Transactions of the Royal Society of Edinburgh: Earth Sciences, **95**, 1–10, 2004

Towards a unified model for granite genesis

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ABSTRACT: Most granites result from partial melting within the crust. Granite melts produced at the lowest temperatures of partial melting mainly comprise close to equal amounts of the haplogranite components *Qz*, *Ab* and *Or*, with H_2O. Many felsic granites were formed by partial melting under such conditions and are low-temperature types, with crystals of zircon and other restite minerals present in the initial magma. Such magmas evolve in composition, at least initially, through fractionation of that restite. If one of the four haplogranite components either becomes depleted or too low in amount to contribute further to the melt, then melting may proceed to higher temperatures without a contribution from that component. Melting will advance to significantly higher temperatures if there is a critical deficiency in one or more components and a high-temperature granite magma forms, in which zircon is completely soluble. Such magmas are extracted from the source in a completely molten state and may evolve by fractional crystallisation. They are monzonitic, tonalitic or A-type, depending on whether the critical deficiency occurred in the *Qz*, *Or* or H_2O component. If the *Ab* component is critically deficient, as in pelitic rocks, the rocks may be infertile for granite production. The control that source rock compositions exert on both the physical and chemical properties of granite magmas provides a unifying element in granite genesis.

KEY WORDS: Crystal fractionation, fractional crystallisation, haplogranite, high-temperature granite, low-temperature granite, partial melt, restite fractionation, tonalite.

Since the experimental studies of Tuttle & Bowen (1958), it has generally been accepted that granites are the products of magmatic processes taking place within the Earth's crust. These rocks all have in common that they formed as a result of processes involving reactions (melting or crystallisation) between crystals and silicate melt at the lowest magmatic temperatures appropriate to the bulk chemical composition of a particular system. Therefore, it would be surprising if we did not ultimately find that the genesis of granites can be represented in a more unified way than has been the case up to the present time. The present paper suggests a way in which that might happen. It is illustrated with examples of various Australian granites, mainly from the mid-Palaeozoic Lachlan Fold Belt (LFB), but also from the mainly late-Palaeozoic New England Fold Belt. While the present author's experience of granites has principally been in those two areas, the development of the ideas in this paper has also drawn on personal observations of rocks in other places. Most important among those have been the North American Cordillera, and the Caledonian and Hercynian fold belts of Europe. Granites of the LFB are diverse and they encompass a wide range of rock types, including approximately equal amounts of I- and S-type granites, and a small amount of distinctive A-type granites. But there are important varieties of granites which are not present in the LFB, and therefore, must be examined elsewhere. These include the Cordilleran-like tonalites and, of course, their older compositional analogues, the Archaean tonalite–trondjemite–granodiorite associations (TTGs).

1. Introduction

The Hutton Symposia, the first of which was held in 1987, celebrate the life and work of James Hutton, in particular his observations on granites. In 1785, he observed that dykes of granite in Glen Tilt, Scotland, are intrusive into the adjacent schists, and he made similar observations in Galloway and Arran during the following two years. This showed that granites are plutonic rocks, and not deposits from a primeval ocean as the Neptunists had proposed. However, it was some 50 years before Hutton's views on granites and more generally on the evolution of the Earth (Hutton 1788) became widely accepted (see Repcheck 2003). From that time, an intense debate developed over the origin of these plutonic rocks, i.e. whether granites have an origin that is igneous (magmatic) or metasomatic (produced by granitisation). This debate was only resolved satisfactorily by the publication of the now classic memoir of Tuttle & Bowen in 1958, which undoubtedly has been the most significant single contribution to our understanding of the origin of granites and related rocks.

2. Tuttle & Bowen and haplogranite compositions

Publication of the Tuttle & Bowen (1958) memoir resolved arguments about the origins of granites firmly in favour of the magmatic view. These authors showed that: (1) hydrous silicate melts which occur at the lowest temperatures contain close to equal proportions of the *Qz*, *Ab* and *Or* components; and (2) the most felsic granites and rhyolites containing more than 80% $Qz+Ab+Or$, the haplogranites, have compositions which are very close to those lowest-temperature melts (Fig. 1). Thus, the study of Tuttle & Bowen (1958) showed that haplogranites were once H_2O-bearing melts, or cumulative rocks from such melts (see section 2.3 below), with compositions determined during equilibrium between quartz and feldspars at magmatic temperatures. The fact that felsic granites and related volcanic rocks have that distinctive composition was the defining observation that resolved the Granite Controversy of the mid-twentieth century in favour of the magmatic view. The ideas of granitisation foundered when confronted with the restricted ranges of major element abundances observed in felsic granites, and this marked the beginning of modern, post-granitisation, studies of granites.

The experiments of Tuttle & Bowen (1958) were carried out under H_2O-saturated conditions, and it is likely that most granite melts do not form under those conditions (e.g. Clemens 1984), although they may evolve to H_2O-saturation as a result

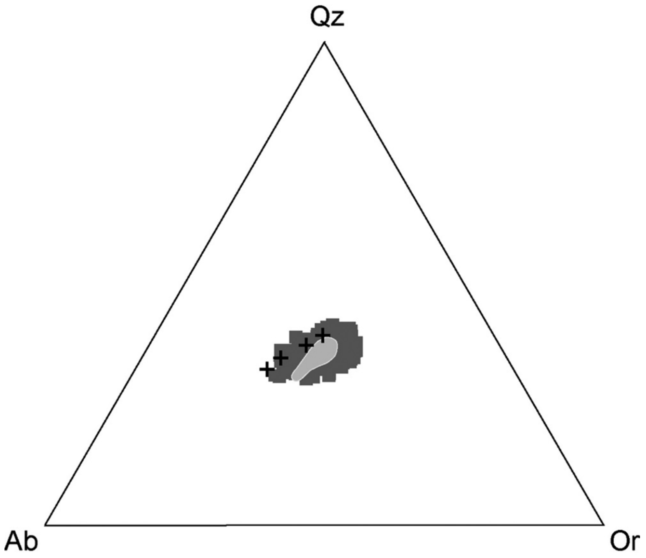

Figure 1 The *Qz-Ab-Or* face of the tetrahedron for the system *Qz-Ab-Or*-H_2O studied by Tuttle & Bowen (1958), with positions of the ternary temperature minima at 50, 100, 200 and 300 MPa shown as crosses in positions of increasing *Ab* content. The central part of the contoured field of 511 analysed haplogranites drawn by the above authors is also shown as a lightly shaded area. The darker surrounding area contains the plotted positions of all 445 analysed granites of the Lachlan Fold Belt which contain more than 90% *Qz*+*Ab*+*Or* on a normative corundum-free basis.

