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Sr, Nd, AND Pb ISOTOPIC COMPOSITIONS OF ARCHEAN BASEMENT ROCKS, BOULDER RIVER REGION, BEARTOOTH MOUNTAINS, MONTANA

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ABSTRACT

The upper part of the Boulder River valley in the western part of the Beartooth Plateau is dominated by granitic rocks that intruded a supracrustal pile of amphibolites and biotite-schists. There appears to be no genetic relationship between the amphibolites and the granitoids. Furthermore, there are significant chemical differences between these rocks and granitoids and amphibolites in the eastern part of the Beartooth Plateau. The granitoids have low contents of LILE and may have formed from a relatively depleted crustal source. The amphibolites, on the other hand, are LILE-enriched and their magmatic protoliths were presumably derived from an enriched mantle.

A Pb-Pb isochron dates the intrusion of the magmas that formed the granitoids at 2.74 ± 0.07 b.y.—within the range of ages recorded by other granitic rocks in the Beartooth Mountains. Sm-Nd isotopic compositions of the granitoids indicate that their source rocks separated from the mantle no more than 3.2 b.y. ago. Sm-Nd model ages of the amphibolites are also consistent with formation of their igneous protoliths 3.0–3.2 b.y. ago. The crust of the western part of the Beartooth Plateau apparently stabilized no more than ~ 3.2 b.y. ago—considerably after crustal formation in the eastern Beartooth Plateau.

INTRODUCTION

The Beartooth Mountains (fig. 1) are a block of Precambrian crystalline rocks with a partial cover of sedimentary and volcanic rocks. The Beartooth block consists of the Beartooth Plateau and the North and South Snowy Blocks (fig. 1), each of which has a distinct geology. The eastern part of the Beartooth Plateau has been most extensively studied. The dominant rock types in that area are granitoids and andesitic amphibolites that formed 2.7–2.8 b.y. ago (Mueller and others, 1985; Wooden and others, 1985). These Late Archean rocks intruded a complex supracrustal pile formed 3.3–3.6 b.y. ago (Mueller and others, 1982).

The boundary between the North Snowy Block and the Beartooth Plateau is the Mill Creek-Stillwater fault zone. The North Snowy Block contains metasupracrustal and granitic rocks that have been tectonically intercalated (Reid and others, 1975; Mogk, 1982). Relationships between basement rocks of the South Snowy Block and that elsewhere in the Beartooth Block are not known because of Phanerozoic cover. The western part of the South Snowy Block is dominated by metasediments, whereas the eastern part is dominated by granitoid intrusions (Casella and others, 1982). Montgomery and Lytwyn (1984) dated metamorphic and igneous events in this area at ~ 2.7 b.y. They interpreted the relatively low $^{87}Sr/^{86}Sr$ of metasediments at 2.7 b.y. as indicating that source rocks of the sediments were not separated from the mantle significantly before 3 b.y. This is in marked contrast to the situation in the Beartooth Plateau.

The geology of the western Beartooth Plateau is more poorly known than that of other parts of the Beartooth Block. Various parts of this area have been mapped by Butler (1966) and by Page and others (1973), who indicate a dominance of granitoids with enclaves of supracrustal rocks. The ages of these rocks are not known and the relationship between them and rocks farther east is unclear. This paper presents chemical and isotopic compositions of basement rocks from a limited area in the westernmost Beartooth Plateau and compares them with data on other rocks of the Beartooth Block.

PRECAMBRIAN GEOLOGY OF THE BOULDER RIVER VALLEY

Figure 2 shows the geology of the Boulder River valley as mapped by Page and others (1973), Weeks (1980; Fountain and Weeks, 1979), Butler (unpublished data), and Meen (1985). The Precambrian basement rocks in the southern part of the Boulder River valley are covered by and intruded by Cretaceous igneous rocks of the Independence volcanic complex (Meen and Eggler, 1987; Meen, 1987). The valley is dominated by granitoids south of the junction of Bramble Creek and the Boulder River and supracrustal rocks form only a small portion of the basement. Farther north, however, the basement is dominated by metasedimentary rocks as noted by Reid and others (1975). This change in basement lithology is neither coincident with nor parallel to the Mill Creek-Stillwater fault zone. Granitoids of similar appearance occur on either side of this fault in the vicinity of the Boulder River.

The predominant Precambrian lithology in the upper Boulder Valley is weakly foliated granitic gneiss that appears to be similar to granitic rocks mapped by Weeks (1980) farther north and called, by him, the Boulder River granite. Figure 3 shows modal quartz-alkali feldspar-plagioclase variations in the granitoids as estimated by Meen (1985) and by Weeks (1980). Compositions of intrusive rocks range from quartz monzodiorite to tonalite and to granite.

The granitic rocks least affected by metamorphic recrystallization contain pink orthoclase-microperthite and white antiperthitic plagioclase up to 3 cm across in a matrix of recrystallized quartz. Mafic minerals (principally biotite) are confined to grain boundaries. More thoroughly reconstituted samples contain sigmoidal porphyroblasts of quartz and alkali feldspar in a groundmass of intensely recrystallized quartz, biotite, and minor muscovite and iron-titanium oxides. The alkali feldspar is microcline-microperthite, some grains containing plagioclase blebs. Secondary epidote is locally a major constituent either disseminated or in ramifying veinlets discordant to the foliation. Granitic pegmatites intrude other granitoids. These rocks contain essential oligoclase, microcline, and quartz, with large books of muscovite and, in a few cases, biotite.

The granitoids intruded a supracrustal sequence of biotite-schists and amphibolites. The schists are fine grained except for locally abundant coarse plagioclase; the groundmass is of biotite, chlorite, epidote, and anthophyllite. Larger biotites, defining the foliation, are partly replaced by small randomly oriented biotite and chlorite. Quartz occurs in irregular patches. Trains of pyrite several cm long parallel the foliation. Amphibolites contain anhedral plagioclase and cordierite grains that are surrounded by, or enclosed within, subhedral amphibole grains. Some amphibolites contain patches of alkali feldspar, muscovite, and biotite.

