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Testing the application of in situ Sm–Nd isotopic analysis on detrital apatites: A provenance tool for constraining the timing of India–Eurasia collision

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ABSTRACT

Provenance tools are applicable to many problems in sedimentary geology as they help unravel the tectonic and metamorphic history of the hinterland and provide insights into the erosional pathways and origins of sediments. In many cases it is more appropriate to use single grain approaches as opposed to bulk sediment methods in order to discover the precise input of the contributing geological terranes since the input of subordinate sources may not be detectable in bulk rock studies. Using a selection of modern river sediments we characterise the Sm–Nd isotopic composition of individual detrital apatites from the main Himalayan geological terranes. Our analyses allow us to effectively distinguish between apatites derived from the Eurasian Plate (relatively high ε_{Nd} values and low $^{147}Sm/^{144}Nd$ ratios), from those derived from the Indian Plate (low to high ε_{Nd} values and moderate to high $^{147}Sm/^{144}Nd$ ratios). We then apply this approach to Tertiary Indus Basin sedimentary rocks to attempt to better determine the timing of India–Eurasia collision. We find that detrital apatites in the Tertiary Indus Basin have been sourced solely from Eurasia, lacking a mixed India–Eurasia provenance input which would document the India–Eurasia collision. This study illustrates the use of this relatively novel provenance tool and provides a sound framework for similar studies in the future concerning the tectono-metamorphic-erosional evolution of the Himalaya.

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1. Introduction

It is widely considered that the growth of the Himalayan orogen has influenced atmospheric circulation, oceanic chemistry, and global climate (Raymo and Ruddiman, 1992; Richter et al., 1992). However, despite its importance, the initial timing of India–Eurasia continental collision and early Himalayan evolution remain largely uncertain. The most commonly suggested age of collision is between 55 and 50 Ma (e.g. de Sigoyer et al., 2000; Hodges, 2000; Leech et al., 2005; Searle et al., 1987), however other estimations range from as young as 34 Ma (Aitchison et al., 2007; and references therein) to as old as ~70 Ma (e.g. Ding et al., 2005; Yin, 2006; Yin and Harrison, 2000).

One method for constraining the timing of collision is through an examination of the sedimentary record (e.g. Clift et al., 2002; Garzanti et al., 1987; Garzanti and van Haver, 1988; Searle et al., 1987; Wu et al., 2007). Throughout the Himalayan orogeny, sedimentary basins have collected detrital material which has been eroded from a combination of geological terranes. A good example of this is the Cenozoic Indus Basin sedimentary rocks; a succession within the Indus-Tsangpo Suture Zone (ITSZ), which separates India from Eurasia (Fig. 1), deposited during the initial phases of India–Eurasia collision. These sedimentary rocks have been the subject of previous studies centred upon constraining the timing of India–Eurasia collision and understanding early Himalayan evolution, in particular, determination of the minimum age of collision as documented by the earliest evidence of mixed Indian and Eurasian detritus in the rocks, and the first evidence of Eurasian detritus deposited on the Indian plate. The application of a number of provenance techniques, applied to different mineral types, is often required for the generation of robust provenance interpretations (e.g. Allen et al., 2008; Carrapa et al., 2009; Maas and McCulloch, 1991; Najman, 2006) since a single mineral type may not occur in all potential source regions and such a source would therefore remain unrecorded.

In order to determine the origin of detrital material contained within the Indus Basin sedimentary rocks, characterisation of both potential source terranes is first necessary, i.e. the Precambrian-Tertiary continental crust of the Indian plate vs. the Mesozoic to Paleogene Andean-type batholiths of the southern margin of Asia intruded through Precambrian-Paleogene Asian crust. Approaches to achieve this source characterisation have included isotopic dating of detrital minerals (e.g. U–Pb of zircon, Ar–Ar of white micas; e.g. DeCelles et al., 2004; White et al., 2000); isotopic characterisation of both bulk sediment (e.g. Sm–Nd; e.g. Allegre and Othman, 1980; Parrish and Hodges, 1996; Fig. 2), and individual minerals (e.g. Lu–Hf;

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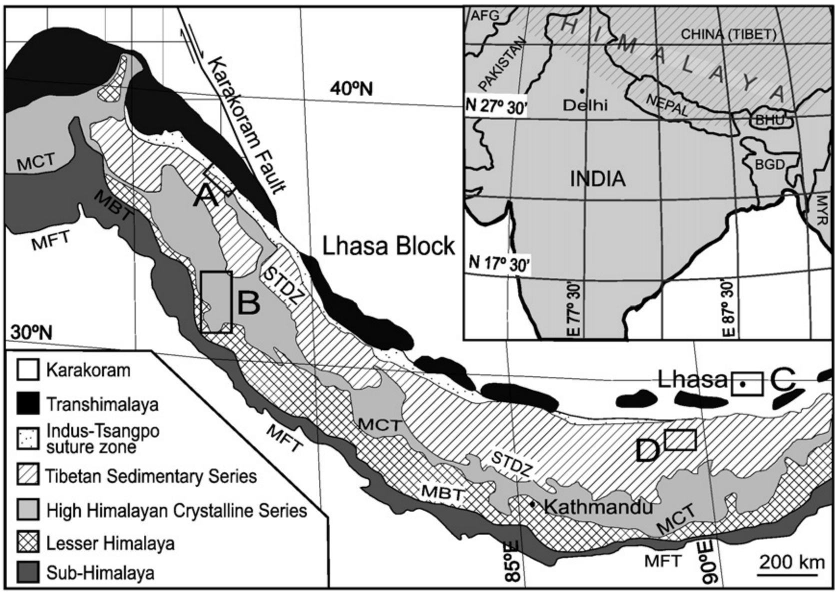

