by Julian Pearce

Sources and settings of granitic rocks

Granitic rocks can have a wide range of sources, over all parts of the spectrum from pure mantle to pure crust. These sources show a significant correlation with tectonic setting. Granites from ocean ridges usually have characteristics that indicate depleted mantle sources. Granites in volcanic arcs usually have depleted mantle sources modified by a component from subducted oceanic crust and sediment. Granites from intraplate settings usually show evidence of enriched mantle (lithosphere and/or asthenosphere) sources together with rare crustal melts. Granites from syn-collision settings are usually characterised by pure crustal sources or by mantle sources containing large subducted crustal components. Granites from post-collision settings usually carry signs of enriched lithospheric mantle sources together with rare crustal melts. Further interaction between mantle-derived magmas and crust is a function of the thickness, temperature and composition of the crust and the residence time and temperature of the magma—variables that are also linked to tectonic setting. These relationships between source and setting provide the basis for the geochemical fingerprinting of granites which, when combined with geological considerations, enable granites to be assigned to their most probable setting of intrusion.

Definitions

For the purpose of this paper:

- **granites** are defined in the broadest sense as any coarse-grained igneous rock containing more than five per cent quartz;
- **source** is defined as the mantle or crustal protolith that contributes directly or indirectly to the granite magma and
- **setting** is defined as the global tectonic environment in which the parent magma is generated.

Sources

To a first approximation, there are two end-member sources of granitic magma: mantle and crust. Some granites originate from these pure end-member sources by melting and fractional crystallisation. Most, however, require a mixed source, i.e. a contribution from both mantle and crust. Granite variability results because the two end-member sources can vary in composition; because there are variations in the degree of melting of these sources, and because of the variety of ways in which mantle (or mantle-derived magma) and crust can interact. Figure 1 summarises the main sources, which are described, together with melting mechanisms, in more detail below.

Figure 1 Summary of the sources and settings of granitic rocks. Note that the melting processes by which these sources generate magma are also variable and dependent on setting.

DMM Depleted MORB Mantle

AFC Assimilation, Fractional Crystallisation

MASH Magma, Assimilation, Segregation, Homogenisation

Mantle source variables

- 1 **Mantle asthenosphere composition** The main reservoir of upper mantle asthenosphere is depleted in incompatible trace elements relative to 'primordial mantle' and often known as Depleted MORB Mantle (DMM). This is the consequence of extraction of these elements over geological time by melting events such as those that form oceanic crust. However, this depleted reservoir may be displaced by, or mix with, more enriched mantle in the vicinity of mantle plumes or delaminated sub-continental lithosphere.
- 2 **Mantle lithosphere composition** The mantle lithosphere can form from the asthenosphere and hence have the same composition. However, the mantle lithosphere can also be ultra-depleted in incompatible trace elements if it represents the residue from a melting event. It can also be enriched by veining by, or interaction with, magma or an aqueous or carbonate-rich fluid. Melting may not be necessary for the mantle lithosphere to contribute to the composition of a magma. Interactions between melt and enriched mantle lithosphere during magma ascent may also be effective in modifying magma composition.
- 3 **Mantle melting** The principal variables are the nature and degree of melting. Mantle melting is now considered to be partial and fractional in nature with potentially variable pooling of the melt fractions. The degree of melting can range from a few per cent (favoured by anhydrous conditions, low temperature, and minimal decompression) to about 30% (favoured by hydrous conditions, high temperature and significant decompression). Small degrees of melting typically give alkalic magmas, whereas larger degrees of melting give tholeiitic or calc-alkaline magmas. Primary melts are typically picrites, basalts and boninites which evolve to granitic composition by fractional crystallisation and magma-crust interaction.

Figure 2 A MASH zone (near Chelan, Washington, USA) caused by injection of basic magma into hot crust. Note that, despite the complexity of this process, the geochemistry of the resulting rock retains the signature of the basaltic end-member and hence of the setting of granite magma generation.

