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# On the formation of granulites

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**ABSTRACT** The tectonic settings for the formation and evolution of regional granulite terranes and the lowermost continental crust can be deduced from pressure–temperature–time ($P$–$T$–time) paths and constrained by petrological and geophysical considerations.

$P$–$T$ conditions deduced for regional granulites require transient, average geothermal gradients of greater than 35° C km$^{-1}$, implying minimum heat flow in excess of 100 mW m$^{-2}$. Such high heat flow is probably caused by magmatic heating. Tectonic settings wherein such conditions are found include convergent plate margins, continental rifts, hot spots and at the margins of large, deep-seated batholiths. However, particular $P$–$T$–time paths do not allow specific tectonic settings to be distinguished at this time. Under different conditions, both clockwise, CW ($P_{max}$ attained before $T_{max}$), and anticlockwise, ACW ($P_{max}$ attained slightly after $T_{max}$), paths are possible in the same tectonic setting. Both CW and ACW end-member paths can yield nearly isobaric cooling, IBC, paths. Such cooling paths are clearly not an artefact of thermobarometry, but can be constrained by solid–solid and devolatilization equilibria and geophysical modelling.

In terms of understanding the evolution of the deep crust, a potentially significant group of regional granulite terranes are those that show evidence for ACW-IBC paths. Such paths are the likely result of: (i) episodic igneous activity resulting in intrusions within all levels of the crust, (ii) thickening of the crust by magmatic underplating, (iii) slow uplift as a result of the formation of a deep, garnet-rich crustal root and (iv) excavation resulting from a later tectonic event unrelated to that resulting in the formation of the granulites. The later event might be triggered by the delamination of the garnet-rich, lowermost crust.

**Key words:** barometry; crustal evolution; granulite; $P$–$T$–$t$ path, thermometry.

## INTRODUCTION

Recent study of rocks from the middle and lower continential crust has produced a wealth of information on the formation of regional granulite terranes. As a result, there is broad agreement on the pressure and temperatures recorded in such rocks, the types of $P$–$T$–time paths that can be resolved and the possible kinds of tectonic environments that might produce such paths. Despite this broad agreement, certain aspects of granulite genesis remain unexplained. These include: (i) the significance of 'peak' $P$–$T$ conditions (i.e. those extant during the thermal maximum) recorded in regional granulites, which occur in broad areas exposed over several hundreds to thousands of square kilometres, and the tendency, if any, for 'peak' values to cluster within narrow limits; (ii) the diversity of $P$–$T$–time paths deduced from mineral textures and thermobarometry and the causes for this diversity; (iii) the conditions causing metamorphism to occur episodically over periods of 100–150 Ma; (iv) initial, nearly isobaric cooling from 'peak' conditions at rates of less than 5° C Ma$^{-1}$; (v) the conditions causing the exhumation of many granulite terranes during a tectonic cycle later, in some areas much later, than that which caused the formation of the granulites.

To date, the general features of the tectonothermal regimes that produce regional granulites have been deduced either from geophysical modelling or petrological studies but rarely from a quantitative integration of both. However, detailed understanding of the evolution of regional granulite terranes will require such integration. This paper reviews the unresolved problems concerning genesis of regional granulites and discusses both the petrological and geophysical constraints that may lead to their resolution.

## PRESSURE–TEMPERATURE CONDITIONS OF GRANULITE METAMORPHISM

Application of thermobarometry in granulite terranes indicates that 'peak' conditions recorded in granulites are in the range of 700–1000° C and 4–12 kbar (Newton & Perkins, 1982; Bohlen *et al.*, 1983; Bohlen, 1987; Harley, 1989). In general, values deduced from independent thermobarometry agree with those deduced from mineral assemblages related by discontinuous reaction equilibria. Newton & Perkins (1982) and Bohlen (1987) have proposed that for regional granulite terranes, 'peak' conditions cluster within the relatively restricted range of 700–850° C and 6.5–9.0 kbar. Harley (1989), on the other hand, argued that no such clustering exists. Part of the discrepancy results from the types of data used for analysis. Newton & Perkins (1982), Newton (1983) and Bohlen (1987) employed a consistent set of thermometers and barometers in terranes for which data for appropriate mineral compositions were available. In contrast, Harley (1989) accepted the values given by various workers in each of ninety granulite localities, many of which cannot be considered regional granulite terranes, as defined above. The scatter of values of metamorphic pressure is reduced if only regional granulites are considered in Harley's analysis. Identification of a group of granulite terranes metamorphosed at very high temperatures (900–1000° C), as determined by both thermobarometry and mineral assemblages (Ellis, 1980; Harley, 1989), indicates that 'peak' metamorphic temperatures exceed the relatively narrow range suggested by Newton, Perkins and Bohlen. Nevertheless, following the analysis of Newton & Perkins (1982) or Bohlen (1987), the metamorphic pressures in such high-*T* terranes are generally between 6.5 and 9.0 kbar.

