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Tectonostratigraphy of the Lesser Himalaya of Bhutan: Implications for the along-strike stratigraphic continuity of the northern Indian margin

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ABSTRACT

New mapping in eastern Bhutan, in conjunction with U-Pb detrital zircon and $\delta^{13}C$ data, defines Lesser Himalayan tectonostratigraphy. The Daling-Shumar Group, 2–6 km of quartzite (Shumar Formation) overlain by 3 km of schist (Daling Formation), contains ~1.8–1.9 Ga intrusive orthogneiss bodies and youngest detrital zircon peaks, indicating a Paleoproterozoic deposition age. The Jaishidanda Formation, 0.5–1.7 km of garnet-biotite schist and quartzite, stratigraphically overlies the Daling Formation beneath the Main Central thrust, and yields youngest detrital zircon peaks ranging from ~0.8–1.0 Ga to ca. 475 Ma, indicating a Neoproterozoic–Ordovician(?) deposition age range. The Baxa Group, 2–3 km of quartzite, phyllite, and dolomite, overlies the Daling-Shumar Group in the foreland, and yields ca. 0.9 Ga to ca. 520 Ma youngest detrital zircon peaks, indicating a Neoproterozoic–Cambrian(?) deposition age range. Baxa dolomite overlying quartzite containing ca. 525 Ma detrital zircons yielded $\delta^{13}C$ values between +3‰ and +6‰, suggesting deposition during an Early Cambrian positive $\delta^{13}C$ excursion. Above the Baxa Group, the 2–3 km thick Diuri Formation diamictite yielded a ca. 390 Ma youngest detrital zircon peak, suggesting correlation with the late Paleozoic Gondwana supercontinent glaciation. Finally, the Permian Gondwana succession consists of sandstone, siltstone, shale, and coal. Our deposition age data from Bhutan: (1) reinforce suggestions that Paleoproterozoic (~1.8–1.9 Ga) Lesser Himalayan deposition was continuous along the entire northern Indian margin; (2) show a likely eastward continuation of a Permian over Cambrian unconformity in the Lesser Himalayan section identified in Nepal and northwest India; and (3) indicate temporal overlap between Neoproterozoic–Paleozoic Lesser Himalayan (proximal) and Greater Himalayan–Tethyan Himalayan (distal) deposition.

INTRODUCTION

Tertiary collision between the Indian and Eurasian plates, and associated crustal shortening, has produced the Tibetan Plateau and Himalayan orogenic belt, two of Earth's most impressive orogenic features. The ongoing convergence between India and Eurasia has produced a composite, south-vergent thrust system that involves the Proterozoic to Paleocene sedimentary cover of northern India (Gansser, 1964; Powell and Conaghan, 1973; Mattauer, 1986; Dewey et al., 1988; Ratschbacher et al., 1994; Hauck et al., 1998; Hodges, 2000; DeCelles et al., 2002; Murphy and Yin, 2003). The original vertical and lateral stratigraphy of sedimentary basins can exert strong first-order controls on regional-scale deformation patterns observed in orogenic belts (e.g., Price, 1980; Hatcher, 1989). For this reason, documenting the stratigraphy and highlighting along-strike stratigraphic similarities and variations in the pre-Himalayan sedimentary packages of the northern Indian margin is a necessary first step in evaluating the timing, kinematics, and geometry of Himalayan deformation. However, since they are now deformed and translated to the south along their entire east-west length, many questions remain regarding the spatial and temporal architecture of the original, composite sedimentary basin (e.g., Brookfield, 1993; Valdiya, 1995; Parrish and Hodges, 1996; DeCelles et al., 2000; Gehrels et al., 2003; Myrow et al., 2003, 2009; Yin, 2006). This problem is further compounded because the Himalayan tectonostratigraphic packages were originally defined by the relationships of rocks to orogen-scale structures such as the Main Central thrust (MCT) (e.g., Gansser, 1964; LeFort, 1975) or South Tibetan detachment system (e.g., Burg, 1983; Burchfiel et al., 1992). Variations in the stratigraphic positions of these structures along strike as well as the extrapolation of geologic relationships observed in more thoroughly studied areas to less studied areas leads to confusion in Himalayan literature regarding both structural and stratigraphic divisions (Yin, 2006).

As a prime example, much of what is now known about the stratigraphy of the northern Indian margin comes from the central part of the Himalayan orogen in Nepal and northwest India (e.g., Srivastava and Mitra, 1994; Hodges et al., 1996; Upreti, 1996; Searle et al., 1997; DeCelles et al., 2000, 2001; Vannay and Grasemann, 2001; Richards et al., 2005; Robinson et al., 2006; Vannay and Hodges, 2003). In the eastern quarter of the orogen, in Bhutan, Sikkim, and Arunachal Pradesh, only local-scale studies describe the stratigraphy of the frontal, Lesser Himalayan portion of the fold-thrust belt (Acharyya, 1980; Raina and Srivastava, 1980; Gansser, 1983; Bhargava, 1995; Kumar, 1997; Yin et al., 2006, 2010b). The original authors' attempts to correlate these units along strike as well as results from orogen-scale studies that review and compile Lesser Himalayan stratigraphy (Brookfield, 1993; Yin, 2006) indicate that many uncertainties remain regarding unit age and both local and regional correlation.

In Bhutan, Lesser Himalayan stratigraphy has been the subject of several local-scale studies (Nautiyal et al., 1964; Jangpangi, 1974, 1978; Gansser, 1983; Gokul, 1983; Ray et al., 1989; Dasgupta, 1995a, 1995b; Bhargava, 1995; Richards et al., 2006; McQuarrie et al., 2008). However, the majority of the Lesser Himalayan section lacks fossils, so most original stratigraphic divisions were based purely on lithology. Significant disagreements in mapping of lithologically similar units (e.g., Gansser, 1983; Bhargava, 1995) have led to difficulties in establishing the exact stratigraphic order for the

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Bhutan Lesser Himalayan section, and make correlation difficult, with rocks even in adjacent areas such as Sikkim (e.g., Raina and Srivastava, 1980; Acharyya, 1994) and Arunachal Pradesh (e.g., Acharyya, 1980; Kumar, 1997; Yin et al., 2010b). Also, due to the lack of biostratigraphic data and minimal radiometric age control on deposition ages, previous age assignments for some Bhutan Lesser Himalayan units have come from lithostratigraphic correlations with units as far along strike as Nepal and northwest India (Nautiyal et al., 1964; Guha Sarkar, 1979). The minimal amount of stratigraphic data obtained thus far for the eastern quarter of the orogen, coupled with detrital geochronology data obtained in recent studies in Nepal and northwest India (Parrish and Hodges, 1996; DeCelles et al., 2001; DiPietro and Isachsen, 2001; Gehrels et al., 2003; Myrow et al., 2003, 2009; Martin et al., 2005) that facilitate along-strike comparison, emphasizes the need for a detailed investigation of Lesser Himalayan stratigraphy in Bhutan.

In this paper, we build a stratigraphy for the Lesser Himalayan portion of the fold-thrust belt in eastern Bhutan, through a combination of new and previous (Gansser, 1983; Gokul, 1983; Bhargava, 1995; McQuarrie et al., 2008) geologic mapping, new U-Pb zircon dates, and $\delta^{13}C$ data. These data provide depositional age constraints, and allow for provenance interpretation and correlation along strike. These age constraints also facilitate evaluating hypotheses proposed for the stratigraphic continuity of the northern Indian margin (DeCelles et al., 2000; Myrow et al., 2003, 2009). This paper will also serve as a valuable foundation for ongoing studies of eastern Himalayan deformation. Our study builds on McQuarrie et al. (2008), which presented a preliminary map, a five-sample detrital zircon age data set from Lesser Himalayan and Tethyan Himalayan units, a preliminary balanced cross section, and a summary of timing constraints from previous studies. Our study expands on this preliminary work with detailed stratigraphic descriptions, 13 new detrital zircon samples, and $\delta^{13}C$ data. A companion paper (Long et al., 2011) uses this stratigraphic framework to present: (1) a comprehensive geologic map of eastern and central Bhutan, (2) detailed structural relationships, (3) four balanced cross sections with accompanying shortening magnitudes, and (4) a compilation of shortening estimates across the orogen.

GEOLOGIC BACKGROUND

The Himalayan orogenic belt has been divided into four tectonostratigraphic zones; from south to north, these are the Subhimalayan, Lesser Himalayan, Greater Himalayan, and Tethyan (or Tibetan) Himalayan zones (Fig. 1) (Gansser, 1964; LeFort, 1975; Hodges, 2000). These zones are defined as distinct structural packages of pre- and syn-Himalayan sedimentary and igneous rocks that have been imbricated and translated to the south during Eocene (Yin and Harrison, 2000; Leech et al., 2005; Guillot et al., 2008) to recent Himalayan mountain building.

Synorogenic deposits of the Subhimalayan zone are exposed along the entire length of the orogen (Gansser, 1964). Synorogenic units as old as Eocene are identified and mapped as part of the Lesser Himalayan zone (DeCelles et al., 1998, 2001; Richards et al., 2005; Najman et al., 2006; Robinson et al., 2006), but the majority of synorogenic deposits are in the Miocene to Pliocene Siwalik Group (Gansser, 1964; Tukuoka et al., 1986; Harrison et al., 1993; Quade et al., 1995; Burbank et al., 1996; DeCelles et al. 1998, 2001, 2004; Ojha et al., 2000; Huyghe et al., 2005; Robinson et al., 2006). The Siwaliks are bound at their base by the Main Frontal thrust (MFT), which coincides with the present Himalayan topographic front.

The Lesser Himalayan zone, which sits structurally above the Subhimalayan zone across the Main Boundary thrust (MBT), contains greenschist-facies sedimentary units as old as Paleoproterozoic, which were deposited on the northern margin of the Indian craton (Schelling and Arita, 1991; Parrish and Hodges, 1996; Kumar, 1997; Upreti, 1999; DeCelles et al., 2000; Richards et al., 2005; McQuarrie et al., 2008; Kohn et al., 2010). Lesser Himalayan strata of Mesoproterozoic age are exposed in Nepal (Martin et al., 2005; Robinson et al., 2006), and Neoproterozoic to Cambrian Lesser Himalayan strata are exposed in northwest India (Myrow et al., 2003; Azmi and Paul, 2004; Richards et al., 2005), Nepal (Brunnel et al., 1985; Valdiya, 1995), Arunachal Pradesh (Tewari, 2001; Yin et al., 2010b), and Bhutan (McQuarrie et al., 2008; this study). The youngest Lesser Himalayan strata include Permian glacial deposits, the laterally variable Permian to Eocene Gondwanas, and Eocene foreland basin deposits associated with early Himalayan orogenesis (Brookfield, 1993; DeCelles et al., 2001; Najman et al., 2006; Robinson et al., 2006; Yin, 2006).

The Greater Himalayan zone consists of amphibolite to granulite facies metaigneous, metasedimentary, and Miocene igneous rocks, which sit structurally above the Lesser Himalayan zone across the Main Central thrust (MCT) (Heim and Gansser, 1939; Gansser, 1964; LeFort, 1975). Greater Himalayan metasedimentary rocks are interpreted as: (1) highly metamorphosed equivalents of the lower Tethyan Himalayan section or upper Lesser Himalayan section (Parrish and Hodges, 1996; Myrow et al., 2003, 2009), or (2) an allochthonous section that was accreted onto the northern Indian margin during an early Paleozoic orogenic event (DeCelles et al., 2000).

The Tethyan Himalayan zone, which sits structurally (Burg, 1983; Burchfiel et al., 1992) and stratigraphically (Stocklin, 1980; Gehrels et al., 2003; Robinson et al., 2006; Long and McQuarrie, 2010) above the Greater Himalayan zone, represents Neoproterozoic to Eocene deposition on the distal northern Indian margin of the Tethyan ocean basin (Gaetani and Garzanti, 1991; Brookfield, 1993; Garzanti, 1999).

MAPPING METHODS

Geologic mapping was performed on 1:50,000-scale topographic base maps. Mapping was focused on the Siwaliks and Lesser Himalayan units, between the MFT and MCT, although structural data were also collected from Greater Himalayan and Tethyan Himalayan units. We mapped three north-south transects (Fig. 2): (1) along the road south of Trashigang, (2) along the Kuru Chu (note: Chu means river), which was on roads north of 27°10′ and trails south of this latitude, and (3) west of the Kuru Chu, along a trail that meets the Manas Chu at its southern end. We also mapped two east-west transects, one on a trail between the Kuru Chu and Pemagatshel, and another on a road connecting Trashigang, Mongar, and Ura (Fig. 2). Our mapping was integrated with published geologic maps of Bhutan (Gansser, 1983; Gokul, 1983; Bhargava, 1995; Grujic et al., 2002) to help trace contacts along strike.

The level of rock exposure in eastern Bhutan varies significantly with elevation and the presence or absence of road or trail cuts. In general, there was much heavier vegetation cover south of ~27°00′, with discontinuous exposures of ~5–20-m-thick sections spaced apart ~250–500 m. One exception to this was on the road north of Samdrup Jongkhar, where road cuts permitted exposures spaced every ~100–200 m. In general, north of 27°00′, vegetation cover was much more sparse and exposures were more closely spaced (~100–200 m). In the Kuru Chu valley, north of ~27°10′, dry climate and road cuts permitted near-continuous exposure on the road to Lhuentse.

