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Petrographic Discrimination of Low- and High-Temperature I-type Granites

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Abstract: The existence of two groups of I-type granites, those formed at relatively low- and high-temperatures, has been established using differences in zircon saturation and patterns of bulk compositional variation between those two groups. Granites of these two groups also show some distinctive petrographic differences. The clearest petrographic distinction between the low- and high-temperature granites is seen in the crystals of plagioclase. In all but the most felsic low-temperature granites these crystals are always complex and commonly have corroded cores, which may be as calcic as An_{80}. Core compositions are fairly uniform in composition compared with the outer parts, which display normal and oscillatory zones of varying widths. In the high-temperature granites the crystals of plagioclase are generally better-shaped with a uniform composition and lack the prominent corroded cores of the low-temperature granites. These differences are due to the fact that homogenization of plagioclase proceeds very slowly at low magmatic temperatures.

Keywords: *Ab-An* system, high-temperature granite, low-temperature granite, petrography, plagioclase cores, plagioclase zoning, restite, zircon saturation

1. Introduction

Our studies in the Lachlan Fold Belt of eastern Australia (LFB) and elsewhere have shown that I-type granites can be placed into two groups with contrasting properties and different potentials for association with mineralization. These are the low- and high-temperature granite groups of Chappell et al. (1998, 2004). The more mafic low-temperature granites contain inherited zircons, indicating that the temperature of the magma when zircons were incorporated was too low to allow dissolution because the melt phase was saturated with zircon at that temperature. In contrast, inherited zircons are absent from the more mafic high-temperature granites. The granites of these two groups have some other distinctive compositional and textural features and it is the purpose of this study to point out some of the distinctive petrographic features that correlate with the compositional differences.

High-temperature granites are by far the less abundant group of I-type granites in the LFB and are restricted to the Boggy Plain Supersuite (BPS) of Wyborn et al. (1987) and the Marulan Batholith (Carr et al., 1992), which together comprise less than 5 % of the total area of I-type granites in that region. Low-temperature granites again dominate in abundance elsewhere in the Palaeozoic fold belts of eastern Australia, but high-temperature granites are also present, e.g. the Clarence River Supersuite of the New England Batholith (Bryant et al., 1997) and its extension into southeastern Queensland.

As far as we are aware, S-type granites always contain inherited zircon, and in the more mafic rocks virtually every crystal of zircon contains an inherited core (Williams, 1995). S-type granites share many of the features both of compositional variation and textures of the low-temperature I-type granites that we are discussing here. However they will not be considered further, since they apparently do not have high-temperature analogues with which they can be compared or contrasted.

2. Compositional Differences between Low- and High-Temperature Granites

Distinctive Zr compositional trends are observed in these two groups of granites that are consistent with the differences in zircon solubility. Zr variation is always simple in low-temperature granite suites, varying in a linear fashion against SiO_2 and generally decreasing with increasing SiO_2. Zr shows more complex variations in those high-temperature suites that extend over sufficiently wide ranges in composition. It increases in abundance in the more mafic rocks with rising SiO_2 contents, conditions where zircon was not saturated in the melt and, following an inflexion, decreases in abundance at more felsic compositions, corresponding to zircon saturation. This is illustrated by Zr data for the Boggy Plain pluton of the LFB in Figure 1. In contrast, rocks of the Cobargo Suite in Figure 1, ranging from quartz diorites to moderately felsic monzogranites (58.9 to 73.0 % SiO_2), show progressively decreasing Zr contents with increasing SiO_2, consistent with zircon having been saturated in the magmas from which all of those rocks were formed.

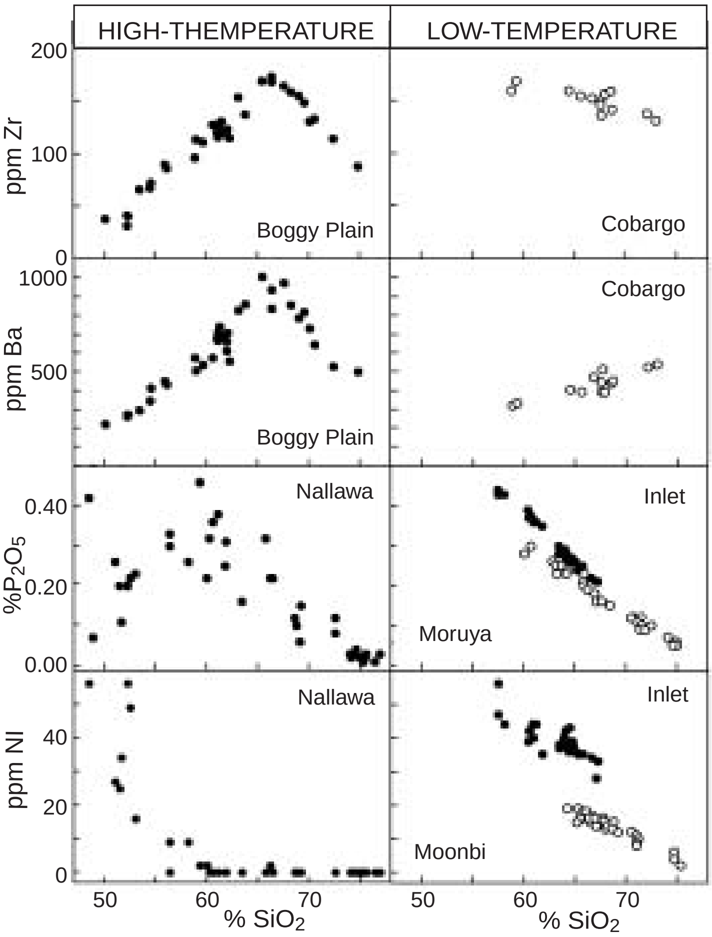

Fig. 1 Variation diagrams for high- and low-temperature granites, showing some of the contrasting patterns of chemical variation between the two groups. Note also the more restricted range in chemical composition of the low-temperature granites (see also Fig. 2). Among the low-temperature granites, filled circles represent "non-minimum temperature" melt suites and open circles are for "minimum-temperature" suites. For the Nallawa Suite, one sample containing 48.89 % SiO_2 and 108 ppm Ni has not been plotted.

The more intricate variations in compositions as seen for Zr in the high-temperature granite suites is also seen more generally with some other elements. As with Zr, the complexities may be caused by a mineral becoming saturated and hence a liquidus mineral, shown again for Ba in Figure 1, where the inflexion in the abundances of that element corresponds to early crystallization of biotite (Wyborn et al., 2001). In other cases, curved trends may result from changes in the proportions of crystallizing minerals, or in the partition coefficients of trace elements with changing physical conditions, or if elements have very high or very low bulk partition coefficients in a precipitating mineral assemblage, such as Ni in Figure 1 for the Nallawa Suite. In contrast, the low-temperature granite suites always show simple variations resulting from the removal of a fixed assemblage of restite minerals from a melt that likewise varied little in composition (Chappell et al., 1987, 2004), as discussed briefly in section *2.2.1*.

P_2O_5 always shows simple linear variations against SiO_2 in the low-temperature granites, with often a very high correlation between those two components. This is illustrated in Figure 1 by the Inlet pluton from the New England Batholith of southeastern Australia and by the Moruya Suite of the LFB. In contrast, the high-temperature rocks of the Nallawa complex (Wyborn et al., 2001), part of the BPS, show a scattered correlation between P_2O_5 and SiO_2 among the more felsic rocks, while P has low and erratic abundances in the most mafic rocks of that complex, that are cumulates (Fig. 1).