Fig. 1. Simplified geological map of the Himalaya, adapted from Foster and Carter (2007) and Dèzes (1999). STDZ (South Tibet Detachment Zone), MCT (Main Central Thrust), MBT (Main Boundary Thrust), and MFT (Main Frontal Thrust). Black squares and associated letters indicate the location of geological and river catchment maps available in Supplementary Figs. S1a–S1d. Inset: location of the Himalaya in its wider context.

e.g. Richards et al., 2005; Wu et al., 2007), and petrographic studies (e.g. Garzanti et al., 1996).

Searle et al. (1990) used palaeoenvironmental evidence from the Indus Basin sedimentary rocks to infer that Neo-Tethys ocean closed by 50.5 Ma, marked by the last occurrence of marine sedimentation represented by the Nummulitic Limestone. Further to this, these authors found a mixed India–Eurasia provenance at a younger stratigraphic level (the Choksti Formation; <50.5 Ma) within the succession, confirming that continental collision had occurred by this time. Conversely, Clift et al. (2002) concluded that the Indus Basin sedimentary rocks show evidence for India–Eurasia collision by 50.5–54.9 Ma (biostratigraphic dating by Green et al., 2008) based on their view that sedimentary rocks at this stratigraphic level (named the Chogdo Formation) contain a mixed Indian and Eurasian provenance, and that this same stratigraphic level of the (in part) Eurasian derived Indus Group is identified to unconformably overlie pre-collisional Indian plate passive margin sedimentary rocks. A recent study by Wu et al. (2007) based on U–Pb dating and Hf isotopic characterisation of detrital zircons from the Indus Basin sedimentary rocks, concluded that early sedimentation was entirely Eurasian derived and there was only possible evidence for a mixed India–Eurasia provenance at relatively young stratigraphic levels (45<35 Ma). However, the success of this approach was hampered by the overlap of Precambrian zircon U–Pb ages which exist both on the Indian and Eurasian plates (DeCelles et al., 2004; Leier et al., 2007). Henderson et al. (In review—a) considered the first robust piece of evidence suggesting a mixed India–Eurasia detrital provenance

