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Modification of geological and geophysical regimes due to interaction of mantle plume with Indian lithosphere.

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Abstract: Plate tectonics has provided a most valuable dynamical framework, which can successfully integrate the geological, geophysical and tectonic features along the plate boundary (or inter plate) corridors. But the intra-plate (or Mid-continental) signatures remain largely much less understood. It is proposed in this context, that the plume tectonics provides a complementary mechanism to comprehend the development of signatures observed/ measured in the intra plate (mid-continental) regions; and dynamical development of the Indian lithosphere, particularly over past ~150 m.y., provides a very ideal setting for this suggestion. Utilizing the geological and geophysical data over the Indian lithosphere it is suggested that on one hand the plume-lithosphere interaction produces the well known geological signatures like flood basalts (or large igneous provinces), igneous complexes and associated dyke swarms (e.g. basalts, tholeiites, alkaline rocks, kimberlites, picrites, carbonatites etc.), on the other hand the geophysical structures (such as density, seismic wave velocity, rheology, electrical conductivity, heatflow etc.) of the crust-lithosphere regime overlying the plume-head would also get significantly modified during the plume-lithosphere interaction. This modification is mostly channelised/concentrated along the mobile belts (MBs). Indian lithosphere seems to have been affected directly or indirectly by 3-4 mantle plumes (viz. Reunion, Kerguelen, Crozet, Marion) since the Cretaceous. The concentration of midcontinental geophysical anomalies and tectonic (particularly vertical or epirogenic) features along the MBs can be, to a large extent, understood in terms of modifications caused by mantle plume activity. Further, from Gondwana lands dispersion it is seen that the breakup history of India taken place along its MBs with contemporaneous plume activity, which also prompts the suggestion that for breakup of the super-continents, a combination of first order MBs and hotspots (or plumes) could often become fatal. The applied significance of the plume-lithosphere interaction in terms of economic and energy resources is also discussed.

INTRODUCTION

Geodynamics, evolution and reactivation of the lithospheric plate are generally interpreted in terms of plate tectonics framework. The latter however explains structure and processes at and adjoining the plate boundaries present or past. But intraplate and/or midcontinental features including epirogenic movements/ vertical tectonics still require causative mechanism. For this the plume mode of convection appears to provide a complementary framework to integrate multiparametric intraplate observations (Raval, 2000). Keeping both plate and plume type tectonics and their consequences much about the lithospheric evolution can be understood.

Breakup of Gondwanaland during the ongoing Wilson cycle the Indian lithosphere exhibits certain unique characteristics. Some of these are:

(i) Three continental breakups (from Antarctica-Australia at ~130 Ma, from Madagascar at ~90 Ma and from Seychelles at ~65 Ma)

(ii) 3-4 mantle plume activities and development of three large igneous provinces (LIPs) viz. Early Cretaceous Rajmahal/Sylhet/Bengal Traps (~117 Ma), Mid-Cretaceous volcanism over Madagascar and intrusive activity over the southernmost part of the Indian shield (~90 Ma) and Deccan flood basalts at the K-T boundary (~65 Ma)

(iii) Reactivation of its mobile belts (MBs) due to breakup and plume activity, and

(iv) A major ongoing continent-continent collision zone along Himalayas.

This lithosphere is thus very suitable to investigate the plume-lithosphere interaction and continental breakup processes. It's long geological history makes it a repository of earlier plate and plume tectonic episodes and hence study of earth's dynamics can be extended to the Proterozoic and the Archaean era. Here, attention is paid to the plume tectonics over the Indian plate mainly during the Phanerozoic by keeping in view the strong laterally heterogeneous nature of Indian continental lithosphere due to presence of old and undeformed cratonic nuclei and their circumscribing mobile belts (or palaeo-sutures) of Proterozoic period. The non-uniformity arises due to the significant variations in the thickness and geophysical structure of the cratons and MBs, which explains the major difference observed in the thermomechanical response of the cratons and MBs to impressed tectonothermal forces.

PLUMES IN GENERAL

In the classical scenario, plate tectonics has been attributed to thermal convection leading to heat and mass transfer in the earth's mantle (Fowler, 1990). This process is considered to be a two-layer process involving upper (~100-650 km) and lower (~650-2900 km) mantles of the earth. Such a convection, in general, forms two independent and isolated convecting systems. However, with the advent of seismic tomography images, it has been revealed that the ongoing subducting slabs sometimes appear to cross the transitional boundary between the upper and lower mantles and their boundary also represents a phase transition of iron-magnesium silicate {or olivine

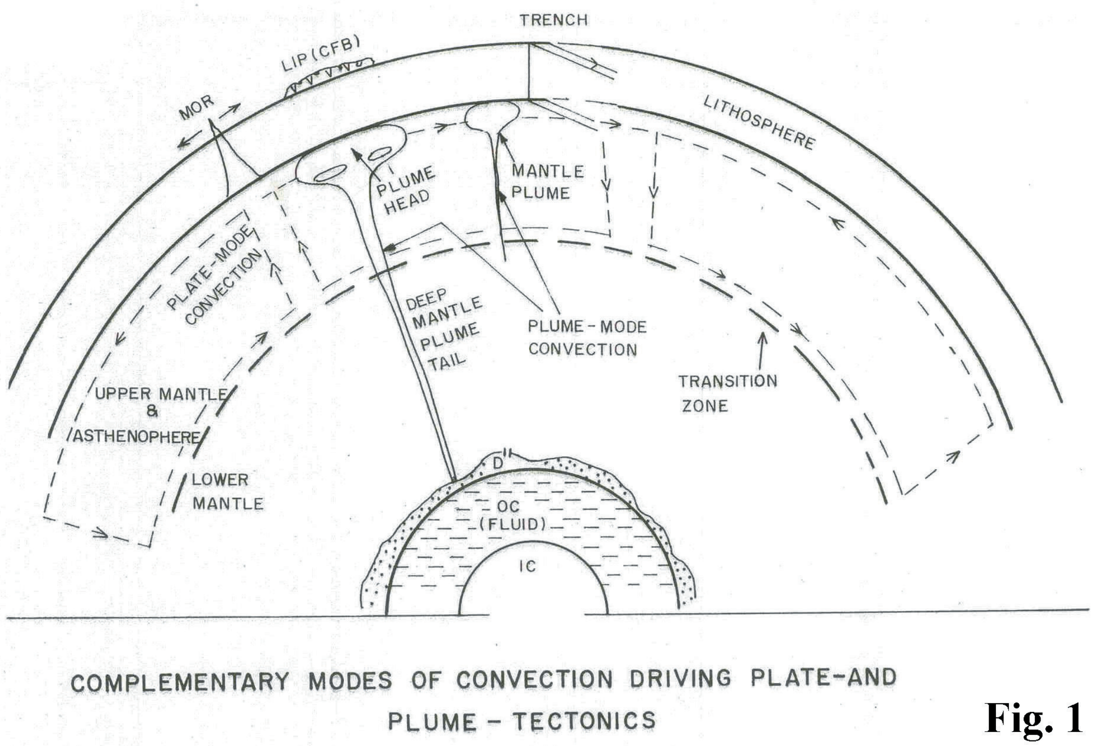

Fig. 1

Figure 1. Plate and plume mode convection inside the earth, the plate mode convection in the upper mantle gives rise to mid-oceanic ridges and trends and lithospheric plate boundary, while mantle plume raising from D" layer assume large plume heads at the base of lithosphere and then give rise to large igneous provinces (LIP) or continental flood basalts (CFB). The bi-model tectonics of the Indian lithospheric plate, one is a horizontal movement of India in the north eastward direction and the other is the vertical upwelling of the plume in the upper mantle giving rise to magmatic process and along with the western margin.

(Fe, Mg)2 SiO4}, induced by high pressure (~140 kbar) and temperature (~1400°C) as shown in figure 1.

In this scenario the tomographic images have produced increasing evidence that the subducting slabs may reach upto the bottom of lower mantle (LM) where another thermal boundary layer (TBL) is encountered (Van de Hilst *et al*., 1997). The latter is sandwiched between top of the outer core and bottom of the LM and is termed as D"- layer (Jacobs, 1987). This TBL is prone to being unstable due to outward flow of heat from earth's core. In such a situation, another kind of convective instability sets in the D" layer giving rise to heat and mass transfer in form of a narrow cylindrical conduit in the LM. After entering the upper mantle region top of the conduit spreads out like a mushroom head and may assume quite large dimensions (~1000-2000 km in diameter) by the time it reaches the litho-asthenosphere boundary (LAB). This form of convection has been commonly termed as deep plume type and is credited to dissipate about 5-10% of internal heat of the earth (Campbell and Griffiths, 1990; Griffiths and Campbell, 1991; Davies and Richards, 1992; Campbell *et al*., 1995; Davies, 1999).

Indian Continental Lithosphere: While considering the Indian continental lithosphere (ICL), it may be noted that it possesses a strongly heterogeneous nature due to the presence of old Archaean cratons sutured along certain palaeo-orogens of Proterozoic era. The latter represents weaker corridors which are vulnerable to thermomagmatic forces and hence over the geological time scale represent mobile regimes of the continental lithosphere in contrast to strong, rigid, cold, undeformed and stable cratonic core.

As shown in figure 2 the ICL at present, consists of three MBs (viz. Delhi-Aravalli DA-MB, Satpura ST-MB, Eastern Ghat EG-MB) along which cratons (Dharwar , Bundelkhand, Singhbhum and Bastar-Bhandara) have been sutured or cemented (Radhakrishna and Naqvi, 1986; Naqvi and Rogers, 1987). It is proposed that prior to ~90 Ma, the Madagascar, WesternGhat and Cambay trends together formed another MB of 'Greater India' (Raval and Veeraswamy, 1991). Along the southern part a breakup did occur while along the northern part rifting was aborted. Further, these Indian MBs, seem part of a much larger network of MBs over the Gondwana supercontinent (e.g. Pan African belt). Further the deep geophysical probing of CL exhibits significant lateral variations including its thickness; it is much thicker beneath the cratonic nucleii (150-300 km) while it is relatively thin under the MBs (< 150 km). It has been found (Rai *et al*., 1992) that Dharwar cratonic keel may extend to the depth of 250 km or more. The cratonic and mobile lithosphere vary not only in their thickness, but also in physico-chemical characteristics because of the accretionary origin and episodic remobilization of the MBs (Raval, 1989, 1993).

PLUME-LITHOSPHERE INTERACTION

Study focuses on the interaction between an upwelling plume-head (P) and the overlying lithosphere (L). Since, the lithospheric plate may be moving laterally also, due to plate tectonic forces, the situation implies a bimodal dynamics. The two modes are: (i) horizontal due to the lateral movement of the lithosphere, and probably a small component follows the lateral spread of plume-head in the asthenosphere, and (ii) vertical due to upwelling of the plume-head which may eventually lead to doming (As an example the case of India and Reunion Plume head is shown in figure 3).

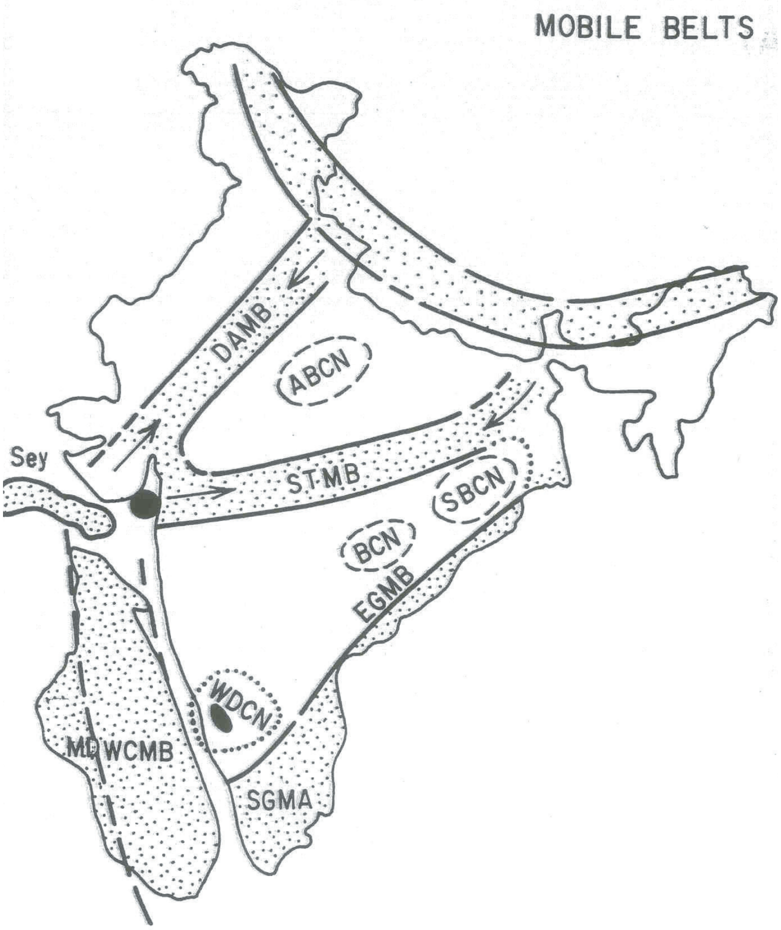

Figure 2. The distribution of mobile belts of greater India before its breakup (T> 80-90 Ma). It may be noted that Madagascar and Seychelles have been included here to the earlier mobile belt networks suggested earlier (Radhakrishna and Naqvi, 1986). The inclusion of Madagascar as a mobile belt explains the continental breakup and the volcanism evidenced at ~90 Ma.

The lithospheric base where a plume-head impinges could be continental or oceanic. In case of young, relatively simple and uniform oceanic lithosphere (T~200 m.y.), the P-CL interaction results in (a) seamount chains like Emperor-Hawaii, Laccadive-Maldive islands, Nikitin seamounts and (b) oceanic plateaus like Chagos, and Ontong Java (Klosko *et al.*, 2001); the latter is also a large igneous province (LIP), similar to that in the North sea etc., (c) aseismic ridges like 900E and 850E, and/or (d) swells or super-swells as in the south-west pacific ocean (McNutt, 1998). On the other hand, a continental lithosphere (CL) could be quite old (T~3.5 b.y.), strongly heterogeneous due to long and episodic tectonothermal history, and hence the P-CL interaction would be much more complex. Among the prominent geological manifestations of P- CL interaction are the LIPs, and/or continental flood basalts (CFBs), (e.g. Parana, Siberia, Deccan and Karoo), kimberlites, lamprophyres, carbonatites (Wilson, 1989) picrites (Krishna Murthy and Udas, 1981), etc. also which, due to their high temperature reservoirs, appear to upwell from relatively deeper parts of mantle (Haggerty, 1994). High temperature metamorphics could also be caused by mantle plumes which are of ~100-3000C temperature higher than the normal mantle.

As noted above CL exhibits strong lateral heterogeneity because cratons and MBs have significantly different thickness, rigidity, fertility (or hydrous nature), thermal state etc (Figure 4).

Cold Cratons: When a plume rises beneath a thick craton (150-300 km), a little or no partial melting may occur near its base, which is largely, refractory in nature. This inhibits passage of the plume-head through cratonic lithosphere (see Figure 4). And hence deep-rooted cratons mostly remain cold and undeformed, as reflected in the gravity lows observed over south Indian shield (SIS) as shown in Figure 5.

