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Tectonic interleaving along the Main Central Thrust, Sikkim Himalaya

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Abstract: Geochemical and geochronological analyses provide quantitative evidence about the origin, development and motion along ductile faults, where kinematic structures have been overprinted. The Main Central Thrust is a key structure in the Himalaya that accommodated substantial amounts of the India–Asia convergence. This structure juxtaposes two isotopically distinct rock packages across a zone of ductile deformation. Structural analysis, whole-rock Nd isotopes, and U–Pb zircon geochronology reveal that the hanging wall is characterized by detrital zircon peaks at *c.* 800–1000 Ma, 1500–1700 Ma and 2300–2500 Ma and an $\varepsilon_{Nd(0)}$ signature of –18.3 to –12.1, and is intruded by *c.* 800 Ma and *c.* 500–600 Ma granites. In contrast, the footwall has a prominent detrital zircon peak at *c.* 1800–1900 Ma, with older populations spanning 1900–3600 Ma, and an $\varepsilon_{Nd(0)}$ signature of –27.7 to –23.4, intruded by *c.* 1830 Ma granites. The data reveal a *c.* 5 km thick zone of tectonic imbrication, where isotopically out-of-sequence packages are interleaved. The rocks became imbricated as the once proximal and distal rocks of the Indian margin were juxtaposed by Cenozoic movement along the Main Central Thrust. Geochronological and isotopic characterization allows for correlation along the Himalayan orogen and could be applied to other cryptic ductile shear zones.

Supplementary material: Zircon U–Pb geochronological data, whole-rock Sm–Nd isotopic data, sample locations, photomicrographs of sample thin sections, zircon CL images, and detailed analytical conditions are available at www.geolsoc.org.uk/SUP18704.

Crustal thickening in major orogenic belts is often achieved by packages of rock being thrust upon one another along major thrust faults. At depth, thrust faults form ductile shear zones and the amount of displacement along these structures is probably much larger than can be evaluated by strain analysis of the exposed rock. The Sikkim Himalaya provides a uniquely preserved window into the mid-crustal levels of one of the largest ductile shear zones on Earth. This study illustrates how isotope geochemistry and geochronology can be used to investigate major orogenic structures, affected by hundreds of kilometres of relative displacement and ductile deformation, to provide a unique perspective on the hanging wall–footwall relationships.

The Main Central Thrust is an orogen-parallel ductile thrust fault or shear zone that separates the Greater Himalayan Sequence in the hanging wall from the Lesser Himalayan Sequence in the footwall (Fig. 1; Heim & Gansser 1939; Le Fort 1975). Despite this simple definition, in reality the specific location and structural characteristics of the Main Central Thrust have long been subject to debate throughout the Himalaya. Our knowledge of this thrust system in the eastern Himalaya is particularly poor.

The Main Central Thrust was originally mapped in the Kumaun region of NW India as the basal contact between the crystalline nappes (Greater Himalayan Sequence) and the underlying metasedimentary rocks (Lesser Himalayan Sequence) (Heim & Gansser 1939). Since that time there has been little agreement on the classification or location of the thrust in many Himalayan sections. A variety of factors have caused controversy over the Main Central Thrust: the divergent criteria used to define the thrust, differences in methods and approach, and variations in appearance of the thrust in the field (Searle *et al.* 2008, and references therein). Different criteria used to define the thrust include the following: (1) lithological changes (Heim & Gansser 1939; Valdiya 1980; Gansser 1983; Pêcher 1989; Davidson *et al.* 1997; Daniel *et al.* 2003; Tobgay *et al.* 2012); (2) high strain in a distinct zone (Stephenson *et al.* 2001; Gupta *et al.* 2010); (3) metamorphic discontinuities (Bordet 1961; Le Fort 1975; Hubbard & Harrison 1989; Stäubli 1989; Harrison *et al.* 1997; Catlos *et al.* 2001; Kohn *et al.* 2001; Daniel *et al.* 2003; Groppo *et al.* 2009; Martin *et al.* 2010); (4) structural criteria (Pêcher 1989; Martin *et al.* 2005; Searle *et al.* 2008); (5) isotopic breaks (Inger & Harris 1993; Parrish & Hodges 1996; Whittington *et al.* 1999; Ahmad *et al.* 2000; Robinson *et al.* 2001; Martin *et al.* 2005, 2011; Richards *et al.* 2005, 2006; Ameen *et al.* 2007; Imayama & Arita 2008; Gehrels *et al.* 2011; Long *et al.* 2011*b*; Tobgay *et al.* 2010; McQuarrie *et al.* 2013; Webb *et al.* 2013).

It has been asserted that ‘the essential criteria to define a shear zone are the identification of a strain gradient and the clear localisation of strain’ (Passchier & Trouw 2005, p. 532; Searle *et al.*, 2008). Although this approach is useful to define the Main Central Thrust in areas where structural criteria are clear-cut, it does not take into account the diffuse nature of the deformation that is associated with the Main Central Thrust in many other transects. This approach also fails to address the difficulties of locating the thrust as a discrete break when it separates rocks of very similar lithologies over a wide zone of ductile deformation, where total strain may not be faithfully recorded by all lithologies.

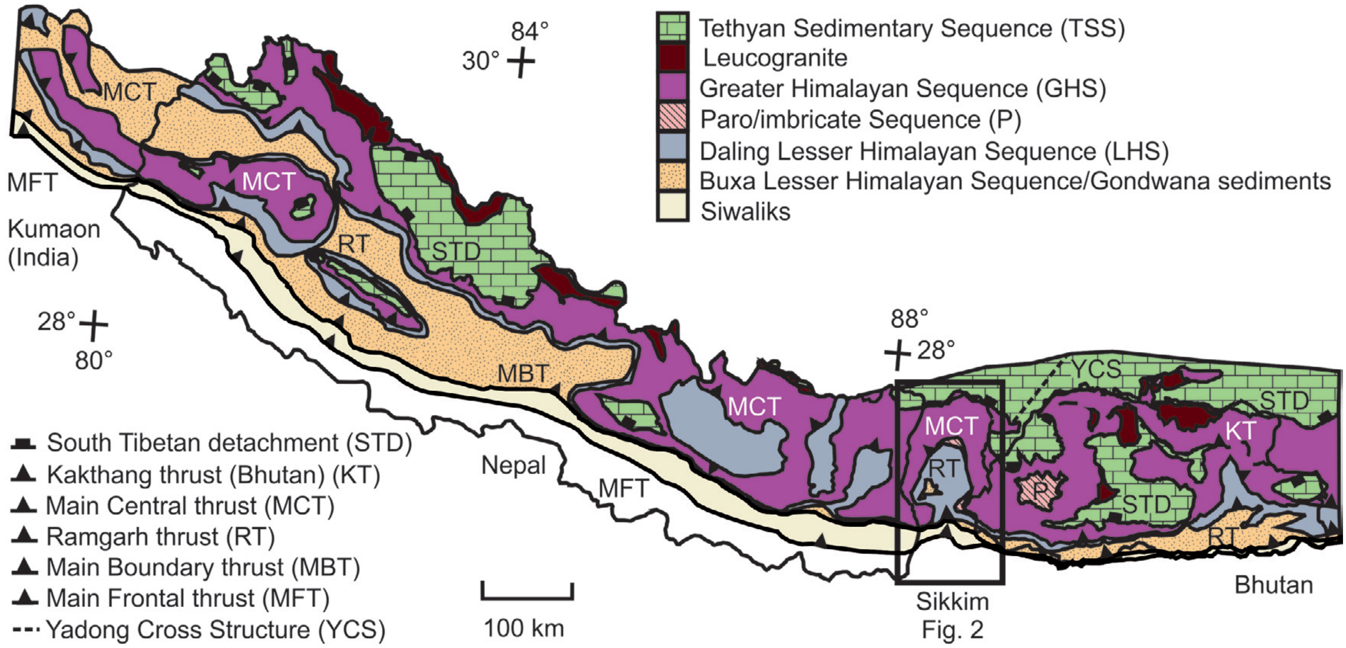

Fig. 1. Geological sketch map of the central and eastern Himalayas. (Adapted from McQuarrie *et al.* 2008 and Greenwood 2013.)

In areas where the structural and stratigraphic criteria are ambiguous, geochemical fingerprinting can provide a complementary tool to identify and investigate the tectonostratigraphic break across the Main Central Thrust, as units either side of the thrust are defined by distinct geochemical signatures. Early studies found that the 'geochemical' boundary associated with the Main Central Thrust coincided with the geological or lithological boundary mapped by others, suggesting that the approach had broad validity in confirming the location of the suspected major fault (e.g. Parrish & Hodges 1996). Most of these previous isotopic studies used to identify the location of the Main Central Thrust have largely focused on the central and western Himalaya (see references above). More recently the eastern Himalaya have become a focus of interest for using isotopic methods (Tobgay *et al.* 2010; McQuarrie *et al.* 2013) after suggestions that the provenance of these rocks differs from elsewhere along the orogen (Yin *et al.* 2010*a,b*; Webb *et al.* 2013). Our study aims to extend the Himalayan isotopic dataset into the eastern Himalaya to allow for cross-correlation of units along the entire orogen and to assess the robustness of the isotopic approach for defining structures across thousands of kilometres of their length along strike.

Here we use lithological, structural and geochemical data to characterize the lithotectonic units of the Sikkim Himalaya, a region that lies between the well-studied regions of Nepal and Bhutan. We demonstrate, for the first time, an isotopic method of defining the location of the Main Central Thrust in the Sikkim Himalaya. The data show that there is a break in the geochemical signature of the rocks towards the top of the Main Central Thrust zone, indicating that the deformation has penetrated down into the 'footwall' of the isotopic discontinuity. In detail, there is a zone of tectonic interleaving in the highest structural levels of the high-strain zone, which implies that tectonic imbrication in the ductile Main Central Thrust zone accompanied thrusting. A model is presented outlining the provenance of these rocks and how they were juxtaposed during Cenozoic movement of the Main Central Thrust. Our study permits correlation between the Main Central Thrust in the Sikkim Himalaya and the Main Central Thrust mapped along strike in the central and western Himalaya using a combined set of comparable data.

Geological setting

The Main Central Thrust broadly represents a protolith boundary that divides two lithological packages, each characterized by distinctive geochronological and geochemical signatures (e.g. Parrish & Hodges 1996). The Lesser Himalayan Sequence is a Palaeoproterozoic metasedimentary sequence with an $\varepsilon_{Nd(0)}$ signature of –20 to –25 that has been intruded by *c.* 1.8 Ga granites. In contrast, the Greater Himalayan Sequence is a younger, Neoproterozoic–Ediacaran (and possibly Palaeozoic) sequence of metasedimentary rocks, characterized by an $\varepsilon_{Nd(0)}$ signature of –15 to –20, indicative of younger source regions, typically intruded by younger, *c.* 500 Ma and subordinate *c.* 830 Ma granites (Parrish & Hodges 1996; Ahmad *et al.* 2000; Robinson *et al.* 2001; Martin *et al.* 2005, 2011; Richards *et al.* 2005; Imayama & Arita 2008; Gehrels *et al.* 2011; Long *et al.* 2011*b*; Tobgay *et al.* 2010; McQuarrie *et al.* 2013; Webb *et al.* 2013).