Each of the approaches above has merit. That used by Harley takes advantage of the direct knowledge of the rocks by those who have performed the field-work, collected the rocks for analysis and obtained microprobe data, etc. That employed by Newton, Perkins and Bohlen is advantageous because precision is enhanced greatly by the application of the same thermometers and barometers using the same or similar solution models for the appropriate minerals in all rocks. I prefer using *P–T* data calculated from published analyses of mineral assemblages related by several, not just one, pressure- or temperature-sensitive equilibria. By so doing, not only are systematic differences eliminated through use of a consistent set of solution properties and experimentally calibrated equilibria, but biases in the *P–T* conditions might be reduced somewhat. Differences of as much as 200–300° C or 2–4 kbar can result from the use of different calibrations of the same thermobarometers. Use of various solution models for impure minerals causes differences of smaller, but still not insignificant, magnitude. Often those thermobarometers deemed 'acceptable' or 'useful' are usually ones that yield results in accord with the prejudices of the investigator. In this regard, there seems to be special emphasis on the presumed great depth of burial of many granulites. For example, early estimates of metamorphic pressures of the Scourie gneisses were 13 kbar (O'Hara, 1975), whereas values deduced from recent, experimentally calibrated barometers are 7–8 kbar. In fact, recent data indicate that regional granulites recording pressures of 10 kbar and above are relatively rare.

The clustering of 'peak' *P–T* values recorded in granulites has significance beyond the arguments concerning accuracy and precision of various thermobarometric techniques and details of their application. A clustering of values, especially metamorphic pressures, from terranes metamorphosed at different times spanning most of Earth history may be an important clue to the tectonic processes affecting the exposure of these deep-seated terranes, the composition of material underlying them and the magnitude of secular variations in processes that cause the formation, and exposure of regional granulite terranes.

Recently, Frost & Chacko (1989) have proposed a granulite 'uncertainty principle', based in part on the discussions of many other workers, among them Ellis & Green (1985), Ellis (1987) and Hensen (1987), concerning the potential for chemical re-equilibrium in high-grade rocks. Like many workers, Frost and Chacko suggested that because the *P–T* conditions for granulite metamorphism are well above the closure temperatures for most thermobarometers, the *P–T* conditions recorded in granulites, as deduced from thermobarometers, are consistently below those of the true 'peak' conditions. However, Frost and Chacko have extended these concepts and have suggested that maximum conditions of metamorphism are indeterminable using thermobarometry and could only be limited using mineral assemblages indicative of high temperatures and pressures.

While Frost & Chacko's (1989) 'uncertainty principle' may be a useful caveat for those unfamiliar with the application of thermobarometers in high-grade rocks, the notion that the 'peak' metamorphic conditions are somehow inherently uncertain and indeterminable is refuted by the data. Application of consistent sets of thermometers and barometers in granulites shows that thermobarometers yield *P–T* values consistent with all phase equilibria (Bohlen *et al.*, 1983; Newton, 1983, 1987). Indeed, thermobarometers yield *P–T* data that are generally near limits allowed by the mineral assemblages. For example, if metamorphic temperatures were higher, then assemblages of spinel–quartz instead of garnet–sillimanite, metamorphic pigeonite in Fe-rich rocks instead of coexisting orthopyroxene–clinopyroxene, wollastonite–plagioclase instead of grossular-rich garnet–quartz, orthopyroxene–sillimanite–quartz or sapphirine–quartz instead of garnet–cordierite would be far more common. This is because the reactions for the breakdown of the high-*T* assemblages noted are kinetically unfavourable, especially in the absence of deformation and fluid in the retrograde environment. Therefore, it seems unlikely that no evidence of precursor high-*T* events would survive. In those terranes in which metamorphic temperatures were very high, both the mineral assemblages and thermobarometry record faithfully the high temperatures (see, for example, Ellis, 1980; Harley, 1985; Powers & Bohlen, 1985; Sandiford *et al.*, 1987). In addition, most of the high-*T* reactions in rocks from these terranes can be deduced from coronal textures and successions of inclusions in garnet and other minerals. This is not to say that retrogression does not occur or is not a serious problem. Retograde features are observed in most, if not all terranes, and in some areas the rocks show extensive re-equilibration at lower *P–T* conditions. Nevertheless with the prudent selection of samples and the critical application of numerous thermobarometers, the data seem to indicate that 'peak' values can be ascertained in many granulite terranes.

