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Notes

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COMMENT

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In a stimulating paper, Collins (2002, p. 535) asserted that “many granulite terrains were too hot to have formed during continental collision” in spite of evidence to the contrary (e.g., Harley, 1989; O’Brien and Rötzler, 2003). Based on this assertion, Collins (2002, p. 535) postulated that “high-grade metamorphic terrains . . . represent thickened hot orogens that . . . formed in another tectonic setting.” The present SW Pacific margin was suggested as a model, and exemplified by the evolution of the Lachlan orogen. In the model, slab rollback drives extension of the overriding plate, backarc basin formation, and adiabatic decompression melting; it is postulated that underplating by basalt causes granulite facies metamorphism. Extension may be interrupted by arrival of a bathymetric high at the trench, which leads to flat subduction and an episode of shortening; as the orogen thickens, it will cool as it becomes isolated from the asthenosphere. A change from extension and heating to shortening and cooling will generate a counterclockwise pressure-temperature (P - T) path. Such a path conflicts with those generated by Sandiford and Powell (1986, their Fig. 2) during simulated extension, who did not propose that “lithospheric extension is . . . a necessity for granulite facies metamorphism” (Collins, 2002, p. 536).

Estimating temperature and pressure in granulites is difficult, due to resetting of Fe-Mg exchange thermometers during cooling, and a simple compilation of data from the literature of the past thirty years is inappropriate. Pattison et al. (2003) have recalculated the P - T conditions of common granulites using garnet-orthopyroxene thermobarometry corrected for retrograde exchange. Based on their compilation, the T - P range of common granulites is 800–900 °C and 0.4–1.0 GPa, respectively. During the past decade, it has become apparent that some granulites record evidence of extreme thermal conditions (ultrahigh-temperature [UHT] granulite metamorphism [e.g., Harley, 1998]), whereas other granulites record evidence of deep burial (high-pressure [HP] granulite metamorphism [e.g., O’Brien and Rötzler, 2003]). The P - T conditions of the former are $T > 900$ °C, with maximum values of perhaps > 1150 °C (e.g., Moraes et al., 2002), at P of 0.5–1.5 GPa, and of the latter are T of 750–1050 °C at P of 1.0–2.0 GPa. Under granulite conditions, prograde reaction commonly is complete and melting is ubiquitous, which obliterates evidence of the prograde evolution, with the exception of mineral and fluid inclusions in porphyroblasts.

Most granulites followed a gross clockwise P - T path, although the prograde path is rarely well constrained and the retrograde path may involve decompression with cooling or heating, or a combination of near-isothermal decompression with near-isobaric cooling segments. This type of P - T evolution is characteristic of convergent margin orogens involving collision (e.g., Brown and Dallmeyer, 1996; Brown, 2001), although at least one margin must have involved subduction. Examples of terrains that record evidence of gross counterclockwise P - T paths are more rare, but include the Pikwitonei (e.g., Mezger et al., 1990), the Acadian (e.g., Schumacher et al., 1990), and the Eastern Ghats belt (e.g., Sengupta et al., 1990). Collins (2002) suggested that a return to rollback leads to a repeat of the orogenic cycle outboard. Although narrow belts of orogenic activity younging outboard is a feature of the Lachlan orogen, this is not the pattern of the Variscan (Paleozoic), Brasilia (Neoproterozoic), or Grenville (Mesoproterozoic)

orogens that record UHT and HP granulite facies conditions and that are interpreted as having a collisional terminal phase.

Modeling the thermal evolution of collisional orogens has proven challenging, and published models involve simplification of the possible processes (which include ridge-trench interactions, thickening due to magmatic additions, thickening due to collision, internal advection of heat by magmatism, and collapse due to slab breakoff or delamination). It is the combination of processes in these orogens that makes modeling their thermal evolution challenging, and the failure of conventional models to achieve the peak T recorded is no surprise.

The model proposed by Collins (2002) is inconsistent with the bulk of the data; it does not explain the range of P - T conditions associated with UHT and HP granulite metamorphism, or the clockwise P - T evolution that is characteristic of most granulites. Without undermining the innovative nature of the model proposed by Collins (2002) for the evolution of the Lachlan orogen, or its possible application to other orogens with broadly similar features, such as the Acadian orogen, broader application of the model to explain most granulites is inappropriate, and the model fails to explain even the first-order features of many granulite terrains.

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REPLY

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This reply touches on several issues that reflect Brown's and my different emphasis on the tectonic setting of granulites. Essentially, Brown suggests that the tectonic switching model should produce counterclockwise pressure-temperature-time (P - T - t) paths, then argues that most documented granulites involve clockwise P - T - t paths, which he asserts form in continental collision zones. However, he concedes that conventional thermal models fail, suggesting it is because collision zones are complex. Unfortunately, this comment does not shed new light on the granulite conundrum, and only reiterates a traditional but uncertain view of granulite genesis.

