	>1.24	0.15
Ga.....	0.0006	0.0006	0.0002	0.0007	0.0001
Yb.....	0.0007	0.0008	0.0008	0.0004	N.D.
Na.....	0.259	0.0821	1.067	0.52	N.D.
Th.....	0.0104	0.0067	0.0292	0.0146	N.D.
U.....	0.0018	0.00247	0.00002	0.001	N.D.
ΣREE	>1.39	0.3713	>5.226	>3.3468	N.D.

waters = −10 to −4 per mil; Taylor and others, 1967) or other nonigneous reservoirs of oxygen ($\delta^{18}O$ for marine limestone=+22 to +30 per mil; Taylor and others, 1967), appears to be minimal.

In figure 2, the $\delta^{13}C$ values for the carbonatites are plotted against $\delta^{18}O$ and compared with the field of PIC (primary igneous carbonatites) established by Taylor and others (1967). Two analyses of Iron Hill, Colo., primary magmatic carbonatite (Taylor and others, 1967) are also included for comparison. Values for Wet Mountains carbonatites plot near or just inside the field of PIC and are bracketed by values from the Iron Hill carbonatite. According to Taylor and others (1967), $\delta^{18}O$ values higher than those in the field of PIC, which are the same as primary magmatic carbonatites, may reflect late stage and secondary exchange

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TABLE 9.—*Oxygen and carbon isotopic compositions of carbonatites from the Wet Mountains area, Colorado*

[Data are in °/oo (per mil). SMOW, standard mean ocean water standard; PDB, Pee Dee belemnite standard. Analyses of WM-samples by Irving Friedman, analyses of remainder of samples by R.O. Rye, both of the U.S. Geological Survey]

Sample No.	$\delta^{18}O$(SMOW)	$\delta^{13}C$(PDB)
Primary carbonatite		
8B.....	9.3	-4.8
94B-2.....	10.0	-4.9
WM-24-63...	9.1	-3.2
WM-25-63...	7.1	-4.7
Replacement carbonatite		
106.....	8.3	-4.9
117.....	7.8	-4.9

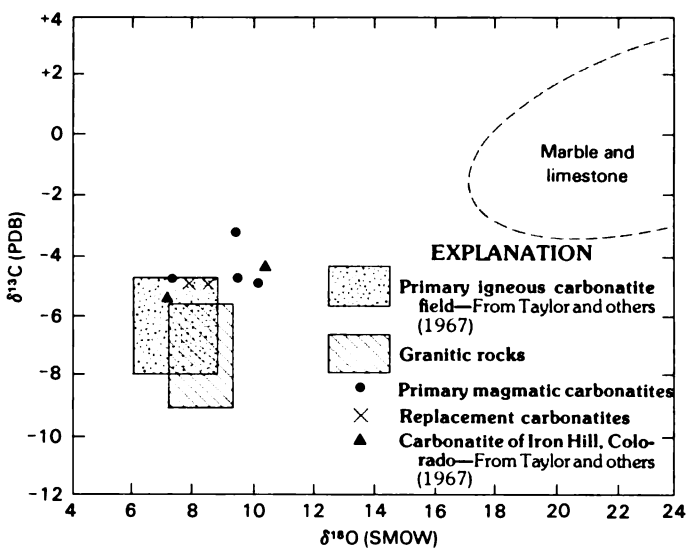


FIGURE 2.—Plot of $\delta^{13}C$ and $\delta^{18}O$ data from table 9. Diagram taken from Armbrustmacher (1979).

effects. Sheppard and Dawson (1973) suggested that $\delta^{13}C$ values beyond the PIC field may reflect isotopic heterogeneities of the deep-seated source zone. Blattner and Cooper (1974) suggested that it may be necessary to redefine the PIC field as new data become available. However, even if exchanges between carbonatite magma and the Precambrian host terrane did occur, and were sufficient to shift the $\delta^{18}O$ values outside the PIC field, the shift in the $\delta^{13}C$ values was not due to any such exchanges, because carbonate rocks are scarce in the Precambrian terrane. The ubiquitous fenitization offers the possibility of some $\delta^{18}O$ exchange with the host rock, but the effects probably could not be detected because of the similarities in the fields of PIC and of carbon in granitic rocks in figure 2.

RED SYENITE DIKES

As part of the study of thorium resources in the Wet Mountains area (Armbrustmacher, 1975, 1976; Staatz and others 1979, 1980), a number of anomalously radioactive red syenite dikes were found to contain small reserves of thorium. Red syenite dikes are commonly difficult to distinguish from fenite formed from alteration of granitic rocks adjacent to the alkaline complexes and adjacent to some other types of associated dikes and veins.

The red syenite dikes intrude Early Proterozoic metamorphic rocks, Precambrian intrusive granitic rocks, and rocks of the McClure Mountain and Gem Park Complexes. No red syenite dikes have been found intruding the syenites at Democrat Creek. This suggests an age between 535 and 511 m.y. However, Olson and others (1977, p. 680) have whole-rock K/Ar dates of 485±24 m.y., 560±28 m.y., and 427±22 m.y., and whole-rock Rb/Sr isochron of 495±10 m.y. for red syenites from the Wet Mountains area, so the age of the red syenites is uncertain.

According to Heinrich and Moore (1970), the red syenite dikes predate the carbonatite dikes and postdate the lamprophyre dikes. Indeed, a carbonatite dike intersects a red syenite dike and a lamprophyre dike contains red syenite xenoliths, which may have originally been part of a red syenite dike or a fragment of fenitized wall rock. Thus, it would seem that the carbonatites are the youngest dikes and the lamprophyre dikes are the oldest. The quartz-barite-thorite veins postdate red syenite dikes and will be discussed in the following pages.

The red syenites have been intruded along the system of fractures with a predominant northwest strike; most are south of the alkaline intrusive complexes. Some red syenite dikes persist for several kilometers along strike; others are difficult to trace for more than a few meters. Thicknesses are extremely variable but a thickness of about 1 meter is typical. At one locality, where a shaft has been sunk on a red syenite dike, the dike wedges out downward even though the fracture zone containing the dike persists. South of the alkaline intrusive complexes, the country rock is chiefly well-foliated Early Proterozoic metamorphic rocks, and the system of fractures is developed normal to the foliation. North

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of the alkaline intrusive complexes, the country rock is chiefly Precambrian intrusive granitic rocks lacking well-developed foliation, and the system of fractures is not nearly as well developed. This same fracture system is occupied by some of the carbonatite dikes, especially replacement carbonatites (Armbrustmacher, 1979), and by quartz-barite-thorite veins. The same fracture that contains a specific dike species or vein at one locality, may contain a different dike species or vein along strike. The same fracture system may have been reused by different intrusive events at slightly different times.

In the field, the red syenite dikes are obvious in outcrop because of their bright-red color. They also tend to be somewhat more resistant to erosion than the surrounding country rocks and stand in slight relief. Their color is caused by finely disseminated grains of red ferric iron oxide contained in the most abundant mineral, potassic feldspar. However, according to Heinrich and Moore (1970), similar-appearing rocks are also found in several different geologic settings in the Wet Mountains area. The similar-appearing rocks occur as dikes and irregular masses replacing granitic and biotitic gneisses, as composite feldspar rock-carbonatite bodies, and as dikes of fine-grained to aphanitic (phaneritic?) and porphyritic trachyte. These rocks probably represent different types of fenite, some in situ, some perhaps rheomorphic. Those rocks called red syenites in this study are not formed by replacement, and all come from dikelike bodies that have sharp, intrusive contacts with the enclosing country rock.

MINERALOGY

Heavy-mineral separates were made of a variety of rocks from red syenite dikes. For the most part, the total heavy-mineral fraction of red syenites was sparse compared to that of many other leucocratic rock types.

Many minerals are found in rocks from red syenite dikes; these are listed in table 10. Some of the minerals are primary, but some are part of a later episode of thorium- and rare-earth-element mineralization superimposed upon the red syenite dikes. This later mineralization is probably part of the same event that resulted in quartz-barite-thorite veins, discussed in an ensuing section. As mentioned earlier, the red syenite dikes occupy some of the same fracture zones as quartz-barite-thorite veins, and fairly high levels of radioactivity, due to thorium, occur in some of the red syenite dikes especially at fractured contacts between dike rock and country rock.

The most abundant mineral is potassic feldspar, chiefly microcline. In thin section, the potassic feldspar is turbid to varying degrees due to finely disseminated ferric iron oxide. Under the Luminoscope[1], with electron excitation, the potassic feldspar luminesces red, the activator element being ferric iron. This bright-red cathodoluminescence is characteristic of feldspars in fenites (Mariano, 1979) because the fenitizing solutions are enriched in ferric iron as well as alkali metals, and recrystallizing feldspar incorporates the ferric iron into its structure as an impurity. The ferric iron oxide causing the turbidity may also result from exsolution of excess ferric iron oxide in the feldspar structure with changing pressure-temperature conditions as well as from slightly later addition of ferric iron oxide along crystal-structural weaknesses. Determinations of composition and structural states of potassic feldspars by Moore (1969) showed a similarity of these properties between feldspars in fenite zones and feldspars in red syenite dikes. The potassic feldspars are chiefly maximum microclines containing less than 5 mol. percent albite (Moore, 1969, p. 99).

