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Detrital chrome spinel evidence for a Neotethyan intra-oceanic island arc collision with India in the Paleocene

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Abstract

Models that support a single collision scenario for India and Eurasia are incompatible with the evidence that an intra-oceanic island arc (IOIA) existed within the Neotethyan Ocean. Understanding the spatial and temporal extent of any IOIA is crucial for India-Eurasia collision studies as the entire ocean, including any intra-oceanic features, must have been consumed or emplaced prior to continental collision. Here, we review what is known about the Neotethyan IOIA and report evidence from sedimentary successions in NW India and southern Tibet to constrain when and where it was emplaced. We use detrital mineral geochemistry and supporting provenance and age data to identify the source of the sediments and compare the timing of erosion of IOIA-derived material in both regions.

Detrital chrome spinels, extracted from distinct sedimentary horizons in southern Tibet (Sangdanlin) and NW India (Ladakh), exhibit similar average geochemical values (TiO_2 = 0.09 and 0.24%, Cr# = 0.66 and 0.68 and Mg# = 0.45 and 0.53, respectively) and supra-subduction zone (SSZ), forearc peridotite signatures. Furthermore, they overlap with in-situ chrome spinels reported from the Spongtang Ophiolite in NW India and the Sangsang Ophiolite in southern Tibet. As with many of the ophiolitic remnants that crop out in and adjacent to the Yarlung-Tsangpo and Indus suture zones (YTSZ and ISZ respectively), the Spongtang and Sangsang ophiolites formed in an IOIA setting. Linking the source of the detrital chrome spinels to those analysed from remnant IOIA massifs in the YTSZ and ISZ is strong evidence for the emplacement of the IOIA onto the Indian margin.

The timing of the IOIA collision with India is constrained by the depositional ages of the chrome spinel-bearing sediments to the end of the Paleocene (Thanetian) in southern Tibet and the Early Eocene in NW India. This indirectly provides a maximum age constraint of Late Paleocene-Early Eocene for intercontinental collision between India and Eurasia. Additionally, this study highlights the importance of targeting distinct sedimentary horizons in collision zones to find evidence for discrete tectonic events that may be obfuscated by later collisions.

Keywords: chrome spinel; Neotethyan Ocean; India-Eurasia collision; Tibet; India; suture zone; ophiolites; arc.

1 Introduction

The Neotethyan Ocean (cf. Neo-tethys (*Sengor*, 1979) and Ceno-tethys (*Metcalfe*, 1996)) was a vast ocean that once separated India from Eurasia. Many reconstructions of this ocean posit a single subduction system consuming oceanic crust underneath Eurasia (*Yin and Harrison*, 2000). However, observations such as the widespread occurrence of IOIA ophiolites within the Indus Suture Zone (ISZ) and Yarlung-Tsangpo Suture Zone (YTSZ), or India's plate convergence rates in the Cretaceous (*Aitchison et al., 2007a; Jagoutz et al.*, 2015) are not accounted for in single collision models. To explain these observations, a sub-set of researchers has proposed that a second (IOIA) subduction zone was present within the Neotethyan Ocean (*Aitchison et al*., 1999, 2000, 2007a; *Hébert et al*., 2012; *Gibbons et al*., 2015; *Jagoutz et al*., 2015). In this paper, we review what is known of this system, from its inception and development. By targeting discrete horizons in southern Tibet and NW India we provide detrital chrome spinel evidence to suggest when and where it was emplaced.

Chrome spinel geochemistry is a powerful method to determine tectonic setting during crystallisation, which includes layered intrusions and ophiolites (*Barnes and Roeder*, 2001). An additional advantage of using detrital chrome spinels comes from their superior resistance to erosion and chemical alteration over all other mafic and ultramafic minerals (*Kamenetsky et al.*, 2001; *Lužar-Oberiter et al.*, 2009).

1.1 Reconstructing the Neotethyan Ocean

Although this study deals directly with the Neotethyan IOIA, we also discuss how it indirectly constrains the timing of the India-Eurasia collision. Any seafloor asperities (island arcs, ocean islands etc.) that were present in the Neotethyan Ocean must have been consumed or emplaced prior to intercontinental collision. Therefore, by discovering evidence of an IOIA collision, its timing indirectly provides a maximum age constraint for any subsequent collision event.

Determining the exact age of the India-Eurasia collision has attracted great interest over the last 30 years (*Garzanti et al.*, 1987; *Rowley*, 1996; *Yin and Harrison*, 2000; *Aitchison et al.*, 2007a; *Najman et al.*, 2010; *van Hinsbergen et al*., 2012; *White and Lister*, 2012; *Zahirovic et al.*, 2012; *Bouilhol et al*., 2013). Unfortunately, these studies fail to agree on the timing of collision, with estimates ranging from 70 to 20 Ma. A crucial step to refine when the collision occurred is to accurately reconstruct the history of the Neotethyan Ocean.

Reconstructing this ocean is inherently complex, as the bulk of associated oceanic crust was recycled back into the mantle. Additional material was lost due to post-collisional erosion. To complicate matters further, ophiolites preserved within and adjacent to the YTSZ and ISZ (Figure 1) formed at different times and in different tectonic settings. This allows significant flexibility for interpretation, with multiple reconstructions proposed. Many published reconstructions are variations of a single- or multi-collision model. Proponents for a single collision model suggest that closure of the Neotethyan Ocean occurred between 70 and 55 Ma as India sutured to Eurasia (*Rowley*, 1996; *Leech et al*., 2005; *Molnar and Stock*, 2009; *Najman et al*., 2010; *Hu et al.*, 2015). Proponents of multi-collision models suggest that India collided with an IOIA at ~55 Ma (*Aitchison et al*., 2007a; *Hall*, 2012; *Hébert et al*., 2012; *Zahirovic et al*., 2012; *Bouilhol et al*., 2013; *Metcalfe*, 2013; *Gibbons et al.*, 2015) and that the main collision occurred some time later. By investigating each facet of the collision in detail, we can refine these models to gain a better understanding of how the Neotethyan Ocean evolved. Here we focus on the hypothesis that an IOIA was present within the Neotethyan Ocean and present a detailed review of the evidence for its existence. We also provide new data to constrain when and where the IOIA was emplaced, which indirectly provides a maximum age constraint for the collision of India and Eurasia.

1.2 Neotethyan IOIA

The concept of an IOIA within the Neotethyan Ocean is not new. *Brookfield and Reynolds* (1981) first suggested the presence and subsequent collision of an island arc with India in the Cretaceous, using data from NW India. Based on work carried on sections further to the east, *Allègre et al.* (1984) proposed that an IOIA collided with Eurasia, based on the presence of an 80 Ma angular unconformity in the Lhasa terrane, but there is little evidence to support this hypothesis. Since these early works other researchers have focused on gathering data from either Tibet or NW India-Pakistan.

1.2.1 **IOIA evidence in Tibet**

Aitchison et al. (1999) were the first to suggest an IOIA source for the ophiolites found in the YTSZ in Tibet. In another study published later that year (*van der Voo et al.*, 1999) suggested a P-wave anomaly, currently residing at a depth of 1100 km under the Indo-Australian plate, represented the northward-dipping slab of oceanic crust consumed at a Neotethyan intra-oceanic subduction zone. The first substantial geological evidence in support of this intra-oceanic subduction system was the recognition of distinct island arc terranes within the YTSZ (*Aitchison et al.*, 2000). In follow-up studies, these terranes (Bainang, Zedong and Dazhuqu) were interpreted as an accretionary wedge complex (*Ziabrev et al.*, 2004), an intra-oceanic magmatic arc

(*McDermid et al*., 2002; *Aitchison et al*., 2007b) and an ophiolitic complex (*Aitchison et al*., 2000, 2002, 2004; *Abrajevitch et al*., 2005) respectively. Subsequently, numerous oceanic remnants found along the YTSZ have been assigned an IOIA origin (see *Hébert et al*. (2012) for a review and for locations refer to Figure 2).

1.2.2 IOIA evidence in NW India and Pakistan

Fragmentary remnants of IOIA systems are abundant in NW India and Pakistan. The largest is the Kohistan-Ladakh arc (KLA), that contains one of the few near completely preserved well-exposed sections through an intra-oceanic island arc anywhere (Figure 2A). There is significant lateral variation within the KLA, with an upper mantle to upper crustal sequence in the west (Kohistan arc), while it correlates to the east (Ladakh arc) only the middle and upper crustal components are preserved. The Kohistan arc consists of (from south to north) (i) imbricate thrust slices containing blueschists; (ii) mantle ultramafics, such as the Jijal and Sapat complexes; (iii) the Kamil amphibolites; (iv) the Chilas Complex (a group of gabbro-norite and peri-norite plutons with associated ultrabasites); (v) the Kohistan batholith and (vi) the Kohistan volcanic and volcaniclastic sequences (*Jan and Howie*, 1981; *Bard et al*., 1983; *Burg et al*., 1998, 2006; *Bouilhol et al.*, 2009, 2011; *Burg*, 2011, *Bouilhol et al.*, 2015). In NW India, the Ladakh Batholith and its extrusive products, the Khardung Volcanics dominate (*Honegger et al.*, 1982; *Dunlap and Wysoczanski*, 2002; *Schaltegger et al*., 2003; *White et al.*, 2011). We note that both the Kohistan and Ladakh arc segments are located to the north of the Indus suture zone.

In addition to the KLA, there are two other significant groups of IOIA-related rocks in this region. The first are the ISZ ophiolites and include those at Muslin Bagh and Bela in Pakistan and the Spongtang, Nidar and Karzog ophiolites in NW India (Figure 2A).

The second group is the Dras Complex, comprising of oceanic crust, calc-alkalic volcanics and an associated fore-arc sequence and accretionary mélange (*Reuber*, 1989; *Cannat and Mascle*, 1990; *Robertson and Degnan*, 1994; *Mahéo et al.*, 2004). Although attempts have been made to link the KLA, the ISZ ophiolites and the Dras Complex to the presence of one or possibly two IOIA systems within Neotethys (e.g. see discussion in *Robertson and Degnan*, 1994), for the purposes of this study we will focus primarily on constraining the first appearance of any IOIA arc-derived material on the Indian passive margin. We will then discuss the possible links between the KLA, the ISZ ophiolites and the Dras Complex in Section 5.3.

1.2.3 Subduction initiation and the oldest arc elements:

To gain a better understanding of how the Neotethyan IOIA developed we review the current evidence for its presence, from the oldest arc elements to the youngest subduction-related magmatism.

1.2.3.1 Tibet

The IOIA must have initiated sometime between the formation of the underlying oceanic crust and, either (i) the age of the oldest arc volcanics, or (ii) the age of oceanic crust with clear SSZ signatures. The oldest oceanic crust reported from the YTSZ is Early Jurassic and is found at Dangxiong, Jungbwa, Kiogar and Luobusa (Figure 2B). The evidence for the oldest IOIA magmatism comes from Luobusa in southern Tibet, where *Chan et al*. (2015) obtained Late Jurassic ages (148.4 ± 4.5 and 149.9 ± 2.2 Ma) for gabbros with SSZ signatures. The crystallisation age of the gabbros are coeval with the eruption ages of volcanic rocks at Zedong, where Late Jurassic shoshonitic volcanics locally overlie island arc tholeiites (IAT) and Middle Jurassic radiolarian cherts (*Aitchison et al*. 2007b). *Zhang et al*. (2014) recently suggested that the Zedong volcanics were produced from Gangdese continental arc, and not IOIA-related, volcanism. However, a continental arc origin is difficult to reconcile with the clear depositional relationship between the radiolarian cherts (deep-marine sediments) and the Zedong volcanics. Although some aspects of the geology at Luobusa and Zedong are yet to be fully resolved (*Aitchison et al.*, 2007b; *Chan et al., 2015*; cf. *Zhang et al.*, 2014) we propose that IOIA initiation in the Neotethyan Ocean began at some time between the Early to Middle Jurassic and the Late Jurassic. Coeval subduction-related processes, such as accretionary wedge development, provide evidence for IOIA subduction in the Late Jurassic. For example, the Bainang terrane in southern Tibet is a series of imbricate chert and tuff thrust slices that conspicuously lack any significant terrestrial input (*Ziabrev et al.*, 2004). It is interpreted as an accretionary wedge that developed due to the accumulation of sediments scraped off a north-dipping, subducting plate. Based on detailed mapping and radiolarian biostratigraphy, *Ziabrev et al*. (2004) concluded that the IOIA was active from the Late Jurassic to the Late Cretaceous. Notably, a long-lived period of accretion at the trench is conducive to preserving arc terranes in collision settings (*Draut and Clift*, 2013).