## *P–T*–TIME PATHS OF REGIONAL GRANULITES

Mezger *et al.* (1990a, b) have shown that the metamorphic histories of two regional granulite terranes, the Pikwitonei

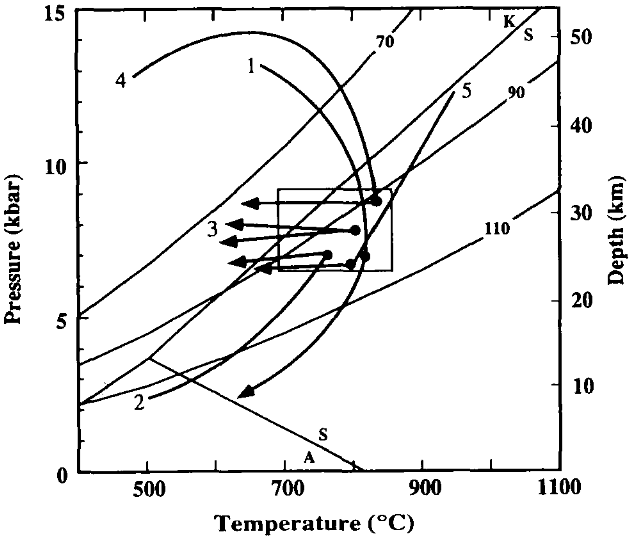

**Fig. 1.** Possible $P$–$T$–time paths in granulites. Path 1, see Harley (1989); path 2, see Bohlen (1987); path 3, see Sandiford & Powell (1986); path 4, see Ellis (1987); path 5, see England & Thompson (1986). Box encloses the relatively restricted range of 'peak' metamorphic conditions preferred by Newton & Perkins (1982) and by Bohlen (1987). Aluminium silicate phase relations after Holdaway (1971). Numbered curves indicate the geothermal gradient calculated from surficial heat flow (numbers given in mW m$^{-2}$) assuming reduced heat flow equals 55% of the values given, see Chapman (1986). Filled circles indicate the likely, 'peak' $P$–$T$ conditions that would be recorded by rocks passing along the respective $P$–$T$–time paths.

granulites of central Manitoba and the Adirondacks of upper New York State, are long, spanning 150 Ma, and are punctuated with episodic, magmatic–metamorphic pulses at intervals of 30–50 Ma. If these are paradigms for other regional granulite terranes, it is likely that the $P$–$T$–time histories of granulites are complicated and may involve distinct cycles of heating and partial cooling. Such complexity of $P$–$T$–time paths has rarely been resolved (Clarke *et al.*, 1990) and much of the essential information may have been eliminated by later, or the latest, high-$T$ events. Nevertheless, relatively simple $P$–$T$–time paths have been deduced from zoned mineral compositions along with textures indicating mineral reactions. These fall into three broad categories: (i) 'clockwise' (CW) paths wherein the barometric maximum precedes the thermal maximum, initial retrograde paths with large initial $dP/dT$, isothermal decompression (ITD) (Fig. 1, path 1); (ii) 'anticlockwise' (ACW) paths wherein heating occurs prior to and during loading, initial retrograde paths with small positive $dP/dT$, isobaric cooling (IBC) (Fig. 1, path 2); (iii) IBC paths with no recognizable precursor path, initial retrograde paths with small positive or negative $dP/dT$ (Sandiford & Powell, 1986; Fig. 1, path 3). Such simple paths have been considered prima-facie evidence for the kind of tectonic settings appropriate for granulite formation. These include continent–continent collisional environments (i above), continental magmatic arc regions (i & ii above), rift environments (ii & iii above) and hot spots (ii & iii above). However these must be considered end-member models. Combination of tectonic processes has been shown to yield other paths. For example, crustal thickening followed by extension yields paths that involve a clockwise $P$–$T$–time path, or at least a period of nearly isothermal decompression, followed by a period of nearly isobaric cooling (Fig. 1, paths 4 & 5; England & Thompson, 1986; Ellis, 1987; Sonder *et al.*, 1987; Sandiford, 1989).

