Crustal melting, ductile flow, and deformation in mountain belts: Cause and effect relationships

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ABSTRACT

Exhumed sections of migmatites are beautifully exposed in the middle crust of old orogens such as the Proterozoic Wet Mountains of Colorado and young Tertiary–active orogens such as the Himalaya and Karakoram. Migmatites and leucogranites occur both on a regional scale (e.g., Greater Himalayan Sequence) and along more restricted shear zones and strike-slip faults (e.g., Karakoram, Jiale, and Red River faults). Melting and deformation are clearly diachronous across orogenic belts over space and time, yet in general, deformation must precede regional metamorphism and melting in order to thicken the crust and increase pressure and temperature. Some deformation can be synchronous with partial melting and there is almost always post-melting deformation along shear zones or faults. The distinction between pre-, syn-, and post-kinematic granites in three dimensions, in pressure-temperature space, and in time becomes critical. In particular, mapping of macro- and micro-structures combined with precise U-Th-Pb dating of migmatitic leucosomes and granitic rocks in deformation zones can be used to constrain the relative timing of metamorphism, melting, ductile shearing and brittle faulting. In the Himalaya, multiple sill intrusions emanating from a regional migmatite terrane fed growth of leucogranite bodies over a time span of ~30 m.y. and channel flow, the southward extrusion of a partially melted section of the mid-crust, occurred along the Himalaya during the Miocene from ca. 24–15 Ma. The Karakoram batholith formed by pre- to post-collisional metamorphism, migmatisation and magmatism over a period lasting at least 65 m.y. Comparisons of the Himalaya and Karakoram migmatite-granite belts with the Proterozoic Wet Mountains in Colorado provide strong evidence for weak middle crust capable of aseismic flow, leading to question models of lithospheric rheology that call on strong middle crust.

INTRODUCTION

Exhumed sections of middle crustal rocks that underwent partial melting and are composed of regional migmatites are known from several mountain ranges including the Proterozoic Wet Mountains of central Colorado (Levine et al., 2013) and the Tertiary–active orogens such as the Himalaya and Karakoram ranges (e.g., Greater Himalayan Sequence) and along more restricted shear zones and strike-slip faults (e.g., Karakoram, Jiale, and Red River faults). Melting and deformation are clearly diachronous across orogenic belts over space and time, yet in general, deformation must precede regional metamorphism and melting in order to thicken the crust and increase pressure and temperature. Some deformation can be synchronous with partial melting and there is almost always post-melting deformation along shear zones or faults. The distinction between pre-, syn-, and post-kinematic granites in three dimensions, in pressure-temperature space, and in time becomes critical. In particular, mapping of macro- and micro-structures combined with precise U-Th-Pb dating of migmatitic leucosomes and granitic rocks in deformation zones can be used to constrain the relative timing of metamorphism, melting, ductile shearing and brittle faulting. In the Himalaya, multiple sill intrusions emanating from a regional migmatite terrane fed growth of leucogranite bodies over a time span of ~30 m.y. and channel flow, the southward extrusion of a partially melted section of the mid-crust, occurred along the Himalaya during the Miocene from ca. 24–15 Ma. The Karakoram batholith formed by pre- to post-collisional metamorphism, migmatisation and magmatism over a period lasting at least 65 m.y. Comparisons of the Himalaya and Karakoram migmatite-granite belts with the Proterozoic Wet Mountains in Colorado provide strong evidence for weak middle crust capable of aseismic flow, leading to question models of lithospheric rheology that call on strong middle crust.
exposed, generally in old Precambrian cratonic regions, they show extensive dry granulite-facies metamorphism with little or no evidence for partial melting. It has been proposed that the thickened crust of the Tibetan plateau is presently undergoing lower crustal flow to the east toward the thinner crust of SE Asia (Royden et al., 1997; Clark and Royden, 2000). There is, however, no exposure of the lower crust anywhere in Tibet or the area adjacent to the eastern margin, and the eastern margin of Tibet shows no evidence of extrusion of middle or lower crust rocks like the Himalaya. Instead, all the metamorphism and most granites have older Indosinian (Triassic-Jurassic) ages (Weller et al., 2013). Only a very few cases of post-collision (<50 Ma) granitic melts are known from the Tibetan Plateau, although there is evidence of widespread shoshonitic (mantle-derived) and adakitic (thickened lower crust-derived, requiring a garnet-bearing amphibolite or eclogite source) intrusions all across the plateau (Chung et al., 2005; Searle et al., 2011). Although present-day global position systems (GPS) does show eastward motion of the surface of North and East Tibet (Gan et al., 2007), there is no geological evidence to support lower crust flow in eastern Tibet, whereas the evidence for mid-crustal channel flow along the Himalaya during the Miocene is overwhelming (Grujic et al., 2002; Searle et al., 2003, 2006, 2010b; Law et al., 2004, 2006, 2011; Searle and Szulc, 2005; Godin et al., 2006).

