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Research paper

Early Cenozoic rapid flight enigma of the Indian subcontinent resolved: Roles of topographic top loading and subcrustal erosion

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ABSTRACT

Intrinsic magmatic processes are considered as critical operators of plate movements. Here we demonstrate the role of extrinsic processes consequent to intrinsic processes as a catalyst for anomalous rapid plate movement. The rapid and accelerated flight of the Indian subcontinent since Deccan volcanism until its collision with Eurasia remains as one of the geological conundrums. Data on seismic tomography, peninsular geomorphology and inferences on continuum of subcrustal structures are utilized to address this enigma. We propose geomorphic isostasy as the mechanism that has driven this fastest drift ever recorded in geological history. It was initiated by sudden instability after the Deccan volcanism and resultant extensive accumulation of lava pile over continental lithosphere of northern India, northern-eastern tilt due to crustal thickness heterogeneity and subcrustal thermal stratification. The drift was sustained by Carlsberg and Central Indian ridge-push until collision and sediment top loading at northeast thenceforth. These inferences and geomorphic isostasy as a catalytic mechanism necessitate variability of drift rates as integral inputs for any continental scale modeling.

1. Introduction

Driven by deep convection currents, continental plates drift over the plastic asthenosphere at rates of few centimeters per year (Jagoutz et al., 2015). Large scale plate reorganization plays first order controls on orogeny, changes in ocean-basin volume, basin evolution, climate and sea level and enforce topographic feedback as a continuum (Campanile et al., 2008). Plate reconstruction theories and models of rifts/drifts often take into account intrinsic magmatic processes as the critical operator of continental drifts (Cande and Stegman, 2011; Müller, 2011; van Hinsbergen et al., 2011; Koptev et al., 2015). And more frequently overlook the inherent nature of these events that always work on differential rates and at highly discontinuous periodicity (Müller, 2011). The resultant surficial disequilibrium operates under the influences of a variety of factors and responds in distinct spatio-temporal scales. Little is known how rapid plate reorganization events that continue for long geological timescales can be highly varied, persistent and produce topographic feedbacks.

The tectono-geomorphic evolution of the Indian subcontinent commenced at ~167 Ma following the breakup of Gondwana supercontinent. The subsequent drift represents exceptional journeys (~9000 km) of all the continents involving plate tectonic and landform diversification events (Chatterjee et al., 2013). Soon after the basaltic eruption at the end of Cretaceous, India drifted northward at about 20 cm/yr; a rate exceptionally high (Chatterjee et al., 2013) as compared to present-day rate of ~5 cm/yr. The driver of this early-Cenozoic acceleration still remains enigmatic. Here we demonstrate the interplay between intrinsic and extrinsic sources as catalysts of anomalous rapid plate reorganization. Based on isostatic compensation, denudation and recurrent reactivation

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of Proterozoic–Cretaceous tectonic structures, and subcrustal dynamism, we establish geomorphic isostasy as the mechanism that initiated the faster drift of the Indian subcontinent in the aftermath of Deccan volcanism.

2. Geological setting

The Indian subcontinent is an assemblage of microcontinents that experienced extensive volcanism, plutonism, metamorphism, and sedimentation preserving structures (Fig. 1) inherited since early Proterozoic (Chatterjee et al., 2013; Collins et al., 2014). A continuum of structural and resultant geological-geomorphic evolution of the Indian subcontinent is evident from the occurrences and/or alignments of Paleozoic, Mesozoic and Cenozoic sedimentary basins (Banerji, 1984) and escarpments, and plateaus (Fig. 1) essentially along older faults/suture zones (Jayalakshmi et al., 2004; Biswas, 2005; Mishra and Kumar, 2005; Ramkumar et al., 2016). Occurrences of Permo-Triassic and early Cretaceous deposits only in the downwarped grabens of Gondwana basins, extensive Cenozoic deposits offshore (Bastia and Radhakrishna, 2012; Chatterjee et al., 2013) and Neogene–Holocene deltaic deposits all along the east coast (Ramkumar, 2003; Campanile et al., 2008), the absence of comparable deltaic sequences in the west coast (Kale, 2014; Kale and Vaidyanadhan, 2014), the historic and ongoing seismicity either at or in the vicinity of paleo-sutures and structures (Radhakrishna,

