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# The Tethyan Himalayan detrital record shows that India–Asia terminal collision occurred by 54 Ma in the Western Himalaya

Y. Najman[a,*], D. Jenks[a], L. Godin[b], M. Boudagher-Fadel[c], I. Millar[d], E. Garzanti[e], M. Horstwood[d], L. Bracciali[a,d]

[a] LEC, Lancaster University, Lancaster, LA1 4YQ, UK
[b] Dept of Geological Sciences & Geological Engineering, Queen's University, Kingston, Ontario, K7L 3N6, Canada
[c] Dept Earth Sciences, UCL, Gower St., London, WC1E 6BT, UK
[d] NIGL, BGS Keyworth, Nottingham, NG12 5GG, UK
[e] Dipartimento di Scienze Geologiche e Geotecnologie, Università di Milano-Bicocca, 20126 Milano, Italy

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ABSTRACT

The Himalayan orogen is a type example of continent–continent collision. Knowledge of the timing of India–Asia collision is critical to the calculation of the amount of convergence that must have been accommodated and thus to models of crustal deformation. Sedimentary rocks on the Indian plate near the suture zone can be used to constrain the time of collision by determining first evidence of Asian-derived material deposited on the Indian plate. However, in the Himalaya, for this approach to be applied successfully, it is necessary to be able to distinguish between Asian detritus and detritus from oceanic island arcs that may have collided with India prior to India–Asia collision. Zircons from the Indian plate, Asian plate and Kohistan–Ladakh Island arc can be distinguished based on their U–Pb ages combined with Hf signatures. We undertook a provenance study of the youngest detrital sedimentary rocks of the Tethyan Himalaya of the Indian plate, in the Western Himalaya. We show that zircons of Asian affinity were deposited on the Indian plate at 54 Ma. We thus constrain terminal India–Asia collision, when both sutures north and south of the Kohistan–Ladakh Island arc were closed, to have occurred in the Western Himalaya by 54 Ma.



## 1. Introduction

Knowledge of the timing of India–Asia collision is critical to models of Himalayan orogenesis, in particular to the determination of the amount of plate convergence that must have been accommodated. Whilst the most commonly quoted age of collision lies within the range of ca. 60 to 50 Ma (e.g. Hu et al., 2016 and references therein), a more recent suggestion has been proposed whereby the above quoted age actually represents a collision between India and an intra-oceanic island arc or Tethyan microcontinent, with later terminal suturing between India and Asia perhaps as late 40 Ma (Bouilhol et al., 2013), 34 Ma (Aitchison et al., 2007) or 23 Ma (van Hinsbergen et al., 2012). Such a degree of difference in the time of final suturing of India with Asia results in differences of >1000 km in the calculation of the amount of continental crust that needs to be accommodated during convergence.

The NW Himalaya, where the Kohistan–Ladakh intra-oceanic island arc (KLIA; labelled as K and L in Fig. 1) is wedged between the Indian and Asian plates, provides the ideal location to study the relative timings of arc and continent collisions due to the excellent preservation and exposure of the arc. Using data from this region, a number of workers have proposed a ca. 60–50 Ma age for collision between India and the KLIA, with the KLIA already sutured to, and representing the southern margin of, Asia to the north. This is based on various factors including the time of elimination of marine facies in the Tethyan Himalaya and intervening Indus suture that provides a minimum age of collision (e.g. Green et al., 2008), age of eclogites indicative of onset of Indian continental subduction (e.g. Donaldson et al., 2013), and first evidence of detritus from north of the suture zone deposited on the Indian plate (e.g. Clift et al., 2002 but see also; Henderson et al., 2011) or sedimentary rocks containing both Indian and Asian provenance (Tripathy-Lang et al., 2013).

The above evidence can be interpreted as documenting the age of India–Asia collision if one takes the KLIA to have collided with the Asian plate prior to its collision with India (e.g.

* Corresponding author.
*E-mail address:* y.najman@lancs.ac.uk (Y. Najman).

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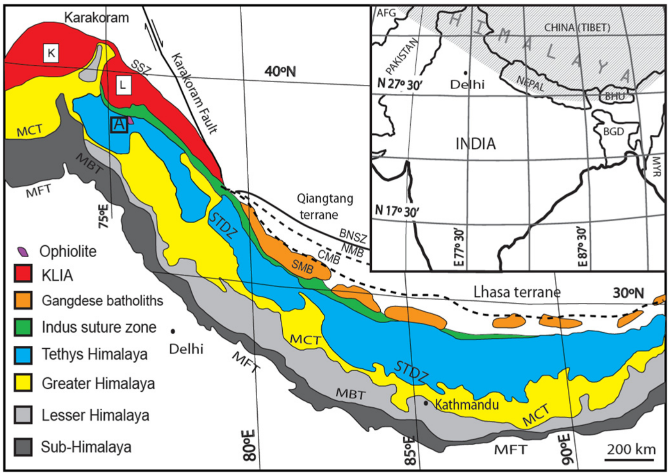


**Fig. 1.** Geological map of the Himalaya and sampling location (A), with location of Lhasa terrane magmatic belts adapted from Zhu et al. (2011). KLIA – Kohistan (K) and Ladakh (L) oceanic island arc; BNSZ = Bangong–Nujiang Suture Zone; SSZ = Shyok Suture Zone; STDZ = South Tibetan Detachment Zone; MCT = Main Central Thrust; MBT = Main Boundary Thrust; MFT = Main Frontal Thrust. "Ophiolite" refers to the Spongtang ophiolite. Magmatic belts of the Lhasa terrane (e.g. Chu et al., 2006) correspond to the Lhasa subterranes of Zhu et al. (2011): SMB = Southern Magmatic Belt of the Lhasa Terrane; CMB = Central Magmatic Belt of the Lhasa Terrane; NMB = Northern Magmatic belt of the Lhasa Terrane. Inset: location of the region in its wider geographical context: AFG = Afghanistan; BHU = Bhutan; BGD = Bangladesh; MYR = Myanmar.

Borneman et al., 2015). However, some workers propose that the KLIA collided with Asia subsequent to its earlier collision with India (e.g. see review in Burg, 2011), and that collision is dated variously as having occurred at 85 Ma (Chatterjee et al., 2013), 61 Ma (Khan et al., 2009) and 50 Ma (Bouilhol et al., 2013). In such a scenario, the criteria quoted above would be dating India–KLIA rather than India–Asia collision, with final collision of India + KLIA with Asia occurring not until later, for example at 40 Ma (Bouilhol et al., 2013). This, plus the questioning by Henderson et al. (2011) of previous work constraining collision by first arrival of material from north of the suture zone on the Indian plate (Clift et al., 2002), suggests that the time is right for a reappraisal of the relative timings of India–arc–Asia collision on the western side of the Himalayan orogen.

