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Processes of initial collision and suturing between India and Asia

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Abstract The initial collision between Indian and Asian continents marked the starting point for transformation of land-sea thermal contrast, uplift of the Tibet-Himalaya orogen, and climate change in Asia. In this paper, we review the published literatures from the past 30 years in order to draw consensus on the processes of initial collision and suturing that took place between the Indian and Asian plates. Following a comparison of the different methods that have been used to constrain the initial timing of collision, we propose that the tectono-sedimentary response in the peripheral foreland basin provides the most sensitive index of this event, and that paleomagnetism presents independent evidence as an alternative, reliable, and quantitative research method. In contrast to previous studies that have suggested collision between India and Asia started in Pakistan between ca. 55 Ma and 50 Ma and progressively closed eastwards, more recent researches have indicated that this major event first occurred in the center of the Yarlung Tsangpo suture zone (YTSZ) between ca. 65 Ma and 63 Ma and then spreading both eastwards and westwards. While continental collision is a complicated process, including the processes of deformation, sedimentation, metamorphism, and magmatism, different researchers have tended to define the nature of this event based on their own understanding, an intuitive bias that has meant that its initial timing has remained controversial for decades. Here, we recommend the use of reconstructions of each geological event within the orogenic evolution sequence as this will allow interpretation of collision timing on the basis of multidisciplinary methods.

Keywords Tibetan Plateau, Indian Plate, Asian Plate, Initial collision, Suturing processes

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1. Introduction

Collision between India and Asia was perhaps the most spectacular geological event to occur over the last 500 million years (Yin and Harrison, 2000). However, although there are numerous records of ocean closures and continental collisions in geological history, the connection between India and Asia has attracted a great deal of attention because of the resultant formation of the vast and high-altitude Tibetan Plateau. The ongoing process of collision also affected Tibet as well as central and southeast Asia (Tapponnier et al., 1982). As a result, collision between India and Asia as the resultant formation of the Tibetan Plateau likely includes a number of unique processes of both continental collision and mechanisms of intracontinental deformation. The initial collision between India and Asia also provides important data to studies of continental lithospheric deformation, environmental change, and paleoaltitude reconstruction. Thus, this collision has significance to our understanding of plate tectonics, continental dynamics, and multilayer interactions.

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Generally, an initial continental collision is defined as the first contact following the complete consumption of oceanic lithosphere between two pieces of continental lithosphere. Thus, strictly speaking, continental collision is an ongoing process, initiated by the obduction of active continental margin and the loading of an accretionary prism onto a passive continental margin and formation of a foreland basin. Consequently, relic oceanic crust can be tectonically emplaced as an ophiolite, while the suture zone experiences deformation, magmatism, and metamorphism during orogeny (Ding et al., 2005). Continental collision is therefore not a simple and short-term process but rather an extended period of long-term evolution from soft collision to hard collision.

During the 1980s and 1990s, geoscientists first proposed that the Indian and Asian continents initially collided along western syntaxis ca. 55 Ma, then diachronously suturing eastwards (Tapponnier et al., 1981; Achache et al., 1984; Allégre et al., 1984; Besse et al., 1984; Patriat and Achache, 1984; Searle et al., 1987; Klootwijk et al., 1994; Beck et al., 1995; Rowley, 1996). However, more recent studies have led to the alternative suggestion that the collision between India and Asia first occurred in the central section of the YTSZ between ca. 65 Ma and 60 Ma, then progressing both eastwards and westwards (Ding and Zhong, 1999; Ding et al., 2001, 2003, 2005, 2016b; Chen et al., 2010; Cai et al., 2011; Yi et al., 2011; Zhang et al., 2012; DeCelles et al., 2014; Wu et al., 2014; Hu et al., 2015, 2016b). This second model, suggesting an earlier collision between India and Asia, predicts that: (1) large-scale continental subduction occurred within the Tibetan Plateau along main suture zones in order to accommodate additional shortening; (2) resultant large-scale continental subduction would have generated far-reaching deformation effects across central Asia, and; (3) post-collisional igneous rocks and mineral deposits would have formed as a result within continental subduction belts.

2. Methods to constrain the initial timing of collision

Collision between India and Asia has been defined independently by different workers in the context of specific research domains, generating a good deal of debate (Table 1). However, because continental collision is a complex process, involving a number of concomitant geological events, we suggest here that all available methods should be applied to constrain both the timing of this event and to reveal the sequence of changes that took place during the tectonic evolution of this major collisional orogeny (Ding et al., 2013).

Table 1 Summary of methods and conditions that have been applied to constrain the initial timing of collision between India and Asia

Dating method	Basic outline of event	Dating caveats	Timing of collision
High Pressure-Ultra High Pressure (HP-UHP) continental metamorphism	Continental margin is subducted to a depth of at least 100 km along the plate boundary under the drag of oceanic lithosphere, forming UP-UHP continental metamorphic rocks. As a result of interactions between deformation and buoyancy, these rocks were then exhumed to the surface. Thus, the age of prograde HP-UHP metamorphism, combined with corresponding depth and an estimate for subduction rate, can be used to calculate the initiation age of continental subduction.	During the process of subduction-exhumation, UP-UHP rocks were subject to decompression and cooling. Thus, it has proved difficult to obtain a complete *PTt* path. In addition, in the absence of a reliable thermobarometer for this region, it has also proved difficult to determine metamorphic conditions with accuracy.	Upper limit
Ophiolite obduction	A metamorphic sole is usually formed when ophiolites are obducted over subducting oceanic lithosphere. Thus, Ar-Ar ages from high-grade amphibolites within a metamorphic sole can be used to determine the age of the obduction event.	Obduction of ophiolites within a subduction zone usually occurs prior to continental collision. Thus, the metamorphic sole within the YTSZ has been dated to between 130 Ma and 120 Ma, significantly older than a Paleocene collision between India and Asia.	Lower limit
Cessation of marine sedimentation	Following continental collision, oceanic crust was completely subducted beneath the active margin while passive continental crust was uplifted as a result of compressive deformation. This caused a cessation of marine sedimentation.	The disappearance of oceanic lithosphere does not necessarily mean the end of oceanic conditions, as peripheral foreland basins often still preserve marine faces after a continental collision. In addition, because continental collisions usually occur at points, residual ocean basins can be retained along the flanks of sutures.	Upper limit
Molasse basin	Molasse basins contain thick and coarse clastic rocks and develop along flanks of collisional orogenies. The lower part of these basins normally comprise shallow marine sediments, transitioning upwards into continental deposits that contain coal interbeds.	Two kinds of molasse basins are known. Of these, one is deposited over the top of a foreland basin (i.e., ‘wedge-top’), a process which can be crucial for constraining a collision age, while the other such as Kailas Molasse is deposited onto the suture zone. Both these cases subduct and override plates while deposition usually takes place subsequent to continental collision.	Upper limit
Mid-ocean ridge spreading rate	Investigation of oceanic magnetic anomalies associated with a subducting plate have shown that a deceleration in spreading rate may be caused by continental collision.	Deceleration in spreading rate may have been caused by both continental collision and a change in the dynamics of the ocean ridge.	Unclear

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Dating method	Basic outline of event	Dating caveats	Timing of collision
Change in direction of plate motion	Durative collision is usually accompanied by plate rotation; thus, the timing of rotation can be used to constrain the timing of continental collision.	Similar to plate velocity variations, changes in plate movement direction do not necessary require continental collision. For example, the Hawaii Ridge experienced a change in movement direction without continental collision.	Unclear
Strike slip faults	In an oblique collision zone, large-scale strike slip faults provide the dominant mechanism for deformation. Examples include the Red River-Ailaoshan and Sagaing strike slip faults in the eastern TP.	An initial collision usually leads to crustal thickening. However, because thickened crust cannot absorb compressive stresses, strike slip faults will develop. Thus, the initiation of these faults must follow continental collision.	Upper limit
Crustal deformation	Convergence between continents usually leads to compression and the thickening of continental crust. In a passive margin, this deformation usually takes the form of a foreland thrust-fold belt.	Not all the thickening of continental crust will be the result of this process; collision between a continent and an intro-oceanic arc can also lead to thickening.	Upper limit
Apparent polar wander path (APWP)	The timing of collisions can be constrained by defining when apparent polar wander paths and paleolatitudes from continental margins start to overlap. In practice, however, post-collisional upper-crustal shortening within both Asia and the Himalayas limits our ability to predict paleo-latitudes from APWPs, and thus robust paleomagnetic poles must be obtained directly for both the Lhasa Block and the Tethys Himalayas in order to constrain collision chronology.	This method is applicable to rigid blocks where there is less crustal shortening and no continental subduction. In these cases, stratigraphy can be precisely dated, and the inclination of shallowing can be evaluated alongside the effects of geomagnetic secular variation.	Initial collision
Peripheral foreland basin	Loading of an obducted arc and suture-zone rocks over a passive margin can lead to flexure and the formation of a peripheral foreland basin over a subducted plate. Because detritus from the active margin will be transported and deposited in the foreland basin, this change in provenance can be used to constrain the collision between continents.	Continental collision can lead to sediments on a passive plate being subducted beneath the active margin, resulting in the disappearance of earlier strata. In addition, migration of a foreland basin towards a craton can lead to the formation of foredeeps as a thrust-fold belt propagates. Thus, recognition of an earlier foreland basin record closer to a suture zone will make it easier to constrain the initial timing of continental collision.	Initial collision
Leucogranite	Leucogranite is well-exposed in thickening crust, for example in the Himalayan orogen. The appearance of contemporary leucogranite can be used to constrain the age of crustal thickening.	Because leucogranite can be exposed in both foreland thrust-fold belts and in thickening volcanic arcs, it could have developed before or after a collision.	Upper limit and/or lower limit
Magmatic transition from oceanic to continental subduction	Aqueous fluids released from a subducted oceanic slab will result in melting of the overlying mantle wedge. The magma produced by continental subduction will therefore be contaminated by continental crust, leading to generation of a characteristic shoshonite series. This transition in magma source between dehydration of the oceanic slab to melting of the continental crust indicates disappearance of the oceanic lithosphere and the initiation of continental crust subduction.	The cessation of volcanic arc magmatism usually lags behind an initial continental collision. Thus, the mantle wedge related to subduction of the oceanic lithosphere can still generate rock assemblages associated with a volcanic arc after continental collision. This magmatic method should therefore be used in combination with consideration of rock type, tectonic setting, provenance, and age.	Upper limit
Faunal migration	Subsequent to continental collision, floras and faunas on separated continental landmasses will have experienced distinct evolutionary processes. Following contact between continental margins, however, lineages will start to interact and be subject to the same evolutionary pressures. Faunal migration therefore provides an independent test of initial continental collision.	Unclear geographic distribution patterns as well as issues in assessing depositional ages affect the reliability of this method.	Upper limit
Numerical and physical simulations	Numerical and physical simulations can reveal the slow processes that underlie continental collisions. Physical simulations depend on the selection of appropriate material to build models, while numerical simulations are based on equations that express rock deformation and software to reproduce this process. If an appropriate strain rate can be input to achieve expected deformation, then the required time output will be equal to the age of collision.	Both physical and numerical simulations require the establishment of geometric models, selection of appropriate constitutive equations, similar materials, and boundary conditions. A model can then be modified on the basis of simulation results and actual deformation until agreement with the actual geological situation is reached. Thus, well-developed simulations can provide valuable predictions for the processes and mechanisms of continental collision.	Unclear

3. History of research on the initial timing of Indian and Asian collision

The initial timing of the collision between India and Asia has been studied for more than 30 years and a great deal of evidence has been identified within the suture zone and associated blocks (Figures 1 and 2). The first study that constrained the initial timing of India-Asia collision was carried out in Pakistan and northwest India. In Waziristan-Kurram area, Pakistan, Beck et al. (1995) proposed the timing of India-Asia collision to be 65–55 Ma relying on the obduction of Indus suture-zone rocks and trench strata over the Indian passive continental margin. Alternative, this tectonic relationship could also be a result of collision between oceanic arc and the Indian continent (Aitchison et al., 2007a). To the east, in the Balakot region, the oldest sequence of lower Eocene (ca. 50 Ma to 55 Ma) continental Balakot Formation is interpreted as part of a foreland basin which implies that continental collision took place around this time (Bossart and Ottiger, 1989). However, revised mapping in this area has also shown that a fossil-rich limestone layer within the Balakot Formation occurs as a fault-bounded slice rather than in a depositional relationship (Najman et al., 2001). In addition, ages from detrital micas within the Balakot Formation are mainly clustered within a range between 40 Ma and 36 Ma, which suggests that initial collision took place ca. 40 Ma in the northwestern Himalayas (Najman et al., 2001). More recent investigations in the same area (Ding et al., 2016b) have also identified a tuff layer in the Balakot Formation that yields a zircon U-Pb age ca. 53 Ma; thus, on the basis of this detrital zircon age as well as an abrupt change in provenance between the Indian and Asian plates, the study constrained initial collision to between ca. 56 Ma and 55 Ma. In addition, provenance analysis of the Lower Indus basin also indicates that collision between India and Asia took place ca. 50 Ma (Zhuang et al., 2015).