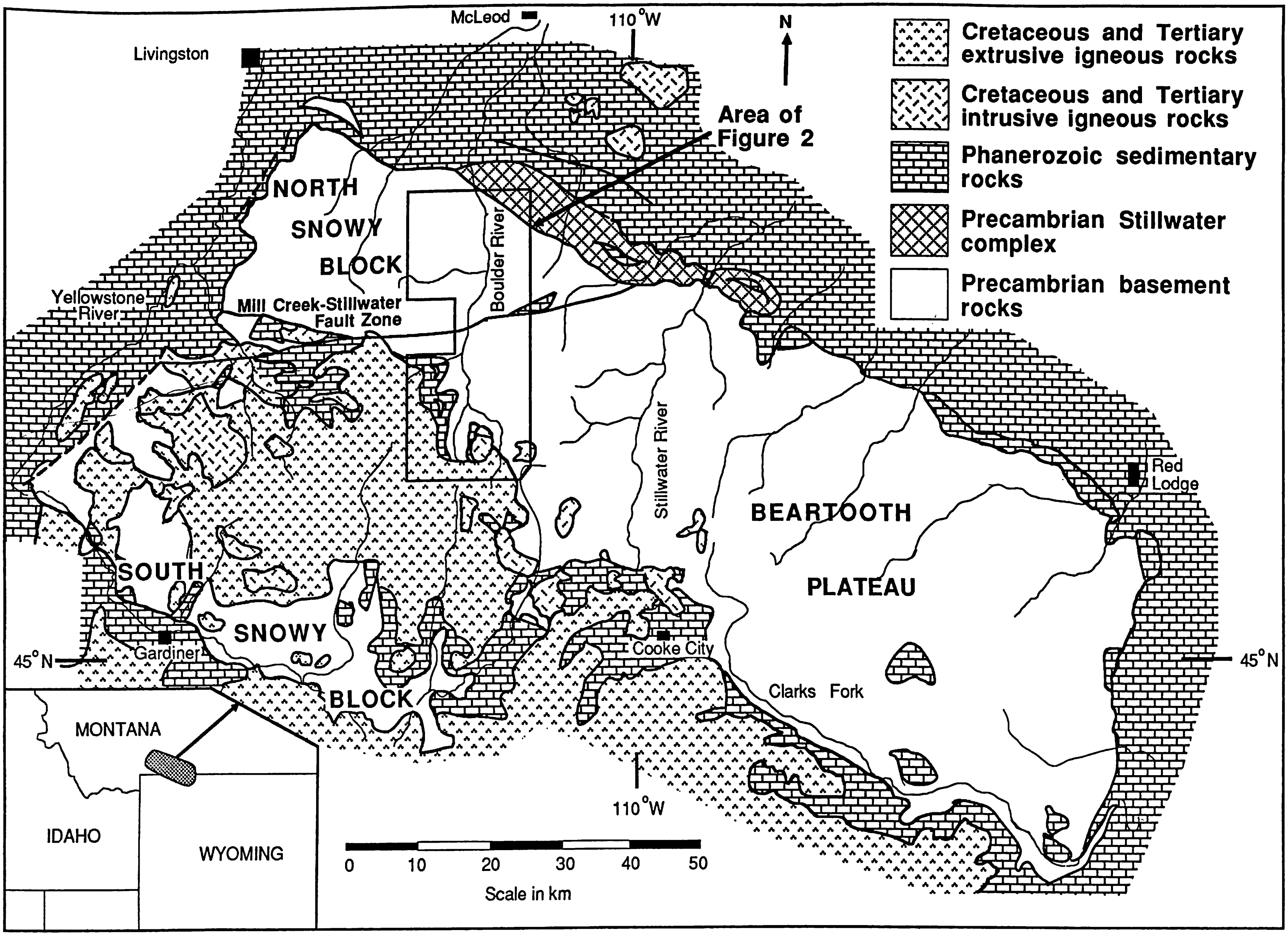

FIGURE 1. Index map of the Beartooth region, Montana and Wyoming, showing the location of the area of figure 2 and the location of the North and Snowy Blocks and the Beartooth Plateau.

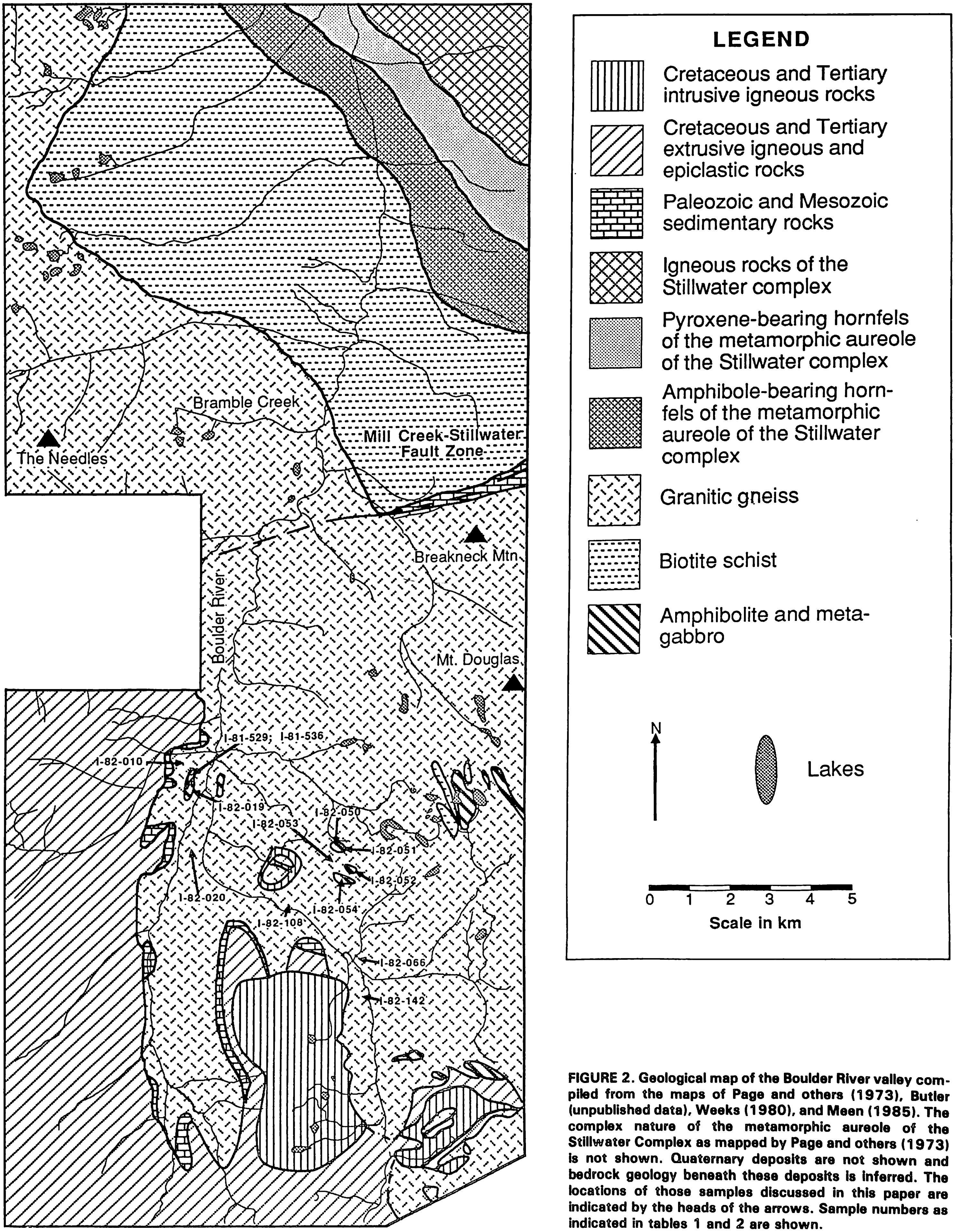

FIGURE 2. Geological map of the Boulder River valley compiled from the maps of Page and others (1973), Butler (unpublished data), Weeks (1980), and Meen (1985). The complex nature of the metamorphic aureole of the Stillwater Complex as mapped by Page and others (1973) is not shown. Quaternary deposits are not shown and bedrock geology beneath these deposits is inferred. The locations of those samples discussed in this paper are indicated by the heads of the arrows. Sample numbers as indicated in tables 1 and 2 are shown.

