Earth and Planetary Science Letters 272 (2008) 105–117

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Preliminary stratigraphic and structural architecture of Bhutan: Implications for the along strike architecture of the Himalayan system

Nadine McQuarrie [a,*], Delores Robinson [b], Sean Long [a], Tobgay Tobgay [a], Djordje Grujic [c], George Gehrels [d], Mihai Ducea [d]

[a] Department of Geosciences, Princeton University, Princeton, NJ, 08544, USA
[b] Department of Geological Sciences, University of Alabama, Tuscaloosa, AL 35487, USA
[c] Department of Earth Sciences, Dalhousie University, Halifax, NS, Canada B3H 4J1
[d] Department of Geosciences, University of Arizona, Tucson AZ, 85721, USA

ARTICLE INFO

Article history:
Received 9 November 2007
Received in revised form 4 April 2008
Accepted 16 April 2008
Available online 4 May 2008

Editor: R.D. van der Hilst

Keywords:
Himalayas
Bhutan
structural cross-section
U–Pb ages
zircon

ABSTRACT

Preliminary mapping and stratigraphic correlation of Lesser Himalayan rock in eastern Bhutan using field characteristics, U–Pb detrital zircon dating, and εNd geochemistry define the first-order stratigraphic architecture of the Indian passive margin sequence in the eastern Himalaya. We use this new image of the lateral and vertical relationships of the original stratigraphy to determine the structural framework of the eastern Himalayan fold-thrust belt in Bhutan. We propose that Lesser Himalayan rock in Bhutan can be divided into lower Lesser Himalayan rocks with a Paleoproterozoic detrital zircon signal, and upper Lesser Himalayan rocks with detrital zircon signals of ~1000–500 Ma. The ~500 Ma detrital grains are from rocks in the frontal portions of the fold-thrust belt north of the Main Boundary thrust as well as directly in the footwall of the Main Central thrust in the hinterland. Our preliminary stratigraphic study coupled with mapping allows us to construct a composite balanced cross-section through the Kuru Chu valley in eastern Bhutan which provides the first image of the geometry and amount of shortening through Bhutan. The Main Frontal thrust tilts a 6 km of thick section of Neogene foreland basin deposits. These deposits are separated from folded and faulted upper Lesser Himalayan rocks by the Main Boundary thrust. North of the Main Boundary thrust, we propose two duplex systems. The southernmost duplex contains 9 repeated sections of upper Lesser Himalayan units, including the Permian Gondwana Sequence and the Cambrian (or younger) Baxa Group. The northernmost duplex is located in the footwall of the Main Central thrust, and is comprised of two repeated sections of the Proterozoic Shumar and Daling Formations. The southern boundary of this northern duplex is the Shumar thrust which acts as a roof thrust for the southern duplex system and may correlate to the Ramgarh thrust in Nepal and India. We propose that the development of the duplex systems passively folded overlying Tethyan and Greater Himalayan rocks. Minimum shortening for this part of the Himalayan fold-thrust belt is 359 km, all of which has occurred from 22 Ma to present defining a long-term shortening rate of 16 mm/yr.

1. Introduction

The Himalayan orogen is the first-order expression of the ongoing collision between India and Asia which began ca. 60–55 Ma (Guillot et al., 2003; Rowley, 1996; LeFort, 1975; Hodges, 2000; Klootwijk et al., 1992; Leech et al., 2005; DeCelles et al., 2004). Throughout Cenozoic time, India has moved northward with respect to Asia. As a result, the sedimentary cover that blanketed the northern Indian craton from early Proterozoic through Paleocene time detached from the underlying basement in a series of large, south vergent thrust sheets. The telescoping of this Greater Indian stratigraphy records a significant portion of the magnitude convergence between India and Asia. However, much of what is known about the architecture of the Himalayan–Tibetan orogenic system and the original geometry of the Indian passive margin comes from the apex of the Himalaya in Nepal and western India (e.g. Hodges, 2000; Srivastava and Mitra, 1994; Hodges et al., 1996; Vannay and Hodges, 1996; Searle, 1999; DeCelles et al., 2000; Robinson et al., 2001; Robinson et al., 2003; Robinson et al., 2006; Richards et al., 2005; Vannay and Grasemann, 2001). When compared to the central Himalaya, key differences in the structural and stratigraphic architecture have been identified in the westernmost portion of the orogen (Pogue et al., 1999; DiPietro and Pogue, 2004) implying the possibility of fundamental variations in the eastern Himalaya as well.

Much of the recent work in the eastern part of the orogen has focused on the metamorphic core of the orogen in Bhutan and adjacent Sikkim (Fig. 1) elucidating the metamorphic and deformation

* Corresponding author. Tel.: +1 609 258 7024; fax: +1 609 258 5275.
E-mail address: nmcq@princeton.edu (N. McQuarrie).

0012-821X/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2008.04.030

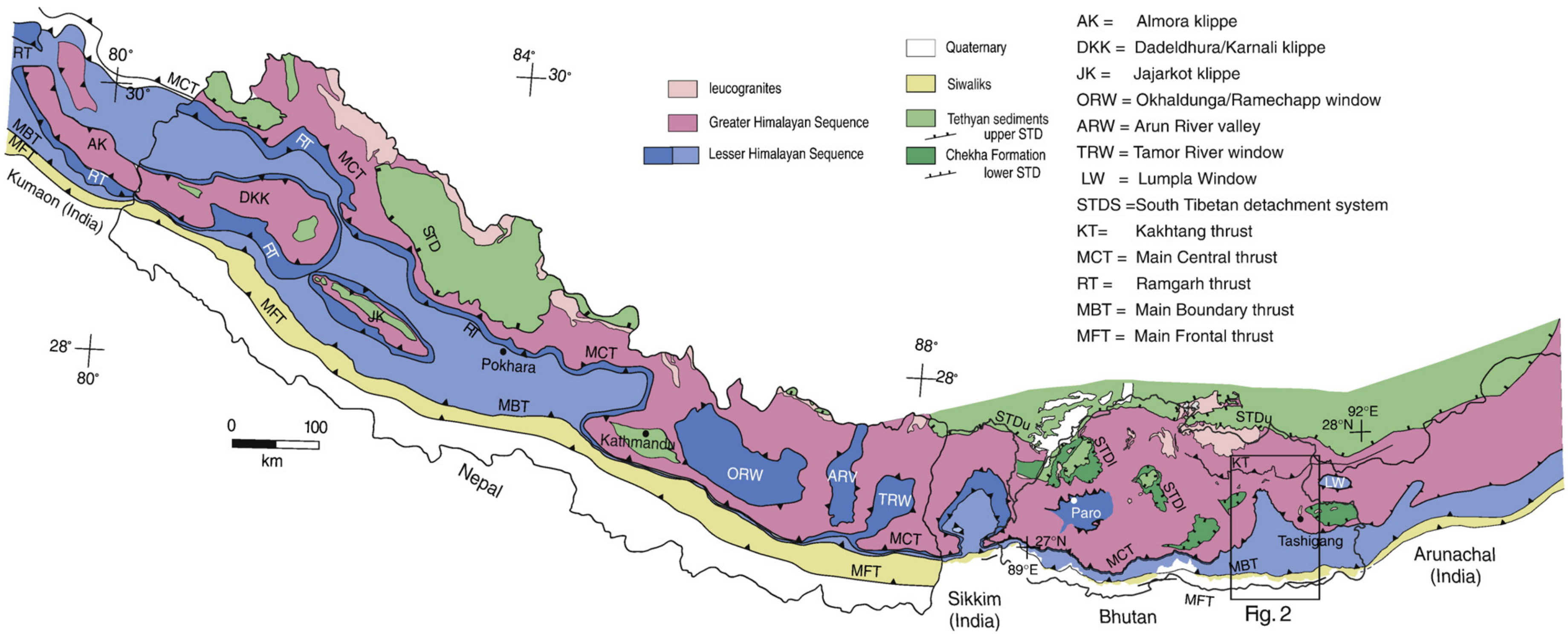

Fig. 1. Geologic map of India, Nepal and Bhutan portions of the Himalayan orogen. India and Nepal from Robinson and Pearson (2006); Bhutan from Hollister and Grujic (2006), Arunachal India from Yin (2006). Black box is location of Fig. 2.

history in Greater Himalayan rocks (Davidson et al., 1997; Neogi et al., 1998; Ganguly et al., 2000; Grujic et al., 2002; Daniel et al., 2003; Catlos et al., 2004; Dasgupta et al., 2004; Harris et al., 2004; Hollister and Grujic, 2006; Searle and Szulc, 2005). Only preliminary data exist regarding magnitude, timing and style of deformation within the Lesser Himalayan portion of the orogen (Ray, 1995; Bhattacharyya et al., 2006; Yin et al., 2006) or how the sedimentary architecture of the eastern Himalaya relates to that of the central and western portions (Yin et al., 2006; Richards et al., 2006).

Because research has been concentrated in the central Himalaya, the eastern Himalaya is ripe for investigation to determine whether similarities and differences in structure and stratigraphy exist when compared to Nepal and India. This integrated view is needed in order to understand the initial stratigraphic architecture of Greater India and the sequence of deformation during the Indo-Asian collision. Shortening variations from west to east across the Himalayan orogen can be used to test hypotheses as varied as: 1) the magnitude of shortening is directly related to the width of Tibetan Plateau (DeCelles et al., 2002) or 2) variations in shortening magnitude (greater shortening in the east than the west) are a function of either the obliquity of collision or climate–tectonic interactions (Yin et al., 2006; Guillot et al., 1999; Grujic et al., 2006). We present initial results of our ongoing work in Bhutan. These include a preliminary balanced cross-section through the eastern Himalaya of Bhutan, which illustrates the geometry of the fold-thrust belt as well as provides critical shortening estimates for this region. We also present new detrital zircon U–Pb ages and εNd isotopic signatures in Lesser Himalayan strata. These data help document the first-order stratigraphic framework of the eastern Himalaya in Bhutan.

2. Methods

Our study presents new geologic mapping at a scale of 1:50,000 along the upper Kuru Chu valley, and along the road from Trashigang to Samdrup Jonkhar in eastern Bhutan, a combined distance of ~130 km across strike (Figs. 1 and 2). We have integrated our mapping with previous mapping (Gansser, 1983; Bhargava, 1995; Gokul, 1983) to infer along strike changes in stratigraphy and structure from east to west along the Kuru Chu valley (Fig. 2). Cross-section construction and balancing was based primarily on surface data with a few constraints from teleseismic data (Mitra et al., 2005), well data and the INDEPTH (International deep profiling of Tibet and the Himalaya) data (Hauck et al., 1998). Samples were collected and analyzed for both detrital zircon U–Pb ages and whole rock εNd signatures. These ages, signatures and our lithostratigraphic observations aided in the regional correlation of Lesser Himalayan rocks as well as provided new constraints on pre-Cenozoic tectonostratigraphic architecture of the region.

3. Tectonostratigraphy

Rocks that were a part of Greater India prior to the development of the Himalayan–Tibetan orogen have traditionally been divided into tectonostratigraphic or structural packages that can be recognized along the length of the orogen (LeFort, 1975; Hodges, 2000; Yin, 2006; Gansser, 1964). Each package of rock is bounded by major brittle faults and ductile shear zones and to a first order, displays a characteristic stratigraphy. From south to north, the classic subdivisions and major bounding faults are the Indo-Gangetic foreland basin, the Main Frontal thrust, Subhimalayan strata, Main Boundary thrust, Lesser Himalayan strata, Main Central thrust, Greater Himalayan rocks, South Tibetan detachment system, Tethyan Himalayan strata, and the Indus-Yalu suture zone, which marks the northern limit of rocks associated with India (Fig. 1).

