The lower Lesser Himalayan sequence: A Paleoproterozoic arc on the northern margin of the Indian plate

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ABSTRACT

The lower Lesser Himalayan sequence marks the northern extremity of the exposed Indian plate, and is generally interpreted as a passive margin. Five lines of evidence, however, collectively suggest a continental arc setting: (1) igneous intrusions and volcanic rocks occur at this stratigraphic level across the length of the Himalaya, (2) ages of intrusive and metavolcanic (?) rocks cluster at 1780–1880 Ma but also indicate a long-lived igneous process, (3) detrital zircon ages in clastic rocks cluster at 1800–1900 Ma, with a unimodal age distribution in some rocks, (4) the mineralogy and chemistry of meta-sedimentary rocks differ from typical shales and suggest a volcanogenic source, (5) trace-element chemistries of orthogneisses and metabasalts are more consistent with either an arc or a collisional setting. Intercalation of volcanic rocks with clastic sediments and a general absence of Proterozoic metamorphic ages do not support a collisional origin. An arc model further underscores the profound unconformity separating lower-upper Lesser Himalayan rocks, indicating that a Paleoproterozoic arc may have formed the stratigraphic base of the northern Indian margin. This, in turn, may indicate disposition of the Indian plate adjacent to North America in the ca. 1800 Ma supercontinent Columbia. Felsic orthogneisses (“Ulieri”) likely represent shallow intrusions, not Indian basement.

INTRODUCTION

Understanding the origins and predeformed geometry of the northern exposed edge of the Indian plate is crucial for unraveling the deformation history attending collision of India with Asia, and hence for reconstructing India’s position in former supercontinents (e.g., see reviews of Gansser, 1964; Le Fort, 1975, 1996; Yin, 2006). The Lesser Himalayan sequence plays a central role in both endeavors. It is directly involved in several major Himalayan thrusts, most significantly the Main Central and Munsiai (or Ramgarh) thrusts. Interpretation of the genesis of Lesser Himalayan rocks also figures prominently in the placement of India in the hypothesized, ca. 1800 Ma supercontinent Columbia. Columbia, in turn, is important for understanding the supercontinent cycle: did supercontinents form in the Paleoproterozoic and Archean, and if so what influence did they play in surface processes (e.g., Reddy et al., 2009)?

Metasedimentary rocks are reported to constitute the lower portion (≥4 km) of the Lesser Himalayan sequence (total thickness 2–8 km; e.g., Stöcklin, 1980; Valdiya, 1980; Schelling, 1992; DeCelles et al., 2001; McQuarrie et al., 2008), and are generally interpreted as the passive margin sedimentary cover to the Indian craton (e.g., Brookfield, 1993; Upreti, 1999; Myrow et al., 2003; Gehrels et al., 2006). Yet, in contrast to the passive margin paradigm, igneous events are also recorded within the lower Lesser Himalayan sequence. Well-constrained radiometric ages are sparse, but zircon U-Pb and Pb-Pb ages for intercalated orthogneisses and metabasalts, and detrital zircon grains from the entire breadth of the Himalaya indicate a common Paleoproterozoic age of 1800–1900 Ma (Fig. 1, Table 1). This age span is not consistent with zircon ages from the Indian shield (Parrish and Hodges, 1996; this study), so a fresh interpretation is warranted. In NW India, plume or rift magmatism is commonly invoked (e.g., Bhat et al., 1998; Ahmad et al., 1999; Ahmad, 2008).

In this paper, we present and discuss several lines of evidence to argue that the Paleoproterozoic assemblage at the base of Lesser Himalayan sequence represents a continental arc, rather than a passive margin, a collisional belt, or a plume- or rift-related environment.

We interpret these rocks to consist predominantly of reworked volcanogenic sediments interspersed with intrusive, volcanic, and volcaniclastic rocks. Supportive data include new field observations in NW India and central Nepal, previously published field descriptions across the Himalaya, new and previously published chronologic results (Table 1), and new and previously published whole-rock, major- and trace-element chemistries (Tables A1 and A2). This active margin sequence has not been identified previously as such but is laterally traceable as a ~2500 km long persistent horizon, albeit in detached outcrops, right from the NW Himalayan sector, through Nepal and Bhutan, into NE India (Fig. 1). We discuss implications of our interpretation for correlating Himalayan stratigraphy, and also for interpreting possible geodynamic scenarios related to the ca. 1800 Ma Columbia supercontinent.

