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Notes

The Kumaun and Garwhal Lesser Himalaya, India: Part 1. Structure and stratigraphy

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ABSTRACT

Our understanding of the geologic evolution of the Himalaya remains incomplete, particularly in regard to structural and geochronologic details of the Proterozoic-Paleozoic Lesser Himalayan Sequence. We conducted an integrated field mapping, geochronological study, and geochemical analysis of the Lesser Himalayan Sequence strata in the Kumaun and Garwhal Himalaya of NW India (78°00′–80°30′E). Structural observations reveal a systematic change in deformation styles from lower to higher structural levels in the Main Central Thrust footwall. In the south, and at lower structural levels, the Main Central Thrust footwall is characterized by parallel folding and sparse development of axial cleavage. Quartz microstructures indicate that deformation occurred at temperatures below 350 °C. In contrast, in the north and at higher structural levels close to the Main Central Thrust, deformation is characterized by replacement of original bedding, the development of penetrative cleavage, and schistosity locally. Folds are tight, in places isoclinal and overturned. The corresponding quartz microstructures indicate that deformation occurred above 350 °C. Dating of detrital zircons from Lesser Himalayan Sequence metasedimentary units, and igneous zircons from schistose gneisses throughout the Lesser Himalayan Sequence allow refinements to the stratigraphic framework. First, unlike what has been observed in western Nepal immediately west of our study area, U-Pb zircon dating suggests the absence of Paleoproterozoic strata in the Ramgarh Thrust hanging wall. This suggests that the thrust cuts upsection laterally along strike. Second, U-Pb detrital zircon dating suggests that metasedimentary strata in the Ramgarh Thrust hanging wall are correlative with basal units of the *Outer* Lesser Himalayan Sequence, removing the necessity that the Ramgarh Thrust hanging wall was allochthonous with respect to its footwall Lesser Himalayan Sequence units. Schistose gneisses with U-Pb ages of ca. 1850 Ma are older than Lesser Himalayan Sequence units in the area, suggesting that they are Lesser Himalayan Sequence basement. We conclude that the Ramgarh Thrust is an out-of-sequence thrust postdating a folding event in its footwall. The earlier proposal that Neoproterozoic-Cambrian Lesser Himalayan Sequence strata are the southern extension of the Tethyan Himalayan Sequence requires that the Tons Thrust, which separates the distal and proximal facies of the Lesser Himalayan Sequence, be a major, south-directed structure with a slip magnitude of >50–100 km.

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INTRODUCTION

Following the development of plate tectonic theory in the 1960s, it was recognized that the Himalayan mountain system represents a unique opportunity to study the response of continental lithosphere to collision (e.g., Dewey and Burke, 1973; LeFort, 1975). Our present knowledge of this spectacular mountain range has been largely derived from studies of the high-grade Greater Himalayan Crystallines in the core of the orogen. The Greater Himalayan Crystallines preserve a wealth of pressure-temperature conditions and exhumation paths under which the mountain range has been developed (see Yin and Harrison, 2000). For this reason, kinematic and dynamic models of the Himalaya have been largely developed based on our current knowledge of the Greater Himalayan Crystallines (see reviews by Yin [2006] and Kohn [2008]). A major problem with the above approach is that the Greater Himalayan Crystallines only represent ~25% of the Himalaya, and its evolution surely does not represent that of the whole orogen. We conducted an integrated geologic investigation of the Lesser Himalayan Sequence in the Kumaun and Garwhal Himalaya of NW India (78°00′E and 80°30′E). There the Lesser Himalayan Sequence is composed of generally low-grade rocks juxtaposed beneath the Greater Himalayan Crystallines by the Main Central Thrust. Our investigations (field mapping, detailed structural analyses, U-Pb zircon dating, and geochemistry) clarify aspects of the chronostratigraphy of the Kumaun-Garwhal thrust belt, indicate basement-involved thrusting, and document a systematic change in deformation mechanism from lower to upper structural levels. These results are combined with thermochronologic and thermometric data in a companion study (Célérier et al., 2009) to constrain a thermokinematic model for the evolution of the region.

REGIONAL GEOLOGY

Structural Framework

The geology of the Kumaun and Garhwal Himalaya has been studied for over a century (e.g., Middlemiss, 1885; Holland, 1908; Auden, 1935; Heim and Gansser, 1939; Misra and Sharma, 1967; Jain, 1971; Rupke, 1974; Valdiya, 1980a; Valdiya, 1995; Srivastava and Mitra, 1994; Richards et al., 2005) (Figs. 1 and 2). It was in this area that Heim and Gansser (1939) first established their classic Himalayan division: the Subhimalayan Sequence, the Lesser Himalayan Sequence, the Greater Himalayan Crystallines, and the Tethyan Himalayan Sequence that are stacked from south to north by the north-dipping Main Frontal Thrust, Main Boundary Thrust, Main Central Thrust, and later recognized South Tibet Detachment (also see LeFort, 1996) (Fig. 2).

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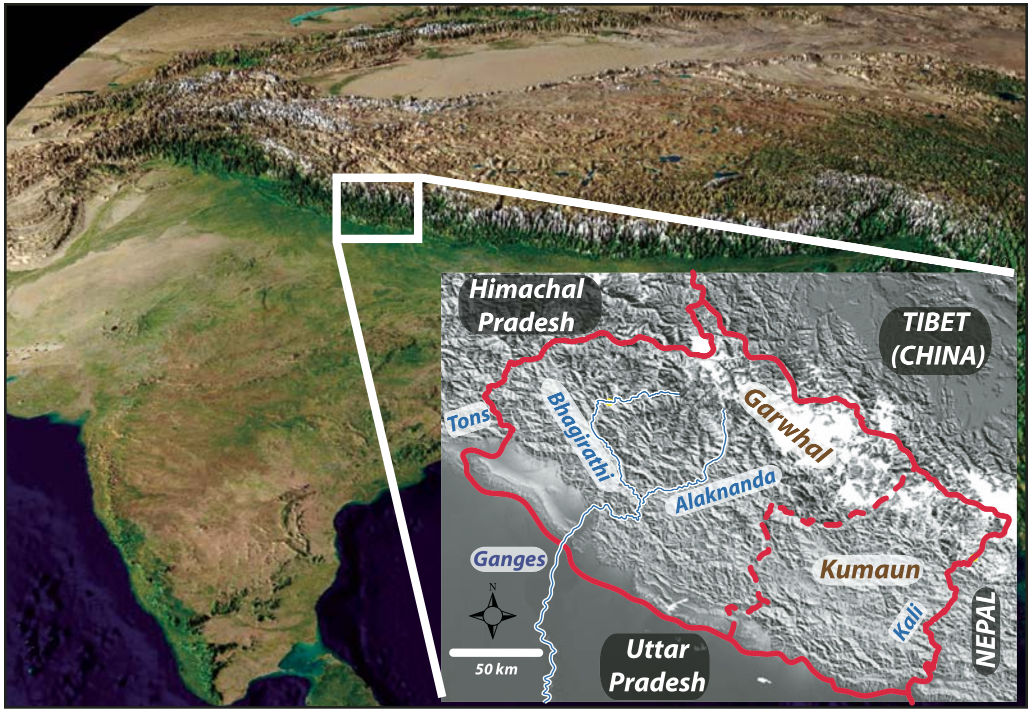
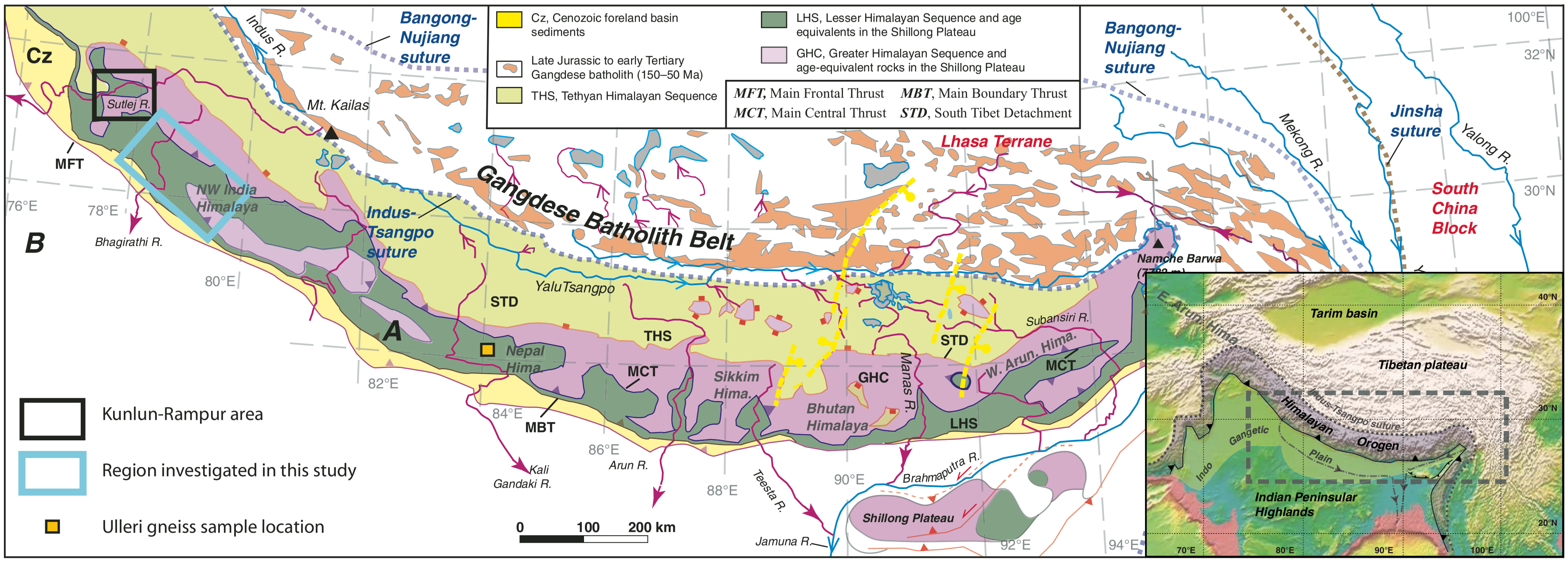


Figure 1 (to left). Digital elevation model of the western Himalaya, Tibetan plateau, and Tarim basin. Inset on bottom right shows the position and physiography of the Kumaun and Garwhal Himalaya.

Figure 2 (below). Simplified geologic map of the Himalaya. The position of the study area within the Himalaya relative to the Kunlun-Rampur regions (location of Richards et al. [2005] and Miller et al. [2000] studies) shown. Location of Ulleri gneiss sample also indicated (sections 4 and 5).



The Main Central Thrust, as defined by Heim and Gansser (1939) in Kumaun, has been correlated across the orogen (see review by Yin [2006]) and is widely recognized to be the most important structure responsible for the development of the Himalaya, but its exact location has been widely debated (e.g., Kohn et al., 2002; Searle et al., 2002). Martin et al. (2005) argued that Nd isotopic composition is the most diagnostic criterion to separate the Greater Himalayan Crystallines and Lesser Himalayan Sequence above and below the Main Central Thrust, while Searle et al. (2008) argue that only the location of maximum shear strain marks the trace of the Main Central Thrust. Multiple strands of the Main Central Thrust have been recognized and are collectively referred to as the Main Central Thrust zone (Bordet, 1961; Bordet et al., 1972). The lower and upper bounding faults of the Main Central Thrust zone have been termed the MCT I and MCT II in Nepal (Hashimoto et al., 1973) and the Munsiari and Vaikrita Thrusts in Kumaun and Garwhal (Valdiya, 1980a). The upper thrust in many parts of the Himalaya generally moved in the early Miocene, whereas the lower thrust moved in the late Miocene and Pliocene (Harrison et al., 1997; Catlos et al., 2004).

The current structural and stratigraphic framework of the Kumaun and Garwhal Himalaya was largely established by Valdiya (1980a). There, the Lesser Himalayan Sequence between the Main Boundary Thrust and Munsiari Thrust is juxtaposed by a series of thrusts, some of which have been broadly folded (Fig. 3). Major faults in the Lesser Himalayan Sequence include the Tons Thrust, the Ramgarh Thrust, and the Berinag Thrust (Fig. 3). Structurally overlying the above thrust sheets are several klippen of the Greater Himalayan Crystallines above a low-angle fault that has been generally correlated with the Main Central Thrust. The Almora-Dadeldhura klippe is the largest and extends ~300 km along strike (Fig. 3).

