Mid-Miocene initiation of orogen-parallel extension, NW Nepal Himalaya

Carl Nagy1, Laurent Godin1,*, Borja Antolín1, John Cottle2, and Douglas Archibald1
1GEOLOGICAL SCIENCES AND GEOLOGICAL ENGINEERING, QUEEN’S UNIVERSITY, KINGSTON, ONTARIO K7L 3N6, CANADA
2DEPARTMENT OF EARTH SCIENCE, UNIVERSITY OF CALIFORNIA, SANTA BARBARA, CALIFORNIA 93106-9630, USA

ABSTRACT

Geologic field mapping surveys integrated with structural, thermochronological, and geochronological analyses confirm the existence of an orogen-parallel strike-slip-dominated shear zone in the upper Karnali valley of northwestern Nepal. This shear zone obliquely cuts through the upper Greater Himalayan Sequence and is characterized by a S-dipping, high-strain foliation and intensely developed ESE-WNW-trending, shallow-plunging mineral elongation lineation. Monazite grains within the Greater Himalayan Sequence are deformed and transposed parallel to the orogen-parallel shear zone and ESE-WNW elongation lineations. In situ U-Th/Pb monazite geochronology constrains metamorphism between 19 and 15 Ma, which is consistent with the timing of Neo-Himalayan metamorphism and S-directed extrusion of the Greater Himalayan Sequence across the Himalaya, and it is therefore interpreted to have preceded orogen-parallel strike-slip deformation. Mineral deformation mechanisms and quartz c-axis patterns of orogen-parallel fabrics record a rapid increase in temperature of deformation from ~350 °C along upper levels of the shear zone to greater than 630 °C at ~2.5 km depth structurally below the shear zone. Symmetric quartz c-axis fabrics further suggest deformation included a significant component of pure shear. The 40Ar/39Ar thermochronology of foliation-defining muscovite indicates that orogen-parallel shearing was active in the area between ca. 13 and 10 Ma while temperatures cooled through the muscovite closure temperature for argon. By integrating these data with the current understanding of tectonic processes in the Himalaya, we interpret a transition from S-directed extrusion of the Greater Himalayan Sequence to orogen-parallel extension between ca. 15 and 13 Ma in the upper Karnali valley. Integration of our findings with chronological constraints from other migmatite-cored domes supports the growing recognition of a Himalayan-wide mid-Miocene initiation of orogen-parallel extension.

INTRODUCTION

The Greater Himalayan Sequence is the high-metamorphic-grade and anatectic core of the Himalaya, typically exposed near the crest of the Himalaya along the length of the orogen (Fig. 1A). It is commonly interpreted to represent a sequence of rocks extruded southward and normal to the orogen from midcrustal depths (Grujic et al., 1996; Nelson et al., 1996; Hodges, 2000, 2006). S-directed extrusion of the Greater Himalayan Sequence occurred from ca. 25 Ma to ca. 16 Ma (see review of ages in Godin et al., 2006a; Cottle et al., 2009a), and may have persisted in the Pliocene (Hodges et al., 2001; Hurtado et al., 2001) in a setting linked to N-S contraction and shortening.

The Himalayan orogen dominantly records orogen-perpendicular shortening resulting from collision of India and Asia commencing at 55–50 Ma (Najman et al., 2010). Despite this, late Oligocene to mid-Miocene orogen-perpendicular deformation affecting the Himalayan arc and the Tibetan Plateau has also been documented. This style of deformation has been interpreted to record the onset of orogen-parallel extension, either related to lateral expansion of the orogen or local strain partitioning (Allègre et al., 1984; Mercier et al., 1987; Pêcher, 1991; Coleman and Hodges, 1995; Coleman, 1996; Murphy and Copeland, 2005; Yin, 2006; Jessup and Cottle, 2010; Styron et al., 2011; Antolín et al., 2012; Xu et al., 2013; Murphy et al., 2014). The onset of orogen-parallel deformation represents a critical stage in the evolution of the Himalaya-Tibet orogen, because it coincides with an increase in the mean elevation of the Tibetan Plateau and a change in the balance of forces applied to the collision zone, resulting in 35%–40% decrease in the convergence rate between India and Eurasia between 20 Ma and 10 Ma (Molnar and Stock, 2009; Iaffaldano et al., 2013).

In this paper, we investigate the potential transition between S-directed orogen-perpendicular extrusion of the Greater Himalayan Sequence and onset of orogen-parallel extension in the upper Karnali valley of northwest Nepal (Figs. 1B and 1C). In this area, a NW-striking, strike-slip-dominated shear zone, the Gurla Mandhata–Humla fault, cuts obliquely across the upper contact of the Greater Himalayan Sequence (Figs. 1B and 1C; Murphy and Copeland, 2005). This setting provides a geologic context in which both S- and ESE-WNW-directed deformation can be studied in the same locality. By integrating geological and structural mapping, microstructural analyses including dynamic recrystallization mechanism and quartz crystallographic preferred orientation analyses, U-Th/Pb in situ monazite geochronology, and 40Ar/39Ar muscovite thermochronology with previously published results, we attempt to constrain deformation conditions and timing associated with S-directed extrusion of the Greater Himalayan Sequence and onset of orogen-parallel extension. Integration of our results with other chronological constraints from across the Himalaya provides growing support for a significant mid-Miocene Himalayan-wide transition in deformation regime.

GEOLOGIC SETTING

The geology of the Himalaya consists of four distinct lithotectonic domains bounded by crustal-scale fault systems, all of which are laterally continuous across the length of the orogen (Fig. 1A). The two northernmost...
domains are the Tethyan Sedimentary Sequence and the Greater Himalayan Sequence, which are typically separated by the South Tibetan detachment system. This study focuses on an area of northwestern Nepal where the South Tibetan detachment system is overprinted by the orogen-parallel Gurla Mandhata–Humla fault (Fig. 1; Murphy and Copeland, 2005).

The Greater Himalayan Sequence lies structurally below the Tethyan Sedimentary Sequence and is bounded at its base by the Main Central thrust, a S-directed thrust fault, and at its upper surface by the South Tibetan detachment system, a low-angle, top-to-the-N normal fault (Fig. 1C; Burchfiel and Royden, 1985; Burchfiel et al., 1992). The rocks of the Greater Himalayan Sequence record two metamorphic stages throughout the Tertiary: Eo- and Neohimalayan metamorphism (Hodges, 2000). Eohimalayan metamorphism is associated with burial of the Greater Himalayan Sequence during the Oligocene (Vannay and Hodges, 1996; Godin et al., 1999, 2001), whereas early to mid-Miocene Neohimalayan metamorphism is recorded throughout the Greater Himalayan Sequence (Vannay and Hodges, 1996; Godin et al., 1999, 2001; Searle and Szulc, 2005; Cottle et al., 2009a, 2009b) and is characterized by broadly synchronous motion along the South Tibetan detachment system and Main Central thrust (for review of ages, see Godin et al., 2006a). Neohimalayan metamorphism is also characterized by isothermal decompression and is associated with S-directed extrusion of the Greater Himalayan Sequence (e.g., Vannay and Hodges, 1996; Godin et al., 2001; Harris et al., 2004). Field relations combined with age data suggest that ductile motion along the South Tibetan detachment system terminated by ca. 16 Ma in Nepal (Godin et al., 2006a, 2009b; Cottle et al., 2015). This suggests that ductile southward extrusion of the Greater Himalayan Sequence had also terminated by mid-Miocene (e.g., Godin et al., 2006b).
Structures related to orogen-parallel extension throughout the Himalaya-Tibet orogen mostly initiated between ca. 16 and 11 Ma, and many are currently active (Coleman and Hodges, 1995; Coleman, 1996; Hurtado et al., 2001; Taylor and Yin, 2009; Styron et al., 2010, 2011; Murphy et al., 2014). One of these structures, the Yadong shear zone in eastern Himalaya, is argued by some to be younger than 11.5 Ma (Ratschbacher et al., 2011). Alternatively, it and other orogen-parallel extensional shear zones in eastern Himalaya may have initiated as early as ca. 28–26 Ma (Xu et al., 2013).

