Stratigraphy, structure, and tectonic evolution of the Himalayan fold-thrust belt in western Nepal

Peter G. DeCelles,[1] Delores M. Robinson,[1] Jay Quade,[1] T. P. Ojha,[1]
Carmala N. Garzione,[2] Peter Copeland,[3] and Bishal N. Upreti[4]

Abstract. Regional mapping, stratigraphic study, and $^{40}Ar/^{39}Ar$ geochronology provide the basis for an incremental restoration of the Himalayan fold-thrust belt in western Nepal. Tectonostratigraphic zonation developed in other regions of the Himalaya is applicable, with minor modifications, in western Nepal. From south to north the major structural features are (1) the Main Frontal thrust system, comprising the Main Frontal thrust and two to three thrust sheets of Neogene foreland basin deposits; (2) the Main Boundary thrust sheet, which consists of Proterozoic to early Miocene, Lesser Himalayan metasedimentary rocks; (3) the Ramgarh thrust sheet, composed of Paleoproterozoic low-grade metasedimentary rocks; (4) the Dadeldhura thrust sheet, which consists of medium-grade metamorphic rocks, Cambrian-Ordovician granite and granitic mylonite, and early Paleozoic Tethyan rocks; (5) the Lesser Himalayan duplex, which is a large composite antiformal stack and hinterland dipping duplex; and (6) the Main Central thrust zone, a broad ductile shear zone. The major structures formed in a general southward progression beginning with the Main Central thrust in late early Miocene time. Eocene-Oligocene thrusting in the Tibetan Himalaya, north of the study area, is inferred from the detrital unroofing record. On the basis of $^{40}Ar/^{39}Ar$ cooling ages and provenance data from synorogenic sediments, emplacement of the Dadeldhura thrust sheet took place in early Miocene time. The Ramgarh thrust sheet was emplaced between ~15 and ~10 Ma. The Lesser Himalayan duplex began to grow by ~10 Ma, simultaneously folding the north limb of the Dadeldhura synform. The Main Boundary thrust became active in latest Miocene-Pliocene time; transport of its hanging wall rocks over an ~8-km-high footwall ramp folded the south limb of the Dadeldhura synform. Thrusts in the Subhimalayan zone became active in Pliocene time. The minimum total shortening in this portion of the Himalayan fold-thrust belt since early Miocene time (excluding the Tibetan zone) is ~418-493 km, the variation depending on the actual amounts of shortening accommodated by the Main Central and Dadeldhura thrusts. The rate of shortening ranges between 19 and 22 mm/yr for this period of time. When previous estimates of shortening in the Tibetan Himalaya are included, the minimum total amount of shortening in the fold-thrust belt amounts to 628-667 km. This estimate neglects shortening accommodated by small-scale structures and internal strain and is therefore likely to fall significantly below the actual amount of total shortening.

1. Introduction

With its extreme elevation, tremendous magnitude of shortening, and large volume of high-grade metamorphic rock exposed at the surface, the Himalayan fold-thrust belt is unique among Earth's active orogenic belts. The fold-thrust belt consists of a series of south vergent thrust systems that have developed in response to ongoing subduction of the Indian plate beneath the Eurasian plate [*Gansser*, 1964; *Powell and Conaghan*, 1973; *Coward and Butler*, 1985; *Mattauer*, 1986; *Dewey et al.*, 1988; *Searle*, 1991; *Molnar et al.*, 1993; *Hodges*, 2000]. Recent GPS studies [*Bilham et al.*, 1997; *Larson et al.*, 1999], regional structural studies [*Lillie et al.*, 1987; *Srivastava and Mitra*, 1994; *Powers et al.*, 1998], mass balance calculations [*Le Pichon et al.*, 1992], and studies of the Himalayan foreland basin system [*Lyon-Caen and Molnar*, 1985; *DeCelles et al.*, 1998a, 1998b] suggest that approximately one third to one half of the ~2500 km of post-collision convergence between India and Eurasia [*Achache et al.*, 1984; *Patriat and Achache*, 1984; *Besse et al.*, 1984; *Besse and Courtillot*, 1988] has been accommodated by shortening in the Himalayan fold-thrust belt. This implies that the total shortening in the Himalaya should range between ~800 and ~1200 km [e.g., *Le Pichon et al.*, 1992]. Actual minimum estimates of horizontal shortening in the Himalaya range from >280 km in eastern Nepal [*Schelling*, 1992] to ~470 km [*Coward and Butler*, 1985] in Pakistan to >700 km in northern India [*Srivastava and Mitra*, 1994] and western Nepal [*DeCelles et al.*, 1998a]. The mismatch between these values and the values predicted from the standpoint of plate-scale tectonics, as well as the twofold difference between estimates from eastern Nepal and northern India, implies that some first-order problems remain to be solved.

Our objective in this paper is to present results of recent regional mapping and structural and stratigraphic studies in remote westernmost Nepal (Figure 1). This portion of the orogenic belt has been studied little, in part because of the difficulty of access. We present a new regional balanced cross

[1] Department of Geosciences, University of Arizona, Tucson, Arizona

[2] Department of Earth and Environmental Sciences, University of Rochester, Rochester, New York

[3] Department of Geological Sciences, University of Houston, Houston, Texas

[4] Department of Geology, Tri-Chandra Campus, Tribhuvan University, Ghantaghar, Kathmandu, Nepal

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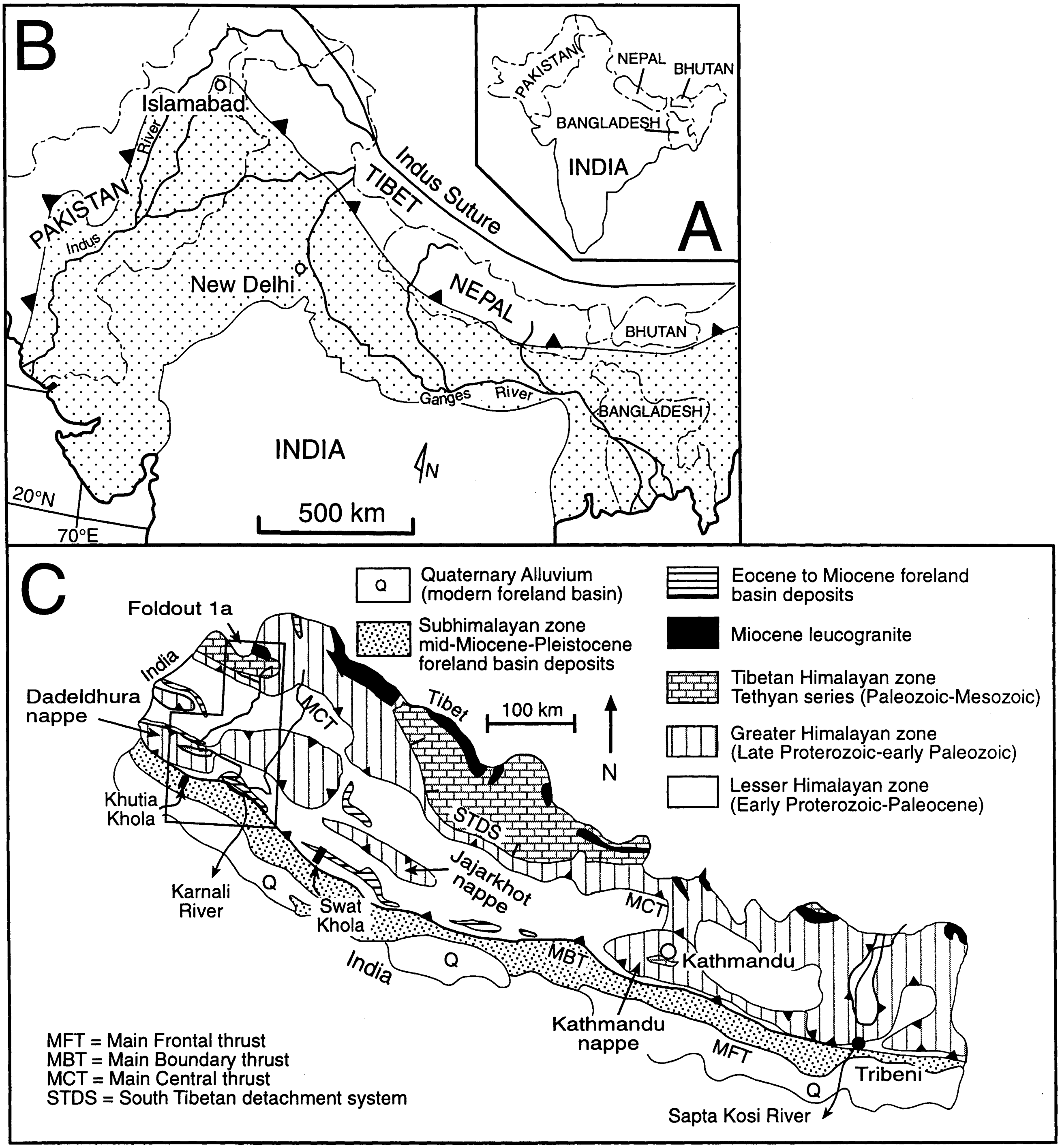


Figure 1. (a) Regional geographic map of south central Asia. (b) Generalized tectonic map of northern India, Nepal, and nearby regions. Barbed line indicates the front of the Himalayan fold-thrust belt. Dotted area is modern Himalayan foreland basin system. (c) Geological map of Nepal, showing major tectonic features and lithostratigraphic zones.

section and provide revised estimates of minimum horizontal shortening for this portion of the Himalaya. The balanced cross section presented herein is based almost entirely on our new mapping, in contrast to a previous cross section that was constructed ~50 km to the west [*DeCelles et al.*, 1998a], which was based mainly on regional map compilations. In addition, $^{40}Ar/^{39}Ar$ thermochronology of selected samples and recent detailed provenance studies in the Tertiary foreland basin deposits of westernmost Nepal and Kumaon, India [*DeCelles et al.*, 1998a, 1998b; *Najman and Garzanti,* 2000] provide an unparalleled opportunity to interpret the chronology of major Himalayan thrust systems.

2. Methods

Our interpretations are based in part on new mapping at scales of 1:50,000 and 1:25,000 along the Seti River corridor from the topographic front of the range to the junction of the Seti and Liyangwan Khola in the Saipal region of the high Himalaya, a cross-strike distance of ~120 km (Foldout 1a). Our mapping was compiled with selected portions of preexisting maps, and a line length balanced regional cross section (Foldout 2a) was constructed based primarily on the surface data, with a few constraints from earthquake seismology, well data, and the International Deep Profiling of Tibet and the Himalaya (INDEPTH) deep crustal reflection seismic profile [*Hauck et al.*, 1998]. Numerous samples were collected for petrographic analysis, and selected micaceous lithologies were sampled for $^{40}Ar/^{39}Ar$ thermochronology. In addition, we have employed regional lithostratigraphic observations and recent U-Pb detrital zircon analyses [*Parrish and Hodges*, 1996; *DeCelles et al.*, 2000] of Himalayan tectonostratigraphic terranes in Nepal to develop a scheme of regional stratigraphic correlation in Lesser Himalayan rocks and to provide some constraints on the pre-Himalayan tectonostratigraphic architecture of the region.

3. Tectonic Setting

The Himalayan fold-thrust belt has developed since ~55 Ma in response to the collision of the Indian and Eurasian plates and the subsequent northward subduction of India [*Powell and Conaghan*, 1973; *Ni and Barazangi*, 1984; *Coward and Butler*, 1985; *Mattauer*, 1986; *Searle*, 1991; *Rowley*, 1996; *Hodges*, 2000]. As India has continued to move northward relative to central Asia, much of the sedimentary prism that accumulated along its northern margin from early Proterozoic through Paleocene time has been detached from the underlying basement in the form of large, south vergent thrust sheets. The Indus suture zone delineates the approximate boundary between the Indian and Eurasian plates (Figure 1). To the south of the suture zone lies the Himalayan fold-thrust belt, which consists of mainly south vergent thrust sheets and related folds. Flanking the fold-thrust belt on its south lies the Himalayan foreland basin system, which onlaps the northern Indian cratonic shield (Figure 1) [*Lyon-Caen and Molnar*, 1985]. The present geomorphic foreland basin is the modern manifestation of a similar system that has existed along the southern flank of the orogen from western Pakistan to eastern Nepal since Eocene time [*Willis*, 1993; *Najman et al.*, 1993; *Pivnik and Wells*, 1996; *Burbank et al.*, 1996; *DeCelles et al.*, 1998b].

4. Tectonostratigraphy of the Himalayan Fold-Thrust Belt

Heim and Gansser [1939] and *Gansser* [1964] divided the rocks of the Himalayan fold-thrust belt in Nepal into four tectonostratigraphic zones that are characterized by distinctive stratigraphy and physiography. From south to north these are the Subhimalayan, Lesser Himalayan, Greater Himalayan, and Tibetan Himalayan zones. The Tibetan Himalayan zone was not studied in this work, but erosional outliers of rocks that are partly equivalent to the Tethyan series of southern Tibet were studied in the central part of the study area. This tectonostratigraphic scheme has proven to be useful from both regional stratigraphic and structural viewpoints in Nepal and northern India because with only minor exceptions the rock units are easy to recognize and the stratigraphic levels of major fault systems are regionally similar along strike from west to east [e.g., *Valdiya*, 1980].

4.1. Subhimalayan Zone

The topographic front of the Himalaya rises abruptly from elevations of ~150-250 m on the fluvial plains of the active foreland basin system to form the Subhimalayan zone, which is the frontal part of the fold-thrust belt. The topographic front is generally mapped as the trace of the Main Frontal thrust, although the fault itself is rarely exposed [*Nakata*, 1989; *Powers et al.*, 1998; *Wesnousky et al.*, 1999; *Lavé and Avouac*, 2000]. The Subhimalayan zone is defined as the 10- to 25-km-wide belt of Neogene Siwalik (or Churia) Group rocks that crop out in several generally northward dipping thrust sheets (Foldouts 1a and 1b) [*Gansser*, 1964; *Valdiya*, 1980; *Schelling*, 1992; *Mugnier et al.*, 1993; *Powers et al.*, 1998; *Lavé and Avouac*, 2000]. The repeated stratigraphy of these thrust sheets forms steep, northwest-southeast trending ridges with elevations of ~500-1000 m.