of the removal of anhydrous phases during fractional crystallisation. Experiments subsequent to Tuttle & Bowen (1958) have shown that the position of the minimum melt compositions in the haplogranite system do not alter greatly under H_2O-undersaturated conditions, moving towards the right in Figure 1 as the a_{H_2O} decreases (Johannes & Holtz 1990). The present paper will refer to melts produced under all of those conditions as Quasi Tuttle & Bowen (QTB) melts.

Bowen had been the chief proponent of a magmatic origin for granites. He took the view that granites result from fractional crystallisation of basaltic magma, perhaps somewhat modified by the solution of granite and other salic material (Bowen 1949). He did not regard granite magmas as likely to be primary, but noted (Bowen 1947) that studies showing that granite is a late-crystallising residuum of fractional crystallisation imply that it would, likewise, be an early product of 'selective fusion' of appropriate material, which we now generally call partial melting. However, the unequivocal establishment of the magmatic nature of granites by Bowen and his colleagues in fact rapidly lead to the almost universal recognition that granites are not only magmatic, but also that, generally, those magmas are primary. Such concepts were incorporated by Read (1948) in his Granite Series, which evolved out of his earlier view that granites are non-magmatic. The Granite Series proposed that all granites are related to each other in their process of formation and are the result initially of the partial melting of metasedimentary rocks. These are what we now call the S-type granites (Chappell & White 2001). It is significant that Read did not recognise the existence of related volcanic rocks, which are now recognised as an important component of such magmatism.

The restriction in compositions of felsic granites is illustrated by the data from the granites of the LFB also represented in Figure 1. These comprise 445 analysed samples from that region containing more than 90% of the three normative components *Qz*, *Ab* and *Or*, from a total of 2220 analyses of granites and other rocks with which they are compositionally gradational. Most haplogranites are peraluminous, those of S-type origin more strongly so, and therefore, the analyses have been selected on a normative corundum-free basis, so as not to discriminate against the S-type granites. The samples which are plotted in Figure 1 include 228 granites which have been classified as I-type, 174 as S-type and 22 as A-type, with 21 unassigned. These data again show the relatively restricted range of haplogranite compositions, in terms of the *Qz*, *Ab* and *Or* components. The point could be made that the compositions represented in Figure 1 are from only one region, but the result would have been very similar if felsic granites from any region were plotted. The LFB simply provides a large number of modern analyses of such rocks to serve as the basis for a more general discussion. Also, the LFB compositions are from a variety of source rocks. They include the products of partial melting of older igneous rocks and sedimentary rocks, in which the partial melts underwent little or no compositional change. Some resulted from fractional crystallisation of less felsic melts, both I- and S-type. We will now examine the processes which constrain those compositions.

2.1. Felsic granites as products of fractional crystallisation or fractional melting

The observations of Tuttle & Bowen (1958) showed that the haplogranites must have attained their compositions within the Earth's crust, where quartz and feldspars are stable. It has been noted above that this could involve an origin by either fractional crystallisation or fractional melting. Granites which formed in both ways undoubtedly occur, but the present author adopts the view that most of the more felsic granites are products of partial melting of the crust, with compositions which may have been modified to a degree by fractional crystallisation. Such an origin, rather than a complete process of fractional crystallisation from initial mafic melts, is favoured in the general case for the following reasons.

2.1.1. Direct observations of rocks of the deep crust. Studies of metamorphic rocks show that the deep crust can reach temperatures high enough for quartzofeldspathic rocks to partly melt under QTB conditions. Also, we can make direct observations of partial melting of the deep crust (e.g. in migmatites), although the leucosome compositions may (e.g. Kalsbeek *et al.* 2001) or may not (e.g. Sawyer 1996) closely match those of granites.

2.1.2. Occurrence of S-type granites. S-type granites are found in many fold belts. These have compositions which show that they were derived largely or entirely from sedimentary source rocks. They clearly are not the products of fractional crystallisation of basalt, even with extensive contamination by sedimentary materials. In eastern Australia, S-type granites occur in each of the three fold belts of early-, mid- and late-Palaeozoic age. They comprise a little more than half of the 63 000 km^2 of granites in the mid-Palaeozoic LFB, and related volcanic rocks are also very important in that region. Elsewhere, they occur widely in Palaeozoic fold belts, such as the Caledonian and Hercynian belts of Europe extending into North America. There is argument about the proportion of basaltic material that might have been present in the source materials for such granites [e.g. the contrasting views of Collins (1998) and Chappell *et al.* (2000)], but even if there was a component of fractionated basalt among the source components, there would be general agreement that the source comprised dominantly solid metasedimentary materials which were partially melted. The occurrence of large bodies of granite formed from S-type magmas tells us that partial melting of the crust on a large scale to produce granite batholiths is possible.