GEOLOGIC SETTING AND STRATIGRAPHY

Richards et al. (2005), Robinson et al. (2006), Upreti (1999), and McQuarrie et al. (2008) provide recent accounts and reviews of the Lesser Himalayan lithologies and radiometric ages from northwestern India, western Nepal, central Nepal, and Bhutan, respectively (Fig. 2). The following stratigraphic descriptions are based on their discussion and references therein (especially Stöcklin, 1980; Valdiya, 1980; Gansser, 1983; Bhargava, 1995; Colchen et al., 1986; Schelling, 1992; DeCelles et al., 2001). In India, lower Lesser Himalayan rocks are variously referred to as the Jutogh metasediments, Munsiai Formation or Group, Jaunsar and Damtha Group, and Rampur Formation or Group (within the Rampur window). In this paper, we correlate all these rocks based on lithologic and age, and generally refer to them as “Munsiai.” In Nepal, this interval corresponds with the lower Nawakot Group, which is further subdivided, most notably into the Kushma and...
Ranimata Formations in the west, the Kuncha Formation in central Nepal, and the Tumlingtar Group in the east. The Kushma Formation is a nearly pure quartzite, stratigraphically below the Ranimata Formation, and not obviously associated with igneous rocks. The Kuncha and Ranimata Formations are dominated by clastic material but contain minor amphibolites and a felsic orthogneiss that is usually correlated with the Ulleri augen gneiss, although neither the Ulleri nor other felsic orthogneisses ubiquitously bear augen structure. In Bhutan, basal quartzite (Shumar Formation) is overlain by chloritic phyllite and quartzite (Daling Formation), which additionally contains sheared orthogneiss. The Shumar, Daling, Kuncha, Kushma, Ranimata, Tumlingtar, and Munsiari units are all part of the lower Lesser Himalayan sequence. The boundary between “upper” and “lower” Lesser Himalayan rocks is not agreed upon but is usually placed below units that exhibit significant carbonate components (Fig. 2).

The Munsiari has been described as containing garnet-staurolite-mica schist, quartzite, marble, calc-silicate, mafic amphibolite and graphitic schist, with occasional quartzofeldspathic gneiss (Richards et al., 2005). The Ranimata, Kuncha, and Daling Formations are generally described as chloritic phyllite with scattered quartzite, and either sparse dioritic intrusions (Ranimata Formation: Robinson et al., 2006; Kuncha Formation: Stöcklin, 1980), or mylonitized orthogneiss (Daling Formation: McQuarrie et al., 2008). We found at least one felsic metavolcanic rock in the Kuncha Formation (Fig. 3), and Richards et al. (2006) interpreted a rock from the Daling Formation as a metarhyolite. Because many sections are dominated by clastic material, previous work has emphasized sedimentary, not igneous origins, essentially describing the units as dominated by metashale, metasandstone, or metacarbonates, with intercalated but uncommon igneous bodies of unspecified origins. For example, rocks in NW India are sometimes referred to as the Jutogh metasediments, and clastic sedimentary protoliths are always listed first among rock types in formation descriptions. Whereas previous workers did faithfully record the occurrence of igneous rocks, and many Indian geoscientists proposed various tectonic scenarios based on igneous geochemistry (e.g., Bhat et al., 1998; Ahmad et al., 1999; Ahmad, 2008), such rocks have been largely ignored in interpretations of the configuration of the northern Indian margin.

Although not a focus of this study, carbonate- and graphite-rich sands of the upper Lesser Himalayan sequence are worth discussing for stratigraphic and tectonic context. In Nepal, these rocks are commonly considered early
to middle Proterozoic in age, and unconformably overlain by upper Paleozoic to Cenozoic rocks of Gondwana affinity (e.g., Upadhyay, 1999; DeCelles et al., 2001). In contrast, upper Lesser Himalayan rocks including carbonates and associated quartzites are reported to contain ~500–600 Ma fossils in NW and NE India (Tewari, 2001; Azmi and Paul, 2004, Hughes et al., 2005), and lower Paleozoic碳酸性和isotopic signatures in Bhutan (Long et al., 2006; McQuarrie et al., 2008). When correlated into Nepal, these observations imply that the upper Nawakot is more likely late Proterozoic into Nepal, these observations imply that the upper Nawakot is more likely late Proterozoic as well as the following text.
with a tuff protolith, originally containing quartz phenocrysts and stretched and flattened pumice fragments (Figs. 3D–3F). Some Lesser Himalayan rocks from central Nepal retain feldspar-rich metaigneous chemistries, mineralogies, and textures, and reflect both volcanic and intrusive felsic phases (Figs. 3G and 3H).