In the Zanskar area, the Chulung La Formation marks the transition from marine-to-continental sedimentation between 52 Ma and 50.7 Ma, coeval with obduction of the Spontang and Ladakh arc over the Indian continent (Garzanti et al., 1987; Searle et al., 1987; Gaetani and Garzanti, 1991; Rowley, 1996). An additional unit of interest in this context is the Indus molasse that overlaps both the Indian and Asian continents and can therefore be used to constrain the timing of collision (Clift et al., 2002; Wu et al., 2007). Thus, based on the presence of the fossil *Nummulites*, the limestone that makes up the lower portion of the Indus molasse can be dated to between 50.8 Ma and 49.4 Ma, implying that collision occurred prior to this time. However, mapping and stratigraphic work by Henderson et al. (2011) has also suggested that the Indus Molasse has a faulted-contacted rather than unconformity-based relationship with the underlying Indian continent

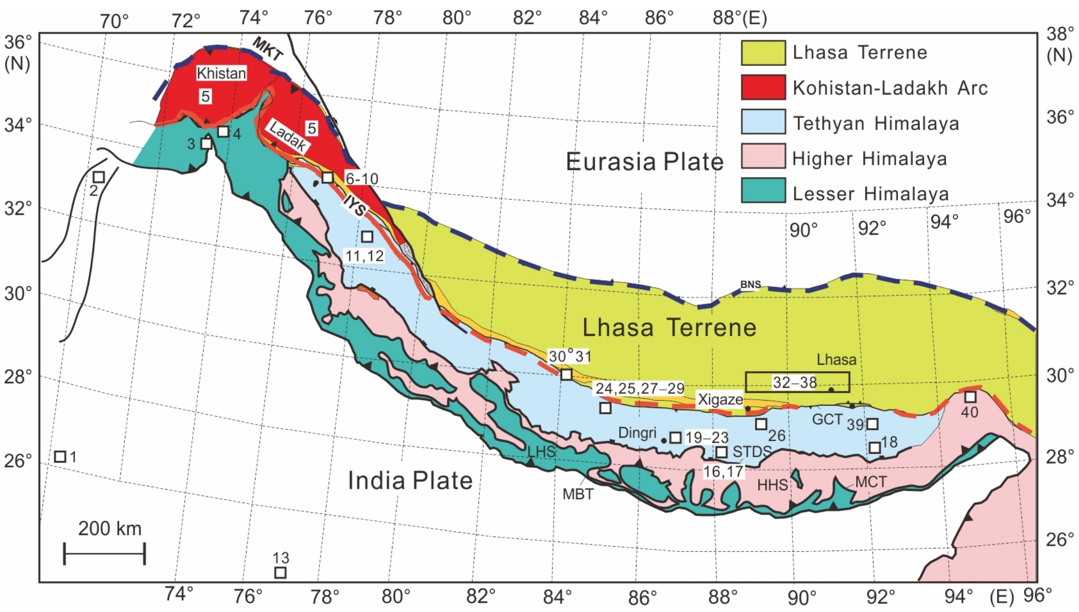

Figure 1 Geological map to show the locations discussed in this paper relevant to dating the timing of collision between India and Asia. Abbreviations (not in the text): BNS, Bangong-Nujiang suture; GCT, great counter thrust; IYS, Indus-Yalung Tsangpo suture; MBT, main boundary thrust; MKT, main Karakorum fault; (1) Zhuang et al. (2015); (2) Beck et al. (1995); (3) Ding et al. (2016a); (4) Wilke et al. (2010); (5) Bouilhol et al. (2013); (6) Garzanti et al. (1987); (7) Clift et al. (2002); (8) Wu et al. (2007); (9) Leech et al. (2005); (10) Fuchs and Willems (1990); (11) Batra (1989); (12) Najman (2005); (13) Jaeger et al. (1989); (14) Patriat and Achache (1984); (15) Klootwijk et al. (1992); (16) Yi et al. (2011); (17) Achache et al. (1984); (18) Yang et al. (2015a); (19) Hu et al. (2012); (20) Zhang et al. (2012); (21) Zhu et al. (2005); (22) Najman et al. (2010); (23) Rowley (1998); (24) DeCelles et al. (2014); (25) Ding et al. (2005); (26) Cai et al. (2011); (27) Hu et al. (2015); (28) Wu et al. (2014); (29) Wang et al. (2011); (30) Hu et al. (2016b); (31) Meng et al. (2012); (32) Chen et al. (2010); (33) Liebke et al. (2010); (34) Sun et al. (2010); (35) Chen et al. (2014); (36) Huang et al. (2013); (37) Huang et al. (2015a); (38) Huang et al. (2015b); (39) Ding et al. (2016a), and; (40) Ding et al. (2001).

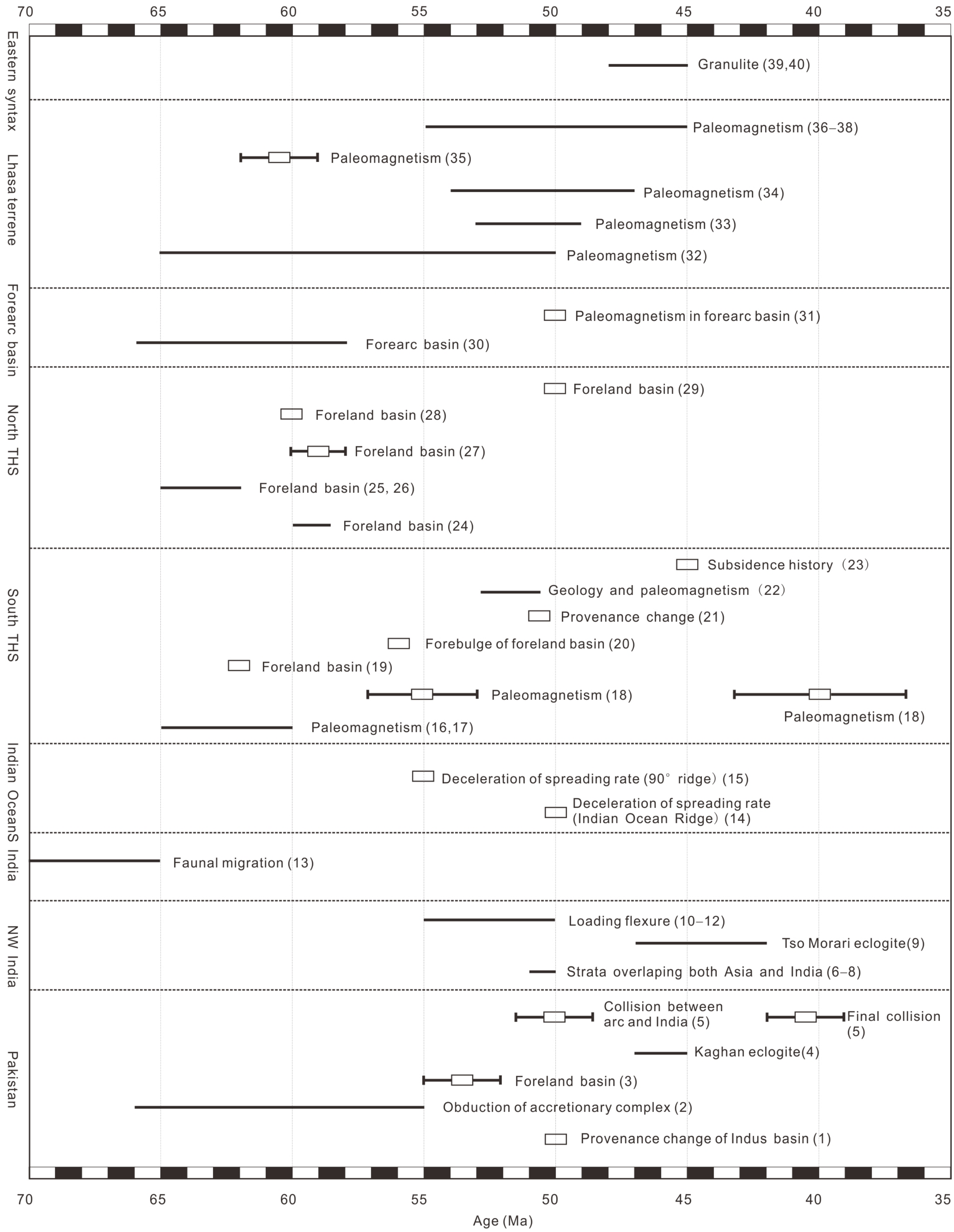

Figure 2 Comparison of different timings for the collision between India and Asia as well as events across the THS resulting from the application of different methods.

and thus might not be an appropriate choice to constrain the age of collision between India and Asia.

In Pakistan and Zanskar, an important progress is the discovery of coesite-bearing eclogite. The Kagan eclogite, for example, is known to have experienced peak metamorphism between 47 Ma and 46 Ma (Tonarini et al., 1993; Kaneko et al., 2003; Treloar et al., 2003; Wilke et al., 2010), while the Tso Morari eclogite in Zanskar experienced early metamorphism between 57 Ma and 53 Ma, and peak metamorphism between 47 Ma and 43 Ma (Donaldson et al., 2013). Combining these ages of peak metamorphism with the subduction velocity of the Indian continent, the initial timing of India-Asia collision is constrained at 57±1 Ma at Tso Morari (Leech et al., 2005).

Another important proxy that has been used to constrain the timing of collision between India and Asia is intercontinental faunal migration. Thus, taking into account the ages of Deccan basalts, Jaeger et al. (1989) proposed that faunal mixing between India and Asia occurred at Cretaceous-Paleocene boundary, dating the timing of collision to 65 Ma.

Over the last ten years, extensive research based on a range of different methods has been carried out in the Tethyan Himalaya Sequence (THS) of southern Tibet aimed at more accurately constraining the age of the collision between India and Asia. These approaches have included determining the cessation of marine sedimentation, as well as analyses of provenance, subsidence history, ophiolite obduction over the continental margin, and paleomagnetism both in Lhasa and the THS. However, these methods are all more-or-less related to the development of the peripheral foreland basin and only differ from one another in the selection of a specific event, which occurred during a phase of collision.

Earlier, Rowley (1998) reviewed the stratigraphic section preserved in the Zhepure Mountain and developed a subsidence history. Relying on the subsidence history of this preserved section, Rowley (1998) argued that there is no evidence for an acceleration in subsidence up to the youngest rocks. Therefore, collision-related loading and accelerated subsidence must post-date preservation of the youngest sediments in this sequence, dated to as early as the Lutetian. Hence, Rowley (1998) argued that accelerated subsidence of the Zhepure Mountain must post-date ca. 45.8 Ma. This study was re-visited more recently by Zhu et al. (2005), who carried out a provenance analysis on the same section and noted a switch in source from the Indian to Asian plate ca. 50.8 Ma. Additional biostratigrahic data collected by Najman et al. (2010) indicates that the youngest marine deposits preserved in the Zhepure Mountain are between 52.8 Ma and 50.6 Ma; these data, combined with double-dating of detrital zircons, show that the initial deposition of detritus in this formation that has an Asian-affinity occurred between ca. 52.8 Ma and 50.6 Ma. This date also provides an initial age for the collision between India and Asia. Another revised biostratigraphic model has proposed a ca. 56 Ma age for a conglomerate within the Zhongpu Formation that was deposited in a forebulge zone of the foreland basin system (Zhang et al., 2012); this also predates the timing of the collision between India and Asia. In addition, Hu et al. (2012) proposed that both coherent and conglomerate units within the Zhongpu Formation formed a part of the forebulge and thus constrained the oldest age of this sequence, 62 Ma, to that of the collision.

