Progression from South-Directed Extrusion to Orogen-Parallel Extension in the Southern Margin of the Tibetan Plateau, Mount Everest Region, Tibet

Micah J. Jessup and John M. Cottle

Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, Tennessee 37996, U.S.A. (e-mail: mjessup@utk.edu)

ABSTRACT

In the South Tibetan Himalaya, major detachment systems exhumed midcrustal rocks from different structural levels that are exposed in the Ama Drime and Mount Everest massifs. The South Tibetan detachment system (STDS) accommodated exhumation of the Greater Himalayan Series (GHS) until the Middle Miocene. Field- and laboratory-based structural data presented here indicate that early melt-present deformation in the footwall of the STDS accommodated large-scale flow of a low-viscosity middle crust. Decompression-related anatexis and emplacement of leucogranites in the structurally highest positions of the GHS (∼16–18 Ma) mark the final stages of south-directed extrusion within a relatively narrow solid-state mylonite zone that progressed into a brittle detachment. Estimates of mean kinematic vorticity and deformation temperatures record a progression in deformation conditions, from ultramylonitic leucogranite (∼400–500°C, 51%–67% pure shear) to mylonitic marble (>300°C, 41%–55% pure shear) to moderately foliated marble ∼200–300°C (46%–59% pure shear). Previous investigations demonstrated that the cessation of movement on the STDS at ∼16–13 Ma was followed by anatexis in the lower portion of the middle crust (∼12–13 Ma, Ama Drime Massif). The Ama Drime and Nyönno Ri detachments (∼8–12 Ma, Dinggyé graben) exhumed rocks from the deepest structural position in the central Himalaya during orogen-parallel extension. Brittle faulting dissected the upper crust (<4 Ma, Tingri–Kung Co graben) in a setting that was kinematically linked to extension in the interior of the Tibetan plateau.

Introduction

Midcrustal rocks exposed along the southern margin of the Tibetan plateau in the Mount Everest region were exhumed by older, orogen-parallel detachments [e.g., South Tibetan detachment system (STDS)] and younger, orogen-perpendicular detachment systems [e.g., Ama Drime and Nyönno Ri detachment; fig. 1]. The STDS is a system of low-angle shear zones and detachments that extends for >2500 km along orogenic strike and consistently records top-down-to-the-north displacement (Burg et al. 1984; Burchfiel et al. 1992). It juxtaposes the anatectic core of the Himalaya [Greater Himalayan Series (GHS)] with the Tibetan Sedimentary Sequence (TSS) in the hanging wall [Burg et al. 1984; Burchfiel et al. 1992]. The STDS is generally interpreted as either a low-angle normal fault [Burchfiel et al. 1992] or a passive roof fault that forms the upper boundary to south-directed extrusion of the GHS [Beaumont et al. 2001; Searle et al. 2003; Law et al. 2004; Jessup et al. 2006; Cottle et al. 2007]. Alternatively, tectonic wedging models interpret the STDS as a passive roof thrust with several phases of reactivation [Webb et al. 2007].

Migmatite-cored domal structures, such as the Ama Drime Massif (ADM; Jessup et al. 2008b; Cottle et al. 2009a), Leo Pargil dome (Thiede et al. 2006), and Gurla Mandhata core complex (Murphy et al. 2002), offset and/or reactivate the STDS [fig. 1, inset]. The ADM reached granulite facies metamorphic conditions (∼750°C and 0.7–0.8 GPa) at ∼12–15 Ma before being exhumed during orogen-parallel extension [fig. 2; Jessup et al. 2008b; Cottle et al. 2009a]. Relatively narrow fault zones containing solid-state fabric development overprinted
early stage, melt-present deformation fabrics during exhumation [Langille et al. 2010]. The eastern limb of the ADM is bound by ductile shear zones and faults that also define the western margin of the Dinggyê graben [Zhang and Guo 2007].

Two (Tingri–Kung Co and Dinggyê) graben that extend from the Himalaya into the interior of the Tibetan plateau [Taylor et al. 2003] are located within the Mount Everest region [Armijo et al. 1986; Mahêo et al. 2007]. The graben are kinematically linked to extension in the interior of the Tibetan plateau [Taylor et al. 2003; Kapp and Guynn 2004]. The interaction between the STDS, domes, and graben provides critical information regarding the progression from a kinematic setting dominated by south-directed extrusion of midcrustal rocks along the STDS to orogen-parallel extension that is accommodated by orogen-perpendicular normal faults and detachments. To explore this aspect of the evolution of the Himalayan-Tibetan plateau orogenic system, we integrate field-based structural data with microstructural and kinematic analysis to characterize two sections of the STDS that are offset by the Tingri–Kung Co graben [Mahêo et al. 2007; fig. 2]. New results are combined with existing data from the GHS and ADM to provide insight into the role of crustal melting and strain partitioning during the progression from south-directed extrusion to orogen-parallel extension.

**Background**

**South Tibetan Detachment System.** In the Mount Everest area, the STDS includes two low-angle, high-strain zones: the structurally lower ductile Lhotse detachment (LD) and structurally higher brittle Qomolangma detachment (QD; Carosi et al. 1998, 1999; Searle 1999b; Law et al. 2004; Sakai et al. 2005; Cottle et al. 2007; Jessup et al. 2008a). The southernmost exposure of the QD occurs on the summits of Mount Everest (8850 m), Changtse (7583 m), and Cheng Zheng (6977 m). From the summit of Cheng Zheng, the QD dips gently to the north and is exposed along the sides of, and drainages into, Rongbuk Valley [Burchfiel et al. 1992; Carosi et al. 1998; Murphy and Harrison 1999; Searle et al. 2003; Law et al. 2004; Jessup et al. 2006; fig. 1]. Between these structures lies a wedge of Everest Series, which includes greenschist to amphibolite facies schist and calc-silicate [Lombardo...
Figure 2. Faded Landsat 7 image with overlay of major fault systems in the Mount Everest region [Armijo et al. 1986; Burchfiel et al. 1992; Mahe´o et al. 2007; Zhang and Guo 2007; Jessup et al. 2008b]. South Tibetan detachment [red line], extensional shear zones and normal faults [black line], normal faults [yellow line]. Ra Chu and Gondasampa transects highlighted by open white circles.