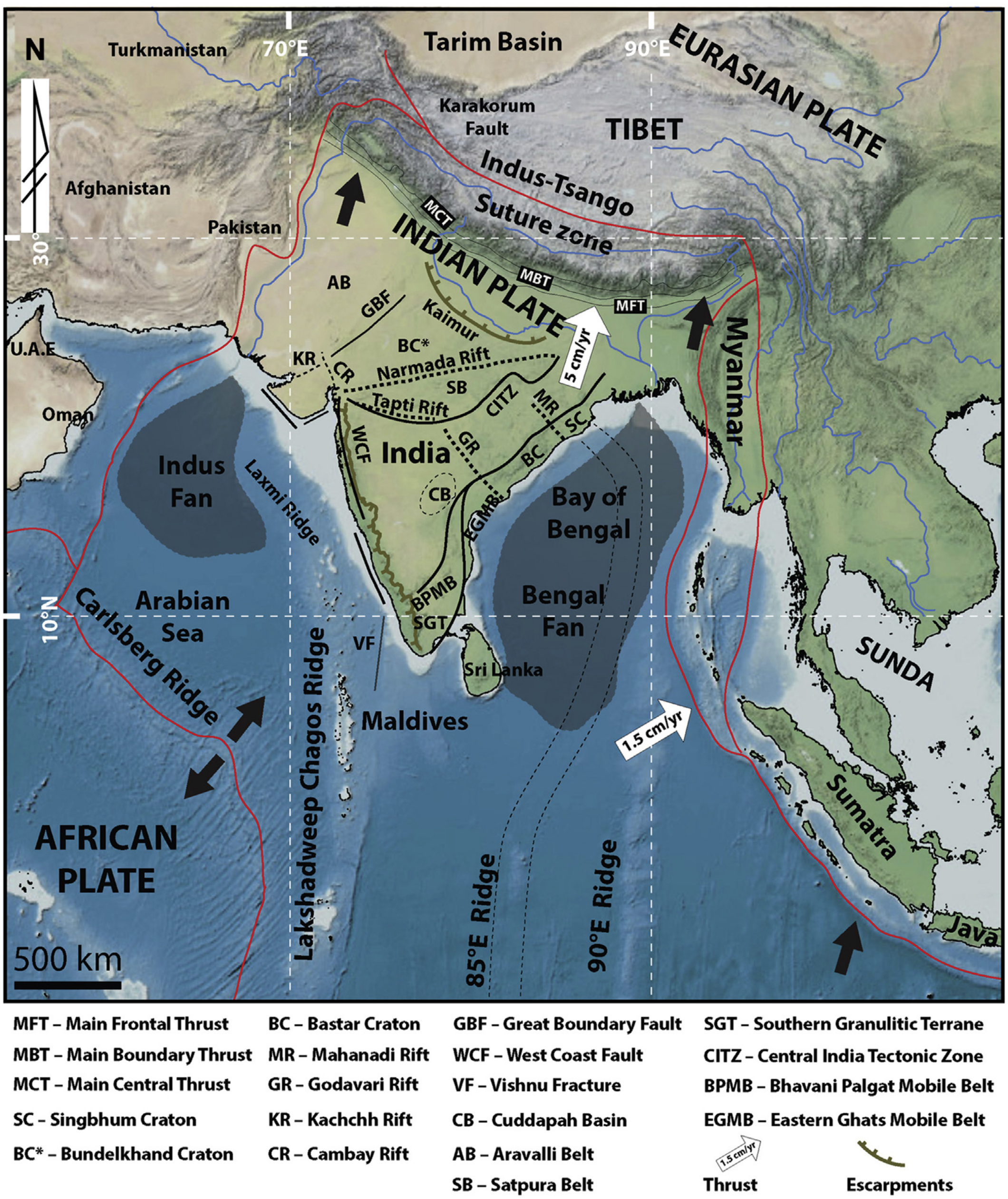

Figure 1. Regional structural trends of the Peninsular India. This figure depicts the inheritance of structural trends from Proterozoic paleo-suture zones. These underwent reactivation during Permo-Triassic, late Jurassic–early Cretaceous, upper Cretaceous, end Cretaceous–early Cenozoic. Occurrences of ongoing seismicity, at or along boundary faults of sedimentary basins, deltaic systems, plateaus, escarpments, strandlines, waterfalls, knick points, terraces, etc., evidence tectonic continuum until recent (Ramkumar et al., 2016). Owing to the connectivity between subcrustal causative mechanism and progressively weakened nature, these suture zones were the zones of reactivation repeatedly, during geologic-historic-recent times. It also evidences to the subcrustal origin for them and single mechanism–subcrustal erosion and periods of intensive mantle plume activity.

1993; Sharma and Rajamani, 2000a; Valdiya, 2001; Jayalakshmi et al., 2004; Roy, 2004; Biswas, 2005; Mishra and Kumar, 2005; Kale and Vaidyanadhan, 2014) and absence of significant Mesozoic deposits on land (Banerji, 1984; Ramkumar et al., 2013) suggest prevalent (Ramkumar et al., 2005, 2013; Ramkumar, 2015) and ongoing tectonic dynamism (Jayalakshmi et al., 2004; Biswas, 2005; Mishra and Kumar, 2005).

Inheritance and tectonic continuum (Roy, 2004) of basement structures (Fig. 1) over climate, and landscape evolution of Peninsular India (Radhakrishna, 1993; Valdiya, 2001; Kale, 2014; Ramkumar et al., 2016) resulted in unique and diverse drainage patterns of major rivers (Valdiya, 2001; Kale, 2014). While most rivers of the Peninsula follow a general easterly direction, the morphology of catchments indicates youthful character (Radhakrishna, 1993; Sharma and Rajamani, 2000b) and tectonically active nature (Radhakrishna, 1993; Sharma and Rajamani, 2000a,b; Valdiya, 2001; Ramkumar, 2003; Jayalakshmi et al., 2004; Biswas, 2005; Mishra and Kumar, 2005). The west coast/Western Continental Margin (WCM) is characterized by narrow (<60 km), rocky, crenulated and coastal cliffs and pocket beaches. The east coast/Eastern Continental Margin (ECM) is characterized by wide deltas built by major rivers that show trellis to dendritic stream patterns and follow major basement faults. These faults are associated with geologic-historic-recent seismic activity (Radhakrishna, 1993; Sharma and Rajamani, 2000a,b; Valdiya, 2001; Ramkumar, 2003; Raval and Veeraswamy, 2003a; Jayalakshmi et al., 2004; Roy, 2004; Biswas, 2005; Mishra and Kumar, 2005; Ramkumar et al., 2005, 2013; Campanile et al., 2008; Kale, 2014; Kale and Vaidyanadhan, 2014). The western boundary of ECM sedimentary basins, delta heads, strandlines and active delta lobes are always limited by basement faults (Ramkumar, 2003, 2015) and mobile belts (Jayalakshmi et al., 2004). These faults and mobile belts have shown activity since Proterozoic (Roy, 2004) and more actively from the Gondwanan times (Banerji, 1984; Roy, 2004; Ramkumar et al., 2005, 2013; Ramkumar, 2015).

When it was part of Gondwanaland, the Indian subcontinent rifted during the Permo–Triassic in the form of triple rift junctions (Banerji, 1984; Roy, 2004) along Precambrian paleo-suture zones (Roy, 2004). During late Jurassic–early Cretaceous, separation of Africa from Gondwanaland occurred (Chatterjee et al., 2013), followed by the rifting of Antarctica-Australia from Greater India consisting of Madagascar–Seychelles-India during Barremian (Roy, 2004; Bastia and Radhakrishna, 2012; Radhakrishna et al., 2012a). Separation of Madagascar-Seychelles from Greater India occurred around 88–80 Ma (Chari et al., 1995; Gombos et al., 1995; Yoshida et al., 1999; Gunnell et al., 2003; Ramkumar et al., 2005; Chatterjee et al., 2013) and the WCM and WGE evolved (Fig. 1) (Raval and Veeraswamy, 2003a,b; Subrahmanyam and Chand, 2006).

The location of the highest peaks of the Western Ghats (Anaimudi: 2695 m ASL; Dota Petta: 2637 m ASL), exposures of Archaen–Proterozoic deep crustal plutonic-metaigneous rocks, crustal thickness of only 29 km (Radhakrishna et al., 2000, 2012a,b) and absence of significantly thick regolith in the vicinity on a regional scale (Sharma and Rajamani, 2000a,b; Gunnell et al., 2003) along the southern part of the Indian peninsula, together with progressive increase of regolith over granitic and laterite over trap rocks (Radhakrishna, 1993; Valdiya, 2001; Kale, 2014; Kale and Vaidyanadhan, 2014) toward north indicate relatively higher quantum of denudation on the surface and subcrustal erosion underneath in the south.

Thus, despite few publications on geologic-historic-recent resurgence of basement structures, control of sedimentary basin structures, deltas, coastal margins and landscape evolution by these structures since initial rifting, topographic feedback of first order tectonic events, and the geotectonic evolutionary history of the Indian subcontinent, the knowledge on the cause(s) of faster flight experienced by the Indian plate during early Cenozoic remains enigmatic.

3. Material and methods

Initially, interpretation of remotely sensed data and generation of a thematic map of regional geomorphology with field checks was carried out. The thematic map was superposed by digital elevation model constructed from SRTM data. The resultant composite map was incorporated with regional structural features mapped in the field and compiled from previous publications of the authors and others. Data on seismic tomography, zero free air gravity and teleseismic residuals were compiled to construct solid-lithosphere thickness heterogeneity map of the Indian subcontinent. It was followed by enlisting of major tectonic and landscape evolution events and integration of published data on crustal thicknesses and causative mechanisms of crustal thickness heterogeneity. Based on these data and maps, idealistic models were developed and discussed in the context of stages, intensity, and timing of subcrustal plume activity and resultant tectonic-geomorphic feedbacks of the Indian subcontinent.

