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Reconstructing Greater India: Paleogeographic, kinematic, and geodynamic perspectives

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ABSTRACT

Key in understanding the geodynamics governing subduction and orogeny is reconstructing the paleogeography of 'Greater India', the Indian plate lithosphere that subducted since Tethyan Himalayan continental collision with Asia. Here, we discuss this reconstruction from paleogeographic, kinematic, and geodynamic perspectives and isolate the evolution scenario that is consistent with all three. We follow recent constraints advocating a ~58 Ma initial collision and update a previous kinematic restoration of intra-Asian shortening with a recently proposed model that reconciles long-debated large and small estimates of Indochina extrusion. Our new reconstruction is tested against paleomagnetic data, and against seismic tomographic constraints on paleo-subduction zone locations. The resulting restoration shows ~1000–1200 km of post-collisional intra-Asian shortening, leaving a 2600–3400 km wide Greater India. From a paleogeographic, sediment provenance perspective, Eocene sediments in the Lesser Himalaya and on undeformed India may be derived from Tibet, suggesting that all Greater Indian lithosphere was continental, but may alternatively be sourced from the contemporaneous western Indian orogen unrelated to India-Asia collision. A quantitative kinematic, paleomagnetic perspective prefers major Cretaceous extension and a 'Greater India Basin' opening within Greater India, but data uncertainty may speculatively allow for minimal extension. Finally, from a geodynamic perspective, assuming a fully continental Greater India would require that subduction rates close to 20 cm/yr was driven by a downgoing lithosphere-crust assemblage more buoyant than the mantle, which seems physically improbable. We conclude that the Greater India Basin scenario is the only sustainable one from all three perspectives. We infer that old pre-collisional lithosphere rapidly entered the lower mantle sustaining high subduction rates, whilst post-collisional continental and young Greater India basin lithosphere did not, inciting the rapid India-Asia convergence deceleration ~8 Myr after collision. Subsequent absolute northward slab migration and overturning caused flat slab subduction, Tibetan shortening, arc migration and arc volume decrease.

1. Introduction

Kinematic reconstructions of past plate motions and plate boundary deformation provide the framework to analyze the geodynamic processes behind plate tectonics and continental deformation. Among the most spectacular regions with intense plate boundary deformation are the Tibetan Plateau that formed in response to major shortening of overriding Eurasian continental crust, in part due to collision between India and Asia, and the narrow Himalayan fold-thrust belt consisting of continental crustal nappes offscraped from now-subducted Indian plate lithosphere (*e.g.*, Argand, 1924; Dewey et al., 1988; Hodges, 2000; Yin and Harrison, 2000) (Fig. 1). A critical constraint for analyzing the geodynamics governing Indian plate subduction, and subduction in general, is constraining the paleogeography of 'Greater India', *i.e.*, the portion of the Indian plate that subducted since initial collision following closure of the Neotethys Ocean between the northernmost

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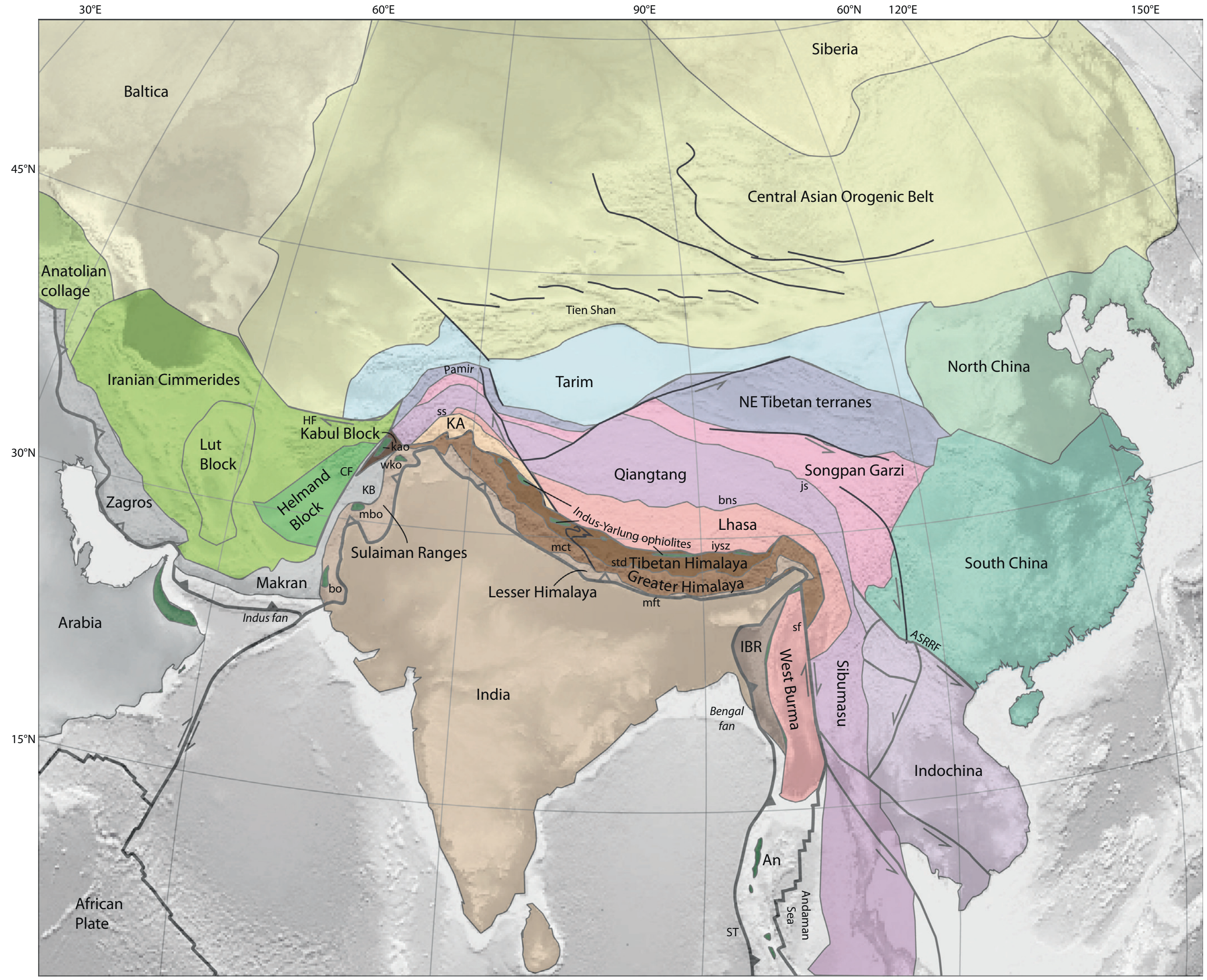


Fig. 1. Tectonic map of the India-Asia collision zone and surrounding regions, and the main outline of the retrodeformed polygons shown in Figs. 3, 9, and 11. Key to abbreviations: An = Andaman Islands; ASRRF = Aliao Shan-Red River Fault; bns = Bangong-Nujiang Suture; bo = Bela Ophiolite; *CF* = Chaman Fault; HF = Herat Fault; MFT = Main Frontal Thrust; IBR = Indo-Burman Ranges; IYSZ = Indus-Yarlung Suture Zone; KA = Kohistan Arc; kao = Kabul-Altimur Ophiolite; KB = Katawaz Basin; js = Jinsha Suture; mbo = Muslim Bagh Ophiolite; mct = Main Central Thrust; mft = Main Frontal Thust; SF = Sagaing Fault; SS = Shyok Suture; ST = Sunda Trench; std. = South Tibetan Detachment; wko = Waziristan-Khost Ophiolite.

continental rocks derived from the Indian plate – the Tethyan (or Tibetan) Himalaya (TH) – and the southern continental block of the Tibetan Plateau – the Lhasa block. Was all this lithosphere continental, as widely assumed (*e.g.*, Ali and Aitchison, 2005; Garzanti and Hu, 2015; Ingalls et al., 2016; Wang et al., 2014; Zhuang et al., 2015), or was it largely oceanic with only a microcontinental fragment from which the TH was derived (Huang et al., 2015d; van Hinsbergen et al., 2012)?

An accurate reconstruction of the paleogeography of Greater India first relies on reconstructing its dimension. This dimension is estimated from the relative position of India *versus* Asia at the moment of initial collision, and estimating the location of the intervening subduction plate boundary relative to the stable, undeformed parts of the Indian and Eurasian plates. Determining the position of the plate boundary at the time of collision shows how much post-collisional convergence was accommodated by deformation of the overriding Eurasian plate, and how much was accommodated by Indian plate subduction.

Estimates for the collision age vary, as will be reviewed below, but are based on several independent lines of evidence, including the age of the oldest high-pressure metamorphic continental rocks in the TH that constrain when it was buried at a subduction plate boundary, the age of the oldest Asia-derived sediments in the TH stratigraphy, and paleomagnetic data constraining the latitudinal separation between the TH and the Lhasa block. Recent age estimates based on high-resolution stratigraphy and sedimentology have converged the statigraphic collision age estimate towards 56–60 Ma (DeCelles et al., 2014; Hu et al., 2015, 2016; Orme et al., 2015). Based on a small set of U/Pb zircon ages from Tethyan Himalayan rocks that were metamorphosed at ultra-high pressure, low-temperature conditions, Leech et al. (2005) called for a minimum 56 Ma collision age (assuming burial rates similar to Indian plate subduction rates), although more recent dating work allows for a younger, 51 Ma minimum collision age (Donaldson et al., 2013). In contrast, paleomagnetic estimates vary widely, but statistically well-constrained paleomagnetic data carefully corrected for typical paleomagnetic artifacts such as inclination shallowing and remagnetization were interpreted to lead to a 52 to 50 Ma collision age (Huang et al., 2013, 2015a; Lippert et al., 2014).

This 10 Myr disparity between collision ages – and both even older and younger age estimates are discussed in the literature (*e.g.*,Ding et al., 2005; Aitchison et al., 2007; Jagoutz et al., 2015) – has major consequences for constraining the size of Greater India. This is because India-Asia convergence rates, reconstructed from marine magnetic anomaly patterns in the Atlantic and Indian oceans, were as high as 15–18 cm/yr between 65 and 50 Ma, the highest convergence rates reconstructed from marine magnetic anomalies globally. Changing the collision age by as little as 1 Myr thus changes the amount of post-collisional India-Asia convergence by as must as 150–180 km.

Accurately reconstructing the paleogeography of Greater India is paramount for the analysis of the geodynamics governing subduction. It has long been realized that the amount of upper crust that recorded crustal shortening in the Tibetan Plateau and Himalayas since initial continental collision is much smaller than the amount of reconstructed contemporaneous India-Asia convergence (*e.g.*, Johnson, 2002; van Hinsbergen et al., 2012). The magnitude of post-collisional India-Asia convergence for a 50–60 Ma collision age range was ~2300–3800 to ~3000–4800 km at the western and eastern Himalayan syntaxis, respectively (*e.g.*, Copley et al., 2010; van Hinsbergen et al., 2011b). The total amount of shortening since that time restored for Tibet and the Himalaya was estimated at some ~1500 km (Long et al., 2011a; van Hinsbergen et al., 2011a) and also pre-and post-collisional crustal volume calculations show that the modern orogen can only contain a fraction of the pre-collisional crustal volume (Ingalls et al., 2016; Yakovlev and Clark, 2014). These conclusions inevitably require that ~1000–3000 km (depending on the interpreted collision age) of Greater Indian lithosphere underwent wholesale subduction without leaving an accreted rock record (Ingalls et al., 2016; van Hinsbergen et al., 2012). Was this entirely subducted lithosphere oceanic, as would be predicted by canonical geodynamic arguments (*e.g.*, Turcotte and Schubert, 2002), or continental, as generally assumed in the community studying the India-Asia collision (*e.g.*, Ali and Aitchison, 2005; Garzanti and Hu, 2015; Ingalls et al., 2016; Wang et al., 2014; Zhuang et al., 2015)?

In this paper, we first re-evaluate the size estimate of Greater India of van Hinsbergen et al. (2011a) by incorporating five new sources of information unavailable when that reconstruction was made: (i) we will discuss the causes of the discrepancies in collision age estimates and update the previous reconstructions of van Hinsbergen et al. (2011a, 2012) who assumed a 50 Ma collision age, where necessary; (ii) we adopt a recent reconstruction of Indochina extrusion that reconciles long-debated large and small extrusion estimates (Li et al., 2017) with implications for the amount of shortening accommodated in the eastern Tibetan Plateau; (iii) we re-evaluate the kinematic necessity of extension in Greater India, as well as the paleomagnetic constraints on the age of collision, in the light of recent evidence that the Upper Cretaceous and Paleogene paleomagnetic poles of the TH were derived from remagnetized rocks (Huang et al., 2017a, b); (iv) we compiled paleomagnetic constraints on vertical axis rotations in the Tibetan Plateau and use these to test our reconstruction based on structural geological and geometrical constraints, using the online paleomagnetic analysis tools on paleomagnetism.org (Koymans et al., 2016; Li et al., 2017); (v) finally, we test our reconstructed position of the India-Asia subduction plate boundary against seismic tomographic images of underthrust and subducted lithosphere.

We then discuss the reconstruction of Greater India's paleogeography from three perspectives. The first is a paleogeographic perspective. A widely-used tool to assess the paleogeography of Greater India is sediment provenance analysis that aims to constrain sedimentary pathways between a source area and a final sink. When analyzing sandstones, a down-slope profile should have existed between a source and sink, and when both sink and source are located on continental crust, it is inevitable that the trajectory connecting the two was as well. Thus, the nature of crust that occupied the once intervening area now lost to deformation or subduction may be constrained.

Then second is a kinematic perspective. Shortening estimates from the Himalaya and Tibet recorded only 30% or less of the total amount of India-Asia convergence as crustal shortening and does not obviously directly constrain the nature of entirely subducted lithosphere. Kinematic constraints on the nature of that subducted lithosphere may be inferred from paleomagnetic data from the TH compared to the global paleomagnetic reference frame in Indian coordinates (van Hinsbergen et al., 2012). In addition, marine magnetic anomalies of the west-Australian margin help constrain the size of Greater India at the moment of India-Australia break-up (Gibbons et al., 2012, 2013).

The third is a geodynamic perspective. The India-Asia collision history is unique in that it was associated with the highest plate convergence rates reconstructed from the modern oceans, and these ultra-high-subduction rates persisted until 50 Ma, *i.e.*, potentially up to 10 Myr longer than widely proposed initial collision ages. Is it from a geodynamic perspective more likely that the Indian plate lithosphere that subducted at ultra-high rates without known accretion was oceanic, or continental? And in case the collision age does not coincide with the age of India-Asia deceleration, how may a delay between these two phenomena be explained?

With this paper, we update the kinematic restoration of Tibet and the Himalaya and review perspectives on the paleogeographic, kinematic, and geodynamic analysis of the India-Asia collision. We will illustrate that these perspectives may suggest mutually exclusive scenarios and propose a way towards reconciliation.

2. Geological setting and tectonic outline

2.1. Tectonic architecture of the India-Asia collision zone

The modern India-Asia plate boundary is here defined as the northernmost boundary of the contiguous Indian plate with the deforming southern part of Asia. It runs from south of the Makran accretionary prism, along the frontal thrust of the Sulaiman ranges to the Main Frontal Thrust, to the western thrust front of the Indo-Burman ranges and connects to the Sunda trench west of the Andaman Islands (Fig. 1). North of this modern plate boundary is the India-Asia collision zone that contains thin-skinned fold-thrust belts consisting of Indian plate-derived rocks; this zone also contains deformed continental fragments of Asia that were once part of Gondwana and their intervening suture zones where ocean basins that separated these fragments have subducted prior to the Cenozoic. These fragments and sutures define the pattern that is kinematically reconstructed into its Early Cenozoic configuration and is briefly outlined below.

The modern plate boundary is separated from the Neotethyan suture zone by a thin-skinned, foreland propagating fold-thrust belt consisting of the Sulaiman ranges, the Himalaya, and the Indo-Burman ranges that comprise Indian-plate derived crustal nappes (Fig. 1). The Neotethyan suture zone is formed by the Chaman Fault and Katawaz basin in the west, the Indus-Yarlung suture zone in the north, and the inner Indo-Burman Ranges in Myanmar in the east (Fig. 1). This suture zone demarcates the trench where Indian plate oceanic lithosphere was subducted until the first collision of Indian continental crust; after this initial collision, the India-derived foreland propagating fold-thrust belts started forming at the southern Asian plate boundary zone during ongoing post-collisional Indian plate subduction (Banks and Warburton, 1986; Bertrand et al., 2001; Gansser, 1980; Treloar and Izatt, 1993; Vigny et al., 2003). Importantly, however, the Sulaiman ranges in the west experienced a Late Cretaceous-Eocene deformation episode associated with ophiolite emplacement. This deformation stage occurred during oblique Indian subduction below oceanic lithosphere of the African/Arabian plate that is unrelated to the India-Asia collision history (Gnos et al., 1997; Gaina et al., 2015). This deformation stage preceded Neogene deformation directly related to the India-Asia collision and is important to take into account for the interpretation of sediment provenance data generally used as evidence for India-Asia collision zone processes; this point will be explained in more detail below.