The tectonic switching model is not based on the assertion that granulites were too hot to have formed by continental collision, though it does overcome the temperature problem that the thermal models highlight. Rather, the model is based on the detailed tectonostratigraphic record of the Lachlan orogen, and on geochemical and experimental data obtained from its voluminous granites. These data indicate granite generation under low- to medium- P granulite facies conditions, assisted by advective mantle heat during prolonged regional extension (Collins, 2002). Such granulites should follow near-isobaric retrograde paths (Sandiford and Powell, 1986), but could have weak clockwise or counterclockwise prograde P - T - t paths generated during the transient thickening phases. The predicted P - T ranges lie within the field of common granulites cited by Brown. Some ultrahigh-temperature (UHT) granulites would form in this setting, but granulites associated with isothermal decompression paths are excluded.

So, are most granulites formed in orogens involving collision? Collisional orogens develop when an ocean closes between continental blocks. However, many orogenic systems have not experienced collision, particularly the circum-Pacific types, which have always faced an ocean. They have been called accretionary (e.g., Coney, 1992), with the Lachlan orogen an excellent example. Furthermore, most collisional orogenic systems have a prior accretionary history (e.g., van Staal et al., 1998), so it is easy to confuse the accretionary and collisional histories in the ancient examples used by Brown.

Let us examine modern Earth to consider where most granulites occur, rather than use ancient examples and speculated tectonic settings. In the two classic modern collisional orogens, the European Alps and Himalayas, coeval granites and granulites are rare, and the general P - T - t paths pass through the Barrovian field as predicted by conventional numerical models (Jamieson et al., 1998, their Fig. 1). The proposed Himalayan P - T - t path for peak thermal conditions is just sufficient to produce sporadic leucogranites (Patiño-Douce and Harris, 1998, their Fig. 3), and these represent an extremely small percentage of granite-type on Earth.

In contrast, broad zones of anomalously high heat flow occur in extensional and accretionary orogens, associated with widespread silicic magmatism. These include the Basin and Range Province of the western United States and Mexico, the Taupo volcanic zone of New Zealand, and the vast circum-Pacific orogenic belts, which are characterized by voluminous batholiths and repeated extension-contraction events. These orogens are underlain by granulites, but few are exposed (e.g., Ducea, 2001), because crustal doubling rarely occurs, although deep crustal granulitic xenoliths in young basalts attest to their existence (e.g., Chen et al., 1998). It appears that granulites are more abundant in accretionary than in collisional orogens.

The Precambrian shield regions contain granites with petrological features most similar to circum-Pacific batholiths, including coeval mafic/dioritic components (e.g., Brew, 1992), with many shields thickened during later collisional orogenesis, exposing the deeper high-grade parts. For example, the vast low-grade Proterozoic terrains of central Australia are similar to the Lachlan orogen, but have been locally up-

lifted during Paleozoic orogeny, exposing low- and medium- P granulites that formed coeval with the granites (Collins and Williams, 1995). Typical Precambrian terrains contain abundant circum-Pacific-type granitoids, rather than sporadic leucogranite, and probably formed in accretionary orogens.

Crustal thickening during collision leads to isostatic rebound and ultimately exposure of granulites formed in that and earlier orogenic cycles (Ellis, 1987). Associated high-grade rocks should record near-isothermal decompression P - T - t paths produced during exhumation, and should be commonly exposed, leading to a sampling bias over those formed in isobarically cooled terrains. If granulites formed in collisional orogens, one must ask why did they have anomalous heat, and perhaps we should be considering extensional events immediately prior to collision to help resolve this problem, as Thompson et al. (2001) have done. Such events are typical of accretionary orogens, and I argue that many granulites of collisional belts formed in the accretionary phase of the orogenic history.

Clockwise P - T - t paths should form during continental collision, at the termination of a Wilson-cycle, but this concept does not explain the tectonic development of circum-Pacific orogens, nor the features of many Precambrian cratons, nor isobarically cooled low- and medium- P granulite terrains. Geological evidence and thermal modeling demand that orogens are not closed systems, and that mantle-derived magmas commonly supply heat, either directly or indirectly via hybridized, circum-Pacific-type granitic magmas. We should be looking at other ways to explain these granulites and granites involved in creation of continental crust, and I have used circum-Pacific rather than Wilson-cycle models. The models should be constrained by all the geological evidence, including igneous petrology, geochemistry, thermal modeling, and by fundamental geodynamic principles. At present, many compromise Wilson-cycle tectonic models involving delamination and slab breakoff tend to ignore at least one of these aspects.

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