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Large ion lithophile elements in rocks from high-pressure granulite facies terrains

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Abstract—A comparison of K, Rb, Th and U concentrations in granulite facies rocks with those of unmetamorphosed common rock types shows that depletion of these elements in granulites is variable. K/Rb ratios for granulites are generally higher than unmetamorphosed rocks, but K/Rb ratios only reach extreme values when K < 1%. The covariation of K/Rb ratio with K concentration suggests that protolith composition, hence mineralogy, is very important in controlling the degree of Rb depletion in granulites. Felsic granulites exhibiting extreme K/Rb ratios are mainly Archean, reflecting the high abundance of low K felsic rocks in Archean terrains. The Scourian granulites of Scotland all have very high K/Rb ratios and cannot be considered to be representative of granulite facies terrains. It is impossible from this data set to state conclusively whether K is depleted in granulites; K/La ratios of granulites show complete overlap with igneous rocks. Th/U ratios in many granulites are greater than 4, indicating U loss relative to Th. Felsic granulites with low Th/U ratios also have high La/Th ratios, indicating that these granulites have been depleted in Th. The low Th/U ratios of these rocks may reflect retention of Th and U in resistant accessory phases.

INTRODUCTION

EARLY GEOCHEMICAL studies of granulites found that they are depleted in the large ion lithophile elements (LILE), particularly K, Rb, U and Th, with concurrent increases in K/Rb and Th/U ratios (HEIER and ADAMS, 1965; LAMBERT and HEIER, 1967; SIGHINOLFI, 1969, 1971; HEIER and THORESEN, 1971). Consequently, LILE depletion generally has been assumed to be a common feature of granulites. More recent geochemical investigations have shown that LILE depletions are not found in all granulite terrains, and some granulite facies rocks may have even experienced LILE enrichment prior to granulite facies metamorphism (*e.g.*, southern Indian granulites, WEAVER, 1980; JANARDHAN *et al.*, 1983; WEAVER and TARNEY, 1983). In addition to southern India, examples of granulite facies terrains which show little or no LILE depletion include: the Archean Jequie Complex, Brazil (SIGHINOLFI *et al.*, 1981; IYER *et al.*, 1984), the Lapland granulites, Finland (BARBEY and CUNEY, 1982) and the Musgrave Block granulites, Australia (GRAY, 1977).

Evaluating the processes controlling LILE concentrations in granulite facies rocks can offer important information on the nature of granulite facies metamorphism and the composition of the lower continental crust. Two processes are commonly cited as potential means of causing LILE depletion in granulites:

(1) removal of a partial melt and associated fluids (*e.g.*, SIGHINOLFI, 1971; FYFE, 1973)

(2) fluxing of fluids through granulites during metamorphism without substantial partial melt removal (*e.g.*, TARNEY and WINDLEY, 1977; WEAVER and TARNEY, 1980, 1981, 1983; NEWTON *et al.*, 1980).

Considerable controversy exists over which process is more important in granulite evolution (*e.g.*, PRIDE and MUECKE, 1980; WEAVER and TARNEY, 1981).

The data set

We have compiled data from the literature on LILE concentrations from granulite facies terrains of many ages. Table 1 lists the age, peak metamorphic conditions (where available) and references for the granulite facies rocks reviewed here. Protoliths are generally igneous rock types; the few metasedimentary granulites are marked by triangles in all figures. An important consideration before discussing the geochemical data is whether these examples are representative of high-pressure granulite facies rocks in terms of their conditions of metamorphic equilibration (we exclude data for low pressure granulites). For consistency, the peak metamorphic conditions listed in Table 1 come from the compilation of NEWTON and PERKINS (1982), when available. Otherwise the source of the *P-T* information is listed at the bottom of the table. Equilibration pressures range from 5 to 12 kilobars, with most of the pressure estimates falling above 8 kilobars. Most of these granulites therefore fall into NEWTON and PERKINS' (1982) massif granulite classification: only the southern Indian occurrence would be classified as transitional granulite.

Another important consideration is the amount of retrogression, if any, experienced by these granulites. Rb and U are known to partition into aqueous fluids more readily than K and Th (SHAW, 1968; BESWICK, 1973; CARRON and LAGACHE, 1980). Therefore, introduction of hydrous fluids during retrograde metamorphism could cause K/Rb and Th/U ratios to decrease. Although retrograde effects are observed locally in some terrains (*e.g.*, Qianxi granulites, Scourian granulites, Lapland granulites, Norwegian granulites), their effect on the trends discussed here are considered negligible. Where retrogression is noted, it is not always associated with a change in the LILE concentrations (HEIER and THORESEN, 1971; BEACH and TARNEY, 1978). SIGHINOLFI *et al.* (1981) sug-

TABLE 1. Summary of granulite facies terrains used in compilation.