4. Results

The Indian shield comprises a number of Archean–Proterozoic cratons. In comparison with the thicknesses of shield areas elsewhere (∼250–300 km; Srinagesh, 2000; Raval and Veeraswamy, 2003b; Pandey, 2016), thinnest nature of Indian crustal thickness (Fig. 2) is indicated by seismic tomography, zero free air gravity and teleseismic residuals data. Major part of the original lower crust was removed into the underlying thermally buoyant mantle due to subcrustal erosion during Proterozoic to early Tertiary (Raval and Veeraswamy, 2003b) and by surficial unroofing (Pandey, 2016). Occurrence of 16 km thick mantle magma plume with an isotherm

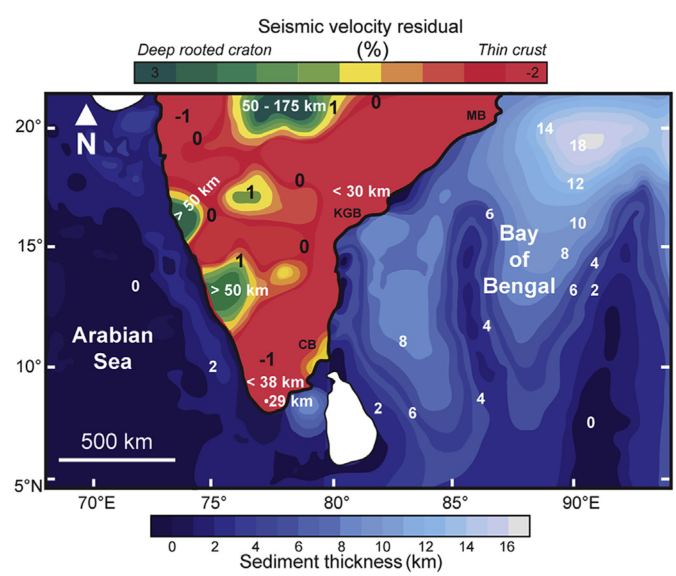

Figure 2. Spatial distribution of crustal thickness of Peninsular India and sediment thickness in the Arabian Sea and Bay of Bengal. Note the relatively thicker lithosphere in the northern part than the south. The continental margin (east and west) are thinner than the north central part. Progressive increase of sediment thickness in the BOB that reaches upto 24 km and forming sediment top load along NE part of the subducting Indian plate could also be visualized. Studies have estimated accumulation of 70 km sediment thickness since hard collision of Indian plate with Eurasian plate.

of ~1300 °C at shallow depth (~100 km) was reported signifying the continuity of plume activity (Raval and Veeraswamy, 2003b; Mishra and Kumar, 2005; Singh et al., 2015) until recent. Crustal thickness estimation from zero free air gravity anomaly showed isostatic under-compensation in the plateau regions, and negative values in the mobile belts (Rao, 2002). The Eastern Ghat Mobile Belt (EGMB) region is characterized by high crustal velocity, dense crust, regional under-compensation and recurrent earthquakes (Rao, 2002) of >5.5 intensity. The velocity residuals computed through seismic tomography (Sen et al., 2009) indicate the occurrences of deep rooted crust in the order of 50–175 km in north-central India, and isolated patches along the western and highly thinned nature in southern India (Fig. 2). Crustal thicknesses of >50 km in central and restricted parts of western India (Radhakrishna and Mahadevan, 2000; Radhakrishna et al., 2000; Srinagesh, 2000; Rao, 2002; Subrahmanyam and Chand, 2006; Sen et al., 2009; Sharma et al., 2012; Singh et al., 2015), <38 km in south, ~30 km under the K-G Basin and 20–23 km at eastern extremity of ECM are reported. The basement below the Cauvery Basin has only a ~3 km thick elastic lithosphere (Bastia and Radhakrishna, 2012) whereas the basement below the K-G basin has 30 km elastic lithosphere (Radhakrishna et al., 2000, 2012a,b). Over 10,000 km of deep seismic profiles observed from more than 600 seismic stations showed a range of crustal thickness from 29 km at the southern tip of India to 88 km under the Himalayan collision zone (Singh et al., 2015).

Tectonic movements along preexistent shear zones (Fig. 1) are evidenced by intraplate stress computations (Mandal, 1999; Mahesh et al., 2012) and the alignments of active seismic zones (Radhakrishna, 1993; Sharma and Rajamani, 2000a,b; Valdiya, 2001; Jayalakshmi et al., 2004; Roy, 2004; Biswas, 2005; Mishra and Kumar, 2005). The Kerguelen, Crozet, Marion and Reunion plumes (Chatterjee et al., 2013) interacted with the Indian lithosphere (Raval and Veeraswamy, 2003b) that led to large-scale shearing (Singh et al., 2015), intraplate magmatism, magma underplating (Srinagesh, 2000; Sen et al., 2009), and crustal physical stretching and thinning (Fig. 2), essentially along the EGMB, ECM, WCM (Radhakrishna et al., 2000, 2012a,b; Bastia and Radhakrishna, 2012). In addition, it has newly created faults giving birth to newer sedimentary basins (Figs. 1 and 3) through structurally weakened pre-existent faults and shear zones (Raval and Veeraswamy, 2003b). This facilitated reactivations during synrift, post rift and collisional phases and considerably reconstituted the Indian subcontinent (Raval and Veeraswamy, 2003b). The ECM and east coast sedimentary basins formed in two stages: the first one in the region between Bengal Basin to north of Cauvery Basin resulted from initial rifting while the second in the region between the Cauvery Basin and the southern extremity of the Indian subcontinent resulted from rifting and shearing (Radhakrishna et al., 2000, 2012b). Movement of intensive plume interaction with subcrustal lithosphere proceeded from NE (present-day) of Indian subcontinent toward south and proceeded along WCM (Sunil et al., 2010; Pandey et al., 2013) before outpouring of lava through Deccan volcanism (Hooper et al., 2010). The subsidence curves developed for each of the subbasins of the Cauvery Basin (Chari et al., 1995) showed that the initial rifting commenced from cratonic interior, evidencing subcrustal plume activity and asthenosphere anisotropy (Srinagesh and Rai, 1996; Srinagesh, 2000; Singh et al., 2004, 2015). Based on the sequences of tectonic, geomorphic and drift events, an idealistic model representing stages of tectono-thermal activity and resultant geological-geomorphic feedback was constructed and presented in Fig. 4. The relatively faster drift of Indian plate in comparison with other plates (Opydyke and Wilkinson, 1998) is shown in Fig. 5a. Apparent variations of drift rates (Lippert et al., 2014) of Indian plate subsequent to major plume activities and rifting phases are presented in Fig. 5b.

