Some geodynamic and compositional constraints on "postorogenic" magmatism

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ABSTRACT

Postorogenic magmatic suites are common to many orogens, in many cases apparently just postdating the cessation of deformation. They differ from preceding orogenic suites in that they have higher temperatures, more primitive isotopic signatures, and bimodal natures, and thus are compositionally similar to suites found in extensional regimes. We propose that thinning of the lithospheric mantle, which may be an automatic response to orogenic lithospheric thickening, is responsible for these magmatic suites. Mantle lithospheric thinning moves the asthenospheric-lithospheric thermal boundary higher in the lithospheric column, thereby raising the overall thermal budget of the orogen and the likelihood of basaltic magmatism. This removal of much of the dense, lithospheric mantle root of the orogen also invokes uplift capable of producing horizontal orogenic buoyancy forces that will oppose and potentially terminate deformation. Extreme fractionation of the magmas is promoted by high temperatures and a noncompressional or tensional lithospheric stress regime to produce accompanying felsic (A-type) magmas. This model explains why the cessation of deformation is coincident with high-temperature bimodal magmatism and inferred uplift, as well as the long-noted similarity and confusion between "postorogenic" and extensional magmatic suites. This arises because both reflect thinning of the lithospheric mantle, not because both reflect extensional tectonics. We suggest that these magmatic episodes may be important in transferring lithospheric mantle material and its compositional signatures into the crust.

INTRODUCTION

Magmatic rocks found in orogenic belts provide a record of the thermal and chemical evolution of the deep lithospheric root of the developing orogen. Although the rocks eventually sampled may be the end product of several generative processes (e.g., assimilation and mixing), an association of magmatic suites with particular tectonic settings is observed and reflects a relation between geodynamic factors and magmatic type. For example, considerable progress has been made in understanding the relation between geodynamics and magma composition in (oceanic) extensional tectonic settings where the magma composition is related to the degree of extension and decompression (McKenzie and Bickle, 1988). Continental orogenic magmatism is less well understood than oceanic magmatism, and here we concentrate on the magmatic suites that postdate compressional deformation. We suggest that geochemical and isotopic data can be combined with knowledge of temporal-spatial relations and other tectonic elements, such as deformation and isostatic responses, to outline some basic causal links that point to a genetic model.

CHARACTERISTICS OF POSTOROGENIC MAGMATISM

Many orogenic belts contain two distinguishable magmatic suites, a series of orogenic I- and S-type granites bearing structural fabrics and an undeformed bimodal suite emplaced following the cessation of convergent deformation. Although these latter are usually referred to as "postorogenic" suites, the end of convergent deformation does not require that orogenesis sensu stricto has ceased by the time of their emplacement. Specific examples and details of the following characteristics have been compiled by Turner et al. (1992, and references therein). Postorogenic suites are widely distributed in space and time, and although most immediately postdate deformed orogenic granites, some formed later, by as much as 40 m.y. This time lag between magmatic pulses does not necessarily imply any lag between the end of deformation and the first appearance of nondeformed granites. Features such as miarolitic cavities, granophyric intergrowths, and bipyramidal quartz in the granites, as well as the association with volcanic equivalents, indicate that the "postorogenic" magmas are intruded to high crustal levels. In addition, many workers argue that their emplacement was accompanied by crustal uplift, on the basis of mineral cooling-age data, associated denudation, and molassic deposits or structural or palynological evidence.

The mafic members of "postorogenic" suites consist of tholeiitic gabbros and basalts, whereas the felsic members are highly siliceous, having negative europium anomalies and being enriched in highly charged cations. These felsic rocks fit the description of A-type rocks by Collins et al. (1982), and A-type rocks are often thought of as being characteristic of "postorogenic" suites. These felsic rocks are isotopically primitive ($^{87}Sr/^{86}Sr < 0.705$) compared to preceding orogenic granites ($^{87}Sr/^{86}Sr > 0.705$), suggesting that they are derived from a different, less evolved source, probably the mantle, consistent with their close association with mafic magmas. The ubiquitous light rare earth element (REE)–enriched patterns of the magmas and recent ideas on the sources of continental magmas (Hawkesworth et al., 1990) indicate a significant lithospheric mantle contribution.