Locality	Peak Meta. Conditions	Geochemical Reference
	ARCHEAN	
Scourian Granulites (Scotland)	890°C 7-8.5 Kb	Weaver and Tarney (1980 Pride and Muecke (1980) Rollinson and Windley (1980b) Okeke et al. (1983)
Qianxi Granulites (China)	825°C [illegible] Kb	Jahn and Zhang (1984)
Kapuskasing Structural Zone (Ontario)	[illegible]0-800°C 6-8 Kb¹	Rudnick (unpub. data)
Southern India	725 ± 80°C [illegible] Kb	Weaver (1980) Condie et al. (1982) Condie and Allen (1984)
Jequie Complex (Brazil)	Hypersthene Zone	Sighinolfi et al. (1981) Iyer et al. (1984)
Napier Complex Enderby Land (Antarctica)	900°C 6.5-7.0 Kb²	DePaolo et al. (1982) Sheraton and Black (1983)
Vestfold Block (Antarctica)	1000°C 8-10 Kb³	Sheraton and Collerson (1984)
Uivak Gneiss (Labrador)		[illegible] et al. (1985)
	PROTEROZOIC	
Lofoten-Vesterålen (N. Norway)	900°C 10 Kb⁴	Heier and Thoresen (1971)
	PROTEROZOIC continued	
Lapland Granulites (Finland)	800°C 8 Kb⁵	[illegible]
Musgrave Block (Australia)	[illegible]	[illegible]
Arunta Block (Australia)		[illegible]
Adirondack Highlands (New York)	[illegible]	[illegible]
Okollo and Rakos (S. Uganda)	[illegible]	[illegible]
Msagali and Pare Mts. (NE Tanzania)	800°C [illegible]	[illegible]
Westport (Ontario)	[illegible]	[illegible]
Rayner Complex Enderby Land (Antarctica)		[illegible]
	PHANEROZOIC	
Fiordland (New Zealand)	750°C 8.9-12.3 Kb	McCulloch, Bradshaw and Taylor (in prep.)
Ivrea Zone (Italy)	[illegible]	Sighinolfi (1971) Dostal and Capedri [illegible]

Additional sources of metamorphic P-T data: ¹Percival (1983); ²Newton (1983); ³Sheraton and Collerson (1984); ⁴Griffin et al. [illegible]; ⁵Barbey and Cuney (1982); ⁶Gray (1977); ⁷Newton and Haselton (1981).

gested that the relatively high concentrations of LILE observed in Brazilian granulites may be a product of re-introduction due to retrogression. There are several difficulties with this. First, such an effect should be readily observable in thin section and should correlate with LILE concentration. Secondly, as noted by IYER *et al.* (1984), the proposed Proterozoic retrogression would disturb the Rb-Sr isotope system, but this has not been observed. Although some granulites discussed here equilibrated at relatively low pressures and retrograde effects are found, the majority of the data are representative of rocks which have equilibrated at deep levels in the crust and show few changes in their LILE concentrations due to retrogressive effects.

Methodology

Since it is unlikely that the *exact* protolith composition of a granulite facies rock will be known, the only reliable way of determining possible elemental depletions is through the comparison of granulite facies rocks with the compositions of unmetamorphosed rock types. The implicit assumption is that rocks in granulite facies terrains had similar origins to rocks which form near the surface of the earth, *i.e.*, granulites simply represent the metamorphosed equivalents of common igneous and sedimentary rock types. Due to the nearly ubiquitous occurrence of sedimentary rocks in granulite facies terrains, this is probably a reasonable assumption.

Element ratios are one way of determining *relative* elemental depletions due to metamorphism in given rock types. If a ratio is well known for common unmetamorphosed rock types (*e.g.*, K/Rb, Th/U), then comparison of such ratios with those of granulites can potentially document relative element depletions. However, for K/Rb and Th/U, it is possible that both elements in each ratio have experienced differential depletion. In this case, comparing a potentially mobile element with an inferred immobile element may provide a useful means of documenting element depletions. A difficulty with this approach is that ratios such as K/La and Rb/La vary enormously in common igneous rocks, thus making element mobility in metamorphism difficult to distinguish from original igneous variations. In the following section, we examine K/Rb and Th/U ratios of granulite facies rocks and compare them with the same ratios in unmetamorphosed rocks. A comparison of K and Th to La, which is presumed to be immobile (*i.e.*, neither depleted nor enriched), attempts to define the degree of K and Th depletions in granulites.

K AND Rb

Protolith concentrations

The K and Rb concentrations in granulites from the data set are presented in Fig. 1. Before generalized statements can be made about the effects of granulite facies metamorphism on K and Rb concentrations, the possible range of K/Rb ratios in unmetamorphosed rock types must first be known. SHAW (1968) compiled K and Rb data for a variety of igneous rock types and defined several igneous fractionation trends on a Rb *vs.* K plot. His main trend ("MT" in Fig. 2) represents the average of 12 linear regressions which characterize K and Rb concentrations in rocks ranging from granite to continental basalts. The field encompassing these 12 linear regressions is shown in Fig. 2. The "main trend" lies near a K/Rb ratio of 230 and shows a slight decrease in K/Rb with increasing K concentration. A second trend, which diverges to higher K/Rb ratios at very low K concentrations, is defined by ocean tholeiite basalts ("OT" trend on Fig. 2). Several igneous rock suites for which trace element data have become available more recently do not plot along any of Shaw's trends: *e.g.*, anorthosites, oceanic plagiogranites and low K rocks from modern island arc environments. A compilation of K and Rb concentrations in anorthosites by DUCHESNE and DEMAIFFE (1978) shows that many of these rocks have very high K/Rb ratios (some above 1000) at K concentrations between 0.3 and 1.0 wt.%. While many of these anorthosites are found within granulite facies terrains, their K/Rb ratios are interpreted to reflect original igneous values (DUCHESNE and DEMAIFFE, 1978). Oceanic plagiogranites, found