The criterion used in this paper to constrain the age of India–Asia collision is that of earliest evidence of Asian detritus deposited within the youngest Tethyan sedimentary rocks on the Indian plate. Differentiation of detritus between ancient passive Indian margin origin vs Mesozoic arcs (of Asian or KLIA origin) is relatively straightforward using petrography and U–Pb dating of detrital zircons. However, dating the timing of terminal India–Asia collision relies critically on the ability to differentiate between Asian- and KLIA-derived detritus. There is large overlap in the field of U–Pb ages of igneous zircons from the KLIA and the southern margin of the Asian plate (the Lhasa terrane), precluding differentiation between these potential sources on the basis of zircon age alone. However, zircons from these two terranes show differences in terms of zircon $\varepsilon$Hf characteristics, which reflect their juvenile vs more evolved sources. Thus, to assess the provenance of the detrital grains, we carried out Hf analyses on Mesozoic detrital zircons to discriminate between Asian vs KLIA source.

We then applied this provenance approach to the biostratigraphically dated Paleogene sedimentary rocks of the Kong and Chulung La Formations of the Tethyan Himalaya, in Ladakh, India (Fig. 1) to determine first evidence of Asian detrital input onto the Indian plate. Given the recent re-interpretation of syn-orogenic rocks in the suture zone in Ladakh (Henderson et al., 2011), and the inability of previous detrital studies to differentiate between an Asian vs island arc provenance (e.g. Tripathy-Lang et al., 2013) our study of these Tethyan rocks is the first isotopic provenance study used to differentiate between India–Asia and India–KLIA collision in NW India.

## 2. Geological background

The Himalaya (Fig. 1) resulted from the closure of the Tethyan Ocean and resultant collision between the northern palaeo-Indian passive margin to the south and the Eurasian active margin to the north.

To the south of the Indus–Yarlung suture zone, the northern margin of the Indian plate is composed of the Palaeozoic–Early Cenozoic Tethyan Himalayan passive margin sedimentary rocks, including the Palaeogene Kong and Chulung La Formations (Critelli and Garzanti, 1994; Garzanti et al., 1987), which are the focus of this study. Obducted onto the Tethyan Himalaya in either the Late Cretaceous (Searle et al., 1997) or Eocene (Garzanti et al., 1987), is the Jurassic Spontang ophiolite and arc (Pedersen et al., 2001).

In the NW part of the orogen, our area of study, the Mesozoic–Paleogene Kohistan–Ladakh intra-oceanic island arc is confined between the Indian plate to its south along the Indus Yarlung suture zone and to its north by the Asian plate Karakoram along the Shyok suture zone (e.g. Schaltegger et al., 2002). As noted above, the relative timings of the collisions between India, Asia and the KLIA are debated, with some researchers considering that the KLIA collided with India first (e.g. Khan et al., 2009), and others proposing it collided with Asia first (e.g. Borneman et al., 2015).

The Karakoram represents the continental arc of Asia in the NW part of the orogen. It consists of (i) a southern belt characterised by Late Jurassic–Cretaceous metamorphism related to subduction-related plutonism and later Cenozoic metamorphism associated with the India–Asia collision, (ii) a northern sedimentary belt characterised by Ordovician to Early Cretaceous sedimentary rocks, and (iii) pre-collisional plutons of Late Jurassic and Cretaceous age and post-collisional plutons as young as Miocene (e.g. Searle et al., 1999). To the east the KLIA dies out, and the Karakoram may be correlated with either the Lhasa or Qiangtang terranes of Tibet across the Karakoram Fault (Fig. 1) (Fraser et al., 2001; Robinson et al., 2012 and references therein). Fraser et al. (2001) speculate that the Karakoram and Lhasa terranes may have had similar magmatic and metamorphic histories prior to and during the early stages of India–Asia collision, with later tectonism causing deeper exhumation, to lower crustal levels, in the Karakoram.

The Lhasa terrane, which represents the southernmost extent of the Asian margin east of the Karakoram Fault, is composed of Phanerozoic low grade metamorphic and sedimentary cover overlying Precambrian–Cambrian basement (e.g. Leier et al., 2007). Along its southern rampart are intruded the Gangdese continental arc batholiths (Scharer and Allegre, 1984). Whilst Gangdese intrusions are Mesozoic–Paleogene aged, post-collisional igneous activity continued into Miocene times (e.g. Harrison et al., 2000). Chu et al. (2006) and Zhu et al. (2011) divide the Lhasa terrane into three magmatic belts or subterranes. The Gangdese batholiths represent the Southern Magmatic belt. The Mesozoic Central and Northern magmatic belts may be the result of either 1) the low angle northward subduction of the Neotethyan slab subducting beneath the Lhasa terrane from the south, or 2) the southward subduction of the Bangong Ocean sea floor that separated the Lhasa terrane from the Qiangtang Terrane to its north, prior to their col-

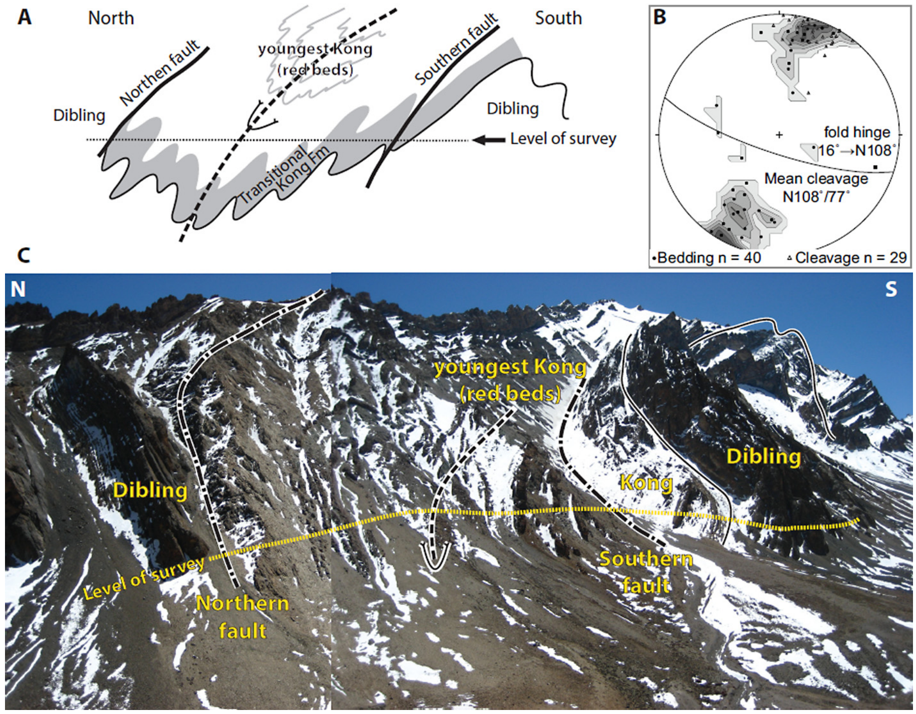


**Fig. 2.** (A) Schematic cross-section showing the shallow east-plunging Chulung Chu syncline at (34°08′21.9″N, 76°36′07.8″E) bounded by two faults and cored by the youngest Kong Formation red beds. (B) Equal area lower hemisphere stereonet of folded bedding surfaces (black dots; 1% area contours) with a cylindrical best-fit fold hinge plunging 16° towards N108°. The average axial plane cleavage (white triangles) strikes N108° and dips 77° towards the south. (C) Oblique panorama photo of surveyed site (yellow line indicates line of survey, as labelled, which corresponds to the line of survey marked in this Figure's Part A). The youngest Kong units are exposed in the core of the syncline, in the upper, more recessive part of the cliff face. The full black lines mark the contact between the Kong and Dibling formations. The base of the rock exposure is at 4300 m above sea level, whereas the top of the ridge is at 5000 m above sea level. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

lision in the Late Jurassic–Early Cretaceous (see discussion in Zhu et al., 2009).