2.1.3. Relative abundance of felsic and mafic rocks. Granites and rhyolites dominate over gabbros and basalts in most plutonic/volcanic rock provinces. There are granite terranes in which the granitic rocks are accompanied by abundant mafic rocks; for example the western half of the Peninsular Ranges Batholith of southern and Baja California (Silver & Chappell 1988). But there are many more areas in which mafic rocks are completely or almost completely absent. Such a comment applies fairly generally to the S-type granite occurrences listed above. In the LFB, a large area containing both S- and I-type granites, the amount of gabbro is very small. Among the 843 named plutonic units on the map of that area (Chappell *et al.* 1991), 26 are gabbro, all of which are relatively small with the largest being 14·4 km^2 in area, with a combined area of 71 km^2. That is slightly more than 0.1% of the total area of plutonic rocks. There is a small additional area of gabbroic rock associated with the high-temperature granites of the Boggy Plain Supersuite, but they are gradational in the field into granites, and are cumulate rocks from a less mafic melt and do not represent primary mafic compositions (Wyborn *et al.* 2001; Chappell & Wyborn 2004). The classic use of fractional crystallisation as a mechanism to account for the production of a series of granitic rocks was that of Nockolds (1940) for the Garabal Hill–Glen Fyne complex (32 km^2) of Scotland. However, granitic rocks in that complex are much more voluminous than their mafic associates. The ratio of areas of granodiorite to pyroxene-mica diorite, Nockold's presumed parent, at Garabal Hill–Glen Fyne, is approximately 100:1. Although such gabbroic rocks are more common among the plutonic rock suites of Scotland than they are in many other granite terranes, a dominance of felsic rocks is typical. While the mafic rocks of that region were probably derived from material that contributed to the partial melting of the crust giving the more felsic rocks, the amount of material that fractionated mafic melts contributed to the mass of the felsic granites was, at most, very small.

2.1.4. Lack of fractionation of trace elements. Trace elements are not strongly fractionated in most felsic granites and their abundances are consistent with the rocks forming from melts which were either primary or only slightly fractionated from primary partial melt compositions. Many felsic granites with major element QTB compositions do not have the elevated Rb contents and lowered Sr contents which would indicate feldspar fractionation, although some do, of course. The rare-earth elements (REE) are sensitive indicators of fractional crystallisation of haplogranite melts. Monazite is a ubiquitous mineral in S-type granites and its removal during fractional crystallisation removes Th and the light REE very rapidly (Chappell 1999), but many felsic S-type granites do not show this feature and cannot have undergone fractional crystallisation to any extent. Those S-type granites which have undergone monazite fractionation are compositionally quite distinctive, with dramatic decreases in the abundances of Th and the light REE down to about one-tenth of the unfractionated levels, but they comprise a very small fraction of all S-type granites. Again, Y and the heavy REE are observed to increase very rapidly by factors of two or more in felsic I-type melts during fractional crystallisation (Chappell 1999), but many more felsic I-type granites show no sign of such enrichments. And when fractionated I- and S-type granites are seen, their compositions can often be traced to less-fractionated granites as the primary composition, not to mafic rocks.

The linear trends on variation diagrams which characterise the low-temperature granite suites often extend to haplogranite compositions and elements whose abundances are sensitive to fractional crystallisation, such as Rb, Sr and Y in I-type suites, are generally not displaced from that trend. For example, this is the case for Sr in the Glenbog Suite of the LFB, which ranges in SiO_2 content from 66·2% to 73·8%. Three analysed rocks from the most felsic unit of the Moruya Suite, the Bodalla Monzogranite, have Sr contents of 255, 123 and 119 ppm, and SiO_2 values of 71·9%, 74·9% and 74·7%. The first of these lies very close to the linear trend for the Moruya suite that extends from 60·1% SiO_2. The displacement of the other two samples from that trend is the result of fractional crystallisation of feldspars, and fractionation is further supported by Y values of 14, 25 and 23 ppm for those three rocks. The first sample from Bodalla represents the composition of the primary unfractionated partial melt. Restite crystals separated from that melt to produce the compositional variation seen in the more mafic units of the Moruya Suite on the one hand, with the much less abundant fractionated granites on the other. Variation diagrams for Sr in the Glenbog and Moruya Suites were provided by Chappell (1996a).

Granites with fractionated trace element abundances generally show petrographic evidence for late-stage hydrothermal activity; for example, in many 'tin granites'. This is not unexpected since H_2O abundances must increase in melts undergoing fractional crystallisation. However, most felsic granites are relatively unaltered, although some are not, which would be consistent with lower H_2O contents related to an origin by partial melting rather than fractional crystallisation.

2.1.5. Evidence for low temperatures. Many felsic granites which are cogenetic with less felsic granites do not lie at the end of a liquid line of descent, and therefore, the melts themselves must be regarded a primary component of that suite of rocks. These are the low-temperature granite suites of Chappell *et al.* (1998, 2004) in which the melt phase of the magma involved in their production existed at low magmatic temperatures and had a felsic composition. World-wide, these low-temperature granites appear to dominate over high-temperature granites.

2.2. Felsic rocks in volcanic arcs

Smith *et al.* (2003) described widespread felsic volcanism in the intra-oceanic Kermadec arc of the SW Pacific. They ascribed the origin of those rocks to crustal anatexis since such processes can account for features of those rocks which are difficult to explain by fractional crystallisation. The volcanic rocks have SiO_2 contents in the range from 64% to 71% and K_2O contents up to 2·2%, and very low Rb contents from 7 to 43 ppm, in the analyses quoted in that paper. Such compositions are appropriate for products of partial melting of mafic source rocks in primitive crust. Such an origin is consistent with a more widespread origin of felsic magmas by partial melting within the crust rather than fractional crystallisation of basaltic parents.