1.2.3.2 NW India and Pakistan

The oldest Neotethyan oceanic crust reported from NW India and Pakistan occurs at Spongtang and is of Early Jurassic age (177 ± 1 Ma) (*Pedersen et al.*, 2001). Early Cretaceous (~140 Ma) intra-oceanic ophiolitic rocks occur at Nidar (*Kojima et al.*, 2001; *Mahéo et al.*, 2004). The oldest arc volcanics at Spongtang were indirectly constrained to the Early Cretaceous (mid-Valanginian–mid-Aptian) using radiolarians preserved in intercalated cherts (*Baxter et al.*, 2010). Intra-oceanic subduction must have initiated sometime between the Early Jurassic and Early Cretaceous. This is similar to the estimates proposed for arc development of the Dras Complex (Late Jurassic - mid-Late Cretaceous) (*Reuber*, 1989), and for the KLA (Late Jurassic) (*Schaltegger et al*., 2003).

1.2.4 Arc development:

1.2.4.1 Tibet

An important period in the development of the Neotethyan IOIA began in the Early Cretaceous when rifting of the IOIA occurred, possibly due to slab rollback (*Hébert et al*., 2012). This resulted in the formation of ophiolites now preserved in massifs (Yungbwa, Dangxiong, Zhongba, Saga, Sangsang, Lhaze, Liuqu, Beimarang, Qunrang and Jiding) found along and to the south of the YTSZ (Figure 2B). Additional evidence for Early Cretaceous IOIA activity is reported from western Tibet (at Dangxiong, Yungbwa and Kiogar) where *Chan et al*. (2015) recognised that the oceanic crust at those three locations exhibited a later stage SSZ signature imparted by IOIA activity and at Dazhuqu in southern Tibet, where *Ziabrev et al*., (2003) demonstrated that pillow basalts, which formed in an IOIA setting, were erupted during the Early Cretaceous (late Barremian to late Aptian).

1.2.4.2 NW India and Pakistan

Although evidence for the existence of any active IOIA system during the Late Cretaceous and Paleocene in Tibet is lacking, IOIA rocks of this age are reported from the Muslim Bagh and Bela ophiolites in Pakistan and the Spongtang Massif in NW India. At Muslim Bagh, *Kakar et al*. (2012) reported a crystallisation age for subduction-derived plagiogranites (80 ± 1.5 Ma), which is contemporaneous with volcanism in NW India in the Spong Arc (88 ± 5 Ma) (*Pedersen et al*., 2001; *Corfield et al*., 2001) indicating ongoing arc activity in the Late Cretaceous. The youngest reported occurrence of SSZ ophiolitic rocks is from the Bela Ophiolite in Pakistan where *Ahmed* (1993) reported zircons from a plagiogranite, with a crystallisation age of 65 ± 1 Ma. Although this evidence is restricted to the western section of the Neotethyan Ocean, it suggests that the IOIA was active and magma generation continued until at least the end of the Cretaceous.

The KLA contains a more complete and younger record of arc magmatism. Estimates suggest that this arc was active from ~150 - 40 Ma (*Jagoutz et al.*, 2009; *Bosch et al.*, 2011; *Burg*, 2011). The ages of the youngest volcanics in the Dras Complex are poorly constrained, but are presumed to be Paleogene (*Reuber*, 1989).

1.2.5 IOIA demise and emplacement

If any IOIA was present in the Neotethyan Ocean, it could not have avoided collision with either India or Eurasia and any evidence for such a collision should be preserved on either one of these margins. Although early studies such as *Allègre et al*. (1984) suggested that the IOIA collided with Eurasia, multiple studies provide a stronger case for its collision with India (*Searle*, 1986; *Garzanti et al*., 2005; *Bouilhol* et al., 2013; this study).

Arc-continent collisions are known to occur over relatively short time periods with a complete evolutionary sequence, from the initial collision to final emplacement, occurring within a 10 m.y. interval (*Dewey*, 2005). We infer the first appearance of ultramafic material on the Indian margin to reflect loading by, and subsequent erosion of, an IOIA with the timing of deposition indirectly providing a minimum age for this collision. Using an example from the former Iaptean Ocean in Ireland, the deposition of the chrome spinel-bearing Sheefrey Formation, was coeval with collision of the Lough Nafooey arc during the Grampian Orogeny (*Dewey and Mange*, 1999; *Dewey*, 2005). Similar examples, such as the Miocene Furenai serpentinite sandstone in Hokkaido, northern Japan have also been used to indirectly constrain the timing of an arc-continent collision (*Arai and Okada*, 1991).

In order to refine estimates for timing of arc-continent collision with India, we examined sedimentary successions that accumulated during the critical time interval (65 – 50 Ma) for evidence of the first arc detritus shed onto the Indian passive margin. Although island arcs are typically discontinuous, narrow (<100 km) and arc-continent collisions are ephemeral geological events (*Dewey*, 2005; *Draut and Clift*, 2013), these systems commonly leave a distinctive, albeit cryptic record of their demise. Here we present field observations, detrital mineral geochemistry and supporting provenance and age data to compare the timing of erosion of intra-oceanic arc-derived material in NW India and southern Tibet. We then briefly discuss how our results influence the timing proposed for the intercontinental collision of India and Eurasia.

2 Outcrop and petrographic observations

2.1 NW India: Zanskar Valley

To find the first appearance of IOIA-derived material in NW India we targeted sedimentary successions that record a transition from multi-cycle mature clastic sedimentation, characteristic of a passive margin to that typical of a collisional setting, with short sediment pathways laden with immature detrital loads. Such a transition is preserved in the Zanskar Valley in Ladakh (Figure 2A). The Lamayuru

Complex represents marine sedimentation on the northern margin of India of which the Khalsi flysch, a series of mudstones, sandstones, shales and limestones (*Brookfield and Andrews-Speed*, 1984) is interpreted here to represent the youngest sediments that do not contain any IOIA-related detritus. It contains purported Eocene foraminifers (*Nummulites* sp., *Rotalia* sp., and *Alveolinas* ex gr. *elliptica*), extracted from limestone clasts, which provide a broad minimum age of deposition for the detrital clasts shed into this unit (*Fuchs*, 1986 in *Henderson et al.*, 2011).

Evidence of a distinct change in sediment provenance occurs amongst sedimentary rocks, which crop out within a 300 m-long road immediately north of the village of Chilling. Two units are present: an ultramafic clast-bearing sandstone unit and a basalt and chert clast-dominated conglomerate (Figure 3). The former is approximately 100 m thick and contains intercalated sandstones and pebble-to-boulder conglomerates, dominated by serpentinized ultramafic detritus. Previous researchers have interpreted this unit as being part of a serpentinite matrix mélange (*Brookfield and Andrews-Speed*, 1984; *Fuchs*, 1986; *Searle et al*., 1990; *Clift et al.*, 2001, 2002) but primary sedimentological features such as planar cross-bedding and repeated fining-up sequences suggest that it was deposited rather than tectonically emplaced (Figure 3A). The interbedded sandstones and conglomerates are dominated by serpentinised ultramafic detritus (approximately 80-90%), with minor carbonate (10%) and opaque (5%) fractions. Serpentinite grains exhibit meshwork (cellular) textures (Figure 4A), which suggests they were derived directly (and not reworked) from an ophiolitic source (*Garzanti et al*., 2002; *Garzanti et al.*, 2013). Chrome spinels dominate the opaque fraction.

A basalt and chert-clast dominated conglomerate overlies the ultramafic sandstone. It contains clasts of amygdaloidal basalt, chert, serpentinite, minor limestones and quartz-arenites, with a maximum clast size of ~15 cm (Figure 3B). *Clift et al.* (2002) initially suggested that this unit contained the first appearance of Eurasian-derived detritus on the Indian margin. However, our observations align with the conclusions of *Henderson et al*. (2011) who, based on a study of clast compositions, detrital zircon provenance and mudstone geochemistry, found no evidence of any continental arc detritus in this sequence.

The Zanskar Valley sediments in NW India contain a significant and tectonically important transition, from typical passive margin sediments to ultramafic clast-bearing, source-proximal sediments, that were deposited during the earliest Eocene.

2.2 Southern Tibet: Tethyan Himalaya

We observed a similar but subtler transition from passive margin to arc-derived sedimentation in southern Tibet. Indian passive margin sediments crop out to the southeast of Saga, near Zheba (Figure 2B) as a succession of cherts, sandstones, siltstones and minor conglomerates. Petrographic observations from a representative sandstone bed within this sequence reveal similar proportions (~40%) of quartz and carbonate grains, with a minor (5-10%) component of opaque iron oxides (Figure 4B). This composition represents typical passive margin facies. There is a distinct lack of any volcanic or ultramafic detritus that suggests an arc source contribution and is interpreted to represent Indian passive margin sediments deposited prior to collision of the IOIA. Five samples within this block contained mid-Cretaceous radiolarian assemblages (*Chan*, 2006).

The first appearance of IOIA material in the Indian passive margin sediments in southern Tibet crops out as a block within a mud-matrix mélange just west of the village of Sangdanlin (Figure 2B). Detailed radiolarian biostratigraphic work by *Chan* (2006) demonstrates that these rock packages are km-scale, internally coherent sequences, enclosed within a regional-scale mélange belt. This interpretation is at odds with those who contend that the sequence is stratigraphically continuous (*Ding*, 2003; *DeCelles et al*., 2014) (see Section 5.2 for more details). Although detailed field mapping is required to resolve the nature of the boundary relationships between the Sangdanlin block, the mélange and the Tethyan Himalayan Sequence, we contend that the first appearance of IOIA-derived material at Sangdanlin can be used to constrain the age of IOIA emplacement in southern Tibet.

Although the Sangdanlin mélange block is dominated by thick sequences of radiolarian cherts, it also contains a distinct horizon of polymict pebbly conglomerates with serpentinite and ultramafic clasts (GPS location: 29º 15.3730 N, 85º 14.9940 E; described in detail by *Aitchison et al*., 2007a) (Figure 3C). A count of 100 clasts within the conglomerate revealed that 45% are quartzite or quartzose sandstones, 21% siltstone/mudstone, 16% basalt, 8% serpentinite, 7% red chert and 3% limestone. Volcanic, (radiolarian-bearing) chert, ooidal limestone, mudstone and quartzite clasts are observed in thin section (Figure 4C). Minor occurences of opaque minerals such as chrome spinels were also observed (Figure 4D). Gastropods, oyster shells and other fragmented macrofossil bioclasts are present, suggesting additional input from a shallow marine environment. Radiolarian assemblages, extracted from cherts within this mélange block constrain the depositional age of this conglomerate to the end of the Paleocene (Thanetian) (refer to *Chan*, 2006).

The appearance and recognition of ultramafic material in this conglomerate is significant because it suggests an important change in provenance, similar to that in NW India. The presence of serpentinite clasts suggests that at least some of the conglomerate was sourced from an eroding ultramafic massif, contrary to *DeCelles et al*. (2014) who reported that there was no ophiolitic material present at Sangdanlin. The conglomerate horizon described herein demonstrates that this is not the case.

In NW India, the first appearance of ultramafic material was closely followed by deposition of basalt and chert clast-dominated conglomerate. In southern Tibet, a very similar unit, the Liuqu Conglomerate, can be found just to the north of Saga. *Davis et al*. (2002) first described this unit from its type locality near the village of Liuqu in southern Tibet. It is dominated by basaltic, serpentinized ultramafic, chert and quartzite clasts that were rapidly deposited in oblique–slip basins that developed along the zone of an arc-continent collision (*Davis et al*., 2002). *Wang et al.* (2010) refuted this interpretation and proposed that the Xigaze continental forearc terrane was the source region for the Liuqu Conglomerate. However, this seems untenable as the feldspathic-dominated volcaniclastics, felsic volcanics and plutonic clasts that dominate the Xigaze forearc sediments (*Dürr*, 1996) are unknown from the Liuqu Conglomerate (*Davis et al.*, 2002; *Wang et al.*, 2010). The maximum depositional age of 53.0 ± 1.6 Ma for the Liuqu Conglomerate (*Aitchison et al*. 2011) is slightly younger than the deposition age for the Sangdanlin conglomerate.

