

RARE EARTH ELEMENTS AND YTTRIUM IN WYOMING - from oddities to resources

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ABSTRACT

Only minor amounts of rare earth elements and yttrium have been mined in Wyoming, but potential exists for future development within the state. At least 2 tons of rare earth-bearing minerals were shipped from the Platt pegmatite mine in Carbon County in the late 1950s. Exploration in the state was originally an outgrowth of exploration for thorium ores in the early 1950s. Early exploration focused on: Tertiary carbonatites in the southern Bear Lodge Mountains; scattered, small Precambrian pegmatites, veins, and carbonate pods; Cambrian placer deposits on Bald Mountain in the Bighorn Mountains; and Mesozoic titaniferous black sandstone placer deposits. The Bear Lodge carbonatite complex, the largest prospect in the state, has been examined as a large-tonnage, low-grade, porphyry-like deposit. To date, the rare-earth mineralization found in Wyoming is not economic if the only products are rare-earths and yttrium. However, several potential co-products or by-products are present with the rare earth deposits at each of the mineralized sites in the state. These include: gold, niobium, titanium, black metallic sand for coating pipes, phosphate, strontium, barium, ceramic-grade feldspar, fluorine, zirconium, and thorium.

INTRODUCTION

Rare earth elements (REE) are also known as the lanthanides. Because these 15 elements and the element yttrium usually occur together in nature they are discussed as a unit. These elements are listed in Table 1 along with their crustal abundances and prices. As shown in Table 1, the REE can be divided into two groups: the cerium group or light rare earth elements (LREE) and the yttrium group or heavy rare earth elements (HREE). The LREE and the HREE yttrium, dysprosium, erbium, and terbium have commercial applications. The exception to this generalization is the LREE promethium, which is almost nonexistent in nature. Commercial applications of HREE were not common until the latter half of the 1980s (Hedrick and Templeton, 1990; Hedrick, 1985).

Minerals that contain REE and are reported in Wyoming are listed in Table 2. Because the composition of these minerals is variable and radioactive elements in them often destroy their crystal structure, the exact mineralogy of REE-bearing minerals is often uncertain.

Worldwide, major production of REE has come from: (1) Quaternary stream placers (Malaysia, Thailand, Idaho); (2) Quaternary beach placers (Western Australia, Queensland, India, Sri Lanka,

Brazil, Mozambique, Georgia, Florida); (3) veins and breccias of uncertain origin (South Africa, Australia); (4) carbonatites (U.S.S.R., China, Burundi, California); (5) alkaline igneous rocks (U.S.S.R., Canada); and (6) Precambrian quartz-pebble conglomerates (by-product, Canada) (Hedrick and Templeton, 1990; Hedrick 1985; Neary and Highley, 1984). The principal REE deposits, including by-product recovery, were most recently summarized in Moller (1989), though this summary was actually compiled in 1986. Significant REE enrichment is also present in pegmatites and Phanerozoic fossil placers.

Uses

Rare earth elements and yttrium have a myriad of uses. Many of these elements go into "high-tech" components like the new higher temperature superconductive materials (Table 3). The manufacture of synthetic zeolites, used as catalysts in petroleum distillation, consumes 53% of all REE and yttrium. In order of consumption, REE and yttrium are also used in metal alloys (22%), in glass and ceramics (18%), and in electronic components, phosphors, magnets, lasers, other catalysts, and diverse applications (7%) (Hedrick, 1989). Because of the increasing use of high-technology materials, the demand for REE and yttrium was increasing at a rate of about 10% per year from 1982 through 1984. In 1985, the method of reporting consumption was changed by the U.S. Bureau of Mines, making it difficult to determine total U.S. consumption.

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Table 1. Chemical symbols, average crustal abundances, and 1980 and 1988 prices for rare earth elements and yttrium.

Element	Chemical symbol	Average crustal abundance (ppm) ¹	Price (US\$/kg.) ²	
			1980	1988
CERIUM GROUP — LIGHT RARE EARTH ELEMENTS				
lanthanum	La	30	115	150
cerium	Ce	64	115	175
praseodymium	Pr	7.1	310	400
neodymium	Nd	26	260	280
promethium	Pm	—	—	—
samarium	Sm	4.5	300	395
europium	Eu	0.88	7,000	7,600
gadolinium	Gd	3.8	440	500
YTTRIUM GROUP — YTTRIUM AND HEAVY RARE EARTH ELEMENTS				
yttrium	Y	22	390	510
terbium	Tb	0.64	2,300	2,800
dysprosium	Dy	3.5	300	630
holmium	Ho	0.80	1,400	1,600
erbium	Er	2.3	530	725
thulium	Tm	0.33	6,900	8,000
ytterbium	Yb	2.2	825	1,000
lutetium	Lu	0.32	12,900	14,200

¹ Abundances are averages for the upper continental crust from Taylor and McLennan (1985). Note that promethium is not listed due to its scarcity. The average value for total REE is 146 ppm.

² Prices are for kilograms (kg) of 99.9% pure elemental rare earth elements as of 1988 from Hedrick and Templeton (1990), and for 1980 from Hedrick (1981). Because promethium is almost nonexistent in nature, no price is quoted.

The current trend in demand is towards the use of individual REE and away from consumption of REE mixtures. For example, neodymium, samarium, and dysprosium separates are used in high-strength permanent magnets (Hedrick and Templeton, 1990; Hedrick, 1987), while lanthanum and yttrium are used in the newer superconductive materials. As an additional example of this trend, Molycorp, the dominant U.S. producer, sells cerium, neodymium, and erbium separates, and was scheduled in 1989 to produce a dysprosium separate (Hedrick and Templeton, 1990). These new applications should increase the demand for individual REE; though in 1990, only a modest increase in overall demand was forecast (Hedrick, 1990).

Production

The United States and China are the number one and two producers of REE in the world, with most of their production from carbonatite-hosted bastnaesite ores. Because China's production is estimated, the exact rankings are uncertain. Australia, though producing far less than the U.S. and China, is the third largest producer of REE in the world. Most of Australia's ores are monazite-rich beach sand placers (Hedrick, 1990; Hedrick and Templeton, 1990).

Rare earth elements are produced in the United States at three locations. Bastnaesite is mined by

Molycorp from a carbonatite at Mountain Pass, California, and accounts for most domestic production. Monazite is recovered with ilmenite and zircon from Quaternary black sand beach deposits at the Green Cove Springs mine in Florida by Associated Minerals. This company is a subsidiary of an Australian company that mines beach sands in Australia. Rare earth elements, yttrium, and thorium are co-products from the processing of these monazite sands (Hedrick and Templeton, 1990). The third location in the U.S., in South Carolina, is operated by Imperial Mining. This company produced mixed heavy minerals as a by-product from a gold and industrial sand and gravel operation (Hedrick, 1990). This material is probably produced from a small stream placer.

Production of REE and yttrium in Wyoming has been almost entirely from the Platt mine. Ten thousand pounds of a REE-bearing mineral were reportedly shipped from this pegmatite in Carbon County (Houston, 1961); the U.S. Bureau of Mines reported this production as about 4,000 pounds of euxenite (Kelly and Mullen, 1958; Kelly and others, 1959). Most of the production from this mine, 13 tons of ore in 1956, was uranium (Wyoming State Board of Equalization, 1957-58). Allanite-bearing ore was removed from the Ramsbottom property in Johnson County between 1952 and 1955 (after Bromley, 1955).

Table 2. Minerals reported in Wyoming that contain rare earth elements and/or yttrium.

Mineral	Chemical formula ¹	Common occurrence ²
MINERALS IN WHICH RARE EARTH ELEMENTS AND YTTRIUM ARE BASIC CONSTITUENTS.		
ancylite	$\text{Sr}_3(\text{Ce}, \text{La}, \text{Dy})_4(\text{CO}_3)_7(\text{OH})_4 \cdot 3\text{H}_2\text{O}$	carbonatites, pegmatites
allanite	$(\text{Ce}, \text{Ca}, \text{Y}, \text{La})_2(\text{Al}, \text{Fe})_3(\text{SiO}_4)_3\text{OH}$	carbonatites, veins
bastnaesite	$(\text{Ce}, \text{La})(\text{CO}_3)\text{F}$	carbonatites
brannerite	$(\text{U}, \text{Ca}, \text{Y}, \text{Ce})(\text{Ti}, \text{Fe})_2\text{O}_6$	placers, pegmatites, veins
brockite	$(\text{Ca}, \text{Th}, \text{Ce})\text{PO}_4 \cdot \text{H}_2\text{O}$	carbonatites
burbankite	$(\text{Na}, \text{Ca})_3(\text{Sr}, \text{Ba}, \text{Ce})_3(\text{CO}_3)_5$	carbonatites, phosphorite, trona
calciansite	$(\text{Ce}, \text{La})_2(\text{CO}_3)_3 \cdot 4\text{H}_2\text{O}$	carbonatites, phosphorite, trona
carbocerianite	$(\text{Ca}, \text{Na})(\text{Sr}, \text{Ce}, \text{Ba})\text{CO}_3$	carbonatites
ewaldite	$\text{Ba}(\text{Ca}, \text{Y}, \text{Na}, \text{K})(\text{CO}_3)_2$	phosphorite, trona
euxenite	$(\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6$	pegmatites
fergusonite	$(\text{Y}, \text{Er}, \text{Ce}, \text{Nd}, \text{La}, \text{Fe})(\text{Nb}, \text{Ta}, \text{Ti})\text{O}_4$	pegmatites
gadolinite	$(\text{Y}, \text{Ce}, \text{La}, \text{Nd})_2\text{FeBe}_2\text{Si}_2\text{O}_{10}$	pegmatites
melcheyite	$\text{Ba}_3\text{Na}(\text{Ca}, \text{Sr}, \text{U})\text{Y}(\text{CO}_3)_6 \cdot 3\text{H}_2\text{O}$	phosphorite, trona
monazite	$(\text{Ce}, \text{La}, \text{Nd})\text{PO}_4$	carbonatites, placers, veins
thabdothane	$(\text{Ce}, \text{La}, \text{Nd})\text{PO}_4 \cdot \text{H}_2\text{O}$	carbonatites
samaraskite	$(\text{Y}, \text{Ce}, \text{U}, \text{Ca}, \text{Th}, \text{Fe})(\text{Nb}, \text{Ta}, \text{Ti})_2(\text{O}, \text{OH})_6$	pegmatites
synchysite	$(\text{Ce}, \text{La}, \text{Nd}, \text{Y})\text{Ca}(\text{CO}_3)_2\text{F}$	carbonatites, pegmatites
xeonotite	YPO_4	placers, veins(?)
MINERALS IN WHICH RARE EARTH ELEMENTS AND YTTRIUM ARE RELATIVELY ABUNDANT ACCESSORY CONSTITUENTS BUT ARE NOT REQUIRED TO FORM THE MINERAL.		
apatite	$\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{OH}, \text{Cl})_3$	carbonatites, phosphorite
fluorite	CaF_2	carbonatites, veins
pyrochlore- microlite	$(\text{Na}, \text{Ca})_2(\text{Nb}, \text{Ta}, \text{Ti})\text{O}_6(\text{OH}, \text{F})$	placers, pegmatites(?)
columbite- tantalite	$(\text{Fe}, \text{U}, \text{Ca})(\text{Nb}, \text{Ta})\text{O}_4$	pegmatites
huttonite- thorite	ThSiO_4	placers, pegmatites
sphene	CaTiSiO_5	various
zircon	ZrSiO_4	placers

¹Chemical formulas from Cesbron (1989), Clark (1984), and Felsche and Herrman (1978). See also Mariano (1989).²Common occurrence from Clark (1984), Hedrick (1985), and Neary and Highley (1984). See also Mariano (1989).