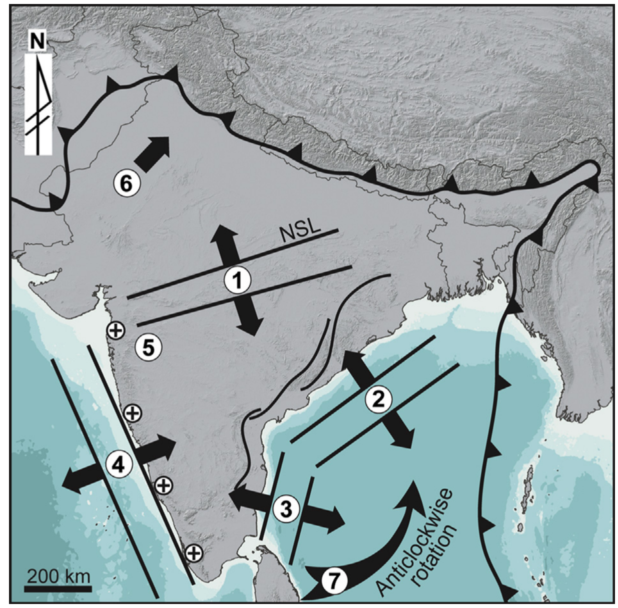

Figure 3. Schematic diagram of tectonic-climatic-sedimentation processes of east and west coasts of India. ① Initial failed rift along Narmada–Son rift, GR and MR (refer to Fig. 1) during Permo-Triassic. These rifts along the Proterozoic structures formed the loci of continental and coastal marine deposits of Gondwana sequences. ② Upper Jurassic rifting occurred initially at the NE (Bengal Basin) and proceeded towards south, creating Mahanadi Basin and the Krishna-Godavari Basin. The basement in these basins is superposed and intruded by volcanic and igneous rocks respectively, followed by extensive intratrappean sedimentary rocks, suggestive of rifting as a result of subcrustal processes and well-differentiated nature of horsts and grabens. Occurrences of the structural trends that resulted due to this rifting either along and/or aligned parallel to preexistent Gondwana trends which in turn were inherited from Proterozoic structural trends (EGMB; refer to Fig. 1), suggest continuum of subcrustal process. ③ Rifting and shearing during Barremian along the Proterozoic structural trends (EGMB; refer to Fig. 1), in the southern extremity. Absence of comparable volcanic and intrusive rocks and the presence of half-graben structure in the Cauvery Basin suggest reduction of intensity of subcrustal process. ④ Rifting and associated separation of Madagascar during Santonian–Campanian. ⑤ Deccan volcanism and outpouring of ~5 km thick trap rock within short duration and sudden topographic top loading. ⑥ Northerly tilt of buoyant, thicker crust top loaded with trap rock (refer to Figs. 2 and 4). It was associated with N–E directed ridge-push from Carlsberg ridge and uplift and northerly ridge-push from Central Indian ridge. All these accelerated the northward flight of the Indian Plate. ⑦ Continued flight of the Indian plate under the influence of geomorphic isostasy, ridge-push and sediment top loading at NE.

5. Discussion

The occurrence and orientation/alignment of the major sedimentary basins, deltaic systems, macrogeomorphic features such as plateaus, waterfalls, delta heads, and strandlines are all either delimited and/or aligned either on or along the major structural trends/sutures in the Peninsular India. Continued activism of these structures and sutures since Proterozoic and inception/termination of basin/delta formation, shifting of prime loci of deposition/erosion concomitant or as a result of these activisms, continued seismicity along these structures are collectively suggestive of tectonism as the first order control over these basins, basinfills, and deltaic systems and also on their spatio-temporal distribution. Examination of these extrinsic processes and features in the light of intrinsic processes and features reveal the following.

The crustal thickness variations and subcrustal anisotropy as revealed by a variety of studies, methods and tools suggest a general increase of thickness from S–N in the peninsular region. This trend in itself is an indication of northerly tilt-uplift of the Indian

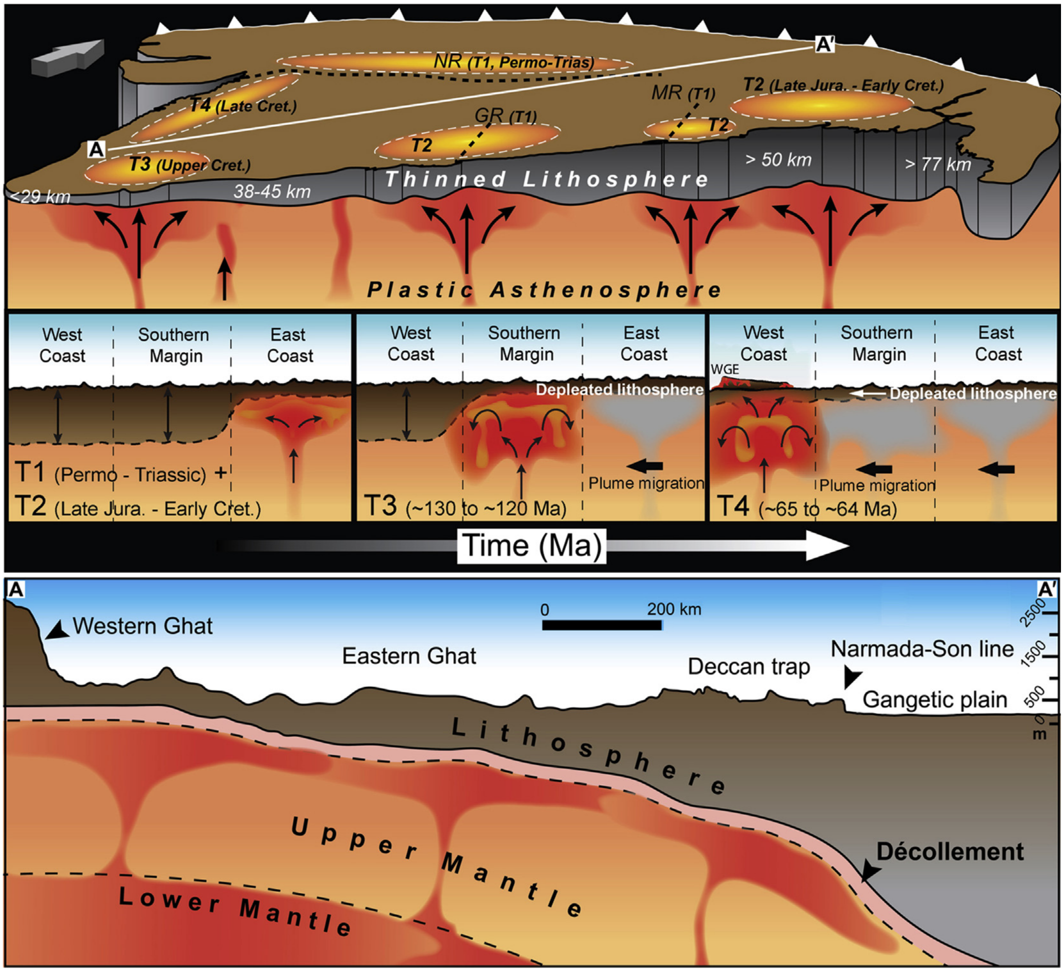

Figure 4. Schematic diagram showing the crustal thickness heterogeneity, the path of plume movement and plume induced subcrustal erosion. T1, T2, T3 and T4 indicate the time slices (refer to Figs. 1 and 3) and zones of significant plume erosion and resultant sub-crustal tectonics. Middle inset diagrams depict the subcrustal erosion due to intensive plume activity. Cross section A–A′ drawn along N–S of the Indian plate as depicted in the top inset is shown in the bottom inset diagram, explaining the resultant rifting, basin formation, differentiation, topographic feedback and geomorphic isostatic compensation. It also depicts how the dècollement layer might have acted as a lubricated surface, on which, the top loaded (by trap rock during end-Cretaceous) and isostatically imbalanced Indian plate slid and commenced the faster flight.

plate due to thrust and isostasy. The southerly thinning could have been due to topographic unroofing (surficial erosion by extrinsic processes) and subcrustal erosion by mantle plumes. As the topographic unroofing is relatively a slow process, and is under the control of tectonics and climate, it is presumed that sudden acceleration of plate movement could not have been affected by it and hence, the intrinsic process is examined.