Stratigraphic Framework

Following LeFort (1996), the Subhimalayan unit comprises Neogene to Quaternary fluvial deposits of the Himalayan foreland basin, the Lesser Himalayan Sequence unit comprises Proterozoic-Paleozoic strata, the Greater Himalayan Crystallines comprise Proterozoic-Ordovician metasedimentary rocks and orthogneiss, and the Tethyan Himalayan Sequence comprises Proterozoic-Eocene sedimentary strata. Protoliths of the various tectonometamorphic units exposed in the Himalaya are interpreted to represent proximal-distal elements of a continuous sedimentary sequence (e.g., Brookfield, 1993; Myrow et al., 2003). In the Kumaun and Garwhal Himalaya, the Lesser Himalayan Sequence can be further divided into the *Inner* (older) and *Outer* (younger) Lesser Himalayan Sequence units; the former is more proximal than the latter with respect to the Indian craton to the south (Ahmad et al., 2000). The Lesser Himalayan Sequence has also been divided into a two-tier, older-and-younger hierarchy (Valdiya, 1980a; Srivastava and Mitra, 1994; Ahmad et al., 2000; DeCelles et al., 2001; Richards et al., 2005), and here we adopt the stratigraphic model of Richards et al. (2005). Although most workers consider the Himalayan units to have been deposited on the northern margin of India (e.g., Brookfield, 1993; Myrow et al., 2003), DeCelles et al. (2000) proposed the Greater Himalayan Crystallines to have derived from an exotic terrane accreted onto India in the early Paleozoic.

Stratigraphic division of the Lesser Himalayan Sequence in the Kumaun and Garwhal Himalaya is as follows. The ca. 1800-Ma Berinag quartzite lies at the base of the *Inner* Lesser Himalayan Sequence (Miller et al., 2000) and is overlain above a regional unconformity by slate and turbidite of the Chakrata and Rautgara Formations that are succeeded by Neoproterozoic Deoban dolomites and Mandhali carbonaceous slates and carbonates (Plate 1[1]). The *Outer* Lesser Himalayan Sequence comprises ca. 850-Ma Chandpur Formation (mostly turbidites) (Richards et al., 2005), Nagthat quartzite, and Blaini conglomerate (Plate 1). The *Outer* Lesser Himalayan Sequence units are capped by the late Neoproterozoic Krol (mostly limestones) and Tal (mostly clastic sediments) Formations. Trilobites from the Tal Formation indicate an Early Cambrian age (Hughes et al., 2005). Cretaceous to Paleocene, shelly limestones and sandstones of the Bansi and Subathu Formations are of limited exposure to the south of the Tons Thrust in the Kumaun and Garwhal Lesser Himalayan Sequence. They occur as thin, thrust-bounded slivers in the southern part of the thrust belt (Plate 1).

Schistose Gneisses—Basement to the Lesser Himalayan Sequence?

To date, no unambiguous exposures of a basement-cover contact in the northwestern Indian Lesser Himalaya have been identified, and thus its nature remains speculative. Given the paucity of convincing age constraints for the *Inner* Lesser Himalayan Sequence, it has been difficult to determine the nature of contacts between crystalline bodies (possibly basement) and sedimentary rocks of the Lesser Himalayan Sequence. Schistose gneisses are widely exposed across the Kumaun and Garwhal Himalaya in the Main Central Thrust footwall (Plate 1). They most commonly occur at the base of thrust sheets such as the Berinag, Ramgarh, and Almora Thrusts. The nature of the schistose gneiss units is unknown due to the lack of modern geochronologic studies focusing on the rocks. At present, only whole-rock, Rb-Sr isochron ages of ca. 1800 Ma with large uncertainties are available for a schistose gneiss in the Ramgarh Thrust hanging wall (Trivedi et al., 1984). This age led Valdiya (1995) to argue that the schistose gneisses represent basement to the Lesser Himalayan Sequence. Similar augen and schistose gneiss units in the Main Central Thrust footwall are also exposed in the Rampur window area directly west of our study area (Fig. 2). There, Vannay et al. (2004) and Richards et al. (2005) argued that the Wangtu-Bandal granitic gneisses (U-Pb age of 1840 ± 16 Ma; Miller et al., 2000) represent the Lesser Himalayan Sequence basement. In the same area along the Sutlej River Valley (Chambers et al., 2008) dated a Paleoproterozoic (1810 ± 10 Ma) leucogranite that intrudes the Jutogh metasediments of the Lesser Himalayan Sequence. Thus these pre–1810-Ma metasediments may also be part of the Lesser Himalayan Sequence basement along with the Wangtu-Bandal granitoid. One of the main goals of this study is to elucidate the nature of the schistose gneisses in the Main Central Thrust footwall by performing U-Pb zircon dating and geochemical analyses.

STRUCTURAL GEOLOGY

We examined the following structures in detail in our study area. From south to north and from lower to high structural levels, they are the Main Boundary Thrust, Ramgarh Thrust, Tons Thrust, and Berinag Thrust (Fig. 3 and Plate 1). Below we describe each thrust and related structures in terms of deformation style, fabric development, and deformation mechanisms.

Main Boundary Thrust and Hanging-Wall Structures

The Main Boundary Thrust hanging wall comprises the Chandpur, Nagthat, Blaini, Krol, and Tal Formations (Plate 1). In Valdiya's (1980a) scheme, the Main Boundary Thrust hanging wall is known as the Krol Thrust Sheet.

Foliations

The Main Boundary Thrust hanging wall preserves several phases of slaty cleavage devel-

[1]Plate 1 is on a separate sheet accompanying this issue.

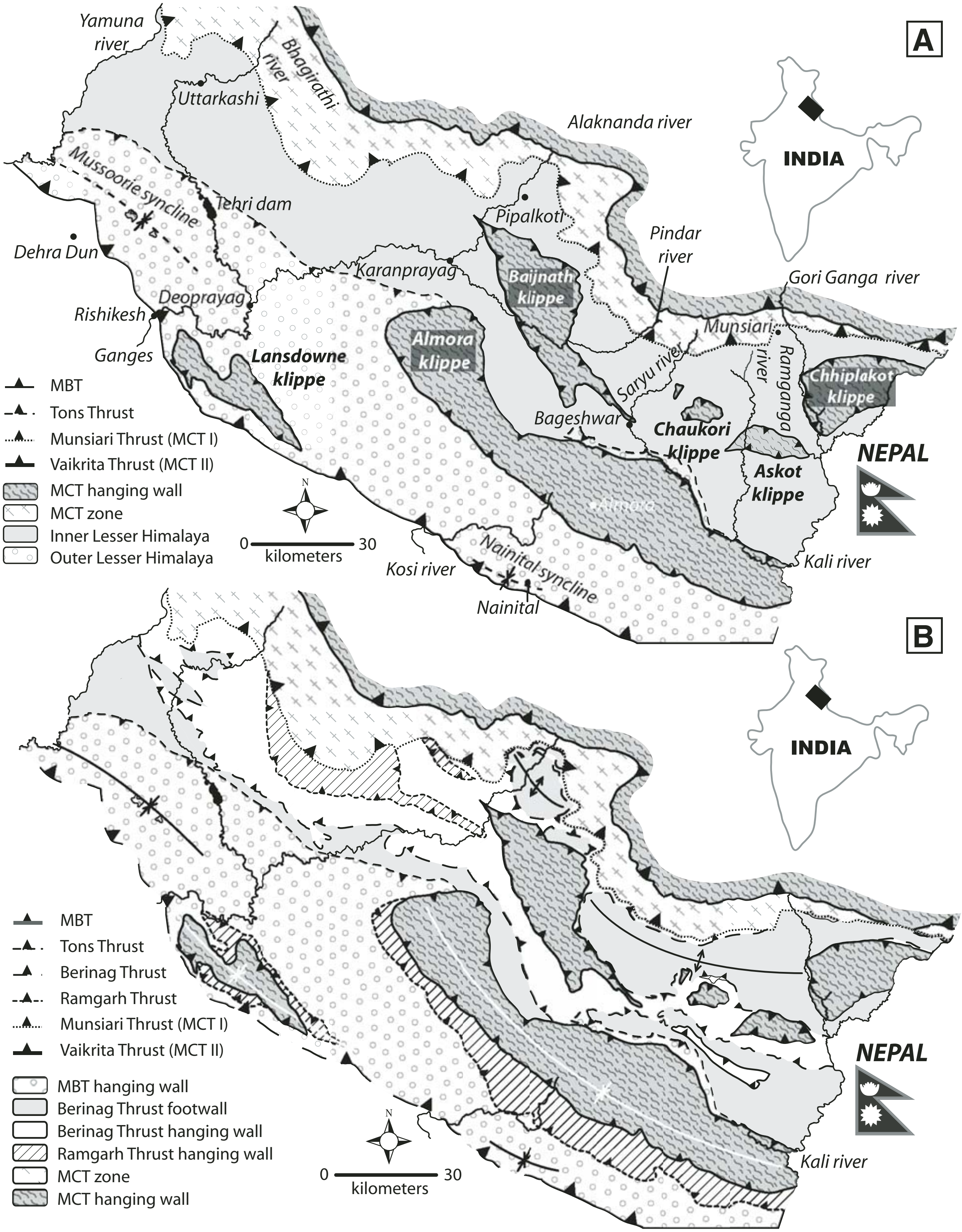


Figure 3. Structural architecture of the Kumaun and Garhwal Himalaya. (A) The first-order structure of the region—a two-tiered stratigraphic sequence juxtaposed along the south-dipping Tons Thrust. These metasediments are overlain by several klippen of the Main Central Thrust hanging wall. Also shown are the major drainages and towns in the region. (B) Represents the structure of the region as proposed by Valdiya (1980a)—a series of stacked thrust sheets. Abbreviations: MBT—Main Boundary Thrust; MCT—Main Central Thrust.

opment, some of which may be related to early Paleozoic contraction across the Himalaya (e.g., Gehrels et al., 2003; Gehrels et al., 2006). Fabrics are strongly linked to rock composition; quartz-rich lithologies generally lack penetrative cleavage, whereas pelitic units exhibit multiple sets of foliations. In addition to bedding, three foliation generations can be recognized in the Main Boundary Thrust hanging wall, although most outcrops only preserve two. At one location (30°27′11.4″, 78°25′10.7″) ~5 km north of the Tehri Dam, slates in the Chandpur Formation display all three sets of foliations (Fig. 4). The dominant slaty cleavage dips at 65° to the southwest and cuts original sedimentary bedding and S_1. Graded beds (3–5 cm scale) indicate that the sequence is right way-up. A weak slaty cleavage (S_1), defined by clay mineral alignment, is developed parallel to bedding. These parallel fabrics are cut by the dominant northwest dipping S_2 foliation and are reoriented by a weak crenulation cleavage S_3. The four foliations displayed in Figure 4 are traceable throughout the Main Boundary Thrust hanging wall with S_2 defining regional-scale structural grain in the Main Boundary Thrust hanging wall.

Quartz Microstructure

Inverted metamorphic field gradients have long been recognized within the Lesser Himalayan Sequence below the Main Central Thrust zone (Medlicott, 1864), but the accompanying changes in deformation style and deformation mechanisms have not been well documented. In this study, we use the well-established relationship between quartz microstructure and temperature and strain-rate conditions by Hirth and Tullis (1992) to elucidate this problem. According to Hirth and Tullis (1992), three temperature and strain-rate regimes of dislocation creep occur in quartz aggregates that are manifested by distinct microstructures (Fig. 5). *Regime 1,* under low-temperature and high strain rate, preserves rounded, detrital quartz grains with patchy, irregular extinction in cross-polarized light; *Regime 2,* under an increased temperature or decreased strain rate, displays flattened detrital quartz grains with sweeping undulose extinction; and *Regime-3* microstructures, under the highest temperature and lowest strain rate, exhibit completely recrystallized polygonal quartz with a foam texture (Fig. 5). Below we present the result of the determined deformation regimes based on observed quartz microstructures in the Lesser Himalayan Sequence (Fig. 6). Photomicrographs of all the studied samples mentioned below can be found in Célérier (2007).

Quartzite and sandstone hand specimens from the Main Boundary Thrust hanging wall contain spherical quartz grains up to 1 mm in diameter visible with the naked eye. Quartz in all of the samples displays patchy, undulose extinction and retains original detrital spherical shapes. The samples also contain detrital muscovite, biotite, zircon, and apatite grains (Célérier, 2007). The above observation indicates deformation under *Regime 1*, which occurred at a temperature below ~350 °C or under a strain rate of $<10^{-6}$ s^{-1} (Hirth and Tullis, 1992).

Structural Facing and Fold Styles

Facing directions based on Bouma sequences, graded beds, and cross-bedding relationships in the Main Boundary Thrust hanging wall are dominantly upright (Fig. 7), precluding large-scale overturned folding. However, overturned beds do exist in phyllites and slates related to small-scale parasitic folds.