Table 3. Uses of rare earth elements and yttrium (Hedrick and Templeton, 1990; Preinfalk and Morteani, 1989; Neary and Highley, 1984).

Metal alloys	iron alloys (structural steel), super alloys (corrosion resistant, impact resistant, hydrogen-cracking resistant, heat resistant), non-ferrous alloys, and lighter flints.
Glass and ceramics	polishing compounds, decolorizers, colorizers, color stabilizers, light and radiation absorbers, optical fibers, lasers, high-temperature refractories, and metal substitutes.
Electronic components	permanent magnets, lights, capacitors, phosphors (color televisions, radar screens, x-ray intensifying screens, data displays), carbon arc lamps, high-temperature superconductors, semiconductors, computer memories and substrates, and radar guidance systems.
Catalysts	petroleum, ammonia, gas sweetening, and auto pollution control.
Other	nuclear reactor components, gas lantern mantles, synthetic gem stones, and hydrogen fuel storage in heat exchangers and fuel cells.

but the ore was apparently never processed and no production was ever recorded. Marzell (1933) also reported production of 800 pounds of samarskite from Wyoming in 1930, but the source of this mineral has never been determined.

There are many prospects, occurrences, and unverified occurrences of REE-bearing minerals in Wyoming. (Figures 1 and 2). The variety of mineral occurrences and sites of REE enrichment in the state are summarized in Table 4.

Because this paper was designed to encourage exploration in Wyoming, the remainder of the paper has been divided into three sections based on explorational significance. The headings for these sections, in order of importance and presentation, are prospects, significant occurrences, and widespread occurrences. More information is available from the Geological Survey of Wyoming.

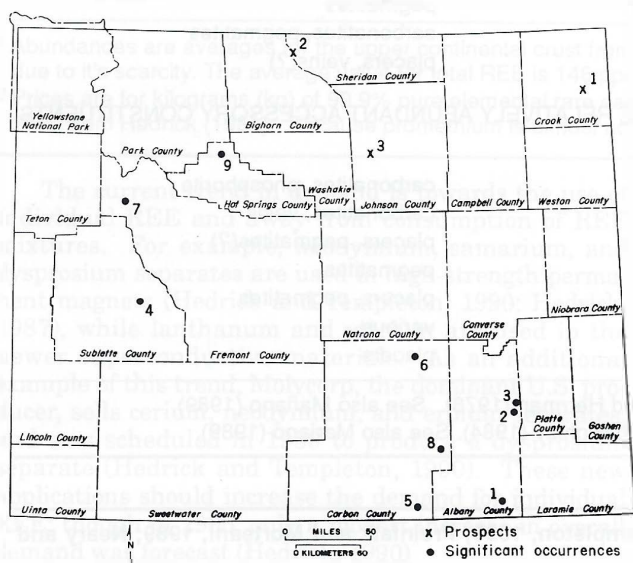


Figure 1. Index map of rare earth element and yttrium prospects and significant occurrences in Wyoming. Numbers indicate the corresponding numbered description in the text.

Prospects (x)

1. Bear Lodge Mountains
2. Bald Mountain
3. Ramsbottom

Significant occurrences (•)

1. Tie Siding
2. Red Mountain
3. Elmers Rock
4. Fremont Butte
5. Big Creek
6. Bates Hole
7. Warm Springs Creek
8. Onemile Creek
9. Grass Creek

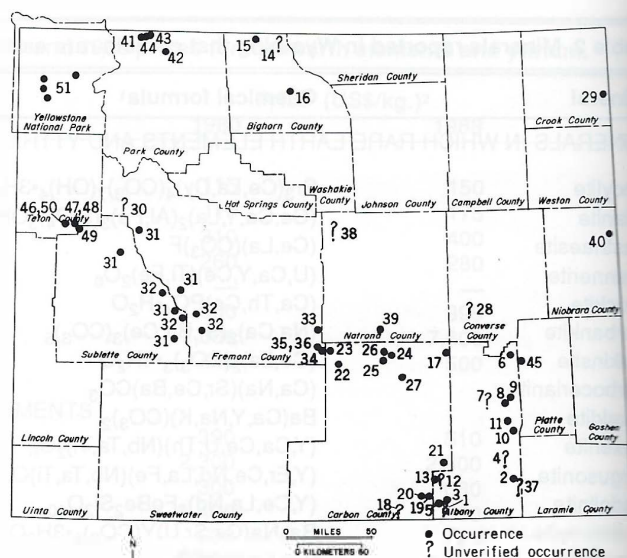


Figure 2. Index map of unverified rare earth element and yttrium occurrences in Wyoming; exclusive of Precambrian quartz-pebble conglomerate, Cambrian placer, Mesozoic black sandstone, Phosphoria Formation and Eocene lacustrine rocks.

1. Many Values
2. Waddle claims
3. Albany area
4. Laramie Range
5. Keystone area
6. Mahoney claim
7. Potato Creek
8. upper Sturgeon Creek
9. lower Sturgeon Creek
10. Taylor prospect
11. unnamed
12. Medicine Peak
13. Gaps Trondhjemite
14. Rainbow claims
15. Crooked Creek
16. Shell Creek
17. Hurda claims
18. Blackhall Mountain
19. Mullen Creek
20. Hubbell Ditch
21. Vagner Formation
22. Ferris Mountains
23. Emigrant Trail thrust
24. Omega claims
25. Poe Mountain
26. Pyramid Peak
27. A #1 and Beaver claims
28. Bruns claim
29. Mineral Hill
30. Dubois claim
31. Bear Ears pluton
32. Louis Lake batholith
33. Sage Hen
34. Gap claims
35. Mohawk claims
36. unnamed
37. unnamed
38. Allie claims
39. Wood claims
40. unnamed
41. Beartooth Falls
42. Bald Ridge
43. Angie claims
44. Long Lake area
45. Richard Riley
46. unnamed
47. unnamed
48. unnamed
49. unnamed
50. unnamed
51. Yellowstone Park

PROSPECTS

Prospects for REE in Wyoming, in order of importance and presentation, are: (1) Tertiary veins and disseminations in igneous rocks related to carbonatites; (2) Cambrian fluvial placers; and (3) Precambrian metacarbonate rocks of uncertain origin.

Table 4. Sites of rare earth element-bearing minerals and enrichment in Wyoming by age, host rock, mode of mineralization, and name. Locations are shown in Figures 1 through 7.

Age	Host rock	Mineralization	Name(s)
Early Archean	gneiss	pegmatite disseminated uncertain	Angie and Allie claims, Bald Ridge Beartooth Falls, Long Lake area Dubois #1 claim, Long Lake aplite
Middle Archean	granitoid	pegmatite	Rainbow claims
Archean	supracrustal	uncertain	Ramsbottom property
Late Archean	gneiss	pegmatite vein(?) uncertain	Riley claim Elmers Rock Bruns property
	granitoid	disseminated epidote-bearing fault and shear zone-related uncertain	several in central Wyoming, Wind River Range several in central Wyoming several in central Wyoming, and the central Laramie Mountains Fremont Buttes, Gros Ventre Range, central Wyoming, Medicine Bow Mountains, and central Laramie Mountains
Late Archean— Early Proterozoic	supracrustal	placer quartz-pebble conglomerate	Sierra Madre, Medicine Bow Mountains
Early Proterozoic	supracrustal older granitic	uncertain vein(?), disseminated	Medicine Peak, Hubbell Ditch, Vagner Formation Gaps Trondhjemite
	gneiss	pegmatite	Big Creek, Many Values
	quartz diorite	disseminated	Keystone quartz diorite
	gabbroic	uncertain	Mullen Creek mafic complex
	younger granitic	pegmatite disseminated	Blackhall Mountain Mullen Creek area
Middle Proterozoic	syenite	disseminated	Red Mountain
	anorthosite	pegmatite(?) apatitic magnetite-ilmenite	southern Laramie Mountains, unnamed southern Laramie Mountains, unnamed Taylor prospect
	Sherman Granite	pegmatite disseminated	Tie Siding, Weddle claims, Albany area Tie Siding, Albany area
Phanerozoic			
Paleozoic			
Cambrian	conglomerate	placer	Bald Mountain and others
Permian	Phosphoria Fm.	phosphorite	Thrust belt, Gros Ventre Range
Mesozoic	sandstone	beach placer uncertain	Grass Creek and others Big Horn County
	shale	uncertain	Niobrara County
Cenozoic			
Tertiary	carbonatites, and alkaline igneous lacustrine sandstone	veins, disseminated uncertain uncertain placer placer(?)	Bear Lodge Mountains Mineral Hill Green River Formation, Beaver Divide, Lysite Mountain Bates Hole Hurda claims
Quaternary	limestone sands geyser deposits	uncertain placer hydrothermal(?)	Sage Hen Bates Hole, Bald Mountain, Warm Spring Creek Yellowstone National Park

Tertiary veins and disseminations in igneous rocks related to carbonatites.