These two detachments merge near the northern limit of exposure in Rongbuk Valley [Carosi et al. 1999; Searle et al. 2003]. Mylonite development within the upper ~300 m of the footwall gneiss, leucogranite, calc-silicate, and marble occurred at ~17 Ma and progressed into a brittle detachment at ≤16 Ma [Hodges et al. 1998; Murphy and Harrison 1999; Searle et al. 2003]. The 300-m-thick ductile shear zone records telescoping of isotherms [Law et al. 2009] and a progression in deformation conditions during exhumation [Law et al. 2004; Jessup et al. 2006]. Detailed kinematic and vorticity analysis indicates that during the early stages [higher temperature] exhumation was accommodated within the upper 300 m of the GHS (~62%–35% pure shear). As exhumation continued, deformation was partitioned into the overlying marble/limestone (45%–28% pure shear), followed by displacement on the brittle detachment [Law et al. 2004; Jessup et al. 2006].

The trace of the STDS toward the northeast, defined by field mapping and Landsat7 image interpretation, extends from Rongbuk Valley across Doya La and into the Dzakaa Chu Valley [fig. 2]. Here, the STDS is significantly thicker (~1 km) than exposures in Rongbuk Valley [Cottle et al. 2007]. U-Th-Pb monazite geochronology on a postkinematic leucogranite dike that crosscuts the mylonitic foliation yields a crystallization age of ~20 Ma and provides a minimum age for high-temperature fabric development in the deepest portion of the shear zone [Cottle et al. 2007]. Unlike exposures in Rongbuk and Dinggyê, no discrete layer-parallel brittle detachment was observed. Instead, a right-way-up apparent metamorphic field gradient of at least 260°C/km across the entire shear zone is interpreted to represent excision of material and telescoping of isotherms within a passive roof fault during south-directed extrusion (Cottle et al., forthcoming).

The STDS is deflected around the ADM and exposed in Dinggyê Valley [fig. 2; Burchfiel et al. 1992;
Cottle et al. 2007). The Dinggyê detachment is parallel to the pervasive fabric in the amphibolite facies GHS of the footwall as well as the greenschist facies calc-silicate rocks in the hanging wall (Burchfiel et al. 1992). The Sa’er detachment is a 1- to 10-m-thick breccia zone that juxtaposes amphibolite facies marble and thin-bedded quartzite in the footwall with unmetamorphosed carbonate phibolite facies marble and thin-bedded quartzite in the footwall with unmetamorphosed carbonate rocks that lack a penetrative fabric in the hanging wall. The Dinggyê and Sa’er detachments were active at deeper and shallower structural levels, respectively (Burchfiel et al. 1992). 40Ar/39Ar thermochronometry in Dinggyê Valley records rapid exhumation along the STDS between ~13 and 16 Ma (Hodges et al. 1994).

**Ama Drime and Nyönnno Detachments.** The ADM is an antiformal structure located ~50 km northeast of Mount Everest (figs. 1, 2) that is bounded to the west and east by the Ama Drime and Nyönnno Ri detachments, respectively (Jessup et al. 2008b). The predominant composition of the ADM is migmatitic orthogneiss with lenses of garnet amphibolite and granulitized eclogite that are boudinaged and folded (Groppo et al. 2007; Jessup et al. 2008b; Cottle et al. 2009a). Granulite facies metamorphism [750°C and 0.7–0.8 GPa] overprinted early eclogite-facies metamorphism and was followed by in situ partial melting at <13.2 ± 1.4 Ma (Groppo et al. 2007; Cottle et al. 2009a). Postkinematic leucogranite dikes that crosscut the pervasive migmatitic foliation and boudinaged mafic lenses in the central portion of the dome provide a maximum age for fabric development and melt-present deformation at 11.6 ± 0.4 Ma during orogen-parallel extension (Cottle et al. 2009a). Low-temperature [U-Th]/He apatite thermochronometry conducted on samples collected along two transects across the range yield a minimum exhumation rate of ~1 mm/yr between 1.5 and 3.0 Ma (Jessup et al. 2008b).

Structural, petrological, and isotopic evidence from the Ama Drime detachment (ADD) indicates that the range-bounding shear zone is potentially a branch of the Main Central Thrust zone (Lombardo et al. 1998, 2000; Lombardo and Rolfo 2000; Groppo et al. 2007; Liu et al. 2007; Langille et al. 2010). This implies that (1) some portion of the ADM may be part of the lowermost GHS or perhaps Lesser Himalayan Sequence (Lombardo et al. 1998; Visoná et al. 2000; Visoná and Lombardo 2002; Groppo et al. 2007) and (2) the ADD potentially experienced an early history as a thrust fault that was subsequently reactivated during orogen-parallel extension (Jessup et al. 2008b; Langille et al. 2010). The ADD juxtaposes upper amphibolite facies GHS rocks in the hanging wall from granulite facies Ama Drime orthogneiss in the footwall. Polyphase folding is overprinted by the main shear zone fabric that strikes NNE–SSW, dips 4°–66°W, and contains a well-developed, approximately down-dip stretching lineation (Jessup et al. 2008b). The ADD is composed of interlayered leucogranite, quartzite, calc-silicate, and marble that consistently record top-down-to-the-west sense of shear (Jessup et al. 2008b). Estimates of deformation temperature obtained using quartz microstructures, strain-induced asymmetric myrmekite, crystallographic slip systems, and quartz c-axis opening angle indicate that top-down-to-the-west shear sense dominated between 400° and 650°C and suggest a minimum detachment-parallel displacement of ~21–42 km (Langille et al. 2010).

