

# **Lateral Zonation around Archean Nucleus of the Dharwar Craton, India: Its Deformation, Segmentation and Subsequent Breakup**

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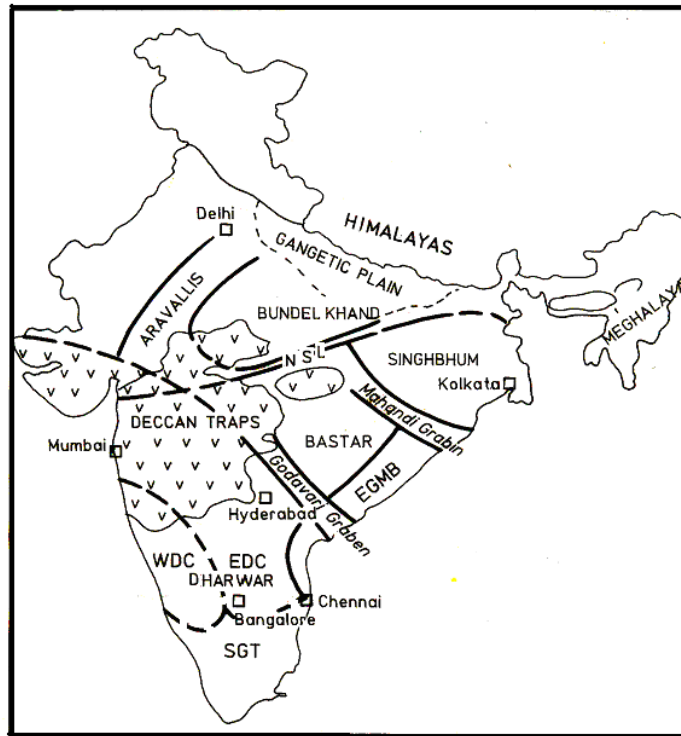
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## **Abstract**

Regional scale variation of the nature of geological units across the earliest evolved regions of the earth may contain fundamental information about continental evolution. Among the Archean blocks, the Indian shield appears to possess certain unique geotectonic and geodynamical characteristics which provide an opportunity to understand its multi-stage crustal evolution both in space and time. Our study of the south Indian shield reveals segmentation and a secular and progressive lateral zonation of the continental lithosphere around Dharwar nucleus since mid-Archean. However, its cratonic nucleus seems to have ultimately broken due to successive crustal remobilization and foundering of the rheologically and tectonically weak Archean lithosphere. Such weakness were caused by (i) episodic plume induced tectonothermal events since 2.7 Ga, and (ii) asthenospheric convective processes associated with a new rifting phase triggered by Marion plume activity along the India's western margin at about 90 Ma. The Antongil block of northeast Madagascar seems to correspond to the broken segment of the western Dharwar craton.

## **Introduction**

The Indian subcontinent with its dynamic history since Late Archaeans forms one of the most deformed regions among the stable areas of the earth (Pandey and Negi, 1987; Pandey *et al.*, 1996, 2002; Pandey and Agrawal, 1999; Pandey and Agrawal, 2001; Agrawal and Pandey, 2004). It exhibits a variety of geological features formed at different times by different geotectonic processes. It is considered unique in several ways, viz. it has been associated with (i) highest rate of mobility (~20 cm /yr.) in the past during 80-53 Ma, (ii) warm and thin lithosphere (~ 105 km on an average), (iii) episodically active rift systems since 1.5 Ga, (iv) several continental breakups, and (v) large basaltic outpourings (McA. Powell, 1979; Negi *et al.*, 1986, 1992; Naqvi and Rogers, 1987; Rogers and Callahan, 1987; Pandey and Agrawal, 1999 etc.). It contains several cratonic blocks (Dharwar, Singhbhum, Aravalli, Bastar, Bundelkhand) , characterized by differing style of evolutionary patterns and surrounded by geotectonically weak early to mid-Proterozoic mobile belts and rift systems like Godavari and Mahanadi grabens and Narmada - Son Lineament (NSL) (Fig.1). In the present work, an attempt is made to synthesize different stages of crustal development around the Archean Dharwar nucleus (South India), its segmentation and subsequent breakup which seems to have played an important role in the crustal development of the east Gondwanaland.