In southern Sikkim and the Darjeeling Hills (referred to collectively as the Sikkim Himalaya) a combination of poor exposure around the Main Central Thrust and widespread diffuse ductile deformation obscure both the location and nature of the Main Central Thrust. Previous studies have identified a zone, up to *c.* 10–15 km wide (in map view), of ductile deformation and inverted metamorphism termed the Main Central Thrust 'Zone' (Goswami 2005; Gupta *et al.* 2010; Fig. 2a). Although this inverted metamorphic sequence is recognized elsewhere along the Himalaya, there are few other localities where there is such a well-developed and complete sequence of Barrovian metamorphic zones (Dasgupta *et al.* 2009), from the biotite-in isograd to the second sillimanite-in zone (Fig. 2b). A late-stage duplex beneath the Ramgarh thrust (Bhattacharyya & Mitra 2009; Long *et al.* 2011*a*) has created the Teesta Dome, deforming the Main Central Thrust and producing one of the largest re-entrants, in map view, across the Himalaya (Fig. 2a and c). Throughout the region, the Main Central Thrust

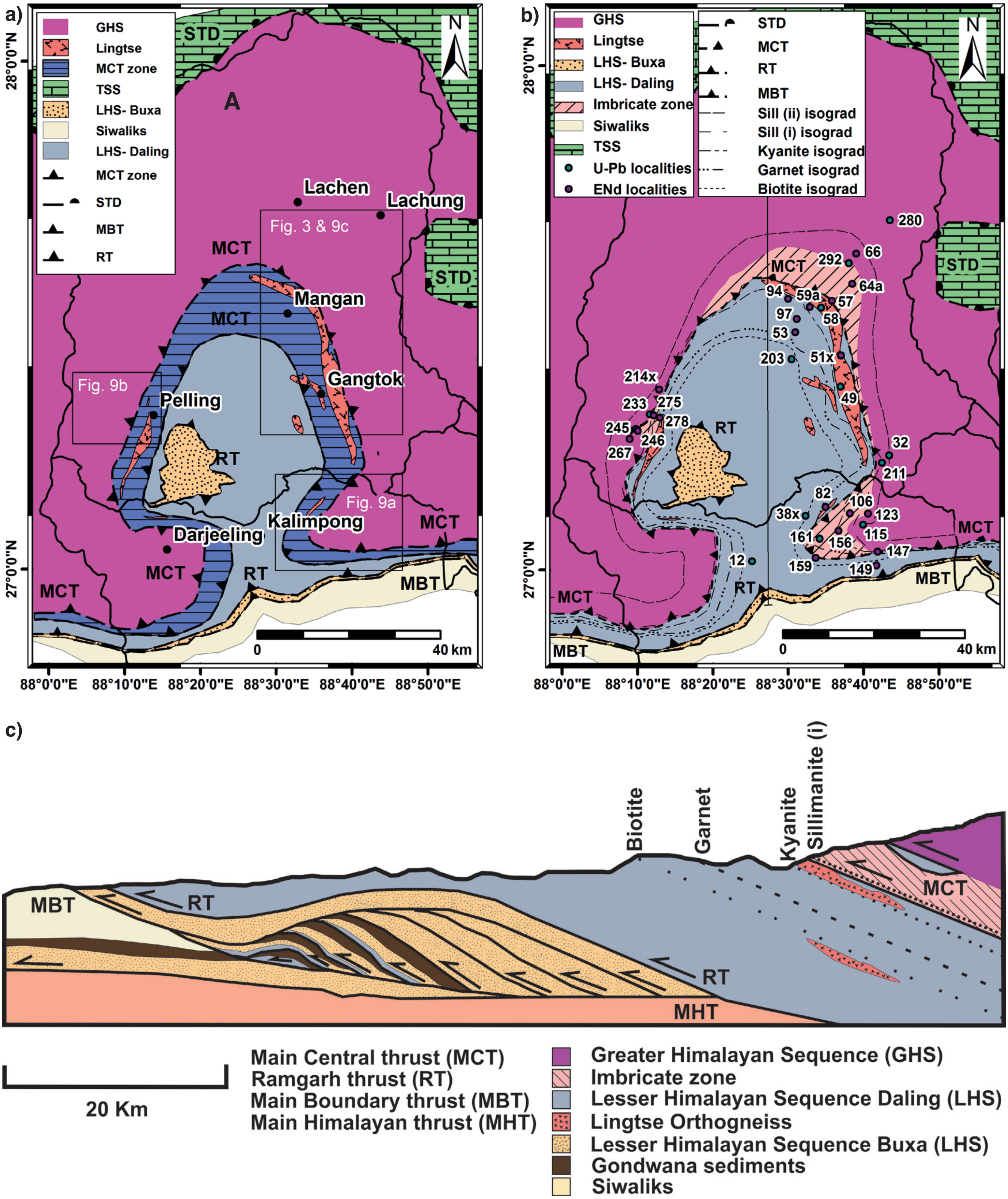

Fig. 2. (**a**) Geological map of Sikkim based on previous maps of the area (Goswami, 2005; Gupta *et al.* 2010). Insets indicate areas shown in Figures 3 and 9. (**b**) Geological map of Sikkim modified from data presented in this study with key sample locations (further sample locations are shown in Fig. 9). Line of section shown in (**c**) is indicated. (**c**) Sketch geological cross-section, with no vertical exaggeration (location of section is shown in (**b**)) from data presented in this study. Lesser Himalayan Duplex taken from Bhattacharyya and Mitra (2009). Abbreviations are the same as in Figure 1.

separates the overlying Greater Himalayan Sequence from the Lesser Himalayan Sequence. The transition between these two rock packages in this ductile shear zone appears gradational in various respects. There is a zone of several kilometres width of penetratively deformed rocks, with no obvious single discrete horizon of much higher strain located within this wide zone. Structurally lower levels of the zone consist of pelitic schists, psammites, quartzites, calc-silicates and orthogneisses known locally as the Lingtse gneiss (Paul *et al.* 1982). Sequences of paragneiss, orthogneiss and migmatites become increasingly abundant in the overlying, highest-grade rocks, but there is no single, abrupt change from one lithology to another. The inverted metamorphic zones appear continuous over a very wide extent, in a *c.* 10 km wide zone, and this gradual change in peak *P–T* conditions lacks a single discrete discontinuity in grade at any level in the zone. The apparent absence of a zone of this width elsewhere in the Himalaya may result from later brittle movement on the Main Central Thrust that has truncated the zone of earlier ductile deformation in these transects (Macfarlane *et al.* 1992).

In the Sikkim Himalaya, there have been many conflicting interpretations of the exact location of the Main Central Thrust. Studies have variously bounded the Main Central Thrust zone with two named thrusts (Catlos *et al.* 2004; Dubey *et al.* 2005; Bhattacharyya & Mitra 2009, 2011), placed the Main Central Thrust at the top of the Main Central Thrust zone (Ghosh 1956; Acharyya 1975; Banerjee *et al.* 1983) or placed the Main Central Thrust at the base of the Main Central Thrust zone (Searle & Szulc 2005). Furthermore, the distinctive Palaeoproterozoic Lingtse gneiss, strongly sheared along the Main Central Thrust zone throughout the Sikkim Himalaya, has been used in other studies as a defining lithology for determining the location of the Main Central Thrust (Neogi *et al.* 1998; Chakraborty *et al.* 2003; Dasgupta *et al.* 2004).

We have collected both structural measurements and samples along several transects across the Main Central Thrust in the Sikkim Himalaya (Fig. 2b). Throughout the region, the Main Central Thrust zone displays well-developed, polydeformational fabrics typical of large-scale shearing and thrusting that have been extensively described and catalogued in previous structural studies (Goswami 2005). Structures are dominated by south-directed thrusting along the Main Central Thrust as typified by the Mangan transect with fabrics detailed in Figure 3. There is a strong north–south stretching lineation identified from boudinage structures (Fig. 3a), stretching fabrics in L-tectonites (Fig. 3b), aligned fold axes, and mineral lineations (Fig. 3d). Extensive shearing has formed the main penetrative Main Central Thrust foliation. Shearing is also localized into well-developed shear bands in metapelites (Fig. 3c) across several kilometres of thickness of the Main Central Thrust zone. Shear indicators indicate a top-to-the-south sense of shear.

Structural mapping reveals that there are high-strain indicators distributed over a distance of *c.* 20 km across and beneath the Main Central Thrust (Fig. 3); hence most previous studies have considered the Main Central Thrust to form a ‘zone’. The rocks within this zone differ in strength and rheology, creating several domains of high strain. The Main Central Thrust cannot be marked or mapped as a single plane within this zone owing to the distributed nature of the strain. This is illustrated in the Mangan section (Fig. 3) where the strain appears to be recorded differently in each lithology. In the metapelites, strain is localized into shear bands, whereas early quartz veins are boudinaged and the mechanically strong orthogneisses develop L-tectonite and LS-tectonite fabrics. The deformation associated with the Main Central Thrust is principally synmetamorphic with earlier strain fabrics being reworked and/or erased by metamorphic recrystallization and new mineral growth.

In summary, the widespread, heterogeneous and diffuse nature of the strain associated with the Main Central Thrust zone in the Sikkim Himalaya obscures the differentiation between the Lesser Himalayan Sequence and Greater Himalayan Sequence purely on the basis of lithology and/or deformation. This has prompted this study into the use of geochemical and geochronological data in addressing the problem of understanding the location and nature of the Main Central Thrust.

Analytical methods

Zircon U–Pb geochronology

Samples for zircon U–Pb geochronology were collected from clastic metasedimentary and igneous protoliths across the Main Central Thrust in the Sikkim Himalaya to investigate the tectonic affinity of these rocks (locations shown in Fig. 2b). Thirteen samples were collected: six quartzites for detrital zircon analysis and seven orthogneiss samples, representing pre-Himalayan granites metamorphosed during the Tertiary orogeny.

Zircon was analysed using laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) at the NERC Isotope Geosciences Laboratory, Keyworth, UK. Samples were crushed and separated following standard procedures. Separated grains were then mounted in epoxy resin and imaged using CL scanning electron microscopy (SEMCL), on a FEI Quanta 600 ESEM, at 10 nA and 15 mm working distance, at the British Geological Survey, UK to investigate zoning patterns and to choose appropriate spots for analysis. The zircons show several stages of growth recorded in the concentric zoning patterns of the magmatic crystals. Some zircons had more complex histories owing to additional post-magmatic metamorphic growth.

Zircons were mainly analysed for U–Pb isotopes by MC-ICP-MS using a Nu Plasma HR system (Nu Instruments, Wrexham, UK) and a UP193FX (193 nm) excimer or UP193SS (193 nm) Nd:YAG laser ablation system (New Wave Research, UK). Measurement procedures followed methods described by Thomas *et al.* (2010). A small number of zircons (sample 292) were analysed using an AttoM single-collector sector field (SC-SF) ICP-MS system (Nu Instruments, Wrexham, UK) and a New Wave Research UP193FX (193 nm), excimer ablation system (New Wave Research, UK). The instrumental configuration and measurement procedures follow previous methods (Thomas *et al.* 2013). Only $^{206}Pb/^{238}U$ data within 5% of concordance were plotted in relative probability plots. Between 80 and 100 grains were analysed for each sample to retain statistically significant numbers of concordant analyses. For this number of grains, no fraction of the population forming more than 5.7–6.8% of the total should be missed at the 95% confidence level (Vermeesch 2004).

Sm–Nd geochemistry

Twenty samples for whole-rock Nd geochemistry were collected along transects across the Main Central Thrust in the Sikkim Himalaya. Schistose pelitic samples (rather than more psammitic samples) were selected because of their high REE concentration and because their fine-grained sedimentary protoliths present a more representative average of the source region (McLennan *et al.* 1989). Sample locations are shown on the map in Figure 2b.

Nd isotope analyses were obtained at The Open University, UK, by thermal ionization mass spectrometry (TIMS) using a Triton instrument. Isotopic analytical techniques are as described by Pin & Zalduegui (1997). $^{147}Sm/^{144}Nd$ ratios were calculated from elemental ratios obtained from quadrupole ICP-MS. ε_{Nd} values were calculated at time zero using present-day CHUR values of 0.512638 (Hamilton *et al.* 1983).

