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## Timing of subduction initiation, arc formation, ophiolite obduction and India - Asia collision in the Himalaya --Manuscript Draft--

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<b>Corresponding Author:</b>	Mike Searle University of Oxford Oxford, UNITED KINGDOM
<b>Corresponding Author E-Mail:</b>	mike.searle@earth.ox.ac.uk
<b>Order of Authors (with Contributor Roles):</b>	Mike Searle (Conceptualization: Lead; Investigation: Lead; Writing – original draft: Lead; Writing – review & editing: Lead)
<b>Abstract:</b>	Reconstruction of the Western Himalaya requires three subduction systems operating beneath the Spong arc, Dras-Kohistan arc and the Asian continent during the Late Cretaceous-Paleocene. The timing of the closure of NeoTethys along the Indus suture zone (ISZ) in Ladakh and South Tibet has been proposed as old as ~65 Ma and as young as ~37 Ma. The definition of India-Asia collision can span >15m.y. from the first touching of Indian continental crust with Asian crust to the final marine sedimentation between the two plates. There is good geological evidence for a Late Cretaceous-Early Paleocene phase of folding, thrusting and crustal thickening of Indian plate shelf carbonates associated with obduction of ophiolites. There is no geological evidence of any oceanic 'Greater Indian basin' separating the northern Tethyan and Greater Himalaya from India. There is clear evidence to support final ending of marine sedimentation along the Indus suture zone at 50 Ma (Planktonic foraminifera zone P7-8). There is no evidence for diachroneity of collision along the Pakistan-Ladakh-South Tibet Himalaya. Timing of Ultra-High Pressure metamorphism cannot be used to constrain India-Asia collision, and timing of high-grade kyanite- and sillimanite-grade metamorphism along the Greater Himalaya can only give a minimum age of collision.
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**M.P. Searle. Timing of subduction initiation, arc formation, ophiolite obduction and India - Asia collision in the Himalaya**

This is a well written paper which builds on a remarkable wealth of experience and should be published with minor revision.

One of the things that I used to say to my students, is that you need to have a robust view on topics which you wish to address. There are two main areas where this paper falls down, and both are easily addressed. There is also a grey area which is also easily addressed.

The first is that there is no clear answer to the question posed in the title. Although lots of data are summarised, there is no clear statement in either the abstract or the discussion as to what is the age of collision. To me, and in the context of the book, this is a great time to make that statement. Mike Searle is probably the only person with the breadth of knowledge to tie this down. Everything in the paper suggests, that although the region has a complex geological history that India-Asia collision is probably (however defined) is probably best dated at between 55 and 50 Ma. That is the defining statement that a review paper for this volume should give. There have been recent papers by Aitchison and von Hinsbergen which appear to suggest younger ages than this. It would be nice to see a proper (but please keep it brief) critique of these papers.

The grey area is how we treat the NW Himalaya. I am biased here as I know Pakistan better than most. North Pakistan is not the same as NW India and certainly not the same as the main Himalayan chain. Metamorphism in N Pakistan is really early, probably pre-dates the Eo-Himalayan stuff in the main Himalayan chain. You need to be a bit more robust here.

Specific points follow. (I have no line numbers so go by page and paragraph!!)

Abstract. Nice to see a personal “best fit” age for collision in here.

P2. “buildt”!!

deleted

P3. End of the first paragraph. Please add references here to the two key Kaghan papers – Parrish et al. (2006) and Treloar et al. (2003).

These papers did not define the I-A collision based on age of UHP (correctly!) so I did not cite them here

P3 – second paragraph. Second line makes no sense as written. ??

Add Treloar et al. (2003) before Parrish et al. (2006).

done

There is a philosophical issue here as to whether UHP metamorphism can be used to date collision. Clearly it does not in Oman, and Stephane Guillot has addressed this elsewhere. However, in N Pakistan there is such a tight window between the timing of UHP metamorphism, the age of non-UHP metamorphism (Foster et al and the cooling back through 500C as documented by hornblende Ar ages that it is very difficult to see that UHP metamorphism does not date India-Asia collision here. Everything happens over such a short period of time.

Yes I know, tricky problem!

P4. Can you cite the ages for the North Himalayan Domes.

P4. Fig 2. Disappointed not to see a review of relevant data from Pakistan on this otherwise very good plot. **That's a whole different story which is covered in the Trellar et al paper so this paper restricts to the main Himalayan chain from Ladakh east.**

P4 – bottom. Are there ages for the Dras 2 unit? **No ages I am aware of**

P5. Although there are garnet granulites at Jijal, Chilas is a large gabbro-norite body emplaced at ca 80 Ma into an extending arc complex. (see papers by Burg et al, and Treloar et al.) **added**

P8. Needs a more robust critique of vH et al. **bits added**

Change 'by' to 'up' on line 16. **??**

P9. Change 'there' to 'they' on page 11.

P9. Needs a more robust critique of Aitchison here. **Its there already and Green paper will expand on this**

P10. What is the age of the Chogdo Fm? **Molasse seds not directly dateable**

Second para. Insert 'are dated' before 'at 47.1' **done**

P11. I know that they are Rb-Sr ages but you need to give an age here for the Indus Valley Confluence sheets. Despite being Rb-Sr think that they sufficiently post-date the main heating event that they are believable. **I prefer to leave these ages out; they are not robust compared to ones I discuss**

I know that they are Rb-Sr ages but I do think that you need to cite the Petterson ages for the Kohistan late-stage batholiths. You run the risk of majoring on Ladakh and minimising Kohistan **this is done on purpose (all this Pakistan data should be summarised in Treloar et al. paper)**

P11. UHP section. Please add references here to O'Brien et al (2001) and to Treloar et al (2003) **done**

Bottom line. Treloar et al (2003) clearly set this out and you do need to reference this. **done**

P12. This is part of the 'grey area' that I reference above. The Himalaya do not stop at Kishtwar. There is a wealth of data from N Pakistan that document cooling back from an Eo-Himalayan metamorphism by 40 Ma. **Yes I know but Kohistan – Pakistan is a much wider bigger story and one that will be covered more in Treloar et al. paper**

P13. Can you put this line of section on to Fig 1.

Last line – first para – 'grnaite'. **fixed**

P15. Point 7. This really is a cop out. Forget obfuscation, tell us what you really think. It gives us all clarity and encourages debate going forward. **What I say is absolutely true! Its not a fixed number! I added a sentence explained the difference**

Point 9. Please proofread the last three lines! **done**

Point 11. Although I find it hard not to see how the KV UHP rocks do not effectively date collision, I can see why the Tso Moriri ones might slightly pre-date it. But that then gives a

lead into a far more challenging debate about diachronous collision somewhere in the system.

P16. I would just delete the last 7 lines. Why are they here.

# Timing of subduction initiation, arc formation, ophiolite obduction and India - Asia collision in the Himalaya

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MICHAEL P. SEARLE <sup>1</sup>

<sup>1</sup> Department of Earth Sciences, University of Oxford, Oxford OX1 3AN, UK.

\* E-mail: [mike.searle@earth.ox.ac.uk](mailto:mike.searle@earth.ox.ac.uk)

**Abstract:** Reconstruction of the Western Himalaya requires three subduction systems operating beneath the Spong arc, Dras-Kohistan arc and the Asian continent during the Late Cretaceous-Paleocene. The timing of the closure of NeoTethys along the Indus suture zone (ISZ) in Ladakh and South Tibet has been proposed as old as ~65 Ma and as young as ~37 Ma. The definition of India-Asia collision can span >15m.y. from the first touching of Indian continental crust with Asian crust to the final marine sedimentation between the two plates. There is good geological evidence for a Late Cretaceous- Early Paleocene phase of folding, thrusting and crustal thickening of Indian plate shelf carbonates associated with obduction of ophiolites. There is no geological evidence of any oceanic ‘Greater Indian basin’ separating the northern Tethyan and Greater Himalaya from India. There is clear evidence to support final ending of marine sedimentation along the Indus suture zone at 50 Ma (Planktonic foraminifera zone P7-8). There is no evidence for diachroneity of collision along the Pakistan-Ladakh-South Tibet Himalaya. Timing of Ultra-High Pressure metamorphism cannot be used to constrain India-Asia collision, and timing of high-grade kyanite- and sillimanite-grade metamorphism along the Greater Himalaya can only give a minimum age of collision.

200 words

## Introduction

The geology of the Himalaya records details of important geological processes operating during the closure of the Neo-Tethyan ocean and the subsequent India-Asia continental collision ([Fig. 1](#)). In particular the presence of obducted ophiolite complexes onto the northern margin of India, the presence of island arc systems within the Indus suture zone (e.g.

Dras-Kohistan arc) and the oceanic subduction beneath the Asian continent to the north can potentially provide information on initiation of subduction zones, obduction mechanisms and the emplacement of island arcs and ophiolites onto continental margins. Himalayan ophiolites include examples obducted onto the previously passive continental margin of India (e.g. Spontang ophiolite; Reuber *et al.*, 1987; Searle *et al.*, 1988; Corfield *et al.*, 2001) and those that mark the suture zone (e.g. Chan *et al.*, 2006; Hébert *et al.*, 2012; Xu *et al.*, 2014). The presence of island arc sequences on top of the ophiolite complex as well as the large Dras-Kohistan arc within the suture zone (Reuber 1989; Clift *et al.*, 2002), require at least two NNE-dipping intra-oceanic subduction zones during the Late Cretaceous – Palaeocene. A third, long-lived N-dipping subduction zone must have been present along the southern margin of Asia beneath the Late Jurassic – Eocene Ladakh – Gangdese granite batholith. The youngest subduction-related I-type granite along the Ladakh – Gangdese batholith could provide a minimum age constrain on the ending of Tethyan oceanic subduction beneath Asia and hence India-Asia collision.