2.1.1. Asian terranes

To the north of the India-derived fold-thrust belts, the Asian lithosphere is comprised of units that since Paleozoic time amalgamated to the Siberian Craton in the far north (Fig. 1). Surrounding Siberia in the west and south is the intensely deformed Central Asian Orogenic Belt that formed largely in Paleozoic time (Wilhem et al., 2012; Xiao et al., 2009, 2015), except in Mongolia and far-east Russia, where the subduction and convergence continued until the latest Jurassic-earliest Cretaceous closure of the Mongol-Okhotsk ocean (Van der Voo et al., 2015). To the south of the Central Asian Orogenic Belt lies the Tarim block in the west and the North China block in the east, which collided with the Central Asian Orogenic Belt in Permo-Triassic time (Xiao et al., 2009). To the east of the collision zone lies the South China Block (Fig. 1) that collided with the North China block in the Triassic (Liu et al., 2015b; Ratschbacher et al., 2003; Zhao and Coe, 1987).

South of the Tarim block and west of the China blocks lies the Tibetan Plateau. This plateau is underlain in the northeast by NE Tibetan terranes that comprise a fold-thrust belt that has probably been part of the North China block since Paleozoic time (Gehrels et al., 2003). To the south is the Songpang-Garzi terrane, a deep-marine Triassic turbidite belt that can be traced from the Pamir towards the western end of the South China block and that is interpreted as an accretionary prism derived from subducted Paleotethys oceanic crust (De Sigoyer et al., 2014; Pullen et al., 2008) that formed during convergence between NE Tibetan terranes and the Qiangtang block to the south until latest Triassic time (Weislogel et al., 2010; Yin and Harrison, 2000; Zhou and Graham, 1996). The northern boundary of the Qiangtang terrane (or terranes, *e.g.*, Zhu et al. (2013)) is known as the Jinsha suture and its southern boundary is the Bangong-Nujiang suture that closed in Early Cretaceous time upon collision with the Lhasa terrane (Kapp et al., 2007; Z. Li et al., 2016; Yin and Harrison, 2000; Zhu et al., 2011) (Fig. 1). The Lhasa terrane is intruded and overlain by the Gangdese volcanic arc that has been active since Early Cretaceous time or before; this arc is interpreted as an Andean-style volcanic arc that formed above subducting Neotethyan lithosphere until it came to an arrest in course of the Cenozoic (Chiu et al., 2009; Huang et al., 2015e; Ji et al., 2009; Laskowski et al., 2017; Zhu et al., 2015).

The Lhasa terrane is bounded to the south by the Indus-Yarlung suture zone that once separated India from Asia. This suture zone is associated with a belt of Jurassic to Early Cretaceous ophiolites, the latter generally being of supra-subduction zone type, and whose plate tectonic and paleographic significance has long been debated (*e.g.*, Chan et al., 2015; Hébert et al., 2012). Paleomagnetic data from Lower Cretaceous radiolarian cherts associated with these ophiolites were originally interpreted to reflect latitudes close to those of the Lhasa terrane at that time, ~15°N (Pozzi et al., 1984), but later data suggested near-equatorial paleolatitudes (Abrajevitch et al., 2005). In addition, mafic minerals in uppermost Cretaceous sandstones of the TH were long interpreted as dating ophiolite obduction onto the Tethyan Himalaya, well before the India-Asia collision (*e.g.*, Searle, 1986; Searle and Treloar, 2010). Collectively, these conclusions invited interpretations that these ophiolites formed at a subduction zone within the Neotethys ocean far south of the terranes of the Tibetan Plateau (*e.g.*, Aitchison et al., 2007; Bouilhol et al., 2013; Corfield et al., 2001; Hébert et al., 2012; Jagoutz et al., 2015; Metcalfe, 2013). Because other paleomagnetic interpretations were consistent with an equatorial position of the TH in the latest Cretaceous (Patzelt et al., 1996), this interpretation was followed for several years and was adopted in our original reconstruction (van Hinsbergen et al., 2012). However, Garzanti and Hu (2015) showed that the mafic debris in the uppermost Cretaceous sandstones of the TH are not consistent with a derivation from ophiolites, but are likely sourced from plume- or rift-related volcanics instead. Moreover, the rocks from which Patzelt et al. (1996) reported paleolatitudes were recently shown to be remagnetized (Huang et al., 2017a, b). Finally, recent paleomagnetic data from Lower Cretaceous turbidite sequences that unconformably overlie the Xigaze and Sangsang ophiolites in this belt showed paleolatitudes, corrected for compaction-induced inclination shallowing, that predict a paleolatitude immediately adjacent to the Lhasa terrane (Huang et al., 2015e). This prediction is consistent with a clear Asia-derived provenance of these turbiditic sandstones (An et al., 2014; W. Huang et al., 2015e; Wang et al., 2017) suggesting that the ophiolites formed in the forearc of the Gangdese arc, likely by (hyper-)extension of the Lhasa terrane's southern margin (Maffione et al., 2015).

The Lhasa terrane disappears westwards (*e.g.*, Schwab et al., 2004) and between the TH and the Qiangtang terrane the Kohistan intra-oceanic arc terrane is found instead (Fig. 1). This terrane consists of a Lower Cretaceous to Lower Eocene volcanic arc built on oceanic crust, separated by the eastern continuation of the Indus-Yarlung suture in the south and the Shyok suture in the north (Fig. 1) (Bouilhol et al., 2011; Heuberger et al., 2007; Yamamoto et al., 2005). The termination of subduction at the Shyok suture was estimated at ~70 Ma (Burtman and Molnar, 1993; Schwab et al., 2004; Searle et al., 1987), although more recently Bouilhol et al. (2013) argued that it continued until ~40 Ma. Borneman et al. (2015), however, showed sediment provenance evidence from 92 to 85 Ma clastic sediments unconformably deposited on the Kohistan arc suggesting these were derived from the Tibetan Plateau, suggesting that the amount of convergence across the Shyok suture after this time must have been limited.

Southwest of the Kohistan Arc and south of the Triassic Paleotethys suture in Afghanistan are the ‘Cimmerian’ blocks, including the large Helmand Block (Debon et al., 1987; Montenat, 2009; Siehl, 2015; Tapponnier et al., 1981) (Fig. 1). The Paleotethys suture is re-activated as the right-lateral, Oligocene-Miocene Herat strike-slip fault with unknown displacement. To the east, the Helmand block is bounded by the Chaman left-lateral strike-slip fault that accommodates the strike-slip component of the highly oblique India-Afghanistan convergence (Treloar and Izatt, 1993). The Helmand block is overlain by the Kandahar volcanic arc with ages of ~155 Ma, intermittently active until the Oligocene (Debon et al., 1987; Faryad et al., 2013; Montenat, 2009), showing that it must have been in an overriding plate position since that time. To the south of the Helmand block lies the Cenozoic Makran accretionary prism formed from deep-marine clastic sediments derived from the (proto-) Indus fan, overlain by Jurassic ophiolites of poorly constrained origin (McCall, 2002).

To the east of the India-Asia collision zone, the Qiangtang terrane of central Tibet is traced towards Southeast Asia as the Sibumasu terrane (*e.g.*, Sengör, (1984). It is there separated from the Indochina Block, which has no equivalent in Tibet, by a Triassic suture zone (Carter et al., 2001; Metcalfe, 2013) (Fig. 1). The Indochina Block is separated from the South China Block along a suture of debated Paleozoic to Triassic age (Cai and Zhang, 2009; Faure et al., 2014). The Indochina-South China suture was reactivated in Oligocene time as the major, left-lateral Ailao Shan – Red River fault with displacement estimates ranging from 250 in the southeast to > 700 km in the northwest (see Li et al. (2017), and references therein). In the Cenozoic, NW Indochina and Sibumasu underwent major shortening and rotation, of which a first-order kinematic reconstruction was recently proposed based on paleomagnetic constraints by Li et al. (2017).

Finally, to the west of the Sibumasu terrane lies the west-Burma block (Fig. 1). Timing of collision of the West Burma block with Sibumasu is debated and may either have occurred in Triassic (Barber and Crow, 2009; Sevastjanova et al., 2016) or in the Early Cretaceous, in which case it was likely contiguous with the Lhasa terrane (Liu et al., 2016; Mitchell, 1993; Royden et al., 2008; Searle et al., 2007). Either way, it was part of the Eurasian plate during Neotethys closure and the India-Asia collision. Since at least Miocene time, the West-Burma Block has formed a forearc sliver that shares the northward motion component of oblique India-Asia convergence. This oblique convergence is partitioned along the right-lateral Sagaing Fault that forms its eastern border, whereas the convergent component is accommodated through subduction along the trench to its west in the Indo-Burman ranges (*e.g.*, Bertrand et al., 2001; Vigny et al., 2003). The West-Burma block is fringed in the west by a belt of ophiolites that likely correlate to the Indus-Yarlung ophiolite belt (Liu et al., 2016; Singh et al., 2016). Northward motion of the West-Burma block was accommodated to its south by the N-S extensional spreading ridge of the Andaman Sea, separating West Burma from Sumatra and the rest of Southeast Asia (Curray, 2005).

2.1.2. *India-derived units*

South of the Indus-Yarlung suture zone and north of the Main Frontal Thrust that is the modern India-Asia plate boundary, the Himalaya fold-thrust belt comprises thin-skinned thrust slices of Indian plate-derived upper continental crystalline and sedimentary crust. These are subdivided into three, internally intensely folded, thrusted, and/or sheared units defined by their metamorphic grade and major bounding fault systems. These include, from north to south, the Tethyan, Greater, and Lesser Himalaya (Gansser, 1964; Hodges, 2000) (Fig. 1). All three zones are thought to have once been part of the northern Gondwana margin of India and attempts have been made to subdivide these three units stratigraphically based on their Neoproterozoic to Ordovician stratigraphy and deformation history using detrital zircon studies (*e.g.*, Cawood et al., 2007; DeCelles et al., 2000; McKenzie et al., 2011; McQuarrie et al., 2013; Myrow et al., 2003; Parrish and Hodges, 1996; Webb et al., 2011b), although no consensus has been reached as to whether these modern Himalayan zones are conclusively distinguishable based on Paleozoic and older stratigraphy. This debate notwithstanding, these studies agree that in Late Paleozoic time, all units of the Himalaya were contiguous with and received sediments from modern cratonic India. This observation requires that if a Greater India Basin ever existed, it should have opened after the deposition of the Himalayan Paleozoic stratigraphy, and juxtaposed these stratigraphic units again upon closure, in a Wilson-cycle fashion.

The TH comprises Neoproterozoic to Paleogene passive margin sediments dominated by carbonates with subordinate volcanics and clastic rocks (Garzanti et al., 1987; Garzanti and Hu, 2015; Jadoul et al., 1998). This stratigraphy contains Carboniferous *syn*-rift deposits and Lower Permian tholeiitic basalts interpreted to reflect continental break-up along the northern Tethyan Himalayan margin followed by Neotethys opening, followed by a Permian to Paleocene, carbonate-dominated passive margin sequence (Garzanti et al., 1999; Garzanti and Sciunnach, 1997). The Mesozoic sequence contains a Lower Cretaceous interval found all along the TH consisting of the Lakang and Sangxiu mafic lavas and Wölong volcanic sandstones, interpreted to reflect an episode of rifting (Hu et al., 2010; Y. Ma et al., 2016b; Yang et al., 2015a). The Tethyan Himalayan stratigraphy shows evidence for shoaling in Campanian times followed by erosion and deposition of Maastrichtian quartz sandstones with mafic and felsic volcanic detritus with compositions consistent with the composition of the Deccan lavas found in India, although they also overlap with the composition of the Wölong volcanics (Garzanti and Hu, 2015). Finally, the oldest interpreted foreland basin sediments in the Tethyan Himalayan stratigraphy derived from the Asian plate, as determined by sediment provenance studies, are dated 59 ± 1 Ma, and appear to be near-synchronous along the width of the TH (DeCelles et al., 2014; Hu et al., 2015; Najman et al., 2005; Orme et al., 2015).

The TH is separated from the high-grade metamorphic Greater Himalayan sequence along a major structure interpreted as normal fault and known as the South Tibetan Detachment (STD) (*e.g.*, Hodges et al., 1992), although other workers interpret this feature as a backthrust (Kellett and Grujic, 2012; Webb et al., 2007, 2011a; He et al., 2016). The Greater Himalayan sequence is separated from the Lesser Himalayan sequence by the Main Central Thrust (MCT) (*e.g.*, Hodges, 2000; Yin, 2006; Martin, 2016). The Greater Himalaya sequence consists of metasedimentary and likely metavolcanic rocks of presumed Paleozoic age metamorphosed under amphibolite-facies conditions, regularly up to partial melting conditions, and intruded by Cenozoic (32–14 Ma; Wang et al. (2015)) leucogranites (Hodges, 2000). Exhumation and related cooling of the Greater Himalayan sequence occurred mainly since Early Miocene time, thought to be aided by normal fault motion along the STD (Hodges, 2000; Hodges et al., 1994). Prograde metamorphic ages interpreted from Lu/Hf garnet ages (~55 Ma) and peak metamorphic ages concluded from zircon (~45 Ma), however, show that metamorphism in the Greater Himalayan sequence was underway by early to middle Eocene time (Lee and Whitehouse, 2007; Pullen et al., 2011; Smit et al., 2014), suggesting that (most of) the sequence has been part of the Himalayan orogen since the Eocene. Similarities in the stratigraphy of the Greater and Tethyan Himalayan zones were previously put forward to argue that these were part of a once more or less coherent stratigraphic sequence (Searle et al., 1992; Martin, 2017).

The Lesser Himalaya is bounded by the MCT at the top, and the Main Boundary Thrust at the base. The Main Boundary Thrust is separated from the Main Frontal Thrust by a narrow zone of Miocene continental foreland basin rocks known as the Siwalik Group (*e.g.*, Chirouze et al., 2012) (the Main Boundary Thrust is not shown in Fig. 1 because of the small distance to the Main Frontal Thrust, except for northern Pakistan where the two are separated by the Salt Range). The Lesser Himalaya consists of Paleo-Proterozoic to, in places, Eocene to Oligocene sedimentary rocks (*e.g.*, DeCelles et al., 2004; Hodges, 2000; Long et al., 2011b). Lesser Himalayan rocks contain exclusively latest Oligocene to Neogene metamorphic ages, interpreted to reflect their underthrusting below the Greater Himalaya along the MCT (*e.g.*, DeCelles et al., 2002; Long et al., 2011a; Robinson and Martin, 2014). These relationships indicate that the MCT was from the moment of accretion of the Greater Himalaya, until the end of its activity, in the Miocene, the India-Asia plate boundary separating material accreted to the upper plate from material still moving coherently with the downgoing plate. Since ~16–17 Ma, the MCT was abandoned as the most frontal thrust between India and Asia and the plate boundary stepped down into the Lesser Himalayan sequence that, as a consequence, became deformed into a foreland propagating fold-thrust belt (DeCelles et al., 2004; Long et al., 2011a; Najman et al., 2009).

DeCelles et al. (2004) analyzed the sediment provenance of the Cretaceous to Oligocene section of the southern Lesser Himalaya in Nepal. They found that the Middle Eocene (~45 Ma) Bhainskati Formation contains Middle to Upper Proterozoic and Cambro-Ordovician detrital zircons and mafic minerals, such as spinel, interpreted to have been derived from ophiolites. Detrital zircon fission track ages of ~45 Ma in the Bhainskati Formation suggest that its sediment source was an Eocene orogenic belt (Najman et al., 2005). DeCelles et al. (2004) consequently interpreted the Eocene and younger sequence as a foreland basin and suggested that it was derived from the Tethyan Himalayan sequence and its overlying ophiolites. There is no unambiguous evidence, however, for an Asian provenance: all that is required by the Bhainskati Formation is a source that includes Indian passive margin sediments and ophiolites that contributed to the sediment source of the Bhainskati Formation, but not the Asia-derived forearc and foreland basin deposits that are found on top of, and below the ophiolites of the TH (DeCelles et al., 2014; Orme et al., 2015).

The northwest Indian passive margin is folded and thrusted in the Sulaiman ranges. This margin was first overthrusted by ophiolites in the Late Cretaceous to Eocene (see below) and is presently separated from the Chaman fault (that demarcates the location of the Neotethyan suture) by an up to 8 km thick clastic sedimentary sequence known as the Katawaz basin (Carter et al., 2010; Treloar and Izatt, 1993) and, in the north, the Kabul block (Badshah et al., 2000; Tapponnier et al., 1981)) (Fig. 1). The Katawaz basin contains a stratigraphy consisting of Eocene limestones overlain by Oligocene to Middle Miocene turbidite sequences (Carter et al., 2010; Treloar and Izatt, 1993). It is interpreted to have been underlain by transitional continental to oceanic crust of the west-Indian margin overlain by the previously obducted ophiolites. The Katawaz basin is interpreted to have formed a pathway of Tibetan detritus found in the Makran accretionary prism before the Indus river chose a pathway east of the Sulaiman ranges sometime after Northwest India-Asia collision and renewed thrusting in the Sulaiman ranges in the Miocene (*e.g.*, Carter et al., 2010; McCall, 1997; Qayyum et al., 1997) (Fig. 1).

