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Plate Reconstructions and Mantle Dynamics Leading to the India–Asia Collision

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1.1. Introduction

The origin of the Himalayan range and Tibetan Plateau, the highest morphological feature of the Earth, has always been highly debated. Following the early thermal contraction models of the 19th century, Argand (1924) was the first to suggest that the Himalaya and Tibetan Plateau orogenesis resulted from the convergence of the Indian and Eurasian continents: *le jeu dominant, c'est le rapprochement de deux serres continentales, l'Indo-Afrique et la vieille Eurasie, avec rétrécissement de la Téthys*[1]. In this early view, India (with Africa) and Eurasia continents (named Sial) are moving on a "Sima" basement (previous name of the mantle) and separated on oceanic basin the Tethys (Figure 1.1). This view was applied by Wegener (1929) in his famous

1. The dominant game is the approach of two continents, Indo-Africa and old Eurasia, with a shrinking of the Tethys.

Himalaya, Dynamics of a Giant 1,
coordinated by Rodolphe CATTIN and Jean-Luc EPARD.

continental drift model. Wegener also recognized the long journey of India across the Tethys Ocean. Based on evidence of Carboniferous glaciation on the Indian continent, and the lack of such features in Asia, he assumed that India used to be located close to the South Pole while Asia was in the northern hemisphere. Most ensuing models then related the Himalayan building with the shortening of the Tethyan "geosyncline" during the northward migration of the Indian continent across the Tethys Ocean, and recognized the remains of these oceanic domains in the rocks constituting the "Tethyan Himalaya Unit"(Gansser 1964; Holmes 1965, see Volume 2 – Chapter 3)

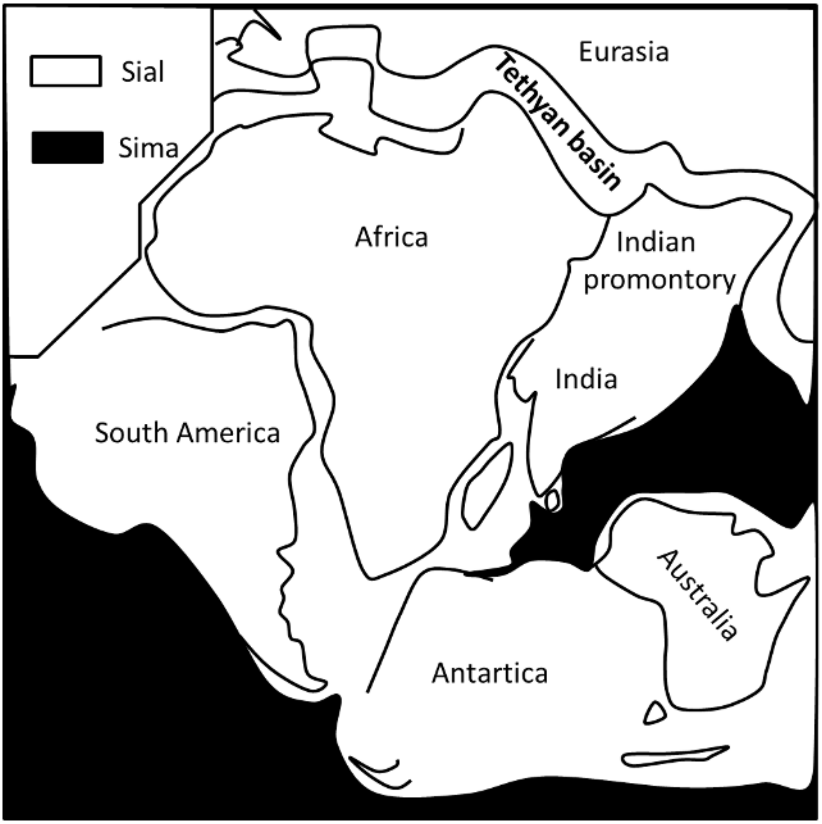

Figure 1.1. *Gondwana configuration before the Atlantic Ocean opening. Redrawn after Argand (1924)*

Then came the plate tectonic model revolution conceptualized by Holmes (1965), initiated by Hess (1962), observations of marine magnetic anomalies and their interpretation to infer tectonic plate motion by Vine and Matthews (1963). Dewey and Bird (1970) proposed that the Tethyan basin was actually made of oceanic crust, recognized oceanic rocks in the Himalaya as remnants of oceanic crust (later called ophiolites) trapped in suture zones between colliding continental plates following closure of the "Neotethys Ocean" (see Volume 2 – Chapter 2).

The first paleogeographic reconstruction of India's northward migration across the Neotethys includes early paleomagnetic results and the development of the global tectonic plate circuits based on marine magnetic anomalies (see section 1.2.1 for methodology; Pozzi et al. 1982; Patriat and Achache 1984; Molnar and Tapponnier 1995). These reconstructions allowed estimating throughout geological history, the rate and direction of the Indian lithosphere displacement with respect to Eurasia (Figure 1.2). A slowdown of India–Asia convergent around 50 Ma was readily interpreted as the timing of continental collision (Figure 1.2; Patriat and Achache 1984).