## 3. Stratigraphy and structure of the Kong and Chulung La Formations

The clastic Kong and Chulung La Formations are the focus of this study. They are the youngest known Tethyan sedimentary rocks in the region, and are of shallow marine and fluvio-deltaic facies, respectively (Garzanti et al., 1987). The Kong Formation's contact with the stratigraphically underlying Paleocene–Early Eocene Dibling Limestone (Nicora et al., 1987) is conformable at some locations (Green et al., 2008) and interpreted as unconformable at others (Garzanti et al., 1987). Where the Kong is not overthrust by the Spongtang ophiolite, its upper contact with the overlying Chulung La Formation is described as transitional (Fuchs and Willems, 1990) although Green et al. (2008) and Garzanti et al. (1987) suggest that the two formations are interfingered, indicating that their deposition was partly coeval.

The Kong Formation has been biostratigraphically dated at different localities between 56–52 Ma (Fuchs and Willems, 1990) and <50.5 Ma (based on a fossil assemblage dated at Shallow Benthic Zone SBZ9–10 and interpreted as reworked from the underlying limestone formation; Green et al., 2008). The Chulung La Formation is unfossiliferous and therefore biostratigraphically undated, constrained only by the debated stratigraphic relations to the Kong Formation (see above).

Both an arc provenance (the southern margin of the Asian plate) and an ophiolitic provenance (the Spongtang ophiolite–arc complex obducted onto the Indian plate) have been proposed for these formations (Fuchs and Willems, 1990; Garzanti et al., 1987; Green et al., 2008).

### 3.1. The Kong Formation at Chulung Chu

The Chulung Chu study site (34°08′21.9″N, 76°36′07.8″E; Supplemental Information DR1 for sample locations) is characterised by a shallow east-plunging tight syncline cored by green Kong Formation sandstone and mudstone and flanked by the Dibling Formation limestone (Figs. 2 and 3). The limbs of the syncline are offset by minor faults. A spaced slaty axial plane cleavage provides clear bedding/cleavage relationships that allow identification of smaller fold closures parasitic to the larger syncline (Fig. 2B). The Dibling and the Kong Formations are folded in a complementary anticline at the southern end of the site.

A 'transitional Kong' series of interbedded clastic and carbonate rocks is found at the contact with the underlying Dibling Formation at both the southern and northern margins of the syncline. A transitional series has previously been assigned, at other locations, to the Dibling Formation (Green et al., 2008). However at this location we assign the interbedded limestone and clastic facies to the Kong rather than Dibling Formation in view of the presence of sandstone, signalling the return of detrital input to the basin, which is absent from the Dibling Formation. The Dibling-transitional Kong Formation contact is conformable at the southern margin of the syncline, and faulted at the northern margin.

To constrain the age of the succession, we primarily use the planktonic foraminiferal zonal scheme of BouDagher-Fadel (2013a), which is tied to the time scale of Gradstein et al. (2012). The samples from the transitional Kong Formation at the southern contact (CC08-3A and B) are micritic wackestone of planktonic and larger benthic foraminifera. The planktonic foraminifera are of Early Eocene age and the presence of *Globanomalina planoconica* (P5a–P10), *Planorotalites chapmani* (P3b–P6) and *M. edgari* (Late P5 to Early P6) indicates Late P5 to Early P6 (planktonic foraminiferal Zone), 56–54 Ma (Supplementary Information DR 2a). The sam-

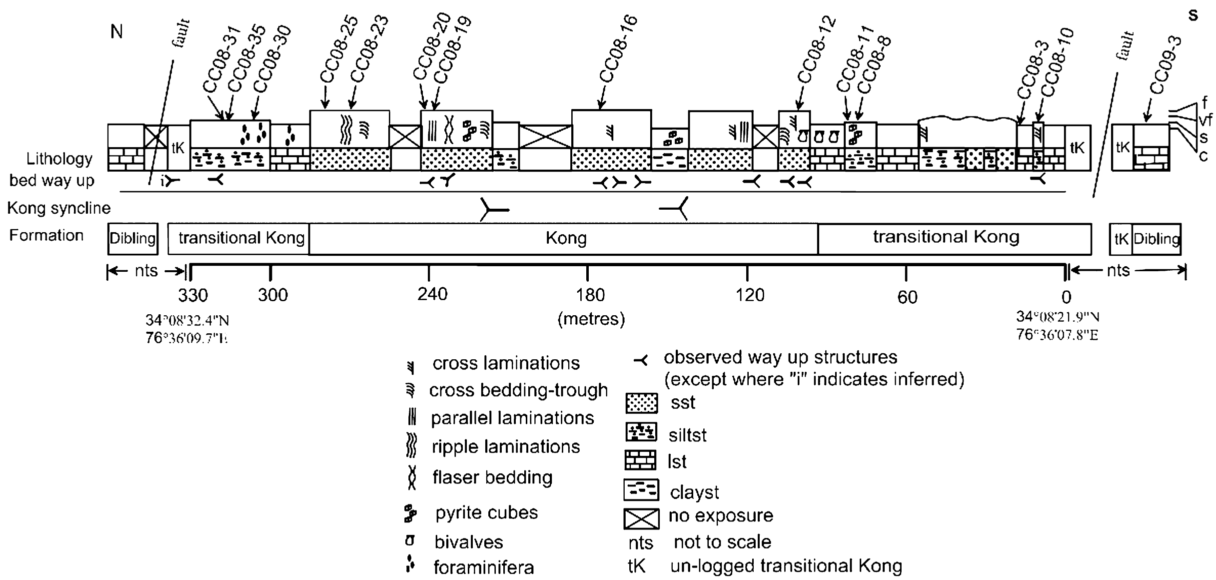


**Fig. 3.** Sedimentary log along line of section shown in Figs. 2A and C, also showing where way-up structures were observed and locations of samples.

ples from the transitional Kong Formation at the northern contact (CC08-30A and 35A) are micritic wackestone of larger benthic foraminifera; *Assilina* spp., *Assilina granulata*, *Assilina granulosa* var. *chhumbiensis*, *Assilina subdaviesi*, *Assilina leymeriei*, *Nummulites exilis*, *Assilina pomeroli* are of Early Eocene age, SBZ8–SBZ9, (54.0–52.3 Ma). These dates are in agreement with previous results from the same location (Fuchs and Willems, 1990) and indicate that this section does not extend to the youngest Kong Formation as dated at other locations (Green et al., 2008).