The initial rifting in the Gondwanaland, now recognized as failed rifts of NSL, GR, MR (Fig. 1) were the earliest evidences of subcrustal plumes induced crustal thinning and subsequent faulting events (Srinagesh, 2000; Sen et al., 2009; Bastia and Radhakrishna, 2012). The late Jurassic–early Cretaceous continental separation was indeed due to the Kerguelen plume activity (Singh et al., 2004), followed by Crozet plume (Bastia and Radhakrishna, 2012; Radhakrishna et al., 2012b) activity both of which led to the formation of 85°E and 90°E ridges (Radhakrishna et al., 2012a), extensive trap rocks over the Precambrian basement as well as intratrappeans in the Bengal and Mahanadi basins (Bastia and Radhakrishna, 2012). Progressive intensification and movement of the plume toward south gave birth to the rifting and initiation of Cauvery Basin (Chari et al., 1995; Sunil et al., 2010; Pandey et al., 2013). Further movement of plume (Marion) thereon along the west rifted Madagascar during Santonian–Campanian (Yoshida et al., 1999; Raval and Veeraswamy, 2003a; Bastia and Radhakrishna, 2012). Finally, the Reunion plume activity during end-Cretaceous led to the Deccan volcanism (McLean, 1985; Hooper et al., 2010). All these plumes, on ascendance, significantly depleted the subcrustal portions of Indian plate all along ECM and WCM, leaving central-northern part thicker and heavier, explaining the crustal thickness heterogeneities of the Indian plate (Figs. 3 and 4). While subcrustal plume controlled geodynamics along the ECM, WCM, and other preexistent rifts stand confirmed, the immediate circumstances that triggered the sudden, accelerated drift of the Indian plate require evaluation.

The occurrence of lower part of the Indian lithosphere along the Main Frontal Thrust underneath the Himalaya (Bastia and Radhakrishna, 2012) and Tibet up to 31°N and a dense continental slab with higher density under Tibet might aid subduction of Indian plate under Eurasian Plate and also form a significant driving force for India–Asia convergence (Lippert et al., 2014). However, the slab pull is reinforced by the ridge-push from the spreading of the Central Indian Ridge and Carlsberg Ridge (Patriat and Achache, 1984; Cande and Stegman, 2011; van Hinsbergen et al., 2011). The WGE, extending for about 1600 km all along the western margin, evolved during Cenozoic–Pleistocene (Radhakrishna, 1993; Gunnell et al., 2003), and the Miocene–Recent tectonic uplift in the Raan of Kutchchh (Gombos et al., 1995) evidence the easterly tilt (Banerjee et al., 2001; Chatterjee et al., 2013), at the

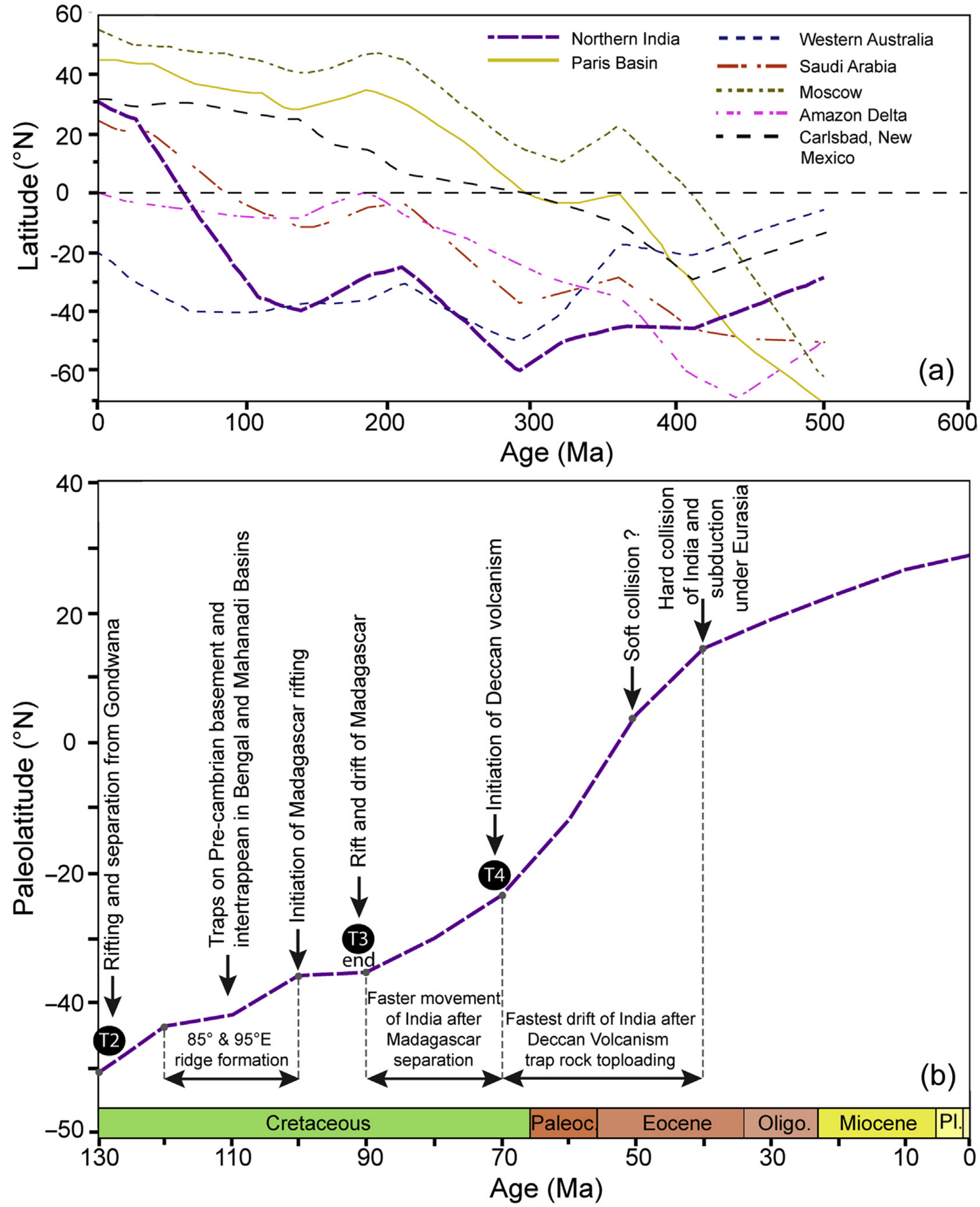

Figure 5. Drift rates of the Indian plate with reference to other continents and time. (a) Relatively different and faster nature of drift history of the Indian plate as compared to other continents is shown by the plot of their paleo-latitudinal positions since 500 Ma. (b) Paleo-latitudinal positions of the Indian plate since 130 Ma. Note the sudden changes in drift rate, immediately after subcrustal erosion events (compare with Figs. 3 and 4) and fastest rate after Deccan Volcanism (T4).

macrogeomorphic scale. Together with the structural trends and geological information, it can be surmised that the Indian subcontinent as a whole experiences thrust and tilt from south since rifting from Gondwanaland perhaps due to its continued northerly flight and rift and tilt towards NE from west since collision with Eurasia.