During Proterozoic and possibly early Paleozoic time, the northern portion of the Indian craton was blanketed with a thick succession (~8–12 km) of clastic and carbonate sediments that is referred to as the Lesser Himalayan sequence (Robinson et al., 2006; Yin, 2006; Gansser, 1964; Gansser, 1964; Upreti, 1996; Upreti, 1999; Schelling and Arita, 1991). In Nepal, these rocks are entirely of Paleoproterozoic and Mesoproterozoic age (DeCelles et al., 2000; Martin et al., 2005), although in western India the Lesser Himalayan sequence may extend into the Cambrian (Richards et al., 2005; Myrow et al., 2003).

The protoliths of metasedimentary rocks and orthogneisses of the Greater Himalaya (GH) are Proterozoic to early Paleozoic in age (DeCelles et al., 2000; Yin, 2006; Martin et al., 2005; Parrish and Hodges, 1996; Gehrels et al., 2003), and are separated from rocks exposed in the Lesser Himalaya (LH) by the Main Central thrust (MCT). The thrust contact between LH and GH rocks raises questions regarding the original paleogeography of the two units. GH rocks are interpreted to represent 1) highly metamorphosed equivalents of uppermost LH strata (Parrish and Hodges, 1996) or Paleozoic Tethyan strata (Myrow et al., 2003), or 2) an accreted terrane tectonically consolidated with Greater India during early Paleozoic time (DeCelles et al., 2000; Gehrels et al., 2003). DeCelles et al. (2000) proposes that the distinctly different U–Pb age spectrum of LH (prominent 1.8 Ga peak) and GH (~700 Ma to 1.3 Ga) rocks in Nepal require that the predominantly Neoproterozoic GH rocks could not have been attached to Greater India prior to the early Paleozoic.

Throughout Paleozoic and Mesozoic time, the northern margin of India was again the locus of passive margin sedimentation (Gaetani and Garzanti, 1991; Brookfield, 1993; Garzanti, 1999). The resulting strata are a composite of two superimposed rift to passive margin sequences, the first early Paleozoic to Carboniferous in age and the second Permian to Cretaceous in age. This succession of rocks that are commonly preserved structurally above and geographically north of the MCT is referred to as the Tethyan sedimentary sequence (TH). The South Tibetan detachment system (STD, Fig. 1) separates GH rock in the south from rock in the Tethyan Himalaya (TH) to the north. More proximal (with respect to India) time equivalents of Tethyan strata are locally preserved as the continental Gondwana sequence (included in LH stratigraphy) and range in age from Permian through Paleocene (see summary in Yin (2006)).

Depositionally above the Gondwana sequence are the Tertiary foreland basin sediments of the Himalayan orogenic system, which include the Siwalik Group. These synorogenic sedimentary rocks were shed from the growing mountain belt in mid-Miocene–Pliocene time (Quade et al., 1995; DeCelles et al., 1998; Najman et al., 2004).

4. Bhutan stratigraphy

4.1. Subhimalaya

One of the most conspicuous aspects of the Subhimalaya of Bhutan is the discontinuity of the Siwalik Group. Unlike adjacent regions of the Himalaya where the Siwalik Group is laterally continuous along strike, in Bhutan, the map pattern of synorogenic sediments is patchy, with 20–40 km portions of the belt either covered by Quaternary sediments, overridden by the MBT or apparently never deposited (Gansser, 1983) (Fig. 1). The most complete Siwalik Group section is in eastern Bhutan. It is 4–6 km thick and dips consistently northward at 30–40°. Similar to Siwalik Group sections in Nepal and India (Quade et al., 1995; DeCelles et al., 1998), the entire package generally coarsens upward from clays and silts in the lowest portions of the section exposed just north of the MFT, to fluvial siltstone and sandstone in the middle sections grading to sandstones and gravelly braided river deposits in the upper sections.

4.2. Lesser Himalaya

Lesser Himalayan rocks in Bhutan have historically been broken into four units (Gansser, 1983; Bhargava, 1995; Gokul, 1983). Although

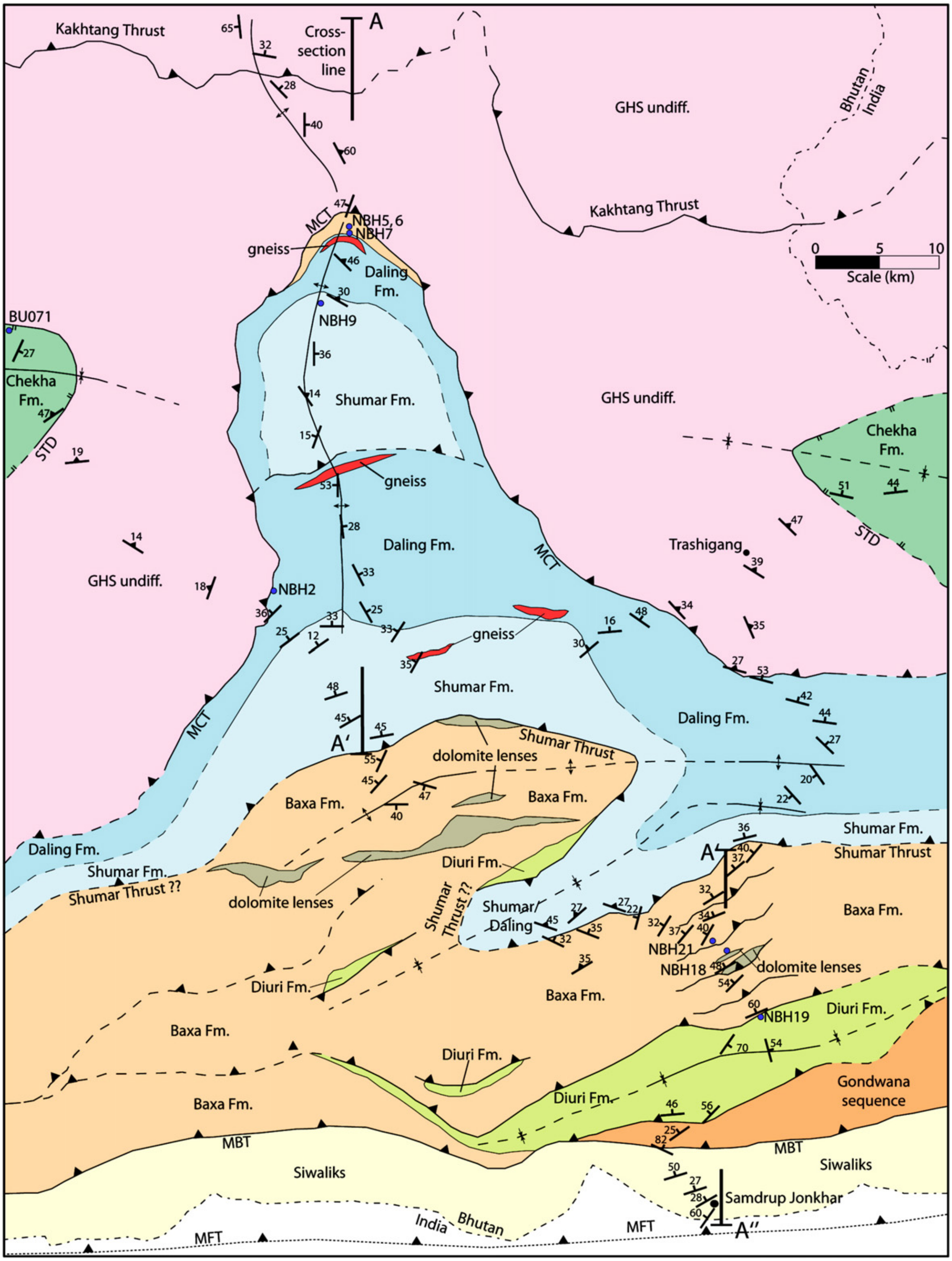

Fig. 2. Geologic map of the Kuru Chu Valley, Bhutan. Mapping from Gansser (1983), Gokul (1983), Bhargava (1995), Hollister and Grujic (2006), and this study. Dolomite lenses (grey) are from Gansser (1983) and indicate presence of the Baxa Group. Location of Diuri formation to the west of our transect is from Bhargava (1995). The folded Shumar thrust is inferred from Bhargava (1995) and Gokul (1983). Strike and dip symbols indicate our mapping and blue dots are sample locations discussed in text; GHS Greater Himalayan Sequence, MCT, Main Central thrust, MBT, Main Boundary thrust, MFT, Main Frontal thrust. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

lack of fossils and radiometric age dates have led to confusion regarding the exact stratigraphic order (Gansser, 1983; Bhargava, 1995), our field observations as well as preliminary geochronology and isotope geochemistry data allow us to delineate the relative ages of the LH from oldest to youngest.

4.2.1. Daling–Shumar Group

The Daling–Shumar Group was named by Gansser (1983) in an attempt to link the predominantly phyllitic Daling Formation identified in Sikkim–Darjeeling (Sengupta and Raina, 1978) with the quartzite rich Shumar Formation in eastern Bhutan (Jangpangi, 1974,