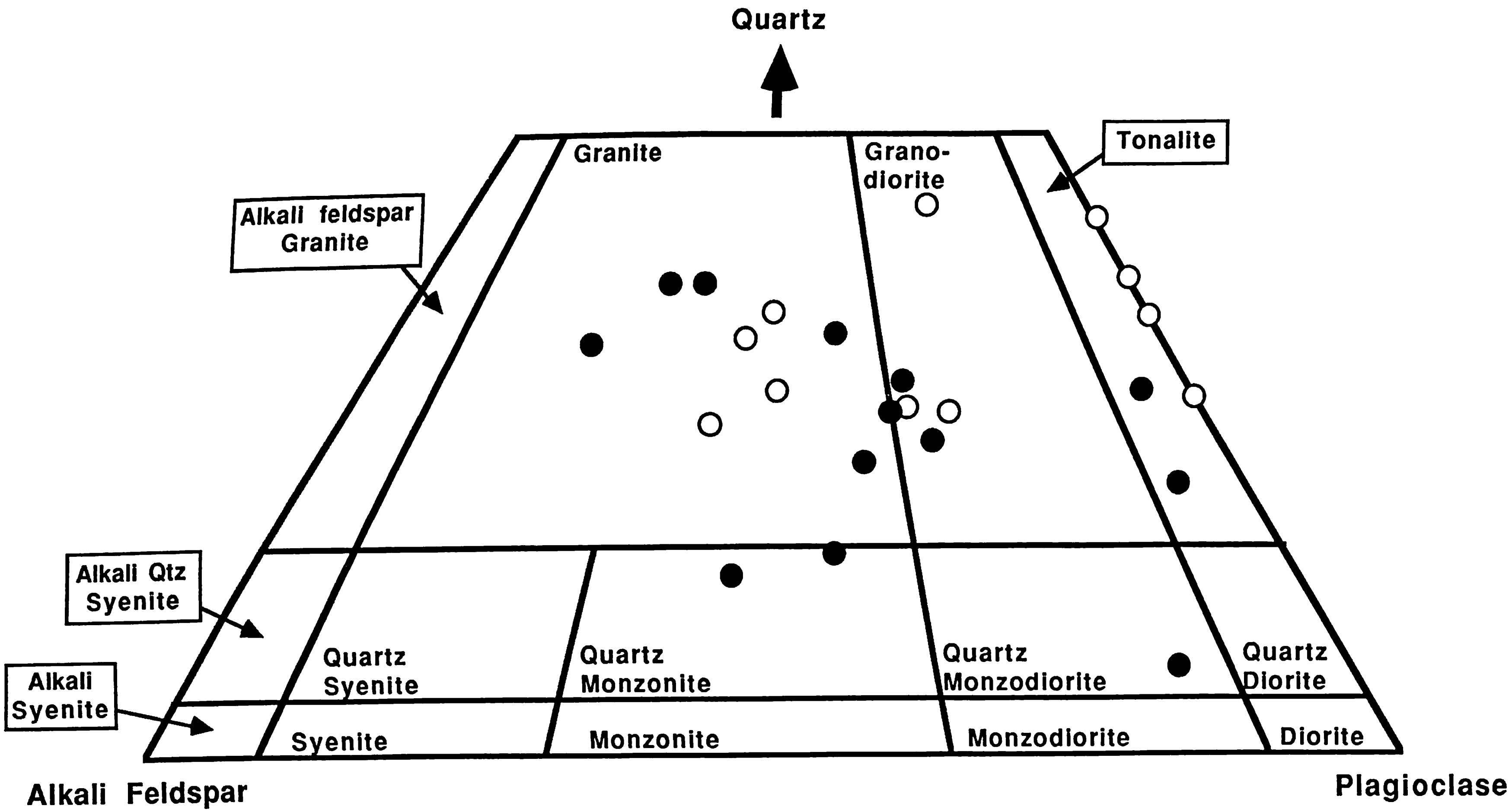

FIGURE 3. Quartz-alkali feldspar-plagioclase modal plot of the granitoid rocks of the Boulder River valley as estimated by Meen (1985) (solid symbols) and Weeks (1980) (open symbols. Fields of various rock types are from Streckeisen (1975).

TABLE 1. Major and trace element compositions of granitic and supracrustal rocks of the upper Boulder River valley, Beartooth Mountains.

	GRANITOIDS						AMPHIBOLITES					BIOTITE SCHISTS	
	I-82-010	I-82-020	I-82-053	I-82-066	I-82-108	I-82-142	I-82-019	I-82-050	I-82-051	I-82-052	I-82-054	I-81-529	I-51-536
Major elements (wt. %)													
SiO_2	67.5	74.5	68.0	72.9	67.9	72.9	51.2	56.2	56.4	59.2	56.2	64.6	62.8
TiO_2	0.54	0.10	0.02	0.17	0.19	0.23	0.77	0.51	0.83	0.75	0.55	0.58	0.62
Al_2O_3	14.6	13.2	12.1	13.7	18.1	13.5	13.7	17.7	15.8	15.7	18.2	15.7	15.2
FeO^t	3.10	0.17	0.13	0.84	1.68	1.69	9.97	7.03	8.90	7.99	6.94	6.82	7.22
MnO	0.05	n.d.	n.d.	0.02	0.01	0.05	0.22	0.11	0.10	0.10	0.12	0.05	0.06
MgO	1.88	0.15	0.05	0.24	0.15	0.47	7.81	4.51	3.76	2.81	4.27	4.91	5.33
CaO	3.24	0.56	10.3	1.66	4.27	1.06	11.3	7.45	6.87	5.66	7.36	1.66	2.12
Na_2O	3.90	3.63	4.67	4.22	4.67	4.44	2.88	3.57	3.93	3.81	3.77	1.31	1.21
K_2O	3.00	5.18	3.11	3.91	2.22	3.56	0.99	1.22	1.60	1.49	1.19	2.05	2.07
P_2O_5	0.16	0.06	0.02	0.63	0.24	0.10	0.09	0.08	0.39	0.32	0.13	0.09	0.14
H_2O+	0.74	1.13	1.35	1.2	0.91	1.64	0.99	0.91	0.79	0.64	0.67	1.22	1.31
H_2O-	0.53	0.55	0.62	0.42	0.47	0.72	0.23	0.50	0.33	0.76	0.41	0.74	0.85
CO_2	0.02	0.02	0.02	0.01	0.02	0.01	0.03	0.01	n.d.	n.d.	0.02	0.04	0.03
Others	0.25	0.10	0.07	0.20	0.12	0.20	0.20	0.24	0.21	0.20	0.41	0.41	0.39
Total	99.5	99.4	100.5	100.1	101.0	100.6	100.4	100.0	99.9	99.4	100.2	100.2	99.4
Trace elements (ppm)													
Ni	14.0	2.1	0.4	1.2	2.2	1.9	142	23.3	38	15.2	30	46	36
Cr	29.1	2.0	1.8	1.2	1.3	2.8	422	48	47	29.1	34	194	172
Sc	27.6	1.9	7.1	0.9	1.0	2.1	33	23.7	20.0	14.2	11.1	12.4	17.9
V	72	7.8	4.0	11.0	15.3	14.0	253	253	140	182	132	127	124
Rb	109	102	13.0	77	60	122	36	48	39	49	37	136	141
Sr	255	61	129	246	258	665	104	618	543	387	503	41	37
Ba	961	588	102	1360	455	1260	211	550	623	517	2660	548	603
Pb	8.3	16.7	8.9	8.3	7.2	2.9	13.1	13.4	13.2	10.8	9.7	7.1	6.6
U	3.2	5.8	2.9	3.1	7.9	5.4	0.84	1.21	0.52	0.38	2.06	2.12	2.01
Th	15.7	23.1	14.1	18.2	10.9	8.4	2.69	3.72	2.49	3.72	7.02	8.7	7.40
Zr	102	101	90	74	79	62	48	29	62	49	77	124	279
La	54.7	22.1	18.4	13.7	9.02	25.3	27.0	31.0	29.4	35.3	28.8	31.6	34.1
Ce	107	42.8	34.2	27.2	14.9	47.0	59.9	59.3	63.1	63.8	58.1	84.4	90.6
Nd	44.5	18.1	14.1	13.5	4.41	20.1	32.0	35.4	32.1	30.7	27.2	39.8	41.0
Sm	7.78	3.44	2.46	2.43	0.89	2.93	5.74	6.30	5.05	4.56	4.50	6.19	6.36
Eu	0.88	0.26	0.67	0.43	0.37	0.47	1.42	1.65	1.43	1.35	1.41	1.03	1.02
Gd	6.74	4.82	1.33	1.51	0.62	1.98	4.72	4.92	3.72	3.79	3.45	4.50	4.61
Dy	6.35	6.29	1.49	1.53	0.62	1.38	3.89	4.12	2.94	3.16	2.65	3.13	3.21
Y	33.4	34.1	7.97	8.32	3.01	7.20	20.7	22.4	16.2	17.3	15.2	16.9	17.2
Yb	3.51	5.02	0.88	0.97	0.33	0.69	2.00	1.86	1.64	1.77	1.60	1.94	1.97