The Nyönnno Ri detachment (NRD) is a 100–300-m-thick zone of pervasively foliated orthogneiss and leucogranite that strike NNE–SSW, dip ~45°E, and contain a down-dip stretching lineation (Burchfiel et al. 1992; Jessup et al. 2008b). Asymmetric tails on feldspar porphyroclasts, S-C fabric, and shear bands within the footwall record top-down-to-the-east sense of shear (Jessup et al. 2008b). The NRD offsets the STDS by 20 km of right-lateral separation (Burchfiel et al. 1992; Hodges et al. 1994; Liu et al. 2007; Zhang and Guo 2007; Jessup et al. 2008b). Quaternary deposits are offset by normal faults located along the base of the triangular facets and record top-down-to-the-east displacement, which is younger than extensive moraine deposits on the eastern limb.

**Dinggyê Graben.** While major shear zone and detachment systems (i.e., ADD and NRD) accommodated orogen-parallel extension largely within the middle crust, brittle normal faults were forming in the upper crust. One such example is the Pumqu-Xianza-Dinggyê graben system (Armijo et al. 1986; Burchfiel et al. 1992; Zhang and Guo 2007) that extends from the margins of the ADM into the interior of the Tibetan plateau, where it intersects the right-lateral Gyaring Co fault (Taylor et al. 2003). Near Sa’er, the western margin of the Dinggyê graben is defined by the NRD and normal faults (fig. 2; Burchfiel et al. 1992; Zhang and Guo 2007; Jessup et al. 2008b). The hanging wall is composed of GHS that is juxtaposed with the TSS along the STDS. This sequence is rotated and dissected by a set of southeast- and northwest-dipping normal faults (Burchfiel et al. 1992). 40Ar/39Ar thermochronometry from the Xainza-Dinggyê rift (~8–13 Ma) are younger than movement on the STDS (~24–13 Ma; Hodges et al. 1994) and provide further evidence for a transition from motion on the STDS to
the NRD at \(\sim 13\) Ma (Hodges et al. 1994; Zhang and Guo 2007).

**Tingri–Kung Co Graben.** The Tingri–Kung Co graben is the southernmost portion of the Tangra–Yum Co graben that extends from near the north face of Cho Oyo (8201 m) northward into the interior of the Tibetan plateau (Armijo et al. 1986). The Kung Co half-graben crosscuts the western portion of the Burta Range (Armijo et al. 1986; Mahéo et al. 2007). The football experienced shallow thermal relaxation and cooling (16 and 7.5 Ma) that was followed by increasing exhumation rates from 7.5 Ma to the present. Because the north-south-striking fault offsets the Gyirong-Kangmar thrust and lacks ductile fabric development, it is interpreted as a brittle upper-crustal normal fault that formed at \(\sim 4\) Ma (Mahéo et al. 2007). The southern termination of the Kung Co fault occurs near the Tsamda hot spring fisure ridge, which formed in response to tectonically induced hydrofracturing during extension (Armijo et al. 1986; Hoke et al. 2000; Newell et al. 2008). A dextral en-echelon array of travertine ridges (trend N 10° ± 11°) records \(\sigma_3\) oriented perpendicular to the fracture plane (Armijo et al. 1986). Water issuing from these faults was shallowly circulated in carbonate-rich country rock (Hoke et al. 2000; Newell et al. 2008).

**Gondasampa Transect on the South Tibetan Detachment System.**

The Gondasampa Transect is located on the western side of a north-south-striking ridge that extends into the central portion of the Tingri graben (fig. 2). The ridge rises toward the southwest, where footwall rocks of the STDs are exposed along a prominent ridgeline that extends into the interior of the Lapchi range (fig. 2).

**Mesoscale Observations.** The structurally highest position reached during this transect (~5890 m) is composed of mylonitic marble [\(\text{Cal + Ca-Plg + Dol + Di + Qtz \pm phyllosilicates}\)]. It contains a pervasive foliation [representative; 100°, 11° NE] and moderate lineation [representative; 10° \(\rightarrow\) 022°] that are defined by aligned calcite grains. Single grains and aggregates of diopside within a matrix of calcite have long axes that are oriented at various angles to the main foliation. The foliation is deflected around angular blocks of mylonitic leucogranite that are suspended in the marble.

Structurally below the marble, ribbons of dynamically recrystallized quartz and white mica define a pervasive S-C fabric in mylonitic leucogranite [representative; 085°, 29° NW]. Elongate quartz and feldspar create a well-developed stretching lineation [representative; 25° \(\rightarrow\) 031°]. Together these record top-down-to-the-northeast sense of shear. Narrow (~4 cm) ultramylonite zones contain rigid feldspar porphyroclasts that are set within a matrix of dynamically recrystallized quartz and white mica (Jessup et al. 2007). Quartz and mica are deflected around rigid feldspar porphyroclasts and define a prominent S-C fabrics (fig. 3B). These are possible equivalents to mylonitic leucogranites exposed in Rongbuk Valley (Burchfiel et al. 1992; Law et al. 2004; Jessup et al. 2006, 2007). Less abundant quartz-rich layers with a pervasive foliation [representative; 081°, 31° NW] and stretching lineation [representative; 26° \(\rightarrow\) 030°] that are defined by slightly anastomosing ribbons of quartz with rare isolated feldspar porphyroclasts are also present.

Amphibolite facies [\(\text{Bt + Kfs \pm Hbl \pm Grt}\)] Rongbuk Formation gneiss, located structurally below the leucogranite, preserves a range of deformation conditions. Near the base of the leucogranite, gneiss contains a pervasive foliation that is defined by aligned biotite and quartz [representative; 069°, 31° NW] and a weak lineation. Biotite-rich layers alternate with quartz- and feldspar-rich layers. Feldspar in these layers lack evidence of internal deformation, are clustered and, in places, separated by ribbons of dynamically recrystallized quartz that define shear bands. Toward structurally deeper positions, rocks contain semirigid feldspar and an increasing percentage of leucosomes. Large (~4 cm × 4 cm) feldspar porphyroclasts are rigid with minor symmetrical tail development, while smaller feldspar porphyroclasts (~1 × 2 cm) are elongate and aligned with the main fabric (fig. 3C). The deepest structural position of this transect contains migmatitic gneiss that records melt-present deformation. Leucogranite bodies are oriented parallel to foliated host rock (fig. 3D). Shear bands are common (fig. 3E). Garnet porphyroblasts occur in the migmatitic gneiss (fig. 3F). Garnet porphyroblasts are also found in relatively high concentrations within a single pelitic layer (fig. 3G).