2.3. Cumulative haplogranites

Tuttle & Bowen (1958) showed that haplogranites have the compositions of hydrous melts occurring in equilibrium with quartz and feldspars. It is generally assumed that haplogranites formed by the solidification of such a melt through crystallisation as a closed system (equilibrium crystallisation). However, the occurrence of sequences of felsic granites with progressive changes in minor element abundances which represent evolved melt compositions (e.g. Chappell & White 1998; Chappell 1999) implies that cumulative haplogranites must also exist, even though they are not often recognised. Such rocks would be produced by the separation of dominantly quartz and feldspars which precipitated under eutectic conditions from a QTB melt. Such rocks would contain approximately the same relative proportions of *Qz*, *Ab* and *Or* as rocks formed by the equilibrium crystallisation of that same melt, with the precise proportions dependent on the *An* and H_2O contents of the melt. Therefore, these cumulative rocks would plot in the same distinctive fashion on the *Qz-Ab-Or* diagram. Thus, such figures cannot be used as a simple criterion for a haplogranite having formed by the equilibrium crystallisation of a melt. While the relative amounts of the *Qz*, *Ab* and *Or* components need not be affected by the presence of accumulated crystals, the abundances of Ca and some trace elements would be. Plagioclase crystals in equilibrium with a felsic melt will be relatively *An*-rich, and accessory minerals such as monazite may be present. Rocks formed by the accumulation of such minerals will show related chemical features. Cumulative rocks are rare at the present levels of exposure of the LFB, although they must occur at depth in some places. They are more common in some other granite terranes and they are the subject of a separate communication (Chappell & Wyborn 2004).

3. Causes of variations within granite suites

There is far less agreement about details of the origins of the less felsic granites, although they are clearly magmatic. Many processes have been proposed to account for the details of formation of such granites and the generation of compositional variation within granite suites. All of these processes probably operate to some extent, and can be firmly established in particular examples. The question is: On what scale and how frequently did a particular process operate? Mechanisms which have been determined in one or a few cases should not necessarily be regarded as general processes. Neither should those processes established in small areas be regarded as necessarily applying to granite bodies of batholithic dimensions. In approximately the sequence in which these different processes could operate to produce compositional variation within granite suites, they are:

(1) variation inherited from heterogeneous source rocks;
(2) varying degrees of partial melting;
(3) magma mixing and/or mingling;
(4) restite fractionation (crystal fractionation of entrained crystals);
(5) fractional crystallisation (crystal fractionation of precipitated crystals);
(6) assimilation or contamination; and
(7) hydrothermal alteration.

These processes all effect granite compositions at some scale. Each could operate alone, or else simultaneously [e.g. (5) and (6) in the AFC process], or sequentially [e.g. (4) followed by (5), or (5) followed by (7)].

Apart from (2), these different processes were examined in some detail at a previous Hutton Symposium (Chappell 1996b), and the reader is referred to that discussion. The two forms of crystal fractionation [(4) and (5)], and more briefly, the varying degrees of partial melting (2) will be considered here as part of the 'unified model'. Magma mixing and/or mingling is not assigned a significant role in that model and the reasons for that are summarised below (see section 3.2).

3.1. Crystal fractionation

Crystal fractionation, either of entrained (4) or of precipitated (5) crystals dominates in producing variation within granite plutons, and in the suites to which such compositionally variable plutons belong. Varying degrees of partial melting of the source rocks (2) probably contribute to, and may dominate, variations within those low-K or 'tonalitic' suites in which most of the variation occurs between the plutons of a suite, with relatively little variation within plutons (see section 6.5 below).

The process of restite crystal fractionation leads to changes in composition through the removal of entrained crystals residual from partial melting of the source (Chappell *et al.* 1987) and is characterised by 'linear' trends on variation diagrams. It is characteristic of the low-temperature granites, i.e. of many I-types and all S-types, and may be followed by low-temperature fractional crystallisation of the separated melt in both types.

Fractional crystallisation is the classic process in which the precipitation and removal of crystals from a largely or completely molten magma leads to a series of more evolved compositions. This occurs among the high-temperature granite magmas and sometimes in the late stages of evolution of the low-temperature granites. It is characterised by curved trends on element variation diagrams. It is an important process in the concentration of metals and H_2O at the magmatic stage, and is more likely to lead to mineralisation (White & Chappell 2004).

3.2. Magma mixing and mingling

Magma mixing and/or mingling is a mechanism that attracts much support, but is regarded here as a process that may be locally important but has no significant role in producing larger scale variations. An important feature of many granite suites used as one argument for such a process are the 'linear' compositional variations which are a distinctive feature of many low-temperature granite suites. The fact that such variations are not seen among the high-temperature granite suites would seem to rule out this process for those rocks. When the variations within the low-temperature suites are examined in detail, a similar conclusion must be drawn, at least for the granites of southeastern Australia. In that region, correlations are observed between the relative abundances of elements at the two extremes of compositions in rock suites. For example, the sequence of increasing abundances of Sr in the more felsic granites of individual suites of the Bega Batholith is the same as for the more mafic granites of those suites. This precludes an origin by mixing or mingling of previously unrelated materials (Chappell 1996a) and is consistent with the suites evolving by the 'unmixing' of felsic partial melt from mafic restite, which would be consistent with that correlation between the compositions of the two 'end-members'. This conclusion is supported by more limited isotopic data which show which there is no systematic variation in isotopic properties as chemical compositions change within those rock suites (Chappell & McCulloch 1990), although there are distinct isotopic differences between the suites.

It could perhaps be argued that the granites of southeastern Australia are unusual in this respect and that large-scale mixing and/or mingling could be important in low-temperature granites in other places. While these granites may well have some aspects which are not commonly found elsewhere, they do have diverse compositions which indicate derivation from a variety of source rocks. The granites display features which are commonly taken as evidence of mixing or mingling processes among plutonic rocks, such as linear patterns of chemical variation, the development of local hybrid rocks and the presence of mafic enclaves. They also show patterns of isotopic variation on a regional scale that could be taken as evidence for mixing processes (Keay *et al.* 1997). Despite these features, the granites of that region, as we have seen, have compositional characteristics which preclude magma mixing or mingling as significant contributors to development of the large-scale variations. In view of the mechanical difficulties of mixing or mingling two components on a large scale, the view is taken that this is likely to be the case elsewhere. These arguments do not exclude the possibility that mixing of different components may have contributed to the compositions of the source rocks of various suites, and the 'unified model' includes that possibility (see section 8 below).