The Siwalik Group consists of an ~5-km-thick, upward coarsening succession of fluvial siltstone, sandstone, and conglomerate. As in other parts of the Subhimalayan zone of Pakistan and northern India [*Burbank et al.*, 1996], the Siwalik Group in Nepal comprises three informal units that are referred to as the lower, middle, and upper members [*Tokuoka et al.*, 1986; *Harrison et al.*, 1993; *Quade et al.*, 1995; *DeCelles et al.*, 1998a]. At Khutia Khola, in the southwestern part of the study area (Foldout 1a), the lower member is ~830 m thick, the middle member is ~2200 m thick, and the upper member is ~2000 m thick. Paleocurrent and modal petrographic data from sandstones and conglomerates indicate that these rocks were derived from the developing fold-thrust belt and deposited within the flexural foredeep of the Himalayan foreland basin system [*Tokuoka et al.*, 1986; *Hisatomi*, 1990; *Critelli and Ingersoll*, 1994; *DeCelles et al.*, 1998a].

4.2. Lesser Himalayan Zone

The northernmost thrust sheet of the Siwalik Group is overthrust by the Main Boundary thrust, which carries low-grade metasedimentary or unmetamorphosed sedimentary rocks of the Lesser Himalayan zone (Foldout 1a). The stratigraphy of the Lesser Himalayan zone in central and western Nepal and Kumaon, India, has been documented by numerous workers, including *Fuchs* [1977], *Fuchs and Frank*, [1970], *Frank and Fuchs* [1970], *Rupke* [1974], *Valdiya* [1980], *Stöcklin* [1980], *Bashyal* [1986], and *Upreti* [1990, 1996, 1999]. These rocks contain few fossils and consequently have been difficult to date and correlate regionally. This problem is alleviated somewhat by recent

Age	Informal Units This Study	Western Nepal This Study	Central Nepal Upreti, 1996	Eastern Nepal modified from Schelling, 1992
Miocene	Tertiary Unit	Dumri Fm.	Dumri Fm.	Dumri Fm.
Eocene		Bhainskati Fm.	Bhainskati Fm.	Bhainskati Fm.
Permian-Cretaceous	Gondwanan Unit	Gondwanas	Gondwanas	Gondwanas
Middle Proterozoic	Upper Nawakot Unit	Lakarpata Gr.	Robang Fm. Malekhu Fm. Benighat Fm. Dhading Fm.	Tumlingtar Gr. (including Ulleri Gneiss)
		Syangia Fm. <1.68 Ga	Nourpul Fm.	
	Lower Nawakot Unit	Galyang Fm.	Dandagaon Fm.	
		Sangram Fm.	Fagfog Fm.	
Early Proterozoic	1.86-1.83 Ga	Ranimata Fm. (including Ulleri Gneiss)	Kuncha Fm. (including Ulleri Gneiss)	
		Kushma Fm.		

Figure 2. Chart showing correlations of Lesser Himalayan, Gondwanan, and Tertiary stratigraphic units across Nepal.

studies of detrital zircon U-Pb ages in Lesser Himalayan rocks throughout Nepal [*Parrish and Hodges*, 1996; *DeCelles et al.*, 2000]. All of the mapped units have been given formal stratigraphic names, and we use those given on the map compilation of *Shrestha et al.* [1987] (Figure 2). Although the entire succession is ~8-10 km thick, detailed information about the thicknesses of individual formations is not yet available. The lower half of the succession is dominated by siliciclastic rocks, and its upper half consists of both carbonate and siliciclastic rocks (Figure 2). The term Nawakot Complex was coined for Lesser Himalayan low-grade metasedimentary rocks in the Kathmandu region [*Stöcklin*, 1980]. *Sakai* [1983] modified the term to Nawakot Group and extended its usage into western Nepal, but *Upreti* [1996] advocated the more informal term "Nawakot unit," in part because the details of regional stratigraphic relationships between the various formations are not sufficiently known to warrant use of the formal term Group. In this paper, we subdivide Lesser Himalayan stratigraphy into four informal units that we have found to be useful for regional mapping: the lower and upper Nawakot units; the Gondwanan unit; and the Tertiary unit (Figure 2).

4.2.1. Lower Nawakot Unit. The lower Nawakot unit in western Nepal consists of, in ascending order, the Kushma, Ranimata, Ulleri, Sangram, and Galyang Formations. With the exception of the Ulleri Formation, which is a granitic augen gneiss, these formations are almost entirely siliciclastic.

The Kushma Formation is an ~500-m-thick, white to tan, fine- to medium-grained metaquartzite that forms several-hundred-meter-high cliffs and holds up precipitous ridges. Along the major rivers, such as the Seti and Karnali, the Kushma is cut by deep, narrow canyons. The Kushma is thickly bedded and dominated by low-angle planar and trough cross stratification (Figure 3a). In most of the sections that we have observed, the Kushma Formation consists exclusively of pure quartzite, but some sections contain significant amounts of interbedded greenish-gray siltite and silty quartzite.

The Kushma Formation is overlain by the Ranimata Formation. Although we did not observe the contact, sandy and silty lithologies in the two units can appear quite similar, and the units are probably conformable. The Ranimata Formation typically is on the order of 2-3 km thick. The Ranimata is dominated by chloritic or sericitic phyllite and phyllitic siltite, with subordinate amounts of fine chloritic schist (Figure 3b). In proximity to the Dadeldhura and Main Central thrusts the Ranimata phyllites and schists contain abundant garnet. Greenish-gray quartzite beds up to ~100 m thick are common. Some horizons in the Ranimata contain lithic-rich sandstones and stretched pebble conglomerates. Where sericitic, the rock exhibits a distinctive silky luster. Milky quartz veins and blebs are abundant in the phyllitic zones (Figure 3b). Thick sills of altered diorite (chlorite + hornblende + plagioclase ± quartz) are common in the upper third of the unit. The diagnostic lithologic suite for the Ranimata Formation is chloritic phyllite with quartz veins and blebs; altered (chloritic) mafic, hypabyssal igneous rocks; and greenish impure quartzites. Because of its abundant finer-grained and mafic lithologies the Ranimata Formation tends to weather into topographically subdued hills and wide valleys.

The details of the relationship between the Kushma and Ranimata Formations remain poorly documented. In many places the typical Kushma quartzite is not present below the typical Ranimata phyllite, yet there is no conspicuous evidence for faulting. In some places the thick Kushma quartzite nearly pinches out laterally over a distance of only a few kilometers (e.g., in the Chainpur area). Because of this uncertainty we have retained lithologic information but mapped the two formations together as the composite Kushma-Ranimata Formation on Foldout 1a. This is consistent with previous studies of Lesser Himalayan rocks in northern India and Nepal that have grouped the Kushma and Ranimata Formations under a single formation name, such as the Ramgarh Group in Kumaon [*Valdiya*, 1980], the Chail Formation of *Frank and Fuchs* [1970], the Kuncha Formation of central Nepal [*Stöcklin*, 1980; *Sakai*, 1985], and the Tumlingtar Group of eastern Nepal [*Schelling*, 1992]. The base of the Kushma-Ranimata succession is marked by the Ramgarh thrust throughout western Nepal (Figure 3c).

The third formation in the lower Nawakot unit of western Nepal is the Ulleri gneiss. Large lenticular bodies of the Ulleri gneiss are present in the upper part of the Ranimata Formation. The largest body of Ulleri gneiss in the study area is ~2 km thick and >8 km in length along strike. The Ulleri is a granitic (quartz + orthoclase + plagioclase + muscovite + biotite) augen gneiss with well-developed mylonitic S-C fabrics and foliation parallel lineations. The augen are rotated and slightly flattened orthoclase crystals, and the matrix consists of stretched and flattened quartz, muscovite, and biotite (Figure 3d). Many local names are used for similar augen gneisses in northern India [*Valdiya*, 1980] and throughout Nepal [e.g., *Schelling*, 1992], but all share the same general lithological features and stratigraphic association with Ranimata-type chloritic phyllites, fine schists, and mafic intrusions.

The Sangram Formation is composed mostly of white quartzite. Along the Dadeldhura road the Sangram has a lower massive quartzite and an upper interval of medium-bedded tan to pink quartzite interbedded with dark gray and reddish weathering slate (Figure 4a). The thickness of the entire unit is ~500 m. On the map of *Shrestha et al.* [1987] the Sangram is

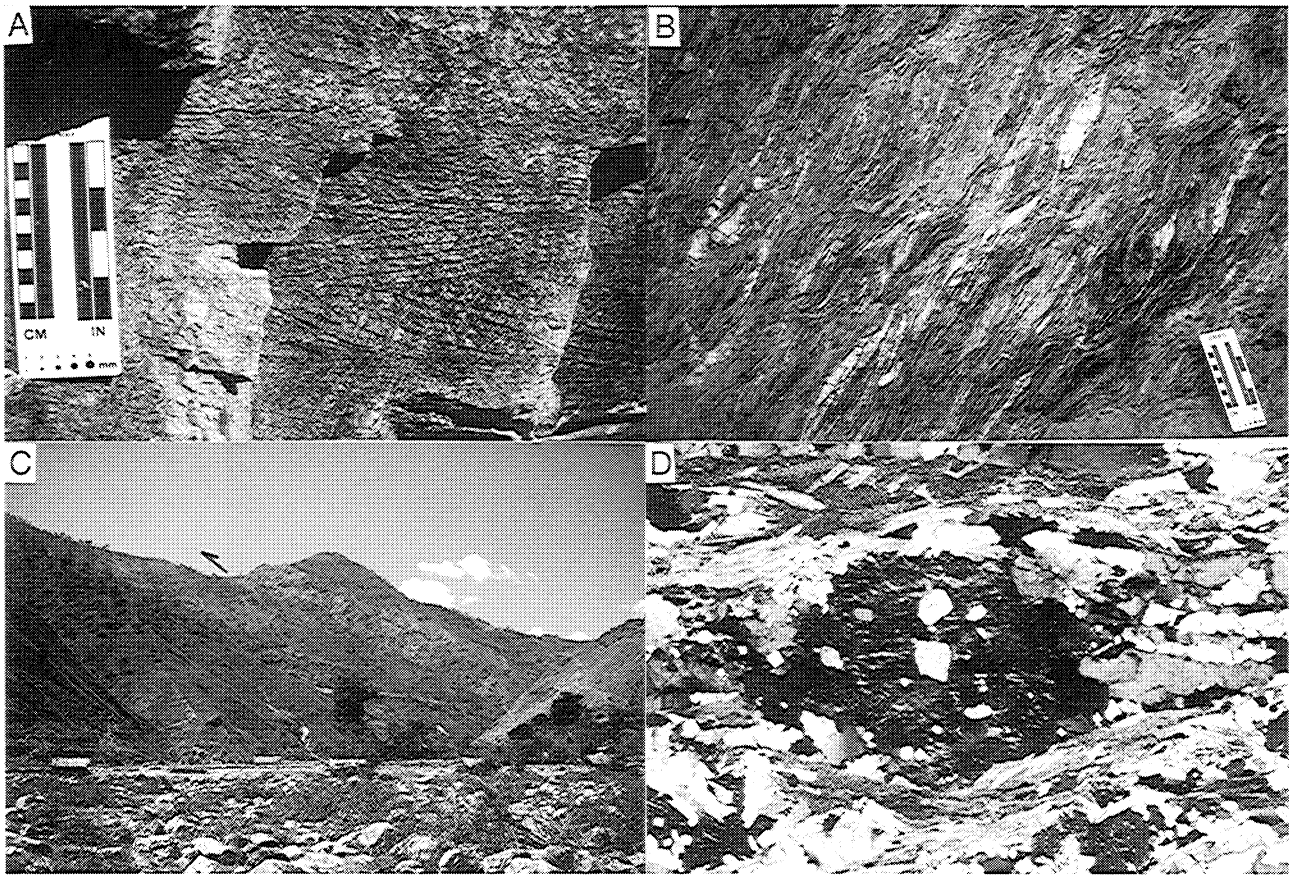


Figure 3. (a) Trough cross-stratified quartzite in the Kushma Formation. (b) Green, chloritic phyllite with quartz blebs in the Ranimata Formation. (c) View toward the west of the Ramgarh thrust near the confluence of Kalanga Gad and Seti River (80°50'E, 29°28'N), where it places the Ranimata Formation on top of carbonate rocks in the upper Nawakot unit. The foreground is underlain by nonresistant phyllite in the Ranimata Formation. Note the hut at lower left for scale. (d) Photomicrograph of highly strained orthoclase augen (with small quartz inclusions) with recrystallized quartz tails and enveloping muscovite and biotite crystals. Width of view is 9 mm.

depicted as overlying the Galyang Formation, but our observations along the Dadeldhura road section suggest that the Galyang is actually above the Sangram. This is also consistent with the stratigraphy of Lesser Himalayan units in central Nepal, where the quartzitic Fagfog Formation is overlain by the phyllitic Dandagaon Formation (Figure 2) [*Upreti*, 1996].

The Galyang Formation is a thick, gray to olive green slate and phyllite. Black slate is locally present. In the region between Dadeldhura and Patan the Galyang Formation is 1.5 km thick. Farther northeast, along the Seti River, the Galyang locally contains a gray recrystallized dolostone interval several tens to ~100 m thick in its lowermost part (the "Baitadi carbonate beds"). The distinguishing features of the Galyang are its monotonous gray-green, slatey lithologies and its great thickness. The Galyang Formation can be easily distinguished from the Ranimata Formation, which is characterized by distinctive chloritic phyllites with quartz veins and blebs and a higher grade of metamorphism.

4.2.2. Upper Nawakot Unit. The upper Nawakot unit in western Nepal consists of the Syangia Formation and the Lakarpata Group. The Syangia Formation comprises pink, red, purple, green, and lavender slate and quartzose sandstone. In the Seti River region the Syangia is ~300 m thick. Locally, along the Seti River the Syangia Formation contains a dark maroon quartzite unit. Sedimentary structures typical of tidal activity and desiccation, such as flaser bedding, symmetrical ripples, and mud cracks, are common. Thick, gray recrystallized dolostones are present in its upper part. The Syangia Formation is distinguished by its variegated colors. The contact between the Syangia Formation and the overlying Lakarpata Group appears to be transitional and is marked by an increase in the proportion of carbonate to siliciclastic rocks. In central Nepal, similar rocks are referred to as the Virkhot and Nourpul Formations [*Stöcklin*, 1980; *Sakai*, 1985].