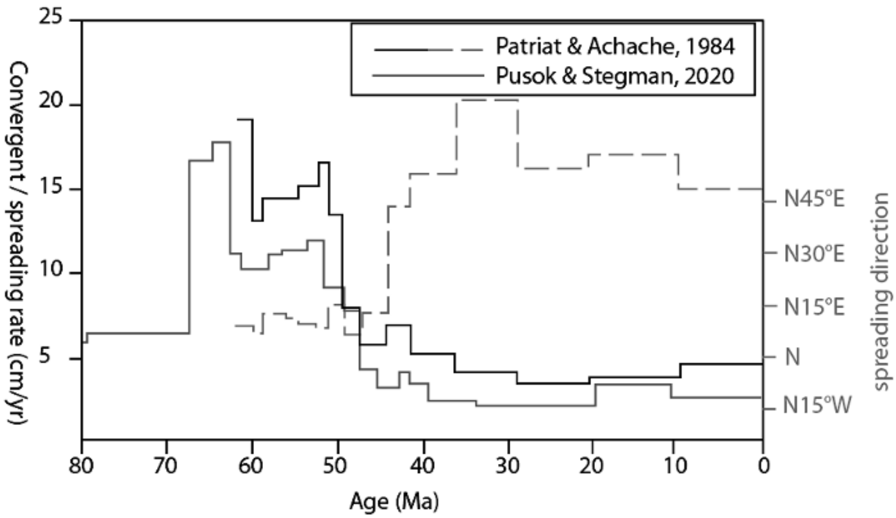

Figure 1.2. *Examples of the spreading rate and direction of the Central Indian Ridge (India–Africa) reconstructions based on marine magnetic anomalies data. For a color version of this figure, see www.iste.co.uk/cattin/himalaya1.zip*

Since this pioneering work, the development of geophysical techniques and the accumulation of geological data has led to refinements in kinematic plate reconstructions and continental deformation allowing for precise models of the paleogeographic evolution and involved geodynamic processes.

In this chapter, we will review current data and models proposed for the India–Asia convergence history, including the age of the continental collision and the geodynamic configuration.

1.2. The India–Asia convergence and the age of the collision

1.2.1. *The India–Asia convergence*

The relative motions of tectonic plates are estimated through time using plate kinematic reconstructions built on the basis of “Euler poles” determined from “marine magnetic anomalies” globally defining a “plate circuit” (Hellinger 1981; Cox and Hart 1986; Torsvik et al. 2012; Müller et al. 2016). Interestingly, in the case of India and Eurasia since 120 Ma, the relative motion cannot be directly measured by marine magnetic anomalies because the oceanic lithosphere of the Neotethys between these plates has been consumed at subduction zones. The convergence is thus estimated indirectly through the plate circuit from India to Africa to South America to North America to Eurasia. Uncertainties thus accumulate and, for example, there are issues in determining the Indian–African kinematics because of the non-rigidity of the eastern African plate separating with the Nubian plate (e.g. Royer et al. 2006). However, uncertainties on the relative positions between India and Eurasia remain relatively low, within a few hundred kilometers depending on how well the corresponding Euler pole is defined and on the age of the geomagnetic reversal defining the marine magnetic anomalies (Capitanio et al. 2010).

The results show that India and Asia have been converging at high rates since 120 Ma with a sharp decrease at approximately 50 Ma that has been originally attributed to the onset of the India–Asia continental collision (Figure 1.2; Patriat and Achache 1984). Note that after 50 Ma, the relative convergence until today amounts to ca. 4,000 km. This implies that, if 50 Ma is indeed the age of the continental collision, this amount of the Indian and Asian continental lithosphere has disappeared in processes such as compressive deformation, continental subduction and lithospheric extrusion and detachment as will be discussed further below. Therefore, kinematic models are constantly being improved to quantify in detail the India–Asia convergence in order to further infer geodynamic processes involved in the continental collision (e.g. Copley et al. 2011; Capitanio et al. 2015; Webb et al. 2017; Schellart et al. 2019). Notably, sharp variations in the convergence have been interpreted to relate to more complex collision models discussed further below (Van Hinsbergen et al. 2012; Jagoutz et al. 2015; Pusok and Stegman 2020, see section 1.4.3 for discussion)). Also, convergence variations have been related to deep processes such as plumes (van Hinsbergen et al. 2011a) or slab break-off (Mahéo et al. 2009), to the nature of ocean floor sediments facilitating subduction (Behr and Becker 2018) or to thickening of the Asian lithosphere hindering subduction (Molnar and Stock 2009). In addition, changes in the convergence direction implying a rotation of India with respect to Asia (Figure 1.2) have been interpreted as resulting from the diachronous collision starting in the West and finishing in the East (e.g. Klootwijk et al. 1992; Patzelt et al. 1996; Hu et al. 2016). Other potential origins include progressive West to East tearing of the subducting Neotethys slab, breaking off the India plate following the continental plate collision (Replumaz et al. 2010) or to surface processes such as monsoons along the Himalayan front (Iaffaldano et al. 2011; Husson et al. 2014).

1.2.2. *The age of the India–Asia collision*

When India collided with Asia has been highly debated in the last decade and remains a major controversy. First of all, the collision age must be defined because the collision involves many processes that may be taking place at different times. The collision age considered here is the time at which the converging continental plates come into contact. This initial contact is potentially associated with the cessation of marine deposition, ophiolite obduction, continental subduction and crustal deformation of the underthrusting plate. The processes leave traces in the rocks that can help decipher their precise chronology of what happened during the collision. In the Indo–Asia convergent zone, the collision has been originally assumed to have occurred along the Indus–Yarlung suture zone (Allègre et al. 1984). This suture zone is characterized by remnants of oceanic lithosphere between the India and the Asian plates. It now separates the Lhasa terrane (the southernmost terrane of Asia, or “Greater Asia”) from the Tethyan Himalaya sediments that are generally interpreted to represent the northern passive margin of India, or “Greater India” (e.g. Figure 1.3).

