Seismicity in the Peninsular Indian Shield: Some geological considerations

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The Peninsular Indian Shield, traditionally considered a stable continental region, underwent significant changes in its crustal character, first during the Jurassic break-up of Gondwanaland, and then through the process of underplating as the cratonic block moved over the plume heads during its northward journey. The break-up resulted in the development of a series of fractures appearing as lineaments on the surface, while the underplating caused subcrustal magmatism as well as surface volcanicity. The reconstituted Indian crust undergoes heterogeneous deformation responding to the north-easterly stress presumably resulting from ocean opening along the Carlsberg Ridge–Rift system. The deformation is comparable to block tectonics, in which movements are restricted to the boundaries of the blocks, while internally these remain rigid. In the context of the Peninsular Indian Shield, the relative movements of rigid blocks trigger earthquakes. The presence of fluid in the deforming medium facilitates movement. There can be several sources of fluid release, influx from the subcrustal magma body or through some deep crustal processes like dehydration metamorphism. In some special instances, water leaking from a reservoir can help trigger earthquakes.

Keywords: Block tectomics, Peninsular Indian Shield, seismicity, stable continental region.

THE Peninsular Indian Shield is traditionally considered a stable continental block remaining rigid even during the Phanerozoic, the last about 550 m.y. of earth's history. The concept of stability receives support from the fact that there is virtually no record of any orogeny-related post-Precambrian tectono-thermal reconstitution of the Indian crust except in the belt of the Himalayas in the north[1,2]. The idea of stability of the Indian crust is so deeply entrenched in our thoughts, that we tend to characterize the incidence of earthquakes in the region as 'stable continental region' (SCR) seismicity. The only basis of this concept could be the assumed similarity in the tectonics of the Indian Shield with the Canadian Shield of North America. On the other hand, the following facts tell us a different story.

1. Not only does the Indian Shield lie close to the active Himalayan belt but a considerable part of it now forms part of the Himalayan edifice. The huge Indo-Gangetic Alluvium Plain, which developed on a depression in front of the rising mountain, has resulted from the bending of the shield under the mountain.
2. There are historical records of high intensity earthquakes (> 8 in the Ritchter scale), which usually occur only in collision-type suture zones. The two most sensitive areas in the respect are (i) Kachchh in northern Gujarat (falling in seismic zone V: Bureau of India Standard, IS 1893 : 2002), and (ii) Kolkata region, which has the dubious record of witnessing the world's third most devastating earthquake in human history, killing over 300,000 people on 11 October 1737 (USGS Earthquake Hazards Programme: Earthquake Report).
3. The localized, unusually high heat flow values (reaching up to 107 m Wm^{-2})[3] over parts of the Peninsular Indian Shield speak of an abnormally hot crust, unlike the heat-flow pattern in different shield areas of the world[4,5].
4. Bouguer gravity anomaly maps published by the National Geophysical Research Institute, Hyderabad[6] show high positive values (over 40 mGal) in several parts of India, which according to Negi *et al.*[7] is a reflection of 'mobility' rather than stability.

All the above features indicate that the Indian Shield is tectonically quite unstable[8], unlike the Canadian and other similar shield areas of the world[9]. An understanding of the unique character of the Indian Shield in geophysical terms needs a critical analysis of the different Phanerozoic geological events, which significantly altered its geological character. The fact worth remembering in this context is that geophysical features unlike geological ensembles, do not possess any memory of when and how they have developed.

In this article, the term lineament has been used for any linear geomorphic feature which marks the trace of a deep-seated fault on the surface. In soil/sand covered areas, geophysical anomaly, especially the gravity pattern may attest to the presence of a lineament.

Phanerozoic reconstitution of the Indian Shield

The Phanerozoic events, that played a role in changing the essentially 'stable Precambrian character' of the Indian Shield are[2]:

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1. Magmatism in different parts during the Pan-African event at around 550 ± 50 Ma (‘Ma’ is an abbreviation for million years age).
2. Opening of the Gondwana rift basins during the late Palaeozoic to the Early Mesozoic.
3. Jurassic break-up of the Gondwana Supercontinent at ca. 165 Ma.
4. Plume–Indian lithosphere interaction during Cretaceous–Eocene.
5. Himalayan collision-related orogeny at around 45 Ma.
6. Post-collision neotectonism and seismicity.

