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 isotope, 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 εNd(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 εNd(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. Geochemical 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.

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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; Pécher 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 (Pécher 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. 2011b; 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.
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 geological 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. 2010a,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 these rocks along the Main Central Thrust, 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. 2011b; 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 zone 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. 2011a) 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; Acharya 1975; Banerjee et al. 1983) or placed the Main Central Thrust at the base of the Main Central Thrust zone (Searle & Szule 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 et al. 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 symmetamorphic 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. $\epsilon_{Nd}$ values were calculated at time zero using present-day CHUR values of 0.512638 (Hamilton et al. 1983).
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 $^{207}\text{Pb}/^{206}\text{Pb}$ ages with 2SD uncertainties. Lingtse gneiss (samples 49 and 58) from the same body of granitic gneiss, 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 $^{207}\text{Pb}/^{206}\text{Pb}$ ages with 2SD uncertainties. Lingtse gneiss (samples 49 and 58) from the same body of granitic gneiss, yield average $^{207}\text{Pb}/^{206}\text{Pb}$ 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 $^{207}\text{Pb}/^{206}\text{Pb}$ 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 $^{207}\text{Pb}/^{206}\text{Pb}$ age of 508±22 Ma (MSWD = 3.3); sample 115 yields an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 604±28 Ma (MSWD = 7);
and the oldest sample (32) yields an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of $829\pm 28\text{Ma}$ (MSWD = 16).

**D 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. $1800\text{Ma}$ with older grains spread throughout the Proterozoic and Archaean, and yield no grains younger than c. $1700\text{Ma}$. In detail, samples 12 and 38x show dominant $1800\text{Ma}$ peaks with a small number of older zircons. Sample 203 shows a peak at c. $1900\text{Ma}$ and relatively more Archaean zircons than samples 12 and 38x. Sample 292 lacks a dominant peak but zircon ages range from c. $1900\text{Ma}$ to c. $2600\text{Ma}$; this sample contains the oldest zircons seen in this study, dating to c. $3600\text{Ma}$. 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. $800\text{Ma}$. Sample 161 yields a dominant age peak at c. $800–1100\text{Ma}$ with minor, older peaks at c. $1500–1700\text{Ma}$ and c. $2300–2500\text{Ma}$. Sample 211 yields a similar age spectrum, but with a slightly older dominant peak at c. $1000–1300\text{Ma}$ and a spread of older zircons from $1300$ to $2600\text{Ma}$. There is also one discordant zircon analysis at c. $500\text{Ma}$, indicative that this sample may contain Palaeozoic zircon populations.

**Sm–Nd geochemistry**

The ε$_{\text{Nd}}$ 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 ε$_{\text{Nd(0)}}$ 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. $1075–2034\text{Ma}$ (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 $1834\pm 37\text{Ma}$ and $1853\pm 19\text{Ma}$ (Fig. 6) 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 $829\pm 28\text{Ma}$, $604\pm 28\text{Ma}$ and $508\pm 22\text{Ma}$ (Fig. 5). These orthog- nes ages are consistent with similar meta-igneous intrusion ages from the Greater Himalayan Sequence elsewhere in the Himalaya. These include an event at c. $500\text{Ma}$ (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. $800\text{Ma}$ (DiPietro & Isachsen 2001; Singh et al. 2002; Ghosh et al. 2005; Richards et al. 2006; Spencer et al. 2012). A widespread Cambro–Ordovician tec- tonic 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. 2010b).

The significance of the c. $800\text{Ma}$ 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 6. The samples with detrital zircon ages that show a dominant peak at c. $1800\text{Ma}$, with no zircons younger than c. $1700\text{Ma}$ (Fig. 6), and those samples with an ε$_{\text{Nd}}$ 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.
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 εNd 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 εNd 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 $e_{Nd}$ values; numbers inside a continuous-line rectangle are $e_{Nd}$ 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.
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 & Nittouer 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 Bhimedian 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 εNd 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 εNd 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 εNd(0) signatures of –16.3 to –21.4. This latter study suggested that variations in the εNd 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 εNd 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 kilometres (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 Bihpæmedian 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 exhumating 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 ε 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 ε 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, 38, 71–90.

AHMAD, T., HARRIS, N., BECKE, 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. Paleoproteozoic 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.

ARELES, 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.

BANEEREE, H., Dashgupta, 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., HOLDWORTH, 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.

BHRIGUDELHI, A.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. 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. & KUPPER, F.C. 2009. Boron and marine life: a new look at an enigmatic bioelement. Marine Biotechnology, 11, 431–440.

CATOSS, E.J., HARRISON, T.M., KENN, M.J., GROVE, M., FRYERSON, F.J., MANNING, C.E. & UPIRET, 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.

CATOSS, 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, V.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.
STEWART, B. J., SCHRIFT, M. R., WATERS, D. J. & REX, D. C. 2001. Structure of the Main Central Thrust zone and extrusion of the High Himalayan deep crustal wedge. Kishwar–Zanskar Himalaya. Journal of the Geological Society, London, 158, 637–652.

THOMAS, R., JACOBS, J., HORSTWOOD, M., UEDA, K., BENGZ, B. & MAIOLA, R. 2010. The Mecubiri 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., BUSIS, A. M., HORSTWOOD, M. S. A. & MEUMA, A. 2013. Structural and geochronological constraints on the evolution of the eastern margin of the Tanzania Craton in the Mwapwpa area, central Tanzania. Precambrian Research, 224, 671–689.

TORGAY, T., LONG, S., McQuARIE, 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. Lithostratigraphic correlations in the western Himalaya—An isotopic approach. Geology, 27, 585–588.

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

YIN, A., DUBAY, C. S., KELTY, T. K., WEBB, A. A. G., HARRESON, T. M., CHOU, C. Y. & CELERIER, J. 2010a. 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., DUBAY, C. S., WEBB, A. A. G., KELTY, T. K., GROVE, M., GEHRELS, G. E. & BERGESS, W. P. 2010b. 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.

YOUNG, 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.

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