BHUTAN TECTONOSTRATIGRAPHY

Subhimalayan Zone

The Siwalik Group in Bhutan is present in discontinuous exposures generally less than 10 km wide (north to south), and are mapped

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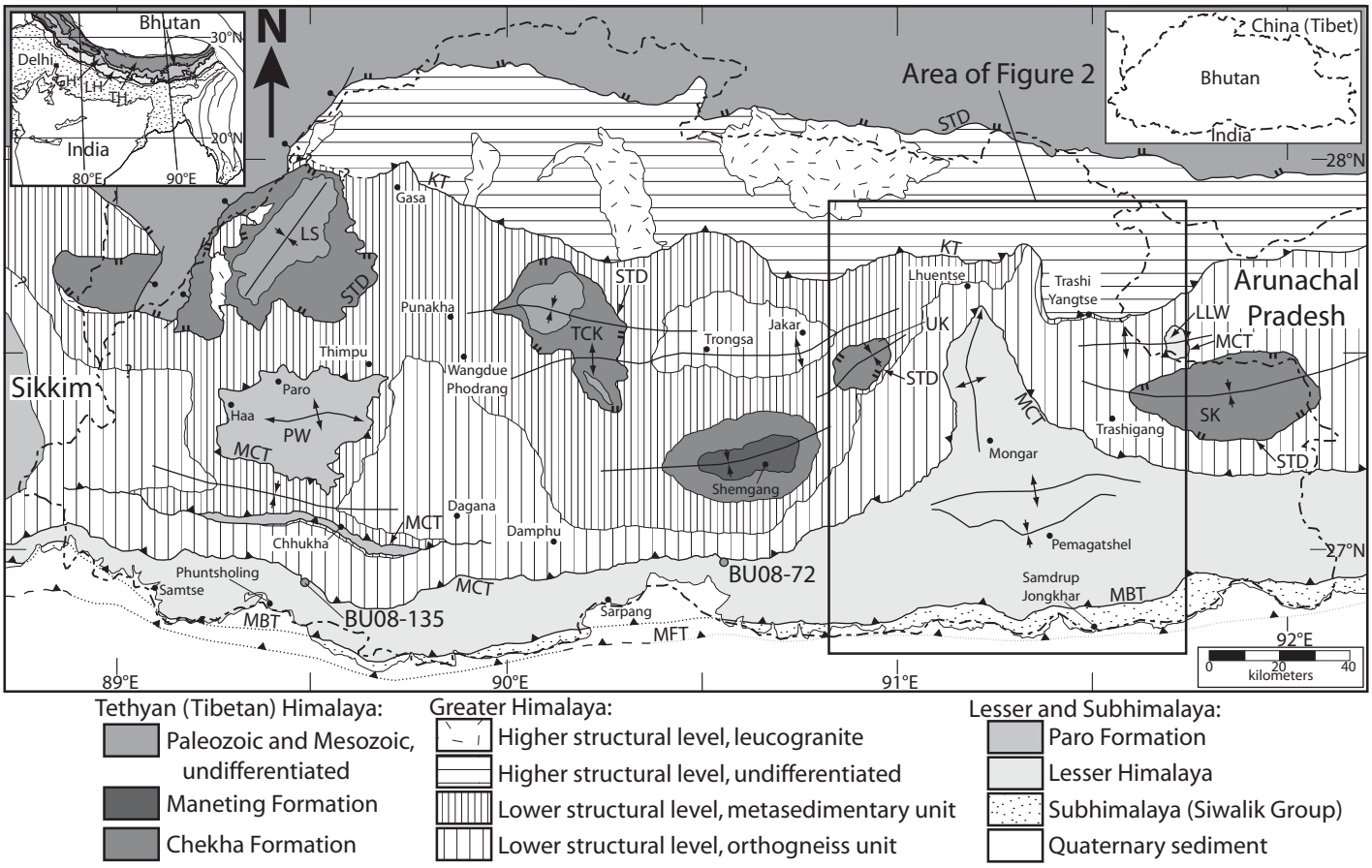

Figure 1. Simplified geologic map of Bhutan and surrounding region, after Gansser (1983), Bhargava (1995), Grujic et al. (2002), and our own mapping. Study area shown in Figure 2 outlined. Upper-left inset shows generalized geologic map of central and eastern Himalayan orogen (modified from Gansser, 1983). Structural detail left out of Tethyan Himalayan section north of Bhutan; map patterns of NE-striking, cross-cutting normal faults northwest of Lingshi Syncline (Yadong cross structure on figure 1 of Grujic et al. [2002]) are simplified. Jaishidanda Formation zircon sample locations in central and western Bhutan are shown. Abbreviations: (1) Inset: GH—Greater Himalaya, LH—Lesser Himalaya, TH—Tethyan (or Tibetan) Himalayan; (2) structures from north to south: STD—South Tibetan detachment, KT—Kakhtang thrust, MCT—Main Central thrust, MBT—Main Boundary thrust, MFT—Main Frontal thrust; (3) windows and klippen from west to east: LS—Lingshi syncline, PW—Paro window, TCK—Tang Chu klippe, UK—Ura klippe, SK—Sakteng klippe, LLW—Lum La window (location from Yin et al., 2010b).

along less than half the length of the country (Fig. 1) (Gansser, 1983; Gokul, 1983; Bhargava, 1995). It is possible that the missing Siwalik Group outcrops have been covered by Quaternary sediment, have been overridden by the MBT, or were never deposited in portions of southern Bhutan (Gansser, 1983). Previous studies of the Bhutan Siwalik Group (Nautiyal et al., 1964; Jangpangi, 1974; Biswas et al., 1979; Gansser, 1983; Acharyya, 1994; Lakshminarayana and Singh, 1995) have split them into informal lower, middle, and upper members. The entire sedimentary package is unmetamorphosed, and coarsens upward from siltstone and claystone to sandstone and conglomerate.

In eastern Bhutan, north of Samdrup Jongkhar, all three members are exposed in a north-dipping thrust sheet (Figs. 2 and 3), and are collectively ~5.5 km thick. The lower member is ~2900 m thick, and consists of medium-gray,

Figure 2. Geologic map of eastern Bhutan (see Fig. 1 for location and structure abbreviations. ST—Shumar thrust). Strike and dip symbols indicate our mapping. Locations of detrital zircon samples shown; refer to Figure 1 for locations of samples BU08-72 and BU08-135. Locations of Baxa Group dolomite intervals sampled for $\delta^{13}C$ shown. Main Central thrust (MCT) and Main Boundary thrust (MBT) locations between transects taken mainly from Bhargava (1995). Folded Shumar thrust (ST) between transects in center of map area taken from Gokul (1983) and Bhargava (1995). Location of Kakhtang thrust from Grujic et al. (1996) and Bhargava (1995). Note that fold axial traces shown within Greater Himalayan section are actually synforms and antiforms, since right-side-up direction is not always known. MFT—Main Frontal thrust.

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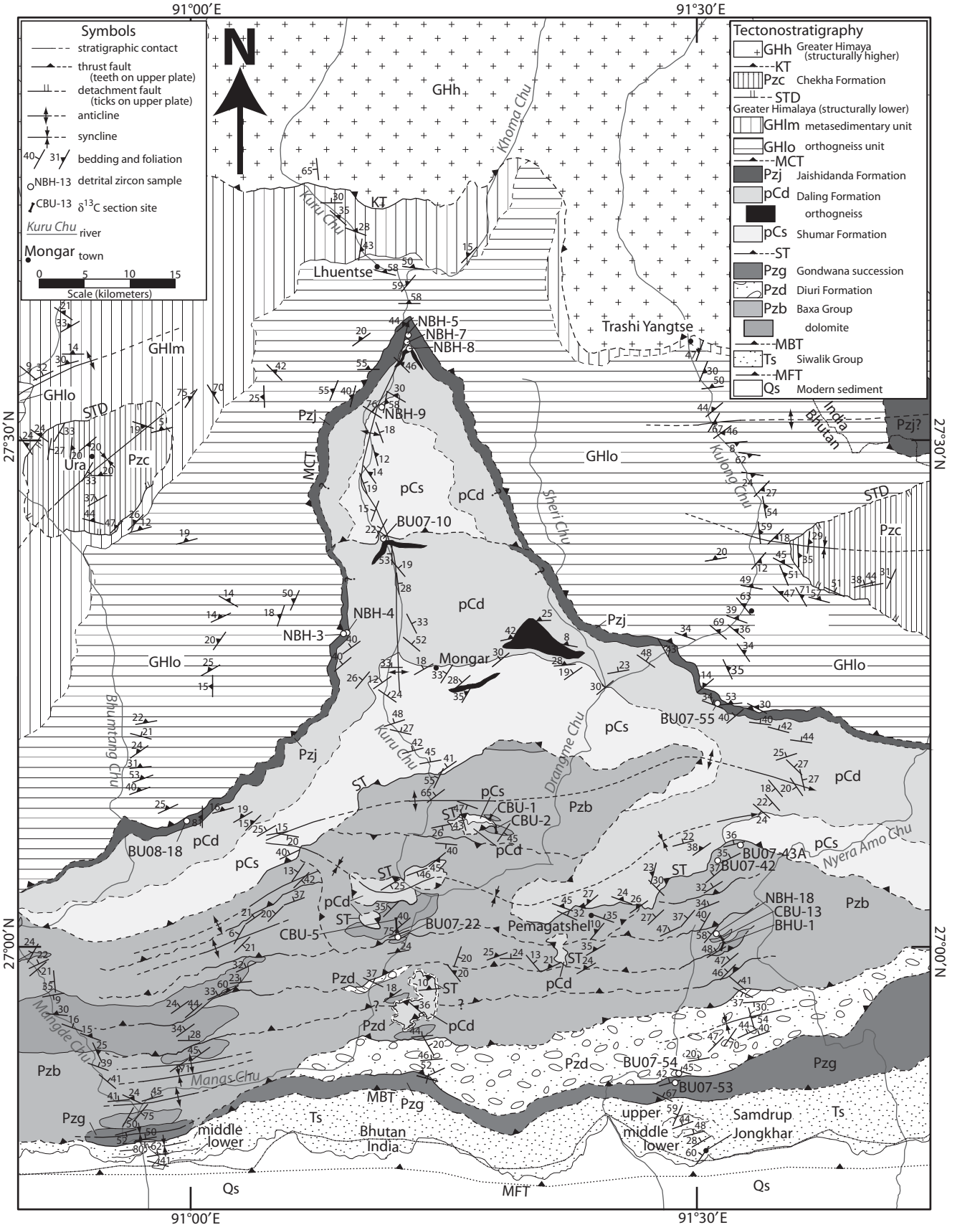

Figure 2.

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green-gray, and tan siltstone and shale, interbedded with tan to light-gray, fine-grained sandstone. Siltstone and shale are micaceous, laminated, medium to thick bedded, and commonly massive weathering. The sandstone has subangular grains, contains a high percentage of lithic clasts, and has a silt-rich matrix. The middle member is ~1300 m thick, and consists of sandstone and conglomeratic sandstone. The sandstone is similar to that in the lower member, but is medium to coarse grained. The conglomerate is generally matrix supported, with pebble- to cobble-size quartzite clasts. The upper member is at least 1500 m thick, and consists of medium- to coarse-grained conglomeratic sandstone and pebble- to cobble-conglomerate, interbedded with tan, micaceous siltstone. It contains beds with cobble to boulder-size clasts of lithic-rich sandstone that could either be intraformational or derived from the Gondwana succession. Sedimentary structures throughout the entire section include tabular bedding, tabular cross-bedding, trough cross-bedding, and soft-sediment deformation features.

Along the Manas Chu (Fig. 2) the Siwalik Group is only 2.3 km thick, and only the lower and middle members are present. Siltstone and sandstone of the lower member are ~1300 m thick, and coarsen upward to conglomeratic sandstone of the upper member, which is ~1000 m thick.

Lesser Himalayan Zone

We divide the Lesser Himalayan section in eastern Bhutan into six map units, which are collectively between 9 and 19 km thick, and consist of two successions (Fig. 3): (1) the Daling-Shumar Group, which is overlain by the Jaishidanda Formation and (2) the Baxa Group, Diuri Formation, and Gondwana succession.

Daling-Shumar Group

The Daling-Shumar Group is the stratigraphically lowest Lesser Himalayan map unit in Bhutan. This succession of quartzite, phyllite, and schist was originally defined as the Shumar "series" in eastern Bhutan (Nautiyal et al., 1964), then renamed the Shumar Formation by Jangpangi (1974, 1978), who defined the type section in the Kuru Chu valley. Gansser (1983) designated it the Daling-Shumar Group, in order to link the quartzite-rich deposits in eastern Bhutan with the more phyllitic Daling Formation, which was defined in the southwest corner of Bhutan, near Sikkim (Sengupta and Raina, 1978). In eastern Bhutan, McQuarrie et al. (2008) split the group into a two-part stratigraphy of quartzite of the Shumar Formation below interbedded schist, phyllite, and quartzite of the Daling Formation. These designations are used in this study.

The Daling-Shumar Group is exposed across the entire east-west length of Bhutan (Gansser, 1983). The lower contact with the Baxa Group is always the Shumar thrust (Ray et al., 1989; McQuarrie et al., 2008), so all thicknesses are minimum estimates. The Daling-Shumar Group is generally between 3 and 4 km thick, but a 9-km-thick section is local to the Kuru Chu valley. We observed no evidence for structural thickening in the form of isoclinal folds or thrust faults within this section, and pervasive N-trending stretching lineation argues against thickening via E-W–oriented ductile flow. Rare cross-bedding suggests that sedimentary bedding is preserved, and consistently indicates a right-way-up orientation. Thus, we interpret the observed thickness variations as the result of along-strike changes in original depositional thickness. In the northern Kuru Chu valley, we observe one repetition of the two-part Daling-Shumar Group stratigraphy, which we interpret as an additional thrust sheet (Fig. 2) (McQuarrie et al., 2008).

The Daling-Shumar Group has been metamorphosed to upper greenschist facies (Gansser, 1983), and displays biotite and muscovite porphyroblasts. In thin section, both Shumar and Daling Formation samples display equigranular, polygonal quartz subgrains (GSA Data Repository Fig. DR1E[1]), typical of subgrain rotation recrystallization (Grujic et al., 1996), which indicates deformation temperatures between ~400 and 500 °C (Stipp et al., 2002).

Bodies of mylonitized granitic orthogneiss that contain distinctive feldspar augen are present in different stratigraphic levels in the Daling-Shumar Group (Fig. 2). Asymmetric feldspar porphyroclasts consistently show a top-to-the-south sense of shear (Fig. DR1C [footnote 1]), and concordance is shown by a subparallel relationship between tectonic foliation in the orthogneiss bodies and quartzite bedding and schist foliation in Daling-Shumar Group rocks above and below. However, despite the concordant relationship of foliation, where exposed the orthogneiss shows highly irregular, intrusive contact relationships with Daling-Shumar Group host rocks (Fig. 4B).

Shumar Formation. The Shumar Formation consists of light-gray to light-green to white, tan-weathering, very fine-grained, medium- to thick-bedded quartzite (Figs. 3 and DR1A [footnote 1]). Massive quartzite cliffs up to several hundred meters high are diagnostic for the unit (Fig. 4A). Bedding and compositional lamination are preserved in quartzite, along with local tabular cross-bedding showing an upright bedding orientation (Fig. DR1A [footnote 1]). Thin- to thick-bedded schist and phyllite interbeds are present, and become more common upsection. The Shumar Formation displays significant along-strike thickness variations, from 1 km in the Bhumtang Chu valley, to 6 km in the Kuru Chu valley, to 2 km south of Trashigang (Fig. 2).

