

## Restites, Eu anomalies, and the lower continental crust\*

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(Received December 14, 1990; accepted in revised form December 6, 1991)

**Abstract**—Dehydration partial melting of the lower continental crust is the main process responsible for granite genesis in the post-Archean. If this melting occurs to undifferentiated mantle-derived rocks (i.e., basaltic protoliths), it should result in a granitic upper crust having a negative Eu anomaly and a mafic restitic lower crust having a positive Eu anomaly. However, most post-Archean high-pressure granulite facies terranes are not chemically complementary to granites because they themselves have bulk granitic compositions. If one restricts the discussion to mafic granulites from terranes, it is apparent that although their bulk composition is complementary to granite, most do not have positive Eu anomalies. Granite residues may, however, be present in granulite facies terranes if the parent rock giving rise to the granite had a negative Eu anomaly and a significant melt fraction were left behind with the residue. Such restitic granulites will have either no Eu anomaly or a negative one and “normal” LILE ratios due to the dominance of the incompatible element-rich melt. Granulite xenoliths do have the requisite compositions to balance the composition of the upper crust (i.e., mafic bulk composition and positive Eu anomalies); however, these samples are generally interpreted as melts or cumulates derived from underplated basaltic magmas rather than restites. Intracrustal differentiation may therefore proceed in several steps: intrusion and fractionation of basaltic magmas in the lower crust serves to (1) create mafic and ultramafic cumulates (having positive Eu anomalies), (2) produce evolved magmas (having negative Eu anomalies) (3) melt the preexisting (evolved) crust to produce granites and evolved restitic granulites. The magmas produced by differentiation of the basalt may remain in the lower crust where they may be subsequently melted in a later underplating event or may mix with the crustal melts and intrude the upper crust.

### INTRODUCTION

THE NEGATIVE EU anomaly documented in the upper continental crust by TAYLOR and MCLENNAN (1985) on the basis of REE patterns in sedimentary rocks requires the presence of a positive Eu anomaly in the lower crust (if the bulk crust has no Eu anomaly). They postulated that feldspar-bearing residues, left after granite extraction, would be the likely hosts for this Eu signature in the lower crust. Since the negative Eu anomaly is a feature of post-Archean sediments only, it follows that only crust that underwent differentiation since the Archean would contain this positive Eu anomaly signature (i.e., one might expect to observe it in post-Archean granulites).

However, the search for the restite that is chemically complementary to the upper granodioritic crust has been largely unsuccessful. Taken from a simple mass-balance viewpoint, the restitic lower crust should be characterized by a net positive Eu anomaly coupled with depletions in incompatible trace elements (i.e., K, Rb, Cs, Th, U, and the LREE) relative to the upper crust. However most granulites from surface outcrops do not have positive Eu anomalies and large numbers are not depleted in incompatible elements (RUDNICK et al., 1985). In fact, most granulite terranes, irrespective of their age, are as geochemically evolved if not more evolved than the bulk upper continental crust (Fig. 1).

In contrast, granulite facies xenoliths (samples of the lower crust carried rapidly to the surface by basaltic or kimberlitic

melts) do have the requisite features of the geochemical complement to the upper crust. They are generally mafic and have low abundances of K, Rb, Th, and U; many also possess positive Eu anomalies (RUDNICK, 1992). From geochemical arguments, however, it can be demonstrated that most of these mafic granulites form as a result of intrusion of mantle-derived basaltic melts near the Moho and, although cumulates abound, very few appear to be restites (ROGERS and HAWKESWORTH, 1982; RUDNICK et al., 1986; RUDNICK and TAYLOR, 1987; DOWNES et al., 1990; KEMPTON et al., 1990; LOOCK et al., 1990). The abundance of mafic compositions in granulite xenoliths coupled with the observation that most xenoliths are older than the basaltic volcanism that carried them to the earth's surface (RUDNICK, 1992) suggests that basaltic underplating has been an important process over a long time span (since the Proterozoic) and in a variety of tectonic settings (RUDNICK, 1990).

This paper addresses the following questions: Is post-Archean lower crust complementary to the upper crust through a melt-restite relationship? If so, where is the corresponding positive Eu anomaly in the lower crust? Is basaltic underplating important in post-Archean intracrustal differentiation? To evaluate these questions I review the composition of granulites, working from a large, literature-derived chemical data base (RUDNICK and PRESPEL, 1990), and compare these data with models of restite composition derived from experimental studies and trace element partitioning behavior. Despite the enormous compositional diversity amongst granulites, inferences may be made about the major processes responsible for the differentiation of the crust and the interplay of partial melting, basaltic underplating, and granulite facies metamorphism on the generation of the lower crust.