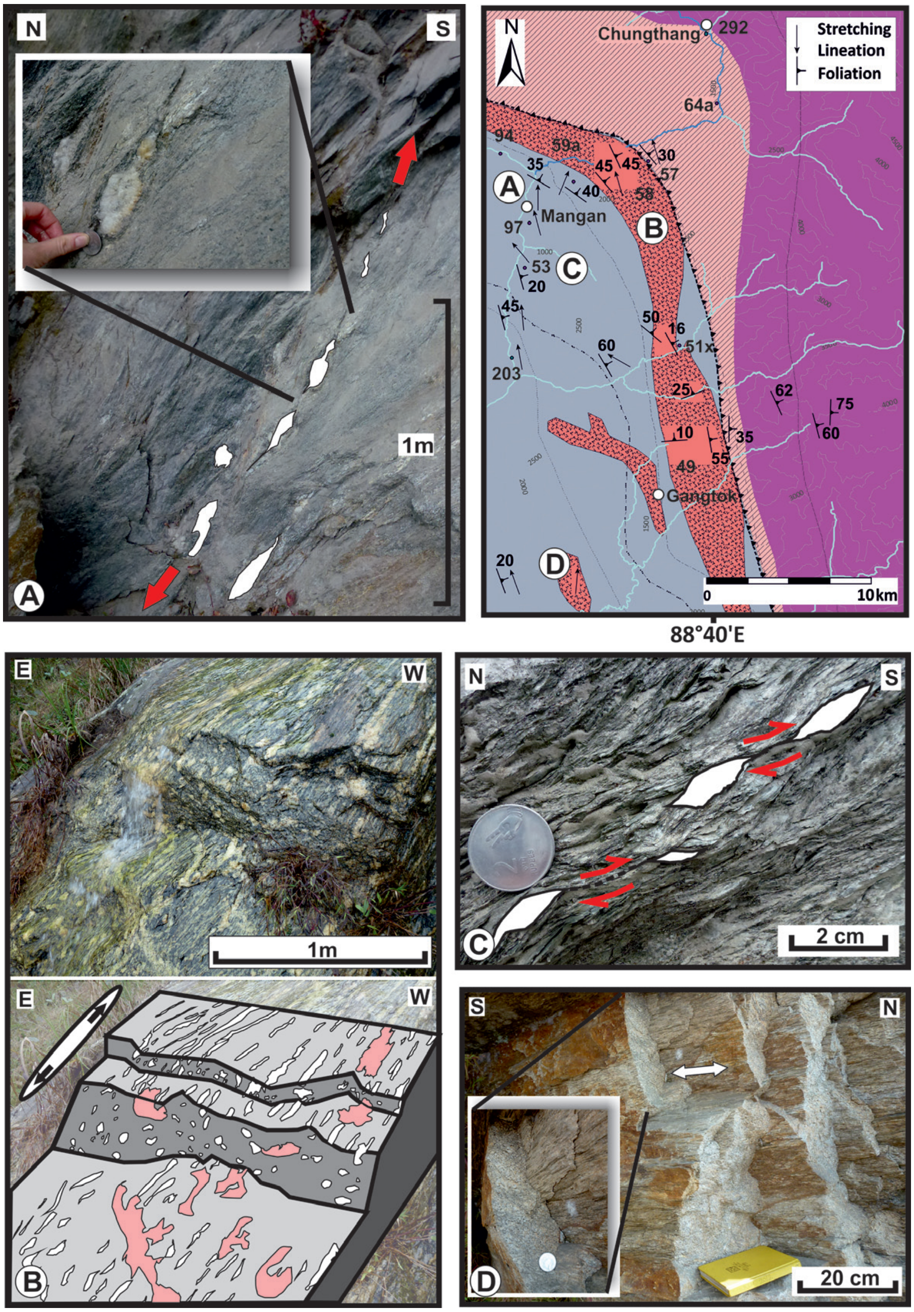

Fig. 3. Summary of structural features beneath the Main Central Thrust in Mangan transect, North Sikkim. (**a**) Stretched quartz vein boudinage. (**b**) L-tectonite fabric in Lingtse orthogneiss. (**c**) Shear bands in garnet–mica schists. (**d**) Stretching lineation developed in an orthogneiss intruding chlorite-grade metasedimentary rocks (note colour changes are weathering on fractured surfaces rather than veins of melt). The orthogneiss body displays a more developed stretching lineation than the surrounding rocks, indicating how contrasting lithologies accommodate strain differently. Localities of the photographs are shown in map, top right of figure. Map units are as for Figures 1 and 2.

Results

Orthogneiss geochronology

The ages of the analysed zircons from the seven orthogneiss samples (Figs 4 and 5) fall into three age groups: Palaeoproterozoic granites (Lingtse gneiss), Neoproterozoic granites, and Ediacaran–Cambrian granites. Each of these samples yield discordant scattered age populations owing to the later metamorphism and subsequent Pb loss which affected these zircons. Ages have therefore been reported as average $^{207}Pb/^{206}Pb$ ages with 2SD uncertainties. Lingtse gneiss (samples 49 and 58) from the same body of granitic gneiss, yield average $^{207}Pb/^{206}Pb$ ages within error of each other (sample 49: 1837 ± 45 Ma, MSWD 11.6; sample 58: 1836 ± 26 Ma, MSWD 11.5). Samples 233 and 245 are from two thin Lingtse gneiss units interlayered with metasedimentary rocks and record average $^{207}Pb/^{206}Pb$ ages of 1834 ± 37 Ma, MSWD 20 (sample 233) and 1853 ± 19 Ma, MSWD 17 (sample 245). These ages are interpreted as the timing of magmatic intrusion of the granite pluton, as the analyses are from zircons with typical magmatic oscillatory zoning. All of the Lingtse gneiss samples contain zircon cores that preserve evidence of older Proterozoic and Archaean magmatic events.

The three analysed Neoproterozoic and Ediacaran orthogneiss samples record three separate magmatic events (Fig. 5). Although all the samples contain inherited zircon cores that match the Palaeoproterozoic age of the Lingtse gneiss, the main magmatic zircon populations of these granites vary in age. The youngest sample (280) yields a spread in age of *c.* 490–520 Ma, which produced an average $^{207}Pb/^{206}Pb$ age of 508 ± 22 Ma (MSWD = 3.3); sample 115 yields an average $^{207}Pb/^{206}Pb$ age of 604 ± 28 Ma (MSWD = 7);

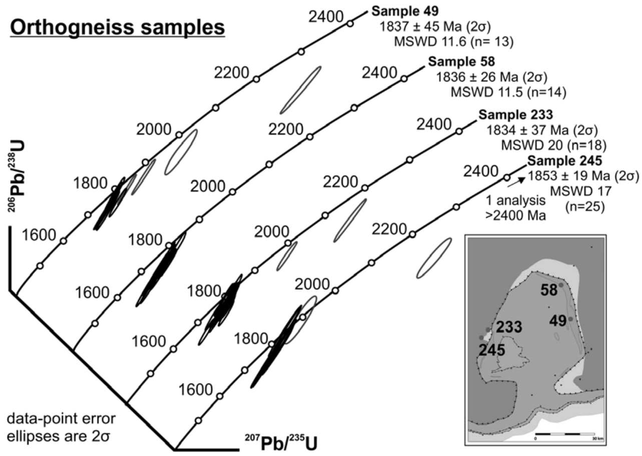

Fig. 4. Orthogneiss concordia plots (1). Ages for each sample are reported as average ^{207}Pb/^{206}Pb ages with 2SD uncertainties. The MSWD of the population is quoted and reflects excess scatter in the Pb/Pb data. Sample locations are shown in the inset map. See supplementary zircon U–Pb data table and zircon images.

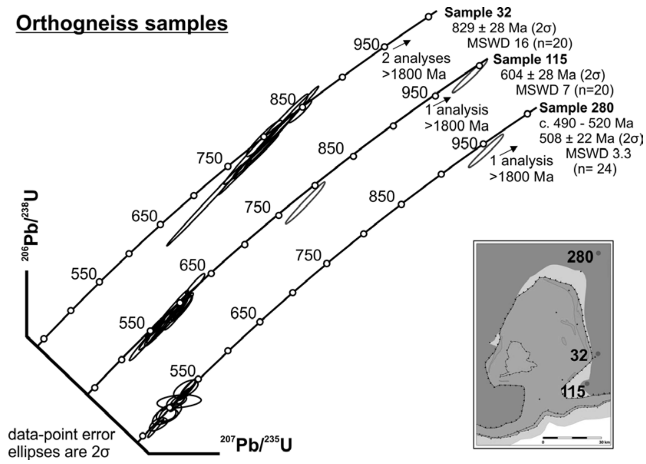

Fig. 5. Orthogneiss concordia plots (2). Ages for each sample are reported as average ^{207}Pb/^{206}Pb ages with 2SD uncertainties. The MSWD of the population is quoted and reflects excess scatter in the Pb/Pb data. Sample locations are shown in the inset map. See supplementary zircon U–Pb data table and zircon images.

and the oldest sample (32) yields an average ^{207}Pb/^{206}Pb age of 829 ± 28 Ma (MSWD = 16).

Detrital zircon geochronology

The detrital zircon data from the six samples analysed are presented in Figures 6, 7 and 8. Four of the samples yield detrital zircon populations that have a prominent peak at *c.* 1800 Ma with older grains spread throughout the Proterozoic and Archaean, and yield no grains younger than *c.* 1700 Ma. In detail, samples 12 and 38x show dominant 1800 Ma peaks with a small number of older zircons. Sample 203 shows a peak at *c.* 1900 Ma and relatively more Archaean zircons than samples 12 and 38x. Sample 292 lacks a dominant peak but zircon ages range from *c.* 1900 Ma to *c.* 2600 Ma; this sample contains the oldest zircons seen in this study, dating to *c.* 3600 Ma. The remaining two samples (161 and 211) also contain minor components of Proterozoic and Archaean material, but display a range of ages down to younger than *c.* 800 Ma. Sample 161 yields a dominant age peak at *c.* 800–1100 Ma with minor, older, peaks at *c.* 1500–1700 Ma and *c.* 2300–2500 Ma. Sample 211 yields a similar age spectrum, but with a slightly older dominant peak at *c.* 1000–1300 Ma and a spread of older zircons from 1300 to 2600 Ma. There is also one discordant zircon analysis at *c.* 500 Ma, indicative that this sample may contain Palaeozoic zircon populations.

Sm–Nd geochemistry

The ε_{Nd} results are plotted in Figures 8 and 9 to demonstrate the geochemical variations with spatial reference to the Main Central Thrust zone. The data range in $\varepsilon_{Nd(0)}$ from –27.7 to –12.1.

Discussion

The magmatic history

The Palaeoproterozoic granites (‘Lingtse gneiss’) from the Main Central Thrust zone were originally dated using Rb–Sr, yielding ages of *c.* 1075–2034 Ma (Paul *et al.* 1982, 1996). The Lingtse gneiss samples from the Sikkim Himalaya analysed in this study provide a U–Pb zircon age cluster within error between 1834 ± 37 Ma and 1853 ± 19 Ma (Fig. 4) and may be age-correlated with other Lesser Himalayan granite gneisses across the Himalaya (Goswami *et al.* 2009; for a summary of ages, see table 1 of Kohn *et al.* 2010). This widespread Palaeoproterozoic magmatic event has been ascribed to a continental volcanic arc that was active during the formation of the supercontinent Columbia (Kohn *et al.* 2010).

