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Tectonic interleaving along the Main Central Thrust, Sikkim Himalaya

Catherine M. Mottram1*, T.W. Argles1, N.B.W. Harris1, R.R. Parrish2,3, M.S.A. Horstwood3, C.J. Warren1, S.Gupta4

1Department of Environment, Earth and Ecosystems, Centre for Earth, Planetary, Space and Astronomical Research (CEPSAR), The Open University, Walton Hall, Milton Keynes, MK7 6AA, United Kingdom
2Department of Geology, University of Leicester, University road, Leicester, LE1 7RH, United Kingdom
3NERC Isotope Geosciences Laboratory, British Geological Survey, Keyworth, Nottingham NG12 5GG, United Kingdom
4Department of Geology & Geophysics, I.I.T., Kharagpur – 721 302, India.

* corresponding author (e-mail: catherine.mottram@open.ac.uk)

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Abbreviated title: Tectonic interleaving along the MCT

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 (MCT) 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 characterised by detrital zircon peaks at ~800-1000 Ma, 1500-1700 Ma and 2300-2500 Ma, an $\varepsilon_{\text{Nd}}(0)$ signature of -18.3 to -12.1, and is intruded by ~800 Ma and ~500-600 Ma granites. In contrast, the footwall has a prominent detrital zircon peak at ~1800-1900 Ma, with older populations spanning 1900-3600 Ma, and an $\varepsilon_{\text{Nd}}(0)$ signature of -27.7 to -23.4, intruded by ~1830 Ma granites.

The data reveal a ~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 MCT. Geochronological and isotopic characterisation allows for correlation along the Himalayan orogen and could be applied to other cryptic ductile shear zones.

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

The MCT was originally mapped in the Kumaun region of NW India as the basal contact between the crystalline nappes (GHS) and the underlying metasedimentary rocks (LHS) (Heim and Gansser 1939). Since this 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 MCT: 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: i) lithological changes (Heim and Gansser 1939; Valdiya 1980;
Gansser 1983; Pêcher 1989; Davidson et al. 1997; Daniel et al. 2003; Tobgay et al. 2012); ii) high
strain in a distinct zone (Stephenson et al. 2001; Gupta et al. 2010); iii) metamorphic discontinuities
(Bordet 1961; Le Fort 1975; Hubbard and Harrison 1989; Stàubli 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); iv) structural
criteria (Pêcher 1989; Martin et al. 2005; Searle et al. 2008); and v) isotopic breaks (Inger and Harris
1993; Parrish and Hodges 1996; Whittington et al. 1999; Ahmad et al. 2000; Robinson et al. 2001;
Martin et al. 2005; Richards et al. 2005; Richards et al. 2006; Ameen et al. 2007; Imayama and Arita
2008; Gehrels et al. 2011; Long et al. 2011b; Martin et al. 2011; Tobgay et al. 2011; McQuarrie et al.

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 and Trouw 2005, p. 532; Searle et al.,
2008). Although this approach is useful to define the MCT 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 MCT 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 potentially provide a complementary tool to identify and investigate the tectono-stratigraphic
break across the MCT, as units either side of the MCT are defined by distinct geochemical signatures.
Early studies found that the ‘geochemical’ boundary associated with the MCT coincided with the
geological/lithological boundary mapped by others, suggesting that the approach had broad validity
in confirming the location of the suspected major fault (e.g. Parrish and Hodges 1996). Most of these
previous isotopic studies used to identify the location of the MCT 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. 2011; McQuarrie et al. 2013) after
suggestions that the provenance of these rocks differs from elsewhere along the orogen (Yin et al. 2010a; Yin et al. 2010b; 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 characterise 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 MCT in the Sikkim Himalaya. The data show there is a break in the geochemical signature of the rocks towards the top of the MCT 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 MCT zone accompanied thrusting. A model is presented outlining the provenance of these rocks and how they were juxtaposed during Cenozoic movement of the MCT. Our study permits correlation between the MCT in the Sikkim Himalaya and the MCT mapped along strike in the central and western Himalaya using a combined set of comparable data.

