

Uranium-Lead Isotope Systematics in Uraniferous Alkali-rich Granites from the Granite Mountains, Wyoming: Implications for Uranium Source Rocks

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Abstract

Evaluation of U-Th-Pb isotopic analyses of whole-rock granite samples from the Granite Mountains, Wyoming, suggests that uranium has been mobilized at least twice since the intrusion of the granite. Whole-rock Th-Pb, whole-rock Rb-Sr, and zircon U-Pb ages are concordant at 2,600 m.y., but the whole-rock Pb-Pb age is distinctly older. This apparent age is attributed to a 10 to 45 percent uranium loss between 1,400 and 1,700 m.y. ago when the granite was subjected to an ill-defined metamorphic event that was probably of a thermal nature.

A second and more extensive uranium loss occurred after the granites were exposed to near-surface conditions by the Laramide event. This loss has left whole-rock U-Pb ages variable and generally impossibly old. Granites that exhibit the largest recent uranium loss are characterized by high silica, thorium, and alkali contents and moderate biotite contents. These features are suggested as more diagnostic of potential granitic uranium source rocks than present-day uranium contents because the general 70 percent or greater recent loss of uranium has left many surface samples with a uranium content that has been considered typical of many granitic units.

A few samples were found to have concentrations of some of the mobilized uranium (as much as 1,460 ppm U). Although these samples are not petrographically or chemically distinguishable from those that lost uranium, most are highly fractured. It therefore appears that fracturing may be an important control in forming ore deposits in granites.

Introduction

THE identification and characterization of source rocks in known uranium districts can be vital to uranium exploration because the data may lead to the discovery of new uranium districts through the recognition of similar source rocks and geologic settings. Uranium leached from granites has been proposed as the primary source for sandstone uranium deposits in Wyoming (Rosholt and Bartel, 1969), vein-type deposits in France (Barbier, 1974), and the calcrete deposits of Yeelirrie, Australia (Von Backström, 1974). In the first two of these examples there is evidence of uranium migration from the proposed source rock, but only in the first example has the timing of uranium loss from granite been shown to be roughly compatible with the timing of nearby ore deposition.

Previous studies in the Granite Mountains, Wyoming, have shown a probable Cenozoic uranium depletion in the granite that averaged 75 percent (Rosholt et al., 1973). Surface and shallow (30-50 m) drill core samples were shown to be 20 $\mu\text{g/g}$ deficient in uranium relative to the radiogenic daughter products ^{206}Pb and ^{207}Pb . Rosholt and Bartel (1969) concluded that the uranium from the granite, avail-

able to the adjacent sedimentary basins, was more than 1,000 times the estimated reserves, this amount in addition to the production of uranium in the basins that surround the Granite Mountains.

Geologic Setting

The Granite Mountains of Wyoming are formed by one of several Precambrian basement blocks, uplifted during the Laramide orogeny (Fig. 1). Most of the Precambrian blocks have a general north to north-westerly trend, but the Granite Mountains are exposed as a more easterly trending block approximately 100 km long and generally 10 to 20 km wide. A secondary trend, shown by the outcrop patterns of Figure 2, is toward the northeast.

The Granite Mountains are of economic interest in that three major uranium districts are disposed about the flanks of the range (Fig. 1). A small amount of uranium was mined from the granite at the Little Man mine (Love, 1970), located about ten km southwest of sample PD-5 (Fig. 2). There is currently no active mining in the Granite Mountains except on small jade (nephrite) claims (Peterman and Hildreth, 1977).

Exposed rocks are Precambrian W in age (Peter-

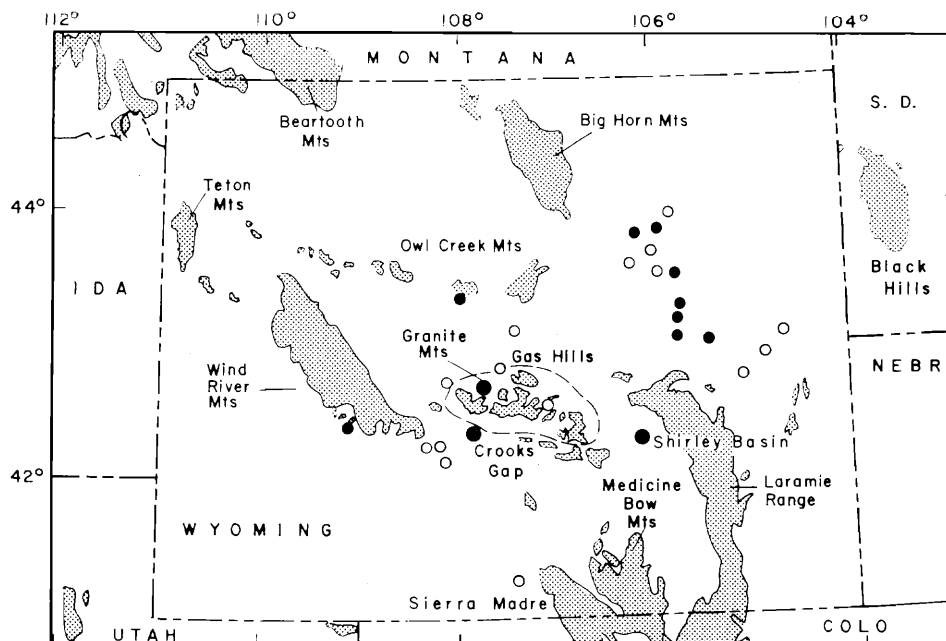


FIG. 1. Index map to the Granite Mountains showing the area of Precambrian uplifts (stippled pattern) and location of Tertiary uranium deposits (circles and dots). The large dots represent the three producing districts with reserves plus production of ore ($>0.1\%$ U_2O_8) of over 1,000,000 tons. Deposits with ore reserves between 1,000 and 1,000,000 tons are shown by small dots, and deposits with reserves between 1 and 1,000 tons are shown by circles (uranium data from Butler, 1972).

man and Hildreth, 1977) and can be divided into three major units: (1) amphibolite-grade metamorphic rocks, (2) intrusive granitic rocks, and (3) diabase dikes (Stuckless et al., 1977). The metamorphic rocks are mostly tonalitic to granitic gneisses with small amounts of schists, amphibolites, and serpentinites. The time of metamorphism has been placed at $2,925 \pm 81$ m.y. by Rb-Sr whole-rock dating (Peterman and Hildreth, 1977) and at $2,910 \pm 120$ m.y. by Pb-Pb (Nkomo and Rosholt, 1972; age recalculated using currently accepted uranium decay constants).

At least two different granites have intruded the metamorphic rocks (Fig. 2). Outcrops of red, generally foliated granite are associated with the metamorphic rocks which form the northern portion of the Granite Mountains. Peterman and Hildreth (1977) have termed this granite the granite of Long Creek Mountain. The zircon age for one sample of this granite is $2,640 \pm 20$ m.y. (Ludwig and Stuckless, 1978). Most of the granite is distinctly different in appearance and is generally separated from the metamorphic rocks. This granite is gray to white and nonfoliated. It yields a slightly younger zircon age of $2,595 \pm 40$ m.y. (Ludwig and Stuckless, 1978). Peterman and Hildreth (1977) have called this younger granite the granite of Lankin Dome and have reported an Rb-Sr whole-rock age of $2,602 \pm 60$ m.y.

Biotitic and leucocratic phases of the granite of Lankin Dome have been recognized (Stuckless et al., 1977). Both the biotitic and leucocratic phases have high alkali contents (average K content $>4\%$, Stuckless et al., 1976) and have calcic plagioclase to alkali feldspar ratios of less than 0.3 (Stuckless et al., 1977). Thus, the granite of Lankin Dome ranges from alkali feldspar granite to granite of type A (IUGS classification, Streckeisen, 1973).

Two types of hydrothermal or late-stage magmatic alteration of the granite have been reported for the granite of Lankin Dome (Stuckless et al., 1976, 1977). Albitized granite has been recognized only in drill cores. Silicified and epidotized granite forms ubiquitous dike-like and sill-like zones within the granite which commonly form topographic highs because of their greater resistance to erosion. Although common, these zones are too small to be shown on the scale of Figure 2.

Steeply dipping diabase dikes that strike northeasterly and easterly cut the granitic and metamorphic rocks as well as some of the silicified and epidotized zones. Some of the larger of these dikes are schematically shown on Figure 2. A sample from one of the larger dikes yielded an $^{39}Ar/^{40}Ar$ age of approximately 2,600 m.y. (Peterman and Hildreth, 1977).