Extensional deformation is commonly manifested throughout Tibet as E-W–to ESE–WNW–oriented strike-slip faults and N-S–striking normal faults (Armijo et al., 1986, 1989; Taylor et al., 2003; Taylor and Yin, 2009). Most of these structures are located within central to southern Tibet and appear to be restricted to the upper crust (Armijo et al., 1986, 1989; Taylor et al., 2003; Taylor and Yin, 2009), although they could be rooted in the underplated Indian lower crust (e.g., Godin and Harris, 2014). Extensional deformation is expressed throughout the Himalaya as orogen-perpendicular normal faults, orogen-parallel to subparallel oblique to strike-slip faults, and tectonically exhumed migmatite-cored gneiss domes (Nakata, 1989; Hurtado et al., 2001; Murphy et al., 2002, 2009, 2014; Murphy and Copeland, 2005; Thiede et al., 2006; Jessup et al., 2008; Li and Yin, 2008; Cottle et al., 2009b; Jessup and Cottle, 2010; Langille et al., 2012; Lederer et al., 2013; McDermott et al., 2013; Xu et al., 2013).

**GEOLOGY OF THE UPPER KARNALI VALLEY**

The upper Karnali valley lies northwest of the village of Simikot, in far-northwestern Nepal (Figs. 1B and 2). First-order mapping reveals low-metamorphic-grade Tethyan Sedimentary Sequence juxtaposed along a S-dipping contact over strongly deformed and metamorphosed rocks of the Greater Himalayan Sequence (Figs. 1C and 2; Fuchs, 1977; Shrestha, 1987; Murphy and Copeland, 2005; Robinson et al., 2006). The Tethyan Sedimentary Sequence of the upper Karnali valley consists of a sequence of low-metamorphic-grade rocks interpreted to be Cambrian through Mesoic based on correlative units to the northwest (Cheng and Xu, 1987; Murphy and Yin, 2003; Murphy and Copeland, 2005).

The Greater Himalayan Sequence of the upper Karnali valley consists of amphibolite metamorphic facies schist and gneiss that have reached pressure and temperature conditions of 10 kbar and 700 °C, respectively (Yakymchuk and Godin, 2012). Metamorphism observed in the upper Karnali valley is consistent with late Oligocene to middle Miocene (Yakymchuk and Godin, 2012). Metamorphism observed in the upper Karnali valley is consistent with late Oligocene to middle Miocene (Yakymchuk and Godin, 2012). Metamorphism observed in the upper Karnali valley is consistent with late Oligocene to middle Miocene (Yakymchuk and Godin, 2012). Metamorphism observed in the upper Karnali valley is consistent with late Oligocene to middle Miocene (Yakymchuk and Godin, 2012). Metamorphism observed in the upper Karnali valley is consistent with late Oligocene to middle Miocene (Yakymchuk and Godin, 2012). Metamorphism observed in the upper Karnali valley is consistent with late Oligocene to middle Miocene (Yakymchuk and Godin, 2012). Metamorphism observed in the upper Karnali valley is consistent with late Oligocene to middle Miocene (Yakymchuk and Godin, 2012). Metamorphism observed in the upper Karnali valley is consistent with late Oligocene to middle Miocene (Yakymchuk and Godin, 2012).

**Domain I—Folded Tethyan Sedimentary Sequence**

Domain I (folded Tethyan Sedimentary Sequence) is the structurally highest domain, and it consists of interlayered tan to gray marbles and calc-silicates (Figs. 2 and 3A). Calcite is fine grained (~30 µm), and no twins are discernible, suggesting a complete lack of microscale deformation (Burkhard, 1993). Both rock types are interpreted to represent the Cambrian–Ordovician stratigraphic level mapped by Murphy and Copeland (2005).

Original bedding is crudely preserved and defines macroscale open to tight folds with axial planes moderately inclined to the south. Folds verge toward the northeast, and fold hinges plunge shallowly (−0° to 25°) to the ESE and WNW (Figs. 2 and 3A).

**Domain II—Transposed Tethyan Sedimentary Sequence**

Domain II (transposed Tethyan Sedimentary Sequence) is located within ~1 km structurally above the Greater Himalayan Sequence–Tethyan Sedimentary Sequence interface (Fig. 2), and it consists of similar rock types to the overlying folded Tethyan Sedimentary Sequence (interlayered marbles and calc-silicates).

Broad open folds of domain I transition to recumbent and isoclinal in the upper structural levels of domain II (Fig. 3B). Fold hinges plunge shallowly to moderately and trend ESE–WNW (Fig. 2). Axial planes of the folds are roughly parallel to the main shear zone foliation. Calcite is deformed and shows thin type I twins, and rare type II twins, suggesting deformation temperatures of less than ~200 °C (Burkhard, 1993; Ferrill et al., 2004). Quartz grains within calc-silicate layers are both undeformed and show patchy undulose extinction, suggesting temperatures of deformation below which quartz dynamically recrystallizes (<280 °C; Stipp et al., 2002).

At lower structural levels within domain II, folds are entirely transposed into a high-strain, shear zone–parallel foliation. At this structural level, calcite is deformed and recrystallized via grain boundary migration, showing abundant tabular thick type II twins and sporadic curved and tapered type III twins (Fig. 4A), suggesting temperatures of deformation between 200 and 300 °C (Burkhard, 1993; Ferrill et al., 2004). Quartz grains show minor dynamic recrystallization (bulging), which imply deformation temperatures reaching at least ~350 °C (Stipp et al., 2002).
Figure 2. Lithostructural map of the upper Karnali valley, northwestern Nepal. Roman numbers I, II, III, IV, V, and VI refer to lithostructural domains; see text for descriptions. Equal-area lower-hemisphere stereonets show the distribution of orientations of elongation lineation, fold hinges, and poles to foliation (1% area contours, with a contour interval = 2%/1% area). Stereonets were constructed using OSX Stereonet, v. 13, developed by N. Cardozo and R. Allmendinger. GMH—Gurla Mandhata–Humla fault; TSS—Tethyan Sedimentary Sequence; GHS—Greater Himalayan Sequence.
Figure 3. Representative macroscale observations from the upper Karnali valley, including: (A) NE-verging, moderately overturned folds of marble and calc-silicate from domain I, (B) recumbent and isoclinal folds of domain II, (C) angular fragments of marble and calcite (outlined in white) within a chaotic carbonate matrix from domain III, (D) C/S/C′ fabrics and a sigma-type feldspar porphyroclast indicating dextral shear within high-strain pelitic schist from domain IV (note that interpreted late-stage warping of the outcrop reoriented sample from ESE-WNW facing to N-S facing), and (E) delta-type rotated leucogranite pod indicating dextral shear from domain V. Location of photos is indicated on simplified cross section of the upper Karnali valley (F); dotted lines correspond to trace of bedding and transposed bedding, where vertical scale (v) equals horizontal scale (h). a.s.l.—above sea level; GMH—Gurla Mandhata–Humla fault.
Figure 4. Representative microscale observations from the upper Karnali valley, including: (A) calc-silicate exhibiting tabular type II calcite twins (thin red arrows) and curved and tapered type III calcite twins (thick red arrows; inset is same scale as the remainder of the thin section) from domain I, (B) high-strain schist composed of feldspar porphyroclasts exhibiting bent twins, patchy undulose extinction, and abundant grain-scale fractures, including antithetic microfaulting (red arrows), within a matrix of fine-grained dynamically recrystallized quartz from domain II, (C) intensely attenuated and dynamically recrystallized quartz grains exhibiting subgrain extinction and bulging (red arrows; dotted red line shows length of a single elongate quartz grain) from domain III, (D) pelitic schist showing sinistral shear band (red arrows) faulting and drawing into plane sillimanite and biotite from domain IV, (E) quartz grains showing interlobate to amoeboid quartz grain boundaries and subgrain extinction (red arrows) from domain V, and (F) quartz chessboard-style extinction from domain VI. Location of photos is indicated on simplified cross section of the upper Karnali valley (G); dotted lines correspond to trace of bedding and transposed bedding, where vertical scale (v) equals horizontal scale (h). Abbreviations: bt—biotite, cal—calcite, fld—feldspar, ms—muscovite, qtz—quartz, sil—sillimanite. a.s.l.—above sea level; GMH—Gurla Mandhata–Humla fault.
Domain III—High-Strain Core