Mafic igneous rocks also occur in the lower Lesser Himalayan sequence, commonly as isolated strata that may be intercalated with metasedimentary rocks such as quartz arenites, but they are also associated with felsic metaigneous rocks. One key observation is that minor but widespread chlorite schist in NW India exhibits textures consistent with a mafic volcanic or sill protolith that has been hydrated and metamorphosed. In rare instances, chlorite schist is localized at the margins of mafic amphibolites (Fig. 4A). We interpret this schist as the tops of flows, altered and hydrated either soon after deposition or during metamorphism as a result of enhanced fluid flow along lithologic boundaries. In other instances, mm-diameter white spheroids are hosted in a mafic matrix (Fig. 4B). In thin section, the spheroids are dominated by plagioclase with subordinate quartz, carbonates, and chlorite (Figs. 4C and 4D). The matrix contains abundant coarse-grained plagioclase. We interpret the spheroids as metamorphosed amygdules and the matrix as metamorphosed porphyritic basalt. More generally, we find a progression of variably hydrated mafic assemblages from chlorite-rich through amphibole-rich schist, with variable retention of original porphyritic textures (Figs. 4E and 4F).

The stratigraphic and structural relationships of felsic and mafic rocks with surrounding metasedimentary rocks help constrain possible genetic and tectonic interpretations. Felsic plutonic bodies (Ulleri gneisses) in Nepal are intercalated with “tuffaceous” metasedimentary rocks (Le Fort, 1975; Le Fort and Raï, 1999). The Ulleri and surrounding schists share fabrics, so must have been codeformed, presumably during the late Cenozoic (Le Fort, 1975). Contacts have been described both as gradational with adjacent schists and quartzites (Le Fort, 1975; Le Fort and Raï, 1999) and as obliterated by later deformation (Yin et al., 2009). So, whereas some have proposed that the lower contacts are thrust faults and that the Ulleri represents Indian basement (Gansser, 1964; Yin, 2006; Yin et al., 2009), others interpret the felsic gneisses to reflect either syngenetic porphyritic extrusive rocks (Le Fort, 1975; Le Fort and Raï, 1999), or intrusions into a dominantly sedimentary sequence (e.g., DeCelles et al., 2000), with transformation to gneisses during later deformation.

Along-strike variations are evident in the abundances of igneous components in the lower

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**Figure 3.** Field and thin-section photographs of felsic rocks from Munsiari rocks, northwestern India (A–F) and from Kuncha Formation, central Nepal (G and H). (A–C) Granites and granitic gneiss in Pabar region, India. (D–F) Hand sample and photomicrographs in plane-polarized light and cross-polars of fine-grained “sandstone,” here interpreted as a metamorphosed altered tuff that originally contained quartz phenocrysts (knots in inset of D; coarse quartz in E and F), and pumice fragments (light streaks in D; compositionally distinct domains in E and F). (G) Felsic metavolcanic rock associated with chlorite-rich schist, Kuncha Formation, Langtang region, Nepal. Zircon rims from this sample give an age of ca. 1880 Ma. (H) Augen gneiss in Langtang region, Nepal that is correlated with Ulleri augen gneiss. Zircon rims from this sample give an age of ca. 1880 Ma.
Lesser Himalayan sequence. For example, plutonic rocks are relatively common in the Munsiari of NW India but are relatively rare in the Kuncha and Ranimata Formations of Nepal, which are instead dominated by chlorite- and feldspar-rich schist. Thus, any putative arc in Nepal must be either largely buried under overlying thrusts (e.g., the Main Central Thrust), or dominated instead by volcanic rocks or volcanogenic sediments whose postdeformational and postmetamorphic physical appearance now masquerades as deformed and metamorphosed passive margin sediments.

**Major- and Trace-Element Geochemistry and Zr-Saturation Temperatures**

The overall mineralogy and major-element chemistry of some lower Lesser Himalayan “sediments” in NW India and Nepal is consistent with a volcanogenic or even volcanic origin. In Nepal, lower Lesser Himalayan schist is generally graphite-poor, uniformly feldspar-rich, and contains low-Al assemblages (Catlos et al., 2001; Kohn, 2008). Some samples from the Munsiari in NW India that were identified as metasedimentary rocks have compositions similar to felsic volcanic rocks (Table A1), specifically exhibiting much lower Fe contents (<5.5 wt% Fe₂O₃) and K/Na ratios (<1.7) than average pelites (>5.7 wt% Fe₂O₃ and >2.0). In fact, these compositions closely match those of dacite and rhyolite.