n.d.—not detected. FeO^t—total iron expressed as FeO. Others—total of trace elements analyzed as wt. % oxide.

ANALYTICAL RESULTS

Table 1 gives major and trace element contents in samples of the three rock types noted above. Rare earth element (REE) patterns are plotted in figures 4 and 5. Patterns for granitoids (fig. 4) show considerable variation. Chondrite-normalized La contents range from 25 to 150, and values of La_N/Yb_N range from 3 to 20. Similarly, these rocks demonstrate considerable ranges in their contents of large ion lithophile elements (LILE). Rb contents are 60–120 ppm; Sr 60–660 ppm; Ba 100–1,300 ppm.

Amphibolites demonstrate more systematic chemical variation. MgO, CaO, and compatible trace elements decrease as SiO_2 increases. LILE and REE contents of amphibolites are less variable than for granitoids. La contents are 74–96 times chondrite and La_N/Yb_N is 9–14 (fig. 5). Schists and amphibolites have similar REE patterns. The latter have positive Ce anomalies and negative Eu anomalies. Most Archean sedimentary rocks, however, have a minor positive Eu anomaly (e.g. Condie, 1981, p. 152–154).

Isotopic compositions of basement rocks are given in table 2 and shown in figures 6–8. Rb-Sr and Sm-Nd isotopic compositions are not coherent. Isochron diagrams (fig. 6) show considerable scatter. Values of $^{143}Nd/^{144}Nd$ of granitoids do not correlate with Sm/Nd, and Rb-Sr correlation is poor. Such variations may reflect initial isotopic heterogeneity or may reflect disturbance of isotopic systematics since formation. Vidal and others (1984) described isotopic heterogeneity in modern granitoids due to variable initial ratios. Sr-Nd isotopic compositions of basement rocks are shown in figure 7. All rocks have $^{143}Nd/^{144}Nd$ much lower than that of bulk earth indicating long-lived enrichment of light REE relative to heavy REE (HREE). Values of $^{87}Sr/^{86}Sr$ vary from similar to those of present-day earth to much higher values. The amphibolites demonstrate a great range in $^{143}Nd/^{144}Nd$ with a relatively small range in $^{87}Sr/^{86}Sr$, due, in part, to the relatively low Rb/Sr of these rocks (fig. 6b). The granitoids, on the other hand, show a wide range in $^{87}Sr/^{86}Sr$ with a relatively limited variation in $^{143}Nd/^{144}Nd$.

Pb isotopic compositions are more coherent than are either Sr or Nd isotopic compositions. $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ values of all samples demonstrate strong covariation (fig. 8b). If interpreted as an isochron, this line defines an age of 2.737 ± 0.072 (2σ) b.y. and indicates that protoliths of basement rocks had time-integrated μ of 8.04 for the period 4.55–2.74 b.y. Time-integrated μ for individual rocks from 2.74 b.y. to the present day are given in table 2. Amphibolites have values of μ of 5–5.7; schists have values close to 30. Granitoids demonstrate a wide range in μ—from < 4 to > 40. $^{206}Pb/^{204}Pb$-$^{208}Pb/^{204}Pb$ values of the same samples show poor correlation (fig. 8a).

DISCUSSION

COMPARISON WITH OTHER BASEMENT SAMPLES FROM THE BEARTOOTH PLATEAU

Mueller and others (1985) gave chemical data on granitoids from the eastern part of the Beartooth Plateau. They distinguished two separate granitoids with 2.8 b.y. ages—the Long Lake granodiorite and the Long Lake granite (divided into high Na and low Na groups). The granodiorite has high contents of LREE (La_N = 250–500 times chondrite), Ba (2,000–2,500 ppm), Zr (> 300 ppm), and Rb (100–200 ppm). The granite has lower LREE contents (La_N = 30–200 times chondrite), Rb, Zr (50–130 ppm), and Ba (1,000–2,000 ppm), and is depleted in HREE (Yb_N = 1–5

TABLE 2. Isotopic compositions of granitic and supracrustal rocks of the upper Boulder River valley, Beartooth Mountains.

Sample	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$T^{Sr}_{B.E.}$	T^{Nd}_{CHUR}	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	μ_{rock}
Granitoids										
I-82-010	1.47	0.75536±5	0.106	0.51097±2	2.51	2.79	17.615	15.616	38.455	8.17
I-82-020	3.96	0.85784±6	0.115	0.51102±2	2.72	3.00	36.368	19.063	47.156	44.8
I-82-053	3.08	0.74737±4			0.99		15.344	15.057	37.608	3.73
I-82-108	1.00	0.75017±3	0.122	0.51112±1	3.37	3.08	17.780	15.662	38.208	8.49
I-82-142	0.378	0.71036±4	0.0880	0.51134±1	1.29	1.82	22.196	16.344	41.049	17.1
Amphibolites										
I-82-019	1.20	0.75238±5			2.92					
I-82-050	0.168	0.71571±4	0.108	0.51115±1	7.78	2.54	16.258	15.305	38.109	5.51
I-82-051	0.105	0.70763±6	0.0950	0.51112±1	6.26	3.00	16.044	15.107	39.706	5.14
I-82-052	0.254	0.71901±7	0.0897	0.51054±1	5.36	2.97	16.348	15.359	37.631	5.69
I-82-054	0.0836	0.70613±4	0.0999	0.51073±2	9.46	2.98				
Biotite schists										
I-81-529	9.43	0.83622±7	0.0939	0.51128±1	0.98	2.01	28.141	17.493	39.642	28.7
I-81-536	11.4	0.83129±6			0.78		29.848	17.953	41.200	32.1

Measured Sr isotopic ratios are fractionation corrected to $^{86}Sr/^{88}Sr$ = 0.1194 and reported relative to $^{87}Sr/^{86}Sr$ = 0.70800 for the E&A standard.