Harley (1989) has reviewed some of the salient features of the various $P$–$T$–time paths in Fig. 1. However, one notable requirement is that, in order to attain the high temperatures of granulite grade metamorphism, an external source of heat, likely that of magma, is required, no matter which of the paths best describes the history of $P$–$T$ conditions. Following the modelling of England & Thompson (1984, 1986), $P$–$T$ paths resulting from tectonic thickening (paths 1, 4 & 5 in Fig. 1) cannot reach temperatures in excess of 800° C without additional sources of heat. Paths passing through such high temperatures that do not require externally derived heat can be calculated (see Harley, 1989) but require unrealistic, special conditions such as low values of thermal conductivity for the rocks and/or high rates of internal heat generation. In addition, the effects of high internal heat generation will be offset to some extent by partial melting within the crust. Path 2 (Fig. 1) is one that results from intrusion of magma into existing crust accompanied by large amounts of magmatic underplating (Wells, 1980; Bohlen, 1987). Path 3 can result from various different ways, but all involve magmatic heating either directly or indirectly: (i) it can result from the retrograde portions of paths 1, 2, 4, or 5, wherein all evidence of the prograde path has been erased; (ii) it can form by the transient, nearly isobaric heating and cooling of rocks heated by magmas in the lower parts of existing continental crust; and (iii) it can be formed in the lower crust during extensional tectonics. The addition of thick sequences of sediments in extensional basins can cause a slight increase in pressure of path 3 during cooling (Sandiford & Powell, 1986). However, since magmatic activity is usually associated with extensional terranes and may be required in areas of thinned crust that show no loss of elevation (Lachenbruch & Morgan, 1989), magmatic heating will likely play a role in the evolution of granulites in extensional settings as well. The role of magmatism is also evident from the high transient thermal gradients necessary to produce the range of 'peak' metamorphic temperatures observed in granulites. The $P$–$T$ conditions require gradients (Fig. 1) that imply surface heat flows of 80–110 mW m$^{-2}$, values equal to or greater than those observed in the Basin and Range region of western North America.

Figure 1 shows that initial, nearly isobaric cooling can result from fundamentally different $P$–$T$–time paths, including both collisional (Ellis, 1987) and extensional tectonics, a fact not widely appreciated (England & Thompson, 1986; Sandiford & Powell, 1986; Sandiford, 1989). However, of the substantial number of regional granulite terranes in which initial, nearly isobaric cooling has been inferred from both reaction textures and zoned mineral compositions, few show evidence of a high-$P$ prograde path. Given that many of these terranes contain rocks in which original igneous textures are preserved, indicating at least locally dry, low-strain conditions, it is surprising that no evidence remains from a prograde path that may have reached 12–18 kbar. Evidence for high-$P$ prograde paths is preserved in many terranes that can be shown to have undergone a clockwise $P$–$T$-time path with initial, nearly isothermal decompression (e.g. Brown, 1988; Harley, 1988). This suggests that paths 4 & 5 (Fig. 1) may not be common for regional granulite terranes.

It has been argued previously (Bohlen, 1987) that path 2 (Fig. 1) is the most common path for IBC regional granulites and indeed is characteristic of a major group of granulites. Evidence for this path includes: (i) the prograde progression from andalusite-bearing rocks to sillimanite-bearing assemblages followed by retrograde kyanite; (ii) the nearly isobaric transition from upper amphibolite to granulite facies rocks in paired amphibolite–granulite terranes; (iii) a rough, positive correlation between depth and the abundance of meta-igneous rocks in regional granulite terranes and xenoliths (Bohlen & Mezger, 1989); (iv) similar 'peak' metamorphic temperatures within a range of depths of the crust suggesting that metamorphic temperatures were controlled substantially by the presence of crystallizing magmas (Waters, 1986); and (v) the relatively narrow range of 'peak' $P$–$T$ conditions recorded in regional granulites, Harley's contention to the contrary notwithstanding.