The timing of the collision between the Indian and Asian plates and the closure of the NeoTethys Ocean that lay between them is important for many reasons and has been the subject of intense debate. The India-Asia collision resulted in closure of the NeoTethyan seaway that lay between the two plates, the uplift and erosion of the Himalaya, the enhanced uplift of the Tibetan Plateau, and affected Northern hemisphere if not global, ocean chemistry, climate, and faunal migrations. The zone of collision is well defined from geological mapping and runs along the Indus and Yarlung Tsangpo suture zones in Waziristan, south of the Kohistan arc in northern Pakistan, and across Ladakh (India) and south Tibet, north of the Himalaya (Heim & Gansser 1939; Gansser 1964; Fig. 1). The southern margin of the Asian plate has a 2000 km long subduction-related I-type granite batholith (Kohistan-Ladakh-Gangdese batholith) with associated calc-alkaline volcanics, overlain by the Indus molasse basin, a post-collision continental basin that runs along the suture zone (Garzanti & van Haver, 1988; Searle *et al.*, 1988, 1990). The suture zone contains a number of structurally disrupted ophiolite complexes, Permian-Mesozoic deep-sea sedimentary rocks, remnant island arcs, tectonic mélanges with exotic blocks and uncommon blueschists (e.g. Colchen *et al.*, 1986; Searle 1986; Garzanti *et al.*, 1987; Searle *et al.*, 1988, 1990; Robertson & Deggan, 1993; Robertson 2000; Henderson *et al.*, 2010; Wang *et al.*, 2012). The Indian continental margin consists of a complete Permian-Mesozoic and Palaeogene shallow marine sedimentary sequence that is extremely highly deformed with intense folding and thrusting (Garzanti & Gaetani 1991; Searle *et al.*, 1988, 1997), and rare

remnant thrust sheets of ophiolites at the highest structural levels (e.g. Spontang ophiolite; Searle, 1986; Corfield *et al.*, 1999, 2001).

At the outset it is important to define precisely the term '*India-Asia collision*'. This could potentially span the time between the first initial meeting of Indian continental crust with Asian crust to the final closure of NeoTethys Ocean and the timing of the ending of marine sedimentation along the ISZ. This early meeting of Indian and Asian crust depends to a large extent on how far north the Indian continental crust extended beneath the shelf and basin (Lamayuru complex) sediments. Several different aspects have been used to constrain the precise timing of India-Asia collision. These include (1) the palaeomagnetic evidence for the slowing of the northward drift of India (Klootwijk *et al.*, 1979; Ali & Aitchison 2005; Najman *et al.*, 2010; van Hinsbergen *et al.*, 2011, 2012), (2) the timing of the final marine sediments within the ISZ and along the northern margin of India (Garzanti *et al.* 1987; Searle *et al.*, 1987, 1988; Green *et al.*, 2008; Hu *et al.*, 2015, 2016), (3) the timing of the oldest continental sediments along the suture zone (Searle *et al.*, 1990; St-Onge *et al.*, 2010; DeCelles *et al.*, 2014), (4) the ending of subduction-related magmatism along the Transhimalayan Kohistan-Ladakh-Gangdese I-type granite batholith (Chung *et al.*, 2005; Chu *et al.*, 2006; St-Onge *et al.*, 2010), and (5) the age of ultra-high pressure (UHP) eclogite facies metamorphism along the leading (northern) margin of India (e.g. Leech *et al.*, 2005).

The time span between initial meeting of Indian and Asian crust and final marine sedimentation along the ISZ could be as much ~20 million years given modern-day examples such as the Arabia-central Iran collision. Collision of Arabia with central Iran occurred at ~20 Ma along the Zagros suture zone, yet marine conditions are present in the Arabian (Persian) Gulf along the flexural foreland basin to this day. The timing of the first meeting of Indian and Asian crust is also contingent on knowing the substrate to the continental margin along the Zaskar shelf – Indus slope – basin, and where exactly the continental – oceanic crust transition was in the reconstruction. We do know that the leading margin of the Indian plate was subducted to UHP depths (~25-27 kbar; 120-140 km depth) at around 58-50 Ma in Tso Moriri, Ladakh (de Sigoyer *et al.*, 2000; St-Onge *et al.*, 2013), or 46.4 Ma (O'Brien *et al.*, 2001; Treloar *et al.*, 2003; Parrish *et al.*, 2006) at Kaghan (Pakistan). However, similar UHP eclogite facies rocks occur in Oman where they are clearly related to the final stage of ophiolite obduction and not to any continental collision, so the Himalayan examples cannot be used to constrain the timing of continental collision. Another important constraint is the age of early crustal thickening and metamorphism along the North Himalayan domes in the

leading margin of the Indian plate. Peak metamorphic ages on these rocks give a minimum age of India-Asia collision, assuming that all the metamorphism was post-collisional.

A Late Cretaceous – Cenozoic time chart is shown in [Fig. 2](#) summarising all the stratigraphic and geochronological age data across the Himalaya, the Indus suture zone and the Ladakh – Gangdese batholith (Asian margin) with interpreted ages of island arc and ophiolite obduction, metamorphism and deformation. In this paper I describe the Indus suture zone in Ladakh, review the ages of ophiolites along the suture zone, and then review each of the tectonic scenarios outlined above. Finally a new tectonic evolution is proposed that satisfies all the known geological and geochronological data.

### **Indus – Yarlung Tsangpo suture zone**

The Indus suture zone (ISZ) in Ladakh, also called the Indus-Yarlung suture zone in Tibet, was first mapped in the south Tibet region by Heim & Gansser (1939) and Gansser (1964) who first described the details of the Kiogar (Amlang-la) ophiolitic ‘coloured mélange’ zone. Gansser suggested that this suture zone was the root zone for the ophiolites scattered along the Ladakh and south Tibetan region. Also present along the suture zone ([Fig. 3a](#)) are a succession of Permian-Mesozoic marine sedimentary rocks of both proximal to slope facies turbidite origin (Lamayuru complex) and distal deep-water sedimentary and volcanogenic origin (Robertson & Degnan 1993; Robertson & Sharp 1998). Mélanges with a sedimentary shaley matrix enclose blocks of Mesozoic alkali basalt, Triassic exotic reef limestones (e.g. Mulbeck exotics), red radiolaria chert and ophiolite fragments including gabbro and basalt (Searle *et al.*, 1988). Serpentinite mélanges are also present sometimes associated by blueschists (e.g. Sapi-la glaucophane schist; Mahéo *et al.*, 2006; Groppo *et al.*, 2016). In western Ladakh and north Pakistan a large intra-oceanic island arc, the Kohistan – Dras arc, is sandwiched within the suture zone (Khan *et al.*, 1993; Pettersen *et al.*, 2010; Jagoutz & Schmid, 2010). The Dras arc in Ladakh was originally mapped by Reuber (1989) and divided into two units, Dras 1, an intra-oceanic arc sequence equivalent to the Kohistan volcanics in Pakistan, and a Dras 2 unit separated by a major unconformity. Based on structural and geochemical data, Clift *et al.* (2000, 2002) interpreted the Dras 1 unit as representing an intra-oceanic arc sequence emplaced SW onto the Indian margin during the Turonian-Santonian (93.5 – 83.5 Ma) and the Dras 2 unit as representing the post-collision Khardung volcanic unit.



The post-collision Indus molasse basin follows the trend of the Indus suture zone along the Ladakh and south Tibet parts of the ISZ. The marine to continental transition is well exposed along the Zaskar river section (Fig. 3b,c). This basin was filled by erosional debris mainly from the north (granites, diorites, andesites, rhyolites of the Ladakh batholith) but also from the suture zone itself (cherts, serpentinites, etc) and uncommon shelf carbonates towards the top (Fig. 3d). All of these Indus suture zone rocks were affected by post-Miocene NE-vergent backthrusting and folding (Fig. 3e) (Searle 1986; Searle *et al.*, 1996; Clift *et al.*, 2002a,b). The base of the Indus molasse in eastern Ladakh is well exposed at Chumatang where continental fluvial and lacustrine sedimentary rocks unconformably overlie Palaeocene – Lower Eocene granites of the Ladakh batholith. The youngest phase of granite intrusion below the unconformity are 47.1 Ma leucogranite dykes at Chumatang (Fig. 3f) (St-Onge *et al.*, 2010).

In Pakistan, the upper part of the Kohistan arc is a late Jurassic – early Eocene sequence of arc volcanics (Dir, Utror, Shamran and Chalt volcanic suites), and associated sediments (Pettersen & Treloar 2004; Jagoutz & Schmidt 2012) that link eastwards to the Dras basalts, andesites, and rhyolites in western Ladakh (Reuber 1989; Clift *et al.*, 2000, 2002). The lower arc sequence includes lower crustal amphibolites (Kamila amphibolites), garnet granulites, gabbro-norites (Chilas complex), and subduction related peridotites, pyroxenites and chromite-layered dunites (Jijal complex) and ophiolites (Sapat ophiolite). The whole Kohistan arc sequence was emplaced southward onto Indian plate metamorphic rocks during the latest Cretaceous (Khan *et al.*, 1993).

### **Indus Suture zone ophiolites**

Numerous studies have since been carried out on ophiolites along the Indus Yarlung Tsangpo suture zone (see reviews by Hébert *et al.*, 2012 and Xu *et al.*, 2015). Ages of the Tibetan ophiolites, constrained by U-Pb dating of zircons in plagiogranites or gabbros, range from Jurassic to Late Cretaceous range from Jurassic to Late Cretaceous (Pedersen *et al.*, 2001; Hébert *et al.*, 2003, 2012). The Himalayan ophiolites can be divided into two types, (a) those that have been obducted south onto the previously passive continental margin of India exemplified by the Spontang ophiolite (Searle, 1986; Corfield *et al.*, 2001; Pedersen *et al.*, 2001), and (b) suture zone ophiolites, such as the Nidar ophiolite in Ladakh (Mahéo *et al.*, 2004), the Kiogar- Jungbwa ophiolites (Gansser 1964; Chan *et al.*, 2007), the Xigase group

of ophiolites (e.g. Hébert *et al.*, 2003, 2012; Chan *et al.*, 2007), and the Zedong-Luobusa ophiolites (e.g. Zhou *et al.*, 2002; Malpas *et al.*, 2003) in SE Tibet.