Based on the ages of ocean-derived sediments and crystalline rocks in the context of Indian Ocean reconstructions constrained by marine magnetic anomalies, Gaina et al. (2015) restored the Kabul Block back to a position between eastern Arabia and northwest India. The block became first separated from Arabia in the Jurassic, when it was still part of India upon breakup of Gondwana. Subsequently, following a brief interval of India-Arabia convergence, it separated during an Early Cretaceous phase of India-Arabia divergence, during which time it remained part of the African/Arabian plate until a phase of Late Cretaceous ~E-W convergence that was induced by a counterclockwise rotation of India during its break-up from Madagascar (see Fig. 9 of Gaina et al. (2015)) that closed the ocean basin between the Kabul Block and the western Indian passive margin. This phase led to obduction of the Waziristan-Khost ophiolite complex (Fig. 1) with a ~96–90 Ma metamorphic sole onto the Indian passive margin around 80 Ma (Beck et al., 1996; J. Robinson et al., 2000). Between ~95 and ~80 Ma, the Kabul block was thus in an overriding plate position of a short-lived subduction zone with the Waziristan-Khost ophiolite in its forearc. The 80 Ma age is interpreted as the age of initial collision of the Kabul Block with India.

The western Indian passive margin is deformed into the Sulaiman Ranges that comprise a Paleozoic to Paleogene passive margin sedimentary sequence. After emplacement of the Waziristan ophiolite, the Sulaiman Ranges, as well as the Kabul Block, were overthrusted during a second phase of obduction by ophiolites in latest Cretaceous to Eocene time. The Kabul Block was overthrusted by the Kabul-Altimur ophiolites (Badshah et al., 2000; Tapponnier et al., 1981). To the south, the Indian passive margin sediments of the Sulaiman ranges were overthrusted by the Bela and Muslim Bagh supra-subduction zone ophiolites with late Cretaceous crustal and metamorphic sole ages (~80–65 Ma), with final thrusting over the Indian passive margin stratigraphically constrained as Early to Middle Eocene (Gnos et al., 1998; Kakar et al., 2012; Kassi et al., 2009; Mahmood et al., 1995). This phase of thrusting also reactivated the Waziristan suture where it led to renewed contraction (Beck et al., 1996). We conclude that the west-Indian ophiolite emplacement led to the formation of a Paleocene to Eocene foreland basin on the Indian continent in the region of Pakistan that filled with sediments derived from the Indian passive margin and overlying ophiolites, but lack a signature that requires an Asian provenance (Waheed and Wells, 1990; Khan and Clyde, 2013). The Late Eocene-Oligocene period in the west-Indian orogen is not associated with significant deformation, but since latest Oligocene-earliest Miocene time, the Sulaiman fold-thrust belt formed by accommodating nearly 400 km of N-S shortening (Banks and Warburton, 1986; Jadoon and Khurshid, 1996; Metais et al., 2009; Welcomme et al., 2001).

The junction between the west Indian orogen, including the Late Cretaceous to Eocene Kabul Block, Waziristan Suture, and Sulaiman ranges, and the Himalaya is located in northern Pakistan and Afghanistan, to the west of the western Himalayan syntaxis, and is not extensively studied. Notably, however, DiPietro and Pogue (2004) observed that west of the western Himalayan syntaxis, there are no equivalents of an MCT or STD. Although these structures are well-defined to the east of the western syntaxis, they disappear to the west of the syntaxis, and no other structures that may have accommodated major, wholesale underthrusting of the Indian plate exist there. The amount of Himalayan shortening to the west of the western syntaxis must therefore be dramatically smaller than to the east.

Carter et al. (2010) studied Lower Miocene sediments in the southern Katawaz basin and argued these were derived from the Himalaya. More recently, Zhuang et al. (2015) conducted a sediment provenance study of Eocene, ~50 Ma sediments from the Indian passive margin immediately south of the Sulaiman ranges and interpreted a derivation from an Asian source based on Nd and Sr isotope signatures. In both studies, however, the authors assumed that the Kabul Block that lies between the study areas and the Himalaya was part of Asia and they did not subdivide between a Kabul Block and a Himalayan-Tibetan source. Likewise, Ding et al. (2016) and Qasim et al. (2018) studied Paleocene sandstones on the Indian foreland east of the Salt Range, and in the Lesser Himalaya of Pakistan, and found in sediments younger than 56 Ma detrital zircons with ages < 100 Ma, which they interpreted to be Asia-derived.

Finally, in the east of the collision zone, the Indo-Burman Ranges (Fig. 1) consist of an accretionary prism developed below Cretaceous ophiolites that contain deep-marine sediments with radiolarian cherts at least as young as the Middle Eocene (Kachovich et al., 2016). This shows that oceanic subduction along the northeastern margin of India continued much longer than in the Himalaya and was peripheral to the India-Asia collision zone. Direct tectonic interaction between the Indian continent and the West-Burma block appears to have occurred largely in the last 10 Myr, when the outer Indo-Burman ranges started to deform and tectonically accrete Neogene sediments of the Bengal fan to the West-Burma forearc (Maurin and Rangin, 2009) (Fig. 1).

2.2. Constraints on the age of the Tethyan Himalaya-Lhasa collision

The discussion on the age of the initial collision between the Tethyan Himalayan margin and Lhasa is based on five lines of evidence: (i) the first arrival of Asia-derived sediment in the Tethyan Himalayan stratigraphy; (ii) the age of the youngest marine sediments in the Tethyan Himalaya; (iii) the age of high-pressure, low temperature metamorphism of Tethyan Himalayan sediments; (iv) the age of the rapid slow-down of India-Asia convergence; and (v) the age of overlap of paleomagnetically derived paleolatitudes from the TH and the Lhasa terrane. These constraints have generally led to collision age estimates clustering between 60 and 50 Ma, with some authors suggesting ages as old as 65 Ma or as young as 34 Ma. Here, we briefly review the validity of these constraints in the light of the most recent data.

The most rigorous constraint of the list above may be the first arrival of Asia-derived sediments in the Tethyan Himalayan stratigraphy. For years, uncertainties with the exact provenance signal of Asian detritus and the age of the sediments persisted, but recent work of *e.g.*, Gehrels et al. (2011), Orme et al. (2015), DeCelles et al. (2014), and Hu et al. (2015, 2016) firmly point to a 59 ± 1 Ma age of the oldest Asian detritus in the Tethyan Himalayas. Since sediments can be transported over perhaps a few hundred kilometers (Stevenson et al., 2014), this age may predate the actual collision, but given the very high India-Asia convergence rates of 150 km/Myr or more in the Paleocene (*e.g.*, van Hinsbergen et al. (2011b), the delay is probably minor.

Aitchison et al. (2007) reported marine sediments in the India-Asia collision zone that would be as young as 34 Ma. Although the age of these sediments is contested (*e.g.*, Garzanti, 2008), marine sedimentation may continue well after collision, as exemplified by the Persian Gulf in the Arabia-Eurasia collision zone. These very young collision ages are, moreover, inconsistent with the growing body of evidence for the oldest foreland basin sediments in the TH mentioned above.

In the northwestern Himalaya, the Tso Morari complex exposes eclogite-facies rocks of the Tethyan Himalayan sequence that mark the arrival of the this sequence in a subduction zone (*e.g.*, De Sigoyer et al., 2000). U/Pb dating of zircons in this complex show metamorphic ages of ~54 Ma, which in combination with their depth of burial and India-Asia convergence rates, led Leech et al. (2005) and Guillot et al. (2008) to infer an onset of continental subduction no later than 57 ± 1 Ma. As noted above, more recent dating of these eclogites at 47–43 Ma would allow for (but does not require) a ~51 Ma initial collision age (Donaldson et al., 2013). However, because the Tethyan Himalayan sequence is overlain by an ophiolite belt of which the plate tectonic setting was debated (see Discussion in previous section), it remained unclear whether this continental subduction occurred at an intra-oceanic, equatorial subduction zone, or along the Asian margin. The recent constraints of W. Huang et al. (2015e) now firmly place the ophiolites in the Lhasa forearc and the age of continental subduction of the TH may indeed be considered to be representative for a minimum age of the India-Asia collision.

The age of the India-Asia convergence rate slow-down from > 15 cm/yr to < 8 cm/yr is firmly dated from marine magnetic anomalies of the Atlantic and Indian ocean and occurred between ~50 and 45 Ma (Copley et al., 2010; Molnar and Stock, 2009; Patriat and Achache, 1984; van Hinsbergen et al., 2011b). The onset of this slow-down has been argued to reflect the age of continental collision (*e.g.*, Copley et al., 2010), but this is not a hard kinematic line of evidence. Instead, it is a dynamic interpretation that may be feasible if independent sources of evidence demonstrate synchronicity between collision and slow-down. If there is no such synchronicity, then the delay between collision and slow-down (or *vice versa*) requires an alternative explanation, which we will return to in the Discussion section.

Finally many workers have in recent years applied a paleomagnetic approach to dating the India-Asia collision (J. Chen et al., 2010, 2014; Dupont-Nivet et al., 2010; Hu et al., 2016; W. Huang et al., 2013, 2015a, b; Liebke et al., 2010; Lippert et al., 2014; Y. Ma et al., 2014; Meng et al., 2012; Najman et al., 2010; Sun et al., 2010, 2012; Tan et al., 2010; van Hinsbergen et al., 2012; Yang et al., 2015b). Almost all of these studies provided new estimates of the Late Cretaceous to Eocene paleolatitude of the Lhasa terrane and compared these with paleolatitudes derived from Upper Cretaceous and Paleocene carbonate rocks of the TH provided by Patzelt et al. (1996) and Yi et al. (2011). These latter constraints suggested a position of the TH ~2000 km north of the location of the modern Main Frontal Thrust during this time period and gave a paleolatitudinal motion rate consistent with the India-Asia convergence rates reconstructed from ocean basins. The thus-derived collision ages, however, varied widely from > 60 Ma to < 45 Ma. Detailed paleo- and rock magnetic research has shown that this disparity results from three causes: (i) insufficient averaging of paleosecular variation of the geomagnetic field (Lippert et al., 2014), (ii) inclination shallowing in sedimentary rocks (W. Huang et al., 2013; Tan et al., 2010), and (iii) erroneously applying a bedding tilt correction on paleomagnetic directions derived from rocks that remagnetized during or after tilting (W. Huang et al., 2015a, b). Large volcanic datasets that were shown to account for paleosecular variation, inclination shallowing-corrected sedimentary sites, and remagnetization-corrected volcanic sites consistently provide a paleolatitude of ~20–21°N for the Paleocene-Lower Eocene Linzizong volcanics of the Lhasa block, which would be consistent with a collision age of 50–52 Ma (W. Huang et al., 2015a; Lippert et al., 2014).

W. Huang et al. (2017a, b), however, recently demonstrated through a detailed paleomagnetic, rock magnetic, and microscopy analyses that the limestones from which the Late Cretaceous to Paleocene paleolatitudes of the TH were derived were remagnetized, likely during or after Eocene folding. They showed that the paleolatitudes interpreted from these rocks by Patzelt et al. (1996) and Yi et al. (2011) may be an artifact of bedding tilt correction of post-tilting remagnetized rocks. On the other hand, W. Huang et al. (2015c, 2017b) used similar lines of rock magnetic and microscopy arguments to conclude that Lower Cretaceous volcanic sandstones still carry their primary magnetizations. However, paleomagnetic results from these rocks (W. Huang et al., 2015c; Klootwijk and Bingham, 1980), as well as from Lower Cretaceous lavas in the Tethyan Himalayan sequence (Y. Ma et al., 2014; Yang et al., 2015b) consistently demonstrate a paleolatitude of the TH relative to India within a few hundreds of kilometers from the location of the modern Main Frontal Thrust. Triassic and Ordovician rocks from the TH also yield paleolatitudes relative to India close to the location of the Main Frontal Thrust (Torsvik et al., 2009; van Hinsbergen et al., 2012, and references therein) (Fig. 2). Although the primary nature of the magnetization of the latter poles was not tested with the same scrutiny as those from the Lower Cretaceous, their consistently southern hemisphere latitudes derived from sites across the TH make a post-collisional remagnetization unlikely. Discarding the Upper Cretaceous and Paleocene poles from the TH (W. Huang et al., 2017a, b), and using instead the Ordovician to Early Cretaceous poles to estimate the paleolatitude of the TH relative to India combined with the hard paleolatitudinal constraints from Lhasa would result in a very young, Miocene collision age between the TH and the Lhasa terrane (Fig. 2). Such a very young collision age is entirely inconsistent with the stratigraphic and metamorphic constraints summarized above, and it is this observation that lies at the basis for the Greater India Basin (GIB) hypothesis of van Hinsbergen et al. (2012), and earlier similar scenarios (Hsü et al., 1995; Sinha Roy, 1976), even though the discarding of the Upper Cretaceous and Paleocene Tethyan Himalayan paleolatitudes now removes the direct paleomagnetic constraints on the size evolution of Greater India. We will return to this point in the discussion.

The summary of Tethyan Himalaya-Lhasa collision age constraints above is valid for the Tethyan Himalaya-Lhasa collision. In the western part of the collision belt, the TH collided with the Kohistan arc that is built on oceanic crust, and that is separated itself by the Shyok suture from Eurasian continental units. If the latter suture is younger than the Paleocene, then continent-continent collision in this portion of the collision zone would technically be younger. The end of subduction along the Shyok suture was recently estimated to be as young as ~40 Ma (Bouilhol et al., 2013). Bouilhol et al. (2013) and Jagoutz et al. (2015) extrapolated this 40 Ma age to the entire India-Asia collision zone, correlated the Kohistan arc to the equatorial subduction zone in Cretaceous time that was postulated by *e.g.*, Aitchison et al. (2007) and suggested that the age of the Tethyan Himalaya-Lhasa collision age should be revised to ~40 Ma. Paleomagnetic data from undated but post-Aptian continental redbeds in the Kohistan arc sequence, which were not corrected for inclination shallowing, suggested paleolatitudes around the equator (Zaman and Torii, 1999). Those authors, however, noted that paleolatitudes they derived from rocks exposed to the north of the Shyok suture also gave equatorial latitudes, which is inconsistent with the large body of paleomagnetic evidence of the Lhasa and Qiangtang terranes to the north of this suture suggesting a ~20°N latitude in Late Cretaceous to Eocene time. Moreover, Zaman and Torii (1999) indicated that the sandstones they sampled postdate the closure of the Shyok suture, which is consistent with the conclusions of Borneman et al. (2015) that 92–87 Ma sandstones in the Kohistan sequence were sourced from Asia. We therefore treat the Kohistan arc as the lateral equivalent of the Gangdese arc, whereby the subduction zone laterally changed from Andean-style to intra-oceanic (van Hinsbergen et al., 2011a; Zaman and Torii, 1999), similar to the Aleutian and Sunda trenches. The Shyok suture may then have localized some of the 100's of km of Cretaceous to Eocene shortening that in Tibet was more regionally distributed (van Hinsbergen et al., 2011a).

Finally, although frequently interpreted as a reflection of the India-Asia collision (*e.g.*, Khan and Clyde, 2013; Robinson et al., 2000), the uppermost Cretaceous-Eocene orogen along the western Indian margin formed at near-equatorial latitudes when the Indian subcontinent was still located at a similar latitude as e.g. Oman (Gaina et al., 2015). Indian ocean basin reconstructions demonstrate that the onset of the uppermost Cretaceous-Eocene orogeny of western India coincided with the onset of transpressional motion of India and Arabia (Gaina et al., 2015; Gnos et al., 1997). Not only the Indian passive margin became thrusted in this stage, but also the Masirah ophiolites of eastern Oman, which were emplaced onto the eastern Arabian margin. These relationships show that this orogeny is unrelated to the India-Asia collision, and instead formed due to oblique subduction at the India-Arabia plate boundary (Gaina et al., 2015; Gnos et al., 1997). The earliest record of deformation associated with the collision of India's western margin, including the Kabul Block, with the Helmand Block is the Early Miocene thrusting of the Sulaiman ranges (Gaina et al., 2015).

In the reconstruction below, we will therefore assume a 58 Ma age of collision of the TH with the Lhasa block and the Kohistan arc to its

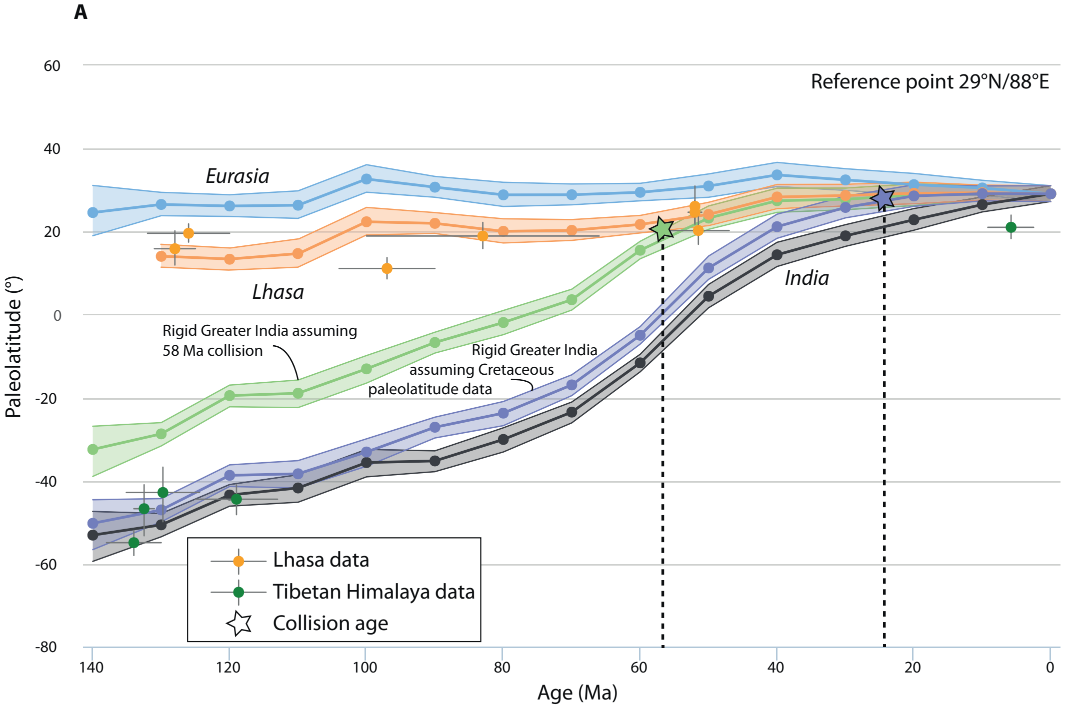


Fig. 2. Paleolatitude curves for a reference point on the Indus-Yarlung Suture (29°N, 88°E). Each curve shows a paleolatitude predicted for the reference point by the Global Apparent Polar Wander Path of Torsvik et al. (2012), assuming the reference point was rigidly connected to Eurasia (blue curve), Lhasa as reconstructed in this paper (see Fig. 3) (orange curve), and India (black curve). In addition, we show the predicted paleolatitude of the reference point when we assume that it was connected to the Tethyan Himalaya assuming that the Tethyan Himalaya was rigidly attached to India before collision, in two end-member reconstruction scenarios. The first scenario assumes a 58 Ma Tethyan Himalaya-Lhasa collision, which predicts a pre-collisional separation that is much larger than Cretaceous data from the Tethyan Himalaya (green dots) suggest. The second scenario assumes a small separation between the Tethyan Himalaya and India consistent with Cretaceous paleomagnetic data. This predicts a ~25 Ma Tethyan Himalaya-Lhasa collision, which is entirely inconsistent with field geological evidence. This illustrates that reconciling a Paleocene collision age with paleomagnetic data from the Tethyan Himalaya is challenging when assuming a rigid Greater India. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

west, a conclusion that falls within the constraints of both the stratigraphic and metamorphic approximations of the collision age.