No other igneous or metamorphic units are known to crop out in the Granite Mountains region, but one

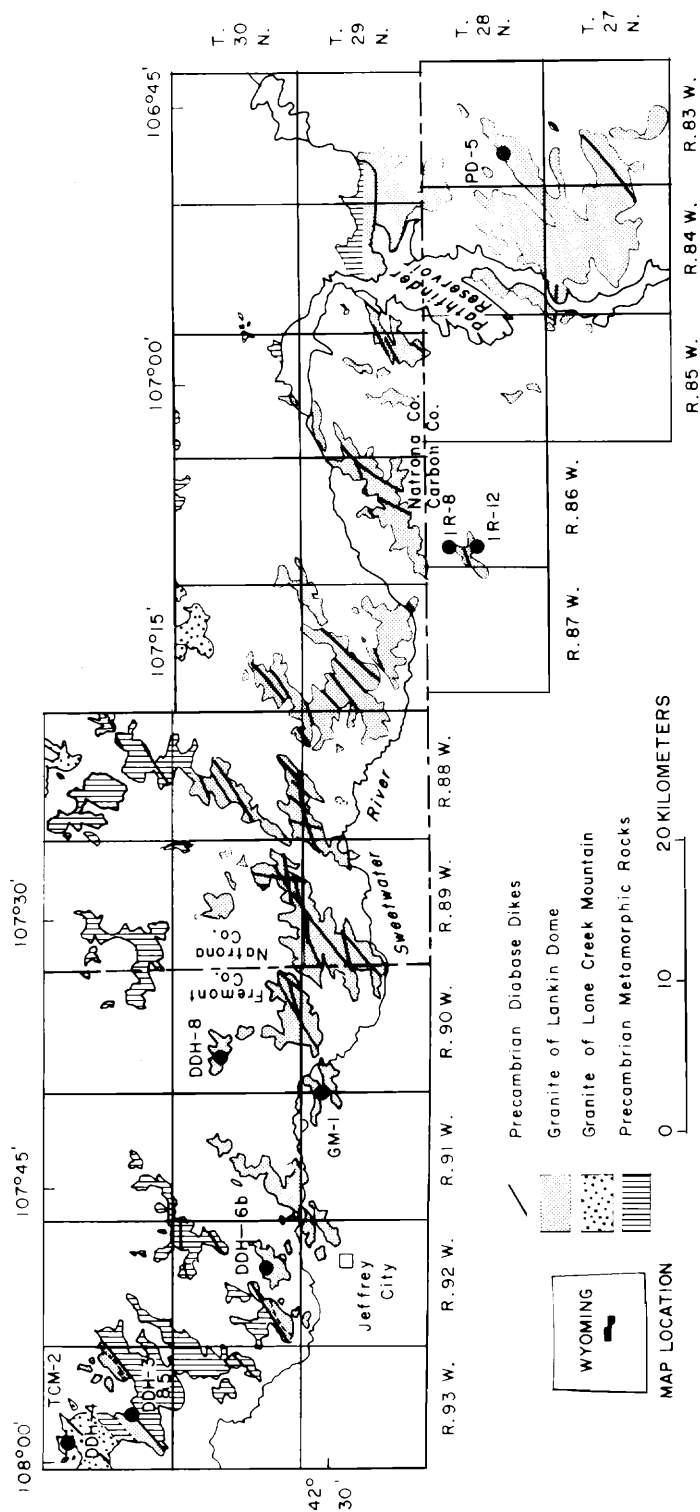


Fig. 2. Sample location (dots) and generalized Precambrian geology of the Granite Mountains, Wyoming. Geology west of R 88 W after Peterman and Hildreth (1977).

or two mid-Precambrian events may be inferred from published isotopic data. Ludwig and Stuckless (1978) reported lead loss from apatites and epidotes which occurred between 1,350 and 2,250 m.y. ago. Rosholt and others (1973) reported evidence for a $1,640 \pm 120$ m.y. thermal event which redistributed lead in feldspars. Peterman and Hildreth (1977) reported a general lowering of Rb-Sr and K-Ar biotite and feldspar ages which they attribute to a late Precambrian Y or early Precambrian X uplift of most of the Granite Mountains.

Investigations south of the Granite Mountains (Divis, 1976) suggest that the Precambrian of Colorado and southern Wyoming was added to the North American continent between 1,600 and 1,900 m.y. ago. In the Medicine Bow Mountains and Laramie Range, the Mullen Creek-Nash Fork shear zone may represent the suture along which the two portions of the continent were joined. Hills and Armstrong (1974) have dated the formation of this shear zone at 1,600 to 1,700 m.y. ago and have suggested this time as one of major orogeny. This event may have been severe enough to affect isotopic systems of minerals as far north as the Granite Mountains.

Most of the reset K-Ar biotite ages in the Laramie Range, Granite Mountains, and southern Wind River Range are 1,400 to 1,600 m.y. These ages suggest that the mid-Precambrian uplift event proposed by Peterman and Hildreth (1977) may be younger than the orogenic event proposed by Hills and Armstrong (1974). It is therefore possible that the rocks in the Granite Mountains were affected by two mid-Precambrian events.

The only other known major event in the Granite Mountains region is a late Cretaceous through early Eocene uplift of approximately 3,000 m in which with subsequent erosion produced a 600-m-thick boulder conglomerate to the south of the Granite Mountains (Love, 1960). Lower intercepts on Concordia for zircon data are interpreted to date the uplift at 50 to 100 m.y. ago (Ludwig and Stuckless, 1978). Apatite fission-track ages support this age because the rocks presently at the surface last cooled below the 100°C isotherm between 45 and 80 m.y. ago, probably in response to uplift and erosion.

At the western end of the Granite Mountains at least part of this movement is documented as southward thrusting. Drill holes have penetrated the thrust sheet (Love, 1970); gravity data suggest that low density rocks underlie the Precambrian section (Case and Keefer, 1966); and heat-flow measurements document a geothermal gradient that is too low if the high radioelement contents of the surface rocks extend to depths greater than 5 km (E. Decker, University of Wyoming, oral commun., 1976).

During middle to late Oligocene, the granitic rocks were eroded down and partly buried by silicic volcanic ash and arkosic debris (Love, 1970). Gentle uplift in late Pliocene or early Pleistocene along reactivated Tertiary fault systems produced the partly exhumed, subdued topography of the present-day Granite Mountains (Rosholt et al., 1973).

Analytical Procedures

Samples analyzed in this study were selected from approximately 200 surface and drill core samples on the basis of γ -ray spectrometric values for Ra equiv. U, Th, and K, petrographic analyses, and considerations of areal and vertical distributions within the granite. The petrographic analyses and potassium contents were used to screen out hydrothermally altered samples which are believed to exhibit different U-Th-Pb isotopic systematics from those of the true granites. The U and Th values were used to obtain the widest range of U and Th contents. As such, some of the general conclusions about the granite as a whole must take into account the typicalness of the analyzed samples.

Procedures for sample preparation are given in Stuckless and others (1977). Chemical and mass spectrometric procedures were the same as those reported by Rosholt and others (1973) except that purified lead was loaded as a silica gel (Arden and Gale, 1974). Sample sizes were chosen such that blank lead (0.01 to $0.02 \mu\text{g}/\text{analysis}$) contributed less than 0.5 percent to the analysis and therefore no blank corrections have been applied to the data. Isotopic analyses of the U.S. National Bureau of Standards lead SRM-981 yielded an average composition of $^{206}\text{Pb}/^{204}\text{Pb} = 16.89$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.43$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.49$. This indicates a 0.15 percent per mass unit discrimination when compared with the values reported by Catanzaro and others (1968), and therefore this discrimination correction has been applied to the data.

Duplicate analyses for U and Th suggest that splitting errors were very significant (Table 1). This was particularly true when U contents were anomalously high or anomalously low ($1 > \text{U} > 20$ ppm, Stuckless et al., 1976). Splitting error effects for Th appear to be significant for the entire range of Th contents and are reflected in the somewhat poorer reproducibility of the $^{208}\text{Pb}/^{204}\text{Pb}$ ratios relative to that of the $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios (Table 1). A similar result was obtained for whole-rock samples for the Pilbara area, Australia (Oversby, 1975b). Averages for the isotopic ratios are considered to be accurate at the 95 percent confidence level within one percent for whole-rock samples and 0.5 percent for mineral analyses for which splitting errors were not observed.