If a convective mantle thermal anomaly rises upto the base of deep-rooted cratonic lithosphere (200-250 km thick), the mode of its upward heat transport would change to slow conductive process. Hence, for detecting the presence of a possible heat anomaly under a craton, one needs deep geophysical probings (seismic tomographic images, long period Magnetotellurics and Controlled Source Seismology

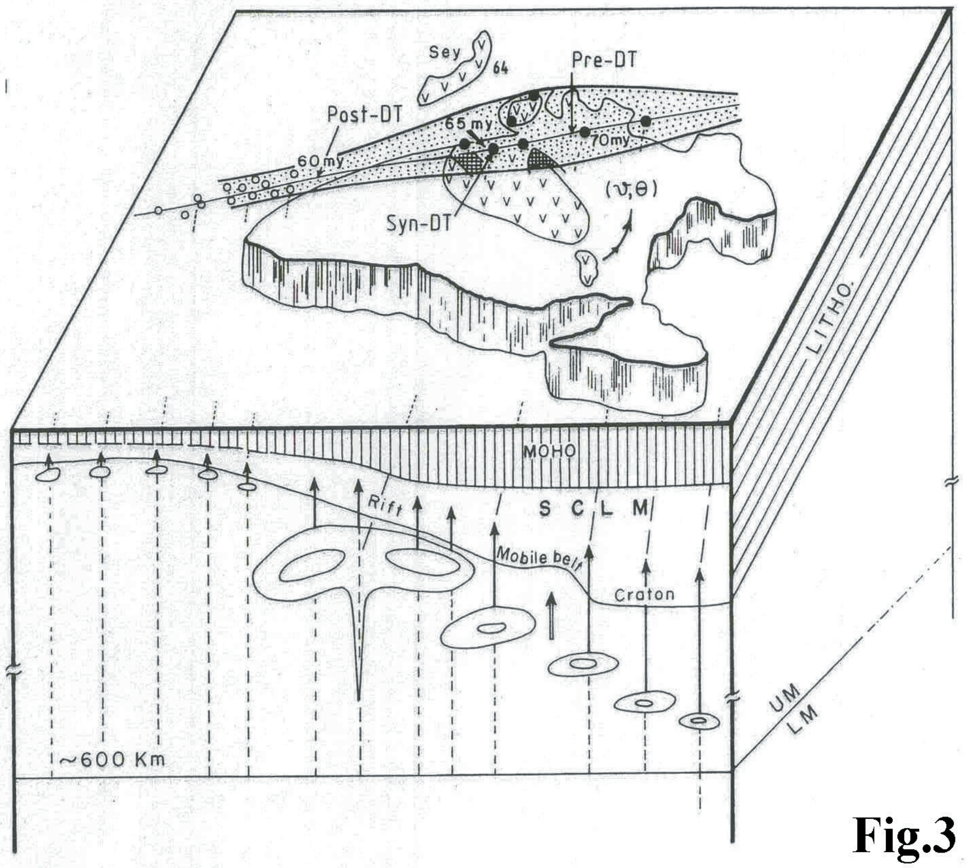

Figure 3. Bimodal dynamics due to interaction between India and Reunion plume. Indian lithosphere moving northward in a horizontal direction while the Reunion plume upwelling in the upper mantle is growing vertically (radially).

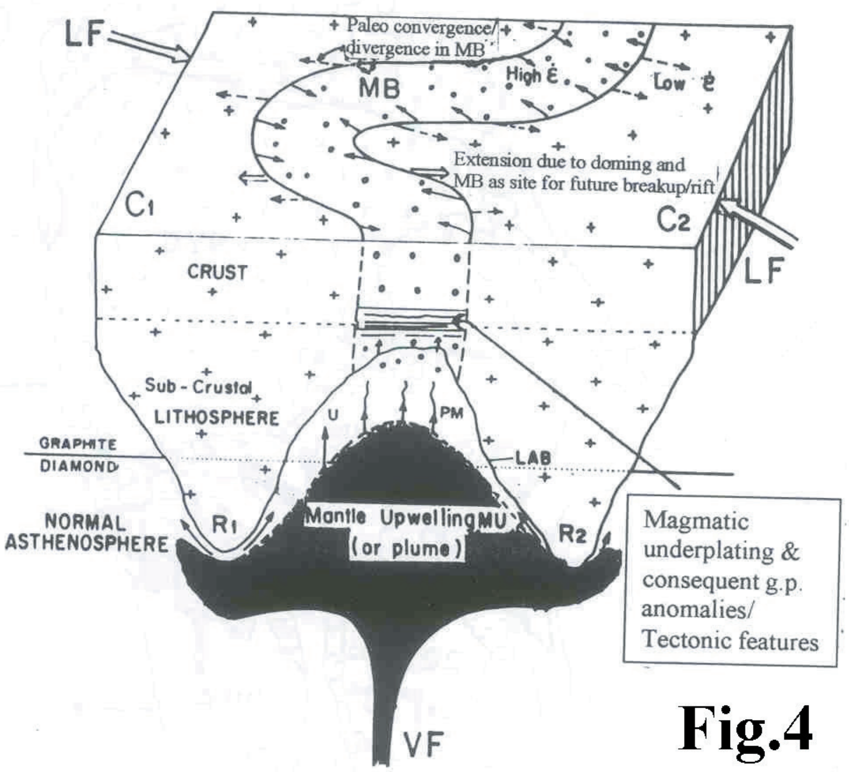

Figure 4 A cartoon depicting the interaction of an uprising mantle plume with continental lithosphere consisting of deep rooted cratons (C1&C2) juxtaposed/ sutured along a mobile belts (MB). MBs often have relatively weak rheology due to greater amount of heat and fluids present within them as a result of periodic reactivation. They represent a sort of rheological wave guides through which thermomechanical forces (lateral and vertical) can diffuse fast. Because of this, a channeling of tectonic, magmatic, metamorphic, metasomatic processes are noticeable along these belts.

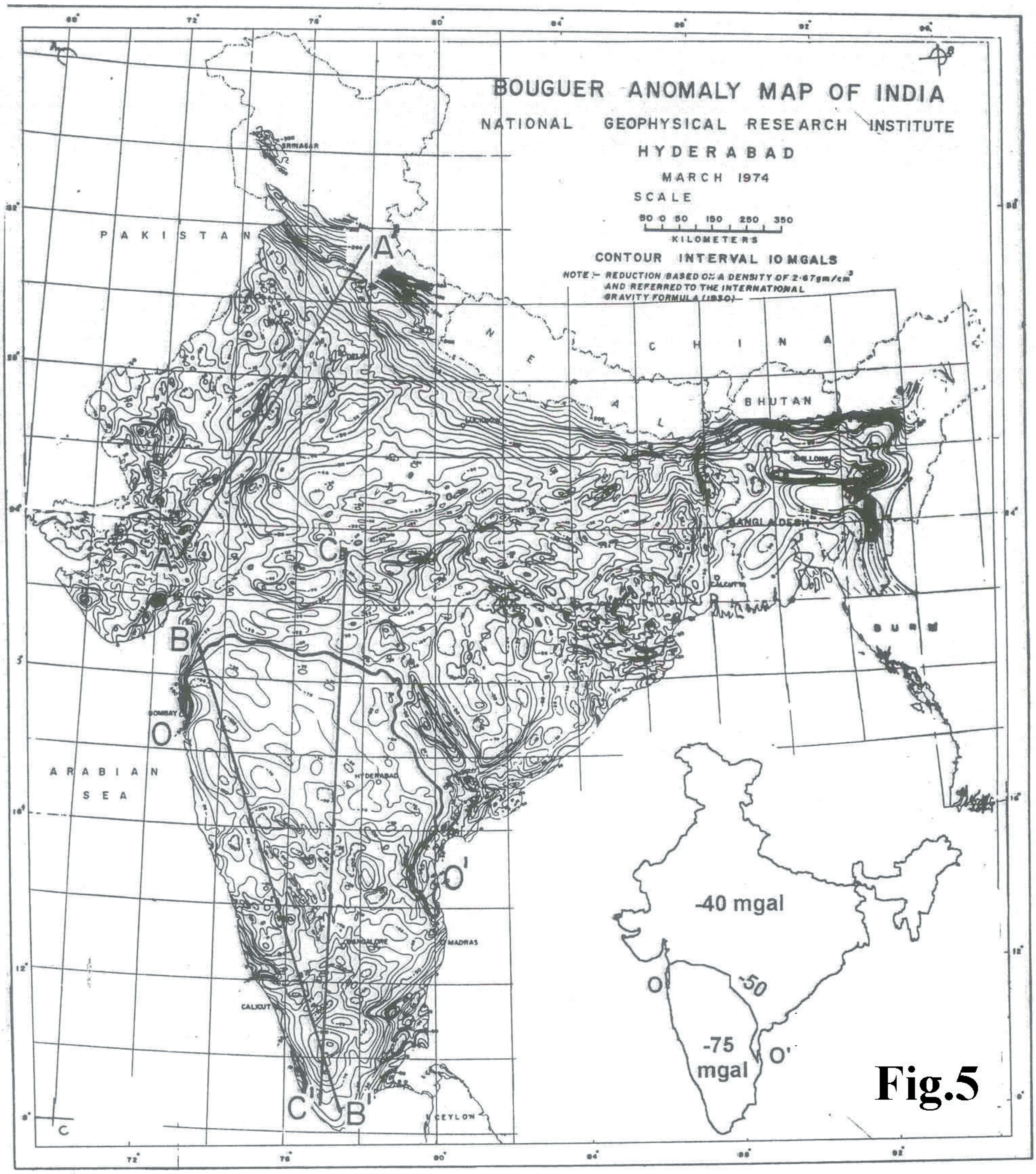

Figure 5. The Bouguer gravity anomalies over India shows relatively high (~ -40 mgal) over a –50 Mgal contour 00', south of 00' exhibits relative gravity low (~ -75 mgal) (NGRI, 1975; Raval, 1993a).

etc.). In this context, presence of low velocity zones under SIS (Srinagesh and Rai, 1996; Kennet and Widiyantoro, 1999) may be an indication of the thermal (or residual) anomaly (see Figure 6). The difference in heatflow of southern cratonized part and largely mobile part north of 001 (Figure 5) is seen in Figure 7.

Hot Mobile Belts (MBs): These are episodically reactivated paleo-orogenic (and/or paleo-rift) corridors, such that magmatic, metamorphic and metasomatic processes tend to channelise along them so that underlying crust and sub-crustal lithosphere (SCLM) are replenished periodically by volatiles and associated thermomagmatic and radiogenic elements, as reflected by the higher radioactive heat generation. In case of paleo-collisions, possibility of doubling of crust implies that crustal heat generation could be in principle, two times the normal crust. Both these factors make MBs as repositories of higher thermal energy.

Other factors that may add to higher heatflow along the MBs could be the Plume-induced magmatic underplating and/or advection, former is generally pronounced in the rift environments like Cambay, Narmada-Tapi-Son, etc.

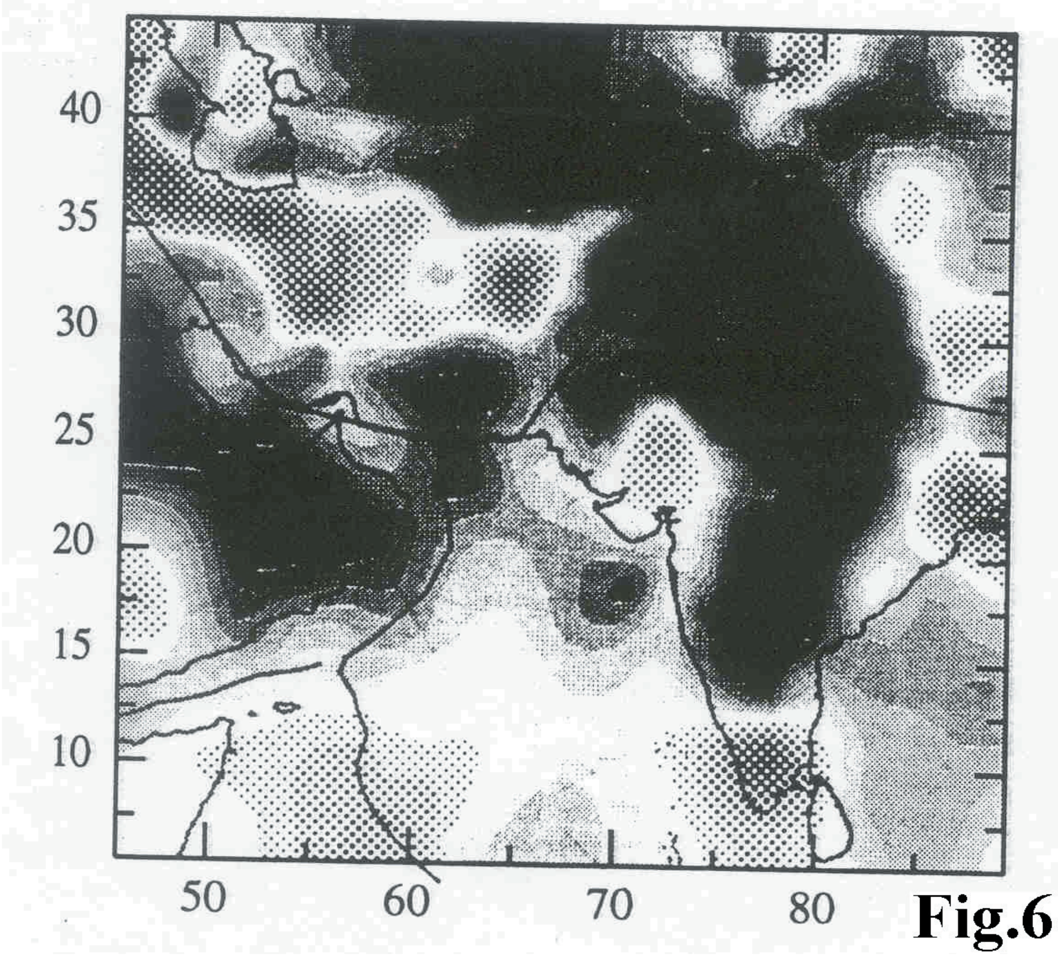

Fig.6

Figure 6. Tomographically derived seismic velocity residuals over the Indian subcontinent and adjoining regions. Circular patches of low velocity zones can be seen in the regions where outburst of thermal plumes (Reunion, Kerguelen & Marion on the western, eastern and southern regions respectively of the Indian subcontinent) took place (after kennet and Widiyantoro, 1999).

Fig.7

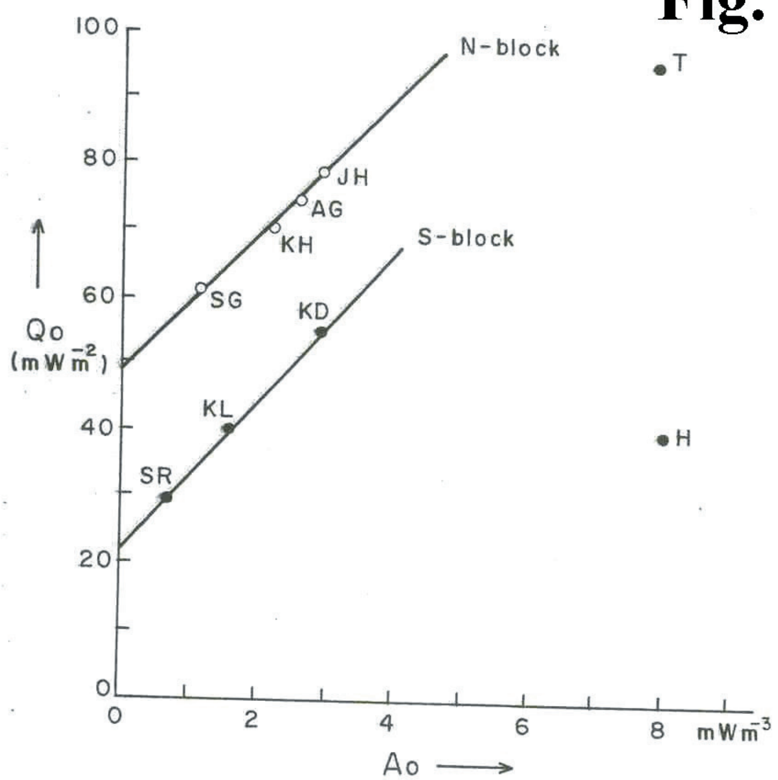

Figure 7 The surface heatflow (Q0) versus heat generation (A0) over the southern and northern blocks of Indian subcontinent. The two blocks approximately coincides with the either side of –50 mgal contour (OO' in Figure 5).