1. Southern Bear Lodge Mountains (roughly T52N, R63W).

Tertiary trachytes, phonolites, and carbonatites intrude lower Paleozoic sedimentary rocks in the southern Bear Lodge Mountains. These igneous rocks, known as the Bear Lodge alkaline igneous complex, are enriched in REE, thorium, uranium, fluorine, barium, strontium, and niobium, with scattered fluorite mineralization in the adjacent sedimentary rocks (Staat, 1983; Staat and others, 1980; Gersic and others, 1990). Unlike some alkaline igneous complexes, these igneous rocks are not noticeably enriched in tantalum (Gersic and others, 1990). The igneous rocks are notably enriched in the LREE, which are presently in demand (Staat, 1983; Staat and others, 1980; Gersic and others, 1990). This thorium-, uranium-, and REE-rich mineralization is disseminated in an extensive system of microfractures that is physically similar to those in porphyry copper deposits. A study that evaluates the combined value of thorium, uranium, REE, strontium, fluorine, barium, niobium, and tantalum in the Bear Lodge igneous complex and surrounding sedimentary units is needed to properly evaluate the economic potential of mining. The Mineral Hill alkaline igneous complex, located to the southeast, also contains some documented REE enrichment (see Gersic and others, 1990).

In the Bear Lodge deposit, REE, uranium, and thorium are concentrated in fracture-filling veins and veinlets that contain manganese and/or iron oxides. Minor quartz, cristobalite, and sometimes altered trachyte and phonolite, fluorite, barite, and/or strontium-rich calcite are also present in the veins and veinlets. The veins and veinlets vary from soft and porous to hard and highly siliceous. Exploration has been largely confined to these radioactive veins and veinlets (Jenner, 1984; Staat, 1983; Wilkinson, 1982; Staat and others, 1980; Wilmarth and Johnson, 1953; Brown, 1952; Gersic and others, 1990).

Gold mineralization is present in fractured areas in the igneous complex (Jenner, 1984; Wilmarth and Johnson, 1953; Brown, 1952; Jamison, 1912; Jenny and Newton, 1880; Hall, 1910; Gersic and others, 1990). However, relatively more abundant gold mineralization seems to be geologically and temporally distinct from the radioactive and REE-bearing, microfracture system. The low-grade gold mineralization at Smith Ridge (sec. 21) is areally separate from abundant REE, radioactive and fluorite mineralization. This gold mineralization occurs in a 120-by-2,000-foot area, with a tenor of 0.01 to 0.05 ounces/ton (see International Curator Resources, 1988 annual report; Gersic and others, 1990).

The igneous complex and surrounding sedimentary rocks have not been completely explored for REE. Rare earth element exploration is incomplete because high REE concentrations do not coincide with areas of high total radioactivity, more abundant fracturing or brecciation, any recognizable alteration or color change, the known locations of carbonatites, or high concentrations of any other elements like uranium, thorium, or fluorine (Jenner, 1984; Staat, 1983; Wilkinson, 1982; Staat and others, 1980; Wilmarth and Johnson, 1953; Gersic and others, 1990). These features were the targets of previous exploration. Rare earth elements are most abundant on the perimeter of areas with the greatest potassium abundances (Staat, 1983; Staat and others, 1980; Gersic and others, 1990; Wilmarth and Johnson, 1953), so the strongest association may be with potassic fenitization.

Because geochemical sampling has been largely confined to areas within the igneous complex, with the previously stated characteristics, an area of REE enrichment could have been completely overlooked. For example, Jenner (1984) described fluorite-bearing igneous and carbonate rocks in the Ogden Creek area south of the highly prospected area, but it wasn't until recently that some REE enrichment was reported in the Ogden Creek area (see Gersic and others, 1990).

In the Bear Lodge igneous complex, two sets of REE prospects are known from surface examinations (disseminated deposits and veins) and another is inferred from sketchy reports on drilling (carbonatites). Other sites of mineralization in the complex are REE-bearing fractures and a fluorite-bearing carbonate xenolith (Ogden Creek). Geochemical data are incomplete for both these types of occurrences. On the margins of the complex, in lower Paleozoic sedimentary rocks, fluorite mineralization might contain abundant REE; but the three reported chemical analyses have not shown this to be true.

Disseminated deposits. The largest prospect is a zone of REE enrichment, as demonstrated by surficial geochemical sampling, where rocks contain more than 5,000 ppm (0.5 %) total REE. This zone is within the disseminated deposits described by Staat (1983). In these disseminated deposits, mineralization is in veinlets and microfractures, but REE-bearing minerals are quite scarce. As noted above, the boundaries of the disseminated deposits have not been defined, because only REE analyses indicate REE abundances, and the zone of REE enrichment is only defined by areally limited geochemical sampling (see Staat and others, 1980; Staat, 1983; Gersic and others, 1990).

The area within the documented zone of REE enrichment is about 1.2 square miles, and data from drill holes indicate mineralization extends to a depth of about 1,200 feet in some areas (see Staat, 1983). A

very preliminary resource estimate for the disseminated deposits, from surface sampling, is 84,000,000 tons of 1.5% REE oxides per short ton ore within 200 feet of the surface in an assumed 0.60 square mile area. This estimate includes the veins discussed below that are within the disseminated deposits (Gersic and others, 1990). Subsurface data and more analyses for surface samples are needed to better define a potential resource.

Rare earth-bearing veins. Rare earth-bearing veins are the most REE enriched prospects in the complex. Staatz (1983) mapped and described 26 veins, with widths of greater than 2 inches, and presented chemical data for 20. Vein color is controlled by the kind and abundance of iron and manganese oxides. Rare earth-bearing minerals are not common in the veins and are fine grained. In order of abundance, the major REE-bearing minerals are monazite, brockite, and bastnaesite. The veins are sinuous, pinch and swell along strike and dip, and have variable dip along strike. The veins are usually steeply dipping, both into and away from the center of the complex, and are from about 1 to 100 inches wide and 1.5 to 400 feet long (Staatz, 1983). The extensive cover in the area implies that larger and more veins could be present.

Nineteen of these veins are higher grade mineralization (5,400 to 98,000 ppm total REE) within the disseminated deposit. The seven veins outside these deposits contain 2,300 to 71,530 ppm total REE, and are therefore a separate potential resource (after Staatz, 1983; Wilmarth and Johnson, 1953). Staatz (1983) concluded that only two of the veins contain mineable inferred reserves; these total reserves are 3,140 tons of REE oxides. Staatz (1983) did not state which two veins were considered mineable.

Carbonatites. Carbonatite dikes and stringers in the Bear Lodge igneous complex are prospects because they contain abundant REE (about 5,800 to 66,000 ppm total REE), though slightly less than the veins (Staatz, 1983). Ninety-five percent of the REE are the commercially important LREE (Staatz, 1983). In addition, the carbonatites are notably enriched in strontium and barium (Wilkinson, 1982; Staatz, 1983; Jenner, 1984; Gersic and others, 1990). Because the carbonatites are only exposed in trenches with no visible float (Wilkinson, 1982; Gersic and others, 1990), the exact extent and size of most carbonatites are not known. The surface exposures are up to about 20 by 330 feet (after Staatz, 1983; Gersic and others, 1990; Wilkinson, 1982). In subsurface, the carbonatites are reportedly tenths of an inch to about 11 feet thick and steeply dipping (Staatz, 1983). Jenner (1984) reported drill core intersects of tenths of an inch to several tens of yards, but didn't report the angles of the holes. The color of surface exposures and altered subsurface carbonatite is controlled by iron oxide staining. In subsurface, fresh carbonatites are usually light gray.

Fresh subsurface carbonatites and weathered and altered carbonatites contain different mineral suites, possibly the result of sulfide oxidation. The only mineral common to both suites is fluorite. Powdery bastnaesite with minor intergrown powdery synchysite occur in surface exposures and altered subsurface cores of carbonatite. In subsurface, the fresh carbonatites contain streaks and lenses of the REE-bearing mineral ancylite, with smaller amounts of burbankite, carbocerianite, and two unidentified minerals (after Staatz, 1983; Jenner, 1984). Fresh subsurface samples also contain streaks and lenses of strontianite, chalcopyrite, galena, sphalerite, pyrite, and pyrrhotite (Staatz, 1983). The sulfide minerals are also present as fine disseminated grains (Jenner, 1984).

The potential REE resource in the carbonatites is apparently not included in estimates of REE resources in the disseminated deposits (see Staatz, 1983; Gersic and others, 1990), and can't be estimated from available data, because the effects of sulfide oxidation on REE distribution is not known.

Thorium- and REE-bearing fractures. Wilkinson (1982) mapped extensive thorium- and REE-bearing fractures in the igneous complex. He described them as radioactive, iron and manganese oxide-stained veinlets and veins with secondary silica and features indicative of open-space filling. This description is much like Staatz's (1983) disseminated deposits, but Wilkinson's (1982) fractured areas are far more widespread. A comparison of the locations of Wilkinson's fractured areas with geochemical studies by Staatz and others (1980) indicates that many of these fractured areas have not been analyzed for REE or other associated elements, while others apparently do not contain abundant REE. In addition to these fractured areas, White (1980), O'Toole (1981), Wilkinson (1982), Staatz (1983), and Jenner (1984) mapped and described intrusive breccias at various and sometimes contradictory locations in the complex. Fluorite, calcite, gold, and pyrite have been reported in the matrixes of some of these breccias (Wilkinson, 1982; Jenner, 1984), and some breccias contain REE enrichment while others do not.

Ogden Creek area. Rare earth element mineralization in the Ogden Creek area merits further examination because of the presence of fluorite and intrusive breccia, and barium, strontium, and REE enrichment, that make it similar to the disseminated deposits to the north. As with most of the Bear Lodge igneous complex, rocks in this area are poorly exposed. The rocks are trachytes and phonolites that surround recrystallized carbonate xenoliths (Jenner, 1984; Wilkinson, 1982; Staatz, 1983). Two samples from this area contained 2,430 and 1,617 ppm LREE with strontium and barium enrichment (see Gersic and others, 1990).

Cambrian fluvial placers.

2. Bald Mountain deposit in the Bighorn Mountains (at least S1/2 sec. 21, sec. 22, W1/2 sec. 23, N1/4 secs. 27 and 28; and S1/2 sec. 30, and sec. 31, T56N, R91W), Big Horn County.