The variation of Ni in the Nallawa complex of the BPS in Figure 1 shows how that element can become depleted very quickly during fractional crystallization. Figure 5 of Wyborn et al. (2001) shows that is also generally the case for Cr in rocks of the BPS. In contrast, the granites of the Inlet and Moonbi Suites of the New England Batholith in Figure 1 show no tendency for Ni to fall as rapidly to lower levels as the SiO_2 contents increase, consistent with those variations not being the result of fractional crystallization. Cr shows similar trends both in Nallawa and in the Inlet and Moonbi Suites.

2.1. *Ranges in SiO_2 contents of the low- and high-temperature granites*

The low-temperature suites represented in Figure 1 do not range much below 57 % SiO_2 and therefore lack the equivalents of the most mafic rocks of the high-temperature suites. This is true more generally, with high-temperature suites often having wider ranges in composition, with SiO_2 contents sometimes less than 50 %. It is seen more specifically in the SiO_2 histograms for all I-type granites of the LFB in Figure 2. That figure shows that the abundance of low-temperature granites drops off very sharply below 63 % SiO_2, and such granites with SiO_2 contents of less than 54 % SiO_2 are not known in the LFB. This lack of more mafic low-temperature granites is consistent with the absence of mafic cumulate rocks among such granites (Chappell and Wyborn, 2004; Chappell et al., 2004), and points strongly to an origin of the compositional variation by a mechanism other than fractional crystallization.

2.2. *A brief petrogenetic interpretation of the two temperature groups*

Although all gradations within that range of tempera-

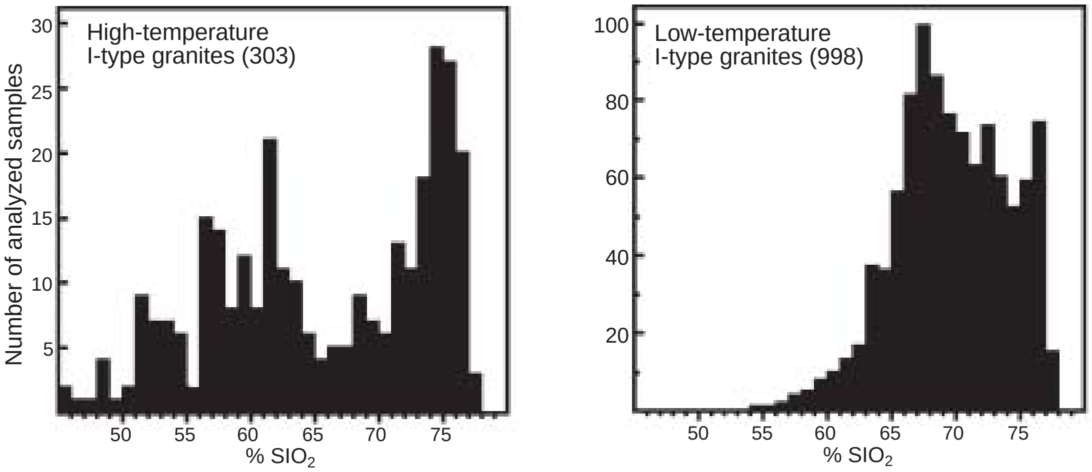

Fig. 2 Frequency histograms of SiO_2 contents of high- and low-temperature I-type granites of the Lachlan Fold Belt.

tures of granite magmas must have existed, we have made a subdivision because the two groups also correspond to significant differences in other physical properties of the magmas and in the mechanisms by which their compositions may evolve (Chappell et al., 2004) (see *2.2.1.* and *2.2.2.*). There are also petrographic differences between the two groups, which this paper discusses. The high-temperature granites are more prospective for associated mineralization and the granites of these two groups have distinctly different compositional relationships with any associated volcanic rocks (Wyborn and Chappell, 1986).

2.2.1. Evolution of high-temperature granites: These granites evolve compositionally from a magma that was initially largely or completely molten at those higher temperatures. The magmas may evolve through fractional crystallization, which process accounts for the formation of mafic cumulate rocks such as those of the Boggy Plain pluton and Nallawa Suite in Figure 1 (Chappell and Wyborn, 2004). It is also responsible for production of very felsic rocks of the BPS, both plutonic and volcanic, which have fractionated melt compositions. Such a mechanism is also consistent with inflexions and curves in the variation diagrams, seen again, for example, in Figure 1.

2.2.2. Evolution of low-temperature granites: We have long been of the view that the distinctly different patterns of variation of the type seen for the low-temperature granites in Figure 1 are the result of a different mechanism of fractionation (White and Chappell, 1977; Chappell et al., 1987). In our view the distinctive linear relations on variation diagrams, and many other features, of what we now refer to as low-temperature granites (Chappell et al., 1998, 2004) can best be accounted for by the process of restite crystal fractionation. According to that "restite model", the primary magma of these granites comprised a relatively felsic melt combined with magmatically equilibrated crystals residual from partial melting (restite). It was variations in the degree of separation of the melt and restite components that produced granites with compositions that vary in the simple way that is characteristic of these low-temperature suites. Such a process is also consistent with distinctive petrographic features of those granites, as we discuss in this paper.

2.3. The magma mixing or mingling model

The linear relations of pairs of elements for the low-temperature granites on variation diagrams could in principle be accounted for by a mechanism of magma mixing or mingling. Chappell (1996) considered that possibility for the granites of the LFB and showed that such a process would not be consistent with the differences that are observed between different suites. Specifically, in each of those granite suites the abundances of elements at the felsic and mafic extremities are correlated, so that for example, if the felsic rocks of a particular suite contain more Sr than some other suites, then that will also be the case for the mafic rocks of that suite. Such behaviour is also illustrated by P_2O_5 and Ni in the low-temperature suites plotted in Figure 1. The probability that felsic melts would so consistently choose mafic mixing or mingling partners that share the same abundances of elements relative to other suites is so low that it can be disregarded. We have no reason to suppose that the low-temperature granites of the LFB are unusual in this respect and this, together with the physical problems of mixing or mingling very large volumes of magma, has lead us to reject mixing or mingling as important or general processes that generate variations in large bodies of magma (Chappell, 1996). Mixing or mingling or both are apparently localized processes sometimes seen at outcrop scale, as indeed they are in the LFB, which should not be extrapolated to larger scales. This observation is significant for this study, as otherwise it might be possible to account for some of the features of plagioclase crystals in low-temperature granites, by a process of magma mingling.

2.4. A possible subdivision of the low-temperature granites

Two separate variation patterns are shown for both P_2O_5 and Ni in the low-temperature suites plotted in Figure 1. For the Inlet Suite the observed range in SiO_2 contents is from 57.5 to 67.2 % SiO_2 and such a limited range that is exclusive of higher SiO_2 contents is typical of what we called “non-minimum temperature” suites, when considering the Jindabyne Suite (Hine et al., 1978). It is in contrast with the “minimum temperature” suites such as Cobargo, Moruya and Moonbi (Fig. 1). All such suites, both “non-minimum temperature” and “minimum-temperature”, are low-temperature in the sense of Chappell et al. (1998, 2004) as they generally contain older zircon and they have the characteristic compositional features of such rocks, that is simple variations and a lack of the most mafic compositions which are seen in high-temperature granite suites. It is likely that it will be possible to separate suites such as Inlet and Jindabyne from the other low-temperature granites when precise criteria are developed. The significant point for this study is that the “non-minimum temperature” magmas contained significantly more Ca, Mg and Fe and some other minor elements in solution in the melt, than was the case for other low-temperature granite magmas. These elements are available for formation of the mafic minerals through precipitation, which may affect the petrographic features of the mafic minerals. In the “minimum-temperature” granites, most of those components are contained in the restite minerals and are incorporated in new mafic minerals through recrystallization and reactions with the melt.