**Microscale Observations.** Marble at the structurally highest position reached during this investigation (G05-05) contains aligned, elongate calcite grains that define the main foliation (table 1). The foliation wraps around diopside and feldspar porphyroclasts. Mica fish record top-down-to-the-northeast sense of shear. Some calcite contains thin (~1 \(\mu\)m) Type I twins (Burkhard 1993; Ferrill et al. 2004) that indicate temperatures \(<170°–200°C\) (fig. 4A). Thick (~1 \(\mu\)m) Type II twins are also present and indicate temperatures between 200° and 300°C (fig. 4B; Weber et al. 2001; Ferrill et al. 2004).
Figure 3. Images from the Gondasampa Transect, Tibet. 

A, South Tibetan detachment exposed on the summit ridge of transect viewed toward the southeast. 

B, Hand sample of ultramylonitic leucogranite with white feldspar porphyroclasts in a matrix of dynamically recrystallized quartz and mica. 

C, Vertical outcrop of semirigid feldspar in dynamically recrystallized matrix. 

D, Migmatitic gneiss in foreground with Tingri graben in background. 

E, Representative migmatitic gneiss with shear band. 

F, Garnet porphyroblast in gneiss. 

G, High-resolution scan of a thin section of G05-10.
Table 1. Ra Chu and Gondasampa Transects

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rock type</th>
<th>Elevation [m]</th>
<th>$W_m$</th>
<th>Deformation temperature [°C]</th>
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Note. Samples are in order of decreasing structural position.

samples define a range of deformation temperatures [200°–300°C] at the structurally highest position of this transect.

Layers (~30 cm) of ultramylonite (G05-01 and G05-03) are oriented parallel to the main foliation in the leucogranite and contain multiple kinematic indicators. Rigid feldspar porphyroclasts with $\sigma$- and $\delta$-type asymmetric tails are suspended in a matrix of fine-grained recrystallized quartz and white mica (fig. 4C). Group 4 (Grotenhuis et al. 2002) white mica fish were formed by removal of material along C′ shear bands. Aligned white mica or domains of dynamically recrystallized quartz define S-C and C′ shear bands. Quartz-rich layers contain a well-developed oblique grain shape fabric defined by aligned recrystallized quartz grains (fig. 4C) and are locally disturbed by asymmetric folds. These independent shear sense indicators consistently record top-down-to-the-northeast sense of shear. Quartz-rich domains are interlayered with very fine-grained biotite and white mica. Quartz grain boundaries record subgrain rotation recrystallization (SGR; 400°–500°C; Stipp et al. 2002).

At intermediate structural positions (G05-06), feldspar porphyroclasts are rigid and set within a matrix of quartz that records grain boundary migration recrystallization (GBM; fig. 4D). Asymmetric biotite tails on rigid feldspar record top-to-the-northeast sense of shear. Biotite also defines extensional shear bands that confirm this sense of shear. Myrmekite is present in some K-feldspar grains. In one example, blades of plagioclase with vermicular quartz are oriented ~90° to the main foliation (fig. 4D). Quartz grain boundaries record GBM recrystallization (>500°C; Stipp et al. 2002).

Large K-feldspar porphyroclasts are semirigid (G05-10/11) in the lowest structural position of the transect. Polygonal intergrowths of plagioclase and quartz record grain boundary area reduction during high-temperature annealing. Biotite laths are wrapped around rigid feldspar porphyroclasts and are interlayered with sillimanite. Fibrolite and elongate blades of sillimanite are present (fig. 4E). Kyanite inclusions (~465 μm × 90 μm) are present in K-feldspar grains (fig. 4F). Garnet porphyroblasts are elongate [4 mm × 2 mm], and the outer ~50
Figure 4. Photomicrographs of samples from the Gondasampa transect. A, Type I deformation twin in calcite (cal). B, Type II deformation twins in calcite with phlogopite (phl) and diopside (di) porphyroblast. C, Mylonitic leucogranite with rigid feldspar (fld), muscovite (ms) fish, and dynamically recrystallized quartz (qtz) matrix. Main foliation (Sa) and oblique grain shape fabric (Sb) are present. D, Semirigid K-feldspar porphyroclast in matrix of recrystallized quartz and plagioclase. Myrmekite is marked by intergrowths of vermicular quartz and plagioclase. E, Prismatic sillimanite in garnet + biotite + kyanite schist (G05-10). F, Kyanite inclusion in K-feldspar grain (G05-10).
µm of the porphyroblast is inclusion free. Toward more internal sections of the grain, an ~300-µm-thick zone of opaque inclusions is followed by relatively inclusion-free garnet. Rare, subhedral kyanite is intergrown with sillimanite and is the first documentation of kyanite from the footwall of the STDS in the central Himalaya.

Ra Chu Transect on the South Tibetan Detachment System

The Ra Chu section of the STDS is exposed along a prominent ridgeline that rises above the Ra Chu [river] on the road from Tingri to Rongbuk Valley (fig. 5; Pertusati et al. 2003). Toward the south, the STDS can be projected to Cho Oyo (8201 m). At its westernmost exposure, the STDS is abruptly truncated by normal faults that define the eastern margin of the Tingri–Kung Co graben (Armijo et al. 1986).

Mesoscale Observations. Two ridges provide exposure of the uppermost section of the STDS (fig. 5). An ~15-m-thick zone of cataclasitic Lower Paleozoic TSS juxtaposes Upper Carboniferous terrigenous sediments above from marble below (Pertusati et al. 2003). An ~5-m-thick zone of moderately foliated marble (representative; 129°, 24° NE) defines the base of the cataclasite zone (fig. 5B). Toward deeper structural positions below the cataclasite (>5 m), the marble (Cal + Ca-Plg + Dol + Di + Qtz ± phyllosilicates) becomes penetratively deformed and preserves a well-developed foliation (representative; 150°, 24° NE) and lineation (representative; 20° → 030°; fig. 5B). When viewed parallel to the foliation and perpendicular to the lineation (XZ section), quartz, feldspar, and diopside grains are suspended in the calcite matrix. Leucogranite and calc-silicate mark the base of this section, which creates the major break in slope between light gray sheared marble above and deep orange calc-silicate and leucogranite below (fig. 5C).