3. Updated kinematic reconstruction of India-Asia collision zone

In absence of direct paleomagnetic constraints, the only way to estimate the size of Greater India at the time of its collision with Asia is to (i) determine the position of the southern Asian margin at 58 Ma; (ii) restore India's position relative to Eurasia at 58 Ma using the Indo-Atlantic plate circuit; and (iii) calculate the distance from the modern northern margin of contiguous India, coinciding with the location of the Main Frontal Thrust, to the south Asian plate boundary. This approach was taken by van Hinsbergen et al. (2011a) (and Replumaz and Tapponnier (2003) before that), who compiled structural geological constraints and reconstructed deformation from the Pamir and the Kohistan arc to Indochina, and from Mongolia to Lhasa. Subsequently, van Hinsbergen et al. (2012) added the Himalaya to this reconstruction and proposed the Greater Indian Basin scenario based on the Early Cretaceous and older paleomagnetic constraints of a small Greater India and a large Greater India at the time of collision, and argued that this also explains the major mismatch between upper crustal shortening in the Himalaya and Tibet and post-collisional plate convergence. Finally, Gaina et al. (2015) added the Pakistan-Afghanistan part of the collision zone to this reconstruction. Here, we update this India-Asia collision zone reconstruction in the light of critical new information.

3.1. Updated Indochina extrusion reconstruction and implications for Tibet

The updated reconstruction of deformation within Indochina (S. Li et al., 2017) requires reconstructing a much larger amount of extrusion than in the van Hinsbergen et al. (2011a) reconstruction, which has implications for shortening within eastern Tibet. The Indochina Block lies in between the Sibumasu and South China sutures. The Sibumasu terrane connects to the Qiangtang terrane in Tibet, indicating that the northwestern, extruded margin of the Indochina block should restore north of the Qiangtang terrane, *i.e.*, along the Jiali suture. Restoring the Indochina block along the Bangong-Nujiang suture between the Qiangtang and Lhasa terranes, as normally portrayed (*e.g.*, Replumaz and Tapponnier, 2003; Royden et al., 2008) is inconsistent with structural evidence of that suture (see van Hinsbergen et al., 2011a, and references therein), and would render the Sibumasu terrane as an equivalent of the Lhasa terrane, which is inconsistent with the ages of its bounding sutures.

The early extrusion of the NW Indochina blocks identified paleomagnetically by S. Li et al. (2017) may have started in Eocene time, around 50 Ma and was accommodated along only the NW part of the Aliao Shan-Red River Fault and by rotations and deformation within NW Indochina. Only in Oligocene-Miocene time did the entire Aliao Shan-Red River Fault accommodate extrusion of all of Indochina. Extrusion of the NW Indochina block from along the eastern Jiali suture would require transpression within eastern Tibet, which may straightforwardly explain the enigmatic 30–25 Ma rapid exhumation phase of the Longmenshan range (E. Wang et al., 2012; Guenthner et al., 2014) just east of the extrusion region (Fig. 1) long before the modern phase of shortening and uplift started around 10–15 Ma.

Restoring the extrusion of NW Indochina requires that the restored Qiangtang, and Lhasa terranes at ~50 Ma were in a WNW-ESE orientation that smoothly curved towards a NNW-SSE orientation towards Myanmar (Li et al., 2018), whereby the Lhasa terrane in the east restores adjacent to (and perhaps contiguously with) the West Burma

Block. The sharp re-entrant of today's eastern syntaxis that remained in the van Hinsbergen et al. (2011a) reconstruction, is thereby removed. This updated reconstruction predicts that the Lhasa terrane underwent a Cenozoic counterclockwise rotation of ~20°.

3.2. Updated Himalaya reconstruction

In their reconstruction of the Himalayan blocks and the proposal of the Greater India Basin, van Hinsbergen et al. (2012) did not explicitly restore documented shortening in the Xigaze forearc and the Tethyan Himalaya. The Xigaze forearc contained oceanic crust relics which are now preserved as ophiolites. This forearc existed between the Gangdese arc and the trench to the south. The present-day distance between the Gangdese arc rocks and the thrust between the ophiolites and the TH – that demarcates the former trench location, is only a few tens of kilometers, whereas typical arc-trench distances (*i.e.*, forearc widths) are typically ~200 km. This suggests that the original forearc must have been dramatically shortened, *e.g.*, along the Gangdese thrust (Yin et al., 1999; Murphy and Yin, 2003). We restore a 200 km wide Xigaze forearc at 58 Ma, and assume that the bulk of the shortening of this forearc (apart from the 50 km that was estimated to occur between 30 and 24 Ma (Yin et al., 1999; Murphy and Yin, 2003)) occurred shortly after collision, between 58 and 56 Ma.

As summarized in Long et al. (2011a), shortening estimates in the TH are up to ~150 km (*e.g.*, Ratschbacher et al., 1994; Searle et al., 1997), which we now restore between the STD and the Indus-Yarlung suture zone. Webb (2013) suggested that the amount of shortening in the TH may be underestimated by ~150–250 km, due to erosion of Tethyan Himalayan section above the Greater Himalaya, and our restored width should thus be considered a minimum estimate. There are no detailed records on the timing of this shortening, and we restore it immediately following collision at 58 Ma, until 50 Ma. In addition, van Hinsbergen et al. (2012) assumed that the Greater Himalaya was part of the Tethyan Himalayan terrane, but they did not explicitly show a palinspastic position of the Greater Himalayan sequence in their reconstruction. Recently, DeCelles et al. (2014) suggested that the Greater Himalaya should be restored south of a conceptual GIB, and they stressed that a major thrust must exist between the Tethyan and Greater Himalayan sequences, coinciding with the modern STD; the argued that this geometry explains the high metamorphic grade of the Greater Himalayan sequence. We have now included the Greater Himalaya in our reconstruction. To this end, we followed the concept that the lowest thrust in the Himalayan sequence at any time represents the Indian plate boundary. We consider rocks structurally above that plate boundary as accreted to Asia, and therefore part of the upper plate. Webb (2013) interpreted the scattered U/Pb ages of 45–30 Ma in the Greater Himalaya as peak metamorphic ages that reflect moments of ongoing accretion of (very thin) continental crustal slivers at the India-Asia plate boundary. We note that already accreted rocks may still be deformed and become metamorphosed after accretion, varying from place to place depending on local structural architecture, since the southern Asian continental margin in Tibet has been continuously undergoing shortening and thickening since the cretaceous (*e.g.*, van Hinsbergen et al. (2011a) and references therein). The Greater Himalaya contains evidence for ~54. ± 0.6 Ma prograde metamorphism in the form of Lu/Hf ages on garnet (*e.g.*, Smit et al., 2014) and contains an internally mostly coherent stratigraphic sequence (Hodges, 2000; McQuarrie et al., 2013). We therefore interpret the Greater Himalayan sequence accreted as a coherent unit and that its accretion must have started before ~55 ma to explain the prograde metamorphism

Throughout the 50–30 Ma period, there is no conclusive evidence for additional accretion of rocks from the downgoing Indian plate to the Himalaya on the upper Euarasian plate. In this time period, the plate boundary must have been within or below the Greater Himalayan sequence forming the structurally deepest thrust of the Himalaya, *i.e.*, the India-Asia plate boundary. Whatever the nature of the lithosphere that underthrusted the Himalaya in this time period, it left no observed accretionary record in the Himalayan geology. From about ~30–25 Ma onward, forward propagating accretion of continent-derived rock started again and accreted the deeper structural levels of the Greater Himalaya (*e.g.*, Carosi et al., 2010; Corrie and Kohn, 2011; Imayama et al., 2012), reached in places eclogite conditions (Corrie et al., 2009), and propagated downward into the Lesser Himalayan sequence as the plate boundary cut deeper into the Indian passive margin sequence. This progression formed the Lesser Himalayan duplex since ~17 Ma. Only the upper part of the Greater Himalaya may thus have accreted in Early Eocene time (Larson and Cottle, 2015; Webb, 2013). Our reconstruction simplifies the evolution of the Greater Himalaya and treats it as a coherent unit that formed as a single thrust slice in the Eocene, but the brief review above shows that the India-Asia plate boundary was likely located within the Greater Himalaya between the Eocene and Early Miocene. Our model simplifies this history and restores the Greater Himalayan sequence as paleogeographically located immediately south of the TH and assumes (an ill-defined) ~80 km of shortening to account for structural overlap between the Tethyan and Greater Himalaya, which we model between 58 and 50 Ma.

We interpret the major and sudden decrease of shortening across the western Himalayan syntaxis and the disappearance of the STD and MCT to the west (DiPietro and Pogue, 2004) to infer the western limit of the major Greater Indian promontory. The absence of major shortening, or of faults that may have accommodated wholesale underthrusting, demonstrates that Greater India west of the western syntaxis must have been narrow. Himalayan shortening in this section is likely young, probably Miocene in age, and earlier Late Cretaceous-Paleocene deformation documented by DiPietro and Pogue (2004) is likely related to Kabul Block-Sulaiman ranges collision and is therefore unrelated to the India-Asia collision. We thus explain the much lower shortening amounts in this section of the Himalaya compared to the rest of the range by a paleogeographically much smaller continental promontory in this region and hence a much wider oceanic domain that subducted entirely, similar as proposed for the GIB (van Hinsbergen et al., 2012).

Before we estimate the size of Greater India at the 58 Ma moment of collision of the TH with the Lhasa terrane and the Kohistan arc, we will first test the modified kinematic reconstruction of the collision zone against independent data to assess whether we may grossly underestimate intra-Asian shortening (*i.e.*, by > 1000 km). To this end, we use paleomagnetic constraints on latitude and vertical axis rotation and test the predicted location of the Paleocene trench along the southern Lhasa terrane and Kohistan arc against mantle tomographic constraints on the location of associated subducted slabs.

4. Paleomagnetic test of updated reconstruction

Snapshots from our updated restoration for Tibetan deformation since 58 Ma are shown in Fig. 3 (reconstruction files are provided as Supplementary Files 1). Restoring a NW Indochina extrusion as shown in Li et al. (2017) requires that we reconstruct a counterclockwise rotation of Lhasa and Qiangtang relative to Eurasia. Such a rotation in turn requires that we assume an eastward increasing amount of N-S shortening in the Tibetan plateau, in contrast to the assumption of first-order cylindricity of shortening within Tibet of van Hinsbergen et al. (2011a). We restore the counterclockwise rotation of the Lhasa and Qiangtang terranes such that our reconstruction remains consistent with the shortening estimates for Lhasa, Qiangtang, and Songpan-Garzi shortening along the sections listed in van Hinsbergen et al. (2011a). If we would assume that the Lhasa and Qiangtang terranes behaved as more or less rigid units along the entire E-W extent of the Tibetan Plateau, then our restored counterclockwise rotations combined with the shortening constraints along the sections in central Tibet as listed in van Hinsbergen et al. (2011a) would generate N-S extension in the Pamir region, for which there is no evidence. We solve this by assuming a pivot at a longitude in western Tibet in the region of the modern

Karakoram fault, west of which we have not significantly changed the reconstruction of van Hinsbergen et al. (2011a).

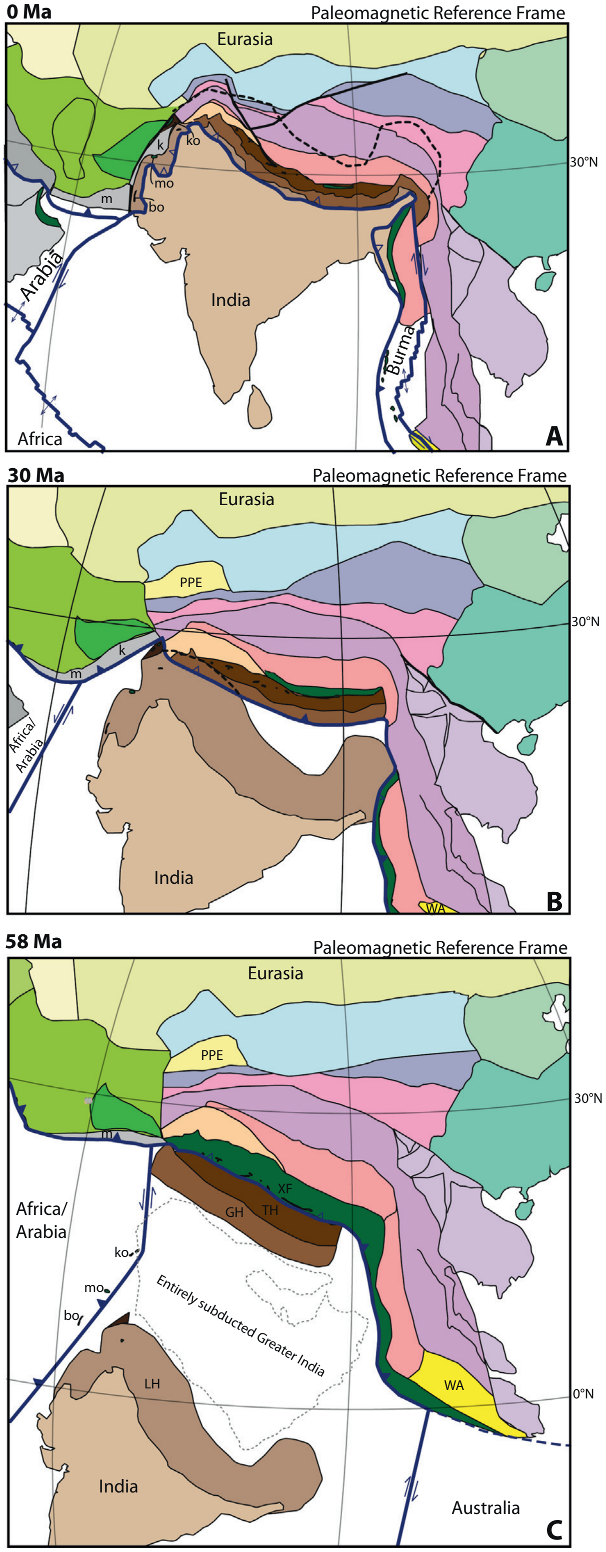
We test our updated kinematic reconstruction of Tibet against a compilation of paleomagnetic data from 32 studies reporting a total of 65 paleomagnetic sites from the Tibetan Plateau (Fig. 4). This compilation is made using the online paleomagnetic analysis platform Paleomagnetism.org (Koymans et al., 2016). The database and references to the papers from which the data are compiled is provided in Supplementary Files 2. We applied the selection and reliability criteria as detailed in S. Li et al. (2017). The compilation shows that the northeastern Tibetan plateau is dominated by moderate clockwise deviating declinations (Fig. 4). These clockwise rotations may on the one hand reflect that shortening in the Qilian Shan-Nan Shan ranges of NE Tibet decreases from the Altyn Tagh fault that accommodated ~400 km of Cenozoic left-lateral strike-slip (*e.g.*, Cowgill et al., 2003; Yue et al., 2004) towards the ESE. In addition, clockwise rotations along the eastern part of the NE Tibetan plateau close to the North China Block may be locally induced due to a dextral shearing between the Tibetan plateau that underwent Late Mesozoic and Cenozoic shortening and the North- and South China blocks, that did not experience such shortening (*e.g.*, Dupont-Nivet et al., 2004; England and Molnar, 1990).

Paleomagnetic data from the Lhasa terrane are scattered, but show a tendency towards counterclockwise deviating declinations (Fig. 4). These data come from sediments and volcanics deposited in the last 130 Ma following the Lhasa-Qiangtang collision (*e.g.*, Li et al., 2016) and thus record rotations associated with the (de)formation of the Tibetan Plateau. Sparse data in the Qiangtang block agree with counterclockwise rotations, whereas the few data points from the Songpan-Garzi terrane show clockwise rotations instead. The counterclockwise rotation of the Lhasa and Qiangtang terrane was thus accommodated in our reconstruction mainly by Cenozoic shortening in the Songpan-Garzi terrane.