Domain III (high-strain core) consists of ~200 m of Tethyan Sedimentary Sequence and Greater Himalayan Sequence cataclastic, protomylonitic, and mylonitic rocks flanking the Greater Himalayan Sequence—Tethyan Sedimentary Sequence interface (Fig. 2).

South of the interface, the Tethyan Sedimentary Sequence is composed of millimeter- to centimeter-thick, high-strain interlayered marbles and calc-silicates that define a pervasive S-dipping foliation. Within 10 m superjacent to the interface, angular fragments of marble and calcite are observed within a chaotic carbonate matrix on a centimeter scale (Fig. 3C), interpreted to be related to overprinting low-temperature cataclastic deformation.

Within 1 m of the interface, microscale observations of high-strain marble show well-rounded and internally deformed (brittle fractures and undulose extinction) clasts of quartz, feldspar, and phyllosilicate within a matrix of fine-grained calcite. These attributes suggest mineral and lithic fragments have been incorporated into the marble from the underlying Greater Himalayan Sequence and rotated during subsequent deformation.

North of the Greater Himalayan Sequence—Tethyan Sedimentary Sequence interface, the Greater Himalayan Sequence consists of mylonitic garnet-bearing quartzite and pelitic schist that exhibit a pervasive S-dipping schistosity. Mineral elongation lineations plunge shallowly to moderately toward the ESE-WNW and are defined by elongation and alignment of quartz, feldspar, and mica, and fractured and boudinaged garnet and tourmaline grains. Asymmetric fabric elements, including rotated feldspar porphyroclasts devoid of noticeable recrystallized mantles and mica fish, are abundant within the high-strain core, but they do not clearly indicate a sense of shear.

Quartz grains are dynamically recrystallized and intensely attenuated into elongate ribbons (Fig. 4). Relict grains show subgrain extinction, bulges, and recrystallized subgrains (Fig. 4). Feldspar grains exhibit bent twins, patchy undulose extinction, and abundant grain-scale fractures (Fig. 4). Coeval dynamic recrystallization of quartz and brittle deformation of feldspar constrain deformation temperatures between 280 °C and 400 °C within the high-strain core (Tullis and Yund, 1991; Stipp et al., 2002).

Domain IV—High-Strain Quartzite and Pelitic Greater Himalayan Sequence

Domain IV, composed of highly strained garnet-bearing quartzite and pelitic schist of the Greater Himalayan Sequence, is located ~1 km structurally below the Greater Himalayan Sequence—Tethyan Sedimentary Sequence interface (Fig. 2). Rock types, structures, and shear sense indicators within this domain are similar to the overlying high-strain core; however, deformation has occurred at higher temperatures. Similar to domain III, shear sense indicators are present but do not show a distinctive sense of shear.

Strongly flattened quartz grains exhibit core and mantle structures, recrystallized subgrains, and subgrain extinction, indicating dynamic recrystallization by subgrain rotation at deformation temperatures of ~400–500 °C (Stipp et al., 2002).

Domain V—High-Strain Gneissic Greater Himalayan Sequence

Domain V, composed of high-strain gneiss of the Greater Himalayan Sequence, is exposed ~1–6 km structurally below the Greater Himalayan Sequence—Tethyan Sedimentary Sequence interface (Fig. 2). Domain V is characterized by increasing deformation temperatures as seen in dynamic recrystallization mechanisms and volume percent of leucosome, and a decrease in strain with increasing depth.

Garnet-muscovite–bearing high-strain gneiss interlayered with rafts of garnet-muscovite-sillimanite pelitic schist containing up to 30 vol% leucosome are dominant at upper structural levels within this domain. Garnets are inclusion rich and intensely deformed. Within the pelitic layers, abundant shear bands both fault and draw into plane sillimanite and biotite (Fig. 4D). Asymmetric fabric elements, including C/S/C' fabrics, α-type feldspar porphyroclasts, and β-type rotated leucogranitic pods, show a near-even distribution of dextral and sinistral senses of shear (Figs. 3 and 4). Along these structural levels, feldspar porphyroclasts are bordered by recrystallized quartz and feldspar in core-and-mantle-type structures, corresponding to deformation temperatures of ~400–500 °C (Tullis and Yund, 1991).

At progressively deeper structural levels in domain V, strain decreases in intensity but continues to exhibit consistent orientations (e.g., S-dipping foliation and a shallow to moderately plunging, ESE-WNW–trending lineation; Fig. 2). In addition, muscovite decreases in abundance, and quartz grain boundaries transition from interlobate to amoeboid, occasionally exhibiting subgrain boundaries (Fig. 4). These textures represent dynamic recrystallization dominantly through grain boundary migration, with a considerable component of recrystallization by subgrain rotation, corresponding to the transition between, or overprinting of, these two recrystallization mechanisms at ~500 °C (Stipp et al., 2002).

Throughout domain V, late brittle structures, including normal faults, cataclastic zones, and pseudotachylyte injections, overprint the high-strain gneiss.

Domain VI—Migmatitic Greater Himalayan Sequence

Domain VI, the northernmost and structurally lowest observed rocks, consists of migmatitic gneiss exhibiting up to 70 vol% leucosome. The mineralogy of this domain is equivalent to the overlying domain V (Fig. 2). Domain VI is characterized by increasing deformation temperatures as seen in recrystallization mechanisms, a weakly developed S-dipping foliation defined by anastomosing leucosome and melanosome, and a lack of mineral lineations.

Fibrolite is rare. Garnets are intensely fractured, and minor muscovite grains show irregular grain boundaries, suggestive of nonequilibrium conditions. Quartz and feldspar grains are equigranular and show interlobate grain boundaries, indicating temperatures of deformation between ~500–700 °C, associated with dynamic recrystallization via grain boundary migration (Stipp et al., 2002). Additionally, quartz displays distinctive chessboard extinction (Fig. 4F), interpreted to represent temperatures of deformation in excess of ~630 °C (Blumenfeld et al., 1986; Mainprice et al., 1986; Stipp et al., 2002).