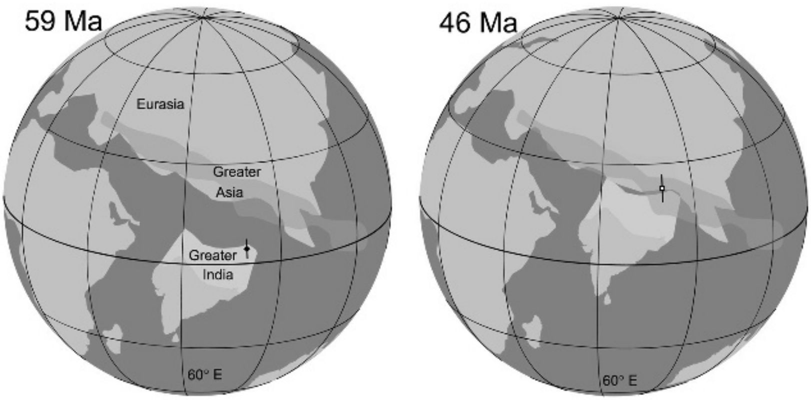

Figure 1.3. *India–Asia collision. The yellow parts of the continents are precisely constrained with the global plate circuit based on marine magnetic anomalies (see the text). The past continental extents are constrained by paleolatitude estimates from paleomagnetic data recovered from rocks of the “Greater India” and “Greater Asia” fragments (black and white dots respectively; modified from Dupont-Nivet et al. 2010). The gray shading indicates a continuous seismic tomography positive anomaly in the mantle, interpreted as the remnant of the subducted lithospheric slab of the Neotethys, that would have broken off at the time and location of the collision (see the text). For a color version of this figure, see www.iste.co.uk/cattin/himalaya1.zip*

Various methods are used to constrain the timing of India–Asia contact (see DeCelles et al. (2014), Hu et al. (2016), Kapp and DeCelles (2019) for detailed reviews).

1.2.2.1. *Decrease in India–Asia convergence rates*

As previously discussed, reconstructions of the Indian plate kinematics based on paleomagnetic data indicate significant variation of the convergent rates with Asia. The evidence of a sharp decrease in the convergent rate at about 55–50 Ma was originally attributed to the collision with the onset of subduction of the Indian Continental margin beneath the Asia plate slowing down the convergence (Figure 1.2; Patriat and Achache 1984). However, deceleration of convergent rates may also be related to other features such as interaction with the Deccan Plume (van Hinsbergen et al. 2011a) or breakoff of the Neotethys oceanic lithosphere which was driving the continental subduction (Mahéo et al. 2009) as discussed above.

1.2.2.2. *Reconstruction of relative plate positions*

Another way to estimate the timing of collision based on paleomagnetism is to reconstruct in time the past latitudinal positions of rocks preserved in the collision zone that formed on the northern margin of Indian and on the southern margin of Asia before and during the collision (Figure 1.3; see the paleomagnetic methods in detail in 1.3.1). The age at which both paleolatitude start to overlap is thus interpreted as the age and paleolatitude of collision. This powerful approach enables us to position past continental slivers involved in the collision, but by itself it cannot resolve if these slivers were really at the end of Indian and Asian promontories or if they were separated from these continents by large oceans.

1.2.2.3. *Provenance of detrital sediments*

As the continent margins of India and Asia are coming into contact, detrital sediments may travel across the future suture zone. The provenance of detrital material usually bears characteristic features that enable us to distinguish its source continent, based on mineralogy, coupled with mineral (especially zircon) geochemical composition and ages (e.g. Critelli and Garzanti 1994; DeCelles et al. 1998). The most recent estimates based on detrital evidence of Asian detritus onto the India passive margin as it arrived in the collision zone pinpoint the collision age precisely ca. 58–60 Ma (e.g. DeCelles et al. 2014; Hu et al. 2016; Najman et al. 2017; Garzanti et al. 2018; Garzanti 2019). However, although the age is well constrained, the source of some detrital sediments is highly debated because its Asian provenance, characterized by distinct signatures from the Yarlung Zangpo suture, may be ambiguous. Indeed, several authors suggest that some of these distinctively Asian sediments may actually be sourced from intraoceanic units, such as the Kohistan–Ladakh arc. The latter came into collision first with India coming northward at about 55–60 Ma and only later with Asia at about 40–50 Ma (Bouilhol et al. 2013; Jagoutz et al. 2015; Bhattacharya et al. 2020; Martin et al. 2020). Such interpretation has strong incidences on plate reconstructions that will be discussed in the following section.

1.2.2.4. *Paleontological records*

Records use Indian fossil first occurrences in Asia to evidence potential land connections for biotic interchange between Asia and India (e.g. Jaeger et al. 1989; Ali and Aitchison 2008). However, changes in landmass connection related to the sea-level change as well as plate tectonic may have induced more complex biological interactions than previously thought (Chatterjee and Scotese 2010). More recently, these results have been combined with statistical analyses of molecular phylogenies showing that interchange can significantly pre- or post-date the collision time depending on various taxon transports and the occurrence of inter-continental weepstake dispersals through rafting (e.g. Krause et al. 2019). In fine, the estimates are relatively imprecise and more relevant to document the impact of the collision on biotic evolution than the opposite.

1.2.2.5. *Continental subduction*

Following collision, the Indian north continental margin is temporally subducted beneath India as a consequence of the subducting Neotethys ocean slab drag, taking rocks to great depths where minerals are formed and transformed at so-called ultrahigh pressures (UHP). Some of these rocks are later exhumed and can be collected today in the collision zone. Then, the timing of the UHP Indian continental rock formation can be dated with the associated thermochronological systems and these ages will provide an upper bond for the onset of collision. Such rocks are only preserved in western Himalaya, as other high-pressure rocks from central Himalaya are relicts partially retromorphosed in granulite facies conditions during collision that has obliterated most of the UHP minerals (see Guillot et al. (2008), and Volume 2 – Chapter 4 for details). The ages of the UHP metamorphism range from 53 to 46 Ma, thus imply that continental subduction of the north Indian margin was already ongoing at that time in western Himalaya and thus that continental collision had already occurred. Note that this timing is consistent with the slowdown of the India convergence rate that was indeed attributed to continental subduction. However, the question remains if this metamorphism is recording the subduction of India beneath Asia or beneath some intraoceanic arc.

