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The Phanerozoic Reconstitution of Indian Shield as the Aftermath of Break-up of the Gondwanaland

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Abstract

The Indian crust, generally regarded as a stable continental lithosphere, experienced significant tectono-thermal reconstitution during the Phanerozoic. The earliest Phanerozoic tectonic process, which grossly changed the geological and geophysical character of the Precambrian crust, was during the Jurassic when this crustal block broke up from the Gondwana Supercontinent. There were two earlier abortive attempts to fragment the supercontinent in the Palaeozoic. Different types of geological processes were associated with these aborted events. The first was the intrusion of anorogenic alkali granites during the Early Palaeozoic (at 500±50 Ma), while the second was linked with formation of the Gondwana rift basins during Late Palaeozoic. The tectonic history of the Indian Shield subsequent to its separation from the Gondwanaland at around 165 Ma is a complex account of its northward journey, which was culminated with its collision with the northern continental blocks producing the mighty Himalayas in the process. Considerable reconstitution of the Indian Shield took place due to magma underplating when this lithospheric block passed over the four mantle plumes. While the underplating events grossly changed the geophysical character of the Indian Shield in isolated patches, the propagation of the underplated materials was assisted by the deep crustal fractures (geomorphologically expressed as lineaments), which formed during the break-up of the Gondwanaland. Several of these deep fractures evolved through the reactivation of the pre-existing (Precambrian) tectonic grains, while some others developed as new fractures in response to either the extensional stresses generated during the supercontinental break-up or the plume-lithosphere reactions. Significant geomorphological changes occurred in peninsular India subsequent to the continental collision. Most of these changes were brought about by the movements along the lineaments, which fragmented the Indian Shield into a number of rigid crustal blocks. The present day seismic behaviour of the Indian Shield is a reflection of movements of the rigid crustal blocks relative to each other. An interesting feature of the Phanerozoic geological history of the Indian Shield is the evolution of a number of sedimentary basins under different tectono-thermal regimes.

Key words: Phanerozoic reconstitution, Indian shield, Gondwana break-up, lineament, plume outbursts.

Introduction

The Indian Shield, which represents a completely cratonised Precambrian continental lithosphere, has presumably remained stable even during the Phanerozoic. 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 region that now constitutes the Himalayas. In fact, the intrusion of the youngest synorogenic granites associated with any fabric-forming event recorded from different parts of the shield dates back to 850 million years before present. A totally different picture about the crustal stability of the Indian Shield emerges when we consider that a part of the Indian Shield area in the Kachchh (*nee* Kutch) region of northern Gujarat lies within the Seismic Zone 5 (cf. Bureau of Indian Standard, IS:1893:2002). The high-seismic susceptibility of the Kachchh region is quite striking considering that the belt does not form a part of a suture zone. Irrespective of the cause, the present-day seismicity of the Kachchh region, therefore, poses a serious question on the stability of the Indian crust as a whole.

The significant information that questions the stability of the Indian Shield during the Phanerozoic comes from the data on the gravity anomaly pattern and the heat flow values over the entire Indian Shield. The Bouguer anomaly gravity maps (cf. National Geophysical Research Institute, 1974) show the dominance of the negative Bouguer anomalies over the major part of the Indian Shield. The strongest negative values occur along the arcuate belt of the Sub-Himalayas and the adjacent Indo-Gangetic Alluvial Plains in the south (discussed later). The belts of positive Bouguer anomalies are recorded in parts of the west coast, over a considerable part in the Saurastra-Kachchh region of northern Gujarat and in southwestern Rajasthan. Similar positive Bouguer anomalies are seen along parts of the east coast and over the belt of Rajmahal-Sylhet Trap in the northeast Indian Shield. According to Negi et al. (1986), the gravity anomaly pattern observed in the Indian Shield is a reflection of its 'mobility'.

The thermal structure of the Indian Shield like the gravity picture is also considered characteristic of stable continental areas (Gupta, 1982). The average heat flow value (~56 mWm^{-2}) of the Indian Shield compares well with the world average of the continental heat flow of 50 mWm^{-2} (cf. Mahadevan, 1994). In strong contrast to this view, workers like Negi et al. (1986), Rao et al. (1976) and Singh (1985) suggest that the Indian Shield represents an abnormally hot and considerably thin lithospheric crust. The higher heat flow values are recorded sporadically over a considerable part of the Indian Shield. The important high heat flow regions include the Mesozoic-Cenozoic basins of Assam-Bengal in northeast India, parts of the east and west coasts, the Cambay Basin in northern Gujarat, and over the linear belt that runs parallel to the Son and the Narmada Rivers (also known as the Son-Narmada Lineament belt or the SONATA belt).

The geophysical features, especially the gravity anomaly and the heat flow values as indicated above seem to counter the commonly held notion of overall stability of the Indian Shield (not considering the part that now constitutes the Himalayan belt). In fact, there are a number of features, which make the Indian Shield quite unique, very much unlike the known stable crustal blocks such as the Canadian, Ukrainian, Baltic and some other shield areas of the world. To understand the unique character of the Indian Shield in geophysical terms it may be necessary to critically analyse the different geological events that might have induced the crust-mantle interactions, thus significantly altering the Precambrian geological as well as the geophysical characters of the Indian Shield. The important Phanerozoic geological events, which have been recorded in different parts of the Indian Shield are:

(1) Anorogenic magmatism during the 500±50 Ma period (Roy, 1999);
(2) Opening of the Gondwana rift basins during the Late Palaeozoic to Early Mesozoic;
(3) Jurassic break-up of the Gondwana Supercontinent at ca. 165 Ma;
(4) Plume-Indian crust interactions during Cretaceous-Eocene
(5) Himalayan collision related orogeny; and
(6) Post-collision tectonism and seismicity.

These are the important global events, which have not only affected the Indian crust but also considerably changed its geophysical and the tectonic character.

Some explanations may be necessary about certain terms used in this paper. The terms like 'Indian Shield', 'Indian continental block' and 'Indian lithosphere' or 'Indian lithospheric crust' have been used more or less in the same sense for the crustal block that collided with the northern continental blocks to form the Himalayas. The term 'India' has been used in the present paper for the entire subcontinent that lies south of the Himalayas and the associated Cenozoic mountain chains.

Lower Palaeozoic Anorogenic Magmatism

An important crust-building event that marked the closure of the Neoproterozoic is the Pan-African Orogeny, which presumably welded the two fragments of the Gondwanaland, the East and the West. A protracted span of over 500 Ma from 950 Ma to 450 Ma has been suggested for this late Proterozoic-Early Palaeozoic crustal event (Kröner, 1984). Kennedy (1964) described the event as the 'Pan-African Tectono-thermal Episode'. Behre (1990) and Stern (1994) on the other hand described this as the East African Orogeny (EAO). Stern (op. cit.) who presented a broad summary of the tectonic evolution of the EAO, described four separate events between 850 Ma and 500±50 Ma. Truly speaking, the period marks the time span between the fragmentation of Rodinia and the formation of the Greater Gondwana (cf. Roy, 1999). The 'Pan-African' events described by Stern (op. cit.) include two distinctly separate events: (i) the events related to the opening and closing of the Mozambique Ocean (representing an orogenic cycle) between 850 Ma and 640 Ma; and (ii) the granulite facies metamorphism and an essentially anorogenic magmatism linked with per-alkaline or alkaline granite intrusions centring around 500±50 Ma.

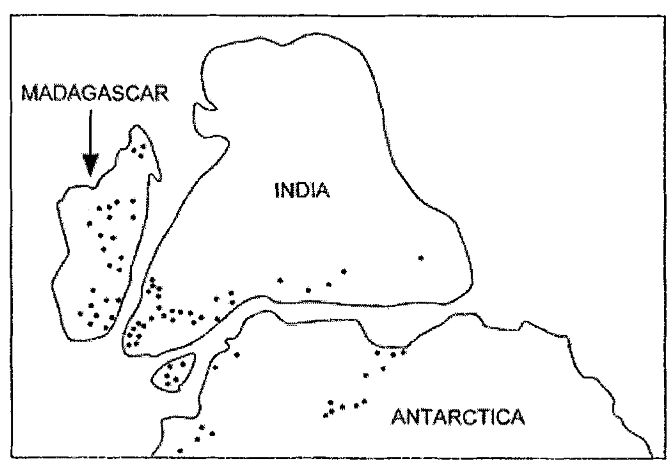

Fig. 1. Schematic map showing generalised occurrences of early Palaeozoic (500±50 Ma old) granites in a part of the Gondwanaland including Indian continental block. After Rajesh et al. (1996).

A number of authors in India described the 'Pan-African' events from the Indian Shield, parts of which presently constitute the Himalayan domain. The recognition of the so-called Pan-African events in the Indian Shield even motivated many geologists to look for a probable connection between the Pan-African 'suture zones' related to the EAO to some shear zones in southern India through Madagascar. A variety of events and features have been described as Pan-African. However, barring the correlation of plume-related Malani magmatism (presumably taking place during 780 Ma to 680 Ma; cf. Rathore et al., 1999; Roy, 2001; Torsvik, et al., 2001) with the Pan-African magmatic event (Bhushan, 1995), all the other Pan-African dates centre around the 500±50 Ma age range, representing the Lower Palaeozoic. These so-called Pan-African dates in the range of 500±50 Ma have been reported from different parts of the Indian Shield (including Madagascar) (Fig. 1) (cf. Choudhary et al., 1992; Jayananda and Peucat, 1996; Kovach et al., 1998; Santosh and Drury, 1988; Santosh et al. 1989; Rajesh et al., 1996; Rathore et al., 1999; Unnikrishnan-Warrier et al., 1993, 1995; Yoshida et al., 1996) as well as from the Himalayan domain (Fig. 2) (cf. Islam et al., 1999; Le Fort, 1988; Le Fort et al., 1983a, b; 1986; Rao et al., 1990; Trivedi et al., 1984; Valdiya, 1998). Considering that the granitic intrusions are essentially syn-orogenic marking 'geosynclinal closures' in the northern part of the Indian Shield, several authors correlated these granite intrusion events with either the Caledonian Orogeny (Fuchs, 1987), or the Pan-African Orogeny (Bhargava, 1980; Bagati et al., 1991; Garzanti et al., 1986; Valdiya, 1993, 1995).