\* Presented at the symposium for S. R. Taylor, “Origin and Evolution of Planetary Crusts,” held October 1–2, 1990, at the Research School of Earth Sciences, ANU.

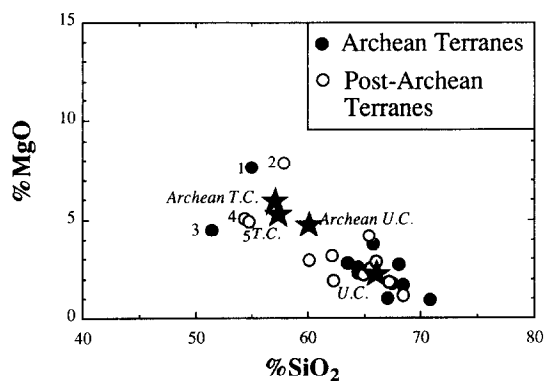


FIG. 1. Average  $\text{SiO}_2$  vs.  $\text{MgO}$ , which reflect degree of differentiation, for individual granulite terranes shown relative to total crust (T.C.) and upper crust (U.C.) compositions. Average compositions of terranes are calculated from the data compiled by RUDNICK and PRESPEL (1990) unless otherwise stated; crustal values are from TAYLOR and MCLENNAN (1985). Terranes for which the average composition is less evolved than the total crust composition are numbered and include: (1) Qianxi, (2) Ivrea zone, (3) Anabar shield, (4) Cabo Ortegal and (6) Furua complex. The remaining granulites are from: Arunta block, Australia (ALLEN, 1979); Jeju complex, Brazil; Limpopo Belt, southern Africa; Minnesota River Valley, USA; Uivak gneisses, Labrador; Kapuskasing structural zone, Ontario; Scourian gneisses (SHERATON et al., 1973), Scotland; S. India; Napier complex, Antarctica; Vestfold Hills, Antarctica; Prydz Bay, Antarctica; Rayner complex, Antarctica; Musgrave ranges, Australia; Lapland; Fenoscandia, Mexico; Adirondacks, USA; Fiordland, New Zealand; and Tromoy, Norway.

#### LOWER CRUSTAL COMPOSITION

Based on our knowledge of the upper crust, which grows mainly through intrusion of granites derived by partial melting in the deep crust, several chemical characteristics of the post-Archean lower crust can be inferred (TAYLOR and MCLENNAN, 1985):

- 1) It should be depleted in the heat-producing elements (K, Th, and U), as well as other large-ion lithophile elements (LILE) such as Rb and Cs, relative to the upper crust.
- 2) It should be more mafic than the upper crust, having higher  $\text{Al}_2\text{O}_3$ , CaO, and MgO, and lower  $\text{SiO}_2$ , and
- 3) It should contain, on average, a positive Eu anomaly complementary to that observed in the upper crust, assuming that the bulk crust has no Eu anomaly.

Such geochemical characteristics may be explained if the lower crust is the residue left after partial melting to produce the upper crust (TAYLOR and MCLENNAN, 1985). Recent experimental studies have sought to model the way in which the crust melts. By combining these results with the observed geochemistry of granulites, the restite origin of granulites can be evaluated.

#### Petrological Constraints on Crustal Melting

Although electrical resistivity measurements indicate that water may exist in the deep crust in some regions (GOUGH, 1986), other lines of evidence suggest that free water is generally not present below 15–20 km depth. These include the low water fugacity of most high-pressure granulites (YARDLEY, 1986) and the ubiquitous occurrence of  $\text{CO}_2$  rather than

$\text{H}_2\text{O}$  as fluid inclusions in granulites (TOURET and HARTEL, 1990). In addition, the heterogeneous oxygen isotopic values of granulites negates pervasive fluid circulation in many granulite terranes (VALLEY et al., 1983) and xenoliths (KEMPTON and HARMON, 1992) and has been used to argue for fluid-absent metamorphism in some terranes (VALLEY, 1986). Recent experimental work has therefore sought to model partial melting processes in the crust on the basis of dehydration reactions, where hydrous phases break down under increasing temperatures to form melt plus an anhydrous mineral assemblage (POWELL, 1983).

Fluid-absent melting of crustal rock produces some interesting features (VIELZEUF et al., 1990):

- 1) Large amounts of melt are formed over narrow temperature intervals, coinciding with the breakdown of the major hydrous phase(s),
- 2) The metamorphic temperature is buffered by the incongruent melting reaction, and
- 3) The high temperature and moderate-to-low  $\text{H}_2\text{O}$  contents of melts thus produced allow them to rise to shallow levels in the crust before they solidify.