Crustal source variables

- 4 **Crustal composition** This varies according to rock type and depth in the crust. The first-order distinction in rock type is between igneous and sedimentary protoliths. Igneous protoliths are mainly, but not exclusively, granites and basalts. Sedimentary protoliths are mainly, but not exclusively, siliciclastic and pelitic. The siliciclastic sediments may be subdivided according to origin into volcanogenic and non-volcanogenic, and according to source proximity into mature and immature. Although the original global classification of granites into S-types (sedimentary protoliths) and I-types (igneous protoliths) (Chappell and White, 1974) underestimates the importance of volcanogenic sediments and mantle-derived magma in the genesis of I-type granites, the melting of non-volcanogenic sediments commonly does produce the 'classic', aluminous characteristics of S-type granites while the melting of igneous protoliths and volcanogenic sediment commonly does produce the 'classic', calc-alkaline characteristics of I-type granites. The main variation with depth is the depletion of large ion lithophile (LIL) elements in the lower crust which, if present for sufficient time, permits upper and lower crust to be distinguished isotopically.
- 5 **Partial crustal melting** This process involves not just partial melting of the crust but also effective separation of melt from residue. The principal controls on the composition of the resulting magma are the composition of the crust undergoing melting and the nature of the residue from melting. For the major elements and some trace elements, the major phase assemblage is most important, but many trace elements are controlled by the solubility of the minor phases (such as zircon, monazite and sphene) and this in turn depends on temperature, time, and other factors. The principal controls on the degree of melting include the presence or absence of free fluid, the mineralogy of the protolith and the temperature and pressure. In general, small degrees of melting give the most siliceous products and the lowest concentrations of those elements that depend on minor phase solubility. Given a sufficient degree of melting, the yield strength of the resultant mush may be sufficiently reduced that the whole crust (melt and restite) is mobilised (Arzi, 1978). The resulting granite body then has the composition of the original crust and can evolve by separation of melt from restite as well by crystallisation of the melt fraction.
- 6 **Volatile fluxing** This may be a cause of some intracrustal melting and may also transport elements into the melting region. There are several potential sources of fluid in the crust. However, simple release of fluids during prograde metamorphism may not be effective in granite generation as these fluids tend to

pass through cooler (and hence infusible) rocks en route to the surface. Most effective may be the fluids released during intra-continental thrusting, where fluids from one thrust sheet can promote melting of the hotter crust of an overlying thrust sheet. When large volumes of basic magma invade the crust, deep circulation of fluids above crustal magma chambers may also create the right conditions to initiate melting around the edges of the chambers.

Mantle–crust source interaction

- 7 **Mantle–crust interaction** The crust, or a component derived from it, may interact directly with the mantle source during subduction. This subduction component may be aqueous fluid and/or siliceous melt and may be derived from one or both of subducted oceanic crust and subducted sediment. The subduction component varies according to the composition and temperature of the subducted lithosphere (see summary by Pearce and Peate, 1995). Geochemically, the significance of this process is that it precedes melting of the mantle. The melting process and any subsequent fractional crystallisation can thus magnify the subduction component in the resulting magmas.
- 8 **MASH (Magma, assimilation, segregation, homogenisation)** This describes the process of injection of mantle-derived magma into the hot base of the crust to produce a complex mixture of basic magma (from mantle melting), acid magma (by crustal fusion) together with products of crystallisation of the basic magma and residues from crustal melting (Hildreth and Moorbath, 1988). The product may range from evolved basalt to dacite in composition. The idea is that a homogenous melt eventually emerges from the blending of mantle- and crust-derived magmas within the MASH zone (Figure 2).
- 9 **AFC (Assimilation, fractional crystallisation)** This describes the process of wall-rock assimilation combined with crystallisation in a magma chamber (De Paolo, 1981). The key variable, in addition to the compositions of the magma and crust, is the relative rate of assimilation and crystallisation.

Tectonic settings

Most authors studying granites on a global scale accept a link between sources and settings of granites, although the methods for defining settings vary (e.g. Pitcher, 1987). Here, the settings are defined entirely in terms of global tectonic parameters, as shown in Figure 1. The characteristics of each of these settings, and their associated granites, are summarised below.

Mid-ocean ridges

These can vary from mid-ocean ridges (*sensu stricto*) to plume-related ridges (e.g. Iceland and the Reykjanes Ridge) to supra-subduction zone ridges (e.g. in many marginal basins). For mid-ocean ridges, the mantle source is usually the depleted asthenospheric mantle reservoir. For ridges linked to plumes, the mantle source is more enriched because of the mixing of plume mantle with the depleted upper mantle reservoir. For ridges above subduction zones, this depleted mantle source may have been modified by subduction fluids before melting; in addition, some supra-subduction zone ridges have ultra-depleted sources and have associated boninite magmas. Although ridge volcanism is predominantly basaltic, acid volcanic rocks do erupt at mid-ocean ridges. They are most common at propagating rifts where cooling rates are high relative to magma input (Christie and Sinton, 1981).