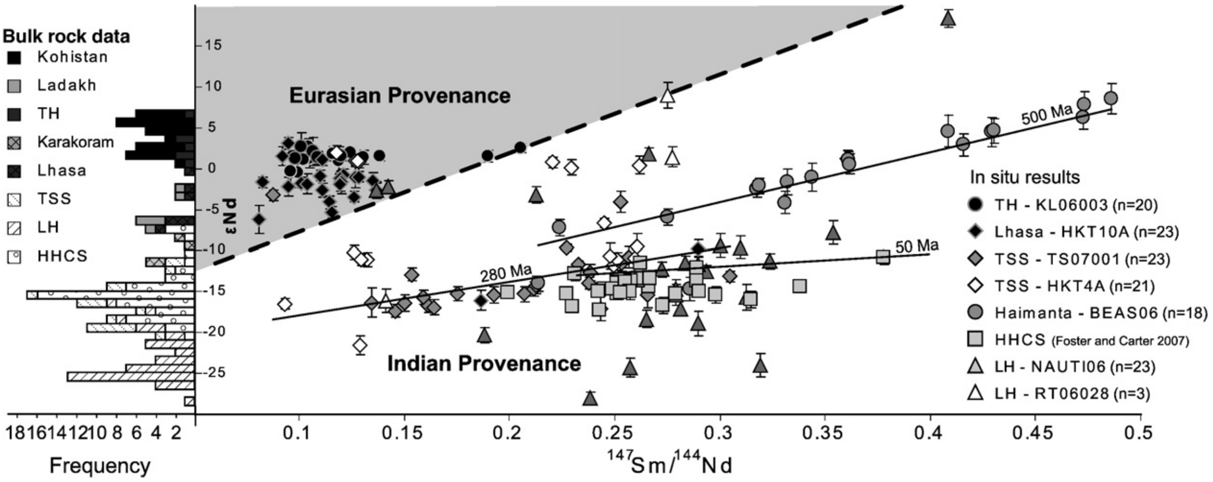

Fig. 2. In situ detrital apatite Sm–Nd isotopic results from Himalayan modern river sand samples, including HHCS apatite results from Foster and Carter (2007). Nd data are displayed in the form of ε_{Nd}; ^{143}Nd/^{144}Nd variation from Bulk Earth (CHUR) in parts per 10,000. Where CHUR ^{143}Nd/^{144}Nd = 0.512638 (Jacobsen and Wasserburg, 1980). ε_{Nd} error bars relate to 2 SE internal uncertainties, whereas the ^{147}Sm/^{144}Nd errors (2 SD) are not displayed on the plot but are always less than 0.002. Isochrons are displayed; see text for explanation. "n" refers to the number of apatites analysed per sample which yielded a ε_{Nd} uncertainty <2 ε-units. Indian versus Eurasian provenance fields (based on the majority of the data) are made distinct. ε_{Nd} values from published bulk rock data are presented as a bar chart on the y-axis, with corresponding frequencies displayed on a separate x axis. Data sources for bulk rock data are: Eurasian plate: TH (Transhimalaya)—Allegre and Othman (1980); Kohistan—Jagoutz et al. (2006), Khan et al. (1997), Petterson et al. (1993); Karakoram—Schärer et al. (1990); Lhasa Block—Debon et al. (1986); and Indian plate: TSS (Tibetan Sedimentary Series), HHCS (Higher Himalayan Crystalline Series), and LH (Lesser Himalaya)—Ahmad et al. (2000), Ayres (1997), Deniel et al. (1987), France-Lanord et al. (1993), Inger and Harris (1993), Parrish and Hodges (1996), Prince (1999), Whittington et al. (1999), and Miller et al. (2001).

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to occur in the uppermost levels of the Indus Basin stratigraphy (named the Nimu Formation), based on detrital Ar–Ar ages of white micas. Despite this controversy, the approach of identifying the earliest stratigraphic level whereby both Indian and Eurasian plate derived material is present is, at least in principal, a useful tool for constraining the timing of collision.

Indian and Eurasian margin sources can also be characterised by different bulk rock ε_{Nd} values reflecting their different ages and lithologies, as documented by a number of workers (e.g. Ahmad et al., 2000; France-Lanord et al., 1993; Parrish and Hodges, 1996; Robinson et al., 2001; Schärer, 1990; Whittington et al., 1999; Fig. 2). Results of bulk rock Nd isotopic analysis conducted by Clift et al. (2001a) on the Indus Basin sedimentary rocks imply that the majority of detrital sediment was sourced from the Eurasian margin, with a shift to encompass a wider range of ^{143}Nd/^{144}Nd values towards upper stratigraphic levels, inferring an additional input. Due to the fact that bulk rock studies only provide a result reflective of the average isotopic value of the analysed sample, (as discussed further in section 3), based on Nd results alone, the authors could not determine whether this change was reflective of an Indian, or additional Eurasian plate source contribution (or both). This uncertainty has hampered the usefulness of bulk rock Nd analysis as a means for detecting evidence of the first mixed India–Eurasian sediment provenance received in the Indus Basin. To rectify this problem, the aim of this contribution is to demonstrate the utility of the newly developed technique of in situ Sm–Nd analyses on single grain apatites as a provenance discriminator tool which is particularly suitable to distinguish between Indian and Eurasian sediment provenance.

2. Geology of the Himalaya

The Himalaya is composed of several metamorphic and structurally distinct geological terranes (Fig. 1). To the northwest outcrop the metamorphic and sedimentary rocks of the Karakoram and, in the northeast, those of the Lhasa Block. These terranes, composed of low grade metamorphosed Palaeozoic to Mesozoic sedimentary rocks overlying over mid Proterozoic–early Cambrian aged basement (Yin and Harrison, 2000) are separated by the Karakoram Fault (Searle et al., 1988). However they are both considered to be of similar affinity, representing the original continental plate of Eurasia (Gaetani et al., 1990). Intruding into the southern margin of the Eurasian Plate is the Transhimalaya; an Andean style continental arc composed of Jurassic-Early Tertiary calc-alkaline granitoids (Scharer and Allegre, 1984), and Tertiary volcanic sequences (e.g. the Linzizong Formation; e.g., Chung et al., 2005). Unconformably onlapping the Transhimalaya to the south lies the ITSZ basin (Gansser, 1977), composed of Tertiary sediments deposited within an evolving forearc to intermontane basin setting during the initial phases of India–Eurasia collision. The basin is thus regarded to contain both pre-collisional forearc basin sediments as well as younger post-collisional intermontane basin sediments (Searle et al., 1990); the Indus Basin sedimentary rocks. However recent work by Henderson et al. (In review—a) has questioned this proposed depositional environment by suggesting that the Indus Basin sedimentary rocks were deposited within an arc-bounded basin. South of the ITSZ the Tibetan Sedimentary Series (TSS) is exposed, representing a siliciclastic and carbonate sedimentary sequence deposited on the northern passive margin of India during the Palaeozoic–Eocene (Gaetani and Garzanti, 1991). A large normal fault system known as the South Tibetan Detachment Zone (STDZ) separates the TSS in the north, from the metamorphosed High Himalaya Crystalline Series (HHCS) to the south (Searle, 1986). The HHCS consists of Neoproterozoic metasedimentary rocks of Indian plate origin, metamorphosed to medium–high grade during the Tertiary Himalayan orogeny (Hodges, 2000). The original Neoproterozoic sedimentary protolith or cover to the HHCS is still preserved within the realms of this terrane, which has been subject to only low grade metamorphic conditions, and is represented by a sequence known as the Haimanta Formation (Miller et al., 2001). The Main Central Thrust (MCT) separates the HHCS and Haimanta from the largely unmetamorphosed Lesser Himalaya in the south. The Lesser Himalaya is composed predominantly of low grade or unmetamorphosed Indian crustal rocks of dominantly Precambrian to Palaeozoic age (Hodges, 2000; Miller et al., 2000; Tewari, 1993; Valdiya, 1980). In some regions, the Lesser Himalaya has been further subdivided into the Palaeoproterozoic Inner Lesser Himalaya and the Neoproterozoic–Cambrian Outer Lesser Himalaya (Richards et al., 2005). The Sub-Himalaya, containing the Himalayan foreland basin sedimentary rocks, lies to the south of the Lesser Himalaya, with the Main Boundary Thrust (MBT) separating the two terranes. A blind thrust system of the Main Frontal Thrust (MFT) exists at the southern limit of the Sub-Himalaya, emplacing it onto the modern foreland basin which contains sediments of Miocene–Pliocene age (Molnar, 1984).