Daling Formation. The Daling Formation stratigraphically overlies the Shumar Formation, and contains similar lithologies, but is dominated by schist and phyllite. The lower contact is gradational with the Shumar Formation over tens of meters of stratigraphic thickness (Fig. 3). The Daling Formation is between 2.3 and 3.2 km thick in eastern Bhutan. Schist and phyllite are massive-weathering, and display diagnostic, cm-scale, sigmoidal quartz vein boudins (Fig. DR1B [footnote 1]). Quartzite intervals are tan-weathering, very fine-grained, and characteristically thin- to medium-bedded, in contrast to the thicker beds in the underlying Shumar Formation. Quartzite displays tabular cross-bedding, and rare ripple marks all indicating right-side-up bedding. Rare interbeds of massive-weathering, medium-gray limestone are also present.

Jaishidanda Formation

An interval of biotite-rich, locally garnet-bearing schist and interbedded biotite-rich quartzite is exposed just beneath the MCT across the majority of Bhutan. This interval has been interpreted as part of the structurally overlying Greater Himalayan zone (Jangpangi, 1974; Sengupta and Raina, 1978; Trichal and Jarayam, 1989), as part of the underlying Daling-Shumar Group (Guha Sarkar, 1979; Gansser, 1983; Ray, 1989), and as a unique lithotectonic unit called the Jaishidanda Formation, which has been mapped as a thin thrust sheet under the MCT, in thrust contact over the Daling-Shumar Group (Bhargava, 1995; Dasgupta, 1995b). The type section for the Jaishidanda Formation is on the road south of Shemgang in south-central Bhutan (Dasgupta, 1995b) (Fig. 1). McQuarrie et al. (2008) mapped these strata in depositional contact above the Daling Formation, and based on a similar stratigraphic position and similar detrital zircon age spectra from a preliminary data set, tentatively correlated these strata with the Baxa Group. In this study, we also interpret a lower stratigraphic contact, but we map the Jaishidanda Formation as a distinct map unit.

[1]GSA Data Repository item 2011134, Data repository items consisting of additional field photographs, a detailed U/Pb methods section, U/Pb databases, and $\delta^{13}C$ and $\delta^{18}O$ data tables, is available at http://www.geosociety.org/pubs/ft2010.htm or by request to editing@geosociety.org.

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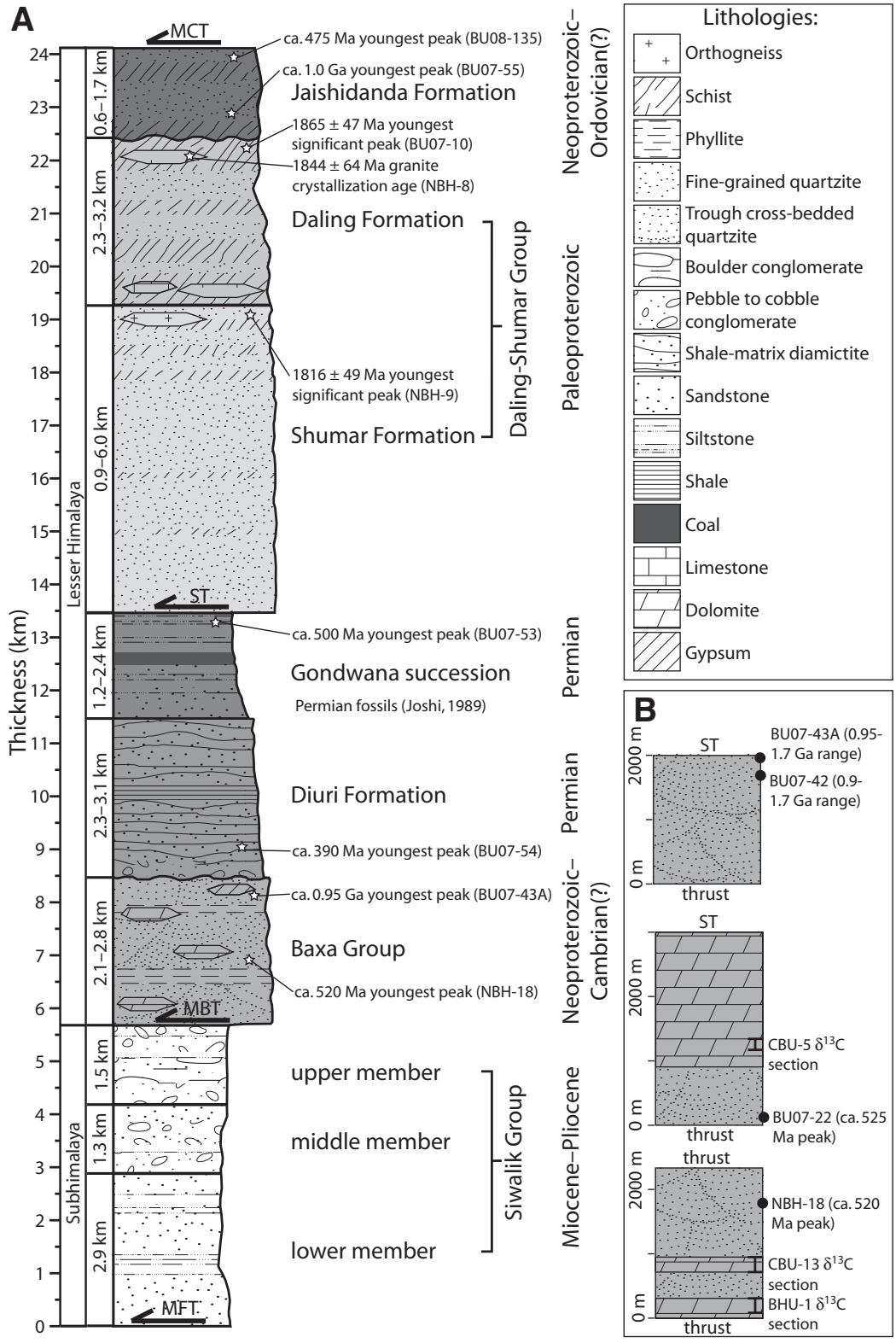

Figure 3. (A) Column showing tectonostratigraphy of Subhimalayan and Lesser Himalayan units in eastern Bhutan. Generalized lithology shown. Ages of detrital zircon peaks that constrain unit deposition are shown. Refer to Figure 1 for structure abbreviations (ST—Shumar thrust). (B) Simplified stratigraphic columns of Baxa Group sections, showing stratigraphic relationships between thrust faults, dolomite $\delta^{13}C$ sections, and detrital zircon samples. Refer to Figure 2 for locations of detrital zircon samples and sampled dolomite intervals. Note that dolomite section CBU-5 is sampled upsection of detrital zircon sample BU07-22, which yielded a Cambrian detrital zircon peak (ca. 525 Ma). Also note that samples BU07-43A and BU07-42, which did not yield Cambrian peaks, are located near the top of the section.

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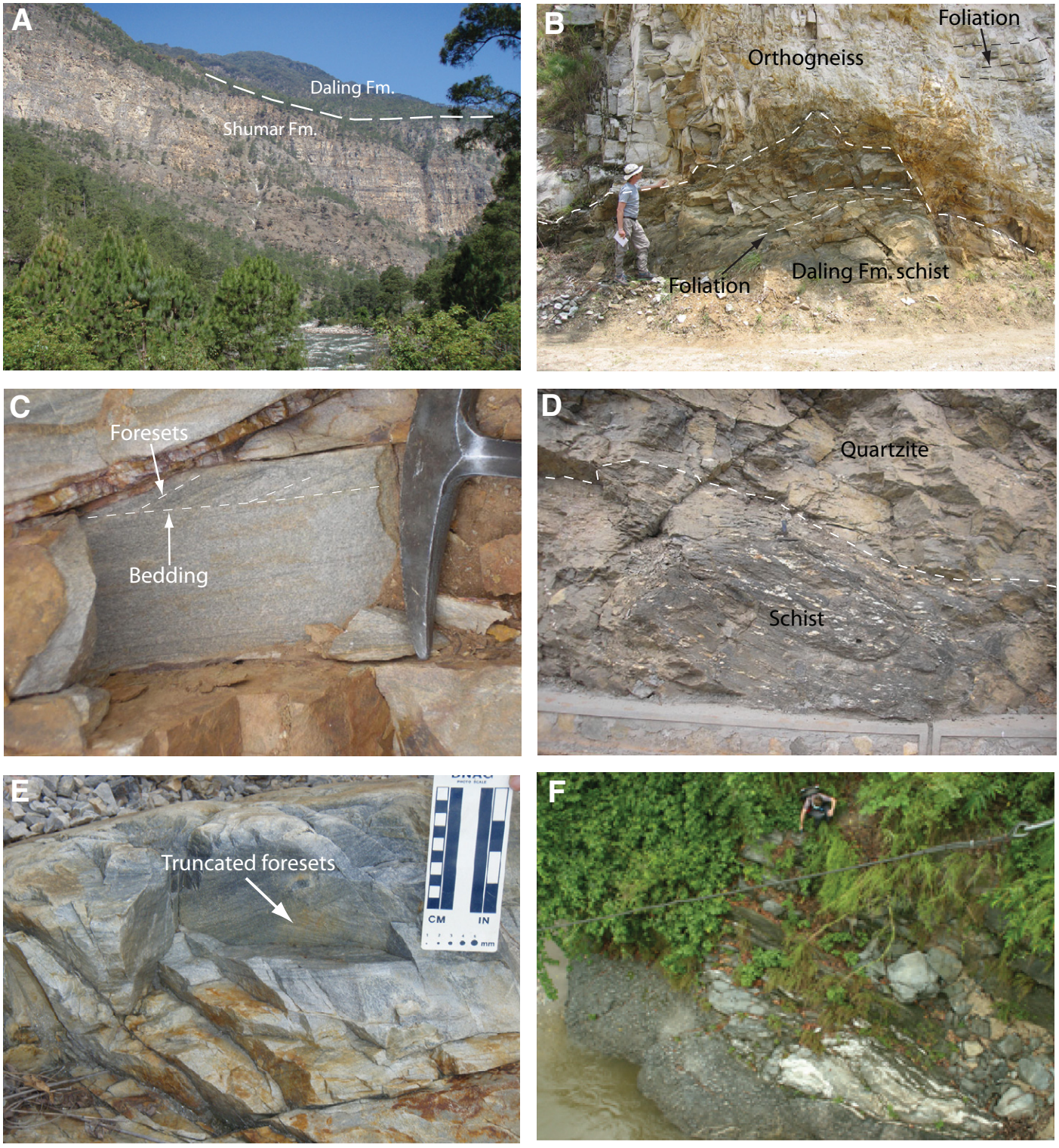

Figure 4. (A) Cliff-forming Shumar Formation quartzite overlain by slope-forming Daling Formation schist and phyllite in northern Kuru Chu valley; cliffs are several hundred meters high. (B) Intrusive contact between Daling Formation schist and granitic orthogneiss body in northern Kuru Chu valley. Note concordant relationship of schist and orthogneiss foliation, and irregular contact that cuts across foliation. (C) Gray Jaishidanda Formation quartzite, displaying tabular cross-bedding with planar foresets showing upright orientation (15-cm hammer head for scale). (D) Characteristic lithologies of Jaishidanda Formation; dark-gray, biotite-rich schist with quartz vein boudins overlain by dark-gray, biotite-rich quartzite; on road west of Trashigang. (E) Thick-bedded, light-gray Baxa Group quartzite, displaying characteristic trough cross-bedding. (F) Conglomerate at base of Diuri Formation, with overlying slate-matrix diamictite beds, in southern Kuru Chu valley.

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The lower Jaishidanda Formation contact is distinguished by the downsection transition to clean, tan, thin-bedded Daling Formation quartzite, which contains sparse biotite porphyroblasts, and contrasts with the gray, lithic clast-rich, biotite lamination-rich quartzite of the Jaishidanda Formation. Garnet-bearing Jaishidanda schist (Fig. DR1F [footnote 1]) is the highest grade metamorphic rock observed in the Lesser Himalayan section. Gansser (1983) noted that this interval is locally metamorphosed to lower amphibolite facies, in contrast to the higher greenschist facies of structurally lower Lesser Himalayan rocks. However, Jaishidanda schist does not universally display garnet, and in many places is distinguished from Daling schist by the dominance of biotite. Thus, since biotite porphyroblasts are present in both the Jaishidanda and Daling Formations, we define the lower contact by a downsection change in quartzite lithology, and not by a change in metamorphic grade. The upper Jaishidanda Formation contact, the MCT, is defined by the abrupt upsection transition to Greater Himalayan rocks, which are distinguished by the presence of leucosomes and often the appearance of staurolite, kyanite, or sillimanite (Grujic et al., 2002; Daniel et al., 2003).

In the northern Kuru Chu valley (Fig. 2), the Jaishidanda Formation is 1700 m thick, and consists of 900 m of light-gray quartzite, with abundant biotite-rich laminations and cm-scale biotite schist interbeds, overlain by 800 m of biotite-rich, garnet-bearing schist, with common cm-scale quartz vein boudins. South and west of Trashigang, and west of Mongar (Fig. 2), the Jaishidanda Formation is between 600 and 900 m thick, and is dominated by light- to medium-gray, biotite lamination-rich quartzite, which preserves planar cross-bedding that shows an upright bedding orientation (Fig. 4C). The quartzite is interbedded with dark-gray biotite schist that locally contains garnet, and exhibits prevalent cm-scale quartz vein boudins (Fig. 4D).

Dasgupta (1995b) and the accompanying geologic map of Bhargava (1995) interpreted a lower thrust contact at the base of the Jaishidanda Formation, based on the "deformational (mylonitized) nature" of the Jaishidanda strata versus those of the Daling-Shumar Group. No further description of this contact was provided in these studies. We did not observe any significant change in deformation characteristics between Jaishidanda and Daling-Shumar lithologies, and note that quartzite in both map units displays subgrain rotation quartz recrystallization textures (deformation temperatures between ~400 and 500 °C [Stipp et al., 2002]) through their entire exposed thickness.