The Lakarpata Group in western Nepal includes ~2-3 km of carbonate rocks and dark gray slates. In central Nepal this thick interval has been subdivided into several different formations [*Stöcklin*, 1980; *Sakai*, 1985], but in recent map compilations for western Nepal [*Shrestha et al.*, 1987] the entire interval remains undivided and is referred to as the Lakarpata Group. Because we have not studied these units in

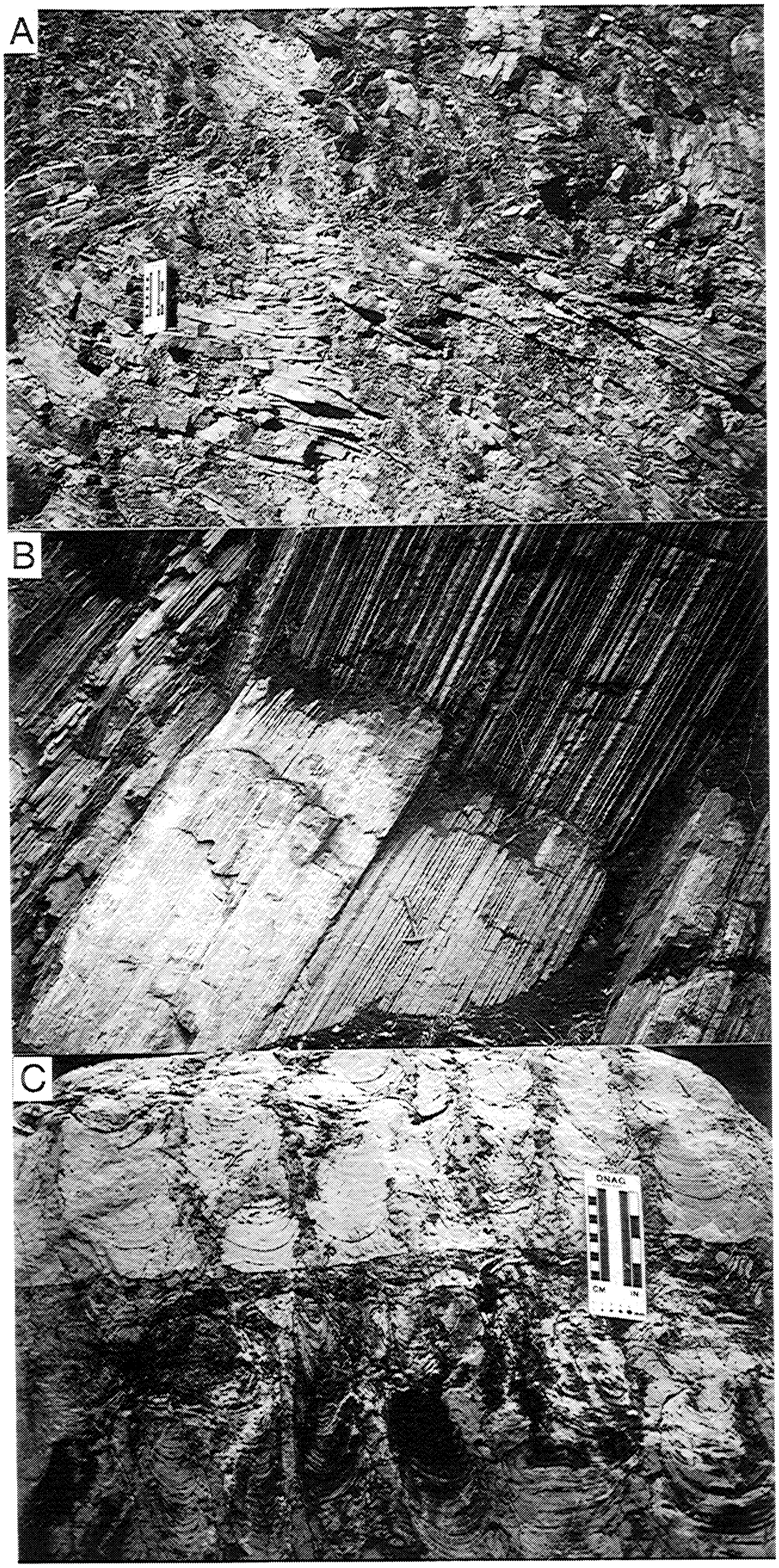


Figure 4. (a) Tightly folded thin-bedded quartzite in the Sangram Formation along the Dadeldhura road, near Anarkoli Khola north of Dadeldhura. (b) Rhythmically banded dolostone in the Lakarpata Group north of Dadeldhura. The hammer is 30 cm long. (c) Overturned bed with *Collenia* stromatolites in the Lakarpata Group, located a few kilometers south of Chainpur.

detail and because they are characterized by locally intense internal deformation that inhibits stratigraphic understanding, we use the term Lakarpata Group in this paper. The dominant lithologies consist of massive gray dolostone, thin-bedded to rhythmically planar-laminated dolostone (Figure 4b), stromatolitic dolostone (Figure 4c), siliceous dolostone, and minor micritic limestone. White quartzose sandstone is present in medium to thin tabular beds in some sections, and along the Seti River a thick black to dark gray slate interval is locally present. Identifiable stromatolites in the dolostones include *Collenia* and *Conophyton* (Figure 4c; compare with works by *Sakai* [1985] and *Upreti* [1996]).

4.2.3. Gondwanan Unit. In western Nepal the carbonate rocks of the Lakarpata Group are overlain by a thin (<200 m) and laterally variable interval of quartzose sandstone, black shale, coal, lignite, and quartz pebble conglomerate that is assigned to the "Gondwanas" of Jurassic-Paleocene age. These rocks have counterparts in central Nepal from which many plant fossils have been recovered [*Sakai*, 1983, 1989]. In western Nepal we recognize the upper part of this interval as the probable equivalent of the Amile Formation in central Nepal, a pebbly quartz arenite associated with carbonaceous shale and coal.

4.2.4. Tertiary Units. The uppermost formal stratigraphic units in the Lesser Himalayan zone are the Bhainskati and Dumri Formations, of Eocene and Early Miocene age, respectively (Figure 4). These units crop out in three east-west trending belts. The Bhainskati Formation consists of up to ~200 m of poorly exposed black shale, thin quartz arenitic sandstone beds, and thin fossiliferous limestone beds. Molluscan debris and age-diagnostic Middle to Late Eocene foraminifera (including Nummulites) are abundant in the Bhainskati Formation [*Sakai*, 1983] in the southernmost outcrop belt, but only black shale is present in the northernmost outcrops that we studied.

The Dumri Formation is 1000-1200 m thick and consists of thick, greenish-gray, trough cross-stratified, fluvial channel sandstones interbedded with reddish paleosols and overbank siltstones. The lower several hundred meters of the Dumri Formation are dominated by sandstone, whereas the upper portion is composed mainly of reddish mudstones with subordinate sandstone bodies. The sandstones of the Dumri Formation are easily distinguished from the other sandy lithologies of the Lesser Himalayan zone (which are typically quartzarenitic) by their lithic and micaceous composition. In contrast to Siwalik Group sandstones, those in the Dumri are more quartzose and contain significant amounts of plagioclase but virtually no K-feldspar. Lithic grains are predominantly phyllite, with minor amounts of limestone/dolostone [*DeCelles et al.*, 1998b].

4.3. Greater Himalayan Zone

The Greater Himalayan zone consists of two regions in western Nepal: (1) the Dadeldhura thrust sheet, which is a large synformal klippe that forms the eastern continuation of the Almora klippe of Kumaon, India, and (2) the region of high-grade metamorphic rocks bounded on the north by the South Tibetan detachment system [*Burg and Chen*, 1984; *Burchfiel et al.*, 1992] and on the south by the Main Central thrust (Foldout 1a). Greater Himalayan rocks consist of paragneiss, schist, migmatite, marble, and orthogneiss. Rocks to the north of the Main Central thrust are metamorphosed to amphibolite facies, whereas the rocks of the Dadeldhura thrust sheet are generally in the upper greenschist facies.

The metamorphic rocks of the Dadeldhura thrust sheet consist of the Kalikhot Schist and the Budhiganga and Salyanigad Gneisses. These are intruded by the Dadeldhura granite and are overlain by Tethyan rocks discussed in section 4.4. The preserved thickness of the thrust sheet is ~7 km. The Kalikhot Schist is a fine to coarse, muscovite + biotite + quartz ± chlorite ± plagioclase ± garnet schist with a pronounced foliation that defines the northern and southern limbs of the Dadeldhura synform (Figure 5a). Locally, bodies of felsic porphyroblastic metavolcanic(?) schist are present within the Kalikhot Schist. The Budhiganga Gneiss is a coarse-grained porphyritic to porphyroblastic augen gneiss (Figure 5b), composed of K-feldspar + quartz + muscovite ± biotite ± plagioclase ± garnet. The Dadeldhura granite is a large (>400 km^2) body of coarse-grained (Figure 5c), locally pegmatitic granite (quartz + K-feldspar + plagioclase + muscovite + biotite ± cordierite ± tourmaline). The granite has yielded a concordant U-Pb zircon age of 492 ± 6 Ma [*DeCelles et al.*, 1998a] and is similar to other Cambrian-Ordovician two-mica granite bodies, which are widespread in the crystalline klippen that rest structurally above the Lesser Himalayan rocks [*Trivedi et al.*, 1984; *LeFort et al.*, 1986; *Schärer and Allègre*, 1983; *Einfalt et al.*, 1993]. The Dadeldhura granite is associated with granitic, mylonitic augen gneiss referred to as the Salyanigad Gneiss, which produced a concordant U-Pb zircon age of 478 ± 10 Ma from a sample collected along the Dadeldhura road [*DeCelles et al.*, 2000]. The similarity in age and composition of the Dadeldhura granite and the Salyanigad Gneiss suggests that the latter is a ductilely deformed envelope around the outer margin of the granite body [*Srivastava and Mitra*, 1996].

The rocks north of the village of Dhuli are coarse biotite-muscovite schists and calcschists (Figure 5d) with abundant garnet. These rocks occur in a zone ~2 km thick below obvious Greater Himalayan high-grade metamorphic rocks and above obvious Lesser Himalayan low-grade metasedimentary rocks. In Foldout 1a these rocks are included in the Greater Himalayan zone north of the Main Central thrust. It is conceivable, however, that these coarse schists were originally Lesser Himalayan protoliths that have been intensely deformed and metamorphosed directly beneath the Main Central thrust or that they are the northern continuation of the Dadeldhura thrust sheet.

We have only briefly studied the medium- to high-grade (garnet ± kyanite ± sillimanite) metamorphic rocks north of the Main Central thrust along the upper reaches of the Seti River gorge up to its confluence with Liyangwan Khola (Foldout 1a). These rocks are referred to as the Vaikrita Group in western Nepal and Kumaon [*Valdiya*, 1980]. We observed and sampled a variety of lithologies including coarse schist (quartz + muscovite + albite + garnet + biotite + kyanite + tourmaline), calcschist (quartz + calcite + albite + epidote + muscovite), and paragneiss (quartz + biotite + muscovite + garnet + kyanite). Map patterns indicate that the Greater Himalayan rocks north of the Main Central thrust zone are ~12 km thick.

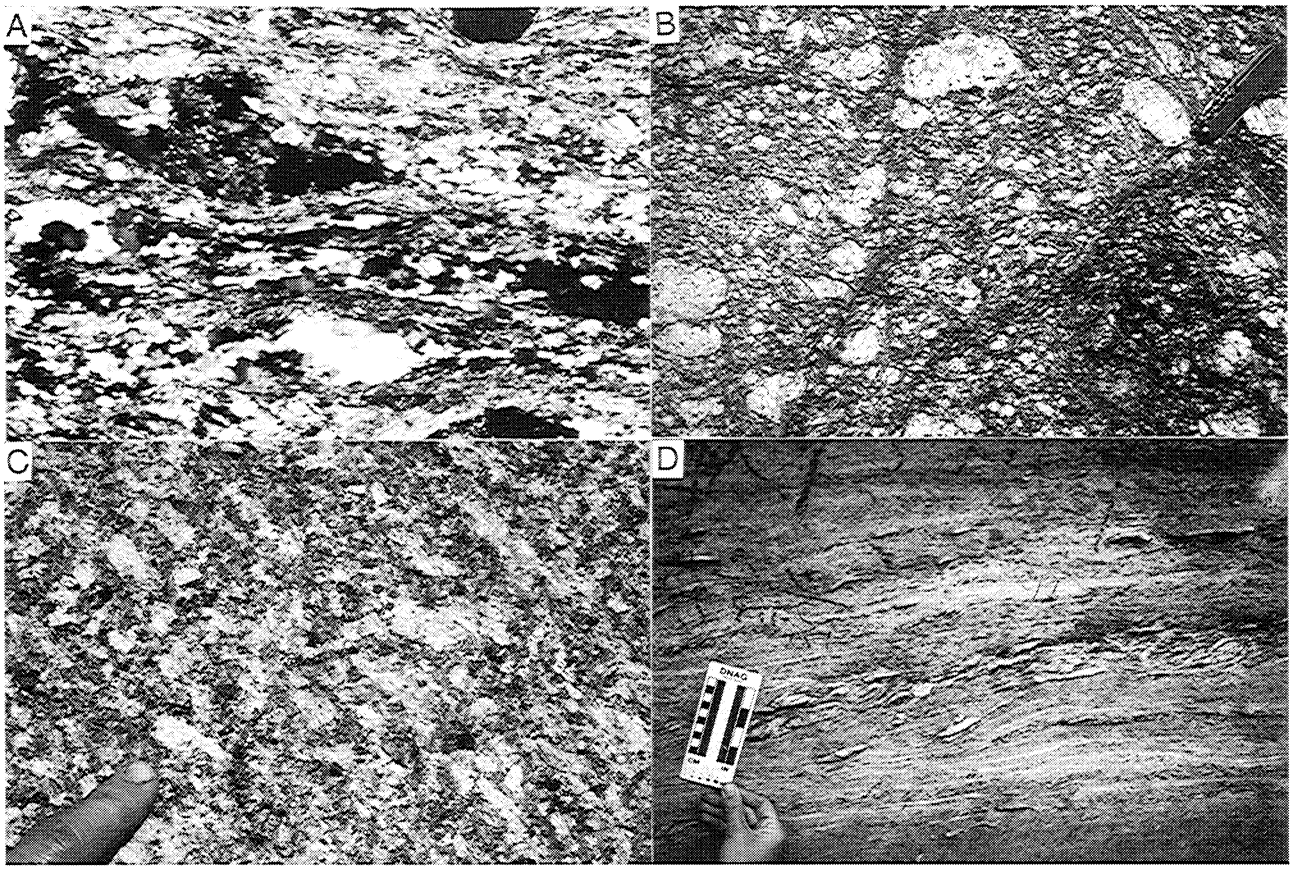


Figure 5. (a) Photomicrograph of a typical quartz-muscovite schist in the Kalikhot Formation. Field of view is 4.5 mm wide. (b) Large porphyroblasts of K-feldspar in the Budhiganga gneiss. Knife is 10 cm long. (c) Typical example of the Dadeldhura granite along the Dadeldhura road. (d) Coarse banded calc schist in the Main Central thrust zone, north of Dhuli.