To test our reconstructed rotation of the Lhasa terrane, we computed.

the Global Apparent Polar Wander Path (GAPWaP) of Torsvik et al. (2012) in the coordinates of Lhasa as predicted by our reconstruction. To this end, we used the thereto designed “Add APWP” tool on Paleomagnetism.org (see Li et al., 2017) for details and tutorial), using the plate circuit of Torsvik et al. (2012) with updates for the Neogene spreading in the North Atlantic Ocean of DeMets et al. (2015). Our updated reconstruction of the Lhasa terrane predicts declinations that fit well with observations (Fig. 5), even though scatter around the predicted path may indicate that local rotations occurred within the Lhasa terrane.

Paleomagnetic data from the Lhasa terrane are thus reasonably consistent with our restoration and permit a larger extrusion of Indochina than restored in van Hinsbergen et al. (2011a), as proposed by Li et al. (2017). The Himalaya to the south of the Lhasa terrane must have shared this rotation. When we include the clockwise rotation of the western Himalaya south of the Pamir segment (van Hinsbergen et al., 2011a, and references therein), this reconstruction restores the Tetyan and Greater Himalayan terranes into a configuration at the time of collision (*i.e.*, ~58 Ma) that is narrower in an *E*-W direction than portrayed in van Hinsbergen et al. (2012) (Fig. 3). Our updated reconstruction predicts a N-S width of Greater India of ~2600–3400 km at 58 Ma, as well as 1050–1200 km of post-58 Ma shortening within Asia, which in eastern Tibet is up to twice as much as reconstructed by van Hinsbergen et al. (2011a) (Fig. 6). The excess shortening is explained by the now restored counterclockwise rotation of eastern Tibet associated with Indochina extrusion, our reconstructed ~200 km of forearc shortening, and some of the 250 km of shortening of Lhasa that occurred between 100 and 50 Ma, already adopted by van Hinsbergen et al. (2011a).



(caption on next page)

5. Mantle tomographic test of the reconstructed Indian subduction zone

We now test the kinematic reconstruction of Cenozoic Asian deformation against seismic tomographic images of the mantle below the collision zone. To this end, we first place the reconstruction in a mantle reference frame using the global moving hotspot reference frame of

Fig. 3. Updated kinematic restoration of deformation in the India-Asia collision zone. GPlates reconstruction files are provided in the Supplementary Information. Dotted line over Tibet in Fig. A represents the northern margin of horizontally underthrust Indian continent below Tibet as imaged by seismic tomography (see Fig. 7). In Figs. B and C, this area is modeled as India's promontory, and given the similarity between its dimension and Lesser Himalayan shortening (Long et al., 2011a) is presumed to form the crustal and mantle lithospheric underpinnings of the Lesser Himalaya. In Fig. C the outline of present-day Arabia is drawn as a dotted line to provide a sense of the scale of the area of Greater India of which no accretionary record is known and that must have undergone wholesale subduction. See text for further explanation. See Fig. 1 for indication of the major tectonic zones. Key to abbreviations: bo = Bela Ophiolite; GH = Greater Himalaya; k = Katawaz Basin; ko = Kabul-Altimur Ophiolite; LH = Lesser Himalaya; m = Makran; mo = Muslim Bagh Ophiolite; PPE = Proto-Pamir Embayment (see (van Hinsbergen et al., 2011a)); TH = Tethyan Himalaya; WA = Woyla Arc and West-Sumatra; XF = Xigaze Forearc Basin.

Doubrovine et al. (2012). Alternative hotspot frames, such as the Indo-Atlantic moving hotspot reference frames of O'Neill et al. (2005) or Torsvik et al. (2008) give similar results. We then explore current mantle structure below the India-Asia collision zone to isolate the relics of subduction and their approximate location during subduction, assuming they sank vertically after break-off (van der Meer et al., 2010, 2018; Domeier et al., 2016). We note that during subduction, slabs below the Himalaya have been interpreted to vary in slab dip from flat to steep (*e.g.*, DeCelles et al., 2014; Leary et al., 2016), which may introduce second-order latitudinal uncertainty in slab-trench correlations. We will compare our kinematic reconstruction placed in a mantle reference frame to positions of corresponding slabs for selected time frames as a first-order test of our kinematic reconstruction, *i.e.*, whether our reconstruction to within a few hundred kilometers correctly predicts mantle structure.

Extensive seismic tomographic analyses in the India-Asia collision zone have demonstrated the existence of high seismic velocity bodies interpreted as remnants of subducted lithosphere (*e.g.*, Hafkenscheid et al., 2006; Li et al., 2008; Negredo et al., 2007; Replumaz et al., 2004, 2010a, b, c; van der Meer et al., 2010; 2018; Van der Voo et al., 1999). We here use the terminology for the slabs as defined in the Atlas of the Underworld (van der Meer et al., 2018).

Active Indian plate subduction occurs along the Makran margin in the west and then jumps north along the Chaman Fault to the Hindu Kush slab, where it may be in its terminal stages of slab break-off (Kufner et al., 2017; Lister et al., 2008) (Fig. 1). Below Tibet, Indian lithosphere horizontally underthrusts Tibet (*e.g.*, Agius and Lebedev, 2013; Nabelek et al., 2009; Sippl et al., 2013). We use the UU-P07 tomographic model (Amaru (2007), see description in Hall and Spakman (2015); available at www.atlas-of-the-underworld.org) to estimate that the length of the flat Indian lithosphere below Tibet reaches as far north as the Pamir slab, consistent with Sippl et al. (2013). In the west, Indian lithosphere reaches to the southern margin of the Tarim basin, ~600 km north of the Main Frontal Thrust, then gradually decreases in N-S width to ~400 km around 90°E, and then abruptly increases again to ~800 km below eastern Tibet (Fig. 7). This is consistent with the image provided by the SL2013sv S-wave tomographic model of Schaeffer and Lebedev (2013), and it confirms the conclusions of Agius and Lebedev (2013) who suggested a similar shape of the northern limit of the horizontal Indian plate below Tibet (Fig. 7).

To the east, active Indian plate subduction forms the Burma slab below the West-Burma Block (J Huang and Zhao, 2006; Li et al., 2008; Pesicek et al., 2010; Replumaz et al., 2010b), and the Sunda slab at the Sunda subduction zone (*e.g.*, Hall and Spakman, 2015). In the northwest, active southward to vertical subduction of the Pamir slab has accommodated Asian plate subduction since at least 25 Ma (Negredo et al., 2007; Sippl et al., 2013; Sobel et al., 2013) (Fig. 1).

Detached slabs have been documented in the mantle below the Indian plate. Between ~400 and 800 km depth below north India lies the subvertical to south-dipping Himalaya slab, which is interpreted as detached, steep to overturned Indian-plate subducted lithosphere (*e.g.*, Replumaz et al., 2010c; van Hinsbergen et al., 2012) (Fig. 8). Below the western part of the Indian plate lies the Carlsberg slab (Fig. 9) that is interpreted to contain Indian and Arabian plate lithosphere associated with oblique subduction below oceanic lithosphere of which the Bela, Muslim Bagh, and Kabul-Altimur ophiolites on the West-Indian margin and Kabul Block, as well as the Masirah ophiolite on the east Arabian margin are remnants (Gaina et al., 2015). Finally, the very large India slab is located in the lower mantle below India, south of the Himalaya slab, between ~1000 and 2100 km depth, running from the Makran to Sumatra with an overall WNW-ESE trend (Figs. 8 and 9). This anomaly is generally interpreted to contain all Indian Plate lithosphere that subducted below Tibet prior to the subduction of the Himalaya slab (*e.g.*, Hafkenscheid et al., 2006; Replumaz et al., 2010c; Van der Voo et al., 1999; van Hinsbergen et al., 2012).

We now test our updated reconstruction against mantle structure. To do this, we first use our reconstruction to date the subduction of the Indian flat portion and the Himalaya slab. Indian flat subduction started after the break-off of the Himalaya slab. We date the onset of flat Indian subduction by determining the moment at which the northern edge of the flat Indian slab passed the Main Frontal Thrust, using our

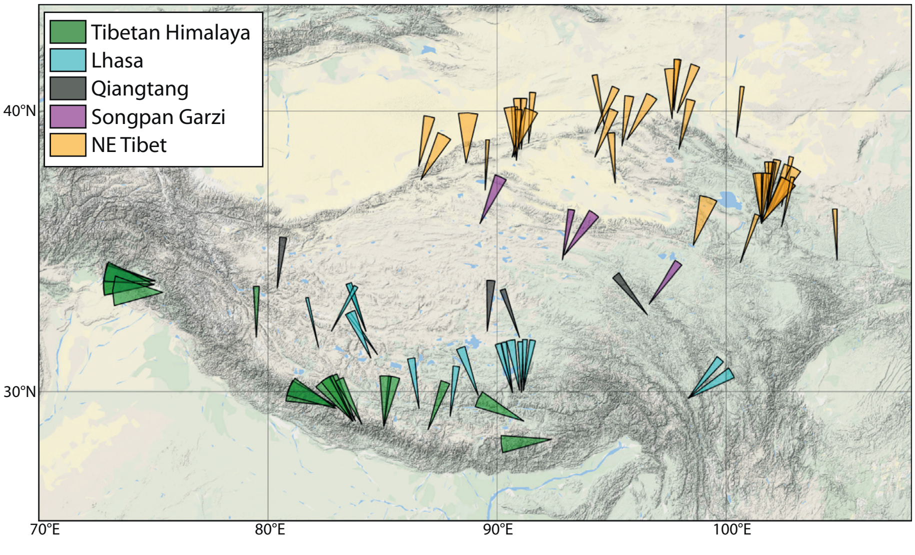


Fig. 4. Map showing declinations and their uncertainties of selected paleomagnetic sites from Tibet. For Tibet, all available paleomagnetic data from rocks younger than the 130 Ma Lhasa-Qiangtang collision are shown, used for the construction of Fig. 5. For the Tethyan Himalaya all sites with primary magnetization from the Mesozoic and Cenozoic are shown. Tethyan Himalayan sites are all (but one) older than collision between the Tethyan Himalaya and Lhasa terrane and have not been used to analyze the rotation history of Tibet. Instead, these sites are used for the paleolatitude plots of Figs. 2 and 10. Data files and references to these data are provided in Supplementary Information 1.

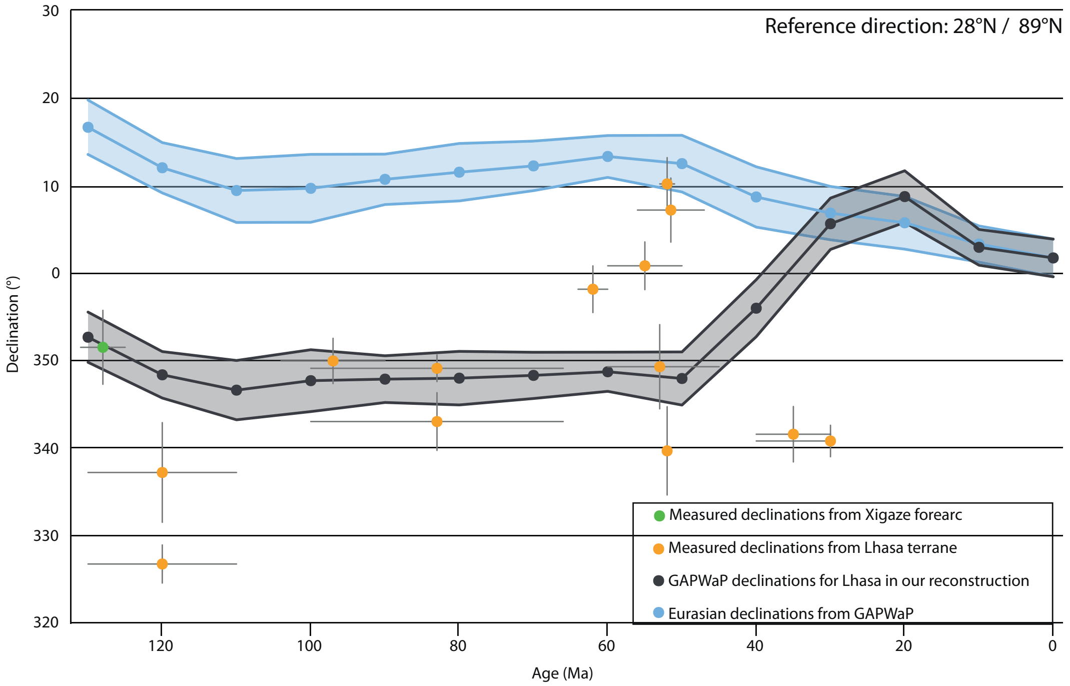


Fig. 5. Global Apparent Polar Wander Path (GAPWaP) of Torsvik et al. (2012) in coordinates of Eurasia (blue line) and Lhasa according to our reconstruction (black line). Yellow dots represent the paleomagnetic data measured from the Lhasa terrane. On average, our data follow the general trend of counterclockwise rotations. On a site-to-site level, local rotations must play a role. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

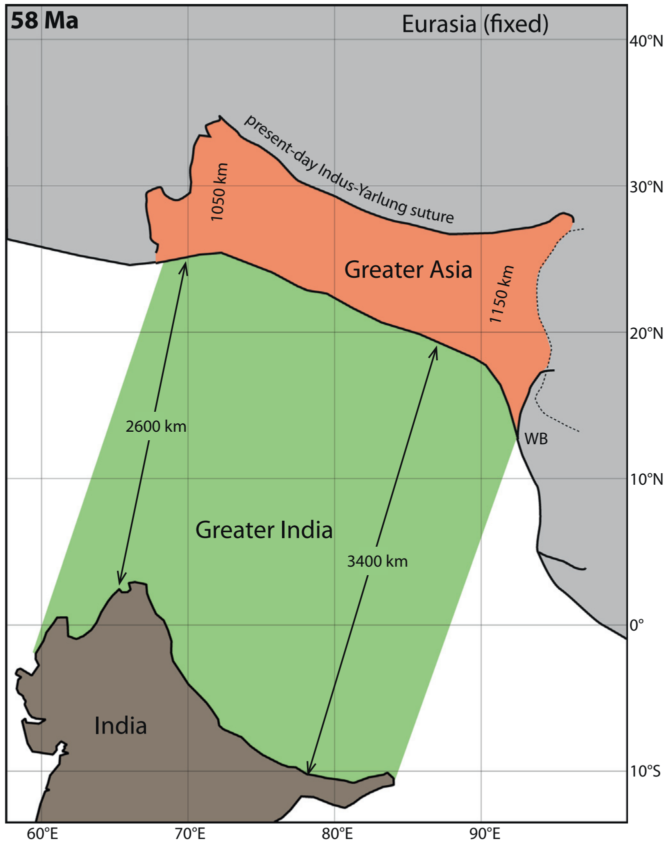


Fig. 6. Reconstructed size of the total area of Asian consumed by shortening (Greater Asia) *versus* the area of Indian plate lithosphere that subducted since the collision (58 Ma) between the Tethyan Himalaya and Asia (Greater India). WB = West-Burma Block.

restoration of Asian shortening. In this way, we estimate a maximum age for the break-off of the Himalaya slab at ~25 Ma in the west and east of the collision zone, decreasing to ~15 Ma around 90°E. These estimates are similar to those of Replumaz et al. (2010b) based on tomography, and to estimates of Webb et al. (2017) for slab break-off based on diachronous geological trends along the Himalaya. The underthrusting of the horizontal portion of India below Tibet thus occurred during the accretion of the Lesser Himalayan sequence, and thus comprises the original lower crustal and mantle lithospheric underpinnings of this sequence.

The Himalaya slab is currently some 400 km long, but it likely thickened during its descent into the lower mantle (van der Meer et al., 2018). Typical slab thickening factors of 1.5 to 3 (Hafkenscheid et al., 2006; van Hinsbergen et al., 2005) would then suggest that the Himalaya slab contains some 600–1200 km of Greater Indian lithosphere, measured parallel to its subduction direction. This would suggest that the deepest part of the Himalaya slab subducted 30–40 Ma ago, corresponding with the age of decoupling of the Himalaya slab from the India slab, once again consistent with previous estimates of Replumaz et al. (2010b). When we place our reconstruction at 35 Ma on top of a horizontal cross section through the mantle at 750 km, the Himalaya slab is located immediately north of the MCT which at that time was the India-Asia plate boundary (Fig. 9).