Crystallographic Preferred Orientation of Quartz

Quartz crystallographic preferred orientation (CPO) patterns are the result of deformation temperature, strain rate, noncoaxiality of flow, and distortional strain geometry (Sullivan and Beane, 2010, and references therein). Their analysis has proven effective in characterizing the strain of exhumed metamorphic rocks in the Himalaya (e.g., Bouchez and Pêcher, 1976; Brunel and Kienast, 1986; Grujic et al., 1996; Grasemann et al., 1999; Bhattacharya and Weber, 2004; Law et al., 2004, 2013; Larson and Godin, 2009; Larson et al., 2010; Yakymchuk and Godin, 2012; Larson and Cottle, 2014).

Complete crystallographic orientation data of quartz for all samples were obtained using the electron backscatter diffraction (EBSD) method (Prior, 2009). Data were collected through an HKL EBSD detector installed on a JEOL JSM6360LV scanning electron microscope (SEM) at Colgate University, located in Hamilton, New York, USA. Oxford Intru-
Results

Quartz CPO patterns follow the classification of Lister (1977), in which the plane normal to the lineation (γ plane) is defined as the symmetry plane. Fabrics that do not mirror themselves across this plane are described as asymmetric. A summary of the orientation of principal strain axes, active slip systems, fabric geometries in different strain fields, and evolution of CPO patterns during noncoaxial strain at various temperatures can be found in Schmid and Casey (1986) and Passchier and Trouw (2005). Quartz CPO lower-hemisphere equal-area projections are oriented normal to the foliation and parallel to the lineation (Fig. 5). Complete c- and a-axes data sets of analyzed samples from domains III through V are presented in Figure 6.

CPO patterns for domain III, the high-strain core, were obtained from millimeter-thick bands of fine-grained ribbon quartz (~100 µm wide) for samples HK124B2 and HK125. The c-axis fabrics are characterized by type I single-girdle fabrics with dominant contributions of rhomb <a> and prism <a> slip and a lesser component of basal <a> slip. The c-axis fabric of sample HK125 shows a minor sinistral asymmetry, indicating sinistral-normal displacement along a moderately SW-dipping shear zone, or top-down-to-the-S displacement (see orientation of fabrics in Fig. 6). The a-axis fabrics are concentrated in point maxima of similar intensity around the edge of the stereonet, which is typical of plane strain conditions (Fig. 6; Passchier and Trouw, 2005).

CPO patterns for domain IV, the high-strain quartzite and pelitic Greater Himalayan Sequence, were obtained from samples HK131A, HK139D, HK123, and HK140. With the exception of sample HK123, analyzed quartz grains are moderate to coarse grained and represent greater than 85 vol% of the sample. Quartz crystals analyzed from sample HK123 are located in millimeter-thick mylonitic bands. With increasing depth, CPO patterns record a progression from (1) type I single-girdle c-axis fabrics with a component of basal <a> slip (HK131A), into (2) a loss of basal <a> and rhomb <a> slip and an intensification of prism <a> slip (HK139D and HK123), and ultimately into (3) the formation of pseudo-type II cross-girdle c-axis fabrics (HK140). All c-axis fabrics are roughly symmetrical, with the exception of sample HK139D, which exhibits a right-lateral asymmetry, indicating dextral-reverse displacement along a moderately SSW-dipping shear zone, or top-up-to-the-NW displacement (see orientation of fabrics in Fig. 6). The a-axis fabrics are concentrated in point maxima of similar intensity around the edge of the stereonet, typical of plane strain conditions (Fig. 6; Passchier and Trouw, 2005).

In summary, quartz c-axis fabrics show a systematic progression with increasing depth. From domain III through to domain V, quartz c-axis fabrics transition from (1) type I cross-girdles with a component of basal <a> slip, to (2) type I cross-girdles lacking basal <a> slip and approaching a y-maxima, to (3) weakly defined type II cross-girdles. This transition in dominant slip systems active during deformation corresponds to an increase in temperatures of deformation (Law, 1990; Toy et al., 2008), from ~350 °C within domain III, to ~600 °C within domain IV, to possibly as high as ~630 °C as evidenced by the chessboard textures in domain VI (Fig. 6). The dominance of symmetric c- and a-axis patterns (Fig. 6) suggests that the state of strain, as recorded by the CPOs, was primarily pure shear.

GEOCHRONOLOGY AND THERMOCRONOLOGY

U-Th/Pb geochronology and 40Ar/39Ar thermochronology were performed on a suite of samples from domains III, IV, V, and VI to constrain the absolute timing of metamorphism, deformation, and cooling in the upper Karnali valley.

U-Th/Pb Monazite Geochronology

Three samples, HK109, KH118, and HK117, were selected for U-Th/Pb in situ monazite geochronology. The presence of monazite was confirmed through backscatter electron images from a scanning electron
Figure 6. Quartz crystallographic preferred orientation (CPO) c- and a-axes. Columns from left to right: sample number and approximate distance from Greater Himalayan Sequence–Tethyan Sedimentary Sequence interface, measured perpendicular to the average foliation (fill shades and patterns are the same as Figs. 2 and 4); c-axis fabric with shear sense when applicable, lineation and foliation data; a-axis fabric, and multiples of uniform density (mud). For each analysis, point and contoured data are shown; n—number of grains measured. All stereonets are lower-hemisphere equal-area projections oriented normal to the foliation and parallel to the lineation.
microprobe and analyses from high-speed energy dispersive X-ray spectroscopy at Queen’s University. Detailed textural relationships between monazite grains and their host fabrics were investigated by examining high-resolution backscatter electron images of entire thin sections.

To target individual compositional domains within each monazite grain, X-ray chemical maps were produced for Th, Y, U, and Nd/La using a JEOL JXA-8230 electron microprobe at Queen’s University. The following electron microprobe conditions were used: accelerating voltage of 15 kV, a beam current of ~350–500 nA, a dwell time of 100 ms, and a step size of 0.5–1.2 μm. High- and low-magnification backscatter electron and secondary electron images were also collected to establish the textural context and physical condition of the monazite grains.

Monazites were analyzed using a laser ablation–multicollector–inductively coupled plasma–mass spectrometer (LA-MC-ICP-MS) system housed at the University of California, Santa Barbara, following methods outlined in Cottie et al. (2012). Complete methodology is provided in GSA Data Repository supplementary information 2 (see footnote 1).

Results

Monazites exhibit a variety of textures, including elongate, rounded, and comminuted into masses of fine-grained fragments, and are typically between 20 and 200 μm in diameter or width/length (Fig. 7). The majority of monazite are strongly deformed and characterized by rounded and ragged edges, brittle fractures, and occasional pitted interiors. Rounded grains often show a greater degree of internal deformation, consisting of internal fracturing and pitting of the grain. Elongate monazite grains are largely aligned parallel to the main ESE-WNW–trending lineation and located adjacent to or within pristine muscovite and biotite grains defining the dominant foliation (Fig. 7A).