Magmatic temperatures of the deformed and nondeformed orogenic granite suites appear to be distinctly different. Typical orogenic I- and S-type granites are thought to have magmatic temperatures in the range 750–850 °C (Hildreth, 1981; Wyborn et al., 1981). In contrast, natural and experimental data indicate that the "postorogenic" A-type granites crystallized from wholly molten magma at temperatures >900 °C (Clemens et al., 1986; Turner et al., 1992), whereas their accompanying mafic magmas would have magmatic temperatures well in excess of 1000 °C.

Bimodal magmatic suites similar to those described above are also recognized from areas undergoing crustal extension where lithospheric thinning is related to magma genesis and composition. These include suites such as those at Loch Ba and St. Kilda in the British Tertiary province, the alkalic-ring complexes of the Nigerian and Kenyan rift valleys, and basalts with associated A-type granites from the Yeman Plateau (summarized in Turner et al., 1992). In both "postorogenic" and extensional settings, large positive gravity anomalies provide evidence for extensive volumes of contemporaneous mafic magma (e.g., Walsh et al., 1979; Turner et al., 1992), and there is commonly field evidence indicative of mingling between the mafic and felsic magmas (Sparks and Marshall, 1986; Whalen and Currie, 1984; Foden and Turner, 1991). There may also be examples of a gradation between the "postorogenic" and extensional suites, "postorogenic" crustal relaxation leading into extension, as in the Basin and Range province (Gans et al., 1989).

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INFERENCES AND POSSIBLE MODELS

Although there are various models for the distinctive chemistry of these "postorogenic" magmatic suites, the critical geodynamic problems related to their genesis remain unanswered. However, the geodynamic and compositional data allow some inferences regarding their origin. First, the broad distribution of "postorogenic" magmatic suites through space and time suggests that a common process is responsible for their origin. Furthermore, the appearance of similar suites in extensional settings suggests that this process is largely independent of tectonic history and that preceding orogenesis is not mandatory in preparing some unique source, as has been proposed by some workers (e.g., Collins et al., 1982). Bimodal volcanic rocks of the compositions described above also occur on oceanic islands such as Iceland and Ascension Island (Macdonald et al., 1990; Harris, 1983), confirming that the source of these magmas is largely independent of crustal setting, albeit thermally and compositionally tied to the mantle.

The variable time lag between the deformed and nondeformed magmatic suites of orogens and the higher magmatic temperatures of the later suites would seem to preclude their having the same thermal source. The isotope and geochemical data indicate that the source is often different from that of the preceding granites. It seems that during the 4–40 m.y. following the appearance of orogenic granites, a new process and source replace the complex crust-mantle interaction characteristic of orogenic magmatism. The appearance of the later, high-temperature magma suites clearly requires a significant perturbation in the thermal regime of the orogen, and the coincidence of this with the termination of deformation suggests a causal link between this thermal pulse and the cessation of deformation. The apparent association with uplift indicates a simultaneous isostatic response. Changing or halting the external tectonic driving forces is one way of terminating deformation; however, this provides no explanation for the thermal pulse.

Another means of halting convergent deformation is through major uplift, one result of which is to produce externally directed buoyancy forces that oppose those driving convergence (e.g., Turcotte, 1983). This could result from increased topography built up by compressional deformation, although this would not explain the thermal pulse. Thickening of the lithosphere by injection of basalt from the asthenosphere may also produce uplift and would explain the thermal pulse; however, the amount of uplift and corresponding buoyancy force appears to be small—only 2.7 km uplift for an addition of 15 km of basalt into the lower crust (McKenzie, 1984). It is also unclear why injection of large volumes of basalt should occur after some finite amount of convergent strain, particularly in light of the currently popular model that links asthenospheric magmatism with thinning and decompression (McKenzie and Bickle, 1988).