TABLE 1. U, Th, and Pb Concentrations and Isotopic Compositions of Pb in Granite Samples from the Granite Mountains, Wyoming¹

Sample number	U (ppm)	Th (ppm)	Pb (ppm)	²⁰⁶ Pb ²⁰⁴ Pb	²⁰⁷ Pb ²⁰⁴ Pb	²⁰⁸ Pb ²⁰⁴ Pb	Sample depth (m)	Sample type ²
DDH-3	3.09	19.92	43.27	25.60	16.99	38.39	6.7	LD-B
DDH-4	2.29 2.16	16.95 16.33	20.87	21.09 21.22	16.24 16.24	42.73 42.83	1.6	LCM
DDH-5	2.66	25.11	50.57	23.10 23.10	16.68 16.68	38.94 39.02	2.0	LD-B
DDH-6b	2.13	22.69	40.54	19.38 19.37	16.16 16.16	40.00 39.36	2.1	LD-B
DDH-8	7.45 8.00	32.65 32.23	61.95	35.55	19.01	40.62	2.7	LD-B
GM-1-66.5	13.08	62.79	59.62	29.08 29.34	17.80 17.83	46.28 46.60	20.4	LD-B
GM-1-85.8	23.00 24.14	59.24 63.17	56.44	29.04 29.22	17.78 17.88	46.16 46.04	26.7	LD-B
GM-1-163.9	1459.0	62.27	55.36	37.57	18.44	49.37	50.1	LD-B
GM-1-257.3	27.32 26.02	63.84 64.01	62.57	41.55	20.07	48.07	78.5	LD-B
GM-1-285.5	56.21	43.86	53.63	29.93 29.84 29.95	17.95 17.89 18.00	42.80 42.80 43.03	87.1	LD-B
GM-1-374.3	10.76	68.58	56.20	31.51 31.84	18.19 18.31	48.32 48.33	114.1	LD-B
GM-1-739.0	5.52 5.62	13.54 13.78	53.99	22.86	16.74	35.55	222.0	LD-L
GM-1-814.0	23.27	15.06	41.63	25.26	16.91	37.43	243.1	LD-L
GM-1-825.5	3.07 3.11	1.39 1.41	49.23	17.54	15.79	34.67	246.3	LD-L
GM-1-851.4	12.83 12.72	6.33 5.51	64.33	19.95 19.84	16.01 16.06	34.27 34.78	253.4	LD-L
GM-1-1021.7	7.77	11.27	57.28	20.88	16.33	35.40	297.7	LD-L
GM-1-1278.0	4.12 4.31	18.40 21.04	54.80	25.59 26.37	17.22 17.27	36.36 37.74	357.4	LD-L
GM-1-1325.9	21.52 22.07	23.98 25.00	56.60	24.75	17.07	37.97	366.4	LD-L
IR-8	0.92 0.86	37.71 33.78	18.67	15.88	15.50	53.81	0	LD-B
IR-12	0.39 0.36	4.51 4.45	24.49	15.22	15.35	35.89	0	LD-L
PD-5	10.90	72.68	42.17	51.83	22.15	62.99	0	LD-B
TCM-2	3.77 3.74 3.65	18.95 19.18 17.40	24.94	19.58 19.54	15.86 15.80	39.62 39.39	0	LCM

¹ Isotopic data normalized for mass discrimination of 0.15‰ per mass unit.² LD-B = granite of Lankin Dome, biotitic phase; LD-L granite of Lankin Dome, leucocratic phase; LCM = granite of Long Creek Mountain.

Five microclines were analyzed during this study (Table 2). These were separated by standard physical techniques, finely powdered in an agate mortar, and left in a bomb for 12 hours with 6N HNO₃ at 80°C. After this treatment the microclines contained too little uranium to affect the lead isotope composition. One of the microclines was also analyzed using a series of partial HF attacks (Ludwig and Silver, 1977).

Best fit lines were calculated by the methods of

York (1969), using the errors cited above and concordia intercept errors were calculated by the method of Ludwig and Stuckless (1978). All ages are reported at the 95 percent confidence level.

Results and Discussion

Present-day uranium and thorium concentrations

Uranium, thorium, and lead concentrations and the isotopic compositions of analyzed granites are given

TABLE 2. Isotopic Composition of Leads in Microclines from Granites of the Granite Mountains, Wyoming

Sample number	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
GM-1-825.5	15.46	15.55	34.58
GM-1-771.2	15.88	15.62	34.55
TCM-2	14.28	15.16	34.15
CR-26-99	19.78	16.66	35.47
CR-14-157	18.30	16.33	37.41
CR-14-157-L1	20.11	16.46	38.25
CR-14-157-L2	18.59	16.32	37.41
CR-14-157-L3-L5	—	—	—
CR-14-157-residue	44.12	19.94	44.59

L = leach step; no data obtained for leaches 3, 4, or 5. Analysts: K. R. Ludwig and C. T. Fogg.

in Table 1. Uranium contents of the analyzed samples vary from 0.38 to 1,400 ppm, and thorium contents vary from 1.40 to 72.7 ppm. The large apparent range for uranium concentrations is due to selective choosing from the over 200 samples that had been analyzed by γ -ray spectrometry. Stuckless and others (1976) report mean uranium and thorium contents as 11.5 ± 8.9 (1σ) and 51.0 ± 16.9 (1σ) for the biotitic granite and as 8.6 ± 8.0 (1σ) and 13.3 ± 7.9 (1σ) for the leucocratic granite. These averages suggest that the granite (including both

phases) currently contains two to three times as much uranium as the average granite ($\text{SiO}_2 > 70\%$) of Rogers and Adams (1969). Thorium contents in the biotitic phase are also two to three times greater than the average reported by Rogers and Adams (1969), but the leucocratic phase of the granite is close to average or possibly a little low.

The high uranium contents are not surprising as uranium contents tend to increase with increasing silica in differentiated suites (Rogers and Adams, 1969; Tilling et al., 1970) and, at any given silica content, uranium tends to increase with increasing alkali contents (Tilling and Gottfried, 1969; Killeen and Heier, 1975). Most of the granites of the Granite Mountains are high in silica and alkalies (Stuckless and Ferreira, 1976; Stuckless et al., 1976), and although there is no evidence for the origin of the granites by differentiation, partial melting of intermediate to silicic crustal rocks could produce a magma that was strongly enriched in incompatible elements.

Age relationships

Two of the analyzed samples have been omitted from all of the age regressions (DDH-4 and TCM-2). These were collected from the granite of Long

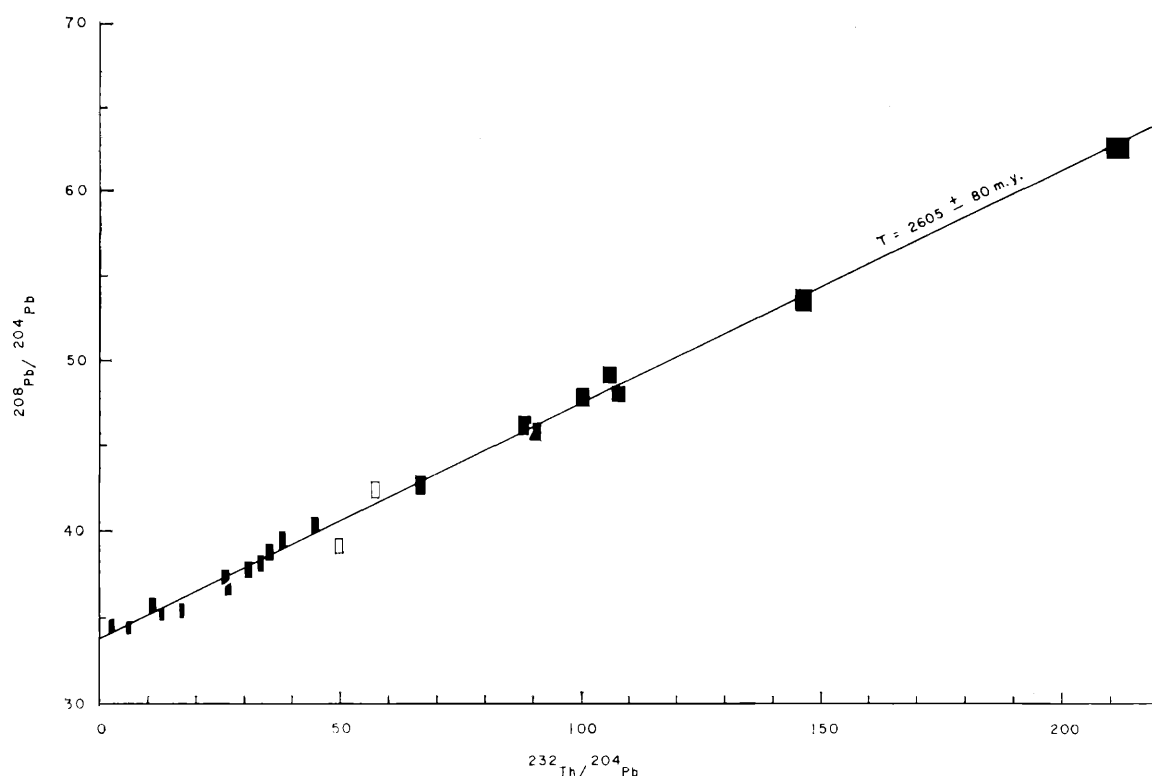


FIG. 3. Th-Pb whole-rock isochron plot for samples from the Granite Mountains, Wyoming. Samples from the granite of Lankin Dome are shown as solid symbols. Samples of the granite of Long Creek Mountain are shown as open symbols and were not used in the best-fit regression. Symbol sizes equal ± 1 standard deviation.