**Fig.1:** Geotectonic subdivision of the Indian shield along with the location of Archean-Proterozoic cratonic blocks and major graben structures. NSL: Narmada-Son Lineament; WDC: Western Dharwar craton; EDC: Eastern Dharwar craton and SGT: Southern granulite terrain

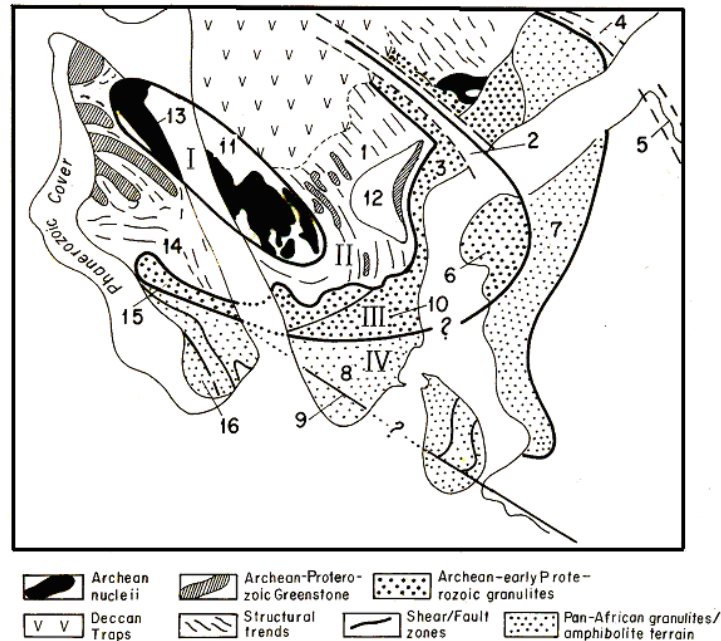
## Geological Characteristics

The structural, tectonic and geologic patterns among some of the segments of east Gondwanaland are shown in Fig. 2, which reveals a systematic and progressive lateral crustal zonation from Zone I to Zone IV around the mid-Archean Dharwar cratonic nucleus. By and large, a broad similarity between the rock types of south India, Madagascar, Sri Lanka and east Antarctica is fairly evident.

### Zone I: Cratonic nucleus

This region corresponds to an elliptical mid to Late Archean nucleus situated in the western part of the craton. It is made up of thin primordial basic crust, over which lies vast exposures of probably the oldest and extensively developed greenstone schist belts (3.0–3.4 Ga), granitic and gneissic core, characterised by low temperature metamorphism. This is quite in contrast to those found in the surrounding regions. Most of the ages of gneisses are around 3.0 Ga (Radhakrishna and Naqvi, 1986). The Archean nucleus is covered by Deccan Traps in the north, while in the west; it resembles a passive continental rifted margin. It is now known that until ~90 Ma, India and Madagascar were a single unit in the erstwhile Gondwanaland (Agrawal *et al.*, 1992; Storey *et al.*, 1995; Raval and Veeraswamy, 2003), before they rifted apart to occupy the present positions. We conjecture, that in this rifting process, Dharwar cratonic nucleus was broken, a part of which now forms Antongil cratonic block of the northeast Madagascar (Figs. 2 & 3). This block is also made up of 3.2 Ga migmatitic biotite gneiss (Tucker *et al.*, 1997) to 3.4 Ga old granite (Cohen *et al.*, 1984). Subsequently, it was again intruded by about 2.55 Ga old granitic bodies (Collins, 2000). The entire rock suites of cratonic nucleus of both

India and Madagascar have remained literally unaffected by later Proterozoic events (Radhakrishna and Naqvi, 1986; Collins, 2000). As expected, the sub-Moho  $P_n$  velocity below the Dharwar cratonic nucleus is found to be very high (8.4 km/s) (Reddy *et al.*, 2000). Our calculations indicate presence of a relatively thick (~175 km) and cool lithosphere (Moho temperatures ~ 410° C) below this region compared to adjacent regions in the east and south.

