Review Article

India's Northward Drift from Gondwana to Asia During the Late Cretaceous-Eocene

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The northward drift of the Indian plate from its original Gondwana home in the late Jurassic to its current position in Asia since the Early Cenozoic provides a unique natural laboratory for tracking its changing geography, climate, tectonics, and biotic evolution for the past nearly 150 million years. With the breakup of Gondwana, India began to disintegrate into a smaller plate, becoming partially isolated during the Early Cretaceous Period, but possibly retaining a biotic link with Africa via Madagascar. Around 80 Ma, as the Indian plate collided with the Kohistan-Ladakh (KL) Arc and Arabia collided with the Oman Arc, a continuous accreted terrane - the Oman-Kohistan-Ladakh (OKL) Arc- was formed that possibly served as a biotic filter bridge between India and Africa. The biotic connectivity with Africa and South America helps to resolve a major conundrum of Indian paleobiogeography, namely the lack of endemism among Late Cretaceous Indian tetrapods. Later, two catastrophic events at the Cretaceous-Paleogene (K/Pg) boundary, with possible links to the dinosaur extinction, marked the terminal phase of India's northward drift. The Deccan volcanism and the possible Shiva impact. Around the same time, Seychelles was separated from India. During the Late Cretaceous (~67 Ma), the Indian plate suddenly accelerated its motion to 20 cm/year between two transform faults that facilitated its northward movement: the Owen-Chaman Fault on the west and the Wharton Ridge-Sagaing Fault on the east. As a result, the Neotethyan plate, bordered by these two transform faults, became a separate oceanic plate (Kshiroda plate). India continued its acceleration during the Paleocene as a passenger ship with a mobile gangplank of the OKL Arc, carrying its impoverished Gondwanan fauna. A pronounced global warming took place during the Paleocene-Eocene Thermal Maximum (PETM), when India collided with Asia causing significant changes to tectonics and tetrapod radiation. India slowed down dramatically to 5 cm/year during its initial collision, and its tetrapod fauna underwent an explosive evolution in response to a new ecological opportunity resulting in the Indo-Eurasian interchanges. The occurrence of several stem groups of tetrapods supports the Gondwanan Indian origin (i.e. the *Out-of-India* hypothesis) of several modern mammal orders such as the perissodactyls, primates, artiodactyls and whales whose antiquity can now be traced phylogenetically to the Indian taxa.

Keywords: Gondwana; India-Asia collision; Cretaceous; Biogeography; Evolution

Introduction

India has been a record-holder in many aspects of plate tectonics. India made the longest journey of all drifting continents, about 9,000 km in 160 million years from Gondwana to Asia. During its northward drift, India developed a variety of plate boundaries and associated features: ridges, trenches, transform faults, and two spectacular intraplate hotspots that created immense flood basalt volcanism on its two sides. India provides an elegant natural laboratory for the study

of continental rifting and continental collision. Among the most dramatic and visible creations of continent-continent collision are the lofty Himalaya, which stretches 2,900 km along the border between India and Tibet. Before collision, India accelerated suddenly between 67 and 52 Ma, racing northward about 20 cm/year – about twice as fast as any plate motion. The collision of India with Asia had a profound effect on Cenozoic topography, faunal turnover, climate, and oceanography. The paleogeography of the Indian plate, especially during the Late Cretaceous-Early

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Eocene period, provides an unparalleled opportunity to examine its complex tectonic evolution during its northward drift until it collided with Asia.