This paper firstly reviews the metamorphism and melting processes along the Himalaya (Indian plate) and Karakoram (Asian plate) and the granite wet melting reactions that form partial melts in the appropriately named Wet Mountains and the Himalaya. I then discuss how melts migrate from their source to make granites of batholithic proportions using the ~35 km of structural depth exposed in the Himalaya and Karakoram. The relationships between partial melting, granite movement along shear zones and deformation temperatures and fabrics, as shown in ancient and modern examples have a key bearing on interpreting the large-scale rheology of the lithosphere, whether the “jelly sandwich” model (strong upper crust, weak lower crust, strong upper mantle; e.g., Burov and Watts, 2006) is more applicable or whether the “crème brûlée” model (strong upper crust, weak lower crust, weak upper mantle; e.g., Jackson, 2002; Jackson et al., 2008) is more appropriate.

**METAMORPHISM—MELTING ALONG THE HIMALAYA AND KARAKORAM**

The India-Asia collision resulted in crustal thickening and shortening, metamorphism and partial melting along the 2200-km long Himalayan range. The Himalaya shows a relatively simple evolution from early deep crustal subduction along the northern margin at ultra-high-pressure coesite eclogite grade (late Palaeocene–early Eocene) through kyanite (late Eocene–Oligocene) and sillimanite + muscovite, sillimanite + K-feldspar and sillimanite + cordierite grade, culminating with widespread partial melting in the middle crust and generation of anatectic leucogranites (Early Miocene). In the core of the Greater Himalaya widespread in situ
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Partial melting in sillimanite + K-feldspar gneisses resulted in formation of migmatites and Ms + Bt + Grt + Tur ± Crd ± Sil ± And leucogranites, mainly by muscovite dehydration melting (Harris et al., 1995; Harris and Massey, 1994; Visona and Lombardo, 2002) and in the latter stages by biotite dehydration melting (Streule et al., 2010; Groppo et al., 2012; Visona et al., 2012). Initial melting occurred in the kyanite stability field (~10–12 kbars) forming Late Eocene–Oligocene kyanite-bearing leucosomes and leucogranites (e.g., Zanskar, Langtang), but the bulk of melting occurred at shallow depths (4–6 kbar; 15–20 km) in the middle crust, during the Miocene resulting in sillimanite, andalusite or cordierite-bearing leucogranites (e.g., Everest, Makalu, Langtang). $^{87}$Sr/$^{86}$Sr ratios of the leucogranites are very high (0.74–0.79) and heterogeneous, indicating a 100% crustal protolith. Melts were sourced from fertile muscovite-bearing pelites and quartzo-feldspathic gneisses of the Neoproterozoic Haimanta-Cheka formations. Melting was induced through a combination of thermal relaxation due to crustal thickening and from high internal heat production rates within the Proterozoic source rocks in the middle crust. Himalayan granites have highly radiogenic Pb isotopes and extremely high uranium concentrations. Little or no heat was derived either from the mantle or from shear heating along thrust faults.

Mid-crustal melting triggered southward ductile extrusion (channel flow) of a mid-crustal layer bounded by a crustal-scale ductile shear zone - thrust fault (Main Central Thrust) along the base, and a low-angle ductile shear zone and normal fault (South Tibetan Detachment or Zanskar shear zone) along the top (Fig. 2). Multi-system thermochronology (U-Pb, Sm-Nd, $^{40}$Ar-$^{39}$Ar, and fission track dating) show that partial melting triggered mid-crustal flow between the simultaneously active shear zones of the MCT and STD. Melts were channeled laterally along giant sill complexes via hydraulic fracturing into sheeted sill complexes from the migmatitic source region, and intruded for up to 100 km parallel
to the foliation in the host sillimanite gneisses (e.g., Everest–Rongbuk profile). Crystallization of leucogranites was immediately followed by rapid exhumation, cooling, and enhanced erosion during the Early-Middle Miocene. The channel flow hypothesis for the Greater Himalayan Sequence fits all known geological (Searle et al., 2003, 2006, 2010b; Law et al., 2004, 2006, 2011) and geophysical (Nelson et al., 1996; Hauck et al., 1998; Tilmann et al., 2003) parameters. The thermal-mechanical model of Beaumont et al. (2001) using all the Himalayan-specific geological and geophysical parameters shows that Miocene mid-crustal channel flow along the Himalaya is a viable process. The upper, middle, and lower Himalayan crust are decoupled and each show different rheology, fluid composition, seismic properties, and structural evolution. Although southward-directed channel flow must have been operative during the Miocene along the Himalaya, it is possible that the same process could still be active beneath southern Tibet where an active mid-crust layer of partial melt has been imaged. In the Nanga Parbat Western Himalayan syntaxis region of the GHS very young (Placocene-Pleistocene) sillimanite + cordierite grade metamorphism and anatexis may provide insight into active thermal structure of the deep crust today (Crowley et al., 2009).