Ocean ridge granites (ORG) are typically of small volume. They are dominantly tonalite and 'oceanic plagiogranite', metaluminous, and alkali-calcic to calcic, with clinopyroxene and amphibole as the principal mafic minerals. The vast majority can be interpreted in terms of fractionation of olivine, clinopyroxene and plagioclase from a parental basalt. In terms of sources, their small volume reflects the low crustal input and the open-system magma chambers which enable the magma to be regularly reset to more basic compositions. Their sodic character reflects the low abundance of potassium in the depleted mantle source and the lack of continental crustal input. Their trace element contents are most strongly dependent on the nature of the mantle source of the parental magma, which primarily depends on the setting of the ridge in question (normal, plume-related or supra-subduction zone).

Volcanic arcs

Volcanic arcs may be oceanic or continental (active continental margins). They usually form by melting of mantle asthenosphere modified by a subduction component. This asthenosphere is typically similar to, or more depleted than, the MORB reservoir although there are exceptions. The effect of added water, coupled with decompression, is to induce high degrees of partial melting, especially beneath thin lithosphere. Estimates indicate that about 10% of the melting can be attributed to volatile addition, with a further 15% dependent upon decompression and thus lithospheric thickness (Pearce and Peate, 1995). The large volumes of magma intruded into the crust means that magma-crust interaction is the norm. This interaction is most obvious at active continental margins (the Andes is a type area for the AFC and MASH processes) where the crust is thick and chemically more different from the invading magma, but magma-crust interaction has also been demonstrated isotopically in oceanic arcs even where the crust and magma are cogenetic.

Volcanic arc granites (VAG) form discrete, often zoned plutons in island arc terranes and linear, composite batholiths at active continental margins. They commonly form I-type granodiorite and tonalite intrusions which are metaluminous, calc-alkaline, with amphibole, pyroxene and biotite as common ferromagnesian minerals. Some intra-oceanic arcs may have pyroxenes rather than hydrous minerals as the dominant ferromagnesian minerals. Volcanic arc granites have standard subduction signatures with enrichment in LIL elements relative to HFS (high field strength) elements. Although crustal interaction is common, it has little effect on these signatures as the subduction component is itself crust-derived. The common presence of hydrous phases, especially amphibole, in their crystallisation sequences also means that elements partitioned into these minerals (e.g. middle-heavy REE) are depleted with respect to ocean ridge basalts.

Attention has recently turned from the common types of volcanic arc intrusion to intrusions that might be indicative of specific supra-subduction zone settings. Granites in accretionary complexes are one example. Hill et al. (1981) first found, in Alaska, I-type granitic complexes with a major volcanosedimentary component in the accretionary prism. Hill et al. (1981) also used isotope mass bal-

ances to infer the presence of a basic component of MORB composition. Maeda and Kagami (1996) identified similar complexes in Japan and confirmed the presence of the MORB end member. They explained the genesis of the granite as due to ridge subduction, enabling MORB magmas to invade the accretionary complex and assimilate and fuse the sediments. This is important because the progressive subduction of a ridge along an arc-trench system can leave a 'trail' of granite in its wake, the total volume of which can be substantial. Because the crustal component comprises arc-volcanogenic sediment, these granites have typical subduction signatures.

Another potential link between granites and ridge subduction followed the recent identification of 'adakites' (dacitic melts thought to be formed by melting of subducted oceanic crust) in volcanic arcs above subducting ridges. Many scientists have noted that Archaean tonalite-trondhjemite complexes have characteristics similar to adakites (e.g. subduction signatures coupled with steep rare earth profiles) and hence may also originate by fusion of basalt in a subduction setting (Rapp et al., 1991). The options remain, however, as to whether such complexes formed by fusion of subducted crust itself or by fusion above a subduction zone of the basaltic roots of an oceanic plateau or volcanic rifted margin.

Within-plate settings

These include ocean islands and continental intraplate settings. There are two principal causes for intraplate magma generation: mantle plume activity; and passive rifting. In the former, mantle plumes impact upon the base of oceanic or continental lithosphere. In the latter, there is sufficient lithospheric extension for the mantle to melt by decompression without the extra heat that a plume can supply. In some cases, as at volcanic rifted margins and some intra-continental flood basalt terranes, the two mechanisms can act together, and it is here that the greatest volumes of magma are likely to be generated (White and McKenzie, 1989).