A vast majority of granites reported from the different parts of the Indian Shield as well as from the Himalayan domain are, petrographically speaking, alkali granites and syenites having A-type anorogenic characters. Because of the fact that anorogenic granites are normal associates of extensional tectonics such as continental rifting (Rasmussen et al., 1988) and in certain instance of post-collisional collapse (Sylvester, 1989), it may not be proper to describe these granites as syn-orogenic marking the closure of basins. Thus, apart from the contemporaneity of ages of the granitic rocks (mainly in the 500±50 Ma age range), there is hardly any evidence to prove (except perhaps in the Kerala block in the Southern Granulite belt) that these Early Palaeozoic ages in India represent orogenic events. In view of this, the correlation of 500±50 Ma anorogenic granite intrusion ages with the orogeny-related events in the EAO appears unwarranted (Roy, 1999, 2001).

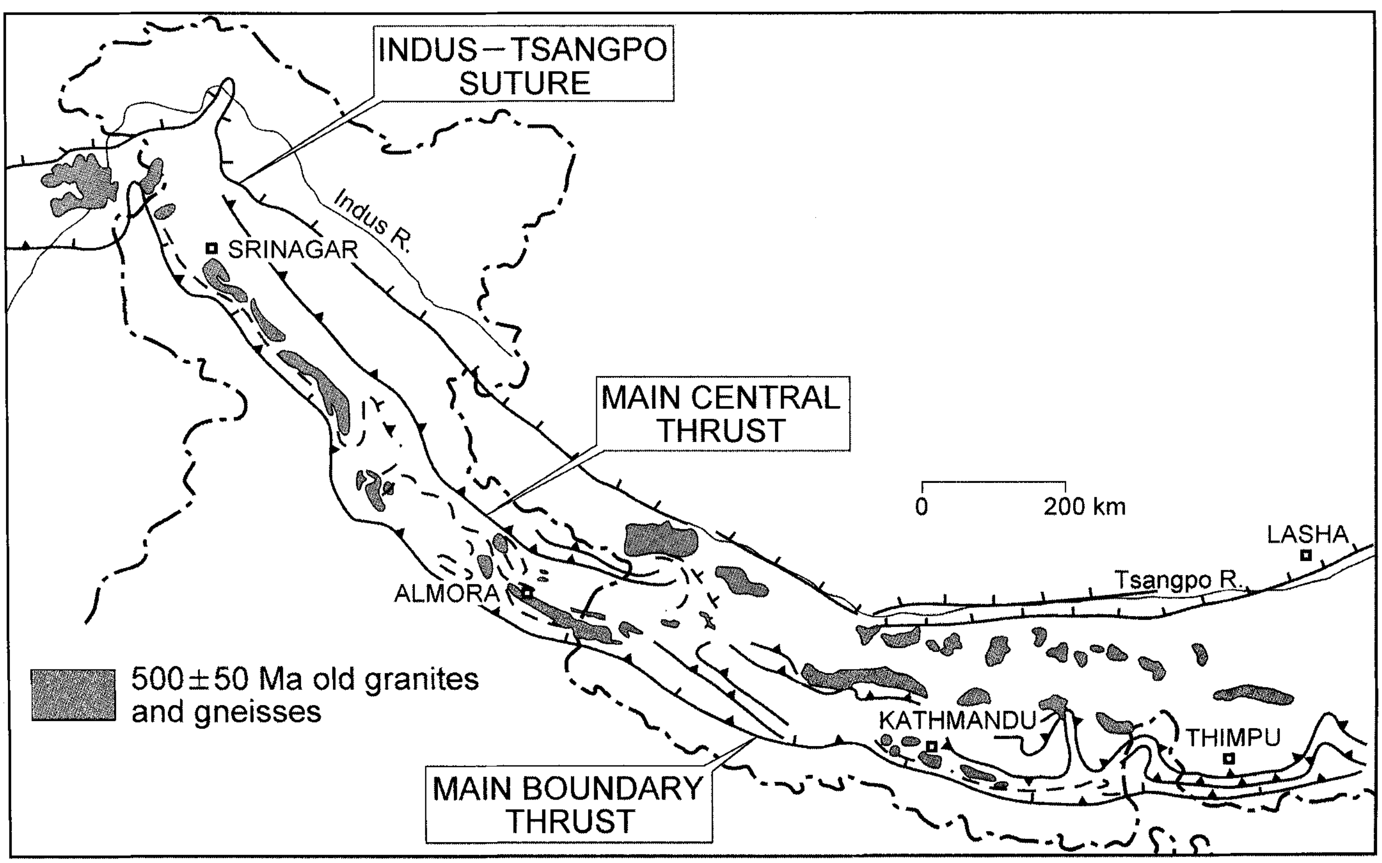

Fig. 2. Occurrences of early Palaeozoic (500±50 Ma old) granites in the Himalayan domain. After Valdiya (1998).

The near peripheral concentration of these anorogenic extension-related granites, virtually defines the known boundaries of the Indian Shield (including Madagascar and the Himalayan domains). This particular feature further precludes any correlation between the granite intrusions and the contemporary event in the EAO. On the other hand, there lies a strong possibility that the anorogenic magmatism noted in the Indian cratonic block might be related to the global rifting process that ensued after the formation of the 'Greater Gondwana' (cf. Stern, 1994).

Evolution of Gondwana Basins

Barring the Early Palaeozoic granitic activities, there is virtually no record of any geological activity in the Indian Shield region for over 200 million years between the Early Ordovician and Early Carboniferous. There are, however, a few references in the literature about the continuity of sedimentation in shelf sea region in some isolated northern part of the Indian Shield during the Early Palaeozoic that ultimately became a part of the 'Tethys Himalayas' at a later stage. It was during the Late Carboniferous when a number of continental rift basins started to evolve as the receptacle of land-worn sediments. Marine incursions took place only locally, in the central Indian region as an extension of the arm of the sea through northern Gujarat region of western India. There is also some evidence of the formation of isolated epicontinental basins in the northern shelf region of the Tethys belt. The Gondwana sedimentation took place along several linear intra-continental rift-basins comprising sags and depressions (Fig. 3), which at a later stage developed into half or full grabens. The most significant feature about the Gondwana basins is that these evolved along the contacts of the protocontinents or along the passive rifts (cf. Mahadevan, 1994). The Godavari and the Mahanadi basins are the classic examples of such basins. Manifestations of magmatism in the Gondwana basins are not very common. Several intrusions of lamprophyres are observed in the eastern Indian basins. The dolerite/gabbro intrusions, which are observed in the central Indian basins, are presumably the manifestations of the later plume related magmatism in the region.

The progressive as well as the repetitive movements along the block faulted basement slabs underlying the basins controlled sedimentation in different Gondwana basins. Several authors during recent years (Mishra, 1987; Mishra et al., 1987; Qureshy, 1964; Qureshy et al., 1967; Verma and Ghosh, 1977; Verma and Subrahmanyum, 1984; Verma et al., 1976, 1983) attempted estimations of crustal thickness based on the gravity data below the different Gondwana basins. These studies coupled with the inferences made from the study of the Deep Seismic Sounding profiles (Kaila, 1982; Kaila and Krishna, 1992; Kaila et al., 1990) failed to confirm any significant contribution of the crustal thinning process in the development of the horst-graben structures in the Gondwana basins (cf. Mahadevan, 1994). Similarly, the available heat flow data from Gondwana basin regions also do not suggest any noteworthy thermal perturbation. Higher heat flow values observed in some of the central and eastern Indian coalfields are attributed to either the Deccan or the Rajmahal plume related magmatism (Rao and Rao, 1982.).

The Precambrian ancestry of some of the Gondwana basins, specially the Godavari and the Mahanadi basins has been suggested (cf. Mahadevan, 1994). This seems to be quite an unlikely proposition in view of the fact that the development of Gondwana basins is linked with the global tectonic phenomenon, which affected all the components of the Gondwana Supercontinent only during the Upper Carboniferous. Nevertheless, it is quite apparent that the rift zones that evolved to form the Gondwana basins developed almost exclusively along the ancient structural grains, such as the contacts of the Precambrian protocontinents. One significant feature in the development of Gondwana basins in the Indian Shield is the fact that there is a total lack of any such rift basin in the entire Aravalli-Bundelkhand 'protocontinent'. The tectonic margin represented by the Son-Narmada Lineament and its eastern continuation known as the Munger-Saharsa Ridge (MSR), constitutes the northern limit of all the Gondwana (rift) basins (Fig. 3). There may be some tectonic explanation for this preferential development of the Gondwana basins. It is well known that the development of rift zones (grabens) is easier where the extensional stresses act at high angles to the weak structural grains such as palaeo-rifts or the contact zones of protocontinental margins (suture zones). Non-development of any such rift zone or basin would imply that the operative stresses were either parallel or at low angles to the structural grains in the Aravalli-Bundelkhand 'protocontinent'. Since the prevailing structural grains in the Aravalli-Bundelkhand 'protocontinent' is dominantly NE-SW, it may be inferred that the stress vectors that caused the opening of the Gondwana basins were also NE-SW directed (all the directions refer to the present day position of India). Such a stress system would help in opening all the earlier grains/rifts in the southern block, which were oriented at high angles to it but not in the northern block where the structural grains were subparallel to it. The same stress system might also have helped opening a 'chasm' along the Son-Narmada Lineament zone causing marine incursion.

Jurassic Gondwanaland Break-up

The Indian lithosphere underwent significant changes as the result of dismemberment of the Gondwanaland at around 165 Ma ago. The initial separation resulted in the marine incursions in western Rajasthan and in the Kachchh region of northern Gujarat. Tell tale evidence of this Early break-up history is well recorded in the Jurassic formations in the Jaisalmer region in western Rajasthan. The Jurassic succession in the region began with the deposition of typical continental deposits, constituting the Lathi Formation. The typical rift-related Jurassic basins marking the gradual encroachment of sea developed later possibly during the Callovian, about 155 million years ago. A similar marine incursion is noted in the Kachchh region of northern Gujarat (Fig. 4). The Jurassic break-up of the Gondwanaland (which induced rift type basin opening and sedimentation in the Jaisalmer and Kachchh region in western India) also has had a pronounced effect on the Indian lithosphere, mainly through the development of sets of new fracture systems as well as through reactivation of some ancient tectonic grains. The fracture systems along with the reactivated older tectonic grains, helped to fragment the Indian Shield into a number of rigid crustal blocks. Geomorphologically expressed as lineaments, these fracture systems have significantly affected the geomorphotectonic and seismic behaviour of the Indian crust during its subsequent tectonic history.