Trace-element geochemistry further supports either an arc or collisional setting. Mafic rocks have been variously interpreted as arc, rift, or flood basalt magmas (Bhat et al., 1998; Ahmad et al., 1999; Miller et al., 2000; Ahmad, 2008). However, high large ion lithophile elements (LILE), low TiO₂, and negative Ta and Nb anomalies are more consistent with an arc (Miller et al., 2000). Discrimination diagrams (Pearce et al., 1984) were considered for Y, Nb, and Rb in felsic rocks because data for these elements are available for many samples. For Nb versus Y, data plot within the volcanic arc and sycollisional fields, implying that within-plate plume or ridge settings are unlikely (Fig. 5A). For Rb versus Nb + Y, data plot near the triple point of the fields for within-plate, volcanic arc, and collisional granites (Miller et al., 2000; Fig. 5B). These interpretations should be viewed with caution because Nd-model ages (Miller et al., 2000; Richards et al., 2005) exceed crystallization ages, perhaps indicating crustal contamination that would bias trace-element compositions, particularly for Rb, which is generally viewed as more mobile than Y and Nb. Nonetheless, Zr-saturation thermometry (Watson and Harrison, 1983) for felsic gneiss and some possible volcanic rocks indicates magmatic temperatures.

Figure 4. Field and thin-section photographs of mafic rocks from Munsiari rocks, northwestern India. These observations suggest that widespread chlorite schist that we observed in the field was, in fact, sourced by basaltic material. (A) Multiple amphibolites with chlorite schist at top, interpreted as possible basalt flows. Mori region, NW India. (B) Metamorphosed amygdaloidal basalt. Most white spheroids are plagioclase, but some also contain carbonate, quartz, or chlorite. These are interpreted as metamorphosed zeolitic infillings. Pabar region, NW India. (C–F) Photomicrographs of greenschist- and amphibolite-facies metabasalt from the Pabar region, NW India, illustrating relict igneous textures and progressive development of chlorite schist from a basaltic precursor. (C and D) Metamorphosed amygdaloidal basalt in plane polarized light and in crossed polars. Amygdules in this rock are now dominated by plagioclase, which probably represents the metamorphosed equivalent of original infilling zeolites. Amygdules in other rocks contain carbonate + plagioclase ± chlorite, or quartz. Matrix silicate assemblage is plagioclase + hornblende + chlorite + biotite + epidote + quartz. (E) More deformed and hydrated amygdaloidal metabasalt, showing sheared relict amygdule and relict porphyritic feldspar texture. Matrix silicate assemblage is plagioclase + chlorite + biotite + epidote + titanite + quartz. (F) Chlorite schist, retaining a few relict porphyritic feldspars. Silicate assemblage is plagioclase + chlorite + biotite + titanite + quartz.
of 800 ± 50 °C (Table A2; Fig. 6), again consistent with relatively wet melting at low temperature in an arc or collisional setting rather than the higher temperatures anticipated for a flood basalt or rift setting. Chambers et al. (2008) identified even lower temperatures for ca. 1810 Ma leuco granites in northwestern India, and ascribed these to wet crustal melting. Correction of Zr contents for any zircon inheritance would lower calculated temperatures, further underscoring low magmatic temperatures.

### Geochronology

Published dates for mafic rocks, orthogneiss, and crosscutting leucogranite generally fall between 1810 and 1870 Ma (Table 1). These ages are distributed across the length of the Himalaya, and their relatively limited age range and common geochemical characteristics imply a single coeval origin for these igneous rocks. The curvilinear distribution of these coeval rocks may reflect their original orientation, although later Cenozoic deformation could have changed their distribution. New data from Arunachal from felsic gneisses appear younger (ca. 1745 Ma; Yin et al., 2009) than most other lower Lesser Himalayan ages. These ages could represent a younger phase of the same magmatic event we propose across the Himalaya. Alternatively, ages of plutonic rocks in Bangladesh are as old as 1720–1730 Ma (Ameen et al., 2007; Hossain et al., 2007), and a discrete younger magmatic event may be regionally significant. It is important to note that Sharma and Rashid (2001) recognized the common ages for some of these rocks along the Himalaya and argued for formation in some consistent tectonomagmatic setting. However, they did not propose a geodynamic setting for these rocks, or otherwise offer any other genetic explanation.

New zircon geochronologic data (Table 1; Fig. 7; see GSA Data Repository1) further support the occurrence of a Paleoproterozoic arc in Nepal but expand the possible age range to 1780–1880 Ma. Sampling and analytical methods are described in the Appendix, and results are shown on standard Concordia diagrams (Fig. 7). These zircons are interpreted as igneous, rather than metamorphic, based on high Th/U ratios (see data repository; Hoskin and

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**Figure 5.** Trace-element data (Rb, Y, Nb) for Lesser Himalayan felsic igneous and metavolcanic (?) rocks plotted on discrimination diagrams (Pearce et al., 1984), showing best agreement with either volcanic arc or syn-collisional origin. Compositions of Langtang (LT) samples, leucogranites from the Sutlej Valley, and possible metavolcanic rocks are slightly more consistent with an arc. Some specific outliers are identified.