The Asian-plate Karakoram terrane in North Pakistan shows a much more complex and long-lasting structural and thermal evolution. During and following accretion of the Kohistan Arc to the southern margin of Asia and collision with the Indian plate, crustal thickening along the Karakoram resulted in polyphase deformation, metamorphism and melting. Abundant Middle Jurassic and Cretaceous (170–90 Ma) Andean-type subduction-related granite intrusion is recorded as well as widespread kyanite and sillimanite grade regional metamorphism spanning at least 65 m.y. (Searle et al., 2010a). U-Pb monazite ages from the Baltoro granites range between 25 and 13 Ma, very similar to most of the Himalayan leucogranites along the Indian plate. Metamorphism along the Karakoram is diachronous in space and time and it is quite likely that, given the extreme crustal thickness (up to 85–90 km) active granite or eclogite facies metamorphism occurs today at depth beneath the Karakoram.

**PARTIAL MELTING IN CONTINENTAL CRUST**

Through careful field observations and mapping of melt microstructures, shear zones, and melt reactions at all scales, Levine et al. (2013, see “Relationship between syn-deformational partial melting and crustal-scale magmatism and tectonism across the Wet Mountains, central Colorado.” Lithosphere, v. 5, no. 5, p. 456–476) document widespread partial melting in the middle crust of the Wet Mountains, Colorado, that appear to have many similarities to the Tertiary and active Himalaya-Karakoram orogenic belt in Asia. During progressive Barrovian metamorphism volumetrically significant anatexis first occurs as a result of the muscovite dehydration reaction:

\[
\text{Qtz} + \text{Ms} + \text{Pl} = \text{Als (Sil)} + \text{Kfs} + \text{Melt} \pm \text{Grt} \pm \text{Tur}. \tag{1}
\]

This fluid-absent reaction occurs over a temperature range of ~710–790 °C (Petö, 1976; Patiño-Douce and Harris, 1998) and produces the first in situ melts in migmatites. In standard pelitic compositions, the muscovite dehydration reaction could occur at temperatures as low as 670–690 °C. Melts are preferentially localized along anisotropic planes of weakness, foliation planes, forming layered or stromatic migmatites (Fig. 3A). In the Himalaya, these muscovite dehydration melts are typically peraluminous garnet + muscovite + tourmaline leucogranites, although the leucogranites are almost certainly not pure melts, but mixtures of melt plus crystals inherited from the restite. The first crustal melts formed along the Himalaya are kyanite-bearing migmatitic leucosomes indicating that the earliest melts were the deepest (~10–12 kbar), with progressively later, shallower sillimanite and then cordierite-bearing partial melts (~6–3 kbar).

The second slightly higher temperature reaction is the biotite dehydration melting reaction:

\[
\text{Qtz} + \text{Ms} + \text{Pl} + \text{Bt} = \text{Als (Sil)} + \text{Kfs} + \text{Melt} \pm \text{Grt} \pm \text{Tur}. \tag{2}
\]
that occurs at temperatures in the range 760–850 °C (LeBreton and Thompson, 1988; Spear et al., 1999). At lower pressures (<5 kbar) cordierite is the stable peritectic phase whereas at pressures above 5 kbar, peritectic garnet is stable. In the Himalaya, these crustal melts typically form cordierite-bearing leucogranites (Groppo et al., 2012; Streule et al., 2010) or analadusite-bearing leucogranites (Visona et al., 2012). Analadusite can be residual and/or peritectic.

On a broad scale, deformation and partial melting are usually synchronous leading to a positive feedback. Deformation enhances melting by aiding diffusion and reaction rates, and strain is frequently partitioned into rheologically weaker partial melt zones. On a more local, outcrop scale, batch melting throughout an actively deforming migmatite region results in intrusion of multiple sills and dykes showing varying levels of strain through time and space (Fig. 3B, and 3C).