1.2.2.6. *Magmatism (cessation and onset)*

Magmatic pulses and associated sources generated by the subduction of various materials during the convergence and collision may also help reconstruct the geodynamic evolution and in turn constrain the timing of collision. The closure of the Neotethys Ocean by subduction is related to several magmatic episodes, especially the emplacement of the Gangdese or Transhimalaya arc along the south Asian active continental margin (Allègre et al. 1984; Kapp and DeCelles 2019). However, the magmatic evolution of the Gandese arc is relatively complex with arc-like magmatic rocks emplaced from Paleocene to Miocene time (e.g. Chung et al. (2005), Zhu et al. (2015), Ma et al. (2022), for review). Actually, several processes may explain this magmatism including oceanic and continental subduction, slab breakoff, roll-back or delamination. Using the magmatism to constrain the transition from oceanic to continental collision is thus complex and led to various collision estimates ranging from 40 Ma to 60 Ma (see Hu et al. (2016), for detailed review).

1.2.2.7. *Sedimentary evolution*

Contact between previously separated continents and ongoing crustal deformation will have significant impact on sedimentary evolution and basin dynamics. Sediment records related to collision include cessation of oceanic sedimentation, change in basin dynamic recorded by major unconformities as well as the developement of a foreland basin on the India continent or detrital sedimentation on the suture zone. These sedimentary records may postdate collision, but some, such as cessation of marine sedimentation, may occur several million years after collision depending on sea level changes. One of the most convincing and well-constrained sedimentary records of the collision is the developement and evolution of a foreland basin related to Indian plate flexuration following continental subduction as well as ophiolite obduction (Garzanti et al. 1987; Beck et al. 1996; DeCelles et al. 2002). Detailed stratigraphic studies in the western Himalaya (e.g. Garzanti et al. 1987; Guillot et al. 2003) evidence sedimentation change at about 55 Ma related to flexuration of the Indian Continental margin beneath the obduction Neotethys ophiolite. This implies that Indian continental subduction was already ongoing at about 55 Ma as suggested by UHP rock age as well as convergent rate decrease and thus place collision before 55 Ma. Similarly, stratigraphic data from the westernmost Himalaya (Beck et al. 1996; Rowley 1996) evidence that collision occurred as early as late Cretaceous, leading to the suggestion of a West to East diachronous collision, as confirmed by the more recent stratigraphic compilations along the Himalaya (Hu et al. 2016).

1.2.2.8. *Crustal deformation*

During the collision, the Indian continental crust underthrusted beneath the Asia margin (or beneath an intraoceanic arc) records significant deformation that can be quantified and dated. Especially south verging deformation (top to the south thrusting and recumbent folding) within the Indian continental margin sedimentary cover, the Tehyan Himalaya is expected. The oldest of such shortening-related structures and contemporaneous metamorphism are comprised between 44 and 54 Ma (seeHu et al. (2016), for review). 66 to 55 Ma accretionnay-wegde structures have also been recognized in the Tethyan Himalaya sediments from northwestern Pakistan (Beck et al. 1995). Once again, potential arc-continent collision may also account for such features.

In summary, several methods suggest that India–Asia collision occurred at about 60–55 Ma. However, earliest (65 Ma) and latest (40 Ma) timings were also proposed. The convergence between India and Asia has been originally mostly viewed as a simple convergence associated with a unique subduction zone. However, as already suggested above, more complex settings have been proposed in approximately the last 15 years. Notably the Aitchison et al. (2007) seminal study involving possible intraoceanic subduction zones and a related intraoceanic arc that may have come into collision with the Indian continent as it was arriving from the south. In that view, India would then continue to move pushing northward the intraoceanic arc at its front until reaching the southern margin of the Asian continent. These ideas have led to a resurgence of models, data and controversies to better reconstruct the India–Asia collision. Crucial to testing these various models are the aforementioned methods to reconstruct the chronology of events associated with the collision and the position and shape of the Indian and Asian continents before collision. We now review the plate configuration models in the following two sections and discuss their implications on the current debate on the evolution of the India–Asia collision.

TO GO FURTHER ON PALEOMAGNETISM.

The tectonic plate circuit, based on retro-fitting marine magnetic anomalies of the same age, enables us to constrain only provides the motion of large tectonic plates relative to each other. However, the position through time of the plate circuit with respect to the Earth's axis still needs to be defined. On geologic time scales, the geographic north it is indistinguishable from the position of the Earth's magnetic pole which can be determined with paleomagnetic data properly acquired (Butler 1992). Because of tectonic plates moving, the resulting paleomagnetic poles appear to move through geologic time on a path called the apparent polar wander path (APWP). Using the plate circuit, the paleomagnetic data from all tectonic plates can be rotated into a synthetic global APWP (Besse and Courtillot 2002; Torsvik et al. 2012). This enables us to combine paleomagnetic datasets from all plates and reduce uncertainties on the position of the plate circuit with respect to the Earth's axis. An alternative method consists of using the position of plates with respect to hotspot tracks (e.g. Müller et al. 2018). But hotspots in the mantle move with respect to the Earth's axis and still require to be referenced using paleomagnetic data from hotspots.