Although the Himalayan–Tibetan Orogen has been extensively investigated during the past few decades, a number of issues continue to be hotly debated, especially the timing of India–Asia collision, the northern extent of India and the paleogeography of the Neo-Tethyan ocean (e.g. Zhuang *et al.*, 2015). A variety of approaches (paleomagnetism, magnetic lineations, magmatic and metamorphic records, geochemical constraints, changes in sedimentation patterns and provenance, stratigraphy, faunal affinities, oceanic microplate formation) have been used to constrain the timing of collision but there is no consensus yet, with estimates of collision timing ranging from latest Cretaceous (~65) to earliest Miocene (~25 Ma). Furthermore, current models favour either a direct, single continent–continent collision between Greater India and Asia (Yang *et al.*, 2015), or a dual collision involving initial India–Arc collision followed by a final collision between the combined India/Arc and Asia (Clift *et al.*, 2014; Jagoutz *et al.*, 2015). Models invoking the initial collision of the Tethyan Himalayan microcontinent with Asia (Lhasa terrane) followed by a final collision of the Indian craton with the Tethyan Himalaya have also been proposed (van Hinsbergen *et al.*, 2012). Here we identify six major geodynamic events during the Late Cretaceous–Early Eocene period: (1) Rifting of Madagascar from India (~88 Ma); (2) collision of India with the Kohistan–Ladakh (KL) Arc during the Late Cretaceous (~80 Ma); (3) acceleration of the Indian plate (~20 cm/year) between 67 and 52 million years ago; (4) Deccan volcanism at the Cretaceous/Paleogene boundary (~65 Ma); (5) separation of Seychelles Island from India (~64 Ma); (6) subduction of the Neotethyan Kshiroda plate during the Paleocene followed by the onset of India–Asia continental collision at ~55 Ma. Here we briefly discuss these major geodynamic events of the Indian plate during the terminal phase of its northward drift and their biogeographic implications.

Major Events During India's Northward Drift

Rifting of Madagascar from India (~88 Ma)

The separation of Madagascar from India was preceded by uplift that resulted in the reorientation of

the fluvial systems on the continental island (Gombos *et al.*, 1995). Madagascar drifted southward in relation to India and the right-lateral strike-slip motion produced a long, relatively straight, rifted passive margin. The break-up was associated with the opening of the Mascarene Basin and widespread volcanism induced by the Marion hotspot during the Late Cretaceous (e.g. Morondava flood basalts, Bardinitzeff *et al.*, 2010). The volcanic rocks occur along the 1500-km length of the east coast of Madagascar, which marks the rifted margin. On the opposing side of the rift, along the western coast of India, occur the St. Mary flood basalts, which are dated between 84 and 93 Ma.

During the Late Cretaceous, the dispersal of continents produced physical barriers for terrestrial taxa and separated dinosaur communities into distinct Asia–American (hadrosaurs, ceratopsids, and tyrannosaurids) and Euro–Gondwana (titanosaurs and abelisaurids) groups. As the Indian plate separated from Madagascar ~88 Ma, it became a continental island for a relatively short time and provided greater more opportunities for allopatric speciation, and therefore peaks in biological diversity. Unfortunately, the tetrapod record from this crucial, post-Gondwana (pre-Maastrichtian) interval is virtually non-existent in India except for the recent record (Prasad *et al.*, 2016) of a few fragmentary teeth of abelisaurid dinosaurs from the uppermost unit (Green Sandstone) unit of the Bagh Group or the 'Supra-Bagh'.

Collision of India with the Kohistan–Ladakh (KL) Island Arc (~80 Ma)

During the Late Cretaceous (~88 Ma), India rifted away from Madagascar and began to move northward, isolated from other Gondwana continents. As a result, the Neotethyan ocean floor began to subduct beneath Asia to accommodate the northward journey of the Indian plate. Two north-dipping subduction zones existed between India and Asia, which became active one after another. The southern subduction zone, the Makran–Indus Trench, which fringes the Arabian margin of Africa, continues across the Kohistan–Ladakh Trench to the Wyola Trench of Sumatra (Allegre, 1988; Ali and Aitchison, 2008; Chatterjee and Scotese, 2010). This subduction zone separated the Neotethys into two segments, a northern Neotethys, and the southern, short-lived Indotethys

(Chatterjee *et al.*, 2013). The northern subduction zone, i.e. the Shyok-Tsangpo Trench, is found north of the Neotethys along the southern margin of Asia. Both subduction zones, the Makran-Indus Trench and Shyok-Tsangpo Trench were active during the Middle to Late Cretaceous.