A number of lineaments, small and large (varying between a few kilometres to over 300 km) have been mapped in Rajasthan (Bakliwal and Ramaswamy, 1987; Barkatiya and Gupta, 1983; Kar 1995). Quite a few of these lineaments continue from Rajasthan into the northern Gujarat (Fig. 5). The relationships of these lineaments with the different geological as well as geophysical features in this terrain help to understand the different aspects of reconstitution of the Indian crustal block as it moved northward subsequent to the Jurassic break-up of the Gondwanaland.

The orientation and disposition of the lineaments in relation to the Precambrian tectonostratigraphic units help to categorise the lineaments of Rajasthan and

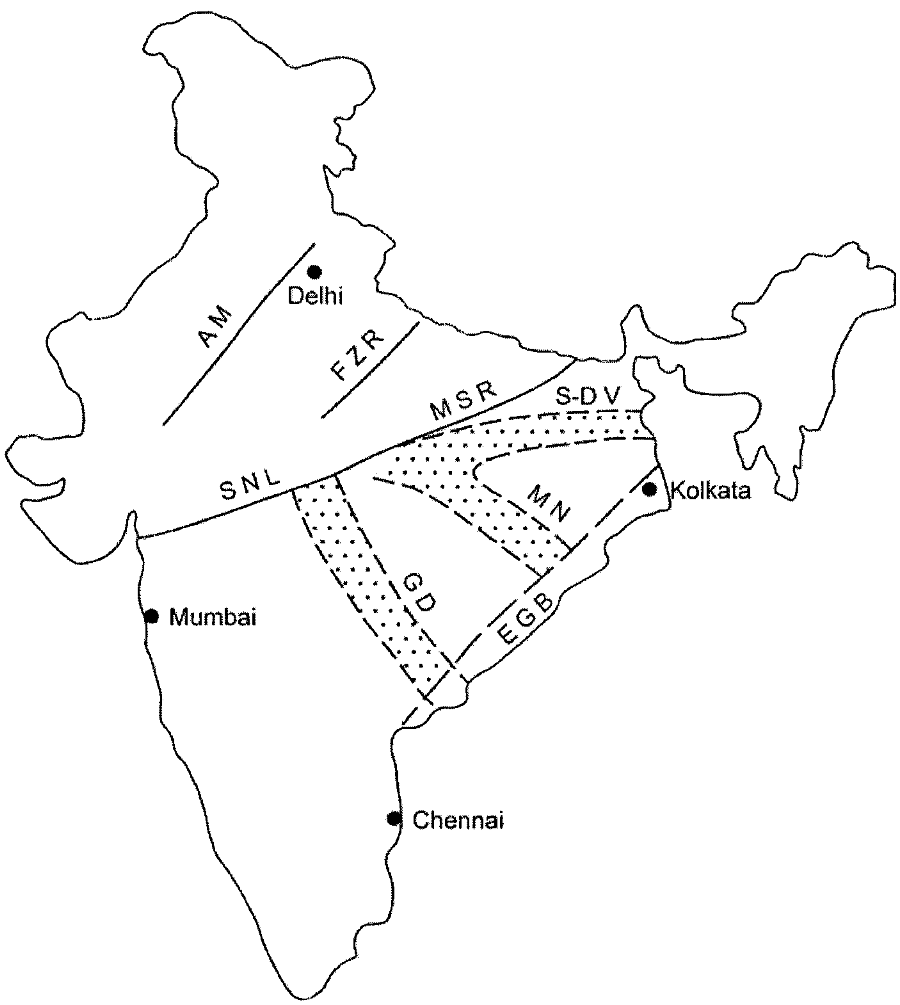

Fig. 3. Schematic map showing the distribution of Gondwana rift basins exclusively in the south of the Son-Narmada Lineament (SNL), which is shown to continue in the east as the Munger-Saharsa Ridge (MSR). (After Cassyap et al., 1993; and Raval, 1993). Index: AM–Aravalli Mountain belt (the faulted western margin); GD–Godavari Basins; FZR–Faizabad Ridge; SNL–Son-Narmada Lineament; MSR–Munger Saharsa Ridge; S-DV–Son-Damodar Valley Lineament; MN–Mahanadi Basins; EGB–Eastern Ghats belt.

neighbouring regions into two broad groups: (i) the lineaments which are constrained almost entirely within the Precambrian rocks, and (ii) the lineament, which intersects all the rock formations from the Precambrian to the youngest Cenozoic. Included in the first category are those which are Precambrian tectonic elements, and evolved as high-angle (very steep to almost vertical) thrust and/or as shear zones, or as inverted basin margin (peri-basinal) faults (A, B, C, D, E and F in Fig. 5). Barring a few, all these lineaments have azimuth orientations conformable to the prevailing Precambrian tectonic grains. The characterisation of all these lineaments as vertical fracture systems helps to identify them as very young features, and also to classify these as reactivated Precambrian grains.

The second group of lineaments, which transect almost all the geological formations including the youngest Phanerozoic rocks, have persistent azimuth orientations corresponding approximately to N35°W–S35°E and N65°E–S65°W trends. Out of these, the NW–SE trending lineaments (L, M, N, O, P, Q and R in Fig. 5) are quite rectilinear in their trends compared to the NE–SW oriented ones. The latter set of lineaments (G, H, I, J and K in Fig. 5) partly conforms to the Precambrian trends. Most of these lineaments show a little deviation to the west as they crosscut the tectonostratigraphic ensembles.

Apart from being expressed as important geomorphotectonic and/or geophysical features (Fig. 6), some evidence of movements is also noticed along the lineaments. Whereas the strike-slip movements (dextral or sinistral) are detectable in the displacements of geological formations as well as lineaments, normal faulting occurred where, small or large grabens formed. These grabens became the sites of thick deposition in between the adjacent horsts.

All the lineaments irrespective of their antiquity are virtually rectilinear (Fig. 4). Such an orientation even in terrains of very high relief, suggest that these geomorphotectonic features have very steep dip or are vertical. Some generalisations are necessary in order to understand the nature of palaeo-stresses responsible for generating these steep or vertically dipping fractures.

The parallelism as well as the conformity of some of the Precambrian lineaments, indicate how the presence of palaeo-fractures prevented the growth of new ones across them. The lineament that follows the Great

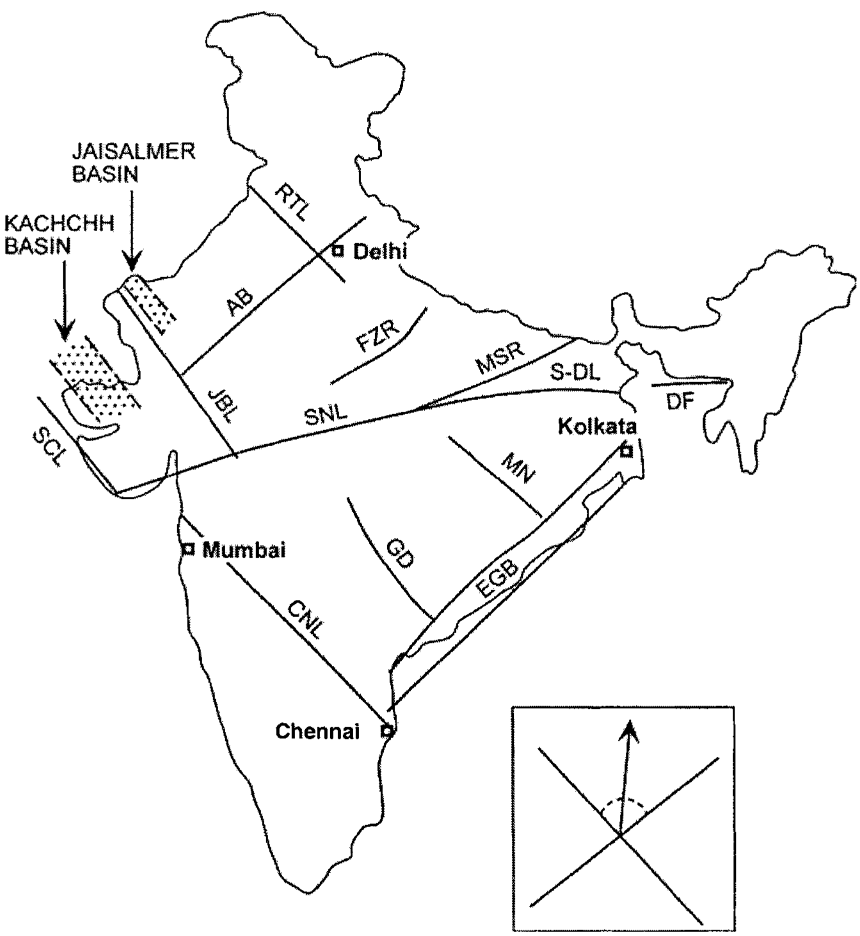

Fig. 4. Schematic map showing the distribution of important lineament and fracture zones in the Indian continental block. Jurassic marine incursions in western India are shown as stippled areas. The direction of the obtuse bisectrix of the two common sets of lineaments is shown in the inset. Index: AB–Aravalli belt; CNL–Chennai-Nasik Lineament; DF–Deuki Fault; EGB–Easteren Ghats Belt; FZR–Faizabad Ridge; JBL–Jaisalmer-Barwani Lineament; MN–Mahanadi Basins; MSR–Munger-Saharsa Ridge; RTL–Rajkot-Lathi Lineament; SCL–Saurastra Coast Lineament; S-DL–Son-Damodar Valley Lineament; SNL–Son-Narmada Lineament.