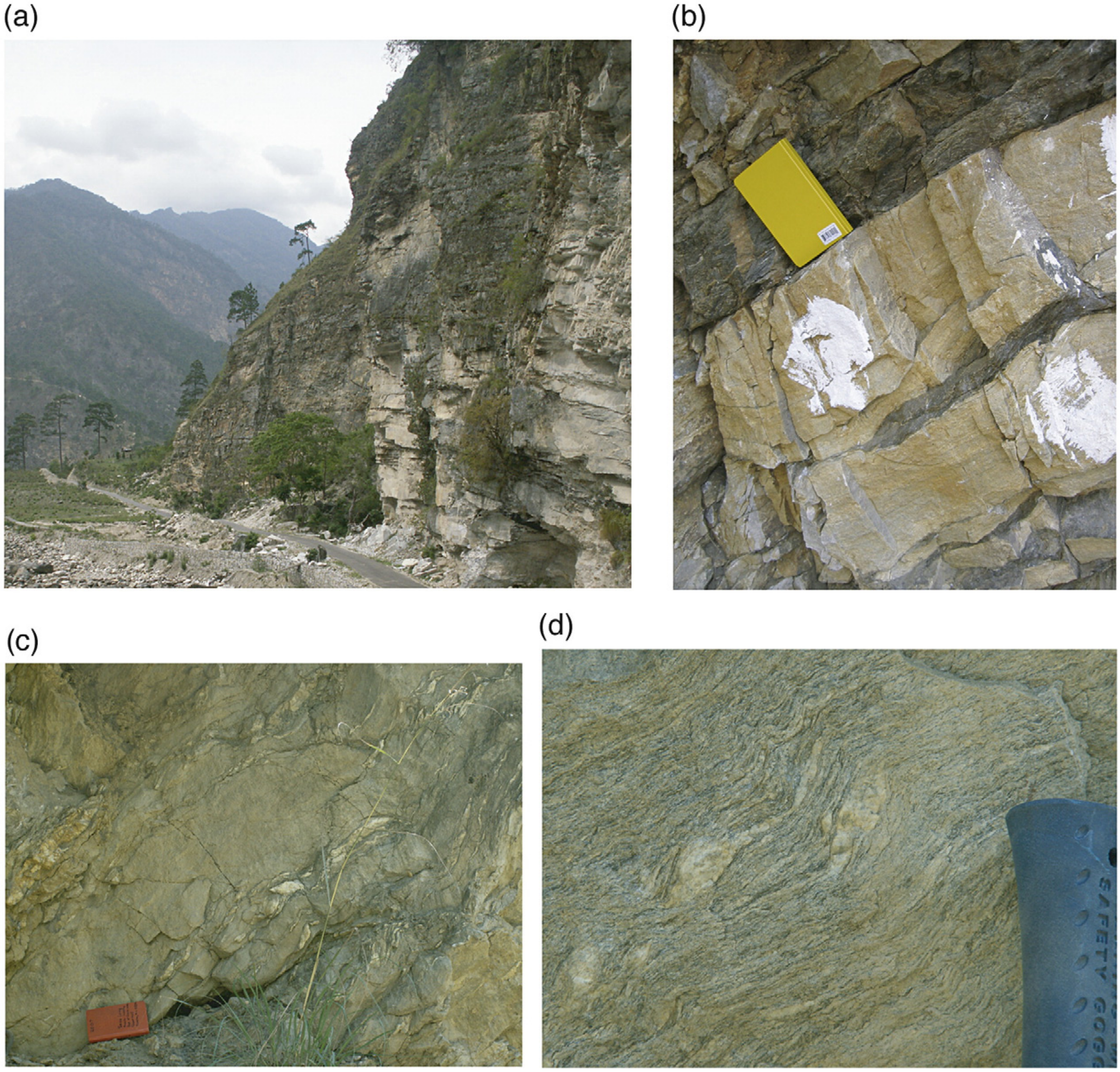

Fig. 3. (a) Shumar Formation cliffs; Road for scale at base of picture. (b) Interbedded quartzite and phyllite near the Shumar/Daling contact. 19 cm-long notebook for scale. (c) Daling Formation, showing phyllite with quartz veins and blebs. 19 cm-long notebook for scale. (d) Feldspar augen in mylonitized orthogneiss lenses within the Daling Formation; 8 cm of rock hammer for scale.

1978). The correlation is complicated in that the quartzite and phyllite of the Daling–Shumar Group and the quartzite and slate of the Baxa Group (see below) have similar weathering patterns, with thick bedded, cliff forming quartzite and more recessive phyllite and shale, and can be difficult to differentiate one from another (compare Gansser, 1983; Jangpangi, 1978; Dasgupta, 1995; Tangri, 1995a). We found that the Shumar–Daling Group in Bhutan can be broken into 2 distinct formations, the Shumar Formation quartzite and the overlying Daling Formation phyllite. An entire Shumar–Daling Group section is exposed in the Kuru Chu valley.

The basal unit of the LH in Bhutan is the Shumar Formation quartzite (Fig. 3a). This quartzite has variable thickness from west to east Bhutan and reaches a thickness of 6 km in the Kuru Chu valley. It is a well-bedded, white to greenish grey, fine-grained, recrystallized quartzite. The Shumar Formation can be medium to thickly bedded and often forms several-hundred-meter-high cliffs. Quartzite layers can be separated by thin to 3 m thick interbeds of phyllite or schist, with the interbeds becoming more common up-section near the transitional contact with the Daling Formation (Fig. 3b). White mica and sericite define foliation planes. A key feature of the Shumar quartzite is the continuous planar bedding.

Overlying the Shumar Formation is the 4 km thick Daling Formation (Fig. 3c). The contact is transitional with more quartzite at the base of the Daling Formation and more green phyllite near the top of the Shumar Formation. It is dominated by a chloritic to sericitic schist (in the north) and becomes more phyllitic to the south. Intercalated quartzite beds are common especially near the base of the unit. The quartzite ranges from a clean, white, fine-grained rock with 5–10 cm thick beds (identical to quartzite found in the Shumar Formation, although much more thinly bedded) to a lithic-rich, thinly bedded (mm scale) rock, with grey, green, or salt-and-pepper color. Sedimentary structures include ripple marks and planar cross-beds. The schist and phyllite display irregular and scaly foliation with common quartz veins and blebs. The Daling Formation rarely forms cliffs but rather has a characteristic blocky weathering that is typically 50% schist/phyllite and 50% quartzite. Carbonate (thinly bedded to massive) beds are rare and where present, 5–30 m thick. In addition, concordant sheet-like bodies (~0.5 km thick) of mylonitized orthogneiss are preserved at

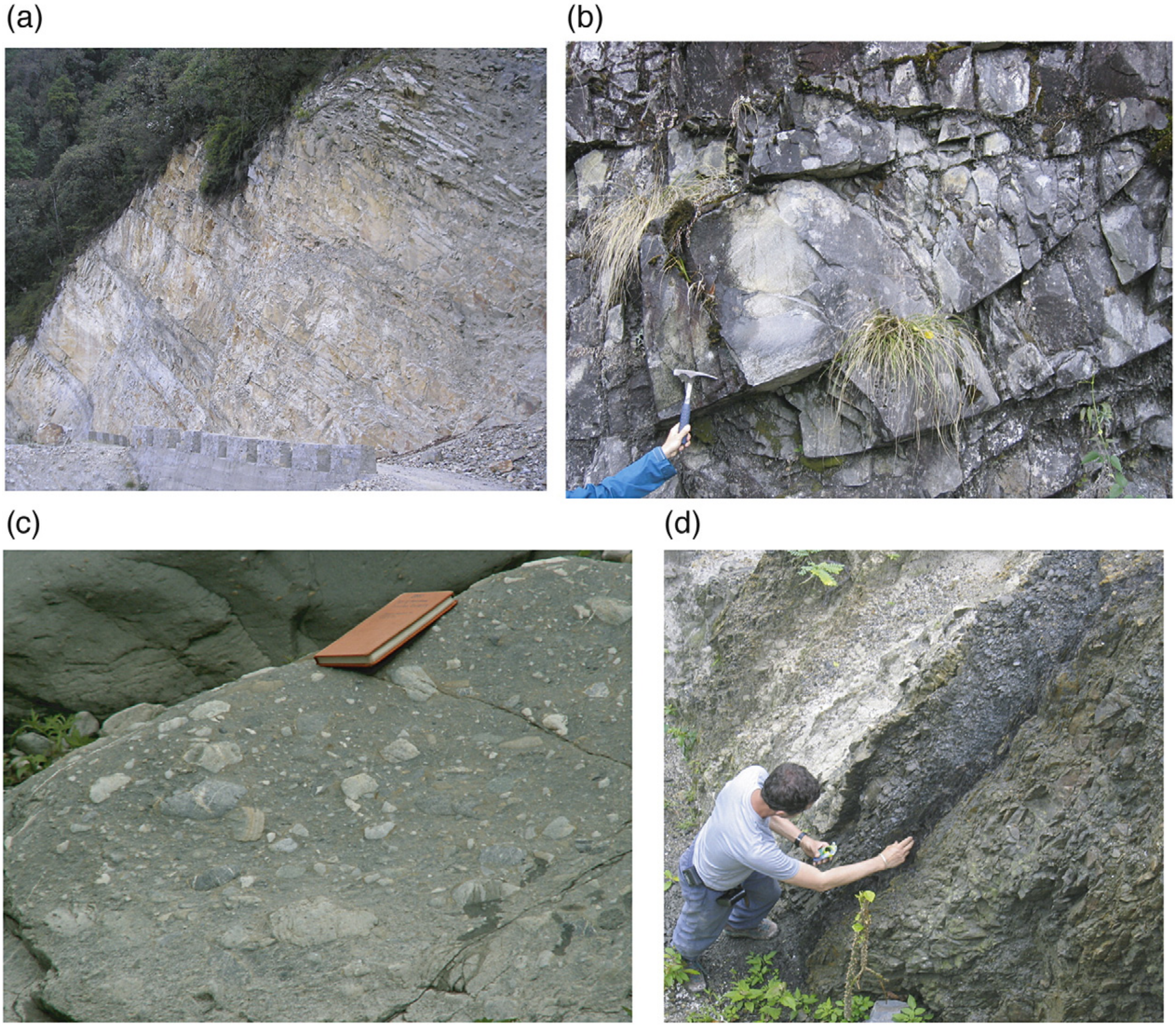

Fig. 4. (a) Road cut of quartzite cliffs of the Baxa Group. (b) Baxa Group quartzite displaying trough cross bedding. (c) Diamictite within the Diuri Formation, 19 cm-long notebook for scale. (d) Coal seam in the Gondwana Sequence.

different levels through the Daling Formation (Gansser, 1983) (Fig. 2). The orthogneiss (quartz + orthoclase + plagioclase + biotite + muscovite) bodies are lenticular to sheet-like, and contain 1–5 cm-long plagioclase and orthoclase augen. The augen are flattened and sheared as part of a well-developed mylonite S-C fabric with ~ N–S trending stretching and mineral aggregate lineation (Fig. 3d). A gneiss sheet, ca 30 km west of Trashigang, yielded monazite data which argue for a magmatic crystallization age of 1.76 ± 0.07 Ga (Daniel et al., 2003). Zircons from this body provided ages between 1.76 and 1.84 Ga, and are in part inherited (Daniel et al., 2003; Thimm et al., 1999). A 1.75 age of a metarhyolite deposited within the Daling–Shumar Group (Richards et al., 2006) further substantiates the depositional age of the strata.

4.2.2. Baxa Group

The Baxa Group is broadly comprised of white to buff, gritty to pebbly quartzite, meta-siltstone, greenish grey to grey slate, and massive to bedded, grey to yellow dolomite and limestone (Tangri, 1995a). Tangri (1995a) divided the Baxa Group into 4 formations (Pangsari, Phuntsoling, Manas and Jainti Formations) with the various formations most likely representing significant lateral variations during deposition. For simplicity, we use the Baxa Group nomenclature to refer to all Baxa formations. In the Kuru Chu valley, the Baxa Group is primarily a massive cliff forming quartzite (Fig. 4a). It is a fine- to medium-grained gritty quartzite, locally pebbly to conglomeratic and contains distinct clasts of jasper and rose quartz. Intercalations of light to dark grey phyllitic slate and non-persistent limestone–dolomite horizons are common. Dolomite horizons are lenticular in map view and may represent patch reefs deposited in a deltaic environment (Fig. 2). Quartzite beds are lenticular, often separated by thin beds of shale and display ubiquitous trough cross bedding (Fig. 4b). The road from Trashigang to Sandrup Jonkhar exposes an 11 km thick consistently northward dipping section of Baxa Group rock (Fig. 2). We propose that the minimum thickness of the Baxa Group is 2.5 km, but is tectonically repeated along 5 thrust faults (see Section 6.2 below).

4.2.3. Diuri Formation

The Diuri Formation is an ~ 2–2.5 km thick diamictite with interbedded slates (Fig. 4c) (Gansser, 1983; Jangpangi, 1974; Tangri, 1995b) which overlies the Baxa Group. The Diuri Formation contains pebbly shale, slate and minor sandstone. Pebbles vary from 0.5 to 5 cm and are subangular to well-rounded. Clast types include white and dark grey quartzite, white vein quartz and yellowish dolomite. Ground mass shows clear schistosity.

