



Structure and Geological Processes of the Earth: Seismic Evidences from the Indian Shield

V. Vijaya Rao and Damodara Nara

Abstract

The Earth is a dynamic planet with a large number of geological processes taking place inside it. The internal processes lift and build the Earth's surface, whereas the external processes tend to destroy the shape of the Earth's relief by weathering, erosion and hydrological cycle. The paper places the crustal structure of the Indian shield in the context of global processes and evolution of the Earth. It summarizes internal structure of the Earth from core to crust and addresses numerous geological processes, like evolution of continental crust, operation of plate tectonics, convection currents, mantle plumes and supercontinental episodes using seismic and seismological images. Seismic images provide key evidences of the geological processes that are being taking place inside the Earth. Seismic images from the Archean and Proterozoic terrains of the Indian shield show evidence for operation of plate tectonics since Neoproterozoic. Further, they suggest differences in mode of subduction process during these periods. They provide evidences for the associated processes, like delamination, asthenospheric upwelling, and generation of younger Moho due to crust-mantle interaction. Evolution of sedimentary basins, passive continental margins, the Deccan Volcanic Province, Rajmahal traps and magmatic underplating are interpreted in terms of mantle plume activities using seismic images. Seismological data from Burmese arc region suggest an overturn of subducted Indian lithospheric slab at the transition zone (410–660 km depth) and its slow sinking leading to detachment. Further, remnants of detached lithospheric slabs from the Himalayan-Alps orogenic system are observed at various mantle depths ranging between 1000 and 2300 km beneath the Indian shield. Such displaced slab material pushes the other material to rise somewhere and thereby generate plumes/super plumes. These plumes

break the supercontinent, which in turn cause plate movements on the surface. Tomographic studies suggest whole-mantle convection and provide key evidences for the mantle processes. The role of both the internal and external geological processes that shape the Earth are explained from the evolution of Himalayas and generation of huge sediments from it with the formation of world's largest Bengal fan.

Keywords

Geological processes • Crustal structure • Plate tectonics • Lithosphere • Convection currents • Mantle plumes • Large Igneous Provinces • Active–Passive seismics • Indian shield

1 Introduction

Geological processes contribute kinetic and dynamic forces that help to shape various zones including lithosphere, surface, and crusts of each planet. These processes may be linked to interaction with external environments like impact cratering, the atmosphere, the hydrosphere, and internal mechanisms like tectonism and volcanism. For example, impact cratering played a prominent role in forming and shaping the planetary crusts in the beginning of solar system history. The planet's geological history tells how these geological processes are involved in generating the products or deposits and their arrangements relative to one another. The geological processes are responsible for the Earth's landforms and surfaces. Some of the processes are destructive and others constructive. The geological processes are classified as internal and external.

Both internal and external processes need a source of energy to drive them. The Earth was very hot when it was formed at ~4.56 Ga (Ernst 2007). Slowly it has started cooling by releasing the internal heat at the mid-oceanic

V. V. Rao (✉) · D. Nara
CSIR-National Geophysical Research Institute, Uppal Road,
Hyderabad-500007, India

ridges, volcanoes, mantle plumes, etc. in the form of volcanism. Further, disintegration of radioactive elements also generated heat inside the Earth. This heat of the Earth drives the internal geological processes, which usually occur far from the surface. They are responsible for movement of lithospheric plates, occurrence of earthquakes and volcanos, opening of new oceans and closing of old ones, formation of mountain ranges, etc. Rock deformation, crystallization and metamorphism are other important internal processes. The internal processes build the Earth's landforms and surfaces.

External processes shape the relief created by internal processes. Internal processes lift and build the Earth's surface, whereas external processes tend to destroy the shape of the Earth's relief. Weathering and erosion, hydrological cycle, deposition and soil formation, glaciers, rivers, streams, mass movement, land-sea interaction etc. are the major external processes. Solar energy is responsible for the external geological processes. It creates difference in atmospheric temperature, causes winds, responsible for water-cycle- evaporation and rain fall.

The main activities of the geological processes are erosion, weathering, operation of plate tectonics and associated processes. Gravity also plays a vital role in both internal and external geological processes. Gravity contributed in forming the convection currents in the Earth's interior. These convection currents will sink the dense (cold) material by replacing the lighter (hotter) materials that rise towards the surface. On the Earth's surface, gravity plays a role in moving the accumulated water and ice on the continents towards the sea by forming rivers and glaciers, which shape the rocks along their path due to erosion in due course.

In this contribution we attempt to evaluate the role of convection currents, plate tectonics, mantle plumes and other geological processes on the structure, composition and evolution of continental crust. Surface manifestations of some of these geological processes are discussed. The main objective is to show the important deep seismic images acquired along various transects within the Indian plate that constitute key evidences of the geological processes that are being taking place inside the Earth. A brief discussion of the role of external geological process on the evolution of plate tectonics and biosphere and the relief created by the internal processes is included.

2 Structure and Properties of the Earth

It is believed that the Earth along with the solar system was evolved from the dense cloud of interstellar gas by condensation at ~ 4.56 Ga (Ernst 2007). As Earth started cooling slowly chemically distinct layers, namely, the core,

mantle and the crust were formed due to differentiation process, where high-density (Fe, Ni) melts settle at the bottom (core) and lighter ones to the top (crust) (Fig. 1a). Evidence for the various layers of the Earth is provided by the earthquake and active source seismic data. Radius of the earth is ~ 6400 km.

Core The core is the innermost layer, located at the centre of the Earth that is rich in iron and nickel. It is divided into two layers—the inner and outer cores. The inner core is solid with a density of 13 g/cm^3 and a radius of ~ 1220 km. The outer core with a density of 11 g/cm^3 surrounds the inner core and has an average thickness of ~ 2250 km. It is identified as a fluid layer by the earthquake data using the P and S-waves (Fig. 1c). The boundary between the mantle and core is marked by a substantial drop in P-wave velocity and S-waves do not propagate beyond this boundary as the outer core is in fluid form.

Mantle The mantle is located just above the core and surrounds it. It has a thickness of ~ 2900 km and comprises about 83% of the Earth's volume. It is divided into upper mantle, lower mantle and asthenosphere based on composition, rheology and P and T conditions. The upper mantle exists from the base of the crust downwards to a depth of ~ 670 km. This region is believed to be composed of ultramafic peridotite made up of the olivine and pyroxene minerals. The rocks in the upper portion of the mantle are more rigid and brittle because of cooler temperatures and low pressures. The lower mantle located below the upper mantle extends from a depth of 670 to 2900 km. This layer is hot and plastic. Minerals that are formed here are different from those of the upper mantle due to the presence of higher pressure and temperatures.

Crust The cool, rigid, and brittle part located on top of the mantle is called the crust. There are two types of crust—the oceanic crust and continental crust (Fig. 2). Both types of crust are less dense than the rock found in the underlying upper mantle. The Oceanic crust is thin and measures between 5 and 10 km thick. It is composed of basalt and has an average density of about 3.0 g/cm^3 . The continental crust is 20 to 80 km thick and composed mainly of lighter granitic rocks (Christensen and Mooney 1995). The density of continental crust is about 2.84 g/cm^3 . The continental crust is a layer of igneous, sedimentary and metamorphic rocks. The continental shelves are part of it. The continental crust is also less dense than oceanic crust although it is considerably thicker. About 40% of the Earth's surface is now covered by continental crust, but continental crust makes up about 70% of the volume of Earth's crust. The continental crust is

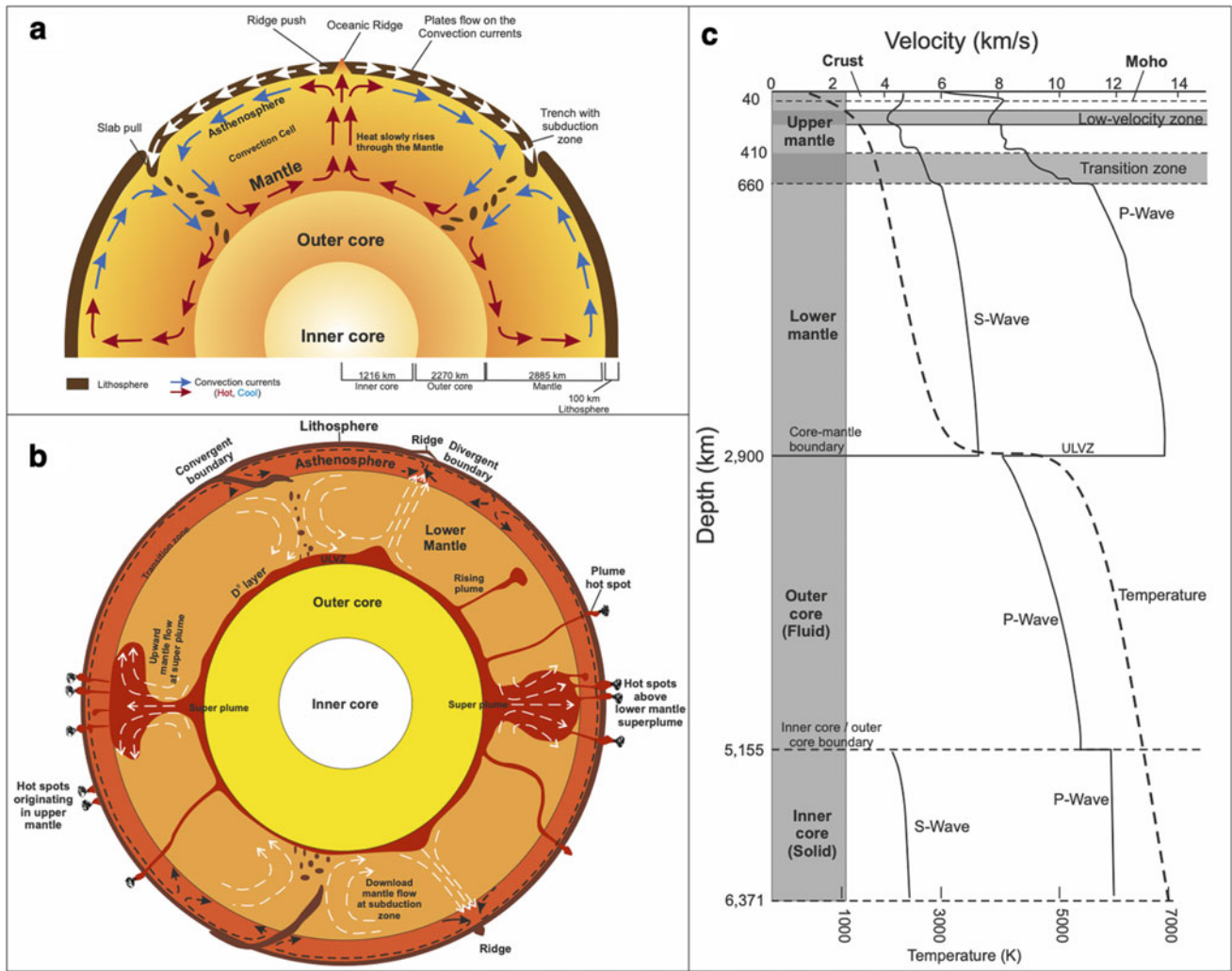


Fig. 1 a Structure of the Earth with convection currents and lithospheric plates, b Structure of the Earth along with mantle plumes and ultra-low-velocity-zones (ULVZs) located at the core-mantle boundary (D'' layer). Partially molten rocks are identified as ULVZ

by seismic tomography. Presence of ULVZ beneath the broad mantle plume indicate a close dynamical link between them, c P- and S-wave velocities-depth along with temperature profile of the Earth

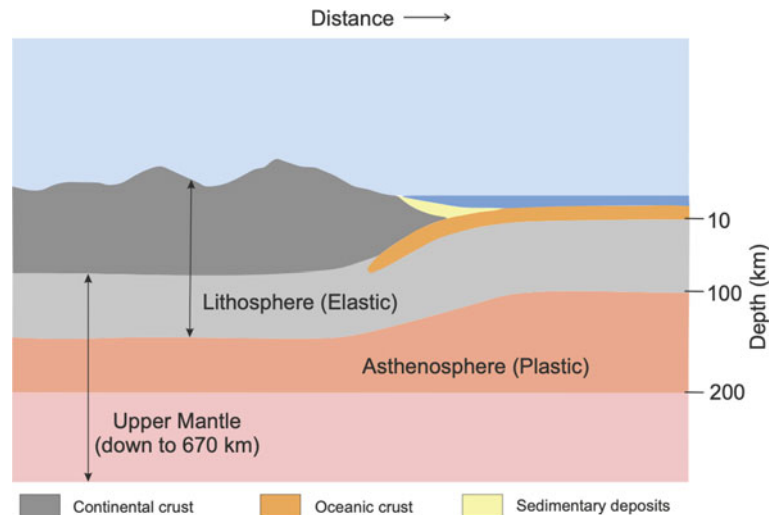
thinnest in areas like the rift valleys of East Africa and the Basin and Range Province, USA and thickest beneath mountain ranges like the Himalayas. The Mohorovicic discontinuity/the Moho is a compositional (chemical) boundary that separates silica-rich rocks of the crust from olivine-rich rocks of the mantle.

Lithosphere The lithosphere is a solid layer that includes the crust and the upper most portion of the mantle, which constitute the hard and rigid outer layer of the Earth (Figs. 1a and 2). The thickness of the lithosphere is the depth to the ~1300 °C isotherm where olivine begins to deform viscously. It is associated with the transition between brittle and viscous behaviour. Lithospheric thickness varies depending on the tectonic and magmatic activity of the region. It is between 80 and 280 km for continental regions,

50 to 140 km for oceanic regions and very thin beneath the mid-ocean ridges. The lithosphere is buoyant because it is attached to the crust of lower density and glides over the rheologically weak asthenosphere. Heat transfer in the lithosphere is by conduction process, unlike convection in the mantle.

The Earth exhibits two types of lithospheres—the oceanic and continental. New oceanic lithosphere is constantly being produced at mid-ocean ridges and is recycled back to the mantle at subduction zones, so oceanic lithosphere is much younger than its continental counterpart. The oldest oceanic lithosphere is about 200 Ma compared to the continental lithosphere, which is ~4.00 Ga old. The oceanic lithosphere thickens as it ages and moves away from the mid-ocean ridge. It mainly consists of mafic crust and ultramafic mantle and is denser than continental lithosphere.

Fig. 2 Structure of the crust and topmost layer of the upper mantle —the lithosphere and asthenosphere



Asthenosphere The asthenosphere located just below the lithosphere is a layer where the mantle material, peridotite become weaker than both overlying and underlying mantle at ~ 1300 °C, corresponding to a depth of 80–280 km. Heat generated from the radioactive decay of elements also helps to create magma (molten rock) in the asthenosphere. This layer has physical properties that are different from rest of the upper mantle. The asthenosphere is the highly viscous, mechanically weak and ductile region of the upper mantle. Rocks in the asthenosphere are “plastic”, meaning that they can flow in response to deformation. Even though it can flow, the asthenosphere is still made of solid (not liquid) rock. The asthenosphere is identified as a low-velocity layer in the seismological studies (Figs. 1c and 2). The maximum thickness of the asthenosphere can be around 350 km.

Lithosphere-Asthenosphere Boundary (LAB) LAB is defined as a rheological boundary (mechanical) boundary and its upper and lower units, namely, the lithosphere and asthenosphere respond differently to the applied stress. For very long periods of geological time, the lithosphere deforms elastically and remains rigid through brittle failure. In contrast, the asthenosphere deforms viscously and accommodates strain through plastic deformation. Although the thermal boundary differentiates the lithosphere and asthenosphere, they are chemically similar.