Samples 32, 115 and 280 analysed in this study yield ages of 829 ± 28 Ma, 604 ± 28 Ma and 508 ± 22 Ma (Fig. 5). These orthogneiss ages are consistent with similar meta-igneous intrusion ages from the Greater Himalayan Sequence elsewhere in the Himalaya. These include an event at *c.* 500 Ma (Bhargava 1995; Marquer *et al.* 2000; Miller *et al.* 2001; Ghosh *et al.* 2005; Richards *et al.* 2005) and an earlier Neoproterozoic event at *c.* 800 Ma (DiPietro & Isachsen 2001; Singh *et al.* 2002; Ghosh *et al.* 2005; Richards *et al.* 2006; Spencer *et al.* 2012). A widespread Cambro-Ordovician tectonic event has been documented across the Greater Himalayan Sequence (Argles *et al.* 1999; Marquer *et al.* 2000; Gehrels *et al.* 2003, 2006). This has been termed the ‘Bhimpedian orogeny’ (Cawood *et al.* 2007), and has been related to the Cambrian formation of Gondwana (Yin *et al.* 2010*b*).

The significance of the *c.* 800 Ma magmatism is somewhat more enigmatic but has been tentatively linked to the presence of a superplume beneath the Rodinian continent resulting in intracontinental rifting (Li *et al.* 2008). This has been linked to the Malani magmatic event (750 Ma) on the Indian craton, during which volcanism resulted from the final rifting and break-up of this part of the supercontinent (Sharma 2005). The precise cause of the magmatism at this time remains unclear, but suggestions include back-arc extension (Zhou *et al.* 2002), the arrival of a mantle plume (Guynn *et al.* 2012), or post-orogenic slab break-off (Wang *et al.* 2006).

The Main Central Thrust zone in the Sikkim Himalaya

The geochronological and geochemical data from this study can be categorized into two isotopic groups, shown in Figure 8. The samples with detrital zircon ages that show a dominant peak at *c.* 1800 Ma, with no zircons younger than *c.* 1700 Ma (Fig. 6), and those samples with an ε_{Nd} signature of –27.7 to –23.4, are indicative of an Lesser Himalayan Sequence signature when compared with

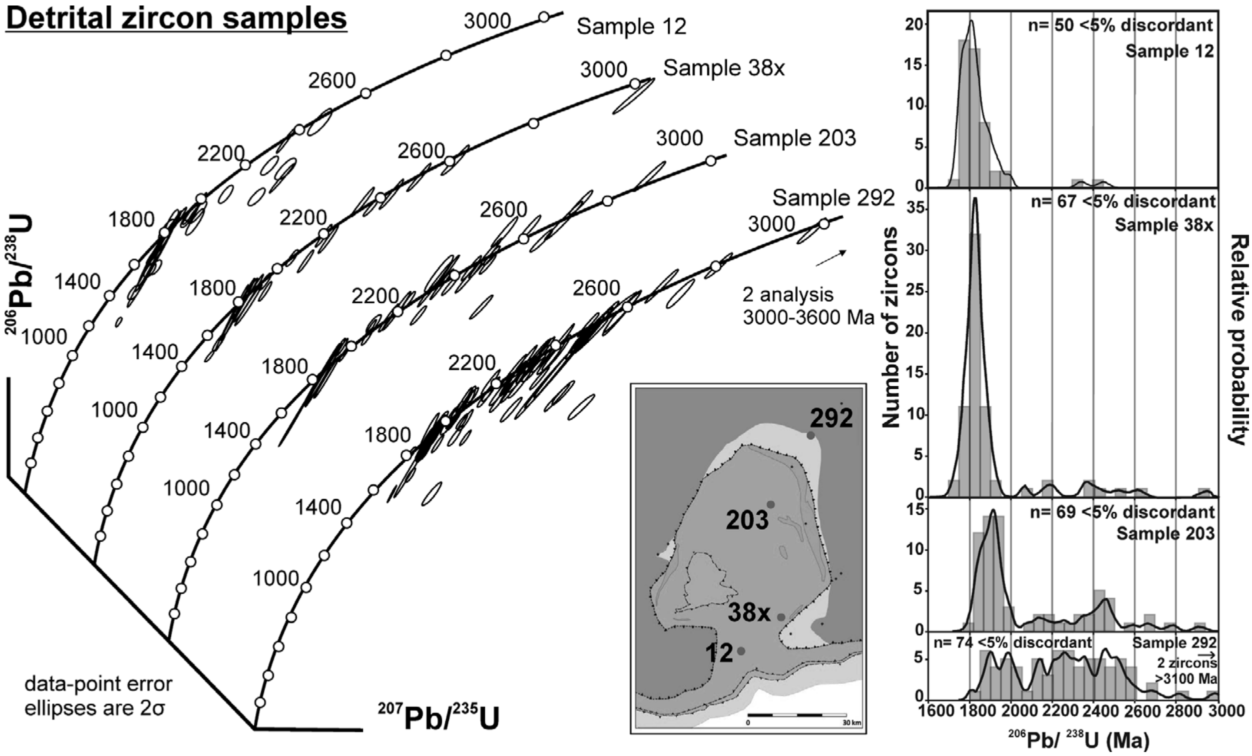

Fig. 6. Data for detrital zircon in clastic metasedimentary samples (1): concordia plots reporting all analyses; probability density plots based on analyses with discordance lower than 5%. Sample locations are shown in the inset map. See supplementary zircon U–Pb data table and zircon images.

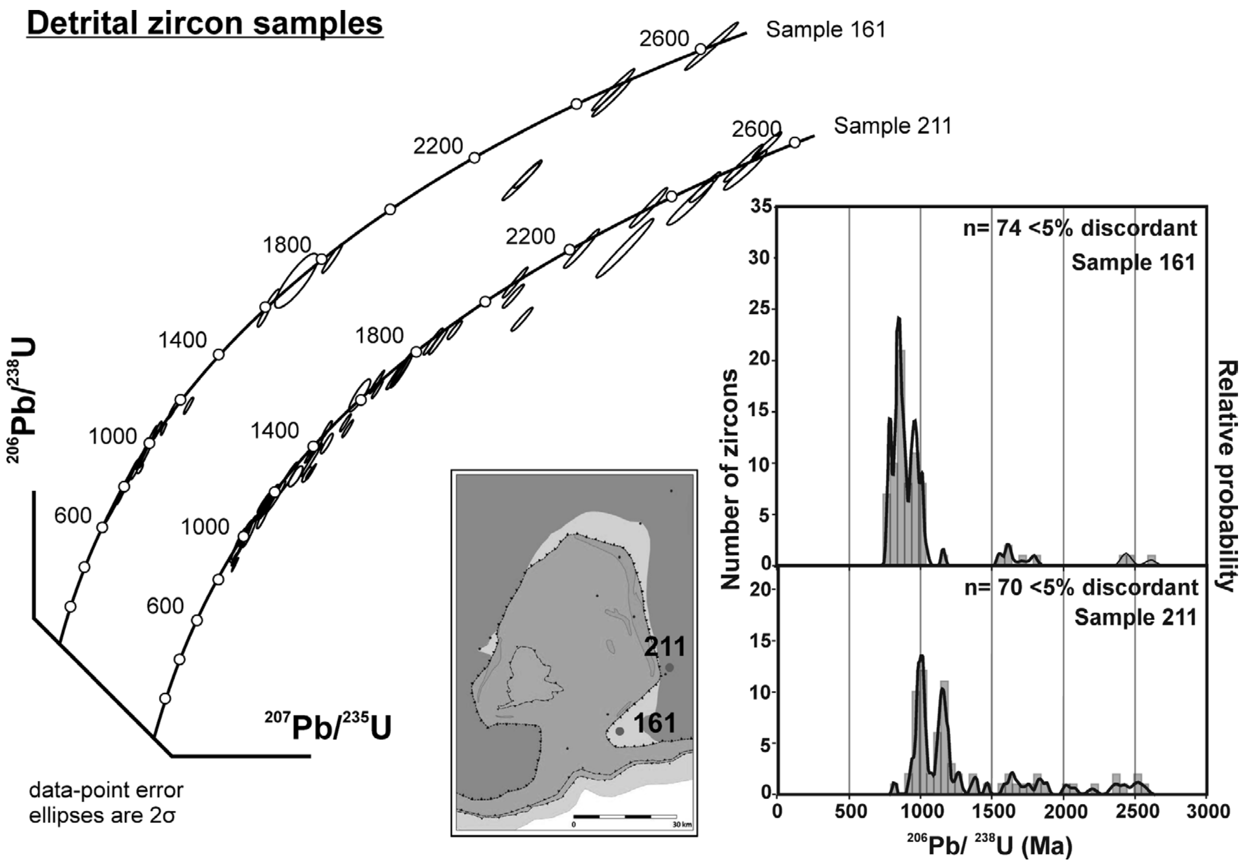

Fig. 7. Data for detrital zircon in clastic metasedimentary samples (2): concordia plots reporting all analyses; probability density plots based on analyses with discordance lower than 5%. Sample locations are shown in the inset map. See supplementary zircon U–Pb data table and zircon images.

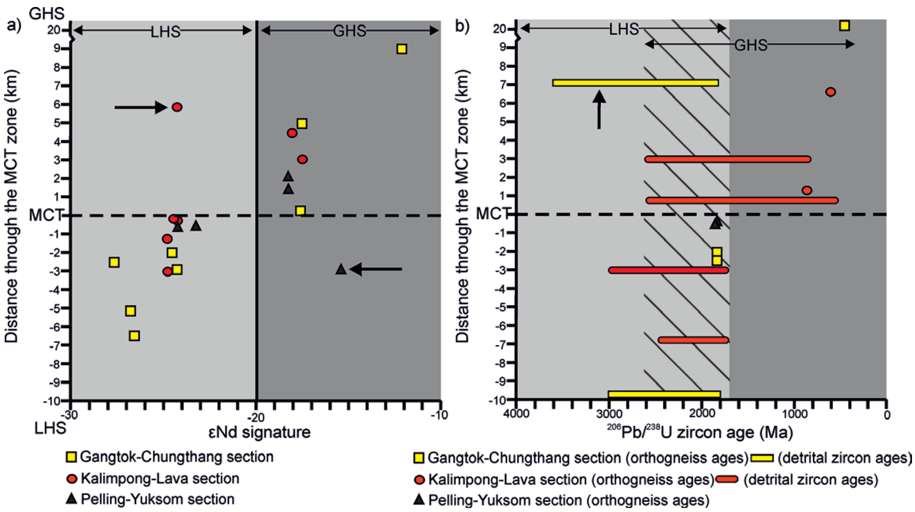

Fig. 8. Plot of (**a**) ε_{Nd} signature and (**b**) detrital zircon and orthogneiss U–Pb age, as a function of depth above and below the Main Central Thrust (positive numbers indicate up section into Greater Himalayan Sequence; negative numbers indicate down section into Lesser Himalayan Sequence). The Main Central Thrust is defined here as the protolith boundary as outlined in the text and in Figure 2b. The Lesser Himalayan Sequence–Greater Himalayan Sequence classification is based on previous Himalayan studies; these signatures overlap slightly in the zircon plot (**b**), marked by the hatched area. The Lesser Himalayan Sequence signature, however, does not extend younger than 1700 Ma. There are three outliers marked with arrows, which demonstrate the location of proposed interleaved slices. See supplementary Nd table.

the published literature as reviewed above. The youngest detrital zircons in the Lesser Himalayan Sequence sediments are coeval with the granite intrusion ages, which date from *c.* 1800 Ma. The samples that have a detrital zircon age signature that ranges down to younger than 800 Ma (Fig. 7) or an ε_{Nd} signature of –18.3 to –12.1 can be characterized as Greater Himalayan Sequence samples when compared with previous studies. The youngest concordant Greater Himalayan detrital zircons are roughly contemporaneous with the oldest granite intrusion (*c.* 800 Ma), suggesting that these were deposited in an active tectonic environment.