It is these features that lead some petrologists to suggest that fluid-absent melting is the main process by which the lower crust melts and consequently is the major means of crustal differentiation (CLEMENS and VIELZEUF, 1987; VIELZEUF et al., 1990).

The residual mineralogies produced by fluid-absent melting of a variety of rock types are listed in Table 1. The percent melt produced corresponds to the complete consumption of the original hydrous phases, leaving an anhydrous residue. In each case this amount of melt is sufficient to allow separation of the melt from its source region (WICKHAM, 1987). The residual mineralogies are similar to those observed in many granulites: residues produced by melting of gabbro (amphibolite) and tonalite correspond to mafic granulites while residues produced by melting of graywacke and pelite correspond to various types of felsic and aluminous granulites, respectively.

#### Trace Element Signatures

The chemical composition of restite is a function of the proportions and character of the residual phases in addition to the composition of the parent rock. In theory, the restites shown in Table 1 should all possess positive Eu anomalies (due to the presence of residual feldspars) and be depleted in large-ion lithophile elements (LILE), showing high K/Rb and K/Cs. The latter feature is attributable to the fact that the residual minerals contain no sites for accommodating such large cations as Rb and Cs. These features have been considered by geochemists to typify restites (e.g., FYFE, 1973; PRIDE and MUECKE, 1980, 1981).

However, these "classical" restite features will not be produced if the parent has a negative Eu anomaly and/or a fraction of the melt remains behind with the residue. In addition, if biotite is not completely consumed during the melting reactions (i.e., for metagraywackes and metapelites), then the K/Rb ratio of the residue will not be elevated compared with that of the parent. It is more difficult to predict the Th and U abundances in restites, as these elements are controlled

Table 1. Restite mineralogy produced by fluid-absent melting of various rock types

Parent Composition	Amphibolite	Tonalite	Granodiorite	Graywacke	Pelite
Reference	1, 2	3	4	4, 5	6
Mineralogy*	Hb+Opx+Cpx+Pl+Ilm (R) Pl+Cpx+Opx+Mt (B&L)	Cpx+Pl+Mt	Cpx+Opx+Pl±Q	Pl+Gt+Opx+Q	Gt+Q+Pl+Sill
Melting reaction	Hb breakdown	Hb breakdown	Hb breakdown	Bio breakdown	Bio breakdown
Temperature of reaction	950-1000°C	925-975°C	825-850°C	825-850°C	850-875°C
% Melting	≥35%	≥35%	≥40%	≥35%	≥40%
Melt Composition	Tonalite	Granodiorite	Granite	Granite	Granite

\*Minerals listed in order of abundance

1. BEARD and LOFGREN (1989), 2. RUSHMER (1991), 3. RUTTER and WYLLIE (1988), 4. CONRAD et al. (1988), 5. VIELZEUF et al. (1990), 6. VIELZEUF and HOLLOWAY (1988)

mainly by the abundance of accessory phases, although U may also be affected by expulsion of metamorphic fluids. Each of these features is discussed in turn.

*Eu Anomalies*

The Eu anomalies (Eu/Eu\*) observed in granulites from terranes and xenoliths are plotted in Fig. 2. Of the mafic

granulites from surface outcrops (SiO<sub>2</sub> < 55%, which may correspond to residues left from melting of gabbro to tonalite), only one-third possess positive Eu anomalies. In contrast, 70% of mafic granulite xenoliths possess positive Eu anomalies. In most cases, positive Eu anomalies in granulite xenoliths have been attributed to accumulation of plagioclase feldspars during differentiation of mafic, underplated magmas