Boundary Fault separating the Aravalli 'horst' from the Vindhyan basin is the case in point (Lineament 'G' in Fig. 5). The unmistakable crosscutting relationship of this lineament with the Precambrian tectonostratigraphic units in its southern continuity is indicative of its younger evolution. We know from the theory of development of fractures how their growth is controlled by the presence of pre-existing defects in rocks. The experimental studies

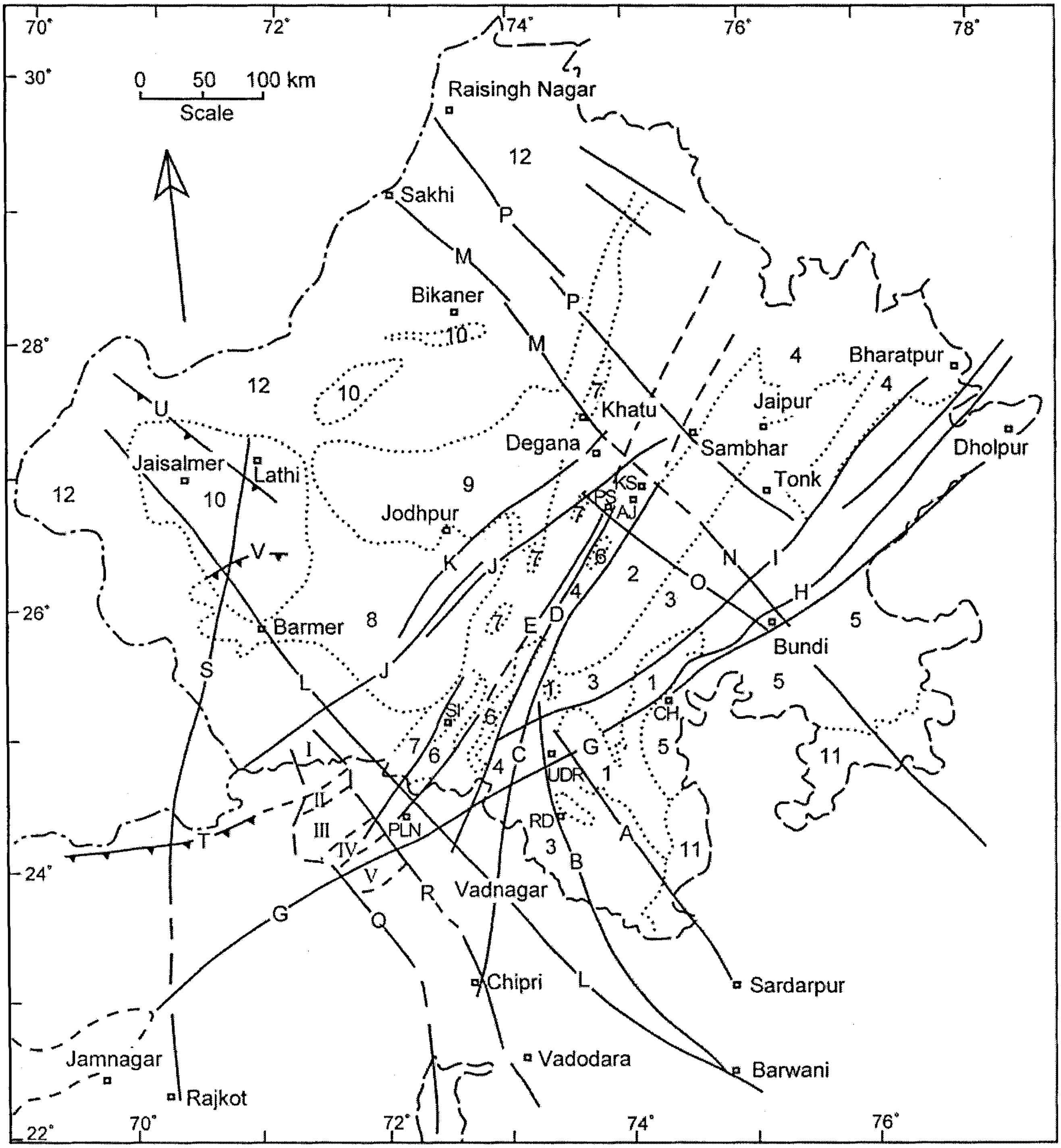

Fig. 5. Map showing the distribution of major lineaments and faults in Rajasthan and the neighbouring areas (modified after Bakliwal and Ramaswamy, 1987). Index: 1–Mewar Gneiss Complex and Archaean granitoids. 2–Tectono-thermally reworked basement. 3–Aravalli Supergroup. 4–Delhi Supergroup. 5–Vindhyan Supergroup. 6–Granitoids in the Delhi Fold Belt. 7–Sirohi Group. 8–Malani Group. 9–Marwar Supergroup. 10–Mesozoic-Cenozoic formations. 11–Deccan Trap. 12–Quaternary and Recent. 'A' to 'R' – lineaments described in the text. AJ–Ajmer, CH–Chittaurgarh, KS–Kishangarh, PLN–Palanpur, RD–Rishabdev,, SI–Sirohi, UDR–Udaipur.

and mathematical calculations have shown that the fractures prefer to develop along zones of pre-existing defects instead of forming strictly along the circular cross-sections of stress ellipsoids. This is specially so where the orientations of the defects are not parallel to but make small angles with the circular cross-sections of the stress ellipsoids (Griffith, 1920; Griggs and Handin, 1960). A very similar phenomenon is observed in the case of development of the younger lineaments, which tend to follow the pre-existing defects (in the present cases the pre-existing Precambrian grains) irrespective of the orientation of the stress system. Out of all the lineaments,

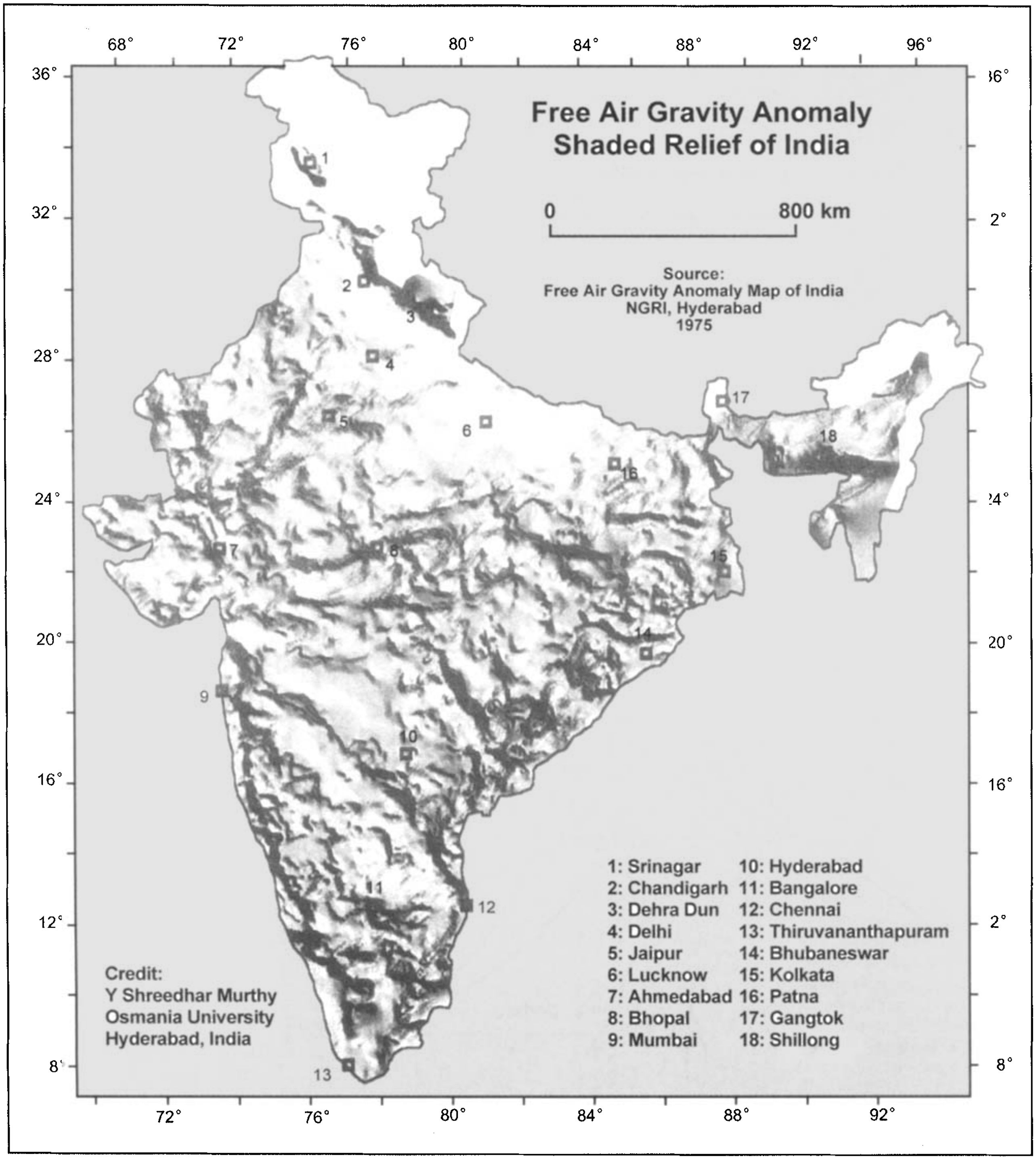

Fig. 6. Free Air gravity anomaly shaded relief image of India showing the distribution of the geophysically expressed lineaments (after Murthy, 1999).

the two sets having WNW–ESE and NE–SW trends respectively are the most persistent pair of lineaments that developed in Rajasthan and Gujarat. A survey of available data would indicate that this pair has not only developed in this part of the shield but also in the entire peninsular region (Fig.7) (Rakshit and Rao, 1989; Varadarajan and Ganju, 1989). It has already been mentioned that the two sets of lineaments having N35°W–S35°E and N65°E–S65°W trends make N-S obtuse angles of about 100°. The application of the common theory of brittle fractures makes it possible to determine the N-S (or more precisely N15°E and S15°W) trending obtuse bisectrix as the extensional stress vector (Fig. 4). There may be some valid reasons to assume that such a stress system prevailed at the time of fragmentation of the Gondwanaland during the Jurassic.

Effects of Plume Outbursts on Indian Lithosphere

As the Indian continental block (along with Madagascar and Seychelles, and the Antarctica remaining attached to it) moved northward following the dismemberment of the Gondwanaland, it had to endure the outbursts of four plume heads like the Marion, Reunion, Crozet and Keruguelen at different times before the collision with the northern cratonic fragments. The influence of the individual Plume outbursts, barring perhaps that of the Reunion, is yet not fully understood. Overall, the underplating and magmatism associated with the plume outbursts are manifested by the patches of gravity highs and zones of high heat flow as well as the occurrences of magnetic and telluro-magnetic anomalies over the entire Indian Shield (Qureshy, 1982; Qureshy and Midha, 1986).

The Bouguer gravity anomaly colour image map (Fig. 8) prepared by Murthy (1999) appears quite illustrative in this regard. The most spectacular feature in the Bouguer anomaly colour image map is the presence of a continuous gravity low all along the Himalayan frontal belt, which extends in the east as the Burmese Arc Zone. This belt of gravity low is a reflection of the huge crustal thickness that resulted from the telescoping of continental blocks during the Himalayan collision.