The deposition of an ultramafic clast-bearing unit, succeeded by a basalt and chert clast-dominated conglomerate, records a subtle but significant transition in source provenance when compared to the Cretaceous passive margin sediments at Zheba. This transition suggests that a specific, albeit cryptic, erosional event supplying ultramafic detritus to the Indian margin occurred at the end of the Paleocene in both southern Tibet and NW India.

3 Methods

We selected chrome spinel geochemistry to determine the source of the ultramafic detritus, as it is a powerful method to determine tectonic setting during crystallisation. Chrome spinels are diagnostic of a number of lithologies and tectonic settings, including kimberlites, layered intrusions and peridotites (*Barnes and Roeder*, 2001). By comparing the detrital chrome spinels extracted from Sangdanlin and Chilling to potential sources in the region, we can infer whether they were derived from the ophiolites in the YTSZ and ISZ, or from a different source.

Samples were crushed at the University of Hong Kong and sent to Langfang Laboratory at the Hebei Bureau of Geology and Mineral Exploration and Development for mineral separation. Chrome spinels were isolated using liquid separation methods. The spinels were then individually mounted on a thin section slide with double-sided tape and enclosed in an epoxy resin. After the mount had hardened, the thin section was removed and the mount was polished with successively smaller degrees of diamond paste until the majority of spinel grains were smooth and featureless. The samples were scrutinised using backscatter-imaging with a scanning electron microscope to identify any alteration rims, bands of magnetite or other spinel group minerals or inclusions that should be avoided (Supplementary Figure S1(A-D)). The degree of alteration and weathering were compared with the stages of alteration in *Pooley* (2004). Fortunately, most grains in this study exhibited low, or no signs of weathering or alteration. Features less than 10 μm were excluded from consideration for analyses, due to the technical limitations of the microprobe. Photomicrographs of the grains were taken to use as a map during analysis (Supplementary Figure S1(E)).

Electron microprobe analyses of chrome spinels was undertaken at the EPMA Laboratory, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China. We analysed the elements Si, Al, Mg, Cr, Fe, Ni, V, Mn, Zn and Ti using a 'Superprobe' JEOL JXA-8100 Electron Probe Microanalyser (EPMA). For minor elements, the machine ran for 100s to ensure sufficient collection time, while major elements ran for 40s. We excluded analyses that returned SiO_2 values >1%. We inputted the data into a macro-based spreadsheet (from *Barnes and Roeder*, (2001), with a correction by CJ De Hoog, 21st December, 2004) that uses the stoichiometric formulae of spinels to divide total FeO into Fe^{2+} and Fe^{3+}. Representative analyses are provided in Tables 1 and 2 and the full dataset is available in the Supplementary Material (Table S1).

4 Results

4.1 NW India: ultramafic sandstone

4.1.1 Analyses

We analysed 41 chrome spinel grains, extracted from a sample of the ultramafic sandstone (GPS sample location: 34º02.739 N, 077º12.729 E). Representative analyses are shown in Table 1. TiO_2 values range between 0.08 - 0.30% (average of 0.09%) with the majority <0.15% (only 3 grains contain values >0.20%). Mg# (Mg/(Mg+Fe^{2+})) atomic ratio values range between 0.38 and 0.67 (average of 0.53). Cr# (Cr/(Cr+Al)) atomic ratios, which are traditionally used in spinel discrimination plots, range between 0.39 and 0.87, with an average value of 0.68.

The low TiO_2 values exhibited by the chrome spinels are indicative of an ophiolitic source (*Lenaz et al.*, 2000). The Cr# and Mg# values suggests a forearc peridotite (*Azer and Stern*, 2007) or SSZ harzburgite (*Lenaz et al*., 2000) source.

The ophiolitic signature, crystallised in a forearc setting is confirmed when the spinels are plotted on the Cr–Al– Fe^{3+} data density plot (Figures 5A–B). We can further discriminate the source of the spinels by plotting TiO_2 values against Al_2O_3. They sit within the SSZ forearc peridotite field (*Kamenetsky et al*., 2001) (Figure 5C). The source of the spinels analysed from NW India is a forearc SSZ peridotite, with a minor island arc tholeiite (IAT) or boninite signature.

4.1.2 Comparison with potential sources

The dominance of serpentinite and chrome spinels in the Chilling ultramafic sediments suggest that it is a primary deposit and that little or no reworking occurred prior to deposition. Several ophiolitic massifs in NW India are considered as potential sources, including the Spongtang and Nidar ophiolites, which are related to the ISZ, and the Jijal and Sapat complexes, which are part of the KLA (Figure 6A). The detrital chrome spinels analysed from the ultramafic sandstone in NW India exhibit a clear Spongtang Ophiolite signature. Only seven of the 41 detrital chrome spinels analysed lie outside the Spongtang Ophiolite field. Six of the chrome spinels analysed overlap with the Jijal Complex (KLA), which may therefore be considered as a source. However, considering the long distance between the Jijal Complex and Chilling in the context of the short source to sink pathway commonly associated with ultramafic sandstones (*Lockwood*, 1971; *Arai and Okada*, 1991), we prefer a nearby single Spongtang Ophiolite source and suggest that the compositional field in *Mahéo*, (2000) for the Spongtang Ophiolite may be incomplete.

The Spongtang Ophiolite is an amalgam of mantle lithologies, including lherzolites and harzburgites in the western part and crustal lithologies in the eastern part (*Mahéo*, 2000). The chrome spinels analysed from the Spongtang Ophiolite fall into two broad groups, those found in abyssal peridotites (with Cr# values ~0.3 – 0.4 and those with arc characteristics (Cr# values >0.6). The presence of these two groups supports the theory that the Neotethyan IOIA developed over MORB-type crust (*Reuber*, 1989; *Pedersen et al*., 2001). The presence of detrital chrome spinels with high Cr# values in the ultramafic sandstones suggests that they were primarily derived from the arc component of the Spongtang Ophiolite.

4.2 Southern Tibet: Sangdanlin conglomerate

4.2.1 Analyses

Forty-five chrome spinel grains were analysed from the Sangdanlin conglomerate horizon (GPS sample location: 29º 15.3730 N, 85º 14.9940 E). Of these, three analyses had SiO_2 values >1% and were discarded. Representative analyses are presented in Table 2. TiO_2 values are elevated (between 0 – 1.58%) with an average of 0.24% (Figure 5A-C). Cr# values vary from 0.42 to 0.94 with an average of 0.66. Mg# values range between 0.02 and 0.63 (average of 0.45).

The spinels analysed from Sangdanlin are geochemically diverse. Overall, the majority exhibit low TiO_2 values and when coupled with an average Cr# value of (0.66) this suggests a dominant forearc peridotite (*Azer and Stern*, 2007) or SSZ zone (harzburgite) (*Lenaz et al*., 2000) source. Elevated Cr# values may also reflect increased partial melts in the mantle (*Dick and Bullen*, 1984). The spinels with elevated Fe^{3+} (Figure 5A) and TiO_2 (Figure 5C) may have been eroded from the crustal components of the island arc (see Figure 10 in *Barnes and Roeder*, (2001)), suggesting a mixed mantle and crustal signature from the IOIA.

The geochemistry of the detrital spinels exhibits a dominant ophiolitic signature (Cr–Al– Fe^{3+} data density plot, Figure 5A), suggesting they crystallised in a forearc setting (Figure 5B). When plotted on the TiO_2 vs. Al_2O_3 diagram (Figure 5C) all but three values plot in the arc peridotite and SSZ peridotite fields (*Kamenetsky et al*., 2001) (Figure 5C). The high Cr#, low TiO_2 and high Fe^{3+} are indicative of a SSZ (arc or back-arc) source with an increased partial melt component.

4.2.2 Comparison with potential sources

Previous attempts to constrain the source of the spinels at Sangdanlin compared them to a broad grouping of all YTSZ ophiolites (*Wang et al*., 2011). Comparing the Sangdanlin spinels to those from individual ophiolitic occurrences along the YTSZ may reveal direct relationships lost using a 'grouped' approach (see Section *5.2* for more details). Furthermore, the spinels analysed in this paper were extracted from a conglomerate horizon that contains serpentinite clasts, which is unique to the stratigraphic section at Sangdanlin (cf. *DeCelles et al*., 2014). This horizon is a record of a subtle, but significant erosional event that occurred at the time of deposition, rather than the basin-wide erosion recorded in the sandstones above and below the conglomerate horizon (cf. *DeCelles et al*., 2014).

Due to the presence of serpentinite clasts in the conglomerate, the chrome spinels are compared to those analysed from nearby ophiolitic massifs in southern Tibet. They include Zhongba, Saga, Sangsang, Beimarang, Qunrang, Dazhuqu, Jiding, Jinlu and Luobusa (Figure 6B). The detrital chrome spinels extracted from the pebbly conglomerate horizon broadly overlap with those from the Sangsang Ophiolite, however a number of analysed spinels lie outside of the known range and therefore must be accounted for. Six of the analyses, with Cr# values between 0.5 – 0.6, lie outside of the known Sangsang Ophiolite field. However, they overlap within the field for the nearby Saga ophiolite as well as detrital chrome spinels analysed from a sandstone horizon at Saga (Figure 6). This suggests that the detrital chrome spinels were sourced from an IOIA with overall similar characteristics to the Sangsang Ophiolite but also to the other IOIA massifs known from along the YTSZ. Seven additional grains (with Cr# values >0.8) do not fall into any known IOIA fields. These values may indicate that a minor component of the analysed spinels were altered or they were derived from an as yet unidentified source. Based on a similar geochemical signature, the most likely source for the majority of the detrital chrome spinels is the Sangsang Ophiolite (*Hébert et al.*, 2003; *Bédard et al.*, 2009) or an equivalent, now foundered ophiolite and arc edifice that also formed in an IOIA setting.

5 Discussion

The overall sequence of sedimentation in NW India and southern Tibet, from the Late Cretaceous to the end of the Paleocene, is remarkably similar. In the Late Cretaceous, Tethyan Himalayan sediments exhibit typical passive margin facies, including mature to supermature well-sorted sandstones and shallow marine sediments. The appearance of discrete sedimentary horizons containing serpentinite clasts represents an important change in sediment provenance that suggests partial derivation from an ultramafic source. Furthermore, the detrital chrome spinels extracted from these sediments exhibit SSZ signatures that overlap with those analysed from known IOIA remnants found within and adjacent to the ISZ and YTSZ. This source-to-sink connection records the erosion and subsequent deposition of IOIA detritus onto the northern margin of India at the end of the Paleocene (Thanetian) in southern Tibet and the Early Eocene in NW India. This transition is not solely restricted to the Zanskar Valley and Sangdanlin but was also observed by the authors in the tributaries of the Markha and Miru valleys east of Zanskar, in Nidar NW India, east of the Zhada basin in western Tibet and at Mt. Kailas in central western Tibet. These sites may provide additional evidence to constrain the timing of the IOIA's collision with India.

5.1 Evidence for IOIA collision in NW India

The chrome spinels extracted from the Chilling ultramafic sediments overlap with those analysed from the Spongtang Massif, a remnant klippe of oceanic crust (Spongtang Ophiolite) and arc volcanics (Spong Arc) that formed in an IOIA setting (Reuber, 1986; *Pedersen et al.*, 2001). This direct source-to-sink connection provides strong evidence for the emplacement of the IOIA onto the Indian margin in the Early Eocene in NW India.

Although our study provides important sedimentological evidence for the emplacement of the Neotethyan ophiolites in NW India the suggestion of a collision in this region is not new. *Robertson and Degnan* (1994) suggested that an ophiolitic mélange began to accrete at a trench within the Neotethyan Ocean, to the north of India, but they found no evidence for direct emplacement onto the Indian passive margin. The presence of serpentinite and chrome spinels at Chilling supports their interpretation for the development of an early Eocene foredeep, after which emplacement of the Spongtang Massif and related mélange occurred (*Robertson and Degnan*, 1994).