**Geological setting**

The MCT broadly represents a protolith boundary that divides two lithological packages, each characterised by distinctive geochronological and geochemical signatures (e.g. Parrish and Hodges 1996). The LHS is a Palaeoproterozoic metasedimentary sequence with an $\varepsilon_{Nd}(0)$ signature of -20 to -25 that has been intruded by ~1.8 Ga granites. In contrast, the GHS is a younger, Neoproterozoic-Ediacaran (and possibly Palaeozoic) sequence of metasedimentary rocks, characterised by an $\varepsilon_{Nd}(0)$ signature of -15 to -20 indicative of younger source regions, typically intruded by younger, ~500 and subordinate ~830 Ma granites (Parrish and Hodges 1996; Ahmad et al. 2000; Robinson et al. 2001;
In southern Sikkim and the Darjeeling Hills (referred to collectively as the Sikkim Himalaya) a combination of poor exposure around the MCT and widespread diffuse ductile deformation obscure both the location and nature of the MCT. Previous studies have identified a zone, up to 20 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 recognised 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 and see photomicrographs in the supplementary material S2 for metamorphic minerals). A late-stage duplex beneath the Ramgarh thrust (Bhattacharyya and Mitra 2009; Long et al. 2011a) has created the Teesta Dome, deforming the MCT and producing one of the largest re-entrants, in map view, across the Himalaya (Figs 2a, 2c). Throughout the region, the MCT separates the overlying GHS from the LHS. The transition between these two rock packages in this ductile shear zone appears gradational in various respects. There is a several kilometre-wide zone 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, up to 50km across strike, 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 MCT 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 MCT. Studies have variously bounded the MCT zone with two named thrusts (Catlos et al. 2004; Dubey et al. 2005; Bhattacharyya and Mitra 2009; 2011), placed the MCT at the top of the MCT zone (Ghosh 1956; Acharyya 1975; Banerjee et al. 1983) or placed the MCT at the base of the MCT zone (Searle and Szulc 2005). Furthermore, the distinctive Palaeoproterozoic Lingtse gneiss, strongly sheared along the MCT zone throughout the Sikkim Himalaya, has been used in other studies as a defining lithology for determining the location of the MCT (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 MCT in the Sikkim Himalaya (Fig. 2b). Throughout the region, the MCT zone displays well-developed, polydeformational fabrics typical of large-scale shearing and thrusting that have been extensively described and cataloged in previous structural studies (Goswami 2005). Structures are dominated by south-directed thrusting along the MCT as typified by the Mangan transect with fabrics detailed in Figure 3. There is a strong N-S 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 MCT foliation. Shearing is also localized into well-developed shear bands in metapelites (Fig. 3c) across several kilometres of thickness of the MCT 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 ~20 km across and beneath the MCT (Fig. 3); hence most previous studies have considered the MCT to form a ‘zone’. The rocks within this zone differ in strength and rheology, creating several domains of high strain. The MCT cannot be marked or mapped as a single plane within this zone due 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 MCT is principally syn-metamorphic 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 MCT zone in the Sikkim Himalaya obscures the differentiation between the LHS and GHS 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 MCT.

**Analytical methods**

**Zircon U-Pb geochronology**

Samples for zircon U-Pb geochronology were collected from clastic metasedimentary and igneous protoliths across the MCT in the Sikkim Himalaya to investigate the tectonic affinity of these rocks (locations shown in Fig. 2b, and in the table and photomicrographs in the supplementary material S1 and S2). 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. Separated grains were imaged using cathodoluminescence scanning electron microscopy (SEMCL), on a FEI Quanta 600 ESEM, at 10nA, 15mm working distance at the British Geological Survey, UK to investigate zoning patterns and to choose appropriate spots for analysis (see CL images in the supplementary material S3). The zircons show several stages of growth recorded in the concentric zoning patterns of the magmatic crystals. Some zircons had more complex histories due to additional
post-magmatic metamorphic growth (see the supplementary material S3 for atlas of zircon textures).

Zircons were mainly analysed for U-Pb isotopes using a Nu Plasma HR multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) (Nu Instruments, Wrexham, UK) and a UP193FX (193nm) excimer or UP193SS (193nm) Nd:YAG laser ablation system (New Wave Research, UK). Measurement procedures followed methods described in Thomas et al. (2010) and full analytical conditions are given in the supplementary material S4. A small number of zircons (sample 292) were analysed using an AttoM single collector sector field (SC-SF) ICP-MS (Nu Instruments, Wrexham, UK) and a New Wave Research UP193FX (193nm), excimer ablation system (New Wave Research, UK). The instrumental configuration and measurement procedures follow previous methods (Thomas et al. 2013) and full analytical conditions are shown in the supplementary material S5. Only $^{206}\text{Pb}/^{238}\text{U}$ data within 5% of concordance were plotted in relative probability plots in Figures 6 and 7. Between eighty and one hundred grains were analysed for each sample in order to retain statistically significant numbers of concordant analyses. For this number of grains, it has been calculated by Vermeesch (2004) that no fraction of the population comprising more than 5.7-6.8% of the total is missed at the 95% confidence level. All data, quoted at 2σ confidence level, are shown in the U-Pb data table in the supplementary material.

