CHAPTER: 8

GEOPHYSICAL EVIDENCE
OF
NARMADA-SON RIFTING
This chapter presents a comprehensive account of the recent geophysical investigations carried out along the Narmada - Son Lineament. An attempt has been made to analyse and interpret the seismic and gravity data in the light of recent taphrogenic concepts. Rift-related geothermal anomalies have also been identified.

8.1 SEISMIC EVIDENCE.

This section deals with the recent Deep Seismic Sounding (DSS) studies, the earthquake epicentre distribution and the seismic zoning of Peninsular India which throw decisive light on the rifted structure of the Narmada - Son Lineament.

8.1 A DEEP SEISMIC SOUNDING STUDIES.

In 1976-77, the National Geophysical Research Institute shot a 220 km long N-S trending Mehdavad - Bilimora DSS profile in collaboration with the Oil & Natural Gas Commission. In 1980-82,
under the Geological Survey of India sponsored project

CRUMANSONATA (Crust and Upper Mantle studies of Son, Narmada and Tapti), DSS investigations were also carried out along it 320 km long N - S profile across Narmada - Tapti rivers from Ujjain to Mahan, ii) 80 km long N - S profile from Popatkheda to Patur across Purna River, iii) 300 km long Khajuriakalan - Chicholi - Multai - Pulgaon profile and, iv) 220 km long Hirapur - Mandla profile. These profiles lying across the Narmada - Son Lineament (Fig. 8.1) reveal valuable information pertaining to the deep and shallow structure of the crust including the thickness of the Traps, Vindhys and Gondwanas as well as the depths of crystalline basement, Conrad discontinuity and Mohrovcicic discontinuity (Kaila 1982, Kaila et al. 1982 c). Though, the results of Khajuriakalan - Pulgaon and Hirapur - Mandla profiles have not been published, the remaining profiles clearly establish the 'rift - zone' structure of the Narmada - Son - Tapti Valleys:


The N - S trending Ujjain - Mahan profile (Fig. 8.2 and 8.5) reveal four crustal blocks, viz., I Ujjain - Sanawar, II Indore - Dorwa, III Dorwa - Tapti, and IV Tapti - Mahan which were displaced up or down during different times along deep faults bounding them and extending upto the Moho discontinuity (Kaila et al. 1985). In Gondwana times, tectonic movements resulted in down faulting of Dorwa - Tapti block in which Gondwana sedimentation took place
FIG. 8.1 MAP OF INDIA SHOWING THE LOCATION OF VARIOUS DSS PROFILES COVERED BY NGRI FROM 1972 TO 1982.
FIG. 8.2: DETAILED LOCATION MAP OF UJJAIN-MAHAN AND POPATKHEDA-PATUR DSS PROFILES INDICATING POSITION OF VARIOUS SHOT POINTS.

FIG. 8.3: MAP SHOWING MEHMADABAD BILIMORA DSS PROFILE.
Fig 8-4  Shallow depth section up to the crystalline basement along (1) Ujjain-Mahan profile and (2) Popatkhes-Patur profile in Madhya Pradesh, India, as obtained from refraction DSS data.

Fig 8-5  The observed Bouguer anomaly as obtained from NGR1 Gravity map series of India (1975) is shown at the top of the figure.
giving rise to a maximum of 1.7 km thick Gondwana succession (Fig. 8.4). During this period the blocks I & II formed the land part and hence no Gondwanas were deposited there (op. cit.) but 200 m thick Lameta Beds suggest the down faulting of block I & II during Cretaceous Period (Fig. 8.4). Based on the findings of these DSS profiles presence of the 'Tapti Graben' (Kaila 1984) and the Narmada - Son Rift (Kaila et al. 1985) was established.

b. Mehmadabad - Bilimora DSS Profile.

Mukherjee (1980) considered the south Cambay basin to be the western extension of the Narmada Rift and therefore the Mehmadabad - Bilimora profile, shot at the intersection of Cambay and Narmada grabens (Fig. 8.3), being at right angle to the latter, reveals its rift faults and the underlying crustal structure. Kaila (1981c) reported that the Cambay basin, known to be bounded by step faults on the eastern and western margins is also dissected into seven major crustal blocks in N-S direction from Mehmadabad to Bilimora, which are displaced, up or down due to movements along faults bounding them (Fig. 8.6). The Jambusar - Broach block, with maximum thickness of Cenozoic sediments and deepest granitic basement (6.0 to 6.5 km), is a major graben north and south of which the basement is found at relatively shallower depths in various crustal blocks (op. cit.).
Fig. 8. Crustal depth section along the Mahanadish-Bilimora profile in the Coober Pedy region, Central State, India, as obtained from the IRS data. The observed Bouguer gravity anomaly along the profile is also shown for comparison.
c. The Basement Ridge.

Kaila (1984) suggested that the four DSS profiles shot across the Narmada - Son Lineament have shown that the Narmada River outside the Broach depression is flowing over a basement ridge and the Narmada River alluvium in the Hoshangabad region is only about 300 m thick in the form of a surficial half - graban. Upward swing of reflectors in the southern part of Ujjain - Mahan profile (Fig. 8.5) may represent such a basement ridge which may emerge more distinctly if different parameters assuming this model are chosen during the seismic data processing. The presence of such a ridge supports author's contention of an eastern swing of Aravali - Delhi strike, development of Precambrian craton bounding fault and deposition of Vindhyan molasse in the frontal zone of this eraton, proposed on the basis of structural evidence (Section 6.3A). Remarkably similar description of these processes was put forward by Kaila et al. (1985) while describing the Ujjain - Mahan profile: "It is concluded that during the Precambrian, blocks I & II north of Dorwa were downthrown with respect to block III leading to the development of the Vindhyan basin in that region. Blocks III & IV being uplifted at that time, formed the land part and hence no Vindhyan sedimentation took place there. Subsequently, during Gondwana times, reverse tectonic movement resulted in downfaulting of block III where Gondwana sedimentation took place".
8.1 B CRUSTAL DOMAL UPWARP.