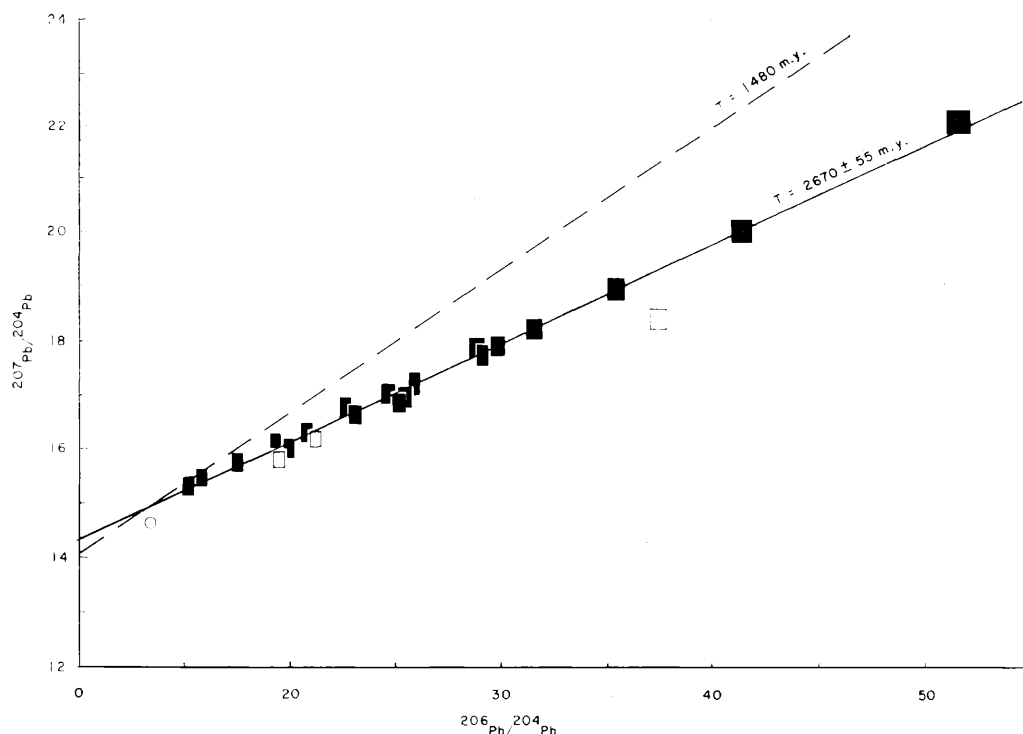


FIG. 4. Pb-Pb isochron plot for whole-rock samples from the Granite Mountains, Wyoming. Samples from the granite of Long Creek Mountain and sample GM-1-163.9 are shown by open symbols and were not used in the best-fit-line regression. Symbol sizes equal ± 1 standard deviation. The dashed isochron is for the microcline analyses (Fig. 5). Samples from the granite of Lankin Dome are shown by solid symbols. Common lead composition used for concordia calculations is shown by a circle.

Creek Mountain (Peterman and Hildreth, 1977). This granite has been shown to be slightly but significantly older than and different in chemistry from the Granite of Lankin Dome (Ludwig and Stuckless, 1978). Although the age difference is too small to be resolved by the techniques used for this paper, the age difference and different chemistry appear to cause an increased error in calculated ages.

The age calculated from the Th-Pb whole-rock system is $2,605 \pm 80$ m.y. This agrees well with the Rb-Sr age of $2,602 \pm 60$ m.y. (Peterman and Hildreth, 1977) and with the U-Pb zircon age of $2,595 \pm 40$ m.y. (Ludwig and Stuckless, 1978). The data points, particularly for the unradiogenic samples, do not fit an isochron within the expected $\pm 1\sigma$ errors, but all of the points fit the regressed line within $\pm 2\sigma$ (Fig. 3). The data therefore suggest that the thorium-lead system has approximated a closed system since the intrusion of the granite.

The Pb-Pb age of $2,670 \pm 55$ m.y. for the whole-rock isochron is significantly different by 41 m.y. (by a student's T-test) from the Th-Pb age at the 95 percent confidence level, and it is significantly different by 46 m.y. from the U-Pb zircon age. All of the samples fit the regressed isochron within the ex-

pected limits of error (Fig. 4), but it might be argued that the two very unradiogenic samples (IR-8 and IR-12, Table 1) have biased the isochron. These samples contain nearly three times as much biotite and one fourth as much microcline as any of the other analyzed samples. Furthermore they are spatially separated from the other analyzed samples and there is no independent age evidence to indicate that they are coeval with the granite of Lankin Dome. However, omitting these samples from the age regression results in an age of $2,790 \pm 50$ m.y. which is very much older than the apparent age of the granite. We therefore believe that there is no good reason to separate these granites from the granite of Lankin Dome. Because the Pb-Pb whole-rock system yields an age that is too old, we conclude that it has not acted as a closed system.

Ages calculated from the $^{206}\text{Pb}/^{238}\text{U}$ system are also too old, in fact eight of these ages are older than 5,000 m.y. Fifteen of the ages are significantly older than the known age of the granite. These erroneously old ages are attributed to recent uranium loss as shown below.

Rosholt and others (1973) used lead analyses of microcline to calculate the age of a mid-Precambrian

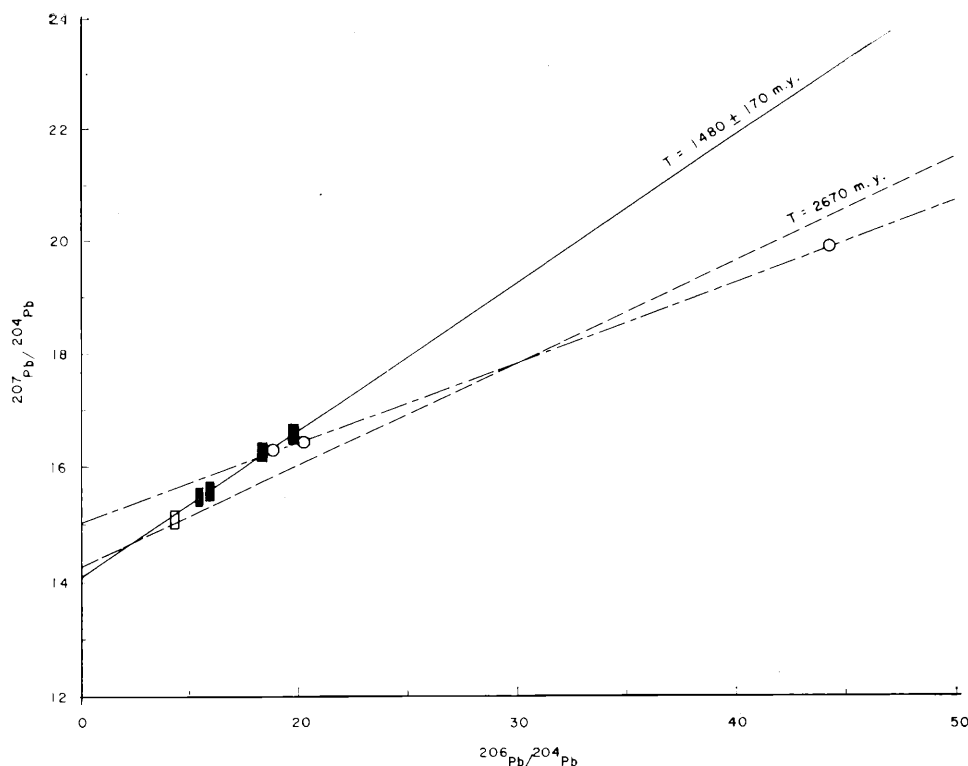


FIG. 5. Pb-Pb isochron plot for microcline separates from the Granite Mountains, Wyoming. Microclines from the granite of Lankin Dome are shown by solid symbols. Results for the step-wise leaching of the microcline from sample CR-14-157 are shown by circles. Microcline TCM-2 from the granite of Long Creek Mountain is shown by the open rectangle and was not used in the best-fit-line regression. The broken isochron is drawn through the step-wise attacks for microcline CR-14-157. Dashed isochron is the 2,670-m.y. whole-rock isochron. Rectangle sizes equal ± 1 standard deviation.

disturbance and, in conjunction with the whole-rock lead analyses, to calculate the common lead composition for the granites. We have analyzed four microclines from the granite of Lankin Dome and one of these by stepwise hydrofluoric acid attack (Table 2). The results are shown on Figure 5. The data points for the bulk feldspars fit a secondary isochron well within the limits of experimental error and suggest an age of $1,480 \pm 170$ m.y. (calculated using the U-Pb zircon age as the initial age of the system). The points from the stepwise attack of the single feldspar separate, however, define a different isochron and therefore suggest that the feldspars contain more than two components of lead.

Ludwig and Silver (1977) have shown that multi-component leads are common in Precambrian potassium feldspars and that some feldspars may contain a pure ^{206}Pb component derived by the long-term diffusion of ^{222}Rn from ^{238}U sites. A pure ^{206}Pb component in the microclines from the granite of Lankin Dome is suggested by the very shallow slope of the isochron defined by the stepwise attack data. Alternatively, the feldspars may contain a modern lead

component. The effect of either component would be to lower the apparent secondary age of each feldspar and thus the age of $1,480 \pm 170$ m.y. must be considered a minimum age for the mid-Precambrian disturbance.