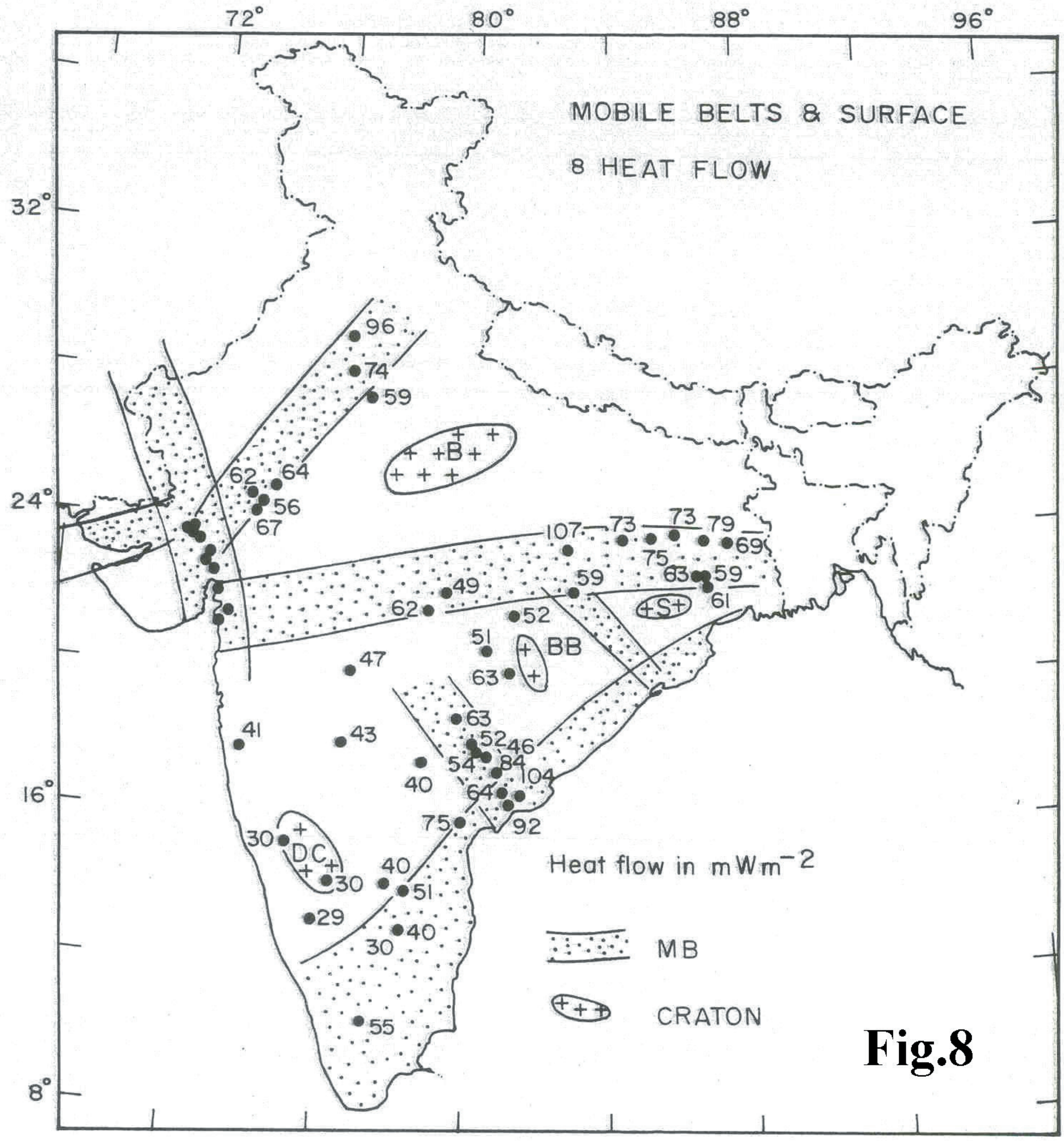

Figure 8 Surface heatflow values according to Roy and Rao (2000), the cratons and mobile belts are also plotted in this diagram. High heatflow values bias along the MBs can be seen clearly.

surface geological evidence could be absent, then deep geophysical structures may be the only means to detect the effects of plume. Such interactions require a careful examination of paleao-reconstructions also, for delineating the thermomagmatic effects of the paleo-plume activity. As outlined below above scenario, helps in understanding the development of surface geophysical observations and tectonic features.

Gravity field over India: Figures 5&9 depicts the BGA and axes of the major gravity highs (NGRI, 1975; Raval, 1993a; Raval and Veeraswamy, 1996) respectively, the latter coincides with MBs of the I-CL (Raval, 1995c). In Figure 5 a -50 mgl contour (001) is also seen which stretches from Mumbai to Chennai such that north of 001 the BGA is relatively high (-35 mgl), while south of 001, it is quite low (-75 mgal) except along the eastern and south-western margins. The high BGA would have developed at least partly, by the partitioning (or branching) of mantle upwelling (or TMF) during P-CL interactions and rifting (Figure 14).

From Figure 16 the Kerguelen and/or Crozet plumes would have caused the Sylhet/Raj-Mahal/Bengal-traps at ~117 Ma (Mahoney *et al*., 1983; Raval, 1989b; Curray and Munasinghe, 1991; Baksi, 1995). And since Kerguelen was a long-lived plume (Kent, 1991), it would have formed the node of a triple junction (Burke and Dewey, 1973) between greater India, Australia and Antarctica, results in breakup of greater India from Antarctica along the eastern margin of India (or EGMB). At ~90 Ma the Marion Plume affected greater India (or Central Gondwanaland) resulting in large scale magmatism over Madagascar and breakup latter from greater India (Mahoney *et al*., 1991; Raval and Veeraswamy, 1991). The dykes along south-western margin i.e. Kerala coast (Radhakrishna *et al*., 1994, 1999),

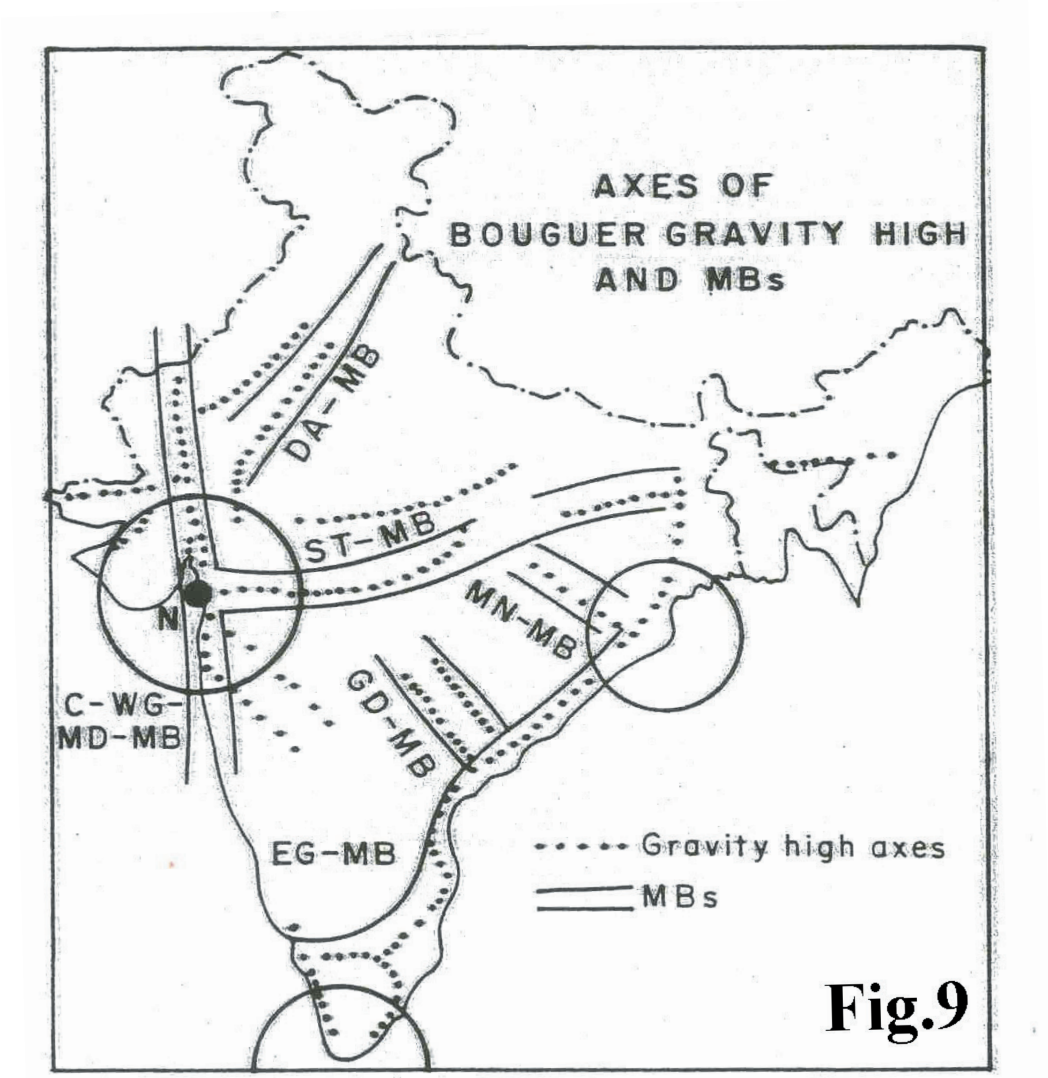

Figure 9. The figure depicts major gravity high axis and which clearly overlaps with the mobile belts (Raval and Veeraswamy, 2000b).

St. Mary's Island (Subba Rao, 1988) and mafic dykes (Anil Kumar *et al*., 1988) near Bangalore, have been dated at ~90 Ma by Ar/Ar method. Similar ages have been estimated for the Cretaceous volcanism over Madagascar especially along its eastern margin (Storey *et al*., 1995). The TMF from the outburst and trace of the Reunion plume would have initially affected the north-western part of the subcontinent, particularly the mobile belts in the western Rajasthan and Gujarat regions e.g. like Jaisalmer-Mari arch, (Raval, 1989a; McCormick, 1991; Basu *et al*., 1993; Mahoney et al, 1996; Raval and Veeraswamy, 1996; Raval and Veeraswamy, 2000b) Cambay and Kutch rifts (Raval, 1989b; Courtillot *et al*., 2000), southern part of the Delhi-Aravalli belt (Tewari *et al*., 1991; Sivaraman and Raval, 1995), the Narmada-Son rift or Satpura corridor and the western margin (Raval, 1995b, Tewari *et al*., 2001). As seen in figure 12 anomalously high concentration of positive Bouguer gravity is evidenced over the regions most affected by plumes.

Crust-mantle interactions under MB facilitate magmatic underplating in the deep crust (Raval, 1989b, 1995a; Fyfe, 1993). After cooling, underplated material would have higher than normal density and seismic wave velocity, as evidenced by the high positive BGA and anomalous seismic velocity in the crust and upper mantle along the MBs (Kaila *et al*., 1990; Singh and Meissner, 1995; Tewari *et al*., 1997; Vijaykumar and Rai, 2000) as shown in Figure 17. From figs. 4&13 it may be seen that north of 001 more number of mobile belts exist, for example DAMB, Narmada-Son-Tapi (or STMB), Cambay, Kutch, Mahanadi, Damodar, etc. And since MBs facilitate magmatic underplating, higher BGA is expected north of 001. However, south of 001, the terrain consists of Western Dharwar craton (a thick cold lithosphere 180-250 km), late Archaean eastern Dharwar mobile belt (EDMB), granulite terrains of late Archaean (2600 Ma) and Neoproterozoic (550 Ma) episodes. However, since these MBs seem to have been substantially cratonized and would have relatively thicker lithosphere, the crust-lithosphere column, the region south of 001 would have been affected much less by the later thermal (or plume) activity except the mobile corridors along the margins.

In case of Reunion (Ru) Plume, two major thermomagmatic pulses have occurred one near Cambay (at ~65 Ma) resulting in ~80% outpouring of the Deccan flood basalt (Courtillot *et al*., 2000), and second in the offshore near Mangalore (~130 N) at ~60Ma, resulting in Laccadive-Maladive island chains. Due to cratons and

(Figure 8). During plume upwelling melting occurs due to release of pressure under thinner lithosphere below MBs. The partial melting is enhanced further by relatively warm and hydrous nature of MBs. Hence, in case of flood basaltic eruptions, the MBs probably form major corridors of large- scale magmatism (a significant part of which is intrusion/underplated). For example, Cambay rift, Western margin, Narmada-Tapi-Son, etc., for the case of Deccan volcanic province (DVP) as corroborated by the axes of gravity highs (Figure 9). The flood basalt outpouring from these corridors covered the adjoining cratonic regions following the topography existing then. Further, the junctions of mobile trends, would be still weaker and to allow greater heat and mass transfer; Tusham/ Sonapat, Tharad, Cambay, Parasia, Tatapani, Jharia, Chintalpudi, Agnigundala, etc. appear to represent such junctions (Figure 10). This is supported by the distribution of hotsprings along the MBs following in the zones of influence of plume (Figure 11).

Since lithospheric thickness is much less (Cambay/ Western margin) under the first order MBs, heat from base of the lithosphere (or LAB) might also reach the surface in some situations. This may be an additional reason for higher 'mantle heatflow' reported recently by the NGRI geothermal group (Rao and Srinivasan, 2000) for the SGT. The LAB under this region would have been heated during plume pulses and breakups and 'residual' heat might reach the surface. Replenishment (or enrichment) of SCLM beneath MBs may also contribute to 'higher mantle heatflow' in the SGT. Thus, factors for higher heatflow in a MB regime are: (i) greater radioactive heat generation caused by episodic replenishment of crust-lithospheric regime, and doubling of crust, (ii) advection and magmatic underplating and/or (iii) heatflow from the asthenosphere provided LAB is at shallower depth.

On the other hand, the deep-rooted refractory cratons remain mostly undisturbed. If the base of the craton, often below the 'graphite-diamond stability' boundary, contains the primitive diamonds then the plume-triggered kimberlite magma uprising from still deeper parts (Gurney, 1990) may carry these diamonds and deposit them near the craton mobile-belt boundary; the latter often manifests as sedimentary basins. For instance, interfaces between - Dharwar and Cuddapah, Bhandara and Chhattisgarh; Aravalli-Bundelkhand and Vindhyan, Chhota Nagpur/Singbhum and Jharia. All these regions, except Jharia have kimberlites emplaced at ~1100 Ma (Anil Kumar *et al*., 1993) i.e. around accretion of the Rodinian supercontinent (Meert and McPowell, 2001). The Jharia lamprophyre is of early Cretaceous age i.e. coeval with the Kerguelen/Crozet plume activity (Anil Kumar *et al*., 2001b).

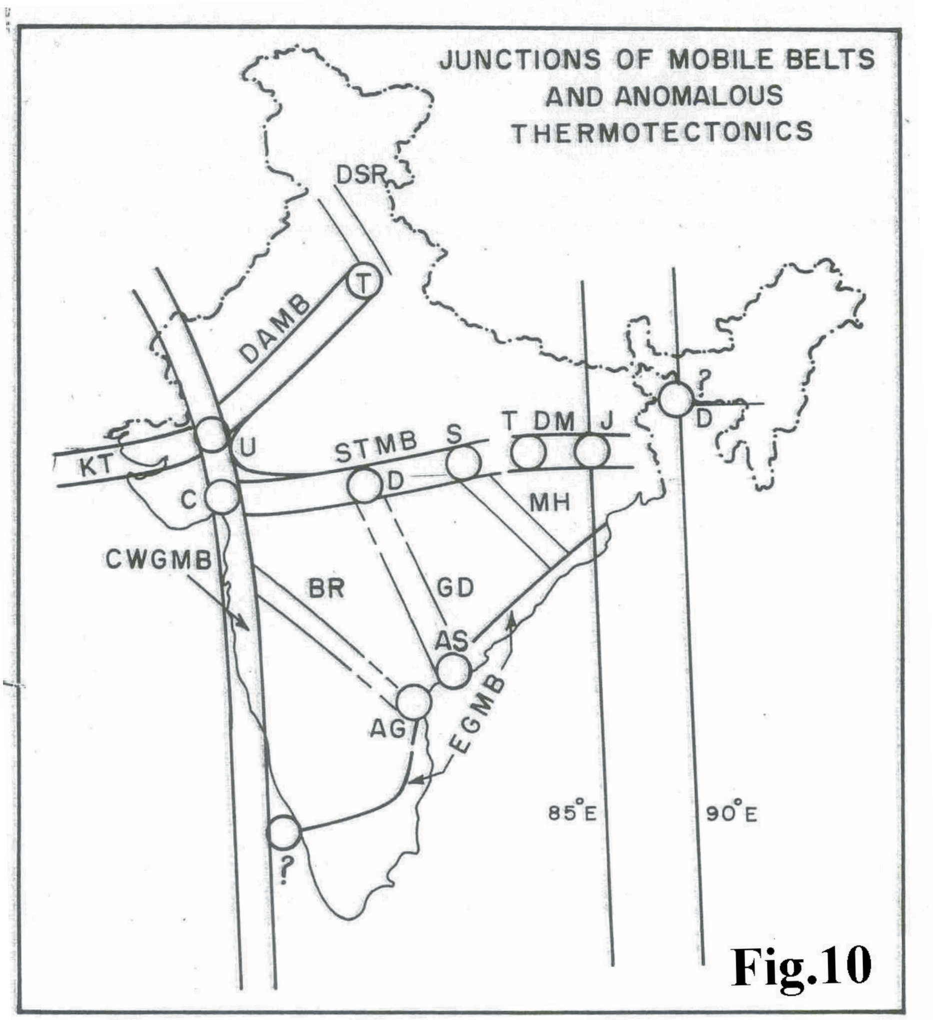

Figure 10. Zones (junctions) where the major mobile trends meet. Higher heat and mass transfer (hydrothermal activity) is expected and evidenced.