**MELT MIGRATION AND BATHOLITH GENERATION**

Partial melting promotes flow in rocks since viscous material has no yield strength and will flow given any deviatoric stress. Along the Himalaya migmatites up to 10 km in structural thickness occur in the middle crust above the MCT zone with its inverted and condensed metamorphic sequence, and beneath the STD low-angle normal fault with its right-way-up and condensed metamorphic sequence (Fig. 2). These migmatites are dominantly stromatic or layer-parallel migmatites with abundant garnet, tourmaline, and muscovite in the melt phase. The melts percolated along the schistosity planes and can be traced both along and across strike (down-dip) for great distances. At higher structural levels the melts merge into layer-parallel sills intruding the high-grade gneisses. Individual sills become progressively thicker at higher levels eventually forming sills up to 3 km thick in the Everest, Makalu, and Kangchenjunga regions for example (e.g., Searle et al., 2003, 2010b; Streule et al., 2010). Along the Rongbuk valley north of Everest the foliation-parallel sills die out along the ductile strand of the STD, the Lhotse detachment (Searle et al., 2003, 2006).

Leucogranite dykes emanating from the top of the Everest-Nuptse granite are deflected to the north beneath the Lhotse detachment (Fig. 3D), which merges toward the north with the upper brittle Qomolgangma detachment (Cottle et al., 2007). Himalayan crustal melting has occurred by multiple batch melting over a time span of ~10 m.y. (U-Pb ages of all granites ranging 24–15 Ma; Cottle et al., 2009). Melts migrated laterally along giant foliation-parallel sills complexes with dykes feeding magma to higher sills, and even later cross-cutting sets of dykes feeding the highest level, younger biotite-dehydration granites that contain cordierite and analadusite.

Whereas Himalayan crustal melting is exposed in the form of stromatic migmatites and giant sill complexes, crustal melting along the Karakoram (Asian side of the collision) has produced far greater volumes of melt that have amalgamated to form a large batholith (~700 × 20 km dimension). The Karakoram batholith includes pre-collision subduction-related I-type granites (diorites, tonalites, and amphibolites) as well as post-collision S-type granites (garnet, muscovite, tourmaline monzogranites, and leuco-granites). The latter have also built up from giant sill complexes intruding a high-grade metamorphic (kyanite- and sillimanite-zone) metamorphic terrane to the south (Searle et al., 1992, 2010a).

**RELATIONSHIP OF PARTIAL MELTING TO SHEAR ZONES**

The close spatial association between high-grade metamorphic rocks, migmatites and granitic melts and crustal-scale shear zones and faults has been noted along many orogenic belts. Prime examples are the South Armorican Shear Zone in Brittany (Brown and Dallmeyer, 1996), the Karakoram Fault in Ladakh (Searle et al., 1998; Phillips et al., 2004, 2013; Lacassin et al., 2004) and the Red River shear zone/fault in Yunnan and North Vietnam (Leloup et al., 1995, 2001; Searle, 2006; Searle et al., 2010c, 2011). Partial melting leads to a dramatic decrease in strength when the melt fraction is relatively small (Rosenberg and Handy, 2005). Strain partitioning into the rheologically weaker areas can be preferentially localized into early melt channels (Brown, 2006, 2007; Brown and Solar, 1998; Rosenberg and Handy, 2005) and deformation can also promote partial melt reactions through enhanced diffusion and reaction rates (Brodie and Rutter, 1985) by the positive feedbacks noted earlier.

In the Wet Mountains of Colorado, Levine et al. (2013) document strain differences where the upper crust has mainly vertical foliations with localized discrete granite bodies, and the middle crust has widespread migmatites with horizontal foliations and abundant mid-crust melt channels. This is very similar to the Karakoram region of Ladakh and North Pakistan where transpression along the dextral strike-slip Karakoram fault has exhumed Cretaceous and early Tertiary pre-collisional I-type diorites and granodiorites, Cretaceous amphibolite facies metamorphic rocks, mid-crustal migmatites, foliation-parallel leucogranite bodies, and Miocene sills and dyke swarms in between two strands of the fault (Phillips et al., 2004, 2013; Phillips and Searle, 2007; Searle and Phillips, 2007; Streule et al., 2009). Levine et al. (2013) suggest that deformation is concentrated along areas where melt-producing reactions occur, and inversely that melts are concentrated along shear zones, suggesting a strong correlation between partial melting and deformation. The obvious question that arises is which is the chicken and which is the egg? Do shear zones control the generation and ascent of magmas (Brown and Solar, 1998; Brown, 2006, 2007) or do magmas trigger nucleation of shear zones? Are crustal melt migmatites and granites formed as a result of shearing and fed upward through ductile shear zones to the surface (Leloup et al., 1995; Lacassin et al., 2004; Weinberg and Mark, 2008; Weinberg et al., 2009) or are they the migrmatites and granites produced by regional Barrovian metamorphism unrelated to the faults (Searle, 1996; Phillips et al., 2004, 2013; Phillips and Searle, 2007; Streule et al., 2009). The key to answering these vexing questions lies in the interpretation of partial melt textures in granities and migmatites and the deformation temperatures recorded in the rock fabrics.