Transition Zone (Upper-Lower mantle boundary) At shallow depths (<410 km) mantle peridotite contains olivine. But at greater depths (410–660 km) the atoms in the olivine lattice rearrange to form more compact denser material called β -phase without affecting the overall chemical composition. This zone between 410 and 660 km is called the “Mantle Transition Zone”. The bottom of this transition zone is called as 660 km discontinuity. When a subducting slab

reaches this depth, seawater that was trapped in it is squeezed out of minerals. This results in an abrupt increase in seismic velocity in this transition zone because of dryer and ultra-dense features of the material present there (Fig. 1c).

Core-Mantle Boundary Complex geological processes are thought to take place at the core-mantle boundary which separates the mantle convection and a silicate mantle from the fluid outer core. Seismic studies from earthquake data identified an Ultra-Low Velocity Zone (ULVZ) with thin localized patches of material (15–30 km height) at D” layer of the core-mantle boundary (Garnero et al. 2016). They are of different sizes and shapes. They are identified as partially molten roots of plumes of hot rock (Fig. 1b) that slowly rise through the mantle to feed volcanoes (Yuan and Romanowicz 2017). These ULVZ are identified as the signature of the base of the world’s plumes and upwellings (Fig. 1b and c). Swirling convection currents in the mantle drive the plumes. The seismic studies provided connections between the ULVZ and the plumes beneath the Hawaii, Samoa and Iceland.

3 Geology of India

Indian shield is a mosaic of cratons and mobile belts with 3.8 Ga geological history. It shows a variety of geological features of different periods manifested by different geotectonic processes. The Archean Dharwar, Bastar, Singhbhum, Bundelkhand and Mewar cratons were collided and sutured with the evolution of several orogens/mobile belts between them during different periods since Archean (Fig. 3). Some of these collision/suture zones are reactivated as rifts. The Dharwarian, Aravalli, Delhi, Satpura, Eastern Ghats are the

important orogens evolved during the collisional process (Vijaya Rao, 2009). The Western Ghats, the Karnataka, Deccan, Chotanagpur and Shillong plateaus are the important epigenetic uplifts of the Indian shield. The Vindhyan (VB), Chattisgarh (Ch B), Bastar (Ba) and the Cuddapah (CB) basins are the undeformed and unmetamorphosed Proterozoic basins (Fig. 3). The Kutch (KB), Saurashtra (SB), Narmada (NB) Cambay (CB), and west Bengal (BB) are the sedimentary basins formed during the Mesozoic (Fig. 3). These petroliferous basins are located either between the cratons or continental margins. The granulite terrain located in the southernmost part of the Indian shield is evolved during the Late Neoproterozoic and also Late Neoproterozoic (during the East-African orogen at ~ 550 Ma). The Indian plate is unique as it was traversed by four major plume activities, namely, the Kerguelan, Crozet, Marion and Reunion mantle plumes between ~ 130 and 65 Ma after separating from the Gondwanaland at ~ 200 Ma (Fig. 4). Separation of India from the Gondwana fragments, its rapid northward movement ($15\text{--}18$ cm/year) and final collision with the Asian plate at ~ 55 Ma is responsible for the evolution of Himalayas. A 2500 km long world's highest mountain chain and highest plateau Tibet makes the Himalaya a natural laboratory and a unique feature of the Indian shield.

Internal Geological Processes

Many geological processes operate inside the Earth. But, only a few relevant ones, like evolution of continental crust, operation of convection currents, plate tectonics, mantle plumes and supercontinental episodes are discussed here with reference to the Indian shield. Deep crustal seismic reflection images, velocity-depth models and the geological cross-sections derived from various seismic transects (vertical rectangles numbered 1–6 in Fig. 3) are interpreted in terms of the geological processes. They provide the knowledge of the Earth's working pattern.

4 Evolution of the Continental Crust

The continental crust is evolved from the mantle during the fractional differentiation process, which involves chemical separation by partial melting and outgassing of volatiles. Initially, due to very high temperatures the basaltic lava was erupted, and magma ocean was formed on the surface of the Earth. In an active planet the surface layers are returned back into the mantle and form a continuous distillation like process. Such a recycling process over a very long period produced highly differentiated magma that is distinctly different from basaltic composition and closer to the igneous rock granite. This process was primarily a result of volcanism and subduction. Evolution of the continental crust of

granitic composition is a continuous process, and it has been taking place since 4.0 Ga, even after 4.56 Ga years of formation of the planet. The crust produced at the mid-oceanic ridges is cycled back into the mantle at the subduction zones and then upward again. The crustal material continues to undergo chemical processing from basalt to andesite and eventually to granite.

5 Convection Currents

Pressure and temperature increase with depth inside the Earth. The core being at higher temperature than mantle, the heat liberated by it is transferred to the mantle. Further, heat is also transferred from the mantle to the crust and finally to the surface of the Earth. Average temperature of the mantle is ~ 3700 °C, and the crust is around 500 °C. There exists a huge temperature difference between the mantle and crust. As temperatures rise with depth, rocks reach temperatures that would cause them to melt if they were at the surface. The rocks remain solid at depth despite their temperature because of the extreme pressures acting upon them. However, they do become plastic. Subjected to immense forces, and with vast amounts of time, such rocks will flow very slowly over a very long period.

The hot material being lighter (less-denser) rises and the heavier (more-dense) cold ones sink. Similar process generates the convection currents in the mantle. Heat from the core and mantle itself causes convection currents. Mantle convection is the very slow creeping motion of Earth's solid silicate mantle caused by convection currents carrying heat from the interior to the planet's surface. Convection currents are movements of the mantle material that are less dense. The hot convection cells start from the core-mantle boundary and slowly rise up to the bottom of the lithosphere. They form mid-oceanic ridges above it, dissipate heat and thereby cool down. These cooled convection cells elongate in the asthenosphere and may be aligned in long cylinders that drive the overriding lithosphere plates along like a conveyor belt (Fig. 1a). A larger-scale circulation transports heat from the volcanic mid-ocean ridge to a deep-ocean subduction trench, where the convection cells travel their backward journey to the lower mantle. Large-scale convection currents may lift and/or lower entire continents. This results in earthquakes, volcanic activity, mountain building and ocean recycling. Thus, the Earth's convective system exerts major influence on mantle as well as on continental dynamics. It is the engine that drives the plates to move across the surface.

There is a debate as to whether convection is "layered-mantle" or "whole-mantle" convection. Even though this debate continues, results from seismic tomography, numerical simulations of mantle convection and examination of Earth's gravitational field all suggest the

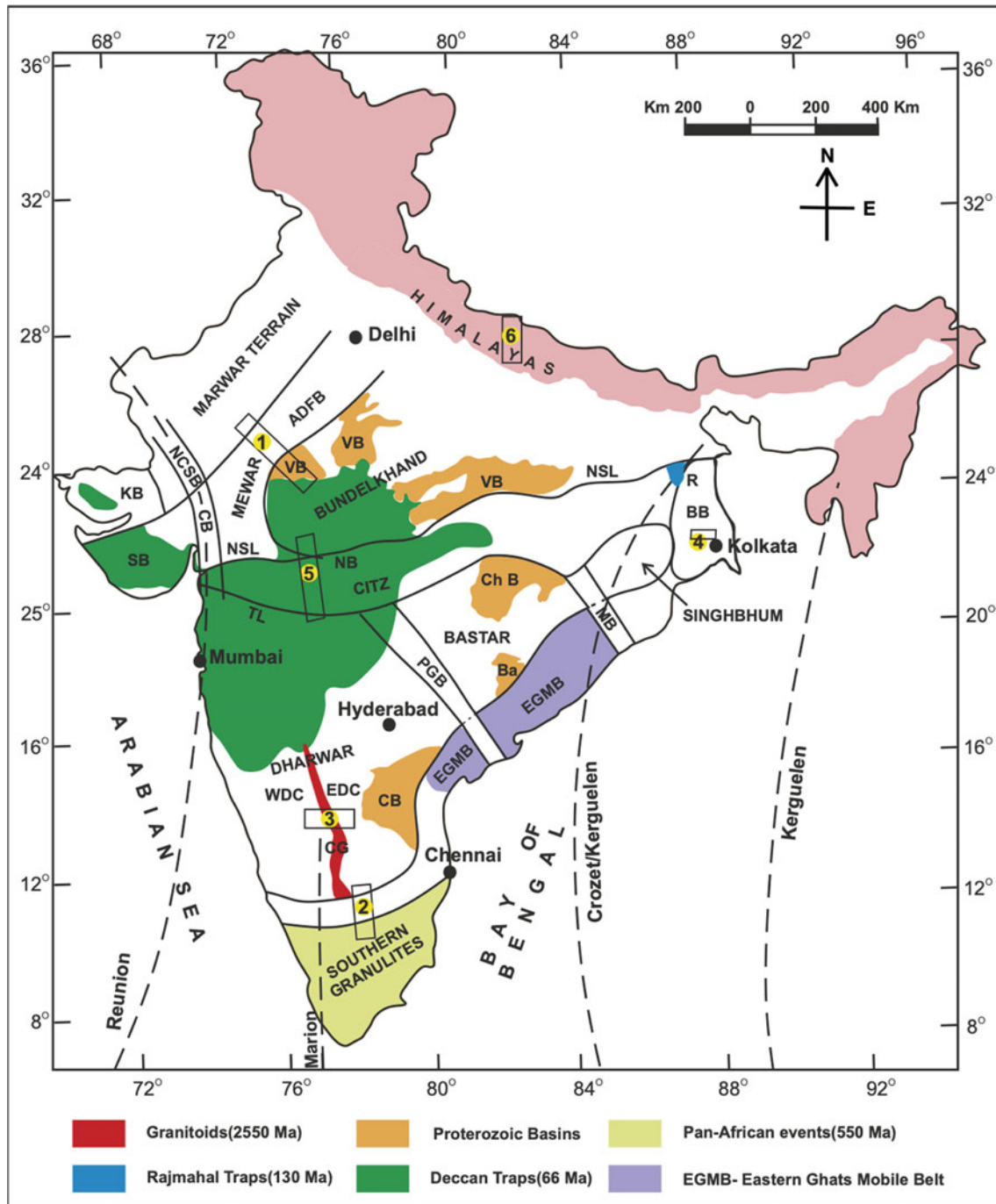


Fig. 3 Geological map of India along with various mantle plume paths superimposed over it. Numbers 1–5 indicate the areas discussed in the text. 1: Aravalli-Delhi fold belt; 2: Dharwar craton-southern granulite

terrain boundary; 3: across western and eastern Dharwar cratons (WDC-EDC); 4: West Bengal sedimentary basin; 5: across the Narmada-Son and Tapi lineaments; 6: across the Himalayas

existence of ‘whole’ mantle convection, at least at the present time (Fig. 1a). In this model, cold, subducting oceanic lithosphere descends from the surface to the core–mantle boundary (CMB) and hot plumes rise from the CMB to the surface (van der Hilst et al. 1997). This picture is strongly based on the evidence from the global seismic tomography

models, which identified remnants of subducted lithospheric slabs based on high seismic velocity anomalies in the mantle (van der Meer et al. 2018). An evidence from India further constrain the subducted slabs reaching the core-mantle boundary. Tomographic imaging of India and adjacent regions revealed high P-wave velocities at depths between 1000 and

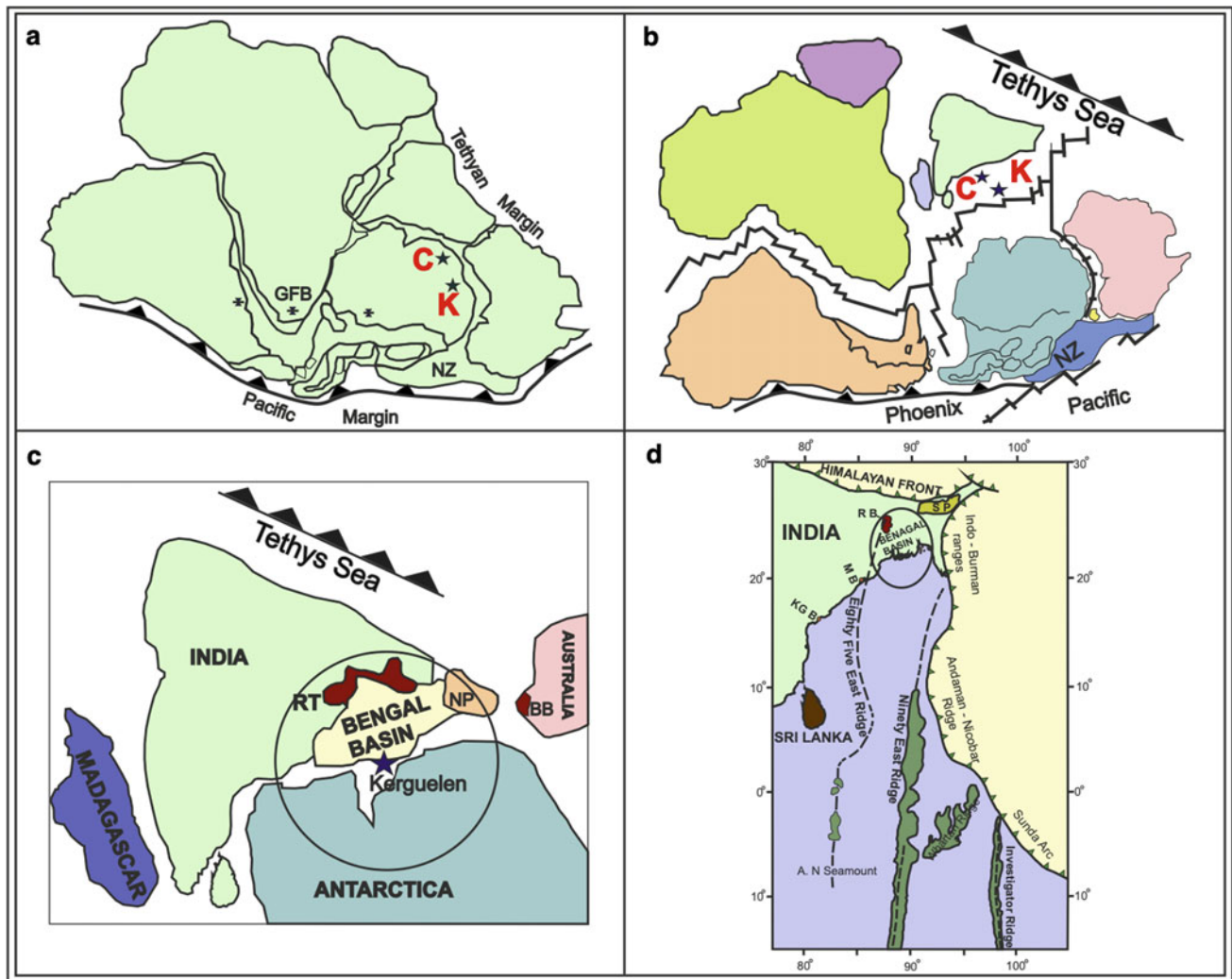


Fig. 4 Breakup of Gondwanaland due to plume activities. **a** Gondwanaland during ~ 200 Ma, **b** Separation of combined Antarctica and Australia from India due to the Kergulean-K and Crozet-C mantle plume activities during ~ 130 Ma, **c** Formation of the Bengal basin and

evolution of the Rajmahal traps during ~ 117 Ma, **d** Formation of the Himalayan orogeny during the Eocene. (modified after Damodara et al. 2017)

2300 kms (Fig. 5). They are interpreted as remnants of detached oceanic lithospheric slabs from the Mediterranean-Himalayan-Indonesian orogenic system at various depths (Van der Voo et al. 1999). They were developed due to subduction of the Tethyan oceanic lithosphere that sink into the lower mantle. The Indian plate appears to have overridden its own detached and sinking lithospheric slabs. Similar conclusions are drawn from the paleomagnetic data (Torsvik et al. 2006). Tomographic images also show the origin location of mantle plumes from the ultra-low velocity-zone located at the D'' of the core-mantle boundary, then rising and crossing the mantle transition zone (Fig. 1b).