It has recently been suggested that the significance of detrital age information is obscured in some Himalayan regions, because some of the Lesser Himalayan formations overlap in characteristics with some of the Greater Himalayan lithologies (Myrow *et al.* 2010). The Lesser Himalayan Sequence units in the eastern Himalaya are divided into three distinct supracrustal formations (Fig. 1): the Palaeoproterozoic Daling formation, the Neoproterozoic–Cambrian Buxa formation and the much younger Permian Gondwana sediments. Whereas the Buxa and Gondwana sediments (sometimes termed the Outer Lesser Himalaya; Richards *et al.* 2005) have an isotopic signature that can overlap with the Greater Himalayan Sequence (McQuarrie *et al.* 2013), the older predominant Daling unit has an isotopic signature that contrasts markedly with that of the Greater Himalayan Sequence, producing a geochemical contrast across the thrust zone wherever the Daling and Greater Himalayan Sequence are juxtaposed, such as in the Sikkim Himalaya.

The geochemical and geochronological characterization of the samples from this study has allowed for a more precise trace of the Main Central Thrust to be proposed in the Sikkim Himalaya (Fig. 2b), which is generally consistent with that presented by Rubatto *et al.* (2013). Our study, which presents the first isotopic data from the rocks of the Sikkim Himalaya, demonstrates that rocks sometimes mapped as a separate lithological unit, the 'Main Central Thrust zone' (Fig. 2a), are primarily of Daling Lesser Himalayan isotopic affinity. This is an important conclusion because it implies that the deformation associated with the Main Central Thrust has mainly penetrated downwards from the 'protolith boundary' marked by a distinct break in isotopic signature and granite intrusion age, several kilometres into the footwall of the structure. The deformation associated with thrust faults is known to migrate down into the footwall of the structure when there is progressive failure of the footwall ramps. This results in the abandonment of the old thrust surface and the development of new thrusts in the footwall that eventually leads to the formation of an imbricate stack (Butler 1982). This suggests that as movement on the Main Central Thrust occurred in the Sikkim Himalaya at *c.* 22–10 Ma (Catlos *et al.* 2004), deformation migrated down-section from the original isotopic break, interpreted as the location of the original décollement zone of the Main Central Thrust, into the underlying Lesser Himalayan rocks.

Tectonic imbrication

Three transects (Fig. 9a–c) provide exceptions to the simple division between the hanging wall and footwall of the Main Central Thrust, as outlined above. Samples in these locations yield abrupt out-of-sequence, alternating shifts in ε_{Nd} and detrital zircon characteristics in a *c.* 5–10 km thick zone (shown as outliers in Fig. 8). This has important implications both for the geochemical 'fingerprinting' of rock units on either side of the Main Central Thrust, and potentially other obscure ductile faults with major displacements worldwide, and for understanding the mechanics of thrusting.

There are several possible alternative explanations for these shifts, as follows.

(1) Fluid alteration. The Sm–Nd system could have been perturbed by fluid alteration or some other process, giving an anomalous signature. However, the unperturbed Sm/Nd values (*c.* 0.11) for the rocks measured in this study do not support significant disturbance of the Sm–Nd system (Ahmad *et al.* 2000).

(2) Sediment sources. It has been proposed that the Paro and Jaishidanda sequences in Bhutan were deposited in a tectonically active, distal foreland basin associated with the 'Bhimpedian' orogeny, affected by shifts in sediment source, with material sourced from both the Greater Himalayan Sequence rocks (younger detritus) and the Indian shield (older detritus) (McQuarrie *et al.* 2013). The Bhutan sequences probably correlate to the along-strike Main Central Thrust zone of the Sikkim Himalaya. Sample 292 in this study lacks a prominent 1800 Ma detrital zircon peak and has a larger spread of older zircons than other typical 'Lesser Himalayan Sequence' rocks (Fig. 6), potentially supporting the theory of different sediment sources for certain rocks within the Main Central Thrust zone.

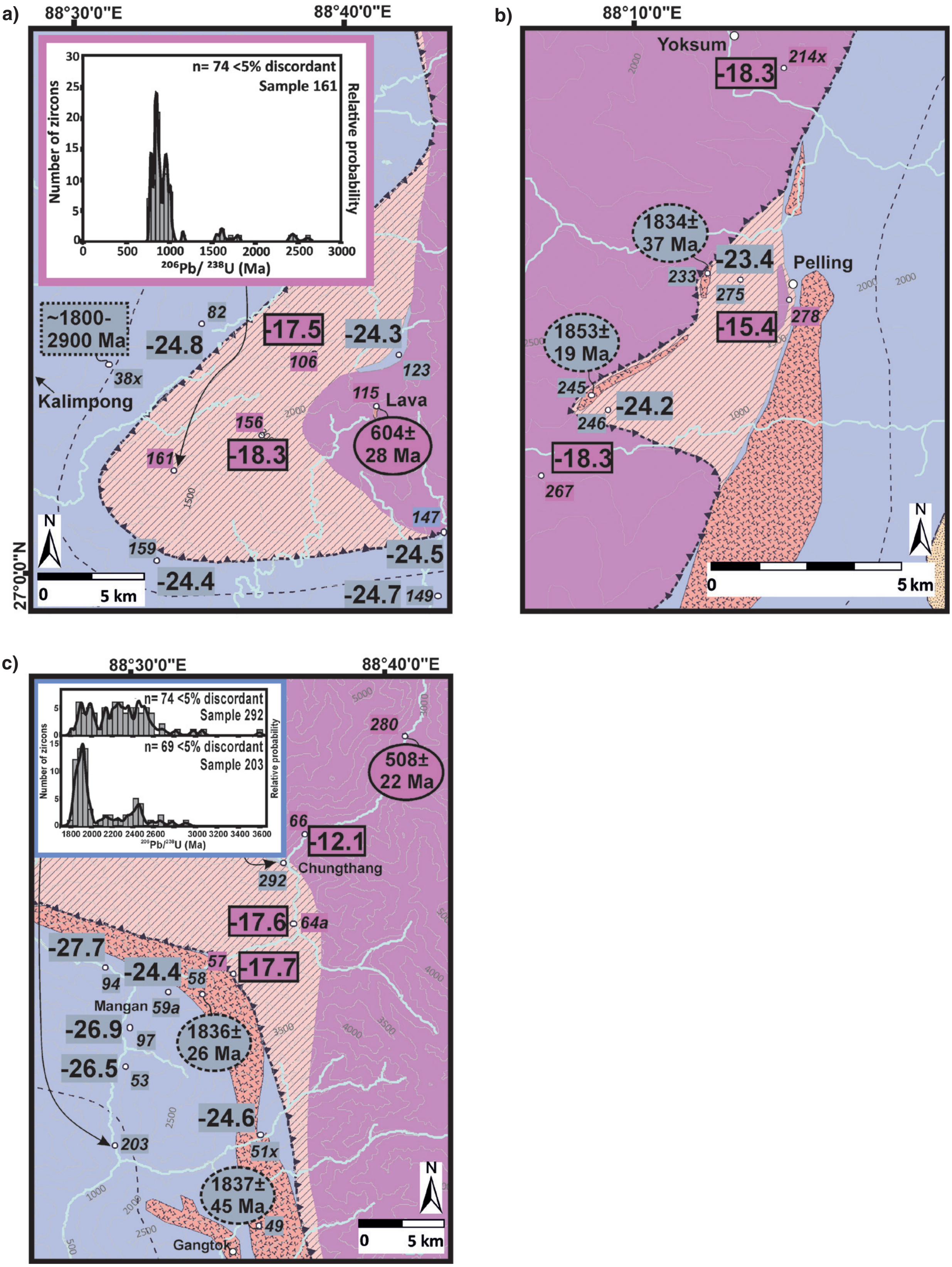

Fig. 9. Detailed maps of combined Nd and U–Pb isotopic data. (**a**) Kalimpong–Lava transect. (**b**) Pelling–Dentam–Yoksom transect. (**c**) Mangan transect. Geological units are the same as in the legend in Figures 1 and 2. Large numbers preceded by minus signs are ε_{Nd} values; numbers inside a continuous-line rectangle are ε_{Nd} values for the Greater Himalayan Sequence. Small numbers in italics are sample locations. Orthogneiss ages are shown in ellipses (dashed line for Lesser Himalayan Sequence values; continuous line for Greater Himalayan Sequence samples). Detrital zircon populations are shown as probability density plots or inside a dashed-line rectangle (see (**a**)). Full concordia and probability density plots can be found in Figures 4–7.

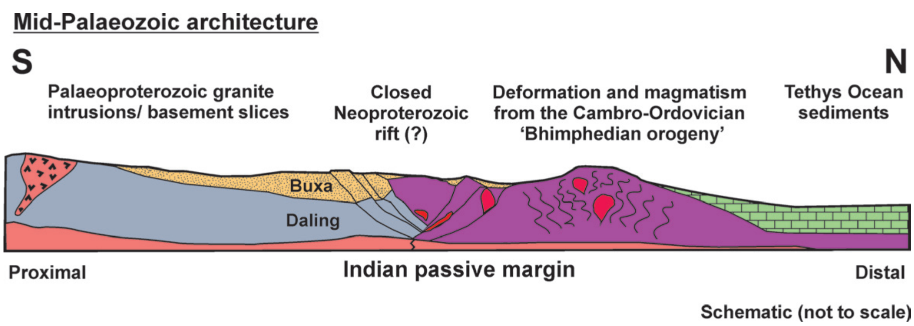

Fig. 10. Schematic illustration showing the pre-Himalayan architecture of the Sikkim rocks, during the mid-Palaeozoic. The Lesser Himalayan Sequence lithologies were once separated from the Greater Himalayan Sequence rocks by a Neoproterozoic rift. The Bhimpedian orogeny was responsible for closing the rift and thickened the Greater Himalayan Sequence, causing metamorphism and intrusion of granites. The failed closed rift may represent a weak structure later exploited by the Main Central Thrust. Lithologies are the same as in the legend in Figures 1 and 2.

The 'interleaved' signatures could therefore reflect abrupt shifts in the nature of detritus being deposited in the Main Central Thrust zone sedimentary protoliths (Tobgay *et al.* 2010; McQuarrie *et al.* 2013). These shifts could result from one or more of the following: specific depositional settings; sediment transport processes; erosion processes in the catchments.

A marine depositional environment is indicated for Main Central Thrust zone rocks in the Sikkim Himalaya by the abundance of tourmaline (implying high boron concentrations; Carrano *et al.* 2009), and the interbedding of pelites and quartzites. In the relatively near-shore (delta or continental shelf) setting suggested by these lithologies, sediment can be deposited in a dynamic environment (Allen 2005), which could explain the observed abrupt shifts in geochemical signature in different rock packages. However, the dispersal of sediment from rivers into marine systems may be unpredictable (Wright & Nittrouer 1995), suggesting that detritus from a single river can become dispersed and mixed with other sediment, causing signatures of single rivers to be obscured in the final depositional marine setting. The abrupt shifts in geochemical signature we observed in the Sikkim Himalaya would require very distinct sediment sources for certain rocks, with little basin-scale mixing.

Differences in isotopic signature between two sedimentary packages may also be due to a difference in their duration of transport, and hence time of deposition. For instance, it has been proposed that grain size can act as a buffer, with larger grains (i.e. in the quartzite) being transported faster to the final deposition site than the finer grains that characterize the pelitic lithologies (Allen 2008).

The third controlling factor could have been changes in the catchment and erosion areas of rivers in a tectonically active region. Recent work has shown that the route of the Yarlung–Tsangpo–Irrawaddy system was modified by river capture during Himalayan uplift (Robinson *et al.* 2013). A similar catchment shift could have occurred during the Palaeozoic, perhaps associated with uplift during the Bhimpedian orogeny when the Greater Himalayan Sequence rocks were deposited. However, such shifts in river catchment are likely to result in a single switching of sediment source and isotopic signature; because we observe repeated reversals of the signatures, this scenario seems less likely in the Sikkim Himalaya.