**Figure 6.** Zirconium saturation temperatures from Paleoproterozoic felsic gneisses, showing typical (maximum) temperatures of ~800 °C. Data from Le Fort and Raï (1999), Richards et al. (2005), Miller et al. (2000), Chambers et al. (2008), Sharma and Rashid (2001), and this study.
Figure 7. New U-Pb zircon ages from Lesser Himalayan rocks from central and eastern Nepal, showing inferred crystallization ages ranging from ~1780 to ~1880 Ma. Note that sample AS01-5 is from type Ulleri augen gneiss, and gives a significantly younger age than other felsic intrusions (e.g., LT01-102) that are correlated with it.
Schaltegger, 2003) and elongate morphologies (Fig. 7; Corfu et al., 2003). Many zircons show evidence for major recent Pb loss that is either modern or Himalayan (<40 Ma) or both. Yet considering analytical errors and the antiquity of these rocks, young Pb loss does not significantly obscure crystallization ages. For samples from the Arun Valley in eastern Nepal, zircon ages range between 1780 and 1830 Ma, overlapping but somewhat younger than most published ages of other igneous rocks across the orogen (Table 1).

Type Ulleri augen gneiss from Ulleri, Nepal (AS01-5), gives a similarly young, preferred crystallization age of ca. 1780 Ma, but with a likely inherited component of ca. 1880 Ma. Sample LT01-102, from Langtang, Nepal, is correlated with Ulleri augen gneiss, yet gives an age of ca. 1880 Ma—clearly older than type Ulleri, but indistinguishable from the age we infer for a felsic metavolcanic rock intercalated with Kuncha schist (LT01-44a). Note that we focused on analyzing zircon rims, as determined from cathodoluminescence images, but in LT01-44A we also analyzed numerous, presumably inherited cores. Core analyses show a radically different pattern compared to rim analyses: whereas rims strongly cluster at ca. 1880 Ma, cores range widely from 1880 to 3300 Ma.

Putatively detrital zircons in the lower Lesser Himalayan sequence across Nepal show a preponderance of 1800–1900 Ma ages, implying abundant primary magmatic material of that age (e.g., DeCelles et al., 2000, 2004). In at least two instances, metasedimentary rocks yielded a single zircon age peak in that range (DeCelles et al., 2000, 2004). Similarly, we found a pronounced age peak in pelitic schist from Arun (AR01-4), although our analyses are strongly biased toward rims. Possibly some of these sedimentary rocks are of volcanic origin or have a major volcanic component, with zircons derived from local contemporaneous sources. These zircons probably did not derive from cratonal India, which exhibits a distinct age gap between 1750 and 2450 Ma (Parrish and Hodges, 1996; Fig. 8). The only ages from the Indian craton that overlap the age distribution of Lesser Himalayan rocks are of volcanic origin or have a major volcanic component, based on low-Al, feldspar-rich mineral assemblages and mesoscopic and microscopic textures (Figs. 3 and 4). These observations and interpretations differ markedly from previous studies in northwest India (e.g., Vannay and Grasemann, 1998; Richards et al., 2005) but agree better with reports from western Nepal (e.g., DeCelles et al., 2001; Robinson et al., 2006). Although some sections do contain abundant schists of sedimentary origin, we found abundant intrusive and volcanic rocks in the Munsiari of NW India, especially in the Pabar region (Figs. 1, 3, and 4), whereas in Nepal such obvious igneous rocks are relatively rare at the same stratigraphic level. Instead, we hypothesize that the abundant schist in Nepal and Bhutan has a major volcanic or volcanioclastic component, based on low-Al, feldspar-rich mineral assemblages and mesoscopic and microscopic textures (Figs. 3 and 4). These differences along strike could simply reflect geographic variations in magmatic intensity, differences in exposure through the arc sequence, or both. In India and Bhutan, a thick, lower Lesser Himalayan sequence of ca. 1830 Ma arc-related rocks overlie a thick, upper Lesser Himalayan sequence of post-ca. 600 Ma rocks further underscores the fundamental stratigraphic disparity highlighted by Azmi and Paul (2004) and Hughes et al. (2005). Altogether our model implies that a Paleoproterozoic arc forms the stratigraphic base to the northern edge of the