The Kohistan-Ladakh (KL) block at the northwestern corner of the Trans-Himalayan Mountains has long been recognized to represent an island arc formed during the Late Cretaceous. Between the Asian and Indian plate, two suture zones bind the KL complex: the Shyok Suture to the north, and the Indus Suture to the south. It is crucial to know when and how the KL Arc became sandwiched between India and Asia. While some authors (e.g. Clift *et al.*, 2002) suggested that the KL Arc first collided with Asia around 95-75 Ma, many others (e.g. Burg *et al.*, 2011; Chatterjee *et al.*, 2013) hold the view that the KL Arc first collided with India during the Late Cretaceous (95-65 Ma) before India's terminal collision with Asia. Recently, Bouihol *et al.* (2013) and Jagoutz *et al.* (2015) suggested that the collision of India with the KL Arc occurred at ~50 Ma. However, along the western extension of this trench, Arabia collided with the Oman Trench to form the Semail Ophiolite ~80 Ma (Searl *et al.*, 1987). Similarly, along the eastward continuation of the KL Arc, the Wyola Arc was obducted onto the continental crust Sumatra around ~80 Ma. Great slabs of ophiolite complexes are preserved in the mountains of Oman, Kohistan, Ladakh and southern Tibet, and as far east as Andaman Islands and Indonesia that bear the testimony of continent-island collision during the Late Cretaceous time (Searle, 2013). Since it a long subduction zone stretching from west to east across the Neotethys, it is likely that the collision of India with the KL Arc occurred synchronously during the Late Cretaceous (~80 Ma). This collisional history is also consistent with the radiometric and paleomagnetic data showing that the KL Arc occupied a position close to the equator not far from the Indian plate (~30°S). On the other hand, the Lhasa block was more than 3000 km north, indicating a vast expanse of the Neotethys north of the Indian plate (Khan *et al.*, 2009; Burg, 2011).

The Oman-Kohistan-Ladakh (OKL) Arc serves as an important biotic corridor between India and Africa (Chatterjee and Scotese, 2010; Chatterjee *et*

al., 2013). In most plate reconstructions, India is shown as an island continent during the Late Cretaceous for millions of years. Such an extended period of continental isolation should have produced a highly endemic vertebrate fauna and we should surely find some evidence of it, if in fact it ever existed. On the contrary, the Late Cretaceous vertebrates of India appear to be cosmopolitan (e.g. Prasad, 2013), and in some cases (e.g. abelisauroid dinosaurs), phylogenetic analysis (Carrano & Sampson 2008) has revealed possible sister-group relationships of the Indian taxa (*Rajasaurus*, *Indosuchus*) from the Maastrichtian Lameta Formation with nearly coeval forms such as *Majungasaurus* from the Maevarano Formation of Madagascar. This similarity may be a reflection of pan-Gondwanan distribution of abelisauroids prior to Gondwana break-up, and their subsequent evolution in isolation (vicariance). Alternatively, such close relationships may suggest faunal exchanges between India with other Gondwanan continents possibly via intermittent land connections. When India collided with the Kohistan-Ladakh (KL) Arc during the Late Cretaceous (~80 Ma), a western migration filter bridge with Africa was re-established. At the same time, Arabia collided with the Oman Arc to form the Semail Ophiolite (Searl *et al.*, 1987). The conjoined Oman-Kohistan-Ladakh (OKL) Arc formed an effective ephemeral filter bridge between India and North Africa allowing faunal exchanges (Fig. 1A). This hypothesis (Chatterjee and Scotese, 2010; Chatterjee *et al.*, 2013) may account for the occurrence of similar family-level taxa in India, Madagascar and South America during the latest Cretaceous. Three ephemeral biotic filter bridges may possibly have connected India with other Gondwana landmasses: (1) the OKL Arc allowed faunal interchanges between India and Africa; (2) the Laxmi Ridge-Seychelles island bridged the gap between India and Madagascar; and (3) the emergent Ninetyeast Ridge-Kerguelen plateau-Antarctica formed a circumpolar biotic filter bridge between India and South America. However, apart from dinosaurs and alligators, most of the late Cretaceous tetrapods in India were small-sized (Prasad and Sahni, 1999), so it is plausible that the biotic exchanges between India and other landmasses involved transoceanic (*sweepstakes*) dispersal via Africa. Recently, Goswami *et al.* (2013) reported an isolated troodontid tooth with typical coarse denticles from the Kallamedu