Albite may be fairly abundant in some rocks from red syenite dikes. It displays characteristic albite twinning, and it also may contain abundant finely disseminated ferric iron oxide grains. This sodic feldspar also displays bright-red cathodoluminescence with electron excitation under the Luminoscope. Moore's (1969) studies of compositions and structural state show the albites contain less than 3 mol. percent microcline and are similar to the highly ordered, low-temperature structural type of albite (Moore, 1969, p. 105).

Mafic minerals are rare and include a pleochroic green pyroxene that has all the optical properties of acmite and of biotite and its alteration product chlorite. The other rock-forming minerals listed in table 10 are chiefly accessory minerals that occur in amounts of less than 1 percent.

The epigenetic minerals (table 10) belong to the episode of thorium mineralization (Christman and others, 1959; Armbrustmacher, 1976, 1981). They are found in the red syenite dikes either along fractures, especially near the contact between dikes and country rocks, or as replacements of the original silicate minerals. Barite replaces potassic feldspar and may become a major constituent of the rock, but it is typically present in highly variable amounts. Calcite and dolomite may also replace potassic feldspar, but typically in amounts less than barite, and they occur as narrow veinlets. Quartz is interstitial to potassic feldspar, and the paragenesis is uncertain—it may be late-stage magmatic or hydrothermal, or it may be both. The rare-earth and thorium minerals are sparse and have been identified by X-ray diffraction techniques. The iron

[1]Nuclide Corp., model ELM-2B. Use of brand or trade names does not constitute endorsement by the U.S. Geological Survey.

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TABLE 10.—*Minerals in red syenite dikes in the Wet Mountains area, Colorado*

[Identifications are based on visual inspection and X-ray diffraction techniques. Query (?) means data are insufficient for positive identification]

Rock-forming minerals	Formula	Epigenetic minerals	Formula
Acmite.....	$NaFe^{+3}Si_2O_6$	Barite.....	$BaSO_4$
Albite.....	$NaAlSi_3O_8$	Bastnaesite(?)...	$(Ce,La)(CO_3)F$
Anatase.....	TiO_2	Brockite.....	$(Ca,Th,Ce)(PO_4)\cdot H_2O$
Biotite.....	$K(Mg,Fe^{+2})_3(Al,Fe^{+3})Si_3O_{10}(OH,F)_2$	Calcite.....	$CaCO_3$
Chalcopyrite.....	$CuFeS_2$	Dolomite.....	$CaMg(CO_3)_2$
Chlorite.....	$(Mg,Al,Fe)_{12}(Si,Al)_8O_{20}(OH)_{16}$	Galena.....	PbS
Fluorapatite.....	$Ca_5(PO_4)_3F$	Goethite.....	$\alpha\text{-}Fe^{+3}O(OH)$
Fluorite.....	CaF_2	Hematite.....	$\alpha\text{-}Fe_2O_3$
Potassic feldspar...	$KAlSi_3O_8$	Lepidocrocite....	$\gamma\text{-}Fe^{+3}O(OH)$
Pyrite.....	FeS_2	Quartz.....	SiO_2
Rutile.....	TiO_2	Thorite.....	$ThSiO_4$
Xenotime.....	YPO_4		
Zircon.....	$ZrSiO_4$		

oxide minerals and interstitial ferric oxide stain are at least partly products of weathering, but the presence of hydrothermal specular hematite in quartz-barite-thorite veins suggests a hydrothermal genesis for some of the hematite in the red syenite.

GEOCHEMISTRY

The mean and range of 46 analyses of rocks from red syenite dikes are given in table 11. For comparison, data for the average igneous rock of the upper continental crust (Wedepohl, 1971, p. 65) are also given.

Rocks from the red syenite dikes contain more than 3 times as much barium, beryllium, lanthanum, niobium, lead, yttrium, zirconium, phosphorus, cerium, ytterbium, ΣLREE, ΣHREE, thorium, and uranium than the average igneous rock (table 11). All these elements, except perhaps phosphorus and zirconium, are probably present in relatively large amounts in the epigenetic minerals (table 10). The minor element content of the red syenites cannot be meaningfully compared to that of either the hornblende-biotite syenite or the nepheline syenite because of hydrothermal addition of some of these elements to the red syenite. Thus, it is not possible to test the idea that the red syenites may be more highly fractionated products of magmas that produced either of the other syenites. Kinship with Precambrian rocks cannot be tested for the same reasons.

A whole-rock rubidium-strontium isochron of red syenites given by Olson and others (1977, p. 683) yields an initial $^{87}Sr/^{86}Sr$ ratio of 0.7048 and a whole-rock date of 495±10 m.y. When compared with initial $^{87}Sr/^{86}Sr$ ratios of other rocks from the Wet Mountains area (Armbrustmacher and Hedge, 1982), the ratio of the red syenite is nearly identical to ratios for a plagioclase-clinopyroxene cumulate (0.70477) at Iron Mountain and for a sample of hornblende-biotite syenite (0.70475) both in the McClure Mountain Complex. This suggests that these rocks have been derived from a similar magmatic source. If the red syenites had been derived from rheomorphic fenites, the initial $^{87}Sr/^{86}Sr$ ratios would be expected to have values nearer that of crustal rocks.

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TABLE 11.—*Arithmetic means and ranges of 46 analyses, in percent, of rocks from red syenite dikes in the Wet Mountains area, Colorado*

[Data are in percent. All elements except Th and RaeU determined by semiquantitative spectrographic analysis; Th and RaeU determined by gamma-ray spectrometric analysis; igneous rocks in the upper continental crust from Wedepohl (1971, p. 65)]

Element	Red syenite		Average igneous rock
	Mean	Range	
Ba.....	0.33	0.003-7.	0.059
Be.....	.0019	<0.0001-0.02	.0002
Co.....	.0006	<0.0005-0.002	.0012
Cr.....	.0029	<0.0001-0.015	.007
Cu.....	.0019	.0001-0.015	.003
La.....	.02	<0.005-0.15	.0044
Mo.....	.0003	<0.0003-0.002	.0001
Nb.....	.022	<0.001-5.	.002
Ni.....	.0015	<0.0005-0.01	.0044
Pb.....	.011	<0.001-1.	.0015
Sc.....	.001	<0.0005-0.005	.0014
Sr.....	.039	.0007-2.	.029
V.....	.0066	<0.0005-0.02	.0095
Y.....	.051	<0.002-0.7	.0034
Zr.....	.058	.0015-0.5	.016
P.....	.27	<0.2-3.	.081
Ce.....	.031	<0.01-0.15	.0075
Ga.....	.003	.001-0.01	.0017
Yb.....	.0041	<0.0002-0.03	.00034
ΣLREE[1]..	.078	<0.06-0.5	.0165
ΣHREE[2]..	.077	<0.05-1.	.0059
Th.....	.27	.011-4.	.0011
RaeU[3] ...	.0034	<0.0002-0.04	.00035

[1] ΣLREE, total light rare-earth elements.
[2] ΣHREE, total heavy rare-earth elements.
[3] RaeU, radium-equivalent uranium.

QUARTZ-BARITE-THORITE VEINS AND FRACTURE ZONES

Quartz-barite-thorite veins and fracture zones contain the largest resources of thorium in the Wet Mountains area. They form a continuous series ranging from solid quartz-barite-thorite veins at one extreme to fracture zones devoid of obvious megascopic gangue minerals at the other. They most likely would be the first type of deposit to be exploited.

The distribution of vein minerals along strike is irregular and unpredictable, and thus it is difficult to determine how well a sample represents a particular vein. Workings on any vein and fracture zone are not extensive; few underground workings are accessible. Little ore-grade material exists on the dumps, because the ore that was mined was hand sorted.

Quartz-barite-thorite veins and thorium-bearing fracture zones have not been found east of the Ilse fault nor west of the Texas Creek and Westcliffe faults. The northern limit of their outcrop is probably near the Amethyst carbonatite deposit (pl. 1) and the southern limit is probably near the Custer–Huerfano County line. Thorium-bearing veins and fracture zones typically strike normal to the pronounced foliation in the Proterozoic metasedimentary rocks and have a vertical dip. Veins and fracture zones appear to be more abundant south of the alkaline complexes because of the greater abundance of foliated metasedimentary and metavolcanic rocks; the terrain north of the complexes has more of the Proterozoic intrusive igneous rocks that are not foliated. Veins and fracture zones appear to cut across rocks of Proterozoic age and rocks of the alkaline complexes, but no thorium-bearing veins and fracture zones have been found in Tertiary volcanic or sedimentary rocks. Thus, the quartz-barite-thorite veins and fracture zones appear to be products of the youngest event associated with the episode of alkaline magmatism that also produced rocks of the McClure Mountain Complex, Gem Park Complex, the complex at Democrat Creek, and dikes of carbonatite, lamprophyre, and red syenite.