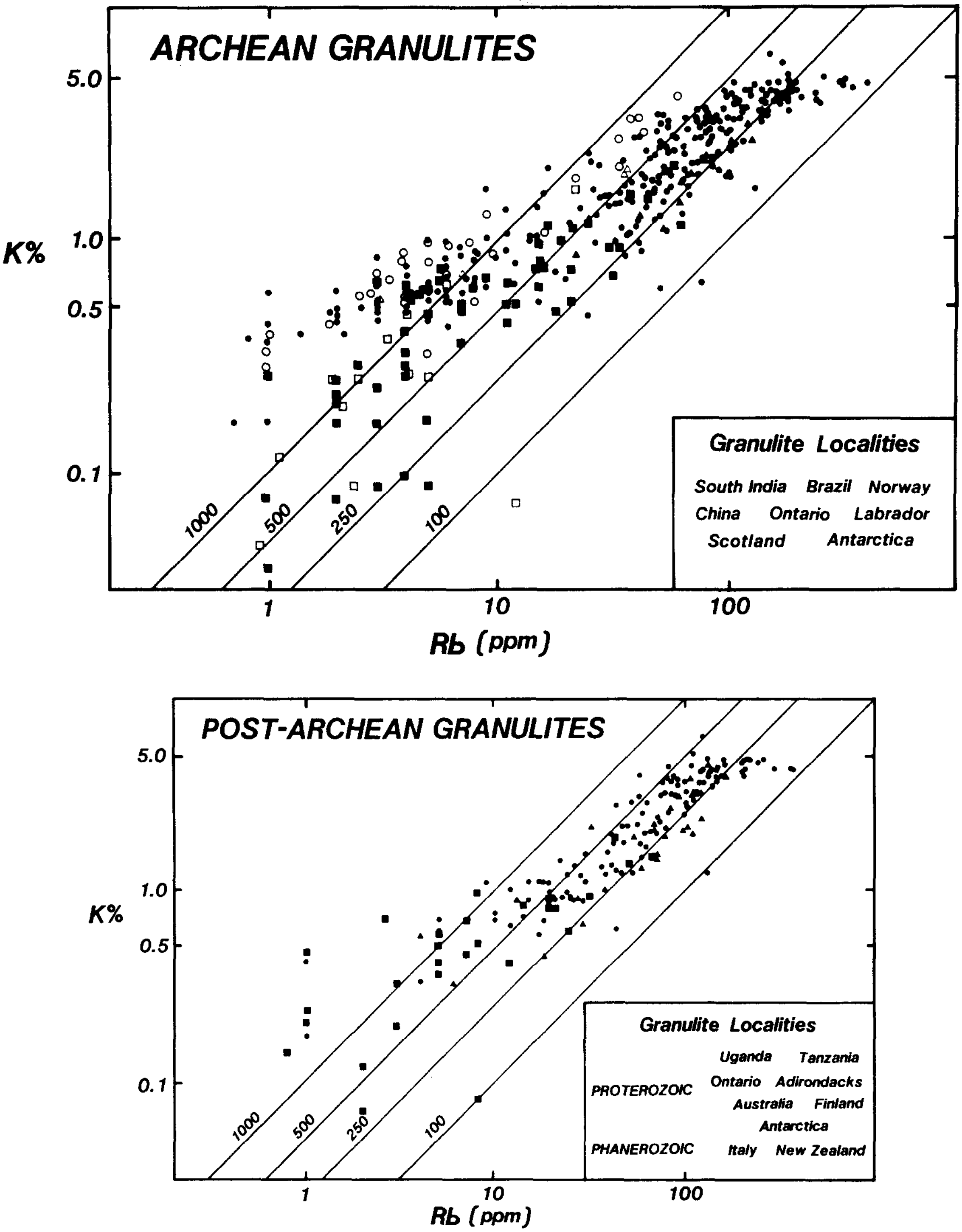


FIG. 1. Plot of Rb (ppm) *versus* K (wt.%) for (a—upper) Archean granulites and (b—lower) Post-Archean granulites listed in Table 1. Circles represent intermediate to felsic granulites ($SiO_2 \geq 55\%$), squares represent mafic granulites ($SiO_2 < 55\%$), and triangles represent metasediments. Open symbols in (a) are Scourian granulites of Scotland.

as minor components of ophiolite sequences, also have elevated K/Rb ratios which in some cases may be in excess of 1500 (*e.g.*, COLEMAN and DONATO, 1979). Low K suites of modern island arcs also show generally higher K/Rb ratios than rocks used in SHAW's (1968) main trend. Figure 3 shows the variation in K/Rb ratio with K_2O content for a variety of orogenic andesites (after GILL, 1981). Most andesites in Fig. 3 have K/Rb ratios higher than Shaw's main trend, but in general, only andesites with K_2O contents less than 1 wt.% have K/Rb ratios above 500. Some of these andesites have K/Rb ratios above

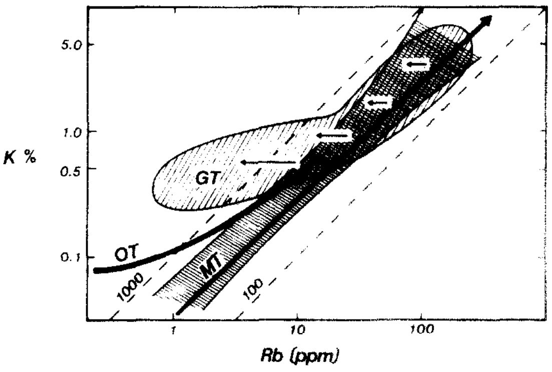


FIG. 2. Plot of Rb (ppm) *versus* K (wt.%) showing Shaw's main trend (MT) and ocean tholeiite trend (OT) compared with the "granulite trend" (GT) derived from the data in Fig. 1. Shaded field surrounding MT line represents field of 12 linear regressions which were averaged by SHAW (1968) to obtain the MT line. Horizontal arrows represent the relative amounts and direction of Rb depletion caused by granulite facies metamorphism.