Fig. 1: Paleogeographic reconstruction of India in relation to other Gondwana continents during the Late Cretaceous-Early Eocene period. A: Paleogeographic position of India showing collision of the Indian plate with the Oman-Kohistan-Ladakh (OKL) Arc during the Late Cretaceous (~80 Ma) along the Makran-Indus Trench. The OKL Arc formed an important corridor for tetrapod migration between India and Africa, B: Paleogeographic reconstruction of India in relation to other Gondwana continents during the Cretaceous-Tertiary boundary (~65 Ma). The Oman-Kohistan-Ladakh Arc maintained the biotic link between India and Africa (modified from Chatterjee *et al.*, 2013), C: Paleogeographic reconstruction of India in relation to other Gondwana continents during the Paleocene (~60 Ma). India maintained biotic links with Africa and Europe via the Oman-Kohistan-Ladakh Arc and D: Paleogeographic reconstruction of India during the initial collision with Asia at the Paleocene-Eocene boundary (~55 Ma). (modified from Chatterjee *et al.* 2013 and Jagoutz *et al.*, 2015)

Formation of Cauvery Basin, Tamil Nadu. Troodontid is a small-bodied, maniraptoran theropod, predominantly restricted to North America, Europe, and Asia. Discovery of a troodontid from India indicates faunal migration from Laurasia to India via the OKL Arc during the Late Cretaceous.

Acceleration of the Indian Plate (~67–52 Ma)

The superfast motion of the Indian plate during the Late Cretaceous-Early Paleocene period, starting around anomaly 30 (~ 67 Ma) and ending around anomaly 22 (~49 Ma), was recognized long ago from magnetic anomalies on the Central Indian Ridge and Southeast Indian Ridge (McKenzie and Sclater, 1971). Using seismic techniques, Kumar *et al.* (2007) measured the lithospheric thickness of the Indian plate, and found it was only 100 km thick, about half the thickness of other Gondwana plates. They argued that the originally thick lithosphere beneath India was preferentially thinned by the Kerguelen plume after the Gondwana breakup around ~130 Ma. Subsequently, the lower half of the Indian lithosphere was considerably degraded by the Marion (~90 Ma) and Reunion (~65 Ma) plumes. The thinned Indian plate became decoupled from the deeper interior, reducing the drag of the lithosphere against the asthenosphere, thus permitting faster motion of the Indian plate due to ridge push or slab pull. Cande and Stegman (2011) linked acceleration of the Indian plate to the Reunion plume. They proposed that as the rising Reunion plume hit the lower surface of the Indian plate at the K/T boundary time, it spread in all directions, and the push-force from the plume head propelled India towards Asia, subsequently sustaining accelerated speed for the next 15 million years. The plume created a volcanic lubricant material under India, allowing the subcontinent to effectively 'surf' over the asthenosphere at a high speed. After the continental collision with Asia (~55 Ma), India's plate motion slowed down to ~5 cm/year. Recently, Jagoutz *et al.* (2015) suggested that India was pulled northward by double subduction that may explain India's rapid move to Asia. However, these two subduction episodes were probably not synchronous, but happened one after another (Ali and Aitchison, 2008; Khan *et al.*, 2009; Van der Voo, 1999; Burg, 2011; Chatterjee *et al.*, 2013). The most active subduction during the acceleration period was in the northern zone along the Shyok-Tsangpo Trench. The southern zone

subduction along the Kohistan-Ladakh had ceased by that time.

Deccan Volcanism at the Cretaceous/Paleogene Boundary (~ 65 Ma)

At the Cretaceous-Paleogene (K/Pg) boundary, the Indian plate had moved considerably northward with the subduction of the Kshiroda Plate and glided smoothly along two parallel transform faults on its two sides. The Deccan Traps continental flood basalt province of peninsular India, with the present area of about half a million sq km, represents one of the largest volcanic eruptions in earth's history, comprising >1.3 million km³ of erupted lava flows throughout west-central India. The main phase of Deccan volcanism, which accounts for about 80% of the 3,500-m-thick pile, appears to have erupted within a short time in C29R (Chenet *et al.*, 2007), possibly within a 50,000 year period (Schoene *et al.*, 2014). Furthermore, it has been proposed that around the same time as the Deccan eruptions, an extraterrestrial impact took place on the western shelf of India and may have excavated a large, multiringed complex crater, the Shiva Crater (Chatterjee *et al.*, 2006). Together with the Deccan Traps volcanism, the twin extraterrestrial impacts (Chicxulub-Shiva) may have led to the global demise of dinosaurs and other taxa on land and in the sea (Lerbekmo 2014).