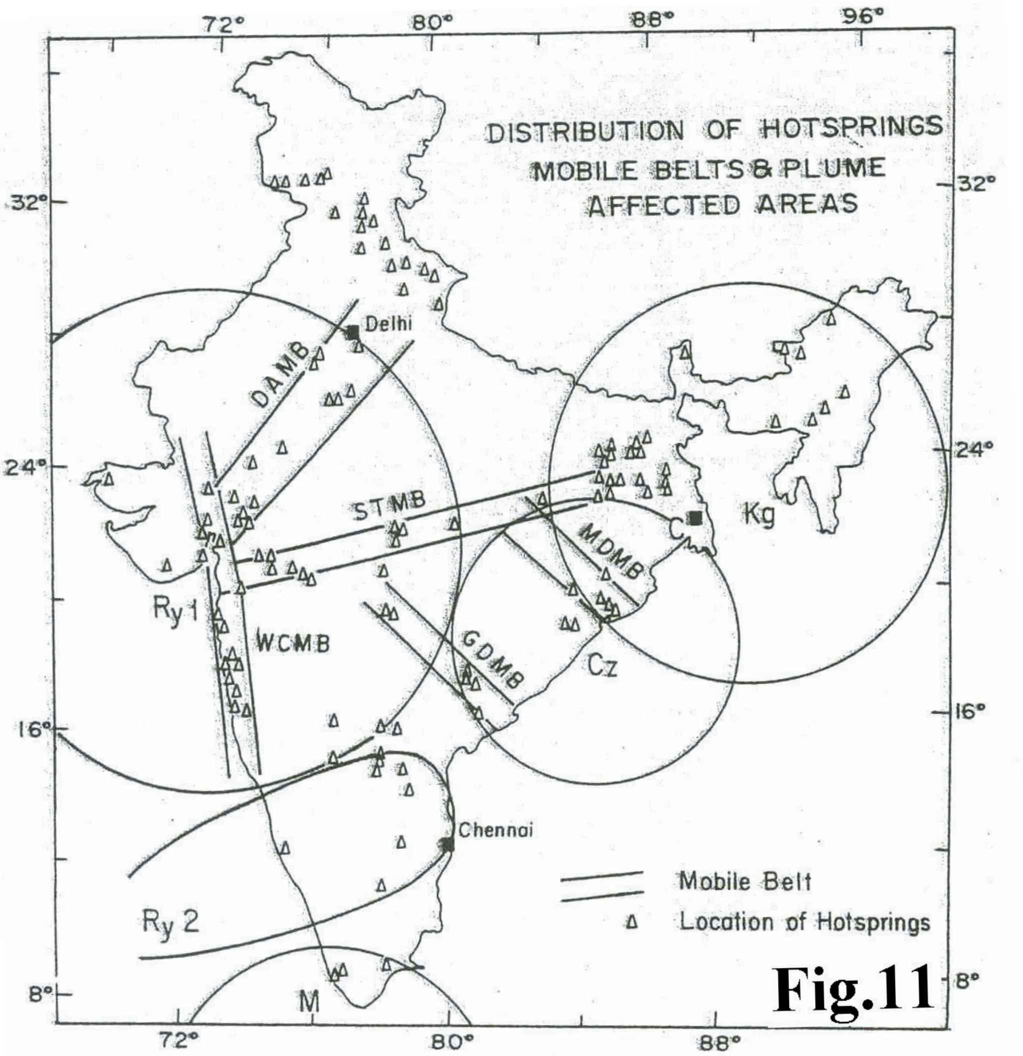

Figure 11. Distribution of hotsprings with plume affected regions. Concentration of hotsprings along the mobile belts indicates the channeling of TMF due to plume-CL interaction.

Channelling and Partitioning of Thermomagmatic Activity (TMA): Owing to their characteristics, the MBs facilitate both upward and lateral channelling of TMA resulting in a lateral network of TMA at the base of CL (Raval, 1989; Ebinger and Sleep, 1998). Hence, greater interaction (heat and mass transfer) exists between plume(s) and the MB(s) and manifest an unusually large concentration of tectonics and geophysical anomalies along MBs (Figure 12). Because of large vertical and lateral flow along MB a partioning/branching of TMA may take place near the junctions of MBs. Another channelling of much significance is governed by permeable MBs along which TMA is conducted quite fast, and relatively impenetrable cratons which resists the flow of TMA. A clear reflection of this process can be seen along the trace of the Reunion Plume (Raval, 1993). It implies that MBs (paleoconvergences) are not only repositories of the plate boundary processes but are also the focus of mantle plume activities (Figure 13). Alternatively, evolution/dynamics of the MBs is governed by a mixed mode process (i.e. both plate as well as plume type convection). Now, these MBs may be graded as of different order depending upon the time elapsed since last reactivation (or cratonization). Obviously, higher order MBs would get less disturbed and/or more cratonized e.g. late Archaean eastern Dharwar mobile belt (EDMB) in the southern shield (Radhakrishna, 1994). It means TMF from an upwelling plume-head would mostly enter the MB-type lithosphere (see Figure 4) which facilitates (or channelises) the TMF like a 'waveguide' (Raval, 1990). Large scale channelling of TMF along transcontinental MBs may in turn, influence the rheology of the overlying crust-lithosphere and allow migration of omagmatic activity to large lateral distances (Sleep, 1990; Ebinger and Sleep, 1998).

Continental breakups and failed rifts

Episodic rejuvenations of a MB would make it gradually weaker. Such a MB when passes over an upwelling mantle (or plume), the continental breakup may nucleate along the MB. Thus, two of the conditions for breakup of a supercontinent are: (a) the transcontinental MBs may have become sufficiently weakened, and (b) the underlying (plume) upwelling is intense and/or long-lived. A combination of MB and Plume could therefore become fatal for the super-continental stability (Raval, 1999b). As described earlier, it seems to be case with regard to three breakups of India since the early cretaceous. This is important because in the classical plate tectonics, it is

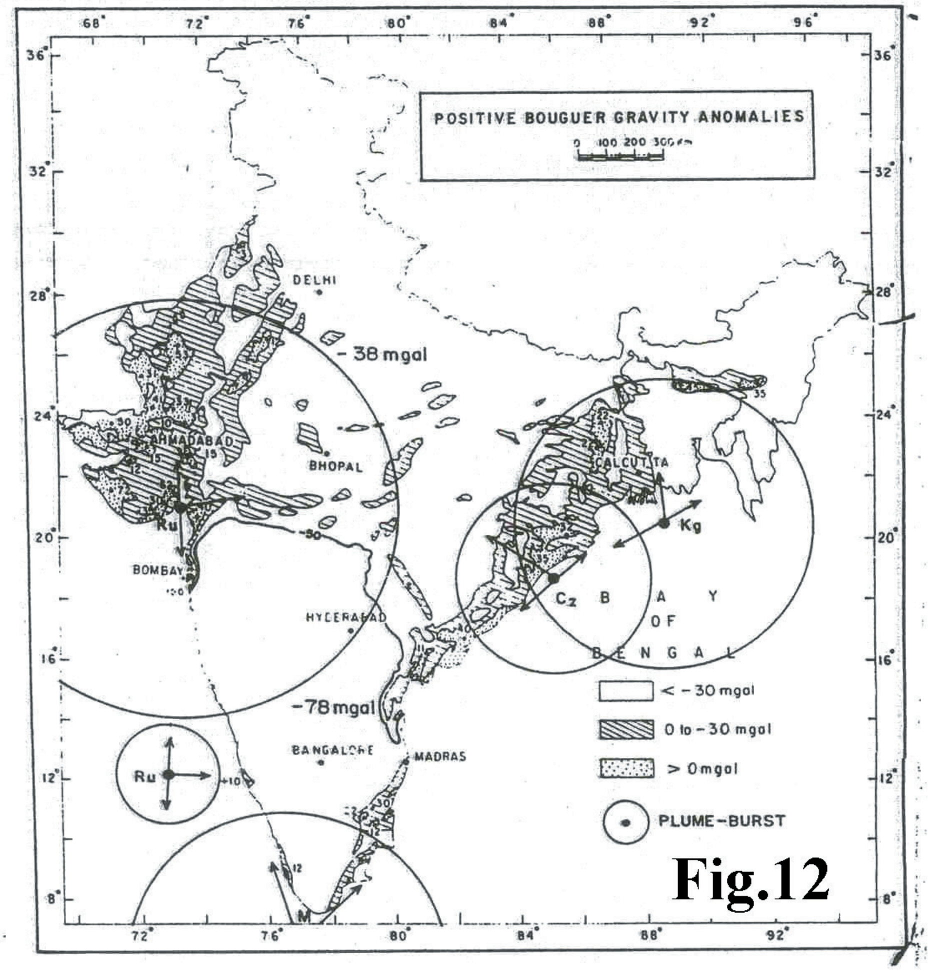

Figure 12. The plume affected regions show consequently Bouguer gravity highs.

not clear how and where a supercontinent breaks, and as seen here conjunction of weakened MBs and an intense mantle Plume could characterize the spatial localization of break-up process (Raval and Veeraswamy, 2001a). Further, MBs are transcontinental (or trans-lithospheric) and facilitate large-scale lateral channeling of TMF, which is corroborated by the coevality of major thermomagmatic events over widely separated MBs; on different continental blocks. For example, the lateral spread of (a) Pan African activity along Mozambique belt (Kroner *et al.*, 2001), Madagascar (Basairie, 1967), Seychelles (Tucker *et al.*, 2001), Western Rajasthan (Rathore *et al.*, 1991), Southern Granulite Terrain (Choudhary *et al.*, 1992) and Eastern Ghat Mobile belt (Mezger and Cosca, 1999) running probably upto Eastern Himalayan syntaxes. Similarly, the Karoo mantle plume activity is found to run up to Tasmania via Antarctica (Duncan *et al.*, 1997) on one side, and Mozambique, Madagascar, Seychelles and Western India on the northern side (Raval, 2001). As noted earlier, the failed Kutch rift may have formed during the northward lateral spread of the Karoo mantle plume activity during Jurassic (at ~180 Ma) along Mozambique-Somalia-Madagascar-Seychelles mobile corridors. The latter seem to be extending into Kutch and Western Rajasthan belts (e.g. Ambaji Devi belt; Deb, 2000) and DAMB. This is corroborated by (i) the Mesozoic basins and a complete sequence of Mesozoic sediments in both Kutch (Biswas, 1987) and Western Madagascar (Ashwal and Tucker, 1999), (ii) presence of volcanics, under Mesozoic sediments, in a deepwell (Lodhika) situated in the southern side of Kutch rift, and (iii) coevality of 550-880 Ma magmatism all along these corridors and possible presence of a paleoarc (Tucker *et al.*, 2001, Torsvik *et al.*, 2001). This rift (Kutch) would have again got remobilized by the thermal episode, which gave rise to Masirah island in Northwest Arabian sea (Peters and Mercolli, 1998); Reunion Plume activity (Raval, 2001), breakup of Seychelles (Norton and Sclater, 1979) and probably a bolide impact (Bhandari *et al.*, 1995). Thus, if an MB is not weak enough, the breakup would be aborted (a failed rift), examples are Cambay, Kutch, western part of the Narmada-Tapi, Godavari, Mahanadi and probably the Palghat-Cauvery trend.

It also emerges that combination of MBs and mantle plumes may become ‘fatal’ for the stability of a super-continent (Raval, 1999b). For example, between 130- 115 Ma India’s eastern margin would have been shaped by the interaction between Kerguelen/Crozet mantle plumes and Easternghat mobile belt (EGMB). Similarly, Marion plume and Madagascar/Seychelles-Western-margin mobile belt (M-WM-MB) seems to have led to the breakup of Madagascar from Greater India (at ~90); Agrawal *et al.* (1992) ascribe it to rifting of Dharwar craton. Further, the pre-breakup location of

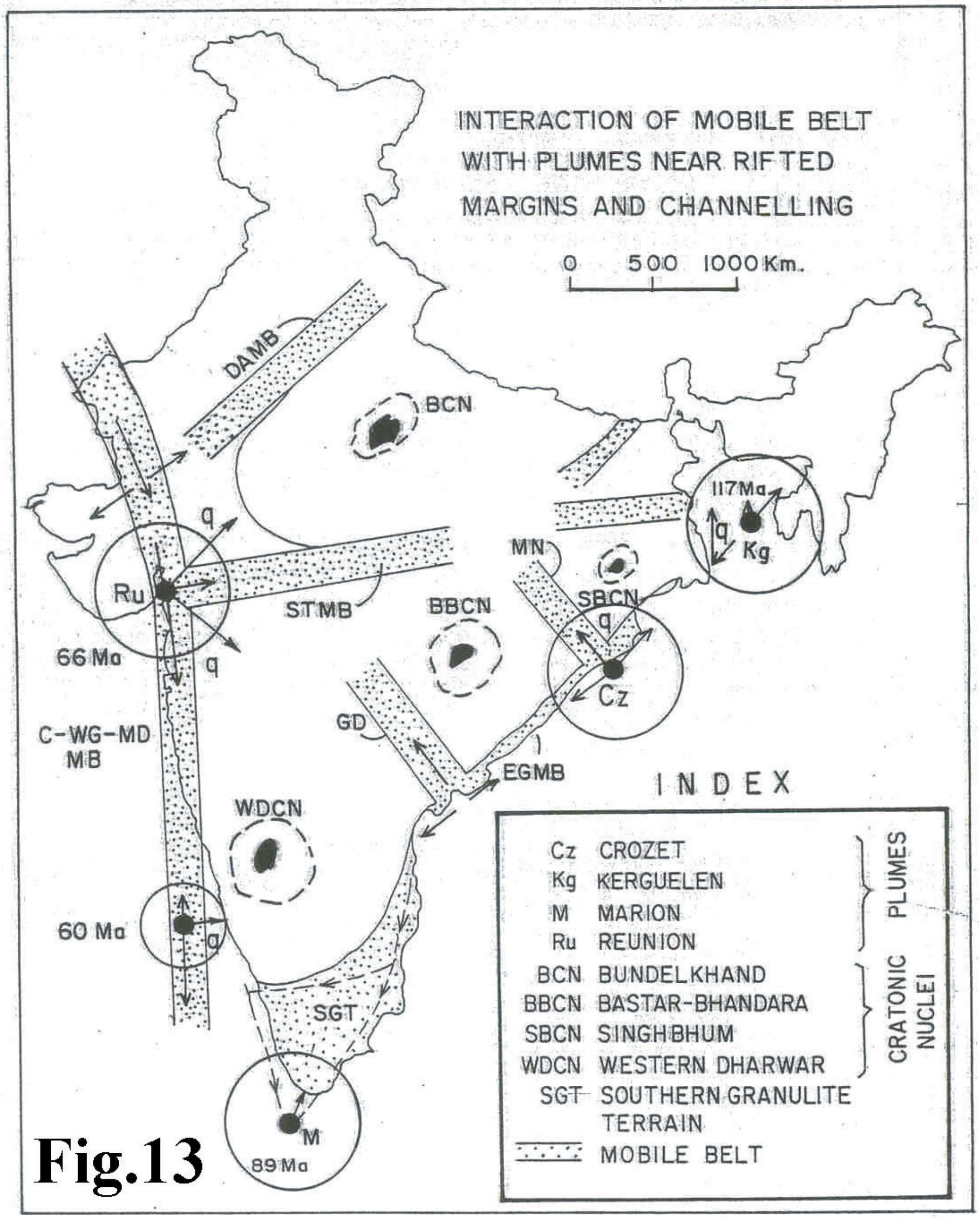

Figure 13. The mobile belts over Indian subcontinent and possible channeling of TMF along MBs due to plume CL interaction are shown. The associated cratons are also seen.

Seychelles is at the junction between DAMB, STMB and M-WM-MB. And it broke apart (at ~64 Ma) i.e. soon after the Reunion Plume burst (at ~65.5 Ma) as shown in Figure 14. MBs thus, seem to characterize the corridors along which the probability of continental breakup increases with each episode of tectonothermal reactivation, and eventually reached the breaking threshold if the thermal anomaly/or plume is intense enough/or longlived and/or MBs have been optimally weakened (Raval and Veeraswamy, 2001a).