Characteristic yttrium (Y) and thorium (Th) compositional zoning is present in all monazite grains. Locations of the spot analyses were based on Y/Th compositional zoning and were selected to constrain ages associated with different chemical domains (Fig. 7A). Results of U-Th/Pb analyses are summarized in Figure 6B and graphically presented as 208Pb/232Th versus 206Pb/238U concordia and 208Pb/232Th age probability distribution diagrams in Figure 8. The full U-Th/Pb data set is available in GSA Data Repository supplementary information 3 (see footnote 1).

In total, 65 meaningful analyses were obtained on six monazite grains from sample KH18a, a high-strain garnet-bearing pelitic schist within domain IV (Figs. 6B and 7). These data yielded minor peaks in age distribution at ca. 26 Ma and ca. 24–22 Ma, with the bulk of ages occurring between ca. 21 and 15 Ma. The oldest grouping of ages at ca. 26 Ma corresponded to a minor group of Y-poor cores. The next youngest age population corresponded to a minor peak of Y-rich rims between ca. 24 and 21 Ma. The bulk of the ages recorded a secondary metamorphic event with a maximum age population at ca. 19 Ma. These ages were characterized by a ca. 21–18 Ma peak of Y-poor cores and a ca. 18–16 Ma peak of Y-rich rims.

In total, 54 meaningful analyses were obtained on seven monazite grains extracted from the melanosome portion of sample HK117, a garnet-bearing migmatic gneiss of domain VI (Figs. 6B and 7). These data yielded a main age population at ca. 15 Ma, and a minor distribution of ages between ca. 14 and 12 Ma. The main age population consisted of a high frequency of 16–15 Ma Y-poor cores and a lower frequency of 16–14 Ma Y-rich rims. Ages between 14 and 12 Ma were derived from a mix of Y-rich rims and Y-poor cores.

Combined, our data reveal a span of 208Pb/232Th ages from ca. 26 to 12 Ma, with peaks at 19 Ma and 15 Ma (Fig. 8). Distinct older and younger age groups correspond to Y-poor cores and Y-rich rims, respectively (Figs. 6A and 7). As garnet has a higher partition coefficient for Y than does monazite, it essentially acts as a Y sink during crystallization (Foster et al., 2002). Therefore, older age groups associated with Y-poor monazite cores are interpreted to correspond to a period of simultaneous garnet growth and monazite crystallization. Younger age groups associated with Y-rich rims are interpreted to reflect monazite crystallization concurrent with garnet breakdown. Garnet breakdown is evidenced by intensely elongated garnet aggregates and fractured garnet grains aligned parallel to the main ESE-WNW–trending lineation and foliation-defining minerals.

Older and younger age groups do not always correspond to Y-poor cores and Y-rich rims, respectively (Fig. 8; GSA Data Repository supplementary information 3 [see footnote 1]). This can be attributed to size and depth of individual in situ analyses during laser ablation (diameter of ~7 μm and a depth of ~5 μm). Due to the size of each crater, analyses occasionally include underlying zones of different composition and age, leading to a mixing of age domains and a continuous spread of data between age peaks.

40Ar/39Ar Thermochronology

Fourteen muscovite-rich samples located throughout domains III, IV, V, and VI were selected for 40Ar/39Ar thermochronology. Muscovite grains with good clarity, greater than or equal to 500 μm in diameter, and void of inclusions and intergrowth were selected for dating. The 40Ar/39Ar thermochronology was performed at Queen’s University Argon Geochronology Laboratory. Complete methodology is provided in GSA Data Repository supplementary information 4 (see footnote 1).

Results

Results of the 40Ar/39Ar thermochronology are divided into well-defined and moderately defined plateaus. Well-defined and moderately defined plateaus consist of a minimum of three consecutive steps with ages of overlapping error, releasing greater than 90%, or greater than 40%, of the total 39Ar, respectively. Moderately defined plateaus constitute upward- and downward-stepping profiles. The reason for these anomalous age spectra is unknown, but it may be the result of mixing with recrystallized muscovite, or crystal lattice damage resulting from continued deformation below the argon closure temperature (McDougall and Harrison, 1988).

A selection of typical step- heating profiles is presented in Figure 9A, and a summary of 40Ar/39Ar thermochronology results is presented in Table 1 and Figure 9B. All step-heating profiles can be found in GSA Data Repository supplementary information 5 (see footnote 1). Of the 14 samples selected for 40Ar/39Ar age determination, 10 yielded well-defined plateaus, and 4 yielded moderately defined plateaus (Table 1).

Sample HK125 is a high-strain pelitic schist of domain III. Analyzed muscovite grains define a shallow W-plunging lineation and show extensive postcrystallization deformation. The sample yielded a well-defined plateau age of 13.01 ± 0.30 Ma corresponding to 92.8% of released 39Ar (Fig. 9; Table 1).
Figure 7. (A) Backscatter electron images (BSE image) of monazite (mnz) showing textural relationships with adjacent minerals and the dominant fabric (S), and microprobe-generated yttrium and backscatter electron maps (BSE map). $^{208}\text{Pb}/^{232}\text{Th}$ ages ± 2σ are shown on yttrium maps for all points analyzed. Diameters of analyzed points (black circles) are 7 μm. Ages indicated as "N/A" refer to analyses not used in the final age interpretation due to common Pb contamination. Note that yttrium gray scales are not all identical, and that darker and brighter shades of gray indicate higher and lower elemental abundances, respectively. (B) Map showing locations and ages of monazite; legend same as Figure 2.
Figure 8. U-Th/Pb concordia (left column) and probability (right column) diagrams for dated monazite. Dark gray and light gray in both concordia and probability curves correspond to analyses of Y-high rims and Y-low cores, respectively. Black analyses are interpreted as mixtures between Y domains. Color coding within probability diagrams shows general age trends of Y-rich/poor chemical domains. The low-frequency area of HK117a, between 12 and 14 Ma, is not color coded because it does not show a distinct distribution of high/low-Y analyses. n—total number of analyses per sample. Concordia diagrams plot \(^{206}\text{Pb}/^{238}\text{U}\) against \(^{208}\text{Pb}/^{232}\text{Th}\) to avoid complications from \(^{230}\text{U}-^{207}\text{Pb}\) disequilibrium. All plots were constructed with Isoplot v. 3.75 (Ludwig, 2012).
Figure 9. (A) Select muscovite 40Ar/39Ar age spectra. Plateau ages are calculated from gray steps. All errors are reported at 2σ. Plots were constructed with Iso-plot v. 3.75 (Ludwig, 2012). Additional age spectra can be found in GSA Data Repository supplementary information 5 (see text footnote 1), and are summarized in Table 1. (B) Map showing locations and ages of muscovite; legend same as Figure 2.
Sample KH13 and samples KH18, KH131c, and HK138 were taken from a quartzite and from pelitic schist of domain IV, and they yielded moderately well-defined plateau ages (Fig. 9; Table 1). Analyzed muscovite grains define a shallow ESE-WNW lineation and are located along, and offset by, shear bands. Sample KH13 yielded an age of 14.25 ± 0.23 Ma corresponding to 42.3% of released 39Ar. Sample KH18 was analyzed in two separate analytical sessions and yielded ages of 13.52 ± 0.16 Ma and 12.79 ± 0.53 Ma, corresponding to 43.0% and 69.5% of released 39Ar, respectively. Sample KH35 yielded ages of 13.03 ± 0.17 Ma, corresponding to 54.2% and 60.7% of released 39Ar, and samples HK131c and HK138 yielded ages of 12.29 ± 0.30 Ma and 12.08 ± 0.09 Ma, corresponding to 100% and 100% of released 39Ar, respectively.