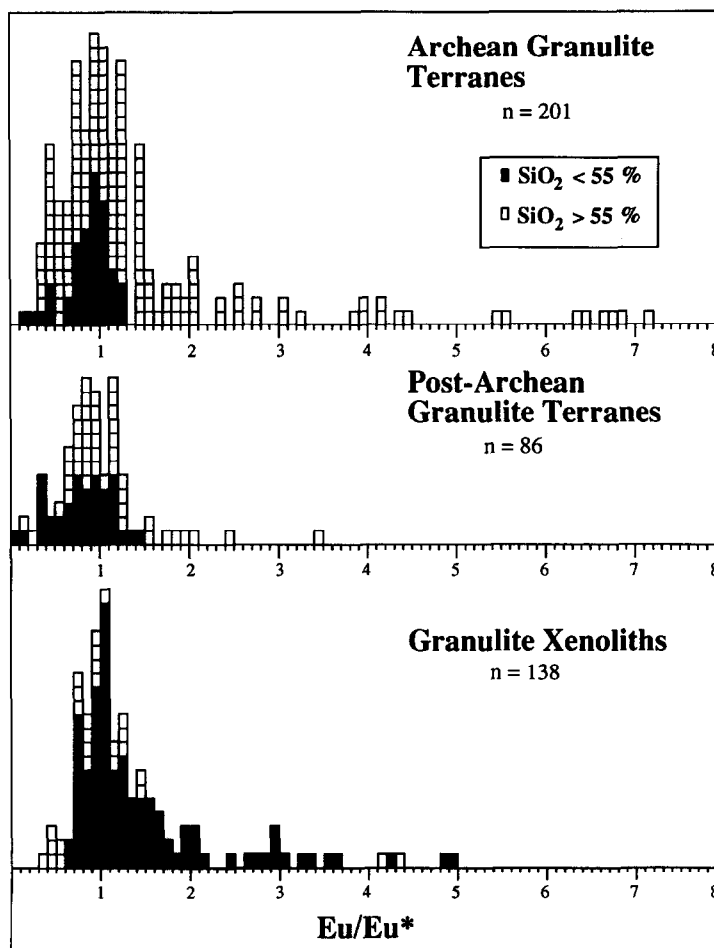


FIG. 2. Histogram of Eu/Eu\* (= observed Eu divided by interpolated Eu) for granulites from Archean terranes (top), post-Archean terranes (middle) and xenoliths (bottom). Eu/Eu\* > 1 corresponds to a positive Eu anomaly, whereas Eu/Eu\* < 1 corresponds to a negative Eu anomaly.

(ROGERS and HAWKESWORTH, 1982; RUDNICK et al., 1986; DOWNES et al., 1990; KEMPTON et al., 1990), rather than to residual plagioclase.

The size of the Eu anomaly produced in mafic restite due to residual feldspar is plotted in Fig. 3 against the Eu anomaly present in the parent rock. The partition coefficients and percentage of melting were held constant for the calculations (see caption for Fig. 3), but changing these parameters has negligible effects on the outcome. Two different proportions of residual plagioclase and clinopyroxene have been modelled, which bracket the variations produced by fluid-absent melting experiments (RUTTER and WYLLIE, 1988; BEARD and LOFGREN, 1989). Note that the largest Eu anomaly produced in the residues is  $\sim 1.5$ . Moreover, if the parent rock had a negative Eu anomaly similar to that observed in most upper crustal rocks, then the residue will have no Eu anomaly. Also shown in Fig. 3 is the effect of leaving 10% melt behind in the residue, which causes a corresponding decrease of  $\sim 10\%$  in the positive Eu anomaly.

Several conclusions can be drawn from the above observations and calculations:

- 1) Large (that is,  $>1.5$ ) positive Eu anomalies in mafic granulites are difficult to produce through partial melt extraction. This supports the conclusion reached by many xenolith workers that the large positive Eu anomalies commonly observed in granulite xenoliths are due to accumulation of igneous plagioclase during fractionation of a magma in the lower crust.
- 2) About one-third of the analyzed mafic granulites from terranes have positive Eu anomalies and could therefore represent partial melting residues; however, the majority of mafic granulites from terranes do not have positive Eu anomalies.
- 3) If the parent rock has a significant negative Eu anomaly, then the residue will have no Eu anomaly. Many of the

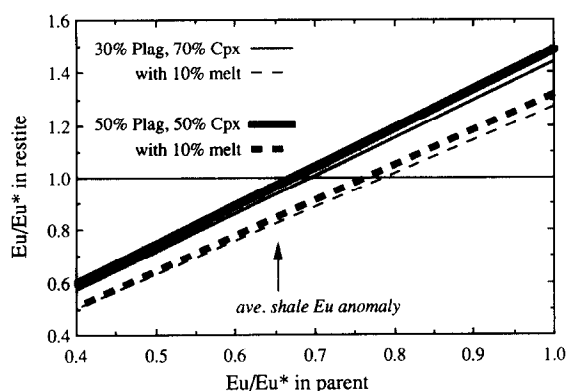


FIG. 3. Plot of Eu anomaly ( $\text{Eu}/\text{Eu}^*$ ) in the parent rock versus the Eu anomaly produced in the residue after 35% melting of a gabbro or tonalite (see Table 1), which leaves a residue composed of variable proportions of plagioclase and clinopyroxene. Modelling was carried out assuming batch melting with constant  $F$  (degree of melting) and using partition coefficients from FUJIMAKI et al. (1984). Two cases are calculated: (1) 30% plagioclase and 70% clinopyroxene (heavy line) and (2) 50% plagioclase and 50% clinopyroxene (light line), which correspond to the range of plagioclase:clinopyroxene proportions observed in the melting experiments. In addition, the effects of adding 10% melt to the residues are shown by the dashed lines.