**Sm-Nd Geochemistry**

Twenty samples for whole-rock Nd geochemistry were collected along transects across the MCT 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). Full sample locations and rock types are shown on map in Fig. 2b and in the Sm–Nd whole rock data table, and photomicrographs in the supplementary material S2.
Nd isotope analyses were obtained at The Open University, UK, by thermal ionisation mass spectrometry (TIMS) using a Triton instrument. Isotopic analytical techniques are as described by Pin and Zalduegui (1997). Full details of sample preparation and analytical conditions can be found in the supplementary material S6. \(^{147}\text{Sm}/^{144}\text{Nd}\) ratios were calculated from elemental ratios obtained from quadrupole ICP-MS (full conditions in the supplementary material S6). Epsilon Nd values were calculated at time 0 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, 5 and 8) fall into three age groups; Palaeoproterozoic granites (Lingtse gneiss), Neoproterozoic granites, and Ediacaran-Cambrian granites. Each of these samples yield discordant scattered age populations due 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 and 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 yielded from zircons with typical magmatic oscillatory zoning (see zircon atlas in the supplementary material S3). All of the Lingtse gneiss samples contain older 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 ~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 ± 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 ~1800 Ma with older grains spread throughout the Proterozoic and Archaean, and yield no grains younger than ~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 ~1900 Ma and relatively more Archaean zircons than samples 12 and 38x. Sample 292 lacks a dominant peak but zircon ages range from ~1900 Ma to ~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 ~800 Ma. Sample 161 yields a dominant age peak at ~800-1100 Ma with minor, older, peaks at ~1500-1700 Ma and ~2300-2500 Ma. Sample 211 yields a similar age spectrum, but with a slightly older dominant peak at ~1000-1300 Ma and a spread of older zircons from 1300 Ma to 2600 Ma. There is also one discordant zircon analysis at ~500 Ma, indicative that this sample may contain Palaeozoic zircon populations.

**Sm-Nd geochemistry**

The $\varepsilon_{\text{Nd}}$ results are shown in the Sm-Nd whole-rock data table in the supplementary material and are plotted on Figures 8 and 9 to demonstrate the geochemical variations with spatial reference to the MCT zone. The data range in $\varepsilon_{\text{Nd}}(0)$ from -27.7 to -12.1.

**Discussion**
The magmatic history

The Palaeoproterozoic granites (‘Lingtse gneiss’) from the MCT zone were originally dated using Rb-Sr, yielding ages of c.1075-2034 Ma (Paul et al. 1982; Paul et al. 1996). The Lingtse gneiss samples from the Sikkim Himalaya analysed in this study provide an 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; see Table 1 from Kohn et al. 2010 for summary of ages). 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 GHS elsewhere in the Himalaya. These include an event at ~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 ~800 Ma (DiPietro and 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 GHS (Argles et al. 1999; Marquer et al. 2000; Gehrels et al. 2003; Gehrels et al. 2006). This has been termed the ‘Bhimphedian orogeny’ (Cawood et al. 2007), and has been related to the Cambrian formation of Gondwana (Yin et al. 2010b).

The significance of the ~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 MCT zone in the Sikkim Himalaya

The geochronological and geochemical data from this study can be categorised into two isotopic groups, shown in Fig. 8. The samples with detrital zircon ages that show a dominant peak at ~1800 Ma, with no zircons younger than ~1700 Ma (Fig. 6), and those samples with an εNd signature of -27.7 to -23.4, are indicative of an LHS signature when compared to the published literature as reviewed above. The youngest detrital zircons in the LHS sediments are coeval to the granite intrusion ages, which date from ~1800 Ma. The samples that have a detrital zircon age signature which ranges down to younger than 800 Ma (Fig. 7) or an εNd signature of -18.3 to -12.1 can be characterised as GHS samples when compared to previous studies. The youngest concordant Greater Himalayan detrital zircons are roughly contemporaneous with the oldest granite intrusion (~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 LHS units in the eastern Himalaya are divided into three quite 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 GHS (McQuarrie et al. 2013), the older predominant Daling unit has an isotopic signature which contrasts markedly with that of the GHS, producing a geochemical contrast across the thrust zone wherever the Daling and GHS are juxtaposed, such as in the Sikkim Himalaya.

