

FIGURE 1. Schematic geologic map (after Cohenour 1959, and Christie-Blick 1983) of the Sheeprock granite showing the distribution of the specimens collected for this study. Symbols are used to distinguish the three geochemical groups discussed in the text. Sample localities without numbers represent unpublished analyses. Locations mentioned in text include *CJ* — Copper Jack mine; *U* — Utah mine; *FD* — Flying Dutchman mine; *JC* — Joes Canyon (samples from these localities have these labels); *SLC* — Salt Lake City; *GB* — Great Basin; *CP* — Colorado Plateau.

tal crust. Decomposition of small amounts of F-rich biotite in high-grade metamorphic rocks controlled the degree of partial melting. Most of the geochemical variation within the Sheeprock granite is the result of in situ fractional crystallization with marginal accretion of cumulate phases. These processes produced a marked geochemical zonation in the pluton defined by three distinctive groups of specimens. The fractionation of accessory minerals played an important part in the trace-element evolution of the magma.

Geologic Setting

Late Cenozoic magmatism of the eastern Great Basin, western U.S.A., produced a number of aluminous A-type rhyolites. These rhyolites are part of a bimodal (basalt-rhyolite) suite and are contemporaneous with lithospheric extension in the Basin and Range province. Many contain topaz and are rich in Be, U, Rb, Ta, and F and appear to be the volcanic equivalents of rare-metal granites (Christiansen *et al.*, 1983, 1986). The eruptions of these rhyolites have resulted in several small uranium and fluorite deposits and an important beryllium deposit within the 21 Ma Spor Mountain Formation, Utah (Lindsey, 1982; Burt *et al.*, 1982). A small pluton of chemically and temporally equivalent granite is preserved in the Sheeprock Mountains, about 60 km to the northeast (Fig. 1).

The Sheeprock granite is only one of a number of igneous complexes exposed along the length of the east-trending Deep Creek-Tintic mineral belt (Shawe and Stewart, 1976; Stewart *et al.*, 1977). This trend is marked by basement highs, plutonic and volcanic rocks, aeromagnetic highs, and by mineral deposits generally associated with the igneous rocks. Although the plutonic rocks are of a variety of ages (Precambrian, Jurassic,

middle and late Tertiary), most are Cenozoic. Mid-Tertiary intermediate to silicic pyroclastic rocks, lavas, and plutons were emplaced in a southward migrating volcanic belt that may have been part of a broad volcanic arc related to lithospheric subduction at the continental margin (Stewart *et al.*, 1977; Lindsey *et al.*, 1975; Lipman, 1980). A fundamental change in the nature of Cenozoic magmatism occurred approximately 23 Ma (Best *et al.*, 1980) and was marked by the onset of bimodal mafic and rhyolitic volcanism in western Utah. These A-type granites and rhyolites (many of which contain topaz) are geochemically distinct from older I(Caledonian)-type (Pitcher, 1982) and S-type granitoids of western Utah and eastern Nevada. Even before this change in magma chemistry, tectonic extension of the Great Basin in a west-southwest direction was underway behind a calc-alkaline volcanic arc, which by this time was restricted to areas near the coast (Zoback *et al.*, 1981; Eaton, 1984). As a result of the development and growth of a transform boundary at the western margin of the continent, the extension direction changed to approximately east-west sometime between 10 and 6 Ma ago and formed the present fault-controlled topography of the Great Basin (Zoback *et al.*, 1981).

The Sheeprock granite is a small pluton (ca 25 km²) exposed along the southwest flank of the Sheeprock Mountains horst in the eastern Great Basin of west-central Utah (Fig. 1). The pluton intrudes Late Proterozoic quartzites, slates, phyllites and diamictites as well as Paleozoic sedimentary rocks. Portions of its margins are covered by Cenozoic alluvium (Christie-Blick, 1982; Cohenour, 1959). Several types of geologic information suggest that the pluton crystallized at a relatively shallow level; the lack of a regional metamorphic aureole, the presence of miarolitic cavities, the extreme variations in texture, and the

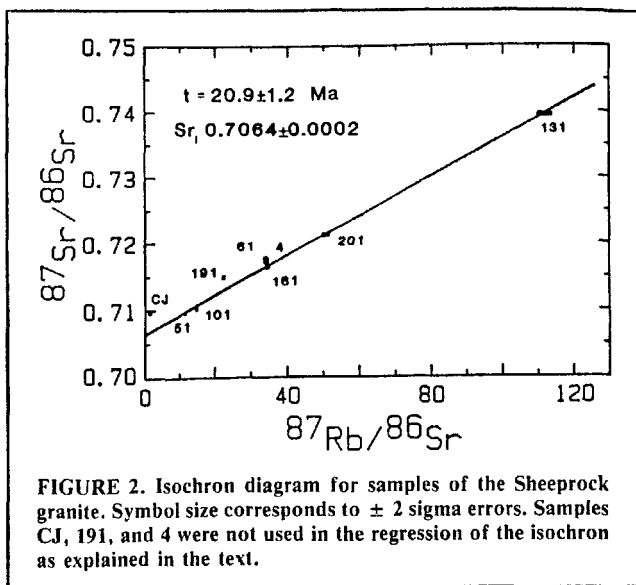


FIGURE 2. Isochron diagram for samples of the Sheeprock granite. Symbol size corresponds to ± 2 sigma errors. Samples CJ, 191, and 4 were not used in the regression of the isochron as explained in the text.

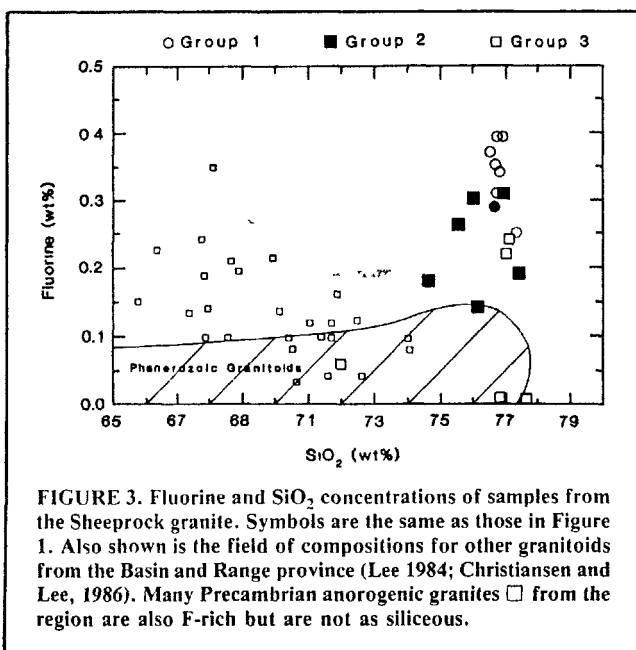


FIGURE 3. Fluorine and SiO_2 concentrations of samples from the Sheeprock granite. Symbols are the same as those in Figure 1. Also shown is the field of compositions for other granitoids from the Basin and Range province (Lee 1984; Christiansen and Lee, 1986). Many Precambrian anorogenic granites \square from the region are also F-rich but are not as siliceous.

Electron probe analyses (E.H. Christiansen, in prep.) show that the hydrothermal white micas found in the greisens are ferriphengite-muscovite solid solutions with molar $\text{Fe} = 0.5$ to 1.0 per $24 (\text{O} + \text{OH} + \text{F})$. The white micas contain low concentrations of TiO_2 (typically less than 0.35 wt%). Calculated at 350°C , $\log f\text{H}_2\text{O}/f\text{HF}$ ranges from 3.9 to 4.9 . These micas contain up to 2.5% F and have fluorine intercepts (Munoz, 1984), that cluster around 0.7 . Igneous biotites have high $\text{Fe}/(\text{Fe} + \text{Mg})$ ratios — 0.8 to 0.95 — and are relatively aluminous ($3.4 \text{ Al}/24 \text{ O} - 4 - \text{OH} + \text{F}$). The biotites are also F-rich (1.1 to 3.5 wt%). These values are similar to those found in biotites from rhyolite vitrophyres from Spor Mountain, Utah. Fluorine intercepts for the biotites range from 0.7 to 1.7 , whereas chlorine intercepts range from -4.4 to -3.3 . According to Munoz (1984), these values are typical of those found in F-rich magmatic and hydrothermal biotites related to porphyry Mo and Sn-W-Be deposits. At 700°C , calculated $\log (f\text{H}_2\text{O}/f\text{HF})$ ranges from 4 to 2.8 ; the lowest values come from the core of the pluton.

Geochronology and Sr-Isotope Geochemistry

Armstrong (1966) initially reported a K-Ar (biotite) age for the Sheeprock granite as $19.2 (+3 - 2)$ Ma using instrumental neu-

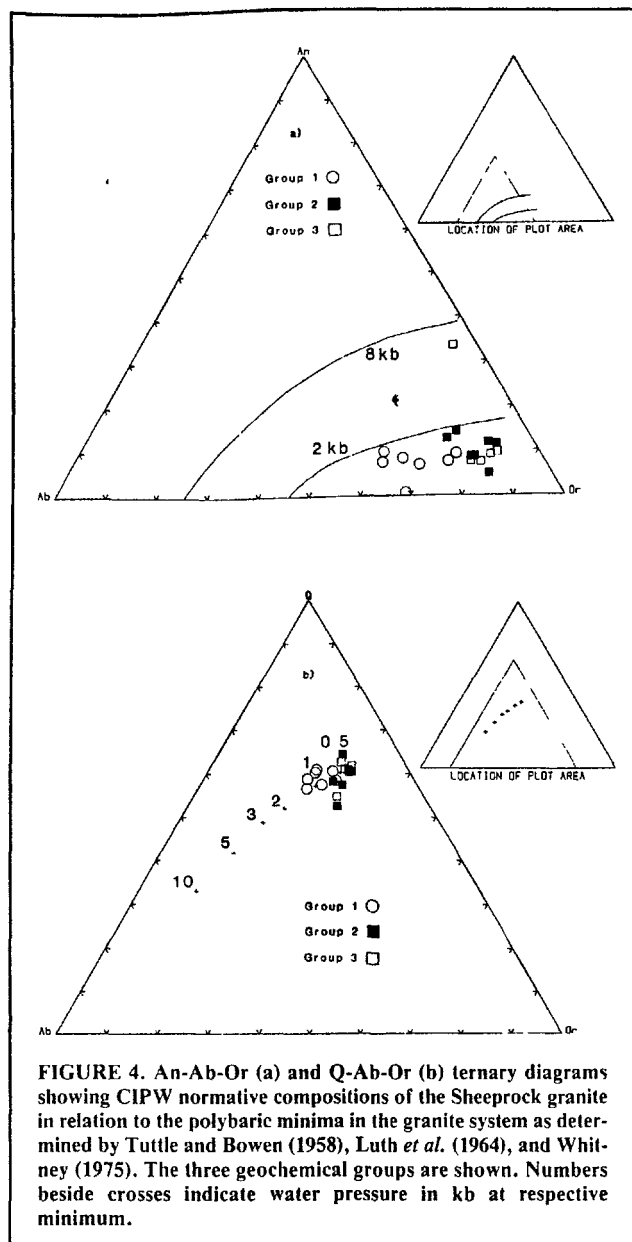


FIGURE 4. An-Ab-Or (a) and Q-Ab-Or (b) ternary diagrams showing CIPW normative compositions of the Sheeprock granite in relation to the polybaric minima in the granite system as determined by Tuttle and Bowen (1958), Luth *et al.* (1964), and Whitney (1975). The three geochemical groups are shown. Numbers beside crosses indicate water pressure in kb at respective minimum.

tron activation analysis of Ar. Armstrong (1970) later modified this value using mass spectrometric determination of Ar on the same specimen to 17.4 ± 0.3 Ma (recalculated using new decay constants). D.A. Lindsey (written coram., 1981) obtained a fission-track (zircon) age of 16.3 ± 0.9 Ma for the intrusion.