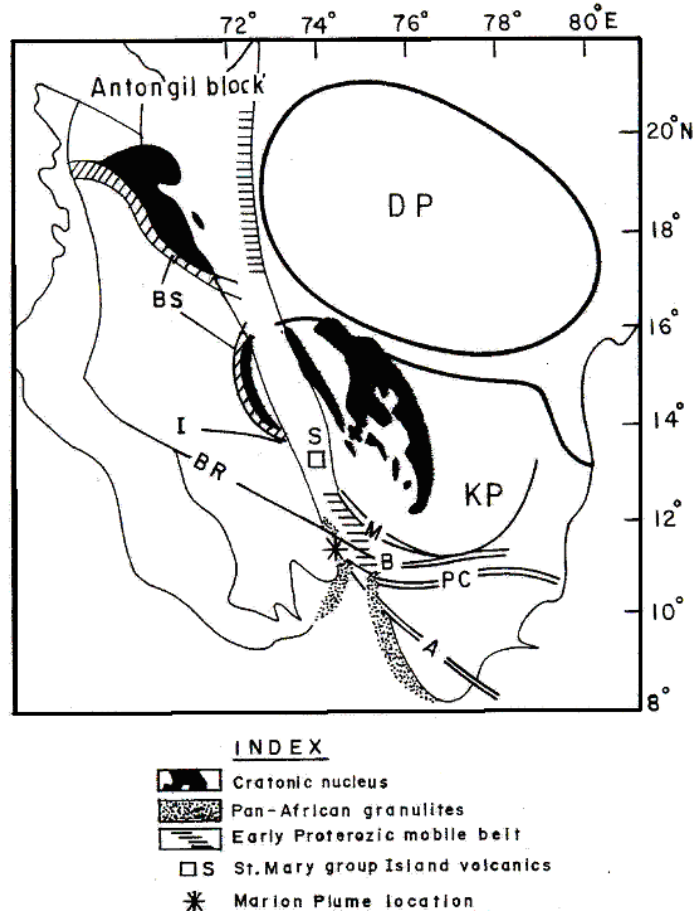


**Fig.2:** Lateral crustal zonation pattern around western Dharwar craton nucleus. I: Cratonic nuclei, II: Late Archean – Early Proterozoic crystalline terrain, III: Late Archean – Early Proterozoic granulite terrain, IV: Pan-African metamorphic terrain, 1: granite-gneiss and metamorphic complexes, 2: Godavari graben, 3: Eastern Ghat mobile belt, 4: Mahanadi graben, 5: Lambert rift, 6: Napier complex, 7: Reyner complex, 8: Southern granulite terrain (SGT), 9: Achankovil shear zone, 10: Archean – Early Proterozoic granulites, 11: Archean Dharwar nuclei, 12: Cuddapah basin, 13: Antongil cratonic block, 14: granite-gneiss-greenstone block of central Madagascar, 15: Ranotsara shear zone, 16: Pan-African granulites of south Madagascar.

### Zone II: Late Archean – Early Proterozoic crystalline terrain

This zone is comprised of Late Archean – Early to Mid-Proterozoic cratonic growth. In the Indian subcontinent, it covers the eastern part of the Dharwar craton, which is marked by low pressure regional metamorphism and large scale crustal remobilisation. It experienced extensive plume related tectono-thermal magmatic activity at around 2.7- 2.2 Ga, 1.9-1.8 Ga and 1.2-1.1 Ga (Naqvi and Rogers, 1987; Acharya, 1997; Anil Kumar *et al.*, 1993; Jayananda *et al.*, 2000; Radhakrishna and Naqvi, 1986). It contains abundant calc-alkaline to K- rich granitoids (Harish Kumar *et al.*, 2003), gneisses and metamorphic complexes, besides being extensively intruded by mafic dyke swarms (Murthy, 1995). The last major event (~ 1.1 Ga) which may have been related to a deep mantle plume (Mall *et al.*, 2008), resulted in the emplacement of kimberlites at several places (Anil Kumar *et al.*, 1993). In this region, lithosphere is thinner and Moho warmer compared to that of Dharwar Craton Nucleus. Here, the  $P_n$  velocities are much lower at ~ 7.8 km/s (Reddy *et al.*, 2000).