The geochemical and geochronological characterisation of the samples from this study has allowed for a more precise trace of the MCT to be proposed in the Sikkim Himalaya (Fig. 2b), which is generally consistent with that presented in Rubatto et al. (2012). 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 ‘MCT 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 MCT 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 MCT occurred in the Sikkim Himalaya at ~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 MCT, into the underlying Lesser Himalayan rocks.

Tectonic imbrication

Three transects (Figs 9a, b and c) provide exceptions to the simple division between the hanging wall and footwall of the MCT, as outlined above. Samples in these locations yield abrupt out-of-sequence, alternating shifts in $\epsilon_{\text{Nd}}$ and detrital zircon characteristics in a ~5-10 km thick zone (shown as outliers in Figure 8). This has important implications both for the geochemical “fingerprinting” of rock units on either side of the MCT, 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:

i) 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 (~0.11) for the rocks measured in this study do not support significant disturbance of the Sm–Nd system (Ahmad et al. 2000).

ii) 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 GHS rocks (younger detritus) and the Indian shield (older detritus) (McQuarrie et al. 2013). The Bhutan sequences probably correlate to the along-strike MCT 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 ‘LHS’ rocks (Fig. 6), potentially supporting the theory of different sediment sources for certain rocks within the MCT zone.

The ‘interleaved’ signatures could therefore reflect abrupt shifts in the nature of detritus being deposited in the MCT zone sedimentary protoliths (Tobgay et al. 2011; McQuarrie et al. 2013). These shifts could result from one or more of the following: 1) specific depositional settings, 2) sediment transport processes, and 3) erosion processes in the catchments.

A marine depositional environment is indicated for MCT 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 and Nittrouer 1995), suggesting that detritus from a single river can become dispersed and mixed with other sediment, causing signatures of individual 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 characterise the pelitic lithologies (Allen 2007).

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 GHS rocks were deposited. However, such shifts in river catchment are likely to result in a single switching of sediment source and isotopic signature; since 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 MCT (Fig. 8). Moreover our observation, based on detailed geochemical studies, that rock packages characterised 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.

iii) Tectonic interleaving

The observed signature of the rocks could have been caused by tectonic interleaving of LHS and GHS rocks associated with the tectonic movement along the MCT. This model is supported by evidence in Figures 9a and 9b where narrow slivers of pelites are exposed that yield distinct $\varepsilon_{Nd}$ signatures from their immediately adjacent orthogneisses and pelites with contrasting geochemical signature. Since such complexities are only found in the area surrounding the MCT, 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 MCT. Gansser (1991) observed that the MCT can form either 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 regarding the nature of the MCT. To the east, detrital zircon and $\varepsilon_{Nd}$ signatures from the Paro window in Bhutan (Tobgay et al. 2011) are also suggestive of an imbricate zone similar to the MCT 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 MCT to the west. Although Martin et al. (2005) found no evidence of an imbricate zone associated with the MCT in the Annapurna region of western Nepal, Parrish and Hodges (1996) termed a relatively narrow conspicuous zone of lithological and structural imbrication around the MCT in the Langtang region of central Nepal as the “MCT imbricate zone”, characterised by $\varepsilon_{Nd}(0)$ signatures of -16.3 to -21.4. This latter study suggested that variations in the $\varepsilon_{Nd}$ ratios in this zone showed that the MCT zone was formed from interleaving of slices of both footwall and hanging wall rocks. Studies in other Nepal transects have also reported ambiguous overlapping $\varepsilon_{Nd}$ signatures from the vicinity of the MCT, which could also be interpreted as evidence for imbrication (Robinson et al. 2001; Imayama and 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 LHS rocks of the Sikkim Himalaya (Bhattacharyya and 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 lengthscale of metres (Gilotti and Kumpulainen 1986; Yonkee 1997), to large-scale structures over
hundreds to metres (Barr 1986; Holdsworth and Strachan 1991; Gilotti and McClelland 2008; Leslie et al. 2010). A similar setting to the MCT we describe in the Sikkim Himalaya is 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 and Strachan 1991). In the case of the Sikkim Himalaya, structural evidence for imbrication may be difficult to recognise in a zone of progressive ductile deformation due 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 (LHS) to distal (GHS) parts of the passive margin of India (Brookfield 1993; Myrow et al. 2003; Myrow et al. 2010). Cenozoic movement on the MCT 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 LHS and GHS sedimentary basins of the margin (Li et al. 2008). This would explain the exposure of the distal GHS sediments to the Cambro-Ordovician Bhimphedian orogeny, in marked contrast to the more southerly, proximal, LHS package that was apparently unaffected by this event (Fig. 10).
The juxtaposition of the exposed parts of the GHS and LHS 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 GHS package. Following this burial and northward subduction of the Neoproterozoic-Mesozoic northern Indian margin, the GHS sediments were detached from their (unknown) depositional basement along a deep-seated décollement (the proto-MCT) and began to be translated southwards, while undergoing syn-metamorphic deformation. It is possible that the MCT exploited the closed, failed Neoproterozoic rift as the thrust propagated southwards, which could help to explain the striking coincidence of the MCT with the isotopic break along the entire Himalaya. Progressive convergence and crustal thickening triggered extrusion of the ductile and weak GHS between the South Tibetan Detachment and the Main Central thrust, which transported the GHS 140-500 kilometres over the previously proximal Lesser Himalayan rocks that originally lay to the south (Dewey et al. 1989; Schelling and 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 MCT suggest that some Daling sediments were both strongly deformed and heated during MCT motion, as heat was transferred from the hotter GHS rocks above. Simultaneous footwall heating and hanging wall cooling caused the inverted metamorphism which 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 MCT. In this ductile setting, ramps and flats on the MCT resulted in imbrication or interleaving of the LHS and GHS in the immediate vicinity of the thrust. Deformation was subsequently transferred to the Ramgarh thrust (Pearson and DeCelles 2005; Webb 2013; Robinson and Pearson 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 LHS (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 LHS and GHS packages in this region. The GHS rocks are characterised by detrital zircon age peaks at ~800-1000 Ma, 1500-1700 Ma and 2300-2500 Ma and by an $\varepsilon_{\text{Nd}}(0)$ signature of -18.3 to -12.1. This rock package was intruded by granites of Neoproterozoic (~800 Ma) and Ediacaran-Cambrian (~500-600 Ma) age. In contrast, the Daling part of the LHS rocks comprise a Palaeoproterozoic rock package with prominent Archaean and Palaeoproterozoic detrital zircon populations and an $\varepsilon_{\text{Nd}}(0)$ 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 have been 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 MCT has 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 which spans over 2500 kilometres 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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**Figure Captions**