1000. Based upon this additional data, the field of K/Rb ratios characteristic of igneous fractionation processes should be extended to include higher K/Rb ratios at K concentrations between 0.1 and 1 wt.% (*i.e.*, the region above the OT trend, at K/Rb ≤ 1000).

Little work has been done to evaluate the systematic behavior of K/Rb ratios in sedimentary rocks. Although both K and Rb are quite soluble in low temperature aqueous solutions, K/Rb ratios do not appear to be severely affected during most stages of continental weathering (NESBITT *et al.*, 1980). This is due to the relative stability of K-feldspar and high cation exchange capacity of the clay mineral alteration products of biotite and K-feldspar. Increases of K/Rb ratio of less than 30% are most common, and even the most severely weathered residue will have K/Rb ratios lower than the parent rocks by factors of less than 2–3. Thus, most shales have fairly constant K/Rb ratios of 100–250, averaging about 200, which are not greatly different from typical igneous rocks. Archean shales may have slightly higher K/Rb, averaging about 300, possibly reflecting a more mafic upper crust at that time (MCLENNAN, 1981).

Granulite concentrations

Following this summary of K and Rb concentrations found in igneous and sedimentary rocks, we evaluate the degree of Rb and K depletion in granulites produced through metamorphism. Figure 1 shows Rb *vs.* K for Archean granulites (a) and post-Archean granulites (b). In this and subsequent plots, circles represent intermediate to felsic granulites (SiO_2 > 55%), squares represent mafic granulites (SiO_2 < 55%) and triangles represent granulites with sedimentary protoliths (as determined by the original investigators listed in Table 1). The open symbols in Fig. 1a represent the Scourian granulites of Scotland.

This plot of K and Rb in granulites (Fig. 1) reveals several interesting features. First, the K/Rb ratio of granulites is related to absolute K concentration: granulites with K concentration > 1 wt.% have K/Rb ratios generally between 250 and 500 and plot within the field of Shaw's main trend. Granulites with K concentrations < 1 wt.% have K/Rb commonly in excess of 500, and as high as 4700. These high K/Rb granulites overlap the K/Rb ratios characteristic of anorthosites, but range to distinctly higher ratios than those of oceanic plagiogranites and low K island arc suites. (None of the low K granulites plotted are anorthosites or oceanic plagiogranites, so K/Rb ratios for these rocks are not considered relevant to the following arguments.)

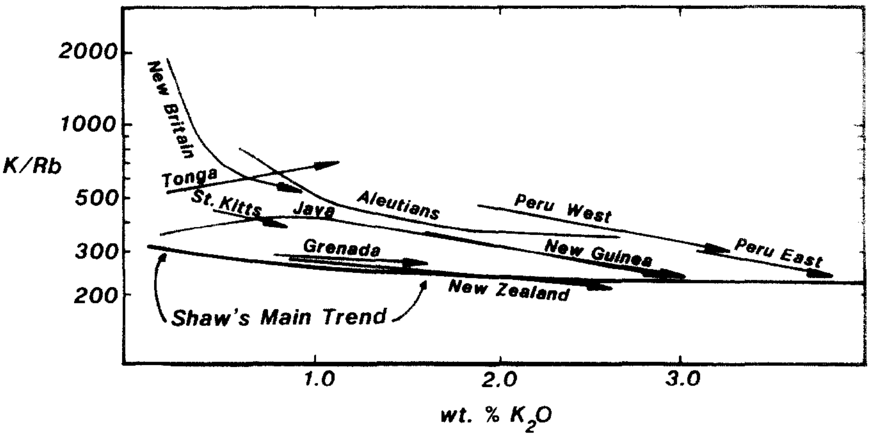


FIG. 3. Plot of K_2O (wt.%) *versus* K/Rb ratio for modern orogenic andesites (from GILL, 1981). Arrows indicate direction of increasing SiO_2 content. Note that, in general, K/Rb decreases with increasing K_2O content. Most andesites have K/Rb ratios that lie above the main trend, but very few have K/Rb ratios greater than 1000.

At first glance, the K/Rb ratios for granulites with K concentrations > 1 wt.% appear to require no metamorphic effects to explain their ratios; such K and Rb concentrations could reflect primary igneous fractionation processes. However, because the majority of these granulites fall above the main trend line, and because case studies of individual terrains do show an increase of K/Rb correlative with granulite facies metamorphism (LAMBERT and HEIER, 1967; HEIER and THORESEN, 1971; SIGHINOLFI, 1971; FIELD and CLOUGH, 1976), it appears that some depletion of Rb has occurred in these rocks. Comparing the mean K/Rb ratio for granulites with K > 1 wt.% (about 300) to the main trend K/Rb ratio for similar K concentrations (about 230 at 2.5 wt.% K) yields an average increase in K/Rb by a factor of 1.3, which may be attributed to granulite facies metamorphism.