Calc-silicate (Cal + Ca-Plg + Dol + Di + Qtz ± phyllosilicates) with a pervasive foliation (representative; 175°, 16° NE) and lineation (representative; 04° → 014°) marks the base of the mylonitic marble unit. Where exposed on the top of foliation surfaces, the foliation within the calc-silicate wraps around leucogranite pods (fig. 5C). Although Pertusati et al. (2003) document sheath folds in the calc-silicate, we were unable to confirm their presence and instead prefer to interpret these as isoclinal folds with strongly attenuated limbs (fig. 5D). Pods and lenses of mylonitic leucogranite with a well-developed foliation (representative; 144°, 6° NE) and lineation (representative; 02° → 004°) are folded and boudinaged. Elongate tourmaline within mylonitic leucogranite is exposed in orthogonal sections. Tourmaline is aligned so that it appears as elongate, boudinaged clusters (fig. 5E), whereas in sections that are oriented perpendicular to the stretching lineation, the terminations of elongate tourmaline are exposed (fig. 5F).

Pseudotachylite crosscuts the pervasive foliation within mylonitic leucogranite at a high angle (fig. 5G). The contact between the pseudotachylite and the leucogranite is sharp. Angular to rounded leucogranite fragments are suspended in the thicker portions of the vein. An intensification of the foliation defines localized high-strain regions within the leucogranite (fig. 5H). Strain gradients occur on various scales and record the interplay between strain rate, lithology, and fluids.

Microscale Observations. Samples from the highest structural position (T07-01-03) are predominantly composed of calcite that defines a moderately developed foliation with a moderate lineation (table 1). Quartz grains are set within a calcite matrix (fig. 6A). The lack of undulose extinction in quartz indicates that they are undeformed. Quartz grains are generally dispersed throughout the sample and only occasionally form clusters of several grains. Calcite grains preserve thin Type I twins (fig. 6A) and tabular Type II thick twins (fig. 6B). Rare curved and tapered Type III twins are also present. Types II and III indicate temperatures >200°C (Burkhard 1993; Ferrill et al. 2004). Since there is no evidence for dynamic recrystallization (>300°C; Weber et al. 2001), these bracket the temperature of deformation between 200° and 300°C (fig. 7). White mica fish consistently record top-down-to-the-northeast sense of shear.

A decrease in the grain size of calcite occurs at an intermediate structural position between samples T07-03 and T07-04. Beneath this threshold, calcite twins are absent (fig. 6C–6E). The foliation, defined by elongate calcite, is wrapped around rigid diopside and feldspar porphyroclasts. Diopside porphyroblasts presumably grew during an earlier, higher-temperature event (Cottle et al., forthcoming) and were subsequently rotated during shearing at lower deformation temperatures. Quartz grains contain undulose extinction, and some are lensoidal and aligned parallel to the main foliation (fig. 6D). Lack of twins indicates complete dynamic recrystallization of calcite at temperatures >300°C (fig. 7; Weber et al. 2001; Ferrill et al. 2004). Feldspar and diopside porphyroclasts have δ and σ tails and long axes that are oriented at a range of angles from the foliation (fig. 6C, 6D).
Figure 5. Field images of the Ra Chu transect. A, Ra Chu is located at the base of the image and flows from the northern slopes of Everest into the Tingri graben. Total structural thickness of the transect is $\sim$30 m. Lower-hemisphere equal area stereonet of foliation and stretching lineation from transect ($n = 27$). B, Mylonitic marble located at the top of the transect. C, Well-foliated calc-silicate warped around pod of leucogranite. View is oblique across the foliation. D, Folded calc-silicate at the base of transect. E, F, Mylonitic leucogranite with boudinaged tourmaline viewed in orthogonal exposures. Black line work highlights the orientation of the foliation and stretching lineation. G, Pseudotachylite crosscutting mylonitic leucogranite viewed in vertical outcrop. H, Strain gradient in mylonitic leucogranite viewed in vertical outcrop.
Figure 6. Representative photomicrographs of samples from the Ra Chu section. A, Type I deformation twins in calcite [cal] from structurally highest sample of the mylonitic marble section (T07-01). B, Type II twins in calcite from intermediate structural position in mylonitic marble section (T07-02). C, Dynamically recrystallized calcite in the lower portion of the mylonitic marble section (T07-05). Diopside [di] and feldspar [fld] porphyroclasts are rigid objects in a fine-grained calcite matrix with a pervasive foliation [Sa]. D, Rigid diopside porphyroclast with δ-type tails in the dynamically recrystallized calcite matrix (T07-07). E, Diopside grains in the structurally highest section of the calc-silicate portion of the transect (T07-08). F, Dynamically recrystallized quartz [qtz] and muscovite [ms] grains from a mylonitic leucogranite within the calc-silicate (T07-16).
Figure 7. Mean kinematic vorticity estimate ($W_m$) and estimates of deformation temperatures for the upper ∼20 m of the Ra Chu transect. Arrows indicate minimum temperature estimates for dynamically recrystallized calcite.

The top of the calc-silicate section is near the location of sample T07-08. This sample contains a greater concentration of diopside and plagioclase porphyroclasts that are set within a very fine-grained calcite matrix. Porphyroclasts are closely packed and lack tails that are common in structurally higher positions. Calcite grains in the matrix lack twins and indicate dynamic recrystallization at 280°–400°C (Ferrill et al. 2004). Grain boundaries in quartz-rich layers are bulging into each other, suggesting that bulging recrystallization (BLG) was the dominant mechanism at 280°–400°C (Stipp et al. 2002).

Calc-silicate extends to deeper structural positions [T07-10] where bulging quartz grain boundaries are still dominant with minor development of SGR. As structural depth increases [T07-12], SGR becomes dominant (400°–500°C; Stipp et al. 2002). A lens of leucogranite [T07-16] is transitional between SGR and GBM (>500°C; Stipp et al. 2002). Mica fish, S-C fabric, and sigma-type asymmetric tails on feldspar porphyroclasts define top-to-the-northeast sense of shear. The deepest structural position exposed in the Ra Chu transect [T07-18] contains amoeboidal quartz grain boundaries that record GBM (>500°C).