![Figure 8. Compilation of zircon U-Pb and Pb-Pb ages of igneous rocks from the Indian craton (black bars), showing pronounced peaks at ca. 2500 and ca. 1700 Ma, but paucity of ages at ca. 1800 Ma. Zircon ages from Table 1 shown as white bars. Age of proposed arc overlaps with ages of only two cratonal rocks: a ca. 1885 Ma mafic dike complex in the Bastar craton and a ca. 1850 Ma intrusion in the Aravalli belt. Relatively young ages of Lesser Himalayan igneous rocks in Arunachal (ca. 1745 Ma; Yin et al., 2009) overlap with tail of a ca. 1700 Ma peak (e.g., data from Bangladesh and the Aravalli belt). The Arunachal gneisses may represent rocks formed in a different setting, or continuation of arc activity to ca. 1750 Ma.](gsabulletin.gsapubs.org)

**DISCUSSION**

**Most Evidence Points to an Arc**

Several lines of evidence support an arc interpretation for the origin of many lower Lesser Himalayan rocks. Field observations reveal a widespread felsic igneous component within the Ranimata, Kuncha, and Daling Formations across the ca. 1000 km breadth of the Nepal (Le Fort and Rai, 1999) and Bhutan sectors (Gansser, 1983). Metamorphic rocks are even more widespread (Stöcklin, 1980; Valdiya, 1980; Gansser, 1983; DeCelles et al., 2001; Robinson et al., 2006; McQuarrie et al., 2008), both as amphibolite and as mafic chlorite schist (Fig. 4). These geographic variations in magmatic intensity, differences along strike could simply reflect geographic variations in magmatic intensity, differences in exposure through the arc sequence, or both. In India and Bhutan, a thick, lower Lesser Himalayan sequence of ca. 1830 Ma arc-related rocks overlie a thick, upper Lesser Himalayan sequence of post-ca. 600 Ma rocks further underscores the fundamental stratigraphic disparity highlighted by Azmi and Paul (2004) and Hughes et al. (2005). Altogether our model implies that a Paleoproterozoic arc forms the stratigraphic base to the northern edge of the
exposed Indian plate, and provides a stronger basis for correlating rocks along the Himalaya and for inferring structure, particularly along the Main Central Thrust, where Greater and Lesser Himalayan rocks are juxtaposed. The arc is mostly preserved as volcanically derived sediments but with important felsic and mafic intrusive and volcanic components.

Although the northern edge of the arc, including any accretionary material, is likely buried beneath the Himalaya and Tibet, some enigmatic rocks on the Indian craton could perhaps be genetically linked. Specifically, a suite of mafic dikes in the Bastar craton has recently been dated at ca. 1885 Ma (French et al., 2008), at the beginning of the time when we propose the arc was active. Possibly this dike swarm reflects thermal disturbances related to arc initiation or, alternatively, to backarc spreading. Further geochemical analysis of the dikes might help elucidate their origin(s) and links to Lesser Himalayan rocks. Note that the long hiatus between deposition of lower and upper Lesser Himalayan rocks complicates any attempts to infer postsubduction processes.

Indian “Basement” and a Paleoproterozoic Collision?

Several studies have interpreted the orthogneisses in the lower Lesser Himalayan sequence (e.g., “Ulleri”) to represent Indian cratonal basement (e.g., Gansser, 1964; Ray et al., 1989; Richards et al., 2005; Yin, 2006; Yin et al., 2009). In this model lower Lesser Himalayan sediments were either deformed and metamorphosed during the early Proterozoic, or deposited unconformably on crystalline plutonic rocks and gneisses. In principle, the crystalline rocks could represent new crustal additions at ca. 1830 Ma, i.e., the roots of a Proterozoic arc, or alternatively recrystallized Archaean material, i.e., older plutons and sediments that were deformed and metamorphosed during a ca. 1830 Ma collisional event (e.g., see Fig. 9 of Richards et al., 2006). Such a model does have some supporting evidence: relict zircon cores are as old as 3300 Ma, and trace-element geochemistry for many plutonic rocks is as consistent with a collisional origin as with an arc. Two key observations, however, do not favor either a wholly plutonic origin for 1800 Ma igneous rocks or collisional reworking of older materials.

(1) The oldest metamorphic age (for alvanite) yet recovered from Lesser Himalayan rocks is less than 500 Ma (Catlos et al., 2000). For example, garnet ages are 7–11 Ma (Vannay et al., 2004), and monazite ages are as young as ca. 3 Ma (Catlos et al., 2001, 2007; Kohn et al., 2004). Thus, there is as yet no direct metamorphic evidence for a Paleoproterozoic collision.