If the lower Jaishidanda contact were a thrust, as proposed by Dasgupta (1995b) and Bhargava (1995), our new U-Pb age control on unit deposition (see Jaishidanda Formation, below) shows that this structure would place younger on older rocks, and would carry a hanging wall that is in most places less than 900 m thick, based on the sections we observed, and in some places is as thin as 30 m (Dasgupta, 1995b). We argue that Jaishidanda Formation strata depositionally overlying older Daling-Shumar Group rocks is a much more plausible relationship than the emplacement of such a thin and laterally persistent younger-on-older thrust sheet across the full length of Bhutan.

Baxa Group

The Baxa Group (Tangri, 1995a) has been the subject of numerous studies (Nautiyal et al., 1964; Ray, 1976; Sengupta and Raina, 1978; Gansser, 1983; Gokul, 1983; Tangri, 1995a), and the type locality was originally defined in the Duars (foothills) of southwest Bhutan (Mallett, 1875; Acharyya, 1974). However, due to laterally variable lithologies and lithologic similarities between quartzite and phyllite of the Baxa and Daling-Shumar Groups, there are multiple inconsistencies in how the group has been described and mapped. Gansser (1983) mapped the Baxa Group as discontinuous dolomite and limestone intervals interbedded with the Daling-Shumar Group. Gokul (1983) mapped the Baxa Group as interbedded quartzite, phyllite, and dolomite lithologies, each with no specific stratigraphic or structural order, and also included Diuri Formation diamictite. Bhargava (1995) divided the Baxa Group into four formations, of which only the Manas Formation is present in eastern Bhutan, and the other three are local to central and western Bhutan.

We observed significant lateral lithologic variability within the Baxa Group, and in this study we do not split out individual formations, and thus refer to the deposits as undifferentiated Baxa Group. We examined Baxa Group sections on the road south of Trashigang, along the Kuru Chu, west of the Kuru Chu valley, and along the Mangde Chu (Fig. 2). Along the Trashigang transect, the Baxa Group is dominated by gray to white, light to medium-gray weathering, medium- to thick-bedded quartzite (Figs. 3 and 4E; Figs. DR1D and DR1H [footnote 1]). The quartzite is medium to coarse grained, with subangular, poorly sorted clasts, and commonly displays clasts of dark lithics, rose quartz, jasper, and orthoclase feldspar. The quartzite is locally coarse grained to conglomeratic, with rare beds of pebble conglomerate. Sedimentary structures include trough cross-bedding (Fig. 4E) and lenticular bedding, with meter-scale beds swelling and pinching over meters to tens of meters of lateral distance (Fig. DR1H [footnote 1]). The texture, clast composition, and sedimentary structure characteristics listed above distinguish Baxa Group quartzite from Daling-Shumar Group quartzite. Interbedded lithologies include cm- to m-scale, dark-gray to green, thin-bedded to thinly laminated slate and phyllite, and two intervals of medium-gray dolomite, 250 and 600 m thick. Also, near the town of Pemagatshel (Fig. 2), the Baxa Group contains green to white, medium-bedded gypsum.

Along the Kuru Chu, Manas Chu, and Mangde Chu (Fig. 2), identical quartzite, phyllite, and dolomite lithologies are observed, but in significantly different proportions. The majority of exposures are still quartzite, but slate and phyllite intervals are up to 100s of m thick, and dolomite sections are much more common, and up to 2 km thick.

Gansser (1983) designated the metamorphic grade of strata that we map as Baxa Group as lower greenschist facies. In thin section, Baxa Group quartzite often displays evidence for subgrain formation localized at grain boundaries (Fig. DR1G [footnote 1]), which is indicative of bulging recrystallization, and corresponds to deformation between ~280° and 400 °C (Stipp et al., 2002). Quartz subgrains can locally comprise over half the volume of the rock, but unlike the totally recrystallized Daling Shumar quartzite, large, relict detrital grains are always present.

The Baxa Group is in structural contact beneath the Daling-Shumar Group across the Shumar thrust (Fig. 2) (Ray et al., 1989; Tangri, 1995a). The basal contact is not observed in Bhutan, but the Baxa Group is in depositional contact above the Daling Formation in Sikkim (Bhattacharyya and Mitra, 2009). An upper stratigraphic contact with the Gondwana succession is present along the Manas Chu (Fig. 2), and upper stratigraphic contacts with the Diuri Formation are observed in the southern Kuru Chu valley (Fig. 2). The Baxa Group is at least 2.8 km thick between lower thrust contacts and upper stratigraphic contacts with the Diuri Formation in the southern Kuru Chu valley (Fig. 2). Also, a minimum thickness of 2.5 km is exposed in the hinge of an anticline just south of the Shumar thrust trace in the Kuru Chu valley (Fig. 2). On the Kuru Chu and Manas Chu transects, we observed localized zones of brecciated and complexly folded quartzite and dolomite as well as highly sheared and complexly folded phyllite with pervasive top-to-the-south–sense shear bands, which we interpret as fault zone rocks. These narrow (~1–10-m-thick) zones of deformation divide the Baxa Group into stratigraphic sections 2.5–3 km thick and are often

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associated with hot springs or tufa deposits. We interpret these zones as sites of intraformational thrust faults which repeat the Baxa section. On the Trashigang road, prominent ENE-trending valleys spaced ~3 km apart supported dividing the Baxa Group into thrust-repeated sections (McQuarrie et al., 2008). The Trashigang road, Kuru Chu, Manas Chu, and Mandge Chu transects expose 11-, 6-, 7, and 7-km-thick Baxa Group sections, respectively. We interpret these thick sections as representing the same 2–3-km-thick section being structurally repeated in a thrust duplex system (Fig. 2), which is discussed in detail in Long et al. (2011).

Diuri Formation

Diamictite in southeast Bhutan has previously been mapped as part of the Baxa Group (Nautiyal et al., 1964; Gokul, 1983), the Diuri Boulder Slate Formation (Jangpangi, 1974), and the Diuri Formation (Gansser, 1983; Bhargava, 1995; Tangri, 1995b). This latter name is the designation used in this study. The type section is on the road north of Samdrup Jongkhar (Jangpangi, 1974) (Fig. 1).

The Diuri Formation consists of 2.3–3.1 km of dark-gray to green-gray, matrix-supported diamictite, with a micaceous slate matrix (Figs. 3 and 4D). Slate interbeds free of large clasts are common, and interbeds of fine- to medium-grained quartzite are rare. A bed of pebble- to cobble-, clast-supported conglomerate is found near the base of the section in the southern Kuru Chu valley (Fig. 4F). Diamictite clasts are generally pebble to cobble size, and consist of gray, red, and green quartzite (Fig. DR1I [footnote 1]). Less abundant clast lithologies include dolomite, black slate, and potassium feldspar. In thin section, matrix material displays schistosity, which bends around elongated sand-size clasts that are flattened parallel to the primary fabric (Fig. DR1J [footnote 1]). We map the Diuri Formation in stratigraphic contact above the Baxa Group in two localities in the southern Kuru Chu valley (Fig. 2), but all other contacts are interpreted as tectonic. Along the Manas Chu, the Gondwana succession is in stratigraphic contact above the Baxa Group, which indicates that the Diuri Formation pinches out to the west by this point (Fig. 2).

Gondwana Succession

A map unit composed of sandstone, siltstone, shale, and coal in southeast Bhutan has been called the Damudas (Gansser, 1983), Damuda Group (Gokul, 1983), Damuda Subgroup or Damuda Formation (Lakshminarayana, 1995), and Setikhola Formation (Bhargava, 1995; Joshi, 1995). Sinha (1974) correlated this unit with the Barakar and Barren Measures formations of the Gondwana Supergroup, and Gansser (1983) and Gokul (1983) also recognized this correlation. We use this terminology and refer to this unit as the Gondwana succession. The type section for these strata in Bhutan is east of Samdrup Jongkhar (Jangpangi, 1974; Sinha, 1974) (Fig. 1). Bhargava (1995), Gokul (1983), and Gansser (1983) all map the Gondwana succession as pinching out, or being faulted out, in western Bhutan. However, the Gondwana succession is exposed west of Bhutan, in Sikkim (Acharyya, 1971; Bhattacharyya and Mitra, 2009).

North of Samdrup Jongkhar, and in the southern Kuru Chu valley, the Gondwana succession is between 1.2 and 2.4 km thick, the upper contact is a thrust contact with the Diuri Formation, and the lower contact is the MBT (Fig. 2). The lower part of the section consists of light- to medium-gray, medium-grained sandstone, interbedded with dark-gray, thin- to medium-bedded, carbonaceous siltstone and shale (Fig. 3). The sandstone is friable, contains subangular, poorly sorted clasts, and it is commonly feldspathic and lithic rich. The upper part of the section consists of dark-gray to black, thin-bedded to laminated, carbonaceous shale and argillite (Fig. DR1K [footnote 1]), interbedded with very fine grained sandstone and rare black coal beds.

Along the Manas Chu, we observe a minimum of 500 m of Gondwana succession strata (Fig. 2), in stratigraphic contact above the Baxa Group. This section consists of medium-grained sandstone with dark-gray siltstone interbeds, and resembles the lower part of the section observed in southeast Bhutan.

Greater Himalayan and Tethyan Himalayan Zones

Bhutan is dominated by exposures of amphibolite- to granulite-facies metasedimentary, metaigneous, and igneous rocks of the Greater Himalayan zone (Gansser, 1983; Gokul, 1983; Bhargava, 1995; Golani, 1995), which are thrust over Lesser Himalayan rocks across the MCT. Grujic et al. (2002) divided the Greater Himalayan section into a lower structural level above the MCT and below the Kakhtang thrust, and a higher structural level above the Kakhtang thrust (Figs. 1 and 2). The higher structural level is dominated by migmatitic orthogneiss and metasedimentary rocks, and contains the bulk of leucogranite exposed in Bhutan (Dietrich and Gansser, 1981; Gansser, 1983; Swapp and Hollister, 1991; Davidson et al., 1997) (Figs. 1 and 2). The lower structural level consists of a lower, granite-composition orthogneiss unit with metasedimentary intervals, and an upper metasedimentary unit consisting of quartzite, schist, and paragneiss (Long and McQuarrie, 2010) (Figs. 1 and 2). Based on a 487 ± 7 Ma U-Pb (zircon) crystallization age, Long and McQuarrie (2010) interpreted a Cambro-Ordovician age for intrusion of granitic protoliths of the orthogneiss unit, which is supported by the presence of Cambro-Ordovician orthogneiss in Greater Himalayan rocks throughout the orogen (e.g., Stocklin and Bhattarai, 1977; Stocklin, 1980; Parrish and Hodges, 1996; DeCelles et al., 2000; Gehrels et al., 2003; Martin et al., 2005; Cawood et al., 2007). Detrital zircon age spectra from quartzite in the metasedimentary unit in central Bhutan yielded Cambrian and Ordovician (ca. 500 and ca. 460 Ma) youngest peaks (Long and McQuarrie, 2010), indicating that parts of the Greater Himalayan metasedimentary interval must be as young as Cambro-Ordovician. However, ca. 900–980 Ma youngest detrital zircon peak ages obtained from Greater Himalayan metasedimentary rocks in eastern Bhutan may bracket the oldest permissible deposition age of Greater Himalayan sedimentary protoliths as Neoproterozoic (Richards et al., 2006; Long and McQuarrie, 2010). Studies in Nepal and northwest India have interpreted Greater Himalayan sedimentary protolith deposition as Neoproterozoic based on detrital zircon ages (Martin et al., 2005), between Neoproterozoic and Cambrian–Ordovician, based on detrital zircon ages and the ages of cross-cutting orthogneiss bodies (DeCelles et al., 2000), and between Neoproterozoic and Ordovician, based on correlation of Greater Himalayan and Tethyan (or Tibetan) Himalayan strata (Myrow et al., 2009).

Gansser (1983) recognized several isolated exposures of greenschist-facies Precambrian (inferred) through Mesozoic metasedimentary rocks that lie above the Greater Himalayan section in the hinges of synforms (Fig. 1), and these strata have since been mapped as part of the Tethyan (or Tibetan) Himalayan zone (Bhargava, 1995; Edwards et al., 1996; Grujic et al., 2002; Kellett et al., 2009). The base of the section in all of the Tethyan (or Tibetan) Himalayan exposures has been mapped as the Chekha Formation, which consists of quartzite interbedded with biotite-muscovite-garnet schist. A lack of fossils in the Chekha Formation, combined with a stratigraphic position below fossiliferous Tethyan Himalayan units as old as Cambrian in central and northwest Bhutan (Gansser, 1983; Bhargava, 1995; Tangri and Pande, 1995; Myrow, 2005; McKenzie et al., 2007), has led to an inferred Neoproterozoic deposition age. However, youngest detrital zircon peak ages from Chekha quartzite near Shemgang in central Bhutan (Fig. 1) indicate an Ordovician (ca. 460 Ma) maximum deposition age (Long and McQuarrie,

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2010). These differing age estimates across Bhutan indicate either: (1) structural complication which has telescoped the Tethyan Himalayan section, or (2) discrepancies in Tethyan Himalayan stratigraphy as currently defined, which have given the same name (Chekha Formation) and stratigraphic description to both Ordovician- and Precambrian-age quartzite.

U-Pb GEOCHRONOLOGY

Methods

U-Pb geochronologic analyses were conducted on individual zircon grains using laser-ablation, multicollector, inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) at the University of Arizona LaserChron Center. See Discussion DR1 (footnote 1) for a detailed discussion of the methodology of this laboratory. Approximately 100 grains were dated per sample. We analyzed 12 detrital samples and one igneous sample from Lesser Himalayan units in Bhutan. Sample locations and lithologies are listed in Table 1, and map locations are shown on Figure 2, together with four samples originally presented in McQuarrie et al. (2008). The 1065 U-Pb zircon analyses that yielded less than 30% isotopic discordance are shown for each sample in Figure 5 in relative age probability plots (1σ errors), and data and analytical errors (1σ) for individual analyses are listed in Table DR1 (footnote 1), and are shown in Pb/U Concordia plots in Fig. DR2 (footnote 1). This range of accepted discordance is justified because we interpret clustering as a more powerful tool than concordance for determining the reliability of ages, given that both Pb-loss and inheritance commonly move analyses along concordia, particularly for analyses <1.0 Ga. Therefore, single analyses that overlap concordia do not necessarily yield robust ages. In contrast, analyses that yield a cluster of ages are more likely robust, even if slightly to moderately discordant, because Pb-loss and inheritance will always tend to increase scatter. Therefore, in this study we accept analyses with discordance up to 30%, and we place the most significance on clusters (peaks) supported by at least three analyses that overlap within error. Peaks defined by only one or two analyses are interpreted as less significant.