The Spontang ophiolite in Ladakh is the best example of an ophiolite complex thrust southwards onto the Indian passive margin sediments. A complete Penrose type ophiolite 'stratigraphy' is exposed with mantle sequence peridotites, crustal gabbros, sheeted dykes and pillow lavas (Corfield & Searle 2000; Corfield *et al.*, 2001). A sequence of island arc andesitic volcanics (Spong arc) overlies the ophiolite sequence. A U-Pb zircon age of  $177 \pm 1$  Ma (mid-Jurassic) was obtained from a high-level gabbro of the main ophiolite and an age of  $88 \pm 5$  Ma from the Spong andesitic arc sequence above (Pedersen *et al.*, 2001). The Spontang ophiolite may be one of the few oceanic crustal sequence ophiolites which subsequent to its formation had a subduction-related arc sequence erupted on top during the Late Cretaceous. The age of the arc sequence (Coniacian) probably corresponds to the age of subduction initiation, that led to obduction of the Spontang ophiolite. The entire complex was emplaced onto the Indian margin during the Coniacian-Maastrichtian some 80 m.y after its initial formation (Pedersen *et al.*, 2001; Corfield *et al.*, 2001). A major phase of Late Cretaceous crustal shortening and thickening is documented from the Zaskar River section (Fig. 4) where gently folded Palaeocene – Eocene shallow marine carbonates are in contrast to the isoclinally folded and highly deformed shelf carbonates beneath the Spontang ophiolite (Searle 1986; Corfield & Searle 2000; Searle & Treloar 2010). Late Cenozoic breakback thrusts, such as the Photoksar thrust cut through the entire sequence resulting in the present reversal of strapping order with the western margin of the Spontang ophiolite thrust above Eocene limestones (Corfield & Searle, 2000; Corfield *et al.*, 1999, 2001).

The Nidar ophiolite in eastern Ladakh is a suture zone ophiolite that shows a complete ophiolite sequence including Jurassic to Lower Cretaceous radiolarian cherts and 500 meters thickness of andesitic and rhyolitic lavas with boninites, overlying gabbros and mantle sequence harzburgites and dunites. A prominent ophiolitic mélange zone with blueschists and exotic blocks lies adjacent to the ophiolite. In south Tibet Jurassic U-Pb zircon ages have also been obtained from the Kiogar ophiolite ( $159.7 \pm 0.5$  Ma; Chan *et al.*, 2007), the Jungbwa ophiolite ( $123.9 \pm 0.5$  Ma; Chan *et al.*, 2007), the Donqiong ophiolite ( $122.3 \pm 2.4$  Ma; Xu *et al.*, 2008), and the Zhongba ophiolite ( $125.7 \pm 0.92$  Ma; Dai *et al.*, 2011). The Xigase ophiolite has a U-Pb zircon age of  $132.0 \pm 2.9$  Ma from a pegmatitic gabbro (Chan *et al.*, 2007), and amphibolites from the ophiolitic mélange beneath gave  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of  $\sim 127 - 123$  Ma, interpreted as relating to the timing of emplacement (Malpas *et al.*, 2003; Guilmette *et al.*, 2009). The Luobusa ophiolite in SE Tibet is interpreted as having formed along a mid-

ocean ridge at  $177 \pm 31$  Ma with a supra-subduction zone component around 126 Ma (Zhou *et al.*, 2002; Malpas *et al.*, 2003). Thus ophiolites within the ISZ show that there was active spreading at least as old as the mid-Jurassic with subduction-related island arc forming during the Late Cretaceous. Emplacement of ophiolites occurred during the Latest Cretaceous – Palaeocene (Searle *et al.*, 1987; 1997; Beck *et al.*, 1995, 1996; Clift *et al.*, 2000, 2002; Searle & Treloar 2010; Hébert *et al.*, 2012).

### **India – Asia collision: Palaeomagnetic constraints**

The break-up of the Gondwana supercontinent during early Mesozoic time led to the rifting of India away from southern Africa-Madagascar and Antarctica around ~140 Ma, and its subsequent rapid northward drift across the Indian ocean (Fig. 5). This northward motion can potentially be constrained by palaeomagnetic data. Plate motion reconstructions and palaeomagnetic data show that India was at equatorial latitudes during the early Eocene (Besse *et al.*, 1984; Besse & Courtillot 1988), and that since collision India has moved north, with respect to stable Asia by between 2600 and 3700 km (Rowley, 1996, 1998). Palaeomagnetic data for the Lhasa block (southern margin of Asia) suggest that it rifted away from Gondwana in the Late Triassic and moved north by ~40° of latitude (~4500 km) at a rate of about 5 cm/year, until it collided with the Qiangtang block in the Early Cretaceous (Li *et al.*, 2016). The Lhasa terrane shows a divergence away from India (and its Himalayan terrains) from ~200 Ma (Late Triassic), after the Late Permian-Triassic opening of Neo-Tethys, until ~55 Ma, the timing of the final closure of Neo-Tethys along the Himalaya (e.g. Searle *et al.*, 1987, 1997; Garzanti *et al.* 1987). These data confirm that Neo-Tethys was a wide ocean separating the Lhasa terrain from India throughout the Mesozoic. As India moved northwards the ocean gradually closed, with initial contact of India and Lhasa block crust at approximately 55-50 Ma (Guillot *et al.*, 2003; van Hinsbergen *et al.*, 2011a,b, 2012; Li *et al.*, 2016). The timing of the India-Asia collision has been a little more disputed.

Klootwijk *et al.* (1989) and Copley *et al.* (2010) used palaeomagnetic evidence to suggest a slowing down of the northward drift of India at 55 Ma which they attributed to the India-Asia collision. Guillot *et al.* (2003) related this to the slowing or ending of continental subduction. The reconstructions of Ali and Aitchison (2008) and Aitchison *et al.* (2007) however, showed a wide separation of India and Asia at this time and they proposed two collision ‘events’, the first a collision of India with an intra-oceanic arc at ~55 Ma and a

much younger age of main India – Asia at ~35 Ma. Their model was taken further by van Hinsbergen *et al.* (2011a,b; 2012) who proposed an early ‘soft collision’ of the Tethyan + Greater Himalaya ‘microplate’ with Asia at ~52 Ma followed by a later ‘hard collision’ of Greater India (Lesser Himalaya + India) between 25-20 Ma (Fig. 6). Their reconstruction shows an ocean approximately 1000 km wide along the Greater Himalaya (GHS) or Main Central Thrust (MCT) zone. This model completely ignores decades of geological work along the GHS which shows no evidence of any oceanic rocks, or ophiolites along the MCT (LeFort 1975). The MCT is a continental thrust fault and ductile shear zone where footwall and hangingwall rocks can be restored (Searle *et al.*, 2008). The relatively unmetamorphosed Lesser Himalayan rocks beneath (south of) the MCT have Paleoproterozoic to Neoproterozoic protoliths with thin Mesozoic Gondwana sedimentary rocks and early molasse sediments above. The Greater Himalayan sequence (GHS) above (north of) the MCT are Neoproterozoic to Mesozoic rocks affected by widespread Cenozoic regional Barrovian metamorphism and partial melting. In the reconstructions Indian plate Neoproterozoic rock occur across the Lesser and Greater Himalaya (Haimanta series) without any intervening suture zone. The GHS is a mid-crustal ~10-20 km thick series of mainly high-grade metapelitic rocks, migmatites and leucogranites. There are no suture zone rocks anywhere along the MCT zone and there was never an ocean along the GHS so the model of van Hinsbergen *et al.* (2011a,b; 2012) can be comprehensively discarded. The discrepancy in the palaeolatitudes of the Tethyan Himalaya and India can be accounted for instead by internal crustal shortening and thickening by folding and thrusting.

Van Hinsbergen *et al.* (2011) suggested from plate reconstructions since 50 Ma that between 2400 km (west) and 3200 km (east) India-Asia convergence had occurred, most of it taken by north of the Indus suture zone in Tibet. These shortening estimates are considerably more than most estimates from the Indian plate Himalaya. Crustal shortening estimates across the Himalaya are of the order of 700-900 km (e.g. Guillot *et al.*, 2003; Guillot & Replumaz 2013; Robinson & Martin 2014), or ~900-1100 km (Webb 2013), although it is impossible to restore the ductile deformed gneisses and partially molten migmatites of the GHS section. Post collision crustal shortening in Tibet is also hard to ascertain with certainty. It is apparent that a regional phase of shortening occurred across southern Tibet before eruption of the 70-60 Ma Linzizong volcanics, before India-Asia collision (Kapp *et al.*, 2005, 2007; Searle 2015). Most of the plateau seems little affected by post-collision crustal shortening or metamorphism with a few local exceptions (e.g. Nyenchen Tanggla range; Weller *et al.* 2016). For these reasons Searle *et al.* (2011) and Searle (2015) suggested that large-scale

underthrusting of Indian lower crust occurred across much of the plateau resulting in the ‘passive uplift’ of the plateau, similar to the original Argand (1924) model. This underthrusting model could account for the ca 1000 km shortening discrepancy from the palaeomagnetic data.

### **India-Asia collision: Marine – Continental transition**

According to Hu *et al.* (2015, 2016) the earliest contact of Indian and Asian continental crust occurred at ~59 Ma (middle Paleocene), based on the change in provenance in the Sangdanling Fm. along the distal margin of India. In the Zaskar Himalaya Garzanti *et al.* (1987) recognised an unconformity at the Palaeocene – Eocene boundary (Planktonic foraminiferal zone P5-6). The final marine sediments were also dated at Planktonic foraminiferal zone P8 (middle Early Eocene) corresponding to an age of 50.5 Ma (Garzanti *et al.* 1987; Green *et al.*, 2008) and SBZ zone 11, 51-49 Ma (Henderson *et al.*, 2010). Along the Indian passive margin in the Zaskar mountains south of the ISZ, the Kong slates are the youngest marine sediments which are upper Ypresian (P8 and SBZ 9-10) (Green *et al.*, 2008) or lower Ypresian (SBZ 6-8; 54 Ma; Najman *et al.*, 2016). The youngest U-Pb ages of detrital zircons in the Kong Fm. are 56.3 Ma and in the overlying Chulung-la redbeds are 53.7 Ma (Najman *et al.*, 2016). South of the Greater Himalaya marine sediments persisted along the early foreland basin into the Lutetian (SBZ 14-16) in the Subathu Fm in northern India and the Blainskati Fm in Nepal. These rocks do not date India-Asia collision as there were deposited well away from the zone of collision along the ISZ.