MINERALOGY

Two types of minerals have been identified in heavy-mineral separates prepared from rocks from quartz-barite-thorite veins and fracture zones (table 12). One type is made up of epigenetic minerals that were deposited by hydrothermal fluids; the other type is made up of minerals contained in the host rocks of the veins and fracture zones. These minerals are especially abundant in rocks collected from fracture zones where epigenetic minerals are sparse.

The most abundant epigenetic mineral in the thorium-rich veins is smoky quartz. This mineral formed fairly early in the paragenetic sequence and is commonly seen lining the walls of a vein with euhedral, singly terminated crystals projecting from the walls toward the vein interior. At the Little Maude claim (pl. 1), euhedral smoky quartz crystals project into vugs, are stained red, and commonly attain a diameter of 10 cm. The crystal faces are etched, and the crystals are strongly zoned parallel to crystal faces. In thin section, quartz

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TABLE 12.—*Mineralogy of quartz-barite-thorite veins and fracture zones in the Wet Mountains area, Colorado*

[Query (?) indicates insufficient data for adequate identification]

Epigenetic minerals	Formula	Host rock minerals	Formula
Ancylite(?).....	$SrCe(CO_3)_2(OH)\cdot H_2O$	Acmite.....	$NaFe^{+3}Si_2O_6$
Barite.....	$BaSO_4$	Anatase.....	TiO_2
Brockite.....	$(Ca,Th,Ce)(PO_4)\cdot H_2O$	Biotite.....	$K(Mg,Fe^{+2})_3(Al,Fe^{+3})Si_3O_{10}(OH,F)_2$
Calcite.....	$CaCO_3$	Chlorite.....	$(Mg,Al,Fe)_{12}(Si,Al)_8O_{20}(OH)_{16}$
Cerussite.....	$PbCO_3$	Epidote.....	$Ca_2(Al,Fe^{+3})_3(SiO_4)_3(OH)$
Chalcopyrite.....	$CuFeS_2$	Garnet.....	$Mg_3Al_2(SiO_4)_3$
Dolomite.....	$CaMg(CO_3)_2$	Ilmenite.....	$Fe^{+2}TiO_3$
Fluorapatite.....	$Ca_5(PO_4)_3F$	Magnetite.....	$Fe^{+2}Fe_2^{+3}O_4$
Galena.....	PbS	Muscovite.....	$KAl_2(Si_3Al)O_{10}(OH,F)_2$
Goethite.....	$\alpha\text{-}Fe^{+3}O(OH)$	Potassic feldspar.....	$KAl_2Si_3O_8$
Hematite.....	$\alpha\text{-}Fe_2O_3$	Quartz (clear, milky)..	SiO_2
Jarosite(?).....	$KFe_3^{+3}(SO_4)_2(OH)_6$	Rutile.....	TiO_2
Magnesite(?).....	$MnCO_3$	Sphene.....	$CaTiSiO_5$
Monazite.....	$(Ce,La,Nd,Th)PO_4$	Vermiculite.....	$(Mg,Fe^{+2},Al)_3(Al,Si)_4O_{10}(OH)_2\cdot 4H_2O$
Potassic feldspar...	$KAlSi_3O_8$	Zircon.....	$ZrSiO_4$
Pyrite.....	FeS_2		
Quartz (smoky).....	SiO_2		
Siderite.....	$FeCO_3$		
Sphalerite.....	$(Zn,Fe)S$		
Synchysite.....	$(Ce,La)Ca(CO_3)_2F$		
Thorite.....	$ThSiO_4$		
Xenotime.....	YPO_4		

is seen to contain abundant two-phase fluid inclusions. Detailed studies of one sample of quartz by C.G. Cunningham, Jr. (written commun., 1976), showed a bimodal population of fluid inclusions consisting of low temperature, moderate salinity, two-phase inclusions and moderate temperature, CO_2-rich inclusions. The two-phase inclusions have homogenization temperatures ranging from 118 to 145 °C; the most common temperature is about 125 °C. Salinities range from 8.4 to 15.1 weight percent NaCl equivalent; the most common salinity is near 12 weight percent. The CO_2-rich inclusions have partial homogenization behavior to a liquid CO_2 phase at 27.5 to 29.8 °C. Cunningham stated that most of the CO_2-rich inclusions would

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homogenize to a vapor phase but final homogenization temperatures were not obtained because of decrepitation above 200 °C. Cunningham also suggested that both the two-phase inclusions and the CO_2-rich inclusions are primary and may represent effervescence of CO_2, possibly causing deposition of the quartz and associated ore minerals.

Barite occurs in highly variable amounts in the quartz-barite-thorite veins. It may be the dominant mineral, such as at the Big Chief claims (pl. 1) where the veins were originally prospected for barite, or it may be virtually absent, such as at the Little Maude claim (pl. 1). In veins that have smoky quartz crystals growing from vein walls, the interstices between the quartz crystals are usually filled with barite, indicating that the barite is younger than the smoky quartz in those veins. In other deposits the paragenetic sequence is not so obvious. Barite is chiefly white or pink, but in a few instances it is bright orange. Veins that have a high barite/quartz ratio tend to contain smaller amounts of thorium. Although mineral analyses are not available, the barite appears to be quite pure and may be suitable for some industrial uses, but none of the deposits in the Wet Mountains area appear to contain sufficient tonnages.

Primary hematite is a common constituent of the thorium deposits, but it never exceeds a few percent in abundance. Secondary iron oxides are also fairly abundant. Goethite is generally the most common mineral. Other secondary minerals include hematite and noncrystalline iron and manganese oxides. The presence of primary hematite suggests that the fluids depositing the vein materials had high f_{O_2} and that deposition occurred within the hematite stability field.

Thorite has a characteristic dark-red color and waxy luster. Generally it is closely associated with the secondary iron oxides and can be most easily identified using X-ray diffraction techniques. At many localities strongly radioactive, bright-red iron-oxide-rich material yields no X-ray diffraction pattern characteristic of thorite until the material is heated for 1 hour at 1,000 °C, which indicates that the thorite is in a metamict form. Thorite is typically highly variable in distribution, both along strike and along dip. Prospect pits were only dug at localities where radioactivity was high, which indicated that thorite was abundant; however, most of the thorite was subsequently removed by hand sorting of the vein material by the prospectors. It was available in large amounts for study and analysis only at the Schwarz Ranch (pl. 1), where thorite-rich material had been stockpiled.

Potassic feldspar is found in variable amounts and may have originated from several different sources. Some potassic feldspar appears to have a hydrothermal origin and is primarily microcline with abundant disseminated grains of red ferric oxide. This gives the feldspar a distinctive pink to red color. The mineralizing hydrothermal solutions have caused alteration of host rock identical in every respect to fenitization immediately adjacent to veins and within fracture zones. The hydrothermal alteration of host rock feldspars produces potassic feldspars indistinguishable from that which crystallized from hydrothermal fluids.

Galena is a common, though sparse constituent of many veins. It appears to be more directly associated with barite than with the other gangue minerals. In a few occurrences it is partly or entirely altered to cerussite. Other sulfide minerals, including sphalerite, chalcopyrite, and pyrite, have been found in heavy-mineral separates of some vein and fracture zone samples, but they are neither common nor abundant.

Several types of carbonate gangue minerals and fluorapatite have been found in various veins and fracture zones. They are not very common nor are they abundant. Their parageneses are uncertain, and it is difficult to determine whether they are related to the thorium ore-forming process.

The thorium- and(or) rare-earth-bearing minerals have been identified exclusively by X-ray diffraction techniques. The possibility of additional mineral varieties associated with those identified, but present in trace amounts, is not discounted. Brockite, synchysite, ancylite(?), monazite, and xenotime are chiefly associated with ferric iron oxides, and apparently they form relatively late in the mineral paragenesis. Brockite, the thorium-bearing analog of rhabdophane, was originally first described from the Wet Mountains area (Fisher and Meyrowitz, 1962).

GEOCHEMISTRY

Barium, beryllium, lanthanum, lead, yttrium, cerium, ytterbium, and thorium occur in veins and fracture zones in amounts at least eight times greater than that in average igneous rocks (table 13). Copper and niobium are enriched by a factor of four. The ΣLREE and ΣHREE are also considerably more abundant. All of the selected elements occur in anomalous amounts in at least some samples (table 13).