Some recent studies indicate slab stagnation in the mantle transition zone (410–660 km depth) may be due to reduced viscosity (Fukao et al. 2009; Fukao and Obayashi 2013). The reduced viscosity provides some sort of lubrication on

the slabs, which make the slab to slip and slide sideways instead of continuing their downward plunge. Seismological data using 60 earthquakes has suggested an overturn of the subducted Indian lithospheric slab at the transition zone in the Burmese arc region (Purnachandra Rao and Kalpana 2005). The data also suggests slow sinking of the overturned slab leading to detachment which is presented in Fig. 6. These deflected slabs move horizontally to a distance of ~ 1500 km in the transition zone. These overturned lithospheric slabs can be responsible for extension, tectonism and volcanism in overriding continental/intra-plate regions. The 3D convection model studies (Mao and Zhang 2018) suggest that the slabs are trapped only for 20 Ma. Subsequently, they penetrate the lower mantle indicating a transit nature of slab stagnation. It supports whole mantle convection models.

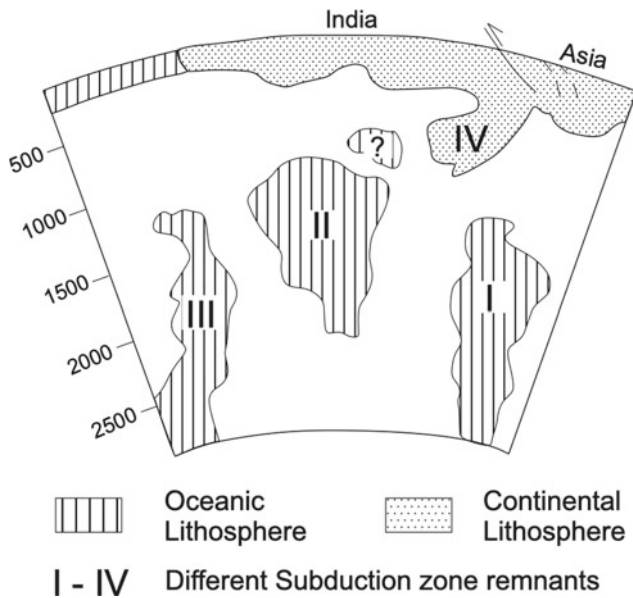


Fig. 5 Schematic diagram showing subduction of the Tethyan sea during the Mesozoic and delamination of subduction slab during India-Asia collision. Different detached slabs at various depths (modified after van der Voo et al. 1999)

The electrically conducting moving currents in the Earth's fluid outer core, which is composed of molten iron, are found to be responsible for generating and sustaining the Earth's magnetic field. Geophysical studies suggest that the route of polar (north-south) waves through the Earth gradually shifting eastward through the Earth's interior because of slightly faster movement of the solid inner core than the rest of the planet. This faster rotation of the inner core also helps to understand Earth's magnetic field reversals (Anderson 2007).

6 Plate Tectonic Processes

The lithosphere is not a continuous layer. The present-day lithosphere is divided approximately into 12 (big and small) movable tectonic plates located just above the asthenosphere. The plates are continuously being created and consumed at the divergent and convergent boundaries, i.e., the mid-oceanic ridges and subduction zones, which are located on either side of the plates. Heat and gravity are fundamental

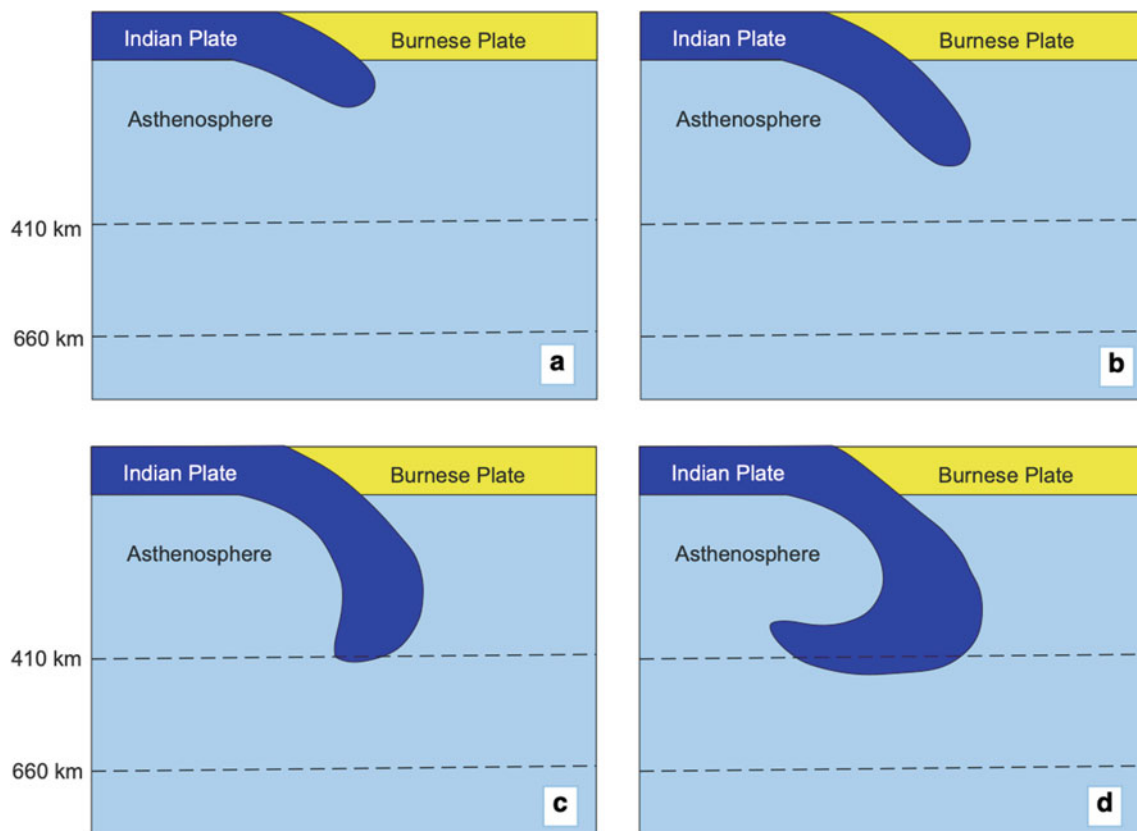


Fig. 6 Schematic model illustrating various stages of subduction of Indian plate beneath the Burmese arc. **a** Subduction of Indian plate, **b** slow subduction and sinking of the slab, **c** overturn of subduction slab

at the transition zone located at 410 km depth discontinuity, **d** cessation of subduction and slow sinking of overturned slab (after Purnachandra Rao and Kalpana 2005)

to the process of plate tectonics. Lithospheric plates are part of a planetary scale gravity-driven thermal convection system. The energy source for plate tectonics is Earth's internal heat, whereas the gravity forces move the young hot plates away from spreading ridges (ridge push) and pulls old cold plates down into subduction zones (Slab pull) (Anderson 2007). The plate tectonics are responsible for opening of new oceans, closing of old ones, generation of volcanism and earthquakes, formation of mountain ranges, continental drifting, generation of continental crust and many more activities. The theory of plate tectonics is one of the great scientific advances of the present period that can be compared with the Darwin's theory of evolution and the Einstein's theory of relativity. Mantle convection is the main mechanism for operation of plate tectonics.

Convection currents in the asthenosphere drive the overriding lithospheric plates from the mid-oceanic ridges to the subduction zone. When tectonic plates come together, the Oceanic plate invariably sinks due to its own weight during the processes of subduction at an oceanic trench underneath the overriding continental plate. Then two plates collide with each other forming mountain ranges, like the present-day Himalayas, the Alps, the Andes etc.

Many large-scale surface features are manifestations of deep-seated geological processes. Thus, an understanding of crust may resolve some of the fundamental questions related to the mantle dynamics and evolution of the Earth. In order to understand the origin of crustal structure, it is essential to know the crust-mantle interaction and chemical exchange processes between them. In this context, seismic refraction/wide-angle reflections and high-resolution deep crustal normal-incidence seismic reflection images from several parts of the Indian shield provide necessary inputs. Few such studies, namely the DHARSEIS experiment of the Archean Dharwar craton and the Nagaur-Jhalawar transect across the Paleoproterozoic Aravalli Fold Belt (AFB) of the NW India (Fig. 3) are discussed to understand the evolution of continental crust and the geological processes responsible for the operation of plate tectonics since Neoproterozoic (Tewari et al. 1997; Vijaya Rao et al. 2000; Krishna and Rao 2011; Vijaya Rao and Krishna 2013; Mandal et al. 2018).

6.1 Paleoproterozoic Aravalli Fold Belt

NW part of the Indian shield exhibits 3.3 Ga geological history. It consists of Paleoproterozoic Aravalli and Late Mesoproterozoic Delhi orogens extending linearly to a distance of 700 km (rectangle-1, Fig. 3). The region consists of intensely folded, deformed and metamorphosed rocks deposited over the Archean basement. It contains ophiolites, high-grade granulites and granitic plutons of different periods starting from Mesoproterozoic. The region has unique

distinction of having the highest reserves of Pb-Zn, phosphorites and evaporate minerals in the country.

A 400 km long multi-fold seismic reflection study across the Paleoproterozoic Aravalli fold belt imaged a crustal-scale dipping reflection fabric extending from the surface to a depth of 38 km (Fig. 7). It is interpreted as the signature of subduction of the Bundelkhand craton beneath the Mewar craton (Fig. 8). Subsequent collision of these two cratons resulted in the formation of Aravalli Fold belt (Vijaya Rao et al. 2000). During this period various crustal blocks in different parts of the world, including NW India, were involved in the process of accretion and formation of Paleoproterozoic Columbia supercontinent (Rogers and Santosh 2004). Generally, mountain belts represent regions where oceans might have opened and closed and they are the products of continental collision (Dewey and Bird 1970).

During the initial stage of collision process there was an increase in crustal thickness at the subduction zone (Fig. 8b). Once the oceanic crust has been consumed in the subduction zone, a continent-to-continent (Mewar-Bundelkhand) collision took place resulting in a further increase in crustal thickness (Fig. 8c). This large crustal thickness becomes gravitationally unstable. Considering the pressure and temperature conditions at depth, metamorphic process that took place within the crustal root as well as the subduction derived magmas resulted in the eclogitization of the crustal root. The high density of the eclogite initiate a delamination process, sink into the mantle and finally thinning out the crust (Fig. 8d). Finally, the orogen collapsed under its own weight due to gravitational instability (Dewey 1988). Then the rise of magma produced by decompression melting of upwelling asthenospheric crept into shallow depth thereby post-collisional extension took place (Fig. 8d). During this crust-mantle interaction process basaltic magma accreted at the crust-mantle boundary, referred as magmatic underplating. The injected mantle material into the lower-crust results in a layered structure with alternating physical properties, consisting in high and low rock densities and seismic velocities (Mooney and Meissner 1992). Such geological structures with layered mafic intrusions (Deemer and Hurich 1994) resulted in a laminated sub-horizontal seismic signature in the lower crust (Fig. 7). The bottom of this reflection fabric represents the Mohorovicic (Moho) discontinuity. It is an important mechanism of the crustal growth in the vertical direction. This horizontal smoothening process is manifested by the presence of 12 km thick sub-horizontal reflection band at the crust-mantle boundary. Geodynamic processes responsible for the evolution of orogen and its subsequent stabilization are presented in Fig. 8. These processes are similar for most of the orogens observed in any part of the world.

During the collisional episode, crustal material is transferred to the mantle at the subduction zone due to

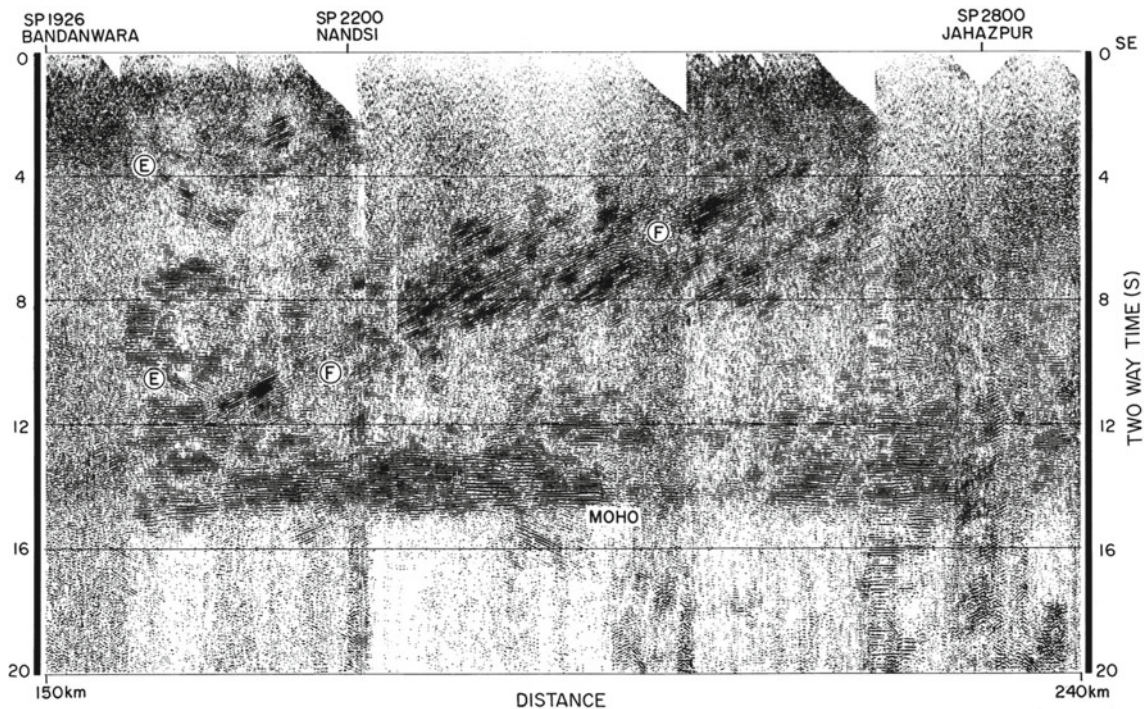


Fig. 7 Crustal-scale dipping reflection fabric identified from seismic reflection study along Nagaur-Jhalawar transect (vertical rectangle-1, Fig. 3). It represents a collisional suture in NW India and responsible

for the evolution of Paleoproterozoic Aravalli Fold Belt. Sub-horizontal lower-crustal reflection band indicate post-collisional extensional processes in the region

compressional activity and due to delamination of thickened crust. The mantle material is transferred to the crust as magmatic underplating during the post-collisional extensional processes. Such a dynamic crust-mantle interaction process creates an equilibrated younger Moho that is represented by a sub-horizontal lower-crustal feature in a seismic reflection image (Cook 2002; Carbonell et al. 2013; Reddy and Vijaya Rao 2013). Thus, a two-way material exchange created a new crust-mantle boundary in the Aravalli fold belt region. The life cycle of an orogen, from its formation to destruction, provides the main mechanism for the evolution of continental crust at the convergent margins and its growth at the crust-mantle boundary. The present study suggests that the crustal structure as revealed by seismic data preserves the record of both the past tectonic processes responsible for its formation as revealed by the presence of deeply-penetrating crustal-scale reflection fabric and structural and chemical modification as exhibited by sub-horizontal lower crustal fabric. Vijaya Rao (2009) provides a detailed description of the geodynamics of the collision zones of the Indian shield.