Measured Nd isotopic ratios are fractionation corrected to $^{146}Nd/^{144}Sr$ = 0.7219 and reported relative to $^{143}Nd/^{144}Nd$ = 0.51186 for the La Jolla standard.

A fractionation correction was applied to measured Pb isotopic ratios as determined by replicate analyses of NBS 981 relative to the values recommended by Catanzaro and others (1968).

Errors quoted on isotopic compositions are relative to the last decimal place quoted in the relevant ratio. Within run precision for Pb isotopic analyses averaged 0.03% (2σ).

Rb-Sr model ages calculated assuming present day bulk earth has $^{87}Sr/^{86}Sr$ = 0.70475 and $^{87}Rb/^{86}Sr$ = 0.074.

Sm-Nd model ages calculated assuming present day chondritic undepleted reservoir has $^{143}Nd/^{144}Nd$ = 0.512638; $^{147}Sm/^{144}Nd$ = 0.1967.

μ_{rock} values assume that the individual rocks separated from a source with time-integrated μ = 8.04, 2.74 b.y. ago.

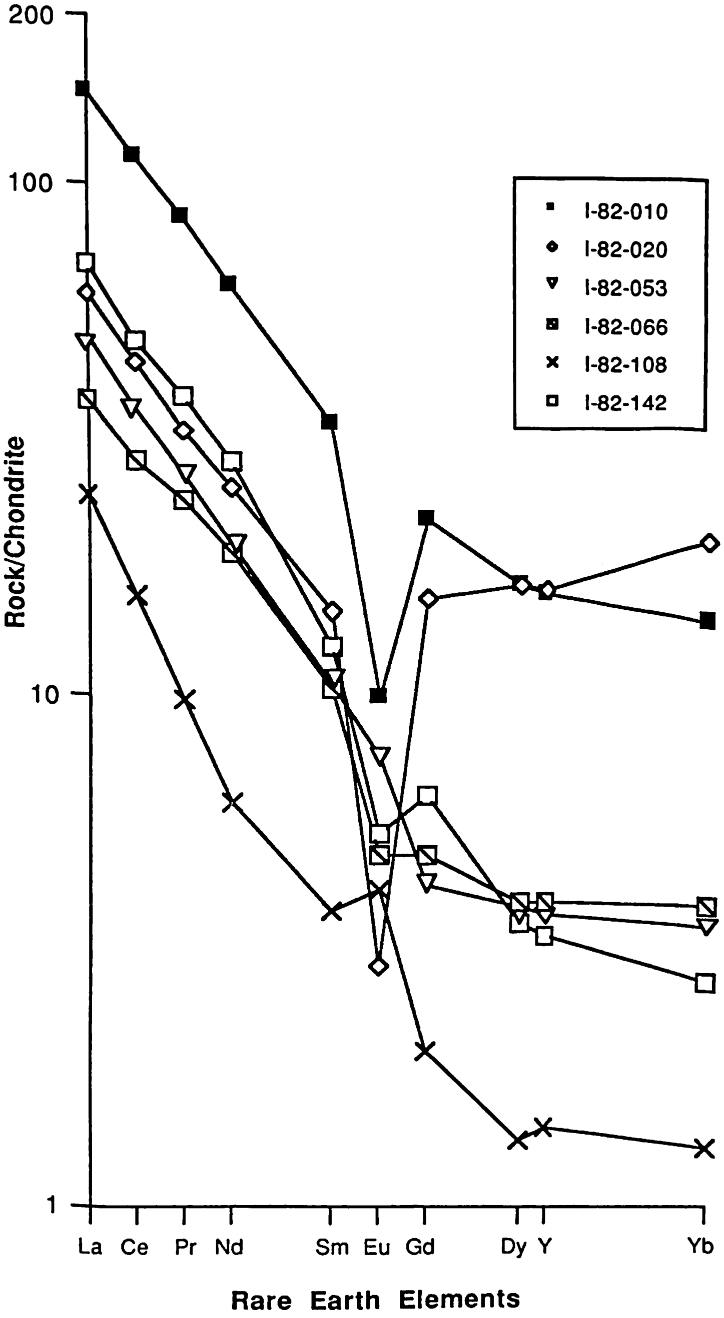

FIGURE 4. Rare earth element patterns of the granitoids of the upper Boulder River.

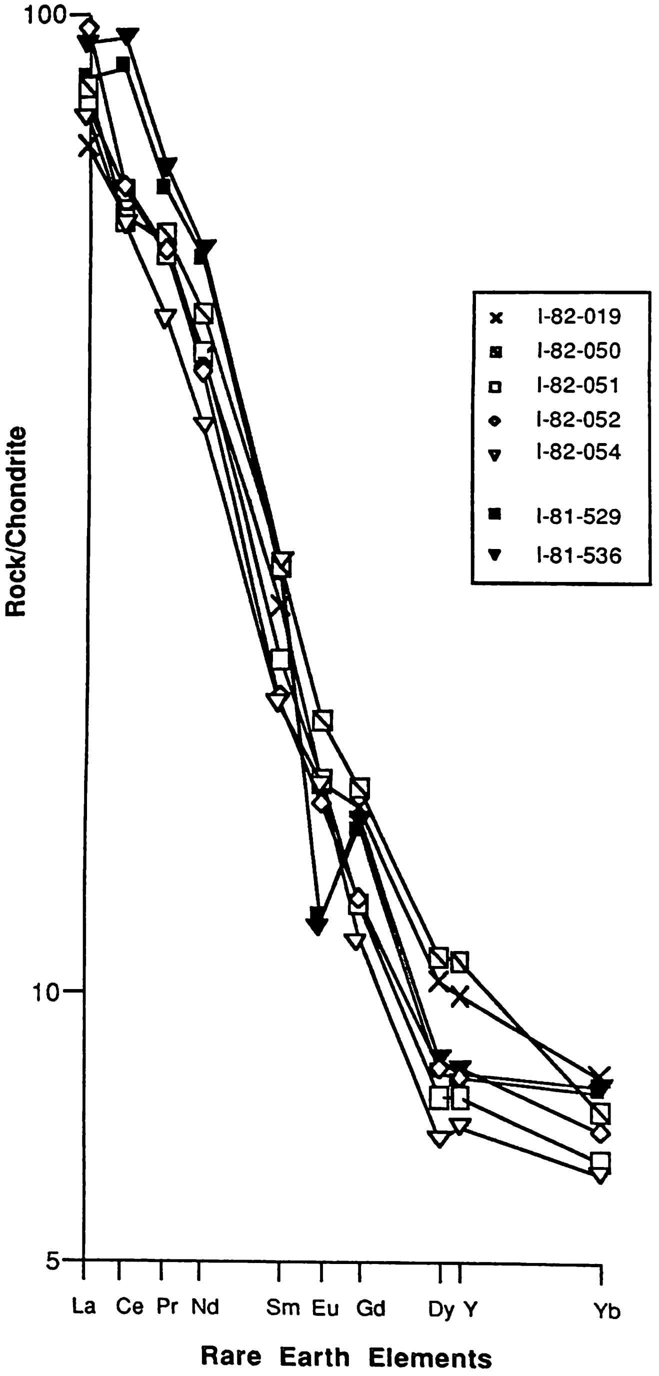

FIGURE 5. Rare earth element patterns of the supracrustal amphibolites (open symbols) and biotite schists of the upper Boulder River valley.