Rb-Sr isotopic data for the Sheeprock granite (Table 1) do not fit a straight line within the limits of analytical precision ($\text{MSWD} = 68.1$). Regression of all the data yields an age of 19.8 ± 2.0 Ma and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7075 ± 0.0022 in a Model 3 fit. Data for three specimens (CJ, 191, and 4) plot distinctly above the trend defined by the other six specimens. These three specimens come from a small area near the southeastern margin of the pluton, and contamination by assimilation or reaction with the Proterozoic wall rocks seems probable even though they show no petrographic evidence of such assimilation, e.g. they have no muscovite. Exclusion of these specimens from the regression reduces the MSWD to 9.57 , but a Model 3 fit to the data is still required. The resulting age is 20.9 ± 1.2 Ma, and the initial $^{87}\text{Sr}/^{86}\text{Sr}$ is 0.7064 ± 0.0002 (Fig. 2). The relatively large errors and the Model 3 fit suggest that even the remaining six specimens were not isotopically homogenous at the time of crystallization. The effect of such contamination on elemental concentrations is likely to be very small. De Paolo (1981) has shown that assimilation of wall-rocks by a magma may be obvious from isotopic studies but will be essentially invisible in terms

TABLE 2. Whole-rock chemical analyses of the Sheeprock pluton, Utah

Sample Number	Group 1							Group 2							Group 3					Topaz Rhyolites*	
	11	21	121	131	151	231	FD	51	61	101	111	161	171	211	4	81	191	201	CJ	Spor Mtn	Thomas R
	Weight Percent																				
SiO ₂	76.9	76.8	76.7	76.8	76.5	76.7	77.3	74.6	77.4	75.5	76.9	76.6	76.0	76.1	76.8	77.0	77.6	77.1	72.0	74.2	75.9
TiO ₂	0.07	0.06	0.07	0.06	0.06	0.07	0.06	0.23	0.17	0.28	0.18	0.17	0.20	0.20	0.08	0.13	0.08	0.14	0.26	0.05	0.10
Al ₂ O ₃	12.6	12.9	13.1	12.9	12.8	12.9	12.7	13.5	12.4	12.8	12.2	12.6	12.6	13.0	12.5	12.3	12.3	12.4	14.5	13.5	12.7
Fe ₂ O ₃	0.89	0.87	0.88	0.91	1.00	0.88	0.84	1.35	1.26	1.46	0.99	1.21	1.36	1.19	0.87	0.86	0.83	0.89	2.01	1.29	1.07
MnO	0.03	0.02	0.02	0.02	0.03	0.02	0.05	0.05	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.01	0.02	0.04	0.06	0.06
MgO	0.10	0.10	0.10	0.11	0.10	0.12	0.11	0.26	0.19	0.31	0.20	0.20	0.24	0.21	0.12	0.13	0.12	0.15	0.69	0.11	0.14
CaO	0.49	0.51	0.37	0.43	0.40	0.39	0.06	0.77	0.43	0.73	0.60	0.26	0.58	0.46	0.45	0.47	0.39	0.49	1.83	0.61	0.80
Na ₂ O	3.37	3.75	3.62	3.58	3.86	3.32	3.59	3.48	3.04	3.34	3.08	3.10	3.01	3.30	3.13	3.11	3.15	3.01	3.14	3.95	3.78
K ₂ O	5.16	4.53	4.92	4.61	4.65	4.95	4.67	5.34	4.94	4.97	5.24	5.26	5.26	5.29	5.18	5.32	5.05	5.27	4.81	4.86	4.92
P ₂ O ₅	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.08	0.02	0.02	0.02	0.02	0.07	0.02	0.02	0.02	0.09	0.00	0.00
Total	99.63	99.56	99.80	99.44	99.42	99.55	99.42	99.60	99.87	99.50	99.43	99.45	99.33	99.79	99.17	99.36	99.55	99.66	99.36	100.00	100.00
LOI	0.56	0.51	0.64	0.66	0.59	0.75	0.42	0.40	0.69	0.45	0.55	0.69	0.79	0.56	0.43	0.56	0.51	0.75	0.56	—	—
CIPWC	0.63	0.95	1.20	1.29	0.74	1.43	1.69	0.65	1.32	0.79	0.42	1.39	0.96	1.06	1.10	0.62	1.00	0.91	1.02	0.79	0.0
A/CNK	1.05	1.08	1.10	1.11	1.06	1.12	1.15	1.05	1.11	1.05	1.03	1.12	1.08	1.08	1.08	1.05	1.08	1.07	1.06	1.05	0.98
DI	95.77	95.39	95.82	95.36	95.98	95.43	96.82	93.38	94.75	93.4	95.0	95.52	94.08	94.84	95.68	95.79	95.94	95.34	86.23	94.15	94.54
	Parts Per Million																				
F	3900	3900	3100	3400	3700	3500	2500	1800	1900	2600	3100	2900	3000	1400	100	2200	nd	2400	600	1100	5400
Rb	903	757	951	811	963	921	958	485	456	507	522	596	524	516	367	511	327	539	173	1060	585
Sr	16	18	16	20	14	11	11	121	39	99	54	50	68	65	31	36	42	31	327	5	12
Y	63	43	52	52	61	54	21	30	44	33	33	36	42	40	24	45	15	40	13	135	43
Zr	123	120	112	97	122	109	129	147	159	186	139	163	165	163	99	125	103	131	108	120	115
Nb	113	98	96	91	96	94	101	60	71	69	57	59	56	75	43	71	24	72	16	120	70
Li	236	223	234	153	262	269	423	40	67	98	90	182	105	121	14	66	11	94	27	80	—
Be	14	9	50	9	9	10	23	14	14	13	27	12	46	14	9	14	8	13	2	52	—
Ta	21	18	30	26	32	23	33	11.6	14.6	14.2	10.0	11.2	10.5	12.7	12.3	10.6	8.50	8.21	1.55	25	6.4
Cs	13	13	21	12	10	18	43	6.1	5.1	7.2	4.9	13	6.8	11	2.7	3.5	3.9	7.6	4.1	58	14.1
Sc	2.3	2.5	3.0	2.6	2.9	2.6	2.8	2.3	2.0	2.9	2.1	2.01	2.13	2.23	2.04	1.76	1.75	1.72	4.12	2.7	2.2
Sb	0.2	0.09	0.09	0.14	0.09	0.08	0.79	0.08	nd	nd	0.05	0.17	0.11	0.12	0.06	0.04	0.1	0.07	0.05	—	—
Hf	7.1	7.4	7.0	6.7	7.4	7.9	9.2	5.79	7.00	9.00	5.35	6.71	6.31	6.72	4.40	5.26	4.72	6.27	4.11	7.1	5.7
Th	46	45	46	46	49	49	42.2	61.0	81.8	74.5	66.1	73.6	71.3	67.7	65.2	60.1	68.4	62.4	19.4	69	56
U	44	30	12	17	12	15	8.1	17.5	28.3	24.7	11.9	6.48	9.05	8.94	32.9	14.8	15.5	8.09	6.53	38	25
La	28.5	29.0	32.4	32.9	33.0	29.9	25.4	69.6	77.1	76.9	63.4	70.5	62.9	61.6	38.2	47.0	42.4	45.1	33.5	59	25
Ce	56.8	56.9	66.2	67.5	68.3	60.7	63.4	125	146	141	117	127	118	113	70.9	87.2	81.3	85.3	62.3	137	64
Nd	19.9	18.1	25.4	22.6	23.8	22.0	15.9	38.6	47.5	45.2	38.4	40.7	41.5	38.1	28.3	32.7	30.1	28.9	22.6	51	31
Sm	4.9	3.6	5.0	5.4	5.5	4.2	1.5	6.13	8.93	7.26	6.99	7.62	7.45	7.10	5.61	7.13	5.57	5.15	3.78	17.8	4.9
Eu	0.17	0.20	0.18	0.18	0.17	0.14	0.10	0.72	0.41	0.65	0.49	0.46	0.59	0.54	0.33	0.37	0.43	0.29	0.81	0.04	0.06
Tb	0.68	0.49	0.68	0.73	0.82	0.60	0.36	0.66	1.21	0.74	0.80	0.93	1.03	0.88	0.86	1.09	0.64	0.71	0.39	3.4	—
Dy	4.2	3.2	4.5	4.5	5.7	3.8	2.1	3.82	6.42	3.59	4.90	4.84	5.85	4.78	4.81	6.02	3.57	4.23	2.37	—	—
Yb	6.25	5.5	6.5	6.9	7.5	6.2	2.4	3.51	5.78	4.36	3.64	3.99	4.30	4.11	5.33	5.12	2.59	3.94	1.71	15.7	7.9
Lu	1.1	0.97	1.1	1.1	1.2	1.1	0.42	0.57	0.89	0.68	0.57	0.60	0.63	0.66	0.91	0.80	0.39	0.62	0.25	2.6	1.6
Cr	1.4	nd	nd	2.6	2.1	nd	nd	0.3	0.7	0.6	nd	0.03	nd	nd	nd	0.4	nd	nd	3.9	3.2	nd
Co	2.3	0.36	0.39	0.44	0.47	0.47	0.52	1.6	0.88	1.2	0.75	0.91	1.1	0.96	0.2	0.7	0.2	0.7	4.3	0.4	nd

CIPW C = Normative corundum calculated from fluorine-free analyses. Fe₂O₃/FeO ratios were calculated using Sack *et al.* (1980).

DI - Differentiation index.

LOI = Loss on ignition at 1000°C for 4 hours.

A/CNK = Molecular Al₂O₃/(CaO +Na₂O+K₂O).

nd - Not detected.

* = Analyses of Spor Mtn and Thomas Range, Utah, rhyolites from Christiansen *et al.* (1984).

Analysts: A. Bartel, E.H. Christiansen, E. Brandt, H. Nieman, M. Malcolm, J. Budahn, and R. Knight.

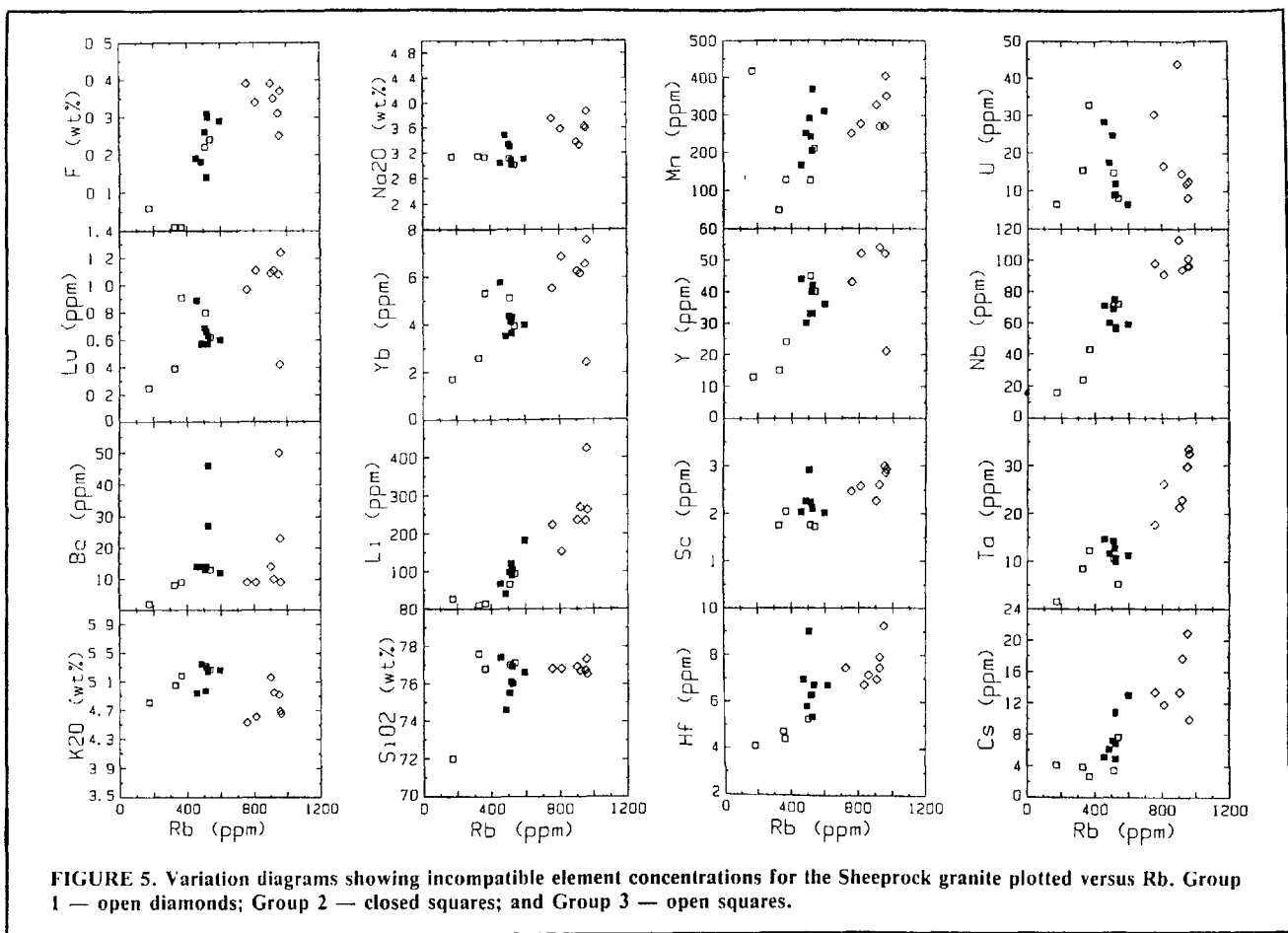


FIGURE 5. Variation diagrams showing incompatible element concentrations for the Sheeprock granite plotted versus Rb. Group 1 — open diamonds; Group 2 — closed squares; and Group 3 — open squares.

of trace element abundances until large amounts of assimilation have occurred (Lee and Christiansen, 1983). For example, assimilation of approximately 1% of radiogenic Proterozoic wall rocks of the sort intruded by the Sheeprock granite could raise the Sr-isotope ratio of a Sr-rich specimen like CJ from 0.7060 to 0.7070. Even less contamination could produce significant isotopic changes in the Sr-poor rocks. We, therefore, suggest that the trace element concentrations of all of the specimens are petrogenetically meaningful.