Above mantle plumes, magma genesis involves melting of plume-related asthenosphere and/or enriched lithosphere. The degree of melting is linked to the temperature and composition of the plume and the thickness and composition of the lithosphere. Thick lithosphere leads to low degrees of melting and an alkalic primary magma which tends to evolve to phonolitic rather than granitic compositions, unless crustal interaction can drive the composition across the 'thermal divide' on the phase diagram. Thin lithosphere leads to more melting and a more tholeiitic magma that can evolve to granitic compositions even without crustal interaction.

Passive rifting is typically linked to ocean opening or to the formation of extensional, intracontinental basins that never developed into oceans. Here, magmatism can mainly be attributed to decompression of depleted mantle asthenosphere. Passive rifting may also be related to subduction in an ensialic back-arc setting (e.g. at the margins of the Japan Sea).

Within-plate granites (WPG) typically comprise small-volume intrusions in continental rift and ocean island settings, where they are typically alkali granites with peralkaline compositions containing sodic pyroxenes and amphiboles. The well-known alkali ring complexes of Nigeria fall in this category. Geochemically, they show a strong enrichment in both LIL and HFS elements, characteristic of derivation of an enriched mantle source, although crustal assimilation can selectively increase the LIL element content. Volatile-related processes, either supra- or subsolidus may also redistribute many elements.

In flood basalt terranes and at volcanic rifted margins, the degree of melting increases and asthenospheric mantle becomes as, or more significant than lithospheric mantle. This increase in magma flux, causes large volumes of basic magma to invade the crust and many of the granites from such settings show evidence of significant magma-crust interaction and bimodal, basic-acid magmatic products. At volcanic rifted margins (e.g. the British Tertiary Province), isotopic and trace element evidence indicates an origin by melting of variably enriched mantle to produce a basaltic or picritic primary magma, followed by AFC at a range of crustal levels to produce a

basaltic magma enriched in crustal components, and then fractional crystallisation at shallow level to give the final, granitic composition. The granites are typically granites (*sensu stricto*), peralkaline or metaluminous, A-types. The mafic minerals are typically olivines and pyroxenes, reflecting an essentially dry petrogenesis. Pure crustal melts, though rare, have also been recognised in this setting, for example above the Bushveld intrusion and on Skye.

In regions of passive rifting, granites combine the range of mantle sources that contribute to mid ocean ridge granites with the effects of crust–magma interaction. In some intracratonic basins (e.g. in the Proterozoic rocks around Broken Hill), plagiogranites similar to oceanic plagiogranites can be found, though the potassium content is higher than in ocean ridge granites because there is still some crustal input. Granites associated with passive rifting are also marked by an anhydrous fractional crystallisation history of mainly olivine, clinopyroxene and plagioclase.

Collision settings

Collision settings can be subdivided into syn-collision and post-collision (Harris et al., 1986). Syn-collision settings are linked to the process of crustal thickening, usually by the underthrusting of one crustal 'slice' beneath another. Post-collision magmatism is linked to rapid, post-closure uplift, which may take place some time after the collision itself. It is also linked to the subsequent collapse of the orogenic belt.

Thus, volcanic arc and syn-collision magmatism can merge, as can post-collision and within-plate magmatism. For the purposes of this review, syn-collision magmatism is taken to begin once oceanic crust ceases to be subducted. Post-collision magmatism is taken to end once magmatism ceases to be linked to orogenic processes. Both boundaries are, of course, difficult to identify precisely.

The collision event may involve a continent and a volcanic arc (continental or oceanic) or, rarely, two arcs following a period of ocean crust subduction. Alternatively, it may involve two continents that were separated by insufficient oceanic crust to generate a volcanic arc before the collision.

Some of the best examples of continent–arc collision at the present day can be found in the Banda arc (collision of Australia with the eastern Indonesian arc) and in the Northern part of the Philippine arc (collision of Taiwan with the Philippine arc). Geochemical studies have shown that this setting is characterised by extensive subduction of terrigenous sediment into the mantle (McDermott et al., 1993). The mixture of fused sediment and mantle then undergoes partial melting to produce magmas with extremely high contents of LIL elements.

Possible examples of continent–continent collision include: Northern Italy where the Adriatic lithosphere underthrusts the Apennines (Serri et al., 1993) and incorporation of crustal melt into the mantle wedge causes the volcanic rocks to resemble those associated with continent–arc collision; and the Himalayas where the Indian lithosphere underthrusts Tibet and pure crustal melts are generated.