3. In situ Sm–Nd analyses of apatite grains

In the Himalayas, the various lithotectonic units (the Lhasa Block and Karakoram, Transhimalaya, TSS, HHCS and Lesser Himalaya; Fig. 1) have distinct and characteristic Nd whole rock values (see data compilation within Clift et al., 2001a; 2001b; Fig. 2) and these isotopic distinctions are largely consistent along strike all along the Himalayan orogen (e.g. Richards et al., 2005). Of particular relevance for this study, it has been documented that the Eurasian crust is more radiogenic than the Indian crust (see data compilation within Clift et al., 2001a; 2001b).

In regions where source terrains have different Sm–Nd characteristics and different crustal residence times, the ^{143}Nd/^{144}Nd isotope ratio of bulk detrital sediment has successfully been applied as a provenance discriminator (Depaolo, 1981). This isotopic system has also been widely used as a provenance tool applied to bulk rock analyses in the various Himalayan sedimentary units (Clift et al., 2001b; Huyghe et al., 2001; Najman et al., 2001; Robinson et al., 2001). However, despite the major differences in isotopic characteristics between the different lithotectonic units, in this bulk method, the isotopic composition of each detrital sample reflects the input from all contributing source terrains, weighted according to its Nd concentration. Thus, more minor source contributions are probably undetectable in the detritus using a bulk sediment approach and, given the range of Himalayan sources, mixing between sources could easily lead to ambiguous provenance determinations.

A novel provenance technique has been recently developed by Foster and Carter (2007) based on the Nd isotopic composition of individual detrital apatite crystals analysed in situ using laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC–ICPMS; Foster and Vance, 2006). With this in situ method, isotopic measurements of *individual* detrital apatites can be obtained from each detrital sample, making it a much more suitable technique when analysing detrital sediment containing a mixed source contribution. In particular it is very useful for identifying subordinate source contributions, which are typically masked in bulk rock studies.

To improve Himalayan provenance identification both Foster and Carter (2007) and Carter and Foster (2009) used the in situ method for measuring Nd isotopic ratios of individual apatites. Provenance of Holocene and modern Himalayan river sands was determined by comparing grains in the sands to grains from the potential source region, either separated from local bedrock samples or from river sands from restricted catchments in the source region being characterised. Their results indicated that apatites from the HHCS often had relatively young ages of crystallisation and metamorphism (<100 Ma) and therefore possessed ^{143}Nd/^{144}Nd (but not ^{147}Sm/^{144}Nd) values very similar to the values of bulk rock analyses from the same sample (Fig. 2). The reason for this is due to their relatively young age (<100 Ma) and the relatively long half life of ^{147}Sm (half life $= 1.06 \times 10^{11}$yr). Given their relatively young crystallisation ages the expectation is that apatites from Eurasian

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source rock, and in particular the Transhimalayan Mesozoic and Tertiary granitoids and volcanics, will also record ^{143}Nd/^{144}Nd ratios that are similar to their bulk rock values (e.g. Clift et al., 2001b; Fig. 2). Therefore these grains will be easily distinguishable from apatites sourced from the high grade portion of the HHCS because they should record ^{143}Nd/^{144}Nd ratios typical of the Transhimalayan granitoids and volcanics. Foster and Carter (2007) also found that apatites sourced from an older, pre-Himalayan low grade metamorphic mineral assemblage (produced by earlier metamorphism) from the high structural levels of the Chekha Formation in Bhutan (regarded as being equivalent to the Everest Series of the TSS; Searle et al., 2003), have ^{143}Nd/^{144}Nd ratios very different to the bulk rock result, since the isotopic ratios of the apatites have not been sufficiently reset by the Himalayan metamorphic event or grew during it. These older grains roughly define a ~500 Ma isochron, reflecting the amount of radiogenic ^{143}Nd ingrown with time, with an initial ^{143}Nd/^{144}Nd similar to typical HHCS. Although this may complicate source identification because the ^{143}Nd/^{144}Nd ratio of an apatite depends on ^{147}Sm/^{144}Nd, initial ^{143}Nd/^{144}Nd and age (Carter and Foster, 2009; their Fig. 3), Foster and Carter (2007) suggested that this adds an extra level of source discrimination that is not possible using only a bulk rock method.