Recently, detailed studies carried out in the Yarlung Zangpo peripheral foreland basin have also made a great contribution to an improved understanding of the timing of this collision. For example, a great deal of research in this basin has been focused on the Sangdanlin section, a classical example of a foreland basin sequence that has captured the attention of numerous geologists around the world. As discussed below, although minor controversy remains, it is now widely accepted that this sequence provides evidence that the collision between India and Asia took place 10 Ma to 15 Ma earlier than previously thought (DeCelles et al., 2014; Ding et al., 2005; Hu et al., 2015; Wu et al., 2014).

Finally, contrasting with exposures of eclogite in the western syntaxis of this collision, this rock type is generally absent across the eastern syntaxis. However, granulites found at many sites evidence a wide range of metamorphic ages (Ding et al., 2001). Recent studies have shown that metamorphic rocks in the eastern Himalayas underwent medium-pressure metamorphism in the early Eocene, between 48 Ma and 45 Ma, which is indicative of collision between India and Asia. Thus, in combination with metamorphism conditions, these data suggest an age of 50 Ma for the collision (Ding et al., 2016a).

4. Research progress regarding the initial timing of the collision between India and Asia

As discussed above, while a number of methods have been applied to constrain the initial timing of continental collision, provenance analysis of the peripheral foreland basin and paleomagnetism have proved the most effective (Table 1).

4.1 Tectono-sedimentary responses to the initial collision

4.1.1 Deformation of the northern THS in the early collisional stage

Deformation of the subducting continent took place immediately after complete subduction of the oceanic lithosphere. Thus, in response to collision with Asia, the Indian continent experienced deformation. As a result, the island arc, accretionary complex, and trench strata of the southern Asian margin were emplaced onto northern India during the latest Cretaceous (Tapponnier et al., 1981; Ding et al., 2005; DeCelles et al., 2014; Hu et al., 2016b; Wang et al., 2017), which led to the development of tectonic flexure in the northern Indian continental margin as well as the formation of the first peripheral foreland basin system (Ding et al., 2005, 2009; DeCelles et al., 2014). In the central section of the YTSZ, the foreland thrust-fold belt related to this initial basin system is the Zhongba-Gyangze thrust (ZGT), which acted as a part of the collision boundary fault system. The hanging wall of the ZGT fault, a Neo-Tethyan subduction accretionary complex, is penetrated by primary fold (F1) foliation and kink band structures (Wang et al., 2017). Thermochronological ^{40}Ar-^{39}Ar dating of amphiboles and micas from the ductile shear zone of the ZGT fault indicate activity between 71 Ma and 60 Ma (Ding et al., 2005; Wang et al., 2017). In the Namche-Barwa region of the eastern Himalayan syntaxis, the boundary fault that marks collision between India and Asia probably includes both the Pailong-Layue and Dongjiu-Milin strike-slip thrusts that both exhibit well-developed mylonitic fabrics comprising amphibolite facies and medium-high temperature quartz slip systems (Zhang et al., 2004; Xu et al., 2012). Results from ^{40}Ar-^{39}Ar amphibole cooling ages and U-Pb dates from syn-tectonic zircons suggest that these faults were active between 62 Ma and 54 Ma (Zhang et al., 2004; Xu et al., 2012).

Data show that foreland flexure resulting from the collision between India and Asia gradually migrated southwards into the Indian hinterland. During the early Eocene, a second peripheral foreland basin system was established as the thrust front migrated into the Kangma-Gyiong thrust (Ratschbacher et al., 1994) and the foredeep depo-center switched into the Gamba-Tingri basin (Willems et al., 1996; Ding et al., 2009; Hu et al., 2012; Zhang et al., 2012; DeCelles et al., 2014). Indeed, as this foreland thrust front advanced, a series of vergent folds orientated to the south formed on the northern Indian continental margin, constituting a typical foreland thrust-fold belt (Burg and Chen, 1984; Ratschbacher et al., 1994). The ZGT fault and the first foreland basin were both involved in this stage of deformation (Ding et al., 2005); K-Ar dating of white micas from this thrust-fold belt in the Renbu area reveals that this stage of deformation occurred ca. 50 Ma (Ratschbacher et al., 1994). Thickening of the crust during this stage of deformation triggered high-grade metamorphism and partial melting at deep structural levels, between 48 Ma and 43 Ma (Ding et al., 2005, 2016a; Aikman et al., 2008; Zeng et al., 2011). These dates can be used to constrain the time of activity of the second stage of collisional deformation.

The lower crust that forms the leading edge of the passive continental margin was subducted, or underthrusted, during the process of collision, while the upper crust was deformed and ultimately formed the thrust-fold belt that migrated towards the hinterland of the passive continental margin. It should be noted that contraction and deformation structures in plate suture zones could have been initiated by island arc-continent collision; thus, the underlying causes of these tectonics must form the subject of future research projects. In addition, because the structures that characterize this early deformation stage might be brittle and/or ductile, this creates difficulties in the determination of actual deformation time. Even in well-developed ductile shear zones, uncertainties still exist in explaining some thermochronological data, for example Ar-Ar ages. Thus, in order to precisely constrain the time of initial collision, tectonic deformation should be coupled with sedimentary evidence from peripheral foreland basins.

4.1.2 Development of a peripheral foreland basin system

The development of a peripheral foreland basin system in the collision zone directly marked the continental collision (Ding, 2003; Ding et al., 2009). Conventional studies have argued that a peripheral foreland basin system was only developed along the southern flank of the Himalayas, represented by the Miocene-Pliocene Siwalik Group. However, Ding (2003) identified a second peripheral foreland basin system formed immediately to the south of the YTSZ, the Yarlung Tsangpo foreland basin system. Compared with other Cenozoic examples, however, the Yarlung Tsangpo foreland basin system developed much closer to the suture zone and much earlier than its counterparts within the Himalayan orogen.

Recent studies have also indicated that the Yarlung Tsangpo foreland basin system first developed between 65 Ma and 60 Ma (Figure 3a; Ding, 2003; Ding et al., 2005; Cai et al., 2011; Wang et al., 2011; DeCelles et al., 2014; Wu et al., 2014; Hu et al., 2015). In the Saga region, the sedimentary environment of the Tethyan Himalayan sequences changed from the Indian passive continental margin to a foredeep depozone of peripheral foreland basin at about 65 Ma. The synchronous peripheral foreland basins also developed in the Gyangze region to the east (Cai et al., 2011; Wu et al., 2014).

The Sangdanlin section in the Saga region, located in the northern Tethyan Himalayas (THS), comprises the most representative section for research on the initial timing of continental collision. The first detailed work to be carried out in this area included analyses of the structure, biostratigraphy, and sedimentary provenance of this section (Ding, 2003). This section is subdivided into the late Cretaceous Zhongzhuo Formation that consists of limestones and quartz sandstones, the Paleocene (Danian-Thanetian) Sangdanlin Formation that consists of radiolarian cherts, and the overlying Zheya Formation that consists of clastics. Specifically, the Zhongzhuo Formation is composed of siliceous shales, cherts, and quartz sandstones, the latter of which comprise typical turbidity deposits derived from the Indian passive continental margin, while the Sangdanlin Formation consists of cherts and siliceous shales. Studies on radiolarians have constrained the age of the Sangdanlin Formation to Paleocene-early Eocene, between 65 Ma and 55 Ma) (Ding, 2003). Although this formation contains typical foredeep de-

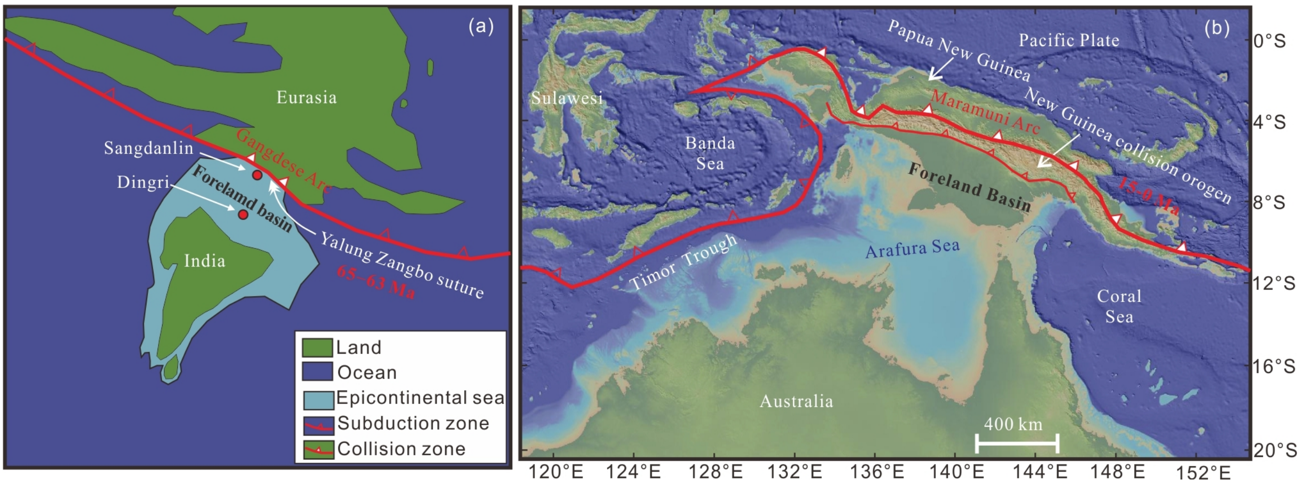

Figure 3 Comparison of the evidence for the existence of an epicontinental sea and foreland arc basin in front of the Indian-Asian collision belt, including (a) scenario for collision between India and Asia, and (b) an example from present-day Australia and Papua New Guinea.

posits characteristic of a foreland basin, the small proportion of detrital materials suggests that it was starved of sediments during the Paleocene. In contrast, the Zheya Formation is mainly composed of flysch sediments interbedded with conglomerates that are characteristic of turbidites, channel, and wedge-slope deposits.

Although a number of research projects have been carried out in the Saga area aimed at constraining the initial timing of the collision between India and Asia, each has reached a slightly different conclusion. For example, Ding et al. (2005) studied the sedimentary environments of this region and observed an environmental change between 65 Ma and 63 Ma related to the switch between the Indian passive continental margin and the starved peripheral foreland basin. While Ding et al. (2005) suggested that collision took place ca. 65 Ma. Wu et al. (2014) studied the area in more detail to determine the sedimentary provenance of detrital zircons. This latter study indicated that sediments of the Sangdanlin Formation were derived alternately from the Indian and Asian continents, and suggested an earlier time for the first appearance of Asian clastics. Thus, combined with a series of younger detrital zircon (i.e., 62±1 Ma and 57±2 Ma) and synchronous radiolarian ages (i.e., RP4; between 63 Ma and 61 Ma), Wu et al. (2014) argued that the date of the collision was ca. 60 Ma. In contrast, DeCelles et al. (2014) reported on a volcanic tuff at the top of the Zheya Formation within the Sangdanlin section which yielded a U-Pb age of 58.5 Ma. Taking into account that the age of the youngest Asian detrital zircon is 60.6 Ma, DeCelles et al. (2014) therefore considered the collision occurred between 60.6 Ma and 58.5 Ma. Hu et al. (2015) reworked both the paleontological chronology and detrital zircon geochronology of these strata, achieving similar results to DeCelles et al. (2014) and Wu et al. (2014), and constraining the time of initial collision to 59±1 Ma. In sum, if the time of initial collision can be constrained by the first appearance of Asian clastics in the foredeep region of the foreland basin system, then continental collision must have occurred earlier than a time between 60 Ma and 59 Ma. However, if integration of the initiation of foreland basin formation and tectonic deformation turns out to be more sensitive to continental collision than alternation of provenance, then the initial collision between India and Asia can be said to have occurred between 65 Ma and 63 Ma.