3. Samples Studied

On the basis of the compositional criteria noted in section 2 we selected a group of samples of both low- and high-temperature granites for detailed petrographic examination. We are using the term granite in a general way for rocks within suites of dominantly granitic compositions that may include a component of gabbroic rocks. To simplify the petrographic comparisons, we have chosen samples from various suites, each containing as close as possible to 60 % SiO_2, within the range of overlapping SiO_2 contents in Figure 2. For the low-temperature granites this means that we have examined samples near the extreme mafic limit of compositions, and more typical granites of that type contain ~10 % more SiO_2. Also, for the high-temperature granites this means that we have not considered the petrographic features of the most mafic cumulate rocks (Chappell and Wyborn, 2004).

Field locations and major element analyses of the samples that we have studied petrographically are given in Tables 1 and 2. Rock types range from high-K diorite (e.g. AB126, LTS258) and tonalite (MG42, R72094) to quartz monzodiorite (G322). The most significant variation among the major elements is in K_2O contents, from 1.29 to 3.90 %. Na_2O contents are much higher, and CaO lower, in the two samples from Scotland.

Table 1 Major element analyses of selected low-temperature granites.

	AB126	83SR26	MG42	KB5	AB150	G322
SiO_2 wt%	59.30	60.01	60.13	60.18	60.55	61.23
TiO_2	0.85	0.82	0.99	0.62	0.60	0.71
Al_2O_3	17.10	15.98	16.42	17.45	15.50	15.52
Fe_2O_3	1.80	4.42	2.04	2.34	2.73	2.17
FeO	3.70		3.73	3.44	4.01	2.84
MnO	0.11	0.08	0.11	0.10	0.13	0.10
MgO	3.37	2.49	3.27	3.25	3.90	3.50
CaO	6.32	2.99	5.91	6.67	6.90	5.28
Na_2O	3.80	5.40	3.94	2.62	2.09	3.08
K_2O	1.37	2.67	1.41	1.66	1.78	3.90
P_2O_5	0.23	0.33	0.28	0.11	0.15	0.36

AB126	Quartz diorite, Murrabrine pluton, Cobargo Suite, Bega Batholith, Australia (36°26.28'S, 149°52.98'E).
83SR26	Granodiorite, Strontian complex, Scotland (total Fe expressed as Fe_2O_3).
MG42	Tonalite, Tuross Head pluton, Moruya Suite, Bega Batholith, Australia (36°00.90'S, 150°09.72'E).
KB5	Tonalite, Round Flat pluton, Jindabyne Suite, Kosciuszko Batholith, Australia (36°13.92'S, 148°40.20'E).
AB150	Tonalite, Bombala pluton, Bombala Suite, Bega Batholith, Australia (36°57.18'S, 149°11.04'E).
G322	Quartz monzodiorite, Inlet pluton, New England Batholith, Australia (30°56.49'S, 150°54.62'E).

4. Field Distinction of Low- and High-Temperature Granites

High-temperature granites may have a close association in the field with gabbros, with which they may be transitional in exposure, e.g. in several complexes of the BPS. Alternatively the granites may have a close association with mafic bodies with which a consanguinity can be established when more detailed compositional studies are made, e.g. in the Marulan Suite.

High-temperature granites containing ~60 % SiO_2 all have an even distribution of minerals compared with the heterogeneous distribution in the low-temperature granites of the same general composition. Mafic minerals such as hornblende, biotite and titanite are commonly well-shaped in the high-temperature granites, whereas in the low-temperature granites they more commonly occur in mafic aggregates or clots, which are the recrystallized products of pyroxene components of the primary restite. In some low-temperature granites, such as the Tuross Head Tonalite (MG42 in Table 1), the complexities of plagioclase crystals that are discussed in section 5 can easily be seen with a hand lens.

Table 2 Major element analyses of selected high-temperature granites.

	NB6	BP40	GH38	LTS258	BP14	R72094	LTS270	LTS203	BP6	BP15	Z7
SiO_2 wt%	56.38	58.88	59.01	59.28	59.69	61.53	59.90	61.35	61.45	62.02	64.96
TiO_2	0.71	0.66	0.70	0.82	0.64	0.84	0.71	0.95	0.57	0.56	0.60
Al_2O_3	16.30	13.80	16.43	16.14	15.69	15.71	17.20	16.28	14.20	15.15	15.97
Fe_2O_3	2.68	2.35	2.05	1.63	2.71	2.49	2.01	1.79	2.11	2.24	2.34
FeO	5.69	4.83	3.04	4.65	3.92	4.03	4.08	3.88	3.92	3.49	1.62
MnO	0.16	0.12	0.10	0.10	0.12	0.13	0.10	0.09	0.10	0.10	0.07
MgO	4.58	5.32	4.22	3.70	3.38	2.87	3.08	2.51	4.18	3.55	1.51
CaO	8.72	7.30	4.38	6.58	6.22	6.52	6.33	5.72	6.30	5.91	4.16
Na_2O	1.77	2.47	5.07	3.25	3.22	3.13	3.55	3.78	2.61	3.10	3.87
K_2O	1.29	2.14	2.77	1.46	1.71	1.41	1.37	1.54	2.57	2.17	3.21
P_2O_5	0.11	0.23	0.22	0.13	0.23	0.17	0.14	0.18	0.20	0.22	0.21

NB6	Quartz diorite, Wylora pluton, Marulan Suite, Marulan Batholith, Australia (34°50.90'S, 149°56.75'E).
BP40	Quartz monzodiorite, Boggy Plain pluton, Kosciuszko Batholith, Australia (35°50.31'S, 148°34.52'E).
GH38	Quartz diorite, Garabal Hill complex, Scotland.
LTS258	Quartz diorite. Peninsular Ranges Batholith, Baja California, Mexico (32°11.7'N, 116°09.8'W).
BP14	Quartz diorite, Boggy Plain pluton, Kosciuszko Batholith, Australia (35°50.41'S, 148°34.99'E).
R72094	Tonalite, Towgon Grange pluton, Clarence River Supersuite, New England Batholith, Australia (34°50.90'S, 149°56.75'E).
LTS270	Tonalite, Peninsular Ranges Batholith, California, USA (33°18.6'N, 116°51.7'W).
LTS203	Tonalite, Peninsular Ranges Batholith, California, USA (33°03.9'N, 116°45.1'W).
BP6	Quartz monzodiorite, Boggy Plain pluton, Kosciuszko Batholith, Australia (35°50.25'S, 148°35.00'E).
BP15	Granodiorite, Boggy Plain pluton, Kosciuszko Batholith, Australia (35°50.52'S, 148°34.86'E).
Z7	Granodiorite, Tuolumne pluton, Sierra Nevada batholith, California, USA (37°52.6'N, 119°28.1'W).

The "non-minimum temperature" granites formed at slightly higher temperatures than other low-temperature granites. Under those conditions, more Ca, Mg and Fe were dissolved in the melt phase of the magma, as well as being present in restite minerals, and some well-shaped crystals of mafic minerals are seen, particularly of hornblende. Such granites include the Jindabyne, Bombala and Inlet Suites (samples KB5, AB150 and G322 in Table 1). Samples AB126 and MG42 of Table 1 are "minimum-temperature melt" granites.

4.1. *The occurrence of enclaves*

Accidental xenoliths can occur in any granite pluton. Such enclaves of country rock origin can generally be distinguished and they mainly occur near the margins of the body. It is possible that eventually some differences in the abundance of accidental xenoliths between low- and high-temperature granites might be found, because of the contrasting rheologies of the magmas, resulting both from those different temperatures and the proportions of crystalline material. We have no field observations that bear on this issue.