The Bald Mountain deposit is a Cambrian paleoplacer with anomalous concentrations of monazite and gold. The locations given above encompass two separate sites where samples of the basal Middle Cambrian Flathead Sandstone (locally known as the Deadwood conglomerate) contained at least 2 pounds of monazite per ton of rock (after Kline and Winkel, 1952; McKinney and Horst, 1953a, 1953b). The exact extent of these monazite-rich placers is not known because documented examinations were not rigorous (see King and Harris, 1987). This paleoplacer also contains gold and ilmenite. Wilson (1951) mentioned that Quaternary monazite placers are also present in the area.

The basal Flathead Sandstone is interpreted as the product of fluvial deposition in a westward flowing braided stream system during major flooding episodes in Cambrian time (Middleton, 1980). Regionally, the source of the arkosic and conglomeratic material was probably to the east. The basal Flathead Sandstone was previously interpreted as a beach or nearshore marine deposit (Lochman-Balk, 1971).

In the Bald Mountain area, the basal Flathead Sandstone is a poorly sorted arkosic sandstone that is 10 to 50 feet thick and contains irregularly distributed lenticular conglomerates. The conglomerates contain subrounded, pebble-sized, quartz clasts that were apparently derived from quartz veins. These clasts are in a sand-sized matrix of angular to subangular feldspar grains, with minor rounded to subangular quartz grains. The arkosic sandstones enveloping the conglomerates are similar to the matrix material (Wilson, 1951; Cardinal, 1958; McKinney and Horst, 1953a; Middleton, 1980).

Zones of monazite enrichment within the basal Flathead Sandstone are easily recognized by their high radioactivity. Monazite is usually most abundant in poorly cemented, iron-stained, irregularly distributed, lenticular, 2.5- to 10-foot-thick conglomerates on or near the underlying Precambrian granitic rocks (Wilson, 1951; McKinney and Horst, 1953a). Preliminary isopach, elevation contour, and monazite-content contour maps of zones of monazite enrichment indicate the conglomerates are irregular and lenticular, as first noted by Wilson (1951). These data also indicate that these conglomerates might be stacked upon each other. Wilson (1951) described the monazite concentrations as containing pepper-sized, reddish brown, monazite grains.

The paleoplacers were first examined for gold near the turn of the century, but gold concentrations proved

to be unprofitable. Gold concentrations of about 0.1 oz/ton were reported (Darton, 1906; Darton and Salisbury, 1906). From six samples, McKinney and Horst (1953b) reported much lower gold concentrations of 0.001 to 0.005 oz/ton. These are probably lower than actual concentrations because they are composited samples from the entire depth of dry rotary-drilled holes (see King and Harris, 1987).

In the early 1950s, the deposit was examined for monazite as a source of thorium. At this time, numerous pits and trenches were dug and holes were drilled. About 27 tons of drill cutting samples were taken and analyzed (Kline and Winkel, 1952; McKinney and Horst, 1953a, 1953b). Reported monazite abundances were from less than 2 pounds of monazite per ton up to about 30 pounds of monazite per ton of rock. Zones in which all samples contained greater than 5 pounds of monazite per ton varied from less than 2.5 feet thick up to 15 feet thick. Ilmenite contents of samples were 4.5 to 5 times greater than monazite contents (McKinney and Horst, 1953b).

From this examination, we infer that potential high-grade (>10 lbs. monazite/ton rock) monazite resources are in a 48.3 acre area in the center E1/2 sec. 22 and center W1/2 sec. 23. A less well-defined area of high monazite content is located in sec. 31. The potential monazite resources in secs. 22 and 31 are in a zone that was estimated to be about 6 feet thick and overlain by 0 to 30 feet of overburden. The potential resource contains an estimated 4,447 tons of monazite in 674,160 tons of rock, with an average 13.2 pounds of monazite per ton. The area also contains about 22,000 tons of ilmenite. Lower grade resources are far more extensive and abundant. For example, the area in sec. 31 at the base of Bald Mountain contains about 7,800 tons of monazite in 3,500,000 tons of rock that averages about 4.5 pounds of monazite per ton of rock (McKinney and Horst, 1953b).

Precambrian metacarbonate rocks of uncertain origin.

3. Beaver Creek allanite prospect (Lyle Ramsbottom property); NW1/4 sec. 5, NE1/4 sec. 6, T47N, R83W; and S1/2 sec. 31, T47N, R83W, Johnson County.

Allanite occurs in metamorphosed calc-silicate rocks at the Lyle Ramsbottom property in the south Bighorn Mountains. The allanite is apparently most abundant in calc-silicate rocks that are adjacent to citic marble. The calc-silicate rocks occur as lens, bands, layers, and pods that are concordant with N60°W foliation in the enclosing Precambrian quartzofeldspathic gneiss. These discontinuous calc-silicate bodies apparently form a zone 3,750 feet long and

inches to 6 feet wide. Because these calc-silicate rocks are poorly exposed, the exact extent of the bodies and zone is not known. In 1955, 300 or 600 tons of allanite-bearing rock were removed from workings in sec. 31 and stored Casper, Wyoming. This ore was never processed (Sargent, 1960; Bromley, 1955), and the present location of this radioactive ore is not known. The concentration of allanite in this prospect is thought to be related to regional amphibolite-grade metamorphism during Archean time (Sargent, 1960; Armbrustmacher and Sargent, 1982; Hose, 1955; Wilson, 1952; Magleby, 1952). Alternatively, the host rocks might be a metamorphosed Precambrian carbonatite.

The prospect contains an estimated 400,000 tons of mineable allanite-bearing material. From four samples, it was estimated that these calc-silicate rocks average 4.44% total REE, 0.04% Nb, 0.03 percent U and 0.06% Th. Concentrations of these important elements vary from 30 to 1000 ppm Nb, 0.01 to 0.12% Th, 0.004 to 0.090% radiometric equivalent uranium (eU), and 1.27 to 7.68% LREE (the commercial REE). Tantalum was not detected in the samples (Armbrustmacher and Sargent, 1982).

SIGNIFICANT OCCURRENCES

Other than the previously described prospects, the most significant occurrences and sites of REE enrichment are found in: (1) Middle Proterozoic pegmatites and the granitic rocks enclosing them; (2) syenite in the Middle Proterozoic Laramie Anorthosite Complex; (3) veins(?) in Archean granite gneiss terranes; (4) pegmatites and veins (?) in Early Proterozoic gneiss terranes; (5) Tertiary and Quaternary stream placers; (6) Precambrian quartz pebble conglomerates; and (7) Mesozoic black sandstone beach placers.

The Grass Creek black sandstone and Onemile Creek quartz-pebble conglomerate have been chosen as significant occurrences due to their well-documented thickness, extent, and abundant REE, thorium, uranium, and/or titanium contents. Several other black sandstones and quartz-pebble conglomerates in Wyoming might also be significant occurrences, but more REE analyses and other documentation are required for this determination. More information on these fossil placers are presented in the section titled *Widespread occurrences*.

Middle Proterozoic pegmatites and associated granitic rocks

1. Tie Siding area (T12N, R71W; T12N, R72W; and T13N, R72W), Albany County.

Many REE-bearing, highly radioactive (up to 900 times background), potash-rich, pod-like pegmatites

that contain bull quartz are present in the Middle Proterozoic Sherman Granite near Tie Siding (Smith, 1954). Potassium feldspar was produced from a few of these pegmatites in the 1940s (Osterwald and others, 1966). The mineralogy of the REE-bearing minerals or materials in these pegmatites is obscure. Pockets in these pegmatites contain yellow-brown iron oxides, at least one highly radioactive mineral, crytolite (impure zircon) and pyrochlore. High radioactivity was associated with biotite. The crytolite and pyrochlore in these pegmatites contain minor yttrium (Smith, 1954). Rare earth-bearing minerals were noted in only one pegmatite during 1978 examinations. Given the association of REE and radioactive elements (Griffin and Warner, 1982), REE might be present in fine-grained minerals that are obscured by the dark biotite. Five pegmatites and two samples of granite from the Tie Siding area show REE enrichment (up to 1,000 ppm La, >200 ppm Y, with up to 4.1% ThO₂, and 1,000 ppm Nb). Two other pegmatites are at least 20 times more radioactive than background. Also, the REE enriched Weddle pegmatite is located about 20 miles north in the Sherman Granite (sec. 2, T15N, R71W) (Griffin and Warner, 1982), and samples of the Sherman Granite near Albany contain at least 2.8 percent allanite (N1/2 T14N, R78W) (Mussard, 1982). Therefore, REE mineralization is probably more widespread than just the reported sites.

Syenite in the Middle Proterozoic Laramie Anorthosite Complex.

2. Red Mountain Syenite (roughly E1/2 T22N, R71W), Albany County.

Carl Anderson (personal communication, 1987) reported that one minor phase of the Red Mountain Syenite is allanite bearing. The syenite is part of the Middle Proterozoic Laramie Anorthosite Complex. Anderson determined that an olivine-free but clinopyroxene-bearing phase of the syenite contains between 1.5 and 3.6% allanite. This clinopyroxene phase makes up less than 5% of the syenite, though in 1987 this phase had not been completely mapped. Allanite is apparently most abundant in the N1/2 sec. 36 (Anderson, personal communication, 1987). Chemical analyses of this pluton also demonstrate REE enrichment; samples reportedly contain up to 731 ppm Nd, 119 ppm Sm (Geist and others, 1990), and 754 ppm Ce (Fountain and others, 1981).

This occurrence is important because of the size of the syenites that accompany the anorthosite in the complex and the common enrichment of REE in alkaline igneous rocks. Other REE-rich phases of the various syenites probably exist and would be large, at least low-grade, potential resources. These syenites need to be examined in more detail, particularly for

apatite and allanite concentrations, to determine the actual potential.

The phosphatic magnetite-ilmenite bodies and other apatite-bearing phases of the Laramie Anorthosite Complex are probably other sites of REE enrichment, given the association of REE with phosphate. Chemical analyses from a single iron-titanium prospect show up to 200 ppm La, 479 ppm Ce, 235 ppm Nd, and 70 ppm Sm (Goldberg, 1984), while a sample of apatite- and iron-rich troctolite contained 180 ppm Nd and 38 ppm Sm (Geist and others, 1990). Both sites are in T21N, R71W.