4.2.4. Gondwana Sequence

This sequence of feldspathic sandstone, siltstone, shale, coal lenses and plant fossils was initially designated as the Damuda Formation and later correlated to the Gondwana Supergroup (Lakshminarayana, 1995). In Bhutan both the northern and southern boundaries of the Gondwana sequence are faulted making its initial relationship to older units uncertain. However, the stratigraphic age of the unit is Permian (Lakshminarayana, 1995). Along the road to Samdrup Jonkhar the Gondwana Sequence contains finely-laminated, dark, salt-and-pepper sandstone and quartzite, coal seams and carbonaceous shale and slate. Sandstone and quartzite have thick- to massive-bedding (Fig. 4d). Total thickness of the Gondwana sequence is ~2 km.

4.3. Greater Himalaya

Much of Bhutan is dominated by exposed GH rock, which crops out over a north–south width of 60–100 km between the STD and the MCT (Fig. 1). GH rocks in Bhutan are composed of paragneiss, orthogneiss, (increasingly migmatitic in the higher structural levels) schist, quartzite, Miocene age leucogranites, and less common marble and amphibolite layers. In the Kuru Chu valley, the MCT places GH augen gneiss (with leucosomes) over LH quartzite and pelitic schist (2 mica + quartz + lithics +/− garnet) in the footwall. Within GH rocks, paragneiss and quartzite become more common up-section until the Kakhtang thrust which places migmatite over garnet-staurolite schists (Davidson et al., 1997; Grujic et al., 2002; Daniel et al., 2003).

5. Geochronology and regional correlations

Multiple studies using a combination of whole rock Nd isotopes and U–Pb detrital zircon (DZ) spectra have documented the first-order geochemical and geochronological signal of LH and GH rocks across the Himalaya (DeCelles et al., 2000; Robinson et al., 2001; Richards et al., 2005; Richards et al., 2006; Martin et al., 2005; Parrish and Hodges, 1996; Whittington et al., 1999; Ahmad et al., 2000). Important distinctions are young (1.1–0.5 Ga) zircons in GH rocks, combined with less negative (~−17–0) εNd values (Richards et al., 2005). Martin et al. (2005) also clarified that young ~500 Ma GH zircons are commonly derived from Cambrian–Ordovician orthogneiss, while GH paragneiss rarely have zircons younger than 600 Ma. LH rocks typically contain older zircons (1.6–1.8 Ga) and have more negative (~−25 to −14) εNd values. This study tests the continuity of the Greater India passive margin stratigraphy and builds a regional stratigraphic framework for Bhutan through field identification and mapping of regional strata, as well as U–Pb geochronology and εNd isotope geochemistry to determine the maximum age of strata as well as defining isotopic signatures.

5.1. Detrital U–Pb geochronology

U–Pb geochronologic analyses were conducted on individual grains using laser-ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS). 485 U–Pb zircon analyses from our 5 samples that yielded less than 10% error for both $^{206}Pb/^{238}U$ and $^{206}Pb/^{207}Pb$ ages and less than 30% isotopic discordance are shown in Fig. 5 in relative age-probability plots, which are a sum of probability distributions for all analyses from a sample. Age peaks on the plots are considered robust if supported by multiple grain analyses, and peaks defined by one analysis are considered less significant (see Appendix A). The U–Pb data for individual grains are presented in Appendix B, and sample locations are listed in Table 1. In general, $^{206}Pb^*/^{238}U$ (asterisk denotes correction for common Pb; all ages described in the text have had this correction) ratios are used for ages younger than 1.0 Ga, and $^{207}Pb^*/^{206}Pb^*$ ratios are used for ages older than 1.0 Ga. Instrument errors for measuring the Pb, U, and Th ratios are shown in Appendix B. Other possible sources of error that are not factored into shown errors

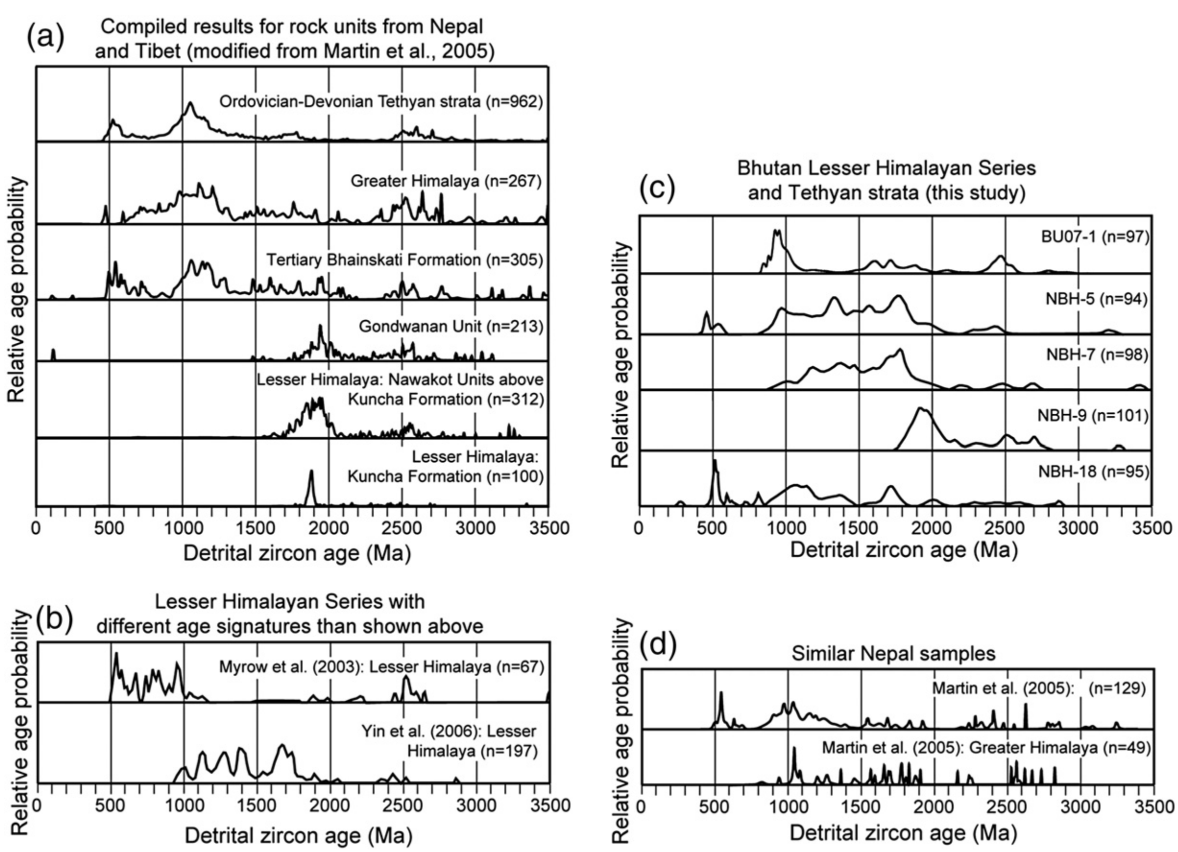

Fig. 5. Comparison of detrital zircon age signature of samples from Bhutan (c) with age signatures for known TH, GH, LH and Tertiary samples from Nepal (Martin et al., 2005) (a). b. "young" Mesoproterozoic through Cambrian age spectra from Himachal Pradesh (NW India (Myrow et al., 2003)) and Arunachal (NE India (Yin et al., 2006)). d. Nepal Samples that could be equivalent to the "young" LH recognized in Bhutan and India (Martin et al., 2005).

Table 1
Sample locations for eastern Bhutan

Sample	°N (dd.ddddd)	°E (dd.ddddd)	Analysis	Formation	Lithology
NBH-2	27.30917	91.15002	εNd	Baxa?	Phyllitic schist
NBH-5	27.60173	91.21473	DZ	Baxa?	Quartzite
NBH-6	27.60173	91.21473	εNd	Baxa?	Schist
NBH-7	27.59659	91.21401	DZ	Baxa?	Quartzite
NBH-9	27.53238	91.18916	DZ	Shumar	Quartzite
NBH-18	27.01200	91.52072	DZ	Baxa	Quartzite
NBH-19	26.95792	91.54864	εNd	Diuri	Diamictite
NBH-21	27.01961	91.50954	εNd	Baxa	Phyllite
BU07-1	27.50831	90.87008	DZ	Chekha	Quartzite

include uncertainties in U decay constants, common Pb composition, and calibration to the zircon standard used. These errors could shift the age-probability peaks by up to ~3% (2σ).

We collected 4 samples from LH rock of Bhutan and one sample from the TH Chekha Formation. Three of the LH samples were from outcrops previously mapped as the Daling–Shumar Group (Gansser, 1983; Bhargava, 1995) and one from the Baxa Group. From north to south, BU07-1 was collected from quartzite strata at the base of the Chekha Fm and has a strong peak at 845 Ma. NBH-5 has DZ age populations as young as 485 Ma, which was collected from a medium to thinly bedded lithic-rich quartzite sample with minor biotite schist interbeds. NBH-7 was collected ~1 km south of sample NBH-5 from an ~25 m thick, clean white quartzite interbed in a two-mica schist. NBH-7 has a similar DZ spectrum as NBH-5 (plateau from 1.0 Ga to 1.8 Ga) but does not contain young Cambrian grains (Figs. 2 and 5). NBH-9, collected at the Daling–Shumar contact, shows a peak at 1.8–1.9 Ga (Figs. 2 and 5). NBH-18 (Figs. 2 and 5) was collected ~17 km north of the MBT in Baxa Group strata. It has a strong peak at ~520 Ma with smaller peaks between 1.0 and 1.7 Ga.

5.2. Epsilon Neodymium isotope geochemistry

Sm and Nd isotopic ratios were measured using an IsoProbe multicollector inductively coupled plasma mass spectrometer at the University of Arizona. Nd isotopic measurements were normalized to $^{146}Nd/^{144}Nd=0.7219$. Analytical procedures are outlined in Appendix C. Table 2 contains the data from the samples collected (calculated at time $T=0$). We report Nd isotopic data using εNd(0) values because both age of deposition as well as age of pre-Tertiary, concurrent metamorphism are both unknown for LH and GH rocks. εNd(0) are commonly reported values allowing for straight forward comparisons to previous work.

Four samples were collected from LH rock, two samples from outcrops previously mapped as the Daling–Shumar Group (Gansser, 1983; Bhargava, 1995), one from the Baxa Group and one from the Diuri formation. NBH-2 was collected from a schist 50 m into the footwall of the MCT from the western side of the Kuru Chu valley while NBH-6 was collected from a schist 1 km into the footwall of the MCT along the northern boundary (within a few meters of sample NBH-5) (Fig. 2). εNd (0) values for these samples are −19 (NBH-2) and −21 (NBH-6) (Table 2). Sample NBH-21 was collected from a shale ~18 km north of the MBT within the Baxa Group (Fig. 2), and has an εNd(0) value of −21, identical to that of NBH-6. Sample NBH-19, collected from a phyllite at the base of the Diuri Formation ~10 km north of the MBT, has an εNd(0) value of −20 (Fig. 2, Table 2).

5.3. Preliminary interpretations and regional correlations

BU07-1 was collected from the basal part of the TH Chekha Formation that is preserved in a fault bounded klippen in eastern Bhutan (Grujic et al., 2002) (Fig. 2). Previous work on TH strata in Bhutan indicates that the TH extend from the Neoproterozoic through the Cretaceous (Gansser, 1983; Bhargava, 1995). Initial DZ and paleontological work on rocks immediately above the Chekha Formation (Pele La Group) show a strong Cambro-Ordovician DZ peak with strong fossil evidence that indicates these strata are latest Cambrian through Ordovician (Myrow et al., 2005; McKenzie et al., 2007). This previous work combined with our data from BU07-1 suggests that the maximum age at the base of the Chekha formation is ~850 Ma, and that lower TH strata extends from the Neoproterozoic through Ordovician.