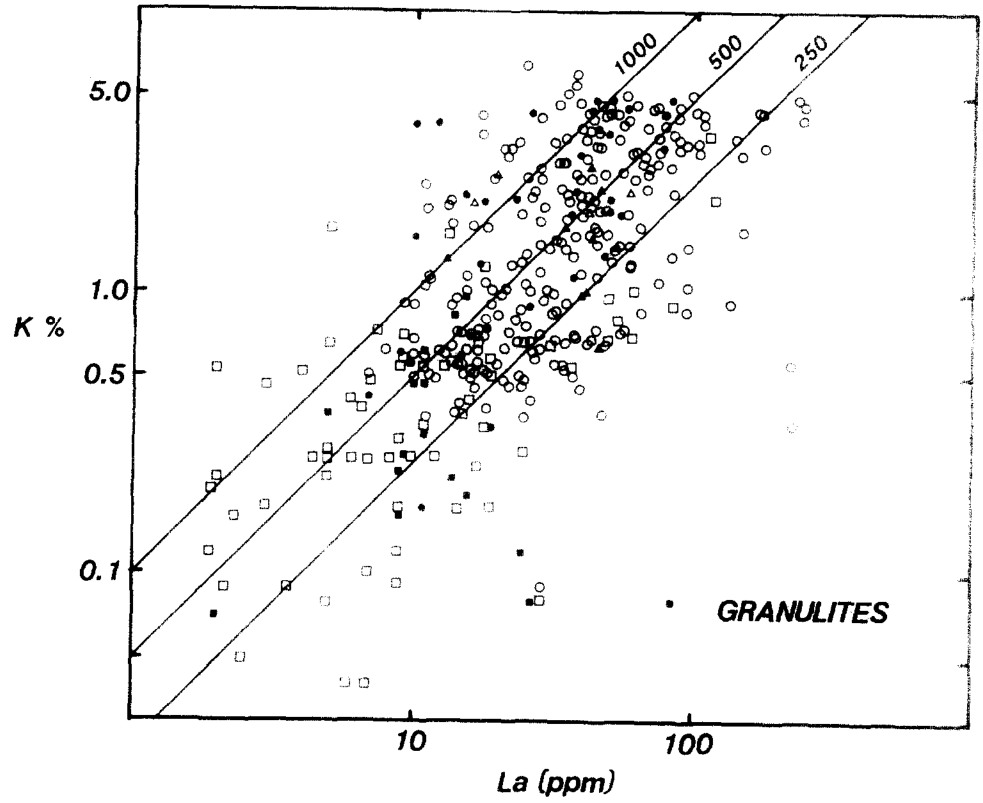
This Rb depletion, however, is small when compared with Rb depletion in granulites with K < 1 wt.%. Felsic granulites with high K/Rb and low K come mainly from Archean terrains (Fig. 1a). (Proterozoic felsic granulites from southern Norway also exhibit extremely high K/Rb ratios (COOPER and FIELD, 1977), but are not plotted here because only average values were reported.) Unmetamorphosed or low-grade Archean and Proterozoic low K felsic rocks have K/Rb ratios which fall near Shaw's main trend (*e.g.*, ARTH *et al.*, 1977; JAHN *et al.*, 1981; BICKLE *et al.*, 1983; MARTIN *et al.*, 1983; HUNTER *et al.*, 1984) unlike modern low K island arc suites, and we may assume that the Archean granulite protoliths with <1% K had similar K/Rb ratios (about 300, JAHN and SUN, 1977). Therefore, the K/Rb ratios for granulites with <1% K show an increase in K/Rb ranging from 1.7 to 17. It seems clear that granulites with lower K concentrations underwent proportionally greater Rb depletion than granulites with higher K concentrations.

Archean granulites form the greatest proportion of granulites with high K/Rb ratios (Fig. 1). Investigations of several of these depleted granulite facies terrains suggest that significant melt extraction has not occurred, and fluxing of CO_2-rich fluids has been proposed as the most likely process responsible for the LILE depletion (WEAVER and TARNEY, 1980, 1981; SHERATON and BLACK, 1983; JAHN and ZHANG, 1984). In support of this model, the ubiquitous occurrence of high density CO_2-rich fluid inclusions in granulite facies rocks is often cited. However, the presence of CO_2-rich fluid inclusions is not limited to granulites with very high K/Rb ratios. High-density, CO_2-rich fluid inclusions occur in granulites of the Kapuskasing Structural zone, Ontario (RUDNICK *et al.*, 1984) and in granulites of southern India (JANARDHAN *et al.*, 1983; HANSEN *et al.*, 1984). The Kapuskasing granulites do not exhibit high K/Rb ratios, while southern Indian granulites show high K/Rb ratios only in some of the highest pressure granulites (HANSEN *et al.*, 1984). Therefore, either the presence of CO_2 fluid inclusions does not imply CO_2 fluxing, and/or CO_2 fluxing alone is not the only factor causing an increase in K/Rb ratios of granulites. While both may be true, the second alternative gains support by the apparent compositional dependence of K/Rb in granulites. If CO_2 fluxing were the only cause of increased K/Rb ratios, one would not expect to see the K/Rb ratio co-vary with K concentration.