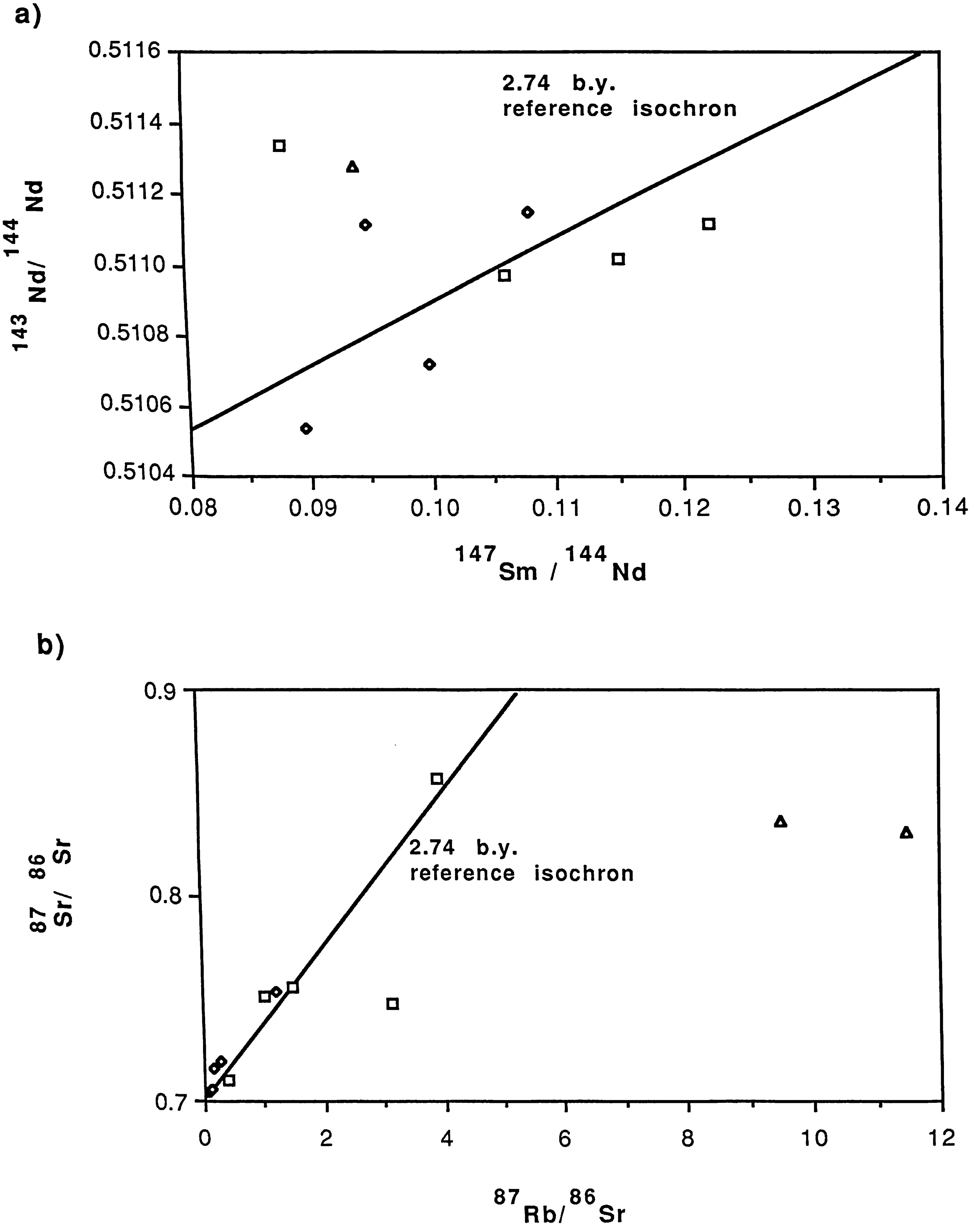

FIGURE 6. Isochron diagrams showing variation of Sm-Nd (a) and Rb-Sr (b) isotopic systematics. 2.74 b.y. reference isochrons are shown. Open squares show compositions of granitoids, open diamonds represent amphibolites, and open triangles denote schists.