The first two events, which are linked with abortive attempts to fragment Gondwanaland, did not alter the Indian crust in any significant way[2]. Thus, in order to find an answer to the seismic instability of the region, we have to look at the short geological history of extreme reconstitution slotted between two important global tectonic events, the Jurassic break-up of the Gondwanaland at around 165 Ma and the colossal Himalayan collision at around 45 Ma and its aftermath. Between these two events, the Indian Shield endured the brunt of the plume impingements as it passed over four plume heads centred at Crozet, Kerguelen, Marion and Reunion Islands in the Indian Ocean[2].

The effects of Jurassic break-up on the Indian Shield

The Jurassic break-up of the Gondwana Supercontinent affected the Indian Shield in two different ways. The first is the opening of rift basins that allowed encroachment of sea in the Jaisalmer region in western Rajasthan and the Kachchh region in northern Gujarat. The second and the most important one is the development of lineaments, either as a new set of fractures or through the reactivation of ancient tectonic grains (Figure 1).

Considering the importance of lineaments in seismic studies, a brief description based on the studies made in Rajasthan and neighbouring regions would appear quite informative[10,11]. The Rajasthan lineaments (Figure 2) have been classified into two groups[2]: (i) lineaments developed as new features cross-cutting all the rock formations, and (ii) lineaments formed as reactivated Precambrian grains (fabric). The lineaments, irrespective of their antiquity and occurrences, are virtually rectilinear. Exception is noticed where a lineament following the ancient fabrics tends to depart from the orientation of the inherent grain fabric. The roughly rectilinear orientation even in terrains of high relief suggests steep dip or vertical orientation of fracture surfaces representing the lineaments. Among all the lineaments, two sets are important having N35°W–S35°E and N65°E–S65°W trends. The development of this pair of lineaments is not only confined to Rajasthan and its neighbouring areas, but also the entire Peninsular region[12] (Figure 3). Application of the common theory of brittle fracture makes it possible to trace N15°E–S15°W obtuse bisector as the direction of the extensional stress system. The strict parallelism of one set (NW) of lineaments with the Jurassic basin boundaries, helps confirm that such a stress system prevailed at the time of fragmentation of Gondwanaland during the Jurassic[2].

Plume outburst-related geological signatures

During the period between the Jurassic break-up of Gondwanaland and the Himalayan collision, the Indian crust underwent dramatic changes as it came under the influence of four plume-heads centred at Crozet, Kerguelen, Marion and Reunion Islands. We know little of the plume–lithosphere crust interaction in the case of the Crozet and the Marion plumes. On the other hand considerable data are available on the Reunion and the Kerguelen plume outburst events.

Recent information about the Kerguelen[13,14] suggests a large area of manifestation of plume outbursts, that took place during 107 and 133 Ma. Borehole data in the Bengal basin detected the continuity of this phase of magmatism from Rajmahal in the west to near Shyllet in the east[15,16]. The aerial extent of this plume activity in the south has now