All Greater Indian lithosphere that subducted prior to the likely 30–40 Ma age of break-off must therefore reside in the India slab, together with Neotethyan lithosphere that subducted prior to the Tethyan Himalaya-Lhasa collision. We place our reconstruction at 80 Ma above the India slab at 1210 km depth, concordant with globally averaged net mantle slab sinking rates of 10–15 mm/yr (van der Meer et al., 2010). Contrary to the earlier reconstruction of van Hinsbergen et al. (2011a) that still preserved the sharp reentrant of the eastern Himalayan syntaxis, our updated restoration now places the south Tibetan subduction zone (*i.e.*, the future Indus-Yarlung suture zone) above the India slab: the reconstructed trench is consistent with the orientation of the slab (Fig. 9). At this depth, the Carlsberg slab is visible west of India

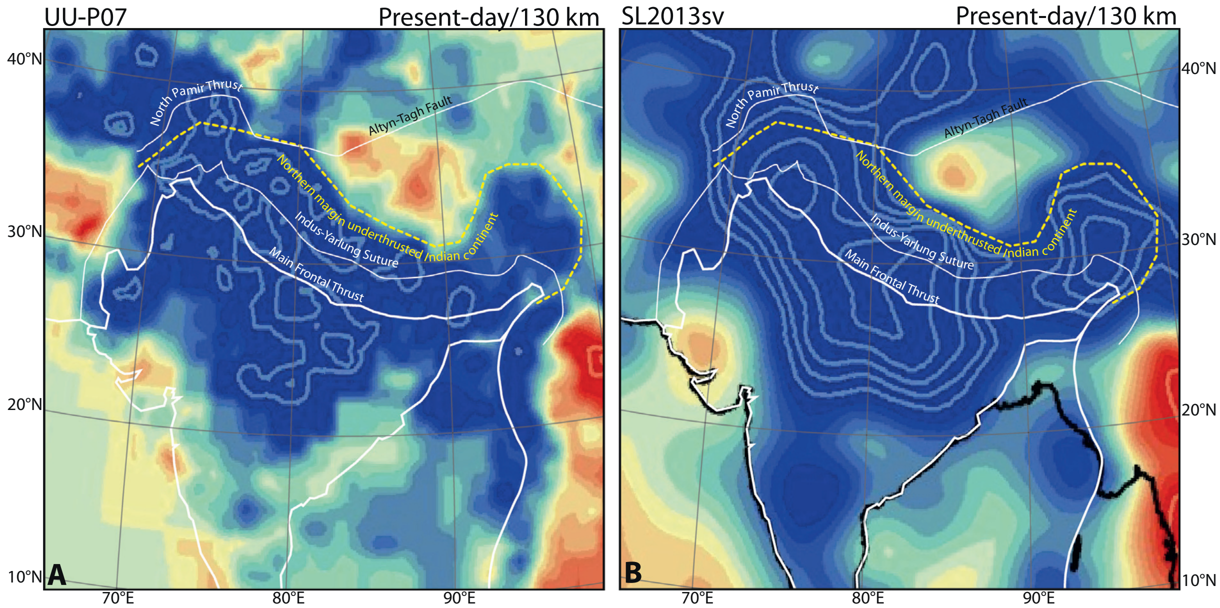


Fig. 7. Horizontal cross sections at 130 km depth below India and Tibet through seismic tomographic models of (A) UU-P07 (Amaru, 2007) and (B) SL2013sv (Schaeffer and Lebedev, 2013). Dotted yellow line is the interpreted northern continental margin of India that horizontally underthrusted Tibet. See also Agius and Lebedev (2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

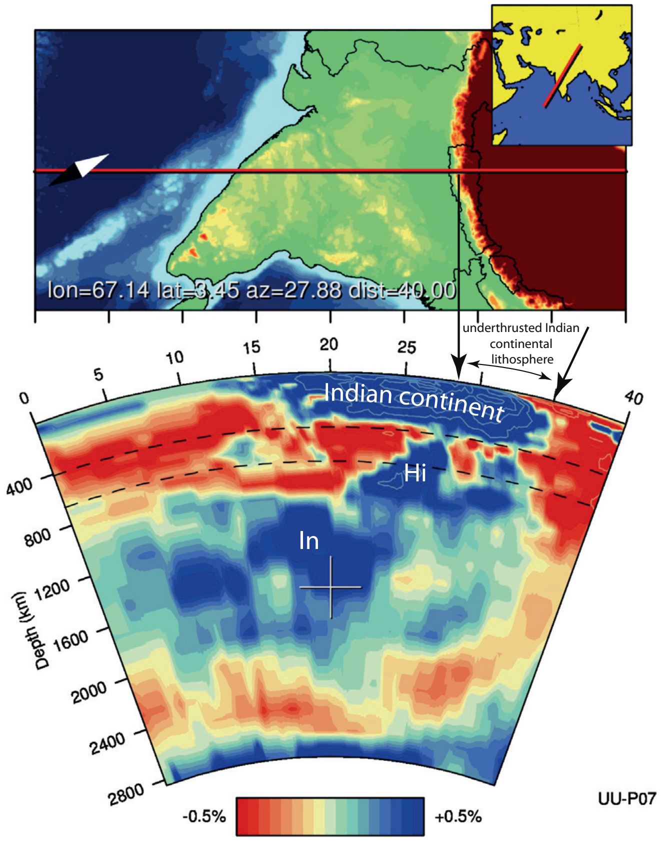


Fig. 8. Vertical cross section across the across the UU-P07 seismic tomography model (Amaru, 2007), showing the subducted and underthrusted parts of Indian plate lithosphere. In = India slab; Hi = Himalaya slab. See Figs. 7 and 9 for horizontal cross sections.

consistent with oblique India-Arabia subduction during the Late Cretaceous and Paleocene (Gaina et al., 2015).

6. Discussion

6.1. Reconstructing greater Indian paleogeography

We use our updated restoration of intra-Asian deformation and the 58 Ma Tethyan Himalaya-Lhasa collision age to constrain the size of Greater India at the time of collision at ~2700–3400 km in the west and east, respectively (Fig. 6). Balanced cross-sections across the Himalaya consistently provide minimum shortening estimates of 600–1100 km (Long et al., 2011a; Webb, 2013); the majority of this shortening accumulated during the Miocene. When reconstructed and taking the modern ~200 km width of the Himalaya into account, this restores the Lesser Himalaya to an original width of up to some 800 km, and the Tethyan and Greater Himalaya to a width of some 300–400 km. The amount of shortening accommodated within the Greater Himalaya is poorly constrained as will be addressed below.

Subtracting the upper crust of Greater India that was accreted to the Himalayas according to balanced cross sections (*e.g.*, Long et al., 2011a) from the area lost to subduction (Fig. 6) reveals that an area of ~1500–2100 km in N-S direction and ~2500 km in an E-W direction subducted without leaving a known geological record. As illustrated in Fig. 3, this reconstructs an area larger than the modern Arabian continent. Because balanced cross sections provide only minimum estimates of shortening, one can speculate that the upper crust of this entire 'missing' area was accreted in the Himalaya, but was subsequently eroded. Assuming accretion of 5–10 km thick nappes, this scenario requires a volume of 30–50 million km^3 of crust that was lost to erosion: this is 3–5 times the volume of the Bengal fan (a large volume of which was derived from the Tibetan plateau rather than the Himalaya) (Curray, 1994). Thus, the vast majority if not all crust must have been consumed by subduction, either directly, or as sediments on the downgoing plate. Because there is no known accretionary record of this subducted area, inferring its continental or oceanic nature relies on circumstantial geological and geophysical arguments. We will below discuss perspectives – a paleogeographic one deduced from sediment provenance, a kinematic one deduced from paleomagnetism, and

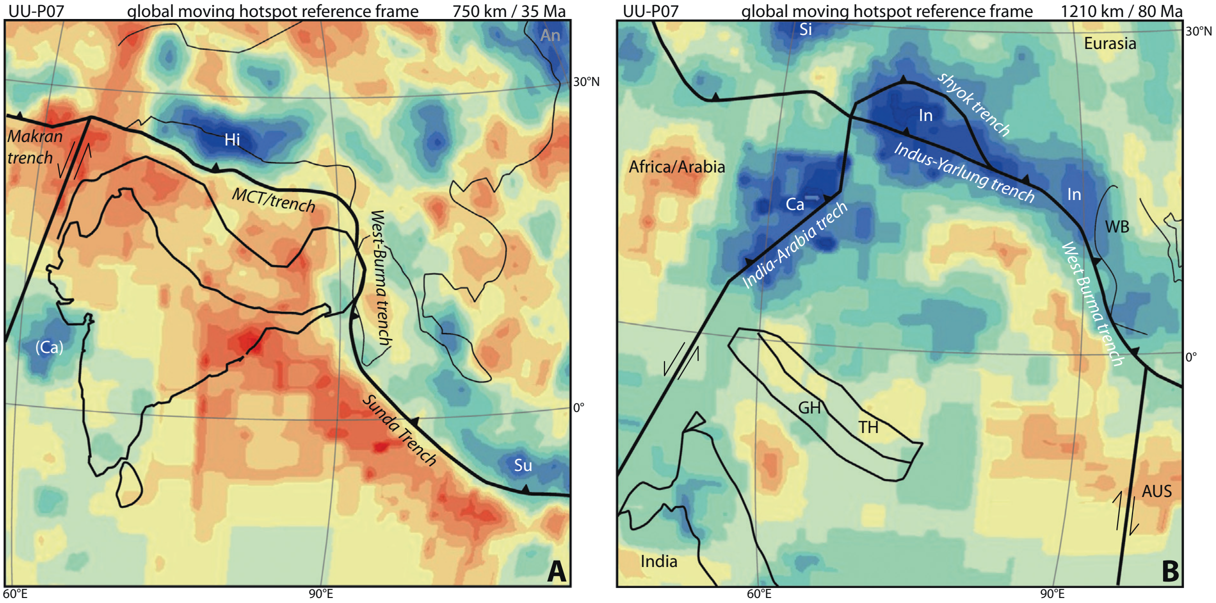


Fig. 9. Horizontal cross sections across the UU-P07 seismic tomography model (Amaru, 2007), and overlay of the kinematic restoration of the subduction zones consuming the Indian plate at (A) 750 km and 35 Ma, respectively, and (B) 1210 km and 80 Ma, respectively. Kinematic reconstructions are shown in the global moving hotspot reference frame of Doubrovine et al. (2012). For detailed description of slabs and resolution tests, see van der Meer et al. (2018). Key to abbreviations: An = Anhui Slab; AUS = Australian plate; Ca = Carlsberg Slab; GH = Greater Himalaya; Hi = Himalaya Slab; In = India Slab; Si = Sistan Slab; Su = Sunda Slab; TH = Tethyan Himalaya; WB = West-Burma Block.

dynamic one deduced from physical properties of continental and oceanic crust and lithosphere – that may be used to infer the continental or oceanic nature of subducted Greater Indian lithosphere and discuss the uniqueness of the solution from each perspective.

6.1.1. *Paleogeographic perspective*

Since most rocks of Greater India that were exposed at the surface some 58 Ma ago have now been lost to subduction, burial, or erosion, sediment provenance studies provide a circumstantial line of evidence that tests hypotheses of paleogeographical configuration and source-sink relationships. We highlight three recent studies that concluded that (most of) Greater India must have been continental and emergent in latest Cretaceous and Eocene time and discuss whether alternative interpretations are possible.

First, DeCelles et al. (2004, 2014) described the occurrence of detritus interpreted to derive from Indian passive margin rocks as well as ophiolite from the Middle Eocene (~45 Ma) Bhainskati section in Nepal. Those authors concluded that this section must have formed in a distal foreland basin setting. They calculated that the distance of the section to the TH 45 Ma ago was consistent with dynamic models of foreland basin geometry, and concluded that if Greater India hosted oceanic crust then it must have subducted prior to 45 Ma. We recall, however, that the Bhainskati section contains no Asia-derived detritus (DeCelles et al., 2004, 2014), even though such detritus was present at that time both on top of and below the Tethyan Himalayan ophiolites (An et al., 2014; Cai et al., 2011, 2012; DeCelles et al., 2014; Huang et al., 2015e; Metcalf and Kapp, 2017; Orme et al., 2015). We therefore suggest that the data of DeCelles et al. (2004, 2014), as well as their constraints on foreland basin dynamics, are also, or even more, consistent with a source in the Eocene obduction-related orogen of Pakistan in the west, which 45 Ma ago was at a similar distance to the Bhainskati section as the Tethyan Himalaya. Moreover, derivation of the Bainskhati sediments from the west would explain the absence of Asia-derived detritus, since the west Indian orogen was unrelated to the India-Asia collision (Gaina et al., 2015).

Second, Ding et al. (2016) and Qasim et al. (2018) reported detrital zircon ages from Paleocene-Eocene sediments on the Indian continent just east of the Salt Range of Pakistan, and in the Pakistan Lesser Himalaya and interpreted the first influx of < 100 Ma old zircons in the section around 56 Ma as reflecting India-Asia collision to the north, which would suggest a continuous sediment pathway from the Kohistan arc to the Indian foreland. However, the paleogeographic distance of their study area to the northern Sulaiman ranges, the Waziristan suture, and the Kabul block, which also formed an orogen around this time at the India-Arabia plate boundary (Beck et al., 1996; Gaina et al., 2015) was much shorter. This west Indian orogeny is associated with a well-documented onset of foreland basin sedimentation on the Indian continent (Waheed and Wells, 1990; Khan and Clyde, 2013), and thus provides a straightforward explanation for the zircon patterns of Ding et al. (2016) and Qasim et al. (2018), which therefore are unlikely to be derived from the India-Asia collision zone. Qasim et al. (2018) linked an angular unconformity around the K-T boundary in the Pakistan Lesser Himalaya to Kohistan-India collision, but we suggest that a link to the west India orogeny, unrelated to the India-Asia collision, is a more logical and straightforward explanation. Similarly, Zhuang et al. (2015) found detritus offshore NW India, immediately south of the Sulaiman ranges, with a geochemical composition that may suggest a provenance consistent with intra-oceanic arc volcanism, thought to represent the Kohistan arc. Those authors therefore logically inferred that Greater India since this time was entirely continental. Both the Kabul Block, which was sutured against NW India in Late Cretaceous time with Gondwana-derived basement similar to that of the Tibetan blocks that was in an overriding plate position relative to a Cretaceous subduction zone below the Waziristan-Khost ophiolite, and the intervening and overlying ophiolite belts themselves may provide alternative, and nearer sources.

Third, Garzanti and Hu (2015) provided a compelling case from sections in the northwest and central TH that uppermost Cretaceous sandstones with subordinate mafic debris were derived from India and pre-Deccan volcanics now found, *e.g.*, below the Bela Ophiolite in Pakistan (Kerr et al., 2010). They showed that the deposition of these sandstones was preceded by a phase of uplift that they related to the dynamic topographic effects of the Deccan mantle plume, up to 20 Myr before the eruption of the Deccan large igneous province (LIP). Such a time delay between the first dynamic effects of plume rise and LIP emplacement is consistent with numerical models of plume rise (van Hinsbergen et al., 2011b). Garzanti and Hu (2015) also showed that areas as far as 2000 km away from the center of the Deccan plume, in East Africa, also underwent uplift and such an area would include the Tethyan Himalaya. They thus made an elegant case that the uppermost Cretaceous sediments of the TH may have been derived from India and the precursor lavas of the Deccan traps. This scenario, however, may not be a unique solution. First, Garzanti and Hu (2015) showed that the Wölong volcaniclastic sandstones also contain spinel mineral grains that overlap in composition with those of their uppermost Cretaceous sandstones. Second, during phases of uplift, one would expect that sediment becomes more proximally sourced rather than distally. To successfully explain the sandstones they reported, a quartz-rich sediment source with Indian provenance should have been available: such a source is located deep in the Tethyan Himalayan stratigraphy and would require deep erosion of that stratigraphy, for which there is no evidence. For reasons explained above, the Greater Himalayan sequence, however, must have been located to the south of the TH passive margin sequence in the latest Cretaceous and may have provided such sources when uplifted. The modern Seychelles microcontinent in the middle of the Indian ocean is largely submerged and is the locus of carbonate sedimentation, similar to the TH in the Cretaceous. However, the Seychelles islands expose Precambrian granites (Tucker et al., 2001). A similar paleogeography for a Tethyan and Greater Himalayan microcontinent may thus, when uplifted, have provided the sediments studied by Garzanti and Hu (2015).

In summary, sediment provenance studies are consistent with a fully continental Greater India since latest Cretaceous time. We argue that the admittedly speculative alternative scenarios outlined above would, in the absence of supporting evidence from independent data sources, not provide the most straightforward explanation of the data, but they are permitted.

6.1.2. *Kinematic perspective*

Paleomagnetic data were at the core of the Greater India Basin hypothesis of van Hinsbergen et al. (2012): those authors suggested that the paleolatitudinal northward flight of the TH in Cretaceous time was much faster than that of India, requiring major extension and ocean basin formation. However, with the identification of remagnetization of the Upper Cretaceous and Paleocene poles of the TH (Huang et al., 2017a, b), there is no longer a *direct* paleomagnetic constraint on the growth of Greater India. We therefore test the size of Greater India as a function of collision age against paleolatitudinal separation of the TH from India in Early Cretaceous and Triassic time, following a similar approach as Huang et al. (2015d). In Fig. 10a we portray the paleolatitudinal motion of a reference location at the Indus-Yarlung suture zone (29°N, 88°E), assuming it was part of the TH reconstructed following three proposed scenarios for Greater India basin existence, and width. The first scenario assumes no Greater India extension (Garzanti and Hu, 2015; Ingalls et al., 2016) and moves the reference point as part of the southern Tibetan margin reconstructed as portrayed in Fig. 3, and then as part of the Indian plate back in time from 58 Ma onwards. The second scenario assumes that all of Greater India subducted since 50 Ma was continental and that if a GIB existed, it was closed by 50 Ma: a Greater India basin would thus not be wider than the amount of 58–50 Ma Indian plate subduction (*i.e.*, following Zhuang et al. (2015)). The third scenario is similar, but assumes that the GIB closed by 45 Ma (*i.e.*, following DeCelles et al. (2014)).