Atmospheric intrusion in the upper mantle part of lithosphere with associated crustal domal upwarp appear to have taken place during the main rifting episode of the Narmada Rift Zone in Cretaceous period which can be inferred from its effect on the crustal structure in the form of rise of subcrustal layers. These effects include i) rise of Moho with reduction of P-wave velocity and general obliteration of sharp velocity contrast, and ii) corresponding rise of the Conrad discontinuity by magmatic intrusions from the anomalous upper mantle.

a. Transition Zone.

Van der Linden (1978) suggested that the continental rifts are underlain by anomalous crust, where the P-wave velocities are somewhere between crystalline crust (6.5-7.2 km/sec) and upper mantle (7.8-8.2 km/sec) are encountered frequently. Fuchs et al. (1981) also suggested that continuous transition of velocities from 7 to 8 km/sec in the graben proper and discontinuous transition on the flanks is a general characteristic of the continental rifts. Along the Narmada Rift Zone, only the Mehmadabad - Bilimora profile (Fig. 8.6) is detailed enough to perceive such a development of transition zone where absence of 6.9 to 8.1 km velocity jump, so characteristic of the normal continental crust (Condie 1976), is noteworthy. Instead, a transitional zone of about 15 - 20 km
thickness, with a gradual velocity change from 6.9 km/sec (~15 km depth) to 8.16 km/sec (30 to 40 km) has developed all along the profile.

b. **Rise of Conrad Discontinuity.**

Mueller et al. (1973) suggested that the increase in the thickness of lower crustal layer, as observed in the Rhinegraben, takes place as a result of magmatic intrusions of basaltic magma from the underlying mantle. Such crust–mantle interaction by the injection of upper mantle material combined with phase transition, during the graben formation has also been proposed by Edel et al. (1975, cited in Fuchs et al. 1981). Increase in the thickness of lower crustal layer has also been observed along the Rio Grande Rift by the magmatic intrusion below the rift (Oliver and Kaufman 1976, cited in Mueller 1978). Auden (1949 a ) proposed an increase in the Sial–Sima interface by the upwarp of the basaltic shell into the overlying granitic crust near Bombay and along the Narmada Rift Zone with the help of gravity data. Kaila & Reddy (1982 c ) and Kaila et al. (1985) confirmed the occurrence of Conrad discontinuity with a velocity jump from 6.0 to 6.9 km/sec, at a shallow depth of about 8 – 12 km along the Ujjain – Mahan profile (Fig. 8.5). The rise of Conrad discontinuity along the Mehmadabad – Bilimora profile (Fig. 8.6 ) can also be observed where 6.8 km velocity, possibly representing the Conrad discontinuity (Kaila et al. 1981 c ) can be observed at a shallow depth of 8 – 16 km in different blocks. If a velocity of 6.6 km/sec is taken to mark the Conrad discontinuity
along the rifts as suggested by Condie (1976), its further
shallowing becomes evident. It is suggested that this general rise
of Conrad discontinuity represents impregnation of upper mantle-
derived basaltic magma into the lower crust during the Deccan
Volcanic episode.

c. Rise of Mohorovicic Discontinuity.

Based on seismic evidence several authors have reported
crustal thinning by asthenospheric upwarp along the continental
rifts such as the East African Rifts (Griffiths 1972, and Long
et al. 1973), the Rhinegraben (Mueller et al. 1973, Meissner &
Vetter 1974, Fuchs et al. 1981 and Illies 1981a), the Baikal Rift
(Puzyrev et al. 1973 and Zorin 1981), and the Basin & Range
Province of U.S.A (Condie 1976, Artyushkov 1981). These authors
reported abnormal upper mantle velocities ranging from 7.0 to 7.8
km/sec below the rift proper, and normal Moho velocities from 7.9
to 8.2 km/sec on the flanks. Despite inconsistencies in selecting
vital parameters such as normal and abnormal upper mantle velocities,
a general picture emerges where, depending on the stage and intensity
of rifting process, the abnormal upper mantle causes a rise of the
Mohorovicic discontinuity. This abnormal upper mantle was called a
and Ramberg (1978 b) surmised that in palaeorifts, the depth to the
top of 'palaeorift cushion' roughly represents the thickness of the
original rigid layer which is a measure of the degree of development
that was reached.

Condie (1976) suggested that the continental rifts have thinner crusts (28 km approximately) as compared to the platform and shield areas (35-39 km) because the Moho along the rifts is characterized by a lower P-wave velocity of 7.5 to 7.8 km/sec as compared to the normal velocity of 8.1 km/sec in shield areas. Recent structural model of the Mid-Atlantic Ridge shows that the normal velocity of 8.1 km/sec occurs at least 10 km off the ridge axis on either side, while anomalous mantle with 7.6 km/sec velocity is found at a depth of 7.5 km under the axial trough (Fowler 1976, quoted in Mueller 1978). A general similarity between this ridge structure and the rift model was established by Mueller (1978) where the lower crustal layer filled with mantle derived intrusions in the rift will have lower P-wave velocity of 7.2 km/sec. Though these reflectors can be seen at a depth range of 8 to 18 km in the Mehmadabad-Bilimora profile (Fig. 8.6), it is proposed here that at least the reflectors with 7.4 to 7.5 km/sec velocity occurring at a depth of 15-22 km represent the rise of Moho during the Cretaceous period. It should be noted that whereas Kaila et al. (1981c) chose 8.1 to 8.2 km/sec velocity to mark the Moho in Mehmadabad-Bilimora profile, Kaila et al. (1985) selected 7.8 km/sec reflectors to delineate the Moho in Ujjain-Mahan profile, with the result that the downthrown Mohorovicic discontinuity in the central graben in the former profile is replaced by uplifted Moho in the latter (Figs. 8.5 & 8.6). It is interesting to note that Datta et al. (1983) also suggested that the D.S.S. Profile
along the Narmada graben reflects the phenomenon of domal uplift of the mantle beneath the crust in this region".