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

**Fig. 2.** a) Geological map of Sikkim based on previous maps of the area [Goswami, 2005; Gupta et al. 2010]. Insets for 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 Figure 9). Line of section presented for Figure 2c. c) Sketch geological cross section, with no vertical exaggeration (line of section shown in Figure 2b) from data presented in this study. Lesser Himalayan Duplex taken from Bhattacharyya and Mitra, 2009. Abbreviations are the same as in Figure 1.

**Fig. 3.** Summary of structural features beneath the MCT 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 on map, top right of figure. Map units as for Figures 1 and 2.

**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 shown in inset map.

**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 shown in inset map.
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 shown in inset map.

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 shown in inset map.

Fig. 8. Plot of a) εNd signature and b) detrital zircon and orthogneiss U-Pb age, as a function of depth above and below the MCT (positive numbers=up section into GHS and negative numbers= down section into LHS). The MCT is defined here as the protolith boundary as outlined in the text and in Fig. 2b. The LHS/GHS classification is based on previous Himalayan studies; these signatures overlap slightly in the zircon plot (b) marked by the hatched area. The LHS signature however does not extend younger than 1700 Ma. There are three outliers marked with arrows which demonstrate the location of proposed interleaved slices.

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 legend in Figures 1-2. ‘Imbricate zone’, as discussed in the text, is shown in grey. Large numbers preceded by minus signs are εNd values; εNd values for GHS surrounded by black box. Small numbers in italics are sample locations. Orthogneiss ages are shown in circles (dashed line for LHS values and solid line for GHS samples). Detrital zircons populations are shown as probability density plots or as a rectangular dashed outline box (Fig. 9a). Full concordia and probability density plots can be found in Figures 4-7.

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

Sample 49
1837 ± 45 Ma (2σ)
MSWD 11.6 (n= 13)

Sample 58
1836 ± 26 Ma (2σ)
MSWD 11.5 (n= 14)

Sample 233
1834 ± 37 Ma (2σ)
MSWD 20 (n= 18)

Sample 245
1853 ± 19 Ma (2σ)
MSWD 17 (n= 25)

data-point error ellipses are 2σ
Mid-Palaeozoic architecture

S

Palaeoproterozoic granite intrusions/ basement slices
Closed Neoproterozoic rift (?)

Deformation and magmatism from the Cambro-Ordovician ‘Bhimphedan orogeny’
Tethys Ocean sediments

N

Indian passive margin

Proximal
Distal

Buxa
Daling

Schematic (not to scale)