The work of this study builds on the research of Foster and Carter (2007) and Carter and Foster (2009), by 1) further investigating the distinction of apatite Nd values between the other main Himalayan terrains as predicted by extensive bulk rock data studies (Fig. 2), and in particular characterisation and discrimination between an India versus Eurasian source and 2) based on this new provenance discrimination, evaluate how effective the in situ method is for determining detrital sedimentary provenance of the Indus Basin sedimentary rocks. We explore what new insights this information can provide to our understanding of early Himalayan evolution, with an overall aim of determining if the Indus Basin records evidence of a mixed Indian and Eurasian detrital sourced provenance and so test its use in constraining the age of collision.

4. Sampling approach

4.1. Modern river samples

Modern sediments from rivers draining restricted catchments were used to obtain a representative characterisation of individual source units. Wherever possible, medium grained modern river sand samples were collected from river beds with catchments draining a single geological terrane, including: Lhasa Block (defined here as representing the sedimentary and metamorphic country rock into which the Transhimalayan arc intruded; sample HKT10A); Transhimalaya (sample KL06003); TSS (samples TS07001, and HKT4A); the Haimanta Formation (sample BEAS06); Lesser Himalaya (samples NAUTI06 and RT06028). Fig. 1 (and Supplementary Figs. S1a–S1d) shows the locations from where the samples were collected. To ensure samples were collected from rivers draining single lithotectonic units, small catchments were often chosen, draining a relatively small proportion of the given terrane. Inevitably there will be geological variation along strike, and this work serves to provide the initial stages of a new framework with the potential of creating a much larger database from further sampling and analyses. However, it is important to note that on the basis of extensive previously-published bulk rock work we do not anticipate major along strike variation in Nd (see Richards et al., 2005).

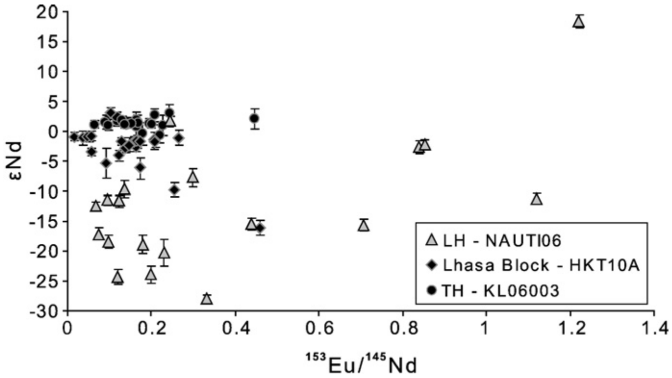

Fig. 3. Plot of ^{153}Eu/^{145}Nd versus ε_{Nd} displaying the differing ^{153}Eu/^{145}Nd values, (but similar ε_{Nd} values) between Eurasian and Outer Lesser Himalayan (OLH) sourced apatites. Internal errors for ε_{Nd} relate to 2 SE internal uncertainties. ^{153}Eu/^{145}Nd errors are typically smaller than the symbols and are not displayed. LH = Lesser Himalaya, TH = Transhimalaya.

4.2. Sedimentary rock samples

In this study we also analyse five Lower Eocene to Upper Miocene aged samples of medium grained sandstone (samples ZG06055, ZG06042, ZG06038, LT07060 and ZG06016) taken from various stratigraphic levels of the Indus Basin stratigraphy in the ITSZ (sample location: Fig. 1, Box A; Supplementary Fig. S1a).

5. Sample preparation and analytical methodology

Samples were crushed and ground using standard rock crushing techniques at the British Geological Survey, Keyworth UK. Typically between 5 and 25 detrital apatites from each sample were picked at random and mounted in epoxy resin which, when set, was ground and polished to expose the apatites. Analysis was hindered by the lack of apatites available in the older Indus Group samples (ZG06055, ZG06042, and ZG06038) where a combined total of 15 grains were analysed. Analysis by LA-MC–ICPMS was conducted at the University of Bristol and closely followed the methodology and approach outlined by Foster and Vance (2006) and Foster and Carter (2007), with some modifications, as outlined in section S2 of the Supplementary data.