8.1 C EARTHQUAKE EPICENTRE DISTRIBUTION.

A study of the distribution of earthquake epicentres for the whole of Africa for a period of 1963 - 1970 revealed that in East Africa, the epicentres are closely associated with the recent rift faulting in the ancient Precambrian crust (Fairhead and Girdler 1972). Mueller (1973) carried out seismic refraction and reflection measurements across the Rhinegraben and also reported that the distribution of epicentres generally follow the strike of graben axis. Sutton (1965, cited in Tipnis and Srivastava 1968) suggested that the continental rifts indicate concentration of the earthquake activity along the bounding rift faults.

Tipnis and Srivastava (1968 a,b) observed the presence of seismicity along the Satpura (Narmada) Rift and the West coast and an increased seismicity at their junction. Seismicity along the Narmada Valley, amidst nearly aseismic peninsular gneissic areas was thought to be related to faults (Guha and Gosavi 1974). Krishnaswamy (1976) showed the presence of earthquake activity and deep seated faults along the Narmada - Son - Tapti Lineament. Ghosh (1976) also suggested that the earthquakes located in Koyna, Broach and in Rann of Kutch lie in the rift zones.
Based on the geological, and historical earthquake data (Table 8.1) Padale et al. (1976) concluded that the narrow coastal strip of the West Coast and the Narmada – Tapti Valleys show mild seismicity. They recognised mild seismic activity in recent times along the fault system of southern flank of Narmada Valley and identified an isolated major fault in the Purna – Tapti Valley. Guha et al. (1980) also suggested the central nucleus of the Indian shield to be generally aseismic except the narrow E–W trending Tapti – Narmada – Son zone.

Mohan (1981) identified and catalogued over 200 tremors of 1967 – 77 duration in the Indian Peninsula, ranging in magnitude from 2 to 5, where a prevalence of low magnitude earthquakes (Mercalli scale < 4) suggest their rift origin as against large magnitude earthquake related to destructive and collisional plate boundaries. Guha and Powar (1982) also observed that within the Deccan Volcanic Province, the earthquake epicentres are associated with the major lineaments including the Narmada – Tapti Lineament.

The Broach earthquake which occurred on March 23, 1970 had a magnitude of 6.0 while the intensity reached was VII. Gupta et al. (1972) studied the relationship between recent seismicity and geological structure in the Broach region, and suggested that whereas Cambay basin had been tectonically active throughout the Cenozoic history, the Narmada fault had been dormant during major part of the Miocene period and was re-activated during post – Miocene period. Based on their studies Gupta et al. (op. cit.) drew the
<table>
<thead>
<tr>
<th>Zone</th>
<th>Earthquake Magnitude</th>
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<tbody>
<tr>
<td></td>
<td>3.0-3.9</td>
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<tr>
<td>Cambay Region</td>
<td>3</td>
</tr>
<tr>
<td>Tapti-Narmada-Son Valleys</td>
<td>4</td>
</tr>
<tr>
<td>West Coast</td>
<td>43</td>
</tr>
<tr>
<td>Other parts of Deccan Trap region</td>
<td>8</td>
</tr>
<tr>
<td>East Coast</td>
<td>27</td>
</tr>
<tr>
<td>Offshore Fault System of the West Coast (data from 1950)</td>
<td>20</td>
</tr>
</tbody>
</table>

following conclusions.

i) The Broach earthquake occurred due to movements along some pre-existing faults in the Eocene sediments at a focal depth of about 3 km in the deepest part of the Cambay Graben.

ii) The plane striking ENE - WSW has been accepted to be the fault plane, and the motion corresponding to this fault plane is left-lateral and represents a compressional action or shortening of the crust.

iii) This seismicity is similar to the recent Godavari Valley earthquake sequence of April (1970).

Though the earthquake was said to belong to the Cambay Graben, the ENE - WSW orientation of isoseismals (Choudhary 1970), ground fissures (Guha et al. 1980), other macroseismic features and the related fault plane proves it to be a part of the tectonic activity associated with the Narmada structural grain at the intersection of Cambay Graben and Narmada Rift. Similarity of this earthquake with the earthquake sequence of Godavari Rift and the shallow focal depth of earthquake also prove it a typical rift-related earthquake. Left lateral movement along the fault plane and an associated compressive stress regime represents rejuvenation along the pre-existing rift faults in the present plate tectonic set-up where the Peninsular Shield is transmitting NE compressive force towards the collision plate boundary along the Himalayas. Guha et al.
(1980) suggested that the activity along Tapti - Narmada - Son zone can be attributed to mild shearing in E-W direction. A similar mechanism was also proposed by Chandra (1977) based on a seismotectonic study of some recent earthquakes of Peninsular India. Chandra suggested that the four seismic zones, viz., Panvel, Narmada, Cambay and Girnar are structurally related to four arms of the Khambhat junction as the continental margin flexures and rifts caused by the plume provide zones of weakness along which slippage may occur to generate earthquakes. The focal mechanism solutions are generally thrust or left - lateral strike - slip type indicating that the stress related to the origin of rift structures are no longer active (op. cit.), unlike the East Africa where Fairhead & Girdler (1972) found that the fault plane solutions of rift related earthquake indicate either strike - slip or normal fault mechanisms and no compression. Chandra concluded that the stress distribution is greatly influenced by the collision of the Indian continent with the Eurasia based on the suggestion by Prof. Lynn R. Sykes. According to N.G.R.I. Reports (1977, 1978, cited in Valdiya 1984) the seismicity in Peninsular India is related to the transcurrent faults which can also be explained in terms of rejuvenation or rift faults in the present day stress field.

Besides Broach earthquake, a number of other significant earthquakes have been reported along the Narmada - Son Rift Zone (Chandra 1977). These are:

Son Valley (Rewa) Earthquake, June 2, 1927: Magnitude 6.5
Satpura Earthquake, March 14, 1938: Magnitude 5.5
Balaghat Earthquake, August 25, 1957: Magnitude 5.5

Although the fault mechanisms of these earthquakes were not studied, their occurrence along the Narmada - Son Rift Zone is noteworthy.