In a marine sedimentary environment any shifts in erosion, deposition or river catchment would be recorded as progressive, not abrupt, changes in the sedimentary record. In addition, the alternating geochemical signatures of packages in the Sikkim Himalaya are uniquely associated with proximity to the Main Central Thrust (Fig. 8). Moreover, our observation, based on detailed geochemical studies, that rock packages characterized by specific detrital isotopic signatures are intruded by granite intrusions of contrasting ages favours a tectonic explanation. Overall, we do not consider that the evidence provided in this study supports a purely sedimentological interpretation of the variation of isotopic signatures.

(3) Tectonic interleaving. The observed signature of the rocks could have been caused by tectonic interleaving of Lesser Himalayan Sequence and Greater Himalayan Sequence rocks associated with the tectonic movement along the Main Central Thrust. This model is supported by evidence in Figure 9a and b where narrow slivers of pelites are exposed that yield distinct ε_{Nd} signatures from their immediately adjacent orthogneisses and pelites with contrasting geochemical signature. Because such complexities are found only in the area surrounding the Main Central Thrust, we suggest that ductile shearing was involved in determining the observed spatial distribution of the hanging wall and footwall rocks.

This study is not the first to discover tectonic complications associated with the Main Central Thrust. Gansser (1991) observed that the Main Central Thrust either can form a 'zone of imbrication or can expose a sharp contact'. Our work confirms that there may be along-strike geochemical and structural variations and complexities in the nature of the Main Central Thrust. To the east, detrital zircon and ε_{Nd} signatures from the Paro window in Bhutan (Tobgay *et al.* 2010) are also suggestive of an imbricate zone similar to the Main Central Thrust in the Sikkim Himalaya. This has important implications for the tectonic affinity of the Paro metasedimentary rocks, and may suggest that the Yadong cross-structure (Fig. 1; Cooper *et al.* 2012, and references therein) does not mark a fundamental orogenic break separating contrasting protolith sources for the constituent metasedimentary lithologies. There are also examples of mixing around the Main Central Thrust to the west. Although Martin *et al.* (2005) found no evidence of an imbricate zone associated with the Main Central Thrust in the Annapurna region of western Nepal, Parrish & Hodges (1996) termed a relatively narrow conspicuous zone of lithological and structural imbrication around the Main Central Thrust in the Langtang region of central Nepal the 'Main Central Thrust imbricate zone', characterized by $\varepsilon_{Nd(0)}$ signatures of –16.3 to –21.4. This latter study suggested that variations in the ε_{Nd} ratios in this zone showed that the Main Central Thrust zone was formed from interleaving of slices of both footwall and hanging wall rocks. Studies in other Nepal transects have also reported ambiguous overlapping ε_{Nd} signatures from the vicinity of the Main Central Thrust, which could also be interpreted as evidence for imbrication (Robinson *et al.* 2001; Imayama & Arita 2008).

Although major brittle thrust faults can form a single sharp contact (Butler 1982; Law 1998), imbrication and duplexing is more likely to develop in a ductile thrust system. The development of new thrusts in the footwall of structures may lead to piggyback thrusting and the development of a duplex (Butler 1982) and has been identified in the Lesser Himalayan Sequence rocks of the Sikkim Himalaya (Bhattacharyya & Mitra 2009). A similar process could occur in ductile structures, with subsequent reworking making it difficult to identify. A mixing zone can be seen in thrust faults around the world on a variety of scales, from centimetres thick (Dickinson 1991), to a few minor structures over the length scale of metres (Gilotti & Kumpulainen 1986; Yonkee 1997), to large-scale structures over hundreds to metres (Barr 1986; Holdsworth & Strachan 1991; Gilotti & McClelland 2008; Leslie *et al.* 2010). A similar setting to the Main Central Thrust we describe in the Sikkim Himalaya has been identified in the Caledonian orogenic belt in eastern Greenland, where imbricate slices, tens of metres thick, are interleaved by ductile thrusting in a zone of inverted metamorphism (Holdsworth & Strachan 1991). In the case of the Sikkim Himalaya, structural evidence for imbrication may be difficult to recognize in a zone of progressive ductile deformation owing to subsequent reworking. Geochemical 'fingerprinting' therefore provides a complementary and potentially more robust tool for identifying such imbrication within any major ductile shear zone.

Provenance and tectonic implications

Several regional studies have proposed that the Lesser Himalayan–Greater Himalayan–Tethyan sediments were deposited on the proximal (Lesser Himalayan Sequence) to distal (Greater Himalayan Sequence) parts of the passive margin of India (Brookfield 1993; Myrow *et al.* 2003, 2010). Cenozoic movement on the Main Central Thrust juxtaposed these once widely separated parts of the Indian continent. We have developed a model for the provenance and pre-Himalayan architecture of the eastern Himalaya, constrained by the geochemical data presented in this study (Fig. 10).

The model shows that Lesser Himalayan Daling and subsequent Buxa sediments were deposited on the proximal margin of India. The Daling sediments were intruded by granites, probably in a continental arc-type setting, during the Palaeoproterozoic (Kohn *et al.* 2010). Palaeoproterozoic zircons from the granites were transported out to the more distal parts of the margin where the Greater Himalayan rocks were deposited. The Neoproterozoic magmatism (820–850 Ma) may relate to a plume-related intracratonic rift separating the Lesser Himalayan Sequence and Greater Himalayan Sequence sedimentary basins of the margin (Li *et al.* 2008). This would explain the exposure of the distal Greater Himalayan Sequence sediments to the Cambro-Ordovician Bhimpedian orogeny, in marked contrast to the more southerly, proximal, Lesser Himalayan Sequence package, which was apparently unaffected by this event (Fig. 10).

The juxtaposition of the exposed parts of the Greater Himalayan Sequence and Lesser Himalayan Sequence postdates the 500 Ma event. During the early stages of the India–Asia collision, following the subduction of the Tethys Ocean, the Mesozoic and Palaeozoic succession on the northern flank of the Indian continental margin was thickened and deformed, causing tectonic burial and prograde metamorphism of the underlying Greater Himalayan Sequence package. Following this burial and northward subduction of the Neoproterozoic–Mesozoic northern Indian margin, the Greater Himalayan Sequence sediments were detached from their (unknown) depositional basement along a deep-seated décollement (the proto-Main Central Thrust) and began to be translated southwards, while undergoing synmetamorphic deformation. It is possible that the Main Central Thrust exploited the closed, failed Neoproterozoic rift as the thrust propagated southwards, which could help to explain the striking coincidence of the Main Central Thrust with the isotopic break along the entire Himalaya. Progressive convergence and crustal thickening triggered extrusion of the ductile and weak Greater Himalayan Sequence between the South Tibetan Detachment and the Main Central Thrust, which transported the Greater Himalayan Sequence 140–500 km over the previously proximal Lesser Himalayan rocks that originally lay to the south (Dewey *et al.* 1989; Schelling & Arita 1991; Brookfield 1993; Robinson *et al.* 2006; Tobgay *et al.* 2012; Webb 2013). The ductile deformation and associated inverted metamorphism in the footwall of the Main Central Thrust suggest that some Daling sediments were both strongly deformed and heated during Main Central Thrust motion, as heat was transferred from the hotter Greater Himalayan Sequence rocks above. Simultaneous footwall heating and hanging wall cooling caused the inverted metamorphism that straddles the hanging wall–footwall contact. The Sikkim Himalaya can therefore be seen as preserving a mid-crustal section of the ductile shear zone associated with the Main Central Thrust. In this ductile setting, ramps and flats on the Main Central Thrust resulted in imbrication or interleaving of the Lesser Himalayan Sequence and Greater Himalayan Sequence in the immediate vicinity of the thrust. Deformation was subsequently transferred to the Ramgarh thrust (Pearson & DeCelles 2005; Robinson & Pearson 2013; Webb 2013), which was responsible for finally exhuming the deformed Daling rocks in its hanging wall and thrusting them upon the Buxa rocks, inverting the original Daling–Buxa sedimentary relationship in the Lesser Himalayan Sequence (Fig. 2c).

Conclusions

The Sikkim Himalaya exposes a window into a well-preserved mid-crustal thrust zone formed during the Himalayan orogeny. New geochemical and geochronological data show that there is a significant isotopic break between the juxtaposed Lesser Himalayan Sequence and Greater Himalayan Sequence packages in this region. The Greater Himalayan Sequence rocks are characterized by detrital zircon age peaks at *c.* 800–1000 Ma, 1500–1700 Ma and 2300–2500 Ma and by an $\varepsilon_{Nd(0)}$ signature of –18.3 to –12.1. This rock package was intruded by granites of Neoproterozoic (*c.* 800 Ma) and Ediacaran–Cambrian (*c.* 500–600 Ma) age. In contrast, the Daling part of the Lesser Himalayan Sequence rocks comprises a Palaeoproterozoic rock package with prominent Archaean and Palaeoproterozoic detrital zircon populations and an $\varepsilon_{Nd(0)}$ signature of –27.7 to –23.4. These rocks were intruded by Palaeoproterozoic granites but not by the younger granites seen in the hanging wall. The Lesser and Greater Himalayan sediments represent older, more proximal, and younger, more distal parts of the Indian margin respectively. The two packages were juxtaposed over several hundred kilometres by Cenozoic thrusting along the mid-crustal shear zone exposed at the surface in the Sikkim Himalaya. The deformation associated with the Main Central Thrust penetrated down into the Lesser Himalayan rocks of the footwall, forming a zone of progressive ductile shearing.

In detail, the data show significant apparent out-of-sequence isotopic signatures in some locations, consistent with local imbrication. These isotopic anomalies are interpreted as representing slices of footwall and hanging wall that became locally interleaved during protracted deformation. Similar isotopic anomalies have previously been reported along strike eastwards, in the 'Paro Window' of Bhutan. This similarity suggests that these rocks may be of similar protolith and have experienced similar tectonic disruption, placing constraints on the amount of displacement caused by the intervening Yadong cross-structure.

Isotope geochemistry is a robust tool for defining differences between, and the juxtaposition of, two distinct terranes across a structure that spans over 2500 km along the Himalayan orogen. It is equally useful for resolving tectonic problems that have proved intractable to conventional structural methods. This approach is applicable to studies of other orogenic interiors where detailed footwall–hanging wall relationships of major terrane boundaries have been obscured by pervasive ductile shearing.

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References

Acharyya, S. 1975. Structure and stratigraphy of the Darjeeling frontal zone, Eastern Himalaya. *Miscellaneous Publications of the Geological Survey of India*, **24**, 71–90.

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. *Geological Society of America Bulletin*, **112**, 467–477.

Allen, P. 2005. Striking a chord. *Nature*, **434**, 961.

Allen, P.A. 2008. Time scales of tectonic landscapes and their sediment routing systems. *In*: Gallagher, K., Jones, S.J. & Wainwright, J. (eds) *Landscape Evolution: Denudation, Climate and Tectonics over Different Time and Space Scales*. Geological Society, London, Special Publications, **296**, 7–28.

Ameen, S.M.M., Wilde, S.A., Kabir, Z., Akon, E., Chowdhury, K.R. & Khan, S.H. 2007. Paleoproterozoic granitoids in the basement of Bangladesh: A piece of the Indian shield or an exotic fragment of the Gondwana jigsaw? *Gondwana Research*, **12**, 380–387.

Argles, T., Prince, C., Foster, G. & Vance, D. 1999. New garnets for old? Cautionary tales from young mountain belts. *Earth and Planetary Science Letters*, **172**, 301–309.