Samples were ablated with a 35-micron–diameter laser beam, except for samples BU07-54, BU07-55, and BU08-72, which contained smaller zircons and were hit with a 25-micron–diameter beam, and therefore have lower precision, particularly for $^{206}Pb/^{207}Pb$ ages (Table DR1 [footnote 1]). Four samples shown on Figure 5 (NBH-5, NBH-7, NBH-9, and NBH-18), which include a total of 388 detrital zircon analyses, were published in McQuarrie et al. (2008), and are not included in Table DR1 (footnote 1).

TABLE 1. DETRITAL ZIRCON SAMPLE LOCATIONS FOR EASTERN BHUTAN

Sample	°N (dd.ddddd)	°E (dd.ddddd)	Formation	Lithology
BU07-53	26.86572	91.48011	Gondwana	Sandstone
BU07-54	26.87497	91.48028	Diuri	Quartzite
BU08-135	26.91667	89.46669	Jaishidanda	Quartzite
BU08-72	26.96631	90.55781	Jaishidanda	Quartzite
BU08-18	27.12556	90.99892	Jaishidanda	Quartzite
NBH-3	27.30882	91.15140	Jaishidanda	Quartzite
NBH-4	27.30970	91.15481	Jaishidanda	Quartzite
NBH-5*	27.60173	91.21473	Jaishidanda	Quartzite
NBH-7*	27.59659	91.21401	Jaishidanda	Quartzite
BU07-55	27.24222	91.52122	Jaishidanda	Quartzite
BU07-43A	27.10161	91.54322	Baxa Group	Quartzite
BU07-42	27.08486	91.52089	Baxa Group	Quartzite
NBH-18*	27.01200	91.52072	Baxa Group	Quartzite
BU07-22	27.00844	91.20628	Baxa Group	Quartzite
NBH-8	27.59306	91.21528	Daling	Orthogneiss
BU07-10	27.40256	91.19078	Daling	Quartzite
NBH-9*	27.53238	91.18916	Shumar	Quartzite

*Indicates data are published in McQuarrie et al. (2008).

In general, $^{206}Pb^*/^{238}U$ (asterisk denotes correction for common Pb; see Discussion DR1 [footnote 1] for details on this correction; all ages described in the text have had this correction) ratios were used for ages younger than ca. 1.0 Ga, and $^{207}Pb^*/^{206}Pb^*$ ratios were used for ages older than ca. 1.0 Ga, because this is the approximate crossover in precision for these two ages (Discussion DR1 [footnote 1]). Specific age cutoffs used for each sample are listed in Table DR2 (footnote 1). Sources of systematic error, which include contributions from the fractionation correction, composition of common Pb, age of the calibration standard, and U decay constants (see footnotes of Table DR1 for these values [footnote 1]), are not added into the errors shown in Table DR1 (footnote 1) (which includes only analytical errors at 1σ), and could collectively shift age-probability peaks by up to ~3% (2σ). Total systematic errors for each sample are listed at 2σ in Table DR2 (footnote 1), as well as data on the standards run for each individual sample.

Data

Sample BU07-10, a quartzite from the Daling Formation in the northern Kuru Chu valley (Fig. 2), yielded a prominent, broad, youngest peak centered at ca. 1.92 Ga, with several older peaks as old as ca. 2.8 Ga (Fig. 5). The ca. 1.92 Ga peak contains multiple concordant (>99%) zircons that are younger than this average peak age (Table DR1 [footnote 1]). The youngest three concordant zircons that cluster closely in age (overlap within error) yield a weighted mean age of 1865 ± 47 Ma (2σ; includes quadratic addition of systematic error; see Discussion DR1 and Table DR2 [footnote 1]). Sample NBH-8 was collected from an orthogneiss in the Daling Formation section, 300 m below the upper contact in the northern Kuru Chu valley (Fig. 2), and yielded a broad peak defined by 56 grains, centered at ca. 1.90 Ga. This peak contains multiple concordant zircons that are significantly younger than this average peak age (Table DR1 [footnote 1]). Since Daling-Shumar Group detrital samples also contain many grains of this age, in an effort to distinguish magmatic grains from inherited grains, we calculate a weighted mean age of 1844 ± 64 Ma (2σ; includes quadratic addition of systematic error; see Discussion DR1 and Table DR2 [footnote 1]) for the youngest three concordant (>99%) zircons that cluster closely in age (overlap within error) analyzed from NBH-8, and interpret this as the best age estimate for crystallization of magmatic zircons. We interpret the older grains within the broad ca. 1.90 Ga peak, and the 13 grains between 2100 and 2540 Ma, as inherited.

Six quartzite samples were analyzed from the Jaishidanda Formation, collected south of Trashigang (BU07-55) (Fig. 2), west of Mongar (NBH-3 and NBH-4) (Fig. 2), just east of the Bhumtang Chu (BU08-18) (Fig. 2), north of Geylegphug in central Bhutan (BU08-72) (Fig. 1), and north of Phuntsholing in western Bhutan (BU08-135) (Fig. 1). BU07-55 yielded a series of peaks between ca. 1.0 and ca. 1.7 Ga, and NBH-3 and NBH-4 yielded a series of peaks between ca. 0.9 and ca. 1.7 Ga. BU08-18 yielded multiple peaks between ca. 0.8 and ca. 1.0 Ga, and a series of peaks between ca. 1.6 and 2.5 Ga. BU08-72 yielded a youngest significant peak centered at ca. 820 Ma, and a peak centered at ca. 1.2 Ga. Note that two concordant grains from BU08-72 have ca. 520 and ca. 549 Ma ages (Table DR1 [footnote 1]); while this does not qualify as a significant (three-grain) peak as defined above in Methods, only 12 grains were analyzed from this sample. We suggest that

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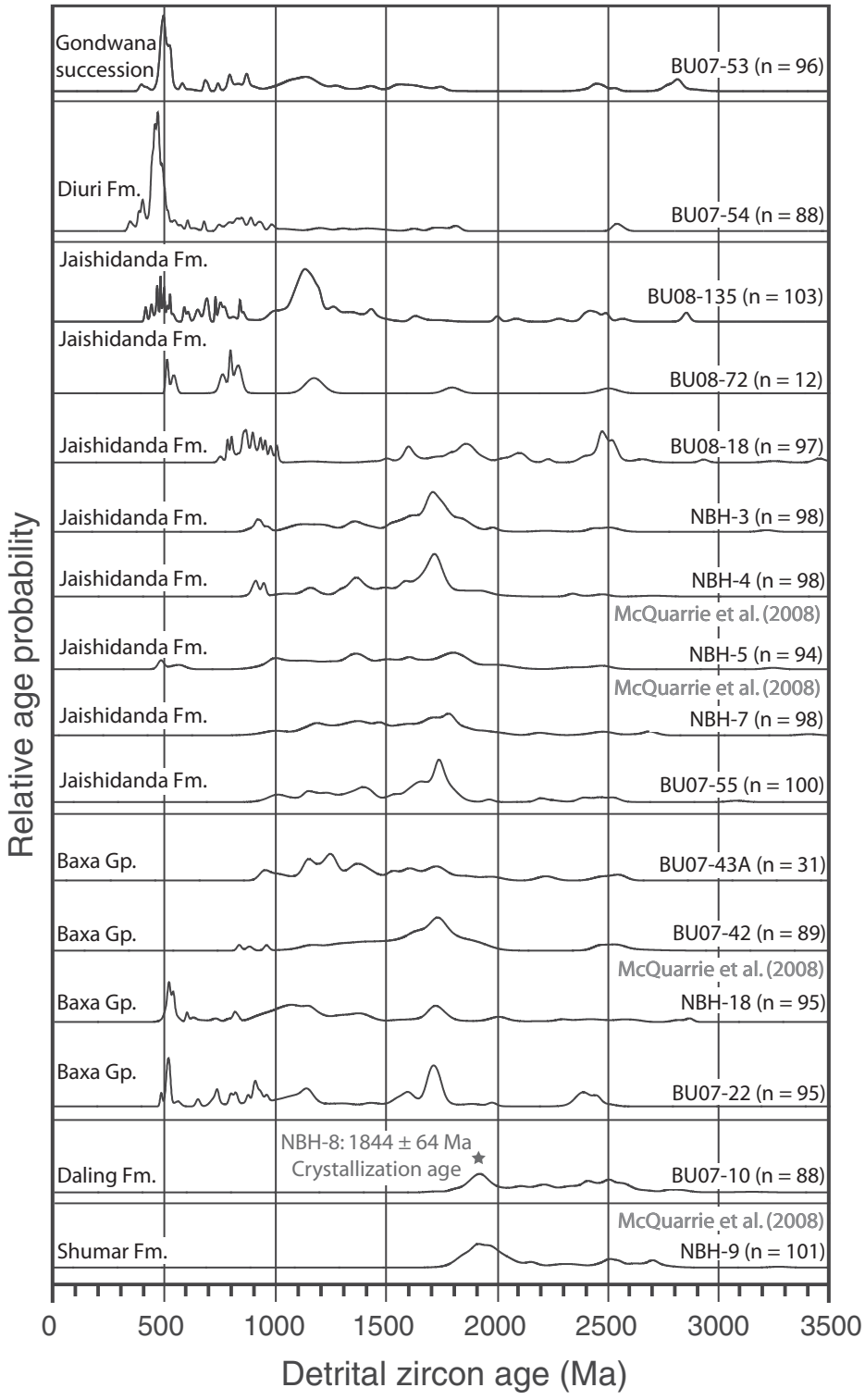

Figure 5. U-Pb detrital zircon age spectra of Bhutan Lesser Himalayan units. Graphs are relative probability plots, which represent the sum of probability distributions from ages and corresponding errors (input errors are 1σ; same as shown in Table DR1 [footnote 1]) for all analyses from each sample. Interpreted crystallization age for Daling-Shumar Group orthogneiss sample NBH-8 shown. See Table 1, and Figures 1 and 2, for sample locations; see Table DR1 [footnote 1] for data from individual analyses and Fig. DR2 [footnote 1] for Pb/U Concordia plots of individual samples. Samples NBH-5, NBH-7, NBH-9, and NBH-18 were published in McQuarrie et al. (2008).

more data would likely reveal a significant population of Cambrian zircons (see Fig. DR3 [footnote 1] for discussion of youngest grains in this sample). BU08-135 yielded a series of peaks between ca. 475 Ma (three grains) (see Fig. DR3 [footnote 1] for discussion of youngest peaks in this sample) and ca. 850 Ma, and a prominent peak centered at ca. 1.15 Ga.

Three Baxa Group quartzite samples (BU07-42, BU07-43A, and BU07-22) were analyzed. Sample BU07-42, collected south of Trashigang (Fig. 2) yielded a broad plateau of ages between ca. 0.9 and ca. 1.7 Ga, with the most prominent peak at ca. 1.7 Ga. Sample BU07-43A, also collected south of Trashigang (Fig. 2), yielded a series of small peaks between ca. 0.95 and ca. 1.7 Ga. A sample (BU07-22), collected in the southern Kuru Chu valley (Fig. 2), yielded a youngest peak supported by six concordant zircons centered at ca. 525 Ma (see Fig. DR3 [footnote 1] for discussion of youngest peak in this sample), and older peaks at ca. 1.7 Ga and ca. 2.4 Ga.

A quartzite sample (BU07-54) (Fig. 2) from the Diuri Formation yielded a youngest peak centered at ca. 385 Ma (five grains), and a prominent peak centered at ca. 475 Ma (69 grains). A sandstone sample (BU07-53) (Fig. 2) from the Gondwana succession, yielded a prominent youngest peak centered at ca. 500 Ma (21 grains), with older peaks including one centered at ca. 1.1 Ga.

DEPOSITIONAL AGE CONSTRAINTS

Daling-Shumar Group

We interpret the 1844 ± 64 Ma (2σ) weighted mean age of the youngest three concordant zircons in orthogneiss sample NBH-8 as the crystallization age of the gneiss' granitic protolith. This age is in agreement (within error) with previous studies in eastern Bhutan, including Richards et al. (2006), who obtained a U-Pb monazite crystallization age of 1.79–1.89 Ga from a Daling-Shumar Group metarhyolite, and Daniel et al. (2003), who reported a 1.76–1.84 Ga (reinterpretation of data originally reported by Thimm et al. [1999]) U-Pb zircon crystallization age from a Daling-Shumar Group orthogneiss east of Mongar. The 1865 ± 47 Ma (2σ) age from the youngest three concordant zircons from Daling Formation sample BU07-10 constrains the maximum deposition age of this sample. Sample NBH-9, a quartzite from the Shumar Formation section (McQuarrie et al., 2008), yielded a broad, youngest detrital zircon peak centered at ca. 1.92 Ga. However, the youngest three concordant (>99%) zircons that cluster together (overlap within error) yield a weighted mean age of 1816 ± 49 Ma (2σ),

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which constrains the maximum deposition age of this sample.

Previous workers have interpreted the Daling-Shumar Group orthogneiss bodies as tectonic slivers of Indian crystalline basement incorporated during thrust propagation (Ray et al., 1989; Dasgupta, 1995a; Ray, 1995). Note that with our reported errors, the crystallization age range of the orthogneiss (NBH-8) is 1780 to 1908 Ma, and the maximum depositional ages of the two detrital samples (BU07-10 and NBH-9) are 1818 to 1912 Ma and 1767 to 1865 Ma, respectively. Based on these age ranges, we cannot state with certainty that the intrusive unit is younger than the detrital samples. However, based on observed intrusive contact relationships (Fig. 4B), and stratigraphic positions that do not correspond with the base of the consistent two-part Daling-Shumar stratigraphy (see Daling Formation), we interpret the orthogneiss bodies as granite intrusions that were originally emplaced in the Daling-Shumar Group section, and were later deformed in Himalayan orogenesis (e.g., DeCelles et al., 2000; Daniel et al., 2003; Kohn et al., 2010). Under this interpretation, the crystallization age of NBH-8 together with the age of youngest detrital zircon peaks in BU07-10 and NBH-9 allow us to bracket the age of Daling-Shumar deposition as Paleoproterozoic, between ca. 1.8 and 1.9 Ga.