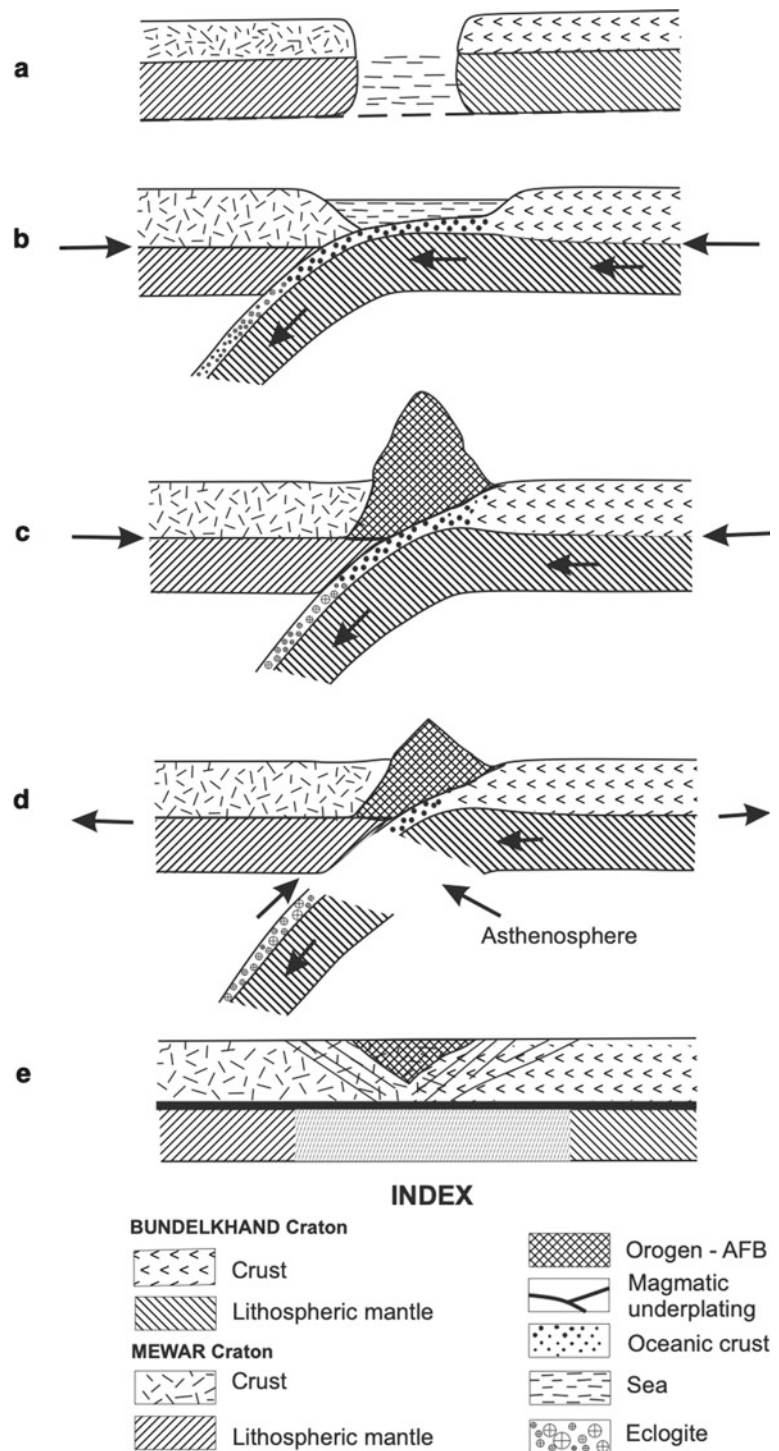
6.2 Archean Dharwar Craton

Operation of plate tectonics during the Neoproterozoic has been suggested using the deep crustal wide-angle and normal-incidence seismic reflection images of the Indian continental plate (Reddy et al. 2003; Vijaya Rao et al. 2011). Results from two seismic profiles (rectangles-2 and 3, Fig. 3) across the Archean blocks are briefly discussed here.

6.2.1 Dharwar Craton—Southern Granulite Terrain

The seismic data across the Dharwar craton and the Southern Granulite Terrain reveal a gently dipping lower-crustal reflection band extending from 33 to 45 km depth across the Dharwar-Southern Granulite Terrain boundary in the southern part of India (rectangle 2, in Figs. 3 and 9). It is interpreted as a Neoproterozoic mantle subduction zone of the Dharwar craton (Vijaya Rao et al. 2006). High thermal regime of the Archean period might have decoupled the crust and mantle due to differences in the rheological properties, such as velocity, density and composition between

Fig. 8 A cartoon illustrating orogenic cycle involving the transition from compressional to extensional tectonic regimes. **a** Different cratonic blocks (Bundelkhand and Mewar) of NW India separated by an ocean between them. **b** Compression leads to subduction of the Bundelkhand craton beneath the Mewar craton. **c** Further convergence leads to collision and formation of an orogenic belt (Aravalli Fold Belt) along with thickening of crust and eclogitization of the lower crustal material. **d** Transfer of crustal material to mantle—delamination of thickened eclogitized lower crust and uppermost mantle. **e** Lithospheric extension, orogenic collapse and crustal thinning. Transfer of mafic/ultramafic mantle material to the crust and accretion at the lower-crust as magmatic underplating with the formation of sharp and flat Moho as depicted in Fig. 7



them. The Moho here acted as a detachment boundary and thereby only mantle subducted, unlike the whole crustal subduction observed at the Proterozoic Aravalli fold belt region as discussed above (Fig. 7). The lower-crustal/mantle subduction is found to be a common phenomenon during the Archean as revealed by several deep seismic reflection studies from different parts of the globe (BABEL Working

Group 1990; Calvert et al. 1995; van der Veldon and Cook 2005). Release of carbonic fluids from the supracrustal rocks and volcanic arc environment of the subduction zone are found responsible for the formation of granulites in the region. P–T–t estimates and seismic reflection images suggest that collision processes are responsible for the exhumation of granulites from the lower crustal depth

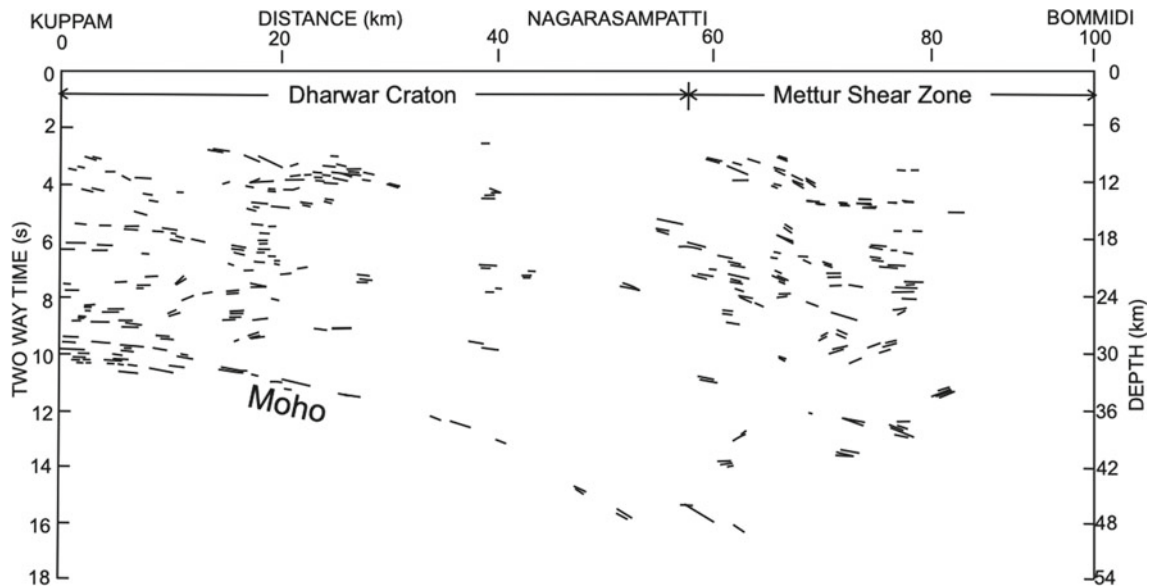


Fig. 9 Neoproterozoic subduction zone identified across the Dharwar craton-southern granulite terrain using high-resolution seismic reflection study along the Kuppam-Palani geotranssect (vertical rectangle-2, Fig. 3)

(Vijaya Rao and Rajendra Prasad 2006; Vijaya Rao and Reddy 2009).

6.2.2 Mesoarchean Western—Neoproterozoic Eastern Dharwar Cratons

The Dharwar craton of southern India represents one of the largest and oldest cratonic blocks available on the Earth, similar to the Superior province of America. It is a classic granite-greenstone terrain with 3.5 Ga geological history. It is covered by Tonalitic Trondjemite Gneisses (TTG) with several greenstone belts of volcano-sedimentary sequences. It is characterized by greenschist-amphibolite facies metamorphism. It comprises of two distinctly different crustal blocks, namely, the Mesoarchean Western Dharwar Craton (WDC) and predominantly Neoproterozoic Eastern Dharwar Craton (EDC).

The data from deep crustal seismic studies across the Dharwar craton identified a Neoproterozoic subduction-collision zone between the WDC and EDC with a mantle suture at the Closepet granite (rectangle-3, Fig. 3). A large number of Paleo-Mesoproterozoic mafic dikes and sills (French and Heaman 2010) are observed over a large area of the Archean Dharwar craton, southern India (Figs. 3 and 10). These dykes constitute large amounts of magma added to the crust. The relatively vertical dyke geometry is indicative of crustal/lithospheric extension processes which might be a result of post-collision (Vijaya Rao et al. 2015; Mandal et al. 2018). Much of the crustal growth in the craton is ascribed to the Neoproterozoic collision process.

Seismic studies from the Archean Dharwar craton described above suggest operation of plate tectonics at least from

the Neoproterozoic. It is further constrained from similar seismic studies from different parts of the world (Calvert et al. 1995; van der Veldon and Cook 2005; Cook 2002). Plate tectonic operation is extended further back upto ~ 3.6 Ga by several researchers using the geological studies (de Wit 1998; Smithies et al. 2005; Moya et al. 2006). Operation of plate tectonics provide one of the important links to understand the mantle dynamics in addition to the knowledge from paleomagnetic data, tomographic models of the mantle, geodynamic modelling, volcanic eruptions etc. Further it links the deep earth processes with surface processes.

6.3 Cretaceous-Tertiary Himalayas

India after separating from the east Gondwana fragments, the Australia, Antarctica and Madagascar started moving in the northward direction during the Cretaceous (Fig. 4). The Tethys ocean located north of the Indian plate started subducting and gradually disappeared resulting in continental collision between India and Asia in the early Tertiary at ~ 55 Ma with the evolution of Himalayan orogen. Surface area of the “Greater India” before collision was around 1000 km more than the present day. This along with the seafloor spreading likely occurred within the Neo-Tethys (during India-Australia separation) suggest at least 4000 km of Tethys oceanic lithosphere has gone down into the mantle during the subduction (van der Voo et al. 1999). Remnants of slab material derived from such a huge subduction are identified in the deep mantle between 1000 and 2300 km depth by tomographic studies (Fig. 5).

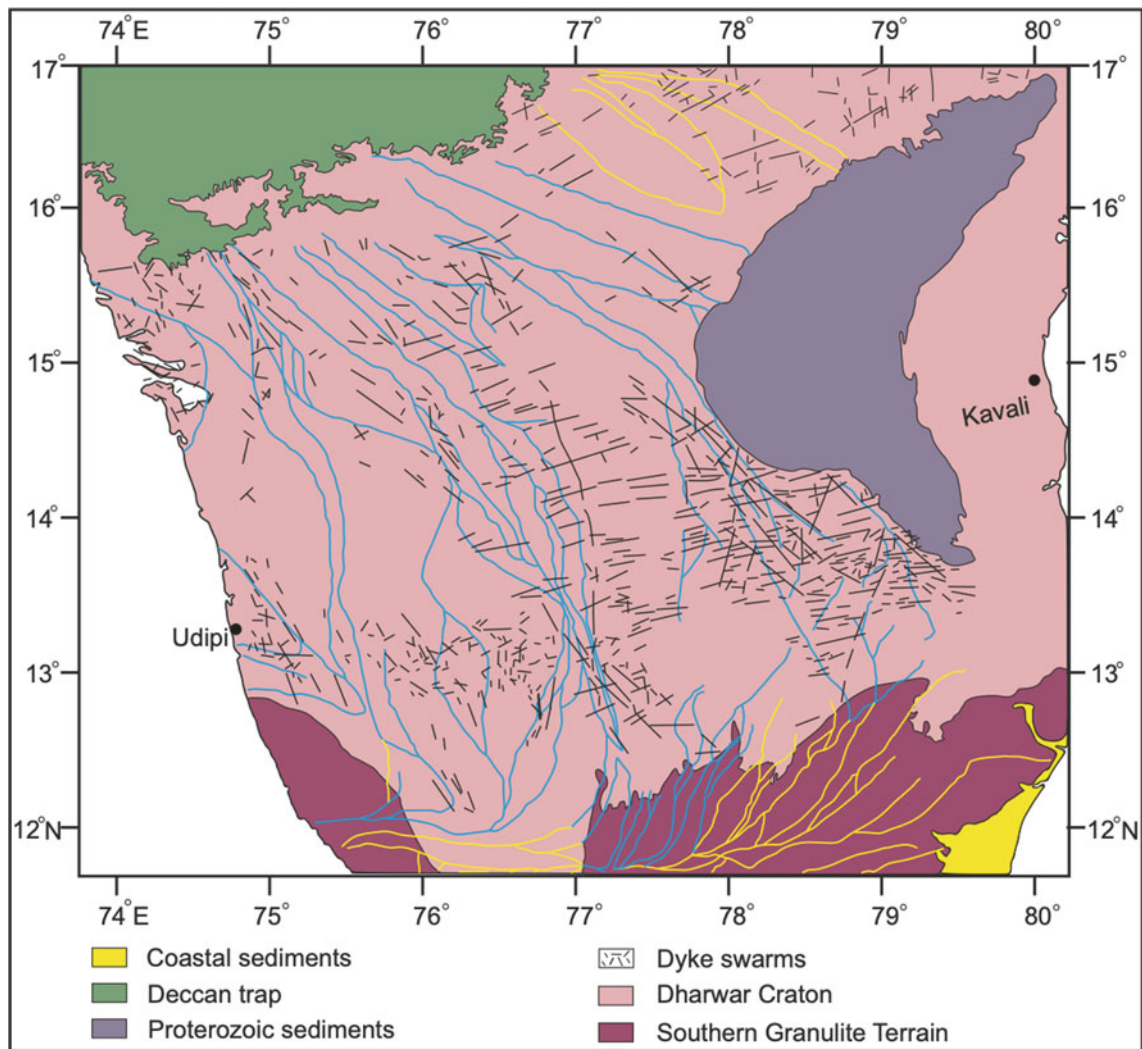


Fig. 10 Proterozoic Dike swarms of the Archean Dharwar craton. They are the manifestation of extensional activity in the region (modified after Vijaya Rao et al. 2015)

To the east of Eastern Himalayan syntaxis, India collided with the Burmese plate with the evolution of Indo-Burmese ranges in the north–south direction (Figs. 4d and 6). Further south of Burmese ranges continental collision transitions into oceanic–continental subduction along the Andaman-Sumatra subduction zone (Fig. 4d). During the continental convergence India rotated anticlockwise direction at an angle of $\sim 20^\circ$ and generated western and eastern syntaxes.