Folds in the Main Boundary Thrust hanging wall are present at all scales—kink-fold geometries of microscopic crenulations to the km-scale Mussoorie syncline (see Fig. 3 and Plate 1). Folds are generally parallel (i.e., constant bed thickness), trend northwest-parallel to regional foliation and thrusts, and have interlimb angles ranging between ~30° and ~120°. Locally, fold limbs are overturned (i.e., the north limbs of the Mussoorie and Nainital synclines [Fig. 3]).

Ramgarh Thrust and Hanging-Wall Structures

Valdiya (1980a) first described the Ramgarh Thrust with its type location near the towns of Ramgarh, Ratighat, and Mukteshwar (i.e., in the *Outer* Lesser Himalaya of Ahmad et al., 2000; see Plate 1). He defined the fault as the structure that "has brought the Ramgarh Group of rocks over the Nagthat Formation of the Krol belt (MBT hanging wall)…." We observed the fault on a roadcut between Almora and Nainital, ~5 km west of the type area (Plate 1). North of Nainital (Fig. 3 and Plate 1), quartzites of the Nagthat Formation in the Ramgarh Thrust footwall are well exposed along the Kosi River (29°29′47.8″, 79°29′55.1″) and dip ~30º N (Fig. 3 and Plate 1). Although the Ramgarh Thrust plane is not exposed, its hanging wall is exposed ~200 m north of the quartzite exposure and consists of east-striking, nearly vertical, fine-grained, chlorite and biotite-rich schistose gneiss (Plate 1). Above the schistose gneiss unit at the base of the Ramgarh Thrust sheet is a sequence of alternating shale and turbidite. Although the contact between the two units is not exposed, geochemical results presented below indicate it to be depositional in a distal portion of a north-facing passive margin (e.g., Brookfield, 1993; Myrow et al., 2003).

Foliations and Bedding Facing Directions

Gneissic foliations at the base of the Ramgarh Thrust hanging wall in the *Outer* Lesser Himalayan Sequence zone are defined by the alignment of chlorite and biotite. The overlying slates and sandstones preserve spaced and crenulation cleavages similar to those observed in the Main Boundary Thrust hanging wall (Célérier, 2007). All occurrences of cross and graded bedding in turbidites of the *Outer* Lesser Himalayan Sequence indicate these sequences are right way-up. The gneissic rocks at the base of Valdiya's (1980a) Ramgarh Thrust hanging wall in the *Inner* Lesser Himalayan Sequence zone preserve similar foliations to those in the *Outer* Lesser Himalayan Sequence zone. Here, along the Mandakini River (Plate 1), retrogressed gneisses dip ~30º NE with biotite and muscovite defining the foliation. Although Valdiya (1980a) mapped phyllites in the Ramgarh Thrust hanging wall along the Mandakini River section, we found instead schistose gneisses.

Quartz Microstructures

Schistose gneisses at the base of the Ramgarh Thrust hanging wall contain recrystallized quartz grains indicative of *Regime-3* quartz dislocation creep. In contrast, overlying slates and sandstones (*Outer* Lesser Himalayan Sequence) preserve slightly flattened quartz grains with patchy, irregular extinction indicative of *Regime 1* (or potentially the lower end of *Regime 2*). Because the two rock units lie against each other in less than a couple of hundreds of meters, differences in deformation mechanisms are mostly likely induced by an increase in strain rate toward the Ramgarh Thrust below rather than by contrasting temperatures.

Tons Thrust and Hanging-Wall Structures

The Tons Thrust of Valdiya (1980a) demarcates the boundary between the *Inner* and *Outer* Lesser Himalayan Sequence zones of Ahmad et al. (2000). In the study area, the fault generally dips south and juxtaposes slate of the Chandpur Formation over quartzite and slate of the Rautgara Formation (Plate 1). The fault terminates at the western edge of the Almora klippe as the Almora Thrust overrides the Tons Thrust (Valdiya, 1980a). This relationship implies that the *Inner* and *Outer* Lesser Himalayan Sequence zones were juxtaposed along the Tons Thrust prior to emplacement of the Main Central Thrust sheet atop the Lesser Himalayan Sequence. The map relationship in Plate 1 also shows that the Almora Thrust cuts upsection southward across the older Chandpur Formation and the younger Nagthat Forma-

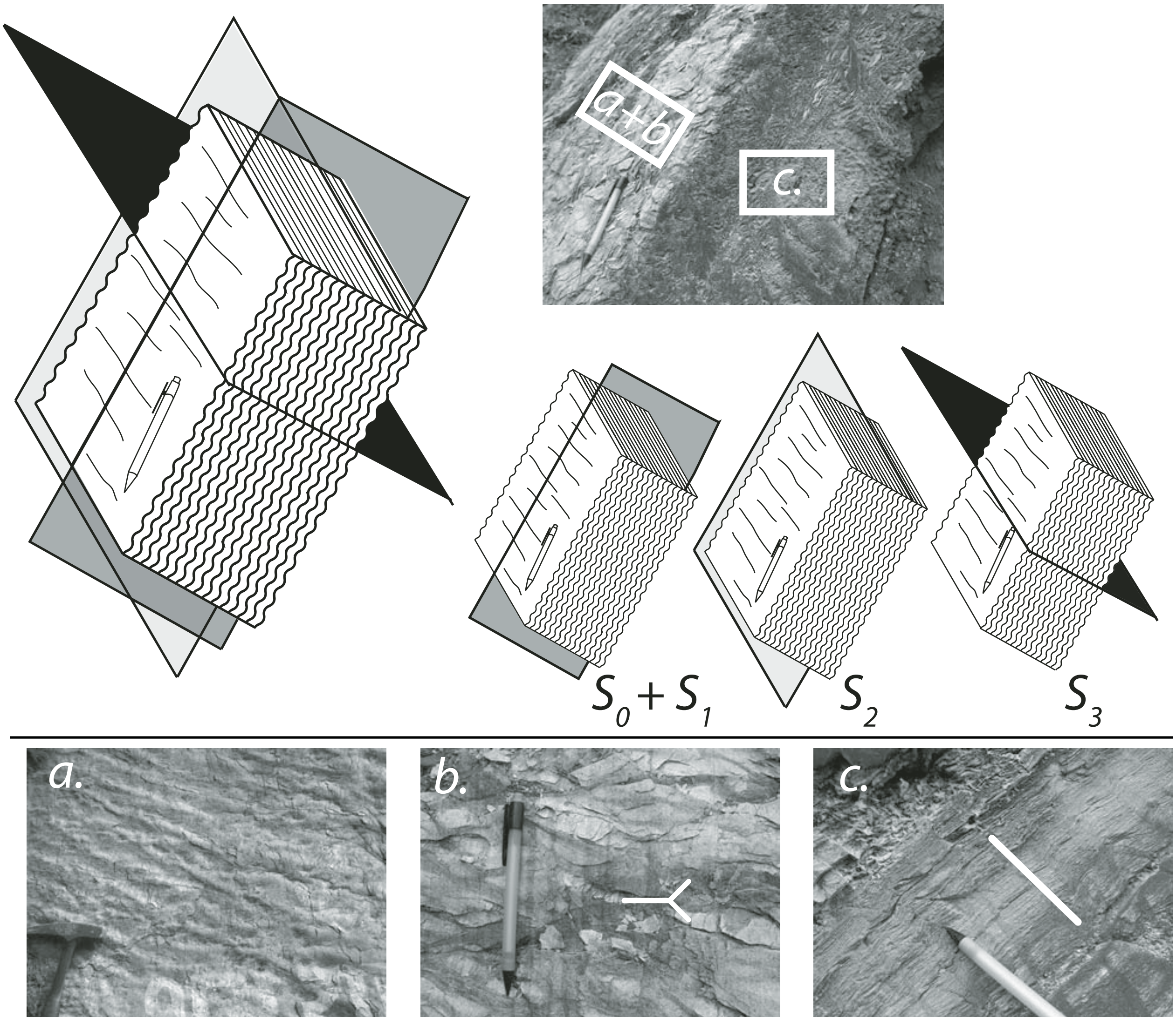


Figure 4. Foliation development from a key locality on the Bhagirathi River (30°27′11.4″, 78°25′10.7″). At this outcrop of Chandpur Formation slates, all four foliations seen in the Main Boundary Thrust hanging wall are preserved and can be related to one another. The upper part of the figure shows the outcrop in question and presents interpretative sketches highlighting overprinting relationships between foliations. The lower part of the figure shows photographs presenting aspects of foliation development. See letters in white boxes of upper photograph for the position of each of the three lower photographs. (A) Surface expression of the intersection of S_2 and S_3. The intersection of these two foliations superficially resembles current ripple marks. (B) Close-up view of (A) showing original sedimentary laminations within the slate (S_0) and S_1. The arrow indicates the direction of younging. (C) Detail of the reorienting of S_2 by S_3 crenulation cleavage. The white line indicates the axial surface of S_3.

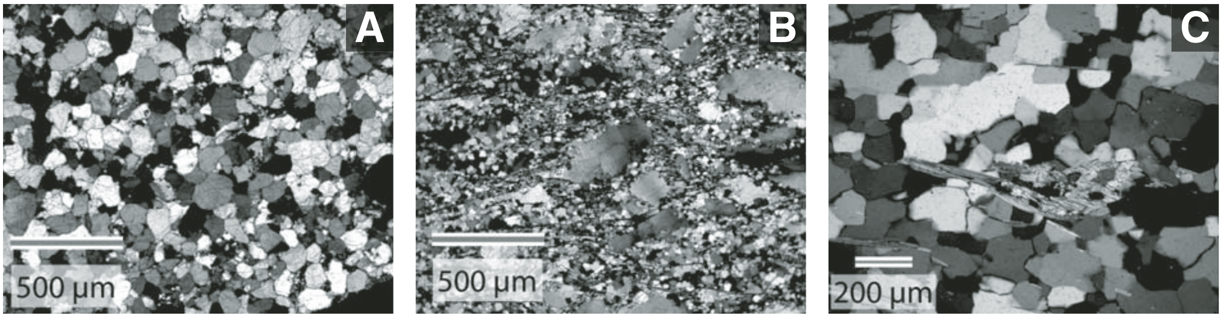
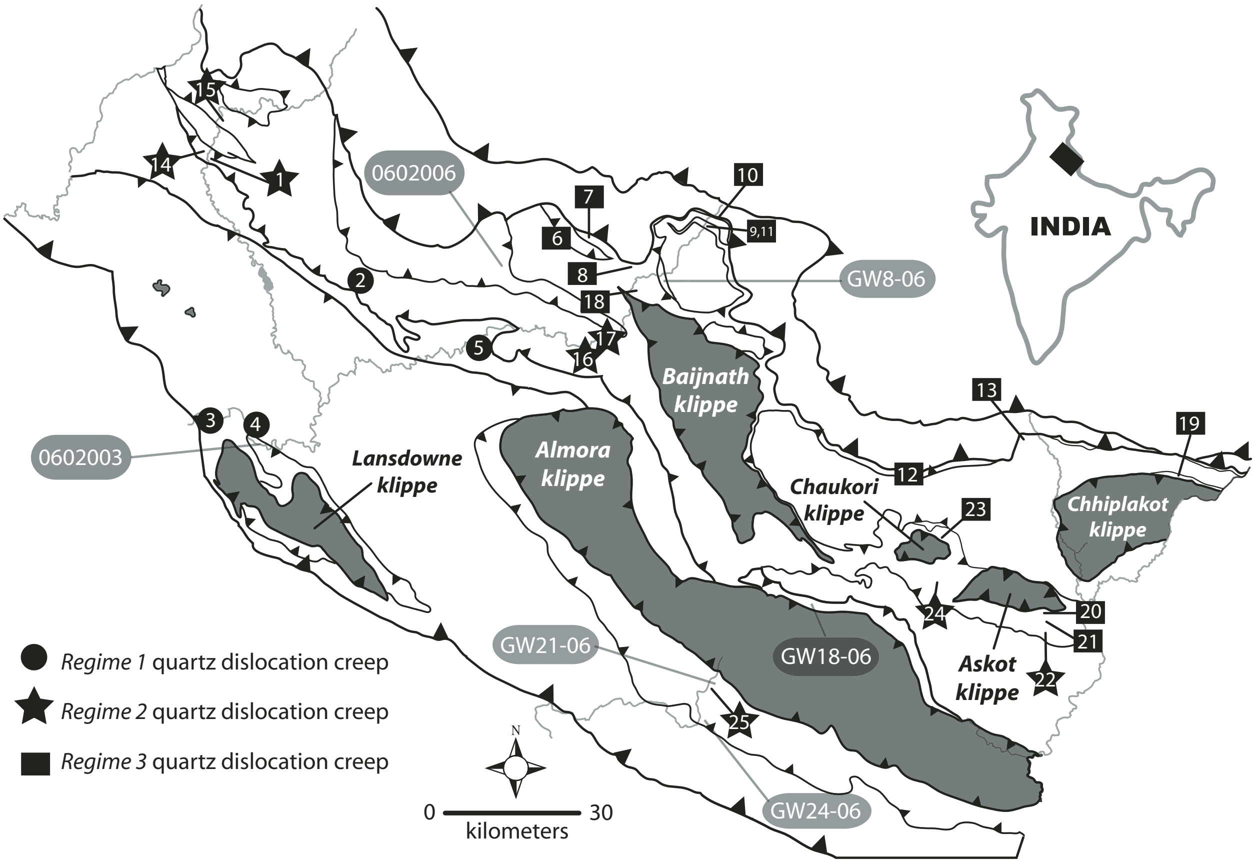


Figure 5. Representative photomicrographs of quartz microstructure evolution in Kumaun and Garwhal Lesser Himalayan Berinag Formation quartzites. (A) Undeformed quartzite displaying rounded detrital quartz grains typical of *Regime-1* quartz dislocation creep. (B) Flattened, highly strained, detrital quartz grains surrounded by a fabric of smaller recrystallized quartz grains typical of *Regime-2* quartz dislocation creep. (C) Recrystallized quartzite displaying *Regime-3* quartz dislocation creep comprising a homogeneous matrix of foam textured quartz.