Mean Kinematic Vorticity

Vorticity analysis on samples from within the STDS and MCTZ attests to its applicability to shear zones in the Himalaya (Grasemann et al. 1999; Law et al. 2004; Carosi et al. 2006; Jessup et al. 2006, 2007; Larson and Godin 2009). Estimating the relative contributions of pure and simple shear [vorticity] during exhumation of the GHS is an important aspect of this investigation because a significant contribution of pure shear predicts an increase in extrusion and exhumation rates relative to simple shear dominated flow (Law et al. 2004).

Kinematic vorticity number ($W_k$) is a direct estimate of pure ($W_k = 0$) and simple ($W_k = 1$) shear during plane strain deformation (Means et al. 1980). Equal contributions of pure and simple shear occurs at $W_k = 0.71$ (Law et al. 2004). Mean kinematic vorticity ($W_m$) uses a time-averaged $W_k$ to accommodate for variability of vorticity during non-steady state deformation (Fossen and Tikoff 1997, 1998; Jiang 1998). Plane strain deformation has been demonstrated for the STDS exposed in Rongbuk Valley (Law et al. 2004). Vorticity estimates (two dimensions) on rocks that deviate from plane strain yield values that may be overestimated by <0.05 (Tikoff and Fossen 1995). This is minimal compared with other errors associated with $W_m$ measurement used during this investigation. $W_m$ was estimated by applying the rigid grain technique (Passchier 1987; Wallis et al. 1993; Jessup et al. 2007) to samples of mylonitic marble and leucogranite from the immediate footwall of the STDS.

Models demonstrate that during simple shear ($W_m = 1$), rigid objects with a range in aspect ratios (R) will rotate infinitely in a ductile matrix. With a higher contribution of pure shear ($0 < W_m < 1$), porphyroclasts will rotate until they reach a stable-sink (Rc) position that is defined by a unique combination of the aspect ratio (R), the acute angle from the foliation ($\varphi$), and $W_m$ (Jeffrey 1922; Ghosh and Ramberg 1976; Passchier 1987; Simpson and De Paor 1993):

$$W_m = \frac{R^2 - 1}{R^2 + 1}.$$  

The rigid grain net (RGN) plots the shape factor ($B*$) versus $\varphi$ on a theoretical net for combinations of $B*$ and $\varphi$ at a range in $W_m$ values:

$$B^* = \frac{M^2 - M^2_n}{M^2 + M^2_n}$$

where $M_l$ and $M_n$ are the long and short axes of the ellipse, respectively (Passchier 1987). The RGN unifies existing methods that use rigid porphyroclasts in a flowing matrix (Passchier 1987; Wallis 1992; Simpson and De Paor 1993, 1997; Wallis et al. 1993), simplifies plotting of data, and limits am-
bigness in estimating $W_m$ by enabling the user to compare complex natural data sets with the theoretical net (Jessup et al. 2007).

Samples analyzed in this study using the rigid grain method were deemed appropriate if they met the following criteria (Passchier 1987): (1) deformed homogeneously, (2) rigid porphyroclasts significantly larger than the matrix grains, (3) high finite strains to rotate objects toward stable-sink positions, (4) porphyroclast shape that is close to orthorhombic, (5) significant number of porphyroclasts with a range in $B_s$, (6) porphyroclast that predates the deformation fabric, and (7) no mechanical interaction between grains. For an overview of systematic source error estimation for the rigid grain method, see Iacopini et al. (2008).

Only two samples from the Gondasampa transect passed the criteria for rigid grain vorticity analysis [G05-01 and G05-03]. These are ultramylonites from within the mylonitic leucogranite near the upper portion of the STDS. G05-01 and G05-03 were the basis for creating the RGN, with original interpretations defining a range of $W_m$ estimates of 0.57–0.60 and 0.65–0.70, respectively (Jessup et al. 2007). In order to maintain consistency with the approach for determining the critical threshold used by this investigation, we prefer to use a broader range of values [G05-01, $W_m = 0.50–0.60$; G05-03, $W_m = 0.60–0.70$] for the critical threshold values using data from both positive and negative sides of the RGN. Together these samples define a range of $W_m$ estimates [0.50–0.70; 51%–67% pure shear] for high-strain ultramylonite in leucogranite that occurred at deformation temperatures of $\sim 400^\circ$–$500^\circ$C.

Mylonitic marble from the upper $\sim 10$ m of the Ra Chu transect proved to be well suited for rigid grain vorticity analysis using the RGN. These samples contain rigid diopside, feldspar, and quartz in a matrix of calcite. Johnson et al. (2009a, 2009b) proposed that an envelope of phyllosilicates around porphyroclasts can potentially decouple it from the matrix and yield vorticity estimates that underestimate the simple shear component. The lack of phyllosilicates around the porphyroclasts in these mylonitic marbles indicates that the potential for decoupling at the clast/matrix interface was minimal. The structurally highest of these samples [T07-02; $\sim 5$ m below detachment] yields a $W_m$ estimate of 0.68–0.75 [figs. 7, 8A; 46%–52% pure shear]. The next structurally lower sample [T07-03; $\sim 6$ m below the top of the section] yields a $W_m$ estimate of 0.60–0.65 [55%–59% pure shear] and represents the upper portion of penetratively deformed marble [figs. 7, 8D]. These two samples record the lowest deformation temperatures estimated during this investigation [200$^\circ$–300$^\circ$C]. Samples T07-04, T07-05, and T07-06 were collected from between 7.5 and 11 m below the detachment in a zone of sheared marble that contains a pervasive foliation and lineation and dynamically recrystallized matrix calcite ($\geq$300$^\circ$C; fig. 7). These samples yield a range in $W_m$ estimates of 0.65–0.80 [41%–55% pure shear] at deformation temperatures $\geq$300$^\circ$C (fig. 8C–8E). Structurally below T07-07, calc-silicate becomes the dominant rock type, and because of grain interaction, these samples are unsuitable for rigid grain vorticity analysis.