On the Madagascar side, this zone is represented by the central region of almost similar age (Late Archean – Proterozoic) Antananarivo and Tsaratanana blocks comprised mainly of greenstones, granites, gneisses and tonalites which were later intruded by Late Proterozoic (~ 500-800 Ma) granites, syenite and gabbros at several places.



**Fig.3:** Juxtaposition of Madagascar and India before breakup and geotectonic correlation. DP: Deccan plateau; KP: Karnataka plateau; M: Moyar shear zone; B: Bhavani shear zone; PC: Palghat-Cauvery shear zone; A: Achankovil shear zone; BS: Betsimisaraka suture zone; I: Itremo lineament; BR: Bongolava-Ranotsara lineament.

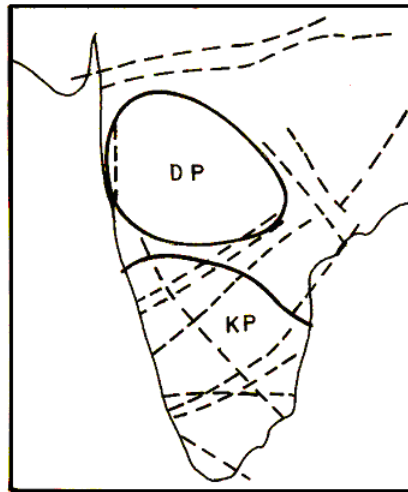
**Zone III: Late Archean – Early Proterozoic granulite terrain**

This granulitic terrain is characterised by Late Archean- Early Proterozoic metamorphic thermal events. In Antarctica, it is represented by the Napier complex ( Late Archeans or even older; Chetty *et al.*, 2003), while in India, it occurs (i) in the region situated north of the Palghat-Cauvery shear zone ( PC in Fig.3) separating Archean granulites in the north from that of Pan-African granulites in the south, (ii) along eastern Ghat mobile belt, and (iii) granulites situated on both the flanks of the Godavari graben (Rajesham *et al.*, 1993; Ramakrishnan *et al.*, 2003). In the granulitic terrain, situated north of PC shear zone, lithospheric thickness, on an average, is ~ 105 km and the mantle lithosphere is much warmer than the adjacent region of the Dharwar craton in the north. In spite of the inadequacy of the data, there are sufficient indications (Janardhan, 1999; Kroner *et al.*, 1999; Rabeloson,

1999) to suggest that this zone extends into Madagascar and covers an area immediately north of the Ranotsara shear zone (Fig. 2).

#### **Zone IV: Pan-African metamorphic terrain**

This terrain, criss-crossed by deep-seated faults/shear zones (Figs. 3&4), has undergone extensive high grade regional metamorphism at around  $550 \pm 30$  Ma. It contains granulite – amphibolite facies rocks. In the Indian subcontinent, it is represented by the granulitic terrain occurring south of the Palghat Cauvery ( PC) shear zone (Fig.3) Beneath this terrain, underlying lithosphere is probably thinnest (  $\sim 95$  km on an average) and warmest compared to any other part of the Dharwar craton. In Madagascar too, it occupies the southern portion lying south of Ranotsara shear zone (Fig. 2). The entire terrain represents mainly P-T conditions of about  $7.5 \pm 1.5$  kb and  $850 \pm 150^\circ$  C respectively, with comparable lithologies on a regional scale. Vast areas of east Antarctica (Reyner complex) and Sri Lanka (Wanni, Highland and Vijayan complexes) are covered with similar grade rocks.



**Fig. 4:** Location of major deep-seated faults, taken from the tectonic map prepared by ONGC. DP and KP refer to Deccan and Karnataka plateaus

The zonation pattern as described above and shown in Fig. 2, reveals gradual but progressive changes in lithologies around the Archean Dharwar nucleus. Such type of crustal development which started during Middle Archean, continued till the fragmentation of erstwhile Gondwanaland that marked the beginning of a new global plate tectonic era. This new era was extremely dynamic involving extensive plate reorientations and an abrupt increase in spreading rates, besides other important geodynamic events like K-T boundary impact near offshore Mumbai, Deccan and Rajmahal basaltic eruptions and interaction with four mantle plumes. These events completely reshaped the underlying lithosphere (Pandey *et al.*, 1995; Pandey and Agrawal, 1999). This was also the period when the Indian Ocean began to form and the island of Madagascar broke away from greater India.