Jaishidanda Formation

Due to a lack of fossils, the Jaishidanda Formation has previously been assigned an inferred Precambrian age (Bhargava, 1995; Dasgupta, 1995b). Based on our eight-sample detrital zircon data set, there are two possibilities for the deposition age of the Jaishidanda Formation: (1) the entire unit is Ordovician or younger, and the observed variability in detrital zircon spectra is the result of variation in sediment provenance. The lack of young detritus in some samples could represent a heterogeneous source region with an aerially limited source for Paleozoic zircons, or could reflect limited sediment mixing during deposition (e.g., Gehrels et al., 2000; DeGraaff-Surpless et al., 2003; Mapes, 2009); or (2) although the lithology of the Jaishidanda Formation is remarkably uniform along strike, the unit could contain strata as old as Neoproterozoic and as young as Ordovician. Note that in the northern Kuru Chu valley, sample NBH-7 is low in the section and displays a Neoproterozoic (ca. 1.0 Ga) youngest detrital zircon peak, and sample NBH-5 is higher in the section and contains an Ordovician (ca. 485 Ma) youngest detrital zircon peak (McQuarrie et al., 2008). However, other than this locality, there is no other systematic decrease in youngest peak age observed between the base and top of the Jaishidanda section. For example, in western Bhutan there is a ca. 475 Ma detrital zircon peak in quartzite near the base of the section (BU08-135), and in east-central Bhutan quartzite at the top of the section contains a ca. 0.8 Ga youngest peak (BU08-18). Regardless of the full age range of the Jaishidanda Formation, the basal contact with the Daling Formation defines an unconformity that spans ~0.9–1.0 b.y. at the minimum.

McQuarrie et al. (2008) cited similarities in stratigraphic position above the Daling-Shumar Group, and similarities in detrital zircon spectra from a preliminary data set, and tentatively correlated strata under the MCT in eastern Bhutan with the Baxa Group. However, new $\delta^{13}C$ data from this study (see Age constraints from $\delta^{13}C$ data) suggests that the youngest part of the Baxa Group may be Early Cambrian in age, and new mapping from this study strengthens the interpretation that the strata under the MCT are lithologically unique, and that at least part of the map unit under the MCT has an Ordovician maximum age. For this reason, in this study we map the Jaishidanda Formation as a distinct map unit. However, under the broad age constraints we obtain in this study (Neoproterozoic to Cambrian(?) for the Baxa Group, Neoproterozoic to Ordovician(?) for the Jaishidanda Formation), strata in these two units could either overlap or be of significantly different age.

Baxa Group

Age constraints from detrital zircons

Previous estimates for the deposition age of the Baxa Group have ranged from Precambrian to Triassic (Jangpangi, 1989; Tangri, 1995a). McQuarrie et al. (2008) obtained a ca. 520 Ma (nine-grain) detrital zircon peak from Baxa Group sample NBH-18 (Fig. 5), indicating a Cambrian maximum deposition age. The NBH-18 age spectrum is very similar to that obtained from sample BU07-22, which yielded a ca. 525 Ma (six-grain) Cambrian youngest peak. However, the zircon age spectra from samples BU07-42 and BU07-43A, which were sampled from characteristic Baxa Group quartzite, lack Cambrian peaks, and have no zircons younger than ca. 0.9 Ga. However, they do share the ca. 0.9 to 1.7 Ga age range that is observed in samples NBH-18 and BU07-22. The lack of Cambrian zircons in BU07-42 and BU07-43A could indicate either: (1) an Early Cambrian or younger deposition age for the whole unit, but with different source regions, one with and one without access to a source for Cambrian zircons, or (2) the strata lacking Cambrian zircons could have an older deposition age. Based on the relative positions of the samples in Baxa stratigraphic columns, i.e., samples containing either ca. 900 or ca. 520 Ma youngest detrital zircon peaks in upper stratigraphic positions and the sample containing the ca. 525 Ma youngest peak in a lower stratigraphic position (Fig. 3B), we argue that the entire section is most likely Cambrian or younger in age.

Age constraints from $\delta^{13}C$ data

Samples were collected for carbon and oxygen isotope analysis from five stratigraphic sections of Baxa Group dolomite. Samples were slabbed and polished perpendicular to bedding and ~5 mg of powder was micro-drilled for isotopic analysis. The most pristine dolomite was targeted, and care was taken to avoid cements and secondary veins or precipitates. The $\delta^{13}C$ and $\delta^{18}O$ values were measured simultaneously on a Finnigan MAT 251 triple-collector gas source mass spectrometer coupled to a Kiel I automated preparation device at the University of Michigan Stable Isotope Laboratory. Data are reported in permil (‰) notation relative to VPDB (Vienna Pee Dee Belemnite), and measured precision is maintained at better than 0.1‰ for both carbon and oxygen isotope compositions. From the five sections (locations shown on Fig. 2), a total of 122 stratigraphic levels were sampled, and a total of 151 analyses (individually shown in Table DR3 [footnote 1]) were performed (29 analyses are duplicates from the same stratigraphic level).

The data for each section are shown in Figure 6. In general, Baxa dolomite $\delta^{13}C$ values range between 0‰ and +7‰, with most values falling between +3‰ and +6‰. Section BHU-1 is stratigraphically below section CBU-13, and both are sampled from dolomite intervals within the same thrust sheet south of Trashigang (Fig. 2). Both sections have consistent $\delta^{13}C$ values between +3.5‰ and +4.5‰. Note that these sampled dolomite intervals are located in the same thrust sheet but downsection of quartzite sample NBH-18, which yielded a ca. 520 Ma youngest detrital zircon peak (McQuarrie et al., 2008) (Fig. 3B). Section CBU-1 is stratigraphically below section CBU-2, and both are sampled from dolomite intervals within the same thrust sheet in the Kuru Chu valley (Fig. 2). The $\delta^{13}C$ values at the base of the CBU-1 section are between +5.5‰ and +6‰, but decrease to +2‰ 50 m higher. Section CBU-2 $\delta^{13}C$ values are constant at +5.5‰, except for one +1.5‰ value at 85 m. Section CBU-5 is located south of sections CBU-1 and CBU-2, in a different thrust sheet in the Kuru Chu valley (Fig. 2). Note that the CBU-5 section is located in the same thrust sheet but upsection of quartzite sample BU07-22, which yielded a ca. 525 Ma youngest detrital zircon peak (Fig. 3B). The $\delta^{13}C$ values at the base of

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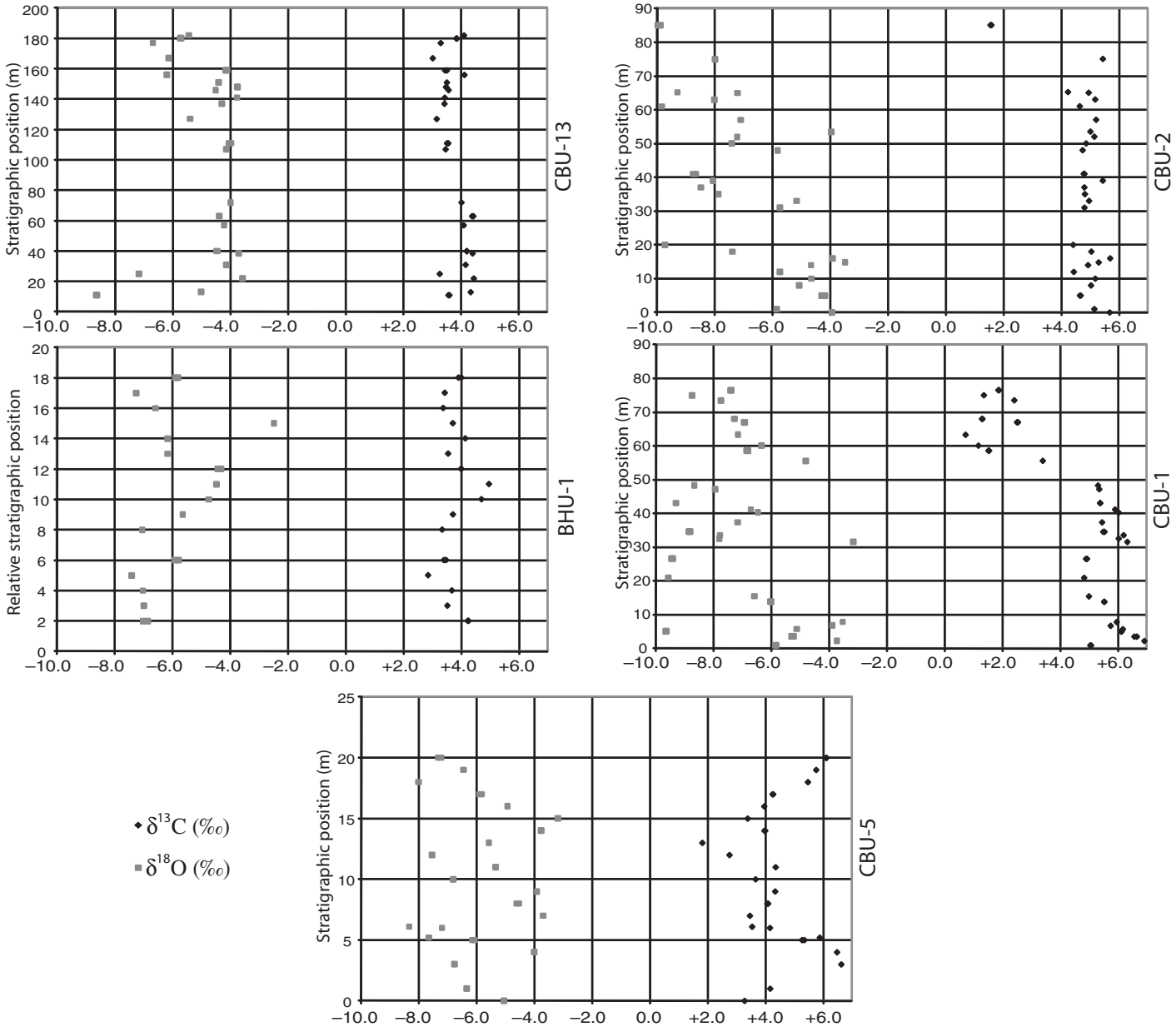

Figure 6. The $\delta^{13}C$ and $\delta^{18}O$ data versus stratigraphic position (note different vertical scales for each section) for five Baxa Group dolomite sections. Section BHU-1 is stratigraphically below section CBU-13 along the Trashigang-Samdrup Jongkhar road, section CBU-1 is stratigraphically below section CBU-2 in the Kuru Chu valley, and section CBU-5 is located in a different thrust sheet, farther south in the Kuru Chu valley (Fig. 2). Note consistent high positive $\delta^{13}C$ values, generally between +3‰ and +6‰. Data for individual analyses are shown in Table DR3 [footnote 1].

section CBU-5 start out at +4‰, increase to +6‰ between 0 and 5 m, decrease to +4‰ between 5 and 17 m (with two values near +2‰), and increase to +6‰ again between 17 and 20 m.

A ca. 525 Ma detrital zircon peak in quartzite stratigraphically below a sampled dolomite section (CBU-5) (Fig. 3B) indicates a lower Cambrian maximum deposition age. A Permian age of the overlying Gondwana succession (see Diuri Formation and Gondwana Succession) limits the youngest age of deposition. Outcrop observation and thin section analysis failed to yield fossils that could allow for a more precise age of deposition. However, isotope records from Paleozoic strata (Saltzman et al., 1998; Maloof et al., 2005; Saltzman, 2005) show that $\delta^{13}C$ values are generally between 0‰ and +4‰ for most of the Paleozoic, with a few short periods where values are as positive as +6‰, indicating likely deposition in one of these periods. Although the coarseness of sampling precludes matching isotopic trends, the high positive $\delta^{13}C$ values of our data may be matched to one of these positive excursions. Meteoric diagenesis, diagenetic reprecipitation of organic carbon, and alteration through metamorphism are the most likely ways to modify the absolute values of $\delta^{13}C$ after deposition. However, since these processes tend to shift absolute values more negative, not more positive (Allan and Matthews, 1982; Kaufman and Knoll, 1995;

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Guerrera et al., 1997; Lohmann et al., 1988; Jacobsen and Kaufman, 1999; Melezhik et al., 2003; Knauth and Kennedy, 2009), these processes cannot explain the high positive values we observe, and we feel that we can place confidence in the high positive $\delta^{13}C$ values measured reflecting global values during Baxa Group deposition.

A series of short-duration positive $\delta^{13}C$ excursions between +4‰ and +6‰ are present in the Late Cambrian (Saltzman et al., 1998; Saltzman, 2005), in the Late Ordovician, throughout the Silurian, and in the Late Devonian (Saltzman, 2005). While these ages are permissible for Baxa Group deposition, these documented positive excursions represent time intervals of a few million years or less between much longer periods with $\delta^{13}C$ values between 0‰ and +4‰ (Saltzman, 2005). It is unlikely that the positive plateau of all six continuously sampled sections would be contained entirely within one of these documented short-term positive excursions, unless sedimentation rates were very rapid. Longer-duration excursions to positive $\delta^{13}C$ values between +4‰ and +6‰ are documented in two Paleozoic time intervals, one in the Early Cambrian, which consists of two closely spaced positive excursions between ca. 533–529 Ma and ca. 525–518 Ma (Maloof et al., 2005), and one in the Early Mississippian, between ca. 359 and ca. 348 Ma (Saltzman, 2005).

Neoproterozoic to Cambrian Lesser Himalayan strata are preserved across much of the orogen (see Regional correlation of Lesser Himalayan units) (Brunnel et al., 1985; Valdiya, 1995; Tewari, 2001; Myrow et al., 2003, 2009; Azmi and Paul, 2004; Hughes et al., 2005; Richards et al., 2005; Yin et al., 2010b). Valdiya (1995) documents an unconformity in northwest India above Cambrian Lesser Himalayan strata (see Regional correlation of Lesser Himalyan units), which are overlain by Permian Lesser Himalayan strata. Paleozoic Lesser Himalayan units between these two ages are not reported across the length of the Himalaya (Fig. 7). For this reason, we interpret the later of the two Early Cambrian positive $\delta^{13}C$ excursions (ca. 525–518 Ma, Maloof et al., 2005), which is compatible with underlying quartzite containing ca. 525 Ma detrital zircons, as the most likely interval for deposition of Baxa Group dolomite. Cross-bedding that indicates the Baxa Group is always upright (Fig. 4E) and fault zones at upper and lower boundaries of repeated stratigraphic sections allow us to place the detrital zircon and $\delta^{13}C$ data in their respective places on a stratigraphic column (Fig. 3B). Figure 3B highlights that although the Baxa Group contains quartzite with a Neoproterozoic maximum deposition age, in places much of the section is most likely Early Cambrian in age.