8.1 D SEISMIC ZONING.

Indian peninsula is normally regarded as a stable shield which is, by and large, aseismic in nature. Recent studies, however, indicate presence of seismicity in this area. Various attempts have been made to systematically study this seismicity, and divide the Peninsula into a number of seismic zones. Gupta and Mittal (1971) presented a review where various seismic zoning attempts (e.g. Tandon 1953, Guha 1962, I.S.I. 1962, 1966, and Gubin 1968, all cited in Gupta and Mittal 1971) were elaborately discussed. Kaila et al. (1972) prepared quantitative seismicity maps of India and suggested that the Godavari Graben, the Mahanandi Graben and the western and eastern parts of the Narmada - Son - Damodar Graben fall in high seismicity zones. Bombay and Kutch regions were also shown to lie in high seismicity zones (op.cit.) Kaila et al. reported that "The Narmada - Son area has been marked by a maximum intensity of VIII on Gubin's (1968) map, whereas on our map, the western and eastern part of the graben are marked, respectively by intensities VIII and VII, and the central part is marked with intensity VI" (op.cit.).
Padale et al. (1976) prepared a map of seismogenic zones and earthquake epicentres of the Deccan Trap region where Narmada-Son Lineament emerges as a distinct seismogenic zone. Chandra (1977) also demarcated linear belts of moderate intraplate seismicity and discussed their relationship with rifts and rift junctions in the Peninsular India.

Figure 8.7 shows the seismic zoning of India (I.S.I. 1982) slightly modified by Mathur (in press) where seismic zones show increase in seismicity from zone I to V. In this map seismic zones I, II, III, IV and V pertain to the earthquake intensities of V or less, VI, VII, VIII, IX, and above respectively, of the earthquake intensities in Modified Mercalli scale. Entire Narmada-Son-Tapti Rift Zone has been classed as seismogenic in nature, as also indicated by recent seismicity which justifies its grouping in zone III in the I.S.I. map. A remarkable correlation can distinctly be observed where zone III characterizes grabens of central Indian Peninsula and the rifted continental margins (Fig. 8.7 and Fig. 9.4).

8.2 GRAVITY EVIDENCE.

Presence of a narrow belt of gravity anomaly 'Low', superposed over a broad positive anomaly as well as the axial positive anomaly along the Narmada Rift has been shown and interpreted in this Section, in the light of recent developments in taphrogenesis and a new criteria to identify 'failed rifts' is
FIG. 8.7: SEISMIC ZONING OF INDIA (I.S.I. 1982, MODIFIED BY MATHUR, IN PRESS).
proposed.

8.2 A **GRAVITY ANOMALY LOW.**

Bhatia and Subba Rao (1974) studied the Bouguer and Residual gravity anomalies associated with the Gondwana deposits of Damodar, Mahanadi, Satpura and Godavari basins and observed conspicuous gravity lows which were explained in terms of Gondwana sediments filling up the basins. Based on this observation, they suggested that "The Godavari and Satpura basins appear to be of rift-type valleys". Rao (1979) observed negative Bouguer gravity anomalies over the Gondwana basins in the gravity map of N.G.R.I. (1978). Mishra (1982, 1984) focussed attention on the relationship of gravity anomalies with the structure and suggested that the Central India is dominated by anomalies from rift valleys of Gondwana period which show features characteristic of the continental grabens. Verma (1985) identified Bouguer and Free Air gravity anomaly lows associated with the Gondwana grabens of Godavari, Damodar and Narmada valleys and also defined the gravity anomaly highs flanking these lows. He also described the gravity low axes associated with the Mahanadi and the West Bengal sedimentary basins. Asthana and Valluri (1984) studied the South Rewa Gondwana basin lying at the junction of Son, Damodar and Mahanadi Grabens and marked various E-W, ENE-WSW, and NE-SW trending faults on the basis of Bouguer gravity anomaly map and prepared several geological cross-sections to reveal complex structure of the basin. They
suggested that the sediments were deposited in a broad rift evolved as a product of non-orogenetic tensional and gravitational forces of 'oscillatory' epeirogenetic movements in the Indian Shield, synchronous with the Hercynian Orogeny from Late Carboniferous to Cretaceous.

Bouguer gravity anomaly lows pertaining to individual Gondwana rifts have been identified by several authors; these include Godavari Graben (Qureshy et al. 1968, Krishna Brahman and Negi 1973, and Bhatia and Subba Rao 1974), Damodar Half-graben (Verma and Ghosh 1974, Verma et al. 1980), and Mahanadi Graben (Subba Rao 1977, cited in Verma 1985, Mishra and Tiwari 1981, and Mishra 1982).

On the basis of the Bouguer and Residual gravity anomaly data Qureshy et al. (1968) reported a gravity low of the order of 50 mgals associated with the Godavari and Satpura basins and interpreted it as being caused by the great thickness of low density Gondwana rocks. The E-W striking Satpura 'low' centered around Pachmarhi, which correlates with the Satpura Gondwana Basin was essentially the basis for interpreting the 'low' over Godavari Valley as being caused by the great thickness of Gondwana rocks (op.cit.). The estimation of thickness of Gondwana sediments in the Satpura Basin varies from 3.6 km (op.cit.) to 2.7 km (Bhatia and Subba Rao 1974) as against 2.4 km (Fox 1931) based on surface dips of the Satpura Gondwanas.
Kailasam (1979) studied the Bouguer gravity anomaly patterns and suggested that the Narmada - Son Valleys and the adjoining Purna and Tapti Valleys clearly bring out the rift structure as indicated by the fault system and the -50 mgal gravity low in the Narmada and Son Valleys. Kailasam (op. cit.) observed discontinuous and en echelon faults associated with the northern and southern parts of the Narmada - Son Rift and also delineated the E-W fault on its southern margin westwards from Jabalpur. An analysis of the gravity profiles indicated these faults to be of normal type extending deep into the crust (op. cit.).

Valdiya (1984) suggested that the Narmada - Son Rift Valleys show a linear belt of negative gravity anomaly of the order of 50 mgals, which implies a considerable magnitude of mass deficiency as a result of displacement of the denser material from the substratum by a narrow belt of crustal subsidence and/or abundant infilling of low density sediments in the depression. In the parallel Tapti - Purna Valleys similar rift-like characters were discerned, so that the Satpura Hills emerge as a horst characterized by gravity high (op. cit.).