The plate circuit and associated global APWP are particularly important to place quantitative constraints on amounts and rates of shortening accommodated in the Himalaya–Tibetan orogen, as well as to identify ages of the India–Asia collision. These arguments eventually lie at the basis of spectacular geodynamic and tectonic processes, such as tectonic extrusion, the possibility of many hundreds of kilometers of continental subduction, and consumption of well over 1,000 km of a continental overriding plate during ocean closure and continent–continent collision. However, the synthetic APWP remains based on too limited low amounts of data. As a result, sliding windows of 10, 20 or even 50 Ma are used, filtering out "details" in plate motions. Recent efforts have identified issues in the statistical methods estimating uncertainties on the APWP and are actively working on developing new methods incorporating various datasets to reduce APWP uncertainties and ultimately better define the India–Asia convergence evolution (Rowley 2019; van Hinsbergen et al. 2021; Vaes et al. 2022).

1.3. Plate collision configurations

1.3.1. *Reconstructing lost continental margins*

During the convergence and the collision, portions of the north Indian and south Asian continental margins have been lost mainly through continental subduction (India) or crustal shortening. These processes must be taken into account to restore the initial shape of the colliding continents and thus better estimate the timing of collision. This can be done with various methods, in particular structural geology to estimate the amount of crustal shortening and paleomagnetism to reconstruct past latitudes of continental blocks involved in the collision.

Early view of the pre-Himalayan India by Argand (1924) already suggested that a vast continental domain, the Indian promontory, disappeared under Asia during collision (Figure 1.1). With the later recognition of the existence of the Neotethys Ocean subduction, the size of such a promontory was significantly reduced. However, the initial size of a Greater India and Greater Asia that disappeared after the collision is still highly debated because of important implications on the geodynamic models that best describe the collision (e.g. Aitchison et al. 2007; Jagoutz et al. 2015). As a result, considerable efforts have been made in constraining the past configuration of the collision zone, usually performed by combining datasets from structural geology and paleomagnetism (e.g. Chen et al. 1993; Van Hinsbergen et al. 2011b).

The vast amount of structural data available from the various components of the collision zone, mostly shortening and strike-slip, has been compiled to provide quantitative estimates of how much convergence may be accommodated by crustal deformation and where (e.g. Dewey et al. 1988; Guillot et al. 2003; Van Hinsbergen et al. 2011b). These generally constitute minimum estimates as cumulative structural offset data is rarely exhaustive and usually fails to integrate ductile deformation. Nevertheless, van Hinsbergen et al. (2011a), end up with 600–1,000 km of cumulated shortening for Greater Asia and about 1,000 km for Greater India since the collision. These values are particularly interesting when compared to the convergence estimates from the plate circuits (Huang et al. 2015; van Hinsbergen et al. 2019). These values virtually exclude simple continental collision models since 50 Ma, let alone 60 Ma, imply more than the double convergence to be accommodated by continental crust deformation. Further insight is gained by comparing paleomagnetic data from Greater India and Greater Asia.

For small fragments of tectonic plates (terranes) that are not incorporated in the plate circuit (such as Greater India and Greater Asia), paleomagnetism enables us to estimate their paleolatitude and orientation with respect to North, by comparing the observed magnetic directions recorded in rocks when they formed. In practice, thousands of samples are collected to obtain an average paleomagnetic direction recorded by rocks from Greater India and from Greater Asia near the collision age (Dupont-Nivet et al. 2010; Yuan et al. 2021, e.g.). The average inclination of these directions enables us to estimate the original latitude of these rocks because the Earth's magnetic field behaves as a geocentric dipole generating a field with increasing inclination from the equator to the poles (Butler 1992; Tauxe 2010). The obtained latitudes of Greater Indian and Greater Asian rocks can then be compared to the latitude expected for the India and Asian continents, respectively, which are constrained by the global paleomagnetic database combined with the tectonic plate circuit based on fitting marine magnetic anomalies (see section "TO GO FURTHER WITH PALEOMAGNETISM"). The difference in latitudes, with associated uncertainties, is used to estimate the extent of Greater India and Greater Asia (Figure 1.3). Similarly, the paleomagnetic declination recording the past north direction in the rocks when they formed can be used to estimate by how much these rocks rotated with respect to Asia or India. These rotations can help estimate the deformation of these terranes and identify tectonic processes associated with them such as strike slip deformation along large faults. Despite the large amount of paleomagnetic data, uncertainties remain of the order of $\pm$ 5° (ca. $\pm$ 500 km in latitude) due to the inherent noise in the magnetic signal and its recording into rocks. Nevertheless, the values obtained from paleomagnetic data can be compared to structural estimates. They grossly show that while the expected Greater Asian extent (1,200 km) at 60 Ma can be compared to its shortening (ca. 600–1,000 km), the expected extent great India (ca. 2800 km) greatly exceeds shortening estimates (ca. 1,000 km). This has led to investigate alternative models that are presented in the following.

Reconstructing pre-collisional configuration of Greater India and Greater Asia is therefore a focus of intense research and controversies. For Greater India, many reconstructions have been proposed since Argand's early views (Figure 1.1). As previously discussed, most are based on estimates of the amount of Indian shortening, according to structural data and paleomagnetic reconstructions. Ali and Aitchison (2005) also proposed using the size of Australia to reconstruct the shape of the Indian continent. Indeed, prior to breaking apart in the Early Cretaceous, northern India was facing Western Australia in the eastern Gondwana Continent. Assuming that India and Australia formed a continuous landmass before they broke apart, the shape of Greater India can then be estimated by carefully putting India and Australia back to their Cretaceous position, and measuring the distance separating them. The size and shape of Greater India was also estimated using seismic tomographic imaging of the crust and mantle that enables us to identify – expressed as positive velocity anomalies – the shape and position of dense lithospheric slab remnants that have been subducted into the mantle (e.g. van der Voo et al. 1999; Kosarev et al. 1999). These geophysical methods have enabled us to track precisely the position of the Indian continental lithosphere currently underplated beneath Asia, as well as lithospheric slabs deeper in the mantle that are interpreted to result from their successive breakoff during the collision (Kind et al. 2002; Nábělek et al. 2009; Chen et al. 2015, and Volume 1 – Chapter 4).