Movement of plumehead initially along eastern margin from Bengal Basin until the Cauvery Basin, prevalence of rifting-shearing in the Cauvery Basin, followed by movement of the plumehead along the western margin has an analogy in the form of Tanzanian craton (Koptev et al., 2015). Jagoutz et al. (2015) analytically calculated the forces related to slab buoyancy, lithostatic overburden, and viscous flow in the asthenosphere and derived the resultant changes on the subducting/drifting plate, including slab buoyancy, viscous pressure, viscous shear stress, frictional stress, and the pressure due to the overburden on the slab. It yielded a set of velocities for all the plates, a new set of velocities for each point on the slabs, and a new value for the total horizontal component of force acting on each of plate elements in the system. The numerical simulation attempted by these authors suggested the rise of the plumehead from a single mantle source and juxtaposition of magma-rich and magma-poor conditions of Tanzanian craton. We assume similar conditions for the Indian plate based on the younging nature of the rifting from NE of the ECM toward south followed by WCM from south toward north, culminating at the Deccan volcanism. It is noteworthy to state that the quantum and intensity of volcanism and volcanic and volcanoclastics in the sedimentary basins along the East coast show a gradual decrease and become absent in the Cauvery Basin, which experienced initial rifting and later shearing, suggestive of prevalence of magma-rich conditions during the formation of Bengal Basin and magma-poor during the formation of Cauvery Basin. After a while, rejuvenation of the magmatic activity and channeling of the rising magma toward western continental margin might have been prevalent, causing rifting along the western margin culminating at the Deccan volcanism. Cande and Stegman (2011) suggested that the mantle plumes play an important part in the Earth's tectonics, yet it has been difficult to isolate the effect that plumes have on plate motions. Based on this premise, these authors have analyzed the plate motions of India and Africa and concluded that the plate motions involved in two apparently disparate events: the unusually rapid motion of India between 67 and 52 Ma and a contemporaneous, transitory slowing of Africa's motion, and showed that the events are coupled, with the common element being the position of the Indian and African plates relative to the location of the Reunion plume head. According to these authors, the synchronicity of these events suggests that they were both driven by the force of the Reunion plume head. The recognition of this plume force has substantial tectonic implications: the speed-up and slowdown of India, the possible cessation of convergence between Africa and Eurasia in the Paleocene epoch and the enigmatic bends of the fracture zones on the Southwest Indian Ridge can all be attributed to the Reunion plume. As premised by Koptev et al. (2015), magma rising under craton experiencing far-field stress get channeled and is why one side of the craton experiences magma-rich conditions while the other side experience magma-poor conditions, explaining the progression of magmatic activity from Bengal Basin towards west coast of the Indian Plate.

Cande and Stegman (2011) hypothesized that if a rising plume head impinges on the base of a tectonic plate long after supercontinent break-up and dispersal, its pushing force may result in a substantial transient acceleration or deceleration of plates. Müller (2011) opined that whether a plate adopts the speed depends on how the plume-push force balances out with other forces acting on the plate. Further, he was of the opinion that some recent studies suggest that the plate-driving forces that can be generated by mantle plumes are too modest to explain the acceleration of the Indian plate proposed by Cande and Stegman (2011). In addition, the boost in speed seems to have lasted several million years longer than the surface eruptions triggered by the Réunion plume. Nevertheless, Müller (2011) concluded that the plume-push mechanism could explain many geophysical puzzles. Similarly, van Hinsbergen et al. (2011) also concluded that the plume-ascendance and resultant plate motion could accelerate drift rates of continents at several cm/yr.

Passing of the Indian plate over the Reunion hotspot (McLean, 1985; Keller et al., 2008) during 68–64 Ma led to one of the largest, yet shortest continental flood basalt volcanic episodes of the Earth. On a geological scale, it is one of the sudden upheavals (Chenet et al., 2007). Outpouring of >5000 m thick trap rocks in the offshore basins of west coast (McLean, 1985), and present-day exposures with thickness of >3500 m (after enduring >55 Ma of denudation) over the continental basement rocks (Gunnell et al., 2003) forming vast plateaus (Kale, 2014; Kale and Vaidyanadhan, 2014) in the northwestern India, evidence the enormity of this episode. It is the most voluminous continental flood basaltic volcanic activity (McLean, 1985; Keller et al., 2009) as the areal extent of basaltic lava was 2.6×10^6 km^2, the volume (McLean, 1985) of the lava ejected was $\sim$1.2 million km^3, and the CO_2 emitted into the atmosphere was $\sim 5 \times 10^{17}$ mol. According to an estimate (Keller et al., 2008, 2009), the entire event lasted only >4 Ma and another study has estimated only 0.53–1.36 Ma (Chenet et al., 2007) duration. Notwithstanding these differences, >80% of the flows were erupted during the last phase that lasted less than 0.8 Ma (Keller et al., 2008, 2009) during the regionally correlative C29R magnetic polarity zone (Keller et al., 2008). It evidences the suddenness of this upheaval.

Withdrawal of such volumes of lava and gas from subcrustal regime and top loading of the lava material over northern part of Indian subcontinent that already had thicker (Fig. 3) and hence relatively heavier lithosphere than its southern counterpart, that was already under ridge-push (Patriat and Achache, 1984) towards north and uplift makes this event a sudden perturbation on a geological timescale, to which, no topographic and or subcrustal isostatic balance could have been established at the rate of occurrence of disequilibrium. We consider this as an isostatic instability caused by sudden (on a geological time scale) geomorphic evolution, *a la*, geomorphic isostasy. A rise of 1 km in the surface elevation was estimated to be required for every 6–8 km increase in crustal thickness (Lamb and Watts, 2010), or 50–100 km decrease in the thickness of the lithospheric mantle to maintain isostatic equilibrium. The crustal thickness of Indian plate below the northern limit of Deccan volcanic province was estimated (Srinagesh and Rai, 1996; Srinagesh, 2000; Sharma et al., 2012) to be between 70 and >250 km. This thicker part, against the plume-depleted southern part that has on an average only a 2 km thick granitic-gneissic upper crust underlain by 24 km thick intermediate to mafic middle crust (Raval and Veeraswamy, 2003b) (even if higher thickness as compared to that of present day is assumed, the thickness difference between depleted and trap rock top loaded northern part against plume-depleted southern part should have existed) tilted the Indian plate towards north, and rapidly as the solid crust was floating (Raval and Veeraswamy, 2003b) over plastic, thermally stratified asthenosphere (Fig. 4). In addition, the pressure-temperature related physical instability in the asthenosphere beneath the Indian plate aided the sudden tilt and or sliding toward north.

Thus, this sudden instability introduced to the Indian plate buoyed and accelerated the northerly drift which in turn was aided by the tilt from west and the ridge-push (Patriat and Achache, 1984). As density contrast between the lithospheric mantle and underlying less dense asthenosphere plays an important role in the elevation of mountain belts, and isostatic compensation (Lamb and Watts, 2010) and mobility of the lithospheric crust, the acceleration of drift was initiated by this density difference, attenuated due to the outpouring of lava in the aftermath of end-Cretaceous volcanism. Enhanced fluidity and dècollement between the partially molten lithospheric crust of the Peninsula that was floating over the ascendant plume and the thermally-stratified asthenosphere (Fig. 4) utilized the inertia provided by the buoyant plate to drift toward north. Owing to the thermal stratification of plume and asthenosphere under the Indian plate (Srinagesh, 2000) the viscous layer acted as a lubricant between the solid lithosphere (that was being buoyed) and the plume head-asthenosphere. Müller (2011) and van Hinsbergen et al. (2011) are of the opinion that the ascendance of plume itself might have contributed towards several cm/yr of drift. Collectively, the geomorphic isostatic imbalance following outpouring of lava from Deccan volcanism, and prevalence of heavier lithosphere over thermally stratified crust might have aggravated the situation and initiated the accelerated drift of the Indian plate, due to the trigger – the Deccan volcanism. From Figs. 3–5, it is also perceived that with the progressive shedding of microplates namely Madagascar and Seychelles from initial landmass separated from Gondwana (Greater India), the Indian plate became lighter and the rate of drift also became faster. Coincidences of these extraordinary and favorable milieus explain the fastest flight of India since end-Cretaceous volcanism until collision during Eocene (Chatterjee et al., 2013).