The pure quartz sandstones of the early Paleocene Jidula Formation in the Gamba-Tingri region were clearly derived from the Indian continent, while the late Paleocene Zongpu Formation comprises nodular limestone deposits containing slump structures (Wan et al., 2001; Li et al., 2002) which imply emplacement of the forebulge after formation deposition (Zhang et al., 2012). Similarly, the Eocene Zhepure Formation comprises mudstones interbedded with lithic sandstones (Wang et al., 2002; Zhu et al., 2005); analyses show that the detrital materials in this Formation were transported from northern THS strata which were involved in the thrust-fold belt and suture zone, for example the Gangdese arc (Zhu et al., 2005). The Zhepure Formation therefore represents foredeep deposits subsequent to the passage of the forebulge; foreland basins in the Saga-Gyantze region must have been involved in the thrust-fold belt at that time, while the foredeep of the foreland section of this belt transferred to the Gamba-Tingri region in southern Laguigangri (Ding et al., 2009).

In sum, the oldest peripheral foreland basin formed in the northernmost THS as a consequence of southward emplacement of the accretionary complex and trench strata from the southern Asian margin moving onto the northern Indian margin between 65 Ma and 63 Ma. Thus, foredeep sedimentary units correspond to the Sangdanlin Formation in the Saga region, while forebulge migration into the Gamba-Tingri region resulted in formation of nodular limestones. Based on these studies of peripheral foreland basins and the foreland thrust-fold belt, the time of the initial collision between India and Asia can be constrained to ca. 65 Ma.

4.1.3 Cessation of marine sedimentation

The transition from marine-to-terrestrial facies has been used as an indicator to constrain the timing of the collision between India and Asia in the 1980s and 1990s (e.g., Searle et al., 1987). Across the western syntaxis, the Balakot Formation, dated to between 55 Ma and 50 Ma, is the oldest terrestrial foreland basin deposit to be interpreted as a marker of this collision (Bossart and Ottiger, 1989). In the Zanskar region to the east, however, this marine-to-terrestrial facies transition is recorded in the early Eocene Chulung La Formation of the THS and also marks the onset of collision (Gaetani and Garzanti, 1991; Rowley, 1996). Paleontological studies have constrained the cessation of marine sedimentation to no later than 50.5 Ma (Critelli and Garzanti, 1994), while in the Tingri area, Rowley (1996) pointed out that the available duration for shallow shelf carbonate formation was between 47.8 Ma and 41.2 Ma (Lutetian). Because these data indicate that the cessation of marine sedimentation occurred subsequent to the Lutetian, Rowley (1996) proposed a later collision time between 47 Ma and 45 Ma, further suggesting that a diachronous event took place from west to east. Subsequent work on microfossils (Wang et al., 2002), however, has constrained the age of the youngest marine strata in the Tingri region to the late Eocene, ca. 34 Ma, while on the basis of both foraminifera and microfossils, other researchers have considered the youngest marine strata to be dated between 53.5 Ma and 50.6 Ma (Zhu et al., 2005; Najman et al., 2010).

However, because the deposition of marine sediments would not have ended immediately after the onset of collision, the age of these strata only reflects an upper bound on collision time, limiting the application of this approach. Marine deposition in a remnant ocean and/or a peripheral foreland basin can still take place even after collision between two plates and the subduction of oceanic crust, as in present-day northern Australia, for example (Figure 3b). In this example, after collision between Australia and Papua New Guinea between 15 Ma and 12 Ma (Hall, 2012), the Arafura epicontinental sea formed in the collision foreland along the northern margin of Australia continent. The Arafura Sea is analogous to the Tibetan Tingri epicontinental sea (Figure 3a), has an average depth of ca. 50 m, and connects the Indian and Pacific Ocean to the west and east, respectively.

4.2 Paleolatitudes during the initial collision between India and Asia

Augmenting the peripheral foreland basin method, data from paleomagnetism can be used to effectively quantify the paleolatitudes of plates and to constrain where, and when, they collided. Over the last two decades, a large number of paleomagnetic studies have been carried out across the greater Indian and Asian regions.

4.2.1 Paleolatitudes of Greater India (GI) and the Tethyan Himalaya

Because GI played a key role in the evolution of the Tibetan-Himalayan mountain region, many studies have been carried out in this region, building on the early work of Argand (1924). Understanding the size and paleolatitude of GI is crucial to constraining the age of initial Indian and Asian contact, uplift history of the TP, and estimating the amount of crustal shortening. Thus, in the first place, we introduce the relevant definitions for GI and the present-day Indian plate. Indian plate rocks can be divided into two types: those currently attached to the craton, i.e., south of the Main Boundary Thrust (MBT), and those north of the fault and south of the Yarlung Tsangpo suture zone (Ali and Aitchison, 2005). GI can thus be defined as the region to the north of the Indian plate, including under-thrusted Indian lithosphere and crustal shortening in the Himalayan mountain belt (Ali and Aitchison, 2005).

Although a number of reconstructions for GI are available, the model presented by Ali and Aitchison (2005) seems most plausible. These workers analyzed the pre-break-up position of GI within Gondwana, as well as the bathymetry of the Indian Ocean west of Australia, and suggested that the Indian continent probably extended for no more than 950 km (Ali and Aitchison, 2005).

The Indian Ocean is notable for the presence of a number of submerged bathymetric promontories that extend out from the western coasts of Australia. From south to north, these promontories include the Naturaliste plateau, the Wallaby-Zenith (W-Z) plateau, and the W-Z fracture zone. Of these, the latter in particular is important for constraining the evolution of GI because oceanic crust is located to the south while continental crust of the W-Z plateau is found to the north (Brown et al., 2003). This pattern of crustal rocks implies that the ridge of the W-Z plateau controls the existence of GI to the east, constraining not just this margin but also to the north and northwest. Thus, in this paper, we apply the definition of GI proposed by Ali and Aitchison (2005) which similar to Hall (2012) that is slightly northward extending (Figure 4).

Because the THS are generally regarded to be the northern region of GI, determining the paleolatitude of this feature is also key to constraining the age of the initial collision between India and Asia. To date, a handful of paleomagnetic studies have been carried out on early Cenozoic rocks from the THS, including Patzelt et al. (1996) who reported on the presence of two poles in late Cretaceous-to-Paleogene strata from the Gamba and Duila regions. These two poles come from rocks of the Zhongshan Formation, dated to between 71 Ma and 65 Ma, and rocks of the Zhongpu Formation, dated to between

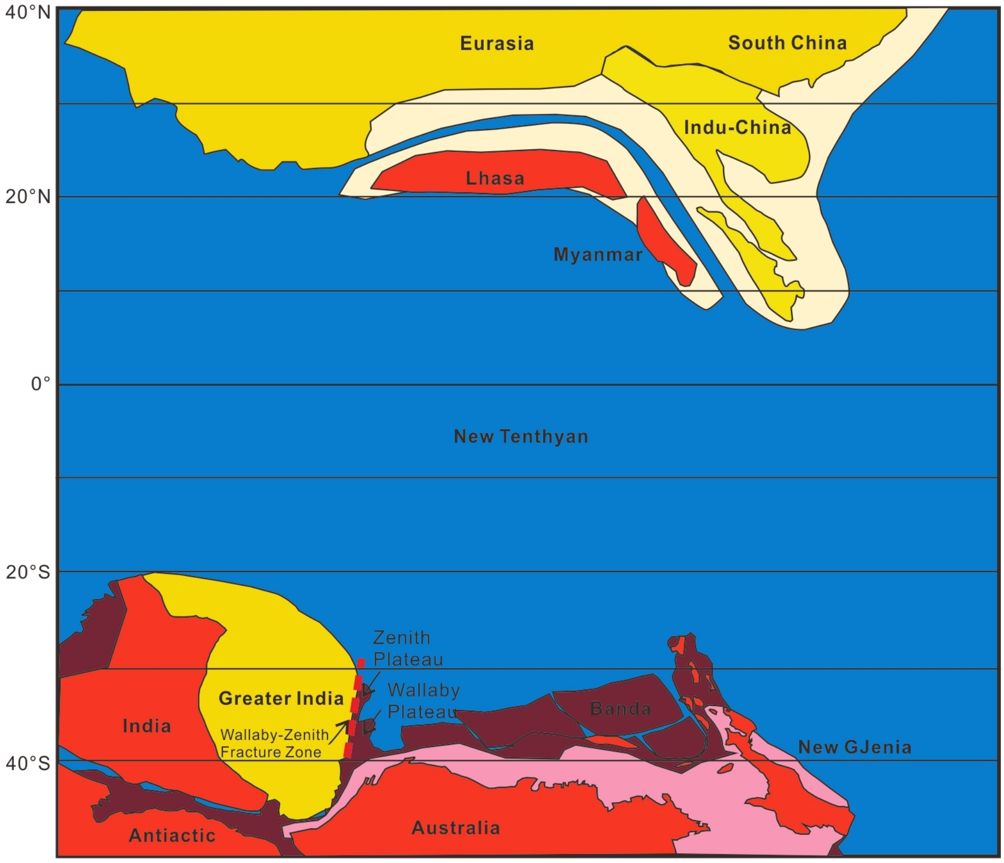

Figure 4 The paleoposition of GI subsequent to detachment from Gondwana. This figure also shows the eastern extent of GI (Ali and Aitchison, 2005; Hall, 2012).

63 Ma and 55 Ma, and yield paleolatitudes of 4.4°±4.4°S and 5.8°±3.8°N, respectively. In a similar paleomagnetic study, Yi et al. (2011) reported results from Zhongpu Formation limestones in the Gamba region. These results show that the paleolatitudes of the THS between 62 Ma and 59 Ma and between 59 Ma and 56 Ma were 7.1°±3.5°N and 11.8°±2.5°N, respectively. Van Hinsbergen et al. (2012) later re-analyzed published Cretaceous paleomagnetic results from the Lhasa and Tethys Himalayan blocks and suggested that a ca. 2675 km Greater India basin (GIB) was accommodated between the THS and cratonic India. This result was corroborated by another recent paleomagnetic study carried out by Yang et al. (2015a).

4.2.2 *Paleolatitudes of the southern margin of Asia*

A large number of paleomagnetic studies have been carried out in recent decades on Cretaceous-to-Eocene lavas and sediments from the Lhasa block (Pozzi et al., 1982; Westphal and Pozzi, 1983; Achache et al., 1984; Lin and Watts, 1988; Chen et al., 2010, 2012, 2014; Sun et al., 2010, 2012; Tan et al., 2010; Huang et al., 2013, 2015a; Tang et al., 2013; Ma et al., 2014; Li et al., 2015; Li et al., 2016; Yang et al., 2015b). However, large discrepancies remain between reported late Cretaceous-to-Eocene paleolatitudes, encompassing a range between 7°N and 32°N and corresponding to a large variation in initial collision-age estimates for India and Asia, between 65 Ma and 43 Ma. The reasons that underlie such a variation in published paleolatitude estimates include compacted sediments (Gilder et al., 2001; Kodama, 2012; Tauxe, 2005; Yan et al., 2005), the incomplete field characterization of lavas (Sun et al., 2012), re-magnetized rocks (Huang et al., 2015a), and the use of inappropriate statistical methods (Lippert et al., 2014). Indeed Ma et al. (2014) and Yang et al. (2015b) reviewed published Cretaceous paleomagnetic results for the Lhasa block, identified 116 volcanic sites, and re-calculated the Cretaceous paleolatitude of this unit at ca. 15°N. Published paleomagnetic data from well-dated sedimentary rocks and lavas within this block have also been re-evaluated within a statistically consistent framework in order to assess the latitudinal history of southern Tibet (Lippert et al., 2014). These workers suggested that the Lhasa block was located at between ca. 16°N and 22°N during the Cretaceous-to-Paleogene and that it moved northwards to its present position since contact between the Indian and Asian plates. In sum, a lower latitude reconstruction (ca. 15°N) for the Lhasa block seems reasonable for the late Cretaceous-Paleogene. Most recently, a combined geochronologic and paleomagnetic study was carried out on upper Cretaceous volcanic rocks from the Shiquanhe and Yare basins within the westernmost Lhasa block (Yi et al., 2015). Comparison of the results of this study (Yi et al., 2015) with earlier work indicates that the southern margin of Asia probably had a quasi-linear orientation, trending approximately 310°, prior to the collision between India and Asia.