An alternative, summarized in Figure 1, is thinning of the lithospheric mantle as proposed by Houseman et al. (1981), which would explain the occurrence of a similar magmatic association in extensional settings. Such a scenario has been proposed for the Himalayan collision of India and Asia (England and Houseman, 1988, 1989). During the late Tertiary the elevation of the Tibetan Plateau increased rapidly, and it changed from a zone of compressive deformation to one of marked extensional deformation, despite the continuing convergence of India and Asia (England and Houseman, 1988). Geophysical data and numerical modeling suggest that

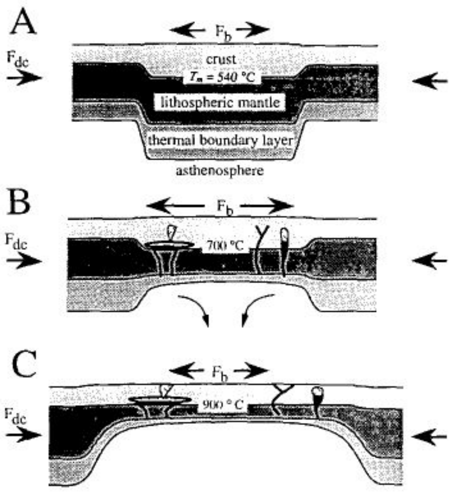

Figure 1. Cartoon illustrating evolution of convergent orogen subject to driving force for convergence, F_{dc}, with resultant development of horizontal buoyancy forces, F_b, that increase with degree of lithospheric thinning from B to C. Prior to convective thinning of mantle lithosphere, maximum elevation of orogenic plateau is dictated by balance between driving forces and buoyancy forces (A). Increase in potential energy of orogen consequent upon convective thinning of mantle lithosphere will preclude further compressional deformation (B) and may induce extensional collapse of orogen if buoyancy forces exceed driving force by amount equivalent to strength of lithosphere to extensional failure (C). Magmas generated as consequence of lithospheric thinning may appear either as "postorogenic" (B) or extensional (C).

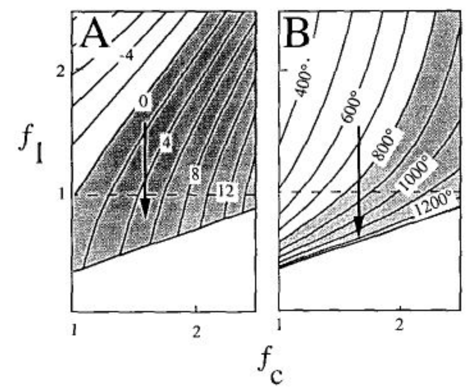

Figure 2. Parameter determination of orogenic lithospheric deformation in terms of crustal thickening, f_c, and lithospheric thickening, f_l, allows evaluation of isostatic and thermal consequences of deformation paths involving processes such as convective thinning of mantle lithosphere. A: f_c-f_l plane contoured for horizontal buoyancy forces arising from deformation-induced gradients on density interfaces between deformed and undeformed lithosphere. Stippled area shows deformation geometries where buoyancy forces result in extension within orogen in absence of tectonic driving force. Initial parameters (see Sandiford and Powell, 1990) are z_l = 100 km, z_c = 35 km, ρ_c = 2800 kg/m^3, ρ_m = 3300 kg/m^3, $\alpha = 10^{-5}$/K, and T_l = 1280 °C. Note that thinning of mantle lithosphere produces extensional buoyancy forces. B: f_c-f_l plane contoured for potential Moho temperatures for lithosphere modeled in A with heat-source characteristics modeled to give initial steady-state Moho temperature of 500 °C and conductivity of 3 W · m^{-1} · K^{-1}. Note that thinning of mantle lithosphere (arrows) results in large buoyancy forces and high potential Moho temperatures.