Linking the erosion of Neotethyan ophiolites to detrital chrome spinels found in the Indian passive margin in NW India has previously been postulated. *Garzanti et al.* (1987) and *Critelli and Garzanti* (1994) reported that chrome spinels, extracted from the Chulung La Formation, found to the south of the Spongtang Massif, exhibited both IOIA and mid-ocean ridge (MOR) signatures and were derived from Neotethyan ophiolites. Unfortunately, due to the unfossiliferous nature of the Chulung La Formation, constraining its age is difficult and a maximum depositional age younger than Late Paleocene is assumed (*Najman et al.*, 2001). Further work is required to constrain the age of deposition of the Chulung La Formation, which could help to refine the age of IOIA emplacement in this region.

Previous studies have attempted to constrain the age of emplacement of the Spongtang Massif and variously suggested 75-60 Ma (*Searle*, 1986) or 55-50 Ma (*Kelemen et al*., 1988; *Garzanti et al*., 2005;). In addition to the evidence provided herein, a 55-50 Ma emplacement age for the IOIA is preferred. It is supported by multiple structural studies that show that the basal thrust of the Spongtang Massif truncates fold hinges in the Paleocene to Early Eocene Lingshet Limestone (*Fuchs*, 1982 and others in *Kelemen et al., 1988*). The age of the sediments that underlie the Spongtang Massif also provide evidence for an Eocene emplacement. *Colchen et al*. (1987) reported Eocene foraminifers and radiolarians, including *Lamptonium pennatum* (Paleocene to earliest Eocene), *Lamptonium fabaeforme fabaeforme* (early to early mid-Eocene) and *Lamptonium fabaeforme chaunothorax* (early to mid-Eocene), extracted from the matrix of the mélange unit underneath the Spongtang

Massif. The presence of these fossils suggests that erosion and obduction of the IOIA continued until the early to mid-Eocene (RP9 = 50-49 Ma).

The ultramafic sediments at Chilling record the initial loading and emplacement of the IOIA onto the Indian margin. Continued erosion and emplacement occurred during the Early and mid- Eocene, confirmed by the maximum depositional age of the sediments underlying the Spongtang Massif and the timing relationships of the basal thrust and the folded Lingshet Limestone it truncates. The period between the first appearance of arc-derived material and the final emplacement of the Spongtang Massif, is within the estimated duration of ~10 Ma suggested by *Dewey* (2005) for a complete arc emplacement cycle to occur.

5.2 Evidence for IOIA collision in southern Tibet

The majority of chrome spinels extracted from the serpentinite-bearing pebbly conglomerate at Sangdanlin overlap with those from the nearby Sangsang Ophiolite, a remnant of oceanic crust that formed during back-arc spreading within an IOIA in the Early Cretaceous (*Bédard et al.,* 2009). This direct source-to-sink connection provides evidence for the collision of an IOIA with India in the latest Paleocene in southern Tibet. This interpretation is at odds with those (e.g. *Ding et al.,* 2005; *DeCelles et al.,* 2014; *Wu et al.,* 2014; *Hu et al.,* 2015) who suggest that the succession at Sangdanlin records the onset of the India-Eurasia collision and the development of syn-collisional basins. For example, *Hu et al.* (2015) proposed that the sediments at Sangdanlin effectively record the disappearance of Neotethyan oceanic lithosphere, which they suggest is constrained to the Middle Paleocene (59 ± 1 Ma). This relies on the presence of Cretaceous to Paleogene zircons at Sangdanlin that are interpreted as evidence of the first appearance of Eurasian material. However, the Neotethyan IOIA was also active at the same time as the Gangdese arc and would produce coeval zircons with ages and Hafnium (Hf) isotope signatures indistinguishable form those of the Gangdese batholith (*Aitchison et al.*, 2011). Therefore, the Himalayan continental arc should not be regarded as a unique potential source for the zircons reported by *Hu et al.* (2015).

In another study on detrital chrome spinels from Sangdanlin, *Hu et al.* (2014) suggested that they were reworked from the Xigaze forearc terrane, or indirectly from the Eurasian margin. The Xigaze forearc terrane is dominated by feldspathic-rich volcaniclastics, intermediate to felsic volcanics and minor plutonic clasts (*Einsele et al.*, 1994; *Dürr*, 1996). Although volcaniclastic material is reported from Sangdanlin it is predominately basaltic to andesitic in composition (*DeCelles et al.*, 2014) and therefore cannot be exclusively tied to derivation from the predominately intermediate to felsic composition of the Xigaze forearc detritus. Crucially, no studies have reported detrital ultramafic material in the Xigaze terrane (*Einsele et al.*, 1994; *Dürr*, 1996; *An et al.*, 2014) and therefore the ultramafic material present in the discrete pebbly conglomerate horizon at Sangdanlin must have come from an alternative source, now proposed to be the Sangsang Ophiolite, a remnant piece of Neotethyan IOIA crust.

The data presented herein suggest a viable alternative interpretation to models that infer derivation of sediments at Sangdanlin from the collision of India and Eurasia. Our analyses show that the chrome spinels extracted from Sangdanlin were most likely derived from IOIA ophiolite sources and suggest that the sediments at Sangdanlin record the collision of an IOIA with India, prior to later collision of India and Eurasia, at the end of the Paleocene.

5.3 Reconstructing the Neotethyan IOIA

Reconstructing the IOIA is a difficult but important step to advance our understanding of how the Neotethyan Ocean evolved. Here we discuss two scenarios that attempt to integrate the IOIA data from NW India and Pakistan with those from Tibet.

The first scenario envisages that at least two subduction systems were present in the Neotethyan Ocean. The first was located at a subequatorial location and extended across the Neotethyan Ocean, envisaged as an Izu-Bonin-Mariana (IBM) Arc equivalent (*Aitchison et al.*, 1999). This IOIA initiated in the Early Jurassic with the majority of the YTSZ and ISZ ophiolites forming in the Early Cretaceous, due to intra-arc rifting and the development of a SSZ spreading centre. In this scenario, a second IOIA subduction system (represented by the KLA) was also active in the northwest of the Neotethyan Ocean, but this island arc transitioned eastwards to a continental arc along southern Eurasia, similar to the model proposed by *Rolland et al.*, (2000). A modern equivalent is the Aleutian island arc transitioning into the North American continental arc (*Fliedner and Klemperer*, 2000). Supporting evidence includes the correlation of the YTSZ and ISZ ophiolites across the Karakoram Fault, using distinct marker horizons such as the Liuqu Conglomerate and its lateral equivalents (including the basalt and chert conglomerate at Chilling) (*Aitchison et al.*, 2007a; this study) and near equatorial palaeolatitudinal estimates for IOIA remnants in Tibet (*Abrajevitch et al*., 2005).

The second scenario proposed is that a single IOIA existed within the Neotethyan Ocean and the various components (ISZ and YTSZ ophiolites, the KLA and the Dras Complex) formed along the same sub-equatorial subduction system. This is supported by the similarities in the timing and development of the IOIA components, the subequatorial palaeolatitudinal estimates the KLA (*Khan et al.*, 2009), the presence of island arc magmatism in the KLA until ~40 Ma (*Jagoutz et al*., 2009) and the isotopic evidence for KLA collision with India at ~50 Ma (*Bouilhol et al.*, 2013). Clearly further work is needed to resolve which of these scenarios more accurately represents the evolution of IOIAs in the Neotethyan Ocean. We note available data require the existence of an IOIA and are incompatible with older models that infer Neotethyan oceanic lithosphere was simply subducted at a single continental convergent plate margin along the southern edge of Eurasia.

5.4 Additional evidence for multiple collision models

If an IOIA collided with India at the end of the Paleocene in southern Tibet and the Early Eocene in NW India then the Neotethyan Ocean must have persisted as an extensive and widespread ocean basin into the Eocene. Many early attempts to constrain the age of the youngest marine sediments in southern Tibet focused on a sequence at Tingri (*Willems*, 1996; *Li et al.*, 2000; *Xu*, 2000; *Zhu et al.*, 2005; *Wan et al.*, 2014) with Paleocene or Late Eocene ages reported. However Eocene (Bartonian to Pribonian) marine successions have now been recognised throughout southern Tibet, most notably at Gamba, Tingri, Zhongba, Saga and Yadong (*Li and Wan*, 2003; *Li et al*., 2002; *Wang et al*., 2002; *Xu*, 2000; *Wan et al*., 2014; *Jiang et al*., 2016). Furthermore, these are only maximum depositional ages as the upper boundaries of these sections are truncated by faulted or erosional surfaces (*Jiang et al.*, 2016). The presence of multiple occurrences of marine sediments throughout southern Tibet not only suggests that the Neotethyan Ocean existed well into the Eocene, but that it was a well-developed and extensive basin. Those that propose continent-continent collision at the end of the Paleocene (e.g. *Hu et al.*, 2015) would require a post-collision seaway to remain open for ~20 Ma, which is unlikely due to the observed convergence rates (140 – 70 $mmyr^{-1}$ from *Jagoutz et al.*, 2015) and assumed collision-related uplift rates during that time (60 – 40 Ma).

The closing of the Neotethyan Ocean represents a complex history of convergence. In the mid-Cretaceous, India began to migrate northward as Neotethyan crust was consumed at along at least two active subduction systems. Continued migration of India towards the IOIA, during the latest Cretaceous and earliest Paleocene (Figure 7A) resulted in the collision with the IOIA (represented by the IS and YTSZ ophiolites) in the late Paleocene-earliest Eocene. The IOIA was emplaced onto the Indian margin and began to deposit its erosive products on the Indian passive margin. These syn-collisional sediments are preserved in NW India at Chilling, with a more subtle signature preserved in Sangdanlin in southern Tibet (Figure 7B). Whether the KLA and Dras Complex were part this collision remains unresolved. Continued migration northwards of India with the newly emplaced IOIAs resulted in the terminal collision of India and Eurasia towards the end of the Eocene (Figure 7C) and the end of marine sedimentation in the Neotethyan Ocean.

6 Conclusions

Ultramafic detritus within in coarse clastic successions in Ladakh, NW India and coeval sediments at Sangdanlin, southern Tibet provides evidence for derivation from an ophiolitic source. The geochemistry of the chrome spinels, extracted from these successions, overlaps with that from IOIA remnants at Spongtang in NW India and Sangsang in southern Tibet. These remnants initially formed in an intra-oceanic island arc setting. Based on this new source-to-sink connection we propose that an IOIA collided with the northern margin of India at the end of the Paleocene to earliest Eocene. Although the collision with the arc temporarily slowed India's northward migration, the Neotethyan Ocean existed until at least the Late Eocene, as evidenced by marine successions reported throughout southern Tibet.

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9 Figure and Table captions

Figure 1: Simplified terrane map of the Himalayan region. Black boxes indicate the approximate areas for maps in Figure 2. MBT = Main Boundary Thrust; MCT = Main Central Thrust; STDS = South Tibetan Detachment System; YTSZ = Yarlung-Tsangpo suture zone; IS = Indus Suture; BNS = Bangong-Nujiang suture zone; JS = Jinsha suture; SS = Shuanghu suture.

Figure 2: (A) Geologic map of NW India and Pakistan (modified from *Bouilhol et al.*, 2013). Potential spinel sources are named. Inset map (represented by the black box) is a stratigraphic map of the Zanskar Valley region (modified from *Sinclair and Jaffey*, (2001)) showing the sample location at Chilling. (B) Geologic map of southern Tibet, showing the main terranes in and adjacent to the Yarlung-Tsangpo suture zone (YSTZ) and the potential sources for the detrital spinels are shown. GCT = Great Counter thrust; STDS = South Tibet detachment system (modified from *Aitchison et al.*, (2007a)).

Figure 3: (A) Photograph of the ultramafic-bearing sandstone unit, Zanskar Valley, NW India. The white lines are erosive bases and the triangles represent repeated fining up sequences. The ruler is 20 cm long; (B) Photograph of the basalt and chert clast-dominated conglomerate that overlies the ultramafic-bearing sandstone unit near the village of Chilling in the Zanskar Valley. It is the lateral equivalent of the Liuqu Conglomerate in southern Tibet. Identified clasts are; bas. = basalt; ch. = chert; vol. = volcanic; sst. = sandstone. (C) Photograph of the ultramafic-bearing pebbly conglomerate at Sangdanlin, the first appearance of ophiolitic material on the northern Indian passive margin in southern Tibet.