Diuri Formation and Gondwana Succession

Previous age estimates for the Diuri Formation have ranged from Neoproterozoic to Permian (Jangpangi, 1974, 1978; Acharyya et al., 1975; Acharyya, 1978; Gansser, 1983; Tangri, 1995b). However, the ca. 390 Ma youngest detrital zircon peak obtained from sample BU07-54 and the Permian age of the Gondwana succession (Joshi, 1989, 1995; Lakshminarayana, 1995) brackets Diuri deposition between Devonian and Permian. With this established age range, the Diuri Formation can be related to the Late Mississippian to Early Permian glaciation of the Gondwana supercontinent (Ziegler et al., 1997; Scotese et al., 1999; Veevers, 2000, 2001; Isbell et al., 2003). Finally, marine fossils obtained from the Gondwana succession (Joshi, 1989, 1995) indicate a Permian deposition age.

PROVENANCE INTERPRETATIONS

Paleoproterozoic Lesser Himalayan Units

Detrital zircon peaks in the Daling-Shumar Group range from Neoarchean (ca. 2.5–2.7 Ga) to Paleoproterozoic (ca. 1.8–1.9 Ga), and similar peak ages have been documented in correlative Lesser Himalayan units along strike in Nepal and northwest India (Parrish and Hodges, 1996; DeCelles et al., 2000; DiPietro and Isachsen, 2001; Martin et al., 2005). A review of geochronology data for basement gneisses within the Singhbhum, Aravalli, and Dharwar cratons of central and southern India shows that all are dominated by Paleoarchean to Paleoproterozoic (ca. 2.4–3.4 Ga) nuclei (Crawford, 1970; Beckinsale et al., 1980; Choudhary et al., 1984; Moorbath et al., 1986; Baksi et al., 1987; Naqvi and Rogers, 1987; Gopalan et al., 1990; Tobisch et al., 1994; Wiedenbeck and Goswami, 1994; Mishra et al., 1999; Chadwick et al., 2000). However, note that the Daling-Shumar Group and correlative units along strike lack zircon peaks >3.0 Ga, even though basement gneisses between ca. 3.0 and 3.4 Ga make up a significant volume of the Indian craton. This may indicate that Indian basement rocks were covered by supracrustal sediment, or that continental India was not the source of sediment during Paleoproterozoic Lesser Himalayan deposition.

It is also important to note that an obvious source for zircons between 1.8 and 1.9 Ga has not been identified on the Indian continent (Parrish and Hodges, 1996; Kohn et al., 2010), although aerially limited igneous rocks of this age have recently been identified in the Greater Himalayan section (Chakungal et al., 2010). The consistent presence of a prominent ca. 1.8–1.9 Ga detrital zircon peak, combined with the observation that the most significant igneous units of this age are the orthogneiss bodies that intrude the Paleoproterozoic Lesser Himalayan rocks themselves (see Daling-Shumar Group, Fig. 7), suggests that ca. 1.8–1.9 Ga magmatism and deposition were localized along the northern Indian margin (Kohn et al., 2010). The depositional environment for Paleoproterozoic Lesser Himalayan units has recently been interpreted as a magmatic arc setting (Kohn et al., 2010).

Neoproterozoic–Paleozoic Lesser Himalayan Units

Circa 0.9 to ca. 1.7 Ga detrital zircons are present in all Baxa Group samples and all Jaishidanda Formation samples from eastern Bhutan, implying a similar source area. The prominent ca. 1.7 Ga peak observed in most of these samples has a likely source just south of Bhutan, from gneisses in the Shillong Plateau (Yin et al., 2010a) and along the Brahmaputra River in Bangladesh (Ameen et al., 2007). Mesoproterozoic–Neoproterozoic zircons could have local sources, including ca. 1.6 Ga basement gneisses in the Shillong Plateau (Chatterjee et al., 2007), or more distal sources, including granite intrusions hosted by the Indian craton (Choudhary et al., 1984; Naqvi and Rogers, 1987; Volpe and MacDougall, 1990; Tobisch et al., 1994), or orogenic belts related to the assembly of the Rodinia supercontinent, situated between northeastern India and Australia (ca. 1.3–1.2 Ga) (Meert, 2003) and southeastern India and East Antarctica (ca. 1.0–0.9 Ga) (Meert, 2003; Li et al., 2008). Finally, ca. 1.7–1.0 Ga zircons could have also been sourced from northern Australia (Cawood and Korsch, 2008).

Samples from the Gondwana succession, Diuri Formation, Jaishidanda Formation (BU08-135, BU08-72, and NBH-5), and Baxa Group (BU07-22 and NBH-18) yield Cambrian to Ordovician (ca. 525 to ca. 475 Ma range) detrital zircons. A local source for Cambrian zircons (ca. 520–500 Ma granite intrusions) is present in the Shillong Plateau (Yin et al., 2010a). More distal but larger volume Cambrian sources could include orogenic belts associated with the assembly of the Gondwana supercontinent, including the ca. 570–530 Ma Kuunga orogeny, which involved the collision of Australia and Antarctica with southern and eastern India (Meert et al., 1995; Meert and Vandervoo, 1997; Meert, 2003; Collins and Pisarevsky, 2005).

Although limited in number, another possible source for Cambrian and Ordovician zircons could be from granite plutons of this age present in the Greater Himalayan section, which are observed along the entire orogen

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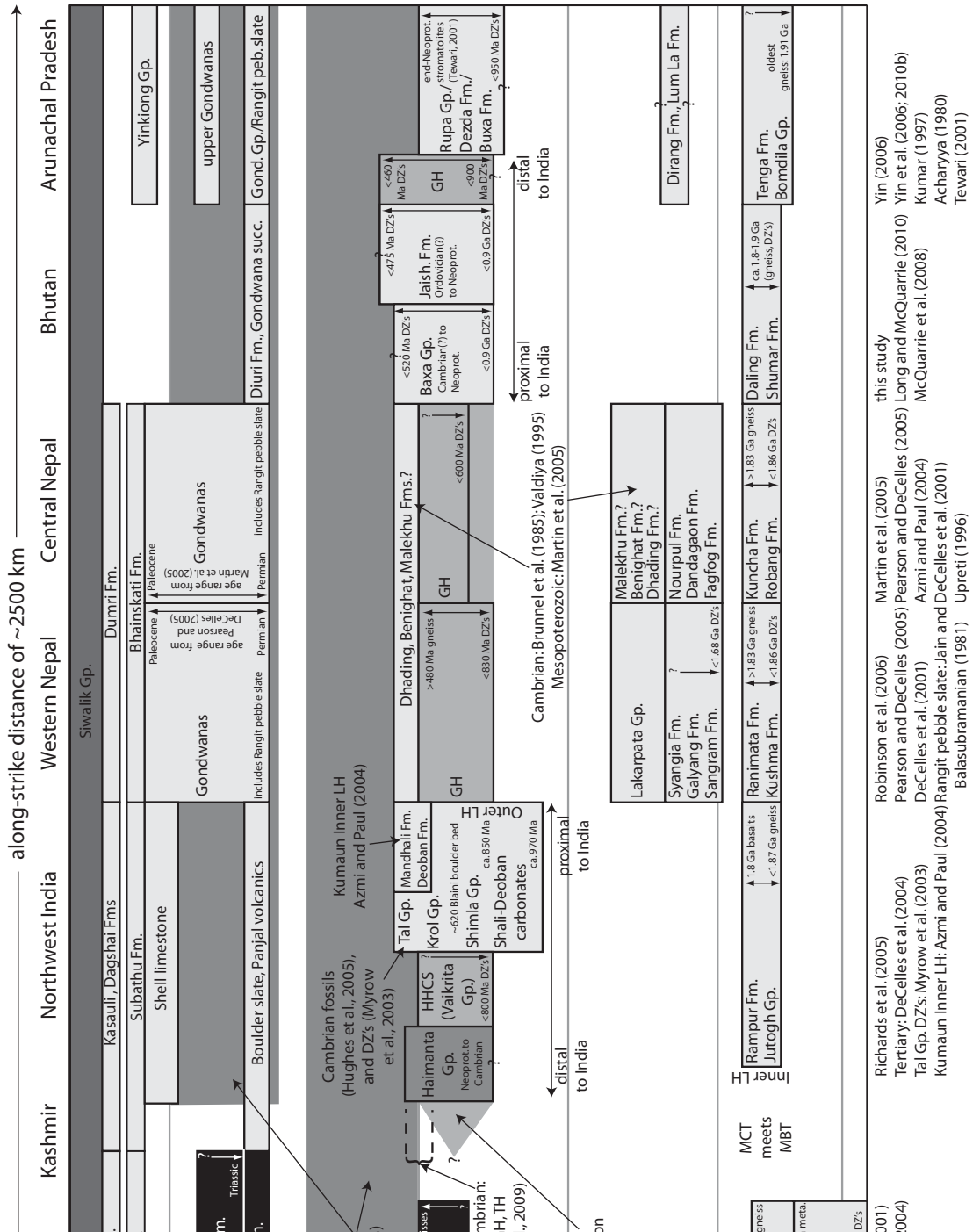

Figure 7. Correlation chart of general deposition age history of the northern Indian margin. Focus is on geochronologic and stratigraphic studies that bracket deposition ages for Lesser Himalayan units. Note along-strike continuity of Paleoproterozoic and Permian Lesser Himalayan units across all of the orogen, and presence of Neoproterozoic–Cambrian Lesser Himalayan units across much of orogen. General age brackets for deposition of Greater Himalayan protoliths, Tethyan (or Tibetan) Himalayan section (TH), and Siwalik Group shown. Note overlaps in time between Tethyan (or Tibetan) Himalayan and Greater Himalayan deposition distal to India and Lesser Himalayan deposition proximal to India. Refer to DiPietro and Pogue (2004) for a more detailed correlation chart of Lesser Himalayan units in the westernmost Himalaya. DZ—detrital zircon; GH—Greater Himalaya; HHCS— Higher Himalayan Crystalline Sequence; MBT—Main Boundary thrust; MCT—Main Central thrust; succ.—succession.

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(Valdiya, 1995; Gehrels et al., 2003; Cawood et al., 2007). This scenario would indicate at least a partial northern provenance, and has been proposed for Ordovician coarse-clastic Tethyan Himalayan units in Nepal and northwest India (Garzanti et al., 1986; Gehrels et al., 2003), attributed to Cambro-Ordovician tectonic activity on the northern Indian margin (Cawood et al., 2007) (see Pre-Himalayan northern Indian margin).

DISCUSSION: BHUTAN LESSER HIMALAYAN STRATIGRAPHY IN MARGIN-WIDE CONTEXT

Regional Correlation of Lesser Himalayan Units

Our new deposition age data from this study allow us to place Bhutan Lesser Himalayan stratigraphy in the margin-wide context of deposition age trends shown on Figure 7. The Paleoproterozoic Daling-Shumar Group represents an eastern continuation of the trend of ca. 1.8–1.9 Ga Lesser Himalayan deposition and magmatism that occurred along the majority of the northern Indian margin (summarized in Kohn et al., 2010). In the eastern Himalaya, the Daling-Shumar Group has been correlated with the Garubathan Formation of Sikkim-Darjeeling (Acharyya, 1989; Jangpangi, 1989; Ray, 1989; Dasgupta, 1995a), which is further correlated with the Tenga Formation and Bomdila Group of Arunachal Pradesh (Acharyya, 1989; Kumar, 1997; Yin, 2006; Yin et al., 2010b). Gneisses in the Bomdila group may be as old as ca. 1.91 Ga (Kumar, 1997). The Kuncha Formation in central Nepal and the Kushma and Ranimata Formations in western Nepal are bracketed between 1.83 Ga, the crystallization age of the Ulleri orthogneiss, which intrudes the lower part of the section (DeCelles et al., 2000), and 1.86 Ga, based on detrital zircon peak ages (Parrish and Hodges, 1996; DeCelles et al., 2000; Martin et al., 2005). In addition, the two-part stratigraphy of the lower Kushma quartzite and upper Ranimata phyllite is broadly similar to the Shumar and Daling Formation division. In northwest India, Paleoproterozoic rocks are observed in the Inner Lesser Himalayan section, consisting of the Jutogh Group, which is intruded by the ca. 1.87 Ga Wangtu orthogneiss (Richards et al., 2005), and the overlying Rampur Formation metasedimentary rocks, in which volcanics have been dated at ca. 1.8 Ga (Miller et al., 2000). The western boundary of the orogen in NW Pakistan contains the Paleoproterozoic Karora and Gandaf Formations, which are bracketed between 2.17 Ga, the age of detrital zircons in the underlying Kishar Formation, and 1.86 Ga, the crystallization age of intrusive orthogneiss (DiPietro and Isachsen, 2001).

The post-Paleoproterozoic Lesser Himalayan section records a more complex history of deposition, with long periods with no preserved rock record (Fig. 7). Yin (2006) documents an orogen-wide unconformity between lower Lesser Himalayan rocks, which are listed as Mesoproterozoic on his figure 5, and overlying Neoproterozoic to Cambrian Lesser Himalayan rocks. We agree with this interpretation of a major unconformity, but since Mesoproterozoic rocks are limited primarily to areas of Nepal and Arunachal Pradesh (Fig. 7), and Paleoproterozoic Lesser Himalayan rocks are much more laterally continuous, we suggest that this unconformity is variable throughout the orogen and represents a more significant amount of time in several locations. In Bhutan, the Neoproterozoic (ca. 0.9 Ga) maximum deposition age of the Baxa Group and Jaishidanda Formation defines an unconformity above the Daling Shumar Group that represents ~0.9–1.0 b.y. at the minimum and may be as long as ~1.4 b.y.