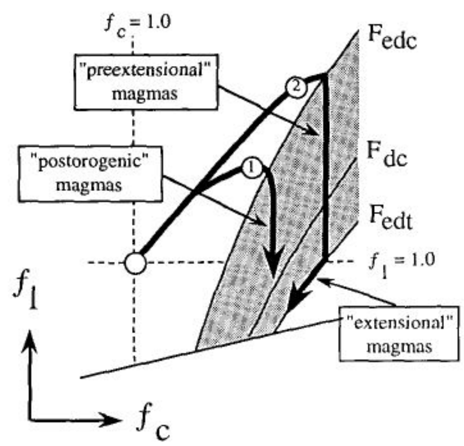

Figure 3. Schematic illustration of deformation (f_c-f_l) paths in orogen subject to driving force, F_{dc}, where convective thinning of mantle lithosphere begins after some finite thickening. Initial homogeneous deformation, (f_c = f_l) leads to onset of convective thinning of mantle lithosphere (f_c > f_l), after small finite lithospheric thickening in path 1 and larger finite lithospheric thickening in path 2. Because lithosphere has finite strength, convergent deformation and crustal thickening will cease when buoyancy force is equal in magnitude to effective driving force for compression, F_{edc}, given by actual driving force minus strength of lithosphere in compression. Continued thinning of mantle lithosphere will increase buoyancy forces. If buoyancy forces exceed driving force by amount equivalent to strength of lithosphere in tension (F_{edt}), extensional failure of whole lithosphere may occur (path 2). With reference to strain history at their site of emplacement, magmas generated by thinning of mantle lithosphere will appear as "postorogenic" in path 1 and either "preextensional" or "extensional" in path 2.

these events resulted from convective instability and removal of the lower lithospheric mantle (England and Houseman, 1989). Late-orogenic magmatism in the Tibetan Plateau consists of late Tertiary to Quaternary bimodal volcanism involving incompatible element–enriched basalts and rhyolites with A-type characteristics (Coulon et al., 1986). In addition to uplift, this model would predict that "postorogenic" magmas may have a lithospheric mantle signature.

GEOPHYSICAL CONSIDERATIONS

During convergent deformation, both the continental crust and the subcontinental lithosphere thicken, and cold, dense mantle lithosphere displaces warmer convecting asthenosphere (Fig. 1). Theoretical considerations suggest that a thermally stabilized mantle lithosphere thickened during convergent deformation must eventually thin in order to balance heat loss through the lithosphere with heat supply to its base (Houseman et al., 1981). One mechanism by which this is likely to occur is localized convective downwelling of the thermal boundary layer (Houseman et al., 1981), which has the effect of drawing out and thinning the mantle lithosphere from beneath the surrounding regions. The thermal and mechanical evolution of the orogen is critically dependent on how fast this potential thermal energy balance is realized relative to the orogenic strain rate (Sandiford and Powell, 1990). Numerical modeling (Houseman et al., 1981) suggests that convective processes may lead to rapid thinning of a thickened mantle lithosphere after some initial critical thickening, a few tens of millions of years following the onset of convergent deformation. The consequences of convective thinning of mantle lithosphere beneath a convergent orogen are isostatic and thermal.

Isostatic Consequences

The isostatic effect of mantle lithospheric thinning is to produce uplift and, consequently, an increase in the gravitational potential energy stored in the orogen. Following the concepts of Turcotte (1983), the relative change in elevation, h, assuming isostatic equilibrium, is obtained by equating the vertical stress of the crust and mantle lithosphere in the deformed and undeformed lithosphere, respectively, down to a common depth; this is the depth of isostatic compensation, which is the greater of the thickness of the initial or deformed lithospheres. Following Sandiford and Powell (1990), it is useful to establish parameters in terms of crustal (f_c) and lithospheric (f_l) thickening factors (i.e., $z_c' = z_c f_c$ and $z_l' = z_l f_l$) to give

$$h = [1 - \frac{\rho_c}{\rho_l}]\,[z_c f_c + z_c] + \frac{T_l\,\alpha\,[f_l z_l - z_l]}{2}, \quad (1)$$

where z_c, z_l, and z_c', z_l' are, respectively, the undeformed and deformed thicknesses of the crust and whole lithosphere, α is the coefficient of thermal expansion, and T_l is the temperature at the base of the lithosphere.