4.4. Tibetan (Tethyan) Himalayan Zone

The Tibetan Himalayan zone, which is defined by the presence of the Tethyan sedimentary series, is north of the region we have studied in the field. The Tethyan series consists of Cambrian through Eocene sedimentary and very low grade metasedimentary rocks: mainly phyllites, limestones, and quartzose sandstones [*Gansser*, 1964; *Searle*, 1986; *Ratschbacher et al.*, 1994]. Within the area that we have mapped, a single ~40-km-long, east-west trending outcrop belt of rocks that probably correlate with the Tethyan series is preserved along the axis of the Dadeldhura synform between the townsites of Dadeldhura and Dipayal (Foldout 1a). Only the lowest part of the succession remains, and it consists of two mappable units called the Damgad and Melmura Formations [*Shrestha et al.*, 1987]. The Damgad Formation is ~500 m thick and consists of gray to white, medium- to thick-bedded, large-scale trough and planar cross-stratified, fine-grained quartz arenite. The Damgad Formation grades upward into the Melmura Formation, which comprises ~1 km of brown and gray phyllite, black carbonaceous slate, and thin, quartzose sandstone beds.

4.5. Geochronology and Regional Correlations

Approximately 450 U-Pb zircon ages from Lesser, Greater, and Tibetan (Tethyan) Himalayan rocks throughout Nepal provide constraints on depositional and intrusive ages [*Gehrels et al.*, 1999; *DeCelles et al.*, 2000]. Detrital zircons from the Kushma and Ranimata Formations have age distribution peaks of ~1866 and ~1943 Ma, with a scatter of older ages. Zircons from the Ulleri augen gneiss, which intruded into the Ranimata Formation, produced an age of 1831 ± 17 Ma. Thus the entire Kushma-Ranimata succession is between ~1866 and 1831 Ma (Figure 2). Ages of detrital zircons from the Sangram Formation are similar to those from the Kushma, but the presence of a younger population of ~1680 Ma zircons indicates that the unit must be younger than that age. The common algal stromatolites in the Lakarpata Group are taken to indicate a Proterozoic age [*Sakai*, 1985]. Our data do not provide a definitive age for the upper Nawakot unit.

Detrital zircon ages from Greater Himalayan gneisses in Nepal are generally between ~750 and ~1700 Ma [*Parrish and Hodges*, 1996; *DeCelles et al.*, 2000], with age distribution peaks at ~851 and ~954 Ma. The granites and granitic mylonites that are common in the crystalline klippen (Dadeldhura and Palung granites and Salyanigad, Budhiganga, and Sheopuri gneisses) have ages of 470-495 Ma [*Schärer and Allègre*, 1983; *Gehrels et al.*, 1999; *DeCelles et al.*, 2000]. Orthogneisses from the Greater Himalayan zone north of the Main Central thrust in Nepal and Tibet also have yielded Cambrian-Ordovician ages [*Ferrara et al.*, 1983; *LeFort et al.*, 1986; *Hodges et al.*, 1996]. Thus the Greater Himalayan rocks are late Proterozoic-early Paleozoic in age [*Parrish and Hodges*, 1996], most likely entirely younger than Lesser Himalayan rocks in Nepal [*DeCelles et al.*, 2000].

The Tethyan series must be younger than the Greater Himalayan rocks upon which it was deposited. Detrital zircon ages from the Damgad Formation and other Tethyan sandstones/quartzites mimic those of the underlying Greater Himalayan rocks, with the addition of a strong component of early Paleozoic grains, most likely derived from the Cambrian-Ordovician granites and orthogneisses [*Gehrels et al.*, 1999; *DeCelles et al.*, 2000]. Paleontological ages of Tethyan rocks in central Nepal indicate Silurian-Devonian ages [*Bordet et al.*, 1960; *Stöcklin*, 1980].

The ages of the Tertiary foreland basin deposits are known from fossils, paleomagnetic stratigraphy, and detrital muscovite $^{40}Ar/^{39}Ar$ ages. The Bhainskati Formation is middle to late Eocene in age based on abundant fossils [*Sakai*, 1983]. An unconformity spanning ~15 Myr separates the Bhainskati from the overlying Dumri Formation. This unconformity may represent the passage of the flexural forebulge through the foreland region in Oligocene time [*DeCelles et al.*, 1998b]. The Dumri Formation must be younger than early Miocene because it contains detrital muscovite grains that have been dated by $^{40}Ar/^{39}Ar$ at ~22-28 Ma in northern India [*Najman et al.*, 1997] and ~20 Ma in western Nepal (Figure 6a). Preliminary paleomagnetic stratigraphy of the Dumri Formation indicates that it was deposited between ~21 and 16 Ma [T. P. Ojha, unpublished data, 2000). Vertebrate fossils [*West et al.*, 1978, 1991; *Corvinus*, 1994] and paleomagnetic stratigraphy [*Ojha et al.*, 2000] of the Siwalik Group in western Nepal indicate an age range of ~14-2 Ma. The apparent time gap between the Dumri Formation and the Siwalik Group is a result of the fact that neither the base of the Siwalik Group nor the top of the Dumri Formation has been found in outcrop in Nepal.

Correlations of Greater Himalayan and Subhimalayan zone rocks from western to eastern Nepal are straightforward (Figure 2). Some debate continues about whether the southern synformal, crystalline thrust sheets of Greater Himalayan rocks are directly correlatable with rocks north of the Main Central thrust [*Upreti and LeFort*, 1999]. To the east of our study area, *Arita et al.* [1984] reported that the kyanite- and sillimanite-bearing Karnali nappe (equivalent to *Fuchs*' [1977] "Upper Crystalline Nappe") rests on top of the eastern continuation of the Dadeldhura nappe, suggesting that the Dadeldhura klippe is not contiguous with the rocks above the Main Central thrust.

Many problems with regional mapping in Nepal owe to the generally poor understanding of Lesser Himalayan zone stratigraphy and chronostratigraphy. An attempt to register the stratigraphy we have observed with *Upreti*'s [1996, 1999] regional correlations is shown in Figure 2. The U-Pb detrital zircon ages obtained from the Nawakot Group provide the first strong constraints on ages and regional correlations of the siliciclastic formations. Our recent (unpublished) work in far eastern Nepal, ~700 km to the east of the present study area, demonstrates that Lesser Himalayan stratigraphic units as discussed in section 4.2 are consistent in lithology, stratigraphic order, and age throughout Nepal (Figure 2).

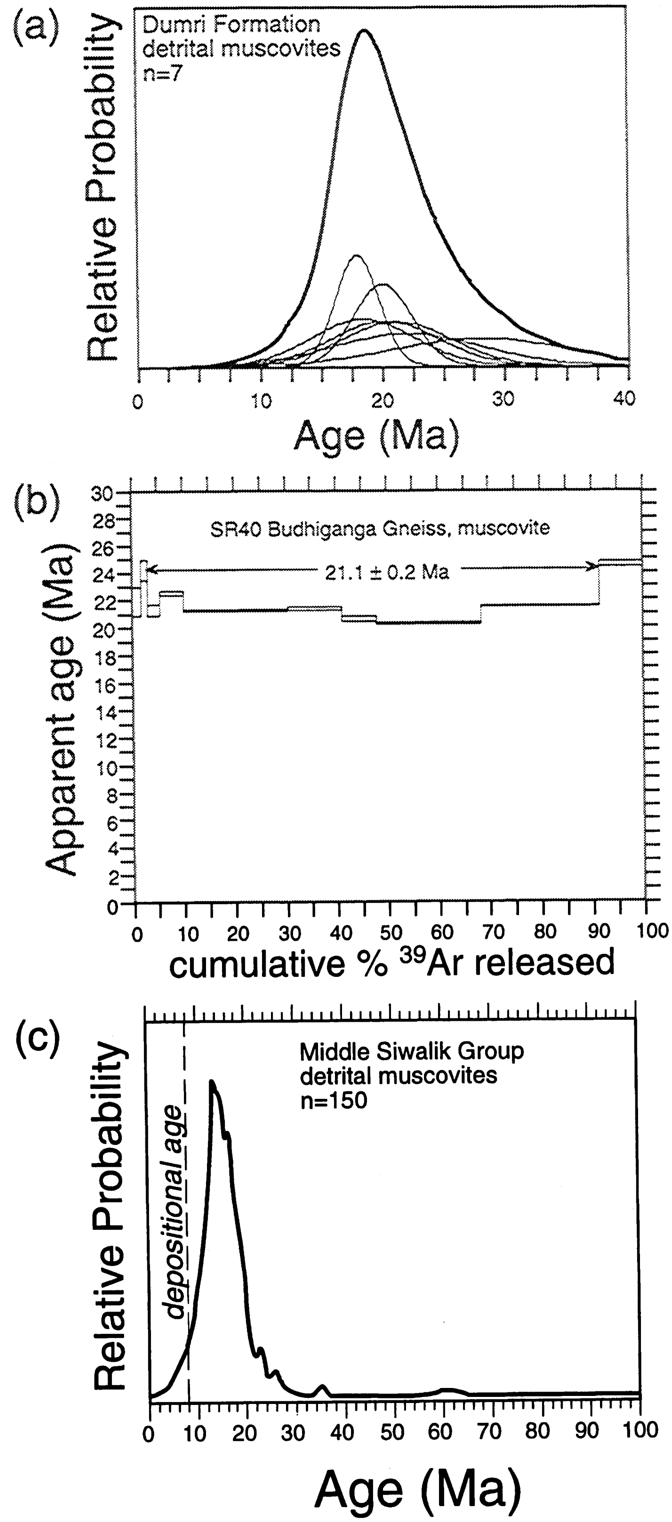


Figure 6. (a) Relative frequency probability of detrital muscovite $^{40}Ar/^{39}Ar$ ages from a sample of the early Miocene Dumri Formation. The thin curves represent individual grains, and the thick curve represents the sum of the total distribution. (b) The $^{40}Ar/^{39}Ar$ age spectra for muscovite from a sample of the Budhiganga Gneiss in the north limb of the Dadeldhura synform. (c) Relative frequency probability of detrital muscovite $^{40}Ar/^{39}Ar$ ages from a sample of the middle Siwalik Group with a depositional age of ~8 Ma.

5. Structural Geology

5.1. General Subdivisions

The regional structural geology of western Nepal to the south of the South Tibetan detachment system is controlled by six major thrust systems (in the sense of *Dahlstrom* [1970]). These include the Main Frontal, Main Boundary, Ramgarh, Dadeldhura, and Main Central thrust systems and, lying between the latter two, the Lesser Himalayan duplex (Foldouts 1a and 1b). Each structural system is discussed in a south-to-north order in the direction of increasing metamorphic grade and structural complexity.

5.2. Main Frontal (or Subhimalayan) Thrust System

The Main Frontal (or Subhimalayan) thrust system contains two or three thrust sheets composed entirely of the Siwalik Group. The southernmost sheet is bounded by a frontal anticline that is considered to mark the trace of the Main Frontal thrust [*Mugnier et al.*, 1993; *Powers et al.*, 1998; *Lavé and Avouac*, 2000]. Excepting 25°-45° southward dipping beds in the southern limb of the frontal anticline, bedding in the Subhimalayan zone dips almost exclusively north-northeastward at angles of 30°-55°. Minor structures include north-south trending cross folds, wedge faults, and normal faults with displacements of centimenters to meters. The depth of the basal thrust in the Main Frontal system must lie below the lower Siwalik member, ~5.1 km below the surface (Foldout 2a).

5.3. Main Boundary Thrust System

The trailing edge of the northernmost thrust sheet of the Main Frontal thrust system is truncated by the Main Boundary thrust and overlain by Lesser Himalayan rocks with a steeply northward dipping cleavage. The Main Boundary thrust sheet consists of the Sangram, Galyang, and Syangia Formations, the Lakarpata Group, and the Amile, Bhainskati, and Dumri Formations. Rocks in the Main Boundary thrust sheet are generally not metamorphosed or are metamorphosed only to lower greenschist facies. The finer-grained rocks exhibit a slatey cleavage at moderate to low angles to bedding. In the region northwest of Chisapani the Main Boundary thrust sheet is cut by several relatively minor, internal faults inferred on the basis of stratigraphic anomalies (Foldouts 1a and 2a). At the surface the northern boundary of the thrust sheet is marked by an inferred fault between chloritic phyllite of the Ranimata Formation and phyllite in the Galyang Formation or dolostone in the Lakarpata Group (Foldout 1a). This fault could be the Ramgarh thrust or, as we have interpreted it in Foldout 2a, a minor normal fault that drops the frontal part of the Ramgarh thrust into the shallow subsurface (see section 5.4). On the basis of the surface data and principles of cross section construction we interpret the Main Boundary thrust sheet to continue northward in the subsurface for >50 km (Foldout 2a).