In southern Tibet at Zhepure Shan, Rowley (1996, 1998) and Zhu *et al.* (2005) also confirmed that the final marine sediments were late Ypresian age (<52 Ma). Wang *et al.* (2002) proposed a much later age of collision using calcareous nanofossils to propose marine sediments as young as ~34 Ma. These fossil ages were disputed and it is now clear that the age of youngest marine sediments is 50.6 Ma as initially suggested by Garzanti *et al.* (1987), Searle *et al.* (1987, 1988), Rowley (1996, 1998), Zhu *et al.* (2005), and Green *et al.* (2008) and also subsequently accepted by Wang *et al.* (2012). Najman *et al.* (2010) noted that youngest marine sediments in south Tibetan Zhepure Shan Fm. contained larger benthic foraminifera and planktonic foraminifera consistent with an age of 54.5 – 52.5 Ma (zone P7-6).

In contrast, Aitchison *et al.* (2000, 2007) proposed that India collided with an intra-oceanic arc at ~55 Ma and with Asia much later at ~35 Ma based partly on palaeomagnetic data of Ali & Aitchison (2008) and the erroneous young nanofossil ages of Wang *et al.*

(2002). Najman *et al.* (2010) re-examined the same sections and found no evidence for marine organisms younger than nanofossil zone NP12 or planktonic foraminiferal zone P7-8, in agreement with the precise ages from the Ladakh section (Green *et al.*, 2008; Najman *et al.*, 2016). They described the transition from 54-53 Ma. shallow marine carbonates of the Zhepure Shan Fm. upwards to 52.8-50.6 Ma clastic sediments of the Pengqu Fm. recording the marine to continental transition. Thus there is no evidence of any diachroneity in the closing of Neo-Tethys between Ladakh and south Tibet.

### **Continental sedimentation along the ISZ**

Following the closure of Neo-Tethys and final marine sedimentation along the ISZ at ~50.6 Ma (Searle 1986; Garzanti *et al.*, 1987; Green *et al.*, 2008), a continental molasse basin, the Indus basin formed along the Indus suture zone in Ladakh, continuing eastward across southern Tibet. This linear basin follows the trace of the Indus and Yarlung suture zone and accumulated debris initially from the Asian margin (Ladakh granites, andesites etc) and later both from the Asian margin and the Indian margin. The transition from marine Nummulitic limestones to reddish brown continental silts and shales is abrupt (Fig. 3b,c). The earliest continental deposits are Lowermost Eocene Chogdo Fm, fluvial and lacustrine sediments derived from the Asian margin and unconformably overlying Late Cretaceous Jurutze and Tar Fms and the Palaeocene carbonates of the Sumda Fm of the Indian distal margin along the southern part of the ISZ (Garzanti & van Haver 1988; Searle *et al.* 1990; Sinclair & Jaffey 2001; Clift *et al.*, 2002b; Green *et al.*, 2008). Thus, contrary to Henderson *et al.* (2011), the Chogdo Fm does seal the ISZ closure structures constraining the age of India-Asia collision (Fig. 7). The youngest marine incursion along the ISZ is the Ypresian (Lowermost Eocene) Nummulitic limestones that lie stratigraphically above the Chogdo Fm and beneath the continental Nurla Fm, comprised of alluvial fans (Garzanti & van Haver 1988; Searle *et al.* 1990; Clift *et al.*, 2002b; Green *et al.*, 2008). Above the Nurla Fm, massive coarse conglomerates of the Choksti Fm. and Hemis Fm. were deposited in high-energy braided rivers derived mainly the north. 90% of the clasts in the Hemis conglomerates are granites and granodiorites derived from the Ladakh batholith to the north with a few red cherts, green volcanics and peridotites derived from the suture zone.

The abrupt transition from Indian-derived to Asian-derived sedimentation in the Indus-Yarlung suture zone in south Tibet has been dated between ~60 Ma and  $58.5 \pm 0.6$  Ma (DeCelles *et al.*, 2014). Along the northern margin of the ISZ in Ladakh the Indus molasse

basin overlaps unconformably parts of the Indus suture zone and Ladakh granites. Conglomerates of the Bazgo Fm. are overlain by reddish sandstones and shales of the Temesgam Fm. The youngest leucogranite dykes truncated beneath the unconformity at  $47.1 \pm 0.1$  Ma (St-Onge *et al.*, 2010). Thus, the base of the Indus molasse basin could be as old as 57 Ma with the major unconformity overlying Ladakh granites younger than 47 Ma (Fig. 7).

### **Ending of Ladakh-Gangdese subduction-related magmatism (Asian plate)**

The Trans-himalayan batholith extends for over 2000 km from the Kohistan region of Pakistan, through Ladakh to the Gangdese batholith in south Tibet. This batholith is composed of hornblende- and biotite-bearing granites, granodiorites and diorites of calc-alkaline I-type affinity, related to northward subduction of a slab of Neo-Tethyan oceanic lithosphere beneath the southern margin of Asia. These granites have an extensive calc-alkaline andesite-dacite-rhyolite volcanic suprastructure and must have formed an Andean-type continental margin prior to the collision of India. U-Pb zircon ages range from Early Jurassic to Early Eocene ( $\sim 198 - 49$  Ma). The youngest phase of granitic intrusion is a restricted series of leucogranite dykes cutting the older granodiorites outcropping at the Indus-Gilgit river confluence in Pakistan and at Chumatang in Ladakh. In Ladakh, U-Pb zircon ages from the granodiorites are  $103 \pm 3$  Ma and  $101 \pm 2$  Ma (Honegger *et al.*, 1982; Schärer *et al.*, 1984) in the Kargil region, and between  $\sim 69 - 45$  Ma in the Leh region (Schärer 1984; Singh *et al.*, 2007). At Chumatang, St-Onge *et al.* (2010) dated the main hornblende-bearing granodiorite at  $57.7 \pm 0.2$  Ma and the later cross-cutting leucogranite dykes are dated at  $47.1 \pm 0.1$  Ma. All of these granites are abruptly truncated by the unconformity along the base of the Indus molasse basin which must be  $< 47$  Ma at this locality. This age provides a minimum age constraint on the India-Asia collision.

### **Ultra-high Pressure metamorphism**

UHP eclogites occur in two major localities along the northern margin of the subducting Indian plate, in Kaghan, Pakistan and in Tso Moriri, Ladakh. The leading margin of the Indian plate was subducted to UHP depths ( $\sim 25-27$  kbar; 120-140 km depth) at around 58-50 Ma in Tso Moriri, Ladakh (de Sigoyer *et al.*, 2000; St-Onge *et al.*, 2013), or  $\sim 46.4$  Ma (O'Brien *et al.*, 2001; Treloar *et al.* 2003; Parrish *et al.*, 2006) at Kaghan (Pakistan). It has been suggested by several authors that the age of UHP eclogite metamorphism at Tso Moriri

and Kaghan dates India-Asia collision (Leech *et al.*, 2005). However, similar eclogites in an identical tectonic position, occur along the leading edge of the subducting Arabian plate in Oman, an area that has not yet undergone continent-continent collision, showing that it is possible to form these rocks prior to India-Asia collision (Searle & Cox 1999). As in Oman they could be related to the youngest stage of the ophiolite obduction event prior to continental collision. In the Himalaya there is good evidence that slab break-off immediately followed peak UHP metamorphism at ~55-46 Ma. Early Eocene slab break-off is required in order to exhume the UHP rocks back up the subduction zone. The UHP eclogites reached lower crust levels by ~46-45 Ma and then became entrained in the regional Himalayan kyanite-sillimanite grade rocks (Treloar *et al.*, 2003; Searle *et al.*, 2007). After ~46 Ma Indian lower crust decoupled from the deforming upper crust and underthrust the southern margin of Asia (Guillot *et al.*, 2003; Searle 2015).

### **Crustal thickening and metamorphism of the Himalaya**

Although there is evidence in the Tethyan Himalaya of Ladakh-Zaskar for a pre-Paleocene phase of folding, thrusting and crustal thickening (Searle 1986; Searle *et al.*, 1997; Searle & Treloar, 2010), most of the crustal thickening most likely occurred post-India-Asia collision. Crustal thickening along the Tethyan Himalaya was certainly underway by 44 Ma (Searle *et al.*, 2007; Aikman *et al.*, 2008) and regional Barrovian metamorphism occurred across the Greater Himalaya and its northern extension exposed along the North Himalayan domes. Crustal thickening by folding and thrusting led to burial of the Tethyan rocks to ~10 kbar and kyanite-grade metamorphism with U-Pb monazite ages ranging between ~39 – 29 Ma (Walker *et al.*, 1999; Godin *et al.*, 2001; Cottle *et al.*, 2009). Decompression led to widespread sillimanite + muscovite and sillimanite + K-feldspar metamorphism and migmatization accompanying decompression melting to form the Himalayan leucogranites. Ages of migmatitic melts and leucogranites peaked during the period ~24-11 Ma. This was the timing of Channel flow, the ductile southward extrusion of a partially molten layer of middle crust, bounded by the Main Central Thrust (MCT) ductile shear zone below and the South Tibetan Detachment (STD) ductile shear zone above (Grujic *et al.*, 2002; Searle *et al.*, 1992, 2003, 2010; Jessup *et al.*, 2006; Cottle *et al.*, 2007). The southward extrusion of the GHS is bounded by the right way-up isograds beneath the STD above and the inverted isograds above the MCT below. Searle & Rex (1989) and Searle *et al.* (2007) first demonstrated by mapping in eastern Kashmir and western Zaskar that these two sequences



could be linked and thus demonstrated southward extrusion or channel flow of the GHS bounded by the MCT and STD shear zones.