Structural architecture of the Himalayan fold-thrust belt is dictated by the underthrusting of Indian plate beneath the Tibetan plateau along the plane of detachment, known as the Main Himalayan Thrust (MHT) (Zhao et al. 1993). The Himalayan orogen joins different tectonostratigraphic domains, namely, the Sub-Himalaya, Lesser Himalaya, Greater Himalaya and Tethyan Himalaya (Fig. 11a). These domains are separated by the Main Boundary Thrust (MBT),

Main Central Thrust (MCT) and South Tibetan Detachment (STD). They lie between Main Frontal Thrust (MFT) in the south and Indo-Tsango Suture (ITS) in the north (Fig. 11b). The Sub-Himalaya is the foreland basin consisting of clastic syn-orogenic sediments derived from the uplift, erosion and deposition by the Himalayan rivers and subsequently folded and faulted to form the Siwalik Hills at the foot of the mountain chain. The imbricated thrust stacks like MFT, MBT and MCT are terminated at the detachment layer, the MHT (Fig. 11b).

Several geophysical and geological studies were conducted to understand the structure, geometry and deformation of the Himalayan collision zone and its causative mechanisms (Zhao et al. 1993; Nelson et al. 1996; Kind et al. 2002; Rajendran and Rajendran 2005; Kumar et al. 2006, 2013; Kayal 2008; Gao et al. 2016 and the references there in). A high-resolution deep seismic reflection study

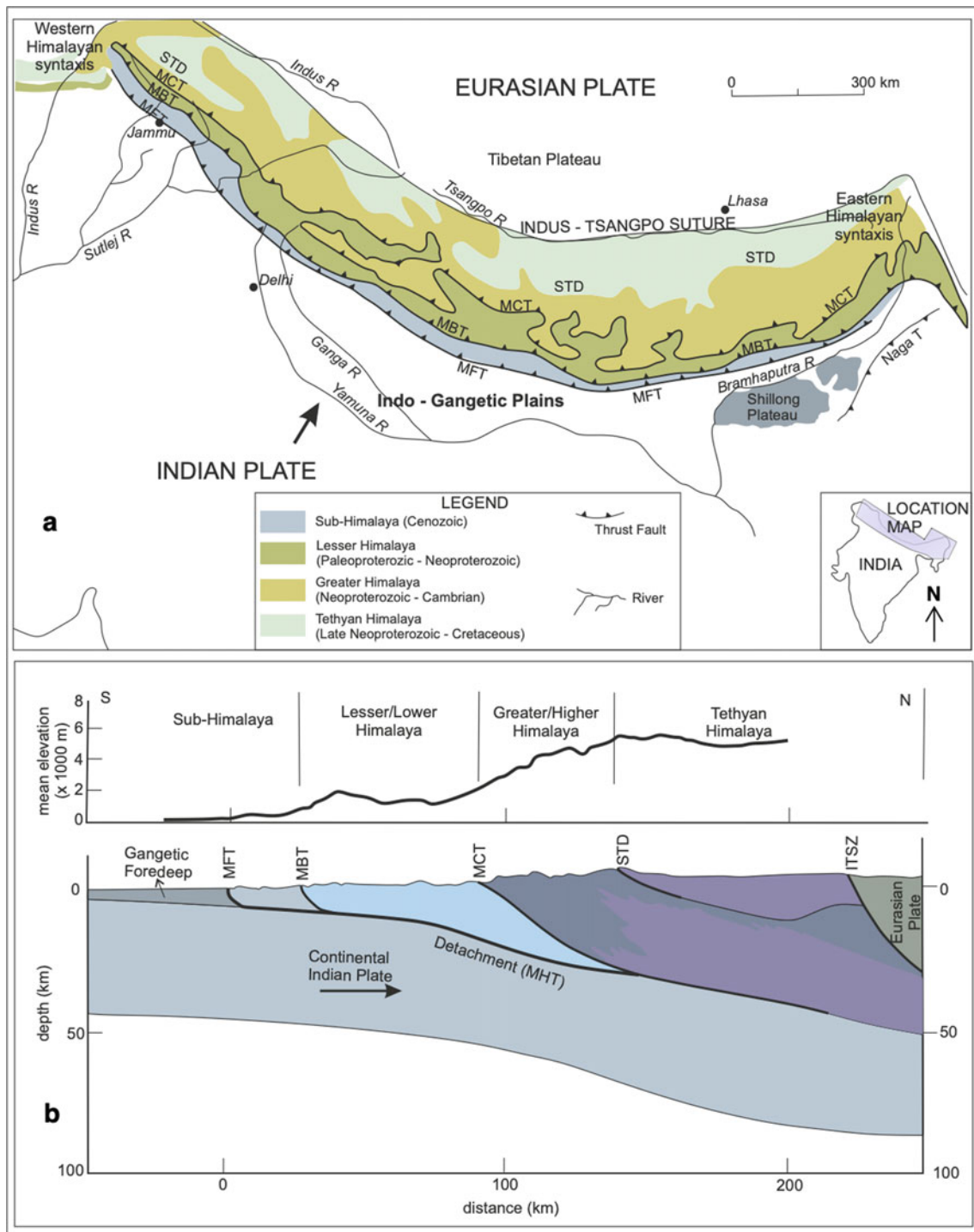


Fig. 11 a Generalized geological map of Himalaya along with the Indian-Eurasian plate boundary marked (vertical rectangle-6, Fig. 3). MFT-Main Frontal Thrust; MBT-Main Boundary Thrust; MCT- Main Central Thrust; STD-South Tibetan Detachment; ITS- Indus Tsangpo

suture. **b** Generalised cross-section across the Himalaya in the general NE-SW direction. Sub-Himalaya, Lesser Himalaya, Greater Himalaya and Tethyan Himalaya along with their tectonic boundaries marked over it

conducted in the western part of Tethyan Himalaya of the southern Lhasa block near the Manasarovar has identified a crustal thickness of 70–75 km beneath the Indo-Tsangpo suture (Gao et al. 2016). Further, the above study imaged the

MHT dipping with an angle of $\sim 20^\circ$ to a depth of 60 km beneath the Indo-Tsangpo suture (ITS). The Indian crust has reduced from original ~ 40 km thickness to ~ 15 km beyond ITS with transfer of material from the lower plate to

the upper plate by crustal duplexing. The lithospheric thickness in the foredeep region of the Himalaya is around 140 km (Kumar et al. 2006).

The underthrust Indian plate generates a lot of stress, and the accumulated strain is released through structures evolved during the collision. Some of these structures generated most damaging earthquakes of $M_w \sim 8.0$. They have caused severe damage in the Indo-Gangetic alluvial plains. Great earthquakes generally initiate at brittle-ductile transition of the MHT and propagate along ramp-flat structures (MFT, MBT, MCT) of the brittle part of the crust. However, significant earthquakes have also been observed above and below the MHT. Seismological data indicate presence of two distinct earthquake zones (Chen and Yang 2004; Monsalve et al. 2006) one above the MHT in the upper crust (<20 km depth) and the other below the MHT in the crust and upper mantle (60–100 km depth). For example, the 2011 Sikkim earthquake of M_w 6.9 is located at the crust-mantle boundary. Similar intracontinental earthquakes ranging between 4.9 and 6.0 magnitude are observed in the mantle portion of the lithosphere around 100 km depth. They are observed beneath the western Himalayan syntaxies in the Kunlun Mountains and the southern Tibet at Xigaze. Arora et al. (2014) using the aftershocks of 2011 Sikkim earthquake and gravity models suggested a strong eclogite body in the lower crust which serves as a repository of high stress. Occurrence of earthquakes in the lower-crust and upper mantle indicates evidence for strong lithospheric lower-crust and upper mantle in the Himalaya to sustain brittle failure.

Some of the processes within the Himalaya are loss of Indian crust by subduction, transformation of mafic crust into eclogites, transfer of Indian crust into the Himalayan thrust sheets by crustal-scale thrust duplexing or partially molten channelized return flow and earthquake generation (Nelson et al. 1996; Sapin and Hirn 1997; Gao et al. 2016).

7 Mantle Plumes—Intraplate Volcanism

Most of the volcanoes occurred at the plate boundaries, e.g., the boundary of the Pacific Ocean, referred as “**the Ring of Fire**”. However, some volcanoes occur in isolation, e.g., the big island of Hawaii erupted in the middle of the Pacific Ocean/plate, far distant from any volcanoes. Similarly, the Deccan and the Rajmahal volcanics of the Indian shield occurred on land in isolation (Fig. 3). The isolated volcanic sites are referred as the hot spots. There are about 100 such hot spots currently active on the surface of the Earth (Zhao 2007). It is believed that hot-spot volcanoes form above mantle plumes with columns of hot mantle rising from just above the core-mantle boundary (Coffin and Eldholm 1994; Duncan and Richards 1991).

The subducting oceanic lithosphere being denser than the mantle above, it tends to accumulate at the 660 km discontinuity. A large number of such subducting slabs reaching the mantle transition zone destabilize the 660 km discontinuity layer and sink into the lower mantle (van der Holst et al. 1997; Bijwaard et al. 1998; van der Meer et al. 2018). This process is known as a “slab avalanche” (Condie 1998). These displaced slab material pushes the other material to rise somewhere and thereby generate plume or super plumes (Fig. 1). Deep mantle tomography, numerical models and paleomagnetic study (Zhao 2004; Torsvik et al. 2006) envisaged the plumes as having narrow central conduit arising from D” thermal disturbance layer at the core-mantle boundary. Plume heads may reach diameters of the order of ~ 1000 km on reaching base of the lithosphere (Fig. 1b).

Based on the source of the plumes, three types of plumes are identified (Courtillot et al. 2003). (1) Primary-deep plumes rising from D” layer of the core-mantle boundary; (2) Secondary-plumes originating from the top of deep plumes; (3) Tertiary-plumes originating from 660 km discontinuity. Plumes have the capacity to generate large quantities of basaltic magma (e.g., continental flood basalts) before continental breakup and to produce chains of volcanic islands when oceanic plates move over fixed hot spots, e.g., Hawaiian Islands. They also cause plate movements on the surface (Gurnis 1988).

Insights brought out on the geological processes from seismic studies from plume affected areas of the Indian shield are presented in the following sections.

7.1 Mesozoic Mantle Plume Activity over the Indian Shield

India, Antarctica, Australia, Madagascar, Africa and South America were part of Gondwanaland, which was major constituent of the Pangea supercontinent during the Phanerozoic (~ 250 Ma). These continental blocks got separated due to several mantle plumes, namely, the Kerguelon, Crozet, Marion and Reunion at different times (Fig. 4). Breakup of the Gondwanaland into smaller continents during the Mesozoic (Storey 1995) is the best example to understand the role of mantle plume activity, mantle dynamics and crustal evolution.

Breaking of the Pangea supercontinent during the Mesozoic developed passive continental/volcanic rifted margins on both the eastern and western part of India. The margins are characterized by seaward dipping reflectors (SDRs), significant volcanism, high-velocity lower-crustal layers, formation of rift basins and presence of mafic dyke swarms.

7.1.1 East-Coast of India

The East Gondwana, one of the major constituents of the Pangea supercontinent started breaking up due to Kerguelen hotspot activity during the early Cretaceous (Storey 1995). India separated from the combined Antarctica-Australia with the evolution of Indian Ocean during ~ 117 Ma (Gaina et al. 2007). Breaking of the East Gondwana due to mantle plume activities is shown in Fig. 4. The east Gondwana breakup episode has developed the Bengal basin and influenced the architecture of the Mahanadi basin in the eastern margin of India (rectangle-4, Fig. 3). During this period widespread volcanism occurred with extrusion of continental flood basalts, the Rajmahal volcanics/traps. Seismic studies identified the Rajmahal traps in the Mahanadi and West Bengal basins. The basin architecture of the west Bengal sedimentary basin derived from the seismic tomographic study (Damodara et al. 2017) is presented in Fig. 12. Deep crustal refraction/wide-angle reflection study identified 10 km thick high-velocity layer at the base of the crust, usually referred as the magmatic underplating, which is related to the plume activity in the region (Mall et al. 1999).

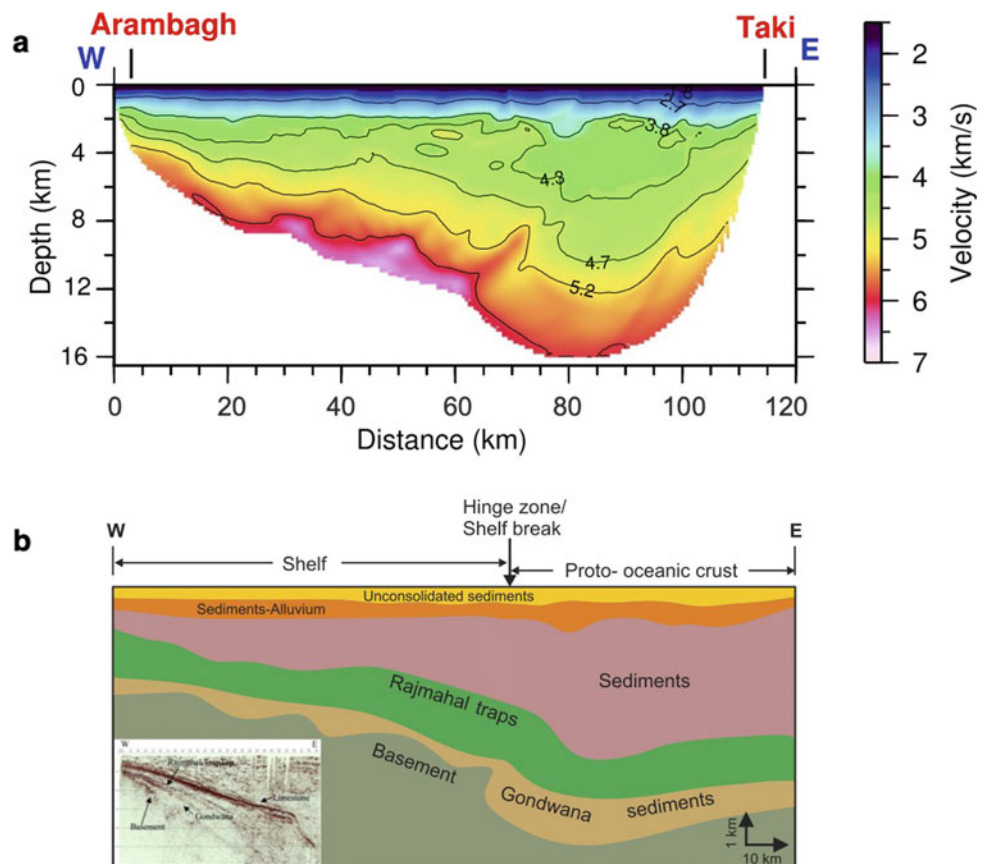
7.1.2 West-Coast of India

The extensional activity during the supercontinent Pangea breakup event developed the Kutch, Saurashtra, Cambay and

the Narmada peri-cratonic rift basins on the western continental margin of India (Biswas 1987). Subsequently, the Madagascar was separated from India due to the Marion plume and the Seychelles due to the Reunion mantle plume activity during 88 Ma and ~ 65 Ma respectively.