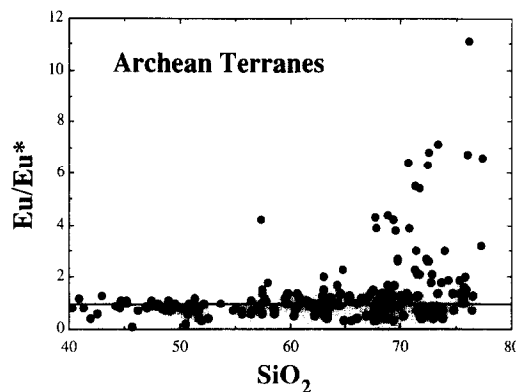


FIG. 4.  $\text{SiO}_2$  vs.  $\text{Eu}/\text{Eu}^*$  for granulites from Archean terranes. Note that very large positive Eu anomalies occur only in the most felsic granulites.

mafic granulites in terranes could then represent residues. However, this then requires that a process other than partial melt removal is responsible for balancing the negative Eu anomaly in the upper crust. On the basis of the xenolith data, this process is likely to be crystal fractionation, a conclusion also reached by RUDNICK and PRESPEL (1990) and VOSHAGE et al. (1990).

An intriguing feature of Fig. 2 is the number of felsic granulites from Archean terranes that have substantial positive Eu anomalies. The largest positive Eu anomalies typically occur in the most felsic rocks, as illustrated in Fig. 4. In terms of major element composition, these rocks range from trondhjemites and tonalites to granites. They often have high Ba contents and most are severely depleted in heavy REE, documenting the role of garnet in their petrogenesis. Some authors have concluded that these rocks are cumulates (DRURY, 1978; CONDIE et al., 1986), although a restite origin is also permissible if the parent was initially granitic. Unlike mafic restites in which the positive Eu anomaly is confined to values of 1.5 or lower, residues left from partial melting of a felsic rock (containing only feldspar, orthopyroxene and quartz; JOHNSTON and WYLLIE, 1988) would possess substantial positive Eu anomalies. This is due to the sole influence of feldspar on the REE pattern of the residue. Feldspar domination of REE patterns in felsic granulites also explains why some authors have found granulitic residues to be more LREE enriched than their protoliths (i.e., BURTON and O'NIONS, 1990). CONDIE et al. (1986) have suggested that these Eu-rich rocks represent the complementary positive Eu anomaly reservoir to that of the upper crust. However, this appears unlikely since these rocks occur only in the Archean, and the average Archean upper crust does not possess a negative Eu anomaly (TAYLOR and MCLENNAN, 1985). Perhaps this places a constraint on the volumetric significance of these Eu-enriched rocks.

#### Large ion lithophile elements (LILE)

In addition to a positive Eu anomaly, another geochemical feature predicted for partial melt residues is depletion in LILE and high  $\text{K}/\text{Rb}$  and  $\text{K}/\text{Cs}$  ratios. The  $\text{K}/\text{Rb}$  ratio of a residue

will depend upon whether biotite is completely consumed and whether any melt is left in the residue.

Figure 5 shows the change in K/Rb ratio for a residue left after variable degrees of partial melting of a metapelite. These calculations are based on the experimental results of VIELZEUF and HOLLOWAY (1988), who found that biotite reacts out over a narrow temperature range, producing up to 57% melt. The three bold lines in Fig. 5 correspond to the calculated restite composition using the range in K/Rb ratio for partition coefficients for biotite and plagioclase reported in PHILPOTTS and SCHNETZLER (1970). The distinctive shapes of the curves reflect the influence of residual biotite (at 0–57% melting) and plagioclase (at >57% melting) on K/Rb. Biotite is assumed to react out continuously between 0 and 57% melting; however, any amount of biotite in the residue will buffer the K/Rb of the residue to relatively low values. Once biotite is consumed (i.e., >57% melting), the K/Rb of the residue is controlled by the partitioning of K and Rb in plagioclase. The extreme range in final K/Rb ratios at 65% melt reflects the large range in relative partition coefficients for K and Rb in plagioclase. Because plagioclase-rich cumulate rocks such as massif anorthosites typically have very high K/Rb ratios, it is likely that the “low  $D_{K/Rb}$ ” curve in Fig. 5 is too low; the other curves are considered more realistic. Thus, once biotite is totally consumed by the melting reaction, the K/Rb ratio of the residue jumps to very high values.

Also shown in Fig. 5 is the effect on K/Rb ratio of adding melt to the residue. It is clear that even adding 1% melt has a dramatic effect on the K/Rb ratio of the residue. If melt segregation is inefficient, as is likely to be the case considering the high viscosities of most felsic melts, then the K/Rb of the residue may not be greatly elevated even though the absolute concentrations of both K and Rb will have been lowered as a consequence of melt extraction.