4. Origin of low- and high-temperature granites

There are two contrasting patterns of Zr variation in granite suites of southeastern Australia, and this led to recognition of the low- and high-temperature granite groups by Chappell *et al.* (1998, 2004). Zircon was saturated throughout the evolution of low-temperature granite suites, which results in Zr abundances plotting on linear trends on Harker diagrams, generally decreasing with increasing SiO_2. In contrast, among the high-temperature granite suites, zircon was not saturated in the magma from which the more mafic rocks (less than ~68% SiO_2) formed, at which compositions Zr abundances increase with increasing SiO_2. In contrast, zircon was saturated at more felsic compositions, and consequently, Zr falls in abundance as the rocks become more felsic. We must now ask why granites have formed at varying temperatures, particularly when it is considered that this is not a function of the composition of an individual granite? For example, tonalites of the Cobargo Suite of the LFB apparently formed at temperatures ~800°C and are 'low-temperature', whereas Cordilleran-like tonalites formed at temperatures greater than 1000°C and are 'high-temperature'. Nevertheless, both types can have very similar major element compositions (see Chappell *et al.* 2004, table 2), and hence, similar temperatures for the start of melting (solidus), and when the H_2O contents of the melts are comparable, of crystallisation (liquidus). The two types cannot be discriminated using major element compositions.

The answer, as with so many things related to granites, lies in the source rock compositions. Granites will be low-temperature in nature if there are sufficient low-temperature melt components in the source region to form an extractable magma at low magmatic temperatures. If one of the low-temperature melt components is low in abundance, then the source is said to be critically deficient in that haplogranite component. In that case, melting must continue to higher temperatures if granite magma is to be produced, and a high-temperature granite then results. The source may have become critically deficient in a haplogranite component (relatively infertile) as a result of igneous, sedimentary or metasomatic processes which occurred prior to the partial melting event. Or it may occur if a component is removed from the solid source materials by partial melting before magma can be extracted.

5. Partial melting at low magmatic temperatures

5.1. Low-temperature haplogranites

To produce a low-temperature I- or S-type haplogranite by partial melting, the source rocks must contain sufficient *Qz*, *Ab* and *Or*, with H_2O, to form either an extractable haplogranite melt, or else an extractable magma containing restite crystals from which a haplogranite melt can later fractionate by removal of those crystals. Such a source composition cannot be too far removed from the central part of the *Qz-Ab-Or* diagram (Fig. 2) and sufficient H_2O must be present. Such source rocks would be broadly quartzofeldspathic, and the H_2O would generally be present in hydrous minerals, of which biotite would generally be the most important immediately prior to melting (e.g. see Whitney 1988). Granites formed in this way are reasonably abundant in the LFB, and examples are the Maffra (I-type) and Happy Jacks (S-type) granites for which analyses were listed by Chappell (1999).

Of course, some haplogranites are, as Bowen (1949) considered, the low-temperature products of fractional crystallisation of higher temperature melts. In the LFB, there are excellent examples of such fractionated haplogranites among the felsic rocks of the high-temperature Boggy Plain Supersuite (Wyborn *et al.* 2001), although their source melts were probably intermediate in composition, rather than basaltic, because the mafic rocks with which they are associated had a cumulate origin (Wyborn 1983; Chappell & Wyborn 2004) and are not primary magmatic compositions.

5.2. Restite-bearing low-temperature granites

To produce an extractable magma containing crystals of restite, the amount of melt must exceed a critical melt fraction (van der Molen & Paterson 1979) or second percolation threshold (Vigneresse *et al.* 1996) so that the restite framework breaks down. To do that, the source rocks must contain enough of each of *Qz*, *Ab* and *Or* to form the required amount of melt. As before, the bulk source composition cannot be too far removed from the central part of the *Qz-Ab-Or* diagram, with H_2O also present. This is indicated by the positions of the less felsic low-temperature Moruya, Moonbi and Bullenbalong Suites in Figure 2. Partial melting again takes place at low temperatures, and in this case, the restite does not completely disengage from the melt, if at all. At least initially, the magma probably moves *en masse* as a mixture of crystals and melt that may later fractionate restite from melt to produce a range of rock compositions. A discussion of magma mobility under these conditions has been provided in section 1 of Sawyer (1996).

Under conditions where magma entrains crystals of restite, the compositions of the more mafic granites will reflect those of their source rocks and crystals of older zircon would always be present, although ages may sometimes not be sufficiently older than the magmatic event for those older ages to be recognised. Low-temperature granites of this type are the dominant plutonic rocks of the LFB, and their associated volcanic rocks are also important. Among the I-type granites, they are exemplified by the Moruya Suite (Griffin *et al.* 1978) and other suites of the large Bega Batholith (8940 km^2), for which the most mafic rocks are tonalites and rare quartz diorites containing a little less than 60% SiO_2. In more potassic systems, the most mafic rocks are monzonites and monzodiorites with similar SiO_2 contents, such as those of the Moonbi Suite of the younger New England Fold Belt (Chappell 1966, 1996a).

Partial melting at low temperatures produces a wide range of S-type granites, depending on the composition of the source rocks. At temperatures sufficient to produce biotite breakdown, magmas such as those of the Bullenbalong Supersuite of the LFB are formed (White & Chappell 1988). The most mafic S-type granites of that supersuite contain ~65% SiO_2 and more than 20% biotite, and have compositions, both chemical and mineralogical, close to those of their source materials. The originally mafic magmas may evolve by restite fractionation to produce a wide range of rock (including volcanic) compositions.