NBH-5, 6, and 7 were collected from rock previously mapped as the lower LH Daling–Shumar Group. Thus, the young ages (0.5 and 1.0 Ga, respectively) of NBH-5 and NBH-7 were not expected. The DZ spectra for these samples are remarkably similar except that NBH-5 has 6 grains, which plot between 564 and 485 Ma (Cambrian–Ordovician period). It is possible that NBH-7 also has these young grains but they were not part of the 100 grains analyzed, allowing the option that NBH-5 and NBH-7 are age equivalents and possibly part of the same formation. The younger DZ ages argue strongly that the rock is not lower LH in origin (Daling–Shumar Group). εNd(0) values from correlative rocks, NBH-2 and NBH6, (NBH-6 was collected within meters of NBH-5) have values of −19 and −21, respectively (Fig. 2). These values are consistent with values from LH rocks in other parts of the Himalaya as well as in lower Tethyan strata (Robinson et al., 2001; Martin et al., 2005). Richards et al. (2005) and Myrow et al. (2003) both identified Cambrian DZ ages in the outer LH of NW India. However, the DZ spectra for those rocks show most grains clustering between 0.5 and 1.0 Ga (Fig. 5). Martin et al. (2005) documented a young 485 Ma peak and a clustering of grains between 0.8 and 1.4 Ga from a rock in the immediate footwall of the MCT in central Nepal. Our samples from Bhutan have a peak at 0.5 Ga, however the unique U–Pb signature in both NBH-5 and NBH-7 is the spectral "plateau" from 1.0 to 1.8 Ga. Recent DZ data from Arunachal Pradesh (east of Bhutan) show a similar spectrum for LH rocks (Yin et al., 2006) directly in the footwall of the MCT (Fig. 5).

Approximately 5 km south of the MCT in the Kuru Chu valley, in definite Shumar Formation quartzite (NBH-9; Fig. 2), we obtained a DZ spectra that are identical to lower LH rocks identified elsewhere in the Himalaya (pronounced peak at ~1.8 Ga) (DeCelles et al., 2000; Richards et al., 2005; Daniel et al., 2003; Richards et al., 2006; Martin et al., 2005; Kumar, 1997). Thus, even though the rocks which are mapped directly in the footwall of the MCT do not suggest a lower LH origin, NBH-9 is definitely a lower LH rock.

Our youngest DZ sample is from the Baxa Group (NBH-18) and displays similar age spectra to NBH-5 and a Nepal sample (sample 502072 (Martin et al., 2005)) (Fig. 5) that must be younger than ~485 Ma. NBH-21, also collected in the Baxa Group, provided an εNd value of −21. The similar DZ spectra of NBH-18 and NBH-5, and the identical εNd values of NBH-6 and NBH-21 (Figs. 2 and 5; Tables 1 and 2) suggest that the strata NBH-5, 6, and 7 were sampled from could be a more northern equivalent to the Baxa Group (NBH-18 and NBH-21). The young LH DZ samples (NBH-5, and 18) show a clear ~500 Ma peak similar to TH Cambro-Orodovician strata in Bhutan (McKenzie et al., 2007) indicating that the LH strata may be proximal continental shelf deposits contemporaneous with more distal Tethyan deposits. Both TH and LH strata may be sourced from and overlap proposed Cambro-Orodovician deformation (Gehrels et al., 2003; Brookfield, 1993; McKenzie et al., 2007).

Table 2
εNd isotopic analyses

Sample	Sm (ppm)	Nd (ppm)	143Nd/144Nd (0)	std err %	E(Nd)0
NBH-2	5.27	25.28	0.511643	0.0015	−19.41
NBH-6	2.95	11.25	0.511540	0.0018	−21.42
NBH-19	2.81	15.42	0.511623	0.0014	−19.80
NBH-21	5.48	22.39	0.511540	0.0015	−21.42

NBH-19 was collected from a phyllitic diamictite in the Diuri Formation. Age estimates of the Diuri Formation range from Proterozoic through Permian (Gansser, 1983; Jangpangi, 1974; Tangri, 1995b). Because εNd values for Permian rock do not exist along the Himalayan arc, it is impossible to compare εNd values between the Diuri and known Permian strata. Field data show that the Diuri directly overlies the Baxa Group, arguing that the maximum age of the Diuri is Cambrian. Like the Baxa Group, the εNd value for the Diuri Formation (−20) falls within the range of other LH rock and within values obtained for Paleozoic Tethyan rock (Robinson et al., 2001).

Correlations in DZ spectra and fossil age control between LH and TH rocks have been used to argue for a continuous passive margin sedimentary package for LH (proximal) and TH (distal) in NW India not only in the late Cambrian through Devonian, but from the Proterozoic on (Myrow et al., 2003). Although our data suggest that basal TH and upper LH strata are time equivalent in Bhutan, the data do not suggest that sedimentation was continuous between lower LH strata and upper LH strata. A significant unconformity could exist between the definitive lower LH Shumar–Daling rocks and the rocks near the MCT (NBH-5–7) but it is masked by metamorphism and deformation. 0.6 km south of sample NBH-7 is an augen gniess body. Correlative augen gneiss in Bhutan, Arunachal, and Nepal have been dated at ~1.8 Ga (DeCelles et al., 2000; Daniel et al., 2003; Kumar, 1997), which supports the interpretation of an unconformity, or very low sedimentation rates between upper and lower LH rocks. The ~500 Ma detrital zircons from Baxa Group rocks as well as Cambro-Ordovician TH were most likely sourced from late Pan-African deformation on the northern and eastern edges of Greater India (Gehrels et al., 2003; Brookfield, 1993; McKenzie et al., 2007; Argles et al., 1999; Hoffman, 1991). Combining Indian and Bhutan data with that from Nepal, which stands out due to a well-defined lack of lower Paleozoic strata in LH rocks, suggests that Nepal occupied a region of significant sediment bypass during early Paleozoic time or that the rocks of that age were eroded before Gondwana sequence deposition.

6. Structural geology

Mapping LH rocks from the MCT to the MBT provides the first-order structural framework of this portion of the eastern Himalayan orogen. To help interpret the structures mapped in the field, we have constructed a composite balanced cross-section on the basis of our initial mapping in eastern Bhutan (1:50,000 scale) and geologic maps compiled by Gansser (1983), Gokul (1983) and Bhargava (1995) (Figs. 1 and 2). The cross-section is comprised of two parts (Figs. 2 and 6): the northern section which follows the Kuru Chu valley (Fig. 2) and the southern section which follows a road from Trashigang to Samdrup Jonkhar. Although the location of the cross-section line may miss additional duplexing of the Baxa Group, and folding of the Shumar thrust, we feel breaking the cross-section line along the Shumar thrust to follow our preliminary mapping is the most conservative approach that will not add excess shortening. Thus we expect as both mapping and cross-sections are refined that shortening values should increase. The cross-section is line-length balanced (Dahlstrom, 1969), but no attempt was made to incorporate small-scale deformation that characterizes some of the stratigraphic units nor brittle and ductile deformation with GH rocks. No subsurface data are available for this region except the deep crustal reflection seismic profile of INDEPTH (Hauck et al., 1998) and broad-band telesesimic data (Mitra et al., 2005) which broadly constrains the dip of the Main Himalayan decollement. As is typical through most of the Himalaya, the hanging wall cut-offs of the thrust sheets are not preserved. However, the southward extent of GH over lower LH rock (as seen to the west and east of the Kuru Chu anticline) and the southward extent of lower LH (Daling–Shumar) over upper LH rock (Baxa Group) limit the magnitude of slip that can be proposed for this region on faults below the MCT. With these caveats, this cross-section should be viewed as a first-order approximation that will undoubtedly be changed as new data become available.

6.1. Siwalik Group

The Siwalik Group section immediately north of Samdrup Jonkhar is an ~8 km north–south exposure of northward dipping rocks with dips varying between 25° and 65° with most dips clustering between 30° and 40° northwest. The section is not repeated by faults although some meso-scale folds with gently west plunging fold hinges are present in the finer-grained units near the base of the section. We interpret the Siwalik Group as a continuous 6 km thick section uplifted by motion along the MFT. The magnitude of slip (9 km) is the minimum required to move the hanging wall cut-off (which, if exposed, would be southward dipping rocks) through the erosion surface (Fig. 6, #1).

6.2. Upper Lesser Himalaya

In the hanging wall of the MBT, a 2.5 km wide surface exposure of steeply northward dipping (40°–86°) Gondwana sequence rocks (Fig. 4d) is followed northward by a 9 km wide exposure of gently folded Diuri Formation. The extra length of the Gondwana sequence shown above the erosion surface (Fig. 6, #2) is needed to align footwall ramps in the upper LH with a change in apparent dips measured at the surface from very shallow dips ~10° to >30° (footwall ramp identified on the cross-section with an *). The two thrust sheets of Gondwana sequence rocks shown in the cross-section fill space between Diuri Formation exposed at the surface and its projected location in the subsurface as well as provide a mechanism for passively folding the Diuri Formation. The broadly synclinal nature of the exposed Diuri Formation implies that much of the original section of Diuri (a length equal to the cumulative length of Baxa Group to the north) has been removed by erosion (Fig. 6). We propose that the last thrust sheet underneath the Diuri syncline is composed of Baxa Group rock, because making that thrust sheet Gondwana sequence rock would push the footwall cut-offs of the upper LH 5+ km to the north, which is incompatible with the surface geology (Fig. 6, #4).

An 11 km thick section of consistently northward dipping Baxa Group was mapped (Fig. 2). This is unreasonably thick for a simple stratigraphic section. We use field observations of a ~2.5 km thick section of Baxa Group in each limb of an anticline immediately south of the Shumar thrust (Fig. 2) and prominent ENE to WNW valleys and saddles spaced ~3 km apart along the Trashigang–Samdrup Jongkhar road to support dividing the Baxa Group into 5 additional thrust repeated sections.