A measure of the increase in potential energy is then provided by the horizontal buoyancy force per unit length of orogen, F_b, arising from gradients on density interfaces between the deformed and adjacent undeformed lithosphere. Following Turcotte (1983) and Sandiford and Powell (1990), F_b is approximated by the difference between the integrals of vertical stress (σ_{zz}), with respect to depth, between two regions of different elevation, integrated from Earth's surface down to a common depth below the lithosphere (z_l). Using the f_c-f_l parameterization of Sandiford and Powell (1990), this can be approximated by

$$\frac{F_b}{\rho_l z_c^2 g} = \delta\,\frac{1-\delta}{2}\,[f_c^2 - 1] - \frac{\alpha T_l}{6\Psi^2}[f_l^2 - 1 - 3(1-\delta)\,(f_c f_l - 1)]$$
$$- \frac{\alpha^2 T_l^2}{8\Psi^2}\,[f_l^2 - 1], \quad (2)$$

where $\delta = \rho_c/\rho_l$, and $\Psi = z_c/z_l$. Figure 2A shows that thinning of a thick mantle lithosphere may produce substantial increases in the horizontal buoyancy forces in the orogen (by up to 10^{13} N · m^{-1}). When the increase in the potential energy results in horizontal buoyancy forces of a magnitude similar, but opposed, to the driving force for convergence (less by an amount related to the effective strength of the lithosphere to convergent deformation), then convergent deformation will terminate or be partitioned elsewhere in regions of lower potential energy and/or strength. Continued lithospheric thinning may cause horizontal buoyancy forces to exceed the driving forces; in that case, if the overshoot exceeds the driving force by an amount greater than the effective strength of the lithosphere to extensional deformation, the orogen will begin to collapse (Fig. 3). Whether mantle lithospheric thinning is sufficient to induce extensional collapse depends largely on the timing of onset of that thinning (Sandiford and Powell, 1990) and the strength of the lithosphere (Fig. 3).

Thermal Consequences

Temperature increases associated with mantle lithospheric thinning may be evaluated by solving the diffusion-advection equation in one dimension for model deformations. Temperature increases with depth due to the additive effects of heat flux from the mantle and that contributed by the heat-producing elements concentrated in the crust. It is assumed for simplicity that heat production (H_s) is constant with depth in the crust. For a steady-state thermal gradient and the boundary conditions $T_s = 0$ °C and $T_l = 1280$ °C, the temperature at depth (z) is given by:

$$T = \frac{2\,T_l\,k\,z + H_s\,z^2\,[z_c + z_l] - 2\,H_s\,z\,z_c\,[z_c - z_l]}{2\,k\,[z - z_c + z_l]}, \quad (3)$$

where k is the conductivity and H_s is the surface heat production in the crust. Following Sandiford and Powell (1990), parameters can be determined in terms of crustal (f_c) and lithospheric (f_l) thickening factors. Accordingly, equation 3 can be written for Moho temperature as a function of varying crustal and lithospheric thickness:

$$T_m = \quad (4)$$

$$\frac{f_c\,p\,[2\,T_l\,k\,\Psi + H_s f_c f_l\,(2\,z_c^2 - p\,z_c^2) - H_s f_c^2\,\Psi\,z_c^2\,(2-p)]}{2\,k\,[f_l - f_c\,\Psi + f_c\,p\,\Psi]},$$

where the initial ratio of the crustal/lithospheric thickness is Ψ (= 0.35), $p = z/z_c$ where p is the depth at which T is to be calculated (for Moho temperatures $p = 1$) and $z = p\,z_c f_c$; $z_l = f_l z_c/\Psi$; $z_c = z_c f_c$.

The potential temperature of the Moho, T_m, calculated from equation 4, in a crust with homogeneously distributed volumetric heat production is shown on the f_c-f_l plane in Figure 2B. This shows that in order to generate temperatures sufficient to induce melting in the lower crust and in low-temperature melting fractions in the upper part of the mantle lithosphere on orogenic time scales (e.g., Sandiford and Powell, 1990), it is necessary that the crust thicken and the mantle lithosphere, beneath, thin. Although both thick lithosphere (f_l ~2) and thick crust (f_l ~2) may also result in very high lower crustal temperatures, the times required for attainment of these temperatures in thickened lithosphere are significantly greater than the expected life spans of the orogens (Sandiford and Powell, 1990) and therefore are nearly unattainable.