Post-collision settings can be of considerable extent. Some of the best examples of post-collision magmatism at the present day can be seen in Eastern Anatolia and Papua New Guinea (continent–fore-arc collisions) and Bolivia (continent–rear-arc collision). One major cause of magmatism is thought to be delamination of the thickened lithosphere, whereby mantle lithosphere is convectively removed from below (either progressively or catastrophically) while the crustal thickness is unaffected. This enables hot asthenosphere to make contact with metasomatised mantle lithosphere which then undergoes small amounts of melting to produce magmas rich in incompatible elements.

Because of the thickened crust, interaction of mantle-derived magmas with the crust is extensive and almost all post-collision eruptive rocks exhibit evidence of significant crustal assimilation. The lithosphere undergoing melting may be of intraplate or subduction zone character depending on the pre-collision history of the lithosphere (Pearce et al., 1990).

Syn-collision granites linked to continent–arc collision are the last intrusions in the life-cycle of a volcanic arc where they form metaluminous, I-type granites (*sensu stricto*) with biotite as the most common ferromagnesian mineral. Those linked to continent–continent collision include the Himalayan leucogranites, for which all evidence points to an intracrustal origin. This melting process is thought to be enhanced by volatile transfer from the lower to the upper thrust sheet and by decompression resulting from uplift. These granites are peraluminous, S-type granites with muscovite and biotite as common minerals.

Post-collision granites probably form some of the largest volumes of granite in orogenic belts. Although there are few recent, exposed examples, they can be recognised in many past orogenic belts (e.g. Caledonides, Hercynides) mainly from their ages and their relationships to deformation events. They can range from A- to I-type in character and are often granites (*sensu stricto*). Analogy with the volcanic products of recent post-collision terranes indicates that the history of the lithospheric source may be a key factor influencing composition: derivation from mantle above an earlier subduction zone gives an I-type character, derivation from the lithosphere beneath the passive margin gives an A-type character. Because of the great thickness of the crust, extensive magma–crust interaction is the norm, further modifying the composition.

One question, not yet resolved, is the extent to which the crust can melt if there is no heat transfer via mantle-derived magma. Theoretically at least, radioactive heating of crust thickened to 70 km should cause the lower crust to reach melting point after about 40 Ma (Harris et al., 1986). The problem is that it is difficult to link examples of lower crustal melting to the tectonic event that caused it. A key study is that of the Trois Seigneurs Massif in the Pyrenees by Wickham and Oxburgh (1987). They provide evidence that the sequence of peraluminous biotite granites, grading upwards into leucogranites and migmatites, was generated by wet melting of sedimentary rocks. In this model, the heat is generated by the large volumes of mafic magma formed by crustal attenuation, the fluids being groundwaters set in circulation by the magmatic heat. The likely setting here is post-collision extension.

Tectonic setting discrimination

Although there are many publications that subdivide granites in terms of geochemistry and petrology (e.g. into I-, S-, A- and M-type), the diagrams of Pearce et al. (1984) remain the principal systematic attempt to integrate granite geochemistry into the plate tectonic framework. These geochemical diagrams have been much used and debated and this review presents a good opportunity to emphasise that the design of the diagrams is linked to the relationships between sources and settings as discussed here.

One of the key diagrams, that of Rb against (Y+Nb), is illustrated in Figure 3 together with some of the petrogenetic pathways that demonstrate the link between sources and settings. The diagram is essentially one of a large ion lithophile, and hence fluid-mobile, element (Rb) against a function based on two high field-strength, and hence fluid-immobile, elements (Y and Nb). The use of the both Y and Nb rather than simply either one of these elements reflects the fact that the two elements behave differently during melting and crystallisation: Nb is almost always incompatible, but Y may be compatible if there is a melt residue or crystallisation assemblage involving garnet or amphibole. The distribution of granite data in Rb–Nb–Y space indicates that the sum of these two elements makes the most effective discriminant.

Ocean ridge granites demonstrate an obvious link between chemistry and source. Rb is in low abundance in granites from both mid-ocean and plume-related ridges as a consequence of their depleted mantle sources and/or lack of interaction with continental crust. Nb and Y reach high levels because the anhydrous character of the magmas cause both elements to increase throughout the fractionation history of the magmas. Samples therefore plot in the bottom-

Figure 3 The Rb-(Y+Nb) diagram for discriminating the tectonic setting of granites (from Pearce et al., 1984). The upper diagram shows the fields for the various tectonically defined granite types, namely: Ocean Ridge Granites (ORG); Within Plate Granites (WPG); Volcanic Arc Granites (VAG); and Syn- and Post-collision Granites (syn-COLG and post-COLG). The lower diagram illustrates the source-dependent petrogenetic pathways by which typical mantle-derived granite compositions can be reached (DMM= Depleted MORB Mantle). It also shows the compositions of Upper, Bulk and Lower Continental Crust (UCC, BCC and LCC), and the pathway for partial melting of fluid-modified bulk continental crust during intracrustal thrusting in a Syn-collision setting. See text for full details.

extent, Nb during fractional crystallisation. Note also that, because average continental crust lies within the volcanic arc field on the diagram, crustal assimilation does not have much effect on the position of volcanic arc granites on the diagram.