In some cases, there are striking differences in the abundances of mafic or microgranular enclaves between the two groups. The more mafic low-temperature I-type granites always contain such enclaves and there is a general correspondence between the abundance of those enclaves and the colour index of the host rock. This is a distinctive feature that is shared with S-type granites in which low silica metasedimentary enclaves also increase in abundance as the rocks become more mafic, as also do quartz enclaves, both as part of the lithic restite assemblage. In contrast, mafic enclaves are very rare in many mafic high-temperature granites, and that is so for the two cases of such rocks in the LFB, the BPS and the Marulan Batholith from both of which we have selected samples for this study.

Mafic enclaves occur in the more mafic rocks of the large zoned high-temperature Tuolumne Meadows pluton of the Sierra Nevada batholith (Bateman and Chappell, 1979) from which sample Z7 was selected (Fig. 3). But their abundance is very much lower than would be the case in low-temperature granites of comparable SiO_2 contents. Larsen (1948) reported mafic enclaves in many of the granites of part of the Peninsular Ranges batholith. He stated, for example, that mafic inclusions in the Bonsall tonalite and associated granodiorites range in abundance from a few per cent up to 60 %; Plate 4 of Larsen's memoir shows three photographs of abundant enclaves in those rocks. Hill et al. (1985) described mafic "inclusions" in the San Jacinto pluton of the Peninsular Ranges batholith and interpreted the bulk of those "inclusions" as samples of quenched magma. Those authors stated that the absence of a restite-derived enclave population at San Jacinto was compatible with the inferred high temperature and relatively low viscosity of these magmas, in contrast with the enclaves in the lower temperature, more viscous plutons of southeastern Australia, which White and Chappell (1977) had interpreted as dominantly fragments of restite.

Our view that the bulk, but not all, of the mafic enclaves in the I-type granites of southeastern Australia are fragments of restite remains controversial (e.g. Maas et al.,

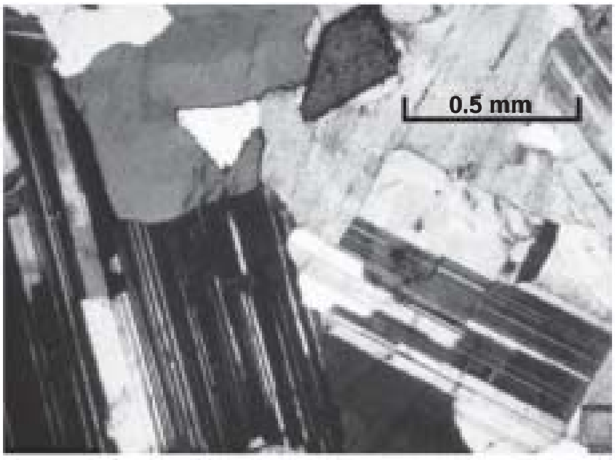

Fig. 3 Well-shaped and compositionally uniform crystals of plagioclase in sample Z7, a high-temperature granodiorite from the equigranular Half Dome phase of the Tuolumne Intrusive Series of the Sierra Nevada batholith. There is a crystal of titanite in the upper part of the figure.

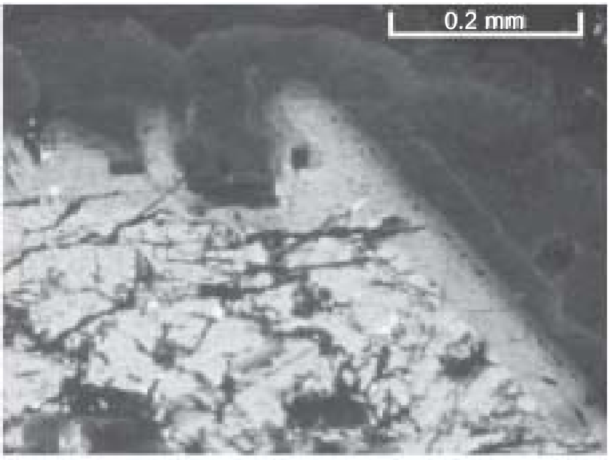

Fig. 4 Part of a plagioclase crystal from sample KB5, a low-temperature tonalite of the Jindabyne Suite, showing part of a resorbed Ca-rich core surrounded by zones of more Na-rich plagioclase.

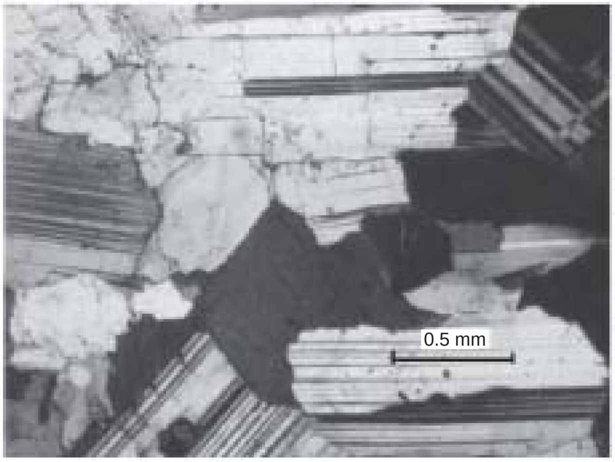

Fig. 5 Compositionally uniform crystals of plagioclase in sample LTS270, a high-temperature tonalite from Palomar Ridge in the Peninsular Ranges Batholith.

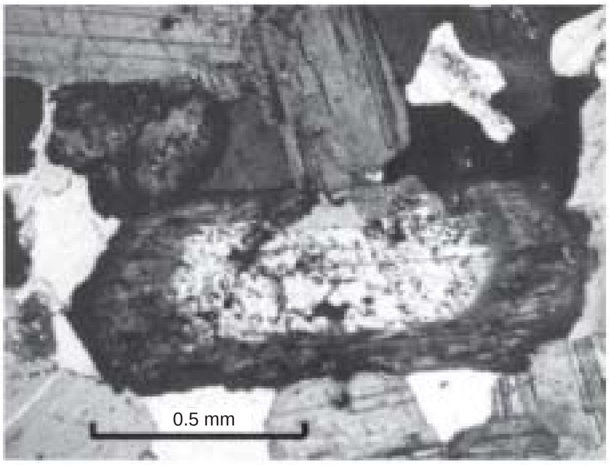

Fig. 6 A complex plagioclase crystal from sample MG42, a low-temperature tonalite from the Tuross Head pluton of the Moruya Suite, showing a resorbed core surrounded by zones of more Na-rich plagioclase.

1997), but in our opinion it is the model that best accounts for all of the available observations on those enclaves (White et al., 1999). It is also the model that accounts for the abundant enclaves in the mafic S-type granites in the most straightforward way. Writing of the enclaves in the granites of the LFB, Chappell (1996) stated that a restite origin "is also the only origin that could be applied generally to both I- and S-type enclaves, which because of their analogous occurrences and consanguinity with the host rocks, might both be inferred to have had similar origins".

Further developments in our understanding of the origin of these mafic enclaves should be enhanced by the recognition of the low- and high-temperature groups, as the enclaves are likely to have had different origins in the two types, as Hill et al. (1985) inferred. It is probably significant that the mafic high-temperature granites of the LFB are devoid of mafic enclaves, whereas those of the Cordillera are not. In that latter case, generation of the batholiths was associated with abundant mafic magmatism in some places, consistent with an association with active subduction. There was a minor, but only minor, input of mantle material into the crust of the LFB during generation of the granites, consistent with those rocks forming in an environment not closely related to subduction (Chappell et al., 2000).