A secondary effect of the excess ^{206}Pb or modern lead component in the microclines is evident from the calculated intersection of the whole-rock and feldspar isochrons (Fig. 5). This intersection yields a common lead composition for the granites of $^{206}\text{Pb}/^{204}\text{Pb} = 13.2 \pm 1.0$ and $^{207}\text{Pb}/^{204}\text{Pb} = 14.9 \pm 0.2$. The means of these values are unreasonable when compared to normal lead composition at 2,600 m.y. (Stacey and Kramers, 1975). If the intersection is calculated from the Pb-Pb whole-rock isochron that excludes samples IR-8 and IR-12, the $^{206}\text{Pb}/^{204}\text{Pb}$ value becomes even smaller and the $^{207}\text{Pb}/^{206}\text{Pb}$ ratio becomes even more unrealistic.

A common lead content is needed in order to calculate either U-Pb concordia ages or uranium mobility. We have used Stacey and Kramers' (1975) two-stage lead at 2,600 m.y. ($^{206}\text{Pb}/^{204}\text{Pb} = 13.86$ and $^{207}\text{Pb}/^{204}\text{Pb} = 14.78$). This lead composition

TABLE 3. Calculated Isotopic Ratios and Changes in Uranium Contents for Granite Samples from the Granite Mountains, Wyoming

Sample number	$\frac{^{206}\text{Pb}^1}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}^1}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}^1}{^{206}\text{Pb}^1}$	% ΔU_m^2	% ΔU_R^2
DDH-3	2.321	60.32	0.1885	-27.6	-75.2
DDH-4	0.974	26.82	0.1997	-37.2	-34.9
DDH-5	2.549	72.23	0.2005	-50.9	-72.3
DDH-6b ³	1.59	54.8	0.249	—	—
DDH-8	2.092	56.26	0.1951	-37.6	-70.3
GM-1- 66.5	0.856	23.35	0.1978	-41.3	-25.1
GM-1- 85.8	0.450	12.40	0.1999	-44.2	46.5
GM-1- 163.9	0.0098	0.21	0.1541	—	>4,000
GM-1- 257.3	0.677	17.83	0.1911	-31.7	-12.5
GM-1- 285.5	0.193	5.26	0.1974	-40.8	213
GM-1- 374.3	1.085	29.17	0.1951	-37.6	-42.8
GM-1- 739.0	1.326	39.77	0.2176	-63.3	-35.8
GM-1- 814.0	0.293	7.54	0.1867	-24.6	92.6
GM-1- 825.5 ³	0.98	37.4	0.276	—	—
GM-1- 851.4	0.492	14.17	0.2086	-54.4	50.8
GM-1-1021.7	0.813	24.71	0.2204	-65.8	-9.6
GM-1-1278.0	2.243	62.92	0.2034	-48.5	-69.2
GM-1-1325.9	0.405	11.74	0.2103	56.1	87.4
IR-8 ³	0.57	28.1	0.357	—	—
IR-12 ³	1.52	88.4	0.420	—	—
PD-5	1.232	32.98	0.1941	-36.3	-50.2
TCM-2	0.582	14.98	0.1867	16.4	5.8

¹ Radiogenic component only assuming a common lead of $^{206}\text{Pb}/^{204}\text{Pb} = 13.8$ and $^{207}\text{Pb}/^{204}\text{Pb} = 14.78$.

² Changes in uranium calculated assuming a recent change at 20 m.y. ago (U_R), a middle Precambrian change at 1,650 m.y. ago (U_m), and an initial age of 2,600 m.y. for all samples except DDH-4 and TCM-2 for which an initial age of 2,640 m.y. is assumed.

³ Calculated ratios and changes in uranium content very uncertain due to large common lead percentages.

lies slightly below the regressed Pb-Pb whole-rock isochron (Fig. 4). Although it lies on the isochron within the limits of error, it has the effect of increasing the concordia intercept ages. The effect on samples that contain small amounts of radiogenic lead is very pronounced and therefore samples that contained less

than 30 percent radiogenic lead have been omitted from the concordia regression.

The corrected ratios are given in Table 3 and are plotted on a concordia diagram on Figure 6. The concordia intercepts indicate an age of $2,830 \pm 45$ m.y. for the age of intrusion of the granite and an

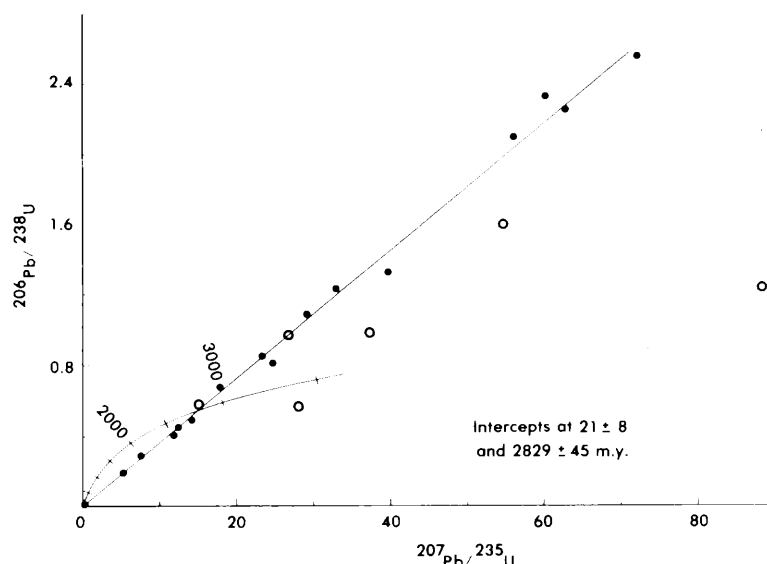


FIG. 6. Concordia diagram for whole-rock samples from the Granite Mountains, Wyoming. Dots are for samples from the granite of Lankin Dome. Circles are for the granite of Long Creek Mountain and other samples which contained less than 30 percent radiogenic lead. These samples were not used for the best-fit-line regression.

age of 20 ± 10 m.y. for the age of a subsequent disturbance of the whole-rock systems. If the uncertainty of the common lead correction is taken into account, the intercept errors are increased by approximately a factor of three.

The relatively recent event has apparently had opposite effects on different samples. Six samples lie below concordia. These have either lost lead or gained uranium in the relatively recent past. Nine samples and most of the samples not used in the regression lie above concordia. These have either recently lost uranium or gained lead.

The scatter about the regressed line on concordia is much greater than that predicted by analytical error even if the uncertainty in the common lead correction is taken into account. This observation together with the knowledge that the Pb-Pb age is too old suggests that the Pb-Pb system has been affected by a third event, which had a somewhat variable effect of adding lead or removing uranium from the whole-rock systems. If lead were added, it would have to have been of an appropriate isotopic composition such that the whole-rock Pb-Pb isochron would not be scattered beyond the limits of analytical precision (Fig. 4). Furthermore, added lead would have to lack ^{208}Pb or be added with exactly enough ^{204}Pb and ^{232}Th to make the Th-Pb system appear to be closed (Fig. 3). These conditions seem to be too fortuitous for 20 samples, and we therefore conclude that some secondary event removed uranium from the whole-rock systems.

Uranium-mobility models

Examples of the effects of uranium loss on a Precambrian system are given in Figures 7 and 8. The ideal Pb-Pb system for two samples (A and B) with different μ ($^{238}\text{U}/^{206}\text{Pb}$) values $\mu_A > \mu_B$ would evolve along the curves shown by the circles in Figure 7. Assuming a uniform initial lead composition, all samples of a 2,600-m.y.-old system would start at a single point (t_0) and, following closed-system evolution today, would lie along a line corresponding to a 2,600-m.y. isochron. If uranium were lost at some intermediate time, the radius of curvature of the growth curves would be increased. In the example shown in Figure 7, the uranium concentrations in A and B were both decreased 20 percent at 1,650 m.y. ago. The resultant apparent age is 2,690 m.y. (indicated by the triangles, Fig. 7). It should be noted that if the uranium losses were not proportional for each sample, the linear relationship would be scattered with the amount of scatter dependent upon the amount of deviation from a constant percentage of lost uranium. Figure 7 also implicitly shows that a relatively recent loss of uranium (or alternatively, uranium loss very near the time of formation of the system) would not affect the calculated Pb-Pb age.