1. GW29-03A	8 . GW70-03A	15. GW58-04	22. GW170-04
2. GW37-03A	9. GW75-03A	16. GW101-04	23. GW12-06
3. GW43-03A	10. GW86-03A	17. GW103-04	24. GW124-03A
4. GW45-03A	11. GW89-03A	18. GW107-04	25. AW4-04
5. GW56-03A	12. GW109-03A	19. GW164-04	
6. GW64-03A	13. GW121-03A	20. GW168-04	
7. GW65-03A	14. GW50-04	21. GW169-04	

Figure 6. Simplified geologic map of the Kumaun and Garwhal Lesser Himalayan Sequence annotated with results of the quartz dislocation creep study. See Célérier (2007) for photomicrographs of each of the samples shown on the map and listed from 1 to 25. Locations of samples investigated using U-Pb geochronology and geochemistry in this study are also shown.

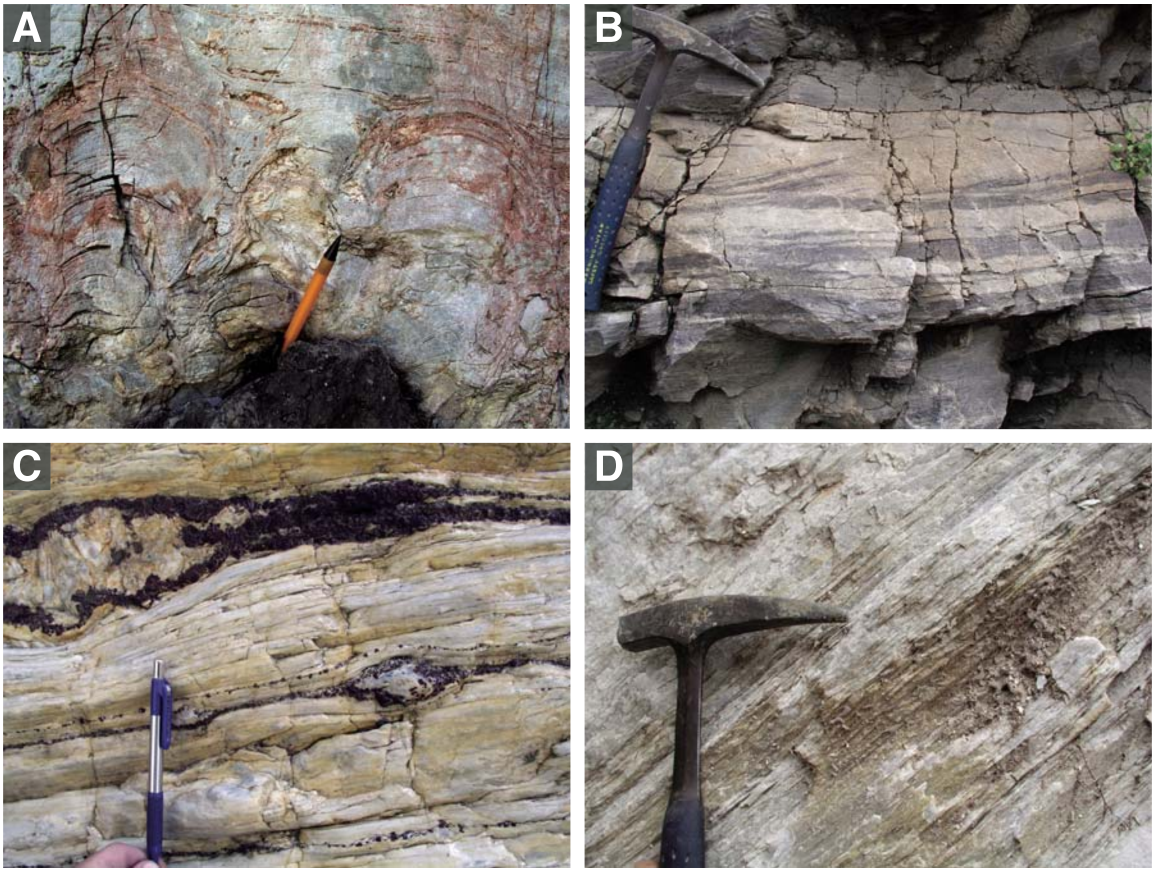


Figure 7. Representative examples of facing direction indicators and transitions in macroscopic deformation styles observed in the study area. (A) Undeformed stromatolites in Deoban Formation dolomites of the Berinag Thrust footwall (29º54′52.8″, 79º24′34.0″). (B) Cross beds in undeformed Nagthat Formation quartzites of the Main Boundary Thrust hanging wall (30º07′58.1″, 78º25′07.2″). (C) Mylonitized, magnesite-bearing Deoban Formation dolomite. (D) Mylonitized Berinag Formation quartzite adjacent to the Munsiari Thrust, Alaknanda River (30º31′32.3″, 79º30′38.7″).

tion. This suggests the presence of a footwall ramp for the Almora Thrust in the Tons Thrust hanging wall. The metasedimentary successions of the Tons Thrust hanging wall belong to the Krol Thrust Sheet of Valdiya (1980a) or the equivalent Main Boundary Thrust hanging wall referred to in this study.

Northwest of Tehri, between the towns of Bhaldiana and Dharasu along the Bhagirathi River (Plate 1), an ensemble of brittle faults marks the position (as mapped by Valdiya, 1980a) of the Tons Thrust (Fig. 8). Here (30°27′11.4″, 78°25′10.7″), five principal and numerous smaller faults cut the Lesser Himalayan Sequence strata (Fig. 8). Exposed in a roadcut (Fig. 8), the five slip zones dip ~60° SW and are parallel to the dominant S_2 foliation. The faults comprise 5- to 40-cm-thick gouge zones. We observed no obvious change in phyllite lithology or metamorphic grade across the fault, and the lack of clear offset marker beds prevents us from estimating the magnitude of fault slip, but the presence of asymmetric drag folds in the gouge zones suggests a top-northeast thrusting. It is not clear if the fault had an early south-directed history, as required by the juxtaposition of *Outer* and *Inner* Lesser Himalayan Sequence units across the fault, and was reactivated later as a north-directed thrust. We also observed the Tons Thrust along the Alaknanda River, where it is a sharply defined surface placing the Chandpur Formation over Rautgara Formation (Fig. 8 and Plate 1).

Berinag Thrust and Its Hanging-Wall and Footwall Structures

Berinag Thrust Zone

The Berinag Thrust juxtaposes lower over the upper *Inner* Lesser Himalayan Sequence strata (Plate 1). Gneisses and quartzites commonly occur at the base of the hanging wall, whereas dolomites and schist of the Deoban Formation typically occur directly below the fault. The thrust is folded into an antiform with large sections of the hanging wall being eroded away, creating thrust windows that expose footwall dolomites, schists, and slates (Plate 1). The uppermost Berinag Thrust hanging wall is cut by the Munsiari and Vaikrita Thrusts (Plate 1). Several klippen of the Main Central Thrust hanging wall are preserved overlying the Berinag Thrust hanging wall (Plate 1).

We observed the Berinag Thrust along the Alaknanda River between Pipalkoti and Helang (Plate 1). There, the fault dips ~35º NE and juxtaposes Berinag quartzite over Deoban dolomite (Fig. 9). A north-dipping mylonitic shear zone comprising kyanite-bearing quartzite with micaceous stretching lineations lies directly above the thrust. Dolomite and schist of the Deoban Formation directly below the thrust is also intensely mylonitized. S-C mylonitic fabrics in

Figure 8. Tons Thrust exposures in the study area. Main frame of photos shows details from an ensemble of brittle faults at the position of Valdiya's (1980) Tons Thrust, along the Bhagirathi River (30°27′11.4″, 78°25′10.7″). Inset photo at bottom right shows the Tons fault juxtaposing slates and quartzites along the Alaknanda River (30°14′23.1″, 78°49′29.7″).

the hanging and footwall shear zones all indicate top-south thrusting. We also observed the Berinag Thrust near Song and Loharket (Saryu River, Plate 1), where it dips ~35° NE and consists of mylonitic shear zones in the quartzite and schist and/or dolomite directly above and below the fault. Similar to the Alaknanda River exposure, S-C fabrics in the shear zones all suggest top-south thrusting.

Foliations in the Hanging Wall

Structural fabrics in the Berinag Thrust hanging wall change systematically from lower to higher structural levels. At lower structural levels the internal sedimentary structures of thick quartzite beds (30–50 cm) are preserved, but weak mineral stretching lineations, as defined by chlorite and white mica, are developed along bedding interfaces. We also observed elongate (~2 mm) quartz grains in hand specimen. With increasing proximity to the Munsiari and sole thrusts of the various klippen, the quartzite beds progressively lose the original sedimentary structures, and foliations, defined by preferred orientations of white mica, become pervasive. Quartzite samples from within <5 km of the Munsiari Thrust are strongly mylonitized with down-slip, stretching mineral lineation (Fig. 7).

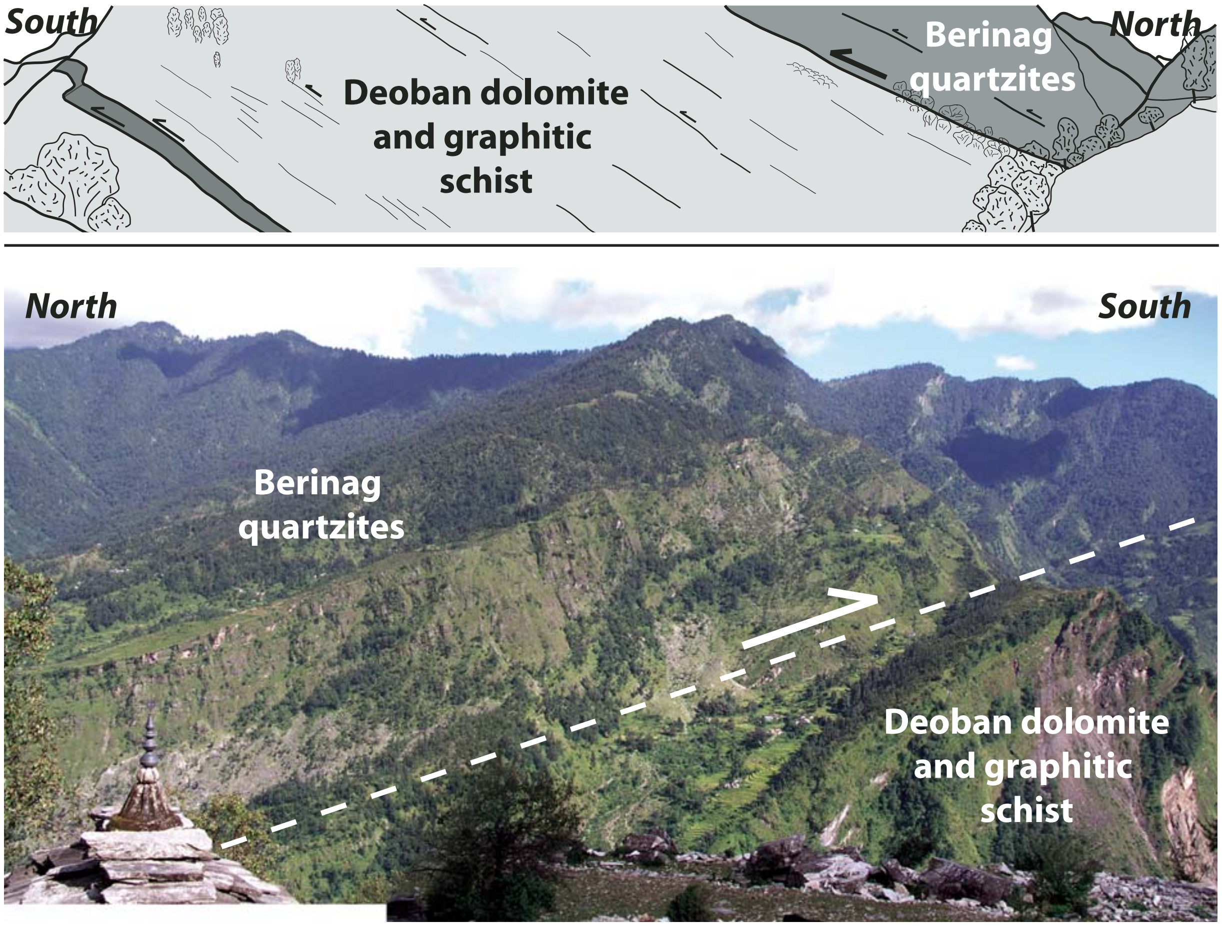


Figure 9. Exposures of the Berinag Thrust in Kumaun and Garwhal Himalaya. Top panel shows relationships along the Alaknanda River, between the towns of Pipalkoti and Helang. Lower panel presents a photo mosaic taken from the village of Loharket (Plate 1), looking southeast across the Saryu River valley toward a spectacular exposure of the Berinag Thrust.