6.3. Lower Lesser Himalaya

The sedimentary package of Shumar–Daling Group with augen gneiss intrusions in the upper Daling Formation is repeated once along the upper Kuru Chu valley (Figs. 2 and 6). Both thrust sheets carry an ~8–11 km thick section, comparable to the LH thickness in the Arun River valley of eastern Nepal (Schelling and Arita, 1991). Apparent dips along the line of section describe northward dipping rocks (~45°) adjacent to the southern Baxa Group contact and then a long section (~30 km) where the apparent dips are very flat (~5°–10°) before significant northward dips are measured again, close to the northern Shumar–Daling Formation contact (Figs. 2 and 6). This pattern of dips defines a ramp–flat–ramp geometry, where the southern ramp is related to the Baxa Group duplex system, the regional flat is above the Diuri Formation and the northern ramp is the regional ramp through upper LH rock (Fig. 6, #5). Maps of Bhutan (Gansser, 1983; Bhargava, 1995; Gokul, 1983) show lower LH rock extending ~30 km farther south along the Kuru Chu valley (Fig. 2). One explanation for this map pattern is a folded roof thrust of lower LH rock (similar to the Ramgarh thrust identified in Nepal) (i.e. Pearson and DeCelles, 2005) over an upper LH rock duplex system (Fig. 6). We use the southern extent of the Daling–Shumar Group to the west to

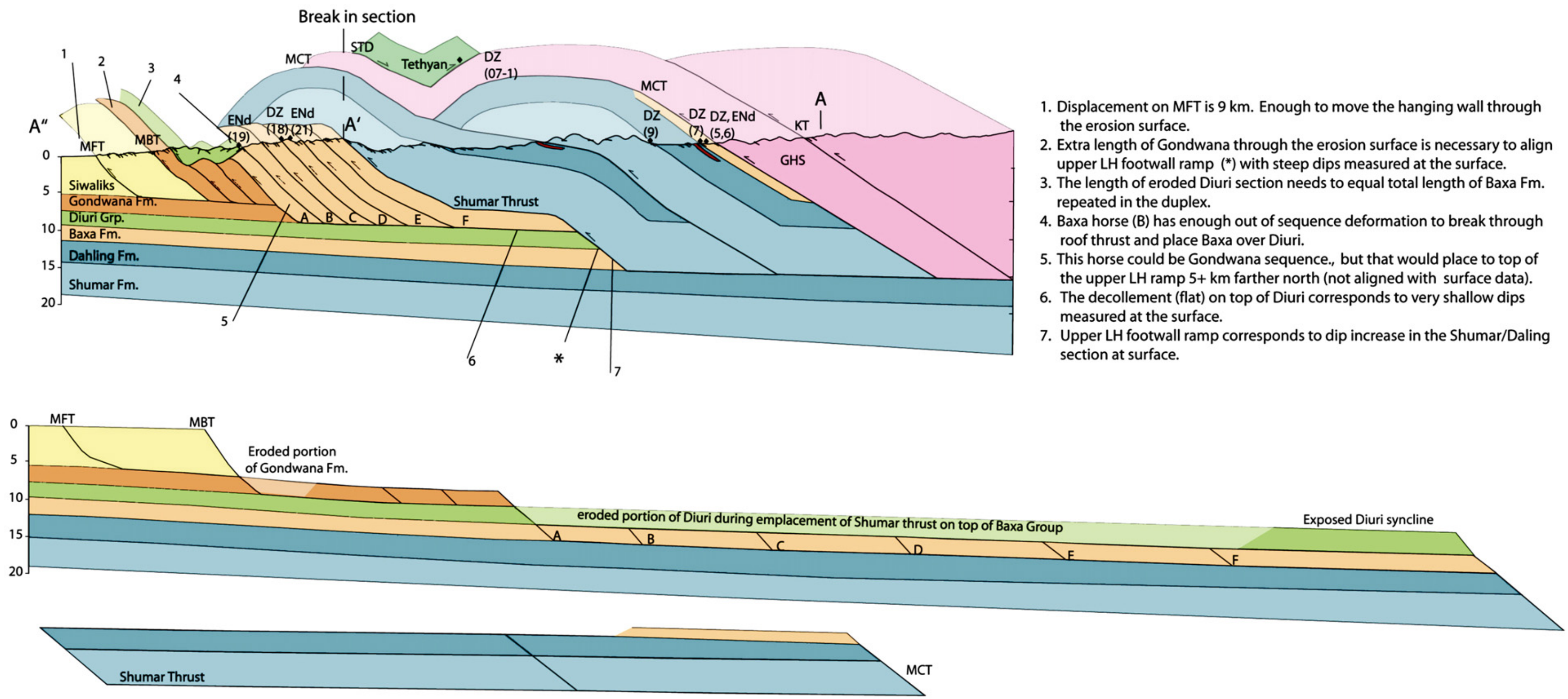

Fig. 6. Balanced cross-section of the Kuru Chu region, Bhutan. Black diamonds are sample locations with sample numbers. DZ is detrital zircon sample location, END is an εNd(0) sample location, MFT, Main Frontal thrust, MBT, Main Boundary thrust, MCT, Main Central thrust, STD, South Tibetan Detachment, KT, Kakhtang thrust. See Fig. 2 for location.

support the extension of the Shumar thrust over the Baxa Group duplex. Displacements on each of the thrusts in the lower LH rocks are 35 km (northern thrust) and 56 km (southern thrust). All of the measured cross-beds in the Daling–Shumar Group indicate that strata are right side up from immediately in the footwall of the MCT to the Shumar thrust. These data combined with structural observations suggest that there is no large scale, tight to isoclinal folding of LH rock near the MCT. Based on our DZ and εNd data, we suggest that there are upper LH rocks stratigraphically above lower LH rocks in the footwall of the MCT. The thickness of this unit is ~2 km.

Comparing the stratigraphy of lower LH rock from western Nepal (3–4.5 km (Robinson et al., 2006)) to Eastern Nepal (11 km (Schelling and Arita, 1991)) and Bhutan (~8–11 km) initially suggests that a first-order change exists in the stratigraphic thickness, which may result in shortening variations between the central and eastern Himalaya.

6.4. Greater Himalaya

Pervasive ductile fabrics through the MCT in conjunction with mineral assemblages, thermobarometric datasets, and the widespread presence of migmatite and leucogranite in most exposures of GH rocks are used to support the idea that the rocks may have flowed at mid-crustal depths (Davidson et al., 1997; Ganguly et al., 2000; Daniel et al., 2003; Hollister and Grujic, 2006; Searle and Szulc, 2005; Grujic et al., 1996; Hodges et al., 2001; Searle et al., 2003). The ductile fabrics throughout GH rocks emphasizes that any estimate of displacement on the MCT is a bare minimum; however, the southernmost extent of GH rock from east and west of our line of section can be used to determine the absolute minimum displacement estimate of ~100 km. On average, throughout Bhutan, the main foliation in GH rocks dips gently (~20–30°) to the north; however, the foliation is affected by long wavelength, low amplitude E–W and N–S trending folds. The interference of the two fold sets produces gentle basin and dome structures seen in the map patterns of the region (Gansser, 1983; Grujic et al., 1996) (Fig. 1). The Kuru Chu valley is the topographic expression of one of the prominent N–S trending antiforms in Bhutan. Normal fault bounded klippen of the TH Chekha Formation (Grujic et al., 2002) exposed east and west of the Kuru Chu valley, are preserved in the core of a prominent E–W trending synform. (Figs. 1 and 2). We propose that many of these map scale folds preserved in GH rocks are a result of duplexing of LH rock at depth. That the LH strata immediately below the MCT contains 500 Ma zircon grains and Chekha Formation directly above the GH only contains grains as young as ~850 suggests that the MCT must have first been emplaced as a thrust over Baxa Group equivalents and that MCT displacement must be greater than STD displacement by ~100 km. North of the MCT the Kakhtang thrust places sillimanite bearing migmatite over lower grade paragneiss (Grujic et al., 2002; Daniel et al., 2003). It also cuts across penetrative fabrics and metamorphic isograds (Davidson et al., 1997). Like the MCT we can only estimate the minimum magnitude of displacement on the Kakhtang thrust. Assuming the Kakhtang thrust roots into the Main Himalayan thrust (Nelson et al., 1996), and that the hanging wall cut-off is immediately above the erosion surface, the minimum amount of displacement on the Kakhtang thrust is 33 km (Fig. 6).

7. Shortening and preliminary kinematic history

7.1. Shortening

Total shortening for the composite cross-section presented here from the MFT to the STD is 359 km or 74%. Motion on the MCT contributes 100 km of the shortening due to overlap of GH rock over top of LH rock, while minimum displacement on the Kakhtang thrust contributes 33 km (see Fig. 2). The two thrust sheets in lower LH rock accommodate 91 km of shortening. Minimum shortening in the upper LH duplex is 126 km, while minimum shortening in the Siwalik Group section is 9 km. Shortening calculated in the upper LH duplex is dependent on our thickness estimate for the Baxa Group quartzite. If the Baxa quartzite is 5 km thick, then shortening would be 50 km less than indicated above. If the Baxa quartzite is only 1 km thick, then the shortening estimate would increase by ~100 km. These shortening estimates are still less (by ~150 to as much as 400 km) than shortening estimates in western Nepal (485–743 km; Robinson et al., 2006), although the percent shortening is very similar to values in western Nepal and India (Srivastava and Mitra, 1994; Robinson et al., 2006; DeCelles et al., 2001). The proposed shortening estimates for Bhutan presented here are greater than the 245–280 km estimates proposed for eastern Nepal (Schelling and Arita, 1991; Schelling, 1992). DeCelles et al. (2002) predicted that Bhutan should have shortening on the order of 350–400 km from the MFT to the STD and an additional 150–200 km of shortening in TH rock from the STD northward (DeCelles et al., 2002; Ratschbacher et al., 1994) if the magnitude of shortening is directly related to the width of Tibet. This study is in agreement with those predicted values. Studies which suggest that greater shortening should be found in the eastern Himalaya because of either the obliquity of collision or climate–tectonic interactions (Yin et al., 2006; Guillot et al., 1999; Grujic et al., 2006) are not supported by our preliminary shortening estimates, or require that shortening is accommodated solely on the MCT pre-16 Ma. These early comparisons are qualified by the preliminary nature of our study and we anticipate that shortening estimates will continue to be refined in conjunction with more detailed mapping of the region.

7.2. Kinematic history

The kinematic history of the Himalayan fold-thrust belt in Bhutan can only be broadly defined by available metamorphic, and geochronologic data. Geothermometry and geobarometry in Bhutan (Grujic et al., 2002; Daniel et al., 2003; Hollister and Grujic, 2006) suggest peak metamorphic conditions in GH rock at ~22 Ma at pressures and temperatures between 10–12 kb and 650–850 °C respectively with highest temperatures recorded in the core of the sequence and highest pressures at the base. Monazite and xenotime in migmatite proximal to the MCT yield U/Pb ages of 16–18 Ma, while growth of metamorphic monazite in LH rock occurred between 18 and 20 Ma (Daniel et al., 2003). Growth age of metamorphic crystals/overgrowths implies that the deformation within LH rocks occurred at greenschist facies conditions (over 400 °C) and was related to the south directed thrusting that was underway by 22 Ma, and continued until perhaps 14 Ma or younger (Daniel et al., 2003).

With the above data as support, we suggest the following kinematic history. Emplacement of GH over LH via ductile shearing along the MCT occurred between 22 and 16 Ma as suggested by crystallization ages in GH migmatite and metamorphic monazite in LH rock (Godin et al., 2006). As currently drawn, the cross-section suggests coeval motion on the northernmost lower LH thrust and the southern extension of the MCT, with the MCT acting as a roof thrust for a single LH thrust sheet. Thus motion on this LH thrust probably started ~18 Ma, concurrent with burial of the rocks carried by the southern lower LH thrust sheet (Shumar thrust). We propose that the 10–15 Ma $^{40}Ar/^{39}Ar$ cooling ages within GH rocks proximal to the MCT are not the result of MCT thrusting but rather are associated with rock-uplift and erosion during the emplacement of the Shumar thrust (~16–13 Ma) and the initial growth of the upper LH duplex. Crystallization ages of leucogranite deformed by the Kakhtang thrust indicate out-of-sequence motion on the thrust at 14–15 Ma (Grujic et al., 2002; Daniel et al., 2003) or younger. Folding and cooling of GH rock during thrusting and duplex development in the lower LH rock is concurrent with motion on the Kakhtang thrust which supports the assertion of Grujic et al. (2002) that folding of the MCT/STD system inhibits motion on the frontal faults and promotes out-of-sequence deformation in the hinterland. In our proposed kinematic history, the folding of the MCT/STD system is a direct result of emplacement of thrust sheets in the two LH duplexes as they developed. The remaining ~100 km of shortening within the upper LH and Subhimalaya most likely occurred post-10 Ma, but a lack of thermochronologic data in LH rock or sedimentological data from the Siwalik Group prevent us from a more detailed shortening history.