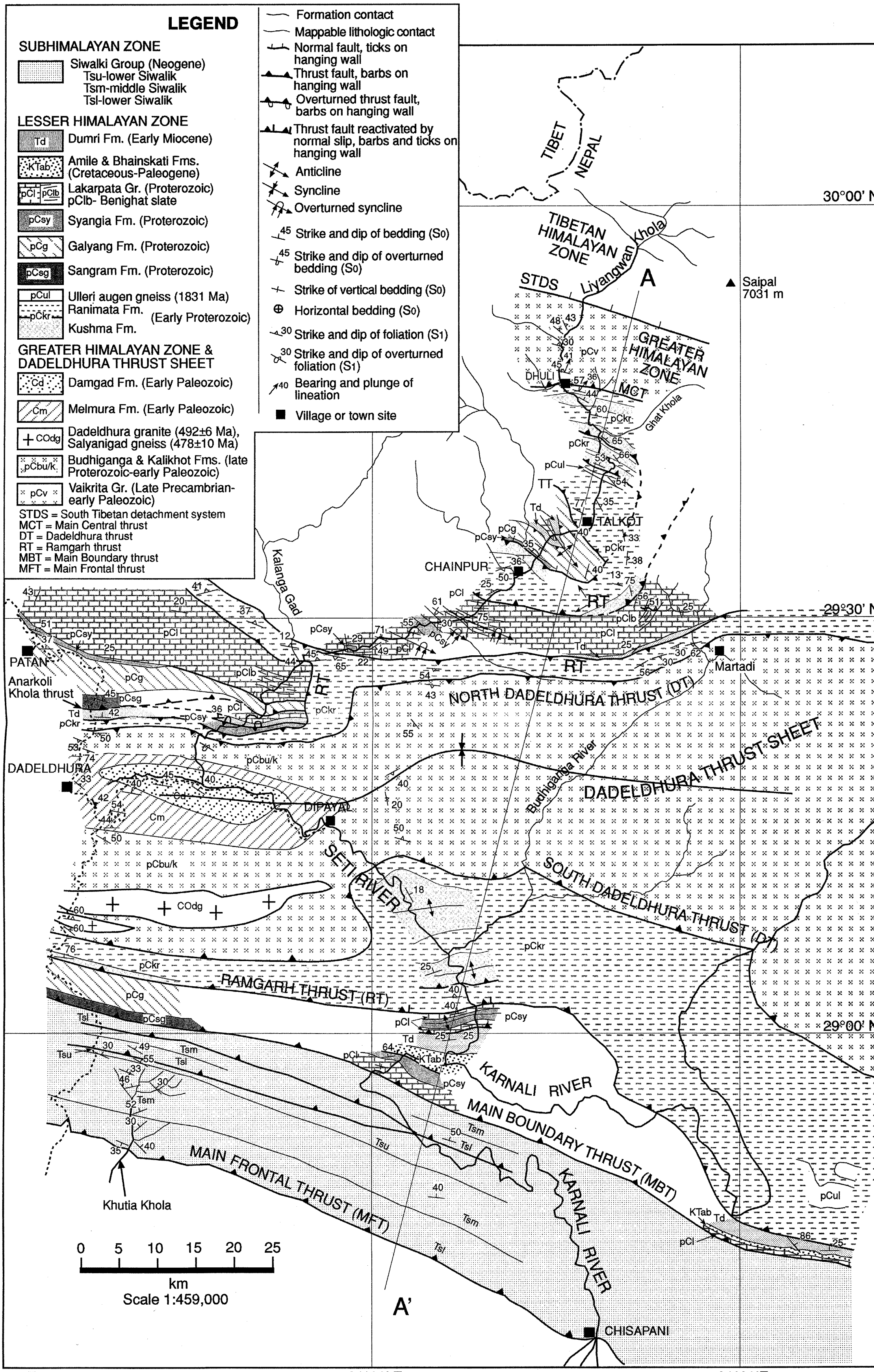
5.4. Ramgarh Thrust System

The Ramgarh thrust system is defined as the major fault system that places greenschist-grade rocks of the Kushma and Ranimata Formations on top of less metamorphosed Lesser Himalayan rocks (Figure 3c) [*Valdiya*, 1980]. Structurally, the Ramgarh thrust sheet rests on top of upper Nawakot and/or Tertiary rocks and beneath the Dadeldhura thrust sheet (Foldouts 1a, 1b, and 2a). *Srivastava and Mitra* [1994] reconstructed the branch line pattern of the Ramgarh thrust in northern India and suggested that it branches from the Almora thrust at the western end of the Almora klippe (equivalent to the Dadeldhura thrust sheet). In western Nepal the Kushma and Ranimata Formations are present on both sides of the Dadeldhura klippe (Foldout 1a) [*Frank and Fuchs*, 1970; *Shrestha et al.*, 1987]. This suggests that the Ramgarh thrust does not branch from Dadeldhura thrust but is folded more or less concordantly along with the overlying Dadeldhura thrust sheet.

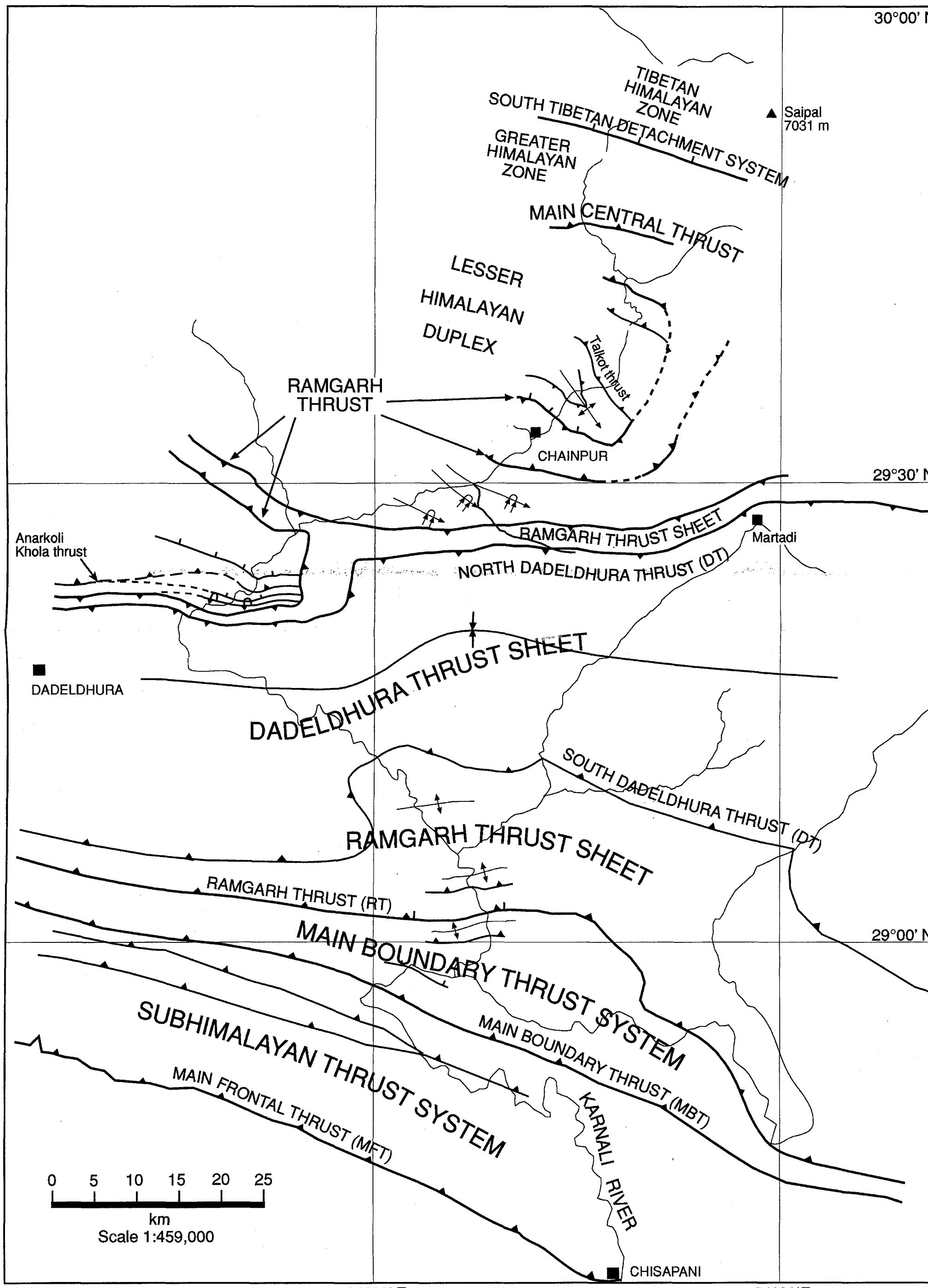
Along the line of our cross section the southern part of the Ramgarh sheet is folded into a pair of broad anticlines with an intervening syncline (Foldouts 1a and 2a, north of the big western bend in the Karnali River). We have mapped the fault that separates Ranimata Formation and Lakarpata Group along the Karnali River as a minor normal fault because surface relationships along strike to the east and along the north limb of the Dadeldhura synform demonstrate that the Ramgarh thrust is resting on Dumri Formation throughout the southern half of the study area. The Ramgarh thrust sheet also crops out in several areas to the north of the Dadeldhura thrust sheet and in a broad, flat-bottomed, east-southeast trending syncline in the Chainpur area. The total bed length of the Ramgarh sheet in a northeast-southwest direction exceeds 125 km, indicating that the Ramgarh thrust has a large amount of displacement. The thrust commonly places the Kushma Formation or Ranimata Formation on top of intensely folded thin-bedded dolostones (Figure 7a) and interbedded slates or shales of the Lakarpata Group and Galyang Formation. These outcrop-scale folds are generally upright and symmetrical and have axes that plunge gently to moderately steeply toward the west, north, and northeast (Figure 8a). In contrast, rocks in the hanging wall of the Ramgarh thrust, although penetratively cleaved and microfolded (Figure 7b), exhibit relatively little mesoscopic short-wavelength folding.

The Ramgarh thrust sheet is remarkably thin for such a regionally extensive, phyllitic thrust sheet. It is plausible that the mechanically competent behavior of the Ramgarh sheet is owed to a combination of the presence of the overlying, very thick and presumably strong Dadeldhura thrust sheet and dehydration metamorphic reactions that took place during burial by the Dadeldhura (and possibly also the Main Central) thrust sheet. Together, the Dadeldhura and Ramgarh thrust sheets are >9 km thick.

We have also recognized the Ramgarh thrust in central and eastern Nepal. Rocks mapped by *Stöcklin* [1980] as the Robang Formation and associated "Dunga quartzite beds" in central Nepal are lithologically identical to the Ranimata and Kushma Formations, respectively. *Stöcklin* [1980] placed these rocks in the upper part of the Nawakot unit (Figure 2, central Nepal column). Detrital zircons from the Dunga quartzite, however, are dominated by ~1860 Ma ages, matching the detrital zircon fingerprint for the Kushma Formation [*DeCelles et al.*, 2000]. We propose that the Dunga quartzite and the associated green phyllites and mafic intrusive rocks of the Robang Formation are juxtaposed by the Ramgarh



Foldout 1a. Geologic map of far western Nepal, based on recent mapping and previous compilations [*Shrestha et al.*, 1987; *Fuchs*, 1977].



Foldout 1b. Tectonic map of the study area in western Nepal, showing major faults and tectonic zones discussed in the text.

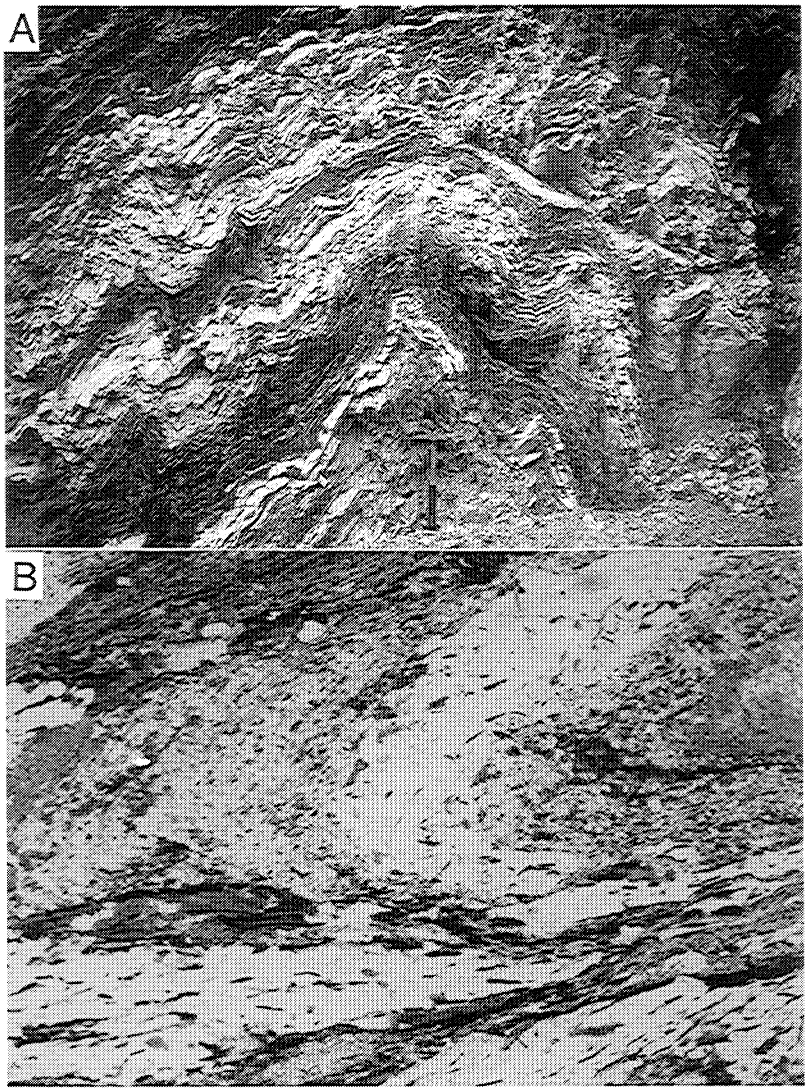


Figure 7. (a) Mesoscale fold in banded dolostone of the Lakarpata Group, below the Ramgarh thrust near Deura. Hammer is 30 cm long. (b) Photomicrograph of a microfold in the phyllitic facies of the Ranimata Formation. Width of the image is 9 mm.

thrust against the Benighat Formation along the south limb of the Kathmandu klippe. In eastern Nepal the Ramgarh thrust is superbly exposed below the bridge over Tamar Khola at the village of Tribeni (Figure 1), where the Kushma Formation (mapped as part of the Tumlingtar Group by *Schelling* [1992]) is in thrust contact with red slates of the probable equivalent of the Syangia Formation.

5.5. Dadeldhura Thrust System

The Dadeldhura thrust sheet is the eastern continuation of the Almora "crystalline nappe" of Kumaon [*Valdiya*, 1980; *Srivastava and Mitra*, 1994]. The southern boundary of the Dadeldhura sheet is marked by the south Dadeldhura thrust, and the northern boundary is marked by the north Dadeldhura thrust (contiguous with the south and north Almora thrusts, respectively [*Heim and Gansser*, 1939; *Valdiya*, 1980; *Srivastava and Mitra*, 1994, 1996]). Like the Almora sheet, the Dadeldhura sheet is a synformal klippe of muscovite-biotite-garnet schist (Kalikhot Schist), mylonitic augen gneiss (Budhiganga and Salyanigad Gneisses), and Cambrian-Ordovician granite (Dadeldhura Granite) that was emplaced on top of greenschist-grade metasedimentary and metavolcanic rocks of the underlying Ramgarh thrust sheet. A remnant of nearly unmetamorphosed Tethyan strata is preserved in the core of the synform between the towns of Dipayal and Dadeldhura (Foldout 1a). The synform is clearly defined by the most prominent cleavage, which dips generally 30°-65° SSW in the north limb of the synform and 35°-55° NNE in the south limb. In central and eastern Nepal the structural equivalent of the Dadeldhura thrust is the Mahabharat thrust, which carries the Kathmandu crystalline nappe [*Stöcklin*, 1980; *Rai*, 1998].