6. Conclusions

(1) A sequence of tectono-geomorphologic evolutionary events, commencing from Gondwana supercontinent is proposed. The Indian subcontinent was part of the Gondwana supercontinent and had inherited basement structures since Permo–Triassic. It was dismembered into microplates such as Madagascar and Seychelles and differentiated into various basins along ECM.

(2) These separations and differentiations were essentially due to crustal thinning as a result of subcrustal plume erosion beneath the lithosphere. Owing to the subcrustal erosion, that proceeded from NE (present day) towards south and along the western margin, culminating with end-Cretaceous volcanism, the southern, western and eastern extremities became relatively thinner than the northern part of the Indian plate (Figs. 3 and 4).

(3) Extrusion of enormous quantities of basaltic lava within a short duration during end-Cretaceous initiated an extraordinary sequence of events, among which accelerated drift of Indian plate toward north was more dramatic and unique. Buoyed by the relatively thicker lithosphere in the northern part against plume-depleted southern-eastern-western parts with fluidized, partly molten lower crust floating over thermally-stratified asthenosphere, the Indian plate started gliding toward north in order to isostatically compensate for the physical instability below that was exacerbated by extruded basaltic rocks as topographic top load.

(4) The buoyant plate aided by the Carlsberg and Central Indian ridge-push and resultant uplift of southern India experienced tilt toward north and accelerated drift. The northern-eastern tilt-drift continued during collision and continues till recent, probably sustained by the sediment top loading by the Ganges-Brahmaputra, that accounts for more than 70 km thick sediment pile (Mikhailov and Dotsenko, 2007) in the NE part of the Indian subcontinent.

(5) This sudden acceleration has wider implications in terms of modeling plate reorganization studies elsewhere. In addition, the acceleration has impacted many other processes-events-features such as overall development of the Indian plate, shortening of time duration between separation of Greater India from Gondwanaland and collision with Eurasia, rapid exhumation of Tethys Sea sediments than it could have occurred, structural style and evolutionary history of the Himalayas and associated evolution, demise and dispersal of oceanic and continental biota.

(6) We conclude that plate reorganization and lithospheric top loading interact through complex, often inexplicable processes and feedbacks, and occur at highly variable spatio-temporal scales. As demonstrated by the schematic model and the variable rates of drift, the intrinsic process could be sudden and dramatic, and the extrinsic processes could be long lasting and at variable rates. Recognition and discrimination of these should be an integral part of any plate reorganization and topographic feedback modeling.

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References

Banerji, R.K., 1984. Post-eocene biofacies, palaeoenvironments and palaeogeography of the Bengal Basin, India. Palaeogeography, Palaeoclimatology, Palaeoecology 45, 49–73.

Banerjee, P.K., Vaz, G., Sengupta, B., Bagchi, A., 2001. A qualitative assessment of seismic risk along the Peninsular coast of India, south of 19°N. Journal of Geodynamics 31, 481–498.

Bastia, R., Radhakrishna, M., 2012. Continental Margin of India. Elsevier, 417 pp.

Biswas, S., 2005. A review of structure and tectonics of Kutch basin, western India, with special reference to earthquakes. Current Science 88, 1592–1600.

Campanile, D., Nambiar, C., Bishop, P., Widdowson, M., Brown, R., 2008. Sedimentation record in the Konkan–Kerala Basin: implications for the evolution of the Western Ghats and the Western Indian passive margin. Basin Research 20, 3–22.

Cande, S.C., Stegman, D.R., 2011. Indian and African plate motions driven by the push force of the Réunion plume head. Nature 475, 47–52.

Chari, M.N., Sahu, J., Banerjee, B., Zutshi, P., Chandra, K., 1995. Evolution of the Cauvery Basin, India from subsidence modelling. Marine and Petroleum Geology 12, 667–675.

Chatterjee, S., Goswami, A., Scotese, C.R., 2013. The longest voyage: tectonic, magmatic, and paleoclimatic evolution of the Indian plate during its northward flight from Gondwana to Asia. Gondwana Research 23, 238–267.

Chenet, A.L., Quidelleur, X., Fluteau, F., Courtillot, V., Bajpai, S., 2007. $^{40}K/^{40}Ar$ dating of the main Deccan large igneous province: further evidence of KTB age and short duration. Earth and Planetary Science Letters 263, 1–15.

Collins, A.S., Clark, C., Plavsa, D., 2014. Peninsular India in Gondwana: the tectonothermal evolution of the Southern Granulite Terrain and its Gondwanan counterparts. Gondwana Research 25, 190–203.

Gombos, A.M., Powell, W.G., Norton, I.O., 1995. The tectonic evolution of western India and its impact on hydrocarbon occurrences: an overview. Sedimentary Geology 96, 119–129.

Gunnell, Y., Gallagher, K., Carter, A., Widdowson, M., Hurford, A., 2003. Denudation history of the continental margin of western peninsular India since the early Mesozoic–reconciling apatite fission-track data with geomorphology. Earth and Planetary Science Letters 215, 187–201.

Hooper, P., Widdowson, M., Kelley, S., 2010. Tectonic setting and timing of the final Deccan flood basalt eruptions. Geology 38, 839–842.

Jagoutz, O., Royden, L., Holt, A., Becker, T., 2015. Anomalously fast convergence of India and Eurasia caused to double subduction. Nature Geoscience 8, 475–478.

Jayalakshmi, K., Nair, K., Kumai, H., Santosh, M., 2004. Late Pleistocene–Holocene paleoclimatic history of the Southern Kerala Basin, Southwest India. Gondwana Research 7, 585–594.

Kale, V.S., 2014. Geomorphic history and landscapes of India. In: Landscapes and Landforms of India. Springer-Verlag, Heidelberg, 271 pp.

Kale, V.S., Vaidyanadhan, R., 2014. The Indian Peninsula: geomorphic landscapes. In: Landscapes and Landforms of India. Springer-Verlag, Heidelberg, pp. 65–78.

Keller, G., Adatte, T., Gardin, S., Bartolini, A., Bajpai, S., 2008. Main Deccan volcanism phase ends near the K–T boundary: evidence from the Krishna–Godavari Basin, SE India. Earth and Planetary Science Letters 268, 293–311.

Keller, G., Khosla, S.C., Sharma, R., Khosla, A., Bajpai, S., Adatte, T., 2009. Early Danian planktic foraminifera from Cretaceous-tertiary intertrappean beds at Jhilmili, Chhindwara District, Madhya Pradesh, India. The Journal of Foraminiferal Research 39, 40–55.

Koptev, A., Calais, E., Burov, E., Leroy, S., Gerya, T., 2015. Dual continental rift systems generated by plume–lithosphere interaction. Nature Geoscience 8, 388–392.

Lamb, S., Watts, A., 2010. The origin of mountains – implications for the behaviour of Earth's lithosphere. Current Science 99, 1699–1718.

Lippert, P.C., Van Hinsbergen, D.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. Geological Society of America Special Papers, 507, SPE507–501.

Mahesh, P., Catherine, J.K., Gahalaut, V.K., Kundu, B., Ambikapathy, A., Bansal, A., Premkishore, L., Narsaiah, M., Ghavri, S., Chadha, R.K., Choudhary, P., Singh, D.K., Singh, S.K., Kumar, S., Nagarajan, B., Bhatt, B.C., Tiwari, R.P., Kumar, A., 2012. Rigid Indian plate: constraints from GPS measurements. Gondwana Research 22, 1068–1072.