Nd isotopic composition is expressed in epsilon units (ε_{Nd}); parts per ten thousand variation from CHUR of ^{143}Nd/^{144}Nd = 0.512638 (Jacobsen and Wasserburg, 1980), and the majority of Nd values for unknown apatites analysed here possessed internal precisions between 0.5 and 2 ε-units. Laser spot sizes were typically between 65 and 90 μm and since the majority of the apatite grains were <100 μm, in some cases grains were destroyed before completion of the full 100 s ablation. This shortcoming was associated with worse precision for these smaller grains and the potential of a slight bias. Full analytical results are presented in Section S2 of the Supplementary data.

6. Characterisation of apatite Nd values of the Himalayan lithotectonic units

Due to the range in Sm/Nd ratios typically exhibited by apatites, plots of ^{147}Sm/^{144}Nd vs ε_{Nd} (or ^{143}Nd/^{144}Nd) are the most useful way of investigating provenance using detrital apatite Sm–Nd data. Fig. 2 shows the success of this method in the discrimination of Indian from Eurasian sources. Despite the relatively large variation in apatites sourced from the Indian Plate, there is generally a clear distinction between the two source terranes, with Eurasian derived Lhasa Block and Transhimalayan apatites predominantly plotting with low ^{147}Sm/^{144}Nd ratios and high ε_{Nd} values in agreement with published bulk rock values (Allegre and Othman, 1980) and the Indian derived grains consisting of apatites sourced from the HHCS, Haimanta, Lesser Himalaya, and TSS dominantly possessing high ^{147}Sm/^{144}Nd ratios and low to high ε_{Nd} values.

In spite of this seemingly well defined source distinction there is some minor overlap between these fields and other features

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that require further discussion. For instance a small but significant proportion (~18%) of TSS grains shows Nd characteristics similar to apatites of Transhimalayan or Lhasa Block affinity (Fig. 2). We believe that in this case it is probably a consequence of the fact that the catchment of the Zanskar River where TS07001 was sampled also drains post-collision Paleogene sedimentary rocks of the Kong and Chulung La Formations which contain Eurasian detritus (Garzanti et al., 1987; Najman et al., 2010). Also, sample HKT4A drains TSS units composed of volcanic rich sediments (Pan et al., 2004). These are plausible sources to explain the occurrence of the apatites with low ^{147}Sm/^{144}Nd, high ε_{Nd} values, and further highlights the difficulties in obtaining modern river sediment which is sourced from a single geological terrane and the general diversity of Himalayan sources. We stress however that the overall majority (>80%) of TSS derived grains are distinct from those of the Transhimalaya and Lhasa Block.

Conversely, there is also a small percentage (~10%) of Lhasa Block sourced apatites whose Sm–Nd characteristics resemble those derived from the Indian Plate. This probably reflects apatites derived from the ancient (metamorphosed) Lhasa Block basement, or the sedimentary rock cover sourced from it. The occurrence of the majority of Lhasa Block grains possessing relatively high ε_{Nd} values and low ^{147}Sm/^{144}Nd ratios reflects that many sedimentary rocks within the Lhasa Block are reworked from their original Transhimalayan igneous provenance as already demonstrated by Leier et al. (2004). There is also the possibility that these apatites have been sourced directly from the TH, minor outcrops of which do occur within the headwaters of the river catchment chosen to represent drainage from the Lhasa Block. There is possibly the potential to distinguish a Lhasa Block from a Transhimalayan sourced apatite based on ε_{Nd} values alone, with grains from the Lhasa Block possessing slightly more negative ε_{Nd} values (Fig. 2). However, due to the large lateral distance between the sampling locations of both the Transhimalayan sample (KL06003) and the Lhasa Block sample (HKT10A), there is a possibility that these variations in ε_{Nd} values result merely from minor along strike variation in igneous isotopic composition.

It also appears possible to further subdivide apatites with an Indian Plate provenance. For example, in contrast to the high grade HHCS samples analysed by Foster and Carter (2007), apatite analysed from Haimanta and Lesser Himalayan units less affected by Himalayan metamorphism spread to considerably higher ε_{Nd} values (Fig. 2) than the bulk rocks, reflecting their higher ^{147}Sm/^{144}Nd compared to bulk rock (^{147}Sm/^{144}Nd $\approx$ 0.12) and an older signature not reset by Tertiary metamorphism. For instance, Sample BEAS06, draining the Haimanta, lie on a roughly defined ~500 Ma isochron, indicative of the presence of a pre-Himalayan aged apatite assemblage. Similarly, the majority of apatites from sample TS07001 draining the TSS plot on a poorly defined ~280 Ma isochron. An investigation of any potential significance of these isochron ages goes beyond the scope of this work but this nevertheless implies that much of the spread in Indian Plate apatites is a consequence of crystallisation age rather than varied initial ε_{Nd}, which is consistent with the tight clustering of bulk rock ε_{Nd} for Indian Plate rocks (Richards et al., 2005; Fig. 2). These data suggest, in the Himalaya at least, that detrital apatite Sm–Nd may allow a distinction between not only apatites derived from parent rocks with different initial ε_{Nd} (e.g. Transhimalaya and HHCS), but also those with similar initial ε_{Nd} but different metamorphic histories (e.g. Haimanta and HHCS).