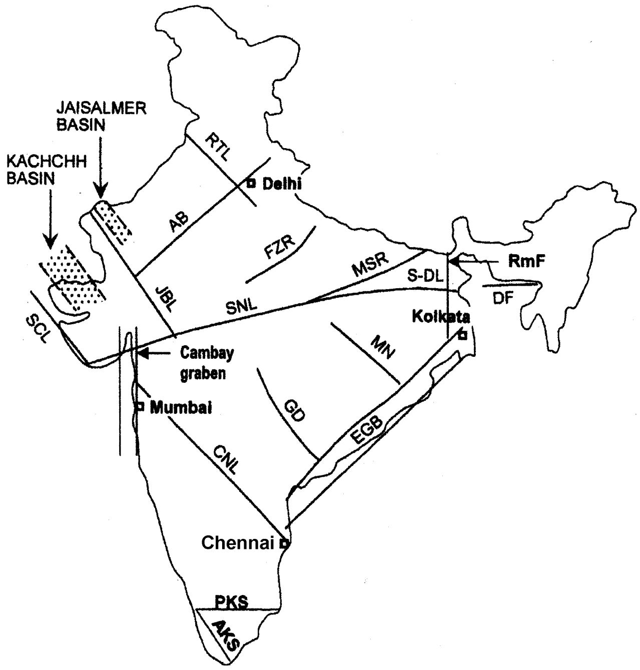

Figure 1. Schematic map showing distribution of important lineaments (adapted from Roy[2]). AKS, Achankovil Shear Zone; CNL, Chennai Nasik Lineament; DF, Deuki Fault; EGB, Eastern Ghats Belt; GD, Godavari Lineament; FZR, Faizabad Ridge, JBL, Jaisalmer Barwani Lineament; MN, Mahanadi Lineament; MSR, Munger-Saharsa Ridge; PKS, Palghat–Cauvery Shear Zone; RmF, Rajmahal Fault; RTL, Raisinhgarh–Tonk Lineament; SNL, Son–Narmada Lineament; S–DL, Son–Damodar Lineament; SCL, Saurastra Coast Lineament.

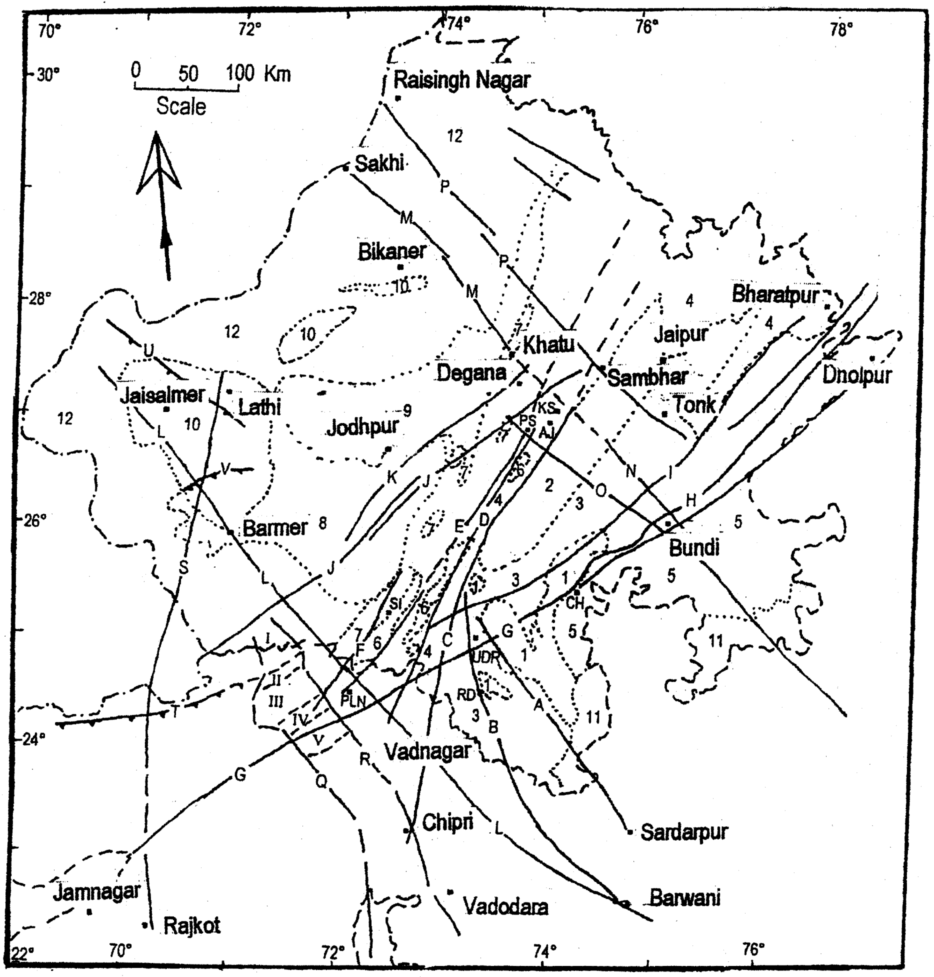

Figure 2. Map showing major lineaments in Rajasthan and adjoining areas (modified after Bakliwal and Ramaswamy[11]). 1–12, Major geological formations from the oldest to the youngest. A–U, Important linaments in Rajasthan. I–V are the block faulted horst-graben structures shown in Figure 6. UDR, Udaipur.