The gravity image picture of both the eastern and the western region is incomplete, as it does not cover the areas outside the India's political territory. Nevertheless, the interactions of the Indian lithosphere with the plume-heads and also the related underplating events during the plume outbursts is quite clearly expressed in the form of significant gravity highs fields that appear in the western as well as in the eastern areas of the Indian Shield. The appearance of two linear gravity highs in the N-S (between Kolkata, *nee* Calcutta, and Patna) and E-W (south of the Shillong Plateau region of eastern India) directions can be correlated with the plume related magmatism in the region. The correlation of two different features depends on the closeness of available age data. An age range of 110–130 Ma has been suggested for the Sylhet volcanics (cf. Baksi et al., 1987), whereas a much narrower age range between 116 and 118 Ma has been postulated for

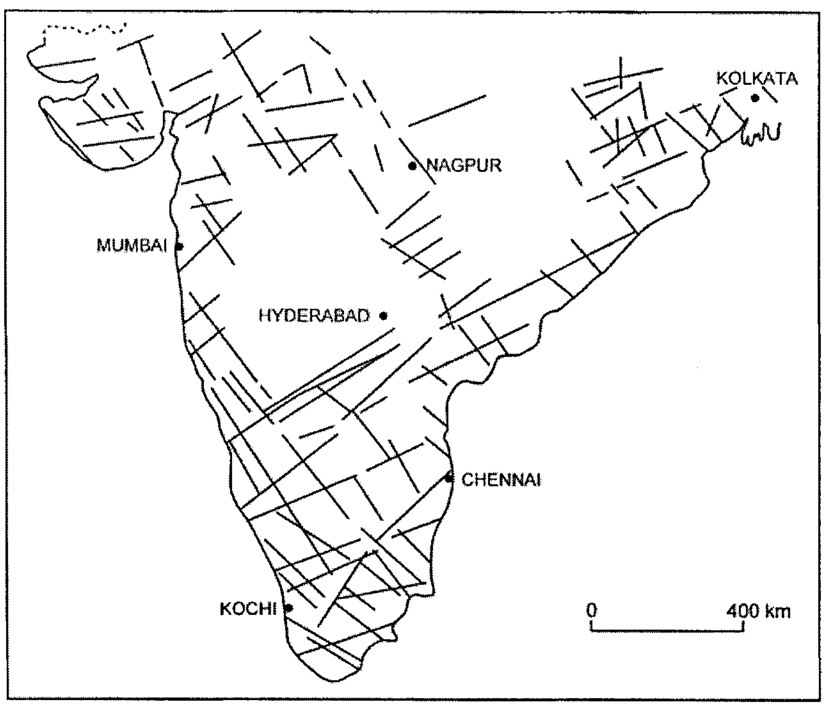

Fig. 7. Map showing distribution of lineaments in the peninsular India. Notable features are the dominance of the NE-SW and NW-SE pairs of lineaments (after Varadarajan and Ganju, 1989).

the Rajmahal Traps (Baksi, 1995; Kent et al., 1997). Based on the considerations of geochemical and petrological characteristics, the magmatism in both the instances has been linked with the Kereguelen Plume outburst. The development of rift fractures subparallel to the directions of the two linear gravity highs has presumably been

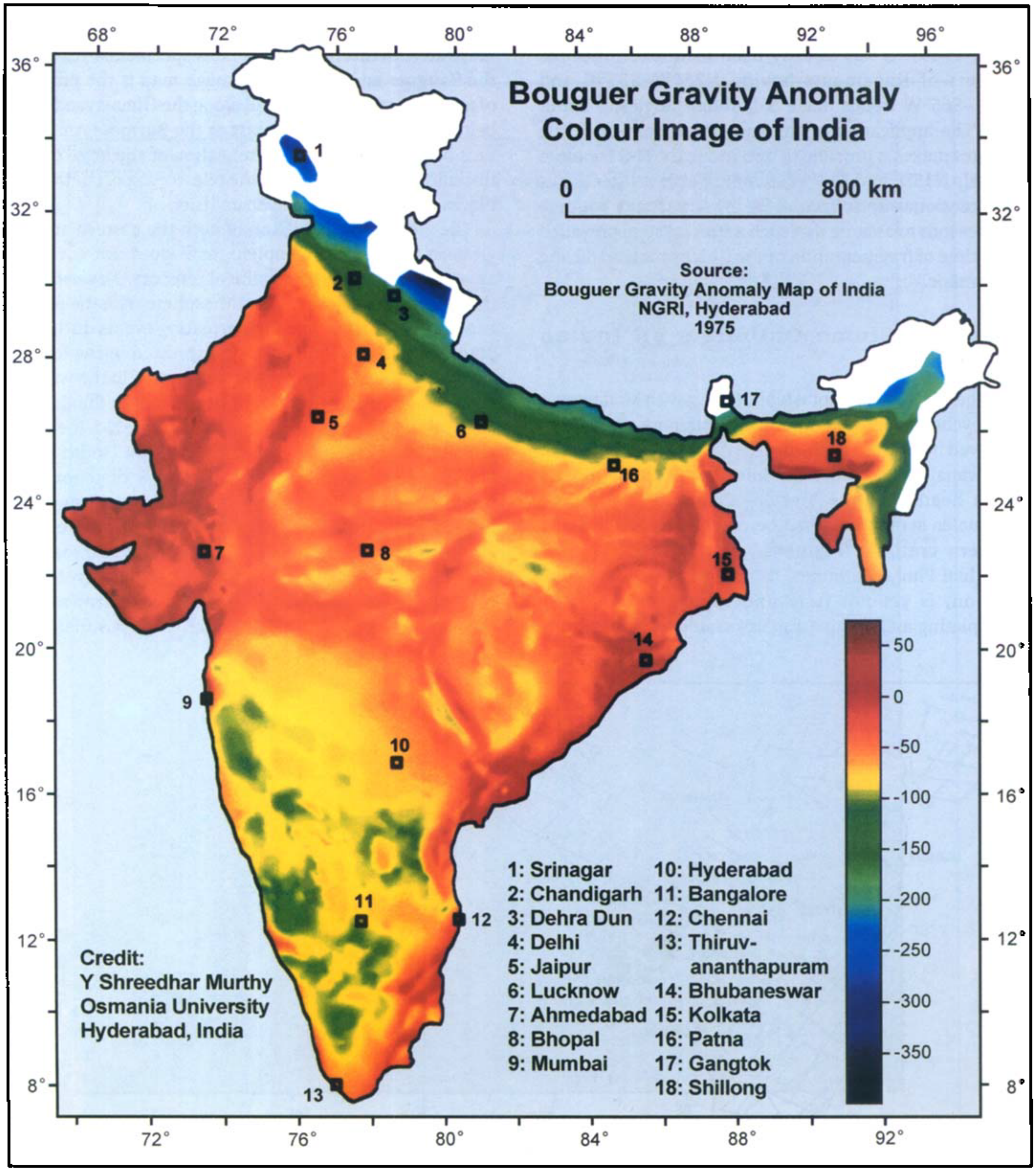

Fig. 8. Bouguer gravity anomaly colour image of India (after Murthy, 1999).

induced by the tensional stresses generated as the result of the outburst. The two rift fractures are: (1) N-S trending fault bordering 'Bengal Shelf' in the west (Fig. 9), and (2) E–W trending Deuki Fault lying south of Shillong (Fig. 4). Both the fracture systems are associated with basin evolution in the respective regions. It is however difficult to categories the occurrence of patches of the gravity highs along the eastern Indian coastline. Based on the presence of two volcanic layers of 107 Ma and 114–116 Ma (cf. Subrahmanyum, 2000) the extension of the Kereguelen plume activity further south of the Bhubaneshwar area has been suggested. The suggestion finds support in the occurrences of patches of gravity high shown in the coastal areas of the Mahanadi basin (cf. Fig. 8). No definite information is available on the gravity high noticed along the coastal line of the Godavari basin and in the region surrounding the Tiruchirapalli belt southwest of Chennai (*nee* Madras). These gravity anomalies may presumably be linked with the plume outburst that triggered off the separation of Antarctica from India at around 130 Ma (U. Raval, pers. comm.). A pertinent question that remains to be addressed in this context is the possibility of linking this geological event with the Crozet Plume outburst!

The Bouguer gravity anomaly colour image map of Murthy (1999) (Fig. 8) shows occurrences of a few very narrow and ill-defined gravity highs, fringing the western Indian continental coastline. The most prominent of these occur in areas around Mumbai, near Mangalore and north of Thiruvananthapuram (*nee* Trivandrum). The geological information which could have a bearing on the occurrences of gravity highs in these region includes (i) the occurrence of ~90 Ma old acid rocks of St. Mary Isles off Mangalore (cf. Subbarao, 2000), and (ii) the presence of ca. 85 Ma old leucograbbro pluton and dolerite dyke from central and north Kerala respectively (cf. Radhakrishna, 2000). The dolerite dyke indicates 34N superchron on the magnetic polarity time scale. The correlation of these rocks with late Cretaceous basalts of Madagascar led to the suggestion that these could be pre-Deccan igneous rocks related to the Marion Plume outburst that caused separation of Madagascar from India (with Seychelles remaining entangled with it). Based on this geological information, though quite inadequate, a suggestion can be made on the possibility of link between the gravity highs in the belt (at least those occurring near Mangalore and north of Thiruvanathapuram) with the Marion Plume related underplating event.

The Bouguer anomaly contour map of northern Gujarat and western Rajasthan shows presence of large patches of high gravity anomaly fields (Figs. 8 and 10). This picture of scattered but very apparent clustered gravity-high anomaly fields has been linked with magmatism associated with the Reunion Plume outburst (Roy, 2003) that possibly took place in two phases (Basu et al., 1993). Raval and Veeraswamy (2000) proposed 3-phase plume activities describing these as the pre-, syn-, and post-outburst features.

Different geophysical features, which characterise this part of the Indian Shield, differ significantly from those of the average shield areas. These include the patches of gravity highs (representing +40 mgal closures, Fig. 10), significantly high heat flow values (55–93 mWm^{-2}) and the seismicity (falling in Zone 5). The important surface geological signatures that resulted from the plume outbursts are (Fig. 10):

(1) N-S and E-W sedimentary basins (of latest Cretaceous and the earliest Cenozoic age) in western Rajasthan and northern Gujarat;

(2) lineaments having roughly E-W and N-S fracture systems (lineaments), and reactivation of early formed lineaments.

(3) intrusions of alkaline and mafic bodies, and bimodal lava flows.