Comparisons of element abundance of the thorium deposits of the Wet Mountains area with other thorium districts is possible only in a general way because of a lack of data. Comparisons based on thorium resources (Staatz and others, 1979, 1980) will be discussed later in this report. Staatz (1974) showed that some common mineralogical and geochemical traits were shared by thorium veins from various U.S. districts. In addition

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TABLE 13.—*Arithmetic means and ranges of selected elements in 201 samples of quartz-barite-thorite veins and fracture zones from the Wet Mountains area, Colorado*

[All values in parts per million. Average igneous rock gives abundances of elements in igneous rocks of the upper continental crust as determined by Wedepohl (1971, table 7.3, p. 65). Enrichment factor equals arithmetic mean/average igneous rock. Leaders (---) indicate insufficient data]

Element	Mean	Range	Average igneous rock	Enrichment factor
Ba.....	51,615	70->100,000	590	87
Be.....	21	1.5-500	2	10
Co.....	17	<2-100	12	1.4
Cr.....	86	<1-1,500	70	1.2
Cu.....	125	<1-3,000	30	4
La.....	381	<30->30,000	44	9
Nb.....	81	<7-2,000	20	4
Ni.....	71	<5-1,500	44	1.6
Pb.....	2,902	<10-100,000	15	194
Sc.....	22	<3-300	14	1.6
Sr.....	635	<5-7,000	290	2.2
V.....	139	<5-7,000	290	0.5
Y.....	788	<10->20,000	34	23
Zr.....	310	<10-7,000	160	1.9
Ce.....	608	<100-20,000	75	8
Ga.....	12	<5-70	17	0.7
Yb.....	77	<1-3,000	3.4	23
[1]ΣLREE..	1,760	0-58,650	164.6	11
[2]ΣHREE..	1,191	0-47,600	60.1	20
Th.....	4,042	0-67,652	11	368
[3]RaeU...	([4])	<5-360	3.5	---

[1]Light rare-earth elements: La, Ce, Pr, Nd, Sm, Eu.
[2]Heavy rare-earth elements: Y, Yb, Gd, Tb, Dy, Ho, Er, Tm, Lu.
[3]Radium-equivalent uranium.
[4]Values were obtained for only 27 percent of the samples because the U photopeaks in the rest were obscured by those of Th.

to thorium, the rare-earth elements, barium, copper, and lead appear to be fairly common constituents of thorium veins. If better analytical data were available, niobium would probably also be found to be a characteristic constituent of many thorium veins.

SELECTED VEIN-FRACTURE ZONE OCCURRENCES

The detailed mapping and sampling done for this study and for previous studies focused on the most important thorium deposits—those most likely to be worked if economic conditions warranted. The following text discusses five of these deposits.

HAPUTA RANCH AREA

The Haputa Ranch area (near lat 38°08'45" N., long 105°16'15" W.) is reported to be the site at which radioactive minerals were first discovered in the Wet Mountains area (Christman and others, 1953). Earlier reports (Christman and others, 1953; Christman and others, 1959) discussed the results of a surface sampling program by the U.S. Geological Survey and a diamond-drilling project by the U.S. Bureau of Mines conducted during 1950-52. For the current study, additional samples were collected from some of the same localities for chemical and mineralogical studies.

The thorium deposits at the Haputa Ranch consist of several en echelon, branching fracture zones (fig. 3), three of which have been extensively explored by dozer cuts and diamond drilling. Although the fracture zones are as wide as 8 m, the strongly radioactive parts seldom exceed about 1 m. Similar structures occur on strike with these fracture zones across alluvial valleys toward the northwest and southeast. The near-vertical fracture zones cut the foliation of the host Proterozoic granitic gneisses and amphibolite at nearly right angles. In places they are closely associated with altered mafic dikes; both probably occurred along the same fracture system. Within the fracture zone, the granitic gneisses are altered and replaced by iron-oxide-bearing potassic feldspar. This altered rock emits a fetid odor when struck with a hammer. Lenses of amphibolite host rock are also altered to vermiculite, and a few excavations were dug by prospectors to determine the quality of the vermiculite.

The fracture zones contain younger, more or less unfractured veins rarely exceeding about 10 cm in thickness. Some of the veins predominantly contain barite; some predominantly contain quartz. Other minerals in the veins and fracture zones include both specular and earthy hematite, galena, and thorite; potassic feldspar, rutile, zircon, magnetite, and an altered mica occur in the fenitized host rock within the fracture zone. The fracture zones are strongly oxidized and altered; therefore, recovery and identification of mineral species is somewhat hindered.

Partial chemical analyses of 10 samples of fracture zones and veins from the Haputa Ranch area are given in table 14. The Haputa Ranch deposits contain considerably more niobium, yttrium, ytterbium, and ΣHREE than the mean values for all vein samples and fracture zones in the Wet Mountains area (table 13). In addition, the ΣLREE to ΣHREE ratio, which is typically greater than 1, reflects the atypical abundance of heavy rare-earth elements relative to light rare-earth elements. The lack of identifiable rare-earth minerals in the veins and fracture zones hampers attempts to explain the anomalous rare-earth distribution in these rocks.

Shear zone no. 1 (fig. 3) averages 0.608 percent ThO_2 based on the analytical data from surface and drill hole

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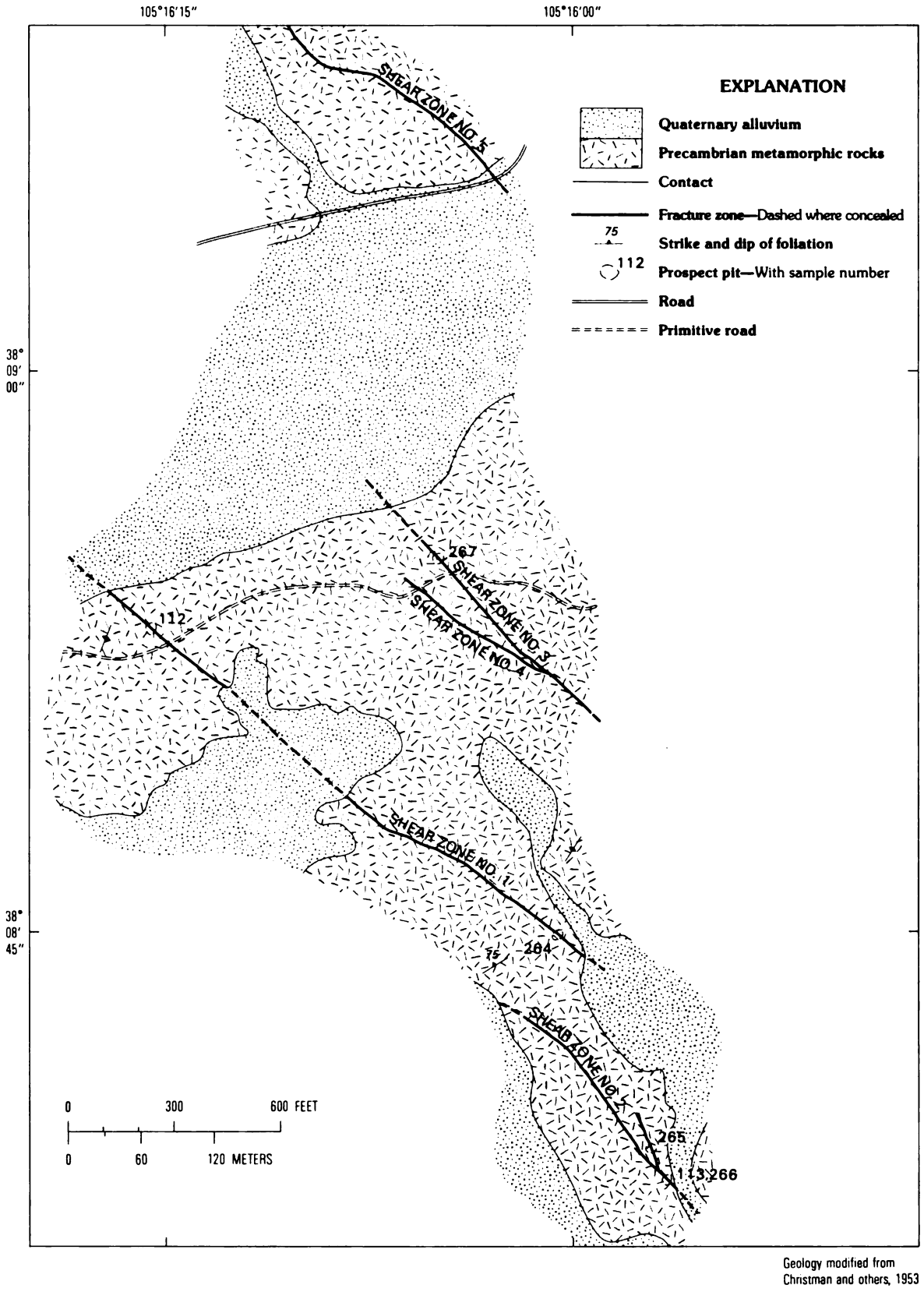


FIGURE 3.—Geologic map and sample localities of thorium deposits at the Haputa Ranch, Wet Mountains area, Colorado. Location shown on plate 1.