RELATIVELY HIGH VELOCITY OF INDIAN PLATE

Northward movement of India since 80 Ma has been reconstructed from the palaeomagnetic study of basement and sedimentary rocks obtained from the 90° E ridge ODP Leg 121 sites 756-758 (Klootwijk *et al.*, 1992). The results indicate that the Indian Plate velocity reached very high values of 18-19.5 cm/yr during the Late Cretaceous and reduced to ~4.5 cm/yr after the India-Eurasia collision at ~55 Ma (with regard to site 758). It has also been suggested that the NW part of Greater India may have reached southern Asia around Cretaceous-Tertiary Boundary (KTB) which is indicative of a link between Deccan Traps and India-Asia convergence -a MOMO episode (Stein and Hofmann, 1994). Figure 15 shows the plate velocity since the Cretaceous (Besse and Courtillot, 1988). This northward flight (or supermobility) of the Indian Plate (covering ~9000 km in ~180 m.y.) has been attributed to thinning of the Indian lithosphere due to large frictional heat generated at the litho-asthenospheric boundary (Negi *et al.*, 1986). An alternative possibility could be an anomalously

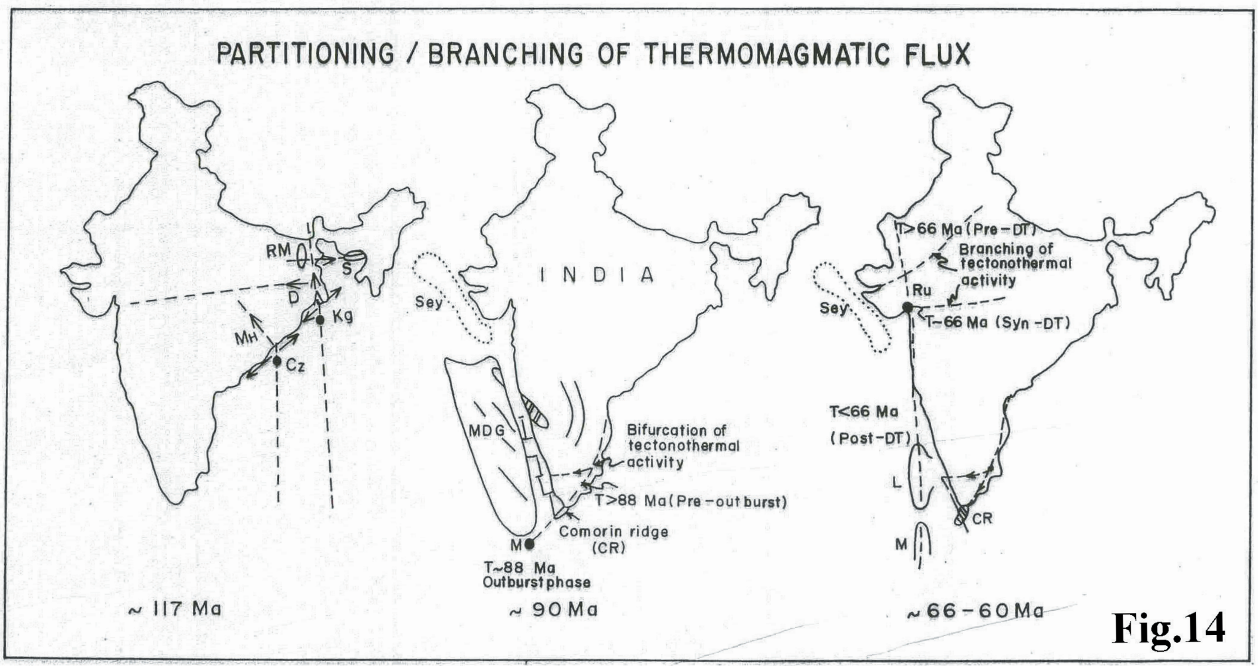

Figure 14. It shows the interaction of different mantle plumes with Indian continental lithosphere at ~115, ~90 and ~65 Ma. And it emphasizes the plausibility of branching (or partitioning) of thermomagmatic activity along preexisting weak trends (or MBs).

Fig.15

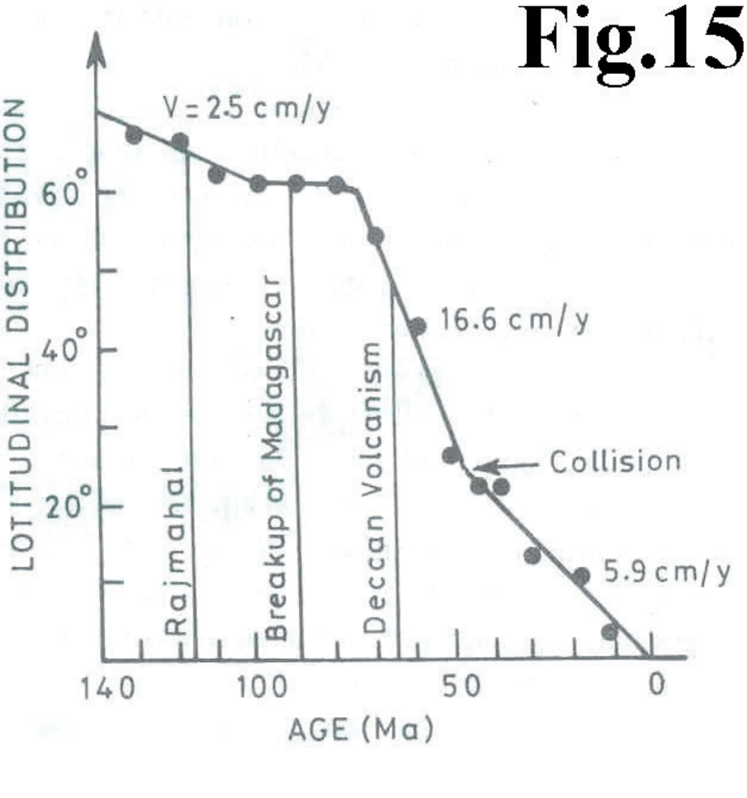

Figure 15. About 3-4 mantle plumes seem to have affected the Indian lithosphere (between 120-60 m.y.). This makes the underlying asthenosphere anomoulsly heat and results high temperature reduces viscosity and resistance to plate movement. This may be a cause for the analysis of high velocity (15-19 cm/cm) of the Indian lithosphere between 90-45 Ma where cratonic events drastically reduce the velocity.

hot asthenosphere, due to mantle plumes (Raval, 1993). It could be envisaged that during the Cretaceous-Tertiary time (130-60 Ma) presence of 3-4 mantle plumes in the asthenosphere underlying the Indian lithosphere would make the upper mantle anomalously warm. As temperature of plume may be ~100-300° above that of the normal mantle, temperature of mantle surrounding the hot plume-head would rise which in turn, would significantly reduce the drag resistance and viscosity. This facilitates faster plate movement.

GEOPHYSICAL CONSEQUENCES OF P-CL INTERACTION

In addition to geological signatures (e.g. CFBs, picrites, kimberlites, etc.) (Wilson, 1989), plume upwelling may modify the density, seismic velocity, electrical conductivity, thermal structure of the affected crust-lithospheric column (Raval, 1989b, 1995a). Hence, while examining the plume-CL interaction, the geophysical anomalies also need to be assessed carefully. Actually, mantle (or plume) upwelling may not be able to penetrate the cratonic CL and hence

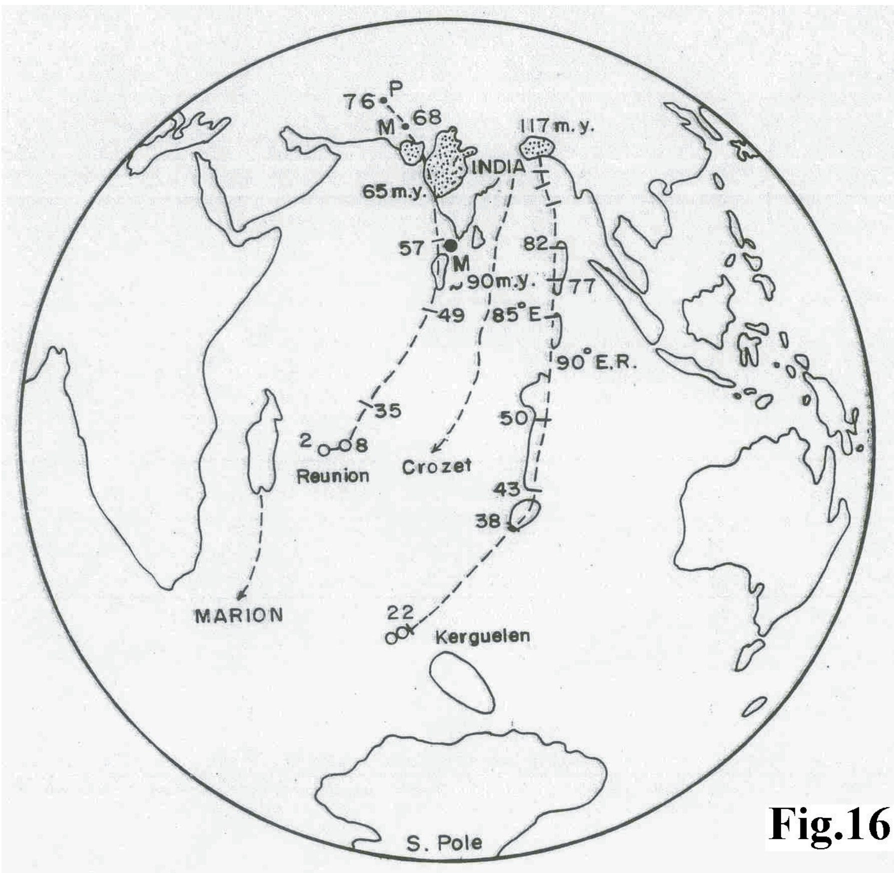

Figure 16. Oceanic traces of Reunion (R), Marion (M), Crozet (C) and Keruguelen plumes (KP) along the 900E, 850E ridges and Nikitin, Alphanzie and Laccadive Chagos seamounts are observed in Bay of Bengal.

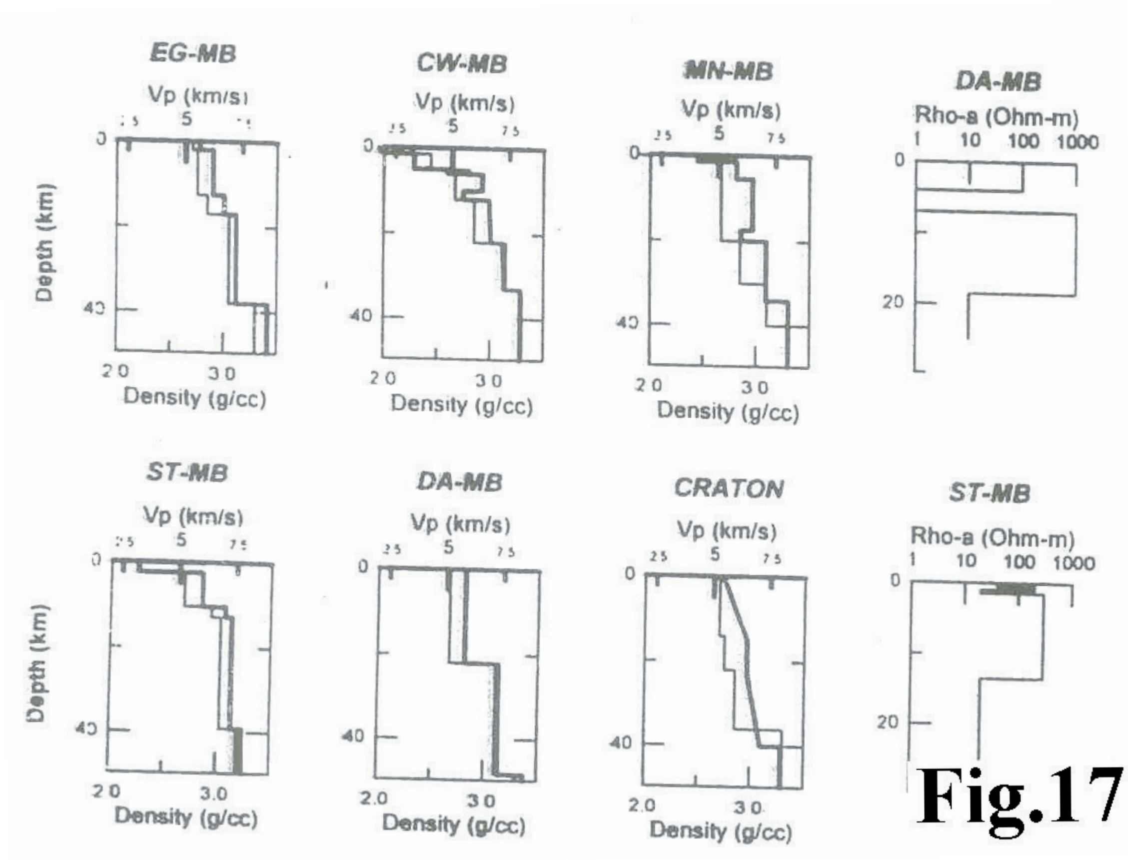

Figure 17. The figure shows the velocity, density and conductivity distribution beneath different mobile belts (EGMB, CWMB, MNNB, DAMB, STMB and Dharwar craton).

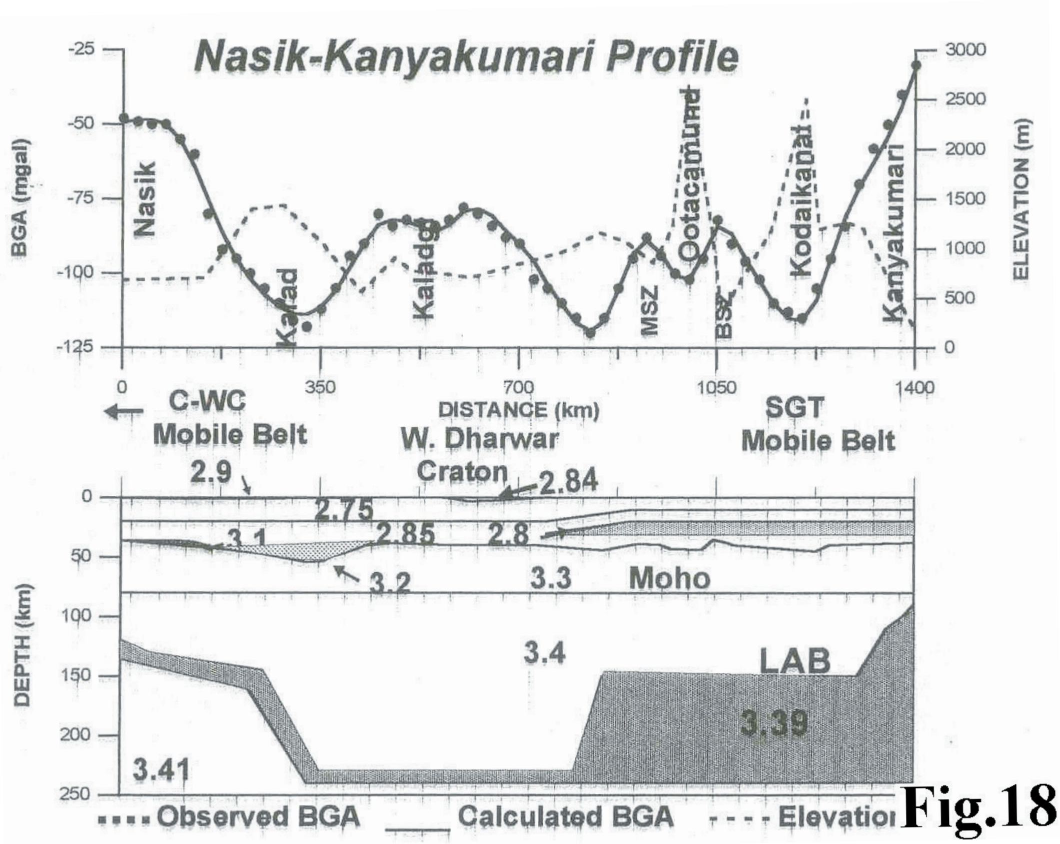

Figure 18. The figure shows in the (upper part), the boundary namely and elevation along a profile which rises from Satpura mobile belt in the North to Southern part of the subcontinent. The lower part shows the possible density model which fits the Bouguer gravity anomaly profile. It depicts a low density region under the litho-asthenospheric boundary (LAB) which may be responsible for the buoyancy of the South Indian Shield. (b) The diagram is adopted from Kennet and Widiyantoro (1999) and show LVZ at the upper mantle depth (or near LAB) beneath the regions affected by the Reunion and Marion Plumes.