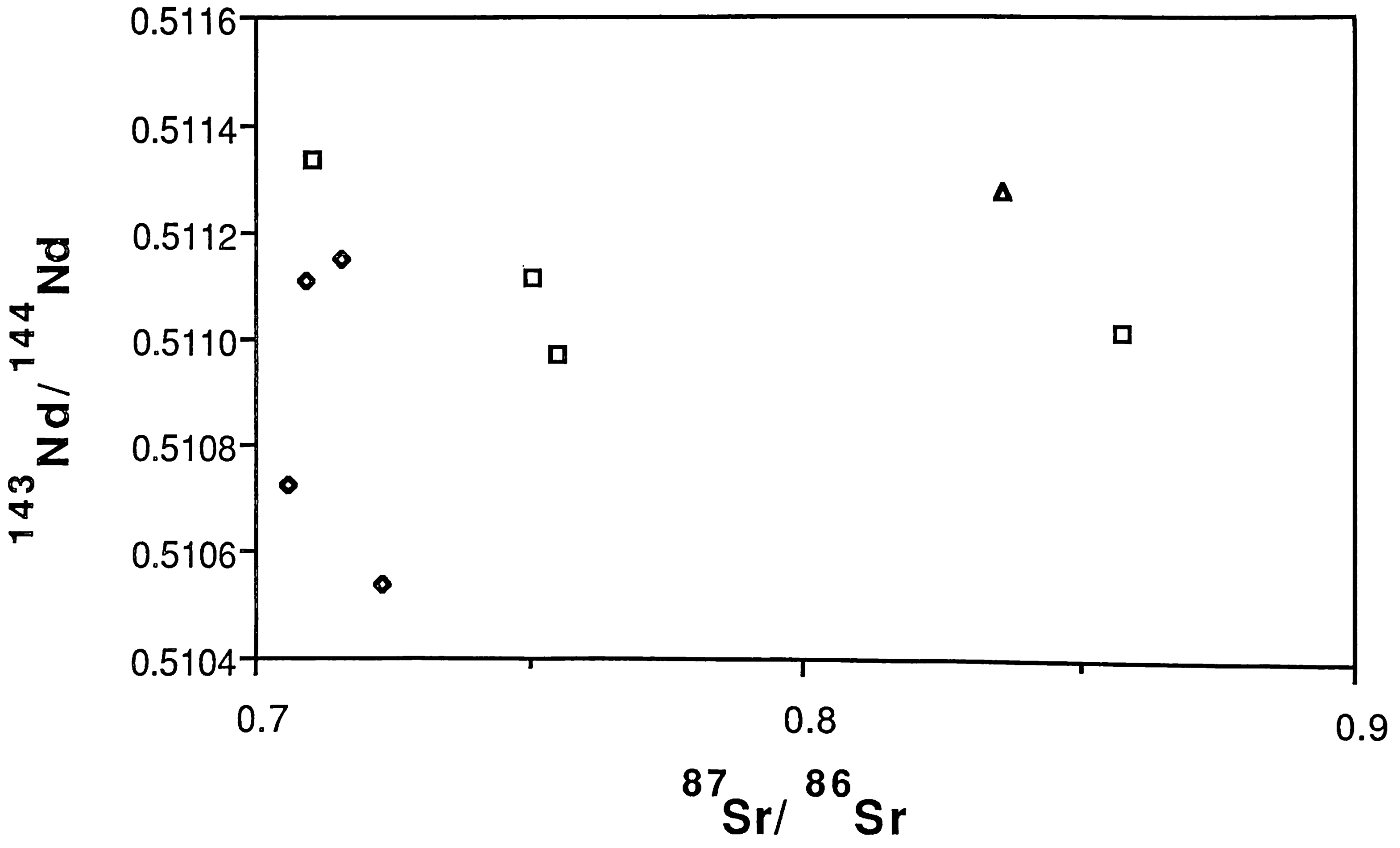

FIGURE 7. Present-day Sr and Nd isotopic compositions of the basement rocks in the upper Boulder River valley. Symbols used are the same as in figure 6. Primitive mantle is believed to have present day $^{143}Nd/^{144}Nd = 0.512638$ and $^{87}Sr/^{86}Sr \sim 0.70475$.

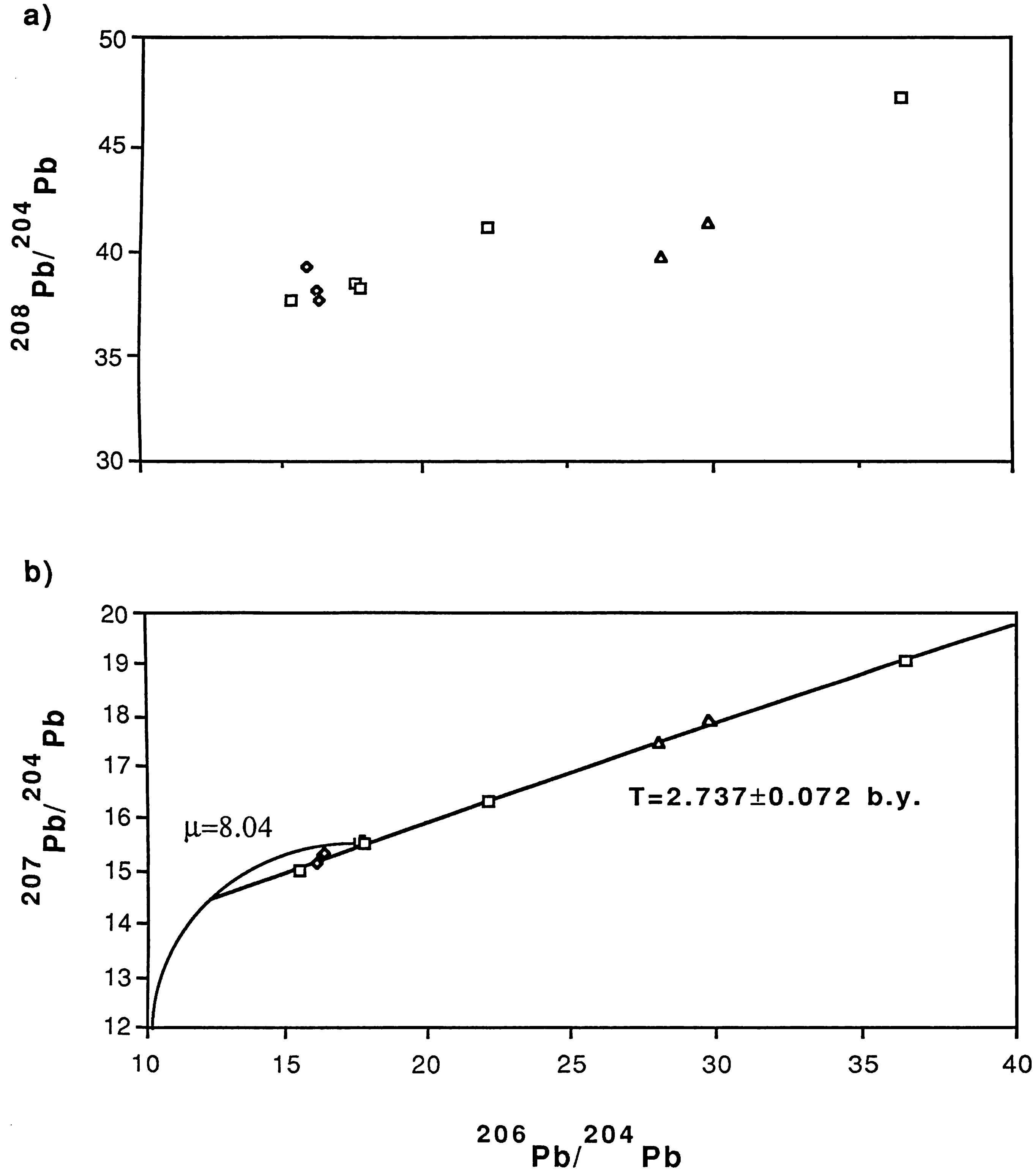

FIGURE 8. Pb isotopic compositions of the basement rocks in the upper Boulder River valley. Symbols used are the same as in figure 6. Values of ^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb are correlated (fig. 6b). This is considered to indicate the age of intrusion of the granitoids—2.737 ±0.072 b.y.—and the appropriate isochron is shown. Such an age requires that protoliths resided in a reservoir with time-integrated μ of 8.04 from 4.55 to 2.74 b.y. A single-stage growth curve with $\mu = 8.04$ is shown. Values of ^{208}Pb/^{204}Pb and ^{207}Pb/^{204}Pb are poorly correlated (fig. 6a). This indicates that the Pb isotopic compositions are unlikely to be the result of mixing of two end-members. Regression performed by method of York (1969). The error estimate is determined by multiplying the calculated 2σ error by the square root of the MSWD in order to account for scatter about the line (e.g. Parrish and van Breemen, 1985).

times chondrite). The chemistries of the Long Lake granitoids and the penecontemporaneous Boulder River granitoids are sufficiently different that they are unlikely to be genetically related.

Mueller and others (1983, 1985) also identified ~2.8 b.y. andesitic amphibolites in the eastern Beartooth Plateau. These rocks have major element compositions similar to those of amphibolites described here and contents of most trace elements are also similar, although there are some conspicuous differences. Zr contents of the eastern Beartooth amphibolites are much higher than Zr contents reported here. LREE abundances in amphibolites of the eastern Beartooth Plateau range widely (50–500 times chondrite) and LREE and Sr contents are strongly correlated. In contrast, REE patterns of the amphibolites described here are all similar (LREE = 75–100 times chondrite) and LREE and Sr patterns are poorly correlated. These trace element characteristics deny a direct genetic relation between these two groups of amphibolites.

Mueller and others (1985) also described Early Archean (~3.5 b.y.) amphibolites. These rocks are mafic to ultramafic, have high contents of compatible elements and low contents of LILE. REE patterns range from LREE-depleted to LREE-enriched, with La_N = 4–40 times chondrite and Yb_N = 4–15 times chondrite. There appears to be no relationship between these amphibolites and those in the Boulder River valley.