Consistent with antiformal folding of the Berinag Thrust, foliations in the hanging wall are warped accordingly.

Foliations in the Foot Wall

Unlike quartzites of the hanging wall, the Deoban and Mandhali Formations are of suitable composition for the preservation of multiple foliations, which are often refolded and highly variable in orientation. Southern exposures of the Berinag Thrust footwall (adjacent to the Tons Thrust) preserve slaty cleavages at moderate to low angles to bedding. At these southerly footwall exposure levels, three foliations in addition to bedding (S_0) were identified at most outcrops: S_1 is a bedding-parallel slaty cleavage; S_2 is also a slaty cleavage at moderate to high angles to bedding and is the dominant fabric at most outcrops. An S_3 crenulation cleavage often reorients S_2. Slaty cleavages evolve to the north as the rocks acquire schistosities defined by chlorite and white mica. Outcrops within ~5 km of the Munsiari thrust are penetratively sheared and mylonitized with chlorite and white mica defining mineral stretching lineations.

Quartz Microstructures

In the hanging wall of the Berinag Thrust, *Regime-1* microstructures are preserved in the frontal part of the thrust sheet along the Alaknanda River. Samples in close proximity to the leading edge of the Berinag Thrust are characterized by nonrecrystallized detrital quartz grains with patchy, undulose extinction under cross-polarized light. Minor detrital muscovite, biotite, zircon, and apatite grains also exist in these samples (Célérier, 2007). At a higher structural level to the north, *Regime-2* microstructures are encountered near Dharasu and Karanprayag along the Bhagirathi and Alaknanda Rivers (Fig. 6; Plate 1).

In eastern Kumaun, *Regime-2* microstructures exist at the leading edge of the Berinag Thrust hanging wall, north of Pithoragarh (Fig. 6 and Plate 1). In central and eastern Kumaun, there is a northward transition toward fully recrystallized quartz grains characteristic of *Regime 3* (Fig. 6). Samples of Berinag quartzite near the basal thrust of the Baijnath, Chaukori, Askot, and Chhiplakot klippen all display *Regime-3* microstructures (Fig. 6). The situation in western Garwhal along the Bhagirathi River is quite different, where all thin sections show only partial recrystallization of quartz—characteristic of *Regime-2* style of dislocation creep (Fig. 6).

Our microstructural observations of quartz texture suggest that the deformation condition changes from *Regime 1* to *Regime 3* with an increase in structural proximity to the Main Central Thrust hanging wall. This relationship is illustrated most clearly from samples we collected directly beneath the Askot and Chaukori klippen in eastern Kumaun (Fig. 6). There, samples GW168-04 and GW12-06 (taken close to the upper- to lower-plate interface of the Main Central Thrust hanging wall) display

Regime-3 quartz microstructures. Sample GW169-04, ~3 km south of the basal thrust of the Askot klippe, also displays *Regime-3* quartz microstructure. Farther south, ~3 km from sample GW169-04, sample GW170-04 preserves only partial recrystallization, characteristic of *Regime-2* quartz dislocation creep. Sample GW124-03A is ~10 km south of the Chaukori klippe and, like GW170-04, preserves *Regime-2* quartz microstructures.

Rocks of the Beringag Thrust footwall are largely unsuitable for the application of the quartz dislocation creep method.

Folds and Folding Styles

Folding style changes systematically from south to north in the Berinag Thrust hanging wall. In the south, beds are gently folded exhibiting parallel-fold geometry and preserving original sedimentary bedding and sedimentary structures. The latter indicates that the facing direction of beds is upright. Northward toward the Munsiari Thrust (and the faults at the base of the Main Central Thrust klippen), original sedimentary bedding is progressively replaced by mylonitic fabrics associated with an increase in the tightness of folds. Accordingly, sedimentary structures required for interpreting the facing directions are mostly absent in these regions. In the Berinag Thrust footwall, parallel and chevron folds are typically open to tight with interlimb angles of between ~100° and ~30° in the vicinity of the Tons Thrust. With an increase in proximity to the Munsiari Thrust and the sole thrusts of the Main Central Thrust klippen, folding intensity increases where, in some cases, pelite or carbonate beds are tight to isoclinally folded with shortening strain >300% (Célérier, 2007).

U-PB GEOCHRONOLOGY

Attempts to reconstruct the geologic evolution of the Himalaya have been hampered by the lack of age constraints on much of the Proterozoic fossil-absent Lesser Himalayan Sequence metasedimentary strata. This problem makes it difficult to unravel the structural relationships across major faults in the Lesser Himalayan Sequence and thus their kinematic history. For example, the age uncertainty of the Berinag Formation led Srivastava and Mitra (1994) to reinterpret the Berinag Thrust of Valdiya (1980a) as having normal-sense kinematics. The controversy was resolved when the Berinag Formation was dated by Miller et al. (2000), indicating that the fault is a thrust placing older over younger strata.

Chronostratigraphic studies of the Lesser Himalayan Sequence west and east of our study area (Parrish and Hodges, 1996; DeCelles et al., 2000; Miller et al., 2000; DeCelles et al., 2001; Myrow et al., 2003; Richards et al., 2005) have significantly improved our current understanding of the Lesser Himalayan Sequence. Dating interlayered volcanic horizons and gneisses in the Lesser Himalayan Sequence provides absolute age constraints for igneous components of the Lesser Himalayan Sequence, while dating detrital zircons from the Lesser Himalayan Sequence clastic sediments provides minimum age constraints for the age of sedimentation. Despite these utilities, systematic U-Pb zircon geochronology has not been carried out in the Kumaun and Garwhal Himalaya. In this study, we focus on the geochronology of the Ramgarh Group, because it is a common unit in Valdiya's (1980a) *Inner* and *Outer* Lesser Himalayan Sequence zones, making it possible to address how the two stratigraphic sequences are related (Valdiya, 1980a; Srivastava and Mitra, 1994; Ahmad et al., 2000). Knowing the age of the Ramgarh Group also allows us to (1) determine the contact nature between the basal gneissic and overlying metasedimentary units in the Ramgarh Group and (2) correlate the Ramgarh Thrust along strike from Kumaun to far-west Nepal, where the same structure was extensively studied (DeCelles et al., 2001; Robinson et al., 2003, 2006; Martin et al., 2005; Pearson and DeCelles, 2005).

Analytical Approach and Sample Selection

U-Pb zircon geochronology was applied to sedimentary rocks of the Ramgarh Group and schistose gneisses at the base of Lesser Himalayan Sequence thrust sheets. In order to compare our results with the age of the Lesser Himalayan Sequence in Nepal to the east, we also conducted U-Pb zircon dating of the well-known Ulleri augen gneiss in central Nepal. Locations of all samples described below are indicated in Figure 6 and documented in Table 1. Analytical methods used in this study are similar to those in Williams (1998) and Célérier (2007). Detailed results of U-Pb zircon analyses for the samples discussed below are tabulated in GSA Data Repository Table DR1[2] accompanying this study.

Results

Detrital Zircon Dating

Valdiya (1980a) considered the metasedimentary rocks of the Ramgarh Group to be allochthonous and different from all of the Lesser Himalayan Sequence units. To assess this interpretation, we analyzed detrital zircons from two sandstone samples (0602003 and GW18-06) belonging to Valdiya's Ramgarh Group. As shown below, the detrital zircon age distribution and age range of the metasediments in the Ramgarh Group are similar to the Chandpur Formation of the Lesser Himalayan Sequence. For this reason, we do not include Ramgarh metasediments as part of the Ramgarh Group but instead reassign them to the Chandpur Formation (Plate 1). Below we describe the detrital-zircon dating results.

Detrital zircons from sample GW18-06 (Rautgara Formation in Valdiya, 1980a) and sample GW21-06 (Ramgarh Group in Valdiya, 1980a) have 800-Ma zircons and clusters at ca. 2500 Ma and ca. 1800 Ma (Fig. 11). The shared age distribution and similar lithology suggests that the two samples and the units they represent are correlative. Because the Rautgara Group is >970 Ma (Richards et al., 2005), the presence of ca. 800-Ma zircons is inconsistent with Valdiya's (1980a) assignment to the Rautgara Formation. Rather, the ca. 800-Ma minimum age and lithological similarities suggest sample GW18-06 to be part of the Chandpur Formation (Plate 1). The presence of Deoban Formation dolomites, unique in the *Inner* Lesser Himalayan Sequence, east of sample GW18-06 (Plate 1), suggests that both *Inner* and *Outer* Lesser Himalayan Sequence lithologies are present below the northern limb of the Almora klippe.

Sample 0602003 was collected from the Chandpur Formation (our assigned unit in contrast to Valdiya [1980a]; same for all samples discussed below) (Figs. 6 and 10 for location). We obtained 102 spot analyses from the sample that yield concordant ages between 800 Ma and 2580 Ma with a dominant cluster at 800–1000 Ma (i.e., 87% of the analyzed zircons fall in this range) (Fig. 10). The analyzed zircons are largely concordant, with the few discordant grains not defining coherent mixing lines (Fig. 10). Th/U ratios of the analyzed zircons are mostly >0.1 (in general, Th/U >0.1 indicates magmatic origin, whereas Th/U <0.1 indicates metamorphic origin; see Williams and Claesson, 1987; Rubatto and Gebauer, 2000; Hoskin and Schaltegger, 2003).

Sample GW18-06 was collected from the Chandpur Formation immediately below the Almora Thrust (Figs. 6 and 10). We obtained 110 spot analyses from the sample that yield concordant ages between 810 Ma and 3290 Ma (Fig. 10). About 10% of the analyses yield discordant results with a mixing line (defined by 10 grains) from ca. 1800-Ma grains trending toward the zero age. The relative age probability plot (Fig. 10) shows distinct age peaks at ca. 1800 Ma and ca. 2500 Ma. A less significant age peak is at ca. 900 Ma defined by four grains.

[2]GSA Data Repository item 2008254, geochronological and geochemical data tables, is available at http://www.geosociety.org/pubs/ft2008.htm or by request to editing@geosociety.org.