(2) Felsic volcanic rocks are intercalated with felsic plutonic and mafic volcanic rocks and yield similar ages as the plutons (Le Fort, 1975; Le Fort and Râi, 1999; Richards et al., 2005, 2006; this study). A shallow origin for these volcanic rocks is indisputable—in addition to relict volcanic textures (Figs. 3 and 4), many are intercalated with sedimentary rocks. Thus, igneous rocks of the lower Lesser Himalayan sequence cannot represent only the crystalline roots of a volcanic arc either. The simplest interpretation is that, although some transposition of contacts and shearing must have occurred in the Cenozoic, the present intercalation is largely primary. Thus, the lower Lesser Himalayan gneisses can be neither assigned to Indian basement nor ascribed to Paleoproterozoic collision.

Reconstruction of the Columbia (ca. 1800 Ma) Supercontinent

A 1780–1880 Ma arc along the northern margin of India may help resolve debate about the configuration of the ca. 1800 Ma supercontinent Columbia. Three basic models have been proposed for the relative placements of India, North America, and East Antarctica (Fig. 9). Rogers and Santosh (2002) and Zhao et al. (2004) sandwich East Antarctica between India and North America, leaving the northern edge of India as a passive margin, in agreement with many views of the origins of the Lesser Himalayan sequence. In contrast, Hou et al. (2008) place India directly adjacent to North America, with a continuous subduction zone that includes the northern edge of India and parts of East Antarctica. Although some models could perhaps be modified to include subduction along the northern edge of India, Hou et al.’s model is the only one proposed so far that conforms to our interpretation of the Lesser Himalayan sequence. We emphasize that several other competing models have been proposed for the configuration of Columbia that infer quite different positions than Hou et al. (2008) for North America, Baltyca, Australia, etc. (Krapez, 1999; Betts et al., 2008; Bispo-Santos et al., 2008; Payne et al., 2009). Our interpretation for India in no way validates or refutes these other models. It does, however, suggest that ≥2500 Ma Indian cratonic provinces should not be extrapolated to the north onto other continents at ca. 1800 Ma, because this margin appears to have been active at that time.

“Detrital” Zircon Analysis

If correct, our model has additional implications for the collection and interpretation of detrital zircon ages. Many laser ablation–inductively coupled plasma–mass spectrometer (LA-ICP-MS) studies of presumed detrital zircons focus on analyzing cores. This approach can minimize potential Pb-loss problems that we clearly encountered in several of our analyses. It further assumes that the resulting age spectrum is diagnostic of the source material and, for the youngest retrieved ages, limits the maximum depositional age (e.g., DeCelles et al., 2001). While we fully endorse detrital zircon dating in such endeavors, we do note that the data distribution for LT01-44A is highly skewed for cores compared to rims. For rims, 44 of 54 analyses yielded indistinguishable ca. 1880 Ma ages that we interpret as a crystallization age. In contrast, only four core analyses indicated this age, whereas the remaining 16 core analyses ranged between ~2100 and 3300 Ma. Had we analyzed only cores, as is

Figure 9. Plate reconstructions for ca. 1800 Ma supercontinent Columbia showing different positions for India (shaded); v’s indicate proposed volcanic arc. (A and B) Models of Rogers and Santosh (2002) and Zhou et al. (2004) showing passive margin for northern India. (C) Model of Hou et al. (2008) showing subduction zone along northern Indian margin, exactly as we propose. NA — North America; EA — East Antarctica; CEA — Coastal East Antarctica; NC — North China craton. Note that several other models for Columbia do not attempt to reconstruct India’s position; therefore, our proposed arc does not discriminate among them.
commonly done, we would still have identified the youngest, ca. 1880 Ma age, but we would have missed just what a vast preponderance of zircon was formed at that time.

Although we presumed this rock was a metamorphosed tuff based on its mineralogy and physical appearance—an interpretation supported by its bulk chemical composition (Table A1)—not all volcanic rocks are so distinctive after metamorphism, and could be interpreted and processed as if they were metasandstones. In that regard, we cannot directly evaluate any possible bias inherent in published zircon age distributions for the Himalaya. Some workers document primary sedimentary features both in the field and petrographically, indicating substantial reworking of detrital zircons (P. DeCelles, 2009, personal commun.), but details are rarely published. Possibly some lower Lesser Himalayan rocks could be metatuffic with inherited zircon cores, much as we interpret LT01–44A. If so, the common >1900 Ma ages obtained from “detrital” zircon cores represent inheritance, and closer consideration of magmatic rim overgrowths will reveal an even more pronounced 1830 ± 50 Ma age peak. Such refined ages might help delineate the extent of the Paleoproterozoic rocks as well as the structure of Himalayan thrusts.