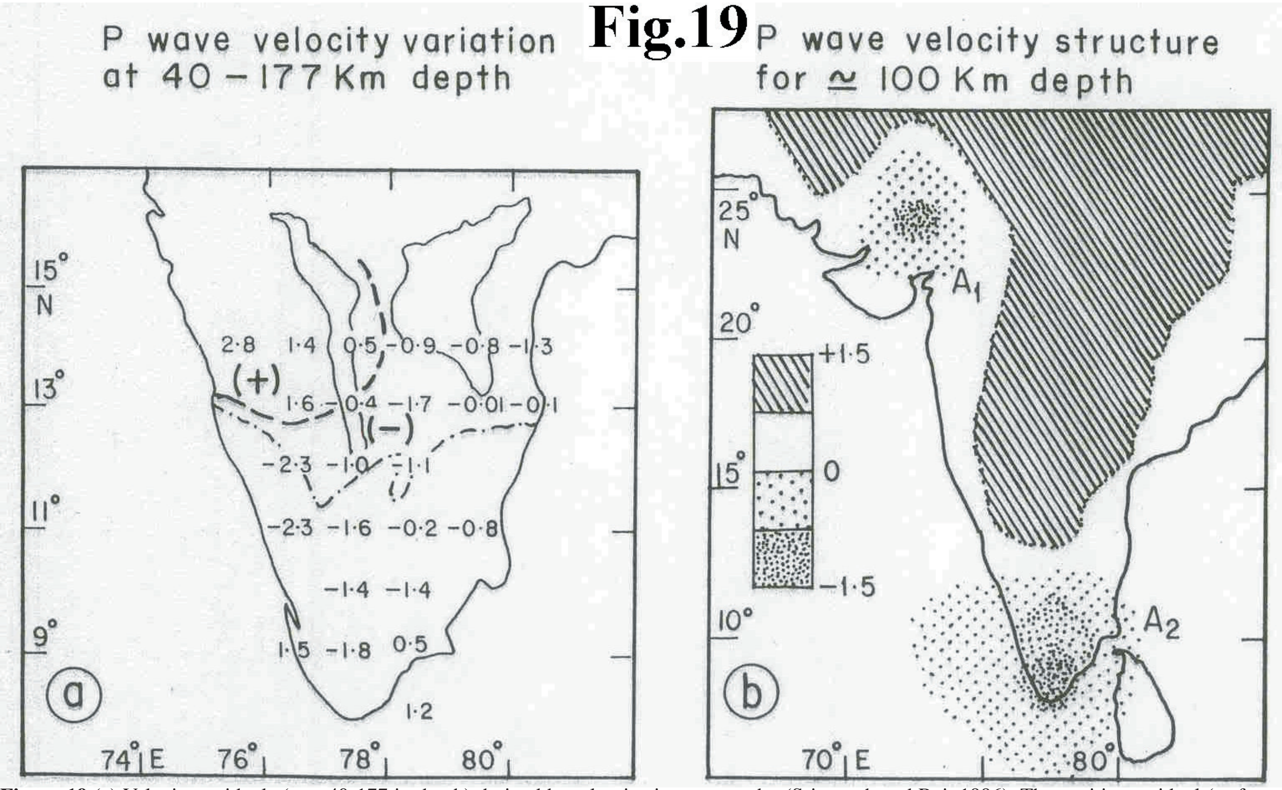

Figure 19 (a) Velocity residuals (at ~ 40-177 in depth) derived by teleseismic tomography (Srinagesh and Rai, 1996). The positive residual (or faster velocity) are inferred beneath Western Dharwar Craton with negative residuals (or slower speed) evidenced under the relatively mobile regions of eastward Dharwar and southern granulite terrain. (b) The diagram is adopted from Kennet and Widiyantoro (1999) and show LVZ at the upper mantle depth (or near LAB) beneath the regions affected by the Reunion and Marion Plumes.

mobile belts of the south Indian shield (SIS), the lateral spread of TMF from these pulses would be partitioned with dominant part channelising along MBs like Cambay trend and its NW and southern extensions, Kutch, Delhi-Aravali, Western margin, NS-L, and probably along Moyer, Bhavani and Palghat shear zones etc.; while another part may lie beneath thick cratons (see Figure 13). This thermal anomaly, until it gets dissipated, may reduce density and contribute to the observed gravity low and uplifts of plateaus like Deccan (~65 Ma pulse) and Karnataka (~60 Ma pulse) and Nilgiri hill, etc. All these points are taken into account while modeling the BGA along a profile from STMB to Trivandrum (Figure 18). The subtle interface exists between the Deccan (DP) and Karnataka (KP) plateaus at ~14.50N possibly due to difference in the space-time positioning of ~65 Ma and ~60 Ma pulses and their interaction with northern and southern parts of Dharwar craton (Raval, 2000a). The outburst of the Marion plume (at ~90 Ma) in the vicinity of the south-western corner of the subcontinent would have similar effect. Analogously, the traces and outbursts of Kerguelen/ Crozet hotspots would have channeled along the Gondwana grabens viz. Bengal Basin (Mall *et al*., 1999), Damodar (Anil Kumar, 2001b), Mahanadi-Lambert (Mishra, *et al*., 1999), Godavari (Prakasam and Rai, 1998; Acharya, 2000) and contributed to the uplifts of intervening cratonic areas viz., Meghalaya-Mikir, Chhota Nagpur, Singbhum, Bastar, etc.

While eastern and western continental margins exhibit gravity highs (Figure 5) the inner parts of SIS exhibit significantly low BGA (~ -130 mgal). The latter is attributable to superposition of: (i) thicker continental crust-lithosphere, (ii) relatively lower density of crust including granitic emplacements; and (iii) thermally-induced low density near LAB due to riftings (at ~130, 90 and 64 Ma) and plume activities (~ 90, 65 and 60 Ma). Last one is supported by the low velocity zone inferred in the upper mantle (Figure 19) from the seismic tomographic images (Srinagesh & Rai, 1996, Kennet and Widiyantoro, 1999). Velocity residuals in Figure 19 may be due to variation in the depth of LAB i.e. deeper beneath Western Dharwar Craton and shallower under Eastern Dharwar and SGT.

From above the space-time positioning of breakups and the Marion/ Reunion plumes activity may contribute to:-

(a) the west-to-east tilt and/or drainage pattern of SIS; because thermal effects of the thermal pulses along the western margin, will decrease eastward. Further, breakup along east coast was ~50 m.y. earlier than along western coast hence relative greater cooling and subsidence along eastern margin which has implication on seawater cover over the eastern margin and resources,

(b) interface between the Deccan (DP) and Karnataka (KP) plateaus (at ~150 N), it may be interesting to examine how Cuddapah basin would have been affected by these two uplifts (Raval, 2000a),

(c) change in the trends of differential uplifts (from NW-SE over DP to NE-SW over KP),

(d) the drainage divide across the Mangalore- Bangalore- Chennai corridor (Subrahmanya, 1994); which passes through (or very close to the core or thickest part) of the western Dharwar craton, hence eastward migrating TMF of the Reunion plume pulse (~60 Ma) is likely to spread across this line due to variation in lithospheric thickness,

(e) development (or reactivation) of certain NE-SW lineaments (Grady, 1971; Katz, 1978; Radhakrishna, 1989) parallel to Fermor line, and

(f) the Palghat morphological gap, as a thermomechanical response of the crust-lithospheric heterogeneity, to thermal influxing, near the junction between the northern and southern parts of the granulite terrains having different thermotectonic histories (and hence rheologies). For instance, while the Pan-African activity remobilized the southern part of the granulite terrain (of 550 Ma event) along with adjoining Madagascar, the more cratonized late Archaean terrain (i.e. northern part of granulite terrain of ~2600 Ma event) seem to have remained generally unaffected.

TECTONIC FEATURES AND PLUMES

Uplifts: Many horsts, plateaus and/or hills etc. (see Figure 20) exist over the subcontinent. To sustain these high topographies over geological time, support is necessary at depth. But they occur over both northern as well as southern parts of the subcontinent, which in turn, exhibit high and low BGA respectively and may characterize different mechanisms. Since north of 001 BGA is high, support for the uplifts (e.g. Delhi- Aravalli, Saurashtra, Satpura, Meghalaya, northern part of Westernghat, Easternghat and SE & SW corners of peninsula) seems to be provided by high density underplated material. On the otherhand, very low BGA over the southern shield requires that the uplifts south of 001 (viz. Deccan/ Karnataka plateau, Palani-Cardmum hills, etc.) could have been caused by (i) larger thickness of crust (ii) relatively less dense crustal rocks and/or (iii) thermally (or plume) induced lower density near base of the lithosphere (Figure 18). In context of (iii) it is pertinent that uplift of south African shield has also been attributed to presence of a plume (Artyushkov and Hoffman, 1998). Thus, morphotectonic uplifts across 001 appear to be held by two different types of supports (Raval & Veeraswamy, 2001b). This is important in understanding developments of continental margins e.g. along the eastern margin of India, MBs like Easternghat, Godavari, Mahanadi, Bengal basin and Singbhum, Bastar and Eastern Dharwar cratons occur. During the breakup and attendant plume activity the thermotectonic responses of these cratons and MBs would differ and would be reflected by the difference in the morphotectonics (Figure 21). Similarly, on the western side there exists Delhi-Aravalli fold belt, Narmada-Tapti (or STMB), Western Dharwar craton, major shear zones (like Moyer, Bhavani, Palghat) and southern granulite mobile belt (SGMB). While analyzing the variability of the thermotectonic development of a rifted margin (divergent boundary) and continent-continent collision (convergent) boundary (Raval, 1999b) it may be pertinent to take into account the distribution of cratons and MBs along these divergence/convergent corridors.

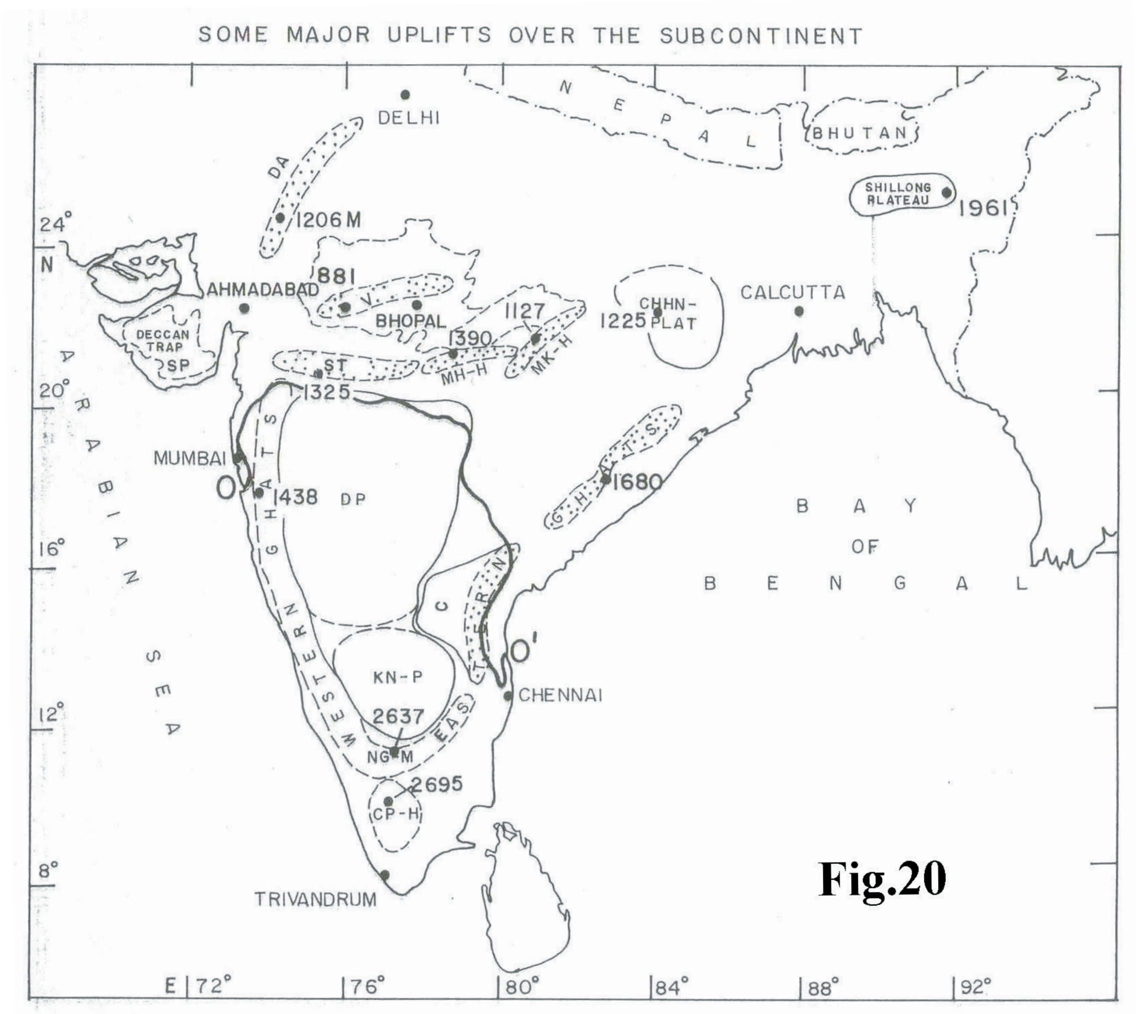

Figure 20. Uplifts over the subcontinent and plume affected regions.

Thermal Picture: Earlier studies of surface heatflow over the subcontinent had concluded that : (i) the surface heatflow for the Indian shield is greater than other shields of the world (Rao and Jessop, 1975), and (ii) the moho-temp beneath the Indian shield is higher imply higher mantle heatflow (Singh and Negi, 1982). However, it was pointed out late that heatflow measurements need to be evaluated separately for the cratonic and MB zones (Raval, 1989b, 1990) and since above studies had combined heat flows over the Archaean cratons and Proterozoic MBs, their average became higher than that over other cratons of the world. Later shield regions were grouped into craton and MBs (Nyblade and Pollack, 1993; Gupta, 1993) and heatflow over the Indian craton was found close to that over other cratons of the world (Gupta and Yamano, 1995).

Figure 8 gives a more recent spatial distribution of heatflow due to Roy and Rao (2000). Earlier, an important heat zonation map has been given by Ravi Shanker (1988) that correlates well with the geology and tectonics. From figure 8 it is clear that the Archaean cratons (age > 2.7 m. y.) and late Archaean MBs (~2.5-2.7 Ma) exhibit low heatflow (30-40 mWm^{-2}), while higher values (©¯ 45- 70) for younger MBs (Cambay-Western margin, DAMB, STMB, Singhbhum MB and EGMB, etc.).

Difference in thermal nature of Northern and Southern DVP: As the heat transfer changes from convective to slower conductive mode, near the base of a thick craton, surface heatflow may not be able to detect a thermal anomaly even if it existed. This may be a reason why the southern DVP, which overlies the thick Dharwar cratonic lithosphere, exhibits normal shield like surface heatflow values of ~40-45 mwm^{-2} (Roy and Rao, 2000) despite two major plume pulses (at ~65, 60 Ma) and continental breakup along the western margin. However, in case of the northern DVP (containing MBs like Cambay, Kutch, NS-L and DAMB) the lithosphere would be relatively thinner under a thinner MB-lithosphere (~60- 120 km), the convective heat transfer may continue upto shallower depths and then become conductive, implying the possibility of mantle heat reaching to the surface. Hence heat of the Reunion Plume outburst and rifting along Cambay and southern DAMB may contribute to the observed higher heat flow (Figure 8). It is supported by the (i) Bouguer gravity high (Tewari *et al.*, 1991, 1997), (ii) high seismic velocity in the lower crust (Tewari *et al.*, 1991), and (iii) a low velocity in the uppermost mantle (d ~100 km) (Zielhus, 1993; Kennet and Widiyantoro, 1999). Strong lateral changes in physico-chemical properties and different modes of heat transfer (conductive/convective) due to variation in LAB depths across the craton-MB transition make the thermal

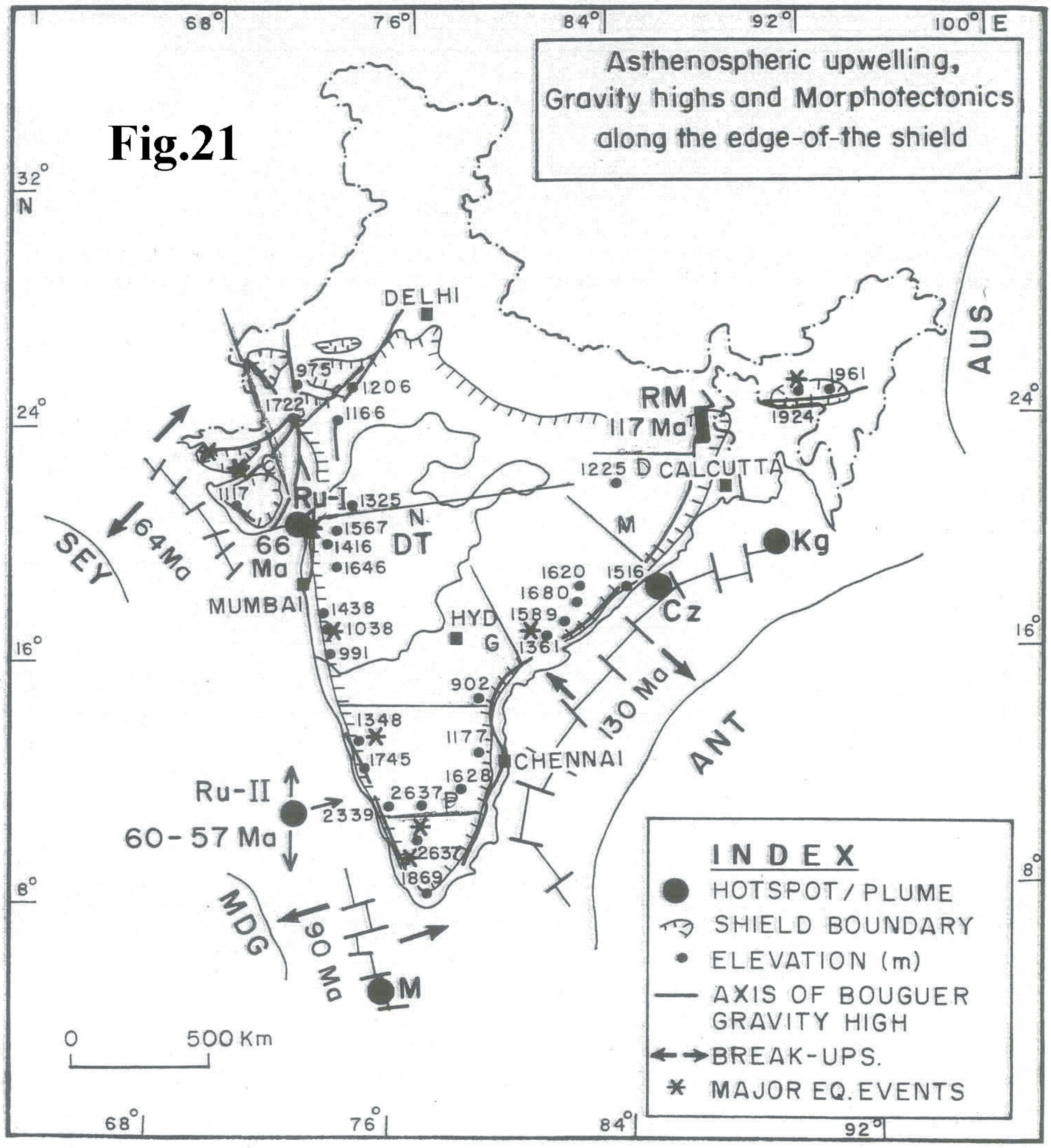

Figure 21 Continental margin of India experienced asthenospheric upwelling due to (a) continental rifting and (b) plume activity. The resulting P-CL interaction seems to have given rise to Morphotectonics along the edge of the Indian shield, depending upon whether the margin meets a craton or a MB.

blanketing by a the CL strongly heterogeneous (see figs.4&17). The latter is also reflected in concentration of seismic activity along such a transition (Thybo *et al*., 2000).