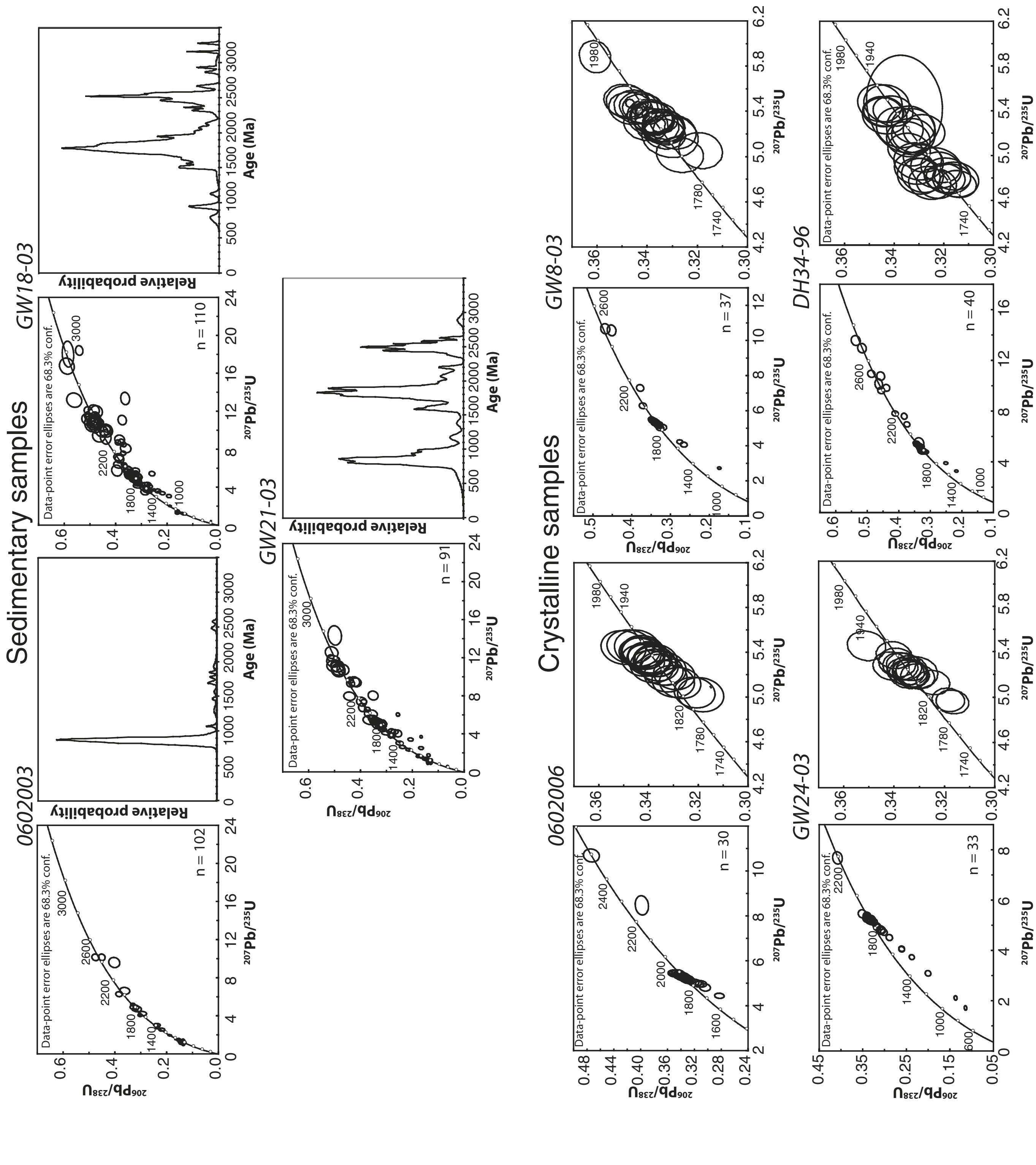


Figure 10. Montage of concordia diagrams and relative age probability plots for samples investigated by the U-Pb geochronologic method. Conf.—confidence.

TABLE 1. SUMMARY TABLE OF U-PB AND GEOCHEMISTRY RESULTS

Sample name	Sample description	Locality	Assigned age
0602003	Thickly bedded, massive sandstone	30°04′13.9″N 78°27′58.4E 454 m	ca. 800 Ma [D]
0602006	Retrogressed, schistose gneiss	30°23′18.8″N 79°00′91.1″E 832 m	1868.3 ± 7.3 Ma [C]
GW8-06	Retrogressed schistose gneiss	30°24′38.9″ 79°21′54.7″ 1043 m	1865.0 ± 3.1 Ma [C]
GW18-06	Thick sandstone bed within package of turbidites	29°45′30.1″ 79°46′38.2″ 426 m	ca. 800 Ma [D]
GW21-06	Coarse-grained sandstone within package of dominantly silty turbidites	29°32′59.3″ 79°32′92.5″ 1048 m	ca. 800 Ma [D]
GW24-06	Green, retrogressed, schistose gneiss	29°29′85.8″ 79°30′17.6″ 914 m	1856.3 ± 9.6 Ma [C]
DH34-96	Augen gneiss	See Colchen et al. (1986)	1800 and 1880 Ma [C]

D—Minimum age of deposition assigned through detrital zircon geochronology.
C—Concordia age assigned to protoliths of gneissic samples.

We consider the 900-Ma peak to represent a significant igneous event because of the concordancy of the zircon age plots, low common Pb values, and spot positions that preclude the ages to represent secondary zircon growth, and Th/U ratios overwhelmingly greater than 0.1.

Sample GW21-06 was collected from the Chandpur Formation in the hanging wall of the Ramgarh Thrust (Figs. 6 and 10). We obtained 91 spot analyses that yield concordant ages between 770 Ma and 2890 Ma (Fig. 10). The great majority of analyses are concordant, although mixing lines between clusters of concordant ages at ca. 1800 Ma and ca. 2600 Ma trend toward an 800-Ma age. The detrital zircon ages cluster at ca. 800 Ma, 1800 Ma, and ca. 2500 Ma (Fig. 10). All spot analyses yield Th/U >0.1, indicating their igneous origin.

Schistose Gneiss Samples

Sample 0602006 was collected from a unit at the base of the Berinag Thrust sheet along the Mandakini River (Figs. 6 and 10). We obtained 30 spot ages from the sample, 24 of which cluster at 1868.3 ± 7.3 Ma (mean square of weighted deviates [MSWD] = 0.56), while the other six ages are normally discordant, suggesting a mixing line with a Tertiary Pb loss event. Ion-probe transects across several grains revealed no age difference from rim to core. Th/U ratios for the large majority of grains were >0.1, but five analyses yielded Th/U ratios <0.1. We obtained a single concordant zircon age at 2490 Ma in the core of a grain, indicating the presence of a Late Archean component in the protolith.

Sample GW8-06 was collected from the base of the Berinag Thrust in the north-central study area (Figs. 6 and 10). We obtained 37 spot ages from the sample that largely cluster (n = 29) at a concordant age of 1865.0 ± 3.1 Ma (MSWD = 0.17) (Fig. 10). Four analyses yield ages from 1870 Ma to 2554 Ma. Thirty-two of the 37 analyses have Th/U >0.1, indicating an igneous origin for the schistose gneiss.

Sample GW24-06 was collected from a large schistose gneiss unit in the hanging wall of the Ramgarh Thrust, close to its type location (Figs. 6 and 10). We obtained 33 spot ages from the sample, of which 17 concordant results cluster at 1856.3 ± 9.6 Ma (MSWD = 0.24) (Fig. 10). An additional 12 analyses define a Pb-loss discordia, and a single concordant age of 2182 Ma was obtained from one zircon core. All zircons yield Th/U >0.1.

Sample DH34-96 was collected in the Ulleri gneiss, Nepal (Fig. 2), which is exposed along the Darondi River ~10 km east of its type locality near the town of Ulleri (Colchen et al., 1986). We obtained 40 spot analyses that yield an age spread of 1730 Ma to 2680 Ma and a dominant clustering between 1750 and 1900 Ma. While ages at the older or younger extremes could be due to inheritance and Pb loss, respectively, this large spread of concordant analyses is challenging to interpret as the data appear to define a continuum rather than a spread about a central tendency. Thus, assigning an average age is deemed inappropriate, and two alternative interpretations are explored here. The first is that the spread results from a Pb-loss event within ca. 100 Ma following crystallization at ca. 1880 Ma. The second is that the spread results from two (or more) distinct, but temporally close, zircon crystallizing episodes with each event characterized by a statistically distinguishable range of ages near concordia. A ca. 30-Ma age spread associated with each crystallization episode would result in populations derived from two distinct zircon growth events defining the suite of ages along concordia (Fig. 10). We note that analyzed zircons are not characterized by particularly high U contents (i.e., <1000 ppm for ~75% of the grains) that would enhance the likelihood of zircons becoming metamict within ca. 100 Ma of formation (see Table DR1 [footnote 2]). Consequently, our tentative interpretation is that the large age spread results from the overlap of two periods of zircon growth at ca. 1800 Ma and ca. 1880 Ma. This hypothesis can potentially be tested using depth-profile methods (e.g., Mojzsis and Harrison, 2002).

GEOCHEMISTRY

The Ramgarh and Ulleri Group samples analyzed by U-Pb zircon dating are fine grained and highly altered, making the identification of their protoliths difficult. To overcome this problem, we obtained the chemical composition of the samples (see Table DR1 [footnote 2], Fig. 6, and Célérier [2007] for analytical details). Major- and trace-element results indicate the samples to have been derived from highly evolved continental crust. All four samples plot within the granitic field of a Quartz-Alkali Feldspar-Plagioclase (QAP) diagram. The trace-element patterns show absolute elemental abundances and "spider-diagram" patterns indicative of crystalline continental crust (Fig. 11). While three of the samples show similar geochemical characteristics, sample 0602006 is significantly richer in silica and thus suggests a higher degree of metasomatic alteration. The granitic compositions are consistent with the view that the Ramgarh and Ulleri schistose and augen gneisses represent the continental basement onto which the Lesser Himalayan sedimentary succession was deposited. In the case of the proximal *Inner* Lesser Himalayan Sequence, the Berinag Formation was the oldest sequence over the crystalline basement, while for the distal *Outer* Lesser Himalayan Sequence, sediments of the Chandpur Formation were the oldest deposits on top of the basement. Furthermore, compositional similarities between the Ramgarh and Ulleri augen gneiss samples lend support to the correlation of the two units as part of the Lesser Himalayan Sequence basement along strike of the Himalayan orogen.

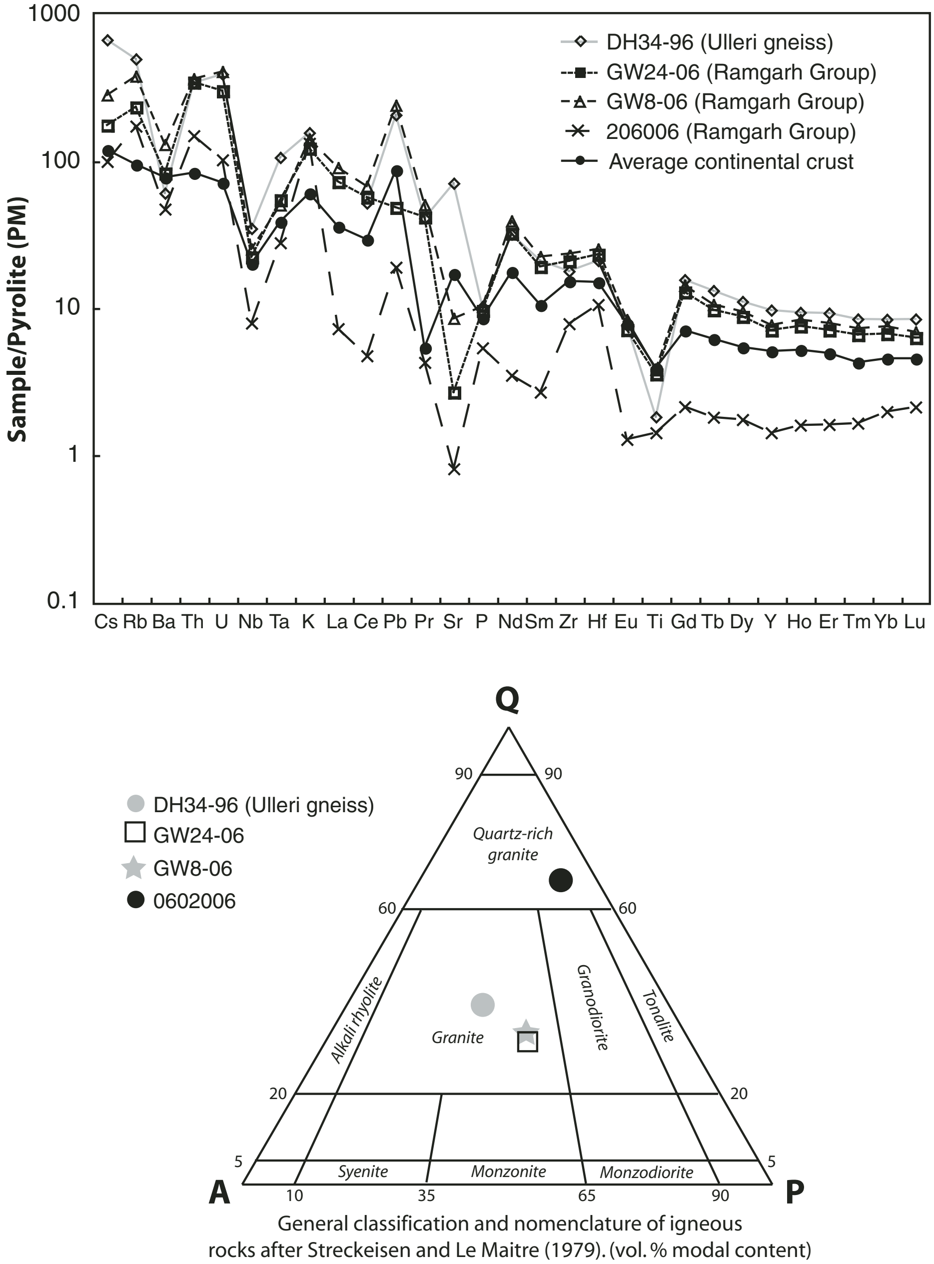


Figure 11. Results of the geochemical study. Upper image presents primitive-mantle (PM), normalized trace-element patterns for the Ramgarh Group and Ulleri Group schistose and gneissic samples. Also plotted is a primitive-mantle, normalized average continental crust. Taken from the GERM compilation (http://earthref.org/). Lower image presents a Quartz-Alkali Feldspar-Plagioclase (QAP) diagram generated using whole-rock, major-element data from the Ramgarh Group and Ulleri Group schistose and gneissic samples. CIPW norms were calculated for each sample and the results projected onto the diagram. All four samples plot within the field of granitic lithologies.