The fossil assemblage from the Dibling Formation directly below the Kong Formation at the southern margin (CC09-3) is a micritic wackestone of small miliolids (*Quinqueloculina* sp.), and larger benthic foraminifera: *Nummulites globulus*, *Lockhartia conditi*, *Nummulites atacicus*, small textularids and *Alveolina* sp. (Supplementary Information DR2b). The presence of the larger benthic foraminifera *Nummulites globulus, N. atacicus* and *Lockhartia conditi* indicates an Early Ypresian age (Late SBZ7 to Early SBZ8 Zone), 55.2–54 Ma. This assemblage is similar to that described for the uppermost Dibling Formation at other locations (Nicora et al., 1987). However, it is of different facies and form to that of the Kong Formation, by which we discount the likelihood that the Kong foraminifera were reworked from the underlying Dibling Formation. The biostratigraphically determined age of the Kong Formation is consistent with the youngest detrital zircon U–Pb age of 56.3 ± 1 Ma (see below).

### 3.2. The Chulung La Formation at Marpo

At Marpo (34°03′42.0″N, 76°29′43.1″E, Supplemental Item DR1 for sample locations), a ridge of red clastic unfossiliferous Chulung La Formation dips gently to the northeast. The base of the section comprises black shale, dark grey sandstone and minor limestone (Supplemental Information DR2b) of indeterminate age. The contact between these facies and the overlying red sandstone is obscured by scree and snow. Garzanti et al. (1987) described the contact as covered and interpreted it as an unconformity with the Dibling limestone below, the top of which is dated at P6 (54.9–52.3 Ma; BouDagher-Fadel, 2013b). The youngest detrital zircon U–Pb age from this section is 53.7 ± 1.5 Ma (our data, see below), which provides a maximum depositional age for the rock.

## 4. Provenance of the Kong and Chulung La Formations

### 4.1. Methods and results

Provenance analysis of detrital grains from the Kong and Chulung La Formations was performed to discriminate between Indian, Asian and KLIA derivation, and thus constrain timing of India–Asia collision by first evidence of Asian material deposited on the Indian plate. Petrographic analyses and U–Pb dating of zircons allowed discrimination between the ancient sedimentary passive margin of the Indian plate versus the predominantly igneous rocks of the southern Asian margin and the KLIA. Hf analyses of the Mesozoic zircons, combined with their U–Pb ages, allow further differentiation between the Asian plate and the KLIA based on their different signatures (see Table 1 and below). Table 1 summarises the source regions' petrographic and isotopic characteristics.

#### 4.1.1. Petrography of the Kong and Chulung La Formations

Modal analyses were carried out on seven Chulung La sandstone samples and three Kong sandstone samples by counting 300 points according to the Gazzi–Dickinson method (Ingersoll et al., 1984) (Figs. 4 and 5; Supplemental Information DR3). Significant late diagenetic carbonate replacement and anchimetamorphic recrystallisation was observed in all samples. In Kong Formation sandstone, detrital modes obtained by point-counting may not accurately reflect the original composition due to the particularly extensive diagenetic modification of the original framework.

*4.1.1.1. The Kong Formation* The Kong Formation in the Chulung Chu section mostly includes calcareous and sericitic or chloritic slate, with intercalated very fine to fine-grained sandstone (average median diameter 2.8 ± 0.3$\phi$). Micritic limestone with sporadic bioclasts (bivalves, benthic forams), and recrystallised bioclastic grainstones (bivalves, echinoderms) also occur. Sandstone layers invariably show strong anchimetamorphic recrystallisation with growth of sericite and stilpnomelane ('zone of quartzitic structures and hydromica-chloritic cement' of Kossovskaya and Shutov (1970). Late diagenetic carbonate minerals are invariably widespread (33 ± 3% of the rock); they selectively replaced chemically unstable grains.

The Kong sandstones are characterised by dominant and commonly twinned detrital plagioclase, with minor chessboard al-

**Table 1**
Summary table of the petrographic and zircon U–Pb and Hf characteristics of the Tethyan margin of the Indian plate, Kohistan–Ladakh Island arc, and Asian margin including both the Karakoram and the Lhasa Terrane – Southern (Gangdese batholiths), Central and Northern magmatic belts. References as given in captions for Figs. 6, 7 and 8, and DR4 and 5.

| | Lithologies | U–Pb zircon characteristics | Zircon $\varepsilon$Hf characteristics |
|---|---|---|---|
| *Northern margin of Indian plate* (predominantly Tethyan Himalaya) | Passive margin carbonates/clastics; minor ophiolite; some material from the metamorphic Greater Himalaya drains north. | Overwhelmingly Precambrian to Palaeozoic except for a small population aged 125–130 Ma derived from the Stumpata Fm, and rare zircons from the Spontang ophiolite arc complex at 177 and 88 Ma. | Predominantly negative values for Precambrian–Palaeozoic populations and for zircons from the Stumpata Fm equivalents. Spontang ohiolite – n.d. |
| *Southern margin of Asia*: Lhasa terrane, Southern (Gangdese), Central, and Northern magmatic belts | Igneous continental arcs, intruded through predominantly sedimentary rocks. | Precambrian–Palaeozoic grains derived from sedimentary rocks, indistinguishable from Indian plate detritus. Magmatic belts consist of zircons of Jurassic to Cretaceous age (Northern and Central belts) and to Cenozoic age (Southern belt). | Northern/Central magmatic belt: predominantly negative $\varepsilon$Hf values. Southern magmatic belt: predominantly but not exclusively positive values for grains >50 Ma. |
| Karakoram | Metamorphic and sedimentary belts intruded by Jurassic to Cenozoic granitoids. | Predominantly Cretaceous and Cenozoic grains, locally Jurassic, from igneous sources. Palaeozoic and Precambrian basement and sedimentary recycled grains. | Very limited data available. Negative $\varepsilon$Hf values for these data. |
| *Kohistan–Ladakh Island arc (KLIA)* | Igneous intra-oceanic island arc. | Cretaceous–Cenozoic, minor older (inherited) grains. | Predominantly positive values until ca. 50 Ma. |

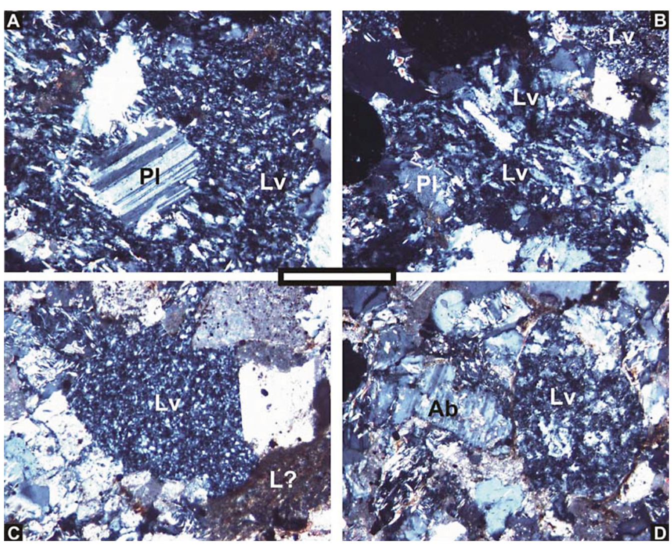


**Fig. 4.** Petrography of the sandstones of the Chulung La (Plates A and B) and Kong (Plates C and D) Formations. Volcanic detritus (Lv = volcanic lithic fragments; Pl = plagioclase; Ab = chessboard albite) is dominant in both units. L? = shale/slate lithic grain (or possibly intrabasinal rip-up clast). White bar = 250 μm. All photos taken under crossed polars.