Bohlen & Mezger (1989) proposed further that granulite terranes showing ACW-IBC paths owe their origins to the intrusion and underplating of large amounts of magma that not only provide heat for the granulite facies metamorphism but also add a large volume of mostly mafic material to the base of the crust (see also Roberts & Ruiz, 1989). If so, then regional granulite terranes of the ACW-IBC type may be manifestations of major crust-forming events, wherein the crust grows vertically by the addition of mantle-derived magmas to the base of the crust, rather than by the lateral accretion of arc and arc-related material to the edges of continents.

Granulite terranes showing ACW-IBC paths are potentially important because they may be indicators of crustal growth and may require a limited set of circumstances for this formation. Igneous material must be added to the crust to generate high temperatures throughout the crust (see below), but in the waning stages of the tectonothermal event, a crust of normal or substantially greater than normal thickness must be in nearly isostatic equilibrium with the surrounding lithosphere.

ACW-IBC paths have been well documented in at least five regional granulite terranes: Adirondacks (Bohlen, 1987), Arunta Block (Warren, 1983; Warren & Hensen, 1989), Namaqualand (Waters, 1986), Pikwitonei (Hensen, 1987; Mezger *et al.*, 1990a) and Willyama Complex (Corbett & Phillips, 1981). It is not clear whether two different types of ACW-IBC granulites are represented among these. Those terranes such as Namaqualand, Willyama Complex and parts of the Arunta Complex wherein relatively low-$P$ rocks (≤5 kbar) are exposed might constitute one type; those terranes wherein higher pressure rocks (7–9 kbar) are exposed (Pikwitonei, Adirondacks) might form a second. As each type is now underlain by a crust of normal thickness, their difference may result from the degree to which the crust was thickened during the tectonothermal event, the first by less than 50%, the second by over 100%. Alternatively, the terranes might represent different cumulative effects of the same tectonothermal processes.

Based on the thermal models of Wells (1980), Bohlen (1987) proposed that the ACW-IBC path in granulites was caused by magmatic underplating beneath existing continental crust and intrusion and crystallization of substantial volumes of igneous material within the crust. A continental magmatic arc environment was proposed as a likely tectonic regime in which such processes could take place, but hot spots or incipient rift environments (Sandiford & Powell, 1986) under certain circumstances might also yield ACW-IBC paths. Indeed, tectonic thickening of crust that had undergone extension (incipient rifting?) just prior to thickening, as proposed by Vielzeuf & Kornprobst (1984), seems a likely, and in some areas, for example the Adirondacks (McLelland *et al.*, 1988), a preferred model for the formation of some granulites that underwent ACW-IBC $P$–$T$-time paths.

For such models, it is essential that magmatic heating takes place both beneath and throughout the existing crust. This is because isostatic equilibration is usually rapid with respect to the rate of conduction of heat through the crust. Figure 2 shows the $P$–$T$-time paths expected if, for example, an approximate 30-km thickness of basaltic magma is accreted instantaneously to the base of continental crust some 30 km thick. Because the basalt will

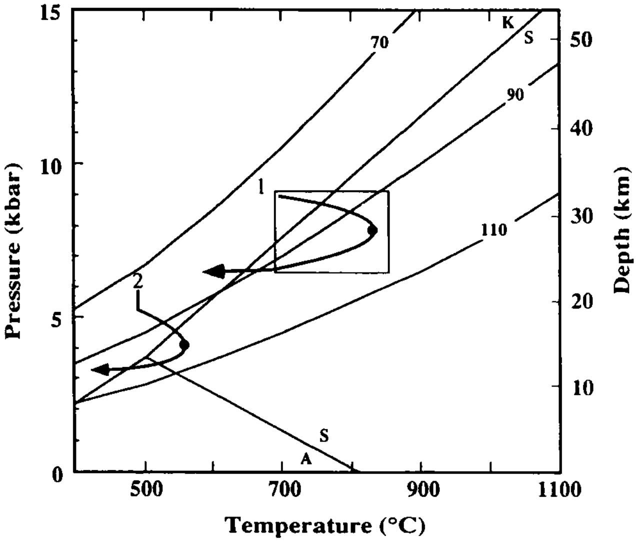

**Fig. 2.** $P$–$T$-time paths that would result from the underplating of 30 km of basalt at the base of a 30-km-thick continental crust. Details as in Fig. 1.