The history of evolution of rift basins contemporary with the Reunion Plume outbursts is very well documented in western Rajasthan (Roy, 2003; Roy and Jakhar, 2002). The stratigraphic records from the Jaisalmer Basin suggest that the sedimentation, which had earlier closed at around 85 Ma, resumed by the late Cretaceous. Two other basins, which formed simultaneously with the Jaisalmer Basin, are the N-S oriented Barmer Basin and the almost E-W oriented Bikaner-Nagaur Basin. Two vital evidences suggest a close interaction between the basin opening and marine transgression in the region with the underplating events related to the Indian lithosphere-Reunion Plume. These are (1) the dominance of the volcani-clastic sediments in these basins particularly in the Barmer Basin; and (2) the contemporaneity of the fossil ages with the early phase of magmatism in the region.

Very significant information is provided by the discovery of a linear low velocity zone (LVZ) at about 100 km depth in the subcrustal upper mantle region that underlies the N-S oriented Barmer Basin. Based on the P-wave seismic tomographic study, Kennet and Widiyantoro (1999) could locate a cylindrical LVZ of about 200 km across in the upper mantle that underlies the region between the north of Gulf of Cambay and the northwest of Barmer. The striking coincidence in the extent of the LVZ in the upper mantle (described as the trace of the Reunion Plume) with that of the N-S orientated Cenozoic Basin of Barmer possibly suggest a cause-and-effect relationship between the underplating event related to Reunion Plume outburst and the formation of the contemporary Barmer Basin.

Barring the E-W and N-S lineament patterns in the 'Bengal-Assam' region, which are possibly related to the Keruguelen Plume outbursts, the section of western

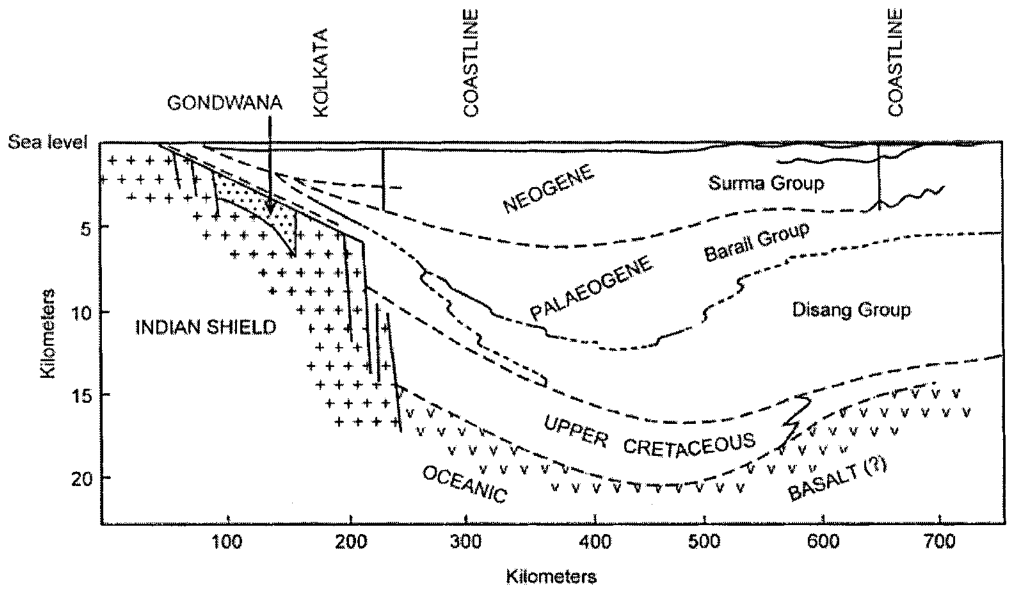

Fig. 9. Schematic regional cross section across the Bengal basin bounded in the west by the subparallel N-S bounding faults (After Balakrishnan, 1977).

Rajasthan and northern Gujarat is the only region in the entire Indian Shield where the E-W and N-S pair of lineament sets are observed. The most important of these lineaments in terms of their extent is the N-S oriented Rajkot-Lathi Lineament (Fig. 10). Parallelism of this lineament with the N-S subcrustal/upper mantle-underplating feature underlying the Barmer Basin suggests a genetic relationship between the two features. In the Rann of Kachchh region of northern Gujarat, there are a series of E-W trending domal features. These domes of Jurassic rocks have formed by the diapiric intrusions of basalts from below (Biswas, 1993a; Kanjilal, 1978). 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 basaltic rocks that occupy the core regions. The domes, which occur as chains of islands are bordered in the north by a major E-W running fault-lineament (Island Belt Fault in Fig. 11). The occurrences of E-W oriented islands formed due to diapiric intrusion of basalts and the subparallel facture-lineament provide the proofs of formation of the fracture systems as the manifestations of underplating related magmatism in the region.

Several isolated plutonic bodies, plugs, minor intrusive bodies of alkaline mafic and syenite suites associated with comagmatic alkaline dykes of different composition along with a number of suites of volcanic rocks ranging in composition from basic to acid occur at Mundwara, Sarnu-Dandali and Tavidar regions in southwestern Rajasthan. The Mundwara rocks occur in two distinct suites: (1) ne normative alkaline association, and (2) hy-ol normative (ne-free) mafic association. A depth of over 100 km has been estimated for the generation of the alkaline magma (unpublished data of R. K. Srivastava, pers. comm.). A depth greater than 125 km has been estimated for the generation of ol-ne normative alkaline magma suites of the Sarnu-Dandali through the partial melting of phlogopite-bearing mantle rocks having a high CO_2/H_2O ratio (Srivastava, 1989). The Tavidar rocks on the other hand constitute a bimodal suite represented by the rhyolite-trachyte and the basaltic associations.

The geochemical characteristics of different rocks of the Mundwara, Sarnu-Dandali and Tavidar indicate that these are the products of partial melting of rocks situated at different levels in the upper mantle as well as in the crust. Although there are some differences in the sets of available isotope ages of these rocks (Basu et al., 1993; Rathore and Venkateshan, 1996; Rathore et al., 1996), the Deccan affinity of these ages is quite apparent. According to Rathore et al. (1996), the magmatic activity continued for about 6 million years from ca. 70 Ma to ca. 64 Ma for the different components of the Mundwara Alkaline Complex. Basu et al. (1993) who could establish a close petrogenetic link between the Mundwara and the Sarnu-Dandali alkaline complexes, on the other hand, suggest a 3.5 million year of incubation history of a primitive, high-^{3}He mantle plume before the rapid eruption of the Deccan flood basalt at ca. 65 Ma.

The occurrences of a number of Mundwara-type volcano-plutonic complexes are also known from the Saurastra and Kachchh regions of northern Gujarat. The most important of these occur at Girnar in central Saurastra. The other important bodies occur at Alec Hills, Osam Hills and the Chamardi Hills in the different parts of the Saurastra Peninsula. In addition to these, innumerable plugs are present in the Kachchh region.

The most striking occurrence of the intrusive plutonic complexes is that of the Girnar Hill in central Saurastra. The central core of the 'Girnar complex' consists of monzonite and diorite constrained within a ring-shaped dyke system of granophyre. There are smaller dyke-like bodies of limbergite, nepheline-syenite, monchiquite and camptonite that intruded into the olivine-gabbro constituting the base (De, 1981; Mathur et al., 1926; Sukheshwala, 1981). In spite of the close regional association, there is no apparent correlation between the zones and patches of gravity high and the occurrences of the igneous complexes that occur as plutons or plugs of various dimensions. The only exception is the high-gravity anomaly field (+50 mgal) marked over the Alec Hills near Porbandar, which is a volcano-plutonic basaltic complex (Fig. 10). The presence of high-gravity Bouguer anomaly over the Alec Hills region indicates the presence of high-density rocks (representing a possible mafic magma pouch) underlying the region (cf. Roy, 2003). It is interesting to note that there is virtually no such high-gravity anomaly field in the entire Deccan Trap volcanic province outside the Kachchh-Saurastra and the western coast region. In conformity with the interpretation of Takin (1966), it may be suggested that the patches of positive Bouguer gravity anomaly of over +30 mgal values in the aforesaid region are due to the mass of high density rocks (such as the olivine gabbro) which were emplaced in the crust as the manifestation of plume-lithosphere interaction in the region.

Based on the occurrences of alkaline rocks at Sarnu-Dandali and Mundwara in Rajastahn, Kadi and Netrang in Gujarat and Jawahar and Salsette in Maharastra, a north-south corridor has been conceived for the southward trace of the plume outburst as the Indian Shield moved

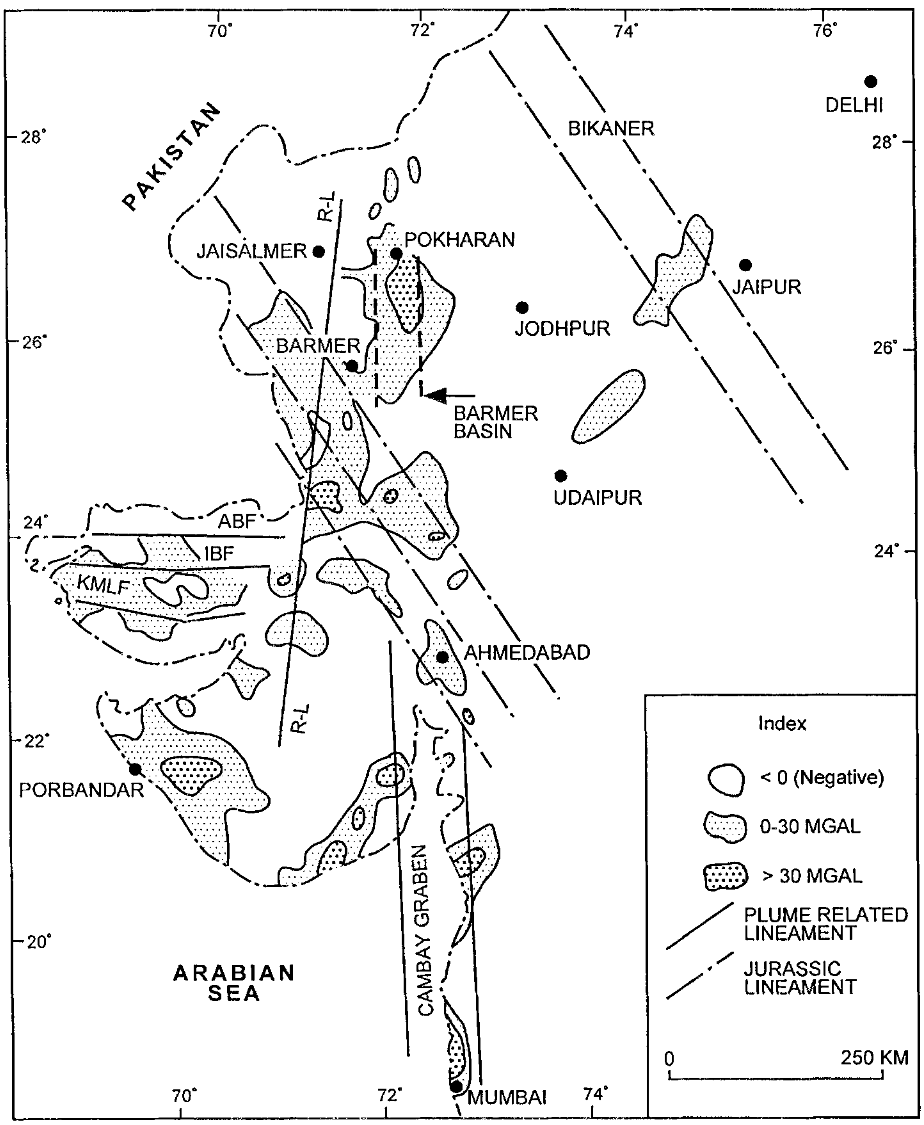

Fig. 10. Bouguer gravity anomaly map of western India showing the distribution of two systems of lineaments and the early Cenozoic Barmer Basins. Bouguer gravity anomaly map is based on the map published by National Geophysical Research Institute, Hyderabad (1974).