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TABLE 14.—*Abundance of selected elements in samples from fracture zones in the Haputa Ranch area, Wet Mountains area, Colorado*

[Sample localities shown on plate 1 and figure 3. Arithmetic means calculated by replacing >20,000 with 30,000, >10,000 with 15,000, and <50 with 30. Enrichment factor equals arithmetic mean/average igneous rock. Analyses for Th by C.M. Bunker and C.A. Bush, all other analyses by H.G. Neiman and N.M. Conklin]

Element	Sample No. 112	113A	113B	263A	263B	264A	264B	265	266	267	Arithmetic mean	Enrichment factor
Ba.....	>20,000	20,000	50,000	50,000	>20,000	20,000	70,000	20,000	300	>20,000	68,030	115
Be.....	50	15	7	30	10	20	15	200	7	5	36	18
Co.....	10	15	20	30	15	30	15	70	30	15	25	2
Cr.....	70	70	50	700	70	150	150	300	70	150	178	3
Cu.....	50	100	50	150	70	150	30	300	70	150	112	4
La.....	30	70	50	150	70	300	70	70	1500	150	246	6
Nb.....	150	200	150	2,000	300	500	700	70	30	300	440	22
Ni.....	50	70	50	200	70	150	30	150	70	30	87	2
Pb.....	200	3,000	1,000	2,000	300	3,000	700	3,000	150	3,000	1,635	109
Sc.....	15	30	15	150	20	70	70	70	20	20	48	3
Sr.....	1,500	300	700	500	1,500	500	700	300	300	700	700	7
V.....	150	200	150	1,500	150	300	200	500	150	300	360	2
Y.....	1,500	5,000	1,500	>10,000	5,000	10,000	1,500	300	500	1,500	4,180	123
Zr.....	200	500	200	1,500	300	700	500	300	150	30	438	3
Ce.....	<50	150	<50	300	150	700	150	150	3,000	500	530	7
Ga.....	15	20	15	70	30	70	50	30	50	30	38	2
Yb.....	70	300	100	3,000	700	1,000	150	15	50	150	554	163
[1]ΣLREE...	80	470	120	3,100	370	2,000	370	320	7,000	950	1,478	9
[2]ΣHREE...	1,905	6,360	1,930	47,600	7,990	14,100	2,320	535	700	2,370	8,581	143
Th.....	1,630	14,500	2,170	6,350	2,700	23,000	1,069	2,050	13,200	1,880	6,855	623

[1]Light rare-earth elements: La, Ce, Pr, Nd, Sm, Eu.
[2]Heavy rare-earth elements: Y, Yb, Gd, Tb, Dy, Ho, Er, Tm, Lu.

SAMPLE DESCRIPTIONS

112. Barite vein within fracture zone.
113A. High-grade sample collected near NE-corner of dozer cut; dark red to black vein material in fracture zone.
113B. Composite sample across 1-m-wide fracture zone.
263A. Composite sample across 1-m-wide fracture zone.
263B. Composite sample across 1-m-wide fracture zone 0.5 m from 263A in same zone.
264A. Dark gray, 5-cm-wide vein in fracture zone.
264B. Composite sample across 2-m-wide fracture zone.
265. Small, anomalously radioactive dump beside incline sunk for vermiculite.
266. Composite sample from radioactive dump.
267. Composite sample from vein material in dump.

samples given by Christman and others (1953) and new analytical data in table 14. The zone is 1,765 feet long,[2] averages 12.5 feet wide, and is known from the drilling to persist to an average depth of 277 feet. It is assumed that there are 12 ft^3 per ton of ore material. Shear zone no. 1 thus contains reserves of 3,100 tons of ThO_2. Shear zone no. 2 is 700 feet long, 5 feet wide, and at least 125 feet deep. This shear zone averages 0.51 percent ThO_2 and this zone thus could yield 185 tons of ThO_2. Shear zones no. 3 and 4 are 925 feet long, 2.5 feet wide, and 225 feet deep. Samples average 0.077 percent ThO_2 yielding about 33 tons of ThO_2. Shear zone no. 5 is 775 feet long, about 2 feet wide, and 125 feet deep. It averages only about 0.056 percent ThO_2 yielding less than 10 tons of ThO_2. In summary, the shear zones at the Haputa Ranch contain reserves of about 3,325 tons of ThO_2.

[2]Inch-pound units are preferred to SI units in reserve calculations.

TUTTLE (OR LEPLEY) RANCH AREA

The Tuttle Ranch (owned by Ed Lepley in 1975) is located near lat 38°16'19" N., long 105°18'53" W. Radioactive deposits were first detected here in 1950 by G.B. Gott and L.F. Dellwig (Christman and others, 1953). These deposits have been sampled only at shallow prospect pits and dozer cuts; no drilling has been done.

The veins and fracture zones (fig. 4) cut across the Precambrian layered gneisses, migmatites, and amphibolites at nearly right angles to their predominant northeast foliation. Most of the veins are 1 m thick or less, and all have a vertical dip. Strike of the major shear zone at the Tuttle (Lepley) Ranch is about N. 45° W.

The chief radioactive mineral in the vein-fracture zones is thorite; no other thorium-bearing mineral has been identified. The principal gangue mineral is quartz: clear, euhedral quartz is followed paragenetically by euhedral, smoky quartz and(or) red-stained quartz.

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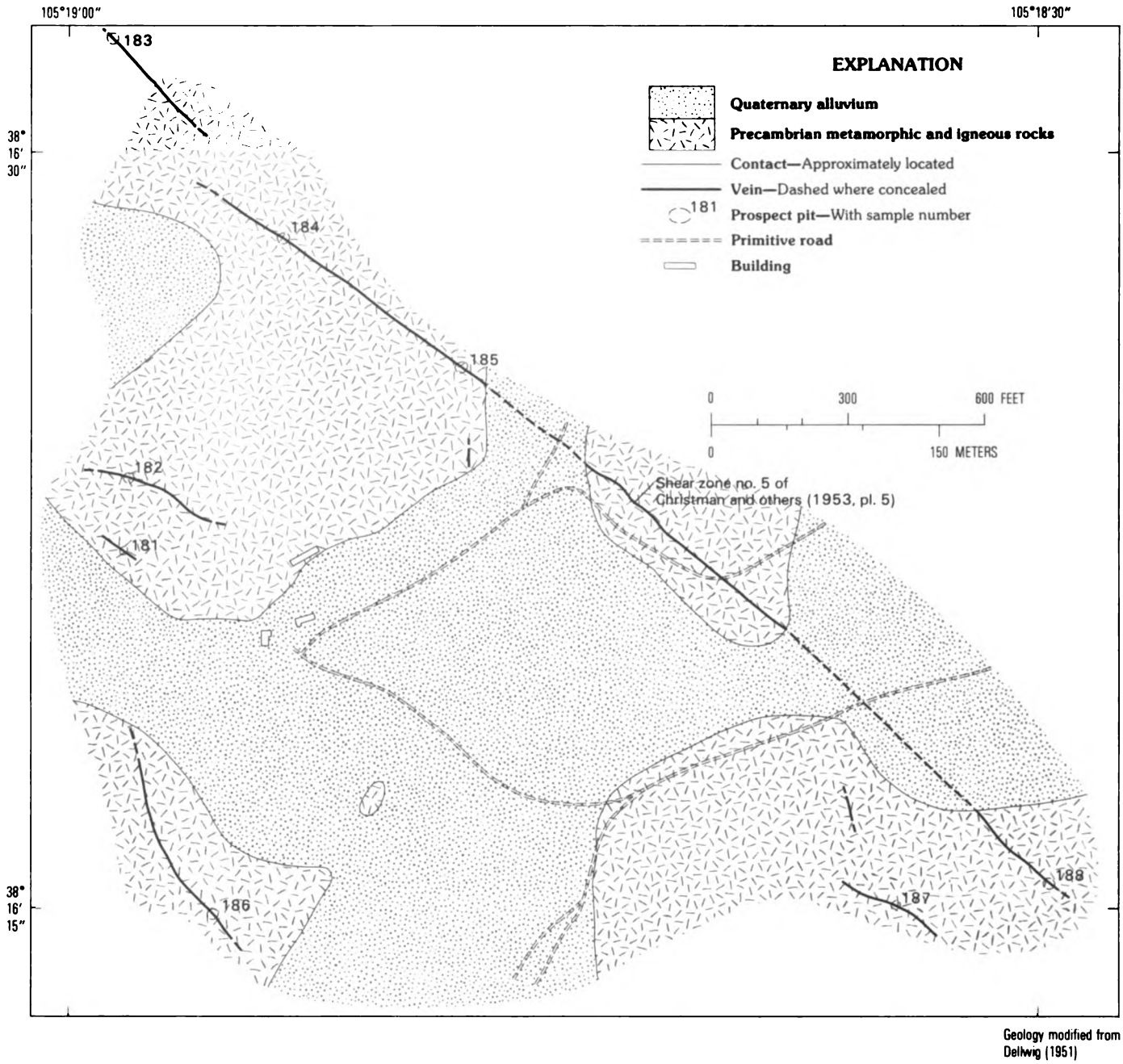


FIGURE 4.—Geologic map and sample localities of thorium deposits at the Tuttle (Lepley) Ranch, Wet Mountains area, Colorado. Location shown on plate 1.