Clearly the U-Pb monazite ages of kyanite- and silimanite-grade gneisses and migmatites along the GHS must be post-India-Asia collision. The fact that these peak metamorphic ages are as old as early or middle Eocene show that the young estimates of India – Asia collision, ~34 – 20 Ma, or ‘hard collision’ (Wang *et al.*, 2002; Aitchison *et al.*, 2007; van Hinsbergen *et al.*, 2011, 2012) cannot be correct.

## **Tectonic Model**

A simplified tectonic model is presented in **Figure 8** which satisfies all the field structural, stratigraphic, and geochronological evidence outlined above. During the middle Jurassic the Indian passive margin comprised the stable Permian-Jurassic shelf carbonates passing laterally outboard to the deep-water Lamayuru and Karamba complexes. The lower unit of the Spong tang ophiolite was generated along a mid-ocean ridge during this time (Fig. 8a). During the Turonian-Coniacian (Late Cretaceous), subduction initiation resulted in a NE-dipping intra-oceanic subduction zone above which the Spong Arc volcanic unit was erupted on top of the main Spontang ophiolite lower unit (Fig. 8b). By this time a second NE-dipping subduction zone was already present beneath the long-lived Kohistan-Dras island arc. A third subduction zone must also have been present along the northern margin of Neo-Tethys in order to generate the Ladakh-Gangdese I-type granite batholith along the southern margin of Asia.

Immediately following Late Cretaceous generation of the Spong Arc, obduction of the whole ophiolite complex occurred spanning the Coniacian to Maastrichtian – Danian (~88-64 Ma) (Fig. 8c). This time period for emplacement of the Spong tang and underlying thrust sheets (Photang, Lamayuru) onto a previously stable passive margin (Corfield *et al.*, 1999, 2001; ~24 m.y.) is similar in length to the emplacement of the Oman ophiolite (Searle & Cox, 1999). It is clear from field evidence along the Zaskar gorge that a major period of crustal shortening, folding and SW-vergent thrusting accompanied this obduction event (Fig. 4). Following obduction of the Spontang and underlying thrust sheets, a period of passive shallow marine sedimentation occurred during the Palaeocene – Ypresian (Lower Eocene) from ~64-50 Ma. At deeper structural levels subduction of the thinned continental crust along the northern margin of India to ~>100 km in the subduction zone occurred by slab pull during

the latest stage of the obduction process and the earliest stage of the continental collision phase. This led to UHP eclogite facies metamorphism of the Kaghan (Pakistan) and Tso Moriri (Ladakh) eclogites between ~55-47 Ma. Slab breakoff led to the return flow of the subducted UHP material towards the surface.

Following final closure of Neo-Tethys at 50.5 Ma crustal thickening was intense, resulting in spectacular folds and thrusts along the northern Tethys Himalaya (Searle, 1986; Corfield & Searle, 2000). Following deposition of the Palaeocene – Early Eocene fossiliferous limestones unconformably on the shelf carbonates and allochthonous Spontang ophiolite, a renewed period of SW-directed thrusting led to re-thrusting of the previously stacked pile with the Spontang ophiolite emplaced over Palaeocene-Early Eocene shallow marine limestones (Fig. 8d). At deeper structural levels this crustal thickening led to kyanite- and sillimanite-grade metamorphism along the GHS during the Late Eocene to Early Miocene (~44 – ~15 Ma).

## Conclusions

Stratigraphic, palaeontological, and isotopic geochronological data from the western Himalaya is shown on the Time Chart (Fig. 2) and the Tectonic Model (Fig. 8). These data support the following conclusions:-

- (1) There is evidence for three NNE-dipping subduction zones in NeoTethys during the Late Cretaceous – Palaeogene, one beneath the Coniacian (Late Cretaceous) Spong arc built on top of the Jurassic Spontang ophiolite, one beneath the Late Cretaceous – Palaeogene Dras-Kohistan island arc, and one beneath the Asian plate margin (Late Jurassic – Eocene Ladakh – Gangdese batholith).
- (2) Subduction initiation during the Coniacian ( $88 \pm 5$  Ma) led to eruption of andesites and volcanic arc rocks above the Spontang ophiolite (Corfield *et al.*, 2001; Pedersen *et al.*, 2001) and initiated southward obduction of the ophiolite and underlying thrust sheets (Photang, Lamayuru complex) onto the passive continental margin of India (Searle 1986; Searle *et al.*, 1988, 1997; Corfield & Searle 1999; Corfield *et al.*, 1999, 2001). Obduction, by definition, has to be pre-continental collision, and was not synchronous with collision (Garzanti & Hu 2015; Hu *et al.*, 2016).
- (3) There is evidence for a phase of intense folding, thrusting and thickening in Indian plate Mesozoic shelf carbonates in the Late Cretaceous, associated with obduction of the Spontang

ophiolite and Photang thrust sheets onto the previously passive continental margin of India (Fig. 4; Searle 1986; Searle *et al.*, 1988, 1997; Searle & Treloar, 2010).

(4) There was no 'Greater Indian basin' separating the northern Tethyan and Greater Himalaya from India (van Hinsbergen *et al.*, 2011, 2012). The GHS is entirely continental Cenozoic metamorphic rocks, migmatites and Miocene leucogranites, with no suture zone rocks anywhere along its >2000 km strike length. The MCT zone is a ductile shear zone and thrust fault, not a suture zone. There is no such process as a 'soft collision' as claimed by these authors. There is simply an ophiolite emplacement - obduction event (Late Cretaceous – Palaeogene) and an India-Asia continental collision event.

(5) The palaeomagnetic discrepancy of shortening estimates from the Tethyan Himalaya and Lesser Himalaya (van Hinsbergen *et al.*, 2011) can be explained by crustal shortening within the Indian plate rocks of the Himalaya. The discrepancy between Indian and Asian crustal shortening can be explained by large-scale underthrusting of Indian lower crust beneath the Tibetan plateau. This also explains the general lack of Cenozoic deformation across the plateau which was uplifted by 'passive' underthrusting of Indian lower crust (Argand 1927; Searle *et al.*, 2011; Searle 2015).

(6) There is no evidence for diachroneity of collision along the Himalaya. The timing of youngest marine sediments and fossils along the suture zone is Early Eocene (50.5 Ma), corresponding to Planktonic foraminifera zone P7-8, in NW Pakistan (Beck *et al.*, 1995), Ladakh (Garzanti & van Haver 1988; Green *et al.*, 2008; Henderson *et al.*, 2010) and south Tibet (Rowley, 1996, 1998; Zhu *et al.*, 2005; Najman *et al.*, 2010).

(7) The precise timing of India – Asia collision can vary from the first meeting of Indian plate crust with Asian crust to the final closure of the Tethyan seaway that separated the two. This may vary by ~10-20 million years. If the proximal oceanic sediments of the Lamayuru complex were underlain by thinned stretched continental crust then the first collision of Indian and Asian crust could have been several million years prior to the final closure of Tethys. Stratigraphic reconstruction of the Indian shelf margin and suture zone reveals distinct facies variations with time during the closure of NeoTethys (Green *et al.*, 2008, this volume).

(8) A post-Eocene phase of folding is apparent from structures within the northern Tethyan Himalaya where the Spontang ophiolite and Lamayuru thrust sheets has been re-thrust southwest over Eocene shallow-marine limestones. This relationship does not represent the original obduction structure but a later post-collision re-thrusting event. This same post-Eocene event resulted in intense folding, thrusting and crustal shortening across the northern

Zaskar range with the SW-verging out-of-sequence Photoksar thrust and the NE-vergent Main Zaskar backthrust (= Great Counter Thrust) forming a giant ‘pop-up’ structure (Corfield & Searle, 2000).

(9) The Indus molasse basin was formed after the India-Asia collision by stitching of the two continental plates. A rapidly subsiding long, narrow basin followed the line of the Indus and Yalung Tsangpo suture zone. The youngest marine excursion dated by foraminifera at 50.5 Ma (Green *et al.*, 2008) probably occurred after meeting of Indian and Asian crust. From 50 Ma onwards the ISZ was elevated above sea-level and the crust was thickened during the collision event. The Indus basin was filled with continental lacustrine, fluvial and flash flood sediments concomitant with the rise of the Ladakh and Gangdese ranges to the north.

(10) The UHP eclogites along the leading margin of the subducting Indian plate at Kaghan, Pakistan, and Tso Moriri, Ladakh are not indicative of the timing of India-Asia collision. They could have been related to final phase of ophiolite obduction, or to the initial stage of continent-continent collision. The timing of peak metamorphism in the GHS kyanite- and sillimanite gneisses (from ~44 Ma) clearly has to be younger than India-Asia collision. The timing of final calc-alkaline volcanism and magmatism along the Trans-himalayan batholith (southern margin of Asia) is likely concomitant with India-Asia collision and ending of oceanic subduction beneath the Asian margin. Younger Miocene intrusions in the Gangdese batholith and further north across the Lhasa and Qiangtang blocks of Tibet are adakitic in composition and not related to subduction I-type magmatism above a descending oceanic slab. The adakites are related more to crustal melting of garnet-bearing amphibolite or eclogite in a thickened crust (Chung *et al.*, 2005).

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## Figure Captions

**Fig. 1.** Geological map of the Himalaya, showing the main geological units and the distribution of ophiolites along the Indus Tsangpo suture zone.

**Fig. 2.** Late Cretaceous – Cenozoic time chart for the Himalaya showing stratigraphic and geological time constraints across the Himalaya, Indus suture zone and Asian margin. The tectonic interpretation is given in the right hand column.