Banerjee, H., Dasgupta, S., Bhattacharyya, P.K. & Sarkar, S.C. 1983. Evolution of the Lesser Himalayan metapelites of the Sikkim–Darjeeling region, India, and some related problems. *Neues Jahrbuch für Mineralogie, Abhandlungen*, **146**, 197–209.

Barr, D., Holdsworth, R.E. & Roberts, A.M. 1986. Caledonian ductile thrusting in a Precambrian metamorphic complex: The Moine of northwestern Scotland. *Geological Society of America Bulletin*, **97**, 754–764.

Bhargava, O.N. 1995. *The Bhutan Himalaya: A Geological Account*. Geological Survey of India Special Publication, **39**.

Bhattacharyya, K. & Mitra, G. 2009. A new kinematic evolutionary model for the growth of a duplex—an example from the Rangit duplex, Sikkim Himalaya, India. *Gondwana Research*, **16**, 697–715.

Bhattacharyya, K. & Mitra, G. 2011. Strain softening along the MCT zone from the Sikkim Himalaya: relative roles of quartz and micas. *Journal of Structural Geology*, **33**, 1105–1121.

Bordet, P. 1961. *Recherches géologiques dans l'Himalaya du Nepal, région du Makalu: Expéditions françaises à l'Himalaya 1954–1955, organisées par la Fédération de la montagne en coopération avec le Club alpin français. Mission scientifique du CNRS*. CNRS, Paris.

Brookfield, M.E. 1993. The Himalayan passive margin from Precambrian to Cretaceous times. *Sedimentary Geology*, **84**, 1–35.

Butler, R.W. 1982. The terminology of structures in thrust belts. *Journal of Structural Geology*, **4**, 239–245.

Carrano, C.J., Schellenberg, S., Amin, S.A., Green, D.H. & Küpper, F.C. 2009. Boron and marine life: a new look at an enigmatic bioelement. *Marine Biotechnology*, **11**, 431–440.

Catlos, E.J., Harrison, T.M., Kohn, M.J., Grove, M., Ryerson, F.J., Manning, C.E. & Upreti, B.N. 2001. Geochronologic and thermobarometric constraints on the evolution of the Main Central Thrust, central Nepal Himalaya. *Journal of Geophysical Research, Solid Earth*, **106**, 16177–16204.

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. *Journal of Metamorphic Geology*, **22**, 207–226.

Cawood, P.A., Johnson, M.R. & Nemchin, A.A. 2007. Early Palaeozoic orogenesis along the Indian margin of Gondwana: Tectonic response to Gondwana assembly. *Earth and Planetary Science Letters*, **255**, 70–84.

Chakraborty, S., Dasgupta, S. & Neogi, S. 2003. Generation of migmatites and the nature of partial melting in a continental collision zone setting: An example from the Sikkim Himalaya. *Indian Journal of Geology*, **75**, 38–53.

Cooper, F., Adams, B., Edwards, C. & Hodges, K. 2012. Large normal-sense displacement on the South Tibetan fault system in the eastern Himalaya. *Geology*, **40**, 971–974.

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. *Journal of Metamorphic Geology*, **21**, 317–334.

Dasgupta, S., Ganguly, J. & Neogi, S. 2004. Inverted metamorphic sequence in the Sikkim Himalayas: Crystallization history, *P–T* gradient and implications. *Journal of Metamorphic Geology*, **22**, 395–412.

Dasgupta, S., Chakraborty, S. & Neogi, S. 2009. Petrology of an inverted Barrovian sequence of metapelites in Sikkim Himalaya, India: Constraints on the tectonics of inversion. *American Journal of Science*, **309**, 43–84.

Davidson, C., Grujic, D., Hollister, L. & Schmid, S. 1997. Metamorphic reactions related to decompression and synkinematic intrusion of leucogranite, High Himalayan Crystallines, Bhutan. *Journal of Metamorphic Geology*, **15**, 593–612.

Dewey, J., Cande, S. & Pitman, W.C. 1989. Tectonic evolution of the India/Eurasia collision zone. *Eclogae Geologicae Helvetiae*, **82**, 717–734.

Dickinson, W.R. 1991. *Tectonic Setting of Faulted Tertiary Strata Associated with the Catalina Core Complex in Southern Arizona, Book and Geological Map*. Geological Society of America, Boulder, Colorado.

DiPietro, J.A. & Isachsen, C.E. 2001. U–Pb zircon ages from the Indian plate in northwest Pakistan and their significance to Himalayan and pre-Himalayan geologic history. *Tectonics*, **20**, 510–525.

Dubey, C.S., Catlos, E.J. & Sharma, B.K. 2005. Modelling of *P–T–t* paths constrained by mineral chemistry and monazite dating of metapelites in relationship to MCT activity in Sikkim Eastern Himalayas. *In*: Thomas, H. (ed.) *Metamorphism and Crustal Evolution*. Atlantic Publishers, New Delhi.

Gansser, A. 1983. *Geology of the Bhutan Himalaya*. Birkhauser, Basel.

Gansser, A. 1991. Facts and theories on the Himalayas. *Eclogae Geologicae Helvetiae*, **84**, 33–59.

Gehrels, G., Decelles, P., Martin, A., Ojha, T., Pinhassi, G. & Upreti, B. 2003. Initiation of the Himalayan orogen as an early Paleozoic thin-skinned thrust belt. *GSA Today*, **13**, 4–9.

Gehrels, G., Decelles, P., Ojha, T. & Upreti, B. 2006. Geologic and U–Th–Pb geochronologic evidence for early Paleozoic tectonism in the Kathmandu thrust sheet, central Nepal Himalaya. *Geological Society of America Bulletin*, **118**, 185–198.

Gehrels, G., Kapp, P., *et al.* 2011. Detrital zircon geochronology of pre-Tertiary strata in the Tibetan–Himalayan orogen. *Tectonics*, **30**, TC5016, http://dx.doi.org/10.1029/2011TC002868.

Ghosh, A.M.N. 1956. Recent advances in geology and structure of Eastern Himalaya. *Proceedings of the Indian Science Congress*, **44**, 85–99.

Ghosh, S., Fallick, A.E., Paul, D.K. & Potts, P.J. 2005. Geochemistry and origin of Neoproterozoic granitoids of Meghalaya, Northeast India: Implications for linkage with amalgamation of Gondwana Supercontinent. *Gondwana Research*, **8**, 421–432.

Gilotti, J.A. & Kumpulainen, R. 1986. Strain softening induced ductile flow in the Särv thrust sheet, Scandinavian Caledonides. *Journal of Structural Geology*, **8**, 441–455.

Gilotti, J.A. & McClelland, W.C. 2008. Geometry, kinematics and timing of extensional faulting in the Greenland Caledonides—a synthesis. *In*: Higgins, A.K., Gilotti, J.A. & Smith, P.M. (eds) *The Greenland Caledonides: Evolution of the Northeast Margin of Laurentia*. Geological Society of America, Memoirs, **202**, 251–271.

Goswami, S. 2005. *Inverted metamorphism in the Sikkim–Darjeeling Himalaya: structural, metamorphic and numerical studies*. PhD thesis, University of Cambridge.

Goswami, S., Bhowmik, S.K. & Dasgupta, S. 2009. Petrology of a non-classical Barrovian inverted metamorphic sequence from the western Arunachal Himalaya, India. *Journal of Asian Earth Sciences*, **36**, 390–406.

Greenwood, L.V. 2013. *Orogenesis in the Eastern Himalayas: a study of structure, geochronology and metamorphism in Bhutan*. PhD thesis, Open University, Milton Keynes.

Groppo, C., Rolfo, F. & Lombardo, B. 2009. *P–T* evolution across the Main Central Thrust Zone (eastern Nepal): hidden discontinuities revealed by petrology. *Journal of Petrology*, **50**, 1149–1180.

Gupta, S., Das, A., Goswami, S., Modak, A. & Mondal, S. 2010. Evidence for structural discordance in the inverted metamorphic sequence of Sikkim Himalaya: towards resolving the Main Central Thrust controversy. *Journal of the Geological Society of India*, **75**, 313–322.

Guynn, J., Kapp, P., Gehrels, G.E. & Ding, L. 2012. U–Pb geochronology of basement rocks in central Tibet and paleogeographic implications. *Journal of Asian Earth Sciences*, **43**, 23–50.

Hamilton, P.J., O'Nions, R.K., Bridgwater, D. & Nutman, A. 1983. Sm–Nd studies of Archaean metasediments and metavolcanics from West Greenland and their implications for the Earth's early history. *Earth and Planetary Science Letters*, **62**, 263–272.

Harrison, T.M., Ryerson, F.J., Lefort, P., Yin, A., Lovera, O.M. & Catlos, E.J. 1997. A Late Miocene–Pliocene origin for the Central Himalayan inverted metamorphism. *Earth and Planetary Science Letters*, **146**, E1–E7.

Heim, A.A. & Gansser, A. 1939. *Central Himalaya: Geological Observations of the Swiss Expedition, 1936*. Gebrüder Fretz, Zurich.

Holdsworth, R.E. & Strachan, R.A. 1991. Interlinked system of ductile strike slip and thrusting formed by Caledonian sinistral transpression in northeastern Greenland. *Geology*, **19**, 510–513.

Hubbard, M.S. & Harrison, T.M. 1989. $^{40}Ar/^{39}Ar$ age constraints on deformation and metamorphism in the Main Central Thrust zone and Tibetan Slab, eastern Nepal Himalaya. *Tectonics*, **8**, 865–880.

Imayama, T. & Arita, K. 2008. Nd isotopic data reveal the material and tectonic nature of the Main Central Thrust zone in Nepal Himalaya. *Tectonophysics*, **451**, 265–281.

Inger, S. & Harris, N. 1993. Geochemical constraints on leucogranite magmatism in the Langtang Valley, Nepal Himalaya. *Journal of Petrology*, **34**, 345–368.

Kohn, M.J., Catlos, E.J., Ryerson, F.J. & Harrison, T.M. 2001. Pressure–temperature–time path discontinuity in the Main Central thrust zone, central Nepal. *Geology*, **29**, 571–574.

Kohn, M.J., Paul, S.K. & Corrie, S.L. 2010. The lower Lesser Himalayan sequence: A Paleoproterozoic arc on the northern margin of the Indian plate. *Geological Society of America Bulletin*, **122**, 323–335.

Law, R. 1998. Quartz mylonites from the Moine thrust zone at the Stack of Glencoul, Northwest Scotland. *In*: Snoke, A.W., Tullis, J. & Todd, V.R. (eds) *Fault-Related Rocks: A Photographic Atlas*. Princeton University Press, Princeton, NJ, 490–493.

Le Fort, P. 1975. Himalayas: The collided range. Present knowledge of the continental arc. *American Journal of Science*, **275**, 1–44.

Leslie, A., Krabbendam, M., Kimbell, G.S. & Strachan, R.A. 2010. Regional-scale lateral variation and linkage in ductile thrust architecture: The Oykel Transverse Zone, and mullions, in the Moine Nappe, NW Scotland. *In*: Law, R.D., Butler, R.W.H., Holdsworth, R.E., Krabbendam, M. & Strachan, R.A. (eds) *Continental Tectonics and Mountain Building: the Legacy of Peach and Horne*. Geological Society, London, Special Publications, **335**, 359–381.

Li, Z., Bogdanova, S., *et al.* 2008. Assembly, configuration, and break-up history of Rodinia: A synthesis. *Precambrian Research*, **160**, 179–210.

Long, S., McQuarrie, N., Tobgay, T. & Grujic, D. 2011*a*. Geometry and crustal shortening of the Himalayan fold–thrust belt, eastern and central Bhutan. *Geological Society of America Bulletin*, **123**, 1427–1447.