The effects of this same amount and time of uranium mobility with the added complication of a recent uranium loss are shown on the concordia diagram of Figure 8. If all samples behaved as closed systems from their time of formation (t_0) through to the

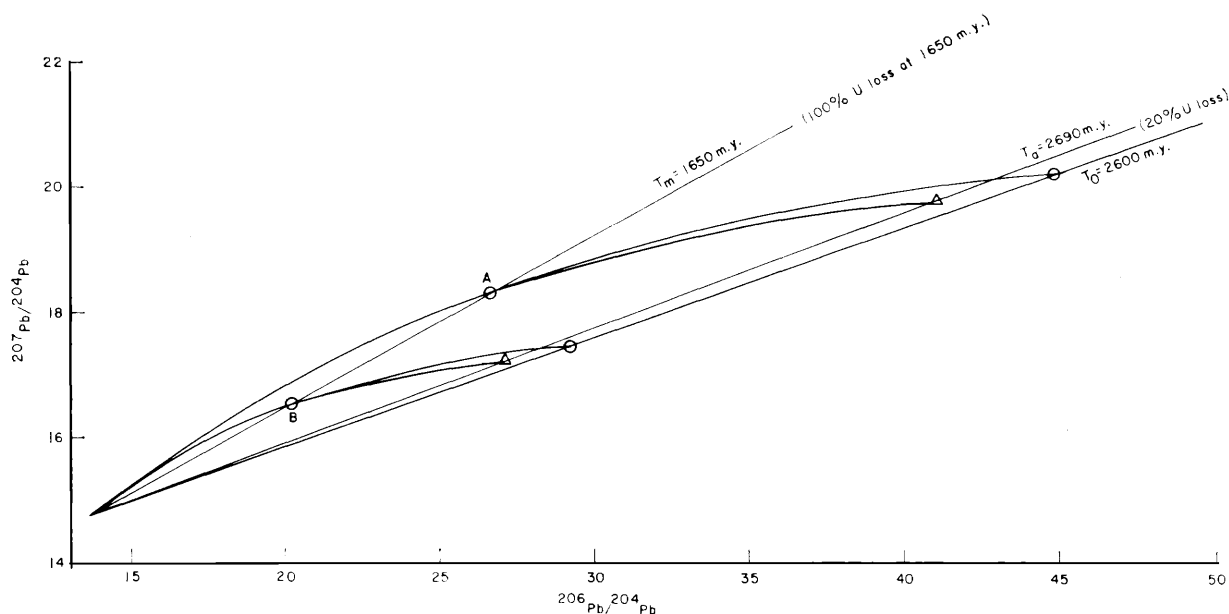


FIG. 7. Pb-Pb evolution diagram showing growth curves and secondary isochrons. Point T_0 is the initial composition of the system. Circled points show the composition of closed systems at 1,600 m.y. and today. Triangular points show the composition of the systems today if each sample lost 20 percent of its uranium at 1,600 m.y.

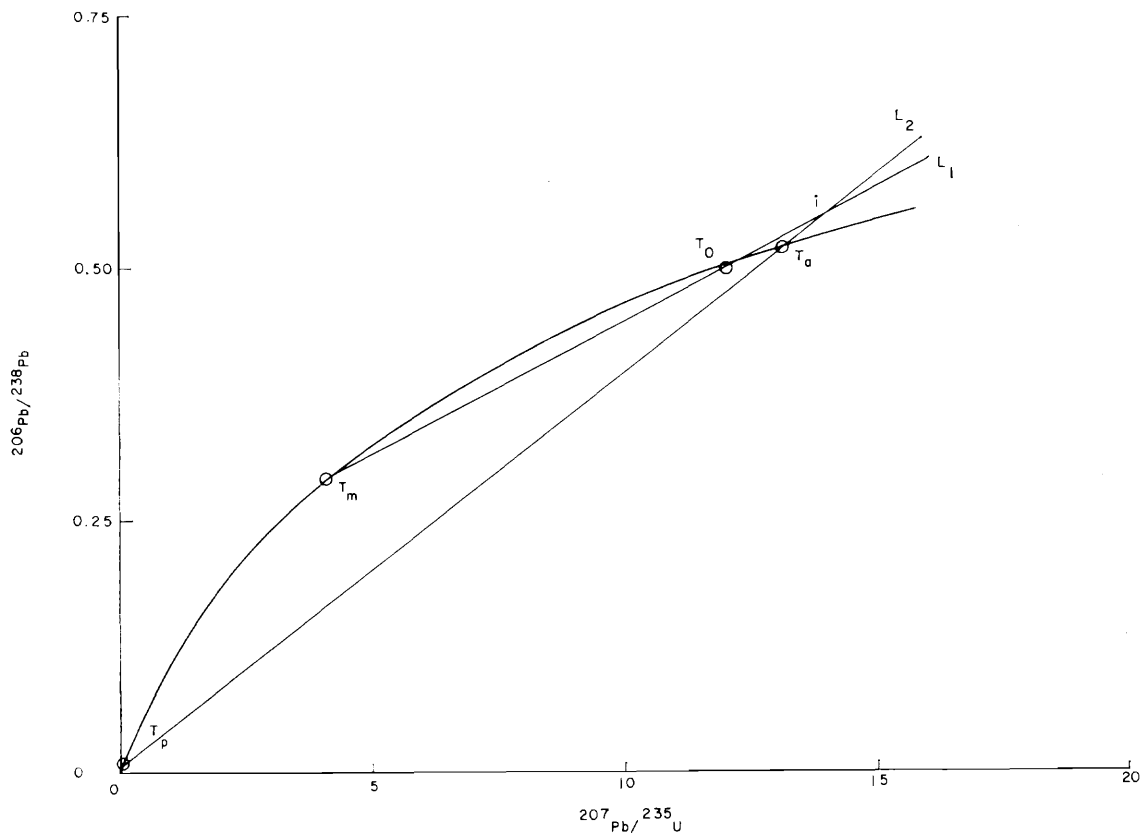


FIG. 8. Concordia diagram showing the evolution of three-stage Pb system.

present, then all samples, regardless of uranium and lead contents, would plot at the point t_0 with the corresponding age of 2,600 m.y. If, however, an event at t_m caused an opening of the systems, the sample data points would lie along line L_1 and, for the specific case of a 20 percent uranium loss (with no subsequent uranium or lead mobility), all of the sample data points would plot at point i . For such a

case, a recent and variable opening of the system would spread points along line L_2 in a perfect linear array.

This type of two-stage, open system behavior for the samples from the Granite Mountains can be modeled by iterating two equations and using the calculated amounts of radiogenic ^{206}Pb and ^{207}Pb currently present in each sample:

$$^{238}\text{U}_R = ^{206}\text{Pb}^* - [^{238}\text{U}_m(e^{\lambda_8(t_0-t_m)} - 1)/(e^{\lambda_8 t_m} - 1)] \quad (1)$$

$$^{238}\text{U}_m = \frac{(^{238}\text{U}_R/137.88)(e^{\lambda_5 t_m} - 1) - (^{207}\text{Pb}^*/^{206}\text{Pb}^*)(^{238}\text{U}_R)(e^{\lambda_8 t_m} - 1)}{(^{207}\text{Pb}^*/^{206}\text{Pb}^*)(e^{\lambda_8(t_0-t_m)} - 1) - e^{t_m(\lambda_5 - \lambda_8)}(e^{\lambda_5(t_0-t_m)} - 1)(1/137.88)} \quad (2)$$

where $^{238}\text{U}_R = ^{238}\text{U}$ just prior to the recent loss, $^{206}\text{Pb}^* =$ present-day radiogenic ^{206}Pb , $^{207}\text{Pb}^* =$ present-day radiogenic ^{207}Pb , $^{238}\text{U}_m = ^{238}\text{U}$ just prior to loss at t_m , $t_0 =$ age of formation of the system, $t_m =$ age of metamorphism, $\lambda_8 =$ decay constant for ^{238}U , and $\lambda_5 =$ decay constant for ^{235}U . With these results, one can calculate the amount of recent uranium loss as:

$$\Delta\text{U}_R = \frac{^{238}\text{U}_P - ^{238}\text{U}_R}{^{238}\text{U}_P} \quad (3)$$

where $^{238}\text{U}_P =$ the measured amount of ^{238}U . The amount of uranium loss at t_m (ΔU_m) can be calculated from:

$$^{238}\text{U}_m' = ^{238}\text{U}_P(e^{\lambda_8 t_m}) \quad (4)$$

$$\Delta\text{U}_m = \frac{^{238}\text{U}_m' - ^{238}\text{U}_m}{^{238}\text{U}_m'} \quad (5)$$

where $^{238}\text{U}_m' = ^{238}\text{U}$ just after loss at t_m .

The most reasonable time for a secondary effect on the whole-rock systems is the mid-Precambrian event

(or events) that affected the K-Ar, Rb-Sr, Pb-Pb and U-Pb systems of many minerals in the Granite Mountains region. The timing of this event is not known accurately enough to allow precise calculations of the effects on the uranium-lead, whole-rock system. However, the linearity of the Pb-Pb and concordia systems seems good enough to justify a choice of some episodic event, and the proposed orogenic event of Hills and Armstrong (1974) between 1,600 and 1,700 m.y. ago appears to be the best choice. The calculated uranium changes at 1,650 m.y. ago and within the last 40 m.y. are given in Table 3. The results for the very unradiogenic samples are unsolvable because of the large uncertainties. Sample GM-1-163.9 (Table 1) appears to have gained almost all of its uranium in the last 40 m.y. and has generated enough ^{206}Pb to mask its Precambrian history.

An estimate of the average uranium loss at 1,650 m.y. for all of the analyzed samples can be made from the $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ value at the upper concordia intercept (0.2005). The resulting average uranium loss is 45 percent. If the uranium were lost at 1,400 m.y., the uranium loss (calculated from the $^{207}\text{Pb}/^{206}\text{Pb}$ value at the concordia intercept) would be 48 percent. These estimates of average uranium losses agree well with those obtained by averaging uranium losses for individual samples.