The Rb-Sr age is somewhat older than the K-Ar and fission-track ages for the Sheeprock pluton, but it is indistinguishable from the radiometric dates obtained from the geochemically similar rhyolite lavas and tuffs of the Spor Mountain Formation which contain North America's largest mineable source of Be. Lindsey (1982) reported a K-Ar age (sanidine) of 21.2 ± 0.9 Ma and a fission-track age (zircon) of 21.5 ± 1.1 Ma for this distinctive volcanic unit. Vents for the Spor Mountain rhyolite lie 60 km west-southwest of the Sheeprock pluton. Thus, although the Spor Mountain rhyolite did not erupt from the Sheeprock granite magma, its similar age and geochemistry (see below) suggest that a very similar magma developed approximately simultaneously.

Geochemistry

Major Elements

Major element analyses and partial CIPW norms are presented in Table 2. Analyses of two topaz rhyolites are also included for comparison — one from the 21 Ma Spor Mountain rhyolite and the other from the 6 to 7 Ma rhyolites from the Thomas Range, Utah. The granites from the Sheeprock Mountains are uniformly high in SiO_2 , ranging from 75% to 77.5% (recalculated volatile-free and normalized to 100%). A coarse-grained variant near the southeast margin of the intrusion contains less silica (e.g. CJ has a silica content of 72.6%). In addition, the specimens all have high Fe/Mg and K/Na ratios and total alkali contents, and low Ti, Mg, Ca, and P. Fluorine concentrations

in the Sheeprock granite are much higher than in most granites (Bailey, 1977), and range up to 0.39% (Fig. 3). Biotite and fluorite are the most important mineralogical hosts of F. The geochemical features of the Sheeprock granite reveal its similarity to topaz rhyolites from the eastern Great Basin and to aluminous anorogenic granites from other parts of the world (Christiansen *et al.*, 1986). All of the specimens are peraluminous and contain 0.4% to 1.7% normative corundum ($\text{Al}/(\text{K} + \text{Na} + \text{Ca})$ ranges from 1.03 to 1.15). CIPW norms were calculated using $\text{FeO}/\text{Fe}_2\text{O}_3$ ratios adjusted by the method of Sack *et al.* (1980).

Normative feldspar compositions (Fig. 4a) plot below the 2 kb cotectic determined by Whitney (1975), and therefore suggest a low pressure of crystallization. The positions of the data points in the Q-Ab-Or ternary diagram (Fig. 4b) indicate that the pluton crystallized at a water pressure between 0.5 kb and 1 kb. This pressure estimate ignores the role of fluorine on the composition of granitic melts. According to Manning (1981) relatively small amounts of fluorine shift the fluid-saturated minimum (at 1 kb) toward more albite-rich compositions; thereby mimicking the effect of increased pressure. It is difficult to estimate the magmatic concentration of fluorine from a non-glassy rock, but fluorine contents of the biotites indicate that the melt may have contained up to 1.0 wt% F. This estimate is based on a biotite/glass partition coefficient for F of 3.5 to 4 as determined for the Spor Mountain rhyolite (E.H. Christiansen, unpubl. data). According to Manning's (1981) experiments, this much fluorine produces a shift in the minimum melt composition analogous to that produced by increasing H_2O pressures up to 2 kb in the absence of fluorine. Thus although not conclusive, all of the evidence is at least consistent with field evidence for crystallization at low pressure.

Trace Element Composition

Concentrations of a wide variety of trace elements are shown in Table 2. The Sheeprock granite is distinctive because of its

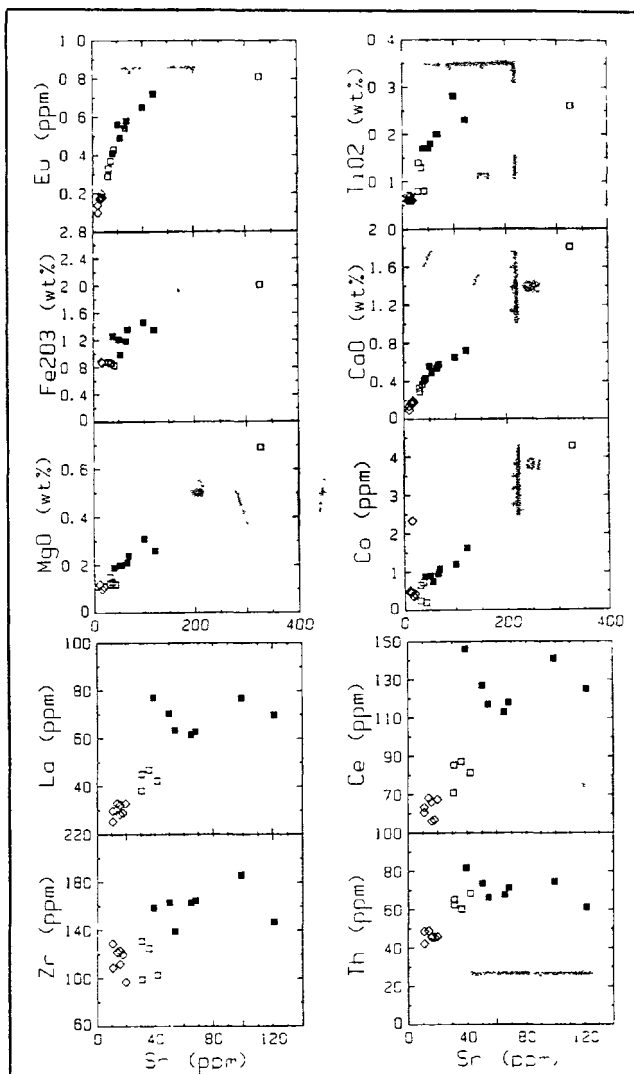


FIGURE 6. Variation diagrams showing compatible element concentrations for the Sheeprock granite plotted versus Sr. Group 1 — open diamonds; Group 2 — closed squares; and Group 3 — open squares.

generally high concentrations of some incompatible trace elements. Rubidium contents range from less than 200 ppm to nearly 1000 ppm. Likewise, the granite is enriched relative to Cordilleran and Caledonian I-type granitoids (Pitcher, 1982) typical of the Great Basin, in Y, Nb, Ta, Li, Be, Cs, U, and Th. Zirconium and rare earth element (REE) concentrations are similar to those in many other silicic rocks, but heavy REE (HREE) contents are slightly elevated. Elements concentrated in feldspars (Sr, Ba, Eu) and mafic silicates (Co, Cr) are strongly depleted. All of these features indicate that the granite is highly "differentiated" or "evolved", in accord with the major element evidence of high Si, and extreme depletions of Ti, Fe, Mg, and Ca. In many compositional regards, the Sheeprock granite is like the anorogenic granites described by Loiselle and Wones (1979), Collins *et al.* (1982), Anderson (1983), Stuckless *et al.* (1983), and DuBray *et al.* (this volume). It also bears geochemical similarity to the biotite-bearing Younger Granites of Nigeria (Bovvden, 1966; Olade, 1980; Imeokparia, this volume; Ekwere and Olade, 1984), the "tin" granites of Alaska (Hudson and Arth, 1983), evolved portions of the greisenized and Sn-mineralized Blue Tier Batholith (McCarthy and Groves, 1979), the tin-specialized granites of the South Mountain Batholith, Nova Scotia (Chatterjee *et al.*, 1983) and especially to the Eurajoki stock of Finland (Haapala, 1977). Soviet geologists would classify the Sheeprock granite as a "rare metal Li-F" granite based on its decided enrichment in Li, F, Rb, and

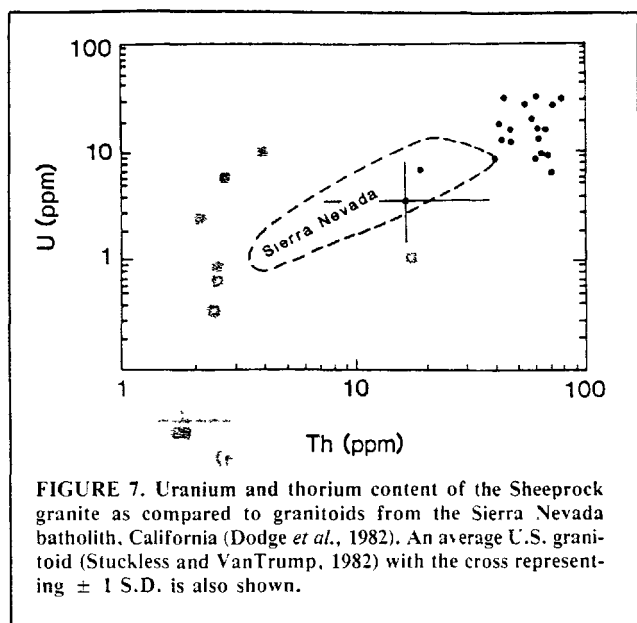


FIGURE 7. Uranium and thorium content of the Sheeprock granite as compared to granitoids from the Sierra Nevada batholith, California (Dodge *et al.*, 1982). An average U.S. granitoid (Stuckless and VanTrump, 1982) with the cross representing ± 1 S.D. is also shown.

Ta (Kovalenko, 1978). Figures 5 and 6 show variation diagrams for some of the major and trace elements where incompatible elements are plotted against Rb and compatible elements are plotted against Sr. Figure 7 clearly shows the uranium and thorium-rich nature of the Sheeprock granite as compared to I-type granitoids from the Sierra Nevada batholith (Dodge *et al.*, 1982) and average U.S. granitic rock of Stuckless and Van Trump (1982).

The major and trace element compositions of the specimens from the Sheeprock granite define three geochemical groups and indicate that the pluton is chemically zoned (Figs. 5 and 6). The three groups produce divergent arrays on plots of two elements that have different bulk partition coefficients (i.e. an incompatible vs a compatible element — Fig. 8). At a given content of an incompatible element, Group 2 specimens are enriched in the compatible elements, relative to specimens from Group 3. Group 1 consists of highly evolved specimens from the core of the pluton. The area that Group 1 specimens were collected from is the exclusive host of the beryl segregations noted above. A somewhat larger area that includes this zone has been termed the "white fades" of the Sheeprock granite (Williams, 1954; H. Htay and W.R. Griffiths, written coram., 1981). Specimens from Groups 2 and 3 surround the core but are not spatially distinct from one another. These specimens were collected from the white facies and the outer "red fades" (iron-stained) of the pluton. The distribution of the red and white facies as mapped by Htay and Griffiths does not correlate with the chemical groups defined here. A contact between the two facies is not visible on colour air photos or from our reconnaissance mapping.

Group 1 specimens have high Rb/Sr ratios (40 to 90) and low La/Yb_N (ca. 3). Group 1 specimens are enriched relative to those of the other two groups in Na, F, Sc (3 ppm — these and other concentrations listed below are maximums), Be (50 ppm), Li (260 ppm with one outlier at 420 ppm), Rb (960 ppm), Cs (20 ppm with one outlier at 43 ppm), Ta (33 ppm), Nb (130 ppm), Y (60 ppm), Hf (9 ppm) and HREE (Yb_N = 35). Relative to Group 2 specimens those from Group 1 are depleted in Th (50 ppm — maximum), Sr (20 ppm), Zr (125 ppm), LREE (La_N = 100), Ti, Fe, Mg, Ca, K, and P and have relatively low Nb/Ta ratios (3 to 5). As a group, these specimens are also depleted in U relative to Groups 2 and 3 (Funkhouser-Marolf, 1985). With the exceptions of the U and Th depletions, these are common geochemical trends produced by the differentiation of aluminous high-silica magmas (Hildreth, 1981).