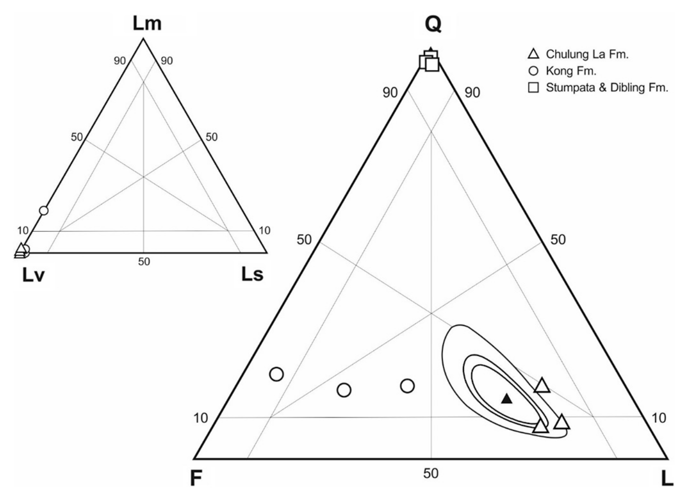


**Fig. 5.** Sandstone petrography. Quartzo–feldspatho-lithic Chulung La sandstones and quartzo–litho-feldspathic to quartzo-feldspathic Kong sandstones indicate undissected to transitional magmatic arc provenance (Garzanti, 2016; Marsaglia and Ingersoll, 1992). Detritus eroded from the Indian subcontinent would plot instead close to the Q pole, as illustrated by the Stumpata Formation data (Garzanti and Hu, 2015). Q = quartz, F = feldspar, L = lithic fragments (Lm = metamorphic, Lv = volcanic, Ls = sedimentary); 90%, 95% and 99% confidence regions about the mean for Chulung La sandstones are shown (data after Garzanti et al., 1987).

bite or albitized alkali-feldspar (Quartz 18 ± 2, Feldspar 60 ± 13 Lithic fragments 22 ± 15; Plagioclase/Total Feldspar 95 ± 4, Volcanic Lithics/Total Lithics 93 ± 12). Detrital quartz, mostly monocrystalline and showing straight extinction if undeformed, is invariably scarce. Among the lithic fragments, volcanic types are dominant (mostly felsites and microfelsites, with subordinate vitric and rare plagioclase-bearing porphyric grains; Fig. 4). Frequently observed microfelsite patches, showing blurred outlines and passing indistinctly to a tectosilicate–phyllosilicate compatible cement, are interpreted as pseudomatrix of volcanic origin. Rare low-rank metamorphic grains (slate, phyllite) also occur, as well as common hematitic rip-up clasts. Muscovite and rare biotite occur. Rare heavy minerals include zircon, tourmaline, ilmenite, and magnetite.

*4.1.1.2. The Chulung La Formation* The Chulung La Formation in the Marpo section includes burrowed silty marl and bioclastic packstone (bivalves, miliolids), passing upward to red mudrock and very fine to fine-grained sandstone (average median diameter 2.9 ± 0.2$\phi$) arranged in fining-upward sequences. Sandstone layers invariably show deformation in upper anchizonal conditions, with growth of sericite and epidote at estimated temperatures around 300 °C ("upper prehnite–pumpellyite facies"; Garzanti and Brignoli, 1989). Carbonate replacement (16 ± 9%) and anchimetamorphic recrystallisation is conspicuous.

The Chulung La sandstones contain dominant volcanic rock fragments, commonly twinned plagioclase, subordinate monocrystalline quartz showing straight extinction if undeformed, and minor chessboard albite (Quartz 15 ± 7, Feldspar 27 ± 5 Lithic fragments 58 ± 10; Plagioclase/Total Feldspar 99 ± 1, Volcanic Lithics/Total Lithics 99 ± 1). Volcanic lithic grains include mainly felsic types (quartz-rich microfelsites, quartz–feldspar felsites, commonly calcitized vitric grains) and subordinate intermediate types (microlitic grains, quartz–plagioclase holocrystalline grains, a few lathwork grains). Sedimentary and metamorphic lithic fragments are rare, but feldspathic to volcanic siltstone, sparite, reworked Globotruncana, possible chert, slate and phyllite were observed. Distinction of lithic grains from hematitic rip-up clasts is locally difficult. Heavy minerals include prismatic zircon, tourmaline, common red to yellow-brown Cr-spinel (Critelli and Garzanti, 1994), apatite, titanite, rutile, magnetite and ilmenite.

*4.1.2. U–Pb analysis of zircon grains from the Kong, Chulung La and Stumpata Formations*

Detailed methodologies, data tables, and concordia plots are given in Supplementary Information DR4. Grains were separated using standard techniques. Samples were annealed and chemically abraded. Three samples did not undergo the annealing/chemical abrasion process, in order to evaluate this approach. However, since nearly all data were concordant, little variation in discordance between annealed and unannealed samples was observed. All grains were imaged using a scanning electron microscope (SEM) by cathodoluminescence (CL) to allow zoning within the zircon grain to be visible. Data were collected using a solid-state 193 nm wavelength laser ablation system (UP193SS, New Wave Research) coupled to a multiple-collector inductively-coupled-plasma mass spectrometer (MC-ICP-MS, Nu Instruments) at the NERC Isotope Geosciences Laboratory (NIGL).

U–Pb data from zircons from the Kong and Chulung La Formations, as well as from the Early Paleocene Stumpata quartzarenite from the region, the youngest Indian passive margin clastic sedimentary rocks deposited prior to the Kong Formation, are plotted in Fig. 6. Grains from both the Kong and the Chulung La Formations are predominantly Mesozoic to Cenozoic with dominant grain populations between 55–70 Ma and 90–100 Ma. In contrast, all grains in the Stumpata Formation are Precambrian except a minor population dated between 125–130 Ma, similar to the data obtained by Clift et al. (2014).

*4.1.3. Hf analyses for selected U–Pb dated zircons from the Kong and Chulung La Formations*

As outlined in Section 1, Table 1 and illustrated in Fig. 7, it is possible to distinguish between Asian and KLIA sources on the basis of the combined U–Pb age and Hf characteristics of zircon. Therefore, in order to differentiate between Asian margin versus KLIA provenance for the Mesozoic–Paleogene zircon population in the Kong and Chulung La samples, these grains were further selected for Hf analysis. Samples were analysed at NERC Isotope Geoscience Laboratories using a 193 nm ArF Excimer laser system (NWR193UC, New Wave Research) coupled to a Thermo Scientific Neptune Plus multiple collector plasma ionisation mass spectrometer. Detailed methodology and data tables are given in Supplementary Information 5.

The majority of the grains (<115 Ma) have positive $\varepsilon$Hf values, dropping down to negative values for the youngest grains. In contrast, grains in the 115–250 Ma range have predominantly, although not exclusively, negative values (Fig. 7).

*4.2. Provenance interpretation*

Petrography of the Kong and Chulung La samples show a dominance of igneous material, consistent with derivation from continental arcs of the Asian plate and/or the KLIA, and inconsistent with a predominantly Indian passive margin source. Subordinate derivation from the Spongtang ophiolite is suggested by serpentine schist grains and Cr-spinel.