### **Segmentation and breakup of Dharwar Craton**

Cratons are usually considered as regions which have exhibited tectonic stability since Late Archean times. They contain relatively cold and thick keels or roots reaching as deep as 450 km (Polet and Anderson, 1995). Going by this definition, it is difficult to contemplate the breakup of any craton specially the old

ones like Dharwar craton. However, a number of studies now suggest that Madagascar was attached to greater India till about 90Ma (Storey *et al.*, 1995; Raval and Veeraswamy, 2003) or it may even have been a splitted segment of Archean Dharwar craton (Agrawal *et al.*, 1992). The probable cause for such a breakup is still debatable. However, what is not debatable is that the underlying Indian lithosphere is not quite as same as other stable regions and certainly it did not remain same as it was during the Early Archean times (Negi *et al.*, 1986; Ramesh *et al.*, 1996; Pandey and Agrawal, 1999 ; Priestley *et al.*, 2006 ; Kumar *et al.*, 2007). It has persistently undergone several cycles of tectono-thermal and geodynamic events during the past viz. between 2.7 – 2.2, 1.9-1.8, 1.2- 1.1, 0.85 – 0.5 Ga besides several Phanerozoic events (Radhakrishna and Naqvi, 1986; Naqvi and Rogers, 1987; Rogers and Callahan, 1987; Anil Kumar *et al.*, 1993; Acharya,1997 ; Jayananda *et al.*, 2000; Harish kumar *et al.*, 2003).

The above events were often related to mantle plumes which time and again reactivated, remobilised and ultimately segmented the entire crustal column. Mid to Neo-Proterozoic reactivations were particularly responsible for the development of uplifted plateaus, rift systems and major shear / fault zones within and around the periphery of Dharwar craton which remained episodically active since then. For example, Dharwar craton is now divisible into three distinct geotectonic regions (Fig. 1): Western Dharwar craton (WDC), Eastern Dharwar Craton (EDC) and Southern granulitic terrain (SGT), all of them exhibiting different geological and geophysical characters. Besides these, it also got segmented into two uplifted plateaus: (i) Deccan Plateau (DP) in the north covering a major part of EDC overlain by Deccan Traps and (ii) Karnataka Plateau (KP) in the south encompassing Archean nucleus (WDC), granulite terrain (SGT) and southern part of EDC (Figs.3-5). Deccan traps covered region of EDC exhibits much higher crustal seismic velocities compared to its adjacent region in the south including SGT. Recent GPS studies indicate a fair possibility of relative motion between DP and KP (Catherine, 2001). These two uplifted blocks also have altogether different geological characters. DP almost solely corresponds to Early Proterozoic mobile belt while southern part of the KP is dominated by Pan-African granulites and numerous mega shear/deep-seated fault zones (Figs. 2&4). Except the cratonic nucleus portion, the entire western margin was occupied either by Early Proterozoic mobile belt terrain (Radhakrishna and Naqvi, 1986) or by late Archean- Pan-African granulite terrain (Fig. 3), before the break up of the Dharwar craton. It appears that in the past, the Betsimisaraka suture zone (BS) of Madagascar (Collins, 2000) may have extended across the Dharwar craton separating DP and KP (Fig. 3). This is well reflected in the patterns of regional uplift (Fig. 5a) and Bouguer gravity images also (Fig. 5b).

It seems the past crustal reactivations resulted into large scale influx of volatiles through weak zones, and greater enrichment of radioactive elements in the already lithophilic element rich Indian crust (Rogers and Callahan, 1987). This made Indian lithosphere rheologically weak and warm besides lowering the viscosity of lithospheric mantle (Negi *et al.*, 1986; Pandey and Agrawal, 1999). It also made the Dharwar craton, in the presence of already existing weak zones (Fig.3& 4); vulnerable for breakup in case it was hit by a rising mantle plume.