**Fig. 3.** (a) View looking east along the Indus suture zone in Ladakh, near Khalsi. I.M. – Indus molasse; S- serpentinised peridotites. Sediments on right are part of the Lamayuru deep-water facies, affected by North-vergent backfolding and back-thrusting. (b) The Nummulitic limestones (50.5 Ma) overlying the earliest molasse desposits (Chogdo Fm.) and underlying the continental Nurla Fm. red-beds and fluvial- lacustrine deposits; Zaskar river gorge. (c) The precise contact between marine Nummulitic limestones and the overlying continental molasse sediments, Zaskar river gorge. (d) Conglomerates of the Hemis Fm. showing mainly granite and andesite clasts derived from the north, but also red chert and greenish serpentinite boulders derived from the Indus suture zone. (e) North-vergent backfolding affecting the Hemis conglomerates, Indus suture zone. (d) Nurla Fm. continental molasse sediments unconformably overlying granites of the Ladakh batholith, Chumatang; eastern Ladakh.

**Fig. 4.** Photograph of the west flank of the Zaskar river gorge taken from the Nerak-la looking west. The big cliffs are composed of Mesozoic shelf carbonates showing extensive tight-isoclinal SW-facing folds and SW-vergent thrusts. Allochthonous Lamayuru complex (blue) and Spongtag ophiolite (snow peaks in background) overlie the shelf and underlie gently folded Palaeocene-Eocene shallow marine carbonates.

**Fig. 5.** Paleo-latitude evolution of India and Asia, after van Hinsbergen *et al.* (2012). Paleomagnetic poles for the Tibetan Himalaya and cratonic India at 118 Ma (A), 68 Ma (B) and 59 Ma (C). D shows paleo-latitudes of a reference site (29°N 88°E) in the ISZ showing the convergence of Greater India with respect to stable Asia during the Cretaceous – Eocene. See van Hinsbergen *et al.* (2012) for details.

**Fig. 6.** Models for the restoration of India and the northward drift of the Indian plate. Model A shows the single Indian contiguous plate with a wide continental margin incorporating Lesser, Greater and Tethyan Himalaya as one plate, and India-Asia collision at 50 Ma. Model B, after van Hinsbergen *et al.* (2012) shows a separated Tibetan Himalaya microplate (THS + GHS) with an intervening ocean, the so-called ‘Greater Himalayam basin’ separating this from the main Indian plate. This model involves a ‘soft collision’ at 50 Ma and a ‘hard collision’ at 25-20 Ma.

**Fig. 7.** Restoration of the Indus Group molasse basin along the Indus suture zone showing timing constraints from biostratigraphy (Green *et al.*, 2008), detrital zircon ages (Clift *et al.* 2002b) and U-Pb zircon geochronology from Ladakh granites (St-Onge *et al.*, 2010).

**Fig. 8.** Model for the tectonic evolution of the Western Himalaya. (a) Jurassic ocean floor spreading resulted in formation of the lower part of the Spongtag ophiolite crust. (b) Late

Cretaceous subduction initiation resulted in the formation of the Dras-Kohistan island arc. A long-lived subduction zone also existed from Jurassic to Early Eocene time along the southern margin of Asia resulting in the Ladakh – Gangdese I-type granite batholith and associated andesite – ignimbrite volcanics (not shown, off the page to north). (c) Late Cretaceous – Paleocene deformation is related to obduction of the Spontang ophiolite onto the Indian continental margin, and the Dras island arc in the ISZ. (d) Mid- to Late Cenozoic crustal shortening along the Indian plate resulted in intense folding and thrusting in the Zaskar shelf carbonates, re-thrusting of the Spontang ophiolite and underlying thrust sheets, and the ginat ‘pop-up’ structure along northern Zaskar resulting in NE-directed backthrusting and folding along the ISZ.

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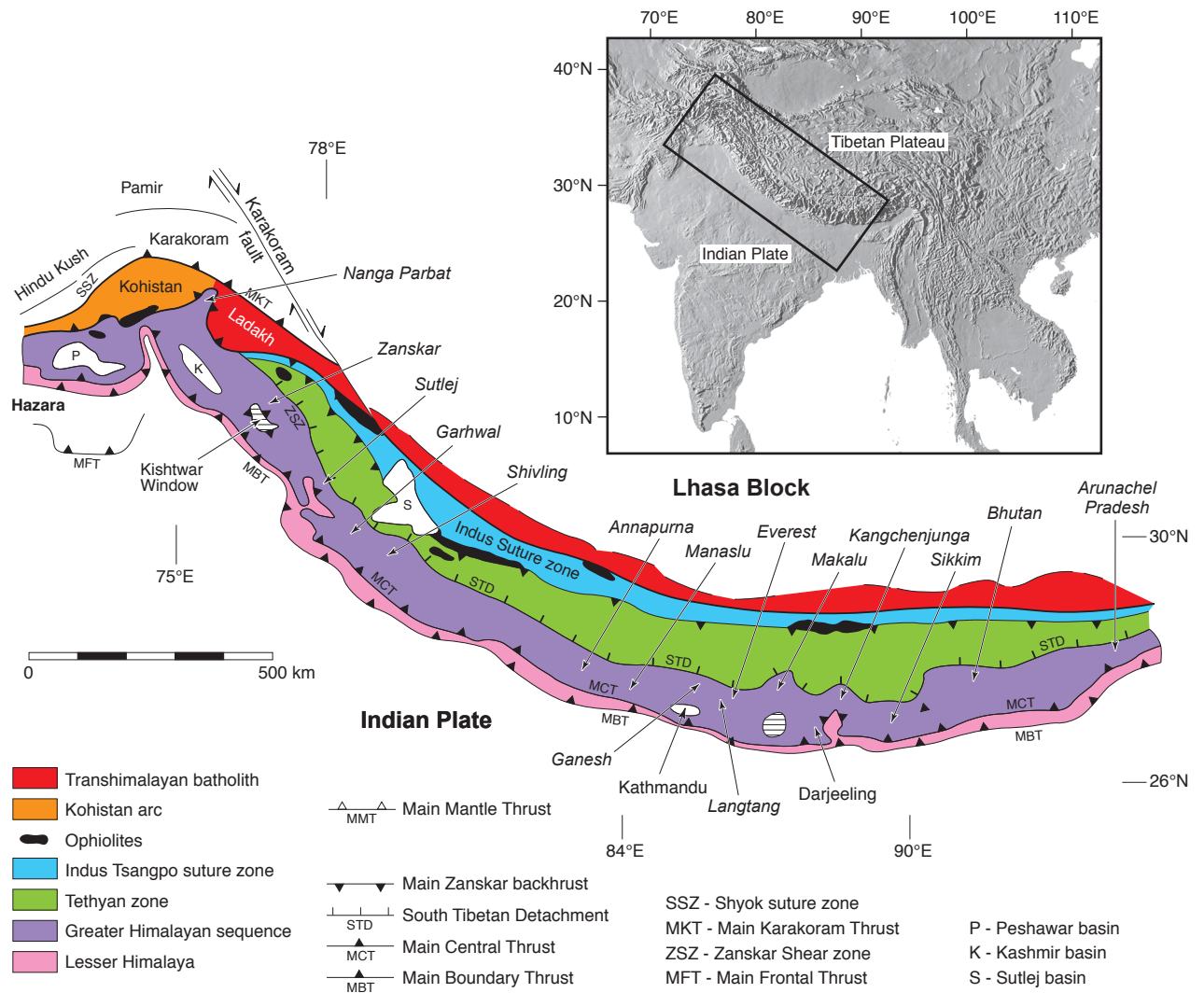


figure 2

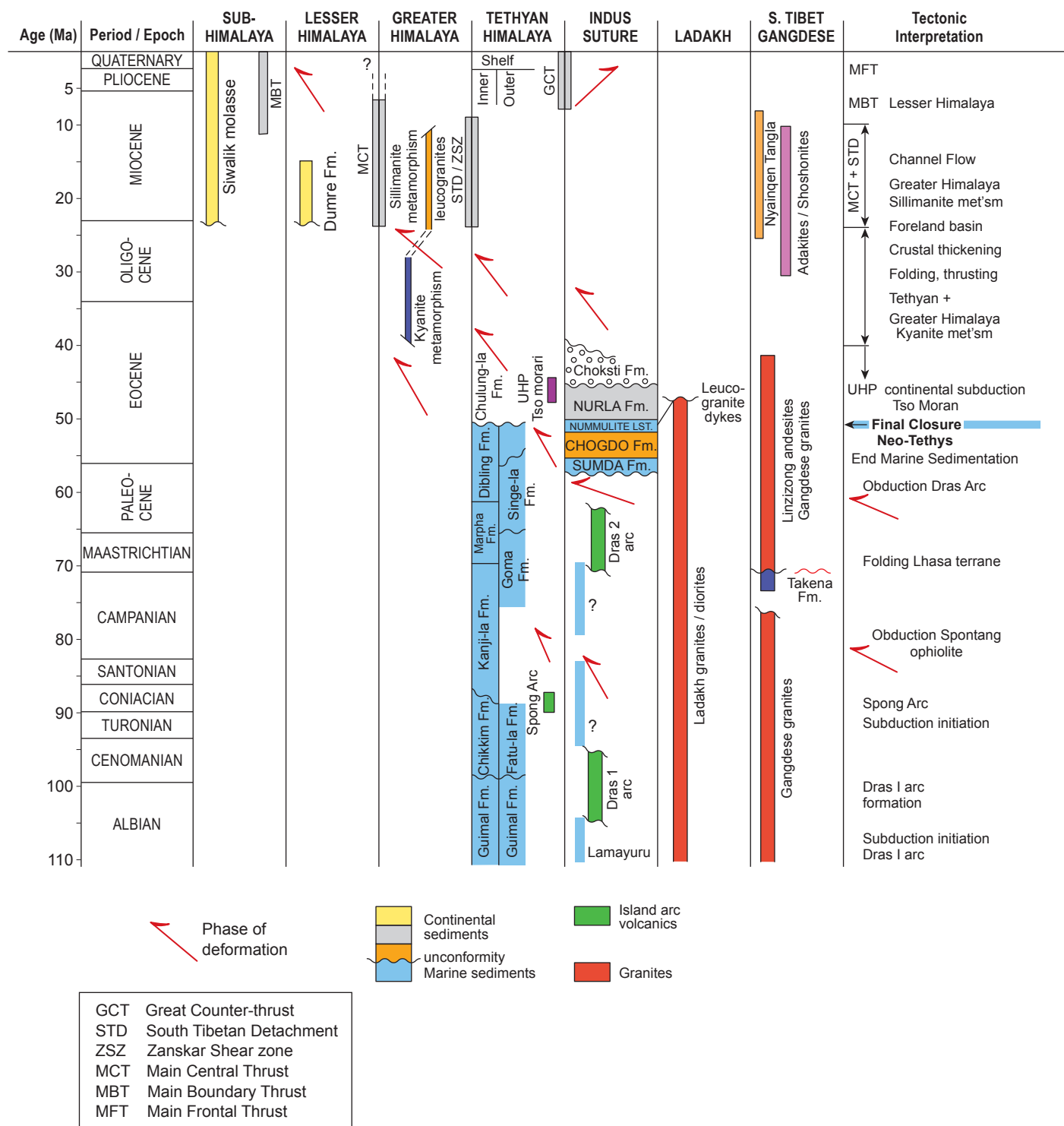
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figure 4