**DEFORMATION TEMPERATURES WITH STRUCTURAL DEPTH**

The brittle-ductile transition marks the change from localized deformation along faults in the seismogenic upper crust (up to 17 km) to distributed ductile deformation in the lower crust (Rutter, 1986; Kohlstedt et al., 1995). Even in deep viscous-deforming crust, strain can still localize into shear zones. There are many factors that will induce strain localization: stress field, temperature, effective confining pressure, melt fraction, etc.

The relationships between granitic melts and shear zones are examined in two case examples here, the South Tibetan Detachment low-angle normal fault along the Himalaya and the Karakoram dextral strike-slip fault in Ladakh and Western Tibet.

**South Tibetan Detachment, Himalaya**

In a petrological and microstructural study of fabrics along the South Tibetan Detachment along the top of the Greater Himalayan Sequence, Law et al. (2004, 2011) determined deformation temperatures from quartz c-axis fabric opening angles. They showed that deformation temperatures increased linearly with depth beneath the detachment from ~480–680 °C over >400 m along with metamorphic grade. Deformation temperatures within 10 m of the detachment were estimated at 490–480 °C steadily
increasing to 625–680 °C at depths of 420 m below the detachment. Leucogranite sills increase down-section from the STD with large-scale sills making up the 2–3 km thick Makalu, Everest and Nuptse granites, located 1.5–2.5 km structurally beneath the STD (Searle, 2007). Deformation temperatures in thin sills are similar to those in the surrounding sillimanite gneiss, and temperatures of fabrics in the larger sills suggest they had cooled to ambient temperatures (~550–525 °C) when plastic deformation of quartz ceased and fabrics were “locked in” (Law et al., 2011). In the case of the STD, the granites were already intruded and cooled to ~550 °C when the fabrics were superimposed on them. Therefore, U-Pb zircon and monazite ages on migmatitic melts and leucogranites beneath the STD will give maximum ages of ductile shearing in each locality. The tight field, structural mapping, microstructural and U-Pb geochronological data from all along the STD in Zanskar, Nepal and Tibet shows that metamorphism and melting was a regional GHS-wide event related to regional crustal thickening and not related to shear heating along the STD.

**Karokoram Strike-Slip Fault, Ladakh and Tibet**

The NW-SE oriented right-lateral Karakoram Fault cuts obliquely across the Pamir, Karakoram, and Trans-Himalayan (Ladakh) ranges of westernmost Tibet for over 800 km (Searle, 1996). In Ladakh and SW Tibet a linear belt of high-grade metamorphic rocks and granites are exposed between two strands of the fault. Mylonites along both strands of the fault zone were derived from a variety of earlier metamorphic rocks, including amphibolites, orthogneisses, marbles, psammites, and pelites. Whereas diorites, amphibolites, and t-type granites of the Pangong Metamorphic complex immediately adjacent to the fault zone are older (mainly Cretaceous–Early Tertiary), most leucogranites formed between 22 and 17 Ma, prior to ductile shearing along the fault (Phillips et al., 2004, 2013). Several studies simply assumed that metamorphism and leucogranite intrusion was syn-kinematic with dextral shearing along the fault (Lacassin et al., 2004; Vally et al., 2007, 2008; Weinberg and Mark, 2008; Weinberg et al., 2009). However, U-Pb dating of metamorphic rocks immediately adjacent to the fault showed that metamorphism was Cretaceous in age (ca. 108–105 Ma: Steure et al., 2009). A range of garnet, two-mica leucogranites includes early sills emplaced parallel to the mylonite foliation and that contain a shear fabric, and uncommon late undeformed dykes that cross-cut the mylonite fabric. Like the deformation temperatures recorded in the GHS rocks beneath the STD, the dextral strike-slip shear fabrics in leucogranites along the Karakoram fault were imposed at high temperatures (550–600 °C) after initial crystallization of the granite. A few late, relatively undeformed, leucogranite dykes cross-cut the ductile fabrics and have U-Pb ages between 15.8 and 12.7 Ma, indicating that ductile shearing along the Tangtse fault strand was over by then (Phillips et al., 2004, 2013; Wang et al., 2012). All leucogranites and metamorphic rocks are cut by brittle fault motion along the Karakoram Fault system. In summary, these data do not support models involving shear heating, syn-kinematic metamorphism, or melt formation and large geological offsets, despite spectacular high-strain mylonite zones. Instead although the Karakoram Fault is one of the largest and most prominent strike-slip faults in Tibet, it has only minor offset, possibly 52 km (Wang et al., 2012) or as little as 17–25 km in the Ladakh-Pakistan sector (Searle et al., 2011), it cuts through all the earlier-formed metamorphic rocks and granites, and it bears little relationship to melt formation.