The Bouguer gravity anomaly map of Narmada Rift Zone (Fig. 8.8) clearly displays an E-W gravity low (-70 mgals) southwest of Bhopal which joins the Pachmarhi low (-90 mgal contour) towards the east, the latter being caused by the low density sediments of the Satpura Gondwana basin (Fig. 8.9). The low which continues northeastwards from Pachmarhi shows NE-SW
FIG. 8.8: BOUGUER GRAVITY ANOMALY MAP OF NARMADA VALLEY REGION
(N.G.R.I., 1978)
Fig. 8.9 BOUGUER GRAVITY ANOMALY AND GEOLOGICAL MAP OF NARMADA VALLEY REGION N.G.R.I. 1978
SCALE 1:5 MILLION; CONTOUR INTERVAL 10 MILLIGALS.

INDEX

J  Alluvium & laterite - quaternary
I  Marine transgressions - tertiary
H  Marine transgressions - mesozoic
G  Gondwanas - Up. carboniferous to Lr. cretaceous
F  Sediments of vindhyas, cuddapahs, delhis & equivalents - Up. precambrian

E  Meta-sediments of dharwar and equivalents - Lr. m. precambrian
D  Unclassified granites & gneisses - Lr. precambrian
C  Granites - precambrian
B  Deccan traps - mesozoic to Lr. tertiary
A  Basic intrusives & effusives - precambrian to recent

Gravity lows
trending rift - arm and should be designated as the Son Rift for
the ease of description, though Narmada River flows along this for
quite some distance. NW - SE trending low, south of Pachmarhi is
a northern extension of the Godavari Rift also suggested by Quershy
et al. (1968) and Krishna Brahman and Negi (1973). It is evident
that the triangular Satpura Gondwana basin (Fig. 8.9) coincides
with the Pachmarhi triple junction formed by the intersection of
Narmada, Son and Godavari Rift arms trending E - W, NE - SW and
NW - SE respectively (Fig. 9.4). This triple junction also emerges
on the Free Air gravity anomaly map (Fig. 8.10) where the contours
fluctuate about zero, with wavelengths similar to topographic relief.
The three rift arms with corresponding elongated 'lows' representing
the graben, flanked on either side by the 'highs' showing the rift
shoulders, can distinctly be seen.

Bouguer gravity anomaly profiles (Fig. 8.11) drawn across
the Narmada - Son Riffs (Fig. 8.8) reveal a central low which can
be explained in terms of i) a topographic valley and ii) the low
density sediments within the rifts. Similar interpretations have been
made in the St. Lawrence rift system where gravity anomaly low
( 15 mgal ) was explained by low density sedimentary rocks within
the rifts, while the gravity low in the Saguenay graben was explained
as resulting from downfaulting of denser rock units within the crust
( Duncan and Garland 1977, cited in Kumarapeli 1978 ). Mueller and
Rybach (1974) also interpreted the negative Bouguer gravity of
about 30 mgal over the Rhinegraben in terms of sedimentary filling.
FIG. 8:10: FREE - AIR GRAVITY ANOMALY MAP OF NARMADA VALLEY REGION
(N.G.R.I., 1978)
Fig B-11: Bouguer gravity anomaly profiles across Narmada-Son rifts displaying gravity lows superimposed over a regional (broken line) gravity high.
Progressive widening of the rift zone from east (Fig. 8.11, profile EE') to west (profile AA') can be observed. Step-like gradients in the southern flank of profile DD' is due to the interference caused by the northern extension of Godavari rift low near the Pachmarhi triple junction.

Three Free - Air gravity anomaly profiles drawn across the Narmada - Son Rifts (Fig. 8.10 and 8.12) exhibit lows corresponding to the rift valley, bordered on the both sides by moderate highs representing the uplifted shoulders. Step-like features in these profiles suggest the presence of normal faults characteristic of rifts. Higher magnitude of the southern rift shoulder corroborates with the Satpura uplifted shoulder which, on an average is 200 m higher than the northern shoulder represented by Malwa Plateau and Vindhyan Range.

8.2 B REGIONAL POSITIVE GRAVITY ANOMALY.

Though a narrow zone of Bouguer gravity anomaly 'low' has been identified along the Narmada - Son Rifts, the presence of a regional high has also been indicated by several authors. Quershy (1964), first pointed out a broad positive anomaly zone on the Bouguer gravity anomaly map of India, trending along the Satpura mountain chain. He interpreted the anomaly as representing the horst-like nature of Satpura and upwarping of the subcrust by approximately 240 m. The rather positive bias for the Narmada - Son Lineament,
FIG 8.12: FREE-AIR GRAVITY ANOMALY PROFILES ACROSS NARMADA-SON RIFTS SHOWING GRAVITY LOWS SUPERIMPOSED OVER A REGIONAL (BROKEN LINE) GRAVITY HIGH.
observed in the Isostatic gravity (Woolard 1972, cited in Pal and Sreenivas 1976) was interpreted as downwarping of the crust, or a graben or a positive upper mantle feature. Besides the axis of gravity 'low' related to the Narmada Rift (Krishna Brahman 1975, cited in Pal and Sreenivas 1976), a parallel axis of gravity high (Qureshy 1970) was observed about 100 km further north of it. Murthy (1979) suggested that the linear positive gravity trends of the Indian Shield reflect mantle upwarp, along endogenic crustal fractures, which were possibly channels for the Deccan magmatic activity. Rao (1979) suggested that the Bouguer and Isostatic gravity anomaly maps (NGRI 1978) show the presence of 'Hidden Burrard Ridge' in the form of an upwarp in the subcrustal surface in Central India between the Gangetic trough and the Deccan Plateau, which in all probability should represent the northern part of the domal upwarp related to the Narmada - Son Rifts.