DISCUSSION

Spatial Variation of Deformation Styles in Main Central Thrust Footwall

Our structural observations suggest that deformation of the Main Central Thrust footwall across the *Inner* Lesser Himalayan Sequence zone is characterized by broad folds, slaty cleavage, and *Regime-1* quartz microstructure at lower structural levels. At higher structural levels toward the Main Central Thrust, deformation is expressed by replacement of sedimentary bedding by penetrative foliation, tight and even overturned folds, and *Regime-2* or *Regime-3* quartz microstructures. While the above transition is evident in the *Inner* Lesser Himalayan Sequence, deformation style and associated fabric development in the *Outer* Lesser Himalayan Sequence are largely homogeneous and characterized by *Regime-1* quartz microstructures (Fig. 6). The above difference suggests that the *Inner* and *Outer* Lesser Himalayan Sequence zones were deformed under different temperature and strain-rate conditions, which can be quantified by correlating our observed quartz microstructures with the corresponding experimental conditions.

Hirth and Tullis (1992) showed that the transition from *Regime-1* to *Regime-3* quartz dislocation creep is driven by thermally activated dislocation climb, which begins to occur under laboratory conditions of ~450 ºC. The spatial association of *Regime-3* quartz microstructures with proximity to the Main Central Thrust hanging wall suggests that the Main Central Thrust hanging wall is the source of heat driving quartz recrystallization in the footwall. The lack of quartz recrystallization in the *Outer* Lesser Himalayan Sequence south of the Tons Thrust suggests that the base of the Main Central Thrust hanging wall is significantly cooler (and thinner?) above the *Outer* Lesser Himalayan Sequence than that above the *Inner* Lesser Himalayan Sequence.

Our study also reveals along-strike variation of quartz microstructures in the Main Central Thrust footwall, which is best expressed in the uppermost sections of the Berinag Thrust sheet, immediately below the Munsiari Thrust (Fig. 6). In the east along the Alaknanda River, quartz microstructures belong to *Regime 3,* while in the west along the Bhagirathi River, quartz microstructures mostly belong to *Regime 2* (Fig. 6). This implies that temperature and/or strain-rate gradients also existed along strike of the Main Central Thrust hanging wall during Cenozoic contraction. In the companion paper (Célérier, 2007), thermochronologic and paleothermometric data are used to further quantify the deformation conditions inferred from the observed quartz microstructures.

Chronostratigraphy of Lesser Himalayan Sequence in Kumaun and Garwhal

Detrital zircon ages obtained from samples in the basal unit of the *Outer* Lesser Himalayan Sequence suggest that their depositional ages must be younger than 770–810 Ma. Schistose gneisses at the base of Lesser Himalayan Sequence thrust sheets in both the *Inner* and *Outer* Lesser Himalayan Sequence yield an age range of 1856 to 1868 Ma. Age constraints from this study as well those from Miller et al. (2000) and Richards et al. (2005) indicate that these schistose and augen gneisses are ca. 60 Ma older than the oldest sedimentary rocks of the *Inner* Lesser Himalayan Sequence and nearly 1000 Ma older than the oldest unit of the *Outer* Lesser Himalayan Sequence. Accordingly we interpret the schistose gneisses as basement to the Lesser Himalayan Sequence. The above observations suggest that thrusting in the Kumaun and Garwhal Lesser Himalayan Sequence involves basement most likely belonging to the Indian craton.

Detrital zircons in sample GW18-06 from the Rautgara Formation of Valdiya (1980a) and in sample GW21-06 from the Ramgarh Group of Valdiya (1980a) have 800-Ma zircons and clusters at ca. 2500 Ma and ca. 1800 Ma (Fig. 10). The shared age distribution and similar lithology suggest that the two samples and the units they represent are correlative. Because the age of the Rautgara Formation is >970 Ma (Richards et al., 2005), the presence of ca. 800-Ma zircons is inconsistent with Valdiya's (1980a) assignment. Rather, the unit from which sample GW18-06 was collected belongs to the Chandpur Formation (Plate 1). In light of aforementioned stratigraphic correlation, particularly the reassigning of Ramgarh Group metasediments to the Chandpur Formation, we suggest that the term Ramgarh Group should only be used in reference to the schistose gneisses exposed at the base of the various Lesser Himalayan thrust sheets. These crystalline rocks are distinguished by zircon crystallization ages of ca. 1860 Ma in their protoliths and geochemistry that is indicative of evolved continental crust.

The above stratigraphic correlation has two structural implications. First, the Ramgarh Thrust cannot be a major tectonic boundary separating two distinctively different stratigraphic sections as envisioned by Valdiya (1980a). Instead the thrust simply repeats units of the *Outer* Lesser Himalayan Sequence. Second, our refined stratigraphy simplifies the interpreted map pattern in the Kumaun and Garwhal Himalaya. For example, the presence of the Ramgarh Thrust north of the Tons Thrust based purely on the stratigraphic argument by Valdiya (1980a) is no longer required. Instead, Valdiya's (1980a) Ramgarh Thrust north of the Tons Thrust is better interpreted as the Berinag Thrust that places 1860-Ma schistose gneiss and Berinag quartzite over younger *Inner* Lesser Himalayan Sequence units (Plate 1). In the case of the *Inner* Lesser Himalayan Sequence, this reassignment is justified on the basis that where Valdiya (1980a) mapped Ramgarh Group sedimentary rocks, we encountered the highly distinctive Berinag Formation quartzites of the regular *Inner* Lesser Himalayan Sequence stratigraphy. The above interpretation implies that only the thrust that lies directly below the southern limb of the Almora klippe should be called the Ramgarh Thrust, where it places schistose gneiss and Chandpur Formation turbidites over younger *Outer* Lesser Himalayan Sequence units (Plate 1).

Geometry of the Ramgarh Thrust

Our new age constraints on Lesser Himalayan Sequence units allow us to examine geometric variation of the Ramgarh Thrust along strike from Kumaun to Nepal. In Kumaun, Valdiya (1980a) suggests different lithologic units below the northern and southern limbs of the Almora/Dadeldhura klippe, which implies that the Almora thrust truncates the footwall units as an out-of-sequence thrust (Plate 1). In contrast, the Ramgarh Thrust has the same lithologic unit in its footwall in Nepal (DeCelles et al., 2001), permitting the fault to be an in-sequence thrust developed synchronously with the footwall thrusts. The age of the Ramgarh Thrust hanging-wall units in Kumaun also differs drastically from those in Nepal. As shown in our study, metasedimentary rocks in the Ramgarh Thrust hanging wall must be <800 Ma. In contrast, the Ramgarh Thrust hanging wall in Nepal consists of the Paleoproterozoic Kushma and Ranimata Formations deposited at 1860–1830 Ma (DeCelles et al., 2000). The above comparison suggests that the Ramgarh Thrust cuts upsection westward along strike from Nepal to Kumaun. Because the geometric relationship in Kumaun suggests the Ramgarh Thrust postdates tilting of the Lesser Himalayan Sequence units, kinematic models for the evolution of the thrust should consider the geologic relationships observed both in Kumaun and Nepal. That is, the simple thrust model advocating southward younging of thrusting by DeCelles et al. (2001) and Robinson et al. (2003, 2006) may need to be revised.

The Ramgarh Thrust adjacent to the MCT I in western Nepal (Pearson and DeCelles, 2005) shares many similarities in structural position and hanging-wall and footwall lithologies to the Berinag Thrust in Kumaun (Valdiya, 1980a, p. 124; also see Plate 1). First, the Ramgarh Thrust of Pearson and DeCelle (2005) is located directly below the MCT I, similar to the Berinag Thrust in Kumaun and Garwhal immediately below the Munsiari Thrust. Second, in each of the examples cited in Pearson and DeCelles (2005) for the hanging-wall lithologies, cross-bedded orthoquartzites and phyllites are similar to the cross-bedded quartzites in the Berinag Thrust hanging wall but drastically different from the slate of the Chandpur Formation in the Ramgarh Thrust hanging wall in Kumaun and Garwhal. Because Valdiya (1980a) defined the type locations of both the Ramgarh and Berinag Thrusts (which form the basis for our own observations) in the region of the present study, we interpret the Ramgarh Thrust of Pearson and DeCelles (2005) in the proximal footwall of the MCT I and Munsiari Thrust as the Berinag Thrust.

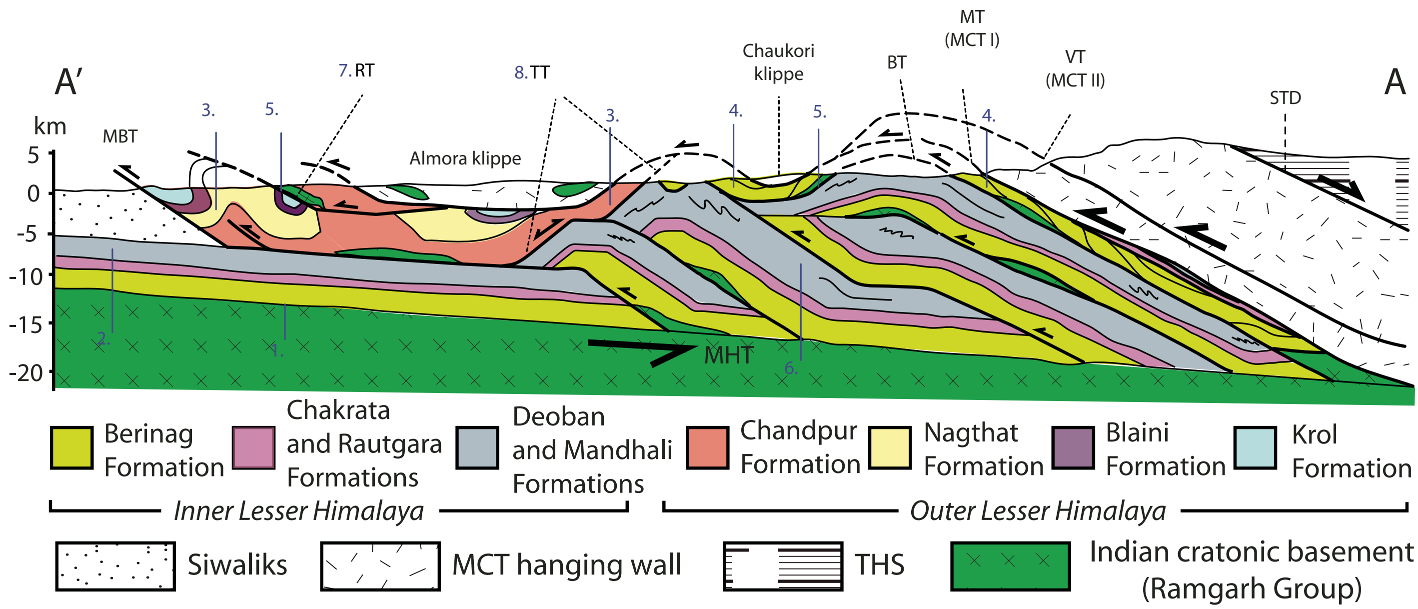
CROSS-SECTION AND KINEMATIC EVOLUTION

Cross-Section Construction

A schematic cross section is constructed mainly based on the projection of map relationships in Plate 1 that show: (1) the Tons Thrust merges (or truncates) upward with the combined Almora-Ramgarh Thrust; (2) the Ramgarh Thrust merges upward with the Almora Thrust, and the combined Almora-Ramgarh Thrust at the western end of the Almora klippe cuts upsection across *Outer* Lesser Himalayan Sequence units in the footwall; and (3) the Ramgarh Thrust truncates a tight syncline involving the Blaini and Krol Formations in its footwall at the southeast edge of the Almora klippe (Fig. 12). In the cross section, we diagrammatically show a change in deformation style from parallel folding to intense development of foliation in the *Inner* Lesser Himalayan Sequence toward the Main Central Thrust. We interpret the ca. 1850-Ma schistose gneiss slivers as representing continental basement of India. Consistent with the relationship shown in Plate 1, we depict the Tons Thrust juxtaposing the *Inner* and *Outer* Lesser Himalayan Sequence units.