The REE patterns of specimens from the three groups are grossly similar, but subtly distinct (Figs. 9 and 10). Rocks from the core of the pluton (Group 1) are the most depleted in Eu

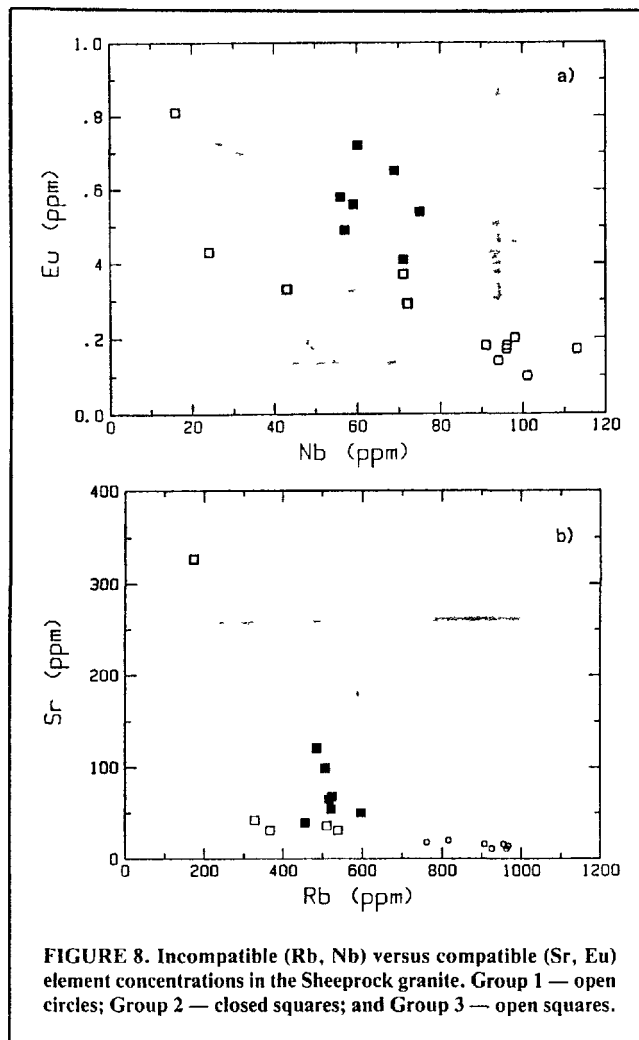


FIGURE 8. Incompatible (Rb, Nb) versus compatible (Sr, Eu) element concentrations in the Sheeprock granite. Group 1 — open circles; Group 2 — closed squares; and Group 3 — open squares.

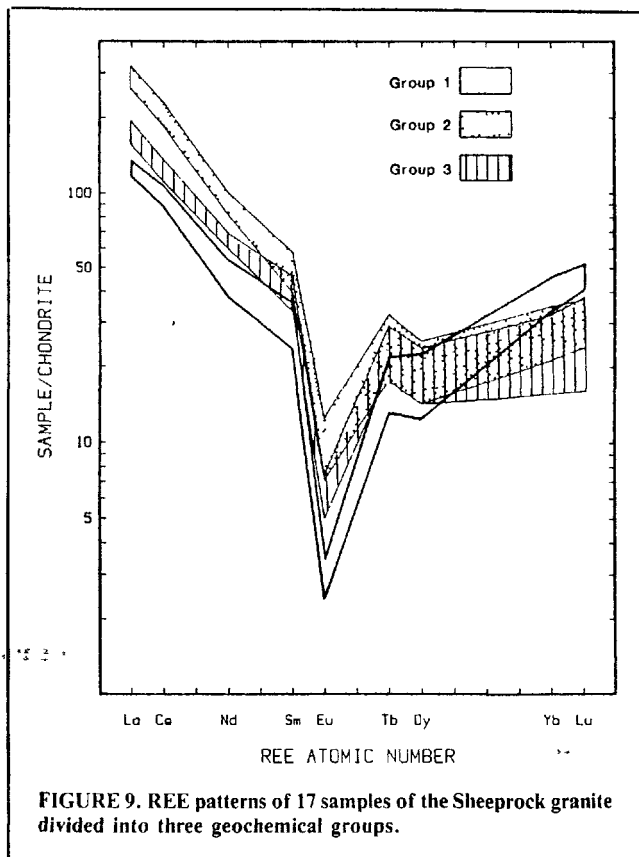


FIGURE 9. REE patterns of 17 samples of the Sheeprock granite divided into three geochemical groups.

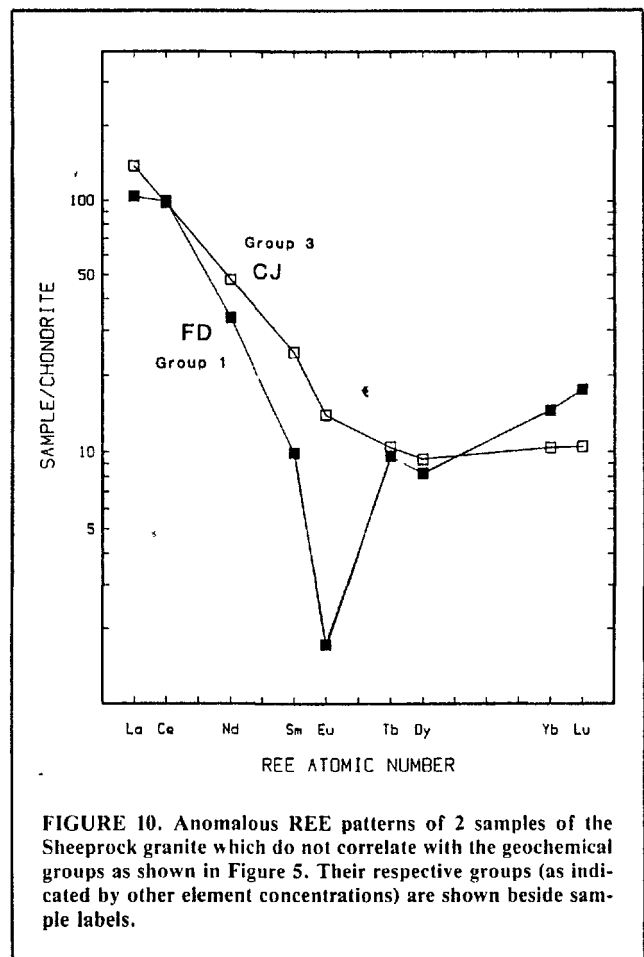


FIGURE 10. Anomalous REE patterns of 2 samples of the Sheeprock granite which do not correlate with the geochemical groups as shown in Figure 5. Their respective groups (as indicated by other element concentrations) are shown beside sample labels.

and LREE and have elevated concentrations of Yb and Lu. Groups 2 and 3 have REE patterns that largely overlap for elements heavier than Tb, but are distinct in LREE concentrations; Group 2 specimens contain higher concentrations of LREE. Specimens from both of these groups contain higher total REE and especially Eu contents than Group 1 specimens. Sample CJ (Group 3) and FD (Group 1) are shown separately because they do not conform to the REE patterns of others from their respective groups. CJ was collected from a small Cu-Zn-F mine dump (Copper Jack) but shows no petrographic signs of significant hydrothermal alteration. Specimens from this small area are the most mafic of those analyzed. FD is the only specimen analyzed that contains topaz visible under a microscope. If, as we suspect, topaz crystallized as a result of post-magmatic alteration, then modification of REE concentrations might be expected (Alderton *et al.*, 1980). This specimen also has lower Y contents than others from the evolved Group 1 (21 ppm vs the 54 ppm average of the rest of the Group 1 specimens). (Yttrium is geochemically similar to the heavier middle RE elements.) However, in terms of major and most trace (Rb, Nb, Sr, Zr, Ta, Sc, Th, and U) element concentrations the specimen is indistinguishable from the others in Group 1. The low fluorine content of this specimen results from its negligible biotite content.

Petrogenesis of the Sheeprock Granite

The Sheeprock granite is geochemically similar to rare-metal granites and to topaz rhyolites. The core of this pluton is typified by extremely high or low concentrations of many elements. In addition, it displays a large internal compositional variation that defines a crude concentric zonation. The following section addresses the origin of the internal variation and the genesis of the magma itself and is based on models of its isotopic and trace-element composition.

Metasomatism

Metasomatic processes may be especially effective in altering the magmatic compositions of a variety of igneous rocks including rare metal granites. In fact, the greisenization of the Sheeprock granite is clearly the result of post-magmatic metasomatism. Hypothetically, the composition of the fluorine and alkali-rich core of the Sheeprock granite could be attributed to metasomatism. However, as shown below, metasomatism was not responsible for producing the major compositional groups and trends described above.

Metasomatism of the Sheeprock granite produced narrow (less than 5 cm across) envelopes of greisen about fractures in the pluton. These envelopes are obvious in the field and show anomalous elemental compositions and petrographic distinctions. Greisen-bordered veinlets are widely spaced and sheeted greisen veinlets are extremely rare. It is therefore unlikely that metasomatically altered rocks would be collected inadvertently. No albitization is present in the rocks described here.

Bulk rock analyses and petrographic studies of greisenized rocks show that metasomatism mobilized Na, K, Rb, Li, Fe, Zn, Pb, W, and Sn (Howell, 1987). These elements show enrichments and depletions in the greisenized rocks beyond those explicable by normal variation of the granite. In contrast, other elements enriched in the core of the pluton were not mobilized by greisenization and were in effect decoupled from the mobile elements. Among the elements analyzed, immobile elements include Sr, Y, Zr, and Nb. For these elements, specimens of greisenized granite had compositions that were indistinguishable from the surrounding granite. Nonetheless, the pluton as a whole shows strong correlations between element pairs that responded very differently to metasomatism. The strong positive correlation of alkalis (Li, Na, Rb, and Cs), that were mobile in this F-rich metasomatic environment with elements (Nb, Y, Sr) that were not (Fig. 8), argues strongly against metasomatic alteration as having produced the compositional groups discussed above. Likewise, greisenized rocks from the Sheeprock Mountains are consistently rich in Fe; ungreisenized specimens from the evolved core of the pluton are poor in Fe (Howell, 1987). In addition, Ti, Ta, and Hf (not analyzed in the greisens) are widely regarded as being immobile in secondary alteration environments and yet they show decided compositional variations in the Sheeprock granite and correlate with "mobile" elements. On the other hand, the observed element trends (Figs. 5 and 6) with enrichments of Rb, Nb, Ta, etc., are very similar to those seen in rhyolitic volcanic rocks whose glassy groundmasses show no evidence of metasomatism (Christiansen *et al.*, 1984). Instead, these elemental variations can be best explained by fractionation of observed minerals.

Fractional Crystallization Model

We interpret the geochemical trends and the existence of geochemical groups as indicating that the Sheeprock granite crystallized in situ. Specimens from the core (Group 1) appear to represent residual liquid confined to the inner and upper parts of a magma chamber that was crystallizing by the accumulation of crystals (Group 3) on its walls. The chemical character of the evolving liquid (Group 2) is partially preserved perhaps as a result of intermittent periods of equilibrium crystallization of large (at the scale of a specimen) parcels of magma. Thus, "primitive" melt compositions appear to be preserved along with crystal cumulates and residual "evolved" liquid.

Elemental variations of Rb and Sr are shown in Figure 11 on which we base a discussion of the crystallization of the Sheeprock granite. The crystallization model shows the evolution of the liquid and solid in a magma according to the Rayleigh fractionation law. The fraction of residual liquid (f) is indicated by tick marks on the curves. Thus a melt composition that plots on the liquid evolution curve at $f = 0.7$ coexists in equilibrium with a mineral assemblage on the solid evolution curve at the point labelled 0.7. This sort of crystallization model, which emphasizes the role of granitic cumulates, has been used by

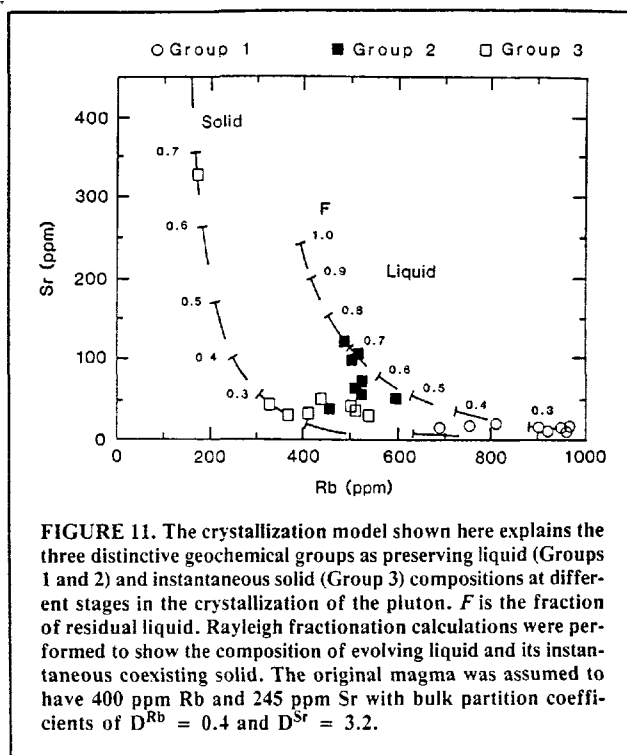


FIGURE 11. The crystallization model shown here explains the three distinctive geochemical groups as preserving liquid (Groups 1 and 2) and instantaneous solid (Group 3) compositions at different stages in the crystallization of the pluton. F is the fraction of residual liquid. Rayleigh fractionation calculations were performed to show the composition of evolving liquid and its instantaneous coexisting solid. The original magma was assumed to have 400 ppm Rb and 245 ppm Sr with bulk partition coefficients of $D^{Rb} = 0.4$ and $D^{Sr} = 3.2$.