Apatites from Lesser Himalayan sample NAUTI06 extend to ε_{Nd} values considerably more negative than that of published bulk rock Higher Himalayan bedrock and its constituent apatites, and consistent with Lesser Himalayan bulk rock values (Fig. 2). These more negative values are typical of the Inner Lesser Himalaya. The apatites with less negative values are most likely derived from the Outer Lesser Himalaya (sample NAUTI06) which shares a common signature with the Higher Himalaya (Ahmad et al., 2000; Richards et al., 2005) and through which the sample's river catchment also drains. Two grains from the Lesser Himalaya (NAUTI06-A and NAUTI06-H) exhibit relatively high ε_{Nd} values and low ^{147}Sm/^{144}Nd ratios, giving the initial appearance of a Eurasian affinity. The exact source of these grains is difficult to determine on the basis of the Sm–Nd method alone. A possible approach to further distinguish Lesser Himalayan grains with high ε_{Nd} values and low ^{147}Sm/^{144}Nd values from a Eurasian derived grain with similar Sm–Nd characteristics, is to examine the Rare Earth element ratios also analysed in this study in tandem with Sm–Nd (see Section S2 of the Supplementary data). Fig. 3 shows that Eu appears to be enriched relative to Nd in Indian plate grains with Eurasian-like ε_{Nd}, facilitating a source distinction.

7. Provenance of the Indus Basin sedimentary rocks

The stratigraphy of the Indus Basin sedimentary rocks combined with the Sm–Nd results is displayed in Fig. 4. Our results show that all grains are of Eurasian affinity and there is no evidence of Indian Plate input, although we recognise that limited number of grains were analysed. Thus, this technique does not provide any detrital evidence for collision documented by mixed Indian and Eurasian detritus, recorded throughout the stratigraphy. The presence of detrital grains originating from Tethyan ophiolites cannot be ruled out; however, we are not aware of any published Nd data that characterises this source and the amount of apatite in ophiolites is usually minor.

We do however observe evidence for a change in the nature of Eurasian provenance up-section. Based solely on ε_{Nd} values, the upper Tar Group and lower Indus Group samples (ZG06055, ZG06042, and ZG06038) have apatites which show positive ε_{Nd} values typical of a Transhimalayan source. In correspondence with stratigraphic younging there is an onset and gradual increase of input from the Lhasa Block (sample LT07060) with the Nimu Formation at the top of the stratigraphy being composed of detritus derived dominantly from the Lhasa Block (sample ZG06016). Our data are consistent with the findings of Clift et al. (2001a) whose bulk rock data also showed a move towards more negative ε_{Nd} values up-section. However, whilst their bulk rock data could not determine if this shift was due to an input of material from the Indian Plate, Lhasa Block, or even a combination of the two, our single grain analysis shows that there is no evidence to suggest that apatites were derived from the Indian Plate. This up-section change has been explained by post-collisional uplift of the Eurasian Margin (Clift et al., 2001a). Alternatively it may be due to significant dissection of the Transhimalaya and the development of a more extensive drainage network towards the north and northeast of the Indus Intermontane Basin, encompassing a greater areal extent of Lhasa Block through time (Wu et al., 2007). If however, the difference in apatite ε_{Nd} values between the Transhimalaya and Lhasa Black samples more accurately reflects merely spatial variation in igneous source region characteristics of the Transhimalayan arc (as discussed in Section 6), the shift in signature of the detrital material up-section may be the result of a change to the river drainage network within the TH. Such a change, if regionally significant, may reflect the rapid exhumation of the Transhimalaya in the region during deposition of the Nimu Formation (Kirstein et al., 2006).

8. Conclusions and wider implications

By applying the in situ Sm–Nd isotopic method to apatites from modern river sands draining each of the main Himalayan geological terranes we have demonstrated the potential of this approach to studies of ancient provenance. However, we recommend that future work build on and augment our detrital apatite Sm–Nd database in order to fully realise its potential.

This study has allowed a discrimination to be made between detrital apatites originating from the Indian Plate and those from the Eurasian Plate. Applying this information to our analysis of the Indus