A 'Regionalized Residual Isostatic Gravity Anomaly Map' (which indicates mass irregularities mainly within the crust) prepared by removing the isostatic effect and the effect of the deep seated mass anomaly indicated by the satellite derived gravity anomaly located south of Sri Lanka, showed the Tapti - Narmada - Son zone to be a broad region of gravity 'high' in which Narmada - Son Lineament appears as a narrow 'low' (Fig. 8.13). In other words, the map revealed a narrow 'low' over the Narmada - Son Rifts with broad 'highs' to its north and south (Qureshy and Warsi 1975, Qureshy 1980). Such a distribution of highs and lows led Qureshy (1982) to suggest that a dominant feature of the Tapti - Narmada Son
FIG. 8.13: REGIONALISED RESIDUAL ISOSTATIC ANOMALY MAP OF NARMADA VALLEY REGION. STIPLED REGION CORRESPONDS TO TAPTI-NARMADA-SON MEGALINEAMENT "LOW" WITH PROMINENT "HIGHS" TO THE NORTH AND SOUTH. THIS INDICATES A DOMAL UPWARP WITH A CRESTAL DEPRESSION IN THE MIDDLE (QURESHY, 1982).

FIG. 8.14: SATELLITE-CUM-SURFACE GRAVITY (FREE-AIR ANOMALY) MAP OF INDIA AND CONTIGUOUS REGIONS (MARSH, 1979). TAPTI-NARMADA-SON MEGA-LINEAMENT IS SHOWN BY BROKEN LINE. CONTOUR INTERVAL IS 4 MILLIGAL.
FIG. 8.15 Regional Bouguer anomaly map of India based on third degree polynomial surface (Verma & Subramanyam 1984).
region is a domal upwarp which may encompass parts of the Satpura Hills, Vindhyan Ranges and Malwa Plateau, and would seem to indicate that the Narmada - Son Line is a depression perhaps on the crest of a domal upwarp. This view also appears to be corroborated by the analysis of Ghosh (1976) who stated that the Narmada - Son Lineament represents an erosional post - Deccan Trap Narmada Valley formed at the crest of a domal upwarp with tension features and probably shallow depressions along the crest.

The broad positive gravity anomaly zone also finds expression on the Satellite - cum - Surface gravity map (Fig. 8.14). Since these anomalies are of long wavelength, the causative masses must lie at great depths (Marsh 1979, and Qureshy 1982).

Verma & Subramanayan (1984) prepared regional Bouguer gravity anomaly map of India (Fig. 8.15) which shows two negative zones in the north and south, separated by a positive zone in the central region broadly coinciding with the Narmada - Tapti - Son Rift Zone. A NW - SE trending 'high' along the Godavari Rift can also be seen. Verma and Subramanayam (op.cit.) suggested it likely that "... some anomalous crustal condition such as thinning of the crust, may be responsible for the positive anomaly belt over Central India". Based on the review of gravity anomaly data of the Indian Lithosphere they also suggested the Vindhyan and Satpura mountains to be horst type features (op.cit.).
8.2 C  **AXIAL POSITIVE GRAVITY ANOMALY.**

Strong positive gravity anomalies have been noticed along the Narmada - Son Rift, Cambay Graben, and the West Coast Fault (Fig. 8.16). Based on the similarity with the areas of known volcanic centres of Saurashtra, these anomalies were interpreted as the subsurface occurrence of localized thick Trap bodies around volcanic centres which are distributed along major tectonic lines (Biswas and Deshpande 1973). Development of a narrow axial positive anomaly within the belt of gravity 'low' has taken place in the western part the Narmada Rift (Fig. 8.10). Bouguer gravity anomaly profile (Figs. 8.8 and 8.11, FF') clearly displays this axial gravity 'high' which appears to represent severe thinning of the continental crust and upliftment of Moho. This upliftment can also be seen in the Mehdavadad - Bilimora DSS profile where Moho occurs at a depth of 20 km in the Navsari - Bilimora crustal block (Fig. 8.3 and 8.6).

8.2 D **INTERPRETATION OF GRAVITY SIGNATURE.**

Bouguer gravity anomalies along the continental grabens display a multitude of interwoven 'highs' and 'lows' of varying amplitude ranges depending on the scale of study.

Burke and Whiteman (1977) carried out detailed analysis of selected gravity profiles across uplifts & rifts, and explained the
Fig. 8.16: Map of western India showing major rift zones, positive gravity anomalies, volcanic cones and plugs and northern limit of the Deccan Trap occurrence (after Biswas & Deshpande 1973, redrawn by Ghose 1976).

1 - Areas of positive gravity anomaly due to thick accumulation of basalt, 2 - Limit of the Deccan Trap (surface and subsurface), 3 - major fault, 4 - Location of volcanic cones and 5 - Location of volcanic plugs.
gravity signatures of active and inactive rifts (Fig. 8.17). Certain characteristic distribution patterns of gravity anomalies associated with rifts are also given in figure 8.18. A comparison of these profiles with that of Narmada - Son Rifts reveal that the latter shows a regional gravity 'high' and a central gravity 'low' (Fig. 8.11) unlike the active rifts which show a regional gravity 'low' which may be further attenuated in the central part by the presence of low density rift sediments (Fig. 8.17 a,b,c,e,f; and Fig. 8.18 a,b,c). A broad similarity of the Narmada Rift although it is much wider in extent, with that of the Rhinegraben, the Baikal Rift and the Hon Graben (Fig. 8.18 d,e,f) may be seen but it is only superficial because even these rifts display a regional gravity 'low' when viewed in totality, unlike the Narmada Rift with a regional gravity 'high'.