northward over the Reunion hotspot (Basu et al. 1993) (Fig. 12). The corridor reportedly passes through the Lakkhadive-Maldive 'Oceanic Island Chain' in the south. The important geomorphotectonic features associated with the passage of the plume outburst is the formation of the Cambay Graben and the straight running west coast of the Indian Peninsula. There are also several fault lines, which divide the coast-shelf zone into a number of parallel N-S trending horst-graben like rift blocks (Biswas, 1993b; Mishra, 2001; Power, 1993; Radhakrishna, 1991, 1993; Widdowson, 1997). This fault system may be linked with the plume outburst related tectonics. Nevertheless there lies a possibility that the present structural setting along the west coast of the Indian Peninsula could have been shaped at a later stage during the ocean opening processes operating in the central part of the Arabian Sea (Subrahmanya, 1998).

Some comments seem pertinent on the occurrence of linear, high-gravity Bouguer anomaly fields that virtually crisscross the Indian Shield, especially in the northern part (Fig. 8). Most of these linear geophysical features show parallelism with the zones of important tectonic belts, represented by the Proterozoic orogenic belts and the Proterozoic–Palaeozoic rift basin zones. In the case of the belt that lies over the Aravalli Mountains, west of Jaipur showing markedly high values of the Bouguer gravity anomaly, there is reported evidence of Mesozoic-Cenozoic underplating event (Roy, 2000; Rao et al., 2002; Sivaraman and Raval, 1995). Extending this interpretation to the other geophysical lineament zones (cf. Murthy, 2002), it may be suggested that these (the gravity highs) are the manifestations of plume induced underplating events. Thus, following the suggestion of Raval (1995, 2000), it may be suggested that the Proterozoic orogenic belts and the Proterozoic-Palaeozoic rift zones have acted as the 'rheologic wave-guides', which helped in canalising tectonic, magmatic, metamorphic as well as metasomatic processes along these belts. These new 'mobile belts' have presumably formed during the passage of the Indian Shield over the different plume heads.

Himalayan Collision: Effects on Indian Shield

The Himalayas, which emerged from the grand continental collision, incorporated a considerable part of the Indian Shield in its fold. The shield elements now occur as the fold-thrust sheets constituting the Lesser as well as the Higher Himalayas south of the Indus-Tsangpo Suture Zone (Fig. 13). A considerable part of the Higher Himalayan rocks, known as the Central Crystallines had undergone a very significant tectono-thermal reconstitution during the Himalayan Orogeny, so much so that it is now difficult to identify the components of these rocks as Indian Shield elements. The rise of the Himalayan Mountains during its initial stages witnessed rapid deposition of 'mollase-type' fluvial and fluvio-glacial sediments in the depression that developed in its frontal parts. This thick sequence of sediments, known as the Siwaliks, became a part of the rising Himalayas at a later

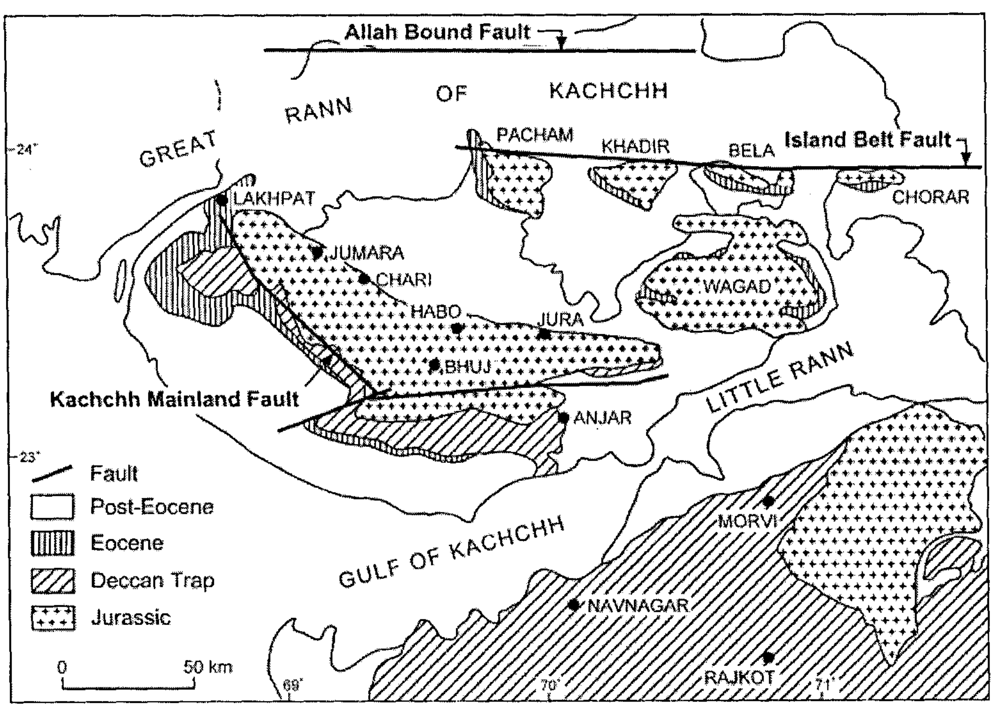

Fig. 11. Simplified geological map of the Kachchh region of northern Gujarat showing the field relationship between the Jurassic outcrops and the major lineament faults. The Nagar Parkar Fault lies north of the Allah Bund fault outside the map area.

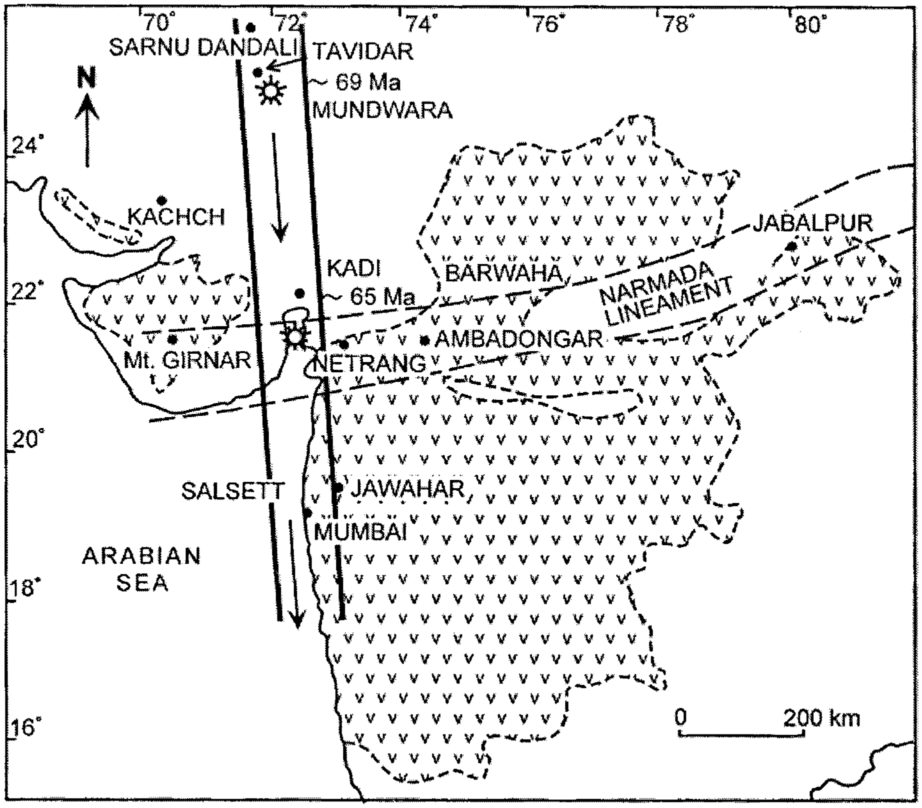

Fig. 12. Map indicating the probable path of the trace of the Deccan (Reunion) Plume grazing the western Indian coast (modified after Basu et al. 1993).

stage (Fig. 14). Besides incorporating a considerable part in its fold, a great depression formed in the front of the Himalayas resulting from the ducking of frontal region (the leading edge) of the shield underneath the Himalayas. This depression, which is filled up by two important river systems, the Indus and the Ganga, constitutes the great basins of the Indo-Gangetic Plains (IGP). The IGP is an asymmetric prism of essentially fluvial sediments having an axis of maximum deposition close to the present foothills (Raiverman, et al., 1983). The maximum estimated thickness of 6 km sediments occurs along the northern fringes of the plain that run parallel to the Sub-Himalayan Siwalik Hills.

The increasing thickness of the sediments filling up the Indo-Gangetic Plains is very prominently reflected in the gravity anomaly data in the form of a wide zone of negative Bouguer anomaly running almost parallel to the length of the basin. The gravity values vary between about –5 mgal along the southern edge of the basin and about –175 to –200 mgal near the northern boundary.

The thickness of sediments is not uniform over the entire length of the basin. This is because of the presence of several transverse 'basement highs' in the basin. The important ones are the Delhi-Hardwar Ridge along the line of the Aravalli Mountains, The Faizabad Ridge marking the northward continuity of the Bundelkhand massif, and the Munger-Saharsa Ridge east of Patna (Fig. 3).