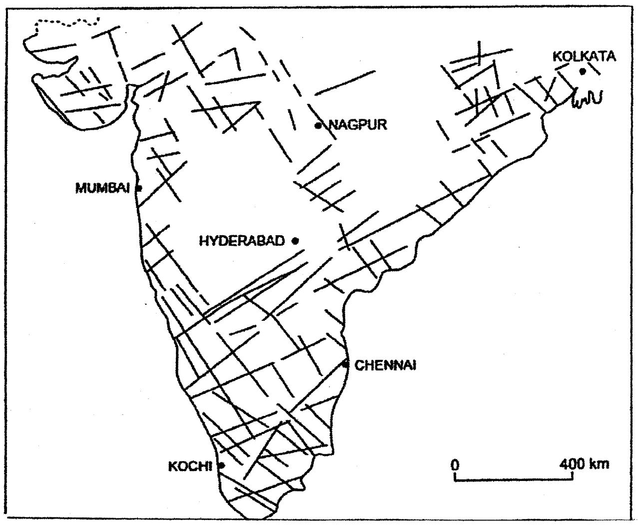

Figure 3. Distribution of lineaments in Peninsular India showing dominance of NE–SW and NW–SE pairs (after Varadarajan and Gunnju[12]).

been traced up to Bhubaneshwar[17]. Evidence is emerging in favour of the suggestion that the Bengal basin initially formed over the down-faulted Rajmahal/Shyllet Traps. Some prominent faults associated with the Cretaceous evolution of the Bengal basin include the N–S trending Rajmahal Fault passing through the west of Kolkata[18] and the E–W Deuki fault and the N–S Jamuna fault along the southern and the western borders of the Shillong Plateau[19] respectively. Apart from these major faults bounding the northern part of the Bengal basin, several N–S faults have been mapped from the Shillong Plateau region, which itself is bounded in the north and south by major E–W faults[19–21]. A variety of alkaline mafic and carbonatite bodies are associated with these faults, especially with the N–S trending ones, which could be geochemically correlated with the Kerguelen plume activities over the region[22].

Several geochemical signatures have been postulated linking the Deccan volcanicity with the Reunion plume outburst at around the *K–T* boundary[23–28]. Apart from the extensive covers of lava flows in the form of Deccan Traps in the west–central part of Peninsula India, several other features are also reported from Rajasthan, northern Gujarat and western Maharastra region. The most important ones are[29]:

1. In the western Rajasthan–northern Gujarat region, several fault-controlled basins formed at around the *K–T* boundary. The presence of the volcani-clastic sediments and the contemporary fossil ages suggest that basin evolution and magmatism occurs during the same time interval. An important feature that also suggests a close correspondence between the two events is the presence of a cylindrical, about 200 km across, low velocity zone (LVZ)[30] at about 100 km depth in the subcrustal mantle region underlying N–S-oriented Cambay–Barmer basins. The striking coincidence in the extent of LVZ in the upper mantle region, which presumably marks the passage of the Reunion plume, suggests a cause-and-effect relationship[29].
2. Barring the Bengal–Assam region, where several E–W and N–S trending lineaments have developed as one of the Kerguelen plume outburst-related features, the belt comprising the western Rajasthan, northern Gujarat and western Maharastra is the only other region where the E–W and the N–S pair of lineaments is also observed. The most important of this is the N–S-oriented Rajkot–Lathi lineament (Figure 4), which runs parallel to trend of the Cambay and Barmer basins. A number of important E–W trending lineaments occur in the Kachchh region (including the Rann of Kachchh) in northern Gujarat (Figure 4). Another intriguing feature in the Kachchh region is the presence of a series of E–W running 'domes' sub-parallel to the lineament trends[31]. Suggestion has been made that these domes formed because of the upward-moving magma mass, which failed to pierce through the overlying Jurassic beds[32]. The intrusive relationship between the basalts exposed in the central parts of the eroded domes and the highly fossiliferous Jurassic sandstones clearly proves the younger age of the mafic rocks that occupy the core regions. Based on these features, a close genetic link between the formation of the lineament fractures and diapirism-related magmatism has been inferred[29].
3. Several isolated intrusive bodies of alkaline mafic and syenitic suites associated with comagmatic alkaline dykes of different compositions along with a number of suites of volcanic rocks ranging in composition from basic to acid occur at a number of places in western Rajasthan and in the Kachchh and Saurastra regions of Gujarat. According to Basu *et al.*[23], magmatism in western Rajasthan occurred in two phases: ca. 68.50 and ca. 65 Ma. Virtually contemporary age range between 64.4 ± 0.6 and 67.7 ± 0.7 Ma has also been suggested by Pande *et al.*[33], for alkali magmatism in the Kachchh region.