The Dadeldhura synform is a remnant of an extensive thrust sheet that must have covered the entire Lesser Himalayan zone

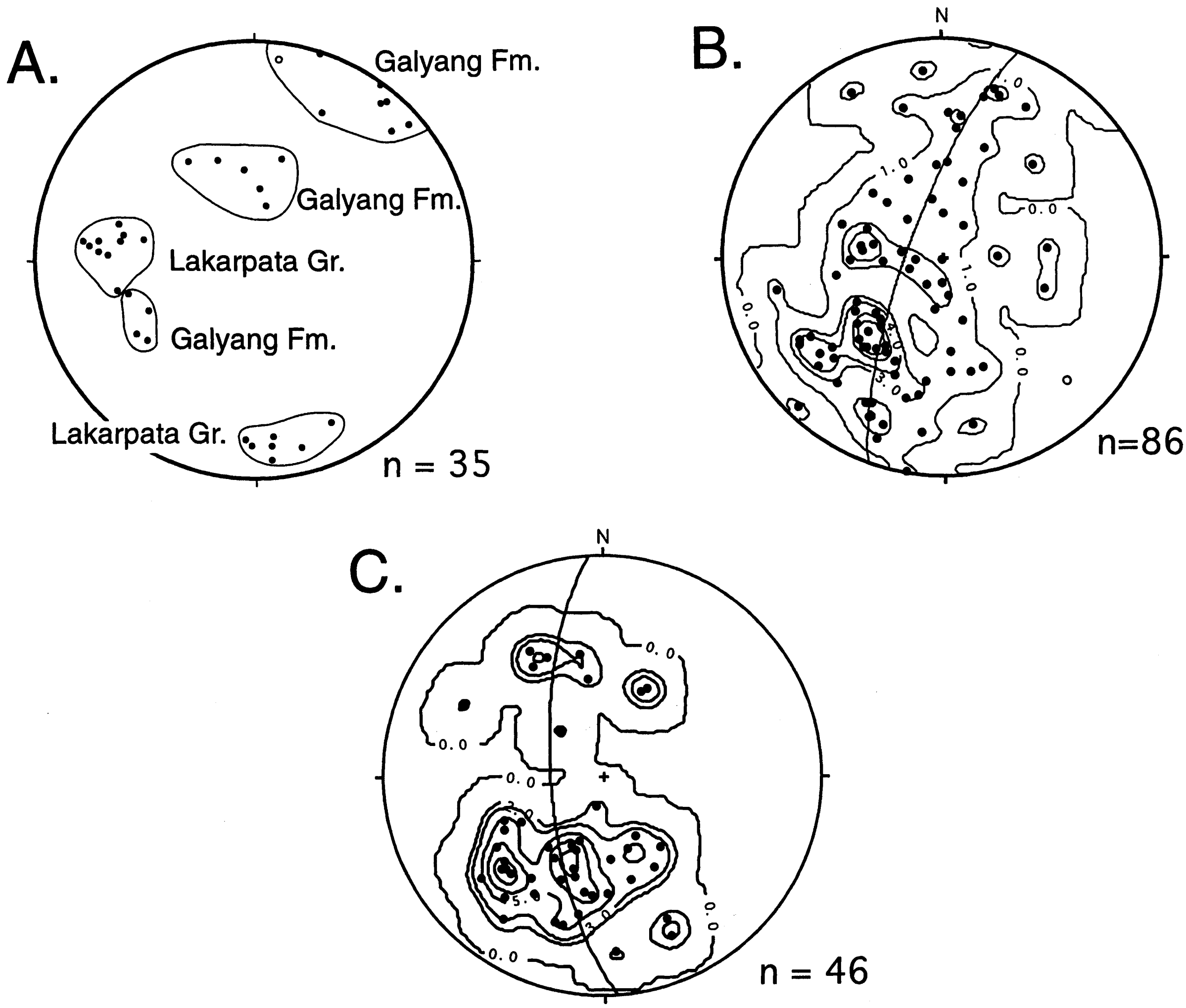


Figure 8. Equal area projections of (a) axes of small-scale folds in Lesser Himalayan rocks north of the Dadeldhura thrust sheet, (b) poles to bedding (with best fit great circle), and (c) poles to cleavage (with best fit great circle) in Lesser Himalayan rocks along Seti River transect.

to the north of the synform. Owing to a shallower level of erosion, this thrust sheet and the overlying Main Central thrust sheet still cover most of the fold-thrust belt in eastern Nepal [e.g., *Schelling*, 1992; *Upreti and LeFort,* 1999].

5.6. Lesser Himalayan Duplex Zone

To the north of the northern trace of the Dadeldhura thrust, Lesser Himalayan rocks in western Nepal consist of steeply southward asymmetric to overturned folds and imbricated panels of lower and upper Nawakot units overlain by Gondwanan and Tertiary units. These imbricated thrust sheets generally dip 40°-55° NNE (Figure 8b). We mapped three separate thrust-bounded panels of the Kushma and Ranimata Formations along the Seti River between Talkot and Dhuli (Sanigaon) on the basis of repetitions of thick packages of quartzite and phyllite and a reasonable northward increase in the thickness of the Kushma-Ranimata succession. Structural facing direction indicators, including cleavage-bedding relationships and various types of cross stratification, demonstrate that the rocks within the imbricated panels of Kushma and Ranimata are consistently upright and are not repeated by folding.

Between the villages of Talkot and Chainpur a complex, southeast plunging antiform is cored by Lakarpata Group, Amile Formation, and Dumri Formation (Foldout 1a and Figure 9). The Dumri is overlain by an enveloping, antiformal thrust sheet of the Galyang and Syangia Formations. This sheet is in turn overlain structurally on both sides of the antiform by the Kushma-Ranimata succession. The southern belt of Kushma-Ranimata (which surrounds Chainpur) is folded into a broad east-west trending syncline (Foldout 1a). We interpret the southern belt as a synformal remnant of the Ramgarh thrust sheet. Approximately 3 km south of Talkot, the Galyang Formation is overlain by the Ranimata Formation along a poorly exposed contact that we infer to be a thrust fault; this will be referred to as the Talkot thrust. The package of Ranimata Formation above the Talkot thrust (we have not found Kushma Formation in the Talkot area) is upright and dips consistently northeastward, indicating that it cannot be structurally contiguous with the synformal Ramgarh thrust sheet in the Chainpur area (Figure 9). Cleavage in the

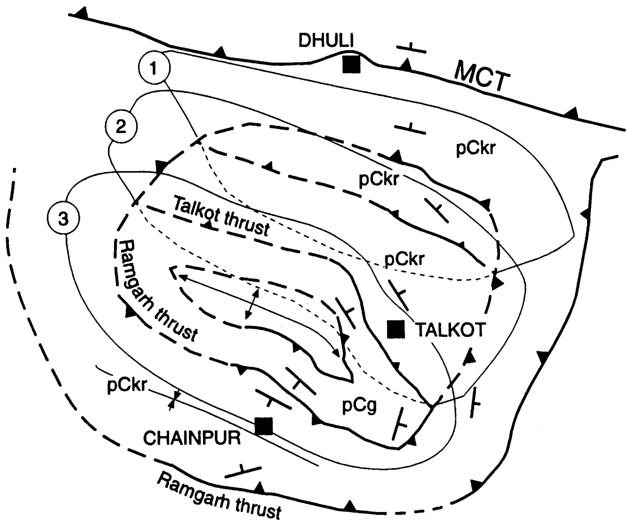


Figure 9. Simplified branch line map of the Lesser Himalayan duplex in the Talkot and Chainpur areas showing buried branch lines (solid lines) and eroded branch lines (dashed lines). Map unit symbols are same as in Foldout 1a.

Ranimata Formation southeast and east of Talkot dips moderately eastward, and we interpret these rocks to be part of the Ramgarh sheet. The structural and stratigraphic relationships suggest that a branch point between the Talkot and Ramgarh thrusts exists ~5 km southeast of Talkot (Figure 9). Between Talkot and Dhuli, two additional thrust sheets of Kushma and Ranimata rocks crop out (Foldout 1a). The northern of these two sheets is interpreted to be the Ranimata thrust sheet, where it roots beneath the the Main Central thrust. The southern thrust may share a branch line with the Ramgarh thrust that intersects the surface ~8 km northeast of Talkot (Figure 9).

The relationships in the Talkot-Chainpur area suggest the presence of a large duplex in Lesser Himalayan rocks. The map pattern, incomplete as it is, is similar to that expected where a hinterland-dipping duplex is breached by an erosional window (Figure 9) [*Boyer and Elliott*, 1982]. The regional map compilation of *Shrestha et al.* [1987] and mapping by *Fuchs* [1977] in the headwaters region of the Karnali River to the east of our study area also suggest that the Ramgarh thrust roots beneath the Main Central thrust and is breached by erosional windows into Lesser Himalayan rocks. The roof thrust for the duplex is the Ramgarh thrust, and the floor thrust is the Main Himalayan thrust, which is the basal décollement of the fold-thrust belt. Construction and restoration of the balanced cross section (discussed in section 5.8) suggests that in detail, the floor thrust is at or near the base of the Kushma-Ranimata succession in the northern part of the duplex and beneath the Sangram or Galyang Formations in the southern part of the duplex (Foldout 2a).

5.7. Main Central Thrust and Greater Himalayan Zone

The Main Central thrust in the study area is expressed topographically as a major increase in elevation from ~3000 to >5000 m, but we did not observe a discrete fault. The inferred fault zone places medium- to high-grade schist and gneiss on top of fine schist and phyllite of the Lesser Himalayan zone. Foliations in the Greater Himalayan rocks dip 30° to 48°N, parallel to foliations in the underlying Lesser Himalayan rocks (Figure 8c). We therefore interpret the fault to be parallel to the regional fabrics in its footwall and hanging wall [*Schelling*, 1992], which implies that the fault juxtaposes a hanging wall flat with a footwall flat. The steep dip of the fault zone must have developed long after the emplacement of the Main Central thrust sheet, presumably during rotation of the north limb of the Lesser Himalayan duplex.

5.8. Regional Structural Cross Section

A regional balanced cross section was constructed on the basis of thickness and orientation data collected in the course of mapping (Foldout 2a). The section is pinned on the south by undeformed Siwalik Group beds penetrated by petroleum exploration wells in northern India [*Karunakaran and Rao*, 1979; *Srivastava and Mitra*, 1994]. The location of the Main Himalayan thrust is crudely constrained by known stratigraphic thicknesses south of and beneath the Dadeldhura thrust sheet, by earthquake foci north of the Dadeldhura thrust sheet [*Ni and Barazangi*, 1984; *Pandey et al.*, 1995, 1999], and by the INDEPTH deep crustal reflection seismic profile in the region beneath the Greater and Tibetan Himalayan zones [*Hauck et al.*, 1998]. Foliations in the metamorphic rocks of the Ramgarh, Dadeldhura, and Main Central thrust sheets are interpreted to be parallel to major lithostratigraphic boundaries in the hanging wall rocks. This was noted by *Schelling* [1992] in eastern Nepal and is justified by map relationships between foliations and faults. Thicknesses in the Siwalik Group and Dumri Formation were obtained from detailed measured sections [*DeCelles et al.*, 1998a, 1998b]. The cross section does not incorporate microstrain or mesoscale folding, which are abundant in the Lesser Himalayan rocks, particularly in the Galyang and Sangram Formations and in the thin-bedded carbonates of the Lakarpata Group. In addition, the rocks of the Greater Himalayan zone are restored in bulk, although they have experienced perhaps as much as 100 km of internal, bed-parallel displacement by ductile simple shear [*Manickavasagam et al.*, 1999]. Other details in the cross section are justified and explained in Foldout 2a.

The key features of the cross section include the following:

1. The Main Frontal thrust system consists of two panels of 30°-40°N dipping Siwalik Group strata and has a frontal ramp anticline.

2. The Main Boundary thrust sheet is broken by a pair of minor thrusts and two inferred normal faults. If these minor faults are rooted in the Main Boundary thrust, as depicted in the cross section, then they provide evidence that the Main Boundary thrust postdates final emplacement of the Ramgarh thrust sheet because the two northern faults also cut the Ramgarh sheet (Foldout 2a, points 7 and 8). It is also possible that these faults are restricted to the hanging wall of the Ramgarh thrust. The Main Boundary thrust sheet is rooted beneath the southern flank of the Lesser Himalayan duplex, under the northern limb of the Dadeldhura synform (Foldout 2a, point 20).

3. The Lesser Himalayan duplex is a composite, hinterland-dipping duplex and antiformal stack. This duplex is the

dominant structure in the northern belt of Lesser Himalayan rocks throughout central and western Nepal and in Kumaon [*Schelling and Arita*, 1991; *Srivastava and Mitra,* 1994; *Paudel and Arita,* 2000]. The southern portion of the duplex contains five horses of the Sangram, Galyang, Syangia, Amile, and Dumri Formations and the Lakarpata Group. Two of these horses are interpreted to contain tight fault propagation anticlines, which are separated by a synform in the overlying Ramgarh thrust sheet in the Chainpur area. A relatively minor normal fault cuts the north limb of the southern anticline and is inferred to merge into and reactivate the thrust fault that underlies this horse (Foldout 2a, point 11). The northern portion of the duplex consists of two horses of the Kushma and Ranimata Formations, with a body of Ulleri augen gneiss in the southernmost of these horses.

4. The Ramgarh thrust sheet is folded into a pair of minor antiforms above the Main Boundary thrust sheet and into a much larger synform-antiform pair in the Dadeldhura synform and above the Lesser Himalayan duplex. As discussed in section 5.4, the Ramgarh sheet is interpreted to be rooted beneath the Main Central thrust in the north limb of the duplex. Although other options for the Ramgarh root zone are feasible in terms of balancing the cross section, we have chosen the interpretation that is both simplest and most easily reconciled with existing geochronology and thermochronology.