The results show that each of these scenarios mispredicts the paleomagnetically determined paleolatitudes for the Early Cretaceous and Triassic of the TH (Fig. 10a). This misfit is smallest for the Early Cretaceous, when India in a paleomagnetic reference frame was rotated strongly clockwise, but is much larger in the Triassic when that rotation was much smaller. As shown by W. Huang et al. (2015d), all data are fitted assuming a small Greater India in Early Cretaceous time and are inconsistent with large, unextended Greater India scenarios, regardless of the rotation of India relative to the spin axis. Every data point collected from the TH plots far south of the three scenarios outlined above. Rowley and Ingalls (2017) recently suggested that the close proximity of the TH to India in Early Cretaceous time shown by paleomagnetic data is because the paleomagnetic sites are located in the southern part of the TH and do not constrain the width of Greater India. They thereby suggested that of their inferred 2600 km width of Greater India, ~1800 km was located between the southern part of the TH where paleomagnetic sites were collected, and the northern part several tens of kilometers to the north where the sedimentary record of Paleocene collision was found. This requires some 1800 km of Cenozoic shortening in the TH alone, approximately 10–20 times more than geologically documented (*e.g.*, Webb, 2013; Wiesmayr and Grasemann, 2002)). We find this quite unlikely.

Thus, whilst it is not impossible that all Tethyan Himalayan poles coincidentally plot in the extreme lower latitudinal positions of the data cloud from which the GAPWaP was calculated, paleomagnetic data favor that almost all of Greater India between the Tethyan/Greater Himalaya and Lesser Himalaya was strongly extended, and as we infer from the magnitude of required extension, largely oceanic. This is consistent with an additional and independent kinematic dataset. Ali and Aitchison (2005) suggested that the Wallaby Fracture Zone on the southwest Australian margin formed the northern limit of continental Greater India in Gondwana reconstructions. Later, Gibbons et al. (2012, 2013) showed that the west Australian margin north of the Wallaby Fracture Zone contains marine magnetic anomalies that show a series of magnetic reversals that are absent to the south of the Wallaby fracture zone. Based on an ^{40}Ar/^{39}Ar age from a dredge sample of ~153 Ma, they correlate these reversals to the Late Jurassic polarity time scale. Whilst the reliability of the ^{40}Ar/^{39}Ar age is contested (Rowley and Ingalls, 2017), all post-India-Australia break-up anomalies are still present on the eastern Indian Ocean seafloor, and no conjugate set of the west Australian reversals shown by Gibbons et al. (2012) has been identified. From this it follows that, whatever their exact age, west Australia has in pre-Early Cretaceous time been conjugate to a plate that was not India, and that formation of this plate was associated with the separation of a microcontinent that was adjacent to both eastern Greater India and western Australia, relics of which are now likely found in SE Asian geology (Gibbons et al., 2012). Any continental crust that may have been contiguous with the Indian continent to the north of the TH must thus have rifted and drifted off prior to the Early Cretaceous, limiting Greater India to ~800–1000 km in Early Cretaceous time, consistent with paleomagnetic constraints as well as Himalayan shortening constraints.

6.1.3. *Geodynamic perspective*

Plate tectonics is thought to be largely driven by slab pull of subducting oceanic lithosphere, with a subordinate role for ridge push (Turcotte and Schubert, 2002). Continental crust is more buoyant than the mantle and resists subduction, while oceanic crust is denser and can subduct once the oceanic lithosphere overcomes its gravitational stability through cooling (Vlaar and Wortel, 1976). This may straightforwardly explain why there is barely any oceanic crust older than 200 Ma today, yet continental crust may be billions of years old. Given the widespread evidence for continental subduction in fold-thrust belts such as the Himalaya, numerical modeling has been performed on the dynamics of continental subduction systems. Such models showed that subduction of continental crust and mantle lithosphere is possible provided that the buoyant upper ~5–10 km of continental crust is decoupled from the downgoing plate. Such upper continental crust is then left behind in accretionary orogens and is available for geological study of *e.g.*, shortening records (*e.g.*, Capitanio et al., 2010; Tirel et al., 2013). In a calculation of pre- and post-collisional continental crustal volumes in the India-Asia collision zone, Yakovlev and Clark (2014) used a small pre-collisional continental volume for Greater India and an

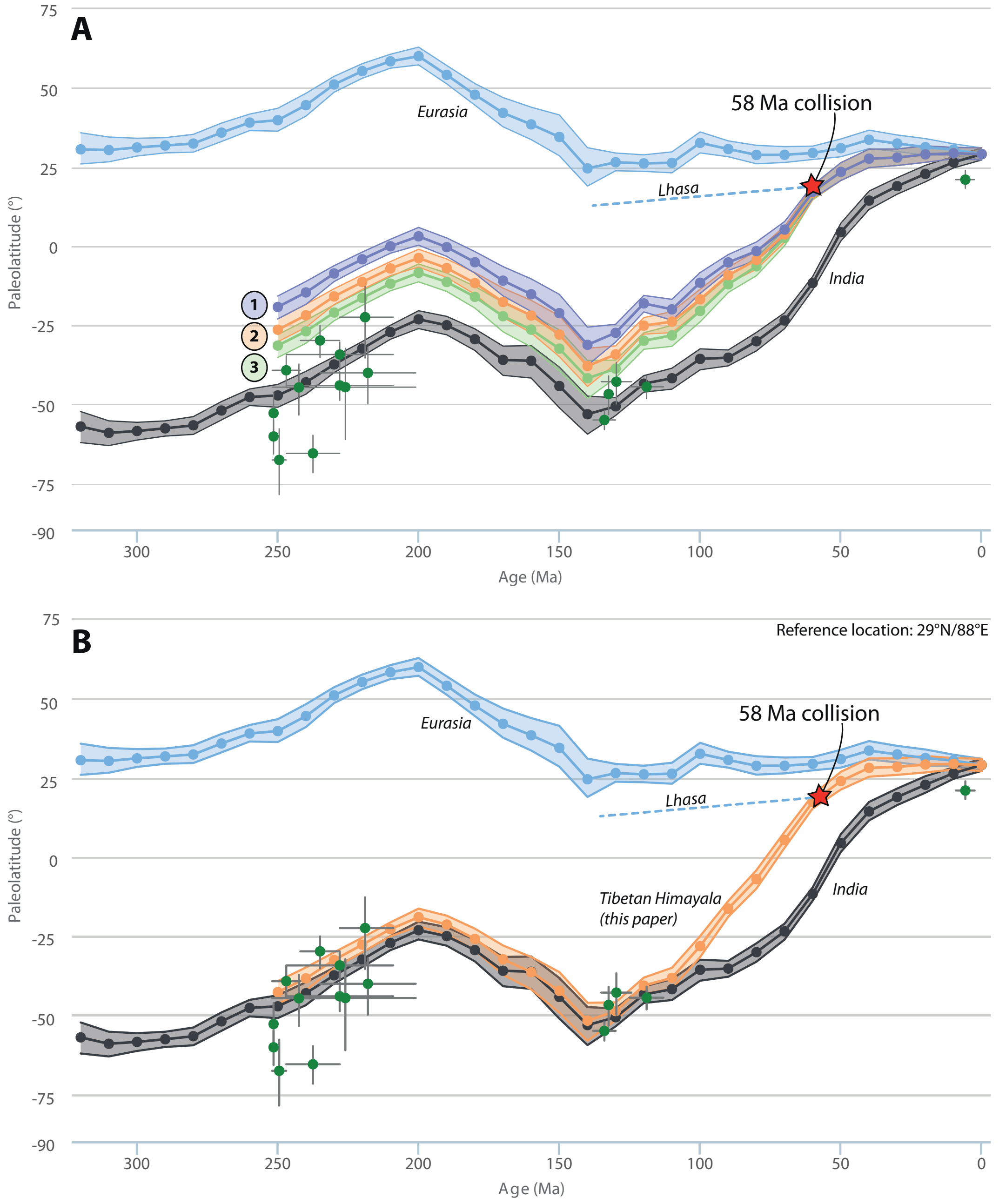


Fig. 10. A) Paleolatitudinal curves for the Tethyan Himalaya based on three proposed scenarios for the size evolution of Greater India, using our updated restoration for Tibetan shortening. Curve (1) assumes no Greater Indian extension (*e.g.*, Garzanti and Hu, 2015; Ingalls et al., 2016); Curve (2) assumes that a Greater Indian Basin must have closed by 50 Ma (Zhuang et al., 2015); Curve (3) assumes that a Greater Indian Basin closed by 40 Ma (DeCelles et al., 2014). All of these curves predict paleolatitudes for the Tethyan Himalaya that are higher than those constrained by paleomagnetism of Triassic and Lower Cretaceous rocks (green dots). See Supplementary files 2 for data compilation. B) Paleolatitude curve predicted by the kinematic reconstruction of the Tethyan Himalaya in this paper, modified from van Hinsbergen et al. (2012), compared against data from the Tethyan Himalaya (green data points). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

amount of intra-Asian shortening that were both similar to the estimates of van Hinsbergen et al. (2012), thereby implicitly assuming a GIB hypothesis. Their calculation shows that even with a small volume of continental crust in Greater India, the present-day volume of continental crust in the collision zone is ~30% smaller than in pre-collisional stages. This difference may be attributed to subduction of lower crust after leaving the upper crust behind in the Himalaya. This mechanism of lower continental crustal and lithospheric mantle subduction stripped from its original upper(most) crust is frequently invoked as a mechanism to explain lower crust and mantle lithosphere subduction of all of Greater India, leaving Greater Indian buoyant upper crust behind as the Himalayan fold-thrust belt (*e.g.*, Capitanio et al., 2010; Ingalls et al., 2016). Similar arguments have been made for Tibet (*e.g.*, Replumaz et al., 2016).

Our objection to this hypothesis is, however, that the Himalaya contains < 1000 km of stacked upper crust – consistent with the estimates of the size of continental Greater India of Yakovlev and Clark (2014) – but the amount of Greater Indian subduction was up to ~3600 km (Fig. 6) and that after 58 Ma, an area larger than Arabia subducted without detected accretion (Fig. 3). It remains unknown how much shortening was accommodated within the Greater Himalaya, but given its limited volume, it cannot contain originally > 2500

× 2500 km, ~5 to 10 km thick upper continental crust. Continental crustal volume calculations also preclude that this crust is present below Tibet (Ingalls et al., 2016; Yakovlev and Clark, 2014).

Wholesale subduction of oceanic crust is common. Whilst there are active margins where episodic accretion of deep-marine oceanic sediments and volcanics occurred (*e.g.*, in Japan (Isozaki et al., 1990), western California (Wakabayashi, 2015), and Costa Rica (Buchs et al., 2013)), long-lived subduction margins such as at the Aleutian, Marianas, Tonga-Kermadec, Sunda, and Andes trenches are devoid of accreted rocks despite thousands of kilometers of Cenozoic subduction. Although finding accreted oceanic rocks around the MCT would provide conclusive evidence of oceanic subduction in the Himalaya, absence of such sediments is thus by no means conclusive evidence against past oceanic subduction below the MCT.

Wholesale subduction of continental crust, including its buoyant upper(most) crust, is problematic. Numerical models of arrival of continental crust at subduction zones driven by slab pull invariably lead to arrest of subduction (*e.g.*, Duretz and Gerya, 2013; Duretz et al., 2014; Pusok and Kaus, 2015; van Hunen and Allen, 2011). The modern setting of India and Asia, or Arabia and Asia, demonstrates that convergence and underthrusting can continue at several centimeters per year despite collision. This may be driven by a combination of large-scale, whole mantle flow (*i.e.*, basal traction) and slab pull of adjacent oceanic subduction zones (Becker and Faccenna, 2011; Faccenna et al., 2013), but again we emphasize that this subduction is associated with ongoing crustal accretion in the Himalaya (or Zagros).

Assuming wholesale Indian continental subduction in the Paleocene and Early Eocene of the India-Asia collision (*e.g.*, Ingalls et al., 2016), particularly in the period before the 50 Ma Indian plate motion deceleration, is especially problematic from a geodynamic perspective. Indian plate motion rates in this time period are the highest that have been reconstructed from marine magnetic anomalies, and they followed a major acceleration of > 10 cm/yr between ~70 and 65 Ma linked to arrival of the Deccan plume head below the Indian plate (Kumar et al., 2007; van Hinsbergen et al., 2011b). To explore the implications of a fully continental Greater India, it is important to first analyze the potential causes of this extremely high Indian plate motion rate.

van Hinsbergen et al. (2011b) explored the causes of these ultra-high rates and suggested that a subordinate acceleration of a few centimeters per year may be attributed to ‘plume push’, *i.e.*, the spreading of the Deccan plume head below the Indian plate. These authors suggested that the bulk of the acceleration of India resulted from plume-induced lubrication of the lithosphere-asthenosphere boundary below India making the already existing slab-pull of the Indian slab more efficient. Recently, Jagoutz et al. (2015) reiterated the paleogeographic conclusions of Aitchison and Davis (2004) and suggested that the high Indian plate motion rates resulted from the combined slab pull of two northward dipping subduction zones, one below an equatorial subduction zone below the Kohistan arc and Indus-Yarlung ophiolites, and one below Tibet. As discussed previously, geological and paleomagnetic constraints are inconsistent with this inferred plate kinematic model and while this model may pertain for areas in the western Neotethys, (*e.g.*, Gürer et al., 2016), it may not apply to the Indian acceleration. Regardless which model is preferred, however, slab pull is considered as the main driver of the very high plate convergence rate.

If the India-Asia collision occurred at 58 Ma, and Greater India was entirely continental, then 1200 km or more of continental crust subducted at record subduction rates of > 15 cm/yr before the 50 Ma onset of deceleration. Of this 1200 km, only perhaps 300 km of upper crust is present in the Tethyan and Greater Himalaya, and some 900 km of continental crust would have undergone wholesale subduction. The length of the resulting slab composed entirely of continental crust and mantle lithosphere is much larger than the depth of the upper mantle where such high subduction rates must be both accommodated and generated, because sinking rates in the top of the lower mantle are at most a few cm/yr and decrease with depth to ~1500 km (van der Meer et al., 2010, 2018). In other words, a fully continental Greater India would require that the highest plate speeds ever reconstructed from marine magnetic anomalies were generated by a slab that throughout the upper mantle was entirely continental in nature, with a negative buoyancy of its lithospheric mantle that is likely less than that of old oceanic lithospheric mantle, and must have included its positively buoyant upper crust (Ingalls et al., 2016). Hence, such ultra-high subduction rates would have been driven by reduced slab pull. We consider this scenario physically unlikely.

In our opinion, a geodynamic perspective on Greater Indian subduction strongly suggests that the GIB scenario is the most feasible option. The scenario with a fully continental Greater India is not independently supported by quantitative kinematic data, and it requires that a continental area the size of Arabia subducted without accretion, at subduction rates that are some of the highest reconstructed in Earth history. We note that if continents would be so dense that their subduction would have sustained these high plate convergence rates, then an alternative explanation is required to explain the observation of extensive continental crust that is billions of years old, whereas *in situ* oceanic crust is not older than a few hundred million years.

6.2. Paleogeography of Greater India within Gondwana

For reasons outlined above, we seek to restore the Tehyan/Greater Himalaya microcontinent close to India in the Early Cretaceous, limited in the northeast by the Wallaby fracture zone (Ali and Aitchison, 2005; Gibbons et al., 2012, 2013). When we restore the horizontal portion of India below Tibet as portrayed by seismological observations (Fig. 7) within Gondwana, it is located between the Wallaby fracture zone and the southwest Australian margin (Fig. 11). This suggests that the horizontal portion of India below eastern Tibet reflects all of continental Greater India. The sharp 400 km step in the shape of underthrust Greater Indian lithosphere is a geometry similar to that of the Wallaby Fracture Zone. When we reconstruct our restored Tethyan/Greater Himalaya microcontinent adjacent to this hypothetical fracture zone, the western limit of this microcontinent coincides with the west Indian

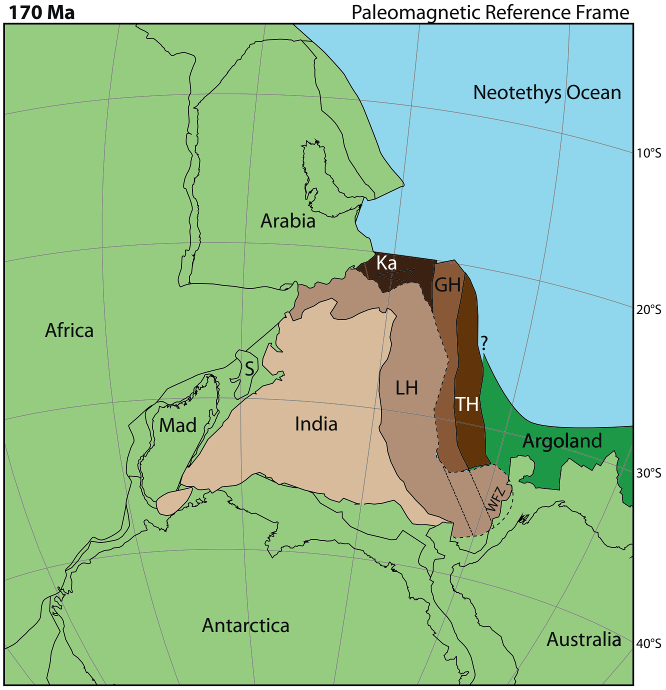


Fig. 11. Reconstruction of Greater India in Gondwana at 170 Ma cast in the paleomagnetic reference frame of Torsvik et al. (2012). Reconstruction of Argoland follows Gibbons et al. (2012). WFZ = Wallaby Fracture Zone.

margin (Fig. 11). We follow the earlier inferences of van Hinsbergen et al. (2012) that rifting within Greater India started in the Early Cretaceous and is reflected by the Wölong volcanics. This is contemporaneous with the break-up of Australia and India, and it suggests that the Tethyan/Greater Himalaya microcontinent was separated by ridges from India as well as Australia. Such a configuration is kinematically feasible and consistent with the constraints of Gibbons et al. (2013; 2012). Finally, our reconstructed position of the Tethyan/Greater Himalayan microcontinent is somewhat farther to the north of the modern Main Frontal Thrust than the previous estimate of van Hinsbergen et al. (2012) since we now restored the shortening within the Tethyan Himalaya. The predicted APWP for the TH based on our updated reconstruction is consistent with paleomagnetic constraints (Fig. 10b), even though these constraints prefer an even tighter fit than we restore here – *i.e.*, a larger amount of pre-drift extension may have occurred than reconstructed – suggesting we restored a minimum amount of Cretaceous Greater Indian Basin extension.