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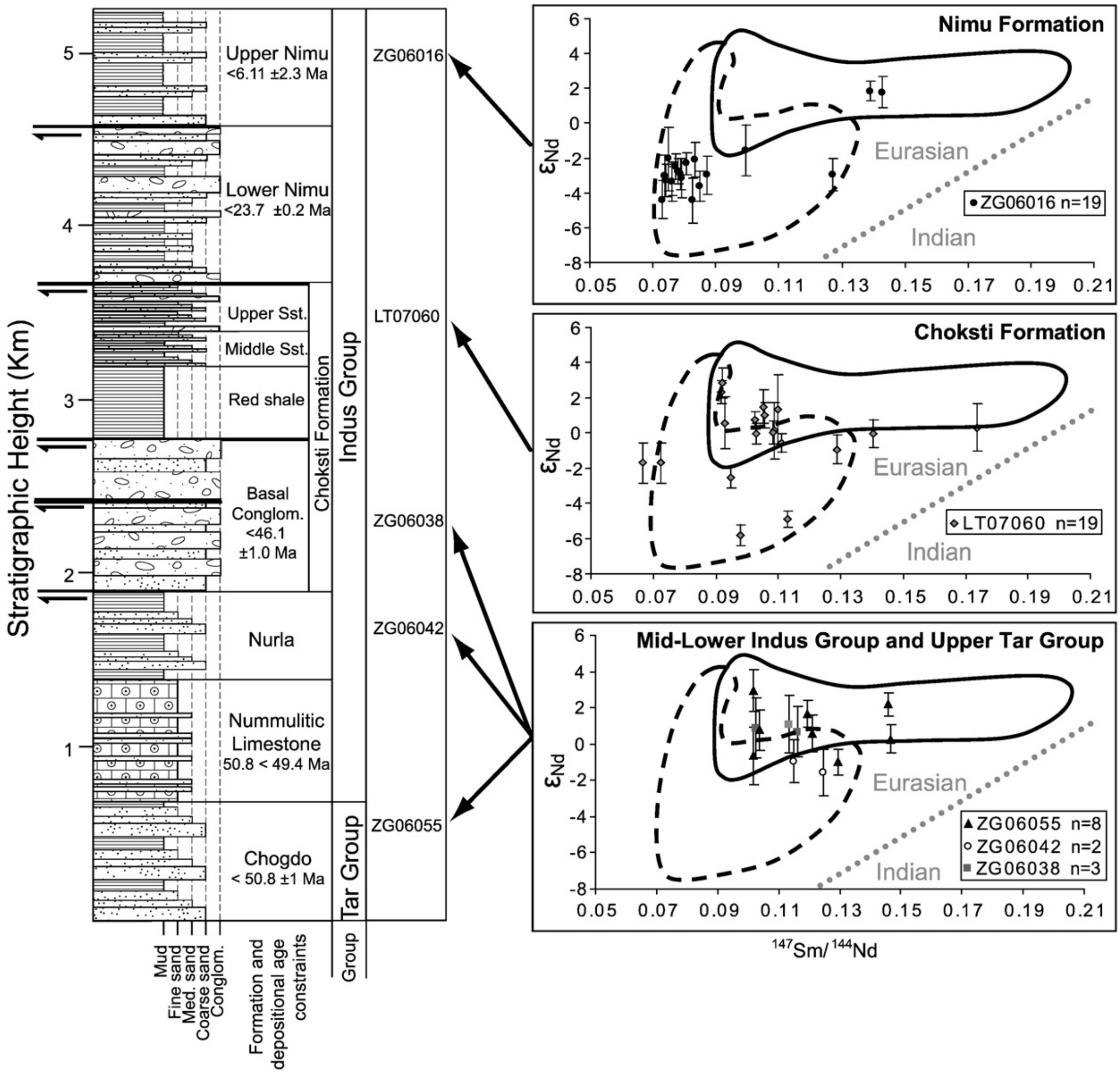

Fig. 4. Detrital apatite Sm–Nd isotopic results from the Indus Basin sedimentary rocks. Nd data are displayed in the form of ε_{Nd}. ε_{Nd} error bars relate to 2 SE internal uncertainties, whereas the $^{147}Sm/^{144}Nd$ errors (2 SD) are not displayed on the chart but are always less than 0.002. "n" refers to the number of apatites analysed per sample which yielded a ε_{Nd} uncertainty <2 ε-units. The field marked with the black solid line indicates values of Transhimalayan derived apatites and the field marked with the black dashed line shows values of Lhasa Block derived apatites. Division between Eurasian and Indian fields shown by dashed grey line. All fields were generated using the data presented in Fig. 2. Stratigraphic log and relative depositional ages are obtained from Henderson et al. (In review—a).

Basin sedimentary rocks, we show that all detrital apatites are Eurasian derived and we see no evidence for mixed Indian–Eurasian input within the Indus Group. Rather, our apatite data show a shift in source at progressively younger stratigraphic levels which likely reflects increasing contribution from the Lhasa Block or from a different sector of the Transhimalaya.

Our lack of evidence for mixed India–Eurasia input is in contrast to previous studies as described above, and throws into question the consequent constraints to the timing of India–Eurasia collision that have been based on that (Clift et al., 2002). It should be stressed again that application of more than one provenance technique is the most robust approach to determination of sources since certain minerals may not occur in a particular contributing source terrain and thus not be identified in the relevant provenance technique. Therefore a lack of apatites with Indian plate characteristics in the Indus Basin Sedimentary rocks may merely reflect a paucity of apatites in Indian plate strata. However, we find no evidence of Indian plate detritus in the lower Indus Basin Sedimentary Rocks when additional techniques are also employed (Henderson, et al. In review—a, b; Wu et al., 2007), and thus conclude that there is no unequivocal evidence for Indian plate input in the older Indus Basin Sedimentary Rocks and they cannot be used to constrain the timing of collision.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2010.06.001.

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