The U–Pb analyses of zircons from the Kong and Chulung La Formations (Fig. 6) show a dominant Mesozoic–Paleogene population, consistent with a predominantly Asian Gangdese Lhasa Terrane or KLIA origin and inconsistent with a predominantly Indian plate origin (i.e. Tethyan Himalaya), which is dominated by Precambrian grains. The dominant detrital population in the Kong and Chulung La Formations between 55–70 Ma mirrors the populations of grains from the KLIA and Gangdese batholiths. A Spontang ophiolite–arc source is unlikely for these Kong and Chulung La grains for two reasons. Firstly, zircons are not common in the ophiolite sequences. Secondly, the population aged 55–70 Ma is significantly younger than the published ages for the Spongtang ophiolite and overlying andesitic island arc; zircons from the Spongtang ophiolite and arc have been dated at 177 ± 1 Ma and 88 ± 5 Ma respectively (Pedersen et al., 2001), and furthermore we have not documented zircons in the 55–70 Ma age range in the modern river sand draining the arc–ophiolite complex (sample BUM2, Supplemental Information DR4).

The rare Precambrian grains in the Kong and Chulung La Formations could be of Indian or Asian origin because grains with such ages exist on both plates (e.g. Leier et al., 2007).

The Hf data allow further discrimination between potential sources for the Mesozoic zircons (Fig. 7). The majority of grains <115 Ma in the Kong and Chulung La Formations have $\varepsilon_{Hf}$ values consistent with both southern Asian margin (Gangdese) or KLIA provenance. However, Mesozoic grains aged >115 Ma have

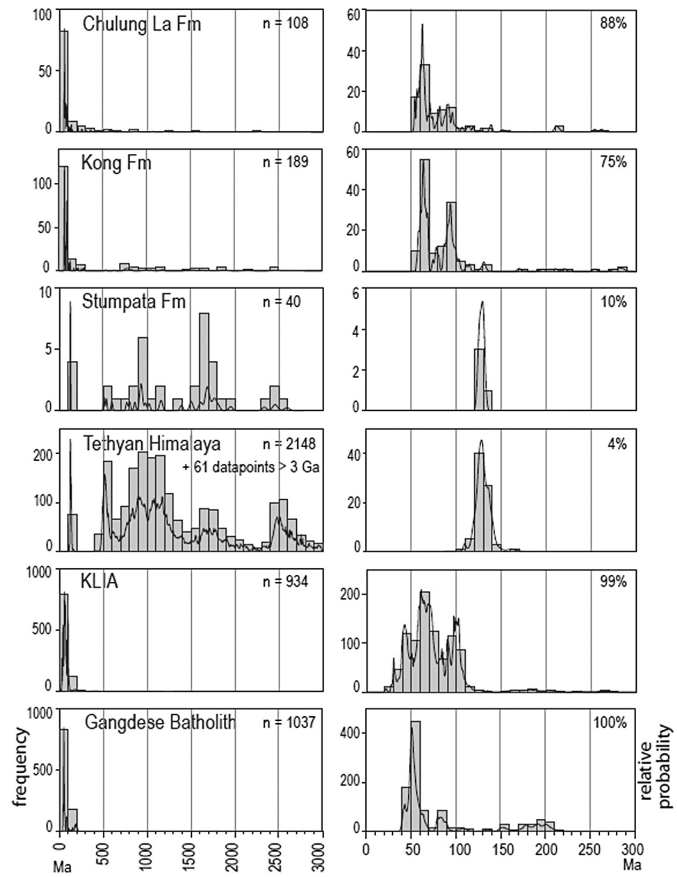


**Fig. 6.** U–Pb zircon data from the Kong Formation (samples CC08-10, CC08-12, CC08-25, CC08-31 and CHU-33A combined) and Chulung La Formation (samples MA08-02 and MA08-04 combined) compared to new (Stumpata Formation) and published data from potential source areas (Tethyan Himalaya, KLIA, Gangdese batholiths; reference sources used to compile compilations provided in DR4). Relative probability plots and frequency diagrams are plotted in the range of 0–3 Ga and 0–300 Ma. Percentages: number of ages younger than 300 Ma as compared to $n$, the total number of individual ablations after rejection of discordant datapoints (Supplemental item DR4). Number of grains analysed (number of grains after discordant data points removed) for Chulung La dataset = 102 (91), for Kong dataset = 133 (131), for Stumpata dataset = 40 (39).

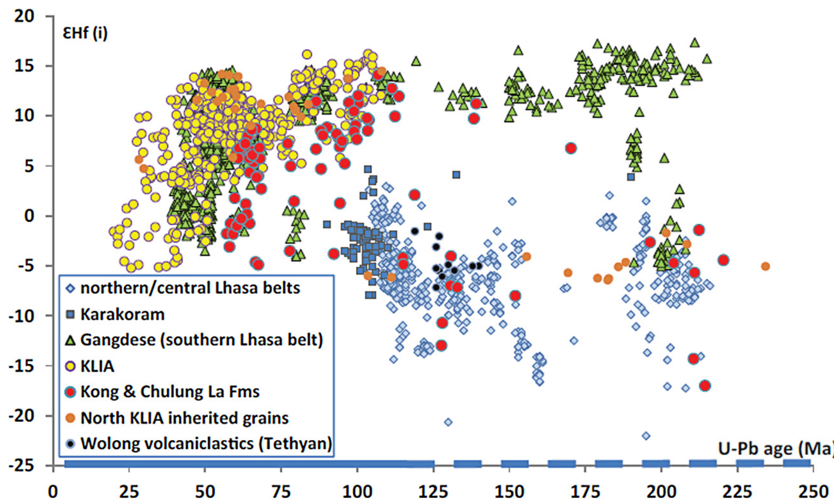


**Fig. 7.** U–Pb vs $\varepsilon$Hf data for Mesozoic and Paleogene detrital zircons from the Kong and Chulung La Formations, compared to zircons from their potential source regions. Note that (i) all North KLIA inherited grains of negative $\varepsilon$Hf values are only documented in rocks 40 Ma and younger, and are interpreted as Karakoram-derived by Bouilhol et al. (2013) and (ii) The Karakoram field plotted here is unrepresentative of the range of zircon ages documented in the Karakoram; a lack of Hf data associated with the majority of analyses precludes plotting such grains on this figure. We therefore depict, along the *x*-axis, the peak of U–Pb ages (blue solid line) and range over which zircon ages have been recorded (blue dashed line) from published data from the Karakoram. This summary is also likely unrepresentative, since such a compilation is heavily influenced by the high proportion of research focused on specific igneous rocks in the area. Cretaceous zircon data from the Wolong volcaniclastics (Cretaceous Tethyan Himalaya in Tibet, Hu et al., 2010) are the probable broadly along strike equivalents of Cretaceous zircons recorded in the Paleocene Stumpata Formation in the western Himalaya, in view of their near identical narrow age range. These Wolong grains are plotted here since there is U–Pb but no Hf data available for Stumpata Formation zircons. Sources of published data used to compile Gangdese, Karakoram, KLIA and Central/Northern Belts of the Lhasa terrane are listed in DR5. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

predominantly negative $\varepsilon_{Hf}$ values. These grains match the two Cretaceous and Triassic–Jurassic negative $\varepsilon_{Hf}$ clusters of the Northern/Central Lhasa terrane magmatic belts. Conversely, KLIA grains with negative $\varepsilon_{Hf}$ values are not known for this >115 Ma Mesozoic age range, except as inherited grains in rocks younger than 40 Ma; these grains are interpreted by Bouilhol et al. (2013) to be of Karakoram provenance, contaminating KLIA magmas after KLIA–Asia collision at 40 Ma.