Higher mantle heatflow over SGT: A result of much significance has been obtained recently by the geothermal group of NGRI (Rao and Sreenivasan, 2000); according to which the 'mantle contribution' to the surface heatflow in the southern-most part of the shield SGT is higher than that over the low grade Dharwar Craton (DC). It is also found that the higher mantle heatflow (HM-HF) over SGT is more in its northern part (with respect to Palghat Cauvery Shear Zone - PCSZ) than to its south. It is proposed here that the higher mantle heatflow follows since SGT is a part of the mobile belt network. And for the difference in the mantle heatflow between northern and southern part of SGT, the geodynamical development of this region (since Cretaceous) need to be considered carefully. From Figure 22, it is seen that,

(a) for T>100 Ma, the Marion hotspot lay near the southeastward extension of the Godavari trend, and

(b) at ~90 Ma this hotspot was near the southernmost end of greater India (Storey *et al*., 1995). This may imply that during the northward drift of India between ~115- 89 Ma, first the eastern margin would have passed over the Marion plume, then the PCSZ and lastly the interface between Madagascar and India which is supported by all these paths exhibit relatively high BGA along these paths following P-CL Interaction.

The PCSZ almost divides the granulite terrain into two parts such that the northern one consist of a ~2600 Ma metamorphic event while its southern part has strong imprints of the ~550 Ma Pan African event, the latter is similar to that over Madagascar (Bessaire, 1967). As

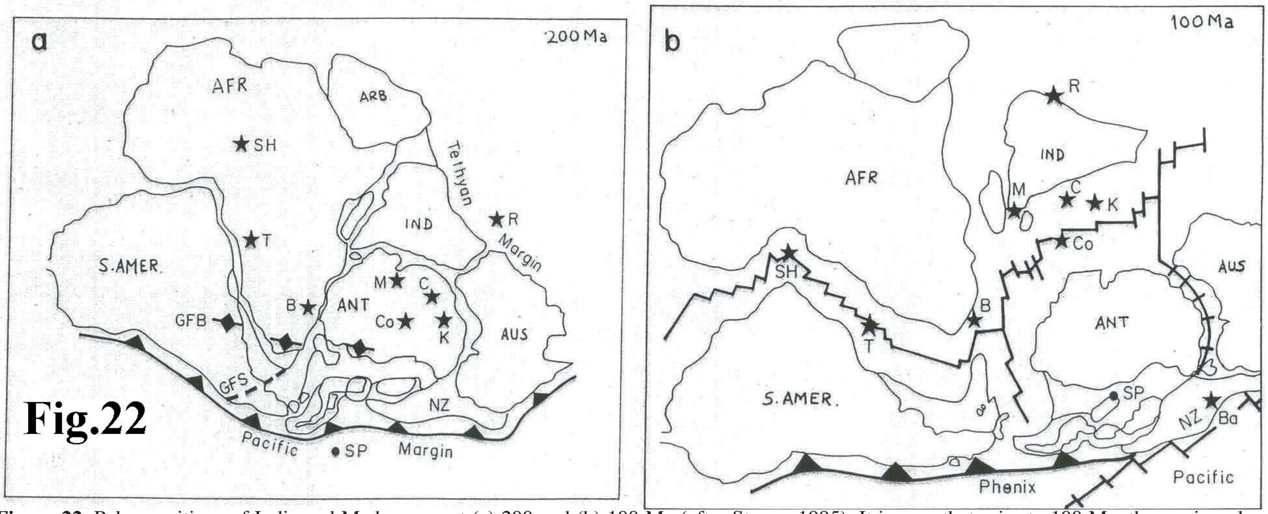

Figure 22. Paleo positions of India and Madagascar at (a) 200 and (b) 100 Ma (after Storey, 1995). It is seen that prior to 100 Ma, the marion plume was close to eastern margin and a little north of Godavari trend at 100 Ma. It is seen near the southern tip of India.

observed earlier also a -50 mgal contour forms a 'westward nose' near the eastern end of the PCSZ, (Figure 5) which probably characterises a branching (or partitioning) of TMF (see Figure 14). Further, the break-up of India from Antarctica seems to take an eastward turn in the offshore near Pondicherry and moves along the east coast of Sri Lanka. This suggests a triple junction (Burke and Dewey, 1973) corroborated by the NNE, SSW and Westward (the westward nose of BGA along Palghat-Cauvery lineament) trending gravity high axes branching out from this zone: very recent earthquake in Pondicherry-Chennai region (~5- 6, Sept.25, 2001) also support presence of a tectonic node. It may also be the line along which the Napier Complex of Antarctica meets the Palghat-trend. The major shear zones over both Madagascar and India exhibit Bouguer gravity highs which might be due to underplating (Pili et al, 1997) because most thermal events (e.g. 550 Pan-African activity, 90 Ma Marion activity, breakups and probably ~60 Ma Reunion plume pulse) get recorded within these shear zones which provide facilitating conduits for the passage of TMF. From this point, the PCSZ might be a failed breakup. On the basis of aeromagnetic data analysis for the SGT, Reddi et al (1988), have also postulated vertical block movements after the Gondwana breakup. Thermal influxing from the plume would also contribute to positive buoyancy and uplift as supported by the Low velocity layer (LVL) in the upper mantle (Kennet and Widiyantaro, 1999).

The plume mode represents 'tectonics and crustal growth' in the vertical direction, and is complementary to the 'horizontal' tectonics and crustal growth driven by plate and accretionary processes. Plume lying close to India and Antarctica (see Figure 22) would have affected both continental and oceanic lithospheres during the breakup and northward drift of greater India. Their consequence on ocean manifest as intraplate features like 900E and 850E ridges, Afanasy-Nikitin seamount chain, the Laccadiv-Maldiv Islands, Chagos plateau, etc. However on land their effects depend on whether the overlying region is cratonic or MB type (i.e. Mahanadi-Sighbhum; Godavari-Baster/ Dharwar; Bengal basin-Meghalaya; Damodar-Chotta Nagpur/Singbhum, Narmadason/ Bundelkhand/Bhandara; Cauvery/Easternghat/ Eastern Dharwar; Cambay/Kutch; Delhi/Aravalli, Western Margin/Western Dharwar craton, etc.).

Some other global/largescale thermal (or superplume) events over I-CL occurred at the ~1100 Ma (accretion of Rodinian supercontinent), a ~750-800 Ma event (breakup of Rodinia), and the 550 Ma Pan-African activity. First one is evidenced from the Kimberlites found near the boundaries of Eastern Dharwar, Bastar-Bhandara, and Bundelkhand cratons and all dating ~1100 Ma. Recently such a superplume activity has been observed in the Cretaceous (Larson, 1991). Many of these megathermal episodes coincide with episodes of large crustal growth (Stein and Hoffman, 1994; Condie, 1995) e.g. late Archaean – early Proterozoic boundary (~2.6-2.7 Ma). The vertical crustal growth is likely seems to be maximum during such superplume activity or episodes.

SEISMICITY AND PLUME AFFECTED REGIONS

Earthquake epicentral distribution over the subcontinent is given in Figure 23. Attention is confined to the mid-continental regions (Chandra, 1977; Khattri *et al.*, 1984), and the Meghalaya Plateau (MP) has also been included, because it lies much south of even the southernmost thrust belt (MFT) of Himalayan collision zone. Secondly, although its present day tectonics would be affected by Himalaya and Burmese collision boundaries; the MP also has a distinct tectonothermal history, atleast since the Cretaceous, follows the development of large igneous province (LIP) consisting of Raj-Mahal/Syhlet/Bengal traps. Below attention is drawn to zones of influence of the plume-CL interaction over the I-CL with reference to seismicity.

Zone - I : This is younger (~65 Ma) than other plume affected zones and is nearly coeval with the Himalayan collision (~50 Ma) characterized by interaction of western part of the I-CL with the Reunion plumehead (diameter of ~1000-2000 km) (see Figure 23). Most SCR earthquakes (M > 6) over past ~180 years in this part have occurred in the Deccan trap (or Reunion Plume)

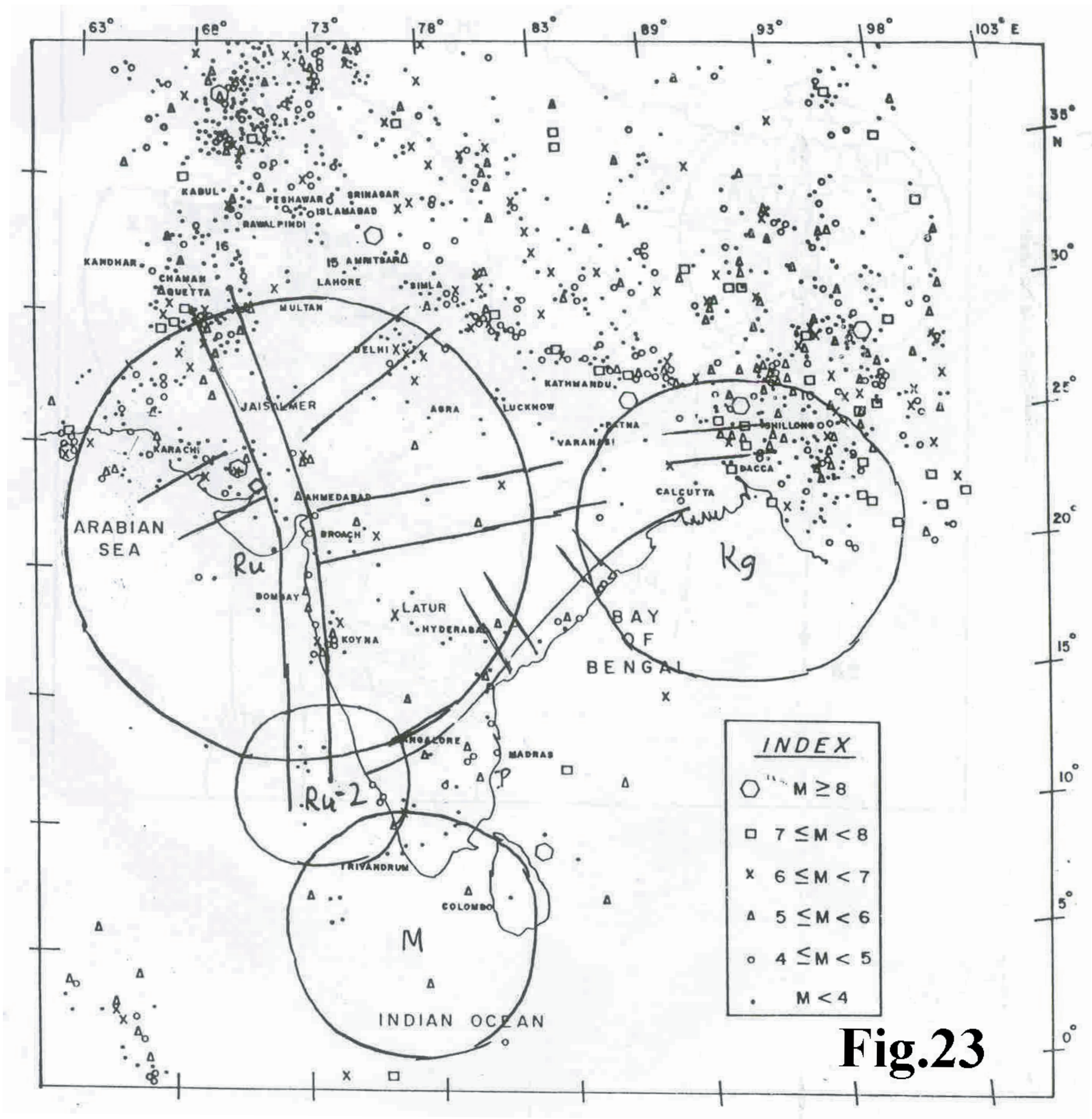

Figure 23. Seismicity (spatial distribution of epicenters) over the Indian subcontinent and different mantle plume affected zones.

affected region. These are Kutch (1819, 1956, 2001), Son (1927), Khandwa (1937), Koyna (1967), Latur (1993) and Jabalpur (1995) : except Latur all these lie along the reactivated MBs. Recently, rocks of alkaline affinity have been reported near Latur also (Talusani, 2001). Perhaps plume activity may be modifying the rheology of the crust-mantle column under DVP such that superposition of ongoing compression makes it more vulnerable. Stress changes may also occur following erosion of Deccan trap cover (Scherer Erik *et al.*, 2001); in this connection it is noted that most thermal springs occur at the periphery of the Deccan trap cover (Figure 24) implying that erosion of traps (release of pressure) facilitate upwelling of deep fluids; the latter often catalyse earthquake nucleation by greasing of faults.

Zone - II : It lies on the eastern part of I-CL and consists of Raj-Mahal, Sylhet and Bengal traps, attributable to interaction of Kerguelen/Crozet hotspots with I-CL (Figure 23) during ~130-110 Ma. This is corroborated by the presence of large Bouguer gravity highs (Verma, 1985) and alkaline (carbonatite) rocks of Cretaceous age (Acthuta Rao, *et al.*, 1996). Further, presence of Cretaceous sediments over the MP suggests that uplift would have commenced then propelled most probably, by the thermal influxing from mantle plumes. Large uplift of MP has an attendant subsidence in the Bengal basin and Bengal Fan and a morphological feature (Garo-Meghalaya gap) which lies between main Indian shield and Meghalaya plateau. In this region, gradients in topography, Bouguer gravity and presence of alkaline rocks correlate with earthquakes. In fact, this correlation is seen over other parts of the Indian shield also (Raval and Veeraswamy, 2000a). In this and adjoining regions, presence of Damodar/ Mahanadi grabens, probably on eastward extension of the Satpura MB into Singhbhum MB, Bengal basin, etc. suggest an inherent weakness and partitioning of TMF along the MBs as corroborated by presence of cretaceous lamprophyres in the Jharia region (Anil Kumar *et al.*, 2001b). Recently, it has been suggested that the loading due to Himalaya to its north and thick Bengal basin sediment to its south, could be a major cause of the horst like uplift of the MP and attendant seismicity (Bilham and England, 2001).