Bulk of the data on latest Cretaceous tetrapods of India come from thin sedimentary deposits associated with the Deccan Traps, either below the basaltic flows (i.e. infratrappeans/Lameta Formation) or within them (i.e. intertrappeans). The presence of several cosmopolitan tetrapod taxa (including dinosaurs) in this assemblage presents a major paleobiogeographic riddle that could be resolved with the northern and southern dispersal routes for faunal migration, one between India and Africa/Europe via Oman-Kohistan-Ladakh (OKL) Arc and the other between India and South America via Ninetyeast Ridge-Kerguelen-Antarctica (Fig. 1B).

Separation of Seychelles from India (~64 Ma)

During the Early Paleocene (Danian), a major reorganization and a rift jump occurred in the Indian Ocean shortly after the emplacement of the Deccan Traps (Fig. 1C). As India began to accelerate northwards, the Seychelles Island separated from India

with the spreading of the Carlsberg Ridge. The initiation of spreading at the Carlsberg Ridge is well constrained by magnetic anomalies at 63.4 Ma (Collier *et al.*, 2008). The proximate causes of the India-Seychelles rift are controversial, but the Deccan volcanism (Reunion plume) has been implicated for the India-Seychelles rifting. However, the lack of volcanism at the opposing continental margins of Laxmi Ridge in spite of a close temporal association between Deccan volcanism and the Seychelles–Laxmi Ridge rifting, is anomalous. Moreover, the continental rift between Seychelles and India was approximately 1000 km from the Reunion hotspot at the time of breakup.

Collier *et al.* (2008) proposed that the external plate boundary forces (such as slab pull or ridge push) rather than the impact of a mantle plume were largely responsible for the rifting of the Seychelles from India. The lithosphere was already thinned by two previous rifting events on the western margin of the Indian plate: the separation of India from Madagascar (~88 Ma), and the rifting of the Laxmi Ridge from India (~70 Ma).

The Paleocene is the ‘dark age’ of Indian paleobiogeography because the record of continental tetrapods, especially mammals, from this interval is almost blank. Although the shrinking Neotethys surrounded the leading edge of the Indian plate left a rich record of marine faunas (Ranikot Formation), the continental Paleocene, unfortunately, has extremely limited exposures in India and generally occurs at the base of the Early Eocene lignite/coal sequences in Rajasthan and Gujarat. The Palana, Barmer, Akli, and Vagadkhol (=Olpad) formations are yet to be sampled adequately for tetrapod fossils. Future discovery of tetrapods from these Paleocene deposits may shed new light on the biotic links of India with adjoining continents. The late Paleocene mammals of India will yield critical clues to our understanding of the biogeographic origins of the modern mammal orders, most notably primates, artiodactyls and perissodactyls.

Onset of India-Asia Continental Collision at the Paleocene-Eocene Boundary (~55 Ma)

The India-Asia continental collision is amongst the most spectacular tectonic events of the Phanerozoic time and is crucial to our understanding of the

Himalayan-Tibetan orogeny, global climate and mammalian dispersal. The collision of India and Asia terminated the period of very rapid Indo-Asia convergence. To avoid ambiguity, the onset of the collision between India and Asia is here defined as the moment when the Neothethyan oceanic lithosphere (Kshiroda Plate, Jagoutz *et al.*, 2015)) was completely subducted and the two continental plates came into direct contact at the Kohistan-Ladakh Arc (around Nanga Parbat). Prior to the continental collision, the southern margin of the Lhasa block of Tibet was an Andean-type margin intruded by Cenomanian-Eocene Gangdese granitoid batholiths (Searle, 2013). At that time, the northern margin of the Indian plate was a passive continental margin with shelf facies in the south that passed into a deep-water Tethyan facies to the north (Indus flysch).