6.3. Slab overturning, Indian plate deceleration, and Paleogene Tibetan shortening

If the Tethyan Himalaya-Lhasa collision occurred around 58 Ma, then it had no marked effect on the Indian subduction rate. This would be surprising if all of Greater India was continental, but it is dynamically feasible if a relatively small microcontinent subducted of which the upper crust accreted (*e.g.*, Capitanio et al., 2010). But why then did convergence rapidly decelerate then around 50 Ma, 8 Myr after collision, and during a period of oceanic subduction? Moreover, much of Tibetan plateau shortening occurred between 50 and 30–20 Ma (*e.g.*, van Hinsbergen et al., 2011a, and references therein). How would ongoing oceanic subduction cause this shortening and the formation of the largest modern orogenic plateau?

To explore a solution for these problems, we first note that India-Asia convergence rates had been high, around 9 cm/yr since ~90 Ma, followed by the increase to > 15 cm/yr around 65 Ma (van Hinsbergen et al., 2011b). In the 30 Myr prior to the India-Asia collision, a > 2500 km length of oceanic lithosphere subducted, half of which in the 7 Myr just prior collision. Furthermore, tomographic images of the India slab show that this subduction occurred along a semi-stationary trench relative to the mantle to form a single, major seismic wavespeed anomaly currently located below India (Fig. 8). Rapid subduction of 1000's of km of crust into a 660 km deep upper mantle is thought to be accommodated on the one hand by thickening, *e.g.*, through buckling of the slab, and on the other hand by transfer of subducted lithosphere into the lower mantle (*e.g.*, Schellart, 2011; Sigloch and Mihalynuk, 2013; Wu et al., 2016; Agrusta et al., 2017) (Fig. 12). With the very high Indian subduction rates, a point in the slab would have reached the 660 km discontinuity within just 5 Myr after it passed the trench. Even with buckling, the slab would have rapidly filled the local upper mantle, unless the throughput into the lower mantle by buckling, thickening, or both was especially efficient. This rapid transfer to the lower mantle may occur at a stationary trench provided the subducted lithosphere is sufficiently dense, in which case slab deflection at the base of the upper mantle need not occur (Agrusta et al. 2017).

The crust that was north of the Tethyan Himalaya must in the eastern part towards Australia have been (at least) Late Jurassic in age (Gibbons et al., 2012). Stratigraphic evidence from the TH shows that farther west, it may even have been Permian in age (Garzanti et al., 1999). The crust that was south of the Tethyan Himalaya, in the GIB, must have formed after ~110 Ma given the paleomagnetic evidence described above and the evidence from the Wölong volcaniclastics for intra-continental rifting until that time (Hu et al., 2010), younging to perhaps as young as ~60 Ma in the center of the GIB. We therefore propose that the > 100 Myr old crust that subducted before the arrival of the TH at the trench was dense enough upon arrival at the 660 km discontinuity to rapidly sink into the lower mantle. The continental lithosphere of the Tethyan Himalaya, and the young, < 50 Myr old GIB crust that subducted after it, passed the trench around 58 Ma, and would have reached the 660 km discontinuity 4–5 Myr later. If that lithosphere had more difficulty to enter into the lower mantle given its higher buoyancy, then it would rapidly fill up the upper mantle through buckling and lateral deflection (Fig. 12; Goes et al. (2017)) and we propose that this lies at the heart of the 8 ± 2 Myr delay between arrival of the Tethyan Himalayan crust at the trench and the Indian plate slowdown.

Seismic tomography of the mantle below the India-Asia collision zone further demonstrates that the Himalaya slab, which subducted likely in Paleogene time, is located to the north of the India slab, and it is overturned. Hotspot reference frames (*e.g.*, Doubrovine et al., 2012) show no significant northward absolute Eurasian plate motion in this time interval. The overturned Himalaya slab, which is offset to the north relative to the older subducted lithosphere, may have triggered slab advance (Funiciello et al. 2008; Schellart 2008). Such a kinematic scenario thus requires that after prohibition of rapid lower mantle subduction, the slab bend (*e.g.*, Schepers et al., 2017) tightened and moved north, thereby creating a flat slab below Tibet (Fig. 12). We note that a flat slab was previously inferred from a northward migration of arc volcanism until ~30 Ma DeCelles et al. (2011, 2014). Flat slab subduction is well-known as a driver of upper plate shortening, *e.g.*, from the Laramide or Andean orogens (*e.g.*, Liu et al., 2010; Schellart, 2017), thereby providing a straightforward alternative explanation for the Paleogene growth of the Tibetan plateau, in absence of continent-continent collision. The presence of large a large slab-like body to the south of the main India slab, and somewhat deeper in the lower mantle, may suggest that such a slab overturning and associated flat subduction episode may have happened also at earlier times, prior to the Cenozoic, perhaps driving the strong Cretaceous shortening of the Tibetan plateau (*e.g.*, Murphy et al., 1997; Kapp et al., 2005, 2007).

The resistance of the lithosphere against tight bending (*e.g.*, Buffett and Rowley, 2006), in combination with the increased friction at the plate contact due to topographic Tibetan rise (which may have caused up to 4–6 cm/yr of Indian plate slowdown (van Hinsbergen et al., 2011b)) induced by flat slab subduction, are the likely drivers of rapid Indian plate deceleration. Ongoing India-Asia convergence subducted GIB lithosphere of decreasing age until the by then likely extinct GIB-India ridge subducted around ~35 Ma. The deceasing lithosphere thickness and strength as the extinct ridge was subducted may have allowed for further tightening of the slab bend, which effectively led to a gradual decrease in flat slab width previously identified as a phase of Oligocene slab retreat, and southward migration of arc volcanism (*e.g.*, DeCelles et al., 2011; Leary et al., 2016). As discussed above, the onset of the horizontal underthrusting of Indian lithosphere that followed slab break-off below Tibet likely varied along-strike owing to the 'embayment' in the northern Indian margin, and occurred around 25–15 Ma, representing the final India-Asia continent-continent collision. In our reconstruction, horizontal continental underthrusting of Indian lithosphere sheared the overturned slab off the Indian continental margin, inciting the last, Miocene volcanism in southern Tibet (DeCelles et al., 2011).

Slab overturning may also explain why arc volcanism decreased rapidly in volume since ~50–40 Ma (X. Ma et al., 2016; Y. Ma et al.,2016; DeCelles et al., 2011; Chapman and Kapp, 2017), which Rowley and Ingalls (2017) argued excludes a GIB scenario. Arc volcanism results from the release of slab-derived fluids into a mantle wedge. When slabs subduct vertically, or even overturn, they are no longer underlying a mantle wedge. We suggest that this absence of a well-defined mantle wedge explains the major decrease of Gangdese volcanic arc activity despite ongoing oceanic subduction.

7. Conclusions

In this paper, we re-evaluate the size of Greater India – the area of

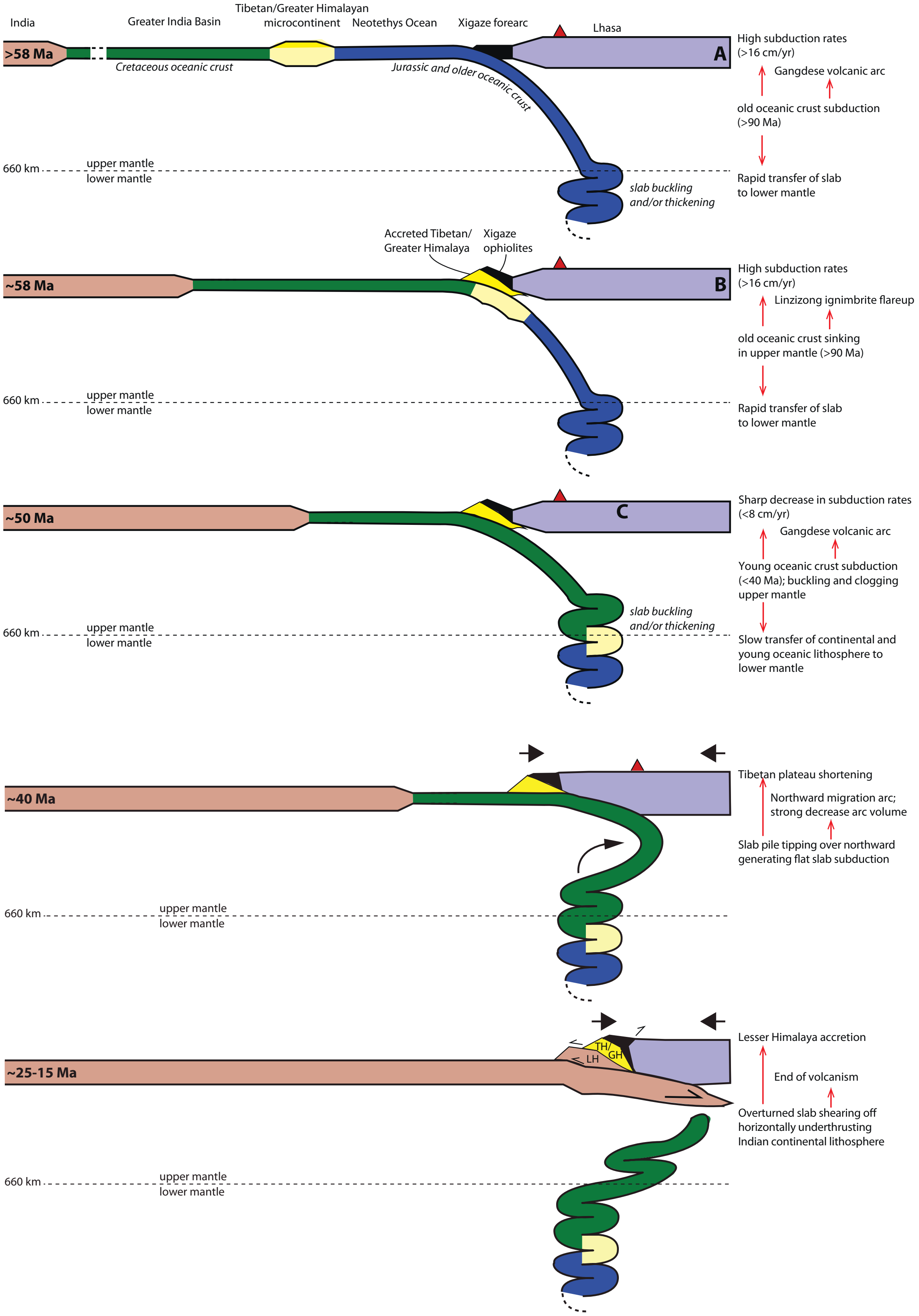


Fig. 12. Cartoons illustrating the potential cause of the delay between the ~58 Ma collision between the Tethyan Himalaya and Lhasa, and the ~50 Ma rapid slowdown of India-Asia convergence velocities. We propose that the old age of the Neotethys lithosphere allowed for rapid transfer of a cold, dense slab into the lower mantle. The continental Tethyan Himalayan lithosphere and the young Greater India Basin lithosphere, upon arrival at the 660 km discontinuity ~4–5 Ma after collision, transferred into the lower mantle much slower, clogging the upper mantle inciting a delayed convergence rate slowdown compared to microcontinent collision. This triggered northward slab advance, and slab bend tightening. This generated a flat slab whose friction caused the Paleogene part of the rise of the Tibetan plateau. Friction at the plate contact in combination with the tightening slab bend caused Indian plate deceleration.

the Indian plate that was lost to subduction following initial collision between the Tethyan Himalaya and the Lhasa block of southern Tibet – and discuss the paleogeography of Greater India from a paleogeographic, kinematic, and geodynamic perspective. We identify what we conclude is the most likely scenario from all perspectives in unison, and subsequently discuss how the preferred scenario may explain the Paleogene formation of the Tibetan Plateau and the delay between initial collision and the rapid deceleration of India-Asia convergence at and after 50 Ma. Our conclusions are summarized as follows:

1) Our new restoration of intra-Asian shortening updates the previous one of van Hinsbergen et al. (2011a) and incorporates a much larger extrusion of Indochina. This includes a Cenozoic ~20° counterclockwise rotation of the Lhasa terrane. We adopt a Tethyan Himalaya-Lhasa collision age of 58 Ma and reconstruct post-collisional intra-Asian shortening of 1000–1200 km.
2) Our restored geometry and location of the south-Asian subduction zone before and after initial collision is consistent with locations and trends of slabs of subducted Indian plate lithosphere in the upper and lower mantle imaged by seismic tomography.
3) Greater India was 2600 km in the west and 3400 km in the east at the time of Tibetan Himalaya-Lhasa collisiojn. No > 1000 km of this area contained the upper continental crust that currently resides in the Himalaya. The crust and lithosphere that was consumed between ~58 Ma TH accretion and before the ~25 Ma onset of LH accretion occupied an area larger than the present Arabian subcontinent, and must have undergone wholesale subduction.
4) Sediment provenance studies argued that Eocene Lesser Himalayan and west-Indian margin sediments were sourced from the Himalaya, Tibet, and/or Kohistan. If true, this would suggest a fully continental Greater India. But alternative sediment sources, particularly associated with Paleocene-Eocene orogeny at the west-Indian margin that is unrelated to the India-Asia collision, allow for a straightforward alternative source for Indian and Lesser Himalayan Paleogene foreland basin deposits. These sediments are thus not conclusively linked to the India-Asia collision zone.
5) Paleomagnetic data of the Tethyan Himalaya shows that only a scenario in which the Tethyan and Greater Himalaya were located in Early Cretaceous and older time within hundreds of kilometers from their modern position relative to stable India provides a straightforward fit to the data. Such a small continental Greater India is required by marine magnetic anomaly patterns on the west-Indian margin and is consistent with continental shortening budgets of the Himalaya. This strongly favors the opening of a major oceanic Greater India Basin.
6) A geodynamic perspective comes from the subduction style and rate of Greater India. Particularly the first 8 Myr following initial collision were associated with the highest subduction rates reconstructed from marine magnetic anomalies of 150–180 km/Myr. Wholesale subduction during much of this time period is required by the limited amount of upper continental crust in the Tethyan and Greater Himalaya, and is straightforwardly explained if the subducting crust was oceanic: oceanic crustal subduction without accretion is at present globally a rule rather than exception. We consider wholesale continental subduction of an area equivalent to the modern Arabian continent without upper crustal accretion, which would require that the ultra-high Indian subduction rates were driven by a slab that was more buoyant than the mantle and did not exert slab pull, implausible.
7) We conclude that the Greater India Basin scenario remains the most, and in some cases only feasible scenario when the three independent scenarios are considered simultaneously.
8) We show an updated reconstruction of Greater India within Gondwana, whereby the restored Tibetan-Greater Himalayan microcontinent broke away from India along a passive margin-fracture zone geometry that is revealed by seismic tomographic images of the portion of the Indian plate that currently lies horizontally below Tibet.
9) We explain the 8 Myr delay between the Tethyan Himalaya-Lhasa collision to result from the differences in density of subducted Indian plate lithosphere through time determining its propensity to sink into the lower mantle. The ultra-high Indian subduction rates of 150–180 km/yr that characterized the 65–50 Ma period would only be sustained if subducted lithosphere was able to rapidly sink into the lower mantle. The Jurassic and older Neotethyan lithosphere that subducted prior to collision must have undergone such a rapid lower mantle entry to allow for the long period of ultra-rapid subduction. The microcontinental and Cretaceous oceanic lithosphere that entered the mantle after 58 Ma would have arrived at the 660 km discontinuity within 4–5 Myr after collision. Resistance of this more buoyant lithosphere to lower mantle penetration may have led to buckling in the upper mantle, rapidly filling the upper mantle reservoir. We propose that this triggered northward migration of the slab bend shown in seismic tomography. This would have tightened the slab bend, leading to the tomographically imaged overturned Himalaya slab. Such northward motion of the slab bend would have caused a previously inferred flat slab below Tibet, which provides a straightforward mechanism driving Tibetan shortening despite ongoing oceanic subduction. The filling of the upper mantle with GIB lithosphere, the consequent tightening of the curvature of the down-going slab, combined with increase friction at the plate contact due to flat slab formation and upper plate topographic rise are the likely trigger for the rapid 50–45 Ma India-Asia convergence rate slowdown from 18 to 8 cm/yr. Slab steepening and overturning as shown by seismic tomographic images of the Himalaya slab may also explain the distinct reduction in arc volcanism after ~50 Ma: such steepening removes the slab from underneath a sub-Tibetan mantle wedge.

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