McCarthy and Hasty (1976), McCarthy and Groves (1979), Tindle and Pearce (1981), and Lee and Christiansen (1983) in examinations of the crystallization of granitoid magmas. A hypothetical parent liquid was chosen to have a Rb concentration of 400 ppm and Sr of 245 ppm. Bulk partition coefficients ($D^{Sr} = 3.2$ and $D^{Rb} = 0.4$) were chosen by an iterative procedure to produce curves that pass through the extremes of the compositional data, such that an envelope for possible compositions is created.

This differentiation model was checked by calculating the proportions of fractionating minerals by a least squares mass balance technique using only major elements. These calculations suggest that the fractionating mineral assemblage consisted of 46% K-feldspar, 27% quartz, 21% plagioclase, 5% biotite and small proportions of Fe-Ti oxides and apatite (sum of the squared residuals was 0.035). This analysis agrees with the trace element model in suggesting that a crystallization interval of approximately 45% (Fig. 11) separates Group 2 (parent) and Group 1 (residue) specimens. The calculated major element composition of the cumulate ($SiO_2 = 73.5\%$, $Al_2O_3 = 13.9\%$) is broadly similar to the observed composition of sample CJ. When combined with crystal/liquid partition coefficients for siliceous magmas (Mahood and Hildreth, 1983; Nash and Crecraft, 1985; Ewart, 1982), these mineral proportions suggest that the bulk partition coefficient for Rb could range from 0.38 to 0.7 and that for Sr could range from 3.4 to 4.1 — very close to our independent estimates. Consideration of the large changes in D 's as a function of both temperature and small changes in melt composition (Leshner, 1984; Nash and Crecraft, 1985) implies that these two sets of estimated D 's are comparable.

In spite of its inherent assumptions, the fractional crystallization model appears to explain some of the major features of the evolution of the Sheeprock granite, especially the divergence of Groups 2 and 3 on compatible vs incompatible element plots. Specimens from Group 2 appear to be most like the original liquid from which the intrusion crystallized. Specimen CJ (Group 3) appears to be an early cumulate from this magma and is poor in incompatible elements and enriched in the compatible elements. The separation of such material drove the residual liquid toward compositions typical of the core (Group 1) which is rich in Rb and other incompatible elements, notably Be. Group 1 specimens are the most evolved. If the bulk

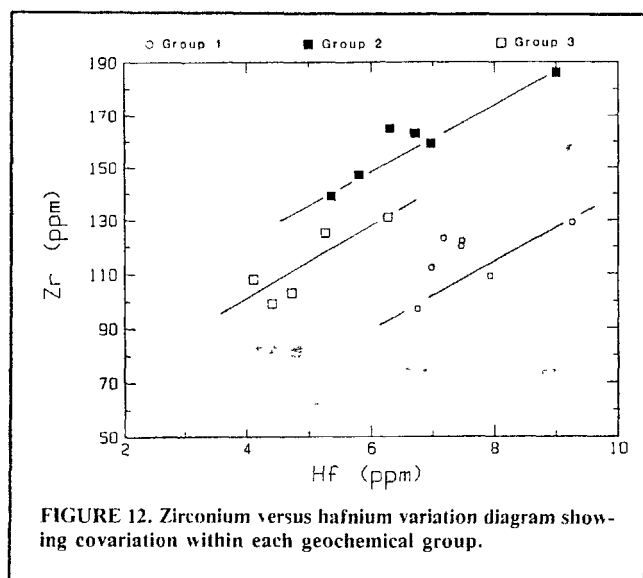


FIGURE 12. Zirconium versus hafnium variation diagram showing covariation within each geochemical group.

D's and initial compositions chosen for the Rayleigh fractionation model are approximately correct, this group has compositions that reflect removal of 70% by mass of the original magma. Crystal cumulates from this evolved liquid also appear to have been preserved in the Group 3 specimens which diverge from Group 1 toward low Rb concentrations at an approximately constant Sr content. Such a pattern is strongly indicative of cumulate processes in magma chambers (McCarthy and Hasty, 1976). Specimens that plot between the liquid and solid evolution curves can be explained readily by the incomplete separation of crystalline material from the evolving melt. In addition, some scatter of the data about the model curves is probably the result of minor wall-rock assimilation, secondary alteration, or weathering.

The degree to which specimens from the Sheeprock granite adhere to the trace element patterns is testimony to the applicability of the crystallization model. Plots of incompatible vs compatible elements (Fig. 8) consistently show a divergence in the concentrations of compatible elements between Groups 2 and 3. This suggests that the elemental composition of the pluton was strongly controlled by fractional crystallization and that specimens with chemical compositions like cumulates and like liquids were preserved during the solidification of the pluton. It follows from the fractional crystallization model that plots of elements with grossly similar bulk crystal/liquid partition coefficients should form linear arrays. This feature is shown in Figure 6. In these diagrams, the compositions of specimens from Groups 2 and 3 overlap substantially. This is predicted from the model because for the case of similar partition coefficients, solid and liquid evolution curves are not readily distinguishable from one another — regardless of the initial concentrations chosen for the model. Linear variation trends such as these are similar to those interpreted as originating from the separation of restite from a granitic magma (Compston and Chappell, 1979). Therefore, attempts to determine the mechanism by which compositional variety arises in granitic plutons should include a comparison of elements with as much geochemical contrast as possible (i.e. elements with substantially different bulk partition coefficients).

Accessory Minerals

The importance of trace or accessory minerals in controlling the composition of the Sheeprock granites is well-displayed by Zr and Hf variations. The variations in these elements are strongly controlled by zircon which (by mass balance calculations) must occur in amounts of only 0.02 to 0.04 wt% of the specimens. Figure 12 shows the covariation of Hf and Zr. The three geochemical groups remain distinct but the compositions of each group lie in semi-parallel arrays with positive slopes but different Zr/Hf ratios. Group 1 specimens have Zr/Hf ratios

that range from 14 to 18, and specimens from Groups 2 and 3 vary from 20 to 28. These trends are most likely caused by small variations in the amount of zircon in each specimen and can be likened to mixing lines between zircon and granite. Nonetheless, by considering group averages, the Zr-Hf variations are consistent with the interpretation of Zr as a compatible element and Hf as an incompatible element. This is the sort of behaviour seen in many high-silica granitic magmas (Hildreth 1979, 1981).

Rare Earth Elements

Accepting a fractional crystallization origin for the chemical variation in the Sheeprock granite, we can examine some implications for the mineralogical controls of the trends of specific REE. Other investigators have noted the difficulty of using REE for granite petrogenetic models because of their occurrence in accessory phases (Fourcade and Allegre, 1981; Gromet and Silver, 1983; Lee and Christiansen, 1983). As a result, the concentrations of the REE are very sensitive to sampling problems because of the heterogeneous distribution of minute quantities of REE-rich minerals. Nonetheless, some conclusions regarding the REE evolution of the Sheeprock pluton can be made. For example, the enrichment of LREE in the Group 3 (cumulates) specimens and the complementary depletion of LREE in the core (Group 1) specimens is indicative of a LREE-rich phase in the cumulus mineral assemblage (Fig. 9). It appears that this phase accumulated in the margin of the crystallizing pluton and enriched the solids in LREE relative to the evolving residual liquid. Conversely, the Group 1 specimens are enriched in heavy REE (Fig. 9) relative to the cumulate group and these must have behaved as incompatible elements.

When first observed in silicic igneous rocks, such depletion patterns for LREE and enrichment of HREE were deemed to be inconsistent with an origin by crystal fractionation and several investigators called on "liquid-state" differentiation (Hildreth 1979; Ludington, 1981; Whalen, 1983). Such differentiation patterns are becoming increasingly recognized as the norm for high silica rhyolites and granites (e.g. Bacon *et al.*, 1981; Christiansen *et al.*, 1983; Crecraft *et al.*, 1981; Miller and Mittlefehldt, 1984; Keith, 1982) and can be reasonably modelled by the fractionation of small amounts of several common REE-rich phases (Christiansen, 1983; Michael, 1983). For example, Christiansen *et al.* (1984) point out that fractionation of 0.04 wt% allanite effectively depleted La (halved after 75% crystallization) in rhyolites from the Thomas Range, Utah, but that this amount of allanite did not reduce HREE contents. Likewise, Christiansen (1983) explained the LREE-depletion of the Bishop Tuff as resulting from fractionation of 0.06 wt% allanite. In a similar manner, monazite effectively removes LREE from differentiating silicic magmas (Mittlefehldt and Miller, 1983). We suggest that the fractionation of monazite, which is the most important REE-bearing phase in the Sheeprock granite (Funkhouser-Marolf, 1985), was important in the REE evolution of the pluton. Mass balance calculations demonstrate that the presence of less than 0.01 wt% monazite in the fractionating mineral assemblage could deplete La from 80 ppm to 30 ppm over the inferred range of crystallization ($f = 0.75$ to 0.25) between Group 2 and Group 1 specimens. In addition, the La and Ce contents of the specimens from Group 3 (cumulates) relative to those of Group 1 suggest that La, Ce and Nd all behave as compatible elements. However, it is important to note that no specimen analyzed here could be regarded as a LREE-rich cumulate formed from the early liquids (Group 2). Sample CJ, which otherwise appears to be an early formed cumulate, is poor in light REE (Fig. 10) and no discrete grains of monazite have yet been located in it with autoradiography. This specimen's apparent depletion in monazite and LREE may not be representative, or the rock may have crystallized before saturation with monazite occurred. Eu and HREE (as well as Ca, Fe, Mg, Ti) concentrations are not as sensitive to the abundance of this trace mineral so the cumulate nature of CJ is more apparent when considering concentrations of these elements. Therefore it is important to note that Eu-variations, controlled

as they are by the fractionation of major phases (the feldspars), indicate that CJ with its high Eu content has a composition appropriate for an early cumulate from Group 2 "liquids" (Figs. 8 and 10). In addition, other Group 3 specimens have higher Eu contents than specimens from Group 1 — as expected for feldspar-rich cumulates derived from "evolved liquids". Enrichment of HREE is produced as a result of their more incompatible nature in accessory phases typical of metaluminous to peraluminous granitoids. Of the accessory minerals in the Sheeprock granite, only zircon has high partition coefficients for HREE. As pointed out by Christiansen *et al.* (1984), the low abundance of zircon (generally < 0.04 wt%) in metaluminous granitic magmas is not sufficient to deplete evolving liquids (or enrich their cumulate counterparts) in HREE. Important distinctions between the behaviour of elements controlled by accessory minerals and those that are controlled by the major minerals are apparent.

U, Th, and Sc Behaviour

The recognition of distinct geochemical groups within the pluton also reveals several important features regarding the behaviour of Th and Sc. For many, indeed most, silicic rocks increasing differentiation is marked by increases in Th and U contents (e.g. Stuckless *et al.*, 1977). The lack of enrichment of these elements in the core (Group 1) of the Sheeprock granite implies that these elements were either mobilized by some late- or post-magmatic process or that some early crystallizing phase removed U and Th from the residual melt. We do not entirely rule out post-magmatic mobility of U. Indeed, the scatter apparent on plots like those in Figure 5 suggest substantial remobilization of U probably occurred during weathering as Ra/U and U values are poorly correlated (Funkhouser-Marolf, 1985). We regard the mobilization of Th less likely under subsolidus conditions (Zielinski *et al.*, 1981). The presence of euhedra of thorite and Th-rich monazite, which occur most abundantly as mineral inclusions and in the groundmass of specimens from the outer parts of the intrusion (H. Htay and W.R. Griffiths, written comm. 1981), suggest that the depletion of Th in the evolved rocks may have occurred due to removal of these Th-rich minerals from the melt (Funkhouser-Marolf, 1985). Examples of the compatible behaviour of Th from volcanic rocks are provided by the Macusani glasses of Peru (Noble *et al.*, 1984) that have low Th/Rb ratios and Th/U ratios (near 1) implying a magmatic depletion of Th content. The zoned rhyolitic volcanic system at Pine Grove, Utah, described by Keith (this volume) shows a negative correlation of Th with generally incompatible elements (Rb and Ta). Monazite and xenotime have been identified as major carriers of Th in these rhyolites. The fractionation of small quantities of these phases could easily deplete the residual melt in Th.

On the other hand, Sc is generally depleted during the differentiation of silicic magmas (Bacon *et al.*, 1981; Christiansen *et al.*, 1984; Hildreth, 1981). However, its higher concentration in the core of the Sheeprock granite (Fig. 5) suggests that it behaved here as an incompatible element, perhaps because of the paucity of biotite ($D^{Sc_{bi,t}}$ 10-20—Hildreth, 1977; 5-20—Nash and Crecraft, 1985) and magnetite ($D^{Sc_{mt}}$ 9-10—Mahood and Hildreth, 1983; 1.5-16—Nash and Crecraft, 1985). Hildreth (1979) and Keith (1982) showed a similar magmatic enrichment of Sc in rhyolitic magmas as indicated by positive correlations with decidedly incompatible trace elements.