Veins(?) in Archean granite gneiss terranes

3. Elmers Rock area (roughly center SE1/4 sec. 19, T23N, R71W), Albany County.

Graff and others (1981) reported that a rock sample from this site contained 1,600 ppm La, 1,200 ppm Ce, 280 ppm Zr, and 350 ppm Th, but only 16 ppm Y and 33 ppm U. From the location given in Graff and others (1981), the rock sample is probably from either of two Archean quartz veins in an Archean granite (Snyder, 1984; Bull Camp Peak 7-1/2 minute quadrangle) or granite gneiss (Graff and others, 1981). These quartz veins and others mapped by Snyder (1984) in the central Laramie Mountains warrant further sampling given this REE enrichment.

4. Fremont Butte claims (NW1/4 sec. 21, T32N, R107W), Sublette County.

Iron-stained fractures along the contact of an Archean mica schist and foliated granite contain radioactive greenish yellow minerals. The contact trends about N60°E with a dip of 80°NW. Radioactivity up to about 50 times background occurs along the contact. A sample of mica schist from the most radioactive portion of the contact (Love, 1954b) contained 0.002 percent uranium (0.030% eU) with >0.1% (>1,000 ppm) each Ce, La, and Nd (>3,000 ppm total REE). Yet, no REE-bearing minerals were reported (Love, 1954a). If confirmed, these rocks contain more neodymium than any other rocks in the State and might be an economic source of REE.

Three other nearby sites are also highly radioactive, but none have been analyzed for REE. A vertical, 1- to 2-foot-wide, N50°W trending, fine-grained granite dike in the Archean granite is located 200 yards southeast of the site sampled on the Fremont Butte claims. This dike was about 30 times more radioactive than background (Love, 1954b). On the John Paul #5 claim in the N1/2SE1/4 sec. 17, T32N, R107W (Love, 1954a, 1954c), an Archean, coarse-grained, brown granite contained an abundant black crystalline mineral. Radioactivity was up to about 30 times background over some 10-foot [square ?] areas (Love, 1954c).

Olson and Adams (1962) listed this claim as a REE-bearing mineral occurrence with the location of 42°44' N latitude and 109°36' W longitude; but this is considered a confusion with the Fremont Butte claims. Gebhardt and others (1982) reported that a sample of Precambrian granite from the center of sec. 17 contained 366 ppm eTh, with no analyses for REE.

All four sites are within granitic rocks that are roughly the same age as or are a part of the Bear Ears pluton (Stuckless, 1989-map) or Louis Lake batholith (Stuckless, 1989-chemical analyses). These Archean granitoid rocks are enriched in REE at many scattered sites in the Wind River Range (see Stuckless, 1989), so other significant occurrences of REE enrichment, like Fremont Butte, might be present in these rocks.

Pegmatites and veins (?) in Early Proterozoic gneiss terranes

5. Big Creek pegmatite area (T13N, R80W; and T13N, R81W), Carbon County.

Six pegmatites in this area contain documented REE enrichment, and the Platt pegmatite in particular produced at least 2 tons of a REE-bearing mineral. These six pegmatites contain one or more of the following minerals: euxenite and/or samarskite, columbite-tantalite, allanite, and monazite (Houston, 1961; Adams and others, 1980; Dribus and Nanna, 1982; Houston, personal communication, 1987). In addition to these pegmatites, at least two other pegmatites and/or veins in the Big Creek area contain elevated levels of uranium and might also contain elevated levels of REE. All these pegmatites and veins are within an Early Proterozoic hornblende and quartzofeldspathic gneiss terrane south of the Cheyenne Belt shear zone. Other pegmatites in this terrane south of the shear zone, as mapped by Houston and others (1968), seldom contain documented REE enrichment. The Many Values pegmatite is an exception (sec. 32, T13N, R78W). However, most of these pegmatites have not been examined for REE, so more exploration is in order.

Tertiary and Quaternary stream placers

6. Bates Hole area (T27N and T28N, R78W, R79W, R80W and R81W), Carbon County.

Harshman (1972) stated that several areas of high radioactivity were detected during aerial surveys within this area on the south rim of Bates Hole. From surface examinations, these radioactive zones are attributable to monazite in sandy and conglomeratic beds in the Wind River and White River formations, and monazite in Quaternary alluvium derived from these formations. Reported concentrations of monazite vary from a few hundredths to 1.43 pounds

of monazite per ton of sand, with most samples containing less than 1 pound of monazite per ton of sand (Harshman, 1972). A sample from the Gafco claims in this area contained about 40 pounds of monazite per ton of sand (see Griffin and Milton, 1982). These occurrences are probably fluvial placers. Within this large area, two sites of REE enrichment have been documented, and two unverified occurrences of monazite have been reported. In addition, three sites of thorium enrichment (>100 ppm Th) and at least six other sites of high radioactivity are known (radioactivity anomalies 1-3, 7 and 8; Hurda claims), where monazite is probably present.

7. Warm Spring Creek placers (secs. 32, 33 and 34, T42N, R108W), Fremont County.

Monazite- and gold-bearing black sands are reported in alluvial material in and adjacent to Warm Spring Creek (Love, personal communication, 1987; Dunnewald, 1958), and possibly in terrace material along this creek (S1/2 secs. 28, 29) and alluvial material in the South Fork of Warm Spring Creek as far upstream as the junction of the South Fork of Cow Creek (secs. 1 and 11, T41N, R109W) (Robertson, *in* Dunnewald, 1958). More recent sampling of Quaternary alluvium in sec. 31 implies an even greater extent; samples contained up to 1,270 ppm eTh and 1,951 ppm Zr, with no REE analyses (Hesse, 1982). Love (personal communication, 1987) believes the monazite placers are also present downstream along the Wind River.

The known monazite-bearing alluvial deposits on Warm Springs Creek are from 1/4 to 5/8 of a mile in width and are about 1 to 2/3 mile long. The highest known terraces are more than 100 feet above Warm Spring Creek. In the summer of 1957, the placers were tested by the Little Jim Mining Company using a portable sluice. A small amount of gold was recovered along with monazite-bearing black sands (Dunnewald, 1958). Radiometric assays of six samples from this operation were 1.3 to 2.33% eThO₂ (Wilson, 1960).

Precambrian quartz-pebble conglomerates

8. Onemile Creek area (sec. 6 and N1/2 sec. 7, T18N, R78W), Carbon County.

These conglomerates in the Early Proterozoic Magnolia Formation are the most economically promising of the Precambrian radioactive conglomerates in Wyoming (see Figure 3 and Table 5). At an average grade of about 300 ppm each U₃O₈ and ThO₂, 1,801 tons of U₃O₈ and 1,106 tons ThO₂ are present in the NE1/4 of sec. 6. The area was not evaluated for REE potential, but data are available in Karlstrom and others (1981a, b) and Borgman and others (1981) to perform a preliminary analysis. Radioactive minerals identified include

coffinite, uranothorite, thoro-gummite, and possibly brannerite (Houston and Karlstrom, 1981), with pyrite being the most abundant heavy mineral (Karlstrom and others, 1981a,b). The uranothorite and brannerite(?) probably contain REE, so radioactivity is indicative of REE mineralization (Houston and Karlstrom, 1981; Karlstrom and others, 1981b).

The 143 surface samples from the Magnolia Formation in the Onemile Creek area had a mean content of 159 ppm Ce, 163 ppm La, 23 ppm Nb, and 12 ppm Y, with 25 ppm U and 99 ppm Th. Most of the maximum REE contents in this sample suite came from a sample of a 12-foot-thick quartz-pebble conglomerate in the NE 1/4 of sec. 6; the sample contained 3,952 ppm Ce, no data for La, and 137 ppm Y, with 757 ppm Nb, 923 ppm Zr, 102 ppm U, and 915 ppm Th. The most lanthanum-rich sample was from a 0.6-foot-thick quartz-pebble conglomerate; it contained 975 ppm La, 825 ppm Ce, and 27 ppm Y, with 43 ppm U and 657 ppm Th (Karlstrom and others, 1981b).

The 335 subsurface samples from the Magnolia Formation in the Onemile Creek area had a mean contained uranium of 118 ppm U, with 112 ppm Th, 102 ppm Ce, 101 ppm La, 21 ppm Nb, and 17 ppm Y (Karlstrom and others, 1981b). These are much lower than surface samples. The origin of this difference is not known. Maximum REE contents for a subsurface sample were also from the NE1/4 of sec. 6. Analyses showed 921 ppm Ce, no data for La, and 142 ppm Y in one sample, with 645 ppm La, 462 ppm Ce, and 97 ppm Y for the most lanthanum rich sample.

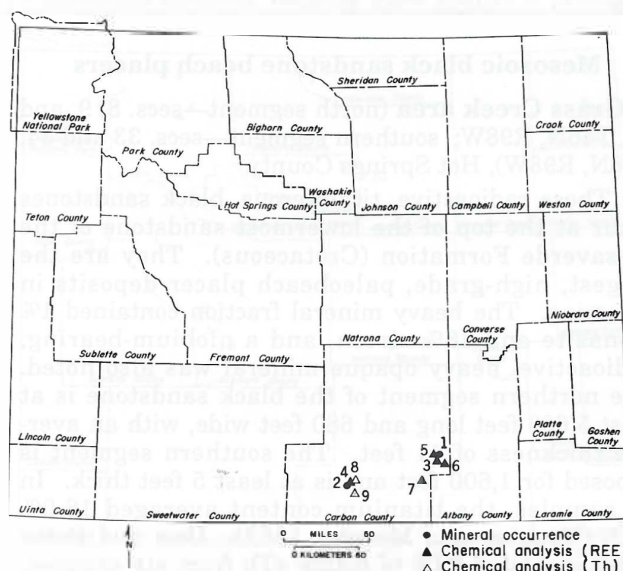


Figure 3. Index map of rare earth element- and yttrium-bearing Precambrian quartz-pebble conglomerates in Wyoming. Numbers by each locality indicate the corresponding number on Table 5.