An alternate estimate for the average mid-Precambrian loss can be obtained from the slope of the Pb-Pb isochron because it yields the average $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ ratio (0.1818). This value is preferable for calculating the average mid-Precambrian uranium loss because it is not dependent on the choice of a common lead composition. However, if the recent uranium loss occurred long enough ago (>60 m.y.), then the calculated average loss would be too large. The average uranium loss calculated from the slope of the Pb-Pb isochron is 16 percent for loss at either 1,650 or 1,400 m.y. If this is the true mid-Precambrian uranium loss, then the recent uranium losses listed in Table 3 are too small.

Migration of uranium in granitic rocks in response to metamorphism has been documented elsewhere. Depletion of uranium in response to granulite metamorphism has been demonstrated isotopically for granitic rocks from Australia by Gray and Oversby (1972) and for granitic rocks from Minnesota (Doe and Delevaux, 1977). Killen and Heier (1975) have suggested that the uranium contents of several Precambrian granites in Norway have been modified by a thermal event in the Permian such that uranium migrated away from the thermal front. Because several radiometric systems seem to reflect a late Pre-

cambrian X or early Precambrian Y thermal event in the Granite Mountains and surrounding portions of the Precambrian W terrain of Wyoming, loss of uranium at that time seems reasonable.

Loss of uranium from igneous rocks in response to near-surface conditions has also been well documented. Examples based on isotopic studies include Rosholt and Bartel (1969), Sinha (1972), Nkomo and Rosholt (1972), Rosholt et al. (1973), Ludwig (1974), Goldich et al. (1975), Oversby (1975a, c), and Doe and Delevaux (1977). Comparison of uranium contents in surface and deep drill hole samples has also indicated uranium loss due to weathering (Rogers et al., 1965; Barbier, 1968).

If uranium is easily lost owing to near-surface conditions, then the calculated timing of that loss in the Granite Mountains (within the last 40 m.y.) would be sensitive to any earlier near-surface history that the granite might have had. Several lines of reasoning suggest that the samples analyzed in this study were first exposed to near-surface conditions in Tertiary time. Fission-track apatite ages (Ludwig and Stuckless, 1978) in conjunction with the current geothermal gradient for the region of 17° to 18° C/km (E. Decker, University of Wyoming, oral commun., 1977) indicate that the present surface was buried to a depth of at least 5 km in late Cretaceous time.

This amount of uplift agrees well with the amount of uplift and subsequent erosion postulated by Love (1960). Furthermore, sedimentological data reported by Love (1960, 1970) suggest that much of the eroded material was granitic and that therefore the surface on which sediments had been deposited, and which had been exposed to earlier near-surface conditions, lay well above the present erosional surface.

The isotopic data themselves yield good evidence for a first, near-surface exposure in the Tertiary. It is reasonable that the samples that recently gained uranium did so contemporaneously with the loss from most of the granite. Because sample GM-1-163.9 (Tables 1 and 3) gained so much uranium in recent times, its $^{206}\text{Pb}/^{238}\text{U}$ ratio yields a good estimate of the maximum age of uranium mobility for the currently near-surface granite samples. This maximum age of recent uranium mobility is 60 m.y.

It is of course likely that each exposed surface of the granite lost uranium and that therefore the granite shed uranium into the surrounding basins from its first exposure through to the generation of the present surface. Furthermore, Stuckless and Ferreira (1976) have shown that uranium has been moving in the currently near-surface granite within the last 100,000

years. This implies that although the loss of uranium appears to be episodic in terms of the lead isotope system, the episode is really of several million years duration.

Relative uranium mobility in different samples

Rosholt and others (1973) reported an average uranium loss in the Granite Mountains of nearly 80 percent and, if the effects of the mid-Precambrian loss are ignored, our results for surface and very near surface samples agree with this conclusion (Tables 1 and 3). In fact even one sample from a depth of 357 m lost that much uranium (GM-1-1278.0, Tables 1 and 3). The granites of Long Creek Mountain are notable exceptions to the general high percentage uranium loss in response to near-surface conditions, but these granites are distinctly different in chemistry from most of the granites analyzed in this study. They generally contain less silica, alkalis, uranium, and thorium (Ludwig and Stuckless, 1978).

High thorium and alkali contents appear qualitatively to have been accompanied by initially high uranium contents. In the case of the very near-surface samples, the initial high uranium contents seem to have resulted in recent, high uranium losses, both in terms of percent loss and weight loss per unit volume. Thus, we conclude that the most favorable granitic source rocks for uranium are those with high thorium and alkali contents.

The short intervals of the drill core that were chosen for their anomalously high uranium contents all appear to have gained uranium in relatively recent times. We have not been able to identify any single feature or combination of features common to these samples and distinct from those for samples that lost uranium. Sample GM-1-163.9, for which the uranium content increased by over 4,000 percent, is the only distinctly different sample. This sample has been weakly albitized, exhibits a cataclastic texture, and was situated in a narrow zone between two strongly albitized sections of granite. It is also possible that its proximity to the water table had an effect in a redox precipitation of uranium, but a second drill hole 60 m north of GM-1 failed to disclose any uranium anomalies at a comparable depth. However, cataclastic rocks were not encountered at this depth in the second drill hole, and fission-track experiments show that uranium is concentrated in the abundant microfractures of samples GM-1-163.9.

Sample GM-1-285.5 exhibits the second largest amount of uranium gain, but this sample is not cataclastic. Samples GM-1-814.0 and 1325.9, which

also show significant amounts of recent uranium gain, are from highly fractured sections of the drill core (Stuckless et al., 1977). It is possible that the essentially two dimensional sampling of the drill hole fails to describe adequately the fracturing in the vicinity of sample GM-1-285.5 and that fracturing of the granite may very well control secondary precipitation of uranium.

With the exception of sample GM-1-1278.0, most of the core samples that have lost uranium are unfractured. Sample GM-1-374.3 was taken from near the center of a 10-m section of core that contained no fractures other than those caused by pulling the core barrel from the bottom of the hole at the end of each 3-m run, and yet this sample has an apparent recent uranium loss of 45 percent (Table 3). Gas permeability studies of this and other sections of core yield fairly high permeability values (20 to 0.03 microdarcy, T. Parks, CSIRO, Australia, written commun., 1976).

Fluid flow studies in granitic rock (Balagna, 1976) have suggested that much of the flow occurs within and around biotite crystals. Core samples from drill hole GM-1 that have lost uranium generally contain moderate amounts of biotite and chloritized biotite (Stuckless et al., 1977). Leaching experiments on biotites separated from the Conway Granite show that approximately 50 percent of the uranium is easily mobilized (D. Seidel, USBM, oral commun., 1976). Fission-track analysis of the Granite Mountains samples (Stuckless et al., 1977) show that much of the currently present uranium is associated with biotite. Hence, it seems reasonable that biotite may be an important constituent of potential uranium source rocks. One of the analyzed samples (IR-8) had a very high biotite content (17%) and a moderate thorium content, and its position on the concordia diagram is suggestive of a recent uranium loss. However, the very low $^{206}\text{Pb}/^{204}\text{Pb}$ ratio indicates that this sample could not have lost a very large quantity of uranium. We therefore conclude that thorium and biotite contents alone are not sufficient to identify potential granitic uranium source rocks.

Conclusions

Three sources have been proposed for the uranium deposits of central Wyoming: granites, arkosic sands derived from the granite, and volcanic ash. We conclude that the granites of the Granite Mountains were a major source of uranium for several reasons: the major uranium districts are disposed about the flanks of the mountains (Fig. 1); large amounts of uranium have been lost from the currently exposed, and presumably from the previously eroded, granites (Rosh-

olt et al., 1973; and this study); if most of the labile uranium is removed from the granite prior to its mechanical disintegration, then the arkosic sands derived from the granite would make a poor source for uranium; Harshman (1972) has reported that altered sands in the Shirley Basin, through which the ore-bearing solutions presumably moved, contain more uranium than the unaltered arkoses; radiometric dating of the ores (Ludwig, 1978) suggests that they are, at least in part, older than the proposed volcanic source rocks (Zielinski and Naeser, 1977; Love, 1970); and the timing for at least part of the uranium loss from the granite agrees with radiometric dates of the ores.

Uranium contents of all favorable granitic source rock, although still anomalously high when compared to average granites (Rogers and Adams, 1969), have been drastically depleted for all surface samples analyzed in this study and for those reported by Rosholt and others (1973). Hence, present-day uranium contents may not be a good indicator of favorable granitic source rocks. Other features common to most of the samples that lost large amounts of uranium in the relatively recent past include high alkali, silica, and thorium contents, and moderate biotite contents.

A few thin zones of uranium reconcentration within the granite were analyzed. These contained 20 to 1,460 ppm uranium. The only feature common to these samples and therefore possibly controlling uranium deposition appears to be intense fracturing.