Other vein minerals include colorless and pink barite, calcite, specular hematite, pyrite, goethite, and rutile. Minerals identified in the samples that are probably part of the altered country rock include pink potassic feldspar, quartz, biotite, garnet, and zircon.

Thorium abundances in the samples (table 15) range from about 38 to almost 20,000 parts per million (table 16). The average thorium abundance of the Tuttle (Lepley) Ranch area is about 15 percent greater than the average thorium abundance in the total samples from veins and fracture zones in the entire Wet Mountains area (table 13). Comparing enrichment factors of the samples at the Tuttle (Lepley) Ranch with enrichment factors of the total samples, it can be seen that Tuttle (Lepley) rocks contain considerably less average lead and barium. Beryllium, zirconium, and thorium are

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TABLE 15.—*Abundance of selected elements in samples from veins and fracture zones in the Tuttle (Lepley) Ranch area, Wet Mountains area, Colorado*

[Sample localities shown on plate 1 and figure 4. Enrichment factor equals arithmetic mean/average igneous rock. Arithmetic means calculated by replacing >10,000 with 15,000, <2 with 1.5, <20 with 15, <100 with 70, and <5 with 3. Analyses for Th by C.M. Bunker and C.A. Bush; all other analyses by L.A. Bradley. N, not detected]

Element	Sample No. 181	182	183	184	185	186	187	188B	188C	Arithmetic mean	Enrichment factor
Ba.....	1000	>10,000	1500	1500	3000	>10,000	7000	700	1000	5078	14
Be.....	5	1	50	1	20	200	50	30	15	41	20
Co.....	15	<2	2	5	15	7	7	30	7	10	.8
Cr.....	30	2	30	30	70	20	30	150	30	44	.6
Cu.....	30	30	7	70	70	70	15	300	100	77	3
La.....	70	<20	N	70	300	300	100	300	500	187	4
Nb.....	70	<5	7	150	150	30	70	300	100	98	5
Ni.....	15	<2	10	10	15	30	7	200	20	34	.8
Pb.....	100	200	15	150	500	50	100	70	150	156	10
Sc.....	5	<2	10	7	15	10	10	10	10	9	.6
Sr.....	30	2000	100	300	500	2000	500	200	500	681	2
V.....	70	5	70	70	1500	50	50	150	50	224	2
Y.....	50	<5	50	5000	700	500	200	100	500	789	23
Zr.....	200	<5	150	500	300	150	1500	700	5000	945	6
Ce.....	150	<100	<100	300	500	500	200	300	700	317	4
Ga.....	10	<2	<2	20	30	<2	30	30	20	16	.9
[1]ΣLREE...	320	N	N	670	1100	1250	550	800	1700	710	4
[2]ΣHREE...	57	N	55	6080	1200	860	490	230	157	1014	17
Th.....	547.3	38.5	1764	548.7	19600	2350	5950	2237	9300	4704	428

[1]Light rare-earth elements: La, Ce, Pr, Nd, Sm, Eu.
[2]Heavy rare-earth elements: Y, Yb, Gd, Tb, Dy, Ho, Er, Tm, Lu.

SAMPLE DESCRIPTIONS

181. Fracture zone 1 m thick partly cemented by clear, vuggy quartz.
182. Vein, 0.5 m thick; contains barite, pink potassic feldspar, maroon iron oxide.
183. Fracture zone, 1 m thick with 2 cm thick quartz vein.
184. Vein, 1 m thick; contains quartz, pink potassic feldspar, reddish brown iron oxide.
185. Vein, 1 m thick; contains quartz, pink potassic feldspar.
186. Vein sample from dump; consists of barite and maroon iron oxide.
187. Vein sample from dump; contains abundant feldspar, iron oxide.
188B. Fracture zone 1.5 m thick containing abundant clayey gouge.
188C. Fracture zone material on dump, rich in iron oxide.

somewhat more abundant. Although the average ΣLREE to ΣHREE ratio is less than 1.0, more than half the samples have a ΣLREE to ΣHREE ratio greater than 1; that is the ΣHREE are more enriched than ΣLREE.

The most prominent structure at the Tuttle (Lepley) Ranch, termed shear zone no. 5 by Christman and others (1953, pl. 5), is about 2,700 feet long, averages about 3 feet wide, and, based on drilling information from the Haputa Ranch deposits, is assumed to continue essentially unchanged to a depth of 250 feet. The average thorium abundance, based on eleven analyses, is 0.69 percent ThO_2. These data yield reserves of 1,165 tons ThO_2 in shear zone no. 5. The other shear zones combined yield about 125 tons ThO_2.

BEARDSLEY DEPOSIT

The Beardsley deposit is located near the southwest corner of the Haputa Ranch property at lat 38°07'30" N. and long 105°18'30" W. It is one of the few deposits that has been developed underground, although the underground workings are not extensive and caving has made the workings inaccessible. In addition to collecting samples from exposures of the vein, radioactivity

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measurements were made with a scintillation counter across a dozed area over the deposit in order to delineate the extent of anomalous radioactivity (fig. 5). Background measurements were made over unmineralized granitic gneiss host rock and averaged 270 counts per second.

The Beardsley deposit consists of a strongly radioactive zone of fenitized granitic gneiss up to 8 m wide surrounding several narrow en echelon zones 0.5 m wide that contain abundant vein minerals in thin veinlets. The structure strikes N. 35–40° W. and appears to dip nearly vertically. Bedrock away from the immediate vicinity of the dozed area is poorly exposed.

Narrow radioactive veins contain abundant potassic feldspar, along with smoky quartz and barite. Other minerals include hematite, goethite, cerussite, and brockite(?). Table 16 gives the results of analyses of one sample (79A) taken from a mineralized fracture zone of the Beardsley deposit. The fracture zone contains small veins of quartz, barite, and thorite. Sample 79A contained anomalous amounts of barium, lanthanum, lead, yttrium, cerium, ΣLREE, ΣHREE, and thorium (table 16).

The Beardsley deposit is about 500 feet long, averages about 15 feet wide, and persists for about 250 feet vertically. Using the average thorium abundance of 3,883 ppm ThO_2 calculated from table 16, the deposit contains about 600 tons of ThO_2.

SCHWARZ RANCH CLAIMS

Several claims, the Honest No. 2 and Honest No. 5, were staked along a radioactive fracture zone and a barite-rich vein, respectively, by Harold Schwarz on his own ranch (pl. 1, fig. 6). The fracture zone is occupied intermittently by quartz vein material and strikes about N. 35° W. and is vertical. It can be traced along strike for about 520 feet and is typically 3 feet wide.

The material from the fracture zone consists of strongly sheared and comminuted country rock to which mineralizing solutions have added quartz, barite, and thorite. Some of the introduced minerals show later fracturing and shearing, indicating postmineralization movement along the structure. Zircon, apatite, and magnetite, present in heavy-mineral separates of fracture zone material, may be original components of the country rock instead of being introduced during the episode of mineralization.

Most of the higher grade parts of this vein have been mined out. Much of this material, however, was still stored on the property at the time of my visit. Some of the highest thorium values in the Wet Mountains area are found in thorite-rich samples collected from the Schwarz property (table 17). These samples contain 1.9–7.0 percent thorium and average nearly 4 percent. This average is nearly 10 times as large as the average thorium for all samples collected in the Wet Mountains area (table 13). The Schwarz samples have a somewhat higher average ΣLREE content (1.2 times the average ΣLREE in the total samples—table 13) and a much greater ΣHREE content (6.5 times the average ΣHREE in the total samples—table 13). The apparent fractionation of rare-earth elements in the Schwarz samples cannot be explained because no rare-earth minerals were identified. Other than thorium and rare-earth elements, the distribution of elements in the Schwarz samples is not unlike that in other parts of the Wet Mountains area.

The thorium-rich vein appears to extend along strike for 600 feet, exists to a depth of 250 feet, and averages 3 feet thick. The average thorium content is 4 percent. These data yield reserves of 1,500 tons ThO_2.