Figure 4: Thin section photomicrographs of the units studied; (A) Cellular serpentinite from the ultramafic-bearing sandstone unit in NW India; (B) Quartz and carbonate Indian passive margin sediments, Zheba, southern Tibet; (C) Sangdanlin conglomerate with quartzarenite, radiolarian bearing chert and volcanic clasts; (D) Large spinel grain within the Sangdanlin conglomerate. Abbreviations used are: carb. = carbonate; ch. = chert; mst. = mudstone; Qm = monocrystalline quartz; qtz. = quartzite; spl. = spinel; vol. = volcanic.

Figure 5: Tectonic discrimination diagrams of chrome spinels from Sangdanlin and NW India. (A) Ternary (Cr–Al– Fe^{3+}) plot to distinguish the tectonic setting during crystallisation. (B) Cr# vs. Mg# tectonic discrimination plot. (C) Tectonic discrimination diagram of *Kamenetsky et al*., (2001). MORB = Mid-ocean ridge basalt; SSZ peridotite = supra-subduction zone peridotite; OIB = ocean island basalt; LIP = Large Igneous Provence.

Figure 6: (A) Cr# vs. Mg# plot of the ultramafic-bearing sandstone spinels against potential sources from the Ladakh and Kohistan area. (B) Cr# vs Mg# plot of the Sangdanlin conglomerate spinels against potential sources from the southern Tibet area.

Figure 7: Reconstruction of the Neotethyan Ocean from the Late Cretaceous to Eocene that documents the demise of the IOIA at the end of the Paleocene and continued marine sedimentation well into the Eocene, before final India-Eurasian collision at the end of the Eocene.

Table 1: Representative EPMA major element oxide analyses for the detrital chrome spinel grains from Chilling (GPS sample location: 34º02.739 N, 077º12.729 E).

Sample	Representative analyses for the detrital chrome spinel grains from Chilling									
Analysis No.	101UM-1	101UM-5	101UM-11	101UM-16	101UM-18	101UM-24	101UM-34	101UM-39	101UM-45	101UM-49
SiO_2	0.0000	0.0490	0.0000	0.0010	0.0270	0.0150	0.0000	0.0200	0.0440	0.0280
MgO	8.1500	9.3070	7.2870	10.4770	11.2680	10.3200	10.3000	10.2990	12.9420	10.2480
Al_2O_3	8.5620	12.0240	7.0080	9.9080	10.8030	7.2150	17.0600	9.9650	28.3410	9.4280
TiO_2	0.1800	0.0250	0.0600	0.0710	0.0530	0.0000	0.0800	0.0850	0.1050	0.1080
FeO	20.4025	19.3921	21.4836	17.2104	16.0779	16.8940	18.6880	17.7127	15.6009	16.9776
Fe_2O_3	3.3746	2.6582	4.4359	2.6024	1.9672	3.1406	2.9817	1.0394	1.4248	3.3679
Cr_2O_3	58.2350	56.1230	58.8750	58.9760	58.8720	61.3400	50.1780	60.8880	38.3580	57.9490
NiO	0.0170	0.0260	0.1050	0.0070	0.0570	0.0500	0.0040	0.0460	0.0830	0.0890
MnO	0.4160	0.3260	0.3580	0.3010	0.2910	0.2870	0.3090	0.3630	0.2180	0.3820
ZnO	0.1470	0.1930	0.1430	0.1410	0.1610	0.0260	0.1240	0.1940	0.1530	0.1310
V_2O_5	0.0670	0.1890	0.1370	0.1160	0.1660	0.1130	0.1760	0.1640	0.1190	0.0610
FeOt	23.4390	21.7840	25.4750	19.5520	17.8480	19.7200	21.3710	18.6480	16.8830	20.0080
Total	99.5510	100.3120	99.8920	99.8110	99.7430	99.4010	99.9010	100.7760	97.3890	98.7690
Cr#	0.8202	0.7579	0.8493	0.7997	0.7851	0.8508	0.6636	0.8038	0.4758	0.8048
Mg#	0.4158	0.4610	0.3767	0.5203	0.5553	0.5212	0.4955	0.5089	0.5965	0.5182

Table 2: Representative EPMA major element oxide analyses for the detrital chrome spinel grains from Sangdanlin (GPS sample location: 29º 15.3730 N, 85º 14.9940 E).

Sample	Representative analyses for the detrital chrome spinel grains from Chilling									
Analysis no.:	2004SDL147 1-1	2004SDL147 2-1	SDL147 1-1	SDL147 2-1	1 1	2 1-1	4 1-1	6 1-1	9 1-1	12 2-1
SiO_2	0.1455	0.1662	0.1772	0.1782	0.2880	0.3277	0.0525	0.3682	0.1012	0.4177
MgO	8.0982	10.9490	9.7945	11.3211	9.5214	13.7530	10.3727	12.8860	11.9683	5.7970
Al_2O_3	8.9218	17.7150	10.7736	14.7791	19.8437	25.5853	19.2640	22.0370	24.9578	4.3370
TiO_2	0.0000	0.0000	0.5359	0.4818	0.5594	0.0668	0.0646	0.1372	0.0684	0.0212
FeO	21.1349	18.2345	19.2736	16.9333	21.0748	15.4123	19.4640	16.1000	18.1964	23.6437
Fe_2O_3	0.1418	0.3812	5.0025	14.4855	8.4327	0.2235	1.7774	0.0000	1.7099	0.3860
Cr_2O_3	62.0330	53.5334	55.2676	42.0206	42.2172	46.3557	49.5874	50.3232	45.1064	66.5494
NiO	0.0314	0.0625	0.1074	0.1166	0.1779	0.0844	0.0448	0.1237	0.0780	0.0001
MnO	0.1910	0.3182	0.0506	0.3851	0.5319	0.1850	0.1766	0.1521	0.3607	0.5120
ZnO	0.2989	0.2630	0.1822	0.1530	0.3534	0.3241	0.2042	0.3075	0.2191	0.2954
V_2O_5	0.2765	0.2899	0.0820	0.0608	0.2344	0.2253	0.3038	0.2099	0.2571	0.0225
FeOt	21.2625	18.5776	23.7750	29.9676	28.6627	15.6135	21.0634	16.1000	19.7350	23.9910
Total	101.2730	101.9129	101.2471	100.9151	103.2347	102.5432	101.3120	102.6446	103.0233	101.9819
Cr#	0.8234	0.6696	0.7748	0.6560	0.5879	0.5485	0.6332	0.6049	0.5479	0.9114
Mg#	0.4058	0.5169	0.4752	0.5437	0.4460	0.6139	0.4871	0.5878	0.5396	0.3041

Figures 1-7

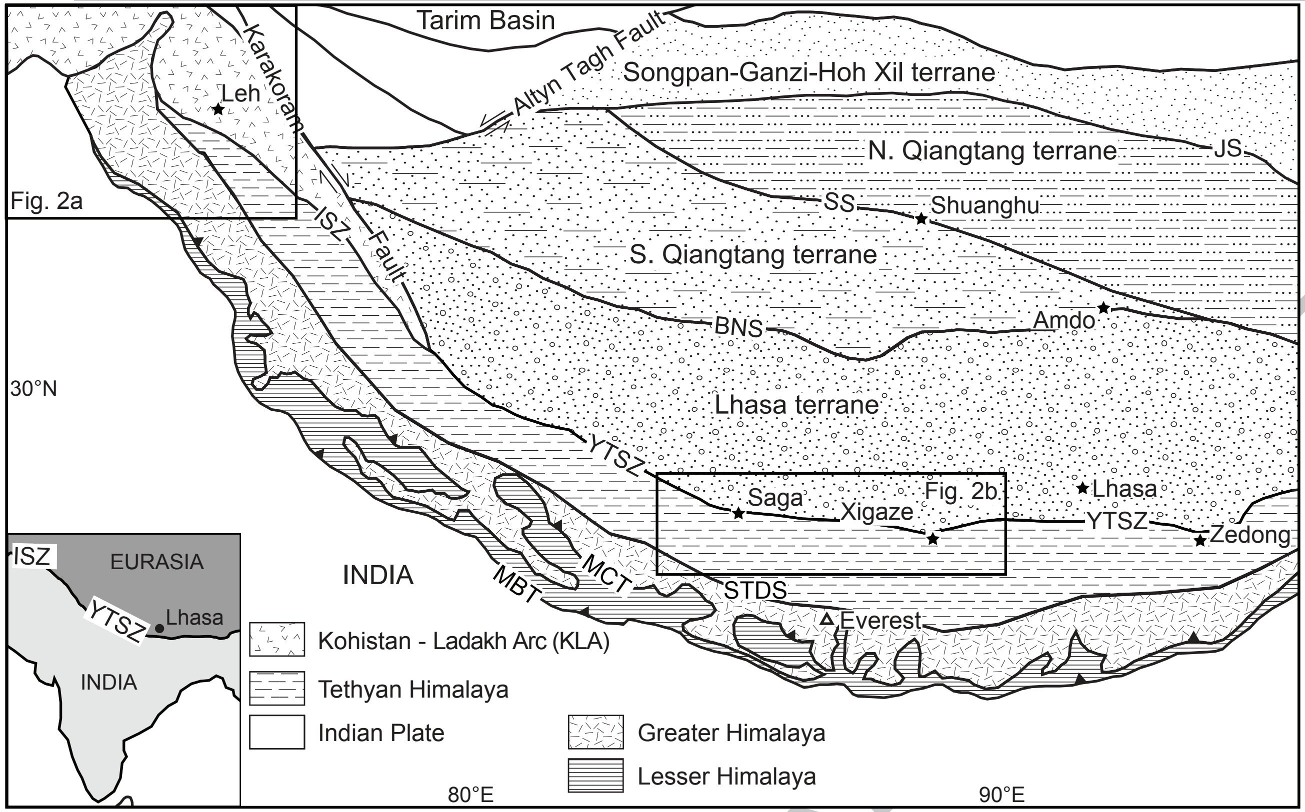
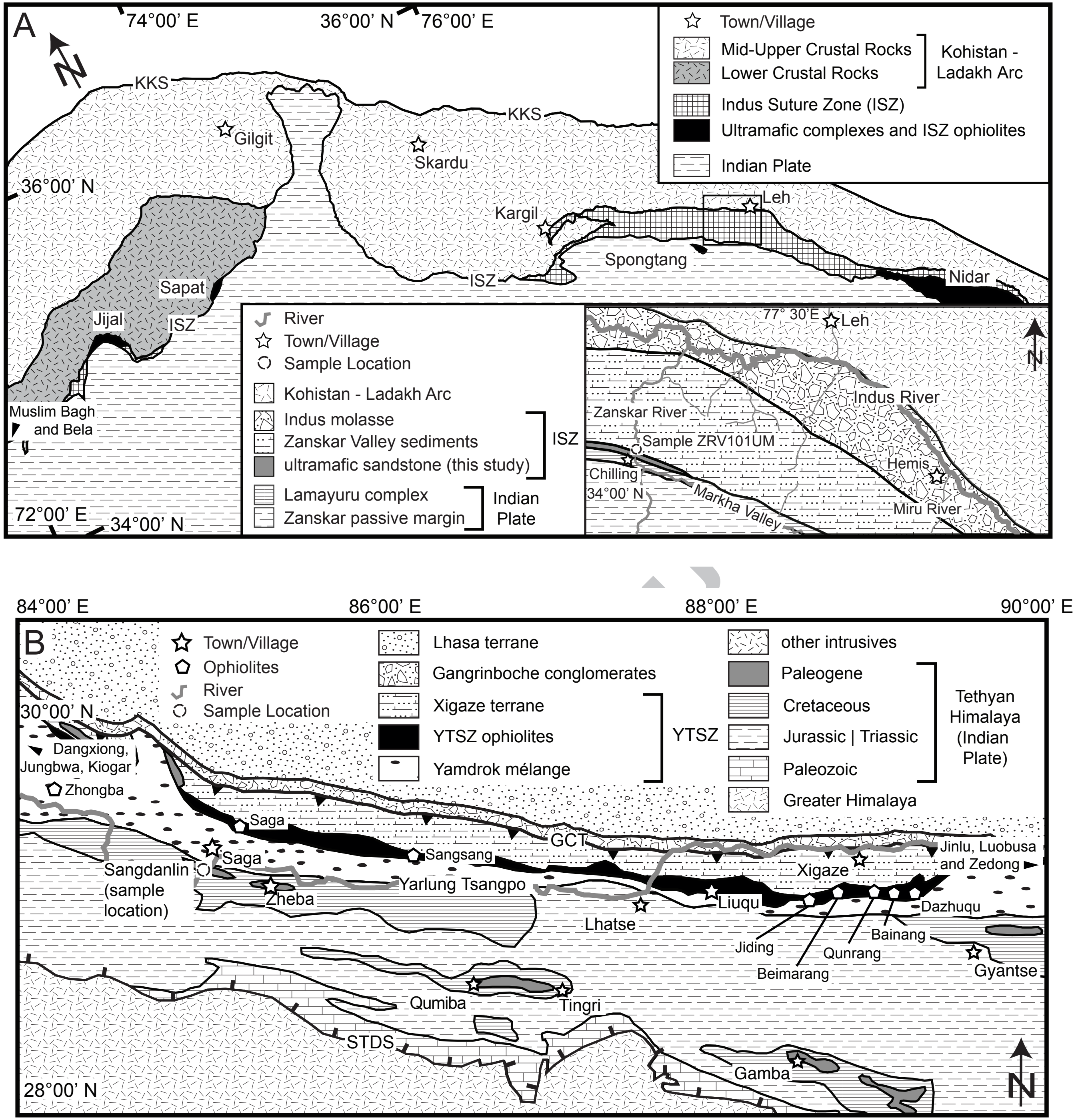