Based on the aforesaid observation, which is vital in understanding the process of crustal upwarping and rift development, author has proposed a new criteria to distinguish between 'active' and 'inactive' rifts. The new model discussed below, answers in affirmative, the question of Girdler (1978) who observed a well defined long wavelength negative Bouguer gravity anomaly over the East African Rifts, unlike the Oslo palaeorift and pondered: "Is it possible that this is a feature associated with recent and active rifts?"
Fig. 8.17: Selected gravity profiles across uplifts and rift structures (after Burke and White 1977). Active rifts and uplifts are associated with broad negative anomalies (a-f) which may be accentuated by sediment fill (e,f). An axial positive anomaly may also occur (d). Inactive rifts may display negative anomalies due to sediment fill (g) or narrow axial positive due to intrusives (h,i,j).
Regional crustal domal upwarps, commonly associated with rifts, alkaline basalts, and regional negative gravity anomalies are caused by widespread thermal perturbation (hot-spot or asthenolith) in the upper mantle part of lithosphere (60 - 120 km) resulting in lowering of density and increase in volume due to the basalt magma generation by partial melting and phase transformation (Thompson 1976, Burke and Whiteman 1977, and Logatchev 1978). Associated long wavelength negative Bouguer anomalies have been reported along the Rio Grande Rift (Bridwell 1978), the East African Rifts (Girdler et al. 1969, Searle and Gouin 1972, Girdler 1978, Darracott et al. 1972, 1978), the Baikal Rift (Puzyrev et al. 1973, Zorin 1981) and the Rhinegraben (Mueller 1968 and 1970, cited in Fuchs 1974). Such a gravity low of about 1000 km width over the East African Rifts, and similar lows over other rifts mentioned above, have been interpreted in terms of thinning of lithosphere and emplacement of low density - low velocity asthenosphere. Puzyrev (1973) and Zorin (1981) reported that the Baikal Rift zone is underlain by 20 km thick anomalous mantle of about 250 - 300 km width with 7.7 to 7.8 km/sec P-wave velocity as compared to 7.7 to 8.1 km/sec under the adjoining Siberian Platform. Based on a study of earthquake phases in Ethiopia, Searle and Gouin (1972) suggested that the upper mantle here is of low density (7.4 km/sec), probably has a high temperature, and is rather plastic. Teleseismic studies also indicated areas of anomalous mantle (Pv ≤ 7.4 km/sec) to a depth of 300 km beneath the uplifted
part of the East Africa which is traversed by the rift system (Thorpe and Smith 1975). An anomalous low velocity body in the subcrustal lithosphere in a depth range of 50 - 150 km has also been reported in the Western Rheinish Massiff (Fuchs et al. 1985).

The asthenospheric intrusion into the upper mantle part of lower lithosphere in the active rifts, also explains the upliftment of Moho and regional crustal domal upwarps as an isostatic response to this mass deficiency (Burke and Whiteman 1977). Such updowning crust - mantle boundary has been shown along the Rhinegraben (Fuchs 1974, Meissner and Vetter 1974, Fuchs et al. 1980 and Illies 1981a), Kenya Rift (Griffiths 1972), Gregory Rift (Long et al. 1973), Baikal Rift (Puzyrev 1973 and Zorin 1981), and the Basin and Range Province of the U.S.A. (Condie 1976, and Artyushkov 1980).

The regional gravity low described above may be attenuated along the rift proper by the presence of low density rift sediments, or may be superimposed by a narrow positive anomaly zone. This 40 - 80 km wide 30 - 60 mgal positive anomaly in the parts of East Africa Rift System (Fig. 8.18 b,c) has been explained in terms of the presence of 20 km wide dense basic intrusion about 3 km below the rift floor (Girdler 1969). This interpretation was neatly confirmed in 1971 by a seismic refraction line along the Kenya Rift which showed a high velocity of 6.4 km/sec at a shallow depth of 2.8 ± 0.5 km (Girdler and Searle 1975). In this way, the wide negative anomaly and smaller superimposed positive anomaly can both be explained by different parts of the same body, the density
contrast being negative with respect to the lower lithosphere (Upper Mantle) and positive with respect to upper lithosphere (Sialic Crust). Support for this model also comes from geomagnetic, D.S.S. studies in Kenya, seismic travel time anomalies, attenuation of Sn waves, and surface wave velocities. Based on all the above findings, Fairchild and Girdler (1972) and Darracott et al. (1972) proposed a model of the lithosphere of continental rifts (Fig. 8.19) which, in the opinion of the present author applies only to the active rifts.

It is suggested here that in the 'Palaеorifts' or 'failed rifts', the low velocity upper mantle will cool down and display near normal upper mantle velocity. However, the densification of crust by the magmatic impregnations during the asthenospheric upwarp phase resulting in the upliftment of subcrustal layers, will now impart broad positive gravity anomaly (more so in a broad failed rift zone) unlike a broad negative gravity anomaly seen along the active rifts. This process has been described by Artyushkov (1981) who inferred that during the rifting phase, crust should be underlain by low velocity - low density anomalous mantle strongly heated upto the melting point of basaltic material (~1200°C); and that this strongly heated mantle material from a depth of 100 - 150 km intrudes the crust. But when the rifting process culminates (i.e. the thermal plume dies out or the continental plate moves away), and the temperature reduces to 700 - 800°C in the basaltic layer of the crust, the gabbro - eclogite phase transition takes place which increases the density of the
FIG. 8.19 The Bouguer gravity anomaly over the rift zone in the neighbourhood of the equator. The model (One possible interpretation) shows thinning of the lithosphere (crust and upper mantle) and emplacement of lower density asthenosphere. Details of the model including specific gravities are shown in the lower diagram. (After Fairhead and Girdler 1972).
rocks ( _op. cit._ ).

In all other respects the gravity signatures of 'active' and 'aborted' rifts will be similar and the presence of a belt of negative gravity anomaly (due to the low density sediments and air gaps) and a narrow positive anomaly (due to axial dyke intrusion) in the aborted rifts will reflect the stage in which it became inactive. In context of the recent structural model of the Mid–Atlantic Ridge (Sub-section 8.1 Bc) it is evident that the absence of a sharp velocity jump (6.9 to 8.1 km/sec) of the Mohorovicic discontinuity and the development of intermediate velocities (Fig. 8.6) shows the upliftment of palaeo–Moho along the Narmada Rift Zone.

8.3 _GEOTHERMAL EVIDENCE_.

Continental rifts are characterized by increased heat flow (Girdler 1963) with high heat flow value of about 2 $\mu$ cal/cm$^2$ sec (HFU) as compared to the shield areas which display normal heat flow values from 0.9 to 1.1 HFU (Condie 1976).
The high heat flow measurements, presence of thermal springs and extensive coalification associated with the Gondwana grabens of the Peninsular India in general and the Narmada - Son Rifts in particular, are considered to be related to the rifting process which was responsible for the formation of these grabens.