The restriction of high K/Rb ratios to granulites with K concentrations < 1 wt.% suggests a mineralogical control; a conclusion reached by several investigators of LILE in granulites (HEIER, 1973; TARNEY and WINDLEY, 1977; ROLLINSON and WINDLEY, 1980a). In high K igneous rocks, most of the K will be in K-feldspar, which should be stable throughout granulite facies metamorphism, provided no melting occurs (BOHLEN *et al.*, 1983). Ratios of partition coefficients (K_D, where K_D = concentration in crystal/concentration in silicate melt) for K and Rb can be used to evaluate the relative partitioning behavior of these elements in different minerals. The higher the $K_D^{K/Rb}$ values, the greater the affinity of the mineral for K over Rb. Even though these values are for partitioning between minerals and silicate melt, we assume they provide an estimate of the relative partitioning behavior of K and Rb between minerals and fluids during metamorphism. K-feldspars in equilibrium with silicic melts have $K_D^{K/Rb}$ = 2.0 to 3.0, with the average $K_D^{K/Rb}$ equal to 2.5 (n = 24) (PHILPOTTS and SCHNETZLER, 1970; LONG, 1978). In addition, mineral/vapor partitioning experiments between sanidine and aqueous chloride fluid show $K_D^{K/Rb}$ = 2.2 to 5.9 (BESWICK, 1973). CARRON and LAGACHE (1980) found that K_D^{Rb} in potassium feldspar is close to, but below, one (~0.8). Therefore, if an originally Rb-poor aqueous fluid equilibrates with K-feldspar, and is then removed, it will lower the Rb content of the rock and increase the K/Rb ratio slightly. This may explain the higher K/Rb ratios, compared with Shaw's main trend, in granulites with K > 1%.

In low K rocks, a significant proportion of the whole-rock K may be incorporated into mafic phases such as biotite prior to metamorphism. At granulite facies pressures and temperatures, biotite plus quartz will break down under high a_{CO_2} to enstatite, sanidine and vapor (BOHLEN *et al.*, 1983). Because biotite will contain proportionately more Rb than K-feldspar due to its large, 12-fold coordination cation sites ($K_D^{K/Rb}$ between phlogopite and aqueous chloride solution = 0.78 to 1.56 (BESWICK, 1973)), this reaction will lead to a dramatic increase in the K/Rb ratio of the rock (as suggested by HEIER, 1973). This process may explain the very high K/Rb ratios of granulites with low K contents.

The above discussions suggest that Rb is depleted relative to K during granulite facies metamorphism. Evaluating whether K is depleted is more difficult. One possible way of doing this is by comparing



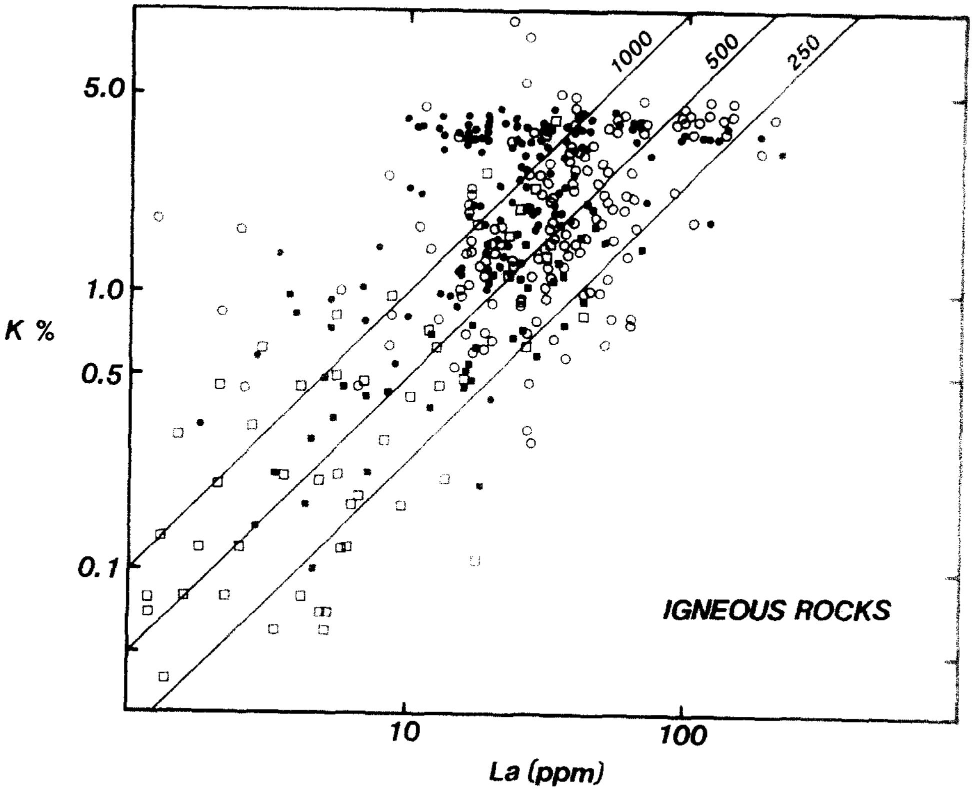


FIG. 4. Plot of La (ppm) *versus* K (wt.%) for (a—upper) granulites and (b—lower) common igneous rocks (data sources used for (b) available from the authors). Symbols as in Fig. 1, except open symbols represent Archean rocks, filled symbols are post-Archean rocks.

granulite K concentrations to the concentration of a presumed immobile element, such as La. Fig. 4a shows La *vs.* K for the granulites listed in Table 1 (where La data are available). Fig. 4b shows La *vs.* K for common igneous rock types of all ages. Unlike Rb *vs.* K, La and K do not behave coherently during igneous fractionation and do not produce a narrowly-defined trend. The granulite data also scatter and show complete overlap with the igneous data. Based upon this, no inference regarding the effects of metamorphism on K can be made. It seems that only very general and qualitative inferences can be made: the very low K content that is characteristic of some Archean felsic granulites (particularly those from the Scourian, Qianxi and Enderby Land terrains), is only rarely observed in unmetamorphosed Archean felsic rocks. This may suggest that these granulites may have lost K during metamorphism, however more data for unmetamorphosed Archean felsic rocks is needed in order to rule out sampling bias.