Grains aged ca. 130 Ma could be derived from the Tethyan Himalayan Paleocene Stumpata Formation, which has a minor zircon population of such restricted age (see Fig. 6 and Clift et al., 2014), and although no Hf data are available, $\varepsilon$Hf values are expected to be negative by comparison with the probably broadly correlative zircons in the Cretaceous Wolong Volcaniclastics of the Tethyan Himalaya of Tibet, which have a zircon population of similarly distinctive and restricted age (Hu et al., 2010). However, regardless of the provenance of the ca. 130 Ma population, such a source could not have supplied the Kong and Chulung La Mesozoic grains of negative $\varepsilon$Hf values > ca. 130 Ma (Fig. 7); Fig. 7 shows that for grains >130 Ma and of negative $\varepsilon$Hf value, the only known source is Asian. Furthermore, the good correlation pattern between these Kong/Chulung La grains and Asian grains in terms of the bimodal distribution (105–155 Ma and 190–215 Ma) strengthens the argument for an Asian source for both populations in our samples.

Critically, we therefore interpret the detrital grains of >ca. 130 Ma, and most probably also >115 Ma, with negative $\varepsilon_{Hf}$ values, in the 54 Ma aged Kong and Chulung La formations as derived from the Asian plate. From which part of the Asian plate these grains were derived, the Karakoram or the Lhasa terrane, is uncertain, given the lack of data for the Karakoram, and its possible correlation with the Lhasa terrane (see above). This is discussed in more detail below.

Supporting evidence for Asian detritus deposited on the Indian plate at this time lies in the two Kong and Chulung La 140 Ma grains of positive $\varepsilon$Hf value, which lie within the field of the Gangdese batholiths of the Lhasa terrane. However, this may simply reflect incomplete characterisation of the KLIA; further analyses undertaken on zircons from the KLIA in the future may lead to documentation of such older grains in these rocks.

## 5. Discussion

### 5.1. *The timing of India–Asia collision constrained by these data*

Asian grains found in Indian Tethyan sedimentary rocks with a depositional age of 54 Ma require the Tethyan Ocean to have closed and therefore India–Asia collision to have occurred by this time. Collision of the KLIA, either with India or Asia first, must have occurred prior to this time since our data require both the Indus and Shyok sutures to be closed by 54 Ma, regardless of which suture accommodated the final collision. We note that this age provides a minimum constraint to collision since it may have taken some time, post-collision, for topography to have been built sufficiently for significant erosion to ensue. Our 54 Ma minimum age of terminal collision is inconsistent with research that proposes that an ocean remained between India and Asia, located in either suture zone, subsequent to 54 Ma (e.g. Bouilhol et al., 2013, who proposed that the Shyok suture zone remained open until 40 Ma, subsequent to India–arc collision at 50 Ma).

Our interpretations are, however, consistent both with previous work that proposes the KLIA collided with Asia first, in the Cretaceous (e.g. Borneman et al., 2015, based on the age of Asian-derived molasse deposited on the KLIA) as well as with those works that propose that the KLIA collided with India first, provided that terminal collision between the conjoined India–arc and Asia then occurred by 54 Ma. An example of the latter hypothesis is the work of Khan et al. (2009). They proposed: 1) India–arc collision by 61 Ma based on cessation of calc-alkaline volcanism in the arc and the arc's close proximity to India at that time as calculated from palaemagnetic data and 2) a minimum age of ∼50 Ma for the collision between Asia and India/arc based on dating of two post-collisional granitoids in the region of the Shyok suture zone.

In the above scenario, i.e. if the KLIA collided with India first, prior to 54 Ma, we might expect there to be some record of this collision in the detrital record preserved in the Tethys Himalaya in this region. There is no evidence of arc detritus in the Tethyan Himalayan Paleocene Dibling or Stumpata Formations which underlie the Kong Formation. This might be considered evidence against the model of Khan et al. However, arc/Asian detritus is recorded in Paleocene Indian continental rise and trench sediments, far to the east in Tibet (Hu et al., 2015). Thus, absence of arc-detritus in Paleocene sediments at the location of our study area may reflect nothing more than differences in palaeogeography, sediment supply routes, and the degree of across-strike proximity to Asia, compared to studied locations further east.

Provenance of grains from the Central/Northern Lhasa Terrane magmatic belts would require a palaeodrainage scenario whereby rivers carrying such grains to the Indus suture zone flowed south through the Gangdese magmatic belt in the southern Lhasa terrane. Such a palaeodrainage configuration was already proposed by Wu et al. (2010) who recorded zircons of similar age, Hf signature and interpreted provenance in the Himalayan Xigaze forearc basin, >1000 km along strike in Tibet. These similar along-strike studies (e.g. Hu et al., 2012; Li et al., 2015) are located in a region far to the east of the KLIA and our study area. In this eastern region, zircons that are interpreted as derived from the Central magmatic belt of the Lhasa Terrane on the basis of age and Hf signature were recorded in the youngest Tethyan sedimentary rocks of the Indian plate by 50 Ma.

However, in contrast to these studies in Tibet, occurrence in our study area, far to the west, of detritus derived from the Northern/Central magmatic belts of the Lhasa terrane, would require a significant transport distance west along the suture zone (Fig. 1). Such a palaeodrainage scenario is not impossible; according to Clift et al. (2001), material from the Lhasa Terrane was being transported by an axial Indus River along the suture zone to the Ladakh region by the Early Eocene, although a number of other researchers believe such axial drainage initiated not before the Miocene (Henderson et al., 2010; Najman, 2006; Sinclair and Jaffey, 2001). An alternative palaeodrainage scenario could be that the more proximal Karakoram, which may be the along-strike equivalent of the Lhasa terrane (see above), supplied grains of similar signature. Zircons of similar age have been documented in the Karakoram hinterland, and those limited Hf data that do exist are of negative $\varepsilon$Hf values, but more data from the Karakoram are required to test this proposal further.

A Karakoram provenance may also explain the paucity of >115 Ma aged detrital grains of positive $\varepsilon_{Hf}$ signature in the Kong and Chulung La Formations, which are common in the Gangdese Batholiths (Fig. 7). If grains were derived from the Northern and Central magmatic belts of the Lhasa terrane, transported by rivers that drained south through the Gangdese, we might also expect some contribution of detritus from that part of the Gangdese that contains zircons of >115 Ma age and positive $\varepsilon_{Hf}$ signature. Such grains are rare in the Kong and Chulung La dataset. However, if the source of the >115 Ma aged grains with negative $\varepsilon_{Hf}$ signature was not the rocks of the Lhasa terrane to the east, but equivalent rocks of the Karakoram to the west, directly north of the study area, south-draining rivers from the Karakoram would flow across the KLIA arc, dominated by grains of younger age. This proposed palaeogeography provides a better match to the overall population distribution of grains recorded in the Kong and Chulung La Formations.