Melt retention in the residue will have similar effects on other LILE ratios such as K/U and K/Cs. In a completely

anhydrous residue there are no minerals that will accommodate large cations such as Rb and Cs. Thus, the concentrations of these elements will be exceedingly low. In contrast, some K may enter into residual plagioclase feldspar causing K/Cs and K/Rb to be high. Even a small amount of melt added to this anhydrous mineral assemblage will greatly decrease the K/Rb and K/Cs. This is because the concentrations of LILE in the melt are orders of magnitude higher than in the residue so that the melt fraction dominates the LILE signature of the rock. Upon crystallization of the remaining melt fraction, hydrous phases are likely to form. This leads to the important observation that residues left from granite production may be sampled in granulite terranes as hydrous granulites having “normal” LILE ratios.

The above discussions illustrate that restitic granulites can have a variety of geochemical signatures. It is best to summarize these features by comparing two parameters of partial melting:  $\text{Eu}/\text{Eu}^*$  and K/Rb.

K/Rb vs.  $\text{Eu}/\text{Eu}^*$  for the different types of granulites are plotted in Fig. 6. The vertical field outlining the region of high  $\text{Eu}/\text{Eu}^*$  but low K/Rb is where granulites that are either cumulates or restites (from felsic parents) that have “normal” LILE ratios would plot. The LILE ratios in these rocks may be controlled by either residual biotite and/or retention of a significant melt fraction. These rocks, therefore, have large positive Eu anomalies but low-to-moderate K/Rb (<500). The horizontal field encompassing the region of high K/Rb at  $\text{Eu}/\text{Eu}^* < 1.0$  is where anhydrous granulites that experienced metamorphically induced Rb depletion would plot. The lack of a positive Eu anomaly indicates that they are either not restitic or that the parent rock had a significant negative Eu anomaly. The high K/Rb of the mafic granulites plotting in this field may be a primary feature of the rocks (see the SHAW (1968) “ocean tholeiite trend”). The large area in the middle of the diagram is where anhydrous restites or cumulates that contain no interstitial melt would plot, having both high K/Rb and  $\text{Eu}/\text{Eu}^*$ . Relatively few of the data lie in this field. The area near the origin, in which many granulites fall, corresponds to granulites that have not suffered significant chemical changes during the metamorphism. Mafic granulites that plot in this area may still be restitic, but a significant amount of melt (>20%) must have been left behind with the residue so that  $\text{Eu}/\text{Eu}^*$  and K/Rb are not changed significantly from the parent. It is unlikely that any of the felsic granulites ( $\text{SiO}_2 > 65\%$ ) that plot here are restites, as even 20% melt would not adequately mask the positive Eu anomaly of a plagioclase-quartz-orthopyroxene residue, as discussed above.

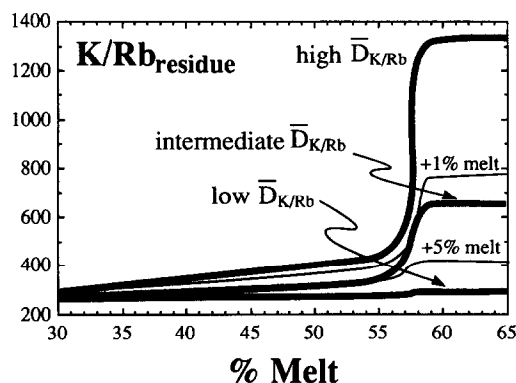


FIG. 5. K/Rb ratio in residue left after partial melting of a metapelite with and without trapped melt. The three heavy curves correspond to different partition coefficients for biotite and plagioclase. Partition coefficients are the range reported from PHILPOTTS and SCHNETZLER (1970) for minerals in equilibrium with a felsic liquid. The light curves show the K/Rb ratio for mixtures of residue and melt: the +5% melt curve corresponds to 5% melt left behind in the “high  $D_{K/Rb}$ ” residue; the +1% melt curve corresponds to 1% of the melt left behind in the same residue.

#### Th and U

Strictly speaking, Th and U are not LILEs because their cationic radii are relatively small when compared with K, Rb, and especially Cs (WHITTAKER and MUNTUS, 1970). Nevertheless, these elements are also depleted in some granulites. It is clear that accessory phases play a large role in the retention of these elements in granulites. Th abundances in granulites are highly variable and, on the basis of comparison with an immobile element such as La, appear to be depleted in some granulites but not in others (RUDNICK et al., 1985).