Long, S., McQuarrie, N., Tobgay, T., Rose, C., Gehrels, G. & Grujic, D. 2011*b*. Tectonostratigraphy of the Lesser Himalaya of Bhutan: Implications for the along-strike stratigraphic continuity of the northern Indian margin. *Geological Society of America Bulletin*, **123**, 1406–1426.

Macfarlane, A.M., Hodges, K.V. & Lux, D. 1992. A structural analysis of the Main Central Thrust zone, Langtang National Park, Central Nepal Himalaya. *Geological Society of America Bulletin*, **104**, 1389–1402.

Marquer, D., Chawla, H.S. & Challandes, N. 2000. Pre-alpine high-grade metamorphism in High Himalaya crystalline sequences: Evidence from Lower Palaeozoic Kinnaur Kailas granite and surrounding rocks in the Sutlej Valley (Himachal Pradesh, India). *Eclogae Geologicae Helvetiae*, **93**, 207–220.

Martin, A., Ganguly, J. & DeCelles, P. 2010. Metamorphism of Greater and Lesser Himalayan rocks exposed in the Modi Khola valley, central Nepal. *Contributions to Mineralogy and Petrology*, **159**, 203–223.

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. *Geological Society of America Bulletin*, **117**, 926–944.

Martin, A.J., Burgy, K.D., Kaufman, A.J. & Gehrels, G.E. 2011. Stratigraphic and tectonic implications of field and isotopic constraints on depositional ages of Proterozoic Lesser Himalayan rocks in central Nepal. *Precambrian Research*, **185**, 1–17.

McLennan, S., McCulloch, M., Taylor, S. & Maynard, J. 1989. Effects of sedimentary sorting on neodymium isotopes in deep-sea turbidites. *Nature*, **337**, 547–549.

McQuarrie, N., Robinson, D., Long, S., Tobgay, T., Grujic, D., Gehrels, G. & Ducea, M. 2008. Preliminary stratigraphic and structural architecture of Bhutan: Implications for the along strike architecture of the Himalayan system. *Earth and Planetary Science Letters*, **272**, 105–117.

McQuarrie, N., Long, S.P., Tobgay, T., Nesbit, J.N., Gehrels, G. & Ducea, M.N. 2013. Documenting basin scale, geometry and provenance through detrital geochemical data: Lessons from the Neoproterozoic to Ordovician Lesser, Greater, and Tethyan Himalayan strata of Bhutan. *Gondwana Research*, **23**, 1491–1510.

Miller, C., Thoni, M., Frank, W., Grasemann, B., Klotzli, U., Guntli, P. & Draganits, E. 2001. The early Palaeozoic magmatic event in the Northwest Himalaya, India: Source, tectonic setting and age of emplacement. *Geological Magazine*, **138**, 237–251.

Myrow, P.M., Hughes, N.C., *et al.* 2003. Integrated tectonostratigraphic analysis of the Himalaya and implications for its tectonic reconstruction. *Earth and Planetary Science Letters*, **212**, 433–441.

Myrow, P.M., Hughes, N.C., *et al.* 2010. Extraordinary transport and mixing of sediment across Himalayan central Gondwana during the Cambrian–Ordovician. *Geological Society of America Bulletin*, **122**, 1660–1670.

Neogi, S., Dasgupta, S. & Fukuoka, M. 1998. High *P–T* polymetamorphism, dehydration melting, and generation of migmatites and granites in the Higher Himalayan Crystalline Complex, Sikkim, India. *Journal of Petrology*, **39**, 61–99.

Parrish, R.R. & Hodges, K.V. 1996. Isotopic constraints on the age and provenance of the Lesser and Greater Himalayan sequences, Nepalese Himalaya. *Geological Society of America Bulletin*, **108**, 904–911.

Passchier, C.W. & Trouw, R.A.J. 2005. *Microtectonics*. Springer, Berlin.

Paul, D.K., Chandy, K.C., Bhalla, J.K., Prasad, R. & Sengupta, P. 1982. Geochronology and geochemistry of the Lingtse Gneiss, Darjeeling–Sikkim Himalaya. *Indian Journal of Earth Sciences*, **9**, 11–17.

Paul, D.K., McNaughton, N.J., Chattopadhyay, S. & Ray, K.K. 1996. Geochronology and geochemistry of the Lingtse gneiss, Darjeeling–Sikkim Himalaya: Revisited. *Journal of the Geological Society of India*, **48**, 497–506.

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**, TC4008.

Pêcher, A. 1989. The metamorphism in the central Himalaya. *Journal of Metamorphic Geology*, **7**, 31–41.

Pin, C. & Zalduegui, J.S. 1997. Sequential separation of light rare-earth elements, thorium and uranium by miniaturized extraction chromatography: Application to isotopic analyses of silicate rocks. *Analytica Chimica Acta*, **339**, 79–89.

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 and Planetary Science Letters*, **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. 2013. Was Himalayan normal faulting triggered by initiation of the Ramgarh–Munsiari thrust and development of the Lesser Himalayan duplex? *International Journal of Earth Sciences*, 1–18.

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 and Planetary Science Letters*, **192**, 507–521.

Robinson, D.M., DeCelles, P.G. & Copeland, P. 2006. Tectonic evolution of the Himalayan thrust belt in western Nepal: Implications for channel flow models. *Geological Society of America Bulletin*, **118**, 865–885.

Robinson, R.A., Brezina, C.A., *et al.* 2013. Large rivers and orogens: The evolution of the Yarlung Tsangpo–Irrawaddy system and the eastern Himalayan syntaxis. *Gondwana Research*, first published online July, 18, 2013, http://dx.doi.org/10.1016/j.gr.2013.07.002.

Rubatto, D., Chakraborty, S. & Dasgupta, S. 2013. Timescales of crustal melting in the Higher Himalayan Crystallines (Sikkim, Eastern Himalaya) inferred from trace element-constrained monazite and zircon chronology. *Contributions to Mineralogy and Petrology*, **165**, 349–372.

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. & Szulc, A.G. 2005. Channel flow and ductile extrusion of the high Himalayan slab—the Kangchenjunga–Darjeeling profile, Sikkim Himalaya. *Journal of Asian Earth Sciences*, **25**, 173–185.

Searle, M.P., Law, R.D., Godin, L., Larson, K.P., Streule, M.J., Cottle, J.M. & Jessup, M.J. 2008. Defining the Himalayan Main Central Thrust in Nepal. *Journal of the Geological Society, London*, **165**, 523–534.

Sharma, K.K. 2005. Malani magmatism: an extensional lithospheric tectonic origin. *In*: Foulger, G.R. (ed.) *Plates, Plumes and Paradigms*. Geological Society of America, Special Papers, **388**, 463–476.

Singh, S., Barley, M.E., Brown, S.J., Jain, A.K. & Manickavasagam, R.M. 2002. SHRIMP U–Pb in zircon geochronology of the Chor granitoid: Evidence for Neoproterozoic magmatism in the Lesser Himalayan granite belt of NW India. *Precambrian Research*, **118**, 285–292.

Spencer, C.J., Harris, R.A. & Dorais, M.J. 2012. Depositional provenance of the Himalayan metamorphic core of Garhwal region, India: Constrained by U–Pb and Hf isotopes in zircons. *Gondwana Research*, **22**, 26–35.

Stäubli, A. 1989. Polyphase metamorphism and the development of the Main Central Thrust. *Journal of Metamorphic Geology*, **7**, 73–93.

Stephenson, B.J., Searle, M.P., Waters, D.J. & Rex, D.C. 2001. Structure of the Main Central Thrust zone and extrusion of the High Himalayan deep crustal wedge, Kishtwar–Zanskar Himalaya. *Journal of the Geological Society, London*, **158**, 637–652.

Thomas, R., Jacobs, J., Horstwood, M., Ueda, K., Bingen, B. & Matola, R. 2010. The Mecubúri and Alto Benfica groups, NE Mozambique: Aids to unravelling *ca*. 1 and 0.5 Ga events in the east African orogen. *Precambrian Research*, **178**, 72–90.

Thomas, R.J., Roberts, N.M.W., Jacobs, J., Bushi, A.M., Horstwood, M.S.A. & Mruma, A. 2013. Structural and geochronological constraints on the evolution of the eastern margin of the Tanzania Craton in the Mpwapwa area, central Tanzania. *Precambrian Research*, **224**, 671–689.

Tobgay, T., Long, S., McQuarrie, N., Ducea, M.N. & Gehrels, G. 2010. Using isotopic and chronologic data to fingerprint strata: Challenges and benefits of variable sources to tectonic interpretations, the Paro Formation, Bhutan Himalaya. *Tectonics*, **29**, TC6023, http://dx.doi.org/10.1029/2009TC002637.

Tobgay, T., McQuarrie, N., Long, S., Kohn, M.J. & Corrie, S.L. 2012. The age and rate of displacement along the Main Central Thrust in the western Bhutan Himalaya. *Earth and Planetary Science Letters*, **319–320**, 146–158.

Valdiya, K.S. 1980. *Geology of Kumaun Lesser Himalaya*. Wadia Institute of Himalayan Geology, Dehradun.

Vermeesch, P. 2004. How many grains are needed for a provenance study? *Earth and Planetary Science Letters*, **224**, 441–451.

Wang, X.-L., Zhou, J.-C., Qiu, J.-S., Zhang, W.-L., Liu, X.-M. & Zhang, G.-L. 2006. LA-ICP-MS U–Pb zircon geochronology of the Neoproterozoic igneous rocks from Northern Guangxi, South China: Implications for tectonic evolution. *Precambrian Research*, **145**, 111–130.

Webb, A.A.G. 2013. Preliminary balanced palinspastic reconstruction of Cenozoic deformation across the Himachal Himalaya (northwestern India). *Geosphere*, **9**, 572–587.

Webb, A.A.G., Yin, A. & Dubey, C.S. 2013. U–Pb zircon geochronology of major lithologic units in the eastern Himalaya: Implications for the origin and assembly of Himalayan rocks. *Geological Society of America Bulletin*, **125**, 499–522.

Whittington, A., Foster, G., Harris, N., Vance, D. & Ayres, M. 1999. Lithostratigraphic correlations in the western Himalaya—An isotopic approach. *Geology*, **27**, 585–588.

Wright, L. & Nittrouer, C. 1995. Dispersal of river sediments in coastal seas: six contrasting cases. *Estuaries*, **18**, 494–508.

Yin, A., Dubey, C.S., Kelty, T.K., Webb, A.A.G., Harrison, T.M., Chou, C.Y. & Celerier, J. 2010*a*. Geologic correlation of the Himalayan orogen and Indian craton: Part 2. Structural geology, geochronology, and tectonic evolution of the Eastern Himalaya. *Geological Society of America Bulletin*, **122**, 360–395.

Yin, A., Dubey, C.S., Webb, A.A.G., Kelty, T.K., Grove, M., Gehrels, G.E. & Burgess, W.P. 2010*b*. Geologic correlation of the Himalayan orogen and Indian craton: Part 1. Structural geology, U–Pb zircon geochronology, and tectonic evolution of the Shillong Plateau and its neighboring regions in NE India. *Geological Society of America Bulletin*, **122**, 336–359.

Yonkee, W. 1997. Kinematics and Mechanics of the Willard Thrust Sheet, Central Part of the Sevier Orogenic Wedge, North–central Utah. *In*: Link, P.K. & Kowallis, B.J. (eds) *Proterozoic to recent stratigraphy, tectonics and volcanology, Utah, Nevada and Southern Idaho and Central Mexico*. Brigham Young University Geology Studies, **42**, 341–354.

Zhou, M.-F., Yan, D.-P., Kennedy, A.K., Li, Y. & Ding, J. 2002. SHRIMP U–Pb zircon geochronological and geochemical evidence for Neoproterozoic arc-magmatism along the western margin of the Yangtze Block, South China. *Earth and Planetary Science Letters*, **196**, 51–67.

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