Table 5. Locations of occurrences of rare earth element-bearing minerals and sites of rare earth enrichment in Precambrian quartz-pebble conglomerates. (Karlstrom and others, 1981b)

No.	Name	Location	Comments
CONFIRMED MINERAL OCCURRENCES			
1	Onemile Creek	sec. 6,7, T18N, R78W Magnolia Formation	uranothorite and possibly brannerite; up to 685 ppm La, 3,952 ppm Ce, 137 ppm Y; 465 ppm Th
2	Carrico Ranch	sec. 12, T15N, R88W Deep Gulch conglomerate	monazite and possibly huttonite; up to 223 ppm La, 185 ppm Ce, 150 ppm Y; 2,596 ppm Th
SITES OF RARE EARTH ELEMENT ENRICHMENT			
3	Rock Creek	sec. 19, T18N, R78W Magnolia Formation	up to 905 ppm La, 610 ppm Ce, 45 ppm Y; 344 ppm Th
4	Deep Gulch	sec. 36, T16N, R88W; sec. 30, T16N, R87W Deep Gulch conglomerate	up to 241 ppm La, 195 ppm Ce, 110 ppm Y; 844 ppm Th
5	Rock Mountain	secs. 2, 11, T18N, R79W Rock Mountain Conglomerate	up to 150 ppm La, 396 ppm Ce 55 ppm Y; 86 ppm Th
6	Cooper Creek	sec. 33, T18N, R78W Magnolia Formation	up to 150 ppm Y; 485 ppm Th
7	unnamed	sec. 15, T16N, R80W Lindsey Quartzite	no data La, Ce, 150 ppm Y; no data Th
SITES OF VERY HIGH THORIUM CONCENTRATIONS (>30 times crustal abundance)			
8	Manning Ranch	secs. 29, 30, T16N, R87W Deep Gulch conglomerate	up to 653 ppm Th
9	Dexter Peak	secs. 21, 28, T15N, R87W Jack Creek Quartzite	up to 667 ppm Th

Mesozoic black sandstone beach placers

9. Grass Creek area (north segment—secs. 8, 9, and 16, T46N, R98W; southern segment—secs. 33 and 34, T46N, R98W), Hot Springs County.

These radioactive, titaniferous, black sandstones occur at the top of the lowermost sandstone of the Mesaverde Formation (Cretaceous). They are the largest, high-grade, paleobeach placer deposits in Wyoming. The heavy mineral fraction contained 1% monazite and 18% zircon, and a niobium-bearing, radioactive, heavy opaque mineral was also noted. The northern segment of the black sandstone is at least 5,600 feet long and 680 feet wide, with an average thickness of 11 feet. The southern segment is exposed for 1,600 feet and is at least 5 feet thick. In 25 samples, the titanium content averaged 16.0% TiO₂ (Houston and Murphy, 1962). Dow and Batty (1961) reported 0.06 to 0.12% eTh from six samples. Other samples contained up to 1,670 ppm Th and 15,229 ppm Zr, with no REE data (Hesse, 1982). Additional samples from the northern and southern segments reportedly contained 1,374 and 1,020 ppm

La, respectively (Madsen, 1978), making this occurrence the second most lanthanum-rich Mesozoic black sandstone known in Wyoming.

Drilling on the northern segment reportedly delimited a 3,000,000 ton potential resource that averaged 21.0% TiO₂ and 4.8% zircon (W.H. Graves personal communication, *in* Hausel, 1990).

WIDESPREAD OCCURRENCES

Widespread occurrences of REE are reported in Wyoming in several rock units. These units, in order of age (oldest to youngest) and presentation, are: 1) Precambrian quartz-pebble conglomerates (fossil placers); 2) basal Cambrian rocks (fossil placers); 3) phosphorite, shale, and black shale in the Phosphoria Formation; 4) Mesozoic black sandstones (fossil placers); and 5) uraniferous phosphatic rocks and trona in Eocene lacustrine rocks. Data on these occurrences are presented for several reasons. First, they are widespread and may not be restricted to the few sites that have been found and sampled to date. Second, prospects and significant occurrences have been found

in the fossil placers (Onemile Creek, Bald Mountain, Grass Creek). Third, each of these rock units contain other potential resources like gold, titanium, and zirconium. Fourth, trona and phosphate are presently processed in Wyoming, and studies might be in order to determine if REE in phosphorite and trona might be recovered as by-products during beneficiation.

Precambrian quartz-pebble conglomerate

North of the Mullen Creek-Nash Fork shear zone (Cheyenne belt) in the the Sierra Madre and Medicine Bow Mountains, some weakly to strongly radioactive, REE-, thorium-, and uranium-bearing, pyritic quartz-pebble conglomerates have been found in Late Archean and Early Proterozoic metasedimentary rocks. These fluvial placers are special because they contain detrital reduced uranium and thorium minerals in metasedimentary rocks (which is associated with their time-bounded age, Late Archean and Early Proterozoic) and large clasts of what is probably vein quartz, and because of the anatomizing nature of the fluvial channels. These conglomerates are thorium rich in the Sierra Madre and uranium rich in the Medicine Bow Mountains (Houston and Karlstrom, 1981). Details of this work are available in Karlstrom and others (1981a,b) and Borgman and others (1981). **Figure 3** and **Table 5** contain data on the REE-bearing localities (see also the Onemile Creek occurrence, page 59). Sites of very high thorium concentrations are included on this figure and table because REE enrichment is usually found with high thorium concentrations in placers.

Gold concentrations reported in these fossil placers are somewhat encouraging, even though only 77 of the 314 samples analyzed contained detectable gold. The 77 samples assayed on average of 0.37 ppm gold and varied from 0.01 ppm (detection limit) to 10.0 ppm gold (Houston and Karlstrom, 1981, p. 180-181).

Basal Cambrian rocks

Occurrences of thorium-, REE- and gold-bearing fossil placers, which are probably fluvial in origin, have been found in the Cambrian Flathead Sandstone, and in the equivalent Deadwood Formation at several sites around Wyoming (see **Figure 4** and **Table 6**). Radiometric indications of Cambrian fossil placers have been found as far south as the Rawlins uplift. Rare earth-bearing minerals found in these placers include monazite, zircon, and xenotime; other heavy minerals are magnetite, ilmenite, garnet, and native gold. Sites of very high thorium concentrations are included on **Figure 4** and **Table 6** because REE enrichment is usually found with high thorium concentrations in placers. The existence of the Bald

Mountain prospect (page 55) indicates that these fossil placers are important potential sources of gold, REE, and titanium.

The information in **Table 6** and **Figure 4** is from Griffin and Milton (1982); Malan (1972); Garrand and others (1982); Damp and Jennings (1982); Gersic and others (1990); Gebhardt and others (1982); and Damp and Brown (1982). The most radioactive of these exposed placers have probably been discovered. But the fact that most of the occurrences listed in **Table 6** were not found until the late 1970s, during the last phase of NURE exploration, implies that undiscovered exposed REE-bearing fossil placers in Cambrian rocks are probably present in Wyoming. Other such placers are probably present in shallow subsurface.

Phosphoria Formation

Phosphorite in the Phosphoria Formation in western Wyoming is a potential source for various metals as by-products from phosphate production (see for examples Love, 1984; Gulbrandsen, 1977). Because REE are often relatively abundant accessory elements in apatite, an important phosphate mineral in phosphorite (Gulbrandsen, 1966), REE might also be recovered during phosphate production (see for example, Lounamaa and others, 1980). To date, the number of analyses for REE in phosphorite, as well as shale and black shale, in the Phosphoria Formation in Wyoming are areally limited (**Figure 5** and **Table 7**). In general, REE concentrations are higher in rocks with higher phosphorous contents, because more apatite is present.

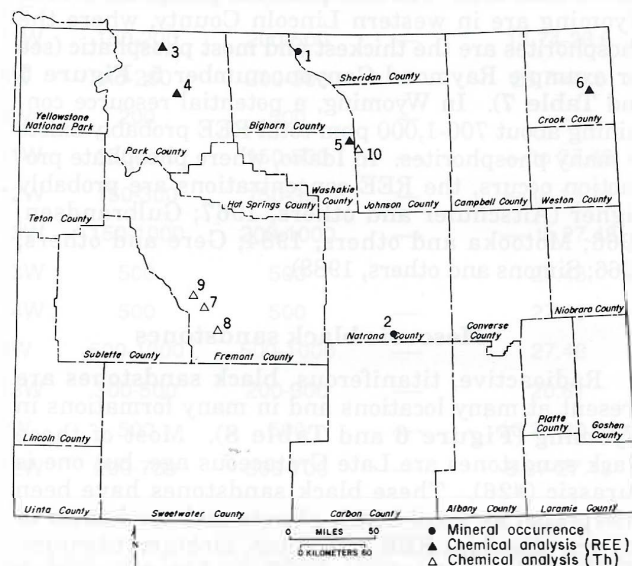


Figure 4. Index map of rare earth element- and yttrium-bearing Cambrian placers in Wyoming. Numbers by each locality indicate the corresponding number on **Table 6**.

Table 6. Locations of occurrences of rare earth element-bearing minerals and sites of rare earth enrichment in Cambrian Flathead sandstones and conglomerates.

No.	Name	Location	Comments
PROSPECT			
1	Bald Mountain	secs. 21,22,23,27,28,30,31, T56N, R91W	monazite see prospects
CONFIRMED MINERAL OCCURRENCE			
2	Little Basin	sec. 21,22,27, T29N, R83W	monazite, xenotime up to 10,300 ppm eTh
SITE OF RARE EARTH ELEMENT ENRICHMENT			
3	Dilworth Bench	roughly sec. 8, T56N, R104W unsurveyed	1,000 ppm La; no data Th
4	Shoshone Canyon	sec. 6, T52N, R102W	150 ppm La, 2 ppm Au; no data Th
5	Prospect Creek	sec. 26, T48N, R86W	215 ppm La, 366 ppm eTh
6	Bear Lodge Mountains	sec. 33, T52N, R63W	174 ppm La, 344 ppm Ce, 108 ppm Th
SITE OF EXTREME THORIUM ENRICHMENT (>30 X crustal abundance)			
7	unnamed	sec. 22,23, T32N, R101W	446 ppm eTh
8	unnamed	sec. 29, T30N, R99W	312 ppm eTh
9	unnamed	sec. 24, T2S, R3W	366 ppm Th
10	unnamed	sec. 18, T47N, R85W	324 ppm eTh; <100 ppm La, <40 ppm Y

Therefore, the best phosphate ores are probably the richest REE ores. The best potential phosphate ores in Wyoming are in western Lincoln County, where the phosphorites are the thickest and most phosphatic (see for example Raymond Canyon; number 5, **Figure 5** and **Table 7**). In Wyoming, a potential resource containing about 700-1,000 ppm total REE probably exists in many phosphorites. In Idaho, where phosphate production occurs, the REE concentrations are probably higher (Altschuler and others, 1967; Gulbrandsen, 1966; Motooka and others, 1984; Gere and others, 1966; Simons and others, 1988).