Kinematic Reconstruction

Below, we present a possible tectonic history of the Kumaun and Garwhal Himalaya (Fig. 13). The Lesser Himalayan Sequence was deposited in a marine setting along the northern Indian passive margin from the Paleoproterozoic to Early Cambrian (e.g., Rupke, 1974; Valdiya, 1980a; Brookfield, 1993; Srivastava and Mitra,



MBT—Main Boundary Thrust, RT—Ramgarh Thrust, TT—Tons Thrust, BT—Berinag Thrust, MCT—Main Central Thrust, MT—Munsiari Thrust, VT—Vaikrita Thrust, STD—South Tibetan Detachment, MHT—Main Himalayan Thrust, THS—Tethyan Himalayan Sequence.

1. Depth and angle of MHT is consistent with INDEPTH (Hauck et al., 1996).
2. Siwalik Group foreland basin sediments lie atop Proterozoic carbonates (Valdiya, 1964; Valdiya, 1969; Srikantia and Bhargava, 1976; Raha and Sastry, 1979; Singh, 1979; Thakur, 1981; Srivastava and Mitra, 1994)
3. Rocks of the *Outer* LHS are uniformly deformed in a brittle (upper-crustal) style.
4. Proximal MCT footwall rocks of the *Inner* LHS are deformed in a ductile (mid-crustal) style.
5. Ramgarh Group crystallines (characterized by a ca. 1860-Ma protolith age) sole the various LHS thrust sheets.
6. *Inner* LHS thrust sheets required to fill space in duplex.
7. The Ramgarh Thrust is a structure of relatively minor importance juxtaposing two panels of *Outer* LHS lithologies.
8. Chronostratigraphic arguments require that the root zone of the Tons Thrust lies in the THS. The geometry of the Tons Thrust has been altered by *Inner* LHS duplex development following southward translation of the *Outer* LHS.

Figure 12. Schematic cross section through the Kumaun Himalaya (A–A′ in Plate 1). Numbers in blue correspond to the text in the lower portion of the figure.

1994; Ahmad et al., 2000; Miller et al., 2000; DeCelles et al., 2001; Myrow et al., 2003; Richards et al., 2005; this study) (Fig. 13). We interpret the protoliths of the metasedimentary units in our study area to represent proximal-distal elements of a continuous sedimentary sequence which accumulated on the northern Indian margin (e.g., Brookfield, 1993; Myrow et al., 2003). While recognizing the likelihood of tectonic activity during this extended period of sedimentary accumulation (e.g., Argles et al., 1999; Gehrels et al., 2003, 2006), this study does not provide conclusive evidence of pre-Tertiary deformation or metamorphism in the Kumaun and Garwhal Lesser Himalayan Sequence.

In the Eocene, the collision of India against Asia results in the initiation of the south-verging, Tethyan fold-and-thrust belt (e.g., Ratschbacher et al., 1994; Wiesmayr and Grasemann, 2002). We suggest that the basal décollement of this early fold-and-thrust belt is the Tons Thrust. This interpretation is based on the work of Myrow et al. (2003), who demonstrated the Tal Formation in the *Outer* Lesser Himalayan Sequence to be the southern extension of age-equivalent units in the Tethyan Himalayan Sequence. Because the *Outer* Lesser Himalayan Sequence and Tethyan Himalayan Sequence are separated for 50–100 km, the above interpretation adopted by this study requires the Tons Thrust to have moved at least 50–100 km southward in order to translate the distal *Outer* Lesser Himalayan Sequence zone south of the proximal *Inner* Lesser Himalayan Sequence zone with respect to the Indian craton (Fig. 13). Crustal thickening of the Tethyan Himalayan Sequence results in prograde metamorphism of the Greater Himalayan Crystallines below as suggested by previous workers (e.g., DeCelles et al., 1998; Searle et al., 1999; Hodges, 2000).

Initiation of the Main Central Thrust and southward translation of the Main Central Thrust hanging wall (Greater Himalayan Crystallines) over the Lesser Himalayan Sequence occurred in the late Oligocene–middle Miocene. Metamorphism and associated recrystallization of quartz in the Main Central Thrust footwall occurs along a carapace up to 10 km thick beneath the Main Central Thrust (see Célérier et al., 2009). Lesser Himalayan Sequence rocks below the leading edge of the Main Central Thrust hanging wall reach ~530 °C and subsequently cool through the muscovite closure temperature at ca. 11.5 Ma, while Lesser Himalayan Sequence units beneath trailing edge experience up to ~560 °C and cool through ~370 °C at ca. 8.5 Ma. The hanging wall of the Tons Thrust is truncated by the Main Central Thrust resulting in the leading edge of the Tons Thrust hanging wall (the *Outer* Lesser

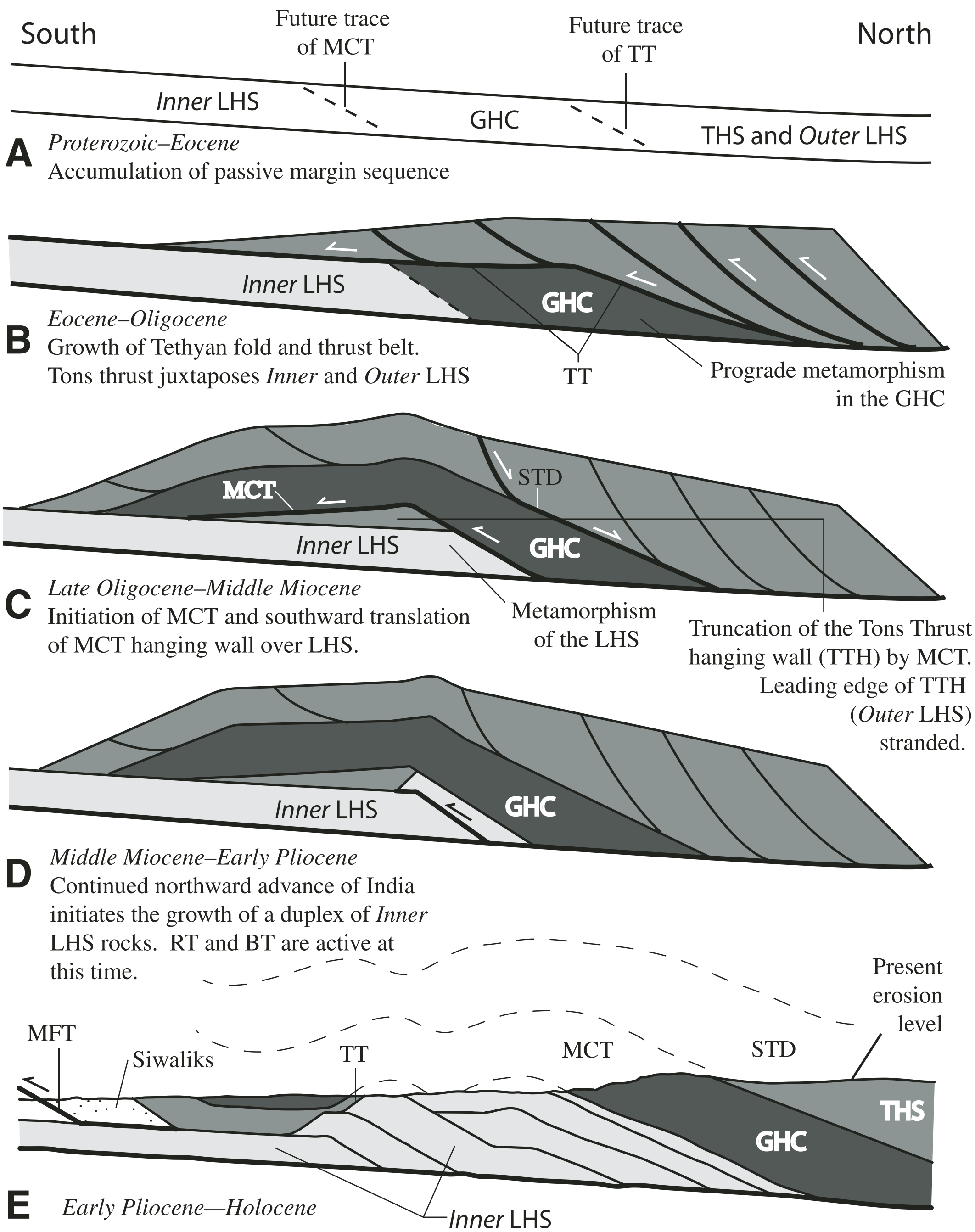


Figure 13. Conceptual kinematic model for the evolution of the Kumaun and Garwhal Lesser Himalayan Sequence. Bold lines indicate active faults. See text for explanation. Abbreviations: LHS—Lesser Himalayan Sequence, GHC—Greater Himalayan Crystallines, THS—Tethyan Himalayan Sequence, MCT—Main Central Thrust, MFT—Main Frontal Thrust, TT—Tons Thrust, RT—Ramgarh Thrust, BT—Berinag Thrust.

Himalayan Sequence) being stranded in the footwall of the Main Central Thrust, while the trailing edge of the Tons Thrust hanging wall is carried southward atop the Greater Himalayan Crystallines (Fig. 13). Southward translation of the Main Central Thrust hanging wall results in its being draped atop the Lesser Himalayan Sequence (e.g., LeFort, 1975).

In the middle Miocene–early Pliocene, continued northward advance of India results in *Inner* Lesser Himalayan Sequence rocks being fed into the thrust pile (Fig. 13). Accretion of material into the wedge generates a duplex of *Inner* Lesser Himalayan Sequence rocks that reorients the overlying *Outer* Lesser Himalayan Sequence and Main Central Thrust hanging wall. It is during this period of *Inner* Lesser Himalayan Sequence duplex development that the Ramgarh, Berinag, and Main Boundary Thrust are active. Duplex development in the *Inner* Lesser Himalayan Sequence does not appear to greatly alter the thermal structure of the Lesser Himalayan Sequence, established during passage of the Main Central Thrust hanging wall over the Lesser Himalayan Sequence (Célérier, 2009). The Siwalik fold-and-thrust belt becomes active, and out-of-sequence thrusting occurs along the Main Central Thrust in the early Pliocene and may even extend to the Holocene (e.g., Harrison et al., 1997; Catlos et al., 2001; Wobus, 2003; Kohn et al., 2004) (Fig. 13).

CONCLUSIONS

(1) Structural observations from the Kumaun and Garwhal Himalaya reveal a systematic change in deformation styles from lower to higher structural levels in the Main Central Thrust footwall. In the south and at lower structural levels, deformation in the Main Central Thrust footwall is characterized by parallel folding and sparse development of axial cleavage. Quartz microstructures are of *Regime-1* type, suggesting that deformation occurred at temperatures below 350 °C. In contrast, in the north and at higher structural levels close to the Main Central Thrust, deformation is characterized by replacement of original bedding, development of penetrative cleavage, and schistosity locally. Folds are tight and in places isoclinal and overturned. The corresponding quartz microstructures belong to *Regime 2* and *Regime 3*, suggesting the deformation under a temperature condition of >350 °C.

(2) U-Pb dating of detrital zircons from metasedimentary units and magmatic zircons from schistose gneiss units in the Lesser Himalayan Sequence allow us to refine the regional stratigraphy of the Kumaun and Garwhal Himalaya. First, our work suggests a lack of Paleoproterozoic strata in the hanging wall of the Ramgarh Thrust as is observed in Nepal, which suggests that the fault cuts upsection laterally westward along strike. Second, our work suggests that the metasedimentary strata in the Ramgarh Thrust hanging wall are correlative with the basal unit of the *Outer* Lesser Himalayan Sequence, removing the necessity that the Ramgarh hanging wall was allochthonous with respect to its footwall Lesser Himalayan Sequence units. Third, schistose gneisses with U-Pb ages of ca. 1850 Ma are older than the oldest Lesser Himalayan Sequence units in the area, suggesting that the schistose gneisses are basement to the Lesser Himalayan Sequence. This inference is also consistent with our geochemical data. The above revelation implies that thrusting in our study area is basement involved.

(3) Our refined stratigraphic framework of the Kumaun and Garwhal Himalaya in conjunction with our mapping and the results of early studies on the regional stratigraphy lead us to conclude that the Ramgarh Thrust is an out-of-sequence thrust postdating a folding event in its footwall. The previously proposed correlation between the *Outer* Lesser Himalayan Sequence zone and the Tethyan Himalayan Sequence requires that the Tons Thrust be a major south-directed thrust that transported the distal facies over the proximal facies of the northern Indian passive margin sequence for ~50–100 km.

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