Figure 1



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and Bela
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34°00' N
Town/Village
Mid-Upper Crustal Rocks
Lower Crustal Rocks
Kohistan - Ladakh Arc
Indus Suture Zone (ISZ)
Ultramafic complexes and ISZ ophiolites
Indian Plate
River
Town/Village
Sample Location
Kohistan - Ladakh Arc
Indus molasse
Zanskar Valley sediments
ultramafic sandstone (this study)
ISZ
Lamayuru complex
Zanskar passive margin
Indian Plate
77° 30' E
Leh
N
Indus River
Zanskar River
Sample ZRV101UM
Chilling
34°00' N
Markha Valley
Hemis
Miru River
84°00' E
86°00' E
88°00' E
90°00' E
B
Town/Village
Ophiolites
River
Sample Location
Lhasa terrane
Gangrinboche conglomerates
Xigaze terrane
YTSZ ophiolites
Yamdrok mélange
YTSZ
other intrusives
Paleogene
Cretaceous
Jurassic | Triassic
Paleozoic
Greater Himalaya
Tethyan Himalaya (Indian Plate)
30°00' N
Dangxiong, Jungbwa, Kiogar
Zhongba
Saga
Saga
Sangsang
GCT
Jinlu, Luobusa and Zedong
Xigaze
Sangdanlin (sample location)
Zheba
Yarlung Tsangpo
Lhatse
Liuqu
Dazhuqu
Bainang
Jiding
Qunrang
Beimarang
Gyantse
Qumiba
Tingri
STDS
Gamba
N
28°00' N

Figure 2

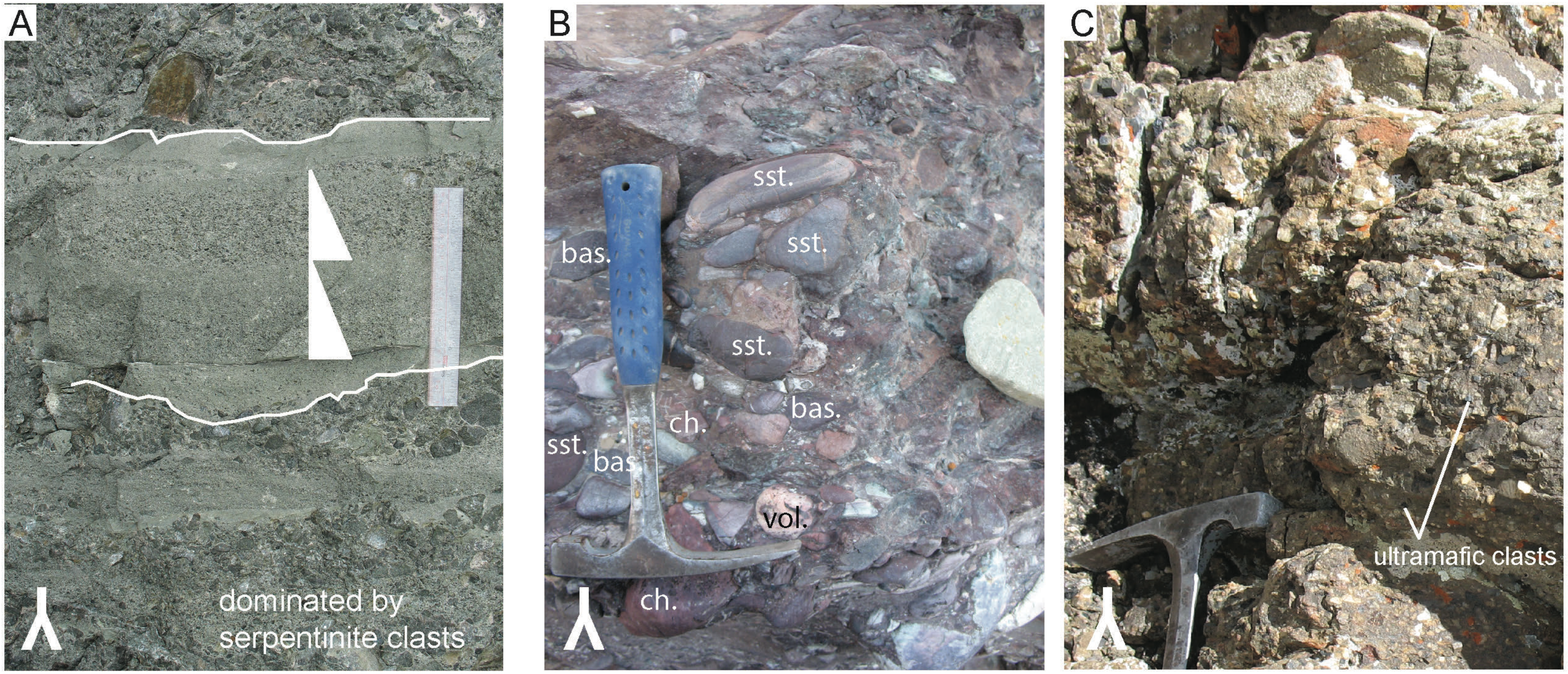

A
dominated by
serpentinite clasts
B
sst.
sst.
bas.
sst.
bas.
ch.
sst.
bas.
vol.
ch.
C
ultramafic clasts