The concept of restite fractionation has been controversial ever since it was first proposed by White & Chappell (1977); for example, see Wall *et al.* (1987) and Collins (1998). However, the presence of inherited zircon in many granites implies that they formed at low magmatic temperatures (Chappell *et al.* 1998, 2004). Suites of these low-temperature granites must have evolved by restite fractionation, at least at more mafic compositions. In some cases, fractional crystallisation operated at more felsic compositions; for example, as in the Koetong Suite of the LFB (Chappell & White 1998), for which the initial magma probably formed at slightly higher temperatures (see section 5.3 below).

5.3. Slightly higher temperatures of partial melting

If there is a small deficiency in the source rocks of one of the components of a minimum-temperature melt, then melting may continue to slightly higher temperatures, at a melt composition further from the component for which the source rocks have become depleted, illustrated schematically by the relative positions of the Jindabyne, Inlet and Koetong Suites in Figure 2. Such melts will also contain less SiO_2, and also more CaO, MgO and FeO, for example. In these early stages of depletion of a component in the source rocks, restite will still be present in the magma, including older zircon. Evolution of the magma may take place by restite fractionation and by fractional crystallisation after the restite has been removed. These are still low-temperature granites in the sense of Chappell *et al.* (1998), although it may be desirable to place them in a mid-temperature group in the future, when their overall characteristics are better defined (Chappell *et al.* 2004).

The Jindabyne Suite of the LFB (Hine *et al.* 1978) comprises nine plutons of I-type granodiorite to tonalite with SiO_2 contents in the range from 56% to 68%. Unlike the low-temperature I-type Moruya Suite, the rocks of the Jindabyne Suite do not extend to SiO_2 contents greater than 70% and the P_2O_5 values do not decrease with increasing SiO_2, as is shown in figure 6 of White & Chappell (1977) and by Chappell *et al.* (2004). Hine *et al.* (1978) ascribed these differences to a higher temperature of partial melting to produce what they called a non-minimum temperature melt. However, the Jindabyne Suite is not high-temperature because it contains calcic cores of plagioclase crystals, interpreted as restite (Chappell & White 2004), the compositional variation was dominantly the result of restite fractionation, and it contains inherited zircon crystals (I. S. Williams pers. comm.). The Inlet Monzonite pluton of the New England Fold Belt (Chappell *et al.* 1998) is a small pluton (12·5 km^2) that is a potassic analogue of the Jindabyne Suite. Formation of the non-minimum temperature Jindabyne and Inlet Suites is ascribed to the disappearance of *Or* and *Qz* components, respectively, from the residual mineral assemblage during partial melting,

The mineralised S-type Koetong Suite of LFB (Chappell & White 1998) formed after melting to higher temperatures, presumably because of a deficiency in *Ab* as a result of the source being slightly more pelitic. The more felsic rocks of that suite evolved by fractional crystallisation, which was an essential precursor to mineralisation. This suggests that a slightly higher temperature of partial melting may be necessary for the concentrating of Sn, W and U, for example, by fractional crystallisation.

6. Production of the high-temperature granites

We have seen that there are four essential components of a source rock, *Qz*, *Ab*, *Or* and H_2O, for the production of a haplogranite melt by partial melting. It follows that there are four end-member cases for which source rocks would not form an extractable low-temperature magma because they are or become critically deficient in one of those four components. These circumstances are illustrated in Figure 2, and each of these cases will now be discussed.

6.1. Source rocks critically deficient in *Qz*

If the source rocks are critically deficient in the *Qz* component, then melting will continue to much higher temperatures by dissolving more of the *Ab* and *Or* components of the source rocks, as well as more CaO, MgO and FeO, for example, leading to more mafic compositions. The melt compositions will be monzonitic or monzodioritic (Fig. 2), and the magmas, being less viscous and hence free of restite, will generally evolve by fractional crystallisation. Old zircon will not be found in these high-temperature granites, except as xenocrysts in felsic fractionated melt. Both the source rocks and the granites are broadly monzonitic. In the LFB, such rocks are represented by the members of the Boggy Plain Supersuite of Wyborn *et al.* (1987).

6.2. Source rocks critically deficient in *Ab*

Source rocks which are critically deficient in *Ab* are mature detrital sedimentary rocks since, when plagioclase is destroyed during weathering, part or most of the *Ab* component is lost. The abundances of the three other haplogranite components would generally be increased by weathering with *Qz*, and *Or* plus H_2O derived from high-temperature products of clay minerals, available in these rocks. Hence, the abundance of *Ab* appears to be the critical factor in this case. If feldspars are absent or low in amount, the low Na contents will make these rocks infertile in terms of granite production, although *Ab* may be present in the restite mineral assemblage as a component of plagioclase crystals, which may be more Ca-rich if some melt has been produced. Since S-type granites that do not contain inherited zircon are not known at the present time, it is possible that high-temperature S-type granites do not exist, so that the corresponding part of Figure 2 is represented by infertile pelites and high-K leucosomes. Most of the exposed Ordovician sedimentary rocks of the LFB, which form the general matrix to the exposed granites of that region, are in this compositional category, and those rocks would generally have been infertile during production of the granites. If more feldspar were present, either in a feldspathic greywacke (Chappell *et al.* 2000) or as igneous material (Gray 1984; Collins 1998), then these rocks may be fertile during partial melting.

6.3. Source rocks critically deficient in *Or*

When *Or*, in part supplied by the breakdown of mica, becomes depleted during the partial melting event, the composition of the melt moves away from the composition of that component with increasing temperatures (Fig. 2). This is by far the most common case of high-temperature granite magmatism, applying as it does to the Cordilleran-like tonalites, the TTGs, and perhaps, to some plutonic rocks of the island arcs. Both the source rocks and the derived granites are relatively low in K. Among southeastern Australian granites, the tonalites and granodiorites of the Clarence River Supersuite of the New England Fold Belt (Bryant *et al.* 1997) provide an excellent example of these rocks. The TTGs are an important component of the Archaean plutonic rocks of Western Australia, which include the rocks to which that acronym was first applied by Jahn *et al.* (1981).