The granites in accretionary prisms are not very dissimilar to 'normal' volcanic arc granites, having assimilated sufficient quantities of arc-like crust to be of arc-like rather than MORB-like character. Granites formed by oceanic crustal fusion have still lower Y contents because of the retention of this element by garnet and amphibole in the melt residue and also lie on the left side the volcanic arc field.

Within-plate granites have geochemical features that reflect enriched mantle sources and anhydrous crystallisation. Their mantle sources are typically enriched in Rb and Nb (though not Y, which is retained in the garnet-bearing residue from small degrees of mantle melting at depth). All three elements are continuously enriched during their evolution by crystallisation of anhydrous phases. The net

effect is that granites from this setting occupy the upper-right field of the discriminant diagram. Note that the extensive crustal contamination in most intraplate settings enable samples to plot in the within-plate granite field even when they have been derived from depleted mantle sources. Only when pure crustal melts are generated (or the ratio of assimilation to fractional crystallisation is extremely large) will the compositions misclassify in the volcanic arc field. As already noted, this is possible though relatively uncommon.

A much-cited problem is that lithospheric, intraplate mantle sources may carry inherited subduction components leading to misclassification of within-plate granites as volcanic arc granites. It is not yet certain how relevant this is to granite genesis; for example, even where such components are known to be present, as in the Southern Paraná of Brazil, the resulting rhyolites still exhibit a clear intraplate character (Garland et al., 1995).

Collision granites have a wide range of compositions. In collision events where continental crust or terrigenous sediments are subducted into the mantle, the source is mantle enriched by crustal melt. This gives a Rb-rich source which is further enriched by partial

Table 1 *The sources of granites in various tectonic settings.*

Ocean ridge granite	Generally depleted mantle sources with no interaction with continental crust.
Within-plate granite	Generally enriched (through intraplate processes) mantle sources with variable interaction with continental crust.
Volcanic arc granite	Generally depleted mantle sources enriched by a subduction fluid $\pm$ interaction with continental crust.
Syn-collision granite	Mantle or crustal sources augmented by melts and fluids from subducted or underthrust continental crust.
Post-collision granite	Enriched mantle sources (through subduction and/or intraplate processes) + extensive crustal interaction.

melting and fractional crystallisation to ultra-high levels. These levels exceed those of volcanic arcs where the subduction component is dominated by aqueous fluids and thus lower in Rb. Sediment melting also increases Nb, so the syn-collision field can extend throughout the upper part of the diagram. Underthrusting of continental crust beneath continental crust causes fluid addition to a crustal source. This will increase the Rb contents of the resulting crustal melts and thus can place their compositions above the upper continental crustal composition (UCC) and into the syn-collision field. However, if melting should take place by decompression without fluid addition, the composition will plot close to the average crustal composition, in the volcanic arc field: the diagram will then be fingerprinting source (crust) rather than setting (syn-collision).

Post-collision granites are the most difficult to classify as they have much the greatest range of sources. It is apparent that some have subduction-like mantle sources and have many of the characteristics of volcanic arc granites on the diagram, whereas others have intraplate-like sources and have many of the characteristics of within plate granites on the diagram. In addition, there is extensive interaction between the mantle-derived sources and the crust which tends to move all compositions to into the volcanic arc field. The result is a restricted range of compositions, but one which overlaps the fields of other magma types. It is thus the most obvious case of the diagram reflecting the source of the granite but, because the source is not unique, the setting is not uniquely characterised. Geology, as well as geochemistry, is therefore essential in classifying granites that plot in the post-COLG field.

In summary, diagrams such as Rb-(Nb+Y) reflect the sources of granites, and the various processes that act upon these sources. Despite some ambiguities, which are likely to remain whatever the geochemical or petrological discriminant used, sources do relate to tectonic settings in simple ways as summarised in Table 1.

Of course, the challenge comes in integrating these geochemical signatures with geological and other parameters to reach the optimum interpretation for the granite in question.

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