Figure 3

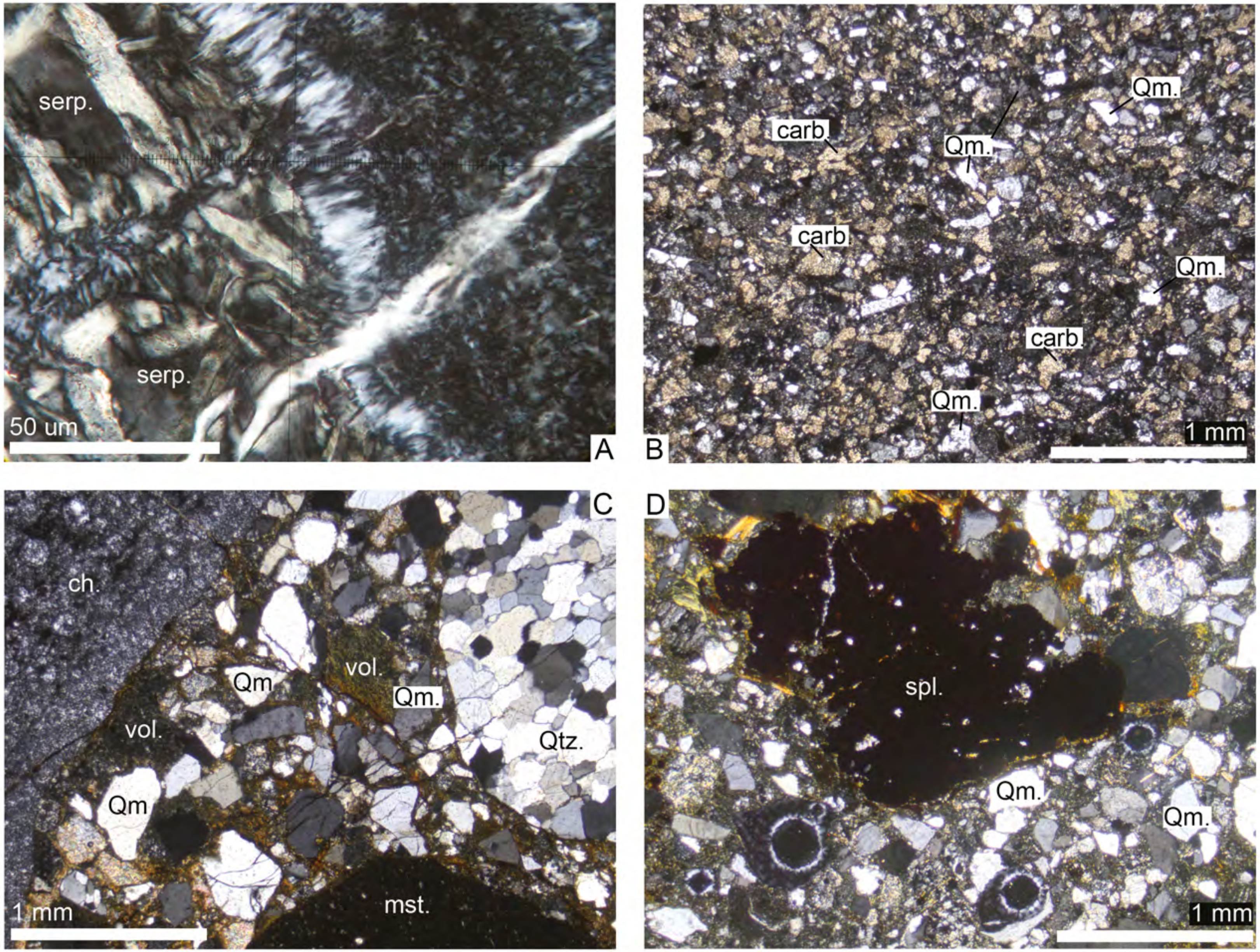
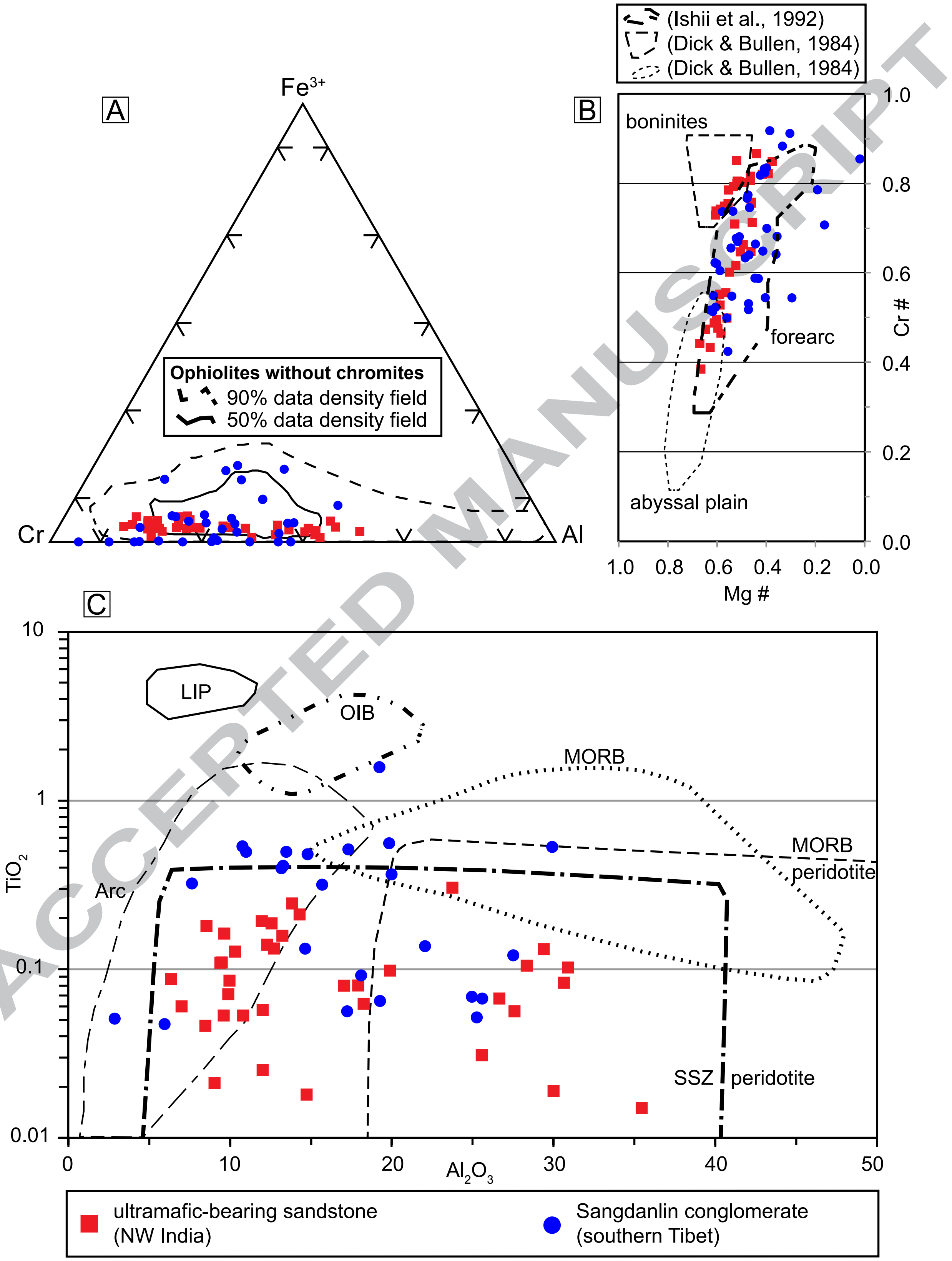
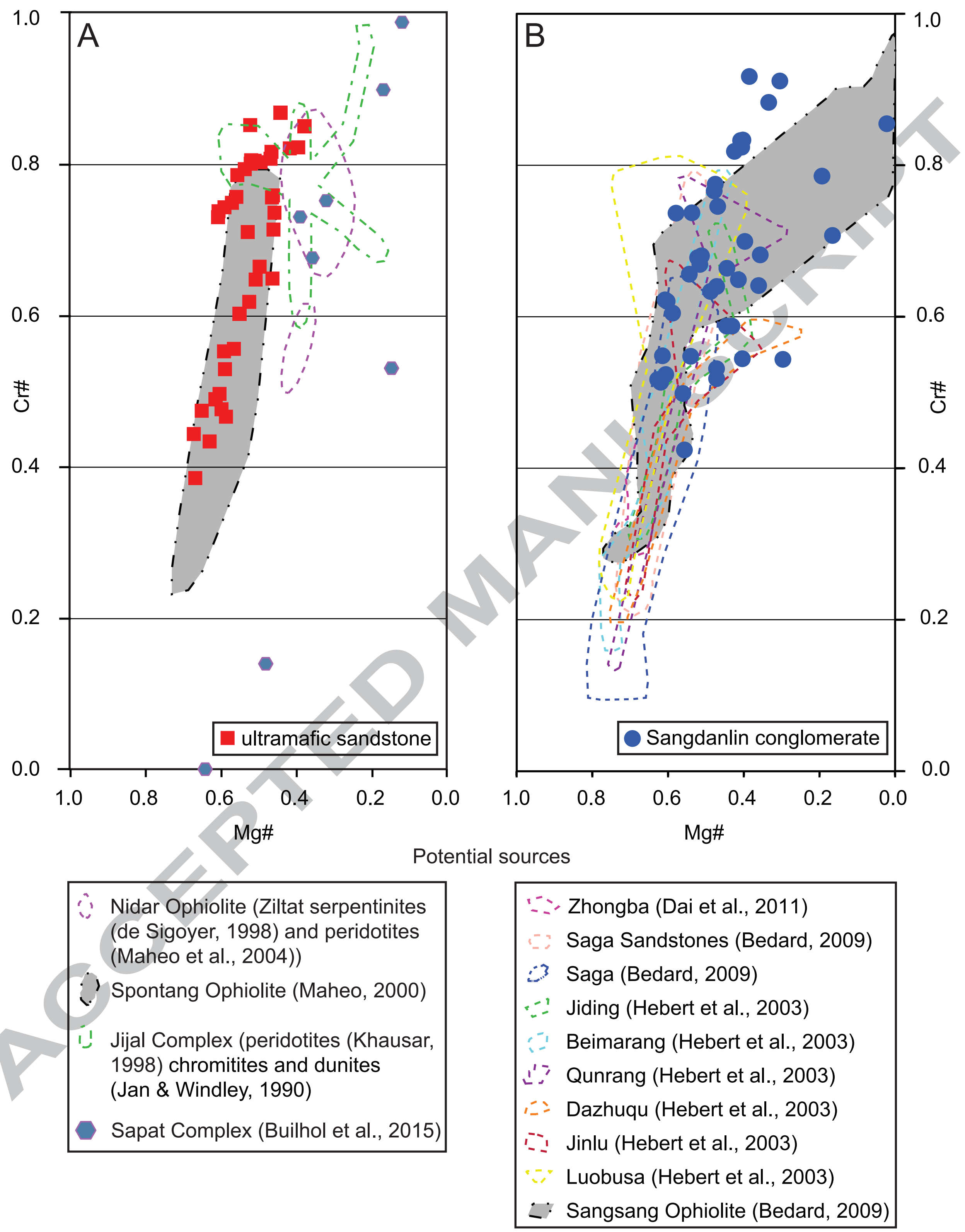

serp.
serp.
50 um
A
carb.
Qm.
Qm.
carb
Qm.
carb.
Qm.
1 mm
B
C
ch.
Qm
vol.
Qm.
vol.
Qtz.
Qm
mst.
1 mm
D
spl.
Qm.
Qm.
1 mm

Figure 4



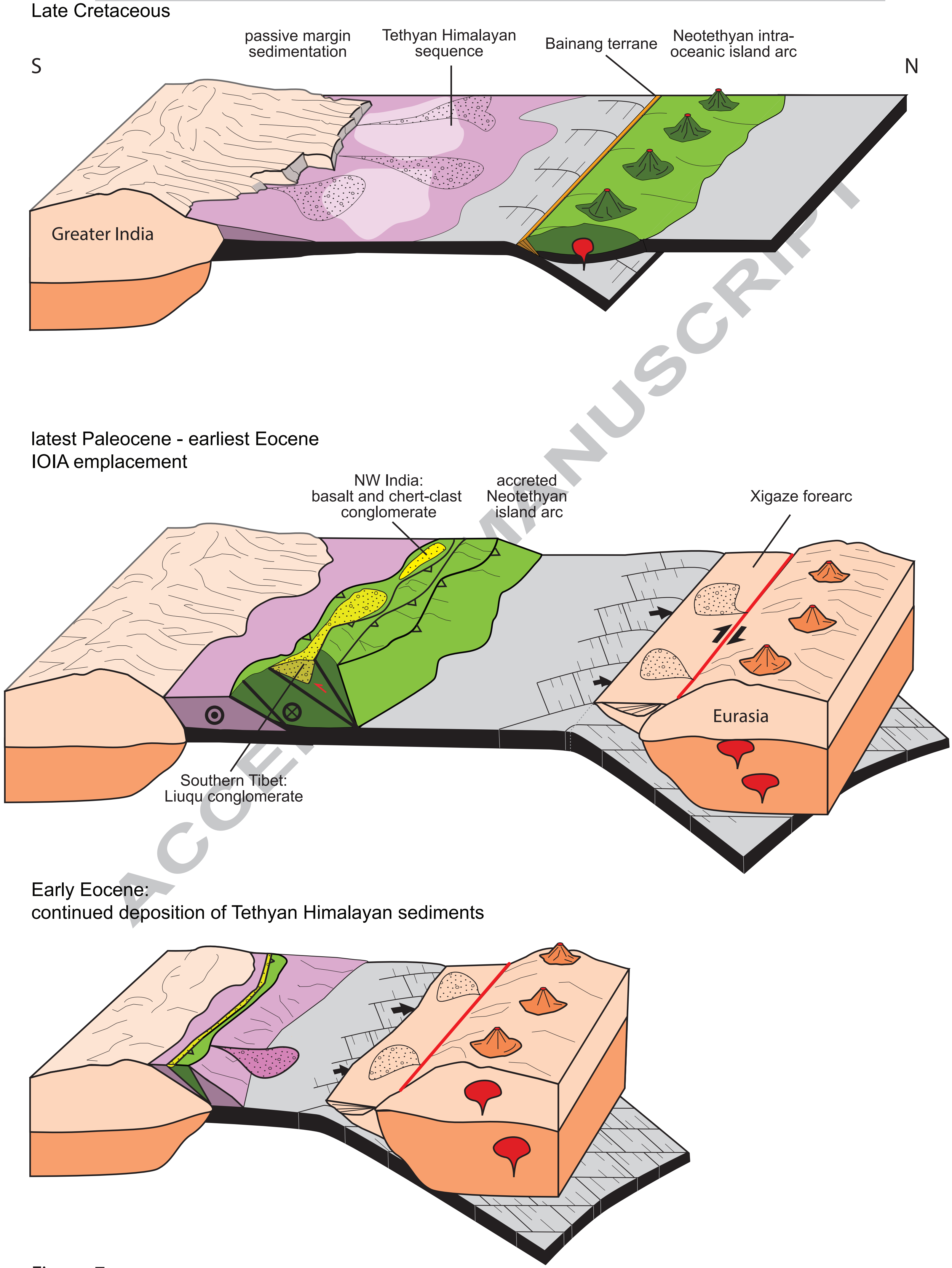
A
Fe3+
Cr
Al
Ophiolites without chromites
90% data density field
50% data density field
B
(Ishii et al., 1992)
(Dick & Bullen, 1984)
(Dick & Bullen, 1984)
boninites
forearc
abyssal plain
1.0
0.8
0.6
0.4
0.2
0.0
Cr #
Mg #
C
10
1
0.1
0.01
TiO2
Al2O3
0
10
20
30
40
50
LIP
OIB
MORB
MORB peridotite
Arc
SSZ peridotite
ultramafic-bearing sandstone (NW India)
Sangdanlin conglomerate (southern Tibet)

Figure 5



A
B
1.0
0.8
0.6
0.4
0.2
0.0
Cr#
Mg#
ultramafic sandstone
Sangdanlin conglomerate
Potential sources
Nidar Ophiolite (Ziltat serpentinites (de Sigoyer, 1998) and peridotites (Maheo et al., 2004))
Spontang Ophiolite (Maheo, 2000)
Jijal Complex (peridotites (Khausar, 1998) chromitites and dunites (Jan & Windley, 1990)
Sapat Complex (Builhol et al., 2015)
Zhongba (Dai et al., 2011)
Saga Sandstones (Bedard, 2009)
Saga (Bedard, 2009)
Jiding (Hebert et al., 2003)
Beimarang (Hebert et al., 2003)
Qunrang (Hebert et al., 2003)
Dazhuqu (Hebert et al., 2003)
Jinlu (Hebert et al., 2003)
Luobusa (Hebert et al., 2003)
Sangsang Ophiolite (Bedard, 2009)