1.3.2. *Alternative collision configurations*

With new age and convergence constraints on the collision, simple continental collision models would require very large Greater India and Asia and thus involve the massive removal of continental lithosphere by the lateral extrusion of continental blocks, wholesale continental subduction and very high estimates of overriding plate shortening that are difficult to account for with existing geological and geophysical data (e.g. Molnar and Tapponnier 1995; Guillot et al. 2003; Replumaz and Tapponnier 2003; Cogné et al. 2013). Several models have thus more recently been proposed to account for the mismatch between large convergence and smaller shortening in the collision zone since the collision. The first type of models invokes a “Greater India Basin” (Van Hinsbergen et al. 2012; Huang et al. 2015; van Hinsbergen et al. 2019; Yuan et al. 2021). They propose that a terrane drifted off northern India in the Cretaceous, carrying ahead Greater Himalayan sequences, and was separated from mainland India by a wide oceanic basin (Figure 1.4, see Poblete et al. (2021), for a review). This small terrane would have collided with Asia at 60–55 Ma; the Greater India oceanic basin then subducted beneath Asia until the final India–Asia collision in the late Oligocene–early Miocene

(Figure 1.4). Another family of models implies the first collision of India with an intraoceanic arc at 60–55 Ma while subduction is kept along the Asian margin until a much later India–Asia collision. Various versions of this arc collision model have been proposed (Aitchison et al. 2007; Guilmette et al. 2012; Hébert et al. 2012; Gibbons et al. 2015; Jagoutz et al. 2015; Müller et al. 2016; Westerweel et al. 2019). These models invoke collision between India and Asia in the Late Eocene to Miocene, depending on the assumed magnitude of intra-Asian shortening. Finally, it should be noted that a set of "neoclassic" models have been proposed but they imply a continuous subduction of the 2,400 km long Greater Indian continental crust below Asia (Ingalls et al. 2016; Searle 2019).

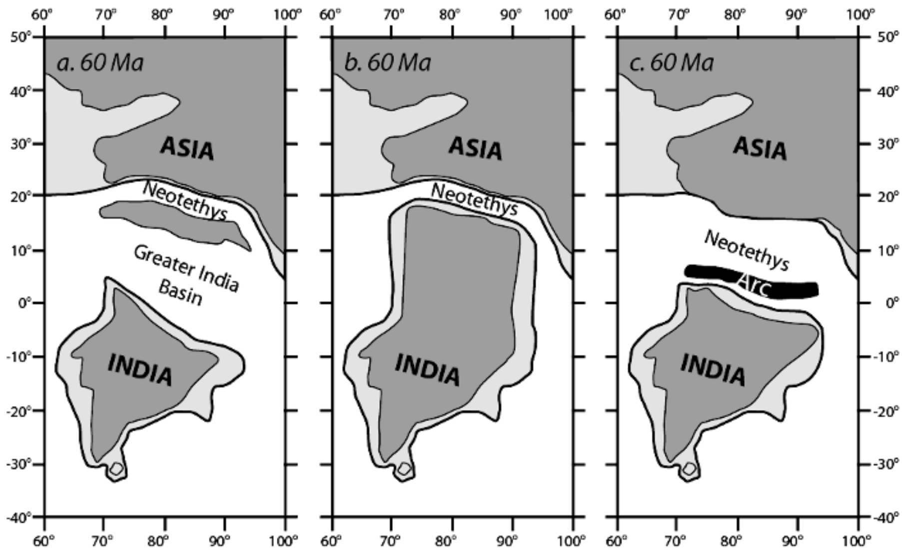

Figure 1.4. *Paleogeographic reconstructions according to the three main models proposed for the collision configuration (after Poblete et al. 2021). (a) Greater Indian Basin model, (b) simple continental collision model and (c) arc collision model*

1.4. Reconstruction of the Neotethys Ocean closure dynamic

1.4.1. *Number of subduction accommodating the Neotethys closure*

Earliest models of Neotethys closure assumed a single subduction zone (Powell and Conaghan 1973; Tapponnier 1981; Honegger et al. 1982; Allègre et al. 1984). The Transhimalaya/Gangdese batholith was recognized as the result of supra-subduction magmatism related to northward Neotethys Ocean beneath the active Asian continental margin starting approximately 250 Ma (Schärer et al. 1984; Ma et al. 2022, for review; Figure 1.5 A). However, detailed studies of the Tethyan ophiolites and associated tectonic mélanges from the Indus-Tsangpo Suture Zone suggested a more complex framework (Aitchison et al. 2000; Mahéo et al. 2000; Hébert et al. 2012, see Volume 2 – Chapter 2 for details). This led to proposing the existence of an intraoceanic subduction, south of the Asian active margin. Such geodynamic setting is also consistent with the tomographic high-velocity anomalies associated with detached oceanic slabs (Spakman 1986; van der Voo et al. 1999; Replumaz et al. 2004, 2013; Hafkenscheid et al. 2006). Based on this observation and interpretation, a range of Neotethys closure models can then be developed assuming a more or less important Greater India and/or the existence of the Greater India Basin (Figure 1.5).

One of the main implications of the existence of an intraoceanic subduction zone is that the north Indian continental margin would have subducted beneath an intraoceanic arc before reaching the south Asian margin (Figure 1.5 B1). This would in turn imply that such proxies used to constrain the timing of the India–Asia collision such as UHP rocks, slowing down the convergent rate, or changing of detrital sediment provenance, may *in fine* rather record an arc–continent collision. Recent reconstructions actually proposed that India collided first with an intraoceanic arc at about 55–60 Ma and then with Asia at about 40–50 Ma (Bouilhol et al. 2013; Jagoutz et al. 2015; Bhattacharya et al. 2020; Martin et al. 2020).