5. Plagioclase

Plagioclase crystals probably provide the clearest petrographic distinction between the low- and high-temperature granites. In all but the most felsic low-tempera-

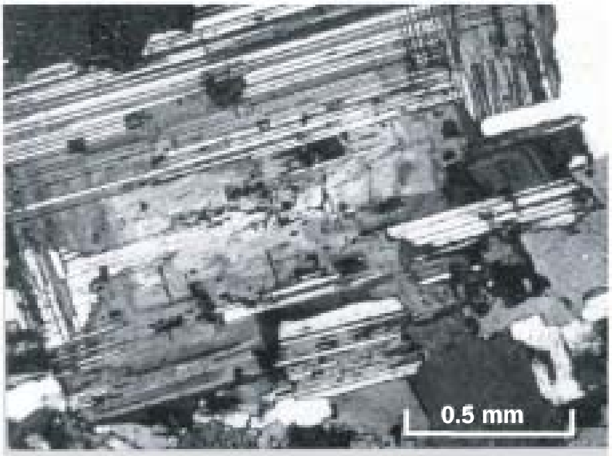

Fig. 7 Compositionally uniform plagioclase crystal in sample BP6, a high-temperature quartz monzodiorite from the Boggy Plain pluton.

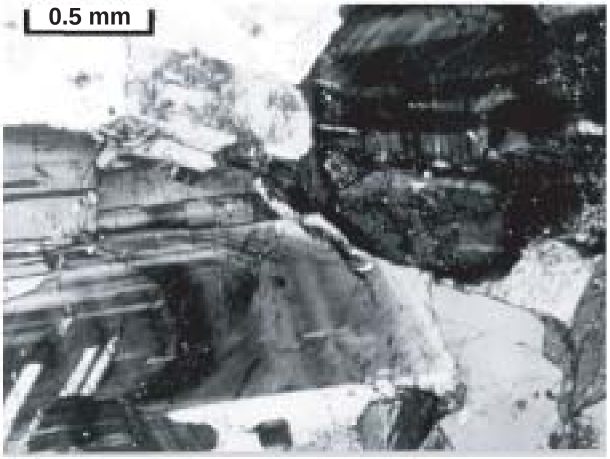

Fig. 8 Portions of two complexly zoned plagioclase crystals in sample G322, a low-temperature quartz monzodiorite from the Inlet pluton.

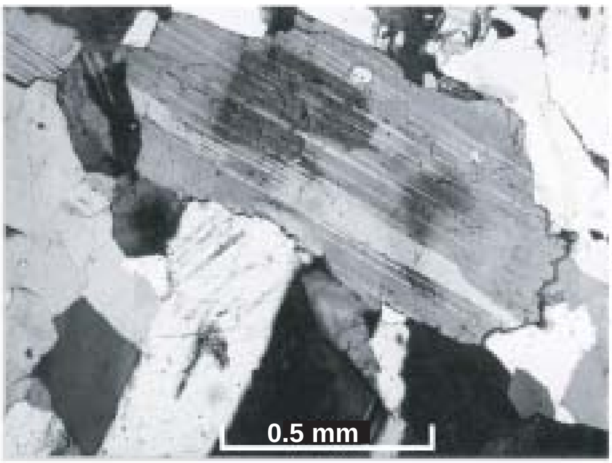

Fig. 9 Plagioclase crystal (with remnants of a core, or slightly zoned) in sample LTS258, a high-temperature quartz diorite from the Rancho San Faustero pluton, Baja California, Mexico.

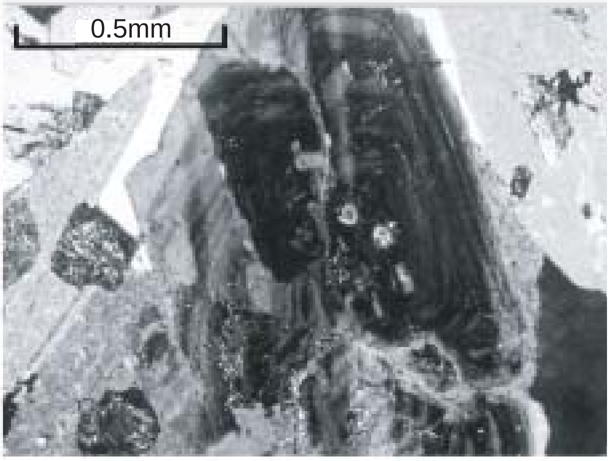

Fig. 10 Complexly zoned crystal of plagioclase in sample AB216, a low-temperature quartz diorite from the Murrabrine pluton of the Cobargo Suite.

ture granites the plagioclase crystals are always complex and commonly have corroded cores, which may be as calcic as An_{80}. Core compositions are fairly uniform in composition compared with the outer parts, which display normal and oscillatory zones of varying widths and with compositions ranging down to around An_{15}. These features of plagioclase crystals in low-temperature granites are shown in Figures 4, 6, 8, 10 and 12. In volcanic rocks that may be matched in bulk chemical composition with plutonic rocks, the plagioclase phenocrysts have compositions near those of the cores in the equivalent granites, with few outer zones (Wyborn and Chappell, 1986).

Plagioclase crystals in the high-temperature granites are generally better-shaped with a uniform composition (Figs. 3, 5, 7, 9 and 11). The crystals lack the prominent corroded cores of the low-temperature granites, but in two samples that we have examined for this study the plagioclase crystals have very large barely corroded cores with strongly zoned outer rims (section 5.2.).

In our view, these distinctive textural features of plagioclase crystals can be related to their different temperatures of formation in a simple way. Two pyroxene geothermometry on the cumulate rocks of the Boggy Plain pluton and magnetite-ilmenite geothermometry on volcanic rocks of the BPS indicate high temperatures, commonly in excess of 1000°C for both (Wyborn and Chappell, 1986). In the low-temperature granites, on the other hand, even in those with the most mafic compositions, temperatures were those appropriate to the felsic melt compositions. Zircon saturation temperatures (Watson and Harrison, 1983) of I- and S-type granites of the LFB with those felsic compositions are consistently in the range from 720 to 800°C.

Information on the rates of homogenization of plagio-

Fig. 11 Compositionally uniform plagioclase crystal in sample GH38, a high-temperature quartz diorite from the Garabal Hill complex, Scotland.

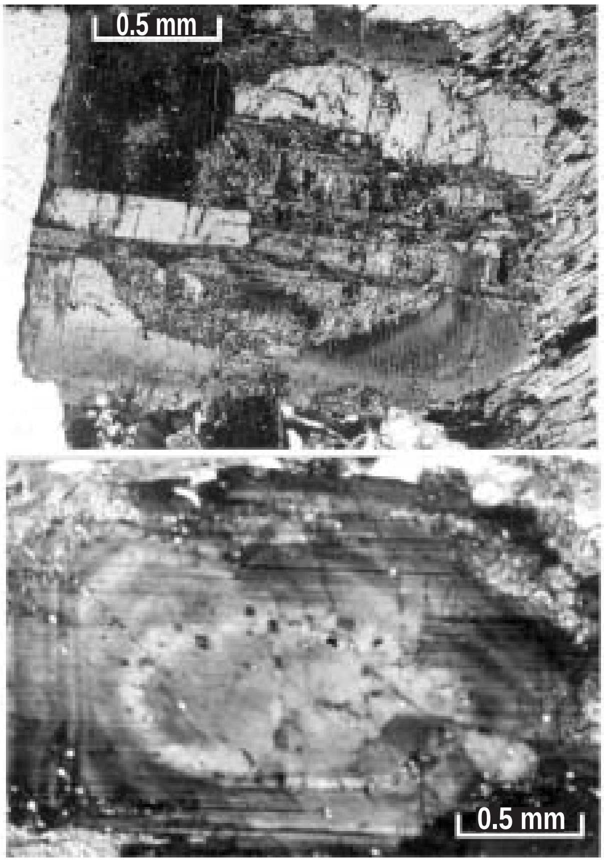

Fig. 12 Zoned plagioclase crystals in sample 83SR26, a low-temperature granodiorite from the Strontian pluton, Scotland.

clase crystals at different temperatures is critical, as we will now discuss.