Since both the Karakoram and the Lhasa terrane are defined as the Asian plate, rather than intra-oceanic island arcs, it makes no difference to our overall interpretation that zircons of Asian origin were deposited on the Indian plate at 54 Ma, thus dating the timing of final suturing between India and Asia.

### *5.2. Integration of our data with previous work on arc magmatic records of the region, and implications*

Bouilhol et al. (2013) analysed zircons from granitoids of the northern, central and southern parts of the KLIA. They showed that in north, south and central regions of the KLIA, each of the analysed granitoid samples older than ∼50 Ma yielded a homogeneous U–Pb zircon age population constraining its crystallisation age. The $\varepsilon_{Hf}$ values of these zircons have juvenile signatures, typical of an intra-oceanic arc.

In contrast, samples <50 Ma on the southern margin of the KLIA, (and with a significant number of zircons with inherited Palaeozoic age), display more evolved $\varepsilon_{Hf}$ values. They interpreted this as the result of crustal contamination due to subduction of Indian crust below the KLIA at this time. A similar shift to more evolved $\varepsilon_{Hf}$ values of zircons, but with documentation of inherited zircons of Mesozoic, rather than Palaeozoic age, is recorded from rocks younger than 40 Ma on the northern margin of the KLIA.

Bouilhol et al. (2013) discuss two scenarios to explain these data: either (i) the shift at ∼40 Ma in the northern KLIA reflects continued collision with India, with crustal contamination affecting first (at 50 Ma) the southern part of the KLIA and then progressively more northern parts of the arc; or (ii) the shift at 40 Ma in the North KLIA reflects collision between the KLIA arc (already accreted to India) and Asia at the time. In this second scenario, the collision of Asia with the already sutured India+arc thus occurred at 40 Ma.

Bouilhol et al. (2013) prefer the latter interpretation based on their proposal that the zircons in question in the northern KLIA closely resemble those from the Asian Karakoram in both their Mesozoic inherited age and Hf composition, and are unlike those of age/Hf compositional field of Indian plate zircons (Fig. 7, Fig. 8, and see their Fig. 4d). We note Bouilhol et al.'s discrimination between Indian and Asian signature in terms of zircons' Lu/Hf composition becomes slightly less clear when data from Cretaceous zircons from the Wolong Volcaniclastics of the Tethyan Himalaya, most probably equivalent to zircons of similar age found in the Stumpata Formation in Ladakh, are included (Fig. 8). Nevertheless, we 1) agree with Bouilhol et al.'s interpretation of an Asian provenance for these inherited North KLIA zircons in view of their Mesozoic age, as discussed above, and 2) note also the Lu/Hf compositional similarity between the Mesozoic zircons of the <40 Ma North KLIA rocks, (interpreted as Karakoram-derived by Bouilhol et al.), with the Mesozoic Kong and Chulung La Formation grains (Fig. 8), which we likewise interpret as Asian-derived.

How can both the dataset of Bouilhol et al. (2013) and our new data be incorporated into a tectonic interpretation consistent with all recorded data? We suggest that Asian grains, already exhumed close to surface in the Karakoram/Lhasa terrane prior to India–Asia collision, were available for final exhumation, erosion and transportation on to the Indian plate at 54 Ma as India–Asia collision commenced. In contrast, as already proposed by Borneman et al. (2015), Karakoram grains documented in northern KLIA rocks aged <40 Ma reflect post-collisional underthrusting of the Karakoram beneath the KLIA to sufficient depths to contaminate KLIA magma by this time.

Finally, it should be noted that future work may reveal the presence of Asian zircons in older KLIA rocks, perhaps the result of processes unrelated to continental collision, such as the dragging of old metasomatically enriched mantle from the hanging wall of the subduction zone into the region of partial melting below the arc (as proposed in Schaltegger et al., 2002). In that case, the interpretations put forward in both this paper and that of Bouilhol et al. (2013) would need to be revised.

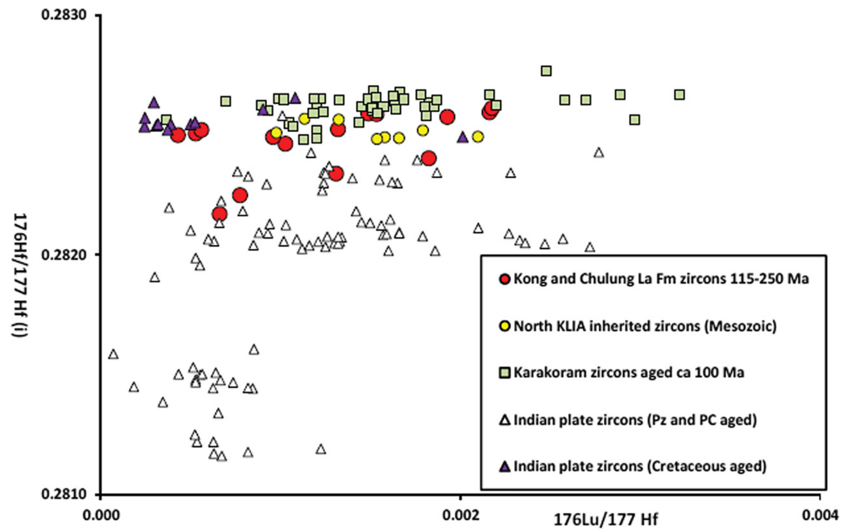


**Fig. 8.** $^{176}$Hf/$^{177}$Hf vs $^{176}$Lu/$^{177}$Hf values for detrital zircons of 115–250 Ma range and negative $\varepsilon_{Hf}$, from the Kong and Chulung La Formations, compared to values from Precambrian and Palaeozoic zircons from the Indian plate (Kemp et al., 2009; Richards et al., 2005), Cretaceous aged zircons from the Indian plate (Hu et al., 2010), Mesozoic zircons from the Karakoram (Ravikant et al., 2009) and northern KLIA (Bouilhol et al., 2013).

## 6. Conclusions

Whereas traditionally ~60–50 Ma has been taken as the time of terminal India–Asia collision, there is now increasing debate as to whether the collisional event at this time reflects collision between India and Asia, or between India and an oceanic island arc, with terminal collision between India and Asia occurring later. This paper uses combined detrital zircon U–Pb with Hf data to constrain the timing of terminal India–Asia collision.

We interpret Mesozoic zircons of >115 Ma and of negative $\varepsilon_{Hf}$ value to be derived from the Asian plate rather than the Kohistan–Ladakh Island Arc. These zircons of Asian affinity, sourced from the Central/Northern magmatic belts of the Lhasa Terrane or from an equivalent source along strike in the Karakoram, are found in Indian plate Tethyan sedimentary rocks dated at 54 Ma. This date represents the time by which terminal collision of India with Asia, rather than with an oceanic island arc, had occurred, and the time by which both the Shyok suture zone and Indus suture zone were closed.

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## Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2016.11.036.

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