The Clarence River rocks are compositionally very similar to the dominantly tonalitic rocks of the Peninsular Ranges batholith, particularly the western part. Silver & Chappell (1988) described the rocks of that batholith as calcic, and pointed to the contrast with the more potassic central and eastern parts of the Sierra Nevada batholith to the north. Variability among the granitic rocks of the Cordillera is further illustrated by the Coastal Batholith of Peru (Pitcher *et al.* 1987), which includes substantial amounts of tonalite, but overall, is more potassic than the Peninsular Ranges batholith and is calc-alkaline in character rather than calcic. The differences in K contents of Cordilleran granites directly reflect

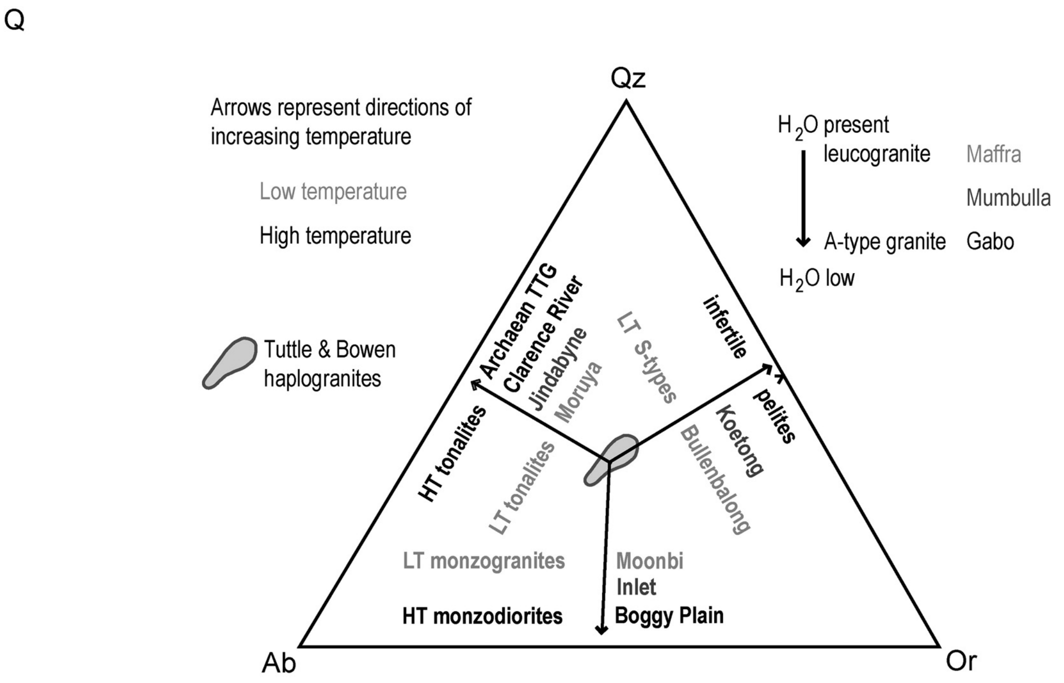

Figure 2 A schematic representation of the relationship between some granite types, and the relative proportions of the four haplogranite components *Qz*, *Ab*, *Or* and H_2O in the source rocks. The shaded area in the centre of the figure is the haplogranite field of Tuttle & Bowen (1958), also shown in Figure 1.

corresponding differences in their source rocks. In all cases, however, the *Or* component in the source rocks became depleted during partial melting, although at a later stage of melting in the more potassic source rocks. This resulted in the formation of plutonic and volcanic rocks which are dominantly, at least, high-temperature in nature. The different K contents of the source rocks and the derived melts was significant for the later high-level evolution of these rocks (see section 6.5 below).

6.4. Source rocks in which the availability of H_2O is restricted

If the source rocks contain sufficient *Qz*, *Ab* and *Or*, but the amount of H_2O available to enter the melt is restricted, at least at lower temperatures, then melting may continue to higher temperatures to produce a high-temperature or A-type haplogranite melt. Such a melt will initially be very felsic and contain similar proportions of *Qz*, *Ab* and *Or* to the low-temperature haplogranites, but will be enriched in certain trace elements, e.g. Zr, Ga, Y and the REE, because these are likely to be more soluble in the melt at higher temperatures and/or lower water contents. Melting may continue to higher temperatures, at which time the A-type melts become slightly less felsic. The LFB contains some excellent examples of A-type granites, although they comprise only 0.6% of the total area of granite exposures. They were initially described in the LFB by Collins *et al.* (1982), and have been discussed further by King *et al.* (1997, 2001). The major element compositions of the A-type granites, being close to the QTB composition, are distinctive but not diagnostic. In cases where these rocks can be distinguished, it is on the basis of their trace element compositions, such as high abundances of Zr (~500 ppm in the Gabo Island and Danswell Creek Suites of the LFB), which show that they formed at higher temperatures than other felsic granites. Those A-type granites of the LFB which are interpreted to represent primary unfractionated compositions have calculated zircon saturation temperatures (Watson & Harrison 1983) close to 900°C. The temperatures of formation of the A-type granites are generally lower than those of other high-temperature granites. Also, the criterion used for recognising those other high-temperature granites, i.e. the absence of zircon in more mafic members of rock suites, is not applicable to such felsic compositions. Fractionated haplogranites which are known to be A-type from their close association with unfractionated A-type granites have calculated zircon saturation temperatures down to about 750°C and are indistinguishable from fractionated low-temperature haplogranites on a purely compositional basis; for example, the Dunskeig A-type granite of King *et al.* (2001).

6.5. Variations within tonalitic and higher-K suites

The Marulan Batholith of the LFB (Carr *et al.* 1992) illustrates an important feature of many high-temperature tonalite suites, i.e. in contrast to the higher-K suites, the amount of variation within individual plutons is restricted, and the within-suite variation is largely provided by variations between different plutons. Large and compositionally uniform plutons of tonalite and granodiorite are a feature of the Peninsular Ranges batholith (Silver & Chappell 1988), and L. T. Silver (pers. comm.) proposes that the variation within cogenetic granites resulted from varying degrees of partial melting of the source rocks, rather than fractional crystallisation (see section 3 above).