5.1. *Diffusion of Na and Ca in plagioclase*

The substitution of Na^+ by Ca^{2+} or the reverse, requires the coupled replacement of Si^{4+} by Al^{3+}, or of Al^{3+} by Si^{4+}. It is because of the need to change those tetrahedral bonds, that homogenization of plagioclase is difficult at lower magmatic temperatures. The most recent data on interdiffusion in plagioclase are those of Baschek and Johannes (1995). While there are no unequivocal data on chemical diffusion in plagioclase, according to their data diffusion is not faster than $10^{-22} m^2/s$ at 800°C and a_{H_2O} of approximately 0.5; it may be much slower for *An*-rich compositions. This means that, for those conditions, linear transport (homogenization) is approximately 100 µm in 1 million years. Plagioclase is therefore a particularly difficult mineral to homogenize within a melt at temperatures near those of the lower end of the range for granitic magmas (Johannes, 1978).

5.2. *Zoning and homogenization in plagioclase*

The strong zoning in the rims of plagioclase crystals from the low-temperature granites results from plagioclase being such a particularly difficult mineral to continually re-equilibrate with a melt, or homogenize, at temperatures below 1000°C. For the same reason, the uniform cores can be interpreted as forming during slow prograde melt-forming reactions (partial melting) of the granite source rocks, so that they represent crystals of restite (Chappell et al., 1987). New plagioclase produced by melt-forming reactions is likely to be in equilibrium with the melt because of increasing reaction rates with rising temperatures and the prolonged period of heating to produce partial melting.

In some low-temperature granite suites, such as the Jindabyne Suite (Fig. 4), the equilibrium plagioclase now seen in the cores has a composition near An_{80}. The first plagioclase to crystallize from the melt would also have had a similar composition. We attribute these very calcic compositions to the flattening of the plagioclase liquidus and solidus due to the greater lowering of the melting point of anorthite relative to albite when quartz and K-feldspar components are present in a granite melt (Johannes, 1989; Johannes and Holtz, 1991). Sketches of various liquidus and solidus relationships of plagioclases

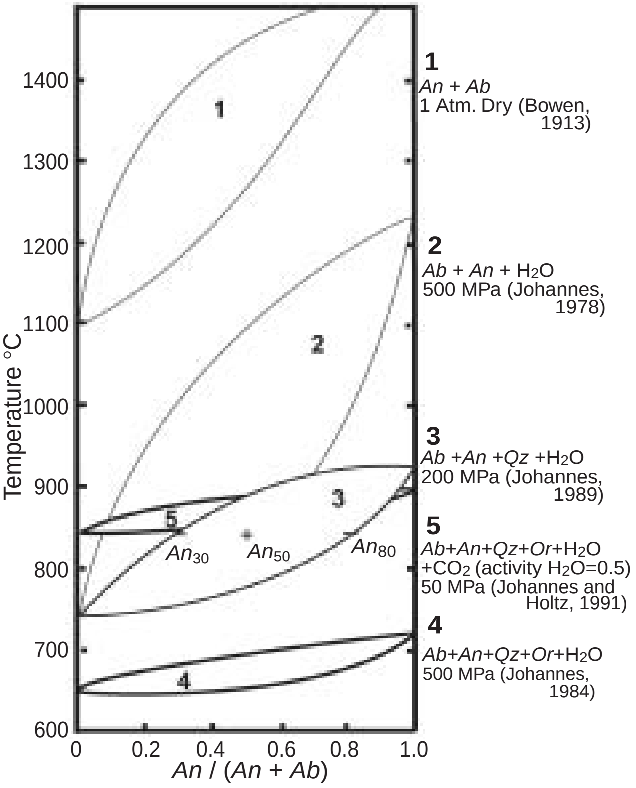

Fig. 13 The *Ab-An* system under different conditions. The addition of H_2O lowers the liquidus and solidus but the addition of *Qz* or of *Qz+Or* components flattens the plagioclase loop as well.

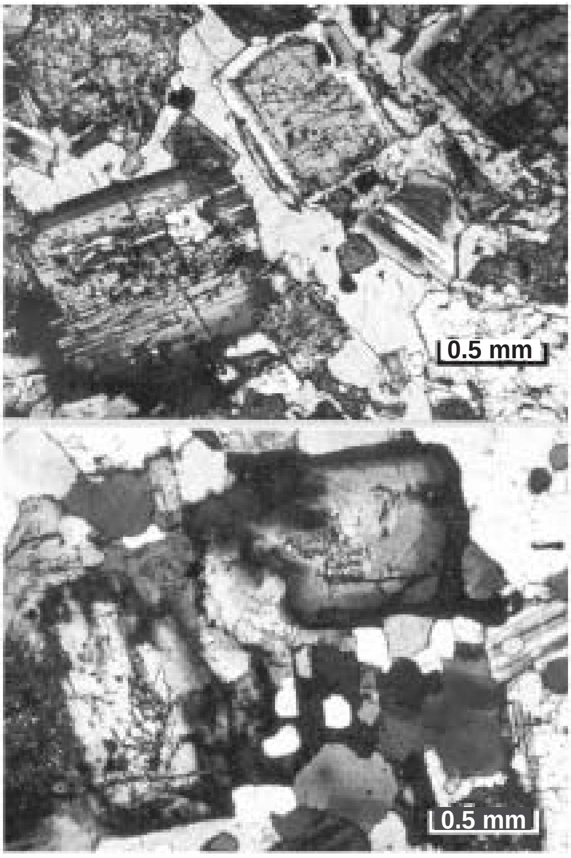

Fig. 14 Photomicrographs of two high-temperature granites in which the plagioclase crystals have strongly zoned outer rims. It is suggested that sample NB6, a sample of quartz diorite from the Wylora pluton of the Marulan Batholith (top), and sample R72094, a tonalite from the Towgon Grange unit of the Clarence River Supersuite (bottom), were quenched before the rocks were fully crystallized.

are shown in Figure 13: (1) the *Ab-An* dry system shows the classical plagioclase loop determined by Bowen (1913) at 1 atmosphere; (2) in the *Ab-An*-H_2O system at 500 MPa (Johannes, 1978) H_2O lowers both the *Ab* and *An* melting points such that the plagioclase loop is lowered but not flattened; (3) in the *Ab-An-Qz*-H_2O system at 200 MPa (Johannes, 1989) the presence of *Qz* lowers the *An* melting point much more than that of *Ab*, resulting in flattening of the loop; (4) in the system *Ab-An-Qz-Or*-H_2O at 500 MPa (Johannes, 1984) the plagioclase loop is further flattened by the addition of the *Or* component; (5) in the system *Ab-An-Qz-Or*-H_2O-CO_2 at 50 MPa (Johannes and Holtz, 1991) in which CO_2 reduces the activity of H_2O to 0.5, it is seen that the flattening of the loop is virtually the same as in (4). These data show that *Qz* and *Or* components but not H_2O cause a flattening of the plagioclase loop with the consequence that in all granitic systems residual plagioclase produced by melt-forming reactions will be much more calcic than that of the plagioclase component in the melt phase. For example, at 850°C and 200 MPa (system 3), partial melts from source rocks with plagioclase compositions near An_{50} will produce tonalitic melts with An_{30} normative composition in equilibrium with residual plagioclase near An_{80}. Likewise, the earliest plagioclase crystals precipitated from the melt will have compositions near An_{80}.

With cooling in a closed-system magma chamber, early-formed calcic plagioclase will be progressively “made over” to more and more sodic plagioclase. Local disequilibrium is more likely with falling temperatures leading to the preservation of corroded early plagioclase and complex zones. Disequilibrium relationships are always seen in low-temperature granites but are less common in the high-temperature granites. This explanation is consistent with the experimental observations on rates of diffusion referred to above. The complex zoning that is characteristic of plagioclase crystals of the low-temperature granites (e.g. Figs. 8 and 10) may also have been produced initially during crystallization of high-temperature granite magmas, but it would have been largely or completely obliterated by diffusion at the much higher temperatures of formation.