8.3 A **HEAT FLOW STUDIES.**

The heat flow measurements of Peninsular India (Table 8.2) reveal an average value of 1.81 HFU for the Gondwana basins as against 1.12 HFU for the Precambrian Shield, which can be explained in terms of higher geothermal gradients during Late Mesozoic to Tertiary rifting accompanied by volcanism and subcrustal intrusions. High heat flow in the Cambay basin was explained as due to igneous intrusion in the crust underneath the basin during Pliocene - Miocene times (Gupta et al. 1970).

- Movement of ground water and hydrothermal fluids along the rift related faults and fractures may act as carriers of heat from the lower crust to the upper parts generating an anomalous thermal regime. Lower average of 1.81 HFU for the Gondwana Basins appear to be justified in view of the older age of Gondwana rifting as compared to the average heat flow of about 2.0 HFU for the Cenozoic continental rifts. Support for higher palaeotemperatures along Gondwana rifts also comes from extensive coalification in these sediments, when viewed with reference to the findings of Auntebarth (1978 - 79, cited in Neugebauer and Temme 1981) who, on the basis of degree of coalification showed higher geothermal
<table>
<thead>
<tr>
<th>Basin/Area</th>
<th>No. of Heat Flow Observations</th>
<th>Heat Flow, M°C/M</th>
<th>Heat Flow, μcal/cm²/Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precambrian Shield</td>
<td>9</td>
<td>14.22</td>
<td>1.12</td>
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<tr>
<td>Andaman Basin</td>
<td>6</td>
<td>106.34</td>
<td>2.10</td>
</tr>
<tr>
<td>Cambay Graben</td>
<td>617</td>
<td>43.52±14.77</td>
<td>1.80±0.44</td>
</tr>
<tr>
<td>Gondwana Grabens</td>
<td>29</td>
<td>30.02±5.77</td>
<td>1.90±0.17</td>
</tr>
<tr>
<td>a. Godavari</td>
<td>7</td>
<td>36.75±3.47</td>
<td>2.06±0.40</td>
</tr>
<tr>
<td>b. Damodar</td>
<td>6</td>
<td>34.52±8.43</td>
<td>1.77±0.09</td>
</tr>
<tr>
<td>c. Son - Mahanadi</td>
<td>2</td>
<td>25.90</td>
<td>1.93</td>
</tr>
<tr>
<td>d. Satpura (Narmada)</td>
<td>14</td>
<td>25.90</td>
<td>1.80</td>
</tr>
<tr>
<td>Continental Margin Basins</td>
<td>43</td>
<td>33.75±9.03</td>
<td>1.77±0.47</td>
</tr>
<tr>
<td>a. Bombay Offshore</td>
<td>19</td>
<td>41.51±15.04</td>
<td>1.81±0.64</td>
</tr>
<tr>
<td>b. Kerala Laccadive</td>
<td>3</td>
<td>25.20±3.17</td>
<td>1.39±0.18</td>
</tr>
<tr>
<td>c. Cauvery (Palk Strait)</td>
<td>3</td>
<td>43.10±1.48</td>
<td>2.37±0.10</td>
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<tr>
<td>d. Cauvery Basin</td>
<td>11</td>
<td>23.34±3.75</td>
<td>1.24±0.09</td>
</tr>
<tr>
<td>e. Krishna-Godavari Basin</td>
<td>4</td>
<td>43.73±15.97</td>
<td>2.41±0.39</td>
</tr>
<tr>
<td>f. Bengal Offshore Basin</td>
<td>3</td>
<td>25.62±9.73</td>
<td>1.41±0.54</td>
</tr>
</tbody>
</table>
gradient of 75 °C/km during the Upper Eocene - Lower Oligocene in the Upper Rhinegraben.

On the basis of temperature data measured in a very large number of boreholes geothermal gradient map and surface heat flow density map of Indian Peninsula as well as isotherms at depth of 500, 1000 and 2000 m have been prepared and presented (Gupta and Sharma, 1984). However, any inferences may only be drawn after the publication and release of these maps.

8.3 THERMAL SPRINGS.

Werner (1970) studied the geothermal anomalies of Rhinegraben and suggested that high heat flow is caused by thermal waters circulating within joints of the fracture zones near the graben borders. The open fractures associated with rifts enable the hydrothermal convection and positive heat flow anomalies which, in addition to the hot springs characterize active rift valleys (Illies 1981a).

N.G.R.I. identified following geothermal provinces in the Peninsular India (Gupta et al. 1982)

i) Narmada - Son - Dauki Geothermal Province

ii) Cambay graben Geothermal Province

iii) Godavari Valley Hot - Spring Area

iv) Konkan Geothermal Province
Rao et al. (1977) reported the presence of eight hot springs in Mailaram - Bhadrachalam area of Godavari Valleys. The temperature of five springs, which are from fissures and joints in Kamthi sandstones and conglomerates, is about 28 – 30°C. The temperature of two springs is 41°C and 43°C, one of which is surrounded by Kamthi - Vindhyan boundary. Maximum temperature of 80°C has been recorded in a spring near a NW – SE fault in the Godavari river bed (op.cit.). Rao et al. (1970) suggested that the high heat flow value at Chintalpudi and Aswaraopet in Godavari Valley may be due to hot water rising up from the deep interior along faults in the Precambrian basement. Gupta et al. (1982) pointed out that a part of Godavari Valley has large reserves of low enthalpy thermal waters and that some wells drilled for ground water resources have trapped thermal waters up to 65°C.

Hot - springs occur along NNW – SSE trending zone of Konkan foot hills over a distance of 320 km (Auden 1975).

The available data pertaining to Narmada - Tapti geothermal province cover only the Gondwana sediments uplifted in the Satpura horst and proved in the bore holes drilled at Mohpani and Lamua (Krishnaswamy 1976). In these two holes, the geothermal gradient has been found to be near normal at 23°C/km. It is necessary to record the thermal gradients and heat flow in holes, located in the graben, both to the north and south of the Satpura horst, where fault - aligned thermal springs are known (op.cit.). A few hot springs also occur between Broach and Central part of the Narmada
rift zone (Kailasam 1979). Varia (1982) suggested that the hot springs are present along the Narmada - Tapti rift zone but available meagre geothermal data suggests normal geothermal gradients.