Figure 2 shows the proposed granulite trend as defined by the data in Fig. 1. The arrows indicate the relative direction and magnitude that K/Rb ratios move during granulite facies metamorphism (note that the arrows could point slightly downwards, indicating slight K depletion, but we are not able to say definitively whether, or how much, K depletion has occurred). Granulite facies terrains with very high K/Rb ratios are mainly Archean, reflecting the higher proportion of sodic granites in Archean terrains, however, the Scourian granulites appear to represent a special case. Most have less than 1% K and very high K/Rb ratios and the few Scourian granites, with 3–4% K, all have K/Rb ratios greater than 500 (Fig. 1a) (ROLLINSON and WINDLEY, 1980a, b) and fall to the left side of the granulite trend. Therefore, the Scourian granulites appear to be the most depleted granulites in the data set. In this respect, as in Sr isotopic systematics (BEN OTHMAN *et al.*, 1984; TAYLOR and MCLENNAN, 1985), the Scourian represents a unique granulite facies terrain and cannot be considered representative.

Th AND U

Th concentrations in igneous rock types range from very low values in basalts (<0.1 ppm, with Th/U ≧ 1.4 (JOCHUM *et al.*, 1984)), to 60 ppm Th in granites (with Th/U ≧ 6 (ROGERS and ADAMS, 1978)). Most igneous rock types have Th/U ratios that fall between 3.5 to 4.0 (ROGERS and ADAMS, 1978), with a general trend of increasing Th/U ratio with increasing Th concentration (hence differentiation) (JOCHUM *et al.*, 1983; ROGERS and ADAMS, 1978). Th/U ratios of sedimentary rocks typically range from about 2 (for some island-arc greywackes) to about 10. Most shales have Th/U ratios of about 4–6 (MCLENNAN and TAYLOR, 1980).

Fewer data are available for Th and U concentra-

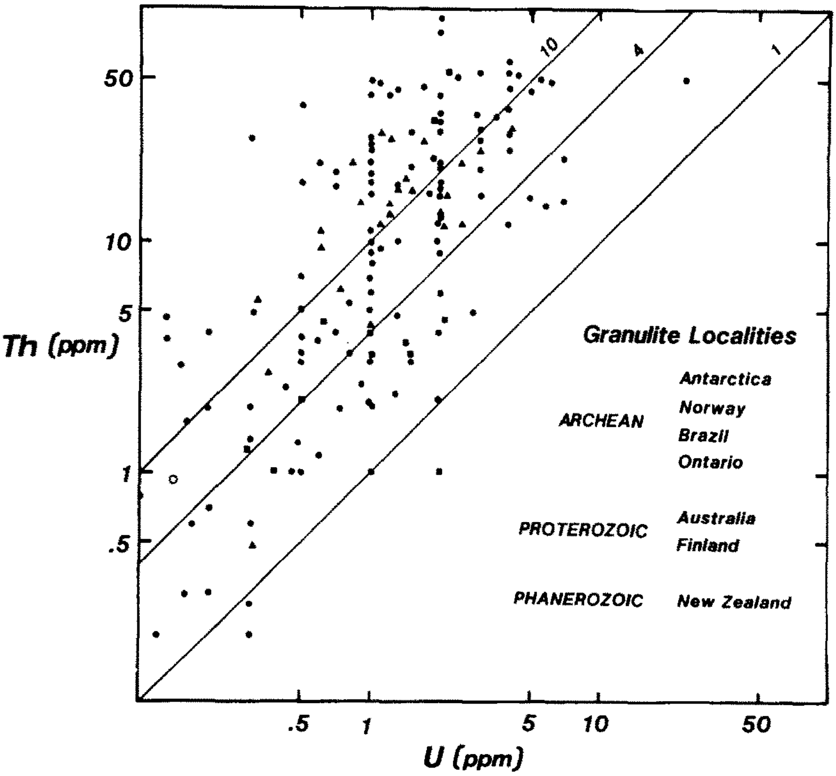


FIG. 5. Plot of U (ppm) *versus* Th (ppm) for granulites listed at right side of figure. Symbols as in Fig. 1.

tions in granulite facies rocks than for K and Rb, but the available analyses are plotted in Fig. 5. Although scattered, the data form a continuum from low to high Th and U concentrations, with the Th/U ratio apparently correlative with absolute concentration. Th/U ratio exceeds 10 generally only at U concentrations > 0.5 ppm.

This plot shows clearly that most granulites exhibit U depletion relative to Th, as evidenced by Th/U ratios > 4. DOSTAL and CAPEDRI (1978) have suggested a mechanism for this depletion whereby U, concentrated along mineral grain boundaries in rocks up to amphibolite facies, is lost to fluids during granulite facies metamorphism. Th, which is contained primarily in mineral lattice sites, is not readily leached. However, U loss may also occur in amphibolite facies rocks. For example, the Amitsoq gneisses of Greenland exhibit very low Th and U concentrations and unradiogenic Pb (TAYLOR *et al.*, 1980) and show no evidence of having reached granulite facies conditions (LAMBERT and HOLLAND, 1976). The Th/U ratio of these gneisses is very low, indicating that Th and U were lost in similar proportions.