In two samples of high-temperature granite that we have studied, the plagioclase crystals have large uniform cores surrounded by relatively narrow more sodic rims (Fig. 14). These are distinct in appearance from the broad rims that surround corroded cores in the low-temperature granites. This and other textures (porphyritic and granophyric) imply that the granites were rapidly cooled before they had fully crystallized, probably as a result of pressure quenching.

5.3. Plagioclase crystals and the magma mingling and fractional crystallization models

An alternative scenario is that the uniform plagioclase cores represent crystals from a mingled mafic magma that originally precipitated and homogenized at high temperatures. However, since magma mixing/mingling cannot have been the cause of large-scale compositional variation within the granite suites of the LFB (Chappell, 1996), the cores cannot be accounted for as crystals from mingled mafic magma, at least in that region, and probably elsewhere.

A diopside component added to basalt does not lower the anorthite melting point relative to albite as shown by Bowen (1916) so that restite or first crystallized plagioclases in granite suites may be more calcic than in basalt suites. Andesites (and high Al-basalts which are best described as mafic andesites) have very calcic plagioclases. We consider that this is because andesites may have a groundmass of granitic composition. Those high-Al basalts and gabbros containing large calcic plagioclases are probably cumulative. In the LFB various geologists have pointed to the calcic cores in certain granite plagioclases as evidence of a basalt component. However, experimental data (Fig. 13) show that very calcic plagioclase cores are not evidence for the mixing/mingling model and if the calcic plagioclases are derived by mixing/mingling it is not with basalt but an andesite that has a granitic groundmass.

Along with magma mingling, fractional crystallization is the mechanism most commonly invoked to account for the compositional variations within granite suites. That process would require that both the cores and rims of these crystals formed by precipitation from a melt. If the cores of the low-temperature granites formed in that way, it means that in all of the many granites in which they are observed, there was a period of either extremely prolonged or very high temperature crystallization that produced homogeneous plagioclase crystals. Those crystals must have the same composition for all rocks and plutons of a granite suite, irrespective of the bulk composition of the rock that is eventually formed. Formation of the cores must always be followed by an interval of resorption, then a further episode of precipitation at lower temperatures. That such a sequence of events might happen occasionally is perhaps feasible. That it would be repeated so consistently during the crystallization of different granite bodies seems unlikely. Such a process cannot compare either in simplicity or probability with the restite model, according to which the cores form during a prolonged episode of partial melting with rising temperature, and the zoned rims during a shorter period of cooling and precipitation, mostly at much shallower depths in the crust.

5.4. The zircon analogue

Evidence that the plagioclase cores are restite cannot by itself be as unequivocal as that provided by the age inheritance in the cores of zircon crystals (Fig. 17). However, confirmation of the restite model through a consideration of zircon saturation (Chappell et al., 1998, 2004), strongly suggests that the plagioclase and zircon cores are somewhat analogous, and that both represent restite. Zircon cores are relicts of zircon not dissolved during partial melting whereas plagioclase cores are relicts of the plagioclase produced by melt reactions that gave rise to the magma.

6. Quartz

Quartz in the low-temperature granites containing ~60 % SiO_2 tends to occur as large crystals, whereas in the high-temperature granites of similar composition the quartz tends to occur interstitially. Quartz is a late crystallizing phase in high temperature granites produced by fractional crystallization and therefore is mainly interstitial to earlier minerals that may be accumulative (Fig. 15). However, in low temperature granites quartz is commonly on the liquidus at the partial melting stage. It may be a restite phase as is always the case in S-type granites if any restite at all is present. Also, as an early crystallizing phase in low-temperature granites, it would have the opportunity to form large crystals in the rock (Fig. 16).

7. Pyroxene and Hornblende

Clinopyroxenes that have been made over to hornblende to varying extents may be present in both low- and high-temperature granites. With some exceptions there appears to be more pyroxene preserved in the high-temperature rocks. It is particularly abundant in those granites in which there is other evidence of quenching, such as the Towgon Grange pluton (Fig. 14), where there may have been incomplete reaction to hornblende because of the loss of H_2O. Many high-temperature granites containing ~60 % SiO_2 are cumulates, e.g. the rocks examined from the Boggy Plain pluton, and the reaction of clinopyroxene to hornblende may have been inhibited by scarcity of H_2O in the intercumulus melt. On the other hand, we have examined six high-temperature rocks from the Peninsular Ranges batholith, four of which contain no pyroxene, which

Fig. 15 Interstitial quartz in sample BP40, a quartz monzodiorite from the Boggy Plain pluton, a feature of that mineral in high-temperature granites that contain about 60 % SiO_2. Width is 1.4 mm.

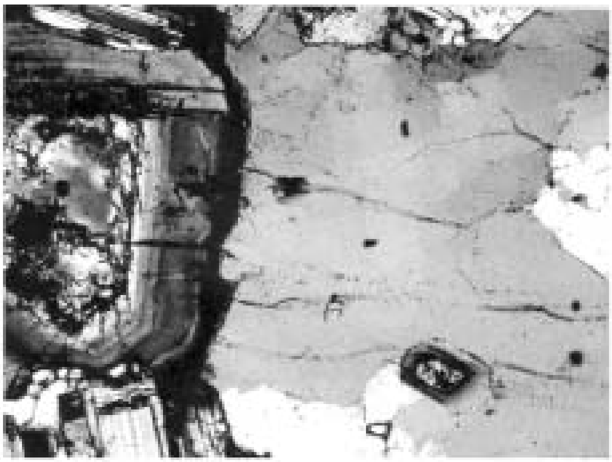

Fig. 16 Large crystal of quartz in sample KB5, a tonalite of the Jindabyne Suite, on right of the figure. The plagioclase crystal on the left has a resorbed core surrounded by complexly zoned more Na-rich material. Both of these features are typical of more mafic low-temperature granites. Width is 1.7 mm.

would be consistent with the view that these are not cumulate rocks (L. T. Silver, pers. comm., 2003).

The occurrence of clinopyroxene in volcanic rocks of equivalent composition to granites containing ~60 % SiO_2, indicates that hornblende is a late crystallizing mineral in both low- and high-temperature magmas. It forms by a peritectic reaction of clinopyroxene. Naney (1983) showed that the crystallization of hornblende in granites requires a H_2O content ~4 wt% in the melt. In our view this amount of H_2O is produced in most magmas by the crystallization of early anhydrous minerals. Despite its late formation, hornblende crystals in both the high-temperature granites and the “non-minimum temperature” granites (see section 2.4.) often form well-shaped crystals. Such crystals are uncommon in the “minimum temperature” granites, which serves as a useful criterion for their recognition when they are sufficiently mafic to contain that mineral.

8. Zircon

The occurrence of older cores in zircon crystals is of course a definitive feature of the low-temperature granites (Fig. 17) but this cannot be observed petrographically. It is worth noting, however, that in the more mafic cumulate rocks of the high-temperature Boggy Plain pluton in which zircon was not a saturated liquidus mineral (Fig. 1), zircon commonly occurs as irregular, interstitial crystals with shapes determined by a framework of earlier-formed crystals, and not as prismatic crystals (D. Wyborn, pers. comm.).