A comparison of paleolatitudes from the northern margin of India with those from the southern margin of Asia is critical if we are to constrain the age of the initial collision between India and Asia (Yi et al., 2011; Lippert et al., 2014; Huang et al., 2015a, 2015b). Most probably, the Lhasa block remained at around 15°N throughout the late Cretaceous-Paleogene, while comparisons of estimated paleolatitudes for Lhasa with the results of Yi et al. (2011) for the Gamba area in the THS imply that the age of the initial collision was as early as 52 Ma, which is probably the youngest age constrained by paleomagnetic data (Hu et al., 2016a). If the northwards extension of GI and the shortening of the THS amount to 950 km (Ali and Aitchison, 2005) and between 120 km and 150 km (DeCelles et al., 2002), respectively were considered, then the initial age of Indian and Asian contact should be between 65 Ma and 60 Ma (Yi et al., 2011).

4.3 Magmatism of the THS during the early stage of collision

The Himalayan orogenic belt is characterized not only by widespread exposures of Oligocene-Miocene leucogranites but also abundant middle Eocene granites (Ding et al., 2005; Wu et al., 2015). These granites are distributed in a linear belt along the south of the YTSZ, emplaced in the north of the THS, from the Xiao Gurla range in the west (ca. 43.9±0.9 Ma; Pullen et al., 2011), to Niuku near northeastern Zhongba (ca. 44.8±2.6 Ma; Ding et al., 2005), in Ramba pluton near eastern Renbu (ca. 44 Ma; Liu et al., 2014), and in the Yadoi-Dala-Quedang area in the east (between ca. 46 Ma and 42 Ma; Aikman et al., 2008, 2012; Qi et al., 2008; Zeng et al., 2011, 2014; Hou et al., 2012). Intrusions of these Eocene granites mainly truncate through early stage fold structures; for example, they are emplaced in the core of folds in the Niuku and Xiao Gurla ranges (Ding et al., 2005; Pullen et al., 2011), as well as into the cores of gneiss domes or cross-cut through upper Triassic sub-greenschist metasediments in the Yardoi area (Aikman et al., 2008).

Eocene two-mica granites, which occur in the core of the Yardoi gneiss dome, as well as at Dala and Quedang, have mainly high SiO_2 (i.e., 68.3 wt.% to 74.8 wt.%), and Al_2O_3 contents (i.e., 13.4 wt.% to 17.0 wt.%, mostly greater than 15 wt.%), as well as high A/CNK ratios (between 1.0 and 1.3) (Xie et al., 2010; Zeng et al., 2011, 2014; Hou et al., 2012). In addition, these two-mica granites are also rich in Na (i.e., Na_2O/K_2O values between 0.95 and 1.42), moderate-to-high rare earth element (REE) concentrations (REE values between 80 ppm and 180 ppm), fractionated REE patterns (i.e., La/Yb values between 17 and 126, with an average of 52), and weak Eu anomalies (i.e., Eu/Eu* values between 0.57 and 1.71, with an average of 0.83). In addition, these granites tend to have high Sr contents (i.e., values between 252 ppm and 1564 ppm, with an average of 358 ppm), Sr/Y ratios greater than 40, La/Yb ratios greater than 30, as well as low Yb (between 0.25 ppm and 0.78 ppm) and Y (between 3.30 ppm and 8.77 ppm) contents, identical to the geochemical features of adakites (Figure 5). Synchronous porphyritic two-mica granites from the Ramba dome exhibit similar geochemical features (Liu et al., 2014), including significantly enriched Sr-Nd isotopic compositions (i.e., $^{87}Sr/^{86}Sr(i)$ values between 0.707696 and 0.719344, $\varepsilon_{Nd}(t)$ values between 8.97 and 14.94, and TDM2 values between 1.49 Ga and 2.05 Ga), similar to leucogranites from the Himalayas (Zeng et al., 2011; Hou et al., 2012; Liu et al., 2014). Most researchers agree that these granites are derived from partial melting of thickened lower crust, a source region that is dominated by garnet amphibolites (Xie et al., 2010; Zeng et al., 2011, 2014; Hou et al., 2012; Liu et al., 2014). As these Eocene granites represent the earliest stage of magmatism from during the collision between India and Asia in the northern THS, they are related to the Neo-Tethyan slab break-off process that was a response to subducted slab roll-back (Pullen et al., 2011; Zeng et al., 2011; Hou et al., 2012). Such a process has also recently been proposed to explain the presence of Eocene volcanism in the southern Lhasa terrane; Ji et al. (2016) recently reported on the discovery of Eocene OIB-like gabbros (45.0±1.4 Ma) from the eastern segment of the THS in southern Tibet, representing the direct evidence for partial melting of the asthenosphere. Combining their results with those of other studies, Ji et al. (2016) further confirmed that Neo-Tethyan slab break-off was almost synchronous along the entire length of the YTSZSZ during the middle Eocene

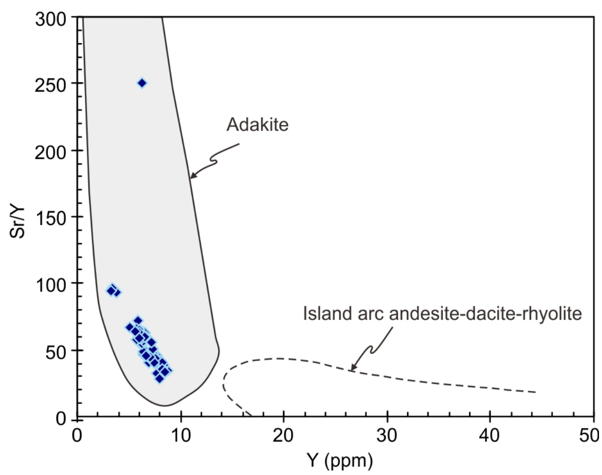

Figure 5 Geochemical characteristics of Eocene magmas in the THS during the time of early collision.

(ca. 45 Ma). The presence of these coeval granites are related to thermal perturbations caused by Neo-Tethyan slab break-off, while Eocene magmatism in the THS also suggests that the collision between India and Asia was initiated earlier than ca. 45 Ma.

5. Collision patterns and suturing processes between the Indian and Asian continents

The processes of continental collision are complex, as some margins are straight while others are more intricate, comprising continental marginal arcs, island arcs, micro-continental massifs, and marginal seas. Initial collisions commence at the bulge between two continents, and while further convergence takes place, collision migrates into open oceanic lithosphere and is characterized by massive overthrusting and lateral strike-slip movements. When the oceanic lithosphere within subduction zone has been completely subducted, and collision deformation has been transferred to both sides of the respective continents, overall collision can be said to have been initiated. Similarly, the process from initial to overall collision is defined as 'soft collision', while the period subsequent to overall collision is referred to as 'hard collision' (Figures 3a and 6).

Debates over the pattern and process of collision between India and Asia focus on whether this event encompassed one, or two, stages. In the context of the latter hypothesis, two models for two stage collision have been proposed, intra-oceanic subduction and the GIB models. Of these, the first suggests that Neo-Tethys was consumed by the combined effect of intra-oceanic subduction as well as subduction along the Lhasa terrane. The idea of an intra-oceanic island arc was first proposed in the 1980s (Allégre et al., 1984), but detailed research on this idea was not published until more recently. In relation to Tibet, Aitchison et al. (2000) considered a suite of late Jurassic basic volcanic and siliceous rock in the Zedong area to be the remnants of a Neo-Tethyan intra-oceanic island arc. The Yarlung Tsangpo ophiolite was treated as a forearc ophiolite and the Bailang block that lack of terrigenous clast was treated as the oceanic subduction mélange. This island-

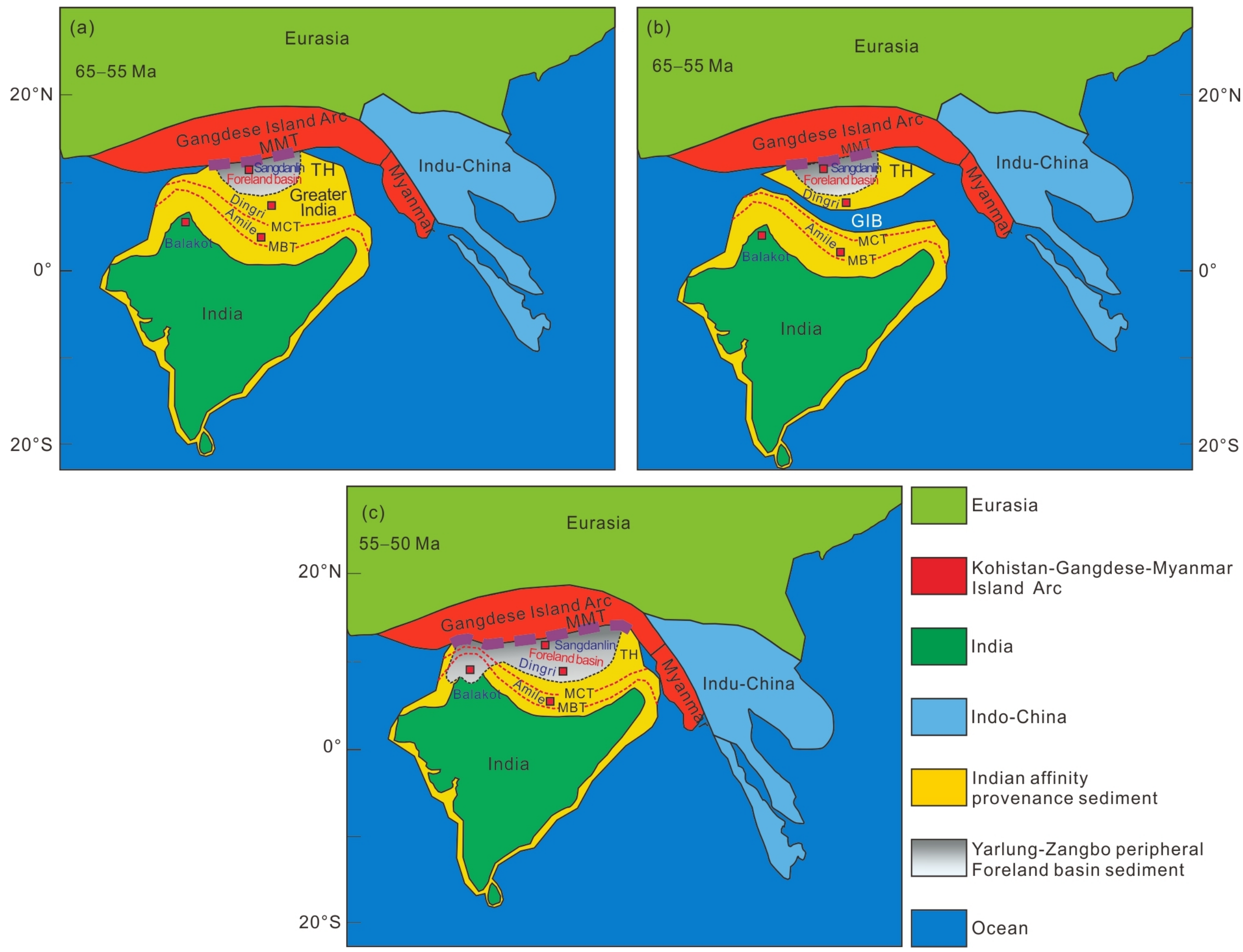

Figure 6 Competing models to explain the processes of collision between India and Asia, including (a) the GI model, (b) the GIB model, and (c) the extent of the foreland basin between the Paleocene and Eocene.

arc system is analogous to the modern Izu-Bonin-Mariana intra-oceanic arc system where the Pacific plate is subducting beneath the Philippine Sea plate (Aitchison et al., 2007b). Aitchison et al. (2007a) criticized the widely-accepted view that collision between India and Asia occurred between 55 Ma and 50 Ma, instead arguing that this event was simply a bi-product of another collision between this intra-oceanic island arc and the Indian continental margin. Evidence for this hypothesis comes from the fact that the northern margin of GI (ca. 14°N; Ali and Aitchison, 2005) was located far away from the southern margin of the Asian continent at this time (ca. 28°N; Ali and Aitchison, 2006). Aitchison et al. (2007a) went further to postulate that both the island arc and Indian continental plate continued drifting northwards after collision, colliding with Asia at about 34 Ma. The argument is potentially corroborated by the cessation of marine sedimentation along the northern margin of the Indian plate, the emergence of molasse-type deposits, and the end of Gangdese magmatism.