GENERAL IKE VEIN

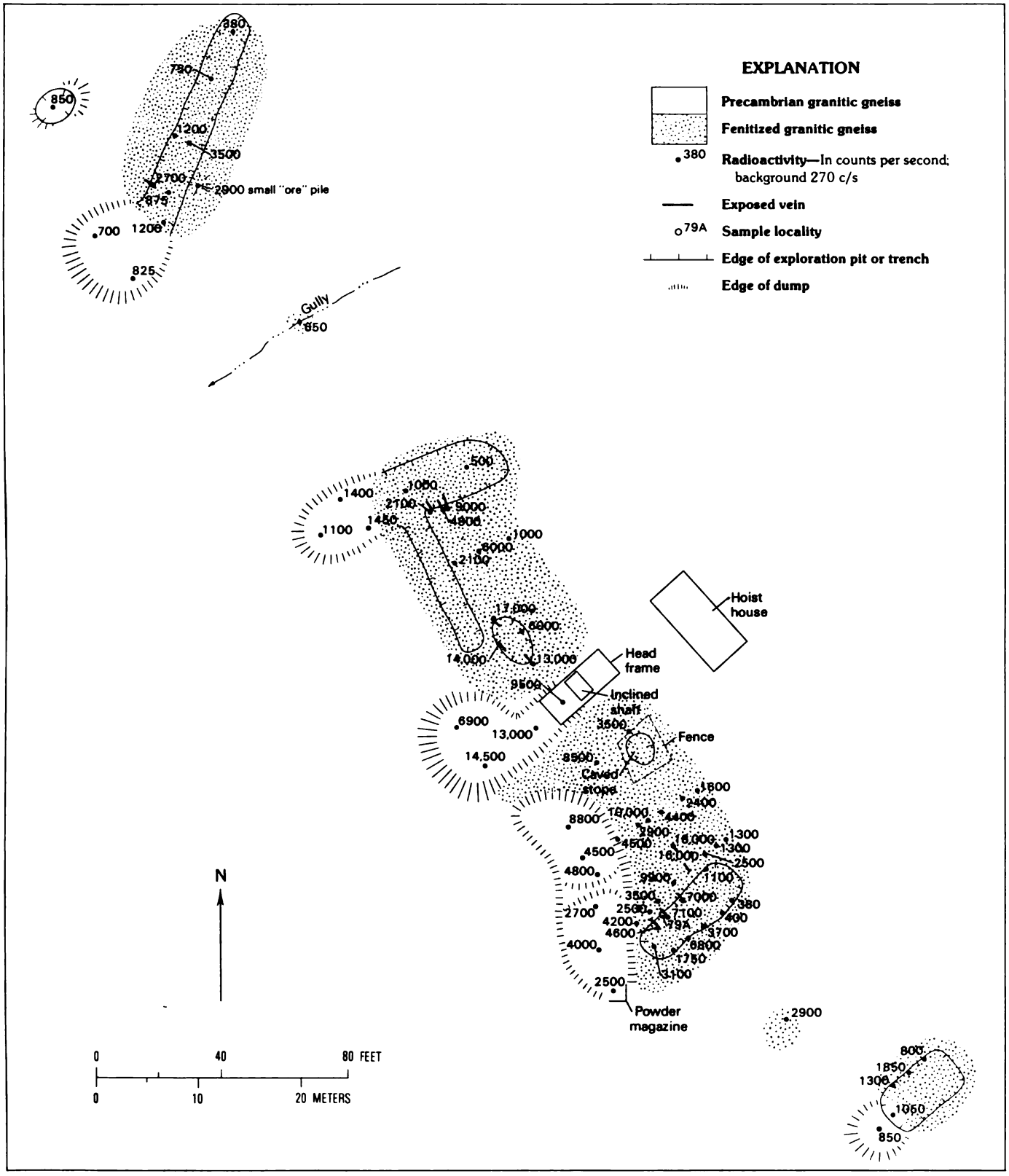
The vein-fracture zone that is covered by the General Ike claim is located near lat 38°12′30″ N. and long 105°20′ W., but it probably extends along a northwesterly strike for over 4 miles (pl. 1). About 10,300 feet of this structure have been informally designated here as the General Ike vein. The General Ike claim was staked by Lawrence Knobbe along with several partners, but the exact date of the staking is not known.

Samples from along the General Ike vein were collected almost exclusively from small prospect pits. At the sample localities the host rocks are chiefly pink to light-gray, strongly foliated granitic gneisses. The pink color of the gneisses near the vein suggests that they are slightly fenitized. As in most cases, the vein is normal to the foliation in gneisses.

The most abundant minerals in the veins are smoky quartz, potassic feldspar, barite, and several iron oxide minerals, especially goethite and hematite. Other minerals include galena, rutile, and calcite. Much of the radioactivity in the veins and fracture zones is associated with the iron oxides, but X-ray diffractograms of that material do not reveal the presence of any thorium-bearing minerals.

Because of the relatively high barite content, barium is abundant in this vein-fracture zone (table 18). Barium averages about 6.6 percent, over 1 percent more than the average amount in all vein samples (table 13). The lead content also appears to be more abundant than that in other veins. The ΣLREE to ΣHREE ratio of 5.6 is considerably higher than the ratio for all samples, which is 1.5, although the average ΣLREE values are comparable.

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Geology by T.J. Armbrustmacher and L.M. Osmonson, 1976

FIGURE 5.—Geologic map and sample localities of thorium deposits at the Beardsley deposit, Wet Mountains area, Colorado. Location shown on plate 1.

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TABLE 16.—*Abundance of selected elements in sample 79A from the Beardsley deposit, Wet Mountains area, Colorado*

[Analysis for Th by C.A. Bunker; all other analyses by L.A. Bradley]

Element	Parts per million	Element	Parts per million
Ba.....	1,000	Sr.....	300
Be.....	2	V.....	30
Co.....	5	Y.....	500
Cr.....	30	Zr.....	150
Cu.....	30	Ce.....	300
La.....	150	Ga.....	15
Nb.....	50	Yb.....	50
Ni.....	10	ΣLREE...	1,090
Pb.....	500	ΣHREE...	810
Sc.....	15	Th.....	3,412

The General Ike vein is 10,300 ft long, averages only about 1 ft wide, and persists to about 250 ft in depth. Using the thorium abundance of 2,187 ppm ThO_2 calculated from table 18, the vein contains about 470 tons ThO_2.

RESOURCES OF THORIUM AND OTHER ELEMENTS

The resources of thorium, rare-earth elements, niobium, and uranium contained in veins and fracture zones and in carbonatite dikes have been reported in Staatz and others (1979) and in Staatz and others (1980), respectively. Data contained in those reports are summarized here.

Total resources are divided into reserves—that is, those resources that are directly measured and

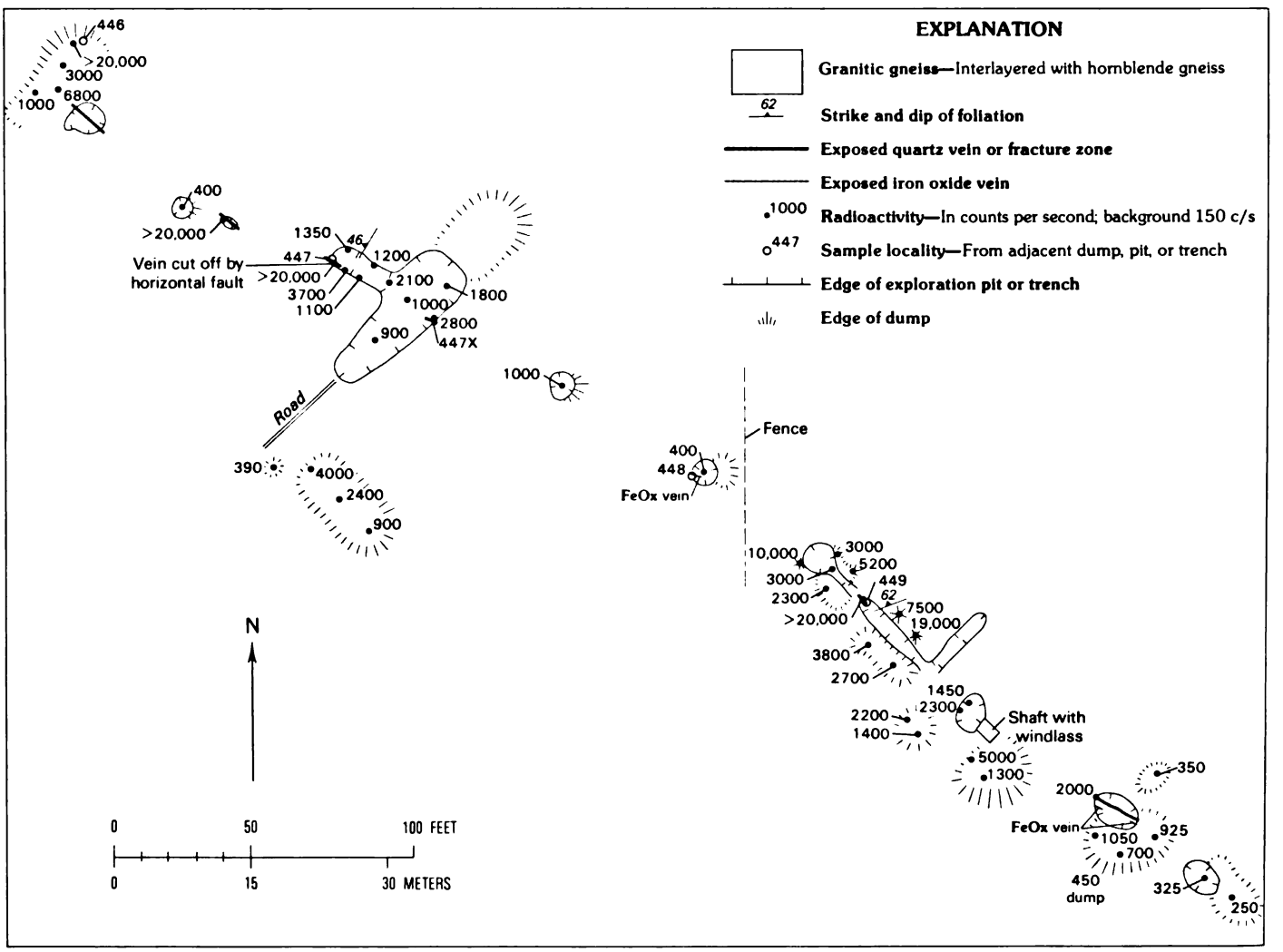


FIGURE 6.—Geologic map and sample localities of thorium deposits at the Schwarz Ranch, Wet Mountains area, Colorado. Location shown on plate 1.