Summary of the Crystallization Model

We interpret the geochemical variety in the Sheeprock pluton to have arisen as the result of the in situ fractional crystallization of a granitic magma with A-type affinities. Early cumulates formed on the wall of the magma chamber (some Group 3 specimens — $f = 0.7$) are sparsely represented in the collection described here. Because crystallization occurred along the walls, residual liquids were displaced inwards and perhaps upwards. Collected from within the outcrop area of these cumu-

lates are specimens that appear to have preserved the compositions of relatively "primitive" liquids (Group 2 — $f = 0.75$ to 0.5); these specimens were perhaps formed during incremental episodes of equilibrium crystallization. They are generally coarse-grained. Complementary solids (Group 3) and liquids (Group 1) continued to form while the crystalline carapace of the magma chamber grew inwards. Specimens from the core of the pluton (Group 1 — $f = 0.40$ to 0.25) represent the residual or most evolved liquids formed from this liquid line of descent. Their porphyritic character and the presence of miarolitic cavities, pegmatites, and beryl segregations in the pluton's central portion suggest that the magma became fluid-saturated during the crystallization of these specimens. Many of the late cumulates (Group 3 — $f = 0.3$ to 0.25) formed during this interval are aplitic, suggesting relatively large amounts of undercooling, perhaps as a result of a pressure-quench induced by hydrofracturing of the country rocks upon fluid saturation. Some element mobility probably resulted from granite-fluid interaction — e.g. depletion of REE and Y in one specimen and redistribution of U in others. However, metasomatism does not appear to explain the bulk of the geochemical data. Thin greisen-bordered veins formed from circulating fluids after the core solidified and attest to *local* mobility of Fe, Cu, Pb, Zn, W and Rb (Howell, 1987). The isotopic heterogeneity of the pluton suggests that minor assimilation of wall rocks occurred.

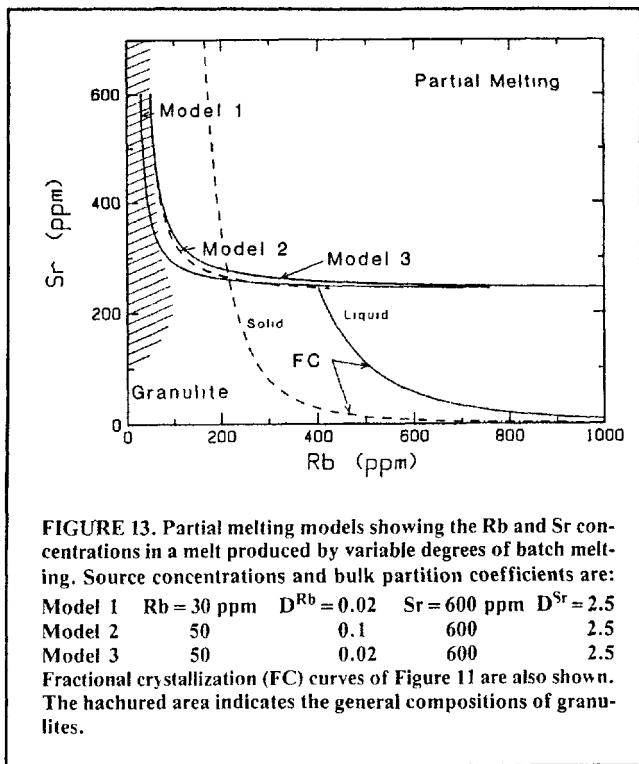
Partial Melting Model

Previous investigations of granites and rhyolites from the western United States and elsewhere have pointed toward a crustal origin for many silicic magmas (e.g. Farmer and DePaolo, 1983, 1984). We present a simplistic batch partial melting model that is consistent with the Sr isotopic, trace element and fluorine data for the Sheeprock granite.

The generally metaluminous nature of the rocks, the moderate Sr-isotope ratios, shallow level of emplacement, absence of boron metasomatism, and only moderate water concentrations demonstrate that the Sheeprock granite, as well as topaz rhyolites from the western United States, are not evolved S-type granites derived from partial melting of pelitic metasedimentary rocks (Clemens, 1984). Such strongly peraluminous two-mica granites are found in the eastern Great Basin (Lee *et al.*, 1981) but they are temporally, geochemically, and isotopically distinct from the F-rich magmas described here (Lee and Christiansen, 1983).

A major constraint on the petrogenesis of the Sheeprock granite is its relatively low initial $^{87}Sr/^{86}Sr$ of 0.7064. Other late Cenozoic rhyolites from the eastern Great Basin have similar $^{87}Sr/^{86}Sr$ ratios (Wilson *et al.*, 1983; Christiansen *et al.*, 1986). If the granite was derived from the crust, then it must have come from a source with a relatively low time-integrated Rb/Sr ratio (0.05 to 0.1) because the basement under the eastern Great Basin appears to be about 2 Ga (Nelson *et al.*, 1983). This requirement is in sharp contrast to the remarkably high Rb/Sr ratios of the Sheeprock granite itself (over 50). Lower to mid-crustal granulites commonly have low Rb/Sr ratios and only moderately elevated modern day $^{87}Sr/^{86}Sr$ ratios (Ben Othman *et al.*, 1984; James *et al.*, 1980; Clifford, 1974). In like fashion, the lower continental crust (by analogy with high-grade metamorphic rocks) is moderately to strongly depleted in K, Rb, Cs, U, Th, Li, Be, Ta and Y (Collerson and Fryer, 1978; Sheraton and Black, 1983; Condie *et al.*, 1982), all elements enriched in the Sheeprock granite. We describe such a magma source as *depleted* when compared to average crustal values or to the sources of strongly peraluminous two-mica granites which we regard as being derived from a different part of the continental crust.

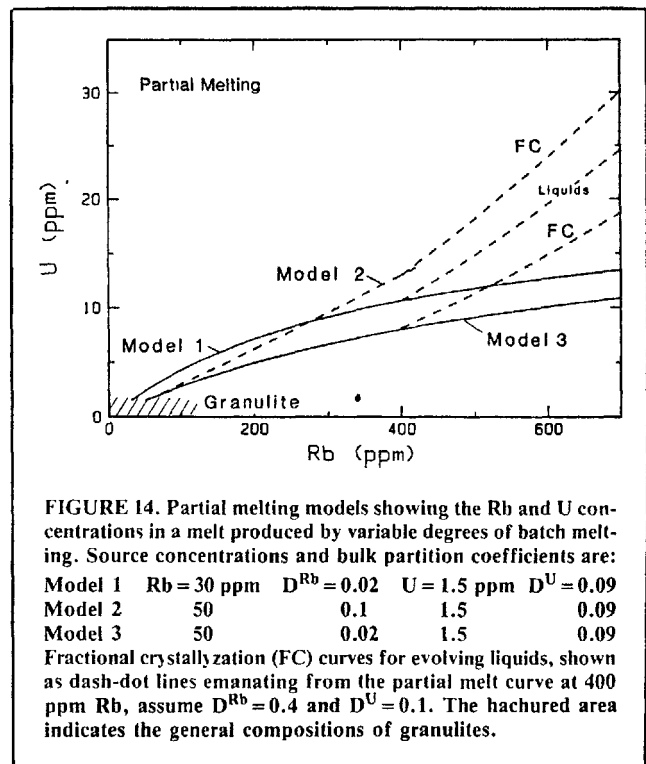
We have used Rb, Sr, and U concentrations for granulites compiled from the literature (Tarney and Windley, 1977; Barbey and Cuney, 1982; Sheraton and Black, 1983; Sighinolfi *et al.*, 1981; Condie *et al.*, 1982; Iyer *et al.*, 1984) and estimates of bulk partition coefficients for these elements to construct the trace element models of *batch partial melting* shown in



Figures 13 and 14. Extending from the partial melting curves are Rayleigh fractionation paths for liquids and instantaneous solids, constructed as in Figure 11. These fractionation curves pass through "parental melt" compositions appropriate for the Sheeprock granite. *Model 1* (Fig. 13) traces the composition of a liquid produced by variable degrees of batch partial melting of a Rb-poor ($Rb/Sr = 0.05$) source with a low bulk D_{Rb} (an alkali feldspar- and biotite-poor source). Approximately 5% to 6% partial melting of this source produces a magma that could be parental to the Sheeprock granite ($Rb = 400$ ppm $Sr = 245$ ppm). For *Model 2*, much smaller degrees (2.5% to 3%) of partial melting are required. This model assumes a higher Rb content (such that $Rb/Sr = 0.083$) and a higher bulk D_{Rb} (simulating a source that contained approximately 15% alkali feldspar or with a maximum of 3% biotite as constrained by the crystal/liquid D 's given by Nash and Crecraft, 1985). A less stringent *Model 3* uses the low bulk D_{Rb} of *Model 1* and the higher Rb concentration of *Model 2*. It shows that about 11% partial melting could produce a magma similar to that parental to the Sheeprock granite. Below, we justify a low D_{Rb} as the result of the decomposition of biotite to produce melting.

Similar partial melting models based on Rb and U variations were constructed to approximate the concentrations of these elements in the Sheeprock granite. We assumed the source contained 1.5 ppm U (appropriate for many felsic granulites) and the Rb concentrations of Models 1, 2 and 3. The bulk D_U (0.09) was chosen to simulate the effect of a small amount of zircon ($Dy = 200$ to 300; Hildreth, 1977) or another U-rich accessory in the residue. The low solubility of zircon in silica- and alumina-saturated igneous rocks (Watson and Harrison, 1983) and the Zr content of high-grade metamorphic rocks (ca. 100 to 400 ppm — e.g. Sheraton and Black, 1983; Condie *et al.*, 1982 — implying 0.02 to 0.08 wt% zircon) indicate that this value may be a reasonable approximation. Within the applicability of the assumptions, these models also require that the parental magma for Sheeprock granite was produced by low degrees of partial melting (less than 12%) to explain the necessary enrichment of uranium.

Small proportions of partial melting are a natural consequence of the water-undersaturated melting of high-grade metamorphic rocks such as granulites. Small amounts (generally less than 10%) of biotite (or amphibole) persist in granulite grade meta-



morphic rocks from a variety of terranes, but the relatively dry nature of these rocks keeps the hydrous mineral content low. Many petrologists (e.g. Burnham, 1979) suggest that decomposition of hydrous minerals provides the volatiles for partial melting. The decomposition of the small quantities of biotite and amphibole that persist in high-grade metamorphic rocks would then of necessity only produce small degrees of melting. For example, Burnham (1981) has shown that the decomposition of 1 wt% biotite would yield approximately 1.2 wt% silicate melt with 3.3 wt% H_2O plus F. Clemens (1984), using Burnham's solubility model, calculated that decomposition of 20% biotite in a felsic granulite at 5 kb would produce 17% partial melting with 4.6% H_2O . A smaller amount of biotite would proportionately reduce the amount of melting. Thus the small degree of melting required by the trace-element models could occur with the complete decomposition of 2% to 12% biotite in the granite's protolith. The decomposition of biotite and its replacement with pyroxene would also lower the bulk D_{Rb} between granite magma and restite to the values used in Models 2 and 3. In addition, biotite-controlled partial melting is consistent with the aluminous nature of the magmas. However, isotopic equilibrium between melt and the residuum is required by the moderate initial $^{87}Sr/^{86}Sr$ ratios that characterize this pluton.

Perhaps just as important as the incompatible element-rich nature of the Sheeprock granite is its enrichment in fluorine. The fluorine enrichment may also be explained by the decomposition of biotite from high-grade metamorphic biotites and amphiboles. As shown by Holloway (1977; see also Holloway and Ford, 1975; Manning and Pichavant, this volume) high $F/(F + OH)$ ratios increase the thermal stability of these minerals. Others have shown that $F/(F + OH)$ ratios in hydrous mafic silicates increase with increasing metamorphic grade, extending to granulite facies (Fillipopov *et al.*, 1974; Padovani pers. comm., 1984) or to the onset of melting (White, 1966). Thus, although the absolute amount of biotite may decrease with increasing grade of metamorphism, it probably becomes more F-rich. The decomposition of small amounts of F-rich biotite would therefore produce small amounts of F-rich melt that, because of the small degree of melting, would also be enriched in incompatible elements (Rb, U, Ta, Be, Li, etc.). Extended differentiation, such as that modelled in the previous section, would further elevate these concentrations until volatile satu-

ration and consequent quenching of the magma prevented further crystallization.

An alternative mechanism for the generation of rhyolitic melts with the typically high F/Cl ratios of aluminous anorogenic magmas calls on the depletion of magmatic Cl as the result of the loss of a fluid phase (Christiansen *et al.*, 1983, 1986; Burnham, 1979). Fluids could be lost as the result of saturation and subsequent escape to the wallrocks or as the result of eruption. In the case of the Sheeprock granite neither of these possibilities appears likely. Judging from biotite compositions the magma was relatively rich in fluorine, long before fluid saturation occurred as indicated by the presence of miarolitic cavities. In addition, no volcanic equivalents of the distinctive Sheeprock magma have been identified in spite of the preservation of older volcanic rocks in the immediate vicinity of the pluton. The absence of such volcanic equivalents suggests venting did not occur.