In contrast to the low-K plutons, those of the high-temperature suites with higher K contents are almost invariably zoned. Wyborn *et al.* (2001) have pointed out that the higher amounts of K mean that the melts would contain more low-melting components. Therefore, if cumulate rocks are forming (e.g. at the walls of a pluton), those components would have too great a bulk to be completely retained between the cumulus minerals, which means that some melt would be displaced back into the main body of melt, modifying its composition. During the crystallisation of tonalite melts, that low-temperature interstitial melt has less bulk and would be retained between the cumulus minerals, and hence, captured within the solidification zone, so that the remaining melt does not change in composition. It may be because the higher-K magmas have a greater propensity to fractionate, rather than any geochemical association between various elements, that results in those magmas being more commonly associated with significant mineralisation.

Atherton & Sanderson (1987) have ascribed compositional variations within some units of the Coastal Batholith of Peru to differentiation (fractional crystallisation) at or near the present level of exposure. The operation of that process is supported by the presence of some concentrically and gradationally zoned plutons in which fractionation occurred *in situ*, while in other cases, separate pulses of magma came from below. Those authors point out that, under those circumstances, the composition of the original magma is not absolutely clear. However, the presence of more K-rich fractionated rocks would imply that it was more potassic than was the case for the tonalitic rocks of the Peninsular Ranges batholith. These observations suggest that the parental magmas of the Coastal Batholith might, at least in some cases, have been sufficiently potassic to undergo fractional crystallisation along the lines proposed by Wyborn *et al.* (2001). In that case, some of the tonalites of the Coastal Batholith could be cumulate rocks, or *cumulate tonalites*, in contrast with the *primary tonalites* of the Peninsular Ranges batholith. Both of these types contrast with the low-temperature *restitic tonalites*, such as those of the Moruya Suite (see section 5.2 above).

7. Granite compositions and the tectonic environment of formation

There has long been an aspiration to link granite compositions and the tectonic conditions of their formation, perhaps most notably by Pearce *et al.* (1984), and more recently, for example, by Barbarin (1999). In contrast, the present paper ascribes the compositional characteristics, at least of the more common types of granites, to the compositional features of their source rocks. Such a compositional nexus does not exclude possible tectonic correlations. However, it must be realised that, to the extent that compositions can be used as tectonic indicators, it is likely to be specifically the source rocks and their conditions of formation which are being assessed, as Chappell & Stephens (1988) pointed out.

Among the more abundant types of granites, it is probably the dominant tonalites and low-K granodiorites of much of the Cordilleran environment which have the closest relationship to a particular tectonic environment. Those rocks have, as their source rocks before them had, compositional features which reflect their primitive nature as relatively new components of the crust. The I-type granites of the LFB include a few rocks with very similar compositions, such as the mafic members of the Moruya Suite (Griffin *et al.* 1978), but they did not necessarily form in an analogous tectonic environment. Rather, they reflect the compositions of their source rocks, which may have previously been produced in a Cordilleran-like environment. Patterns of chemical variation show that the Moruya magmas were all saturated in zircon, that they are low-temperature varieties and that the suite includes significant amounts of felsic granodiorite, all distinct differences from most Cordilleran granites. This illustrates the difficulty of simply using bulk compositions of granites as indicators of tectonic conditions without considering their broader rock associations and petrogenesis. More broadly, Barbarin (1999) stated that most I-type granites of the LFB belong to his 'amphibole-rich calc-alkaline granite' or ACG group. He also assigned the main granite components of the western margins of the American continents to that group, but they are distinctly different from the I-type granites of the LFB, which are mostly low-temperature, on the whole distinctly more felsic and potassic, and in places, associated very closely in the field with abundant S-type granites.

8. A unified model of granite genesis

A unified model can be summarised as follows:

1. Plutonic and volcanic rocks which are associated in space and time are generally cogenetic, and may be comagmatic. Compositions of the two may be the same or they may be complementary.
2. Most granites and related volcanic rocks were formed from processes which were initiated by heating and partial melting of the crust.
3. To a significant degree, both the chemical and physical properties of magmas which formed in a particular case were largely predetermined by the composition of their source rocks. Each source rock responds to heating in a way that is a physicochemical expression of its composition. This applies most precisely if the source rocks behave as a closed system, but it is still relevant in systems which are open for some components (e.g. H_2O), or to any mixed sources.
4. In turn, those magmatic properties largely determine the evolution of the magma.
5. Although granites show a great diversity in their compositions and in details of their evolution, those features mostly relate back to the compositions of their source rocks, which are the unifying element in granite genesis.
6. Source rock compositions are the 'genetic code' for granites which largely predetermine the evolution of a granite magma. However, features inherited from the sources may be partly modified by environmental factors, such as country rock compositions and structures, and the stress regime.
7. Tectonic conditions do not directly determine granite compositions, but may affect them indirectly by an association with distinctive source rock compositions and by providing heat.
8. In detail, individual samples of granite evolve in a many ways, but it is important to distinguish between processes which occur commonly and on a large scale, and those that do not. Crystal fractionation, either of entrained or previously precipitated crystals, appears to be the most common process for compositional evolution. For some conditions, it is likely that diverse melt compositions result from varying degrees of partial melting of source rocks with similar compositions.

9. Acknowledgements

The author is grateful to the organisers of the Fifth Hutton Symposium on the Origin of Granites and Related Rocks for their invitation to present this paper at the opening session of that conference in Toyohashi, Japan. The helpful comments of many persons, particularly Professors Penny King and Allan White, and Dr Carlos Rapela and a second reviewer, are gratefully acknowledged.

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MS received 2 December 2003. Accepted for publication 9 September 2004.