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TABLE 17.—*Abundance of selected elements in veins and fracture zones from the Schwarz Ranch claims, Wet Mountains area, Colorado*

[Data given in parts per million. Arithmetic mean calculated from samples 446 to 451, excluding 448 and 452. To calculate arithmetic mean, <30 is replaced by 20, <10 is replaced by 7. Enrichment factor equals arithmetic mean/average igneous rock. Leaders (---) indicate not looked for. Sample localities shown on plate 1 and in figure 6. Analyses for Th by C.M. Bunker and C.A. Bush; all other analyses by L.A. Bradley]

Element	Sample No.						Arithmetic mean	Enrichment factor
	446	447	448	449	451	452		
Ba.....	2,000	3,000	5,000	1,500	20,000	700	6,625	11
Be.....	70	50	10	100	30	7	62	31
Co.....	70	100	30	30	30	20	58	5
Cr.....	300	150	50	15	300	150	191	3
Cu.....	1,000	200	1,000	70	200	150	368	12
La.....	300	700	<30	300	200	150	375	9
Nb.....	200	70	30	<10	200	700	118	6
Ni.....	300	500	500	50	70	30	230	5
Pb.....	1,000	2,000	<10	300	700	50	1,000	67
Sc.....	70	70	15	15	50	20	51	4
Sr.....	700	2,000	70	500	500	200	925	3
V.....	300	150	150	70	300	300	205	2
Y.....	1,000	15,000	70	1,500	1,500	200	4,750	140
Zr.....	300	7,000	15	30	150	150	1,870	12
Ce.....	700	1,500	<10	1,000	700	300	975	13
Ga.....	20	---	---	7	15	30	10	0.6
[1]ΣLREE...	1,650	3,700	30	2,150	1,200	650	2,175	13
[2]ΣHREE...	2,070	23,200	70	3,150	2,340	220	7,690	128
Th.....	19,000	70,000	126	50,000	19,500	659	39,625	3,602

[1]Light rare-earth elements: La, Ce, Pr, Nd, Sm, Eu.
[2]Heavy rare-earth elements: Y, Yb, Gd, Tb, Dy, Ho, Er, Tm, Lu.

SAMPLE DESCRIPTIONS

446. Strongly radioactive composite dump sample.
447. Thorite-rich, vuggy, FeOx-rich vein material.
448. Nonradioactive FeOx-rich vein material.
449. Composite sample from 3-foot, radioactive fracture zone.
451. Weathered, strongly radioactive fracture zone.
452. Maroon-colored clayey gouge from barite vein.

sampled—and into probable potential resources, which are logical extensions of measured reserves both laterally and vertically. Reserves were calculated by multiplying the known length of the vein by average thickness by a depth equal to one-third the length but not exceeding 3,000 feet. A tonnage factor of 12 ft^3/short ton converts vein volume to vein weight. Vein weight is then multiplied by the average grade of the particular elements. To calculate probable potential resources, the vein was extended along the surface 25 percent of the known length in each direction unless limited by geologic constraints. The same average width is used and vein depth is calculated the same as for reserves.

Exploration of the veins and fracture zones and carbonatite dikes consisted mainly of shallow prospect pits and dozer cuts, many of which no longer expose bedrock. Samples commonly were collected from these pits or from small dumps if the level of radiation suggested a sufficient thorium content. Because of the lack

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TABLE 18.—*Abundance of selected elements in veins and fracture zones in the General Ike vein, Wet Mountains area, Colorado*

[Data given in parts per million. Arithmetic mean calculations: >100,000 is replaced by 150,000; <1 is replaced by 0.7; <10 is replaced by 7; <100 is replaced by 70; <5 is replaced by 3. Enrichment factor equals arithmetic mean/average igneous rock. Leaders (---) indicate not looked for. Sample localities shown on plate 1. Analyses for Th by C.M. Bunker and C.A. Bush; all other analyses by L.A. Bradley]

Element	Sample No.										Arithmetic mean	Enrichment factor
	11	12B	13	14	15	16	17	18	19	21		
Ba.....	>100,000	5,000	70,000	30,000	7,000	>100,000	100,000	70,000	15,000	50,000	65,700	111
Be.....	<1	20	7	15	5	3	3	2	2	15	7	4
Co.....	20	15	20	20	5	50	7	15	5	5	16	1.3
Cr.....	70	30	300	150	70	70	30	30	30	7	79	1.1
Cu.....	50	70	100	70	3	70	150	150	50	30	74	2.5
La.....	1,000	700	200	700	50	150	700	150	150	50	385	9
Nb.....	20	150	500	100	100	20	<10	15	15	<10	93	5
Ni.....	70	70	100	150	30	150	20	20	20	7	64	1.5
Pb.....	15	30	30	15	30	7	15	15	7	5	17	1.2
Sr.....	1,000	200	1,500	700	700	300	300	300	100	100	520	1.8
V.....	50	150	200	50	70	100	50	70	20	7	77	.8
Y.....	70	200	700	70	700	70	150	150	100	50	226	7
Zr.....	30	700	1,500	70	3,000	70	150	70	70	20	568	4
Ce.....	1,500	1,000	500	1,000	<100	200	1,500	200	300	<100	634	8
Ga.....	15	---	15	---	20	---	<5	10	7	<5	10	.6
Yb.....	3	20	70	7	100	7	15	15	10	3	25	7
[1]ΣLREE..	5,100	2,720	1,290	2,870	150	500	3,950	790	720	300	1,839	11
[2]ΣHREE..	73	290	1,040	77	1,010	77	365	215	110	53	331	6
Th.....	3,115	3,090	1,496	2,765	1,482	308	3,566	669	672	2,055	1,922	175

[1]Light rare-earth elements: La, Ce, Pr, Nd, Sm, Eu.
[2]Heavy rare-earth elements: Y, Yb, Gd, Tb, Dy, Ho, Er, Tm, Lu.

SAMPLE DESCRIPTIONS

11. Dump sample containing barite, specularite, minor sulfides, calcite, and quartz.
12B. Fracture zone containing abundant iron oxide.
13. Fracture zone containing abundant iron oxide.
14. Quartz vein containing minor sulfides, iron oxide.
15. Pink feldspar-rich vein containing iron oxide and minor sulfides.
16. Quartz-barite vein containing specularite and minor sulfides.
17. Barite vein containing iron oxide.
18. Fracture zone containing abundant iron oxide.
19. Quartz vein containing abundant iron oxide.
21. Quartz vein containing large euhedral smoky quartz crystals and iron oxide.

of data between prospect pits where the vein or dike is covered, estimates of resources are probably high.

VEINS AND FRACTURE ZONES

The Wet Mountains area contains reserves of 64,200 tons ThO_2 and probable potential resources of 160,500 tons ThO_2 in veins and fracture zones. This estimate is based on a total of 201 samples of veins and fracture zones (localities shown on pl. 1) containing an average of 0.46 percent ThO_2. The Wet Mountains area also contains reserves of 29,300 tons ΣLREE and probable potential resources of 73,270 tons ΣLREE, as well as reserves of 19,540 tons ΣHREE and probable potential resources of 48,850 tons ΣHREE. This estimate is based on samples containing an average of 0.21 percent ΣLREE and 0.14 percent ΣHREE. The Wet Mountains area contains reserves of 1,675 tons Nb_2O_5 and probable potential resources of 4,185 tons Nb_2O_5, based on samples containing 0.012 percent Nb_2O_5.

CARBONATITE DIKES

A total of 52 samples of primary magmatic carbonatite were collected in the Wet Mountains area. Because many of the carbonatites tend to be elongated, lens-shaped bodies that have a limited strike length, resources were calculated only on the seven largest carbonatite dikes. The seven largest dikes have the following average grades and resources: 0.17 percent ThO_2, reserves of 131 tons ThO_2, and probable potential resources of 753 tons ThO_2; 0.0097 percent Nb_2O_5, reserves of 40 tons Nb_2O_5, and probable potential resources of 228 tons; 0.0031 percent U_3O_8, reserves of 17 tons U_3O_8, and probable potential resources of 105 tons; 2.15 percent total rare-earth oxides, reserves of

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2,500 tons total rare-earth oxides, and probable potential resources of 14,300 tons.

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