Conclusions

In spite of recent advances in analytical and theoretical techniques, the construction of unique geochemical models for the origin and evolution of granitic magmas is extremely difficult, if not impossible. In many cases we can at best demonstrate that it is possible that a specific rock evolved by a certain set of geologic processes. In this paper, we have attempted to erect one such possible model that shows how the internal variation of the Sheeprock granite arose and how the parental magma was generated. To do so we have made explicit assumptions regarding the elemental composition of parental materials and the bulk partition coefficients that govern their distributions between crystals and liquids.

Within the limits imposed by the uncertainties in these assumptions, we have shown that relatively simple models of batch partial melting and fractional crystallization can explain the geochemistry of the Sheeprock granite and by analogy other aluminous rare-metal granites. As a source for the Sheeprock granite, we have called upon partial melting of a depleted, "granulitic" protolith in the lower crust. An important requirement of the model is that the amount of partial melting remains small (2.5% to 11%). The decomposition of small amounts of refractory F-rich biotite will yield small quantities of F-rich melt. The extensional tectonic setting of the eastern Great Basin (and in other areas where A-type granites occur) may have been a prerequisite to the separation of small melt fractions from crystalline restite. This sort of tectonic setting may have also set the stage for the intrusion of hot mafic magmas into the crust. Mafic magmas may have acted as a heat source for partial melting. Subsequent high level fractional crystallization enhanced the depletions and enrichments of some elements. The preservation of cumulates on the walls of the pluton carries important consequences for interpretations of the mechanism of crystallization of granitic magmas.

Magmas rich in fluorine and incompatible trace elements (e.g. Rb, Li, U) can be derived from high-grade metamorphic rocks that have relatively low concentrations of these elements and low Rb/Sr ratios. The ratios of element concentration in the probable source to that in the evolved magma are in the order of 20 to 30 for incompatible elements. If these enrichments also hold for economically important elements (Be, Ta, Sn, W, Mo, U, etc.) then efficient magmatic accumulations of such elements to protore status are within reason. Geochemically "enriched" or anomalous crustal sources are not required for the generation of rare-metal granites such as the Sheeprock granite.

Acknowledgments

This work was initiated while EHC was a National Research Council-U.S. Geological Survey Postdoctoral Research Associate. Institutional support was provided by the University of Iowa and the U.S. Geological Survey. In addition to those formally acknowledged in the text, we thank C.E. Hedge, D. Lambert, Z. Peterman, and J. Edie for assistance in some of the analytical work. Discussions with W. Griffiths were extremely valuable.

REFERENCES

- ALDERTON, D.H.M., PEARCE, J.A., and POTTS, P.J., 1980, Rare earth mobility during granite alteration: Evidence from southwest England; *Earth Planet. Sci. Lett.*, V. 49, pp. 149-165.
- ANDERSON, J.L., 1983, Proterozoic anorogenic granite plutonism of North America: *Geol. Soc. Am. Memoir.*, V. 161, pp. 133-154.
- ARMSTRONG, R.L., 1966, K-Ar dating using neutron activation for Ar analysis: Granitic plutons of the eastern Great Basin, Nevada and Utah: *Geochim. Cosmochim. Acta*, V. 30, pp. 565-600.
- ARMSTRONG, R.L., 1970, K-Ar dating using neutron activation for Ar analysis: Comparison with isotope dilution Ar analyses; *Geochim. Cosmochim. Acta*, V. 34, pp. 233-236.
- BACON, C.R., MACDONALD, R., SMITH, R.L., and BAEDCKER, P.A., 1981, Pleistocene high-silica rhyolites of the Coso volcanic field, Inyo County, California: *J. Geophys. Res.*, V. 86, pp. 10223-10241.
- BAILEY, J.C., 1977, Fluorine in granitic rocks and melts: A review; *Chem. Geol.*, V. 19, pp. 1-42.
- BARBEY, P., and CUNEY, M., 1982, K, Rb, Sr, Ba, U and Th geochemistry of the Lapland granulites (Fennoscandia). LILE fractionation controlling factors: *Contrib. Mineral. Petrol.*, V. 81, pp. 304-316.
- BEN OTHMAN D., POLVE, M., and ALLEGRE, C.J., 1984, Nd-Sr isotopic composition of granulites and constraints on the evolution of the lower continental crust: *Nature*, V. 307, pp. 510-515.
- BEST, M.G., MCKEE, E.H., and DAMON, P.E., 1980, Space-time-composition patterns of late Cenozoic mafic volcanism, southwestern Utah and adjoining areas: *Am. J. Sci.*, V. 280, pp. 1035-1050.
- BOWDEN, P., 1966, Lithium in Younger Granites of northern Nigeria; *Geochim. Cosmochim. Acta*, V. 30, pp. 555-564.
- BURNHAM, C.W., 1979, Magmas and hydrothermal fluids; In: Barnes, H.L., ed., *Geochemistry of hydrothermal ore deposits*, 2nd ed., John Wiley & Sons: 71-136.
- BURT, D.M., SHERIDAN, M.F., BIKUN, J.V., and CHRISTIANSEN, E.H., 1982, Topaz rhyolites—Distribution, origin, and significance for exploration: *Econ. Geol.*, V. 77, pp. 1818-1836.
- CHATTERJEE, A.K., STRONG, D.F., and MUECKE, G.K., 1983, A multivariate approach to geochemical distinction between tin-specialized and uranium-specialized granites of southern Nova Scotia: *Can. J. Earth Sci.*, V. 20, pp. 420-430.
- CHRISTIANSEN, E.H., 1983, The Bishop Tuff revisited: Compositional zonation by double-diffusive fractional crystallization (DDFC): *Geol. Soc. Am. Abstr. Programs*, V. 15 p. 390.
- CHRISTIANSEN, E.H., BIKUN, J.V., SHERIDAN, M.F., and BURT, D.M., 1984, Geochemical evolution of topaz rhyolites from the Thomas Ranse and Spor Mountain, Utah: *Am. Min.*, V. 69, pp. 223-236.
- CHRISTIANSEN, E.H., BURT, D.M., SHERIDAN, M.F., and WILSON, R.T., 1983, The petrogenesis of topaz rhyolites from the western United States: *Contrib. Mineral. Petrol.*, V. 83, pp. 16-30.
- CHRISTIANSEN, E.H., and LEE, D.E., 1986, Fluorine and chlorine in granitoids from the Basin and Range province, western United States: *Econ. Geol.*, V. 81, pp. 1484-1494.
- CHRISTIANSEN, E.H., SHERIDAN, M.F., and BURT, D.M., 1986, The geology and geochemistry of topaz rhyolites from the western United States: Geological Society of America Special Paper 205, 82 p.
- CHRISTIE-BLICK, N., 1982, Upper Proterozoic and lower Cambrian rocks of the Sheeprock Mountains, Utah: Regional correlation and significance: *Geol. Soc. Am. Bull.*, V. 93, pp. 735-750.
- CHRISTIE-BLICK, N., 1983, Structural geology of the southern Sheeprock Mountains, Utah: Regional significance: *Geol. Soc. Am. Mem.*, V. 157, pp. 102-124.
- CLEMENS, J.D., 1984, Water contents of silicic to intermediate magmas; *Lithos*, V. 17, pp. 273-287.
- CLIFFORD, T.N., 1974, Review of African granulites and related rocks: *Geol. Soc. Am. Spec. Paper* 156, 48 p.
- COHENOUR, R.E., 1959, Sheeprock Mountains, Tooele and Juab Counties: Precambrian and Paleozoic stratigraphy, igneous rocks, structure, geomorphology and economic geology: *Utah Geol. Mineral. Survey Bull.* 63, 201 p.
- COLLIERSON, K.D., and FRYER, B.J., 1978, The role of fluids in the formation and subsequent development of early continental crust: *Contrib. Mineral. Petrol.*, V. 67, pp. 151-167.
- COLLINS, W.J., BEAMS, S.D., WHITE, A.J.R., and CHAPPELL, B.W., 1982, Nature and origin of A-type granites with particular reference to southeastern Australia: *Contrib. Mineral. Petrol.*, V. 80, pp. 189-200.