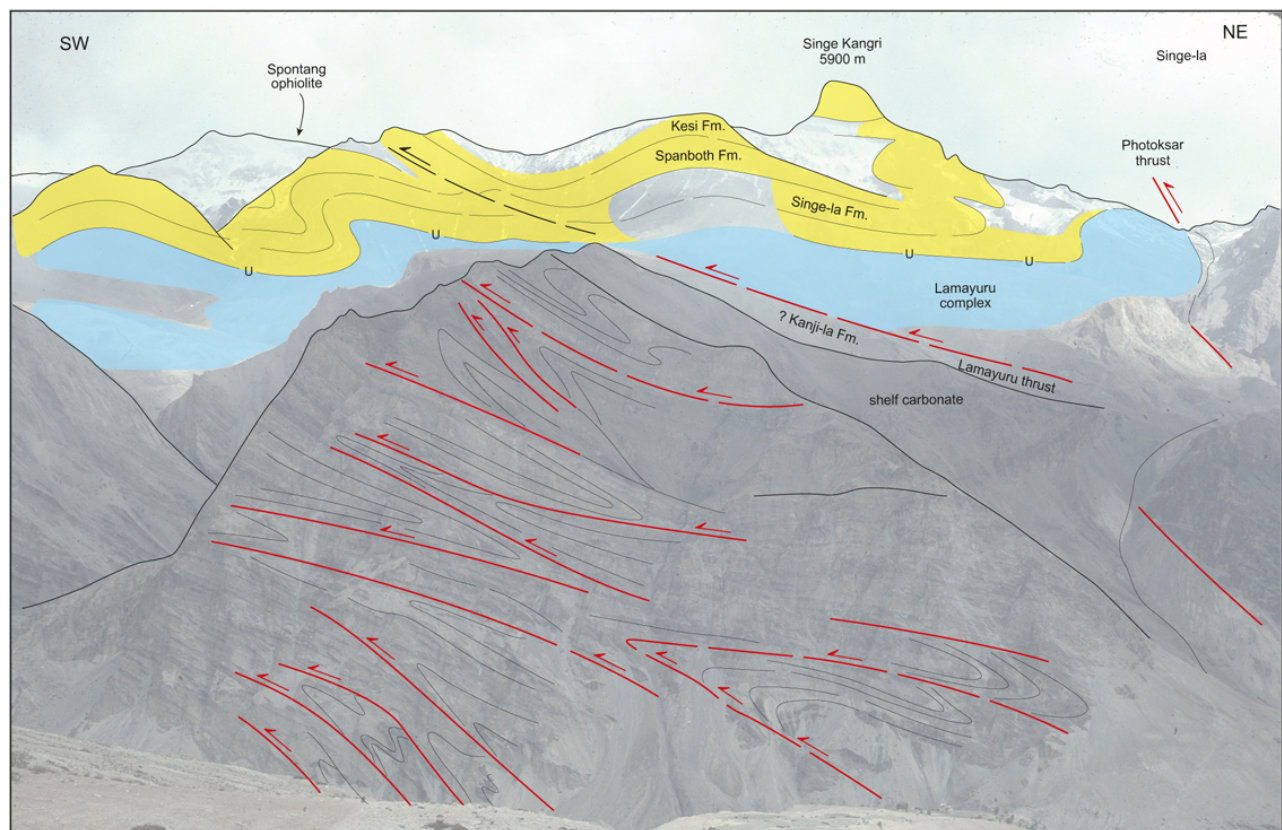
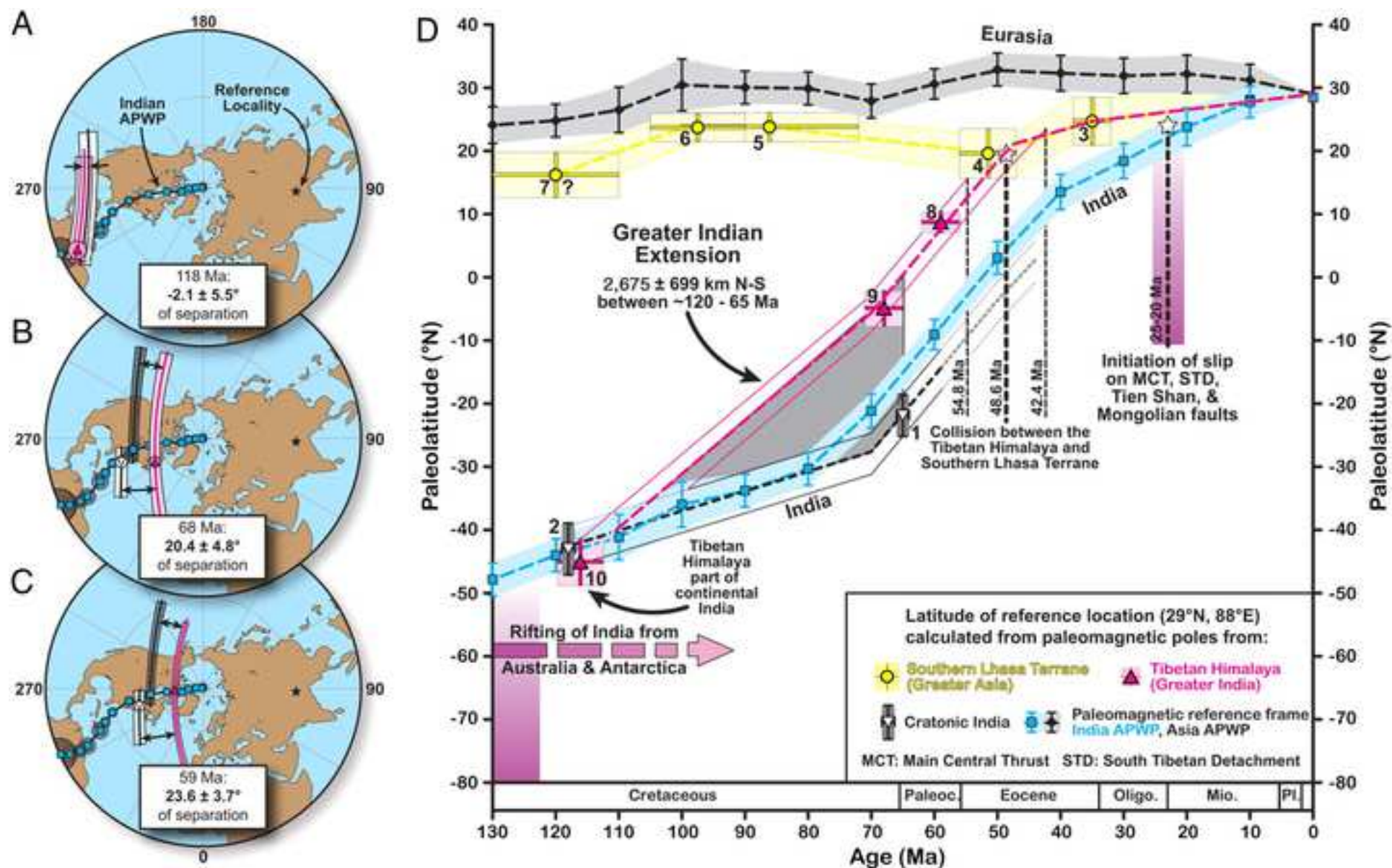
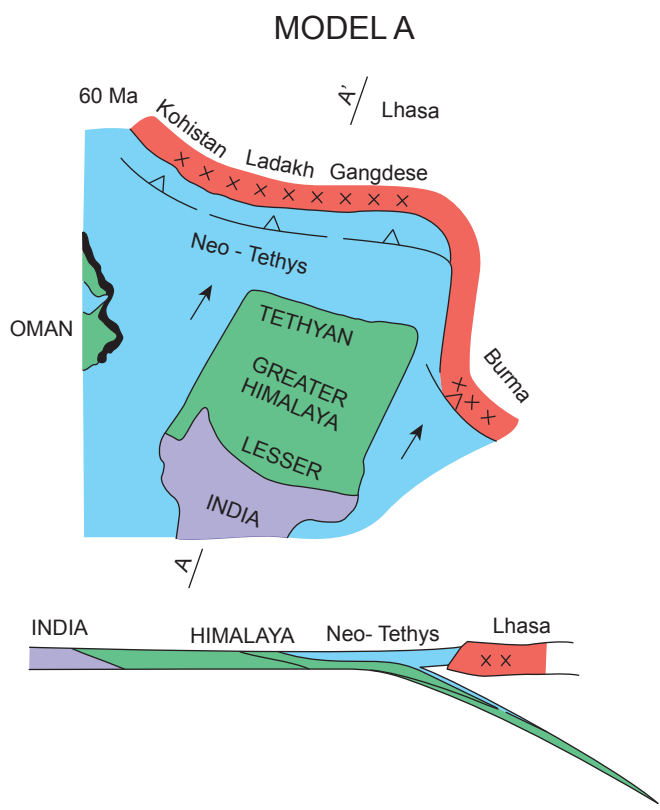