The fact that all samples from the granite of Lankin Dome appear to have lost uranium in response to an apparently mild mid-Precambrian thermal event may have important consequences for uranium exploration in crystalline terrains. If the suggestion of Killen and Heier (1975) is followed, then the mobilized uranium may have migrated away from the thermal front and may have been reconcentrated in the crystalline rocks farther north. As a corollary, whole-rock Pb-Pb ages, which are apparently too old, may indicate terrains in which uranium has been mobilized in the past. Conversely Pb-Pb ages in complex Precambrian terrains may be misleading, if the rocks failed to act as a closed system during thermal or structural events or during periods of exposure and weathering. Finally, the Th-Pb ages do not seem to be as sensitive to these effects as the Pb-Pb ages.

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REFERENCES

- Arden, J. W., and Gale, N. H., 1974, Separation of trace amounts of uranium and thorium and their determination by mass-spectrometric isotope dilution: *Anal. Chemistry*, v. 46, p. 687-691.
- Barbier, Jean, 1968, Alteration chimique et remaniement de l'uranium dans le granite à deux micas des Monts de Blond (Limousin, France): *Sci. Terre*, v. 13, p. 359-378.
- Barbier, M. J., 1974, Continental weathering as a possible origin of vein-type uranium deposits: *Mineralium Deposita*, v. 9, p. 271-288.
- Balagna, John, 1976, Delineation of flow channels in crystalline rock using different radioactive tracers [abs.]: *EOS*, v. 57, p. 1016.
- Butler, A. P., Jr., 1972, Uranium, in Mallory, W. W. ed., *Geologic atlas of the Rocky Mountain region: Rocky Mtn. Assoc. Geologists*, p. 315-317.
- Case, J. E., and Keefer, W. R., 1966, Regional gravity survey, Wind River Basin, Wyoming: U. S. Geol. Survey Prof. Paper 550C, p. C120-C128.
- Catanzaro, E. J., Murphy, T. J., Shields, W. R., and Garner, E. L., 1968, Absolute isotopic abundance ratios of common, equal-atom, and radiogenic lead isotopic standards: *Jour. Research Natl. Bur. Standards*, v. 72A, p. 261-267.
- Divis, A. F., 1976, Geology and geochemistry of Sierra Madre Range, Wyoming: *Colorado School Mines Quart.*, v. 71, no. 3, 127 p.
- Doe, B. R., and Delevaux, M. H., 1977, Lead isotope investigations in the Minnesota River Valley—I. The granite of section 28: Submitted to GSA Members, Selected studies on Lake Superior geology and related topics.
- Goldich, S. S., Doe, B. R., and Delevaux, M. H., 1975, Possible evidence for 3.8 b.y.-old rocks in the Minnesota River Valley of southwestern Minnesota: U. S. Geol. Survey Open-File Rept. 75-65, 11 p.
- Gray, C. M., and Oversby, V. M., 1972, The behavior of lead isotopes during granulite facies metamorphism: *Geochim. et Cosmochim. Acta*, v. 36, p. 939-952.
- Harshman, E. N., 1972, Geology and uranium deposits, Shirley Basin area, Wyoming: U. S. Geol. Survey Prof. Paper 745, 82 p.
- Hills, F. A., and Armstrong, R. L., 1974, Geochronology of Precambrian rocks in the Laramie Range and implications for the tectonic framework of Precambrian southern Wyoming: *Precambrian Research*, v. 1, p. 213-225.
- Killen, P. G., and Heier, K. S., 1975, A uranium and thorium enriched province of the Fennoscandia Shield in southern Norway: *Geochim. et Cosmochim. Acta*, v. 39, p. 1515-1524.
- Love, J. D., 1960, Cenozoic sedimentation and crustal movement in Wyoming: *Am. Jour. Sci.*, v. 258-A, p. 204-214.
- 1970, Cenozoic geology of the Granite Mountains area, central Wyoming: U. S. Geol. Survey Prof. Paper 495-C, 154 p.
- Ludwig, K. R., 1974, Part II: Lead isotope heterogeneity in Precambrian igneous feldspars: Unpub. Ph.D. thesis, California Inst. Technology, 363 p.
- 1978, Uranium daughter migration and U-Pb isotope apparent ages of uranium ores, Shirley Basin, Wyoming: *Econ. Geol.*, v. 73, p. 29-49.
- Ludwig, K. R., and Silver, L. T., 1977, Lead isotope inhomogeneities in Precambrian igneous K-feldspars: *Geochim. et Cosmochim. Acta*, v. 41, p. 1457-1471.
- Ludwig, K. R., and Stuckless, J. S., 1978, Uranium-lead isotopes systematics and apparent ages of zircons and other

- minerals in Precambrian granitic rocks, Granite Mountains, Wyoming: *Contr. Mineralogy Petrology*, v. 65, p. 243-257.
- Nkomo, I. T., and Rosholt, J. N., 1972, A lead-isotope age and U-Pb discordance of Precambrian gneiss from Granite Mountains, Wyoming: *U. S. Geol. Survey Prof. Paper* 800-C, p. C169-C177.
- Oversby, V. M., 1975a, Lead isotopic systematics and ages of Archaean acid intrusives in the Kalgoorlie-Norseman area, Western Australia: *Geochim. et Cosmochim. Acta*, v. 39, p. 1107-1125.
- 1975b, isotopic ages and geochemistry of Archaean acid igneous rock for the Pilbara, Western Australia: *Geochim. et Cosmochim. Acta*, v. 40, p. 817-829.
- 1975c, Lead isotopic study of aplites from the Precambrian basement rocks near Ibada, southwestern Nigeria: *Earth Planet. Sci. Letters*, v. 27, p. 177-180.
- Peterman, Z. E., and Hildreth, R. A., 1977, Geochronology and reconnaissance geology of the Precambrian of the Granite Mountains, Wyoming: *U. S. Geol. Survey Open-File Rept.* 77-140.
- Rogers, J. J. W., Adams, J. A. S., and Gatlin, B., 1965, Distribution of thorium, uranium, and potassium concentrations in three cores from the Conway Granite, New Hampshire, U. S. A.: *Am. Jour. Sci.*, v. 263, p. 817-822.
- Rogers, J. J. W., and Adams, J. A. S., 1969, Uranium, in Wedepohl, K. H., ed., *Handbook of geochemistry*, v. 2, no. 4: Berlin, Springer-Verlag, p. 92-B-92-0.
- Rosholt, J. N., and Bartel, A. J., 1969, Uranium, thorium and lead systematics in the Granite Mountains, Wyoming: *Earth Planet. Sci. Letters*, v. 7, p. 141-147.
- Rosholt, J. N., Zartman, R. E., and Nkomo, I. T., 1973, Lead isotope systematics and uranium depletion in the Granite Mountains, Wyoming: *Geol. Soc. America Bull.*, v. 84, p. 989-1002.
- Sinha, A. K., 1972, U-Th-Pb systematics and the age of the Onverwacht Series, South Africa: *Earth Planet. Sci. Letters*, v. 16, p. 219-227.
- Stacey, J. S., and Kramers, J. S., 1975, Approximation of terrestrial lead isotope evolution by a two stage model: *Earth Planet. Sci. Letters*, v. 26, p. 207-221.
- Streckeisen, A. L., 1973, Plutonic rocks, classification and nomenclature recommended by the IUGS Subcommittee on the systematics of igneous rocks: *Geotimes*, v. 18, p. 26-30.
- Stuckless, J. S., and Ferreira, C. P., 1976, Labile uranium in granitic rocks, in *International symposium on exploration of uranium ore deposits: Proc. Symposium, Vienna, Internat. Atomic Energy Agency*, p. 717-730.
- Stuckless, J. S., Van Trump, George, Jr., Bunker, C. M., Bush, C. A., Hunter, W. C., and Lewis, N. F., Jr., 1976, Radiometric and petrographic results for samples from drill holes GM-1 and GM-2, Granite Mountains, Wyoming: *U. S. Geol. Survey Open-File Rept.* 76-842, 19 p.
- Stuckless, J. S., Bunker, C. M., Bush, C. A., Doering, W. P., and Scott, J. H., 1977, Geochemical and petrologic studies of a uraniferous granite from the Granite Mountains, Wyoming: *U. S. Geol. Survey Jour. Research*, v. 5, p. 61-81.
- Tilling, R. I., and Gottfried, D., 1969, Distribution of thorium, uranium, and potassium in igneous rocks of the Boulder Batholith region, Montana, and its bearing on radiogenic heat production and heat flow: *U. S. Geol. Survey Prof. Paper* 614-E, 29 p.
- Tilling, R. I., Gottfried, D., and Dodge, R. C. W., 1970, Radiogenic heat production of contrasting magma series: Bearings on interpretation of heat flow: *Geol. Soc. America Bull.*, v. 81, p. 1447-1462.
- Von Backström, J. W., 1974, Other uranium deposits, in *Formation of uranium ore deposits: Proc. Symposium, Athens, Greece, May 6-10, 1974, Vienna, Internat. Atomic Energy Agency*, p. 605-624.
- York, Derek, 1969, Least-squares fitting of a straight line with correlated errors: *Earth Planet. Sci. Letters*, v. 5, p. 320-324.
- Zielinski, R. A., and Naeser, C. W., 1977, Fission-track dates from the White River Formation, Shirley Basin, Wyoming: *Isochron West*, v. 18, p. 19-20.