CONCLUSIONS

We hypothesize that the basal part of the Lesser Himalayan sequence represents the edge of a 1830 ± 50 Ma continental arc, based on field and textural observations, whole-rock chemistry, and geochronology. This model explains the occurrence of so many coeval igneous rocks distributed widely along the Himalaya, the chemistry of the metasedimentary and igneous rocks, and the distribution of zircon ages. Younger, ca. 1745 Ma ages in Arunachal (Yin et al., 2009) may extend the duration of the arc by an additional ca. 30 Ma. These results distinguish among models for the placement of India in the ca. 1800 Ma supercontinent Columbia. The model of Hou et al. (2008) is consistent with an active margin for northern India. Thus, although Hou et al. (2008) wrote: “Another subduction zone may have existed...along the northern margin of the Indian Craton, but has been lost beneath the Eurasian Plate,” we find no need to hypothesize a “Lost Arc of the Continent”: a Paleoproterozoic arc is present and can be accounted for. Felsic orthogneisses (“Ulleri”) within the Lesser Himalayan sequence probably do not represent Indian basement but rather relatively shallow intrusions in an arc edifice and associated sedimentary pile.

APPENDIX: SAMPLES AND ANALYTICAL METHODS

Samples that we analyzed for U-Pb zircon ages were collected from the Annapurna (sample prefix AS01), Langtang (LT01), and Arun (AR01) regions of central and eastern Nepal. See the Data Repository (footnote 1) for maps showing sample locations. Arun samples were all collected from a granitic orthogneiss unit sometimes referred to as the Num orthogneiss, but they are also correlated with the Ulleri augen gneiss (e.g. Goscombe and Hand, 2000; Goscombe et al., 2006). Three Arun samples are metagranite, and one sample (AR01–4) is a pelitic schist dominated by quartz, muscovite, and biotite. Sample AS01-5 is from Ulli augen gneiss from its type locality in the town of Ulli, Nepal. Sample LT01-192 is a granitic orthogneiss from the Mustang thrust sheet, and is correlated with Ulli augen gneiss based on stratigraphic position and appearance (e.g. Kohn, 2008). Because some felsic orthogneisses correlated with Ulli augen gneiss give different ages, we refer to them as “Ulli.” Sample LT01-44A appeared texturally to be a metamorphosed felsic tuff (Fig. 3G). Sizicones were separated using standard separation techniques at Boise State University, and mounted as a metamorphosed felsic tuff (FC-3G).

Zircons were separated using standard separation techniques at Boise State University, and mounted as a metamorphosed felsic tuff (FC-1, i.e. the standard deviation, not standard error. As discussed elsewhere (Chang et al., 2006; Kohn and Vervoort, 2008), this error assignment accurately accounts for errors for a single analysis of an unknown, but it overestimates errors for pooled data. Consequently, the mean square of the weighted deviates (MSWD) for age regressions will be erroneously small. This is evident in our data (Fig. 6), where MSWDS are routinely less than ~0.5—mainly a result of how we choose to propagate standardization corrections were based on bracketing analyses of FC-1. No correction for 204Pb was made because, within uncertainty, there was no 204Pb after correcting for 204Hg interference (based on measurements of 206Pb), and because even the raw ratio of mass 206 to mass 204 typically exceeded 5000, implying a negligible common Pb correction. Ratios of Th/U were estimated for analyses at least 10% concordant for 207Pb, 206Pb and 208Pb by assuming concordance between U-Pb and Th-Pb ages.

Corrected ratios, uncertainties, and ages include a ~1%–2% standardization error based on the scatter of analyses of FC-1, i.e. the standard deviation, not standard error. As discussed elsewhere (Chang et al., 2006; Kohn and Vervoort, 2008), this error assignment accurately accounts for errors for a single analysis of an unknown, but it overestimates errors for pooled data. Consequently, the mean square of the weighted deviates (MSWD) for age regressions will be erroneously small. This is evident in our data (Fig. 6), where MSWDS are routinely less than ~0.5—mainly a result of how we choose to propagate standardization...
tion errors. Interstandard errors were not included in our age assignments, and some studies suggest these may contribute an additional 1%–2% systematic error (e.g., Chang et al., 2006). Thus, for intercomparisons of sample ages, an additional ±20–35 Ma systematic uncertainty should be considered.

Two possible metavolcanic rocks were analyzed for whole-rock chemistry (Table A1) were measured by X-ray fluorescence (XRF) at the GeoAnalytical Laboratory, trace-element compositions were determined from T. Argles, P. DeCelles, C. Dehler, D. Evans, N. McQuarrie, and associate editor A. Yin helped improve the presentation and clarify the authors’ understanding of Himalayan stratigraphy.

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REFERENCES CITED

Kohn et al.