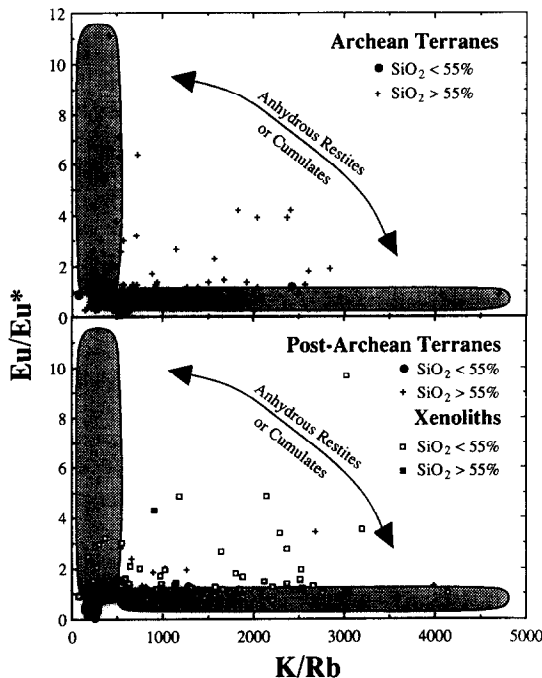


FIG. 6. K/Rb ratio versus Eu/Eu\* in various types of granulites. The vertical field on the left is where restites or cumulates, both of which contain some amount of melt or residual biotite, would plot. The horizontal field at the bottom encloses granulites that are Rb depleted but do not appear to be cumulates, since they do not have a positive Eu anomaly. Some of these could be residues from parents having a negative Eu anomaly, but this is unlikely to be true for all of them. The Rb depletion in these granulites may be caused by metamorphism or may be a primary feature of the mafic granulites (see the SHAW (1968) "ocean tholeiite trend"). The large area in the middle of the diagram is where anhydrous restites or cumulates plot. There can be no trapped melt remaining in these samples. The granulites plotting at  $K/Rb \leq 500$  and  $Eu/Eu^* \leq 1$  in the lower left corner are unlikely to have been modified by either melting or metamorphism.

Monazite is a likely key mineral retaining Th in granulites. In contrast, although also variable, U abundances are typically low in granulites relative to upper crustal rock types (RUDNICK and PRESPEER, 1990). This is demonstrated by the high K/U ratios in granulites (Fig. 7), which are nearly always higher than the upper crustal value of 10,000 and typically are  $>50,000$ .

Given that nearly all granulites are depleted in U but, as discussed above, not all are necessarily restitic, a process must exist that depletes U but leaves other trace elements unaffected. This could be accomplished by dehydration of the rocks as they pass from hydrous, possibly water-oversaturated, low-grade assemblages to anhydrous granulite facies assemblages. The early dehydration reactions may be accompanied by partial melting, but these water-saturated melts would not move far from their source (if they move at all) and may exsolve water on crystallization. These "metamorphic fluids" could then rise in the crust, carrying U with them (see KEPPNER and WYLLIE, 1990). The observation that U in low-grade rocks lies partly on grain boundaries and partly in accessory phases (DOSTAL and CAPEDEI, 1978) leads to the conclusion that U will be significantly depleted by removal of hydrous fluids.

### Summary of Chemical Features

The previous discussion of granulite chemistry shows that some granulites may be restites, but of these only a few represent anhydrous restites containing no trapped melt. Depending upon the composition of the parent, the degree of melting (whether all hydrous phases are consumed), and whether any melt is left behind, the restite may or may not have a positive Eu anomaly and/or high K/Rb. In addition, many granulites are chemically unmodified by the metamorphism except for depletion in U (which appears to be pervasive). When LILE depletion is observed in granulites, no single process is necessarily responsible: fluid expulsion and partial melt removal are both likely to play a role in different granulites.

### A MODEL FOR CRUSTAL DIFFERENTIATION

The notion that crustal differentiation is accomplished mainly through intracrustal melting (TAYLOR and MCLENNAN, 1985; CLEMENS and VIELZEUF, 1987; VIELZEUF et al., 1990) is supported by the data and observations presented above: restitic granulites may have a range of chemical signatures and the long-sought restite may indeed be present in granulite terranes. However, simple partial melting and extraction do not solve all problems of crustal differentiation. First, if fluid-absent melting is the main process responsible for granite formation, then a source of heat external to the crust is required to drive it—a conclusion reached by many experimentalists involved in fluid-absent melting studies (CLEMENS and VIELZEUF, 1987; BEARD and LOFGREN, 1989; RUTTER and WYLLIE, 1988). Second, the negative Eu anomaly in the upper crust is not balanced by granulite ter-