We can combine the above history with the displacement magnitudes predicted by the balanced cross-section to get first-order estimates on rates of deformation. 359 km of shortening in 22 Myr provides a long-term rate of shortening of 16.3 mm/yr. Active GPS shortening rates across the Himalaya are 15–20 mm/yr (Lave and Avouac, 2000; Banerjee and Bürgmann, 2002; Zhang et al., 2004).

8. Conclusions

Although the data presented here are preliminary, several conclusions are derived from this study:

1- Lesser Himalayan strata in Bhutan can be divided into lower LH rocks with a detrital zircon signal of ~1.8 Ga and younger upper LH rock with a detrital zircon signal as young as ~500 Ma. This partitioning of LH strata is similar to that identified in India, but significantly different than LH sequence strata of Nepal, which have only Proterozoic detrital zircon ages. The preliminary data presented here reinforces the suggestions of previous workers that Paleoproterozoic LH rock is continuous along the entire arc. However, they also highlights an importance of correlating the LH stratigraphy across the arc because of regional variations in Mesoproterozoic–Paleozoic stratigraphy.

2- Upper LH strata are time equivalent with Tethyan strata, suggesting both may represent overlap strata after proposed Cambro-Ordovician deformation along the northern Indian margin.

3- The Bhutanese portion of the eastern Himalayan fold-thrust belt has key similarities with structures exposed in the central Himalayan fold-thrust belt. These include: A) a significant overlap (100+ km) of GH over LH rock via the MCT; B) a long (56 km +) thrust sheet (Shumar thrust) of lower LH rock emplaced over an upper LH duplex. This geometry is similar to the emplacement of the Ramgarh thrust over the LH duplex in Nepal and Northwestern India; C) folding of overlying GH and TH rock as a result of growth in the LH duplex; D) 100s of km of shortening due to the development of a LH duplex system.

4- Minimum shortening in this part of the Himalayan fold-thrust belt is 359 km. This estimate is significantly less than estimates farther to the west (~500–700 km). Although this shortening estimate is preliminary and based on a composite section, it implies that along strike variations in shortening along the Himalayan arc are real and significant.

5- The preliminary kinematic history we present emphasizes that the timing of major tectonic events seems to be the same 100s of km along strike of the Himalayan orogen. These include shear displacement of the GH over the LH ~20–18 Ma, emplacement of a long lower LH thrust ~16–14 Ma, and growth of an upper LH duplex system ~10 Ma to present. Similar timing of events but significant differences in slip magnitudes suggests that the rate of deformation in the eastern Himalaya is considerably less than in the west.

Acknowledgements

We would like to thank the Government of Bhutan, particularly Dorji Wangda, Yeshi Dorji, K.S. Ghalley at the Department of Geology and Mines in the Ministry of Economic Affairs for their help and support. This work was partially supported by NSF grant EAR 0738522 to N. McQuarrie. We are grateful for the constructive comments of reviewers and Editor Rob van der Hilst.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2008.04.030.

References

Ahmad, T., Harris, N., Bickle, M., Chapman, H., Bunbury, J., Prince, C., 2000. Isotopic constraints on the structural relationships between the Lesser Himalayan Series and the High Himalayan Crystalline Series, Garhwal Himalaya. Geol. Soc. Amer. Bull. 112, 467–477.

Argles, T.W., Prince, C.I., Foster, G.L., Vance, D., 1999. New garnets for old? Cautionary tales from young mountain belts. Earth Planet. Sci. Lett. 172, 301–309.

Banerjee, P., Bürgmann, R., 2002. Convergence across the northwest Himalaya from GPS measurements. Geophys. Res. Lett.. doi:10.1029/2002GL015184.

Bhargava, O.N., 1995. The Bhutan Himalaya: a Geological Account. Geological Survey of India Special Publication, vol. 39. 245 pp.

Bhattacharyya, K., Mitra, G., Mukul, M., 2006. The geometry and implications of a foreland diping duplex. the Rangit Duplex, Darjeeling–Sikkim Himalayas, India. Abstr. Programs - Geol. Soc. Am. 38, 413.

Brookfield, M.E., 1993. The Himalayan passive margin from Precambrian to the Cretaceous times. Sediment. Geol. 84, 1–35.

Catlos, E.J., Dubey, C.S., Harrison, T.M., Edwards, M.A., 2004. Late Miocene movement within the Himalayan Main Central Thrust shear zone, Sikkim, north-east India. J. Metamorph. Geol. 22, 207–226.

Dahlstrom, C.D.A., 1969. Balanced cross-sections. Can. J. Earth Sci. 6, 743–757.

Daniel, C.G., Hollister, L.S., Parrish, R.R., Grujic, D., 2003. Exhumation of the main central thrust from lower crustal depths, Eastern Bhutan Himalaya. J. Metamorph. Geol. 21, 317–334.

Dasgupta, S., 1995. Shumar Formation. In: Bhargava, O.N. (Ed.), The Bhutan Himalaya: a Geological Account. Geological Survey of India Special Publication, vol. 39, pp. 59–78.

Dasgupta, S., Ganguly, J., Neogi, S., 2004. Inverted metamorphic sequence in the Sikkim Himalayas: crystallization history, P–T gradient and implications. J. Metamorph. Geol. 22, 395–412.

Davidson, C., Grujic, D.E., Hollister, L.S., Schmid, S.M., 1997. Metamorphic reactions related to decompression and synkinematic intrusion of leucogranite, High Himalayan Crystallines, Bhutan. J. Metamorph. Geol. 15, 593–612.

DeCelles, P.G., Gehrels, G.E., Quade, J., Ojha, T.P., 1998. Eocene early Miocene foreland basin development and the history of Himalayan thrusting, western and central Nepal. Tectonics 17, 741–765.

DeCelles, P.G., Gehrels, G.E., Quade, J., LaReau, B., Spurlin, M., 2000. Tectonic implications of U–Pb zircon ages of the Himalayan orogenic belt in Nepal. Science 288, 497–499.

DeCelles, P.G., Robinson, D.M., Quade, J., Ojha, T.P., Garzione, C.N., Copeland, P., Upreti, B.N., 2001. Stratigraphy, structure, and tectonic evolution of the Himalayan fold-thrust belt in western Nepal. Tectonics 20, 487–509.

DeCelles, P.G., Robinson, D.M., Zandt, G., 2002. Implications of shortening in the Himalayan fold-thrust belt for uplift of the Tibetan Plateau. Tectonics 21, 1062. doi:10.1029/2001TC001322.

DeCelles, P.G., Gehrels, G.E., Najman, Y., Martin, A.J., Carter, A., Garzanti, E., 2004. Detrital geochronology and geochemistry of Cretaceous–Early Miocene strata of Nepal: implications for timing and diachroneity of initial Himalayan orogenesis. Earth Planet. Sci. Lett. 227, 313–330.

DiPietro, J.A., Pogue, K.R., 2004. Tectonostratigraphic subdivisions of the Himalaya: a view from the west. Tectonics 23, TC5001. doi:10.1029/2003TC001554.

Gaetani, M., Garzanti, E., 1991. Multicyclic history of the northern India continental-margin (northwesern Himalaya). AAPG Bull. 75, 1427–1446.

Ganguly, J., Dasgupta, S., Cheng, W., Neogi, S., 2000. Exhumation history of a section of the Sikkim Himalayas, India: records in the metamorphic mineral equilibria and compositional zoning in garnet. Earth Planet. Sci. Lett. 183, 471–486.

Gansser, A., 1964. Geology of the Himalaya. Wiley- Interscience, New York. 289 pp.

Gansser, A., 1983. Geology of the Bhutan Himalaya. Birkhäuser Verlag, Basel-Boston-Stuttgart. 181 pp.

Garzanti, E., 1999. Stratigraphy and sedimentary history of the Nepal Tethys Himalaya passive margin. J. Asian Earth Sci. 17, 805–827.

Gehrels, G.E., DeCelles, P., Martin, A.J., Ojha, T., Pinhassi, G., Upreti, B.N., 2003. Initiation of the Himalayan Orogen as an early Paleozoic thin-skinned thrust belt. GSA Today 13, 4–9.

Godin, L., Grujic, D., Searle, M., Law, R.D., 2006. Channel flow, extrusion, and exhumation on continental collision zones: an introduction. In: Law, R.D., Searle, M., Godin, L. (Eds.), Channel Flow, Extrusion and Exhumation of Lower-mid Crust in Continental Collision Zones. Geological Society of London Special Publications, vol. 268, pp. 1–23.

Gokul, A.R., Geological and Mineral Map of Bhutan: Scale 1:500,000, 1 sheet, Geological Survey of India Map Printing Division, Hyderabad, 1983.

Grujic, D., Casey, M., Davidson, C., Hollister, L.S., Kundig, R., Pavlis, T., Schmid, S., 1996. Ductile extrusion of the Higher Himalayan Crystalline in Bhutan: evidence from quartz microfabrics. Tectonophysics 260, 21–43.

Grujic, D., Hollister, L.S., Parrish, R.R., 2002. Himalayan metamorphic sequence as an orogenic channel: insight from Bhutan. Earth Planet. Sci. Lett. 198, 177–191.

Grujic, D., Coutand, I., Bookhagen, B., Bonnet, S., Blythe, A., Duncan, C., 2006. Climatic forcing of erosion, landscape, and tectonics in the Bhutan Himalayas. Geology 34, 801–804.

Guillot, S., Cosca, M., Allemand, P., Le Fort, P., 1999. Contrasting metamorphic and geochronologic evolution along the Himalayan belt. In: Macfarlane, A.M., Sorkhabi, R.B., Quade, J. (Eds.), Himalaya and Tibet: Mountain Roots to Mountain Tops. Geological Society of America Special Paper, vol. 328.

Guillot, S., Garzanti, E., Baratoux, D., Marquer, D., Maheo, G., de Sigoyer, J., 2003. Reconstructing the total shortening history of the NW Himalaya. Geochem., Geophys, Geosyst. 4. doi:10.1029/2002GC000484.

Harris, N.B.W., Caddick, M., Kosler, J., Goswami, S., Vance, D., Tindle, A.G., 2004. The pressure–temperature–time path of migmatites from the Sikkim Himalaya. J. Metamorph. Geol. 22, 249–264.