Based on lithology alone, the Baxa Group had previously been correlated with Neoproterozoic Lesser Himalayan units of northwest India (Nautiyal et al., 1964; Guha Sarkar, 1979) and Arunachal Pradesh (Tewari, 2001). However, our detrital zircon data indicate that deposition must have continued to at least the Early Cambrian. Neoproterozoic to Cambrian Lesser Himalayan strata are exposed along much of the orogen, in northwest India, Nepal, and Arunachal Pradesh (Fig. 7) (Brunnel et al., 1985; Valdiya, 1995; Myrow et al., 2003, 2009; Azmi and Paul, 2004; Richards et al., 2005; Yin et al., 2010b). The Outer Lesser Himalayan section of northwest India contains the Neoproterozoic Krol Group (Richards et al., 2005), which has been correlated with the Baxa Group (Nautiyal et al., 1964; Guha Sarkar, 1979), and the Tal Group, which contains Lower Cambrian trilobite fossils (Hughes et al., 2005) and Early Cambrian (ca. 525 Ma) zircons (Myrow et al., 2003), and contains an upper section that may be Middle to Late Cambrian or younger (Hughes et al., 2005). The Inner Lesser Himalayan section of northwest India contains the Deoban Formation, which has conodont fossils that straddle the Neoproterozoic–Cambrian boundary (Azmi and Paul, 2004). In west-central Nepal, fossils in the Dhading Formation were initially identified as Early Cambrian (Brunnel et al., 1985; Valdiya, 1995), although this is repudiated by Hughes et al. (2005), and Martin et al. (2005) interpret a Mesoproterozoic age for this formation (Fig. 7). East of Bhutan in Arunachal Pradesh, the Rupa Group has been correlated with the Baxa Group (Acharyya, 1980), and also yields ca. 0.9 Ga youngest detrital zircon peaks (Fig. 7) (Yin et al., 2006). Finally, workers in Arunachal Pradesh have argued for a terminal Neoproterozoic age for the Menga Limestone, which has also been correlated with Baxa Group dolomite and yields $\delta^{13}C$ values between +2.8‰ and +5.8‰ (Tewari and Sial, 2007; Tewari, 2001).

Valdiya (1995) documents an unconformity in the Lesser Himalayan section that spans most of the Paleozoic. In Nepal and northwest India, Cambrian Lesser Himalayan units are the youngest exposed under the unconformity, and Permian Lesser Himalayan units overlie the unconformity (Brunnel et al., 1985; Valdiya, 1995; Myrow et al., 2003, 2009; Azmi and Paul, 2004; Hughes et al., 2005) (Fig. 7). If the Baxa Group has a youngest deposition age of Early Cambrian, which we argue is likely based on youngest detrital zircon peaks and $\delta^{13}C$ data from dolomite (see Age constraints from $\delta^{13}C$ data), then Lesser Himalayan stratigraphy in Bhutan demonstrates an eastward continuation of this Permian over Cambrian unconformity (Fig. 7).

Deposition age bracketing of the Diuri Formation (see Diuri Formation and Gondwana succession) allows for correlation with other Permian glacial diamictite Lesser Himalayan units along strike (Fig. 7) (Brookfield, 1993; Yin, 2006). These units include the Boulder Slate in northwest India (Richards et al., 2005), and the Rangit pebble slate units in Arunachal Pradesh (Acharyya, 1981), Nepal, and Sikkim, where they are grouped with the Gondwana succession (Jain and Balasubramanian, 1981).

The Permian deposition age of the Gondwana succession has allowed correlation with similar post-glacial, coal-bearing clastic strata of the Gondwana Supergroup (Sinha, 1974; Gansser, 1983), which are exposed in the Lesser Himalayan section in Nepal (Martin et al., 2005; Pearson and DeCelles, 2005; Robinson et al., 2006), Arunachal Pradesh (Kumar, 1997) (Fig. 7), Sikkim (Acharyya, 1971), and in places on the Indian shield (Brookfield, 1993).

Timing Relationships between Lesser, Greater, and Tethyan Himalayan Deposition

Broad age patterns of Lesser Himalayan unit deposition, when compared to the deposition age ranges of Greater Himalayan sedimentary protoliths and Tethyan Himalayan units farther outboard, show significant temporal overlaps, as illustrated on Figure 7. In Bhutan, Nepal, and northwest India, the deposition age range of protoliths of Greater Himalayan metasedimentary rocks falls between Neoproterozoic

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and Ordovician (DeCelles et al., 2000; Martin et al., 2005; Richards et al., 2006; Myrow et al., 2009; Long and McQuarrie, 2010) (see Greater Himalayan and Tethyan Himalayan zones). In the Tethyan Himalayan section, a continuous record of deposition from late Neoproterozoic to Middle Cambrian time is observed across much of the length of the Himalaya (Valdiya, 1995, and references therein; Richards et al., 2005; Myrow et al., 2009, and references therein). Myrow et al. (2009) argue for a coherent Lower and Middle Cambrian Tethyan Himalayan stratigraphy across Nepal and northwest India, and interpret Lower and Middle Cambrian Greater Himalayan and Tethyan Himalayan strata in Nepal as proximal and distal age-equivalents. This supports an along- and across-strike continuity of Cambrian stratigraphy (the continuous passive margin model of Myrow et al. [2003]; see also Searle [1986], Brookfield [1993], and Corfield and Searle [2000]). Younger Tethyan (or Tibetan) Himalayan units above the Cambrian section are present across the entire length of the orogen, and define an Ordovician to Carboniferous shelf sequence of the Paleotethyan margin and a Permian to Eocene passive margin sequence of the Neotethyan passive margin (Gaetani and Garzanti, 1991; Brookfield, 1993; Garzanti, 1999).

Figure 7 shows that proximal deposition of Neoproterozoic–early Paleozoic Lesser Himalayan units across much of the Indian margin overlaps in time with deposition of more distal Greater Himalayan protoliths and pre-Paleotethyan Tethyan Himalayan rocks. Also, proximal deposition of Permian Lesser Himalayan units overlaps in time with deposition of Tethyan Himalayan strata on the distal Neotethyan passive margin (Fig. 7).

Pre-Himalayan Northern Indian Margin

Although temporal overlaps in deposition between Lesser Himalayan, Greater Himalayan, and Tethyan Himalayan strata argue for a continuous passive margin, significant unconformities in the Lesser Himalayan section, combined with unconformities that represent a smaller time window in the Greater Himalayan and Tethyan Himalayan sections, all suggest a more complicated history for the northern margin of India. Workers across the Himalaya have documented structural and stratigraphic evidence for Cambrian–Ordovician tectonic activity on the northern Indian margin. Gehrels et al. (2003) summarized evidence for Cambrian–Ordovician coarse-clastic deposition in the Tethyan Himalayan section, and widespread Cambrian–Ordovician metamorphism and igneous activity within the Greater Himalayan section, and argued that the Greater Himalayan and Tethyan Himalayan sections were deformed into a south-vergent fold-thrust belt that was active during Late Cambrian–Middle Ordovician time. Ordovician Tethyan Himalayan coarse-clastic strata in Nepal and northwest India are interpreted as foreland basin deposits of this fold-thrust belt (Garzanti et al., 1986; Gehrels et al., 2003). Cawood et al. (2007) interpreted this tectonic event, named the Bhimpedian orogeny, as the result of Andean-type orogenic activity on the northern Indian margin.

Our new deposition age data from Bhutan Lesser Himalayan units allows for tentative interpretation of eastern Himalayan tectonostratigraphy in the context of the Cambrian–Ordovician event. If deposition of the Baxa Group ceased in the Early Cambrian, which we argue is likely (see Baxa Group), then Bhutan contains an eastward continuation of an unconformity documented in the Lesser Himalayan section in Nepal and northwest India, with Cambrian strata below and Permian strata above (Figs. 7 and 8) (Brunnel et al., 1985; Valdiya, 1995; Myrow et al., 2003, 2009; Azmi and Paul, 2004). Some of this missing section could be related to Cambrian–Ordovician orogenic activity, but may also represent periods of nondeposition, or erosion during the Late Paleozoic glacial event. Strata from the Jaishidanda Formation yield Ordovician detrital zircon peaks, which could indicate a northern provenance from erosion of Greater Himalayan granite during the Cambrian–Ordovician event. If this were the case, this unit could represent a southern continuation of syntectonic strata, as suggested for Ordovician Tethyan Himalayan conglomerates in northwest India and Nepal (Garzanti et al., 1986; Gehrels et al., 2003). Paleocurrent directions supporting a northern provenance would support this interpretation; however, cross-bedding exposures for the Jashidanda Formation are limited and do not permit accurate paleocurrent direction measurements. It is interesting to note that the most significant unconformity, ~1.0 b.y. at the minimum and possibly up to ~1.4 b.y., is above the Daling-Shumar Group and below both the Baxa and Jaishidanda formations.

Figure 8 shows a schematic cross section of the pre-Himalayan stratigraphic architecture of the northern Indian margin, based on Lesser Himalayan stratigraphy in Bhutan. This figure focuses on the Lesser Himalayan section. The original architecture of the Greater Himalayan and Tethyan Himalayan sections is complicated by both pre-Himalayan (e.g., Garzanti et al., 1986; Gehrels et al., 2003; Cawood et al., 2007) and Himalayan deformation, as well as possible

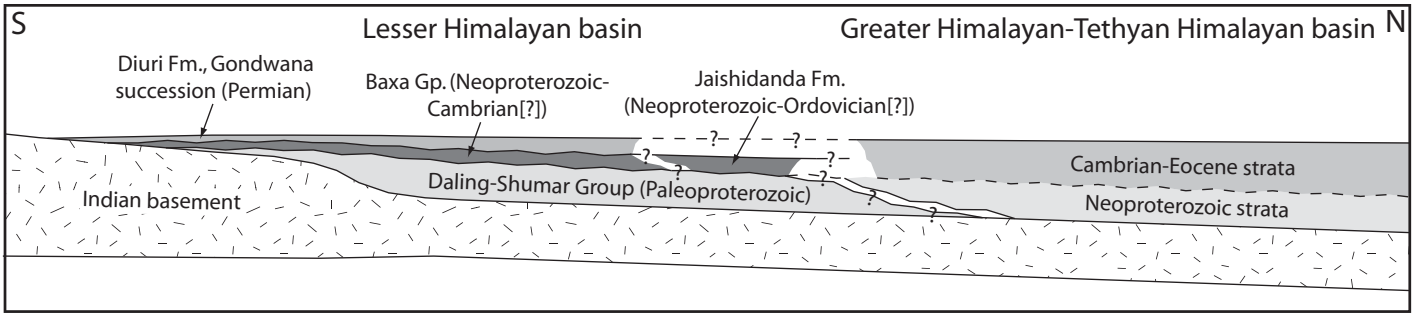

Figure 8. Schematic model for stratigraphic architecture of northern Indian margin based on Bhutan Lesser Himalayan stratigraphy. Note queried relationships of original Greater Himalayan over Lesser Himalayan contact, northern and southern extents of Jaishidanda Formation, and presence of younger Lesser Himalayan strata above Jaishidanda Formation. Note unconformity between Baxa Group and Jaishidanda Formation and underlying Daling-Shumar Group; note unconformity between Baxa Group and overlying Permian Lesser Himalayan units. Note overlap in time between Neoproterozoic–Paleozoic Lesser Himalayan deposition proximal to India and Greater Himalayan and Tethyan Himalayan deposition distal to India (note: change from light to dark gray shown for Greater Himalayan–Tethyan Himalayan basin represents change in time, and is not meant to represent the position of the stratigraphic boundary between Greater Himalayan and Tethyan Himalayan rocks).

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temporally and spatially varying hiatuses in deposition. In Bhutan, parts of the Tethyan Himalayan section may be as old as Neoproterozoic (Bhargava, 1995), while parts of the Greater Himalayan section are as young as Ordovician (Long and McQuarrie, 2010). All stratigraphic relationships that are not observed in the field are queried on Figure 8, including the nature of the original Greater Himalayan–Lesser Himalayan contact, and the northern and southern extents of the Jaishidanda Formation. We want to emphasize that the relationships for Lesser Himalayan units that *are* observed in the field include (1) the lower stratigraphic contact between the Baxa Group (Bhattacharyya and Mitra, 2009; Mitra et al., 2010) and Jaishidanda Formation with the Daling-Shumar Group, (2) the upper stratigraphic contacts between the Baxa Group and the Diuri Formation and Gondwana succession, and (3) the lower thrust contact of the Diuri Formation over the Gondwana succession, and collectively show that the stratigraphic order of Lesser Himalayan units in Bhutan is established. This means that despite uncertainties in the deposition ages of the Baxa Group and Jaishidanda Formation, these units are still constrained in their correct stratigraphic order. This is important for facilitating studies in Bhutan focused on reconstruction of deformation through the fold-thrust belt (e.g., Long et al., 2011).

CONCLUSIONS

(1) New mapping, in conjunction with U-Pb zircon ages and $\delta^{13}C$ data, shows that the Lesser Himalayan section in eastern Bhutan can be divided into six map units: (1) the 1–6-km-thick Shumar Formation, and (2) the 3-km-thick Daling Formation, which together comprise the Daling-Shumar Group, (3) the 0.6–1.7-km-thick Jaishidanda Formation, which stratigraphically overlies the Daling-Shumar Group beneath the MCT, (4) the 2–3-km-thick Baxa Group, which stratigraphically overlies the Daling-Shumar Group in the foreland (Bhattacharyya and Mitra, 2009; Mitra et al., 2010), (5) the 2–3-km-thick Diuri Formation, and (6) the 1–2-km-thick Gondwana succession.

(2) The ca. 1.8–1.9 Ga deposition age of the Daling-Shumar Group adds data to a growing number of studies that suggest that Paleoproterozoic Lesser Himalayan deposition was continuous across the entire length of the northern Indian margin.

(3) The Neoproterozoic–Cambrian(?) deposition age range of the Baxa Group and Neoproterozoic–Ordovician(?) deposition age range of the Jaishidanda Formation, with respect to the ca. 1.8–1.9 Ga deposition age of the underlying Daling-Shumar Group, defines an unconformity in the Lesser Himalayan section that represents ~0.9 to as much as 1.4 b.y.

(4) The Cambrian deposition age that we argue is most likely for the Baxa Group section, and the Permian deposition ages of the overlying Diuri Formation and Gondwana succession, show an eastward continuation of the unconformity in the Lesser Himalayan section with Permian units over Cambrian units that has previously been identified in Nepal and northwest India.

(5) Our deposition age data indicate time-equivalent deposition of Neoproterozoic–Paleozoic Lesser Himalayan units proximal to India and Greater Himalayan and Tethyan Himalayan units distal to India.

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