Samples KH10, HK102a, HK105, HK115, and HK142 were taken from schist and gneiss of domain V and yielded moderately well-defined plateau ages (Fig. 9; Table 1). Analyzed muscovite grains define a shallow ESE-WNW lineation and are located along, and offset by, shear bands. Sample HK10 yielded an age of 13.03 ± 0.17 Ma and 13.00 ± 0.45 Ma, and samples HK115 and HK138 yielded ages of 11.61 ± 0.25 Ma and 12.29 ± 0.30 Ma, respectively. All four analyses correspond to 100% of released 39Ar.

Samples HK105b, HK142, and HK117a were taken from migmatitic gneiss of domain VI and yielded well-formed 39Ar. Sample HK117a yielded ages of 11.57 ± 0.25 Ma and 10.81 ± 0.16 Ma, respectively. All ages correspond to 100% of released 39Ar.

Samples HK117a, HK118a, and HK119a were taken from migmatitic gneiss of domain VI and yielded well-defined plateau ages (Fig. 9; Table 1). Analyzed muscovite grains are not pristine and exhibit ragged and serrate boundaries, possibly indicative of disequilibrium conditions. Samples HK117a, HK119a, and HK118a yielded ages of 11.57 ± 0.25 Ma, 11.39 ± 0.25 Ma, and 10.81 ± 0.16 Ma, respectively. All ages correspond to 100% of released 39Ar.

Based exclusively upon well-defined plateau ages, the Greater Himalayan Sequence of the upper Karnali valley cooled through the argon closure temperature between ca. 13 and 10 Ma (Fig. 9; Table 1). If moderately defined age plateaus are also considered, then the cooling age of the Greater Himalayan Sequence in this region may span from ca. 15 to 9 Ma (Fig. 9; Table 1).

**DISCUSSION**

Geologic mapping and microstructural analyses of the upper Karnali valley (summarized in Fig. 10) reveal low-metamorphic-grade sedimentary rocks of the Tethyan Sedimentary Sequence juxtaposed via a brittle-ductile, high-strain, S-dipping contact over strongly deformed and metamorphosed rocks of the Greater Himalayan Sequence (Figs. 2 and 9). Throughout the Himalaya, this contact is commonly recognized as the South Tibetan detachment system, along which the Greater Himalayan Sequence was extruded southward, normal to the orogen (e.g., Burchfiel et al., 1992; Grujic et al., 1996; Hodges, 2000, 2006). Within the upper Karnali valley, deformation fabrics are parallel to this high-strain contact and exhibit dominant strike-slip and minor dip-slip displacements. Based on our structural and geochronological data and the sequence of interpretations presented next, we argue that the final juxtaposition of units in the upper Karnali valley is the result of S-directed extrusion of the Greater Himalayan Sequence along the South Tibetan detachment system, followed by orogen-parallel strike-slip–dominated shear. In addition, we contend that the transition from S-directed extrusion to orogen-parallel extension in the upper Karnali occurred between ca. 15 Ma and 13 Ma.

**Timing of Orogen-Parallel Deformation**

Structural fabrics observed in the upper Karnali valley define a high-strain ESE-WNW–trending shear zone dominated by strike-slip and minor dip-slip sense of shear (Figs. 2 and 9). Thermochronology of muscovite defining the ESE-WNW ductile fabric reveals that by ca. 15 Ma to 9 Ma, the upper Karnali valley cooled through the argon closure temperature for muscovite (Fig. 9; Table 1). If only well-defined muscovite age plateaus

### TABLE 1. ⁴⁰Ar/³⁹Ar THERMOCRONOLOGIC DATA

<table>
<thead>
<tr>
<th>Sample</th>
<th>Domain</th>
<th>Rock type</th>
<th>Condition of muscovite</th>
<th>Plateau age (Ma)</th>
<th>Error (Ma, 1σ)</th>
<th>Percent ⁴⁰Ar defining plateau</th>
<th>MSDW</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>HK125</td>
<td>III</td>
<td>High-strain pelitic schist</td>
<td>Deformed: faulted, fractured, undulatory extinction</td>
<td>13.01</td>
<td>0.30</td>
<td>92.8</td>
<td>0.33</td>
<td>0.96</td>
</tr>
<tr>
<td>KH13</td>
<td>IV</td>
<td>High-strain quartzite</td>
<td>Well-formed, offset by shear bands</td>
<td>14.25</td>
<td>0.23</td>
<td>42.3</td>
<td>0.16</td>
<td>0.38</td>
</tr>
<tr>
<td>HK18 (1)*</td>
<td>IV</td>
<td>High-strain pelitic schist</td>
<td>Well-formed, offset by shear bands</td>
<td>13.52</td>
<td>0.16</td>
<td>43.0</td>
<td>0.71</td>
<td>0.62</td>
</tr>
<tr>
<td>HK18 (2)*</td>
<td>IV</td>
<td>High-strain pelitic schist</td>
<td>Well-formed, offset by shear bands</td>
<td>12.79</td>
<td>0.53</td>
<td>69.5</td>
<td>0.65</td>
<td>0.62</td>
</tr>
<tr>
<td>KH35 (1)*</td>
<td>IV</td>
<td>High-strain pelitic schist</td>
<td>Well-formed, offset by shear bands</td>
<td>13.03</td>
<td>0.17</td>
<td>100.0</td>
<td>0.40</td>
<td>0.96</td>
</tr>
<tr>
<td>KH35 (2)*</td>
<td>IV</td>
<td>High-strain pelitic schist</td>
<td>Well-formed, offset by shear bands</td>
<td>13.00</td>
<td>0.45</td>
<td>100.0</td>
<td>0.41</td>
<td>0.90</td>
</tr>
<tr>
<td>KH131c</td>
<td>IV</td>
<td>High-strain pelitic schist</td>
<td>Well-formed, offset by shear bands</td>
<td>11.61</td>
<td>0.25</td>
<td>100.0</td>
<td>0.65</td>
<td>0.73</td>
</tr>
<tr>
<td>KH138</td>
<td>IV</td>
<td>High-strain pelitic schist</td>
<td>Well-formed, offset by shear bands</td>
<td>12.29</td>
<td>0.30</td>
<td>100.0</td>
<td>0.27</td>
<td>0.98</td>
</tr>
<tr>
<td>HK102a</td>
<td>V</td>
<td>High-strain gneiss</td>
<td>Well-formed</td>
<td>9.27</td>
<td>0.19</td>
<td>54.2</td>
<td>2.10</td>
<td>0.12</td>
</tr>
<tr>
<td>HK115</td>
<td>V</td>
<td>High-strain gneiss</td>
<td>Well-formed, occasionally offset by shear bands</td>
<td>15.74</td>
<td>0.28</td>
<td>60.7</td>
<td>0.73</td>
<td>0.48</td>
</tr>
<tr>
<td>HK10</td>
<td>V</td>
<td>High-strain gneiss</td>
<td>Well-formed, mantles fsp and qtz porphyroclasts</td>
<td>12.08</td>
<td>0.09</td>
<td>99.4</td>
<td>1.30</td>
<td>0.22</td>
</tr>
<tr>
<td>HK105b</td>
<td>V</td>
<td>High-strain pelitic schist</td>
<td>Well-formed</td>
<td>9.90</td>
<td>0.28</td>
<td>100.0</td>
<td>0.20</td>
<td>0.99</td>
</tr>
<tr>
<td>HK142</td>
<td>V</td>
<td>High-strain gneiss</td>
<td>Well-formed</td>
<td>10.16</td>
<td>0.33</td>
<td>100.0</td>
<td>0.19</td>
<td>0.99</td>
</tr>
<tr>
<td>HK117a</td>
<td>VI</td>
<td>Migmatitic gneiss</td>
<td>Well-formed</td>
<td>11.57</td>
<td>0.25</td>
<td>100.0</td>
<td>1.60</td>
<td>0.14</td>
</tr>
<tr>
<td>HK118a</td>
<td>VI</td>
<td>Migmatitic gneiss</td>
<td>Small, ragged and serrate grain boundaries, possible replacement textures</td>
<td>10.81</td>
<td>0.16</td>
<td>100.0</td>
<td>0.38</td>
<td>0.93</td>
</tr>
<tr>
<td>HK119a</td>
<td>VI</td>
<td>Migmatitic gneiss</td>
<td>Small, ragged and serrate grain boundaries, possible replacement textures</td>
<td>11.39</td>
<td>0.25</td>
<td>100.0</td>
<td>0.46</td>
<td>0.88</td>
</tr>
</tbody>
</table>