SOURCES OF GRANITOIDS

The granitoids are extremely variable in LILE and REE patterns (table 1 and fig. 4) and, for granitoids, relatively depleted in LILE. REE patterns are LREE-enriched but tend to be relatively flat in middle REE (MREE) and HREE. Eu anomalies range from markedly negative to positive (fig. 4). These characteristics suggest involvement of plagioclase (concentrates Eu) and hornblende or pyroxene (concentrate MREE and HREE) in the residues of melting of the granitoids.

Most granitoids have LREE and Ba contents less than those of the amphibolites and schists that they intrude. Ba and LREE are strongly concentrated into the melt relative to crystal residue. Consequently, the granitoids do not appear to have been formed by melting of rocks similar to the supracrustal sequence that they intruded. Mueller and others (1985) came to similar conclusions for the amphibolite-granitoid complex in the eastern Beartooth Plateau. Source rocks for the granitoids are unknown.

IMPLICATIONS FOR GEOCHRONOLOGY OF THE WESTERN BEARTOOTH BLOCK

The linear array of $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ compositions is interpreted as an isochron reflecting time of intrusion of the granitoids. An alternative explanation is that Pb isotopic compositions are due to two component mixing in relatively recent time (so that in situ growth of radiogenic Pb could not disturb the linear array). The isochron interpretation is preferred because $^{206}Pb/^{204}Pb$-$^{208}Pb/^{204}Pb$ compositions are scattered and the defined age is similar to ages of many other bodies in the Beartooth Block. The supracrustal samples and the granitoids lie on the same isochron. This may indicate that granitoids and the rocks they intruded are penecontemporaneous and had similar initial Pb isotopic compositions. Alternatively, Pb isotopic compositions of supracrustal rocks may have been totally reset during intrusion of the granites ~2.7 b.y. ago.

Figure 6 shows 2.74 b.y. reference isochrons. Isotopic compositions scatter about these lines, suggesting either variable initial ratios or open system behavior of isotopic systems. The schists and two granitoids (I-82-053 and I-82-142) have Rb-Sr model ages considerably lower than their true ages (780-1,290 m.y.—table 2), indicating open-system behavior of the Rb-Sr system. Unless the open-system behavior postdates the model age, a severe lowering of $^{87}Sr/^{86}Sr$ must have occurred. As the last thermal event before Cretaceous time occurred at 1.8 b.y., Cretaceous volcanic activity is believed responsible for disturbance of Rb-Sr systematics. The unrealistically ancient Rb-Sr model ages of most amphibolites also indicate disturbance of Rb-Sr isotopic systems. This is most likely to have been a reduction of Rb/Sr, either slightly during intrusion of the granitoids or drastically during Cretaceous time.

U-Pb systematics were probably also disturbed during Laramide activity. The period of time since this event (~90 m.y.) is too short for a corresponding disruption of the Pb-Pb systematics to have occurred, however.

The low value of μ indicated for the source regions of these rocks prior to 2.74 b.y. indicates that these source regions contained little U-rich upper crustal material. Such low values of μ have been interpreted as indicating that protoliths separated from the mantle only 200–500 m.y. before stabilization of the continental crust (e.g. Moorbath, 1977). The amphibolites have had time-integrated μ since 2.74 b.y. lower than that estimated for source rocks. Although little U-rich material was included in the source of the granitoids, the Pb isotopic compositions of these rocks do not exclude the possibility that the granitoids had an old mafic-intermediate provenance.

The apparent alteration of Rb-Sr systematics by Laramide volcanism renders interpretation of these systematics difficult. The granites all had low $^{87}Sr/^{86}Sr$ at the time of their intrusion, as shown by the low model ages of all granitoids. The amphibolites all have relatively low $^{87}Sr/^{86}Sr$ and low Rb/Sr. The low $(^{87}Sr/^{86}Sr)_i$ of the granitoids does not preclude a long crustal residence time of a mafic parent.

Sm-Nd model ages for granites are 2.8–3.1 b.y. (except one value of 1.8 b.y. for a rock with a low Rb-Sr model age). Anatexis usually produces melts with Sm/Nd below that of source rocks, resulting in model ages younger than actual times of separation of source material from the mantle. If Sm/Nd of granitoids is as much as 20% below that of their sources, however, model ages are not older than 3.24 b.y. The granitoids do not indicate the presence of Early Archean basement in the Boulder River area.

Sm-Nd model ages of amphibolites are 2.5–3.0 b.y. (table 2)—similar to the Pb-Pb age. Sm-Nd model ages of amphibolites in the eastern Beartooth Plateau are ~3 b.y. (Mueller and others, 1985) whereas these rocks have ages of intrusion of ~2.8 b.y. (Wooden and others, 1985). The last-named authors suggested that this apparent anomaly reflected involvement of subducted crustal material in the mantle source of the magmas that formed the protoliths of the amphibolites. Meen and Eggler (1987) presented evidence that sub-Beartooth mantle has a history of LREE-enrichment dating back to Early Archean time. Their Sm-Nd growth curves indicate lower $^{143}Nd/^{144}Nd$ than that of bulk earth for the period 2.8–3.0 b.y. If the amphibolites were derived from such a mantle, model ages will be older than true ages. The amphibolites probably formed only shortly before the granitoids were intruded and are unlikely to be Early Archean in age.

CONCLUSIONS

Rocks of the upper Boulder River valley are mildly foliated granitoid gneisses with minor enclaves of amphibolite and biotite schist. Basement of this type continues across the Mill Creek-Stillwater fault zone. Metasedimentary rocks dominate the basement farther north. Although the geology of the Boulder River valley is superficially similar to that of the eastern Beartooth Plateau, chemical considerations indicate that rocks in these two regions are not genetically related. Granitoids of the Boulder River valley are LILE-depleted, suggesting primitive source regions. Residues of melting may have been dominated by plagioclase and hornblende or pyroxene. Amphibolites have greater LILE-enrichment than do granitoids and, therefore, these rocks are probably not genetically related.

Pb and, possibly, Sr isotopic compositions of the supracrustals were reset by intrusion of the granitoids but Nd isotopic compositions were not perturbed during this event. Rb-Sr isotopic systematics of many basement rocks were disturbed during the Cretaceous volcanic activity.

Granitoid rocks of the upper Boulder River valley were intruded 2.74 b.y. ago into a supracrustal sequence of amphibolites and schists. Sm-Nd model ages of the amphibolites are inconsistent with formation of the magmatic protoliths significantly more than ~ 3.1 b.y. ago. Similarly, Sm-Nd isotopic compositions of the granitoids indicate that their source regions did not separate from the mantle prior to ~ 3.2 b.y. ago unless there was extreme fractionation of Sm from Nd during granitoid formation.

This study provides no evidence for ancient crust in the western Beartooth Plateau similar to that in the eastern Beartooth Plateau. Rather, age relations of rocks discussed here suggest a history more closely linked to that of the South Snowy Block (Montgomery and Lytwyn, 1984) than with that of rocks farther east. Furthermore, granitic rocks continue into the North Snowy Block. The separate crustal blocks in the Beartooth Block may not be discrete segments of Archean crust and the edge of the Early Archean continent may lie within the Beartooth Plateau.

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