However, key evidence cited in support of the intra-oceanic island arc model remains problematic for several reasons (Hu et al., 2016a). The geochemical characteristics of Zedong island arc rocks exhibit no apparent differences to those in the Gangdese arc, while no ophiolites or mélanges are present in the north of Zedong island arc which can categorically be linked to remnant ocean (Hu et al., 2016a). As a result, the Zedong island arc more likely belongs to the Gangdese arc rather than representative of an independent intra-oceanic system (Zhang et al., 2014). The paleogeographic reconstruction produced by Abrajevitch et al. (2005) based on ophiolite paleomagnetic data showed a pronounced bias towards shallow inclinations, and thus resulted in lower paleolatitudes. This reconstruction based on a published APWPs placed the southern Asian margin at 28°N in about 50 Ma, a location that is 8° higher than actual paleomagnetic data (Aitchison et al., 2007a). A more reliable paleomagnetic reconstruction places this ophiolite formation closer to the margin of Asia rather than within an oceanic environment (Huang et al., 2015c), and this result suggests that the paleogeographic position of India and Asia have overlapped with one another since at least 50 Ma (Liebke et al., 2010; Lippert et al., 2014).

The GIB model was proposed by van Hinsbergen et al. (2012) based on the presence of a distinctive paleolatitude discrepancy between the THS and the India craton. These two blocks were connected during the earliest Cretaceous, but between 120 Ma and 70 Ma the THS drifted ca. 24° (i.e., ca. 2,675 km) northwards relative to the Indian craton (van Hinsbergen et al., 2012). Although Yi et al. (2011) considered this to be simply a marked extension of the northern margin of GI, van Hinsbergen et al. (2012) argued that this expansion eventually created the GIB. Indeed, approximately 50 Ma, the THS separated from India as an independent block and collided with the southern margin of Asia; this was followed by subduction of the GIB along the main central thrust (MCT) (van Hinsbergen et al., 2012), a conclusion supported by the most recent research on early Cretaceous paleomagnetism of the THS (Yang et al., 2015a).

The comprehensive review published by DeCelles et al. (2014) regarding the GIB model noted that early Cretaceous volcanic rocks that represent the extension of India were only present within the THS zone rather than across the lesser Himalayas which represent the Indian cratonic margin. No sedimentary record of the GIB remains in this region; if it existed, the position of its last suture zone should be located beyond the northern of the southern Tibet detachment system (STDS) rather than the MCT. In addition, provenance research indicates that detritus from the THS was deposited in the Indian foreland basin, within the region of the lesser Himalayas, around 45 Ma, while no such Asian sedimentary record (e.g., the Amile Formation of Nepal) (DeCelles et al., 2004; Figure 6) has been found in this region. Data show that the time of collision between the Indian craton and the Tethyan Himalayan block should have commenced before 45 Ma rather than between 37 Ma to 40 Ma, or by the even later date of 25 Ma. This result explains the presence of crustal shortening, burial metamorphism, and anatectic melting seen within the THS and the high Himalayas (DeCelles et al., 2014; Ma et al., 2016). Detailed work on detrital zircons from Pakistan by Ding et al. (2016b) has shown that Asia was the provenance source region at Balakot region in south of Main boundary Thrust (MBT) in India during the earliest Eocene, 55Ma (Figure 6a and c), which means that suture zones both the GIB and the Indus must have already closed before this time (Figure 6c).

Provenance research on Sangdanlin strata from the Saga area in the middle of the YTSZ demonstrates that the foreland basin was deposited on top of Maastrichtian pure quartz sandstones of the Zhongzhuo Formation, typical gravity flow sediments of the Indian passive margin (Ding, 2003; Ding et al., 2005, 2009; DeCelles et al., 2014; Wu et al., 2014; Hu et al., 2015). Because the Paleocene Jidula Formation in the Gamba-Tingri area also comprises pure quartz sandstones of Indian affinities (DeCelles et al., 2014), suggested that the GIB could not have existed prior to the deposition of this lithology, ca. 65 Ma.

Explaining the late Cretaceous-Eocene sedimentary record of the Sangdanlin-Tingri areas in Tibet and in the Balakot area of Pakistan, located to the north and south of the MCT and the STDS respectively, requires that the GIB opened later than ca. 65 Ma, and closed earlier than ca. 55 Ma. It is impossible to complete a Wilson cycle from ocean expansion to closure within 10 Ma (i.e., between 65 Ma and 55 Ma). Thus, the most parsimonious explanation is that the GIB did not exist; indeed, the fact that this structure, sometimes referred to as the 'intercontinental basin', has been inferred on the basis of paleomagnetic data is most likely related to counter-clockwise rotation of GI during the Cretaceous. This rotational effect led to a relative paleolatitudal change with respect to India and the THS (Figure 4) (Klootwijk et al., 1992; Wang et al., 2014; Zhang and Huang, this volume). Nevertheless, Huang et al. (2015b) argued that this was not enough to equalize the latitude discrepancy.

Compared to a two-stage model, a single stage hypothesis proposes that collision between India and Asia resulted from Neo-Tethyan lithosphere subduction along the southern margin of Asia without the development of an intra-oceanic subduction zone or an island arc. Thus, subsequent to the closure of this subduction zone, the northern margin of India collided directly with the southern margin of Asia (Yin and Harrison, 2000). We therefore consider that a single stage model is more feasible as it is consistent with sedimentary, metamorphic, and magmatic rock records.

6. Conclusions

Continental collision refers to the orogenic processes during which an active margin and accretionary wedge load onto a passive margin to form a peripheral foreland basin system. This emplaces residual oceanic crust as a tectonic ophiolite at the collision site, while, at the same time, strong deformation, metamorphism, and magmatism occur on both sides of the continental lithosphere and suture zone. Taking into account the complexity of processes across the transition from a soft to hard continental collision, if this event was defined by an initial contact to convergence halt between India and Asia, then the whole sequence would have lasted almost 100 Ma.

In practice, however, scholars from different geoscience disciplines have tended to define this event from the point-of-view of their own research, leading to a wide range of estimates for the initial collision time between India and Asia. In this study, we have recommended combining a range of multidisciplinary geoscience research as well as a number of authentication methods to study and date this event. In addition, future efforts must be made to reconstruct the whole evolutionary sequence of this collision as well as to place events into a distinct time series.

Recent research has shown that the initial collision between India and Asia took place within the central section of the YTSZ between 65 Ma and 63 Ma, then spreading diachronously outwards towards both the eastern and western Himalayas. This contrasts with the previously generally accepted model which postulated an initial collision in the western Himalayas at 55-50 Ma then systematically shifted eastwards.

Paleomagnetic studies suggest that the Lhasa block was located between ca. 16°N and ca. 22°N during the Cretaceous and Paleogene, and that it drifted northwards to its present latitude at ca. 30°N subsequent to initial contact between the India and Asian plates. The GIB model, based on an extension of paleomagnetism, has not been confirmed by geological evidence; a change in the relative paleolatitude of India and the THS may be the result of counterclockwise rotation of GI during the Cretaceous rather than north-south extension.

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References

Abrajevitch A, Ali J, Aitchison J, Badengzhu J, Davis A, Liu J, Ziabrev S. 2005. Neotethys and the India-Asia collision: Insights from a palaeomagnetic study of the Dazhuqu ophiolite, southern Tibet. Earth Planet Sci Lett, 233: 87–102

Achache J, Courtillot V, Xiu Z Y. 1984. Paleogeographic and tectonic evolution of southern Tibet since Middle Cretaceous time: NEw paleomagnetic data and synthesis. J Geophys Res, 89: 10311–10339

Aikman A B, Harrison T M, Lin D. 2008. Evidence for early (>44 Ma) Himalayan crustal thickening, Tethyan Himalaya, southeastern Tibet. Earth Planet Sci Lett, 274: 14–23

Aikman A B, Harrison T M, Hermann J. 2012. The origin of Eo- and Neo-himalayan granitoids, Eastern Tibet. J Asian Earth Sci, 58: 143–157

Aitchison J C, Ali J R, Davis A M. 2007a. When and where did India and Asia collide? J Geophys Res, 112: B05423

Aitchison J C, Badengzhu J C, Davis A M, Liu J, Luo H, Malpas J G, McDermid I R C, Wu H, Ziabrev S V, Zhou M. 2000. Remnants of a Cretaceous intra-oceanic subduction system within the Yarlung-Zangbo suture (southern Tibet). Earth Planet Sci Lett, 183: 231–244

Aitchison J C, McDermid I R C, Ali J R, Davis A M, Zyabrev S V. 2007b. Shoshonites in Southern Tibet record Late Jurassic rifting of a Tethyan Intraoceanic Island Arc. J Geol, 115: 197–213

Ali J R, Aitchison J C. 2005. Greater India. Earth-Sci Rev, 72: 169–188

Ali J R, Aitchison J C. 2006. Positioning Paleogene Eurasia problem: Solution for 60–50 Ma and broader tectonic implications. Earth Planet Sci Lett, 251: 148–155

Allégre C J, Courtillot V, Tapponnier P, Hirn A, Mattauer M, Coulon C, Jaeger J J, Achache J, Schärer U, Marcoux J, Burg J P, Girardeau J, Armijo R, Gariépy C, Göpel C, Li T D, Xiao X C, Chang C F, Li G Q, Lin B Y, Teng J W, Wang N W, Chen G M, Han T L, Wang X B, Den W M, Sheng H B, Cao Y G, Zhou J, Qiu H G, Bao P S, Wang B X, Zhou Y X, Xu R H. 1984. Structure and evolution of the Himalaya-Tibet orogenic belt. Nature, 307: 17–22

Argand E. 1924. La tectonique de l' Asie. Brussels: Proceedings of the VIIIth International Geological Congress. 181–372

Batra R S. 1989. A reinterpretation of the geology and biostratigraphy of the Lower Tertiary Formations exposed along the Bilaspur-Shimla Highway, Himachal Pradesh, India. J Geol Soc Ind, 33: 503–523

Beck R A, Burbank D W, Sercombe W J, Riley G W, Barndt J K, Berry J R, Afzal J, Khan A M, Jurgen H, Metje J, Cheema A, Shafique N A, Lawrence R D, Khan M A. 1995. Stratigraphic evidence for an early collision between northwest India and Asia. Nature, 373: 55–58

Besse J, Courtillot V, Pozzi J P, Westphal M, Zhou Y X. 1984. Palaeomagnetic estimates of crustal shortening in the Himalayan thrusts and Zangbo suture. Nature, 311: 621–626

Bossart P, Ottiger R. 1989. Rocks of the Murree Formation in northern Pakistan: Indicators of a descending foreland basin of late Paleocene to middle Eocene age. Eclogae Geol Helv, 82: 133–165