*Note: Data in italics indicate moderately-defined plateaus corresponding to ~40–70% of total ⁴⁰Ar release.
*Indicates multiple analyses of individual samples performed in separate analytical sessions.

The transition from S-directed extrusion to orogen-parallel extension in the upper Karnali occurred between ca. 15 Ma and 13 Ma.
are considered, then the cooling age of the upper Karnali valley can be constrained between ca. 13 Ma and 10 Ma. Undulose extinction and brittle deformation of these muscovite grains indicate that orogen-parallel deformation persisted at progressively cooler temperatures. The argon closure temperature of muscovite in the upper Karnali valley is estimated at ~480 °C (assuming ~5 kbar pressure, ~500 μm grains, and a cooling rate of ~60 °C/m.y.; Harrison et al., 2009). This closure temperature is lower than both peak metamorphic and deformation temperature estimates reached by levels IV, V, and VI (Fig. 10; Yakymchuk and Godin, 2012). The 40Ar/39Ar ages are therefore interpreted to represent the minimum age of ductile deformation and peak metamorphism, or the cooling age.

Overprinting relationships show a temporal and spatial progression from high-temperature ductile deformation at deeper structural levels (630 °C at ~2.5 km below the Greater Himalayan Sequence–Tethyan Sedimentary Sequence interface) to lower-temperature ductile and brittle deformation near the top of the Greater Himalayan Sequence (~350 °C along the Greater Himalayan Sequence–Tethyan Sedimentary Sequence interface). This suggests that Greater Himalayan Sequence deformation persisted at progressively lower structural levels. The temporal relationship is best observed within the high-strain gneiss of domain V, where the dominant ESE-WNW–oriented fabric (deformation temperature of ~500 °C to greater than 630 °C) is locally overprinted by centimeter-thick mylonitic layers (deformation temperatures of ~350 °C), and brittle structures.

Ductile ESE-WNW–oriented deformation is characterized by a significant component of pure shear. This is revealed through: (1) fabrics that show a near-even distribution of opposing shear-sense indicators, (summa-
The potential southeast propagation of a network of kinematically linked strike-slip and normal faults is compatible with the spatial distribution of cooling ages within the upper Karnali valley, which show a decreasing trend toward the ESE parallel to the Greater Himalayan Sequence–Tethyan Sedimentary Sequence interface (Fig. 11). When considering only well-defined age plateaus at varying distances along strike, cooling ages decrease from ca. 13 Ma near the village of Tumkot to ca. 10 Ma ~20 km ESE of this village. This trend suggests that the Gurla Mandhata–Humla fault may have propagated toward the ESE at an approximate rate of 6 km/m.y. It is also possible that this variability in cooling ages could reflect lateral variations in the geometry of the underlying Main Himalayan thrust (e.g., Whipp et al., 2007; Herman et al., 2010; Robert et al., 2011; Coutand et al., 2014).

**Tectonic Significance of Orogen-Parallel Extension**

The aforementioned structural and metamorphic data provide strong evidence for orogen-parallel extension at ca. 13 Ma in the upper Karnali valley. This age is notably younger than the majority of ages associated with S-directed extrusion of the Greater Himalayan Sequence and associated South Tibetan detachment system slip throughout the central Himalaya, which suggest that S-directed ductile extrusion of the Greater Himalayan Sequence ceased by ca. 16 Ma (Godin et al., 2006a, 2006b; Cottle et al., 2009a, 2009b, 2015; Antolín et al., 2013), despite some segments that may have still been extruding in late Miocene to more recent times (Hodges et al., 2001; Hurtado et al., 2001; Kellett et al., 2009; Cottle et al., 2011).

To reconcile these observations, we interpret the observed orogen-parallel fabrics in the upper Karnali valley to postdate the S-directed extrusion of the Greater Himalayan Sequence and associated slip along the South Tibetan detachment system. This interpretation is supported by considerable documentation of a post–South Tibetan detachment system orogen-parallel extensional event throughout the Himalaya and...
Tibet (Pêcher, 1991; Coleman and Hodges, 1995; Coleman, 1996; Jessup and Cottle, 2010), and within the vicinity of the upper Karnali valley (Murphy and Copeland, 2005).

Within the upper Karnali valley, tectonic fabrics documented from our study do not preserve any record of early stage orogen-perpendicular deformation, as they are interpreted to be entirely overprinted by orogen-parallel strike-slip-dominated deformation. Although no direct structural evidence for top-to-the-N deformation was observed, metamorphic contrast between the Tethyan Sedimentary Sequence and Greater Himalayan Sequence and metamorphic age constraints are compatible with the interpretation that deformation and S-directed extrusion of the Greater Himalayan Sequence occurred along the South Tibetan detachment system at the Greater Himalayan Sequence–Tethyan Sedimentary Sequence interface prior to orogen-parallel deformation. This interpretation is consistent with observations made along the Himalayan system (Burchfiel et al., 1992; Godin et al., 2001; Searle and Godin, 2003; Law et al., 2004; Kellett et al., 2010).

Microstructural data show an increase in deformation temperatures of ESE-WNW–oriented fabrics from ~350 °C along the Greater Himalayan Sequence–Tethyan Sedimentary Sequence interface to greater than 630 °C at structural depths ~2.5 km below the interface (Fig. 10). Such steep increases in temperature are commonly associated with telescoping and/or flattening of metamorphic field gradients during S-directed extrusion of the Greater Himalayan Sequence (Law et al., 2011, and references therein). Telescoping of metamorphic gradients may be possible during normal faulting and core complex formation; however, it would require either a significant component of penetrative pure shear resulting in extensive vertical shortening or heterogeneous simple shear resulting in the juxtaposition of different particle paths, or some combination of both (Cottle et al., 2011; Law et al., 2011). These processes are typically documented in channelized flow–type scenarios, as they require high temperatures and significant transport displacement (Law et al., 2011, and references therein). We therefore interpret the steep increases and high deformation temperatures recorded within ESE-WNW–oriented fabrics to be a remnant of telescoped and/or flattened metamorphic gradients resulting from the deformation of isograds during S-directed extrusion of the Greater Himalayan Sequence (e.g., Law et al., 2011). Alternatively, comparable flattening of metamorphic gradients could have been generated via oblique slip during progressive extrusion of the Greater Himalayan Sequence as proposed by Pêcher (1991), Coleman (1996), and Xu et al. (2013).