Continental rifting and associated basin formation due to the Reunion plume activity are related to lithospheric thinning with ascent of asthenospheric mantle. Mafic magma generated during such process extruded as the Continental Flood Basalts (CFB) resulting in the formation of Deccan Volcanic Province at the Cretaceous-Tertiary (K-T) boundary (Fig. 13a). Such flood basalt regions worldwide are referred as the Large Igneous Provinces (Coffin and Eldholm 1994). The Deccan trap of India is one of the largest known CFB provinces on the earth. The Karoo, Columbia River and Siberian traps are other important CFB regions of the world. The Deccan flood basalts are spread over 500,000 sq. km and covered central and western India. The lithospheric extension during this event emplaced 65 Ma old widespread mafic dikes and dike swarms (Fig. 13b) in the general N-S and E-W direction (Bhattacharji et al. 1996). The Narmada-Tapi (E-W), Cambay and North Cambay-Sanchor (N-S) and the western margin (N-S) rifts are evolved or reactivated during the formation of triple junction (Figs. 3 and 13a). The location where all the three rifts cross each

Fig. 12 **a** Basin configuration of the West Bengal sedimentary basin (vertical rectangle-4, Fig. 3) showing 15 km thick sediments in the deeper part of the basin. **b** A schematic diagram showing the basin architecture of the West Bengal sedimentary basin (modified after Damodara et al. 2017)



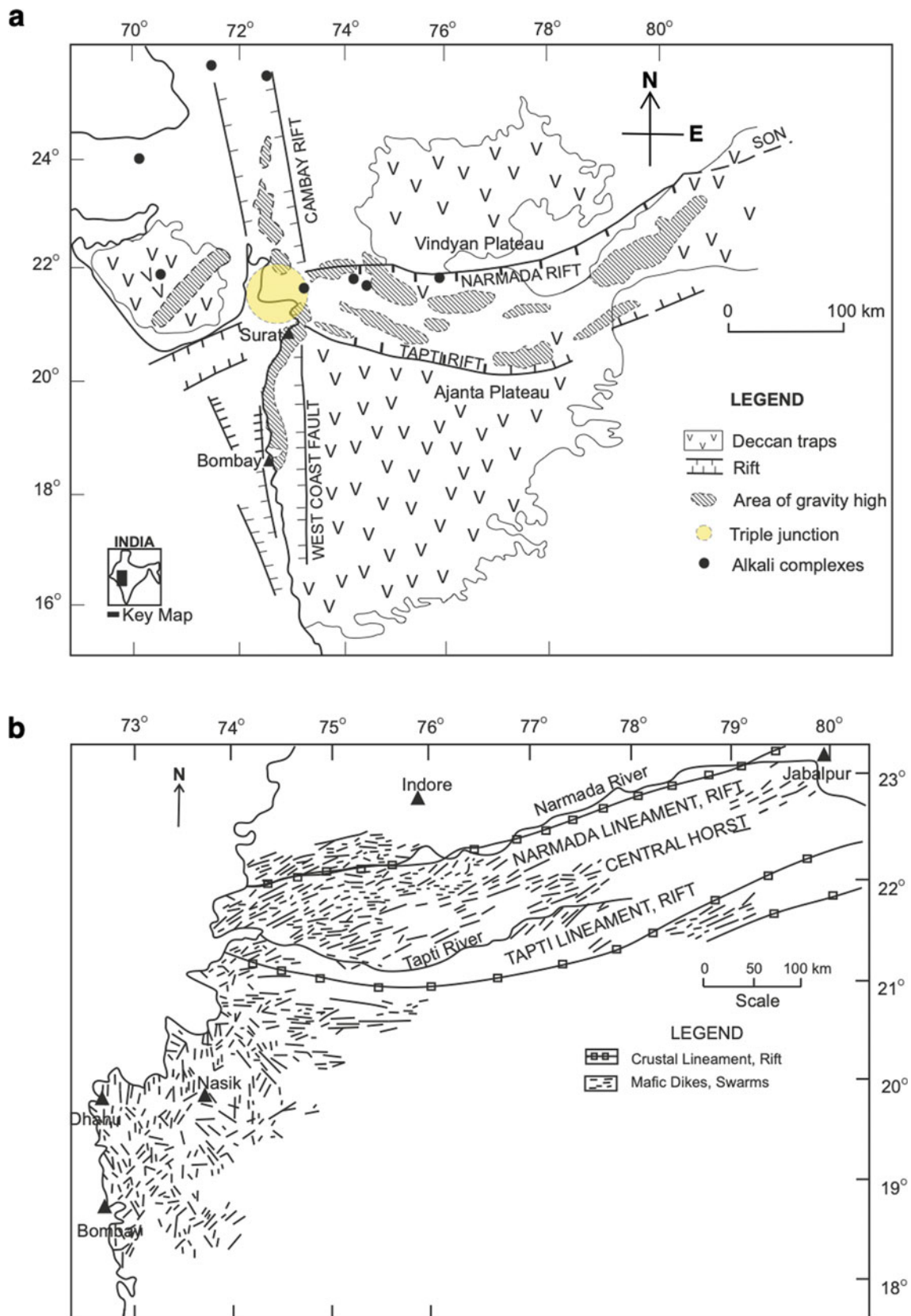


Fig. 13 a Deccan volcanic province located in the central and western India is shown along with gravity high locations marked over it. The Narmada-Tapi, Cambay, western margin rifts marked over it, **b** Mafic

dikes in Deccan volcanic province. Note E-W and N-S trending dikes associated with the Deccan flows and the direction of rifting (modified after Bhattacharji et al. 1996)

other is considered as the triple-junction (Burke and Dewey 1973). 1–5 km thick sediments are deposited in these basins. Some of these basins are producing hydrocarbons.

Basement configuration of the Narmada rift basin (rectangle-5, Fig. 3) is presented in Fig. 14a (Sridhar and Tewari 2001). Structure of the basin clearly shows high-angle rift faulting along the margins. These marginal faults are coinciding with the Narmada and the Tapi lineaments. These faults extend deep into the crust up to the Moho as shown by the crustal velocity model of the basin (Fig. 14b). These faults might have acted as feeder channels to transport the magma from deeper depth to the surface. During the basaltic flow through the crust, a part of it was accreted as magmatic underplating at the rheologically weak lower-crust (Fig. 14b), which is identified as high-velocity layer (7.1 km/s) by deep crustal refraction studies (Sridhar et al. 2007). It is constrained by the presence of mafic dikes for a long distance, covering entire Deccan trap area in the E-W and N-S direction (Fig. 13b) indicating lateral transport of magma in all directions. It is constrained by several other

studies, which also suggest that rifting and mantle plume activity may give rise to a large-scale underplating of mafic/ultramafic material at the crust-mantle boundary (Catching and Mooney 1988; Fyfe 1993; Coffin and Eldholm 1994).

The extensional activity also emplaced several alkaline and carbonatite complexes along all the three rift basins (Fig. 13a). Among these the Amba Donger and Kamathai carbonatites are well studied (Basu et al. 1993; Bhushan and Kumar 2013). They contain large quantities of REE minerals. Pirajno and Santosh (2015) described the relationship between mantle plumes, supercontinents, intra-continental rifting and mineral resources with several examples from different parts of the globe.

When plume rises beneath a continent the dynamic and thermal effects may produce surface uplifts up to 2.0 km in the centre of the extensive dome (Cox 1989). The present western margin of peninsular India is marked by the escarpment of 1500 km long Western Ghats, which are uplifted to a maximum height of 1.5 km due to the Marion

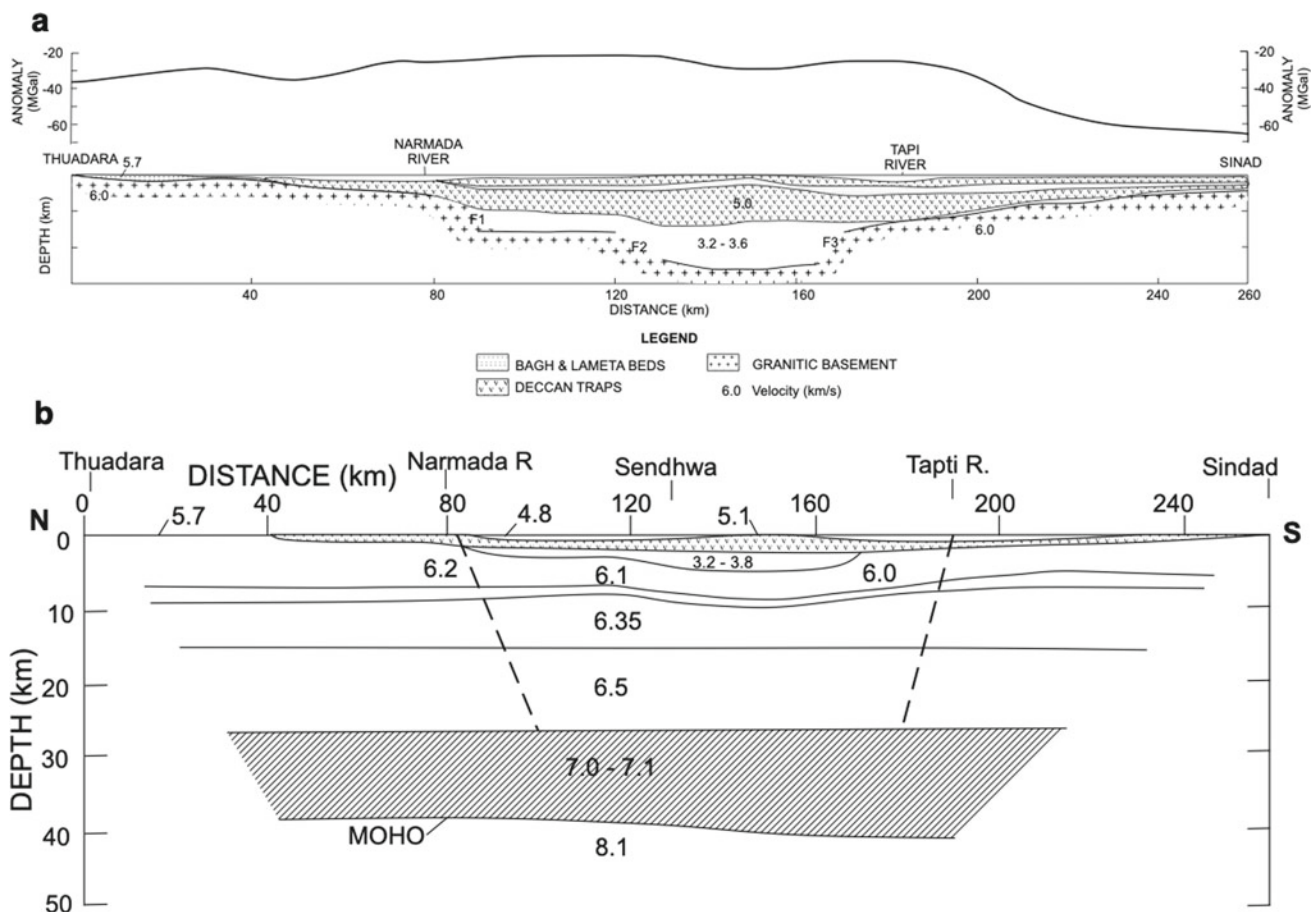


Fig. 14 a Configuration of the Narmada rift basin (vertical rectangle-5, Fig. 3). It is formed during the late Cretaceous period and related to the breakup of Pangea supercontinent (modified after

Sridhar and Tewari 2001), **b** Crustal structure of the Narmada rift basin (Sridhar et al. 2007 with the permission from JGSI)

and Reunion mantle plume activities. Most of the rivers rise close to the west-coast, drain eastwards into the Bay of Bengal after travelling a distance of more than 1000 km. It suggests the role of mantle plumes in the development of geomorphology and drainage patterns of the continental crust (Raval and Veeraswamy 2000). A similar phenomenon is also observed in southern Brazil and southeastern Africa (Cox 1989). Period of the Reunion mantle plume activity at the KT boundary is contemporaneous with the global mass extinction (Dinosaurs) event.

8 Supercontinents

A supercontinent is the assembly of most or all of Earth's continental blocks/cratons to form a single large landmass. It is the most important development in Earth Science since the advent of plate tectonics. Supercontinents have assembled and dispersed multiple times in the Earth's geologic history (Rogers and Santosh 2004). They have profoundly influenced the evolution of the geosphere, hydrosphere, atmosphere and biosphere. The causes of supercontinent assembly and dispersal are thought to be driven by convection processes in the Earth's mantle. The subducting slab after reaching 660 km discontinuity plunges into the lower mantle due to slab avalanche process and generates plumes or super plumes. These rising plumes cause continental rifting and break the plates/supercontinent located above it. The plates will be moved towards a geoidal low or the down going limbs of convection cells, perhaps where the slab avalanche occurred and pushed away from the geoidal high that can be caused by the plumes or superplumes (Condie 1998). Pure oceanic lithospheric plates would probably be consumed and disappear into the mantle. Then, more likely all the unsubductable continental blocks would be pushed together in one area to form supercontinents. The effect of mantle plumes on breakup and assembly of supercontinents is shown in Fig. 15. Orogenic belts are formed due to the accretion of continents during the supercontinental assembly and rift basins during the breakup.

At least four supercontinents Superia-Sclavia, Columbia, Rodinia, and Pangea were identified around 2.7 Ga, 1.8 Ga, 1.1 Ga and 250 Ma in the geological history of the Earth. A supercontinent cycle is the break-up of one supercontinent and the development of another, which takes place on a global scale (Fig. 15). Both these events overlap because the convection currents that cause breakup automatically begin the accretion process elsewhere. For example, separation of the Seychelles from India due to Reunion hot spot activity and formation of the Rocky Mountains due to subduction of Pacific Ocean beneath the western margin of North America were happened at the same time during the Cretaceous-Tertiary (KT boundary) period. The supercontinent cycle exhibits

long-term episodicity in tectonic processes, orogeny and continental crust formation, and all of them are embodied in a cycle.

8.1 Supercontinental Evidences from the Indian Shield

India is one of the regions in the world for evaluating the assembly, evolution and dispersal of supercontinents because of its long 3.8 Ga geological history. Results from deep crustal near-vertical seismic reflection and refraction studies carried out in different geological provinces and constrained from geological data provide important details regarding the supercontinental episodes.

8.1.1 Neoproterozoic Superia-Sclavia Supercontinent

Extensive Proterozoic mafic dyke swarms that occurred in most of the Archean cratons may be genetically linked to major geodynamic processes, such as mantle plume activity, intracratonic rifting and supercontinental breakup (Davis 1997; LeCheminant and Heaman 1989). Paleoproterozoic radiating mafic dyke swarms of 2.37 to 2.18 Ga age identified in the Dharwar craton (Fig. 10) covers an area of ~100,000 sq.km (Halls et al. 2007) and some of them extend over hundreds of kilometers. Occurrence of similar dyke swarms of 2.2 Ga worldwide (Antarctica, Australia, Finland, Greenland and North America) has been implicated in the breakup of an Archean supercontinent (French and Heaman 2010). Based on the similar Neoproterozoic greenstone belts, mafic dyke swarms and other geological evidences, French and Heaman (2010) suggested that the Dharwar and Slave cratons were part of Neoproterozoic Superia-Sclavia supercontinent. Rifting and breakup of this supercontinent at ~2.2 Ga may be responsible for the observed dyke swarms in these regions.

8.1.2 Late Paleoproterozoic Columbia Supercontinent

Several geological and geophysical studies including deep crustal seismic studies have identified late Paleoproterozoic (~1.8 Ga) orogenic activities in the NW, central and eastern part of India with the evolution of Aravalli, Satpura and Eastern Ghat orogenies (Vijaya Rao and Reddy 2002; Mandal et al. 2013; Vijaya Kumar et al. 2010). During the same period a large number of orogenic episodes, like the Trans-Hudson, Wopmay, Sveco-Fennian, Capricorn etc., took place in different parts of the world (Hoffman 1988; BABEL Working Group 1990; Myers 1993). All these orogenies formed a network of late Paleoproterozoic orogenies, which resulted in the formation of the Columbia (Rogers and Santosh 2002; Zhao et al. 2004).