Post-collision Tectonism and Seismicity

We have already discussed about the lineament sets that crisscrossed the Indian Shield. The lineament sets include (i) reactivated Precambrian grains, (ii) the new sets (represented by NW-SE and ENE-WSW pair) evolved during the Jurassic break-up, and (iii) the youngest sets (mainly E-W and N-S pair) formed in response to the plume outbursts during the Cretaceous-Eocene period. The lineaments, which developed as zones/planes of discrete fractures, divided the Indian Shield into several rigid blocks. The tectonism witnessed by the Indian Shield, therefore, is suggestive of block movements that caused significant geomorphotectonic changes including uplifts and tilting of blocks, drainage disorganisation and ponding, etc. It is obvious that the terrain witnessing such movements would be affected by intense seismic turmoil.

The Indian Plate along with its northern continental components was moving at a very fast rate prior to the collision. The northward migration of the continental block was continued, though becoming more sluggish, even after the collision. Presently, the Indian shield is moving at approximately 5 cm/year rate in the northerly direction. The stress regime analysis over the Indian Shield region has been computed from the interpretation of the focal mechanism of a large number of earthquakes (Rajendran et al., 1992). The study indicated operation of a NE-SW directed stress vector over the region. It may be logically presumed that the stresses affecting the Indian Shield are the same that are generated by the process of formation of new crust along the NW-SE oriented Carlsberg Ridge-Rift system in the Arabian Sea region of the Indian Ocean (Fig. 15).

Concluding Remarks

A critical analysis of the geophysical data, especially the gravity anomaly and the heat flow patterns, reveals how a considerable part of the Indian Shield attained mobility through its reconstitution during the Phanerozoic. There are records of a number of geological activities in the Indian Shield area during this short span of time, yet the most significant changes in the crust and the upper mantle took place during the plume outbursts as the Indian lithosphere passed over these mantle hot spots. The principal effect of the lithosphere-plume outburst interaction is the extensive magma underplating in parts of the Indian Shield. Lineaments appear to have played the most effective role in the process of reconstitution of the Indian crust. These lineaments formed either as new sets of very steep or vertical fractures or through the reactivation of the ancient Precambrian grains during the Jurassic break-up of the Gondwanaland. The development of lineaments affected the geophysical character of the Indian crust in two different ways. Firstly, these acted as pathways in channelling the underplated magma materials along their extensions. The process in turn helped to attribute geophysical characters to the lineaments by marking these as zones of high heat flow associated with positive gravity anomalies. It may be worth mentioning in this regard that the lineaments, which formed through the reactivation of ancient tectonic grains, were especially conducive in channelling the underplated magma materials along them. Raval (1995) described such lineaments as the 'rheological wave-guide' that helped in easy transmission (diffusion) of the thermo-mechanical forces. Mention may be made about the Chennai-Nasik Lineament (Chennai-Mumbai Line of Murthy, 2002) (Figs. 4 and 6), which is not expressed by any significant geomorphic feature or by any noteworthy geophysical feature like the positive gravity anomaly or high heat flow values. Evidently, this lineament, which does not follow any ancient tectonic grain, failed to act as a 'rheologic wave-guide'.

Secondly, the lineaments have caused the fragmentation of the Indian lithospheric crust into a large number of rigid blocks. The formation of the lineaments therefore introduced a sort of a structural heterogeneity in the Indian crust in a way similar to that we observe in block tectonics, which involves relative movements of 'rigid blocks'. In such a deformation pattern, the rigid blocks remain as areas of least or no strain, while the stresses or movements are transmitted only along the narrow zones that border the rigid blocks. In the context of the Indian Shield, the

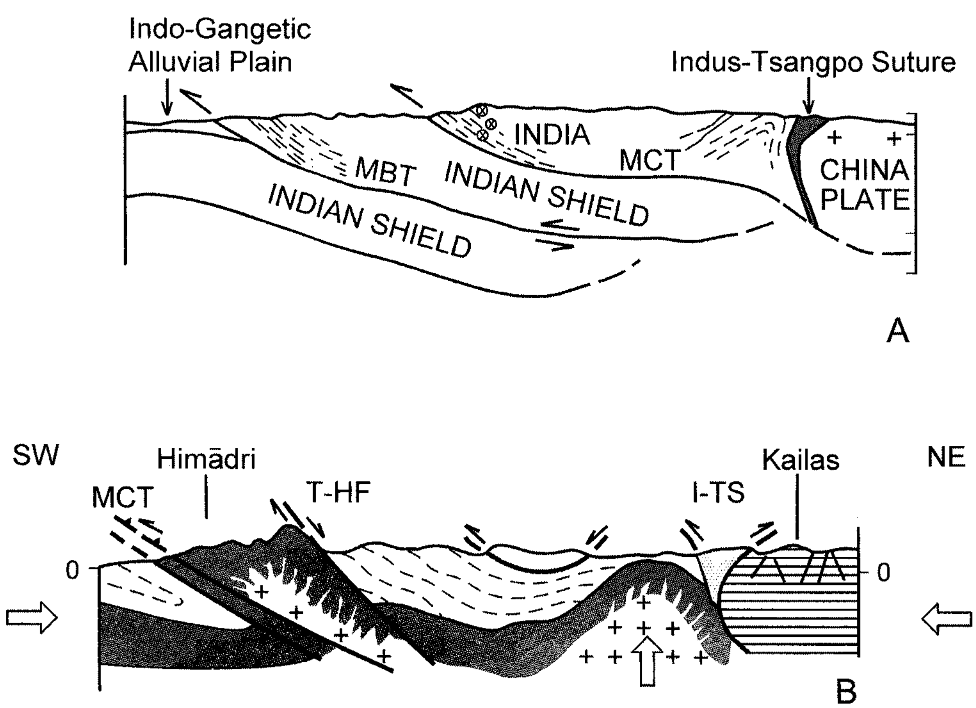

Fig. 13. Geological models indicating the involvement of Indian Shield elements in the evolution of the Himalayas. A. After Le Fort (1975); B. After Valdiya (1984).

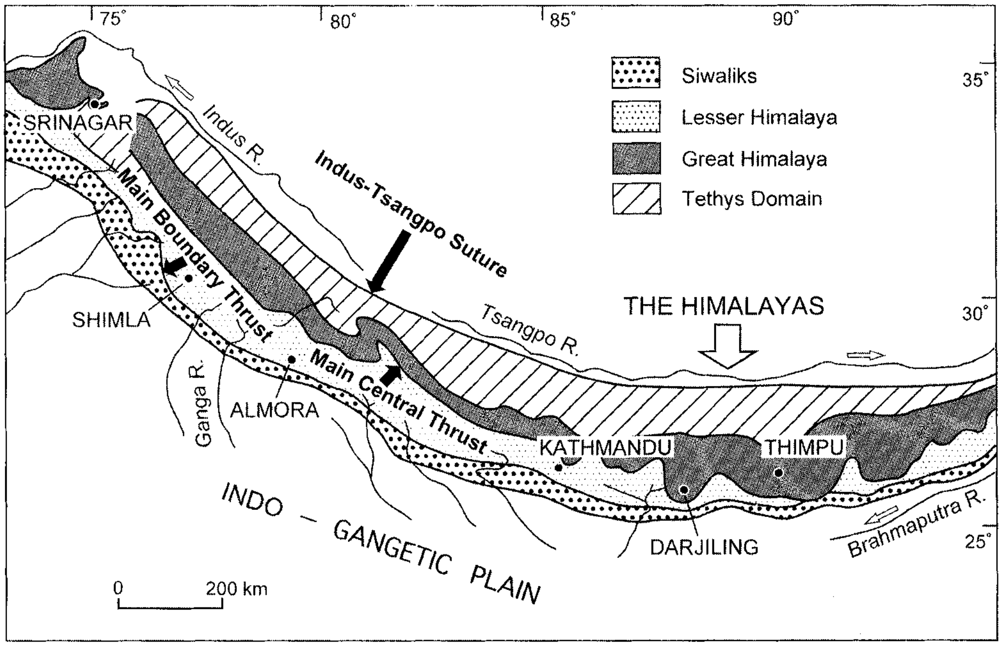

Fig. 14. Occurrence of 'mollase-type' Siwalik sediments in the Sub-Himalayan Ranges (after Valdiya, 1998).

lineaments act as zones of high strain. The relative movements along these lineaments ensues seismicity, while the rigid blocks are the areas without seismic activities. Murthy (2002) has mapped one such area in the free-air gravity shaded relief image map of India. It is possible that more such areas can be delineated if the known epicentres are plotted as small dots on a significantly large map.

Some comments may be made about the extreme mobility of the crust of the Kachchh area, which falls in the Seismic Zone 5. This seismically susceptible belt neither forms a part of any plate margin nor occurs close to any such zone. We may presume, based on the available geological information, that the seismic character of this belt is due to the combined effects of underplating of the magma materials and the development of tensional fractures resulting out of the Reunion Plume outburst. The close spacing of the patches of gravity high zones in the region that surrounds this seismically active terrain may be a reflection of the presence of magma pouches at different levels in the crust. All these features taken together helped to 'strain soften' the lithospheric crust in the region.

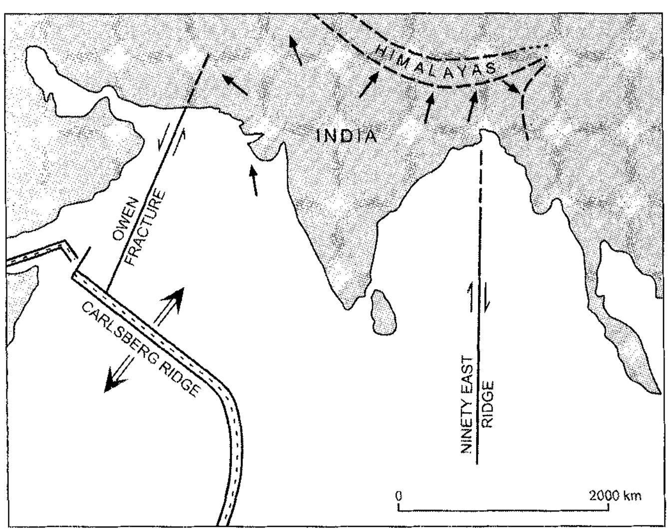

Fig. 15. Schematic map showing the generation of extensional stress at the Carlsberg Ridge in the northwestern Indian Ocean, which presently affects the Indian Shield as compressive stresses.

The lineaments have also played a significant role in bringing about pronounced geomorphologic changes in the Indian crust subsequent to the rise of the Himalayas due to the continental collision. These included topographic changes, like the formation of horst-mountains (Mount Abu in Rajasthan, for example), rift grabens (like the Narmada Basin), drainage disorganisation (migration and extinction of the Vedic Saraswati) and many other features attributed to the neotectonism.

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