PETROLOGICAL CONSIDERATIONS

A lithospheric mantle that is thinning has an increased potential for partial melting. The degree of partial melting and compositional heterogeneities will control magma compositions. Although the composition of the subcontinental mantle lithosphere cannot yet be quantitatively described, it seems likely that the mantle lithosphere is enriched or veined by small-percentage (<1%) partial melts from the convective mantle that are enriched in light REEs and incompatible elements (Menzies and Murthy, 1980; O'Nions and McKenzie, 1988; McKenzie, 1989; Hawkesworth et al., 1990). Parts of a mantle lithosphere previously enriched or veined by such partial melts from the asthenosphere will have a lower solidus than the subjacent convective mantle. Small-degree melting of enriched lithospheric mantle at an early stage is likely to produce alkaline liquids, whereas larger proportion partial melts will be tholeiitic (Gast, 1968). Resultant partial melt compositions will therefore be primitive, but with light-REE– and incompatible element–enriched signatures. Isotopes may record a history relating to the period of lithospheric growth during which enrichment or veining occurred—e.g., during extension of a continental margin prior to incorporation into a collisional orogen. For large-magnitude thinning of the lithosphere, decompression may induce melting of depleted asthenospheric mantle beneath the orogen, the initial compositions being a function of the degree of partial melting (McKenzie and Bickle, 1988). Rising asthenospheric magmas may then become contaminated by the more fusible veins during passage through the overlying lithospheric mantle (e.g., Thompson and Morrison, 1988). There is growing evidence to suggest that many high-silica, A-type magmas result from extensive fractionation, with minor assimilation, from mantle-derived parental magmas (Turner et al., 1992; Sparks, 1988; Foland and Allen, 1991). A-type magmas are invariably accompanied by mafic magmas, and the granophyres found in layered mafic plutons typically have A-type compositions. This suggests that they are fractionated from basaltic magma. A more rigorous assessment of this petrogenesis can be found in Turner et al. (1992).

DISCUSSION

Once begun, convective thinning of a thickened mantle lithosphere may proceed very rapidly (Houseman et al., 1981), with the consequence that the thermal response will be delayed with respect to the isostatic response. The melts generated as a consequence of lithospheric thinning are therefore likely to postdate the termination of convergent deformation in any given part of the orogen (Fig. 1). The resulting magmas will therefore exhibit the classic field relations of "postorogenic" magmatism, although they certainly need not imply that convergent deformation elsewhere in the orogen has ceased. Moreover, if mantle lithospheric thinning continues to the stage where extensional collapse begins, magmas with the same geochemical imprint may preserve field relations of "preextensional" or "extensional" magmatic suites (Fig. 3). Note that although some orogens may evolve into extension, it does not necessarily hold that bimodal suites of the type described here imply extensional tectonics—a confusing belief that is common in light of their similarity with suites from extensional settings. Extensive thinning, or even complete removal, of the mantle lithosphere will result in very high Moho temperatures, and the likelihood of crustal melting. In the Basin and Range province, for example, calc-alkaline magmatism may be the result of mixing of mantle and crustal melts (Gans et al., 1989), and Nd isotopes indicate that the mantle lithosphere is being replaced progressively by asthenosphere (Perry et al., 1988).

Mantle lithosphere enriched by small melt fractions from the mantle (O'Nions and McKenzie, 1988) is likely to be an important contributing component in many magmatic rocks (Hawkesworth et al., 1990). O'Nions and McKenzie (1988) argued that these small melt fractions play a fundamental role in producing the composition of the continental crust. The model outlined here suggests that "postorogenic" magmatism is a mechanism for crustal growth in which additions from the lithospheric mantle transfer these small partial melts and their signature to the crust.

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