**MAJOR CONCLUSIONS**

1. Middle crust layers of migmatite with sills and dykes of leucogranite in some orogens formed as a result of regional metamorphism, partial melting, migmatisation, and melting induced by continent-continent collision processes from Proterozoic (e.g., Wet Mountains, Colorado) to present (Himalaya) times. The volume of crustal melting is controlled by the fertility of the dominantly pelitic protolith, the internal radiogenic heat flow, and the rates of crustal shortening and thickening.

2. Deformation and melting are diachronous across mountain chains. In general, metamorphism may mimic structures with propagation from hinterland toward foreland with time. Outcrop-scale field constraints (e.g., undeformed dykes cross-cutting regional metamorphic fabric) must be extrapolated to a wider area with caution, based on careful field mapping.

3. Batch melting produces numerous “phases” of melting and sill-dyke injection. In the Himalaya, precise U-Pb dating of individual sills/dykes constrains batch melt phases over time scales of 1–20 m.y. Timing of deformation fabrics can also be constrained by using U-Pb ages of cross-cutting granitic dykes.  

4. Himalayan migmatites and leucogranites have remained in their mid-crust depth of formation (in sillimanite + muscovite or sillimanite + K-feldspar + cordierite grade) and migrated laterally along giant sill complexes during channel flow. They have been exhumed by underplating of Lesser Himalayan and Indian shield rocks beneath the MCT from south to north, passively uplifting the overlying GHS, combined with up to 20–25 km of erosion since the Miocene. There are few, if any, vertical diapiric intrusions along the Himalaya.

5. Migmatites and granites exposed along strike-slip shear zones (e.g., Karakoram, Red River, Jiale faults of Tibet and SE Asia) were not formed as a result of shear heating along the faults. Barrovian metamorphism and most granites were formed during regional crustal thickening and partial melting processes prior to, and unrelated to shearing along the fault, but were exhumed either by transpression (e.g., Karakoram fault) or by linear core complex processes beneath low-angle normal faults (e.g., Ailao Shan, Red River fault; Searle, 2006; Searle et al., 2010c).

6. The highest temperature deformation fabrics seen in granite melts (~600–650 °C) are lower than muscovite and biotite dehydration melting temperatures (710–850 °C), and therefore U-Pb zircon or monazite ages that date timing of melt crystallization can only give a maximum age for deformation fabrics in the granite. U-Pb ages of granite melts rarely date timing of shearing along major faults, but can be used to constrain maximum and minimum ages of shearing if the field relationships are interpreted correctly.

7. The mid-crustal partial melting seen in both the Wet Mountains, Colorado (Levine et al., 2013) and along the Himalaya (Searle et al., 2003, 2006, 2010b; Law et al., 2011) do not support either the “jelly sandwich” (strong upper crust, weak lower crust, strong upper mantle) or the “crème brûlée” (strong crust, weak aseismic mantle) models for rheology of the lithosphere. In most cases the brittle upper crust (~0–17 km) is seismogenic; the dry, granulite facies lower crust can be seismogenic, but only if the temperatures are >600 °C (Priestley et al., 2008); the middle crust is hot, weak, aseismic, partially molten and capable of flow (channel flow).

8. Granulitic lower crust is strong, generally devoid of hydrous phases and lacks partial melts, and therefore lower crustal flow is unlikely. Continental lithosphere retains its strength and relative rigidity through its dry, strong granulite facies lowermost crust.

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**REFERENCES CITED**