The timing and nature (diachronous/synchronous) of India-Asia collision remain highly controversial issues. Searle *et al.* (1987) listed several lines of geological evidence from the collision zone to determine the timing of the collision between India and Asia: (1) the change from marine (flysch-like) to continental (molasse-like) sediment in the Indus-Tsangpo Suture Zone, (2) the end of Gangdese I-type granitoid injection, (3) Eocene S-type anatectic granites and migmatites in the Lhasa block, and, (4) the start of compressional tectonics in the Tibetan-Tethys and Indus-Tsangpo Suture Zone (south-facing folds, south directed thrusts). Some previous paleontologic interpretations (Jaeger *et al.*, 1989), based on Eurasian affinities of terminal Cretaceous terrestrial biotas of peninsular India, suggested that the initial contact between Indian and Asian landmasses occurred at the Cretaceous-Paleogene boundary at ~65 Ma. However, plate tectonic, paleomagnetic, and biogeographic constraints suggest that the Indian continental crust more likely made the initial contact with the Lhasa block around the Paleocene-Eocene boundary (~55 Ma) via the Kohistan-Ladakh (KL) Arc (Searle *et al.*, 1987; Najman *et al.*, 2010; Chatterjee and Scotese, 2010; Clementz *et al.*, 2011; Chatterjee *et al.*, 2013). The KL Arc was a filter bridge that allowed faunal migration between India and Eurasia, as exemplified by the basal Eocene mammals from Vastan (e.g. Kapur and Bajpai, 2015). The Paleocene-Eocene boundary (~55 Ma) age of collision is consistent with the slow down of convergence rate and increase in

magmatism at ~52 Ma (Shellnut *et al.*, 2014) as well as with recent sandstone provenance studies from Tibet (Li *et al.*, 2015). However, some still older collision ages (Middle Paleocene, ~59 Ma) have also been suggested recently, based on integrated stratigraphic, sedimentological, petrographic, geochemical and geochronological (U–Pb ages and Hf ratios of detrital zircons) (DeCelles *et al.*, 2014; Hu *et al.*, 2015).

Evidence for the early history of India-Asia collision also comes from the late Paleocene-Middle Eocene Subathu Formation in the northwestern sub-Himalaya foreland basin (Singh 2012, 2013). The tectono-sedimentary evolution of the Subathu succession, which comprises a gradual transition from marine to continental beds with ash beds at the bottom of the succession, is an important proxy for the initial collision event. Recently, Singh (2012), based on a detailed sedimentological study of the Subathu succession, suggested that the development of early Himalayan foreland basin took place in ephemeral streams, barriers, lagoons, swamps and tidal flats, and that with a paleobathymetry less than 55 m, the basin was devoid of deep marine sediments. Bhatia *et al.* (2013) also favoured a similar depositional setting and also re-iterated a biochronologic and lithostratigraphic continuity from the Subathu to the Dagshai formations.

The Neotethyan ocean most likely disappeared completely around the latest early Eocene (~50 Ma) when India was fully sutured to Asia. The closure of the Neotethys is marked by the change from marine to terrestrial conditions displayed by sediments in the suture zone. In the Indus Suture Zone of Ladakh, the youngest marine sediments are latest early Eocene limestones. These beds are succeeded by a continental sequence that is yet to be precisely dated.

Faunistically, there was an explosive radiation of tetrapods, especially placental mammals in India during its initial collision with Asia because of the unprecedented ecological opportunity provided by the vacant niches of dinosaurs and the expansion of new habitats. An extraordinarily warm climate opened up when India became a new member of the Holarctic faunal province. Many species, which were formerly restricted to India from the Gondwanan heritage, moved into Eurasia. Conversely, many species formerly restricted to Eurasia eventually moved into India. India still maintained the OKL Arc land bridge to maintain biotic link with Eurasia (Fig. 1D). India became a crossroad of faunal migration and the 'Great Indo-Eurasian Interchange' was a landmark paleobiogeographic event that led to the origin of the modern orders of mammals. The occurrence of several stem groups of tetrapods including perissodactyls, primates and artiodactyls, in the Vastan Lignite Mine of the Cambay Formation supports the 'Out-of-India' hypothesis (Krause and Mass, 1990; Bajpai, 2009; Chatterjee and Scotese, 2010). India became an important evolutionary center for the spread of tetrapods around the Paleocene-Eocene Thermal Maximum (PETM). An analogous 'Great American Interchange' of mammals occurred in the Pliocene (~3 Ma) when the formerly isolated landmasses of North America and South America were united via Central America.

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