Bouilhol P, Jagoutz O, Hanchar J M, Dudas F O. 2013. Dating the India-Eurasia collision through arc magmatic records. Earth Planet Sci Lett, 366: 163–175
Brown B J, Müller R D, Struckmeyer H I M, Gaina C, Stagg H, Symonds P. 2003. Formation and evolution of Australian passive margins: Implications for locating the boundary between continental and oceanic crust. Geol Soc Am Spec, 372: 223–243
Burg J P, Chen G M. 1984. Tectonics and structural zonation of southern Tibet, China. Nature, 311: 219–223
Cai F, Ding L, Yue Y. 2011. Provenance analysis of upper Cretaceous strata in the Tethys Himalaya, southern Tibet: Implications for timing of India-Asia collision. Earth Planet Sci Lett, 305: 195–206
Chen J, Huang B, Sun L. 2010. New constraints to the onset of the India-Asia collision: Paleomagnetic reconnaissance on the Linzizong Group in the Lhasa Block, China. Tectonophysics, 489: 189–209
Chen J, Huang B, Yi Z, Yang L, Chen L. 2014. Paleomagnetic and $^{40}Ar/^{39}Ar$ geochronological results from the Linzizong Group, Linzhou Basin, Lhasa Terrane, Tibet: Implications to Paleogene paleolatitude and onset of the India-Asia collision. J Asian Earth Sci, 96: 162–177
Chen W, Yang T, Zhang S, Yang Z, Li H, Wu H, Zhang J, Ma Y, Cai F. 2012. Paleomagnetic results from the Early Cretaceous Zenong Group volcanic rocks, Cuoqin, Tibet, and their paleogeographic implications. Gondwana Res, 22: 461–469
Clift P D, Carter A, Krol M, Kirby E. 2002. Constraints on India-Eurasia collision in the Arabian Sea region taken from the Indus Group, Ladakh Himalaya, India. In: Clift P D, Kroon D, Gaedicke C, et al, eds. The Tectonic and Climatic Evolution of the Arabian Sea Region. Geol Soc Lon Spec Pub, 195: 97–116
Critelli S, Garzanti E. 1994. Provenance of the Lower Tertiary Murree redbeds (Hazara-Kashmir Syntaxis, Pakistan) and initial rising of the Himalayas. Sediment Geol, 89: 265–284
DeCelles P G, Gehrels G E, Najman Y, Martin A J, Carter A, Garzanti E. 2004. Detrital geochronology and geochemistry of Cretaceous-Early Miocene strata of Nepal: Implications for timing and diachroneity of initial Himalayan orogenesis. Earth Planet Sci Lett, 227: 313–330
DeCelles P G, Kapp P, Gehrels G E, Ding L. 2014. Paleocene-Eocene foreland basin evolution in the Himalaya of southern Tibet and Nepal: Implications for the age of initial India-Asia collision. Tectonics, 33: 824–849
DeCelles P G, Robinson D M, Zandt G. 2002. Implications of shortening in the Himalayan fold-thrust belt for uplift of the Tibetan Plateau. Tectonics, 21: 12-1–12-25
Ding H, Zhang Z, Dong X, Tian Z, Xiang H, Mu H, Gou Z, Shui X, Li W, Mao L. 2016a. Early Eocene (c. 50 Ma) collision of the Indian and Asian continents: Constraints from the North Himalayan metamorphic rocks, southeastern Tibet. Earth Planet Sci Lett, 435: 64–73
Ding L, Cai F L, Wang H Q, Li Z Y, Li Y P. 2013. The research methods of Continental collision time. In: Ding Z L, ed. The Research Methods of Solid Earth Science (in Chinese). Beijing: Science China Press. 842–853
Ding L, Cai F L, Zhang Q H, Zhang L Y, Xu Q, Yang D, Liu D L, Zhong D L. 2009. Provenance and tectonic evolution of the foreland basin systems in the Gangdese-Himalayan collisional orogen belt (in Chinese). Chin J Geol, 44: 1289–1311
Ding L, Kapp P, Wan X. 2005. Paleocene-Eocene record of ophiolite obduction and initial India-Asia collision, south central Tibet. Tectonics, 24: TC3001
Ding L, Kapp P, Zhong D L, Deng W M. 2003. Cenozoic volcanism in Tibet: Evidence for a transition from oceanic to continental subduction. J Petrol, 44: 1833–1865
Ding L, Qasim M, Jadoon I A K, Khan M A, Xu Q, Cai F, Wang H, Baral U, Yue Y. 2016b. The India-Asia collision in north Pakistan: Insight from the U-Pb detrital zircon provenance of Cenozoic foreland basin. Earth Planet Sci Lett, 455: 49–61
Ding L, Zhong D, Yin A, Kapp P, Harrison T M. 2001. Cenozoic structural and metamorphic evolution of the eastern Himalayan syntaxis (Namche Barwa). Earth Planet Sci Lett, 192: 423–438
Ding L, Zhong D. 1999. Metamorphic characteristics and geotectonic implications of the high-pressure granulites from Namjagbarwa, eastern Tibet. Sci China Ser D-Earth Sci, 42: 491–505
Ding L. 2003. Paleocene deep-water sediments and radiolarian faunas: Implications for evolution of Yarlung-Zangbo foreland basin, southern Tibet. Sci China Ser D-Earth Sci, 46: 84–96
Donaldson D G, Webb A A G, Menold C A, Kylander-Clark A R C, Hacker B R. 2013. Petrochronology of Himalayan ultrahigh-pressure eclogite. Geology, 41: 835–838
Fuchs G, Willems H. 1990. The final stages of sedimentation in the Tethyan zone of Zanskarr and their geodynamic significance (Ladakh-Himalaya). Jahrbuche Geol Bundenstalt, 133: 259–273
Gaetani M, Garzanti E. 1991. Multicyclic History of the Northern India Continental-Margin (Northwestern Himalaya). AAPG Bull, 75: 1427–1446
Garzanti E, Baud A, Mascle G. 1987. Sedimentary record of the northward flight of India and its collision with Eurasia (Ladakh Himalaya, India). Geodin Acta, 1: 297–312
Gilder S, Chen Y, Sen S. 2001. Oligo-Miocene magnetostratigraphy and rock magnetism of the Xishuigou section, Subei (Gansu Province, western China) and implications for shallow inclinations in central Asia. J Geophys Res, 106: 30505–30521
Hall R. 2012. Late Jurassic-Cenozoic reconstructions of the Indonesian region and the Indian Ocean. Tectonophysics, 570-571: 1–41
Henderson A L, Najman Y, Parrish R, Mark D F, Foster G L. 2011. Constraints to the timing of India-Eurasia collision: A re-evaluation of evidence from the Indus Basin sedimentary rocks of the Indus-Tsangpo Suture Zone, Ladakh, India. Earth-Sci Rev, 106: 265–292
Hou Z Q, Zheng Y C, Zeng L S, Gao L E, Huang K X, Li W, Li Q Y, Fu Q, Liang W, Sun Q Z. 2012. Eocene-Oligocene granitoids in southern Tibet: Constraints on crustal anatexis and tectonic evolution of the Himalayan orogen. Earth Planet Sci Lett, 349-350: 38–52
Hu X, Garzanti E, Moore T, Raffi I. 2015. Direct stratigraphic dating of India-Asia collision onset at the Selandian (middle Paleocene, 59±1 Ma). Geology, 43: 859–862
Hu X, Garzanti E, Wang J, Huang W, An W, Webb A. 2016a. The timing of India-Asia collision onset—Facts, theories, controversies. Earth-Sci Rev, 160: 264–299
Hu X, Sinclair H D, Wang J, Jiang H, Wu F. 2012. Late Cretaceous-Palaeogene stratigraphic and basin evolution in the Zhepure Mountain of southern Tibet: Implications for the timing of India-Asia initial collision. Basin Res, 24: 520–543
Hu X, Wang J, BouDagher-Fadel M, Garzanti E, An W. 2016b. New insights into the timing of the India-Asia collision from the Paleogene Quxia and Jialazi formations of the Xigaze forearc basin, South Tibet. Gondwana Res, 32: 76–92
Huang W, Dupont-Nivet G, Lippert P C, van Hinsbergen D J J, Dekkers M J, Waldrip R, Ganerød M, Li X, Guo Z, Kapp P. 2015a. What was the Paleogene latitude of the Lhasa terrane? A reassessment of the geochronology and paleomagnetism of Linzizong volcanic rocks (Linzhou basin, Tibet). Tectonics, 34: 594–622
Huang W, Dupont-Nivet G, Lippert P C, van Hinsbergen D J J, Hallot E. 2013. Inclination shallowing in Eocene Linzizong sedimentary rocks from Southern Tibet: Correction, possible causes and implications for reconstructing the India-Asia collision. Geophys J Int, 194: 1390–1411
Huang W, van Hinsbergen D J J, Lippert P C, Guo Z, Dupont-Nivet G. 2015b. Paleomagnetic tests of tectonic reconstructions of the India-Asia collision zone. Geophys Res Lett, 42: 2642–2649
Huang W, van Hinsbergen D J J, Maffione M, Orme D A, Dupont-Nivet G, Guilmette C, Ding L, Guo Z, Kapp P. 2015c. Lower Cretaceous Xigaze ophiolites formed in the Gangdese forearc: Evidence from paleomagnetism, sediment provenance, and stratigraphy. Earth Planet Sci Lett, 415: 142–153
Jaeger J J, Courtillot V, Tapponnier P. 1989. Paleontological view of the ages

of the Deccan Traps, the Cretaceous/Tertiary boundary, and the India-Asia collision. Geology, 17: 316–319

Ji W Q, Wu F Y, Chung S L, Wang X C, Liu C Z, Li Q L, Liu Z C, Liu X C, Wang J G. 2016. Eocene Neo-Tethyan slab breakoff constrained by 45 Ma oceanic island basalt-type magmatism in southern Tibet. Geology, 44: 283–286

Kaneko Y, Katayama I, Yamamoto H, Misawa K, Ishikawa M, Rehman H U, Kausar A B, Shiraishi K. 2003. Timing of Himalayan ultrahigh-pressure metamorphism: Sinking rate and subduction angle of the Indian continental crust beneath Asia. J Metamorph Geol, 21: 589–599

Klootwijk C T, Conaghan P J, Nazirullah R, de Jong K A. 1994. Further palaeomagnetic data from Chitral (Eastern Hindukush): Evidence for an early India-Asia contact. Tectonophysics, 237: 1–25

Klootwijk C T, Gee J S, Peirce J W, Smith G M, McFadden P L. 1992. An early India-Asia contact: Paleomagnetic constraints from Ninetyeast Ridge, ODP Leg 121. Geology, 20: 395–398

Kodama K P. 2012. Paleomagnetism of Sedimentary Rocks: Process and Interpretation. Hoboken: John Wiley & Sons

Leech M L, Singh S, Jain A K, Klemperer S L, Manickavasagam R M. 2005. The onset of India-Asia continental collision: Early, steep subduction required by the timing of UHP metamorphism in the western Himalaya. Earth Planet Sci Lett, 234: 83–97

Li G B, Wan X Q, Qi H, Liang D Y, Liu W C. 2002. Eocene fossil carbonate microfacies and sedimentary enviroment in Gangba-Tingri, Southern Tibet (in Chinese). Geol China, 29: 401–406

Li Z, Ding L, Song P, Fu J, Yue Y. 2017. Paleomagnetic constraints on the paleolatitude of the Lhasa block during the Early Cretaceous: Implications for the onset of India-Asia collision and latitudinal shortening estimates across Tibet and stable Asia. Gondwana Res, 41: 352–372

Li Z, Ding L, Lippert P C, Song P, Yue Y, van Hinsbergen D J J. 2016. Paleomagnetic constraints on the Mesozoic drift of the Lhasa terrane (Tibet) from Gondwana to Eurasia. Geology, 44: 727–730

Liebke U, Appel E, Ding L, Neumann U, Antolin B, Xu Q. 2010. Position of the Lhasa terrane prior to India-Asia collision derived from palaeomagnetic inclinations of 53 Ma old dykes of the Linzhou Basin: Constraints on the age of collision and post-collisional shortening within the Tibetan Plateau. Geophys J Int, 182: 1199–1215

Lin J, Watts D R. 1988. Palaeomagnetic results from the Tibetan Plateau. Philos Trans R Soc A-Math Phys Eng Sci, 327: 239–262

Lippert P C, van Hinsbergen D J J, Dupont-Nivet G. 2014. Early Cretaceous to present latitude of the central proto-Tibetan Plateau: A paleomagnetic synthesis with implications for Cenozoic tectonics, paleogeography, and climate of Asia. Geol Soc Am Spec Pap, 507: 1–21

Liu Z C, Wu F Y, Ji W Q, Wang J G, Liu C Z. 2014. Petrogenesis of the Ramba leucogranite in the Tethyan Himalaya and constraints on the channel flow model. Lithos, 208-209: 118–136

Ma Y, Yang T, Bian W, Jin J, Zhang S, Wu H, Li H. 2016. Early Cretaceous paleomagnetic and geochronologic results from the Tethyan Himalaya: Insights into the Neotethyan paleogeography and the India-Asia collision. Sci Rep, 6: 21605