5. The Dadeldhura thrust sheet occupies a broad asymmetric synform and is inferred to have extended over the top of the Lesser Himalayan duplex [*Srivastava and Mitra*, 1994] before it was eroded in mid-Miocene time [*DeCelles et al.*, 1998a]. The Dadeldhura thrust is depicted as a separate thrust from the Main Central thrust, with an eroded trailing branch line that connected the two above the northern part of the duplex (Foldout 2a, point 13). The position of the branch line is only constrained to have lain above the present ground surface in order to juxtapose rocks of the Main Central thrust sheet with the Ramgarh thrust sheet. An alternative interpretation is that the Dadeldhura thrust is the southern extension of the Main Central thrust. However, we tentatively favor the two-thrust interpretation because of the presence of the high-grade metamorphic (kyanite- and sillimanite-bearing) Karnali nappe on top of the eastern continuation of the Dadeldhura thrust sheet [*Fuchs*, 1977; *Arita et al.,* 1984]. The Karnali nappe can be extrapolated across a short erosional gap into hanging wall rocks of the Main Central thrust [*Upreti and LeFort*, 1999].

6. The Main Central thrust zone is depicted as a 48° NNE dipping fault, although it is not a single, discrete fault. Although the southward extent of the Main Central thrust sheet is not known, we have projected it along strike from the east in accordance with the relationship between the Karnali and Dadeldhura nappes.

6. Estimates of Shortening and Kinematic Evolution

6.1. Shortening Estimates

Restoration of the cross section provides a minimum estimate of horizontal shortening in the Himalayan fold-thrust belt of western Nepal (Foldout 2b). The minimum shortening in the combined Subhimalayan and Lesser Himalayan zone is ~287 km, with ~122 km of this accommodated by initial displacement on the Ramgarh thrust. Because the Ramgarh thrust also acted as the roof thrust for the Lesser Himalayan duplex, the frontal part of fault remained active in order to accommodate duplex growth. The Main Boundary thrust experienced ~14 km of initial slip, and additional southward displacement of the Main Boundary sheet took place as the Main Frontal thrust system became active. The minimum displacements on the Dadeldhura and Main Central thrusts are 103 and 28 km, respectively. If the Dadeldhura thrust sheet completely buried the Ramgarh sheet, then an additional 23 km of slip is required. Similarly, an additional 52 km of slip is required on the Main Central thrust if it originally reached as far south as the present axis of the Dadeldhura syncline, as suggested by relationships in the Karnali nappe region [*Upreti and LeFort*, 1999] and in eastern Nepal [*Schelling*, 1992].

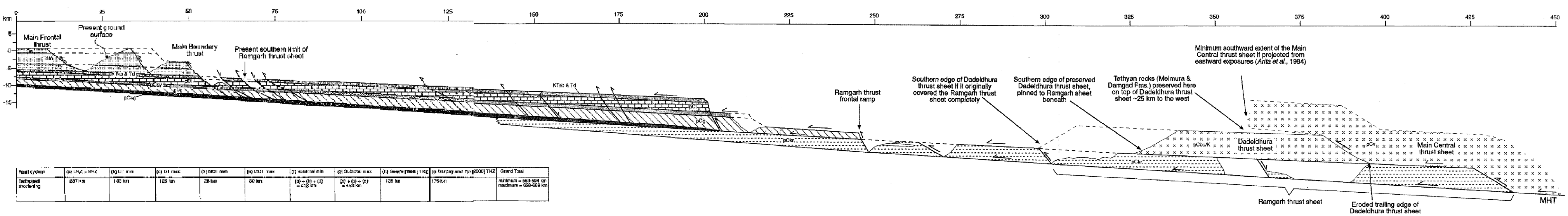
Recent U-Pb and Nd isotopic studies have demonstrated that the Greater Himalayan rocks are not Indian crustal basement [*Parrish and Hodges*, 1996; *Whittington et al.*, 1999; *Robinson et al.*, 1999; *DeCelles et al.*, 2000; *Ahmad et al.*, 2000]. *DeCelles et al.* [2000] suggested that the Greater Himalayan rocks were originally accreted to northern India and structurally emplaced adjacent to the Lesser Himalayan rocks during early Paleozoic time along a tectonic boundary that was subsequently overprinted by the Main Central thrust during the Cenozoic orogeny. Because of the uncertainties of the pre-Cenozoic structural level of the Greater Himalayan rocks, we have made no attempt to restore the Main Central and Dadeldhura thrust systems to their pre-Cenozoic positions.

The total (minimum) shortening estimate from the cross section is ~418 km. Including the additional likely displacements on the Main Central and Dadeldhura thrusts raises the total to 493 km, which is substantially higher than current estimates from eastern Nepal [e.g., *Schelling*, 1992; *Hauck et al.*, 1998]. Adding estimates by *Searle* [1986] for the Zanskar region or by *Murphy and Yin* [2000] for the Tibetan Himalayan zone and Indus suture zone to the northwest of our study area yields an estimate for the entire central part of the Himalayan fold-thrust belt of 628-669 km. However, this should be considered a bare minimum because of the uncertainties regarding the displacements on the Dadeldhura and Main Central thrusts and the abundance of smaller-scale structures and microstrain. For example, in eastern Nepal where the hanging wall of the Main Central thrust is still preserved near the front of the fold-thrust belt, a minimum overlap of ~140 km can be measured, and *Schelling* [1992] suggested that up to ~210 km of slip may have occurred on fault. Inclusion of comparable estimates with our total estimate for western Nepal and adjacent Tibet would increase the total shortening to >750 km. However, it is not advisable to combine shortening estimates from western Nepal with those from eastern Nepal until further mapping in eastern Nepal allows assessment of the roles of the Ramgarh and Dadeldhura thrusts (or their equivalents) in the total shortening budget.

6.2. Kinematic History

The bulk rock kinematic history of thrusting in western Nepal can be deduced from thermochronology, cross cutting relationships, and provenance data from the foreland basin

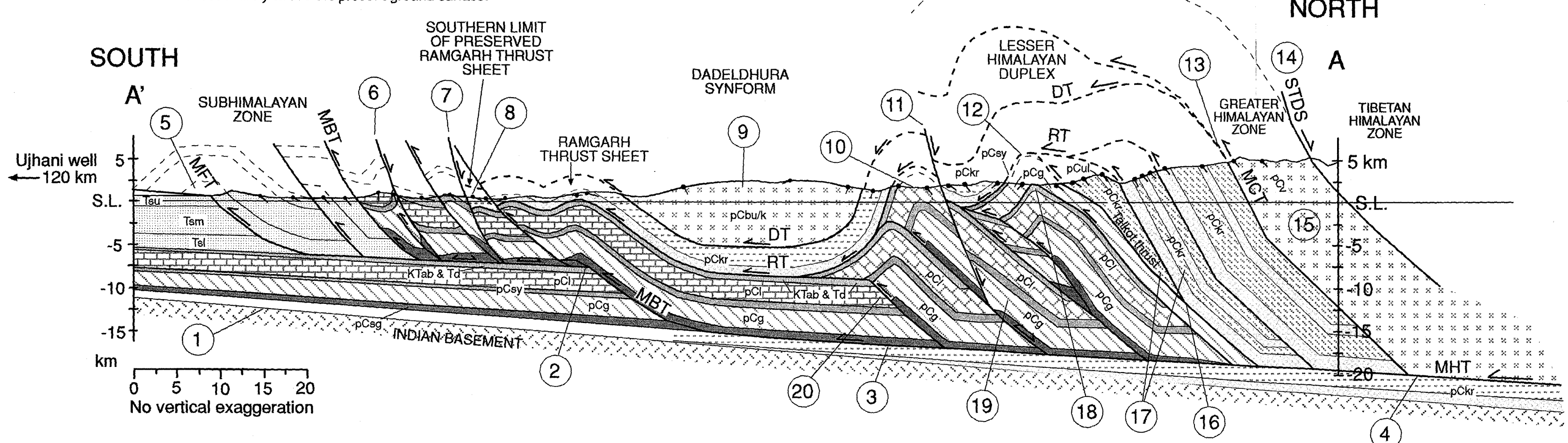
Foldout 2b. Restored cross section A-A'. See Foldout 1a for symbols and lithologic units. Tabulation at lower left provides maximum (max) and minimum (min) shortening estimates. Abbreviations are as follows: LHZ, Lesser Himalayan zone; SHZ, Subhimalayan zone; MHT, Main Himalayan thrust; DT, Dadeldhura thrust; MCT, Main Central thrust; THZ Searle [1986], estimate for Zanskar Tibetan Himalayan zone; THZ *Murphy and Yin* [2000], estimate for Tibetan Himalayan zone in the Mount Kailas region, ~50-100 km north-northwest of this study area. Note the change in scale from that in Foldout 2a.



Fault system	(a) LHZ + SHZ	(b) DT min	(c) DT max	(d) MCT min	(e) MCT max	(f) Subtotal min	(g) Subtotal max	(h) Searle [1986] THZ	(i) Murphy and Yin [2000] THZ	Grand Total
Estimated shortening	287 km	103 km	126 km	28 km	80 km	(a) + (b) + (d) = 418 km	(a) + (c) + (e) = 493 km	135 km	176 km	minimum = 553-594 km maximum = 628-669 km

1. The ~4° N regional dip on basement-cover interface is based on projection of Ujhani well data from ~120 km south of MFT (Karunakaran and Rao, 1979). MHT dips ~4° N on basis of earthquake seismology (Ni & Barazangi, 1984; Pandey et al., 1995, 1999) and INDEPTH reflection seismology (Hauck et al., 1998).
2. Top of footwall ramp constrained by bed length of Siwalik Group in MFT imbricate thrust sheets.
3. Depth of MHT consistent with known thickness of Lesser Himalayan rocks under Dadeldhura synform and seismology (see point 1).
4. Depth of MHT consistent with INDEPTH reflection profile (Hauck et al., 1998).
5. Frontal ramp anticline based on data from Khutia Khola area (25-35 km to west; DeCelles et al., 1998a).
6. Inferred normal fault explains juxtaposition of Eocene rocks with Syangia Formation.
7. Inferred normal fault drops Ramgarh thrust sheet down against Lakarpata Group.
8. Minimum southward extent of Ramgarh thrust sheet preserved in outcrop.
9. Thickness of Dadeldhura thrust sheet is based on dip data in exposed limbs of the Dadeldhura synform.
10. Lakarpata Group contains numerous meso-scale folds and minor faults in surface exposures.
11. Normal fault inferred here to explain the absence of lower Miocene Dumri Formation (Td) beneath the Kushma/Ranimata Formations.
12. Ramgarh thrust here rests on Syangia Formation, requiring a footwall flat at Syangia level. The presence of rocks younger than the Syangia would require an additional break-through thrust.
13. Inferred branch line between Dadeldhura and Main Central thrusts is placed at lowest possible elevation to keep DT sheet entirely above the present ground surface.

Foldout 2a. Balanced regional cross section A-A'. See Foldout 1a for location and meaning of lithologic units and symbols.



14. Location and geometry of South Tibetan detachment system (STDS) are not well constrained.
15. Thickness and internal structure of Greater Himalayan rocks (pCv) are poorly constrained. Dip of the MCT is based on dips of major foliations in rocks above and below the fault zone.
16. Inferred branch line is based on minor changes in foliation dip at surface.
17. Two horses of Kushma and Ranimata Formations (pCkr) are inferred on basis of apparent repetitions of lithologies and excess thickness in the region directly south of the MCT.
18. Cretaceous-lower Miocene (Amile, Bhainskati, and Dumri Fms.) are exposed in core of complex antiform, requiring an overlying thrust sheet of Galyang Formation and a large underlying horse of Lesser Himalayan rocks.
19. Horses of Lesser Himalayan rocks required to fill space within duplex.
20. Ramp here determined on basis of steep southward dips in Dadeldhura and Ramgarh thrust sheets and Lesser Himalayan rocks in the footwall of the Ramgarh thrust. Suggests that the Main Boundary thrust sheet does not extend farther north.

FAULT ABBREVIATIONS:
MHT = Main Himalayan thrust
STDS = South Tibetan detachment system
MCT = Main Central thrust
DT = Dadeldhura thrust
RT = Ramgarh thrust
MBT = Main Boundary thrust
MFT = Main Frontal thrust

deposits. Figure 10 depicts a sequential kinematic restoration. We acknowledge that the cross section, the estimates of shortening, and the deduced kinematic history are rudimentary and will certainly change as more information is obtained.

Structural and provenance evidence for middle Eocene-Oligocene thrusting in the Tibetan Himalaya was discussed by *Searle* [1986], *Ratschbacher et al.* [1994], *Yin et al.* [1994, 1999], *DeCelles et al.* [1998b], and *Najman and Garzanti*