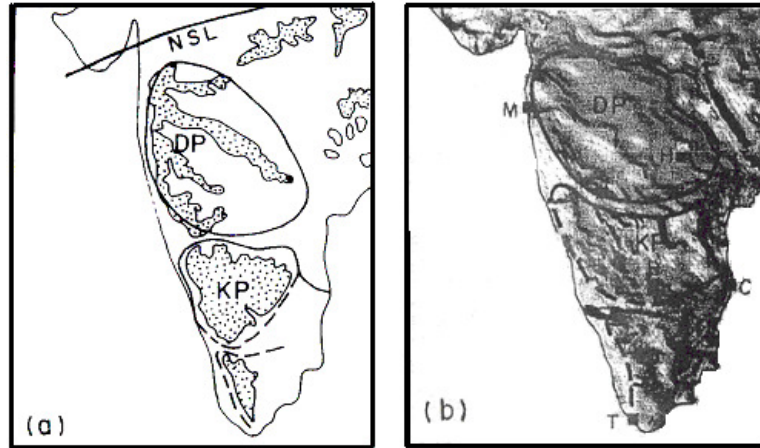
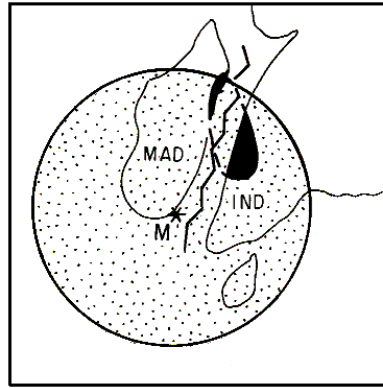


Fig.5: (a) Approximate boundaries of Deccan and Karnataka plateaus sitting over the uplifted blocks (shown by dots) of south Indian shield (Raval, 1995). (b) Bouguer gravity anomaly shaded relief images (Sreedhara Murthy, 1999) over DP and KP. C: Chennai; M: Mumbai; T: Trivandrum.

### Effect of Marion Plume interaction

At around 90 Ma, the Marion plume did hit this region (Fig. 6). Location for the plume is said to be quite close to the southeastern margin of Madagascar (Curry and Munasinghe, 1991; Storey *et al.*, 1995; Raval, 1999; Raval and Veeraswamy, 2003), which incidentally falls at the cross section of several mega shear zones and mobile belts (Fig. 3). These shear zones which extended below Moho facilitated magma upwelling up to the surface. Numerous dykes and flows of Late Cretaceous age (like St. Mary Island group of volcanics along the western margin, dated at 86 Ma; Pande *et al.*, 2001; Fig.3) bear testimony to this magmatic event. Sudden upwelling of magma triggered the ridge, then active between Africa and Madagascar, jump to the east of Madagascar thereby creating a new rifting phase along the India's western margin (Fig. 6). Asthenospheric convective processes associated with the continental breakup are known to give rise to shallow pseudo-plume (Anderson, 2000). Thus, convective processes associated with this new rifting phase together with the past successive plume related thermal events, appear to have degenerated and sheared the once thick cratonic root beneath this craton (Pandey and Agrawal, 1999) which ultimately resulted into the breakup of the Dharwar craton. Progressively sheared lithospheric mantle was then consumed by the asthenospheric mantle. As a consequence, the Dharwar cratonic root has become much thinner compared to 250-450 km found elsewhere in similar terrain (Polet and Anderson, 1995). As stated earlier, our estimated thickness of the lithosphere beneath western Dharwar craton (WDC), based on available heat flow data, is only about 175 km while the average Indian shield lithosphere is even thinner at ~ 100 km only (Negi *et al.*, 1986; Pandey and Agrawal, 1999; Kumar *et al.*, 2007). Available geophysical data support these estimates. Although there is very little information available for the lithospheric structure beneath Madagascar, its present lithospheric thickness is expected to be around 100-125 km only (Chapman and Pollack, 1977).