The number and location of subduction zones may also be constrained by seismic tomography. Especially, assuming that slab sink almost vertically Parsons et al. (2020) used tomographic anomalies to reconstruct past subduction locations and their geometries. This study confirmed the presence of two subduction zones and suggests an early collision between intraoceanic arc and the Indian continental margin. At about 60 Ma, the first subduction zone was active along the southern Asia continental margin approximately 20°N, while a second one was active close to the equator. However, these data do not distinguish between the Greater India Basin or wide Greater India models.

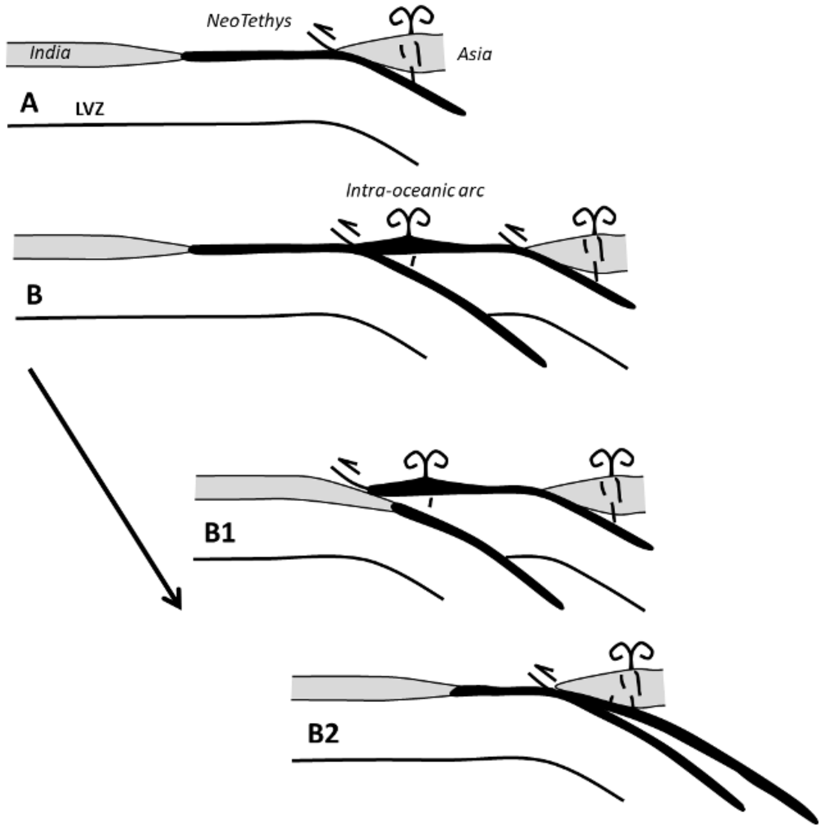

Figure 1.5. *Cross-sectional view of the India–Asia convergent zone during the Neotethys closure. A. Single subduction model, B. Double subduction model. B1: Early obduction of the intraoceanic arc on the India margin, B2: Subduction and accretion of the intraoceanic arc in front of the Asian active margin. Horizontal distance not to scale*

1.4.2. *Location of the Intraoceanic subduction zone and associated arc*

One of the main questions raised by the two subduction zone models is their relative timing. The intraoceanic arc can either be obducted on top of the Indian continental margin as the subduction below the Asian continent remained active (Figure 1.5B1), or can be accreted to the Asian continental margin before obducting the Indian continent (Figure 1.5B2).

Blueschists within the mélange zone associated with the subduction beneath the Asian margin show a volcanic arc signature (Mahéo et al. 2006). This in turn suggests that an intraoceanic arc was subducted/accreted beneath the Asian margin before collision. Additionally, sedimentary records imply that the mélange zone was active at about 65 Ma.

Such reconstruction seems to contradict with recent paleomagnetic data. (Martin et al. 2020) compare the paleo-latitude evolution of the Greater India with those of the intraoceanic Kohistan–Ladakh arc (see Volume 2 – Chapter 1). This study shows that these areas share a similar latitude about 60 Ma ago close to the equator. At that time, the south Asian margin was located much further north (~20°N).

An alternative model is then to consider two intraoceanic arcs and one active margin. The Asian active margin would correspond with the Gangdese and Karakorum arcs, as proposed by Jagoutz et al. (2015), the Kohistan–Ladakh arc being part of an intraoceanic arc. Field observations coupled with geochemical analyses in the western Himalaya of India suggest that two sets of ophiolites and the associated mélange zone exist south of Karakorum. One is indeed related to the Kohistan–Ladakh arc (the Dras arc) and one that may account for the presence of another subduction zone south of this latter (Mahéo et al. 2000, 2004; Robertson 2000; Corfield et al. 2001; Catlos et al. 2019). In this configuration, the southernmost arc may be accreted to the Kohistan–Ladakh arc just before the collision with India, accounting for the arc-related late Cretaceous blueschists.

This model seems consistent with the observation and data from western Himalaya but raise the question of its extrapolation eastward and the possibility of non-continuous subduction zone (see Volume 2 – Chapter 2 for details on the ophiolite belts and ophiolite correlation).