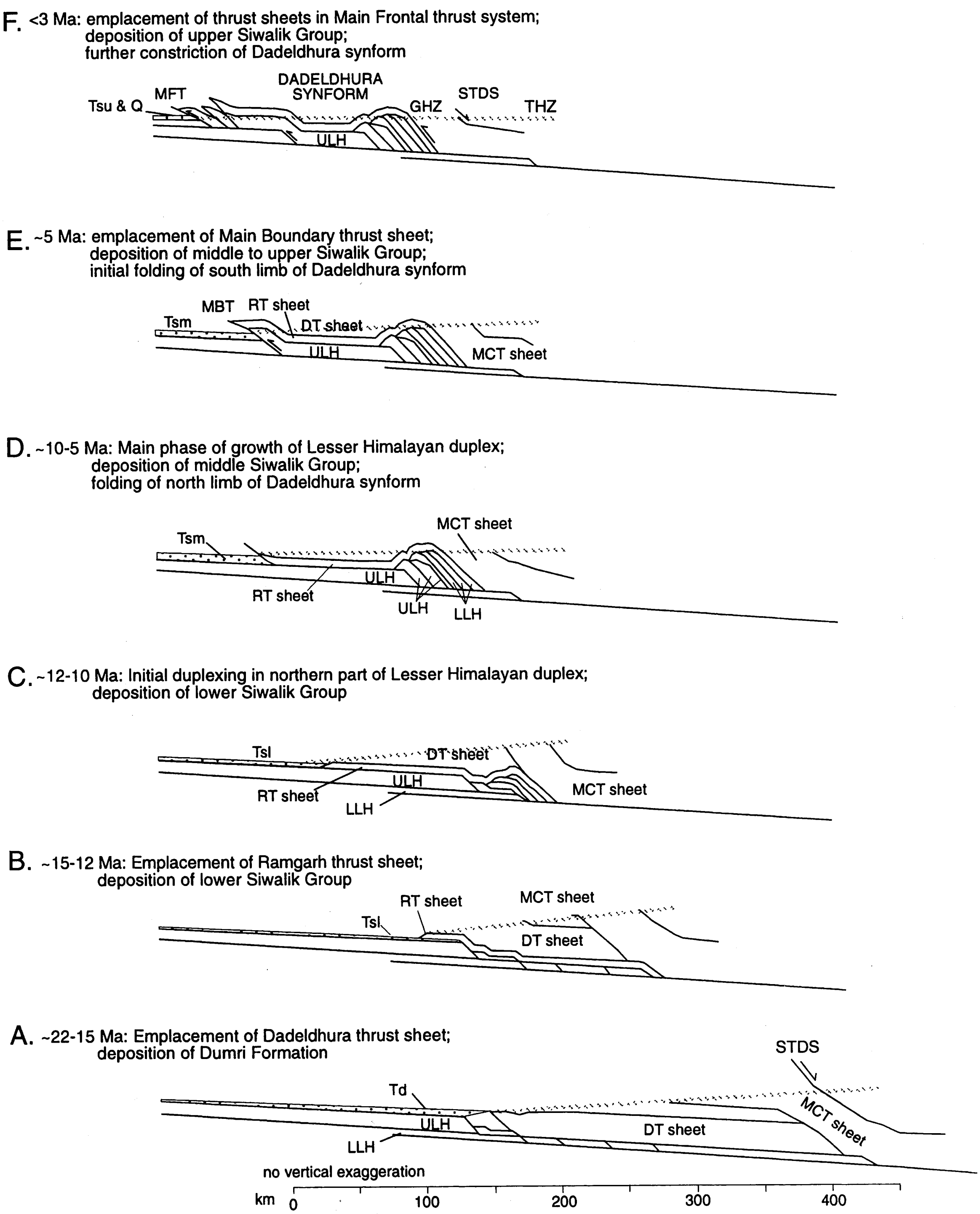


Figure 10. Incremental balanced restoration of the Himalayan fold-thrust belt in western Nepal. Minor faults and some structural details depicted in Foldout 2a are omitted for clarity. The hatched line represents approximate position of the mean ground surface. Abbreviations are as follows for rock units, LLH, lower Lesser Himalayan; ULH, upper Lesser Himalayan; Q, Quaternary; for major faults, STDS, South Tibetan detachment system; MCT, Main Central thrust; DT, Dadeldhura thrust; RT, Ramgarh thrust; MBT, Main Boundary thrust; MFT, Main Frontal thrust; for tectonostratigraphic zones, GHZ, Greater Himalayan zone; THZ, Tibetan Himalayan zone. Other units are labeled as they are in Foldout 1a.

[2000]. Crustal thickening by thrusting also persisted into mid-Miocene time in parts of the Tibetan Himalaya [*Yin et al.*, 1999]. The "Eohimalayan" episode of Barrovian metamorphism in the Greater Himalayan rocks took place during late Eocene and Oligocene time, probably in response to tectonic burial by Tibetan thrust sheets and ductile deformation at depth [e.g., *Hodges and Silverburg*, 1988; *Hodges et al.*, 1988; *Vannay and Hodges*, 1996; *Coleman*, 1998; *Godin et al.*, 1999; *Hodges*, 2000; *Catlos et al.*, 2001b].

Conventional and isotopic provenance data from the Dumri Formation in western Nepal indicate that the most likely time of initial erosion of the Greater Himalayan metamorphic rocks above the Main Central thrust system is early Miocene [*DeCelles et al.*, 1998b; *Robinson et al.*, 1999]. The $^{40}Ar/^{39}Ar$ ages from detrital muscovites in the Dumri Formation suggest that its source terrane cooled below ~350°C during early Miocene time (Figure 6a) [see also *Najman et al.*, 1997]. We suggest that this cooling was associated with emplacement of the Main Central thrust sheet. This is consistent with thermochronologic ages attributed to cooling during emplacement of the Main Central thrust sheet in other parts of Nepal [*Hubbard and Harrison*, 1989; *Copeland et al.*, 1991; *Hodges et al.*, 1996]. Exhumation and erosion of Greater Himalayan rocks during Dumri deposition may also have been facilitated by displacement along the South Tibetan detachment system (Figure 10a) [*Hodges et al.*, 1996; *DeCelles et al.*, 1998a].

The Dadeldhura thrust is folded conformably with the underlying Ramgarh thrust sheet in the Dadeldhura synform and above the Lesser Himalayan duplex, indicating that both sheets must have been emplaced before duplex growth. The conformable relationship between the two thrust sheets suggests that the Dadeldhura sheet was emplaced onto the Ranimata Formation before the Ramgarh thrust became active. A sample of the Budhiganga Gneiss in the north limb of the Dadeldhura synform yielded an $^{40}Ar/^{39}Ar$ plateau age of 21.36 ± 0.09 Ma from muscovite (Figure 6b). We tentatively interpret this age as the time at which the rock passed through the muscovite-blocking isotherm during initial emplacement of the Dadeldhura thrust sheet, probably as it moved up the northernmost ramp that cuts the Lesser Himalayan rocks, onto a regional flat on top of the Ranimata Formation (Figure 10a). Thermochronologic data from the structurally analogous Kathmandu thrust sheet in central Nepal indicate cooling through the muscovite-blocking isotherm between 22 and 14 Ma [*Copeland et al.*, 2001].

The Ramgarh thrust is the roof thrust of the Lesser Himalayan duplex, which implies that it must have developed prior to duplex growth. In addition, the Ramgarh thrust must postdate deposition of the Dumri Formation (~15 Ma) because it rests on top of the Dumri in many places (Figure 10b). This is consistent with the $^{40}Ar/^{39}Ar$ age from the Dadeldhura sheet (which overrode the Ranimata Formation prior to Ramgarh thrust displacement). Also, $^{40}Ar/^{39}Ar$ ages of detrital muscovite grains from a sample in the middle Siwalik Group at Khutia Khola (deposited at ~8 Ma; see Figure 6d) have frequency maxima at ~13 and ~16 Ma. These muscovites could have been derived (at ~8 Ma) from the Ramgarh thrust sheet.

Growth of the Lesser Himalayan duplex (Figures 10c and 10d) must postdate deposition of the Dumri Formation, which is contained in some of the horses that constitute the duplex. In addition, the duplex folded (and therefore must postdate emplacement of) the Ramgarh and Dadeldhura thrust sheets in the north limb of the Dadeldhura synform (Figure 10d). The strongest evidence for the timing of duplex growth comes from detrital zircon ages and conventional provenance data from the Siwalik Group. Beginning at ~12-11 Ma, Siwalik sandstones recorded an influx of potassium feldspar derived from the Dadeldhura granite and metacarbonate lithic grains and Paleoproterozoic zircons derived from Lesser Himalayan metasedimentary rocks [*DeCelles et al.*, 1998a]. In addition, a large upward excursion in the $^{87}Sr/^{86}Sr$ ratio of pedogenic carbonate nodules in Siwalik floodplain mudstones at ~9 Ma indicates erosion of Lesser Himalayan carbonates now exposed in the southern part of the duplex [*Quade et al.*, 1997; *English et al.*, 2000].

The emplacement of the Ramgarh thrust sheet and timing of growth of the Lesser Himalayan duplex have important implications for recent Th-Pb ion microprobe analyses of in situ monazite inclusions in garnets and rock matrix in central and eastern Nepal as discussed by *Harrison et al.* [1997] and *Catlos et al.* [2001a, 2001b]. These authors report geochronological evidence for early Miocene to Pliocene monazite growth in Lesser Himalayan rocks south of the Main Central thrust. In central Nepal the monazite ages generally decrease southward into structurally lower levels of the Lesser Himalayan rocks, from 18-22 Ma directly beneath the Main Central thrust to 7-15 Ma several kilometers south of the fault zone to latest Miocene-Pliocene near the garnet isograd 5-10 km south of the Main Central thrust [*Catlos et al.*, 2001a]. In eastern Nepal, south of Mount Everest, the monazite ages decrease southward in the footwall of the Main Central thrust from ~20 to ~11 Ma. These ages and the associated pressure-temperature estimates suggest that the rocks were rapidly exhumed from midcrustal depths during the Miocene [*Harrison et al.*, 1998], perhaps by major (several tens of kilometers) reactivation of the Main Central thrust. However, the young monazite ages are from Lesser Himalayan rocks that, if our structural model for duplexing in the Lesser Himalayan zone can be extended into central and eastern Nepal, are part of the north limb of the duplex rather than the hanging wall of the Main Central thrust. Moreover, the ages and pressure-temperature conditions are compatible with expected metamorphism in the Ramgarh thrust sheet and in the underlying horses of Kushma-Ranimata succession (Figures 10a-10d). An alternative explanation is that the young monazites grew in response to burial of Lesser Himalayan rocks beneath the north limb of the duplex. As each new horse was incorporated into the infrastructure of the duplex, its passage over the ramp beneath the duplex would have uplifted all the rocks to its north, including the Main Central thrust and the Greater Himalayan rocks. This is essentially compatible with the *Harrison et al.* [1998] kinematic model for the Main Central thrust "zone," but it is important to note that the Main Central thrust (in a strict sense) would not have to be reactivated. It is also possible that elements of both models were involved in bringing the youthful monazite-bearing rocks to the surface in late Miocene-Pliocene time. For example, the development of an out-of-sequence breakthrough thrust in Lesser Himalayan rocks on the north limb of the duplex could explain the Pliocene ages reported by

Catlos et al. [2001a] in central Nepal. Unfortunately, monazite ages from the rocks in our study area are not available, and the regional structure of the Lesser Himalayan zone where the ion microprobe studies have been executed is not well documented.

The Main Boundary thrust cuts rocks as young as the Pliocene upper Siwalik Group (Figure 10e). The upper Siwalik member is composed of abundant quartzite cobbles derived from the Kushma Formation, which was probably exposed in topographic ridges on the Ramgarh thrust sheet above the frontal part of the Main Boundary thrust sheet. The kinematic restoration suggests that it is unlikely that the Main Boundary thrust was active prior to ~5 Ma because, until that time, most of the shortening was being accommodated by duplex growth to the north. In northern India, *Meigs et al.* [1995] suggested that the Main Boundary thrust was active by ~11 Ma on the basis of conglomerate provenance data that suggest sources in Lesser Himalayan quartzites. However, the restoration (Figure 10) makes it clear that other sources of Lesser Himalayan rocks besides the frontal Main Boundary thrust sheet may have existed.

All of the Subhimalayan thrusts carry upper Siwalik Group rocks of Pliocene and younger ages and must therefore be younger than ~3 Ma (Figure 10f). The Main Frontal thrust locally truncates Quaternary syntectonic conglomerates along the topographic front of the Himalaya [*Powers et al.*, 1998; *Wesnousky et al.*, 1999], and a recent study of Quaternary terraces in central Nepal suggests that the fault zone is accommodating most of the convergence between India and Eurasia [*Lavé and Avouac*, 2000].

On the basis of these timing constraints and the estimate of shortening (Foldout 2b), the minimum rate of horizontal shortening since early Miocene time (since emplacement of the Main Central thrust sheet) is ~19-22 mm/yr. This range of rates is consistent with modern rates determined from space geodetic data [*Bilham et al.*, 1997; *Larson et al.*, 1999] and deformed Quaternary terraces [*Lavé and Avouac*, 2000], Neogene rates calculated from balanced cross sections [*Powers et al.*, 1998], and the velocity of the flexural wave across the Himalayan foreland basin during Oligocene-Neogene time [*Lyon-Caen and Molnar*, 1985; *DeCelles et al.*, 1998b]. It would appear that the rate of shortening in the Himalayan fold-thrust belt has been approximately constant throughout much of its history.

7. Conclusions

1. The stratigraphy of the Himalayan fold-thrust belt in western Nepal is consistent with that of adjacent northern India and eastern Nepal. We have proposed a correlation scheme for Lesser Himalayan rocks that is effective throughout Nepal and should help to systematize regional mapping efforts in the future.

2. The regional structure of the fold-thrust belt, from south to north, consists of six major features: the Main Frontal, Main Boundary, Ramgarh, and Dadeldhura thrust systems; the Lesser Himalayan duplex; and the Main Central thrust zone. The Tibetan portion of the fold-thrust belt was active mainly during Eocene-Miocene time [*Ratschbacher et al.*, 1994; *Yin et al.*, 1999]. The Main Central thrust was active during early Miocene time; the Dadeldhura thrust became active during early-middle Miocene (~21-15 Ma); the Ramgarh thrust sheet was emplaced above the lower Miocene Dumri Formation after ~15 Ma; the Lesser Himalayan duplex grew between ~12 and 5 Ma, utilizing the Ramgarh thrust as a roof thrust; the Main Boundary thrust became active ~5 Ma; and the Main Frontal thrust system became active in Pliocene time.

3. Although most of these thrust systems have been previously documented, the Ramgarh thrust has received little attention, in spite of the fact that it has >100 km of slip. Our observations in western, central, and eastern Nepal show that the Ramgarh thrust is present along the entire Nepalese portion of the orogenic belt.

4. The total minimum shortening in this part of the Himalayan fold-thrust belt is ~667 km, comparable with the estimates of *Srivastava and Mitra* [1994] in Kumaon, India, but far greater than *Schelling*'s [1992] estimate in eastern Nepal. Assessment of the veracity of this difference must await further field study. The key structures that increase the shortening estimates in western Nepal are the Ramgarh and Dadeldhura thrust systems, which have not been mapped in eastern Nepal.

5. Because all of the rocks involved in the Himalayan fold-thrust belt appear to be supracrustal, a slab of Indian lower crust, comparable in length to the restored length of the Himalayan orogenic wedge, must have been either subducted or underthrust beneath the Tibetan Plateau. If the latter is true, Himalayan shortening estimates hold great significance for explaining kinematic aspects of the evolution of the Tibetan Plateau.

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P. Copeland, Department of Geosciences, University of Houston, Houston, TX 77204 (copeland@uh.edu)

P.G. DeCelles, T.P. Ojha, J. Quade, and D.M. Robinson, Department of Geosciences, Building 77, University of Arizona, Tucson, AZ 85721. (decelles@geo.arizona.edu; luju@wlink.com.np; jquade@geo.arizona.edu; dmr@geo.arizona.edu)

C.N. Garzione, Department of Earth and Environmental Sciences, Hutchison Hall, University of Rochester, Rochester NY 14627. (garzione@earth.rochester.edu)

B.N. Upreti, Department of Geology, Tri-Chandra Campus, Tribhuvan University, Ghantaghar, Kathmandu, Nepal. (bnupreti@wlink.com.np)

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