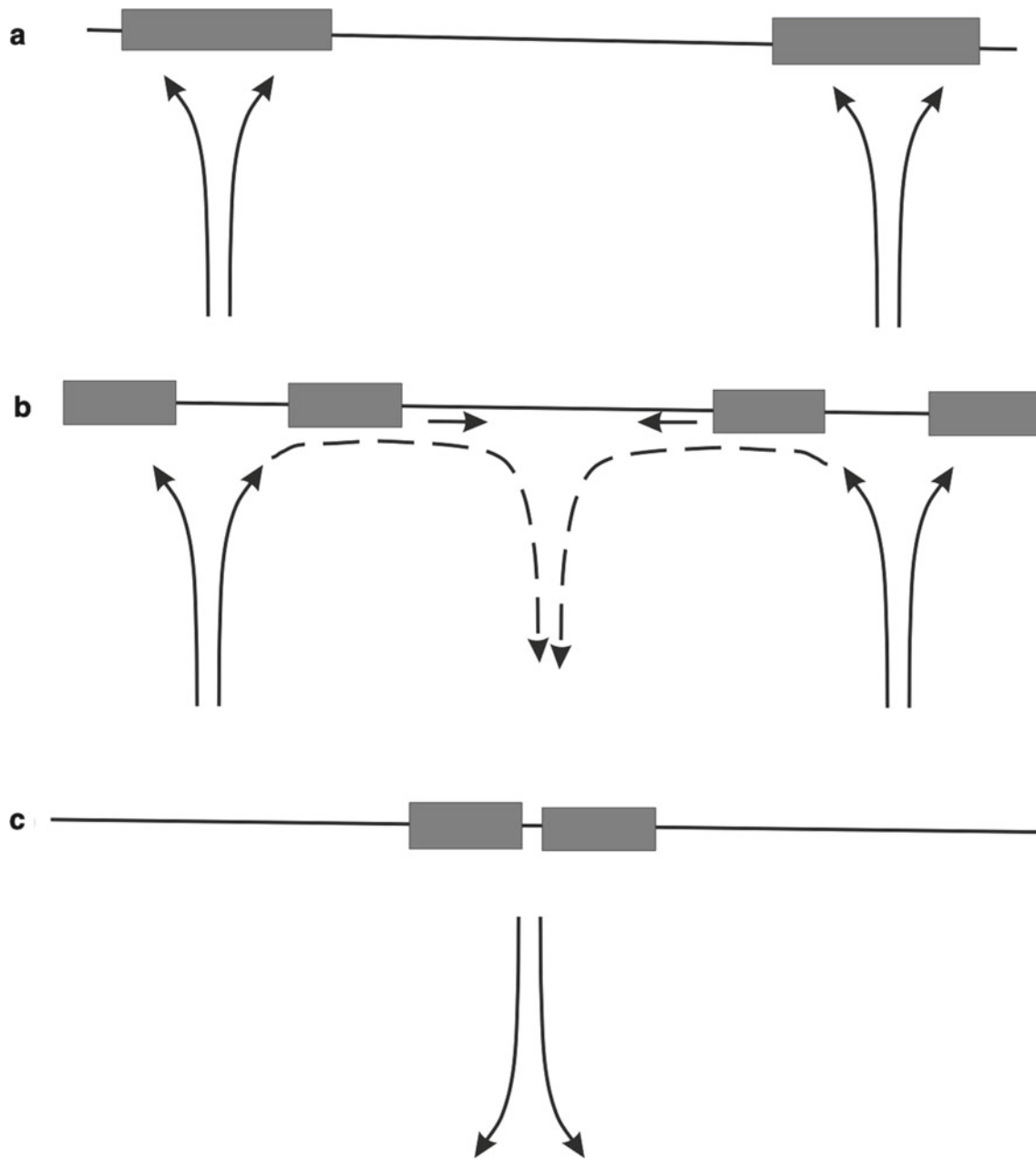


Fig. 15 Effect of mantle plumes on breakup and making of supercontinents. **a** Plumes and super plumes rise under continents, **b** Rising plumes cause continental rifting, **c** continents collide over regions of descending mantle

8.1.3 Late Mesoproterozoic Rodinia Supercontinent

Continental growth and global orogenic activities are found to be episodic and related to the supercontinental episodes (Condie 1998; Nance et al. 2014). The South Delhi fold belt of NW India, the Sausar orogeny of central India and the Eastern Ghat orogeny of eastern India were formed during the early Neoproterozoic (~1.1 Ga). They are contemporaneous with the Grenvillian orogeny, Pinjara Orogeny, the Circum-East Antarctic orogeny and many other orogenic belts in different

parts of the world (Hoffman 1991; Mezger and Cosa 1999; Vijaya Rao and Krishna 2013). A network of all these early Neoproterozoic orogenic belts formed the Rodinia supercontinent at ~1.1 Ga (Rogers 1996; Meert and Torsvik 2003).

External Geological Processes

Erosion and weathering are two main external geological processes that modify the landscape of the Earth by wearing down mountains, filling in valleys and making rivers appear and disappear.

Erosion Erosion is a natural geological process usually made by the rock in which soil being loosened from the Earth's surface at one location and transported to another location by natural forces such as wind or water. This transported material is called as sediment. Erosion is opposite to deposition. It is usually a slow process that occurs over thousands or millions of years. Liquid water is the main agent of erosion on the Earth. Rain, rivers, floods, lakes and ocean carry away bits of soil and sand. Some of the natural factors impacting erosion in a landscape include climate, topography, vegetation and tectonic activity. Erosion can be speeded up by human activities such as farming and mining.

Weathering Weathering processes are similar to erosion, where they cause breakup of rock material in the Earth's uppermost layer but does not involve movement. Air and water are agents of weathering. Some of these processes are mechanical, e.g., the expansion and contraction caused by sudden large changes in temperatures, the expansive force of water freezing in cracks etc. Plants growth can also contribute to weathering by breaking the earthen material as they take root and can create cracks in rocks they encounter. Oxidation, hydration, carbonization and loss of chemical elements by solution in water are some of the chemical weathering processes.

9 Implication of Weathering and Erosion

A large quantity of sediments generated by erosion and weathering of the Himalayan mountain range are being carried away by the Ganges and Brahmaputra rivers during the last several million years to the Bay of Bengal. Thick column of Cretaceous, Tertiary and Quaternary sediments deposited in the Bengal basin covering the west Bengal, India and Bangladesh. A total of ~18 km thick sediments were deposited in the deeper part of the basin. The excess sediments of finer clastics were carried further deep in the Bay of Bengal as submarine fan deposits. The Bengal fan (Fig. 16) with a length of ~3000 km, a width of ~1000 km and a maximum thickness of 16.5 km is the largest submarine fan in the world (Curry et al. 2002). There are number of oils producing wells in the Bengal basin. Basin configuration of west Bengal sedimentary basin is shown in Fig. 12. Similarly, the Indus River originating from Himalaya and flowing through India and Pakistan is also responsible for erosion and weathering of Himalayan ranges. At 1 mm/year erosion rate, the topography is removed at a rate of 1 km per 10 Ma. Thus, great mountain ranges will survive only for a few hundred million years and the

high-topography is transient on water-rich planet like the earth.

Even though surface erosion seems to be a simple and insignificant process, it has great impact on the evolution of global plate tectonics. Recently, Sobolev and Brown (2019) proposed a new theory, based on the geological, geochemical and modelling studies, regarding the onset of present-day plate tectonics. The theory suggests that the surface erosion events control the evolution of plate tectonics and in turn the life on the Earth. Rise of the continents their erosion, generation of sediments and their accumulation at continental edges, subsequently in trenches has provided lubrication for stabilization of subduction. The above process is responsible for emergence and evolution of present-day large-scale plate tectonics on the Earth. Lubrication by sediments could enable both formation of new subduction zones by increasing number of passive margins and extension of existing subduction zones. Subduction should have less stable during the early part of the Earth due to high mantle temperatures. It suggests evidence for the absence of large-scale subduction events prior to ~3.0 Ga as suggested by Dhuime et al. (2012). The theory further suggests stable plate tectonics follow widespread surface erosion events (more sediments), whereas diminished surface erosions (less sediments) lead to reduced subduction and possibly intermittent plate tectonics. It is mainly because sediments reduce the friction between the plates and lack of sediments means higher friction. The new theory indicates two largest surface erosion and subduction lubrication events—one after global glaciation during 2.45–2.2 Ga, leading to the formation of the Columbia supercontinent and other after “Snowball Earth” glaciation during 0.75–0.65 Ga, forming the Gondwana supercontinent.

10 Geological Processes: Evolution of Atmosphere and Biosphere

Geological processes and geochemical environment have played a key role in the origin of life on earth. Though the details of the origin of life are still unresolved, serpentinization in hydrothermal vents, which are mainly distributed along the plate boundaries, is considered the most likely sites to harbour the chemistry necessary for life (Martin et al. 2008). These hydrothermal vents support two key processes necessary for life—(i) a consistent source of chemical energy and (ii) the formation organic molecules (such as methane and other small hydrocarbons) from the inorganic molecules (such as carbon dioxide and hydrogen). It has also been proposed that some of the amino acids could have formed deep inside the crust and have risen via the hydrothermal vents (Tunnicliffe 1991).

Fig. 16 The Bengal and Indus Fans located on the eastern and western continental margins of India are formed due to the sediments from the Himalayan ranges and carried away by the Ganges, Brahmaputra and Indus rivers



Plate tectonics seemed to have played a key role in the evolution of complex lifeforms by supporting the oxygenation of atmosphere similar to the hydrothermal vents in the origin of life (Blaustein 2016). Presence of granitic crust on the earth is the main source of nutrient supply to evolve and sustain life by stimulating photosynthesis activity and generation of oxygen (Lowe and Tice 2004). The continent–continent collisional episodes during the formation of supercontinents are believed to be responsible in increasing the Earth's atmospheric oxygen content. Due to the natural erosion process, these supercontinents would have eroded and the nutrients like phosphorus and iron would have washed into oceans (Santosh et al. 2014). Then the oceans rich in nutrients that are essential to photosynthetic organisms would have helped to respire large amounts of oxygen. It appears to exist a direct relationship between the orogeny and atmospheric oxygen content. The increased sedimentation concurrent with mass oxygenation events probably buried the organic carbon and pyrite beneath sediments.

Thus, these are unable to react with the free oxygen leading to sustained increase of the atmospheric oxygen.

Beginning of the Earth to the end of Proterozoic, the lifeforms were basically small bacteria. The second important event in the birth of life on the earth was during the Ediacaran-Cambrian period. Beginning of the Phanerozoic witnessed the origin of multi-cellular organisms from the unicellular organisms and appearance of metazoans (Santosh et al. 2014). This period is termed as the “Cambrian Explosion”. This period is coinciding with the assembly of the Gondwana supercontinent with the evolution of major ~3000 km long East-African orogen during ~550 Ma. Further, immediately prior to this period, the Earth was in a frozen state termed as “Snowball Earth”. There is a considerable debate over the relation of these major events. The Cambrian Explosion is attributed to the geochemical, ecological and tectonic changes occurred during this period.

11 Summary

Active-source deep seismic studies from different tectonic domains of the Indian shield imaged several crustal structures, which are very important to understand the geological processes of the Earth. Some of these structures are due to horizontal plate tectonic processes, and others are due to vertical plume tectonics. These processes involve several intermediate processes, like the delamination, asthenospheric upwelling, generation of younger Moho etc. During these processes material can undergo physico-chemical changes, like phase change, transformed into different materials, change in velocity/density and viscosity, dehydration etc. due to different heat flow, pressure and temperature conditions. Seismic images from Neoproterozoic and Proterozoic terrains of the Indian shield show mantle and whole-crustal subduction respectively. It indicates differences in the mode of subduction during the Archean and Proterozoic.

Breaking of the Pangea supercontinent/Gondwanaland due to several mantle plume activities developed passive continental margins with the formation of Deccan volcanic province in the west and the Rajmahal traps in the eastern part of India. Further, in the western part rift-basins were formed in the E-W and N-S directions. Crustal velocity model of the Deccan trap covered E-W trending Narmada basin indicate high-velocity (7.1–7.4 km/s) lower-crustal layer formed due to the magmatic underplating in the region, which is attributed to the Reunion mantle activity at ~65 Ma. The crust-mantle interaction played a vital role in forming rift-basins and post-collisional extension as well as generation of mafic dyke swarms and alkaline complexes.

Mantle convection process is found to be responsible for bringing most of the earth's terranes at one location, which will accrete to form supercontinents. Dispersion of supercontinent is caused by accumulation of heat under the supercontinent probably above the rising convection cells due to mantle plume activity. Evidences for the presence of Columbia, Rodinia and Pangea are suggested from the Indian shield.

Erosion and weathering of the Himalayan mountain ranges are responsible for the generation of huge sediments and their deposition in the west Bengal basin and for the formation of world's largest Bengal fan.

Acknowledgements We thank V.M. Tiwari, Director, NGRI for providing the facilities, encouragement and permission to publish the work (vide reference no: NGRI/Lib/2021/Pub-25 and contribution towards MLP-6402-28(PK)) and Prof. Vinod K. Singh for his invitation to contribute the research article. We also thank W.D. Mooney and Ramon Carbonell for their useful suggestions.