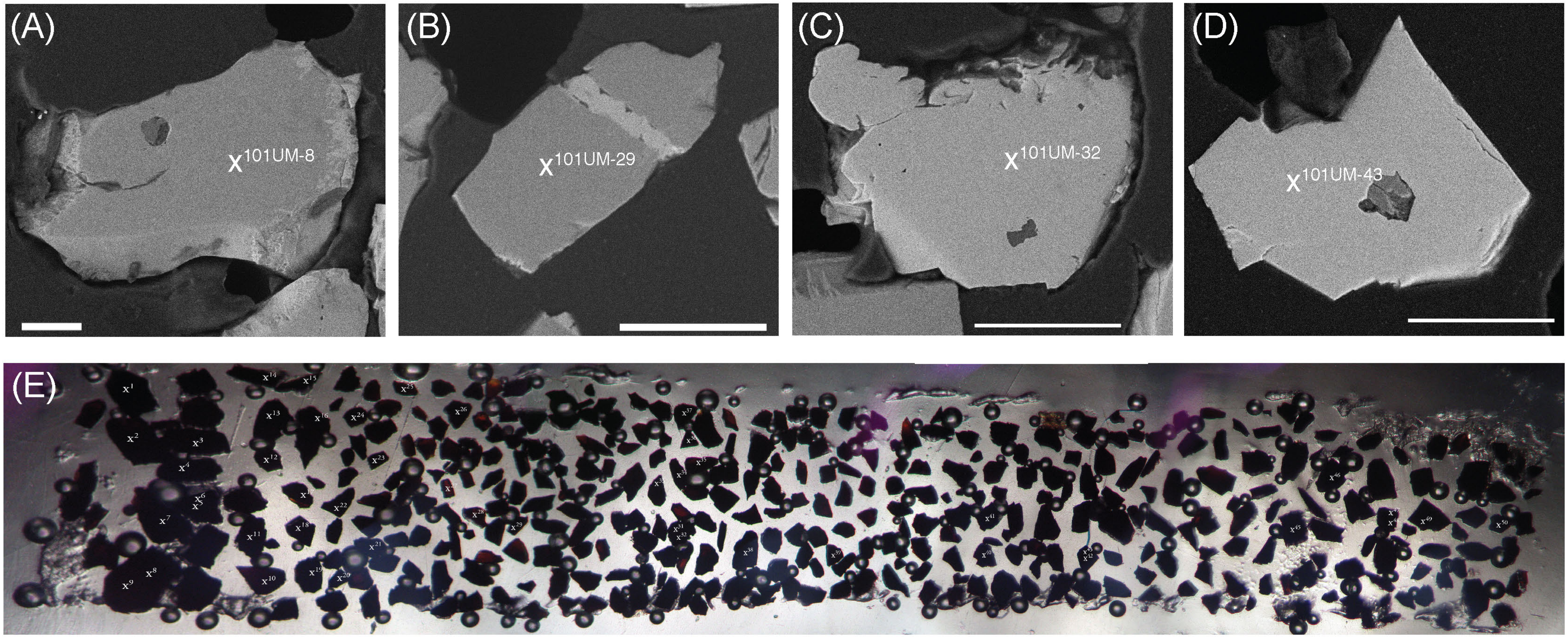
Figure 6



Late Cretaceous
passive margin sedimentation
Tethyan Himalayan sequence
Bainang terrane
Neotethyan intra-oceanic island arc
S
N
Greater India
latest Paleocene - earliest Eocene
IOIA emplacement
NW India:
basalt and chert-clast conglomerate
accreted Neotethyan island arc
Xigaze forearc
Eurasia
Southern Tibet:
Liuqu conglomerate
Early Eocene:
continued deposition of Tethyan Himalayan sediments

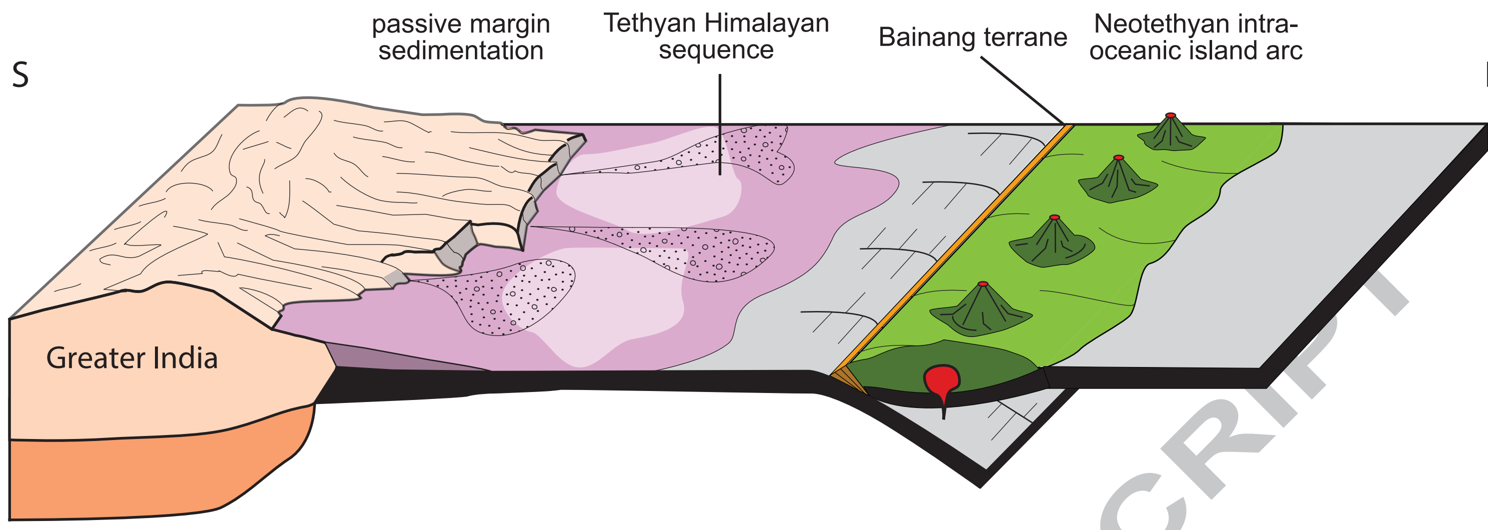
Figure 7

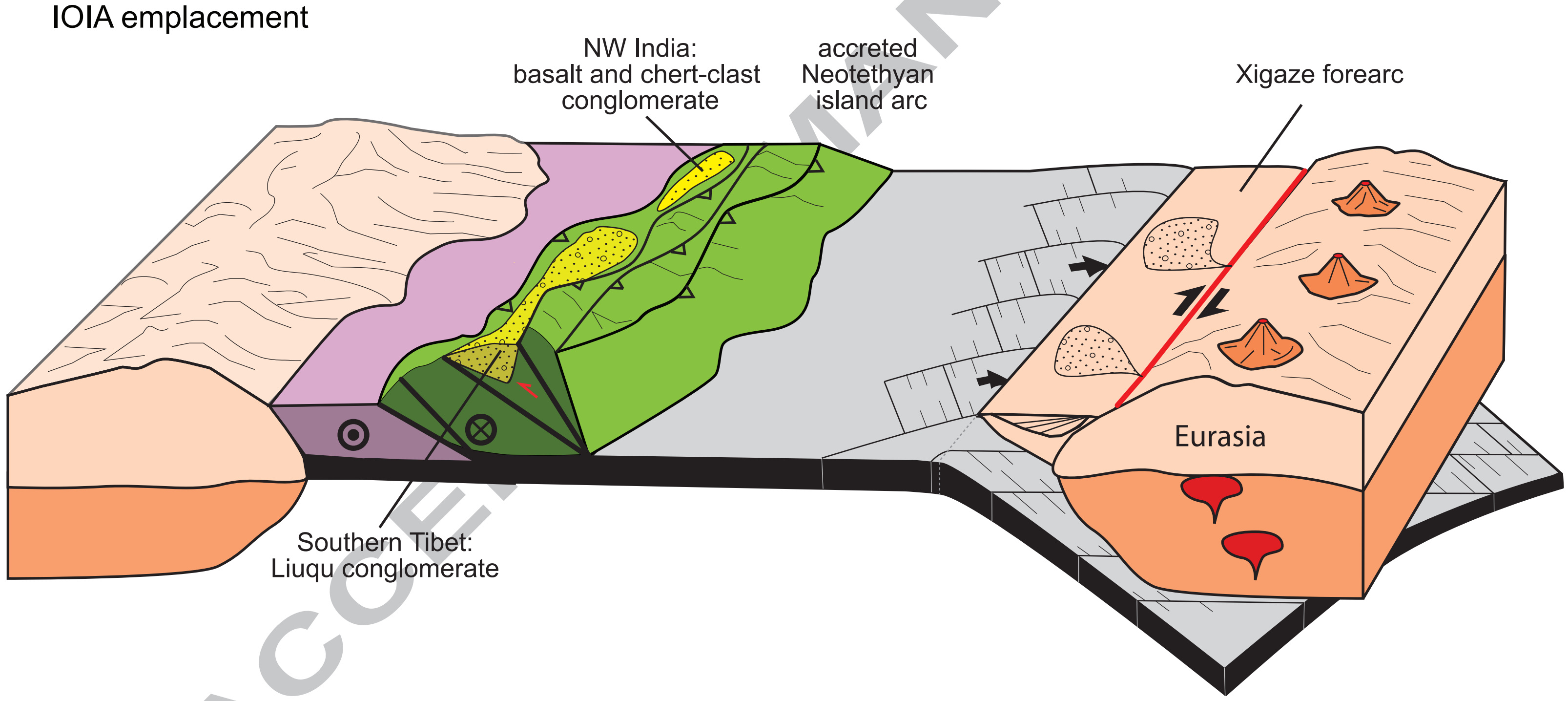
Supplementary Figure 1

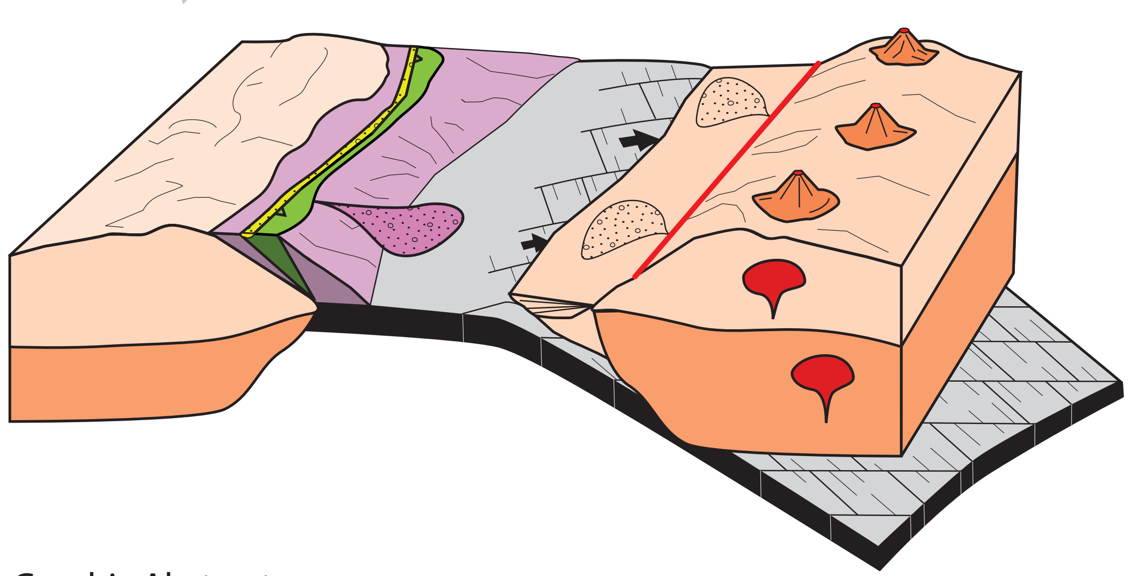


Supplementary Figure S1 (A-D): A selection of backscatter SEM photomicrographs of the chrome spinels analysed. Areas with fractures or inclusions were avoided. The white 'X' marks the approximate location of each analysis. Scale bars are 100um. (E) Composite photomicrograph map for EPMA analyses.

Graphic Abstract







Graphic Abstract

Highlights

Detrital chrome spinels were extracted from discrete, ultramafic-bearing sediments in southern Tibet and NW India

Chrome spinels are geochemically similar to known intra-oceanic island arc (IOIA) remnants along the Yarlung Tsangpo and Indus suture zones and provide evidence for the collision of an IOIA with India

Initial emplacement of an IOIA occurred at the end of the Paleocene in southern Tibet and the earliest Eocene in NW India

Data provide a maximum age constraint of Late Paleocene-Early Eocene for the India-Eurasia collision