Ma Y, Yang T, Yang Z, Zhang S, Wu H, Li H, Li H, Chen W, Zhang J, Ding J. 2014. Paleomagnetism and U-Pb zircon geochronology of Lower Cretaceous lava flows from the western Lhasa terrane: New constraints on the India-Asia collision process and intracontinental deformation within Asia. J Geophys Res-Solid Earth, 119: 7404–7424

Meng J, Wang C, Zhao X, Coe R, Li Y, Finn D. 2012. India-Asia collision was at 24°N and 50 Ma: Palaeomagnetic proof from southernmost Asia. Sci Rep, 2: 925

Najman Y. 2005. The detrital record of orogenesis: A review of approaches and techniques used in the Himalayan sedimentary basins. Earth-Sci Rev, 74: 1–72

Najman Y, Appel E, Boudagher-Fadel M, Bown P, Carter A, Garzanti E, Godin L, Han J, Liebke U, Oliver G, Parrish R, Vezzoli G. 2010. Timing of India-Asia collision: Geological, biostratigraphic, and palaeomagnetic constraints. J Geophys Res, 115: B12416

Najman Y, Pringle M, Godin L, Oliver G. 2001. Dating of the oldest continental sediments from the Himalayan foreland basin. Nature, 410: 194–197

Patriat P, Achache J. 1984. India-Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates. Nature, 311: 615–621

Patzelt A, Li H, Wang J, Appel E. 1996. Palaeomagnetism of Cretaceous to Tertiary sediments from southern Tibet: Evidence for the extent of the northern margin of India prior to the collision with Eurasia. Tectonophysics, 259: 259–284

Pozzi J P, Westphal M, Xiu Zhou Y, Sheng Xing L, Yao Chen X. 1982. Position of the Lhasa block, South Tibet, during the late Cretaceous. Nature, 297: 319–321

Pullen A, Kapp P, DeCelles P G, Gehrels G E, Ding L. 2011. Cenozoic anatexis and exhumation of Tethyan Sequence rocks in the Xiao Gurla Range, Southwest Tibet. Tectonophysics, 501: 28–40

Qi X X, Zeng L S, Meng X J, Xu Z Q, Li T F. 2008. Zircon SHRIMP U-Pb dating for Dala granite in the Tethyan Himalaya and its geological implication (in Chinese). Acta Petrol Sin, 24: 1501–1508

Ratschbacher L, Frisch W, Liu G, Chen C. 1994. Distributed deformation in southern and western Tibet during and after the India-Asia collision. J Geophys Res, 99: 19917–19945

Rowley D B. 1996. Age of initiation of collision between India and Asia: A review of stratigraphic data. Earth Planet Sci Lett, 145: 1–13

Rowley D B. 1998. Minimum age of initiation of collision between India and Asia North of everest based on the subsidence history of the Zhepure Mountain section. J Geol, 106: 220–235

Searle M P, Windley B F, Coward M P, Cooper D J W, Rex A J, Rex D, Tingdong L, Xuchang X, Jan M Q, Thakur V C, Kumar S. 1987. The closing of Tethys and the tectonics of the Himalaya. Geol Soc Am Bull, 98: 678–701

Sun Z, Jiang W, Li H, Pei J, Zhu Z. 2010. New paleomagnetic results of Paleocene volcanic rocks from the Lhasa block: Tectonic implications for the collision of India and Asia. Tectonophysics, 490: 257–266

Sun Z, Pei J, Li H, Xu W, Jiang W, Zhu Z, Wang X, Yang Z. 2012. Palaeomagnetism of late Cretaceous sediments from southern Tibet: Evidence for the consistent palaeolatitudes of the southern margin of Eurasia prior to the collision with India. Gondwana Res, 21: 53–63

Tan X, Gilder S, Kodama K P, Jiang W, Han Y, Zhang H, Xu H, Zhou D. 2010. New paleomagnetic results from the Lhasa block: Revised estimation of latitudinal shortening across Tibet and implications for dating the India-Asia collision. Earth Planet Sci Lett, 293: 396–404

Tang X D, Huang B C, Yang L K, Yi Z Y, Qiao Q Q, Chen L W. 2013. Paleomagnetism and Ar-Ar geochronology of Cretaceous volcanic rock in the middle Lhasa terrane, China and tectonic implications (in Chinese). Chin J Geophy, 56: 136–149

Tapponnier P, Mercier J L, Proust F, Andrieux J, Armijo R, Bassoullet J P, Brunel M, Burg J P, Colchen M, Dupré B, Girardeau J, Marcoux J, Mascle G, Matte P, Nicolas A, Li T D, Xiao X C, Chang C F, Lin P Y, Li G C, Wang G M, Han T L, Wang X B, Den W M, Zhen H X, Sheng H B, Cao Y G, Qiu H R. 1981. The Tibetan side of the India-Eurasia collision. Nature, 294: 405–410

Tapponnier P, Peltzer G, Le Dain A Y, Armijo R, Cobbold P. 1982. Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine. Geology, 10: 611–616

Tauxe L. 2005. Inclination flattening and the geocentric axial dipole hypothesis. Earth Planet Sci Lett, 233: 247–261

Tonarini S, Villa I M, Oberli F, Meier M, Spencer D A, Pognante U, Ramsay J G. 1993. Eocene age of eclogite metamorphism in Pakistan Himalaya: Implications for India-Eurasia collision. Terra Nova, 5: 13–20

Treloar P J, O'Brien P J, Parrish R R, Khan M A. 2003. Exhumation of early Tertiary, coesite-bearing eclogites from the Pakistan Himalaya. J Geol Soc, 160: 367–376 van Hinsbergen D J J, Lippert P C, Dupont-Nivet G, McQuarrie N, Doubrovine P V, Spakman W, Torsvik T H. 2012. Greater India Basin hypothesis and a two-stage Cenozoic collision between India and Asia. Proc Natl Acad Sci USA, 109: 7659–7664

Wan X Q, Liang D Y, Li G B. 2001. Palaeocene strata in Gamba, Tibet and influence of Tectonism (in Chinese). Acta Geol Sin, 76: 155–162

Wang C, Li X, Hu X, Jansa L F. 2002. Latest marine horizon north of Qomolangma (Mt Everest): Implications for closure of Tethys seaway and collision tectonics. Terra Nova, 14: 114–120

Wang C, Dai J, Zhao X, Li Y, Graham S A, He D, Ran B, Meng J. 2014. Outward-growth of the Tibetan Plateau during the Cenozoic: A review. Tectonophysics, 621: 1–43

Wang H Q, Ding L, Cai F L, Xu Q, Li S, Fu J J, Lai Q Z, Yue Y H, Li X. 2017. Early Tertiary deformation of the Zhongba-Gyangze Thrust in central southern Tibet. Gondwana Res, 41: 235–248

Wang J, Hu X, Jansa L, Huang Z. 2011. Provenance of the Upper Cretaceous-Eocene Deep-Water Sandstones in Sangdanlin, Southern Tibet: Constraints on the Timing of Initial India-Asia Collision. J Geol, 119: 293–309

Westphal M, Pozzi J P. 1983. Paleomagnetic and plate tectonic constraints on the movement of Tibet. Tectonophysics, 98: 1–10

Wilke F D H, O'Brien P J, Gerdes A, Timmerman M J, Sudo M, Khan M A. 2010. The multistage exhumation history of the Kaghan Valley UHP series, NW Himalaya, Pakistan from U-Pb and $^{40}Ar/^{39}Ar$ ages. Eur J Mineral, 22: 703–719

Willems H, Zhou Z, Zhang B, Gräfe K U. 1996. Stratigraphy of the upper cretaceous and lower tertiary strata in the Tethyan Himalayas of Tibet (Tingri area, China). Geol Rundsch, 85: 723–754

Wu F Y, Clift P D, Yang J H. 2007. Zircon Hf isotopic constraints on the sources of the Indus Molasse, Ladakh Himalaya, India. Tectonics, 26: TC2014

Wu F Y, Ji W Q, Wang J G, Liu C Z, Chung S L, Clift P D. 2014. Zircon U-Pb and Hf isotopic constraints on the onset time of India-Asia collision. Am J Sci, 314: 548–579

Wu F Y, Liu Z C, Liu X C, Ji W Q. 2015. Himalayan leucogranite: Petrogenesis and implications to orogenesis and plateau uplift (in Chinese). Acta Petrol Sin, 31: 1–36

Xie K J, Zeng L S, Liu J, Gao L E. 2010. Late Eocene Dala adakitic granite, Southern Tibet and geological implication (in Chinese). Acta Petrol Sin, 26: 1016–1026

Xu Z, Ji S, Cai Z, Zeng L, Geng Q, Cao H. 2012. Kinematics and dynamics of the Namche Barwa Syntaxis, eastern Himalaya: Constraints from deformation, fabrics and geochronology. Gondwana Res, 21: 19–36

Yan M, Van der Voo R, Tauxe L, Fang X, M Parés J. 2005. Shallow bias in Neogene palaeomagnetic directions from the Guide Basin, NE Tibet, caused by inclination error. Geophys J Int, 163: 944–948

Yang T, Ma Y, Bian W, Jin J, Zhang S, Wu H, Li H, Yang Z, Ding J. 2015a. Paleomagnetic results from the Early Cretaceous Lakang Formation lavas: Constraints on the paleolatitude of the Tethyan Himalaya and the India-Asia collision. Earth Planet Sci Lett, 428: 120–133

Yang T, Ma Y, Zhang S, Bian W, Yang Z, Wu H, Li H, Chen W, Ding J. 2015b. New insights into the India-Asia collision process from Cretaceous paleomagnetic and geochronologic results in the Lhasa terrane. Gondwana Res, 28: 625–641

Yi Z Y, Huang B C, Chen J, Wang H. 2011. Paleomagnetism of early Paleogene marine sediments in southern Tibet, China: Implications to onset of the India-Asia collision and size of Greater India. Earth Planet Sc Lett, 309: 153–165

Yi Z, Huang B, Yang L, Tang X, Yan Y, Qiao Q, Zhao J, Chen L. 2015. A quasi-linear structure of the southern margin of Eurasia prior to the India-Asia collision: First paleomagnetic constraints from Upper Cretaceous volcanic rocks near the western syntaxis of Tibet. Tectonics, 34: 1431–1451

Yin A, Harrison T M. 2000. Geologic Evolution of the Himalayan-Tibetan Orogen. Annu Rev Earth Planet Sci, 28: 211–280

Zeng L S, Gao L E, Tang S, Hou K J, Guo C L, Hu G Y. 2014. Eocene magmatism in the Tethyan Himalaya, southern Tibet. Geol Soc Lon Spec Pub, 412: 287–316

Zeng L, Gao L E, Xie K, Liu-Zeng J. 2011. Mid-Eocene high Sr/Y granites in the Northern Himalayan Gneiss Domes: Melting thickened lower continental crust. Earth Planet Sci Lett, 303: 251–266

Zhang J, Ji J, Zhong D, Ding L, He S. 2004. Structural pattern of eastern Himalayan syntaxis in Namjagbarwa and its formation process. Sci China Ser D-Earth Sci, 47: 138–150

Zhang L L, Liu C Z, Wu F Y, Ji W Q, Wang J G. 2014. Zedong terrane revisited: An intra-oceanic arc within Neo-Tethys or a part of the Asian active continental margin? J Asian Earth Sci, 80: 34–55

Zhang Q, Willems H, Ding L, Gräfe K U, Appel E. 2012. Initial India-Asia Continental Collision and Foreland Basin Evolution in the Tethyan Himalaya of Tibet: Evidence from Stratigraphy and Paleontology. J Geol, 120: 175–189

Zhu B, Kidd W S F, Rowley D B, Currie B S, Shafique N. 2005. Age of Initiation of the India-Asia Collision in the East-Central Himalaya. J Geol, 113: 265–285

Zhuang G, Najman Y, Guillot S, Roddaz M, Antoine P O, Métais G, Carter A, Marivaux L, Solangi S H. 2015. Constraints on the collision and the pre-collision tectonic configuration between India and Asia from detrital geochronology, thermochronology, and geochemistry studies in the lower Indus basin, Pakistan. Earth Planet Sci Lett, 432: 363–373