References

- Anderson DL (2007) *New theory of the Earth* (2nd edn). Cambridge University Press. doi <https://doi.org/10.1017/CBO9781139167291>
- Arora BR, Prajapati SK, Reddy CD (2014) Geophysical constraints on seismotectonics of the Sikkim Himalaya. *Bull Seis Soc Am* 104 (5):2278–2287
- BABEL Working Group (1990) Evidence for early Proterozoic plate tectonics from seismic reflection profiles in the Baltic Shield. *Nature* 348:34–38
- Basu AR, Renne PR, Dasgupta DK et al (1993) Early and late igneous plumes and a high-³He plume origin for the Deccan flood basalts. *Science* 261:902–906
- Bhattacharji S, Chatterji N, Wampler JM et al (1996) Indian intraplate and continental margin rifting, lithospheric extension and mantle plume upwelling in Deccan flood basalt volcanism near the K/T boundary: evidence from mafic dike swarms. *J Geology* 104:379–398
- Bhushan SK, Kumar A (2013) First carbonate hosted REE deposit from India. *J Geol Soc India* 81:41–60
- Bijwaard HW, Spakman W, Engdahl ER (1998) Closing the gap between regional and global travel time tomography. *J Geophys Res* 103:30055–30078
- Biswas SK (1987) Regional tectonic framework, structure and evolution of the western margin basins of India. *Tectonophysics* 135:307–327
- Blaustein R (2016) The great oxidation event. *Bioscience* 66:189–195
- Burke K, Dewey JF (1973) Plume-generated triple junction: key indicators in applying plate tectonics to old rocks. *J Geology* 81:406–433
- Calvert AJ, Sawyer EW, Davis WJ et al (1995) Archaean subduction inferred from seismic images of mantle suture in the superior provinces. *Nature* 375:670–674
- Carbonell R, Levander A, Kind R (2013) The mohorovicic discontinuity beneath the continental crust: an overview of seismic constraints. *Tectonophysics* 609:353–376
- Catchings RD, Mooney WD (1988) Crustal structure of the Columbia plateau: evidence for continental rifting. *J Geophys Res* 93:459–474
- Chen WP, Yang ZH (2004) Earthquakes beneath the Himalayas and Tibet: evidence for strong lithosphere mantle. *Science* 304:1949–1952
- Christensen NI, Mooney WD (1995) Seismic velocity structure and composition of the continental crust: a global view. *J Geophys Res* 100:9761–9788
- Cook FA (2002) Fine structure of the continental reflection Moho. *Geol Soc Am Bull* 114:64–79
- Coffin MF, Eldholm O (1994) Large igneous provinces: crustal structure, dimensions and external consequences. *Rev Geophys* 32:1–36
- Condie KC (1998) Episodic continental growth and supercontinents: a mantle avalanche connection? *Earth Planet Sci Lett* 163:97–108
- Courtillot V, Davaille A, Besse J et al (2003) Three distinct types hotspots in the Earth's mantle. *Earth Planet Sci Lett* 205:295–308
- Cox KG (1989) The role of mantle plumes in the development of continental drainage patterns. *Nature* 342:873–876
- Curry JR, Emmel FJ, Moore DG (2002) The Bengal fan: morphology, geometry, stratigraphy, history and processes. *Mar Pet Geol* 19:1191–1223
- Damodara N, Vijaya Rao V, Sain K et al (2017) Basement configuration of the West Bengal sedimentary basin, India as revealed by seismic refraction tomography. *Geophys J Int* 208:1490–1507

- Davis WJ (1997) U-Pb zircon and rutile ages from granulite xenoliths in the Slave province: evidence for mafic magmatism in the lower crust coincident with Proterozoic dike swarms. *Geology* 25:343–346
- Deemer SJ, Hurich CA (1994) The reflectivity of magmatic underplating using the layered mafic intrusion analog. *Tectonophysics* 232:239–255
- Dewey JF, Bird JM (1970) Mountain belts and new global tectonics. *J Geophy Res* 75:2625–2647
- Dewey JF (1988) Extensional collapse of orogens. *Tectonics* 7:1123–1140
- Duncan RA, Richards MA (1991) Hotspots, mantle plumes, flood basalts and true polar wander. *Rev Geophy* 29:31–50
- de Wit MJ (1998) On Archean granites, greenstones, cratons and tectonics: does the evidence demand a verdict? *Precam Res* 91:181–226
- Dhuime B, Hawkesworth CJ, Cawood PA et al (2012) A change in geodynamics of continental growth 3 billion years ago. *Science* 335:1334–1336
- Ernst WG (2007) Speculations on evolution of the terrestrial lithosphere-asthenosphere system—plumes and plates. *Gondwana Res* 11:38–49
- French JE, Heaman LM (2010) Precise U-Pb dating of Paleoproterozoic mafic dyke swarms of the Dharwar craton, India: implications for the existence of the Neoproterozoic supercraton Scavia. *Precam Res* 183:416–441
- Fukao Y, Obayashi M, Nakakuki T, Deep Slab Project Group (2009) Stagnant slab: a review. *Annu Rev Earth Planet Inter* 173:197–206
- Fukao Y, Obayashi M (2013) Subducted slabs stagnant above, penetrating through and trapped below the 660 km discontinuity. *J Geophy Res* 118:5920–5938
- Fyfe WS (1993) Hot spots, magma underplating and modification of continental crust. *Can J Earth Sci* 30:908–912
- Gaina C, Muller RD, Brown B et al (2007) Breakup and early seafloor spreading between India and Antarctica. *Geophys J Int* 170:151–169
- Gao R, Lu Z, Klempner SL et al (2016) Crustal-scale duplexing beneath the Yarlung Zangbo suture in the western Himalaya. *Nat Geosci* 9:555–560
- Garnero EJ, McNamara AK, Sim SH (2016) Continental-sized anomalous zones with low seismic velocity at the base of Earth's mantle. *Nat Geosci* 9:481–489
- Gurnis M (1988) Large-scale mantle convection and aggregation and dispersal of supercontinents. *Nature* 332:695–699
- Halls HC, Kumar A, Srinivasan R et al (2007) Paleomagnetism and U-Pb geochronology of easterly trending Dykes in the Dharwar craton, India: feldspar clouding, radiating dyke swarms and the position of India at 2.37 Ga. *Precam Res* 155:47–68
- Hoffman PF (1988) United plates of America, the birth of a craton: early Proterozoic assembly and growth of Laurentia. *Annu Rev Earth Planet Sci* 16:543–603
- Hoffman PF (1991) Did the breakout of Laurentia turn Gondwanaland inside out? *Science* 252:1409–1412
- Kayal JR (2008) *Microearthquake seismology and seismotectonics of south Asia*. Springer, Dordrecht. <https://doi.org/10.1007/978-1-4020-8180-4>
- Kind R, Yuan X, Saul J et al (2002) Seismic images of crust and upper mantle beneath Tibet: evidences for Eurasian plate subduction. *Science* 298(5596):1219–1221
- Krishna VG, Rao V (2011) Velocity modelling of a complex deep crustal structure across the Meso-Proterozoic south Delhi fold belt, NW India, from joint interpretation of coincident seismic wide-angle and near-offset reflection data—an approach by utilizing unusual reflections in wide-angle records. *J Geophy Res* 116: B01307. <https://doi.org/10.1029/2009JB006660>
- Kumar P, Yuan X, Kind R et al (2006) Imaging the colliding Indian and Asian lithospheric plates beneath Tibet. *J Geophy Res* 111 (B6):10.1029/2005JB003930
- Kumar P, Ravi Kumar M, Srijayanthi G et al (2013) Imaging the Lithosphere-asthenosphere boundary of the Indian plate using converted wave technique. *J Geophy Res* 118. <https://doi.org/10.1002/jgrb.50366>
- LeCheminant AN, Heaman LM (1989) Mackenzie igneous events, Canada: middle Proterozoic hotspot magmatism associated with ocean opening. *Earth Planet Sci Lett* 96:38–48
- Lowe DR, Tice MM (2004) Geological evidence for Archean atmosphere and climate evolution: fluctuating levels of CO₂, CH₄, O₂ with an overriding tectonic control. *Geology* 32:493–496
- Mall DM, Rao VK, Reddy PR (1999) Deep sub-crustal features in the Bengal basin: seismic signatures from plume activity. *Geophys Res Lett* 26:2545–2548
- Mandal B, Sen MK, Vijaya Rao V (2013) New seismic images of the Central Indian Suture Zone and their tectonic implications. *Tectonics* 32:1–14. <https://doi.org/10.1002/tect.20055>
- Mandal B, Vijaya Rao V, Sarkar D et al (2018) Deep crustal seismic reflection images from the Dharwar craton, Southern India—evidence for the neoproterozoic subduction. *Geophy J Int* 212:777–794. <https://doi.org/10.1093/gji/ggx427>
- Mao W, Zhang S (2018) Slab stagnation due to reduced viscosity layer beneath the mantle transition zone. *Nat Geosci* 11:876–881
- Martin W, Baross J, Kelley D et al (2008) Hydrothermal vents and the origin of life. *Nat Rev Microbiol* 6:805–814
- Meert JG, Torsvik TH (2003) The making and unmaking of a supercontinent: Rodinia revisited. *Tectonophysics* 375:261–288
- Mezger K, Cosa MA (1999) The thermal history of the Eastern Ghats Belt (India) as revealed by U-Pb and 40Ar/39Ar dating of metamorphic and magmatic minerals: implications for the SWEAT correlation. *Precam Res* 94:251–271
- Monsalve G, Sheehan A, Schulte-Pelkum V et al (2006) Seismicity and 1-dimensional velocity structure of the Himalayan collision zone: earthquake in the crust and upper mantle. *J Geophy Res* 111: B10301
- Mooney WD, Meissner R (1992) Multi-genetic origin of crustal reflectivity: a review of seismic reflection profiling of the continental lower crust and Moho. In: Fountain DM, Arculus R, Kay RW (eds) *Continental lower crust*, Elsevier Publication Company
- Moyen HF, Stevens G, Kisters A (2006) Record of mid-Archean subduction from metamorphism in the Barberton terrain, South Africa. *Nature* 442:559–562
- Myers JS (1993) Precambrian history of west Australian craton and adjacent orogens. *Annu Rev Earth Planet Sci* 21:453–485
- Nance RD, Murphy JB, Santosh M (2014) The supercontinent cycle: a retrospective essay. *Gond Res* 25:4–29
- Nelson KD, Zhao W, Brown LD et al (1996) Partially molten middle crust beneath the southern Tibet: synthesis of project INDEPTH results. *Science* 274:1684–1688
- Pirajno F, Santosh M (2015) Mantle plumes, supercontinents, intra-continental rifting and mineral systems. *Precambr Res* 259:243–261
- Purnachandra Rao N, Kalpana (2005) Deformation of the subducted Indian lithospheric slab in the Burmese arc. *Geph Res Lett* 32: L05301. <https://doi.org/10.1029/2004GL022034>
- Rajendran CP, Rajendran K (2005) The status of central seismic gap: perspective based on the spatial and temporal aspects of the large Himalayan earthquakes. *Tectonophysics* 365:19–39
- Raval U, Veeraswamy K (2000) The radial and linear modes of interaction between mantle plume and continental lithosphere: a case study from western India. *J Geol Soc India* 56:525–536
- Reddy PR, Vijaya Rao V (2013) Seismic images of the continental Moho of the Indian shield. In: Artemieva I, Brown L, Kennett BLN,

- Thybo H (eds) Moho: 100 years after Andrija Mohorovicic, *Tectonophysics* 609:217–233
- Reddy PR, Rajendra Prasad B, Vijaya Rao V et al (2003) Deep seismic reflection and refraction/Wide-angle reflection studies along Kuppam-Palani transect in southern granulite terrain of India. In: Ramakrishnan M (ed) *Tectonics of southern granulite terrain, Kuppam-Palani geotranssect*, *Geol Soc India Mem* 50:79–106
- Rogers JJW (1996) A history of continents in the past three billion years. *J Geol* 104:91–107
- Rogers JJW, Santosh M (2002) Configuration of Columbia, a Mesoproterozoic supercontinent. *Gondwana Res* 5:5–22
- Rogers JJW, Santosh M (2004) *Continents and supercontinents*. Oxford University Press, 289
- Sapin M, Hirn A (1997) Seismic structure and evidence for eclogitization during the Himalayan convergence. *Tectonophysics* 273:1–16
- Santosh M, Maruyama S, Sawaki Y et al (2014) The Cambrian explosion: plume driven birth of the second ecosystem on Earth. *Gondwana Res* 25:945–965
- Sridhar AR, Tewari HC (2001) Existence of a sedimentary graben in the western part of Narmada zone: seismic evidence. *J Geodynamics* 31:19–31
- Sridhar AR, Tewari HC, Vijaya Rao V et al (2007) Crustal velocity structure of the Narmada-Son lineament along the Thuadara-Sendhwa-Sindhad profile in the NW part of central India and its geodynamic implications. *J Geol Soc India* 69:1147–1160
- Smithies RH, Champion DC, Van Kranendonk MJ, et al (2005) Modern style subduction processes in Mesoproterozoic: geochemical evidence from the 3.12 Ga Whundo intra-oceanic arc. *Earth Planet Sci Lett* 231:221–237
- Sobolev S, Brown M (2019) Surface erosion events controlled the evolution of plate tectonics on Earth. *Nature* 570:52–59
- Storey BC (1995) The role of mantle plumes in continental breakup: case histories from Gondwanaland. *Nature* 377:301–308
- Tewari HC, Dixit MM, Rao NM et al (1997) Crustal thickening under the Paleo/Mesoproterozoic Delhi fold belt in NW India: evidence from deep reflection profiling. *Geophys J Int* 129:657–668
- Torsvik TH, Smethurst MA, Burke K et al (2006) Large igneous provinces generated from the margins of the large low-velocity provinces in the deep mantle. *Geophys J Int* 167:1447–1460. <https://doi.org/10.1111/j.1365-246X.2006>
- Tunnicliffe V (1991) The biology of hydrothermal vents: ecology and evolution. *Oceanogr Mar Biol Annu Rev* 29:319–407
- Van der Hilst RD, Widiyantoro S, Engdahl ER (1997) Evidence for deep mantle circulation from global tomography. *Nature* 386:578–584
- Van der Meer DG, van Hinsbergen DJJ, Spakman W (2018) Atlas of the underworld: slab remnants in the mantle, their sinking history, and a new outlook on lower mantle viscosity. *Tectonophysics* 723:309–448
- van der Velden AJ, Cook FA (2005) Relict subduction zones in Canada. *J Geophys Res* 110. <https://doi.org/10.1029/2004JB003333>
- Van der Voo R, Spakman W, Bijwaard H (1999) Tethyan subducted slabs under India. *Earth Planet Sci Lett* 171:7–20
- Vijaya Kumar K, Ernst WG, Leelanandam C et al (2010) First Paleoproterozoic ophiolite from Gondwana: geochronologic-geochemical documentation of ancient oceanic crust from Kandra, SE India. *Tectonophysics* 487:22–32
- Vijaya Rao V, Rajendra Prasad B, Reddy PR et al (2000) Evolution of proterozoic Aravalli Delhi fold belt in the northwestern Indian shield from seismic studies. *Tectonophysics* 327:109–130
- Vijaya Rao V, Reddy PR (2002) A mesoproterozoic supercontinent: evidence from the Indian Shield. In: Rogers JJW, Santosh M (eds) *Special volume on mesoproterozoic supercontinent, Gondwana Research* 5:63–74
- Vijaya Rao V, Sain K, Reddy PR et al (2006) Crustal structure and tectonics of the northern part of the Southern granulite Terrain, India. *Earth Planet Sci Lett* 251:90–103
- Vijaya Rao V, Rajendra Prasad B (2006) Structure and evolution of the Cauvery shear zone system, southern granulite terrain, India: evidence from deep seismic and other geophysical studies. *Gondwana Res* 10:29–40
- Vijaya Rao V (2009) Geodynamics of the collision zones: phases of lithospheric evolution from the Indian Shield. In: Arora BR, Sharma R (eds) *Geodynamics of the collision zones*. *J Geol Soc India Memoir* 72: pp165–194
- Vijaya Rao V, Reddy PR (2009) Deep crustal seismic images of the southern granulite terrain, India. In: Reddy PR (ed) *Seismic imaging of the Indian continental and oceanic crust*. Professional Books Publishers, Chennai, pp 297–323
- Vijaya Rao V, Khare P, Raju S et al (2011) Deep crustal seismic probing of the Dharwar craton by DHARSEIS Experiment. *DST Newsletter* 21(2):5–10
- Vijaya Rao V, Krishna VG (2013) Evidence for the Neoproterozoic Phulad suture zone and genesis of Malani magmatism in the NW India from deep seismic images: implications for assembly and breakup of the Rodinia. *Tectonophysics* 589:172–185
- Vijaya Rao V, Murty ASN, Sarkar D et al (2015) Crustal velocity structure of the neoproterozoic convergence zone between the eastern and western blocks of Dharwar Craton, India from seismic wide-angle studies. *Precambrian Res* 266:282–295
- Yuan K, Romanowicz B (2017) Seismic evidence for partial melting at the root of major hot spot plumes. *Science* 357:393–397
- Zhao D (2004) Global tomographic images of mantle plumes and subducting slabs: insight into deep earth dynamics. *Phys Earth Planet Inter* 146:3–34
- Zhao D (2007) Seismic images under 60 hotspots: search for mantle plumes. *Gondwana Res* 12:335–355
- Zhao W, Nelson KD, Project INDEPTH Team (1993) Deep seismic reflection evidence for continental underthrusting beneath the Tibet. *Nature* 366:557–559
- Zhao GC, Sun M, Wilde SA et al (2004) A paleo-Mesoproterozoic supercontinent: assembly, growth and breakup. *Earth-Sci Rev* 6:91–123