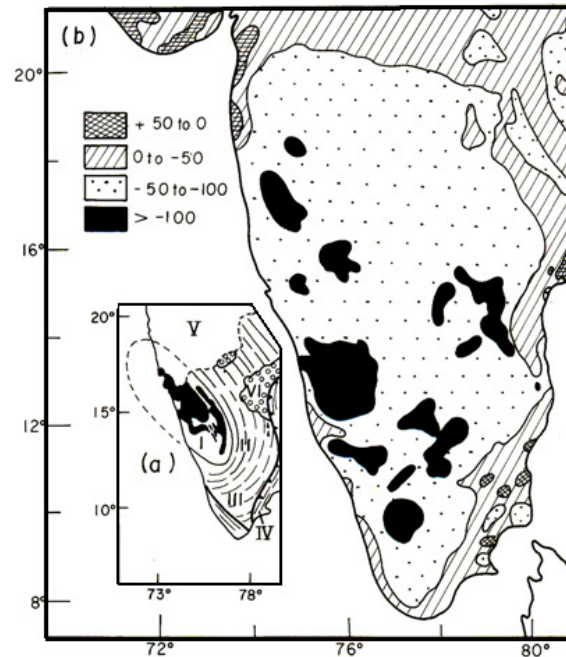


**Fig. 6:** Juxtaposition of Madagascar and India before 90 Ma. Star shows the postulated location of Marion Plume (M) before its outburst (Curray and Munasinghe ,1991;Storey *et al.*, 1995; Raval, 1999 ). Circle with dots indicate the possible area of Marion plume influence

It is interesting to mention here that based on M – sequence anomalies in the Enderby basin (Antarctica), Royer *et al.* (1992) argued for a large strike slip motion between India and Madagascar. If it was so, then it might have further desegregated the Dharwar craton prior to its breakup by Marion plume.

### **Geophysical support and inferences**

The elliptical shaped splitted nucleus of the Dharwar craton (Radhakrishna and Naqvi, 1986) which lies quite close to the western margin (Fig. 7a) is well brought out by the gravity map shown in Fig. 7b. This figure shows modified Bouguer gravity anomaly map of south India contoured at an interval of 50 mgal. Gravity anomalies show an incomplete gravity closure of unusually low magnitude (-50 to -100 mgal) over the Indian side of the Dharwar craton. The high gradient contours around the continental margin represent rifted and possibly uplifted continental blocks. The magnitude and shape of anomalies on Indian side indicates something unusual about the mantle underneath, as such anomalies usually do not occur in other stable regions of the globe. Further, the accurately determined Moho of 33 to 39 km beneath EDC through receiver function (Gupta, 2003) is identical to that of 33 to 39 km found in central Madagascar (Fournon and Roussel, 1994). There is also one to one correspondence between the long wave length MAGSAT anomalies over India and Madagascar (Agrawal *et al.*, 1992) signifying that the two regions have common deep magnetic properties. Regrettably however, compared to Indian shield, not much geophysical information is available over Madagascar.



**Fig.7:** Generalised geotectonic patterns of Dharwar craton (Fig. a) based on Radhakrishna and Naqvi (1986). I: Western Dharwar craton nucleus, II: Late Archean-Proterozoic crystalline terrain, III: Southern granulites, IV: Eastern Ghat mobile belt, V: Deccan traps, VI: Cuddapah basin. Corresponding modified Bouguer gravity anomaly map prepared by NGRI (1975) drawn at an interval of 50 mgal is shown in Fig. b.

We have attempted to demonstrate that a multi-stage progressive lateral crustal growth took place encircling the Archaean Dharwar nucleus which lasted till the beginning of Gondwana breakup. Besides, we feel that not all the Archaean cratonic nuclei remained stable as hitherto believed. Some of them have definitely been affected by past tectonothermal events. For example, the lithospheric keel beneath the Dharwar craton underwent large scale deformation and foundering due to thermal and geodynamic events which segmented the craton and ultimately led to breakup. Remnants of the broken part could be the Antongil block in northeast Madagascar. Our study refutes the idea of cratonic stability of deep continental blocks which in many cases are no longer associated with the ancient old roots (Polet and Anderson, 1995; Pandey and Agrawal, 1999; Kumar *et al.*, 2007). They are liable to deform and break in the environment of extensional tectonism. Apart from Indian cratons, there are several other cases where Archaean cratonic roots have been deformed and destroyed due to Proterozoic tectonothermal/Mesozoic – Tertiary geodynamic events, for example, central African, east African, eastern Sino-Korean, Kaapvaal cratons etc. (Polet and Anderson, 1995; Griffin *et al.*, 1996, 1998; Prestley *et al.*, 2002). In such areas, the ancient roots have been replaced by hot and thin lithosphere.

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