Mesozoic black sandstones

Radioactive, titaniferous, black sandstones are present at many locations and in many formations in Wyoming (**Figure 6** and **Table 8**). Most of these black sandstones are Late Cretaceous age, but one is Jurassic (#26). These black sandstones have been interpreted as fossil beach placers and are known to contain abundant REE, zirconium, niobium, titanium, iron, and thorium. They were formed by wave action on beaches (Houston and Murphy, 1977), as well as long-shore currents, fluvial currents, and wind action

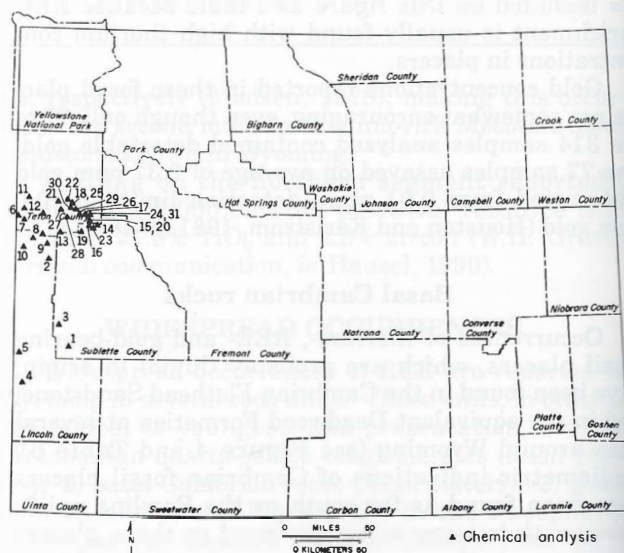


Figure 5. Index map of samples from the Phosphoria Formation in Wyoming that contained abundant (5 times crustal abundance) rare earth elements and yttrium. Numbers by each locality indicate the corresponding number on Table 7.

Table 7. Locations of sample sites of phosphorite, phosphatic rock, shale, and black shale in the Phosphoria Formation where the results of rare earth element analyses are known.

No. ¹	Name	Reference ²	Location		Concentration ³		
			sec., T, R	La (ppm)	Y (ppm)	Nd (ppm)	P ₂ O ₅ (%)
1	Deadline Ridge	2 samples (a; g)	7, T27N, R114W	100-300	300	nd	28.0-31.6
2	Steer Creek	2 samples (a; h)	9, T36N, R116W	100-300	300	nd-300	25.0-29.6
3	Middle Piney Lake	2 samples (a; g)	8, T30N, R115W	300	100-300	nd-300	25.0-28.9
4	Cokeville	2 samples (a; g)	4, T24N, R119W	100	300	300	23.0-32.4
5	Raymond Canyon	31 samples (b; g)	6, T26N, R119W	50-700	50-1000	nd-700	10.73-36.32
6	Siddoway Fork	3 samples (c; i)	unc, T40N, R118W	110-180	150-200	—	19.24-38.93
7	Smokey Hollow	5 samples (c; i)	33, T40N, R118W	130-220	170-270	—	15.11-21.98
8	N. Fork Big Elk Creek	7 samples (c; i)	11, T39N, R118W	97-250	150-520	—	16.26-38.93
9	Hoback	2 samples (c; g; i)	32, T39N, R116W	79-300	86-410	—	15.34-25.19
10	Wolf Creek	9 samples (c; i)	28, T38N, R117W	140-320	170-440	—	27.73-33.44
11	Teton Pass, west pit	1 sample (c; h; i)	23, T41N, R118W	170	220	—	2.34
12	Snow King Mountain	13 samples (d)	9, T40N, R116W	100-700	200-1000	nd-700	15.07-30.98
13	Bear Creek	1 sample (f)	6, T38N, R114W	160	196	96	—
14	West Tosi Creek	1 sample (e)	15, T39N, R111W	200	300	—	13.74
15	Triangle Peak	1 sample (e)	2, T39N, R112W	200	300	—	27.48
16	Wilderness boundary	3 samples (e)	13, T39N, R112W	200-300	200-300	—	13.74-27.48
17	Bear Cabin Creek	1 sample (e)	14, T40N, R112W	500	700	—	27.48
18	Crystal Creek	5 samples (e)	34, T42N, R113W	nd-700	100-300	—	27.5-31.5
19	Dell Creek	1 sample (e)	28, T39N, R112W	<200	300	—	29.8
20	Clear Creek	4 samples (e)	6, T39N, R111W 32, T40N, R111W	150-200	200-500	—	13.74-28.6
21	Flat Creek	4 samples (e)	1, T41N, R115W	nd-200	200-300	—	25.7-40.0
22	East Miners Creek	1 sample (e)	1, T41N, R114W	200	500	—	—
23	Tosi Creek	3 samples (e)	18, T39N, R111W	150-500	150-500	—	— to 27.48
24	unnamed	2 samples (e)	20, T39N, R112W	150-300	150-300	—	— to 13.74
25	Crystal Creek	3 samples (e)	32, T42N, R113W	150-1000	200-1000	—	— to 27.48
26	Crystal Peak	1 sample (e)	35, T41N, R113W	500	500	—	27.48
27	Table Mountain	1 sample (e)	18, T41N, R114W	500	500	—	27.48
28	Granite Creek	3 samples (e)	3, T40N, R114W	500-1000	500-1000	—	27.48
29	Six Lakes	2 samples (e)	12, T40N, R113W	300-500	200-300	—	20.61
30	unnamed	2 samples (e)	8, T41N, R113W	500	500	—	10.31-20.61
31	unnamed	2 sample (e)	26, T40N, R112W	200-700	300-700	—	6.87-27.48

¹Number on Figure 5.²References: a = Gulbrandsen, 1966; b = Vine, 1966; c = Motooka, 1984; d = Gere and others, 1966; e = Simon and others, 1988; f = Schofield and Haskin, 1964; g = Sheldon and others, 1953; h = Cheney and others, 1953; i = Benham, 1985.³nd = not detected; — = no analysis performed.

Table 8. Mesozoic black sandstone fossil beach placer deposits in Wyoming.

No ¹	Name Formation	Location sec., T,R	Extent (ft)		Thickness (ft)		Concentration	
			length	width	max.	ave.	La (ppm) Th (%) ³	Y (ppm) Ti (%) ³
SIGNIFICANT OCCURRENCE								
1	Grass Creek northern southern Mesaverde	8,9,16, T46N, R98W 33,34, T46N, R98W	5600+ un.	680+ 1600	16.0 5.0	11 un	1374 0.17% 1020	33.36%
OTHER MINERAL OCCURRENCES								
2	Cottonwood Creek Mesaverde	26, T45N, R97W	150	150	9.0	un.	1687 0.04%	16.84%
3	Dugout Creek Mesaverde	34,35, T45N, R89W 2,11, T44N, R89W	14,256	1500+	25.0	11	312 0.02%	14.80%
4	Coalbank Hills Mesaverde	5, T34N, R88W	1400+	un.	5.0	un.	0.12%	12.5%
5	Poison Spider Lewis Shale	1, T33N, R84W 36, T34N, R84W	300+	un.	7.0	un.	50-1000 0.08%	10-300 10.99%
6	Clarkson Hill Mesaverde, Parkman	20, T31N, R82W Sandstone member	150+	20+	5.6	un.	0.04%	9.7%
7	Black Butte Creek Rock Springs	30, T18N, R101W	1500+	un.	4.0	un.	1000-1500 0.06%	100-500 33.0%
8	Salt Wells Creek Rock Springs	7, T14N, R103W	500	un.	3.0	un.	500 0.07%	100 35.50%
9	Red Creek Rock Springs	22, T12N, R105W	1500	un.	6.6	5	700 0.07%	36.50%
10	Cumberland Gap Frontier	25, T18N, R117W 18,19,30, T18N, R116W	13,200+	200 un.	un.	0.02%	14.50%	
11	Sheep Mountain Mesaverde	10,14, T15N, R77W	4300	50	17.0	un.	706 0.05%	23.68%
12	Spring Gap Frontier or possibly Aspen	8,17,30, T16N, R117W	900+	30	un.	2.5	230-1000 0.066%	40-80 22.0%
13	Ranger Lance or possibly Lewis Shale	22,27, T34N, R84W	un.	un.	un.	un.	500-1000 0.144%	70-500 0.5%
SITES OF RARE EARTH ELEMENT ENRICHMENT								
14	Cowley Mesaverde	1, T56N, R97W	900+	un.	3.5	1	135-400 0.01%	<10 6.0%
15	Lovell Mesaverde	7, T55N, R95W 12, T55N, R96W	5000+	un.	4.0	3	50-316 0.01%	<10 15.1%
16	Mud Creek Mesaverde	19, T44N, R91W	1500+	100+	7.5	un.	500 0.02%	8.1%

Table 8. Mesozoic black sandstone fossil beach placer deposits in Wyoming (continued).