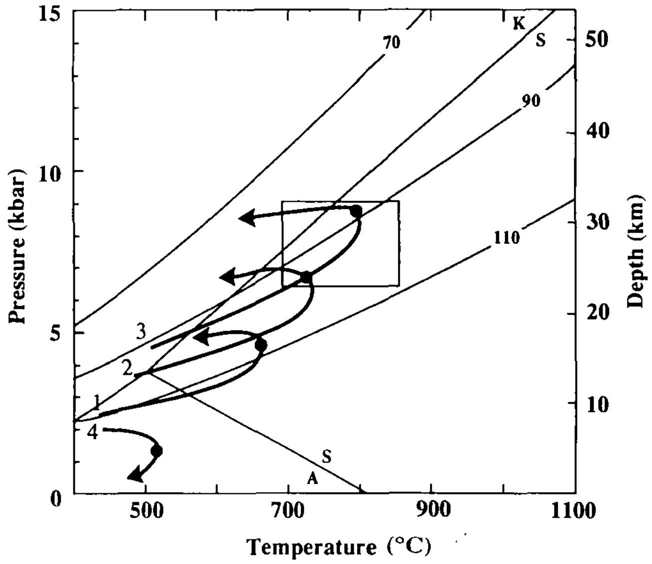

Fig. 3. $P$–$T$-time paths resulting from magmatic underplating and the intrusion of magmas into the crust. Paths 1–3 are within or below the zone of magmatic accretion. Path 4 is above the zone of magmatic accretion. Details as in Fig. 1.

cause an increase in elevation of about 3 km (as a result of isostasy) and thermal expansion of the lithosphere will increase elevation further (Lachenbruch & Morgan, 1989), rocks at the base of the crust will show a CW $P$–$T$-time path, because erosion will decompress the rocks as they are heated. Because thermal conduction scales as the square of the distance or depth (i.e. time = depth$^2$/thermal diffusivity), rocks in the middle crust (path 2 in Fig. 2) will be uplifted before they are heated by the underplated basaltic magma and hence will show initial ITD before being heated along a CW path.

On the other hand, Fig. 3 shows paths that would result at different levels of the crust from the underplating of magma at the base of the crust and simultaneous intrusions of magmas into the crust. Paths 1, 2 & 3 show the effects of heating and increased pressure within the crust as a result of the intrusion of magma and some crustal shortening, especially in the later stages of the prograde path. Taken together, the path is ACW and similar to path 2 in Fig. 1. Rocks in the upper crust that lie above the zone of magmatic accretion will show a CW path like that of path 4 (Fig. 3). Hence, depending on whether the rocks are being regarded from within or above the zone of accretion, the $P$–$T$-time path deduced will be ACW and CW, respectively (see also Harley, 1989). In terranes where an ACW-IBC path has been inferred, metapelites can show the transition of andalusite to sillimanite or kyanite to sillimanite, depending on the original level of the crust at which a particular rock originated. Therefore, the mere presence of relict kyanite inclusions in garnet or sillimanite pseudomorphs after kyanite is insufficient to determine the sense of the $P$-$T$-time path and does not necessarily require a CW path. In fact, the progression of kyanite to sillimanite should be common in ACW-IBC granulites, because the progression of andalusite to sillimanite will only be seen in those terranes for which precursor middle and upper crustal rocks have not been stripped away by erosion. That the progression of kyanite to sillimanite has not been observed commonly suggests that appropriate textures have been either obliterated during prograde metamorphism or overlooked. Depending on the exact placement of magma and the relative effects of heating and erosion, it might also be possible to observe the prograde sequence of kyanite to andalusite to sillimanite in rocks that were originally at pressures near the triple point isobar prior to the tectonothermal event (path 1, Fig. 3).

## PETROLOGICAL MODELS AND GEOPHYSICAL CONSTRAINTS

From the petrological perspective, it seems at least plausible that regional terranes with ACW-IBC $P$–$T$-time paths may have formed in areas of initial rifting or extension followed by compression, in continental rift environments or above hot spots. Such environments can explain all of the features observed in, or deduced from, ACW-IBC regional granulites. The progression of andalusite to sillimanite is explained by an early stage of magmatic heating of the crust during initial extension or at least before the onset of compressional events. The nearly isobaric transition from upper amphibolite to granulite facies marks the locus of deep crust that is unaffected by magmatic underplating and intrusions from the crust which is affected. The abundance of meta-igneous rocks should correlate with depth as a result of extensive plutonism. At some level representing the zone marking the interval between previously existing crust and the igneous underplate, the vast majority of rocks should be meta-igneous. 'Peak' metamorphic temperatures are constrained to a relatively narrow range, because they are controlled to a large extent by the solidi of crystallizing magmas. It is therefore no surprise that the highest metamorphic temperatures are somewhat below the solidi of synmetamorphic intrusives. In addition, the episodic nature of the metamorphism and the fact that metamorphism proceeds at different times in different areas within a single terrane (Mezger *et al.*, 1990a, b) is a consequence of periodic igneous activity taking place at different times within a broad area.