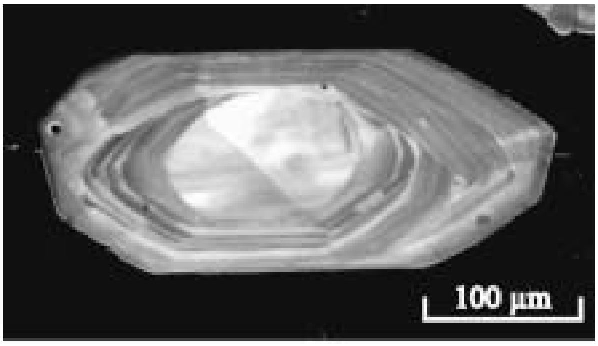

Fig. 17 Cathodoluminescent image of a zircon crystal from sample AB290, a low-temperature tonalite from the I-type Blue Gum pluton of the Bega Batholith. The rounded core has been dated at *ca*. 900 Ma and the outer zones have an age of *ca*. 400 Ma.

9. Conclusions

We have examined a selection of granites containing ~60 % SiO_2 that had previously been identified as either low- or high-temperature on the basis of bulk compositional features. The most distinctive petrographic features of the high-temperature granites are the generally better shapes of their crystals and the uniform composition of the plagioclase. Low-temperature granites are best distinguished petrographically by their plagioclase crystals which typically comprise a corroded core of rather uniform and often very calcic composition, surrounded by zones that become progressively more Na-rich towards the margins of the crystal. We interpret the cores as forming during slow prograde melt-forming reactions (partial melting) within the source rocks, while the outer zones were precipitated at temperatures under which the rate of growth greatly exceeded that of homogenization. The compositionally uniform plagioclase crystals of the high-temperature granites reflect the high rate of diffusion in that mineral at temperatures higher than 1000°C. Narrow rims have been observed on plagioclase crystals in two high-temperature granites that we have examined here, probably caused by rapid crystallization during quenching.

We have not examined S-type granites specifically for this study, but they are always low-temperature in origin according to our definition and they share many of the distinctive petrographic features of the low-temperature I-type granites. A comparative study of the granites formed at different temperatures, at higher SiO_2 contents than we have taken here, would be worthwhile and could incorporate S-type granites.

Because of the greater likelihood that significant granite-related mineralization would be associated with the high-temperature granites (Chappell et al., 2004), developing an understanding of the petrographic features of granites in a particular region could be a useful adjunct to mineral exploration.

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References

Baschek, G. and Johannes, W. (1995) The estimation of NaSi-CaAl interdiffusion rates in peristerite by homogenization experiments. Europ. Jour. Mineral., 7, 295–307.

Bateman, P. C. and Chappell, B. W. (1979) Crystallization, fractionation and solidification of the Tuolumne intrusive series, Yosemite National Park, California. Geol. Soc. Amer. Bull., 90, 465–482.

Bowen, N. L. (1913) The melting phenomena of the plagioclase feldspars. Amer. Jour. Sci., 35, 577–599.

Bowen, N. L. (1916) Das ternäre System: Diopsid-Anorthit-Albit. Zeits. anorg. Chem., 94, 23–50.

Bryant, C. J., Arculus, R. J. and Chappell, B. W. (1997) Clarence River Supersuite: 250 Ma Cordilleran tonalitic I-type intrusions in eastern Australia. Jour. Petrol., 38, 975–1001.

Carr, P. F., Chappell, B. W. and Jones, B. G. (1992) Geochemical contrasts between intersecting Devonian and Carboniferous magmatic belts in the eastern Lachlan Fold Belt (abstr.). Trans. Roy. Soc. Edinburgh, Earth Sci., 83, 487.

Chappell, B. W. (1996) Magma mixing and the production of compositional variation within granite suites: evidence from the granites of southeastern Australia. Jour. Petrol., 37, 449–470.

Chappell, B. W. and Wyborn, D. (2004) Cumulate and cumulative granitic rocks. Resource Geol., 54, 227–240.

Chappell, B. W., White, A. J. R. and Wyborn, D. (1987) The importance of residual source material (restite) in granite petrogenesis. Jour. Petrol., 28, 1111–1138.

Chappell, B. W., Bryant, C. J., Wyborn, D., White, A. J. R. and Williams, I. S. (1998) High- and low-temperature I-type granites. Resource Geol., 48, 225–236.

Chappell, B. W., White, A. J. R., Williams, I. S., Wyborn, D. and Wyborn, L. A. I. (2000) Lachlan Fold Belt granites revisited: high- and low-temperature granites and their implications. Austral. Jour. Earth Sci., 47, 123–138.

Chappell, B. W., White, A. J. R., Williams, I. S. and Wyborn, D. (2004) Low- and high-temperature granites. Trans. Roy. Soc. Edinburgh, Earth Sci. (in press).

Hill, R. I., Silver, L. T., Chappell, B. W. and Taylor, H. P. (1985) Solidification and recharge of SiO_2-rich plutonic magma chambers. Nature, 313, 643–646.

Hine, R., Williams, I. S., Chappell, B. W. and White, A. J. R. (1978) Contrasts between I- and S-type granitoids of the Kosciusko Batholith. Jour. Geol. Soc. Austral., 25, 219– 234.

Johannes, W. (1978) Melting of plagioclase in the system Ab-An-H_2O and Qz-Ab-An-H_2O at P_{H_2O} = 5 kbars, an equilibrium problem. Contr. Mineral. Petrol., 66, 295–303.

Johannes, W. (1984) Beginning of melting in the granite system Qz-Ab-Or-An-H_2O. Contr. Mineral. Petrol., 84, 264–273.

Johannes, W. (1989) Melting of plagioclase-quartz assemblages at 2 kbar water pressure. Contr. Mineral. Petrol., 103, 270–276.

Johannes, W. and Holtz, F. (1991) Melting of plagioclase in granite and related systems: composition of coexisting phases and kinetic observations. Trans. Roy. Soc. Edinburgh, Earth Sci., 83, 417–422.

Larsen, E. S. (1948) Batholith and Associated Rocks of Corona, Elsinore, and San Luis Rey Quadrangles, Southern California. Geol. Soc. Amer. Mem., 29.

Maas, R., Nicholls, I. A. and Legg, C. (1997) Igneous and metamorphic enclaves in the S-type Deddick Granodiorite, Lachlan Fold Belt, SE Australia: petrographic, geochemical and Nd-Sr isotope evidence for crustal melting and magma mixing. Jour. Petrol., 38, 815–841.

Naney, M. T. (1983) Phase equilibria of rock-forming ferromagnesian silicates in granitic systems. Amer. Jour. Sci., 283, 993–1033.

Watson, E. B. and Harrison, T. M. (1983) Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. Earth Planet Sci. Lett., 64, 295–304.

White, A. J. R. and Chappell, B. W. (1977) Ultrametamorphism and granitoid genesis. Tectonophysics, 43, 7–22.

White, A. J. R., Chappell, B. W. and Wyborn, D. (1999) Application of the restite model to the Deddick Granodiorite and its enclaves: a re-interpretation of the observations and data of Maas et al. (1998). Jour. Petrol., 40, 413–421.

Williams, I. S. (1995) Zircon analysis by ion microprobe: the case of the eastern Australian granites. Leon T. Silver 70th Birthday Symposium and Celebration, 27–31. The California Institute of Technology, Pasadena.

Wyborn, D. and Chappell, B. W. (1986) The petrogenetic significance of chemically related plutonic and volcanic rock units. Geol. Mag., 123, 619–628.

Wyborn, D., Turner, B. S. and Chappell, B. W. (1987) The Boggy Plain Supersuite: a distinctive belt of I-type igneous rocks of potential economic significance in the Lachlan Fold Belt. Austral. Jour. Earth Sci., 34, 21–43.

Wyborn, D., Chappell, B. W. and James, M. (2001) Examples of convective fractionation in high-temperature granites from the Lachlan Fold Belt. Austral. Jour. Earth Sci., 48, 531–541.