Hauck, M.L., Nelson, K.D., Brown, L.D., Zhao, W.J., Ross, A.R., 1998. Crustal structure of the Himalayan orogen at similar to 90 degrees east longitude from Project INDEPTH deep reflection profiles. Tectonics 17, 481–500.
Hodges, K.V., 2000. Tectonics of the Himalaya and southern Tibet from two perspectives. Geol. Soc. Amer. Bull. 112, 324–350.
Hodges, K.V., Hurtado, J.M., Whipple, K.X., 2001. Southward extrusion of Tibetan crust and its effect on Himalayan tectonics. Tectonics 20, 799–809.
Hodges, K.V., Parrish, R.R., Searle, M.P., 1996. Tectonic evolution of the central Annapurna Range, Nepalese Himalayas. Tectonics 15, 1264–1291.
Hoffman, P.F., 1991. Did the breakout of Laurentia turn Rodinia inside-out. Science 252, 1409–1412.
Hollister, L.S., Grujic, D., 2006. Pulsed channel flow in Bhutan. In: Law, R.D., Searle, M., Godin, L. (Eds.), Channel Flow, Extrusion and Exhumation of Lower-mid Crust in Continental Collision Zones. Geological Society of London Special Publications, vol. 268, pp. 415–423.
Jangpangi, B.S., 1978. Stratigraphy and structure of the Bhutan Himalaya. In: Saklani, P.S. (Ed.), Tectonic Geology of the Himalaya. Today's and Tomorrow's Publications, New Delhi, pp. 221–242.
Jangpangi, B.S., 1974. Stratigraphy and tectonics of parts of eastern Bhutan. Himal. Geol. 4, 117–136.
Klootwijk, C.T., Gee, J.S., Peirce, J.W., Smith, G.M., McFadden, P.L., 1992. An early India–Asia contact: paleomagnetic constraints from Ninetyeast Ridge, ODP Leg 121. Geology 20, 395–398.
Kumar, G., 1997. Geology of Arunachal Pradesh. Geological Society of India, Bangalore.
Lakshminarayana, G., 1995. Damuda Supergroup. In: Bhargava, O.N. (Ed.), The Bhutan Himalaya: a Geological Account. Spec. Publ. Geol. Surv. India, 39, pp. 29–33.
Lave, J., Avouac, J.P., 2000. Active folding of fluvial terraces across the Siwaliks Hills, Himalayas of central Nepal. J. Geophys. Res. -Solid Earth 105, 5735–5770.
Leech, M.L., Singh, S., Jain, A.K., Klemperer, S.L., Manickavasagam, R.M., 2005. The onset of India–Asia continental collision: early, steep subduction required by the timing of UHP metamorphism in the western Himalaya. Earth Planet. Sci. Lett. 234, 83–97.
LeFort, P., 1975. Himalayas: the collided range, present knowledge of the continental arc. Am. J. Sci. A275, 1–44.
Martin, A.J., DeCelles, P.G., Gehrels, G.E., Patchett, P.J., Isachsen, C., 2005. Isotopic and structural constraints on the location of the Main Central thrust in the Annapurna Range, central Nepal Himalaya. Geol. Soc. Amer. Bull. 117, 926–944.
McKenzie, R.N., Hughes, N.C., Myrow, P.M., Bhargava, O.N., Tangri, S.K., Ghalley, K.S., 2007. Fossil and chronostratigraphic constraints on the Quartzite member. Black Mountain region, Bhutan and its geological significance. Abstr. Programs - Geol. Soc. Am. 39, 416.
Mitra, S., Priestley, K., Bhattacharyya, A.K., Gaur, V.K., 2005. Crustal structure and earthquake focal depths beneath northeasteern India and southern Tibet. Geophys. J. Int. 160, 227–248.
Myrow, P.M., Hughes, N.C., Paulsen, T.S., Willlams, I.S., Parcha, S.K., Thompson, K.R., Bowring, S.A., Peng, S.C., Ahluwalia, A.D., 2003. Integrated tectonostratigraphic analysis of the Himalaya and implications for its tectonic reconstruction. Earth Planet. Sci. Lett. 212, 433–441.
Myrow, P.M., Hughes, N.C., Fanning, M., Bhargava, O.N., Tangri, S.K., 2005. New stratigraphy and geochronologic data for the Tethyan of Bhutan. Abstr. Programs - Geol. Soc. Am. 37, 57.
Najman, Y., Johnson, K., White, N., Oliver, G., 2004. Evolution of the Himalayan foreland basin, NW India. Basin Research 16, 1–24.
Nelson, K.D., Zhao, W., Brown, L.D., Kuo, J., Che, J., Liu, X., Klemperer, S.L., Makovsky, Y., Meissner, R., Mechie, J., Kind, R., Wenzel, F., Ni, J., Nabelek, J., Chen, L., Tan, H., Wei, W., Jones, A.G., Booker, J., Unsworth, M., Kidd, W.S.F., Hauck, M., Alsdorf, D., Ross, A., Cogan, M., Wu, C., Sandvol, E., Edwards, M., 1996. Partially molten middle crust beneath southern Tibet: a synthesis of Project INDEPTH results. Science 274, 1684–1688.
Neogi, S., Dasgupta, S., Fukuoka, M., 1998. High PT polymetamorphism, dehydration melting, and generation of migmatites and granites in the Higher Himalayan crystalline complex, Sikkim, India. J. Petrol. 39, 61–99.
Parrish, R., Hodges, K., 1996. Isotopic constraints on the age and provenance of the Lesser and Greater Himalayan sequence, Nepalese Himalaya. Geol. Soc. Amer. Bull. 108, 904–911.
Pearson, O.N., DeCelles, P.G., 2005. Structural geology and regional tectonic significance of the Ramgarh thrust, Himalayan fold-thrust belt of Nepal. Tectonics 24.
Pogue, K.R., Hylland, M.D., Yeats, R.S., Khattak, W.U., Hussain, A., 1999. Stratigraphic and structural framework of Himalayan foothills, northern Pakistan. In: Macfarlane, A. M., Sorkhabi, R.B., Quade, J. (Eds.), Himalaya and Tibet: Mountain Roots to Mountain Tops. Geological Society of America Special Paper, vol. 328.
Quade, J., Cater, J.M.L., Ojha, T., Adam, J., Harrison, T.M., 1995. Late Miocene environmental change in Nepal and northern Indian subcontinent: stable isotopic evidence from Paleosols. Geol. Soc. Amer. Bull. 107, 1381–1397.
Ratschbacher, L., Frisch, W., Liu, G.H., Chen, C.S., 1994. Distributed deformation in southern and western Tibet during and after the India–Asia collision. J. Geophys. Res.-Solid Earth 99, 19917–19945.
Ray, S.K., 1995. Lateral variations in geometry of thrust planes and its significance, as studies in the Shumar allochthon, Lesser Himalayas, eastern Bhutan. Tectonophysics 249, 125–139.
Richards, A., Argles, T., Harris, N., Parrish, R., Ahmad, T., Darbyshire, F., Draganits, E., 2005. Himalayan architecture constrained by isotopic tracers from clastic sediments. Earth Planet. Sci. Lett. 236, 773–796.
Richards, A., Parrish, R., Harris, N., Argles, T., Zhang, L., 2006. Correlation of lithotectonic units across the eastern Himalaya, Bhutan. Geology 34, 341–344.
Robinson, D.M., Pearson, O.N., 2006. Exhumation of Greater Himalaya rock along the Main Central Thrust in Nepal: implications for channel flow. In: Law, R.D., Searle, M., Godin, L. (Eds.), Channel Flow, Extrusion and Exhumation of Lower-mid Crust in Continental Collision Zones. Geological Society of London Special Publications, vol. 268, pp. 255–268.
Robinson, D.M., DeCelles, P.G., Patchett, P.J., Garzione, C.N., 2001. The kinematic evolution of the Nepalese Himalaya interpreted from Nd isotopes. Earth Planet. Sci. Lett. 192, 507–521.
Robinson, D.M., DeCelles, P.G., Garzione, C.N., Pearson, O.N., Harrison, T.M., Catlos, E.J., 2003. Kinematic model for the Main Central thrust in Nepal. Geology 31, 359–362.
Robinson, D.M., DeCelles, P.G., Copeland, P., 2006. Tectonic evolution of the Himalayan thrust belt in western Nepal: implications for channel flow models. Geol. Soc. Amer. Bull. 118, 865–885.
Rowley, D.B., 1996. Age of initiation of collision between India and Asia: a review of stratigraphic data. Earth Planet. Sci. Lett. 145, 1–13.
Schelling, D., 1992. The tectonostratigraphy and structure of the eastern Nepal Himalaya. Tectonics 11, 925–943.
Schelling, D., Arita, K., 1991. Thrust tectonics, crustal shortening, and the structure of the far-eastern Nepal Himalaya. Tectonics 10, 851–862.
Searle, M.P., 1999. Extensional and compressional faults in the Everest–Lhotse massif, Khumbu Himalaya, Nepal. J. Geol. Soc. 156, 227–240.
Searle, M.P., Szulc, A.G., 2005. Channel flow and ductile extrusion of the high Himalayan slab — the Kangchenjunga–Darjeeling profile, Sikkim Himalaya. J. Asian Earth Sci. 25, 173–185.
Searle, M., Simpson, R.L., Law, R.D., Parrish, R., Waters, D.J., 2003. The structural geometry, metamorphic and magmatic evolution of the Everest Massif, High Himalaya of Nepal–South Tibet. J. Geol. Soc. London 106, 345–366.
Sengupta, S., Raina, P.L., 1978. Geology of parts of Bhutan foothills adjacent to the Darjeeling District. Indian J. Earth Sci. 5, 20–33.
Srivastava, P., Mitra, G., 1994. Thrust geometries and deep structure of the outer and lesser Himalaya, Kumaon and Garwal (India): implications for evolution of the Himalayan fold-and-thrust belt. Tectonics 13, 89–109.
Tangri, S.K., 1995a. Baxa Group. In: Bhargava, O.N. (Ed.), The Bhutan Himalaya: a Geological Account. Geological Survey of India Special Publication, vol. 39, pp. 38–58.
Tangri, S.K., 1995b. Diuri Formation. In: Bhargava, O.N. (Ed.), The Bhutan Himalaya: a Geological Account. Geological Survey of India Special Publication, vol. 39, pp. 59–63.
Thimm, K.A., Parrish, R., Hollister, L.S., Grujic, D., Klepeis, K., Dorji, T., 1999. New U–Pb data from the MCT and lesser and Greater Himalaya sequences in Bhutan. Eur. Union Geosci. Conf. Abstr. 10, 57.
Upreti, B.N., 1996. Stratigraphy of the western Nepal Lesser Himalaya: a synthesis. J Nepal Geol. Soc. 13, 11–28.
Upreti, B.N., 1999. An overview of the stratigraphy and tectonics of the Nepal Himalaya. J. Asian Earth Sci. 17, 577–606.
Vannay, J.C., Grasemann, B., 2001. Himalayan inverted metamorphism and syn-convergence extension as a consequence of a general shear extrusion. Geol. Mag. 138, 253–276.
Vannay, J.C., Hodges, K., 1996. Tectonometamorphic evolution of the Himalayan metamorphic core between Annapurna and Dhaulagiri, central Nepal. J. Metamorph. Geol. 14, 635–656.
Whittington, A., Foster, G., Harris, N., Vance, D., Ayers, M., 1999. Lithostratigraphic correlations in the western Himalaya—an isotopic approach. Geology 27, 585–588.
Yin, A., 2006. Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation. Earth-Sci. Rev. 76, 1–131.
Yin, A., Dubey, C.S., Kelty, T.K., Gehres, G.E., Chou, C.Y., Grove, M., Lovera, O., 2006. Structural evolution of the Arunachal Himalaya and implications for asymmetric development of the Himalayan orogen. Curr. Sci. 90, 195–206.
Zhang, P.Z., Shen, Z., Wang, M., Gan, W., Bürgmann, R., Molnar, P., Wang, Q., Niu, Z., Sun, J., Wu, J., Hanrong, S., Xinzhao, Y., 2004. Continuous deformation of the Tibetan Plateau from global positioning system data. Geology 32, 809–812.