Gravity image picture of the Indian Shield: inferences

The Bouguer anomaly colour image map prepared by Murthy[34] (Figure 5) provides a visual impression of the gravity anomaly pattern over the Indian subcontinent, in spite of the unfortunate lack of information from two sensitive regions which fall outside the political boundary of the country. Reinterpretation of the image pattern[35] helped dividing the gravity pattern into three distinctive types. First, the anomaly pattern in the Dharwar craton (domain 1 in Figure 5), which barring patches of high gravity in the coastal region (significantly more in the east coast rather than in the west) shows a low negative Bouguer anomaly value (between –60 and –120 mGal). The gravity value coupled with low heat flow and evidence of about 40 km MOHO thickness over the major part of the craton, are in conformity with the stable Precambrian cratonic condition[36], which compares well with the gravity pictures of other stable Precambrian shield areas of the world[37]. The Deccan Traps, which cover a considerable part of the craton in the north locally attaining a thickness of over 2000 m, did not affect the Precambrian geophysical character of the craton[34]. In strong contrast to this gravity image pattern, a distinct low-gravity zone (varying from about –5 to

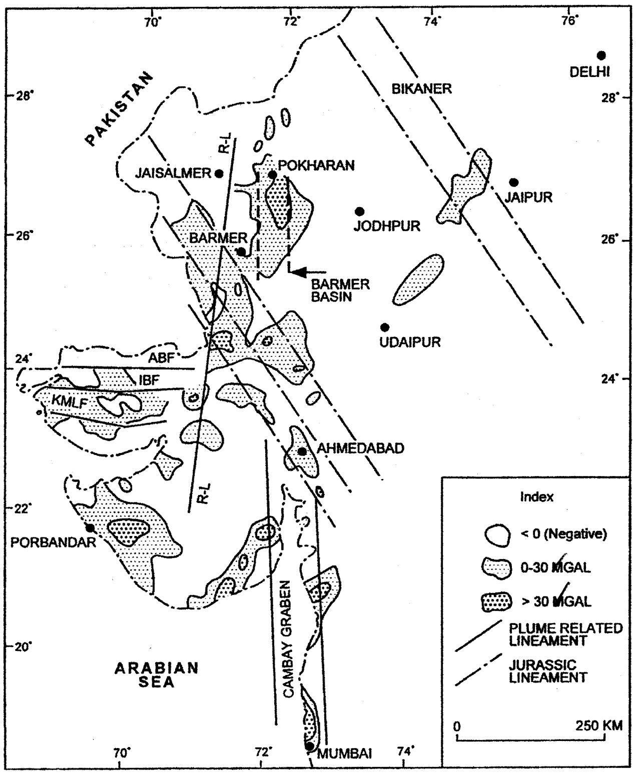

Figure 4. Bouguer gravity anomaly map of West India[6] showing distribution of gravity highs, and important lineaments.