figure 5

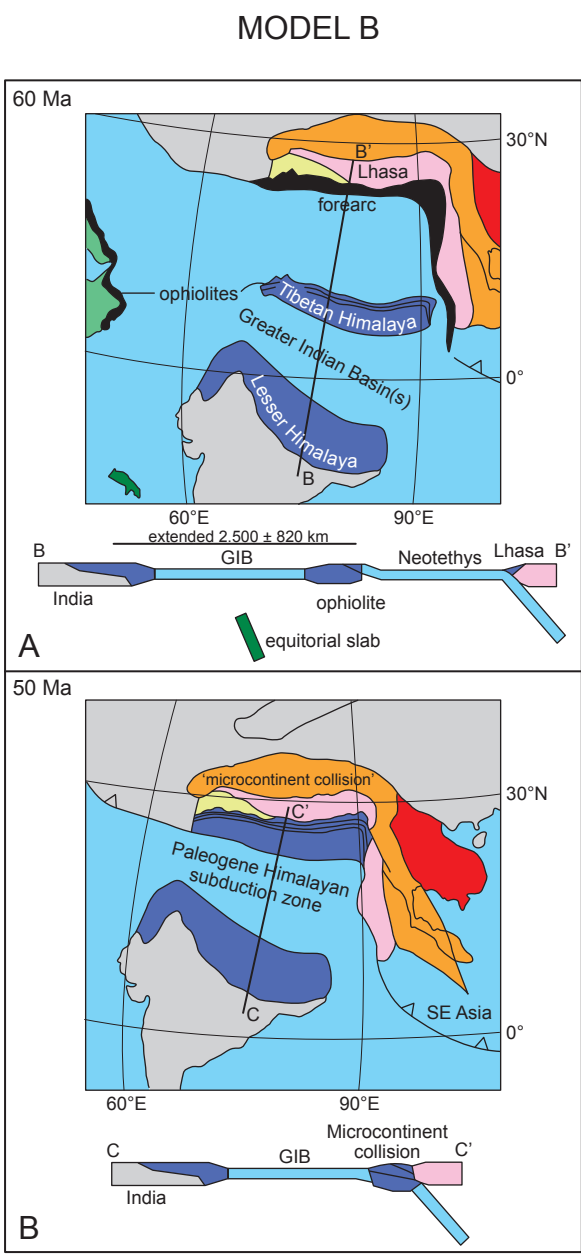
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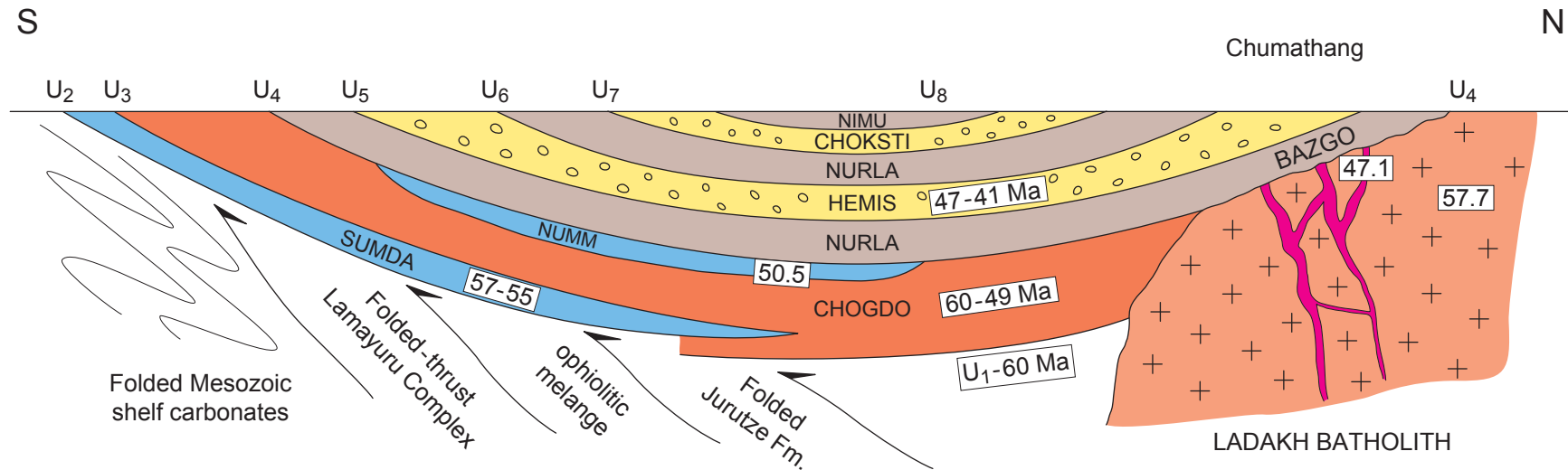


MODEL A  
One contiguous Indian plate  
India - Asia collision ~50 Ma

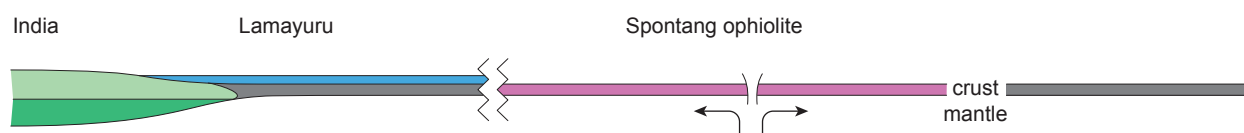
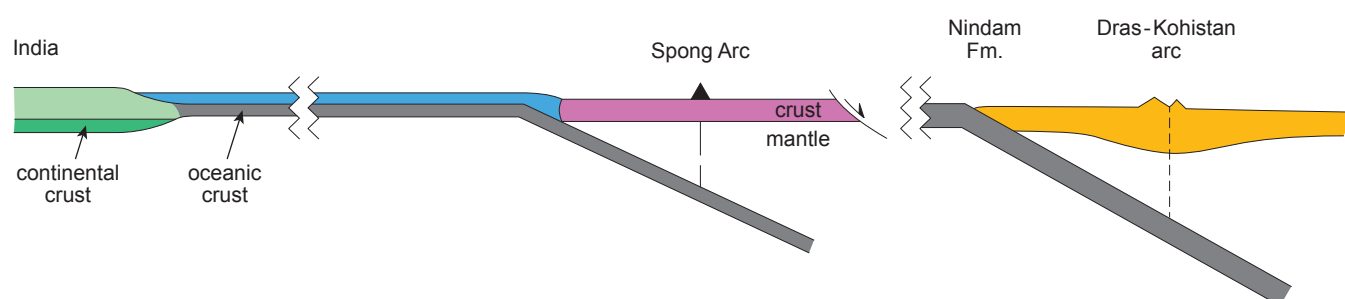
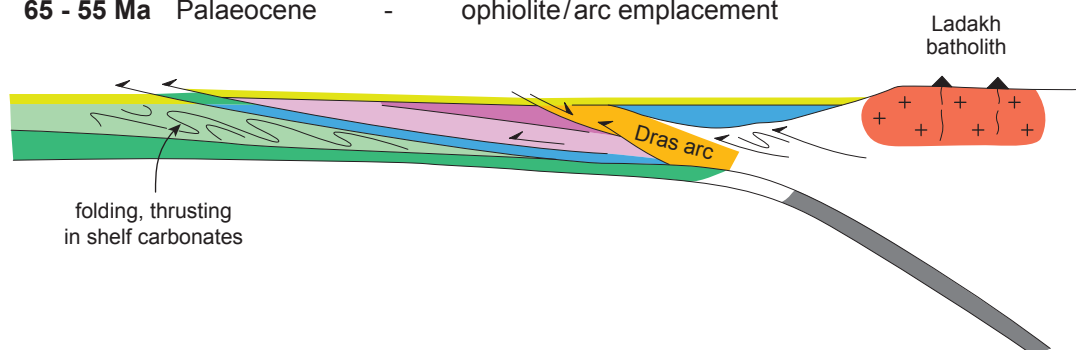
MODEL B  
Tibetan Himalaya plate  
Greater Indian basin  
Indian plate  
'Soft' collision ~ 50 Ma  
'Hard' collision ~ 25-20 Ma



## Restoration of the Indus Group Molasse basin prior to Late Miocene-Pliocene backthrusting



- U<sub>8</sub> ~2 Ma. Quaternary alluvial terraces overlying folded Nimu Fm; Zaskar River.
- U<sub>7</sub> ~ ? Base of Nimu Fm. Ending of massive conglomerates; return to fine-grained sandstones, mudstones, siltstones.
- U<sub>6</sub> ~41 Ma. Return to Nurla facies floodplain muds, silts and lower-energy rivers.
- U<sub>5</sub> ~47 Ma. Base of Hemis - Choksti conglomerates, high-energy fluvial channels derived from north; uplift Ladakh batholith. ? Initiation of Indus River.
- U<sub>4</sub> 50.5 Ma. [Final marine transgression](#) (Nummultic limestones), followed by sub-aerial fluvial and floodplain deposition (Nurla Fm.).
- U<sub>3</sub> ~54 Ma. Marine to continental transition (top Sumda Fm.).
- U<sub>2</sub> ~57 Ma. [Neo-autochthonous marine transgression](#)
- U<sub>1</sub> 60 Ma. Base of Chogdo Fm purple-red sandstones, siltstones, mudstones (60-49 Ma detrital zircons). Unconformity truncates folded and thrust Lamayuru, Nindam, Jurutze, Tar Fms. End of ophiolite-obduction related deformation.
- Late Cretaceous-Palaeocene thrusts, folds ---

**177 Ma** Lower Middle Jurassic - NeoTethyan Mid-ocean ridge**88 Ma** Turonian - Coniacian - subduction initiation**65 - 55 Ma** Palaeocene - ophiolite/arc emplacement**35 - 30 Ma** Oligocene