**Discussion**

**Kinematic Evolution of the South Tibetan Detachment System.** Data from two transects [Gondasampa and Ra Chu] across the STDS exposed on either side of the Tingri–Kung Co graben provide important new constraints on the south-directed extrusion and exhumation of the GHS (figs. 2, 3). Melt-present flow dominates the deepest structural positions in the Gondasampa transect and records the early stages of south-directed flow at high deformation temperatures. At decreasing structural levels, melt-present deformation is overprinted by solid-state fabric development that is recorded by mylonitic and ultramylonitic marble, calc-silicate, and leucogranite. We interpret this as a transition from early, high-temperature melt-present flow to later, lower-temperature deformation that was activated during progressive south-directed exhumation along the STDS.

Microstructures from the Gondasampa and Ra Chu transects provide important qualitative estimates of deformation temperatures. Types I and II twins in calcite are preserved in the uppermost section of the transects and indicate that deformation temperatures reached $\sim 200^\circ$–$300^\circ$C at this structural level (fig. 7). Beneath this, calcite was dynamically recrystallized at higher temperatures ($\geq 300^\circ$C) in the Ra Chu transect. Quartz-rich domains in calc-silicate and leucogranite record a transition from BLG through SGR to GBM. These record an apparent increase of 200$^\circ$–300$^\circ$C over an $\sim 30$-m-thick section of the Ra Chu transect. The 200$^\circ$–300$^\circ$C temperature distribution recorded within these rocks is likely a combination of telescoping and/or flattening of isotherms beneath the detachment and the presence of a range of deformation mechanisms that accommodated exhumation at progressively lower temperature inter-
Rigid porphyroclasts plotted on the rigid grain net (Jessup et al. 2007). \( \theta \), angle between the long axis of a grain and the foliation. \( B^* \), critical threshold values used to estimate mean kinematic vorticity \( |W_m| \).

\[
B^* = \frac{(Mx^2 - Mn^2)}{(Mx^2 + Mn^2)}
\]

Where \( Mx \) and \( Mn \) are the long and short axes of the ellipse, respectively.

Figure 8. Rigid porphyroclasts plotted on the rigid grain net (Jessup et al. 2007). \( \theta \), angle between the long axis of a grain and the foliation. \( B^* \), critical threshold values used to estimate mean kinematic vorticity \( |W_m| \).

Mean kinematic vorticity estimates and deformation temperatures on samples of mylonitic leucogranite and marble quantify three general stages of this exhumation history. Ultramylonite leucogranite records 51%–67% pure shear at ~400°–500°C. During progressive exhumation, strain was partitioned into the structurally higher marble at >300°C (41%–55% pure shear) and finally into the moderately foliated marble at ~200°–300°C (46%–59% pure shear). Mylonitic marble samples collected immediately below the detachment from three locations in Rongbuk Valley (Jessup et al. 2006) yield $W_m$ estimates that range between 0.74 and 0.91 (28%–45% pure shear), a significantly lower contribution of pure shear than our results from the equivalent rock type and structural position in the Ra Chu transect. $W_m$ estimates from mylonitic and ultramylonitic leucogranite in the Gondasampa transect (51%–67% pure shear) record a higher contribution of pure shear than the equivalent rock type and structural position in Rongbuk Valley (39%–61% pure shear; Jessup et al. 2006). The structurally highest samples [lower deformation temperature] in both areas record the highest contribution of simple shear, whereas deeper structural positions [higher deformation temperature] yield higher contributions of pure shear.

Jessup et al. (2006) interpreted the relationship between $W_m$ estimates and deformation temperatures as the result of spatial and temporal partitioning of flow during exhumation. In this model, the structurally lowest samples record early, higher-temperature deformation conditions with a greater contribution of pure shear. These were juxtaposed with later, lower-temperature deformation conditions that are dominated by simple shear that occurred during the later stages of exhumation. Another possibility is that decoupling between the porphyroclasts and matrix is more prominent in the phyllosilicate-rich leucogranites. Higher concentrations of phyllosilicates, particularly around the porphyroclast matrix interface, are predicted to decouple the porphyroclast from the matrix, resulting in data that overestimate the pure shear component [Johnson et al. 2009a, 2009b]. Leucogranite samples that record the highest contribution of pure shear also contain higher concentrations of phyllosilicates, and for these samples, decoupling could offer an alternative explanation.

Strain partitioning within the footwall of the STDS is common. Blocks of mylonitic leucogranite that are suspended in mylonitic marble are evidence for brittle fracturing and rotation of the granite after it developed a mylonitic fabric and before the partitioning of strain into the weaker marble/calcsilicate section at temperatures of ~200°–300°C. Similarly, foliation in calc-silicate is wrapped around rigid leucogranite pods in the Ra Chu section. Pseudotachylite that crosscuts leucogranite records high-strain events associated with seismic slip during exhumation along the STDS. In general, marbles are the weakest rock type, and strain is partitioned into these over a range of deformation temperatures. These observations indicate that melting, rheologic contrasts between rock types, strain rate, and the onset of different deformation mechanisms are the major variables that control the extent to which strain is partitioned and/or localized during exhumation along the STDS.

**Melt-Present Deformation.** Melt-present deformation is widespread throughout the GHS and ADM. Melting within the GHS exposed in the Mount Everest region spans ~8 m.yr. (22–16 Ma). The high-melt fraction present during this time interval had the potential to decrease the effective viscosity of the crust, resulting in dramatic rheological weakening and midcrustal flow. Granite emplacement mechanisms within the GHS are characterized by forceful injection along and across the main foliation (Weinberg and Scarle 1999) and provide evidence for high fluid pressure gradients with the GHS. Within the 30-km-thick GHS, the majority of mylonites are limited to the uppermost [Dzaka Chu, 1000 m; Rongbuk and Gondasampa, 300 m] section of the GHS-STDS system [Law et al. 2004; Jessup et al. 2006, 2008a; Cottle et al. 2007]. Rare occurrences of mylonites have been reported in the interior of the GHS near Mount Everest (Carosi et al. 1999) as well as more extensive areas in western Bhutan (Carosi et al. 2006) and western Nepal (Carosi et al. 2007). The lack of mylonite development and the widespread occurrence of migmatite and leucogranite in the core of the GHS indicates that high-temperature melt-present deformation was the dominant mechanism by which the GHS was extruded southward.