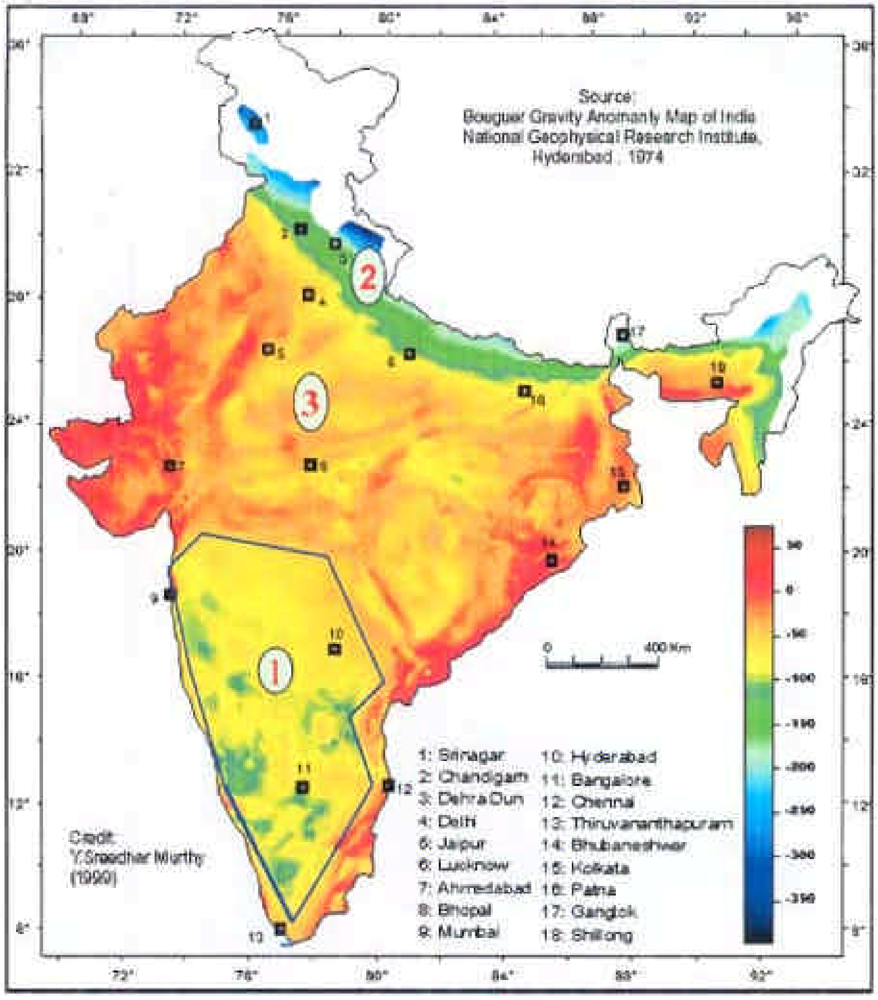

Figure 5. Bouguer gravity anomaly colour image of India (after Murthy[34]) showing three distinctive domains.

–200 mGal) is observed over the Indo-Gangetic Alluvial Plane (IGAP), which borders the Himalayas and its chains (domain 2, Figure 5). The development of this prominent low-gravity belt finds explanation in the presence of thick low-density sediments over a sialic basement ducking below the Himalayas. Increase in the thickness of sediments accounts for the corresponding decrease in the gravity values. Between these two situations of pristine Precambrian character of the Dharwar craton (including areas covered by the Deccan Traps) and the totally reconstituted condition in the IGAP, occurs the domain of high gravity ranging from very low negative to over +50 mGal at places. Some broad generalizations about the Bouguer gravity anomaly colour image of this belt is possible if *a priori* assumption is made that high gravity is a reflection of the presence of denser rocks (like gabbro or dunite/peridotite) in the crust. There are enough data to confirm the effects of repeated plume impingements in changing the gravity anomaly pattern of the once cratonized shield region[2]. In the eastern part of the Indian Shield (Figure 5), there are two linear gravity highs, the N–S Rajmahal 'high' and the E–W Shyllet 'high'. Both these gravity highs can be linked with the Kerguelen plume underplating event. Such a correlation gets support from the age range (between 110 and 130 Ma[13,14]) and the geochemical similarity of the Rajmahal/Shyllet Traps with the Kerguelen plume-related magmatism[22]. Barring these two linear highs and the large patch at Bhubaneshwar[17], it is difficult to decipher the influence of the Kerguelen plume outburst in evolving the 'gravity high' pattern in the eastern region, essentially because of the lack of proper isotope data.

The Bouguer anomaly maps of northern Gujarat and western Rajasthan show highly irregular but clustered gravity high anomaly fields (Figures 4 and 5), which neither shows any specific trend nor any direct relationship with the lineaments that developed in the region. However, a roughly N–S-trending zone (passing through Ahmedabad) is detectable, which coincides with the suggested passage of the Reunion plume in the region. The occurrence of a large number of mafic/alkaline plutonic intrusions in the region provides surface evidence of the possible presence of such bodies in the subsurface. A markedly linear high positive Bouguer gravity anomaly zone is reported[38,39] from the 'midrib' region of the Aravalli mountain, which coincides with a prominent convex, upward-reflecting surface in the middle and lower crust in the Deep Continental reflection surface profile across the mountain[40]. Factors such as: (i) occurrence of undeformed and unmetamorphosed body of komatiite[41] as a possible leaked-out material from the mantle during the C29R Chron[42], and (ii) records of high heat flow measuring about $62\ \mathrm{m\,W m^{-2}}$ over the region[43] strongly support the theory of young Reunion plume-induced underplating. This is in conformity with the paradigm of the 'rheologic waveguide' proposed by Raval and Veeraswamy[27], which suggests channelling of tectonomagmatic processes along such belts. However, some difference is noted if the paradigm is extended to distinctly graben-like features like the Godavari, Mahanadi and Narmada–Son. The gravity features in these domains are suggestive of magma channelling along rift shoulders, while the basins show shield-like negative values suggesting the presence of a thick pile of lighter sediments. However, it cannot be said with certainty if the deep crustal magmatism along the shoulders of these Gondwana basins is related to the Kerguelen or the Reunion plume outburst events.