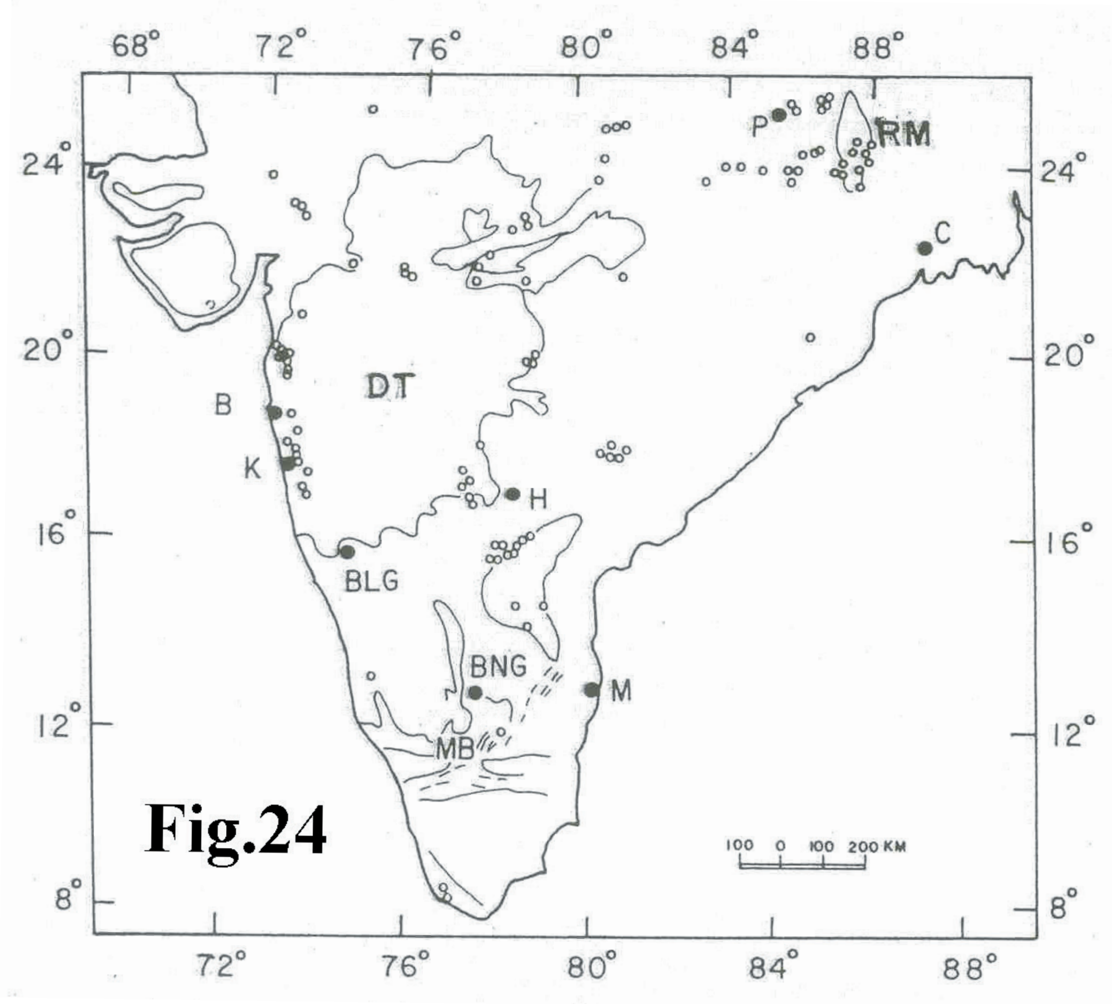

Figure 24. Concentration of Hotspring distribution near the boundary of Deccan Trap and Raj-Mahal regions indicating the upwelling of fluids due to decompression following the erosion of trap cover (Chadha, 1992).

Zone - III & IV : These are areas influenced by the trace and outbursts of the Marion plume (Zone III), and the second pulse (at ~60 Ma) of the Reunion (Zone IV). The latter may have contributed to the uplift of Karnataka Plateau (Figure 20). It is seen that seismic disturbances although of very mild degree (M < 3-4) does occur even in these cratonized parts (Zone III & IV) of the Indian shield. Here too, gradients in topography and gravity highs correlate with earthquake occurrences (Raval, 1995c). The mafic dyke near Bangalore (Anil Kumar *et al.*, 1988) and those along the Kerala coast (Radhakrishna *et al.*, 1994, 1999) and all dated at ~ 90 Ma (Anil Kumar *et al.*, 2001a) imply Marion plume as the cause and indicate mild extension affecting the Dharwar craton during 90-60 Ma.

The stable continental regions (SCR) earthquakes over the Indian shield seems to be governed, mostly by the plume affected MBs. The plume activity often leads to alkaline complexes along the shoulders of rift structures (Thompson and Gibson, 1994). In case of the Reunion plume, this is evidenced along the western margin, over the Kutch/Saurashtra regions and the western part of the Narmada-Son graben. Older alkaline complexes are seen along the Easternghat mobile belt (Leelanandam, 1989). From the spatial distribution of the seismicity over the subcontinent (Chandra, 1977) (Figure 23) seems to correlate with alkaline magmatism (e.g. Tirupattur, Ongole, Bhuj, Meghalaya etc.).

SUPERPLUMES, GEOLOGICAL MANIFESTATIONS AND NATURAL RESOURCES

On combining global magmatic records with corresponding geochronological results it has been found that there exists an episodicity in the global (or large) scale magmatic activity which have been attributed to superplumes. (Condie, 1995). These superplumes are considered to arise from the D" layer at the top of outer core (or CMB). The major episodes recognized are ~2.7, 1.9, 1.2-1.1, 0.8-0.7 Ga during the Archaean-Proterozoic era (see Figure 25). And in the Phanerozoic period Larson (1991) has identified a major superplume at ~120 Ma (?). it is associated with vertical crustal growth, faster production of oceanic crust, major change in magnetic field reversal cycles, sealevel changes etc. In addition 'Greater India' (during 130-60 Ma) underwent major volcanic activities at ~115, 90 and 65 Ma which gave rise to three large igneous provinces (LIPs) or CFBs viz. Rajmahal/Sylhet/Bengal traps (~115 Ma), Cretaceous basalts over Madagascar and intensive activity in southwest India (~90 Ma) and Deccan volcanic province and Laccadive-Maldive island chains (65-60 Ma).

In connection with Archaean-Proterozoic superplume events which may be often corroborated with major changes in the configuration (accretion and/or dispersal) of lithospheric plates it is noticed that Indian continental lithosphere has recorded most of them. For example, (i) Kolar greenstone belts (2.6-2.7 Ga), (ii) dykes under the Cuddapah basin (1.9 Ga), (iii) kimberlites near Wajrakarur, Lattavaram (close to Cuddapah basin), Panna interface at Bundelkhand craton and Satpura orogenic belt, Raipur (near Bastar-Bhandara and Chattisgarh basin), (iv) alkaline complexes along the east coast and in shear zones of south India (Leelanandam, 1989) and Malani rhyolites dating 0.8-0.75 Ga and (v) magmatism and metamorphism at ~550 Ma in almost all the mobile belts of Indian subcontinent, Madagascar and Seychelles. Infact Cuddapah basin itself appears to posses records of all the four major episodes.

Figure 26 shows the approximate zone of influence of plume outburst, their traces and possible channels of thermomagmatic flux of the plume along the MBs. The Figure 26 also gives the major sedimentary basins where presence of oil and gas has been proved. It is evident from this, that plume activity is highly correlated with the presence of hydrocarbon reservoir atleast in the Indian context. Another interesting observation is the distinct possibility of finding Gas hydrates (Methane) along the traces/trails of atleast some of the plumes in the Arabian sea and Bay of Bengal.

The major greenstone belts or schistose rocks over the Indian shield which show economic gold deposits are also associated with komatiites which are Archaean analogue of modern day flood basalts and hence of plume activity. As noted above the 1-1.2 Ga kimberlites near Panna, Wajrakarur, Raipur etc. show lot of diamond prospects, this time is again very well correlated with the superplume activity (see Figure 25).

FIRST CRUST, ORIGIN OF LIFE AND PLUME

Cratonic nuclei seem to form by a process, which is reverse in succession to that from which a MB (or Paleo- suture) develops. In case of latter, first Plate and then Plume-tectonics appear to take part while for the craton it is probably the plume tectonics followed by plate type convection. The oceanic plateaus (and/or OIB) over the primordial oceanic lithosphere would have entered an accretionary zone only when the Archaean mantle had cooled down sufficiently to allow gravitationally supported subduction (at ~ 3.8-4 Ga); and these earliest plume-arc interaction appear to have formed the primordial (or early Archaean) nucleus of continental crust (Abbot, 1996). Mafic/ultramafic population in the Sargur part of the Western Dharwar craton and many indications of paleo-oceans support this model.

Thus, origin and evolution of the continental crust-lithospheric regime appears to be a mixed mode processes (Raval, 1997, 2000b) consisting of both Plate (Steady- state 2-layer convection and horizontal dynamics) and plume (episodic, whole-mantle convection and vertical dynamics) tectonics. Another interesting problem is to find what internal dynamics was operative during the first 500 Ma of earth's life (i.e. from 4.5-4.0). As pointed above, plate dynamics, may not have commenced, in the earliest part of the Archaeans due to unsubductibility of oceanic lithosphere; and recently it has been suggested that the earliest crust was enriched (Tredoux *et al*., 1989; Vearncombe, 1991; Hoffman, 1991, 1997; Punhtel *et al*., 1998; Zimmer, 1999;

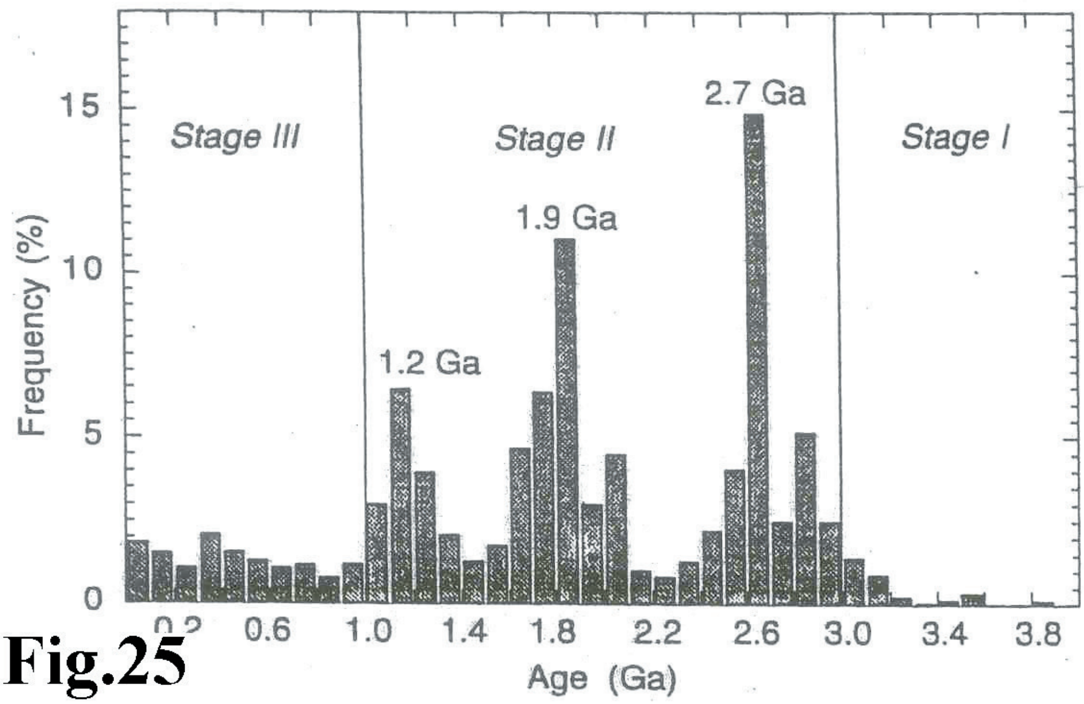

Fig.25

Figure 25 The crustal formation versus the age exhibits certain well defined peaks indicative of anomalously large generation of continental crust. These peaks coincides with the superplume events and super continental reorganization. They also exhibit major thermomagmatic episodes of significant economic importance.

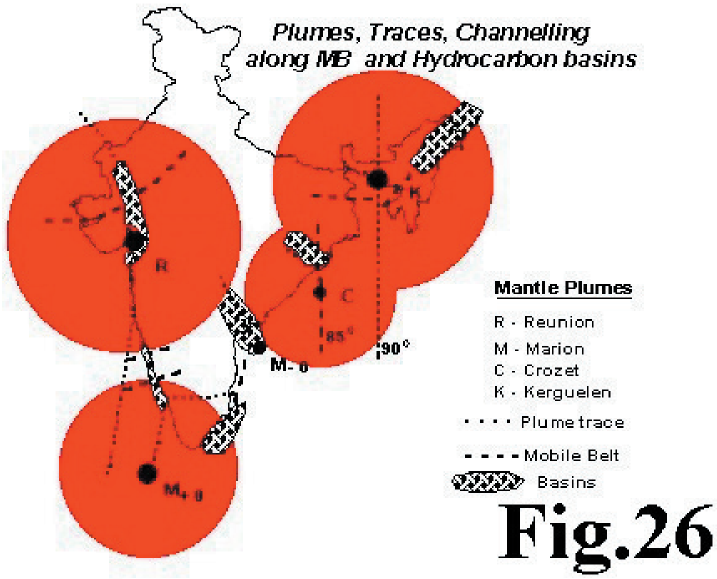

Figure 26. The shaded area shows the probable zones of influence of large plume-heads during their outburst. The dashed line shows the trends of mobile belts. The dotted line shows the plume trace and hatched areas are the basins having high probability of hydrocarbon occurrences. M-0 is the approximate position of Marion plume at T~160 Ma and M+0 is the approximate position of Marion plume at T~90 Ma.

Bateman *et al*., 2001, Kramers, 2001; Scherer *et al*., 2001; Wilde *et al*., 2001;). The latter suggests that some form of plume-tectonics might be operative during the Haydean or earliest Archaean era. Further, recent strides in geo-biospheric studies strongly suggest a thermophylic origin of life in the warm saline ambience of hydro thermal regions under ocean floor (Awramik *et al*., 1983; Schopf and Packer, 1987; Vearncombe, 1991; deRonde and deWit, 1994; Huber and Wachtershauser, 1998; Punhtel *et al*., 1998; Rasmussen, 2000; Nisbet, 2000; Buick *et al*., 2001; Bateman *et al*., 2001). If these earliest hydro-thermal vents, are driven by the plume activity wherein latter brings up, the crucial minerals from depth necessary for catalyzing and commencing the earliest biogeochemical reactions, then plume would be having quite important role in the development of the earliest edifice of life (Raval, 1999a). This means that during the first 500 m.y. of the earth, plume tectonics might be responsible for both origin of life as well as continental crust. It is also seen that major changes in evolutionary process occur at periods which overlap with intense plume activity. That means 'jumps' in the life process could be associated with mantle plume also.

SUMMARY AND CONCLUSIONS

Study focusses on the interaction between mantle plumes (p) and continental lithosphere (CL) and its possible geophysical and tectonic consequences. As an example Indian continental lithosphere is considered which seems to have been significantly affected by more than one plume since the Cretaceous; the latter may be responsible for the anomalously high velocity of the Indian plate. The difference in the thickness and properties of the cratonic and mobile belt type lithosphere appears a crucial factor; channeling (Raval, 1990; Lenardic and Kaula, 1994; Encarnacion *et al*., 1996; Feraud *et al*., 1999; Raval and Veeraswamy, 2001a) along MBs seems responsible for the concentration of geophysical/geochemical anomalies and tectonic features. And large distance lateral channeling along the transcontinental (or translithospheric) MBs (Unrug, 1996) may explain presence of similar and coeval episodes, of different geological times, over widely separated continental blocks (e.g. the 550 Ma Pan African event). Since, MBs represent paleosutures, their interaction with mantle plume indicates a Plate-to-Plume-tectonic succession. Episodic rejuvenations gradually make the MBs weaker such that a combination of sufficiently weakened MB and intense (or long-lived) mantle plume may become fatal for the supercontinental. On the otherhand, cratonic nuclei seem to have been remained undeformed over most of its geological history formed by the reverse succession viz. first plume and then plate tectonics.

An attempt has been made here to investigate the geophysical, tectonic and geological features which seems to have manifested during the Phanerozoic plume and plate tectonics. Owing the 3-4 plume activities within 1500 km and 60 m.y. time span and 3 continental breakups Indian lithospheric plate offers an excellent opportunity to examine the plume-lithosphere interaction. Now main issue is to take the combination of plate and plume tectonics to earlier geological times i.e. Proterozoic and Archaean. This apparently requires much finer data constraints especially geochronological, geophysical and geochemical. The presence of Archaean cratons and their surrounding sutures of Proterozoic period also provide a very ideal setting to investigate the palaeo- plate and plume interactions.

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