1.4.3. *Driving forces of the India–Asia convergence during Neotethys closure*

Reconstructions of slab dynamic coupled with kinematic reconstructions allow us to better discuss the forces involved in the convergence between India and Asia. Convergent results from interactions between ridge push, subduction zone forces (slab pull, slab suction and frictions) and mantle underlying plate basal drags (see Faccenna et al. (2021), for details). Recorded changes in India–Asia kinematic was then used to test the relative effects of these forces (e.g. Capitanio et al. 2010; Becker and Faccenna 2011; Cande and Stegman 2011; Copley et al. 2011; van Hinsbergen et al. 2011a; Jagoutz et al. 2015; Jolivet et al. 2018; Pusok and Stegman 2020). Especially, Jagoutz et al. (2015) proposed the modeling of the impact of two subduction zones on convergent rate evolution. This modeling evidences that the first episode of convergent acceleration at about 80 Ma may be related to the decrease of the intraoceanic subduction zone length when this latter is restricted to the India–Asia convergent zone. The following convergent rate slowdown at about 60 Ma is then related to the termination of the intraoceanic subduction zone subsequent to the arc–Indian continent collision and oceanic slab breakoff. Ongoing slowdown is then linked with the final India–Asia collision and continental subduction followed by Neotethys slab breakoff (Chemenda et al. 2000; Kohn and Parkinson 2002; Mahéo et al. 2009) and thickening of the Tibetan plateau (Copley et al. 2011). Continuous India–Asia convergence following the collision is then mostly controlled by mantle drag (Becker and Faccenna 2011). But other processes may also have influenced the India–Asia kinematic and especially the increase of the convergent rate to about 80 Ma. Interaction with mantle plumes such as the Reunion hotspot would also increase the plate velocity (Cande and Stegman 2011; Van Hinsbergen et al. 2011b; Pusok and Stegman 2020). Actually, Pusok and Stegman (2020) proposed that the Reunion hotspot induced both the plate acceleration and the second subduction zone initiation at about 72–66 Ma. Then, the two subduction settings maintain the high convergent rate until the India–arc and India–Asia collisions. In addition, Behr and Becker (2018) suggested that the subduction of equatorial thick sedimentary deposits would significantly decrease the subduction interface viscosity reducing friction and favoring slab pull.

Following collision, slab dynamic significantly changed and several factors such as slab-breakoff, Tibetan plateau buildup or external forcing due to the monsoon may then significantly influence convergence (e.g. Chemenda et al. 2000; Mahéo et al. 2009; Molnar and Stock 2009; Copley et al. 2011; Iaffaldano et al. 2011; Husson et al. 2014; Webb et al. 2017). These aspects will be developed in the next chapters of this book.

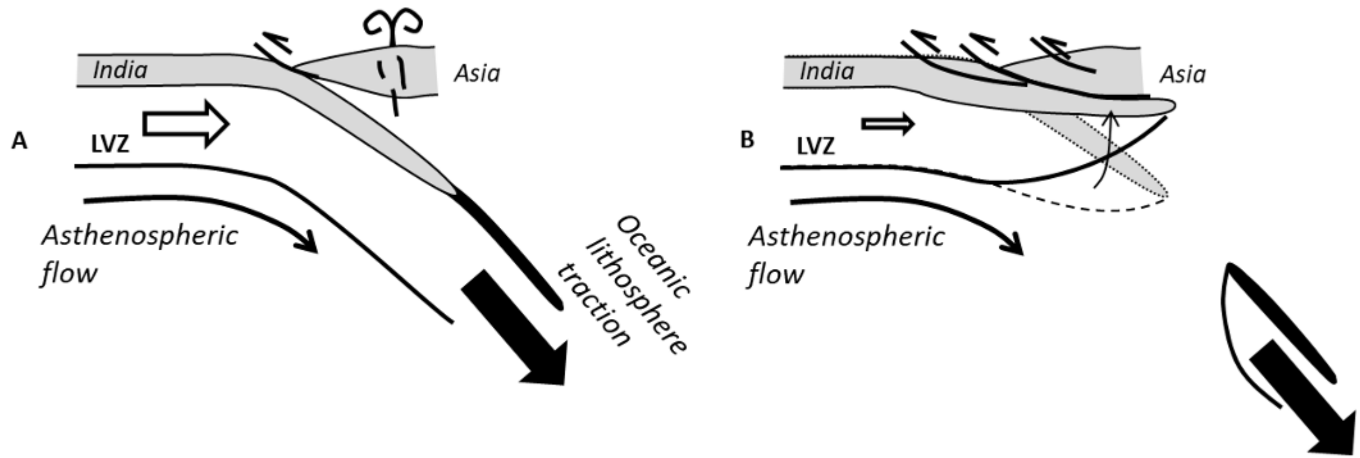

Figure 1.6. *Transition from continental subduction (A) to India underplating Asia (B) induced by Neotethys slab detachment*

1.5. Conclusion

This review evidences that if the kinematic evolution of the India convergence is relatively well constrained, many points remain discussed such as the size of Greater India or the slab dynamics during Neotethys subduction. Recent coupling between petrologic constrains, plate kinematic and tomographic data appears very promising to better reconstruct the geodynamic evolution of the convergent zone up to the collision.

Such detailed reconstructions are crucial to estimate the initial geometry and organization of the collision zone which may significantly influence both the Himalaya and Tibetan Plateau petrologic evolution, tectonism and surface processes that will be discussed in the next chapters. Notably, the cessation of continental subduction followed by Indian continental lithosphere underplating must have drastically changed the mechanical coupling between Indian and Asian crusts as well as the thermal regime of the convergent zone (Figure 1.6, see Volume 1 – Chapter 2 for details).

Despite a century of continuous research on the India–Asia collision since the work of Emile Argand, the debate on how the collision occurred remains fierce. Following from the initial simple models of a single collision between two continental plates, the acquisition of massive geologic datasets and the evolving geodynamic concepts have led to the development of new models involving several collisions of intervening microplates. Deciphering between these competing models in the years to come will be the focus of exciting research and certainly lead to major breakthroughs in understanding geodynamic processes with major implications for Earth, Climate and Life sciences.

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