Figure 6 shows Th *versus* La for the granulite data set. The data show large scatter, but a general trend of increasing La/Th ratio with decreasing La concentration is apparent. This type of trend might be expected to be produced through igneous fractionation processes since Th is, in general, less compatible than La. However, the very high La/Th values of many of the felsic granulites (particularly the Scourian) are larger than typical La/Th ratios for intermediate to felsic igneous rocks (La/Th = 1–10 for island arc lavas (GILL, 1981) and La/Th = 2.7–3.6 for sediments (MCLENNAN *et al.*, 1980), which reflect upper crustal values). Therefore, it appears that some granulites are Th depleted.

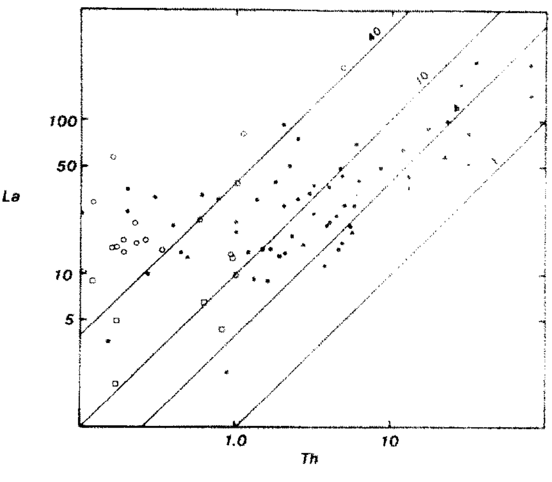


FIG. 6. Plot of La (ppm) *versus* Th (ppm) for granulites. Symbols as in Fig. 1.

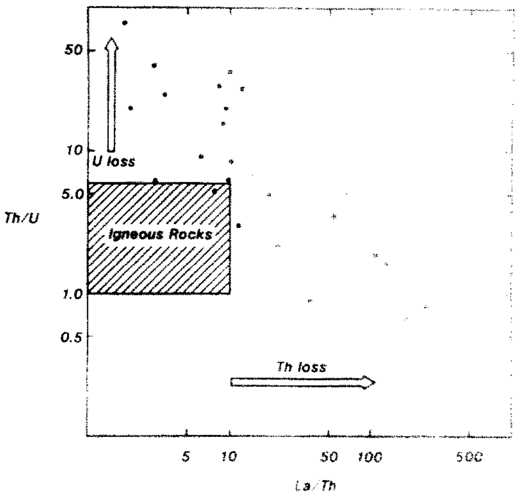


FIG. 7. La/Th ratio *versus* Th/U ratio for felsic granulites (all Archean). Box at left represents field of common igneous rocks (excluding MORB, which have La/Th > 10). The negative correlation is simply a function of Th being plotted on both axes. Granulites plotting above box have lost U relative to Th. Granulites plotting right of box have lost both Th and U (see text). All data determined either by instrumental neutron activation analysis or spark source mass spectrometry.

The behavior of Th and U in granulite facies rocks can be summarized by plotting La/Th *versus* Th/U (Fig. 7). The box on the left side of the diagram represents the field of igneous rock types; few granulites fall within this box. Granulites plotting above the box have experienced U depletion with little to no Th depletion. Granulites plotting to the right of the box have experienced both Th and U depletion, and in some cases, more Th is lost than U (causing the Th/U ratio to be <4). It is not likely that the felsic granulites falling to the right of the box have only experienced Th depletion without U depletion, because the absolute concentration of Th and U in these rocks is extremely low (<0.5 ppm for both elements in all cases), indicating that both have been depleted. These granulites with low Th and U concentrations may be reflecting retention of Th and U in resistant accessory phases such as zircon (with Th/U = 0.1–3.5 (SPEER, 1980; BLACK *et al.*, in prep.)), apatite (Th/U = 1.8–4.5 (SAWKA and CHAPPELL, 1985; SAWKA, pers. commun.)) or sphene (Th/U = 1–11 (DEER *et al.*, 1982; SAWKA and CHAPPELL, 1985)), all of which may be preserved during granulite facies metamorphism (HELLMAN and GREEN, 1979; DEER *et al.*, 1982).

In summary, most granulites exhibit U depletion, while only some granulites are depleted in Th. The degree of U and Th depletion will depend upon: 1) the position of U and Th in the protolith (*i.e.*, are the elements in lattice sites or on grain boundaries), 2) the presence of a fluid phase to transport the elements out of the rocks, 3) the stability of various accessory phases during granulite facies metamorphism.

CONCLUSIONS

(1) The abundances of Rb, Th and U in granulite facies rocks show widely variable degrees of depletion compared to those in unmetamorphosed rocks of similar major element composition.

(2) K/Rb ratios of granulites, although usually higher than in unmetamorphosed rocks, only reach very high values (>750) when the K concentration is <1%.

(3) The dependence of K/Rb with K content indicates that both protolith composition and mineralogy are factors in controlling Rb depletion in granulites. Rb is excluded relative to K in lattice sites. For rocks with low K concentrations, and hence no major K-bearing minerals, the large cation Rb is likely to be extremely mobile.

(4) Scourian granulites have higher K/Rb ratios than granulites from other terrains.

(5) It is difficult to document K depletion in granulites; K/La ratios in granulites show complete overlap with K/La of igneous rocks.

(6) Most Th/U ratios in granulites are >4, indicative of U loss relative to Th.

(7) Felsic granulites with low Th/U ratios have high La/Th ratios, indicating that these rocks are depleted in Th. Their very low Th and U abundances reflect loss of both elements.

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