- COMPSTON, W., and CHAPPELL, B.W., 1979, Sr-isotope evolution of granitoid source rocks: *In*, M.W. McELHINNEY, ed., *The Earth, its Origin, Structure and Evolution*, New York, Academic Press, pp. 377-426.
- CONDIE, K.C., ALLEN, P., and NARAYANA, B.L., 1982, Geochemistry of the Archean low to high-grade transition zone, southern India: *Contrib. Mineral. Petrol.*, V. 81, pp. 157-167.
- CRECRAFT, H.R., NASH, W.P., and EVANS, S.H., 1981, Late Cenozoic volcanism at Twin Peaks, Utah, *Geology and Petrology: J. Geophys. Res.*, V. 86, pp. 10303-10320.
- DEPAOLO, D.J., 1981, Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization: *Earth Planet. Sci. Lett.*, V. 53, pp. 189-202.
- DODGE, F.C., MILLARD, H.T., and ELSHEIMER, H.N., 1982, Compositional variations and abundances of selected elements in granitoid rocks and constituent minerals, central Sierra Nevada Batholith, California: U.S. Geol. Surv. Prof. Paper 1238, 24 p.
- EATON, G.P., 1984, The Miocene Great Basin of western North America as an extending back-arc region: *Tectonophysics*, V. 102, pp. 275-295.
- EKWERE, S.J., and OLADE, M.A., 1984, Geochemistry of the tin-niobium-bearing granites of the Liruei (Ririwai) complex, Younger granite province, Nigeria: *Chem. Geol.*, V. 45, pp. 225-243.
- FARMER, G.L., and DEPAOLO, D.J., 1983, Origin of Mesozoic and Tertiary granite in the western United States and implications for pre-Mesozoic crustal structure: 1. Nd and Sr isotopic studies in the geocline of the northern Great Basin: *J. Geophys. Res.*, V. 88, pp. 3379-3401.
- FARMER, G.L., and DEPAOLO, D.J., 1984, Origin of Mesozoic and Tertiary granite in the western United States and implications for pre-Mesozoic crustal structure: 2. Nd and Sr isotopic studies of unmineralized and Cu- and Mo-mineralized granite in the Precambrian craton: *J. Geophys. Res.*, V. 89, pp. 10141-10160.
- FILLIPOPOV, L.V., SAVIMOVA, Y.N., KAPITONOVA, T.A., and ANDREYEVA, T.P., 1974, Fluorine in Mg-Fe micas from granitoids of various magmatic formations in the folded belt of central Asia: *Geochem. Int.*, V. 11, pp. 185-194.
- FOURCADE, S., and ALLEGRE, C.J., 1981, Trace elements behavior in granite genesis: A case study. The calc-alkaline plutonic association from the Querigut Complex (Pyrenees, France): *Contrib. Mineral. Petrol.*, V. 76, pp. 177-195.
- FUNKHOUSER-MAROLF, M.J., 1985, The mineralogy and distribution of uranium and thorium in the Sheeprock granite, Utah: M.S. thesis, Univ. of Iowa, Iowa City, 60 p.
- GORDON, G.E., RANDLE, K., GOLES, G.G., CORLISS, J., BEESON, M., and OXLEY, S., 1968, Instrumental activation analysis of standard rocks with high resolution gamma ray detectors: *Geochim. Cosmochim. Acta*, V. 32, pp. 369-396.
- GROMET, L.P., and SILVER, L.T., 1983, Rare earth element distributions among minerals in a granodiorite and their petrogenetic implications: *Geochim. Cosmochim. Acta*, V. 47, pp. 925-939.
- HAAPALA, I., 1977, Petrography and geochemistry of the Eurajoki stock, a rapakivi-granite complex with greisen-type mineralization in southwestern Finland: *Geol. Surv. Finland Bull.* 286, 128 p.
- HARRIS, D., 1958, The geology of Dutch Peak area, Sheeprock Range, Tooele County, Utah: Brigham Young Univ. Res. Studies, Geol. Series, V. 5, pp. 1-82.
- HILDRETH, W., 1977, The magma chamber of the Bishop Tuff: Gradients in temperature, pressure and composition: Ph.D. thesis, Univ. of California Berkeley, 328 p.
- HILDRETH, W., 1979, The Bishop Tuff. Evidence for the origin of compositional zonation in silicic magma chambers: *Geol. Soc. Am. Spec. Paper*, V. 180, pp. 43-75.
- HILDRETH, W., 1981, Gradients in silicic magma chambers: Implications for lithospheric magmatism: *J. Geophys. Res.*, V. 86, pp. 10153-10192.
- HOLLOWAY, J.R., 1977, The effect of fluorine on dehydration equilibria: *Geol. Soc. Am. Abstr. Programs*, V. 9, p. 1021.
- HOLLOWAY, J.R., and FORD, C.E., 1975, Fluid-absent melting of the fluoro-hydroxy amphibole paragasite to 35 kilobars: *Earth Planet. Sci. Lett.*, V. 24, pp. 44-48.
- HOWELL, K.A.H., 1987, Mineralogy and geochemistry of greisens from the Sheeprock granite, west-central Utah: in preparation.
- HUDSON, T., and ARTH, J.G., 1983, Tin granites of Seward Peninsula Alaska: *Geol. Soc. Am. Bull.*, V. 94, pp. 768-790.
- IMEOKPARIA, E.G., 1982, Geochemistry and relationships to mineralization of granitic rocks from the Afu Younger Granite Complex, Central Nigeria: *Geol. Mag.*, V. 119, pp. 39-56.
- IYER, S.S., CHIYNDHURI, A., VASCONCELLOS, M.B.A., and CORDANI, U.G., 1984, Radioactive element distribution in the Archean granulite terrane of Jequi—Bahia, Brazil: *Contrib. Mineral. Petrol.*, V. 85, pp. 95-101.
- JAMES, D.E., PADOVANI, E.R., and HART, S.R., 1980, Preliminary results on the oxygen isotope composition of the lower crust, Kilbourne Hole Maar, New Mexico: *Geophys. Res. Lett.*, V. 7, pp. 321-324.
- KEITH, J.D., 1982, Magmatic evolution of the Pine Grove porphyry molybdenum system, southwestern Utah: Ph.D. thesis, University of Wisconsin, Madison.
- KOVALENKO, V.I., 1978, The genesis of rare metal granitoids and related ore deposits: *in*, *Metallization Associated with Acid Magmatism*, V. 3, pp. 235-248. *
- LEE, D.E., 1984, Analytical data for a suite of granitoid rocks from the Basin and Range province: U.S. Geol. Surv. Bull. 1602, 54 p.
- LEE, D.E. and CHRISTIANSEN, E.H., 1983, The granite problem as exposed in the southern Snake Range, Nevada: *Contrib. Mineral. Petrol.*, V. 83, pp. 99-116.
- LEE, D.E., KISTLER, R.W., FREIDMAN, I., and VAN LOENEN, R.E., 1981, Two-mica granites of northeastern Nevada: *J. Geophys. Res.*, V. 86, pp. 10607-10616.
- LESHER, C.E., 1984, Soret fractionation of silicate melts: Bulk compositional control on minor and trace element partitioning; Proc. Conf. Open Magmatic Systems, Dungan, M.A., Grove, T.L., Hildreth, W., eds., pp. 96-98.
- LINDSEY, D.A., 1982, Tertiary volcanic rocks and uranium in the Thomas Range and northern Drum Mountains, Juab County, Utah: U.S. Geol. Surv. Prof. Paper 1221, 71p.
- LINDSEY, D.A., NAESER, C.W., and SHAW, D.R., 1975, Age of volcanism, intrusion, and mineralization in the Thomas Range, Keg Mountain, and Desert Mountain, western Utah; *U.S. Geol. Survey J. Res.*, V. 3, pp. 597-604.
- LIPMAN, P.W., 1980, Cenozoic volcanism in the western United States: Implications for continental tectonics: *In*, *Continental Tectonics*, U.S. Nat. Acad. Sci., Washington DC, pp. 161-174.
- LOISELLE, M.G., and WONES, D.R., 1979, Characteristics and origins of anorogenic granite: *Geol. Soc. Amer. Abstr. Programs*, V. 11, p. 468.
- LUDINGTON, S., 1981, The Redskin Granite: Evidence for thermogravitational diffusion in a Precambrian granite batholith: *J. Geophys. Res.*, V. 86, pp. 10423-10430.
- LUTH, W.C., JAHNS, R.H., and TUTTLE, O.F., 1964, The granitic system at pressures of 4 to 10 kilobars; *J. Geophys. Res.*, V. 69, pp. 759-773.
- MAHOOD, G., and HILDRETH, W., 1983, Large partition coefficients for trace elements in high-silica rhyolites: *Geochim. Cosmochim. Acta*, V. 47, pp. 11-30.
- MANNING, D.A.C., 1981, The effect of fluorine on liquidus phase relationships in the system Qz-Ab-Or with excess water at 1 kb; *Contrib. Mineral. Petrol.*, V. 76, pp. 206-215.
- MANNING, D.A.C., and PICHAVANT, M., 1983, The role of fluorine and boron in the generation of granitic melts: *In*, *Migmatites, Melting and Metamorphism*, Atherton, M.P., Gribble, C.D., eds., Shiva Pub., Cheshire, U.K., pp. 95-109.
- MCCARTHY, T.S., and GROVES, D.I., 1979, The Blue Tier Batholith, northeastern Tasmania. A cumulate-like product of fractional crystallization: *Contrib. Mineral. Petrol.*, V. 71, pp. 193-209.
- MCCARTHY, T.S., and HASTY, R.A., 1976, Trace element distribution patterns and their relationship to the crystallization of granitic melts: *Geochim. Cosmochim. Acta*, V. 40, pp. 1351-1358.
- MICHAEL, P.J., 1983, Chemical differentiation of the Bishop Tuff and other high silica magmas through crystallization processes: *Geology*, V. 11, pp. 31-34.
- MILLER, C.F., and MITTFELDLT, D.W., 1984, Extreme fractionation in felsic magma chambers: A product of liquid-state diffusion or fractional crystallization?: *Earth Planet. Sci. Lett.*, V. 68, pp. 151-158.
- MITTFELDLT, D.W., and MILLER, C.F., 1983, Geochemistry of the Sweetwater Wash Pluton, California; Implications for "anomalous" trace element behavior during differentiation of felsic magmas: *Geochim. Cosmochim. Acta*, V. 47, pp. 109-124.
- MUNOZ, J.L., 1984, F-OH and Cl-OH exchange in micas with applications to hydrothermal ore deposits: *Mineral. Soc. of America Rev. in Mineral.*, V. 13, pp. 469-493.

- NASH, W.P., and CRECRAFT, H.R., 1985, Partition coefficients for trace elements in silicic magmas: *Geochim. Cosmochim. Acta*, V. 49, pp. 2309-2322.
- NELSON, B.K., FARMER, G.L., BENNETT, V.C., and DEPAOLO, D.J., 1983, Sm-Nd evidence for a possible Penokean-correlative basement terrane in the eastern Great Basin: *EOS, No. 18, V. 64, p. 331*.
- NOBLE, D.C., VOGEL, T.A., PETERSON, P.S., LANDIS, G.P., GRANT, N.K., JEZEK, P.A., and MCKEE, E.H., 1984, Rare-element-enriched, S-type ash-flow tuffs containing phenocrysts of muscovite, andalusite, and sillimanite, southeastern Peru: *Geology*, V. 12, pp. 35-39.
- OLADE, M.A., 1980, Geochemical characteristics of tin-bearing and tin barren granites, northern Nigeria: *Econ. Geol.*, V. 25, pp. 71-82.
- PITCHER, W.S., 1982, Granite type and tectonic environment: In Hsu, K. J. ed., Mountain building processes, Academic Press, London, pp. 19-40.
- SACK, R.O., CARMICHAEL, I.S.E., RIVERS, M., and GHIORSO, M.S., 1980, Ferric-ferrous equilibria in natural silicate liquids at 1 bar: *Contrib. Mineral. Petrol.*, V. 75, pp. 369-376.
- SHAW, D.R., and STEWART, J.H., 1976, Ore deposits as related to tectonics and magmatism, Nevada and Utah: *Am. Inst. Mining Engin. Trans.*, V. 260, pp. 225-232.
- SHERATON, J.W., and BLACK, L.P., 1983, Geochemistry of Precambrian gneisses: Relevance for the evolution of the East Antarctic Shield: *Lithos*, V. 16, pp. 273-296.
- SIGHINOLFI, G.P., FIGUEREDO, M.C.H., FYFE, W.S., KRONBERG, B.I., and OLIVEIRA, M.A.F.T., 1981, Geochemistry and petrology of the Jequié granulitic complex (Brazil): An Archean basement complex: *Contrib. Mineral. Petrol.*, V. 78, pp. 263-271.
- STEIGER, R.H., and JAGER, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology: *Earth Planet. Sci. Lett.*, V. 36, pp. 359-362.
- STEWART, J.H., MOORE, W.J., and ZEITZ, I., 1977, East-west patterns of Cenozoic igneous rocks, aeromagnetic anomalies, and mineral deposits, Nevada and Utah: *Geol. Soc. Am. Bull.*, V. 88, pp. 67-77.
- STUCKLESS, J.S., BUNKER, C.M., BUSH, C.A., DOERING, W.P., and SCOTT, J.H., 1977, Geochemical and petrological studies of a uraniferous granite from the Granite Mountains, Wyoming: *J. Res. U.S. Geol. Surv.*, V. 5, pp. 61-81.
- STUCKLESS, J.S., and VANTRUMP, G. JR., 1982, A compilation of radioelement concentrations in granitic rocks of the contiguous United States; Proc. IAEA/OECD Symposium on Uranium Exploration Methods, pp. 198-208.
- STUCKLESS, J.S., VANTRUMP, G., CHRISTIANSEN, E.H., BUSH, C.A., BUNKER, C.M., and BARTEL, A.J., 1983, Preliminary assessment of the geochemistry and mineral favorability of the postorogenic granites of the southeastern Arabian Shield, Kingdom of Saudi Arabia: Saudia Arabia Dep. Ministry Mineral Resources open-file report U.S.G.S.-OF-03-64, 41p.
- TAGGART, J.E., LICHTER, F.E., and WAHLBERG, J.S., 1981, Methods of analysis of samples using X-ray fluorescence and induction-coupled plasma spectroscopy: U.S. Geol. Surv. Prof Paper 1250, pp. 683-687.
- TARNEY, J., and WINDLEY, B.F., 1977, Chemistry, thermal gradients and evolution of the lower continental crust: *J. Geol. Soc. London*, V. 134, pp. 153-172.
- TAUSON, L.V., 1974, The geochemical types of granitoids and their potential ore capacity: In, Metallization Associated with Acid Magmatism, V. 1, pp. 221-227.
- TINDLE, A.G., and PEARCE, J.A., 1981, Petrogenetic modeling of in situ fractional crystallization in the zoned Loch Doon Pluton, Scotland: *Contrib. Mineral. Petrol.*, V. 78, pp. 196-207.
- TISCHENDORF, G., 1977, Geochemical and petrographic characteristics of silicic magmatic rocks associated with rare-element mineralization: In, Metallization Associated With Acid Magmatism, Czechoslovakia Geological Survey, Prague, V. 2, pp. 41-92.
- TUTTLE, O.F., and BOWEN, N.L., 1958, Origin of granites in the light of experimental studies in the system NaAlSi₃O₈-SiO₂-H₂O: *Geol. Soc. Am. Memoir*, V. 74, 153 p.
- WATSON, E.B., and HARRISON, T.M., 1983, Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types: *Earth Planet. Sci. Lett.*, V. 64, pp. 295-304.
- WHALEN, J.G., 1983, The Ackley City batholith, southeast Newfoundland: Evidence for liquid-state fractionation: *Geochim. Cosmochim. Acta*, V. 47, pp. 1443-1458.
- WHITE, A.J.R., 1966, Genesis of migmatites from the Palmer region of South Australia: *Chem. Geol.*, V. 1, pp. 165-200.
- WHITNEY, J.A., 1975, The effects of pressure, temperature, and XH₂O on phase assemblages in four synthetic rock compositions: *J. Geol.*, V. 83, pp. 1-27.
- WILLIAMS, N.C., 1954, Nonpegmatite beryl occurrence, Sheeprock Mountains, Utah, (Abst.): *Geol. Soc. Am. Bull.*, V. 65, p. 1388.
- WILSON, R.T., REHRIG, W.A., and CHRISTIANSEN, E.H., 1983, Silicic volcanism and continental extension: Implications for the nature of the crust in the western U.S.: *Geol. Soc. Am. Abstr. Programs*, V. 15, p. 288.
- YORK, D., 1969, Least squares fitting of a straight line with correlated errors: *Earth Planet. Sci. Lett.*, V. 5, pp. 320-324.
- ZIELINSKI, R.A., PETERMAN, Z.E., STUCKLESS, J.S., ROSHOLT, J.N., and NKOMO, I.T., 1981, The chemical and isotopic record of rock-water interaction in the Sherman Granite, Wyoming and Colorado: *Contrib. Mineral. Petrol.*, V. 78, pp. 209-219.
- ZOBACK, M.L., ANDERSON, R.E., and THOMPSON, G.A., 1981, Cenozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States: *Phil. Trans R Soc. Lond. A*, V. 300, pp. 407-434.