Even the 'double thickness' of crust and the relatively narrow range of 'peak' metamorphic pressures recorded in granulites can be rationalized in the context of the preferred models. In the Adirondacks and Pikwitonei, 8-kbar rocks are underlain by 30–35 km of crust, implying a pre-erosional thickness of about 60 km. (Post-metamorphic underplating seems unlikely as it would require a tectonothermal event that itself would cause a later metamorphism.) In order to generate the initial portions of the ACW path, the crust must be heated throughout by the intrusion of magmas. This increases the thickness of the crust by as much as 20%. The crust is thickened further by the underplating of perhaps a 15–20-km thickness of basaltic magmas (or their differentiates) beneath existing crust. Magmatic thickening of the crust may be augmented by crustal shortening in the later stages of the tectonothermal event. The crust begins to cool following the cessation of magmatism. Isostatic equilibrium of the thickened crust might be maintained, at least partially, by the formation of eclogite and other garnet-rich rocks in the lowermost crust (Bohlen & Mezger, 1989), therefore causing nearly isobaric cooling.

The dense lowermost crust composed of eclogite and other garnet-rich rocks may also control the uplift and erosional exposure of the granulite terranes. It has been shown that many regional granulite terranes are not uplifted and exposed in the same tectonic episode to which they owe their origin, Ellis' 'single cycle' (Ellis, 1987; Harley, 1989), but are uplifted at a later time during a second tectonic event. Assuming that parts of a lowermost crust of basaltic composition can become more dense than the mantle that underlies them, the delamination or spearation of this dense crustal root could be responsible for the initiation of uplift. The formation of the densest parts of the crustal root might occur after the tectonothermal event because some of the garnet in the lowermost crust would nucleate and grow during cooling of the crust and upper mantle. Depending on the density constrast and the rheological properties of the upper mantle, delamination (Bird, 1979; Etheridge *et al.*, 1987) of parts of the deep crust might be delayed for long periods. However, after delamination, the very existence of a relatively dense crustal root, not all of which would be returned to the mantle, may in general prevent the erosional uplift of granulite terranes beyond the level that approximately corresponds to the base of the pre-underplated crust, or pressures of about 8–9 kbar.

The validity of many of the ideas above can be tested for consistency by combining petrological and geochemical constraints with those from geophysics. The $P$–$T$–time path must be consistent with thermal conditions and the flow of heat through the lithosphere, internal heat generation within the lithosphere, isostasy, gravity, magnetotellurics, and reflection seismology. For example, the petrological model outlined above requires that a thick layer of igneous material, dominantly basaltic in character, be added to the base of the existing continental crust. The derivation of such a mass of basalt from the lithosphere requires that a significant fraction of the subcontinental lithosphere be depleted of its basaltic component over a period of 100–200 Ma. This in turn may severely limit the nature of the thermal and rheological conditions appropriate for such a massive basalt-forming episode and may itself require continental extension in the early stages of tectonism. As noted above, the addition of the basaltic underplate will increase elevation by about 10% of the thickness of basalt (Lachenbruch & Morgan, 1989). Elevation will also be increased by the thermal expansion of the lithosphere (Lachenbruch & Morgan, 1989) unless these effects are compensated by the formation of eclogite in the underplated crustal material or thickening of the subcontinental lithosphere. If the modelling showed a net increase in elevation during the granulite-forming tectonic event, this would not necessarily be inconsistent with initial, nearly isobaric cooling as long as elevation gain was over a broad area, such that the erosional baseline was also elevated.

Even though the relationships between elevation, evolution of the lithospheric thermal structure and density of the rock column may provide the most stringent constraints on the petrological models of the formation of regional granulites, important constraints from short- and long-wavelength magnetic and gravity studies, electrical conductivity studies of the crust and upper mantle and seismic studies will also be important in devising a comprehensive model. Geophysical modelling with close attention to the integration of the petrological constraints outlined above would be most helpful.

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