Metamorphic monazite ages within the upper Karnali valley span from ca. 26 to 12 Ma, with the highest frequency ages distributed between 19 and 15 Ma (Figs. 6 and 7). Assuming that the interpretation of an earlier stage of S-directed extrusion of the Greater Himalayan Sequence is correct, we deem it reasonable to suggest that monazites from the upper Karnali valley are associated with 25–16 Ma Neo-Himalayan metamorphism and S-directed extrusion of the Greater Himalayan Sequence as recorded throughout the central Himalaya (Vannay and Hodges, 1996; Godin et al., 1999, 2001; Cottle et al., 2009a). This interpretation is also compatible with the chemical zonation and textural relationships of monazite grains in the upper Karnali valley.

The chemical zonation of monazite grains exhibits older low-Y cores mantled with younger high-Y rims (Figs. 6 and 7). Since garnet has a high affinity for Y during crystallization, the quantity of Y in the system (and hence in the monazite) can be considered as an inverse analogue for garnet growth and prograde metamorphism. Consequently, the transition from older low-Y cores to younger high-Y rims can be interpreted to record the progression from peak to retrograde metamorphism in the final stages of S-directed extrusion of the Greater Himalayan Sequence between ca. 18 and 15 Ma. Studies along the South Tibetan detachment system in Bhutan and Sikkim documented a similar age progression, in which the growth of 16–15 Ma Y-rich monazite rims was interpreted to record retrograde Greater Himalayan Sequence metamorphism during final stages of S-directed extrusion (Kellett et al., 2010, 2013).

Monazite textures exhibit intense internal deformation and alignment of fractured and boudined monazite parallel to the mineral elongation lineation (Fig. 7A). These textures suggest that monazite underwent extensive postcrystallization deformation and transposition. If the crystallization of monazite rims was indeed concurrent with the final stages of S-directed extrusion of the Greater Himalayan Sequence, then the deformation and alignment of monazite parallel to ESE-WNW fabrics must postdate S-directed extrusion of the Greater Himalayan Sequence and therefore may be synchronous with orogen-parallel extension.

It should be noted that the crystallization and subsequent deformation and alignment of monazite grains in an ESE-WNW orientation could alternatively be the result of progressive orogen-parallel–directed strain within the Greater Himalayan Sequence (e.g., Pêcher, 1991; Coleman, 1996; Xu et al., 2013).

**Transition from South-Directed Extrusion to Orogen-Parallel Extension**

In line with previous studies (e.g., Coleman and Hodges, 1995; Coleman, 1996; Jessup et al., 2008; Jessup and Cottle, 2010) and based on the aforementioned series of interpretations, we hypothesize that the Greater Himalayan Sequence of the upper Karnali valley has been progressively exhumed in two distinct tectonic phases: (1) pre–15 Ma S-directed extrusion, followed by (2) 15–13 Ma orogen-parallel extension. If this interpretation is correct, the transition from S-directed extrusion to orogen-parallel extension in the upper Karnali valley can be interpreted to have occurred between ca. 15 and 13 Ma (Fig. 12).

Our data add to the growing recognition that a fundamental period for the initiation of orogen-parallel extension occurred in the mid-Miocene. To demonstrate this, a regional compilation of chronologic data from migmatite-cored domes kinematically linked to extension throughout the Himalaya (i.e., N–S–striking normal faults and kinematically linked E–W–striking strike-slip faults; Taylor et al., 2003) is integrated with our results in Figure 12. Collectively, these data support a potential common mid-Miocene (ca. 16 Ma) transition from cessation of S-directed extrusion of the Greater Himalayan Sequence to onset of orogen-parallel extension. This proposed timing constraint is generally consistent or older than the onset of most structures associated with orogen-parallel and E-W extension throughout the Himalaya and Tibet (e.g., Armijo et al., 1986, 1989; Murphy et al., 2002; Taylor et al., 2003; Thiede et al., 2006; Jessup et al., 2008; Leech, 2008; Cottle et al., 2009b; Taylor and Yin, 2009; Kali et al., 2010; Ratschbacher et al., 2011; Antolin et al., 2012).

Our data do not explain why this proposed transition may have occurred, and what mechanism(s) was responsible for the initiation of orogen-parallel extension. However, this series of interpretations, in conjunction with our results, supports the growing understanding that a fundamental change in tectonic style of the Himalaya-Tibet system occurred in the mid-Miocene (ca. 15 Ma). This transition was coincident with cessation of S-directed midcrustal flow (Godin et al., 2006a, 2006b; Cottle et al., 2009a, 2009b, 2015; Antolin et al., 2013), onset of orogen-parallel extension (Coleman and Hodges, 1995), radial spreading of the lower crust of Tibet potentially related to rapid eastward growth of Tibet (Clark and Royden, 2000; Royden et al., 2008), and an ~35%–40% decrease in convergence rate between India and Eurasia (Molnar and Stock, 2009; Iaffaldano et al., 2013).
CONCLUSIONS

Integrated geological, structural, and microstructural analyses of the upper Karnali valley confirm the presence of a segment of the Gurla Mandhata–Humla fault, a strike-slip–dominated shear zone, juxtaposing low-metamorphic-grade sedimentary rocks of the Tethyan Sedimentary Sequence over strongly deformed and metamorphosed rocks of the Greater Himalayan Sequence.

Assuming that orogen-parallel fabrics in the upper Karnali valley postdate S-directed extrusion of the Greater Himalayan Sequence, results from in situ monazite textural analyses and geochronology can be interpreted to constrain the final stages of S-directed extrusion of the Greater Himalayan Sequence within the upper Karnali valley between ca. 19 and 15 Ma. The $^{40}$Ar/$^{39}$Ar ages from muscovites defining the orogen-parallel ductile fabric indicate that orogen-parallel shear was active by ca. 15–13 Ma.

The interpretation of these data delineates a transition from S-directed extrusion of the Greater Himalayan Sequence to onset of orogen-parallel extension between ca. 15 and 13 Ma within the upper Karnali valley. Integration of our data with migmatite-cored domes kinematically linked to extension throughout the Himalaya supports the growing notion of a fundamental mid-Miocene orogen-wide change in tectonic style of the Himalaya-Tibet system.

ACKNOWLEDGMENTS

This study was supported by a Natural Sciences and Engineering Research Council of Canada (NSERC) discovery grant to L. Godin, a NSERC M.Sc. Canadian Graduate Scholarship, an Ontario Graduate Scholarship in Science and Technology, and a Geological Society of America Student Research Grant awarded to C. Nagy. Field work was made possible with the help of Dawar Tamang, Birval, and their hardworking Nepali crew. B. Joy, D. Gibson, M. Wong, C. Kurzinka, and A. Rudy are thanked for their assistance with electron microprobe, geochronology, electron backscatter diffraction, editorial comments, and geographic information system work, respectively. Stereonets were constructed using OSX Stereonet v. 1.3 by N. Cardozo and R. Allmendinger. Reviewers D. Grujic, K. Hodges, and Associate Editor E. Kirby are thanked for their insightful and constructive comments that helped to clarify our arguments. This paper is dedicated to the victims of the earthquakes that devastated Nepal in the spring 2015.

REFERENCES CITED