No ¹	Name Formation	Location sec., T,R	Extent (ft)		Thickness (ft)		Concentration	
			length	width	max.	ave.	La (ppm) Th (%) ³	Y (ppm) Ti (%) ³
17	Beacon Rock Springs	19, T19N, R101W	2700	150	un.	7	500-700 0.10%	100-300 21.1%
18	Honnes Ranch Rock Springs	11, T17N, R102W	2500	50-100	6	4	1000 0.06%	100 22.2%
SITES OF HIGH THORIUM ENRICHMENT (>30 X crustal abundance)								
19	Pretty Water Creek Rock Springs	8, T16N, R102W	1270	un.	4.2	3	0.07%	26.3%
20	Dans Creek Rock Springs	13, T15N, R103W	un.	250	un.	5.5	0.08%	26.3%
UNVERIFIED RARE EARTH ELEMENT OCCURRENCES								
21	Dry Cottonwood Ck. Bacon Ridge Sandstone	27, T42N, R112W	un.	un.	un.	un.		
22	Shotgun Bench Mesaverde	18, T5N, R1E	un.	300	5.0	un.		
23	Salt Creek northern	24,25,36, T39N, R78W 31, T39N, R77W	8976+	un.	un.	un.		
	southern Fox Hills	19,30, T38N, R77W	5280+	750	un.	un.		
24	Seminole Fox Hills	35, T25N, R85W 15, 28, T24N, R85W	un.	un.	un.	un.		
25	Fiddler's Green Lewis Shale	21, T21N, R80W	2600	un.	13.0	un.	0.005%	
26	Cliff Creek Stump	33, T38N, R114W	un.	un.	un.	4		20.15%
27	Cooper Ridge Rock Springs	1, T17N, R102W	120		3.3	1		28.00%
28	unnamed Mesaverde, Teapot member	5, T40N, R78W	un.	un.	un.	un.	0.007%	
29	unnamed Mesaverde, Teapot member	27, T40N, R78W	un.	un.	un.	un.	0.011%	5.14%
30	unnamed Mesaverde, Parkman member	22, T43N, R81W	un.	un.	un.	un.	0.01%	
31	unnamed Fox Hills	13, T38N, R87W	un.	un.	un.	un.	0.018%	

¹Number on Figure 6.²un. = unknown.³maximum

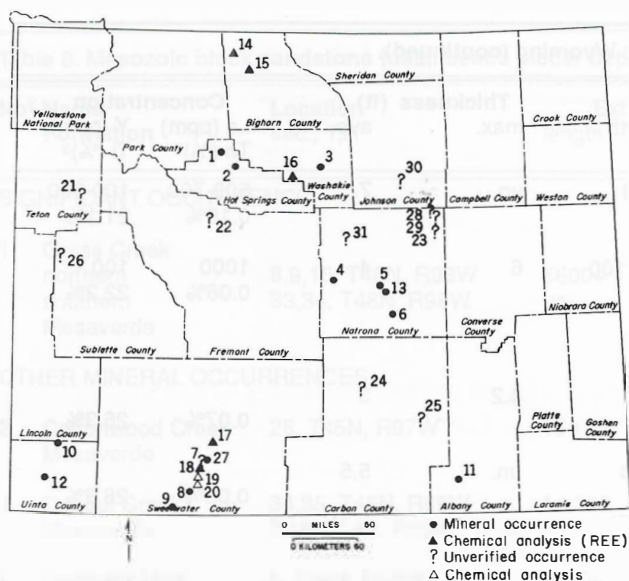


Figure 6. Index map of rare earth element- and yttrium-bearing Mesozoic black sandstones in Wyoming. Numbers by each locality indicate the corresponding number on Table 8.

(Roehler, 1989). REE-bearing minerals present in Wyoming fossil placer occurrences include monazite, uraniferous zircon, and a niobium-bearing, unidentified, opaque radioactive mineral. The most abundant heavy minerals in these beach placers are the non-radioactive minerals magnetite, titaniferous-magnetite, and ilmenite (Houston and Murphy, 1962, 1970, 1977). The typical Wyoming black sandstone contains on average 15% heavy minerals with thin (1/4-inch-thick) individual layers that contain up to 90% heavy minerals. The sandstones are resistant and crop out on ridges (Houston and Murphy, 1962, 1970, 1977). None of the black sandstones have been systematically examined as a source of REE, niobium, or tantalum.

The information in Table 8 and on Figure 6 is from Houston and Murphy (1962, 1970, 1977); Houston and Love (1956); Dow and Batty (1961); Madsen (1978); Morris and Stanley (1982); Garrand and others (1982); Griffin and Milton (1982); Dribus and Nanna (1982); Damp and Brown (1982); Garrand and others (1982); Madsen and Reinhart (1982); Hesse (1982); Love and Christiansen (1985); Hausel and Jones (1982); and Roehler (1989). Sites of high thorium enrichment are included in Table 8 and Figure 6 because REE enrichment usually accompanies thorium in placers. Other black sandstones are included on Table 8 and Figure 6 because of the paucity of thorium and heavy mineral analyses on samples from these black sandstones and the fact that they are potentially REE-bearing placers.

Other undiscovered occurrences of niobium, tantalum, and REE in black sandstones of Late Cretaceous age cannot be ruled out because several previously unreported examples were found during field work for NURE projects in the late 1970s.

Eocene lacustrine rocks

Though reportedly scarce (Milton, 1971), the REE-bearing carbonate minerals burbankite, mckelveyite, and ewaldite have been found in the lacustrine Eocene Wilkins Peak Member of the Green River Formation (Table 9 and Figure 7). Due to admixed organic material, these dark minerals (Milton and others, 1965) might have been overlooked in most examinations, and could be more abundant than previously reported. These REE-bearing minerals are apparently in and associated with uraniferous phosphatic zones (zones 1 and 2a) and a trona bed (bed 17) (Love, 1964). The extent of REE-bearing trona and uraniferous phosphatic rock is not known due to the limited nature of the sampling and the inhomogeneity of REE-bearing trona and phosphatic zones.

It might be possible to obtain REE as a by-product from trona mining and processing. Rare earth-bearing carbonate minerals have been reported in trona bed 17 (Love, 1964), which is presently being exploited, as well as in waste from soda ash production (Milton and others, 1965). No geochemical analyses for REE are available for any trona bed, so this by-product source is conjectural.

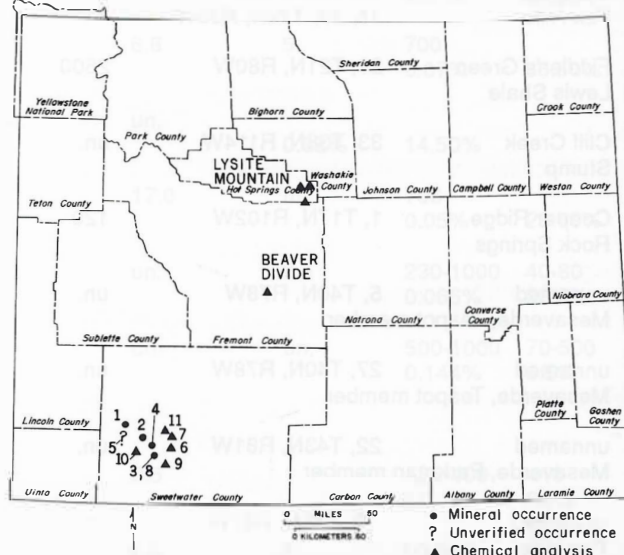


Figure 7. Index map of rare earth element- and yttrium-bearing Eocene lacustrine rocks in Wyoming. Numbers by each locality indicate the corresponding number on Table 9.

Table 9. Locations of occurrences of rare earth element-bearing minerals and sites of rare earth enrichment in the Wilkins Peak Member of the Green River Formation.

No. ¹	Name	Location	Comments
CONFIRMED MINERAL OCCURRENCES (Love, 1964)			
1	FMC Westvaco mine	sec. 15, T19N, R110W (shaft location); in trona bed 17	also green minerals in soda ash waste
2	Diamond Alkali Co. DACO No. 3	NW1/4, NW1/4 sec. 17, T18N, R108W in zone 1 in basal Wilkins Peak	at 1,369 feet deep in lean uraniferous phosphatic rock
3	Diamond Alkali Co. Reid No. 2	SE1/4, SE1/4 sec. 32, T17N, R107W in zone 1 in basal Wilkins Peak	at 1,422.5 feet deep in uraniferous phosphatic rock
4	J.M. Perkins Green River No. 3	SW1/4 sec. 8, T17N, R107W in zone 1 in basal Wilkins Peak	at 1,784 feet deep in uraniferous phosphatic rock
UNVERIFIED MINERAL OCCURRENCE (Milton and others, 1965; Fahey, 1962)			
5	Mountain Fuel Supply Co. John Hay Jr. No. 1	SW1/4, NW1/4 sec. 2, T18N, R110W near trona bed 17 (bed 17 at depth of 1,590 feet)	at uncertain depth
SITES OF RARE EARTH ELEMENT ENRICHMENT; all in uraniferous phosphatic rock (Love, 1964, table 17; Mott, 1978)			
6	Oro and Lulu claims, and both Ridge sites	secs. 10, 11, 14, T17N, R106W in zone 1 in basal Wilkins Peak	5 surface samples
7	Old Log Inn and Northeast area	secs. 12, 25, T18N, R106W in zone 1 in basal Wilkins Peak	2 surface samples
8	Diamond Alkali Co. Reid No. 2	SE1/4, SE1/4 sec. 32, T17N, R107W in zone 2a in basal Wilkins Peak	1 sample at 1,331 feet deep
9	South Firehole Canyon	SE1/4 sec. 20, T16N, R106W in zone 2a in basal Wilkins Peak	2 surface samples
10	UP corehole 41-23	NE1/4, NE1/4 sec. 23, T17N, R109W	1 sample at 1,878 feet deep
11	White Mountain No. 1 corehole	NW1/4, SW1/4 sec. 7, T18N, R106W	1 sample at 831.5 feet deep
¹ Number on Figure 7.			

The lacustrine sediments in the Green River Basin also contain some uraniferous phosphate zones. Averages of semiquantitative spectrographic analyses indicate that seven sites in one unit known as uraniferous phosphatic zone 1 contain over 1,000 ppm total REE, with 3.6 to 14.7% P_2O_5 . Enrichment in zone 2a at three or four sites is somewhat less than 1,000 ppm total REE, with 3.1 to 10.56% P_2O_5 . The rest of the uraniferous phosphatic zones on average are not notably enriched in REE (Love, 1964, table 17). Sample sites with REE enrichment are shown on **Table 9** and **Figure 7**.

Eocene, lacustrine, uraniferous phosphatic zones exposed along the Beaver Divide and on Lysite

Mountain are also enriched in REE, as demonstrated by semiquantitative spectrographic analyses, but no REE-bearing minerals have been reported. The lone sample from Beaver Divide appears to contain more than 2,500 total REE, with 5.67% P_2O_5 , and is in Aycross equivalent rocks. The five samples from Lysite Mountain are on average not notably enriched in REE, except for 150 ppm Nd. The phosphate contents of these samples vary from 2.28 to 5.94% P_2O_5 (after Love, 1964). The Lysite Mountain samples are from the Tepee Trail and possibly Aycross equivalent rocks (Love, 1964). As with the other Eocene uraniferous phosphatic rocks, REE mineralization might be more widespread than shown in **Figure 7**.

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WYOMING
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MINERAL RESOURCES OF WYOMING

Wyoming Geological Association
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Guidebook

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Editors

B. RONALD FROST
SHEILA ROBERTS

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