While the final stages of leucogranite injection and crystallization in the upper 1–2 km of the GHS occurred during south-directed extrusion and exhumation, the lower portion of the middle crust (>30 km below the STDS), as exposed in the central portion of the ADM, reached granulite facies (~15 Ma) and by ~11–13 Ma was experiencing decompression and anatexis during orogen-parallel extension (Cottle et al. 2009a; fig. 9). Partial melting at

this deeper structural position weakened the crust in a kinematic setting that was dominated by orogen-parallel extension.

These data indicate the following: (1) Midcrustal flow on the southern margin of the Tibetan plateau is decoupled from the upper crust via a network of relatively narrow shear zones and fault systems. (2) Between ~24 and 16 Ma, south-directed extrusion and exhumation along the STDS is recorded by the ~30-km-thick GHS. (3) Anatexis at ~11–13 Ma was limited to the lower portion of the midcrust (as exposed in the ADM), where it flowed into areas of localized orogen-parallel extension and was exhumed by the ADD and NRD. (4) The transition from partial melting within the upper (GHS) to lower (ADM) portions of the midcrust resulted in large changes in crustal rheology (i.e., relative strength) and played a substantial role in initiating exhumation of both of these two distinct high-temperature structural domains during the middle and Late Miocene, respectively.

Implications for the Onset of East-West Extension. Two major graben begin in the Mount Everest and Ama Drime areas and extend from the crest of the Himalaya into the interior of the Tibetan plateau. The Tingri–Kung Co graben marks the southern end of the more extensive Tangra-Yum Co graben that extends northward, where it intersects a northwest-striking, right-lateral strike-slip fault (Armijo et al. 1986; Taylor et al. 2003; Kapp and Guynn 2004). Thermochronometry on a portion of the Tingri–Kung Co graben constrains the onset of footwall exhumation and orogen-parallel extension to ~4 Ma (fig. 9; Mahéo et al. 2007). The Dinggye' graben, located ~140 km east of Tingri–Kung Co, initiated at ~8–13 Ma (Zhang and Guo 2007). It extends from the eastern side of the ADM northward between Mabja and Lhagoi Kangri South Tibetan gneiss domes and into the Xianza graben system that terminates at the northwest-striking, right-lateral Gyaring Co strike-slip fault. The Gyaring Co strike-slip fault forms a con-
jugate fault with northeast-striking, left-lateral faults to the north of the Bangong-Nujiang suture [Taylor et al. 2003]. These are kinematically linked in a system of faults where conjugate sets of strike-slip faults and graben accommodate east-west extension [Armijo et al. 1986; Taylor et al. 2003]. The Dinggyê-Pumqu-Xianza and Tingri–Kung Co–Tangra Yum Co grabens as well as some of the mid-crustal rocks exhumed in their footwalls [i.e., ADM] are kinematically linked to active extension in the interior of the Tibetan plateau.

The onset of orogen-parallel extension in the Mount Everest region occurred between ~11 and 13 Ma, when the lower portion of the middle crust [i.e., ADM] experienced muscovite dehydration melting and anatexis [fig. 9; Cottle et al. 2009a]. Melting within the overlying middle crustal rocks [GHS] had ceased by this time, and they as well as the overlying STDS were dissected by normal faults. The penetration depth of Tingri graben was apparently limited to the upper crust (<4 Ma), whereas the Dinggyê graben (~8–13 Ma) appears to record some early component of deformation below the brittle ductile transition zone [Zhang and Gou 2007]. We propose that early [11–13 Ma] melt-present low-viscosity flow weakened the crust in a kinematic setting that was dominated by crustal-scale extension. As a result of lateral gradients in lithostatic pressure, melt-weakened rocks were exhumed from mid- to lower crustal depths within areas of localized extension [ADM], while brittle normal faulting occurred at shallower crustal levels [fig. 9]. The ADD and NRD exhumed rocks from one of the deepest structural positions exposed in the central portion of the Himalayas. Footwall mylonites in the ADD record top-down-to-the-west during a minimum of 22–42 km of down dip displacement [Langille et al. 2010]. These mylonites progressed into a detachment that, along with the Pumqu fault systems, accommodated the final low-temperature ductile-brittle stages of exhumation.

Conclusions

Rocks exposed in the Mount Everest region provide windows into midcrustal processes of deformation, strain partitioning, and melting beneath the southern margin of the Tibetan plateau. Data from two new transects across the STDS record a progression in deformation mechanisms. During exhumation, strain was partitioned into an ~150-m-thick shear zone that records solid-state fabric development. Ultramylonitic leucogranite records 51%–67% pure shear at ~400°–500°C that was followed by partitioning of strain into the structurally higher marble at >300°C [41%–55% pure shear] and the moderately foliated marble at ~200°–300°C [46%–59% pure shear]. By 12–16 Ma, the STDS was inactive and no longer capable of accommodating south-directed extrusion/exhumation. The locus of melting migrated into a structural position in the lower part of the midcrust by 11–13 Ma and was subsequently exhumed within a kinematic setting that was linked to extension.

ACKNOWLEDGMENTS

R. D. Law and M. P. Searle provided the initial motivation and funding for this study. D. Newell, L. Duncan, and D. Breecker provided valuable assistance in the field. S. Wangdu coordinated our trips and brought us to Gondasampa. B. Dunne provided advice on calcite twin morphology. J. Lee, R. Carosi, D. Grujic, and J. M. Langille provided detailed reviews that helped strengthen a previous version of the manuscript. N. Costello helped with initial petrography as part of his undergraduate research project. Funding was provided by grants from the College of Art and Sciences at the University of Tennessee and National Science Foundation grant EAR-207524 to R. D. Law and M. P. Searle.

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