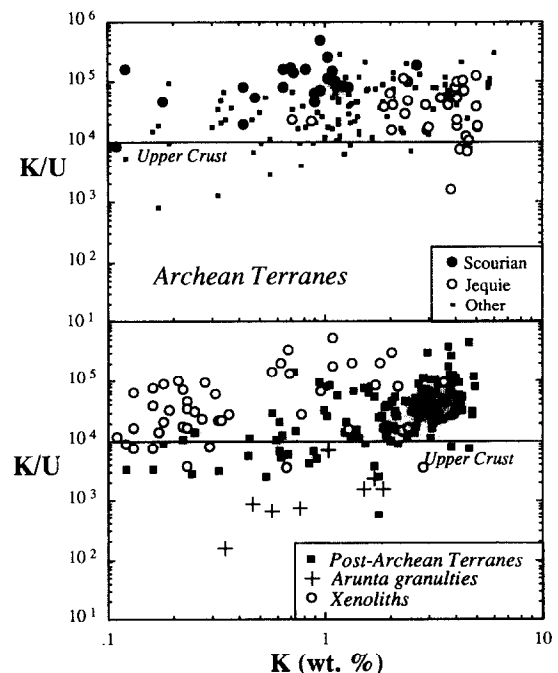


FIG. 7.  $K_2O$  versus K/U for granulites. The monazite-rich Arunta granulites are distinguished from other post-Archean granulites in the lower diagram. Note that most granulites have  $K/U > 10,000$  and many show severe U depletion.

ranes, but may be balanced by granulite xenoliths, which are mainly cumulates derived from underplated basaltic magmas.

Recognition of these problems leads to the conclusion that basaltic underplating is a key element in intracrustal differentiation: underplating will supply the heat required to drive the melting reactions and at the same time impart a bulk positive Eu anomaly to the lower crust through formation of crystal cumulates. In addition, it is likely that the intruding basaltic magma will not only melt the lower crust but also mix with and assimilate some of this surrounding crust, giving rise to chemically and isotopically hybrid magmas (e.g., VOSHAGE et al., 1990; HILDRETH and MOORBATH, 1988). The resulting magmas will have negative Eu anomalies and may intrude the upper crust, or crystallize in the lower crust where they may be subsequently melted to give rise to granitic magmas which intrude the upper crust. The residue left after this melting will have chemical and mineralogical features observed in granulites from terranes.

### CONCLUSIONS

Although intracrustal melting is the means by which the granitic upper crust is formed, most granulite facies terranes are not mafic residues left after partial melting of intermediate rock types. Many granulites from terranes may be residues, but residues derived from melting of evolved sources that already contained negative Eu anomalies. Such residues will have no Eu anomaly or a negative one. In addition, if partial melt removal was inefficient so that ~10% of the melt remains behind in the source, then restitic geochemical features will be masked by the high incompatible element abundances in the melt. Restitic granulites formed in this way will have "normal" ratios of LIL elements (e.g., K/Rb), albeit with lower absolute abundances of these elements.

Granulitic lower crustal xenoliths are mafic and have compositions suitable to mass balance the upper crust. However, most have either melt-like compositions or are crystal cumulates. This suggests that basaltic underplating plays a fundamental role in crustal growth and differentiation. That is, basaltic underplating provides a heat source to melt chemically evolved granulites. These basaltic melts fractionate (and assimilate crust) to produce mafic and ultramafic crystal cumulates plus evolved magmas that may intrude the upper crust or remain in the lower crust where they may undergo subsequent melting to produce granite and chemically evolved granulites.

*Acknowledgments*—I am grateful to Ross Taylor for his encouragement and guidance throughout my time at ANU. K. Mezger, J. Ruiz, D. Vielzeuf, R. Arculus, W. McDonough, C. Pin, M. Leshner, and I. Campbell are thanked for constructive criticisms on earlier versions of this paper.

*Editorial handling:* S. M. McLennan

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#### APPENDIX

The batch melting equation was used to calculate melt compositions (SHAW, 1970):

$$C_f = C_o / (\bar{D} + F * (1 - \bar{D}))$$

where

$C_f$  = concentration of element in melt  
 $C_o$  = concentration of element in parent  
 $F$  = proportion of melt ( $1.0 > F > 0$ )

$\bar{D}$  = bulk distribution coefficient

$$= \sum_i^n D_i^y * X_i + D_j^y * X_j + \dots + D_n^y * X_n$$

where

$D_i^y$  = concentration of element  $y$  in phase  $i$  / concentration of  $y$  in melt  
 $X_i$  = proportion of phase  $i$  (determined from experiments, see Table 1)

and the restite composition ( $C_s$ ) at a given  $F$  is

$$C_s = \bar{D} * C_f.$$