Mandal, P., 1999. Intraplate stress distribution induced by topography and crustal density heterogeneities beneath the south Indian shield, India. Tectonophysics 302, 159–172.

McLean, D.M., 1985. Deccan Traps mantle degassing in the terminal Cretaceous marine extinctions. Cretaceous Research 6, 235–259.

Mikhailov, V.N., Dotsenko, M.A., 2007. Processes of delta formation in the mouth area of the Ganges and Brahmaputra Rivers. Water Resources 34, 385–400.

Mishra, D., Kumar, V.V., 2005. Evidence for Proterozoic collision from airborne magnetic and gravity studies in Southern Granulite Terrain, India and signatures of recent tectonic activity in the Palghat Gap. Gondwana Research 8, 43–54.

Müller, R.D., 2011. Plate motion and mantle plumes. Nature 475, 40–41.

Opydyke, B.N., Wilkinson, B.H., 1998. Surface area control of shallow cratonic to deep marine carbonate accumulation. Paleoceanography 6, 685–703.

Pandey, O.P., 2016. Deep scientific drilling results from Koyna and Killari earthquake regions reveal why Indian shield lithosphere is unusual, thin and warm. Geoscience Frontiers 7, 851–858.

Pandey, O., Vedanti, N., Srivastava, R., Uma, V., 2013. Was Archean Dharwar craton ever stable? A seismic perspective. Journal of the Geological Society of India 81, 774–780.

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

Radhakrishna, B.P., 1993. Neogene uplift and geomorphic rejuvenation of the Indian Peninsula. Current Science 64, 787–793.

Radhakrishna, M., Mahadevan, T.M., 2000. Seismogenesis and deformation in the Deccan Volcanic province, Peninsular India. Current Science 78, 734–742.

Radhakrishna, M., Chand, S., Subrahmanyam, C., 2000. Gravity anomalies, sediment loading and lithospheric flexure associated with the Krishna–Godavari Basin, eastern continental margin of India. Earth and Planetary Science Letters 175, 223–232.

Radhakrishna, M., Rao, S., Nayak, S., Bastia, R., Twinkle, D., 2012a. Early Cretaceous fracture zones in the Bay of Bengal and their tectonic implications: constraints from multi-channel seismic reflection and potential field data. Tectonophysics 522, 187–197.

Radhakrishna, M., Twinkle, D., Nayak, S., Bastia, R., Rao, G.S., 2012b. Crustal structure and rift architecture across the Krishna–Godavari basin in the central Eastern Continental Margin of India based on analysis of gravity and seismic data. Marine and Petroleum Geology 37, 129–146.

Ramkumar, M., 2003. Progradation of the Godavari delta—a fact or empirical artifice? Insights from coastal landforms. Journal of Geological Society of India 62, 290–304.

Ramkumar, M., 2015. Discrimination of tectonic dynamism, quiescence, and third order relative sea level cycles of the Cauvery Basin, South India. Annals of Geology of Balkan Peninsula 76, 19–45.

Ramkumar, M., Subramanian, V., Stuben, D., 2005. Deltaic sedimentation during Cretaceous Period in the Northern Cauvery Basin, South India: facies architecture, depositional history and sequence stratigraphy. Journal of Geological Society of India 66, 81–94.

Ramkumar, M., Sugantha, T., Rai, J., 2013. Lithofacies and granulometric characteristics of the Kallamedu formation, Ariyalur group, South India: implications on Cretaceous-tertiary boundary events. In: On a Sustainable Future of the Earth's Natural Resources. Springer-Verlag, Heidelberg, pp. 263–284.

Ramkumar, M., Menier, D., Manoj, M.J., Santosh, M., 2016. Geological, geophysical and inherited tectonic imprints on the climate and contrasting coastal geomorphology of the Indian Peninsula. Gondwana Research 36, 65–93.

Rao, D.S., 2002. Zero-free air-based gravity anomaly (preliminary) map of South India - a refined and redefined Bouguer map. Current Science 82, 1373–1378.

Raval, U., Veeraswamy, K., 2003a. India-Madagascar separation: breakup along a pre-existing mobile belt and chipping of the craton. Gondwana Research 6, 467–485.

Raval, U., Veeraswamy, K., 2003b. Modification of geological and geophysical regimes due to interaction of mantle plume with Indian lithosphere. Journal of Virtual Exploration 12, 117–143.

Roy, A., 2004. The Phanerozoic reconstitution of Indian Shield as the aftermath of break-up of the Gondwanaland. Gondwana Research 7, 387–406.

Sen, G., Bizimis, M., Das, R., Paul, D.K., Ray, A., Biswas, S., 2009. Deccan plume, lithosphere rifting, and volcanism in Kutch, India. Earth and Planetary Science Letters 277, 101–111.

Sharma, A., Rajamani, V., 2000a. Weathering of gneissic rocks in the upper reaches of Cauvery river, south India: implications to neotectonics of the region. Chemical Geology 166, 203–223.

Sharma, A., Rajamani, V., 2000b. Major element, REE, and other trace element behavior in amphibolite weathering under semiarid conditions in Southern India. The Journal of Geology 108, 487–496.

Sharma, S., Ramesh, D.S., Raju, P.A., Bapanayya, C., 2012. Seismological and mineral physics constraints on the evolution of upper 660-km depth of the Gondwanaland with special reference to India and Antarctica. In: Sen, M.K., Rao, M.R.K., Arora, K. (Eds.), National Geophysical Research Institute, Hyderabad, India, Annual Report 2011-2012, pp. 17–21.

Singh, A., Mishra, D., Gupta, S., Rao, M.P., 2004. Crustal structure and domain tectonics of the Dharwar craton (India): insight from new gravity data. Journal of Asian Earth Sciences 23, 141–152.

Singh, A., Singh, C., Kennett, B., 2015. A review of crust and upper mantle structure beneath the Indian subcontinent. Tectonophysics 644, 1–21.

Srinagesh, D., 2000. Teleseismic tomographic evidence for contrasting crust and upper mantles beneath Archaean and Phanerozoic terrains in south India. Visakha Science Journal 14, 97–105.

Srinagesh, D., Rai, S., 1996. Teleseismic tomographic evidence for contrasting crust and upper mantles in south Indian Archaean terrains. Physics of the Earth and Planetary Interiors 97, 27–41.

Subrahmanyam, C., Chand, S., 2006. Evolution of the passive continental margins of India—a geophysical appraisal. Gondwana Research 10, 167–178.

Sunil, P.S., Radhakrishna, M., Kurian, P.J., Murty, B.V.S., Subrahmanyam, C., Nambiar, C.G., Arts, K.P., Arun, S.K., Mohan, S.K., 2010. Crustal structure of the western part of the Southern Granulite Terrain of Indian Peninsular Shield derived from gravity data. Journal of Asian Earth Sciences 39, 551–564.

Valdiya, K., 2001. Tectonic resurgence of the Mysore plateau and surrounding regions in cratonic southern India. Current Science 81, 1068–1089.

van Hinsbergen, D.J.J., Steinberger, B., Doubrovine, P.V., Gassmöller, R., 2011. Acceleration and deceleration of India-Asia convergence since the cretaceous: roles of mantle plumes. Journal of Geophysical Research 116, B06101. http://dx.doi.org/10.1029/2010JB008051.

Yoshida, M., Rajesh, H., Santhosh, M., 1999. Juxtaposition of India and Madagascar: a perspective. Gondwana Research 2, 449–462.