The aspect of seismicity

Two important features, which have dramatic impact on the Indian Shield in changing its 'SCR stable interior' character are the development of lineaments and the extensive underplating phenomena resulting from the impingement of plumes. The development of lineaments either as new sets of fractures or through reactivation of the ancient Precambrian grains during the Jurassic break-up of Gondwanaland, fragmented the Indian lithospheric crust into a large number of blocks. A few others were introduced during the plume impingement processes. The formation of lineaments thus helped introduce a type of structural heterogeneity in the crust, in a way similar to what is observed in block tectonics, a deformation pattern in which the movements are transmitted only along narrow zones bordering rigid blocks. The Sanchor–Nav Sarovar quadrangle bounded between two major lineaments[44] provides a classic example of rigid-body movement (Figure 6). The relative movement between the rigid blocks triggers seismicity, while the individual block remains free from any internal deformation. Study of this aspect of continental deformation[45] has considerable bearing on the understanding of seismic behaviour of Peninsular Indian Shield. Murthy[34] has been able to delineate one such earthquake-free zone in the free-air gravity shaded relief image map of India, which is apparently free from any seismicity.

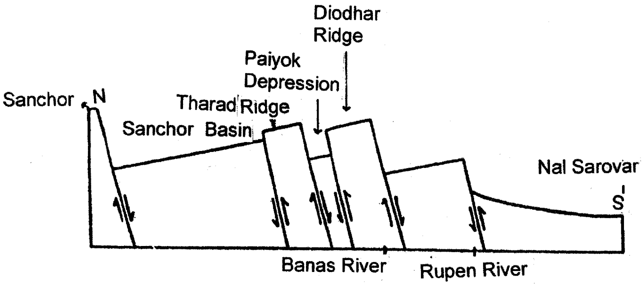

Figure 6. Typical block tectonic pattern illustrated by a series of horsts and depressions in the Nal Sarovar–Sanchor region in northern Gujarat.

Epicentres of all the known major earthquakes lie either on the major lineaments or reasonably close to them[35]. This can be taken as a proof of importance of these features in causing earthquakes. The data available with us are however pitiably few. This is because there was hardly any documentation of earthquakes in the subcontinent before the arrival of the British, over two and a half centuries ago. To overcome this unfortunate constraint, we will have to get information from the records of neotectonic movements, a considerable part of which might have taken place during the Quaternary period (the last phase) of the earth's history. Along with the records of late Quaternary uplift of the Himalayas, geomorphic changes have been noted in different parts of the subcontinent. These include drainage disorganization (correlated with migration and disappearance of the Vedic Saraswati[46,47]) and evolution of saline lakes in western Rajasthan[48], the formation of abysmally deep valleys bordering the Satpura horst-mountain (claimed to be a contemporary event of the Ramayana days[49]) or the possible evolution of the about 1300 km long 'great wall' of the Western Ghats, standing as a huge scarp facing the Arabian Sea during the Neogene–Quaternary[50]. Besides, there are also reports of block uplifts of the Nilgiri Hills, Mount Abu, Chotanagpur Plateau and many other features from different parts of peninsular India. An important point that emerges from the above description is that in all instances of block uplift, down-faulting and horizontal displacements, the actual movements must have been transmitted along the lineaments that bound the affected blocks. These earth movements that brought about all geomorphic changes must also have caused countless high-intensity earthquakes. The understanding of the past earthquakes is an emerging field of palaeoseismic study. Thus, looking at the poor records of the past earthquakes, and the fact that high-intensity earthquakes that result from the movement of steep or vertical planes in a plate-interior setting take place with long time-intervals of several years, there can hardly be any doubt that information from palaeoseismic studies (constrained with proper isotope dates) would be useful in explaining the seismic behaviour of the not-so-stable Indian Shield. Presently, Kachchh appears to be the most susceptible area so far as seismicity is concerned. But it seems likely that tectonism over the entire Peninsular India changed with time, shifting from place to place.

While discussing the high frequency of Kachchh earthquakes, suggestion has been made about the presence of a mafic body at depth between 15 and 25 km, which aides earthquake nucleation through supply of fluids[51]. The earthquake vulnerability of the region might be rooted in the underplating-related magmatism. However, no such generalization about underplating event as an indirect cause of seismicity can be made about the Dharwar cratonic block, which is virtually free from any post-Precambrian underplating-related magmatism. Barring the recent major earthquakes at Latur and Koyna, which occur in the Deccan-Traps covered area of the Dharwar craton, multitude of low and moderate intensity earthquakes have been recorded in Andhra Pradesh, southern Karnataka and northern Tamil Nadu[52]. In this context, it is worth mentioning that the proposition of Veeraswamy and Raval[28] about the 'tectonic boundary' of the Latur and Koyna earthquake epicentres does not hinge on any precise geological evidence. On the other hand, the location of epicentres on two different lineaments is beyond doubt[35,53].

Concluding remarks

The lineaments that criss-cross Peninsular India play an important role as inherent markers of defect for the accumulation and transmission of stress. One important factor that facilitates the rupture process and nucleates earthquakes is the presence of fluid in the region of stress build-up. The fluid supply could be from several sources: water leaking from a reservoir (as in the case of Koyna[53]), fluid released during some deep crustal process like dehydration metamorphism[51], or hydrothermal fluids released from a recent igneous intrusion. The role played by internal fluid pressure is a well-known tectonic process related to nucleation and transportation of thrust sheets.

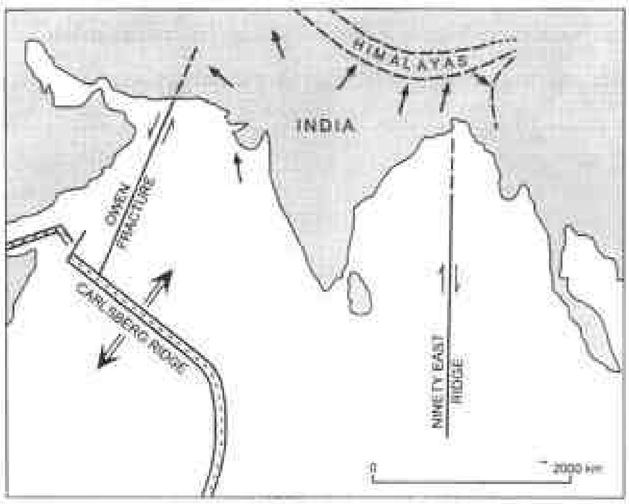

Figure 7. Schematic diagram indicating extensional stress generation at Carlsberg Ridge, northwestern Indian Ocean, and distribution of compressive stress in parts of the Indian Shield.

The understanding of the plate interior seismicity of Peninsular India would be greatly enhanced if we know about the stress sources simulating earthquakes. Several suggestions have been made about the possible stress source, which includes[54]: (i) stresses resulting from forces of collision between India and northern Asia; (ii) potential gradients caused by surface topography and erosion; (iii) loading of sediments deposited in the Arabian Sea and the Bay of Bengal and (iv) the effect of flexural bulge in central India resulting from its collision with Tibet.

All these processes contribute to the process of stress building over the lineament-fragmented Indian continental crust. The stress regime analysis computed from the interpretation of focal mechanism of a large number of earthquakes[55], indicates operation of a NE–SW-directed compressive stress system over the entire Indian Shield. Such a homogeneous, unidirectional stress cannot result from any of the above-mentioned processes, which might be responsible for influencing local stress pattern marginally. The only geological process that can generate such a stress system over the entire Indian Shield is the formation of a new crust along the NW–SE-oriented Carlsberg Ridge–rift system operating in the Arabian Sea of the Indian Ocean (Figure 7).

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