Contrasting deformational systems and associated seismic patterns in Precambrian peninsular India

T. R. K. Chetty
National Geophysical Research Institute, Hyderabad 500 007, India

Distinct geodynamic settings of the precambrian peninsular India exhibit contrasting deformational systems and associated seismic patterns. The architecture of Archaean Dharwar craton, characterized by a mosaic of block structure evident from various geological features, suggests continued tectonic activity since the Precambrian, making the region vulnerable to seismic activity. Block rotation seems to be a plausible model for explaining the mechanism of the Latur earthquake considering its structural fabric and associated geomorphic features. The role of shear zone dynamics appears to be significant in understanding the seismic patterns in the Precambrian mobile belts like the Southern Granulite Terrain (SGT). The interface between the Dharwar craton and the SGT is marked by a crustal-scale shear zone system, namely the Cauvery Shear Zone (CSZ) with prolonged deformational history. The role of the CSZ in understanding the major geomorphic ridge, which lies just north of the CSZ, and associated seismicity, is examined. A new tectonic hypothesis is proposed involving a north-verging blind thrust emanating from the base of the CSZ, which would be responsible in generating the geomorphic ridge, and associated seismic activity. Northward movement of the Indian plate seems to be the root cause of continued tectonic activity in the Indian shield, but differs in the deformational systems depending on their crustal architecture of distinct geodynamic settings.

Keywords: Block rotation, deformation system, Precambrian, reactivation, blind thrust.

THE deformational systems in the earth's lithosphere are characteristically heterogeneous on all scales. Deformation in the continental lithosphere is further broadly diffused across high strain zones of hundreds of kilometres, delineating distinct geodynamic settings. These settings typically comprise domains, regional as well as local, where fault- and shear zone-bounded blocks partition strains into a series of complex displacements, internal strains and rotations in response to far-field plate tectonic processes and large-scale body forces[1]. The pre-existing structures in the continental crust such as old faults and shear zones, which are long-lived zones of weakness tend to reactivate repeatedly, accommodating successive crustal strains often in terms of seismicity and new zones of displacement[2]. The Indian peninsula provides a classic example of Precambrian deformational systems on all scales and their reactivation tectonics and the associated seismic patterns.

The exposed part of the Indian peninsula broadly comprises diverse crust deformation systems (2500–500 Ma) represented by Archaean Dharwar craton, Precambrian mobile belts, intracratonic sedimentary basins, and Godavari and Mahanadi rift structures[3]. They represent distinct geodynamic settings. The Dharwar craton comprises granite–greenstone terrains of variably deformed assemblages of mafic volcanic/plutonic rocks/metasedimentary sequences, remnants of older quartzo-feldspathic gneissic rocks and abundant late granitoids. The Southern Granulite Terrain (SGT) and the Eastern Ghats Mobile Belt (EGMB) represent Precambrian mobile belts constituting multiply deformed and metamorphosed high-grade gneisses, which occur to the south and along the east coast respectively. While the craton is dominated by block rotation dynamics related to large-scale strike-slip shear zones, the mobile belts are marked by early fold-thrust tectonics followed by subsequent large-scale transpressional tectonics. Interestingly, the interface between cratons and mobile belts is a crustal-scale shear system, namely the Cauvery Shear Zone (CSZ), associated with Palaeoproterozoic thrusting and late Neoproterozoic transpressive tectonics[4]. Extensive alkaline and anorthositic (mantle-derived) magmatism (1400–650 Ma) and intrusions of granitoids (700–800 Ma) are a common feature along the shear system. The spatial pattern of seismicity in the Indian peninsula[5,6] reveals that seismicity is spatially related to the major tectonic elements such as shear zones/fault systems, terrane boundaries and rift structures and is well reflected in significant geomorphological changes. In view of the Precambrian crust formation ages, the low deformation rate and relatively less magnitude of seismic events, the region of the Indian peninsula is also considered as a Stable Continental Region[7]. This article aims to review the nature and characteristics of regional deformation systems and associated seismic patterns in the Precambrian Indian peninsula and focuses

e-mail: chettytrk@yahoo.co.in

on three geodynamically distinct regions such as East Dharwar craton, mobile belt, and the interface between the two, choosing critical areas. We present our results from: (i) typical cratonic region reflecting block rotation tectonics citing Latur earthquake as an example, (ii) shear zone tectonics of SGT, and (iii) geomorphic ridge along 13°N latitude-parallel lying at the interface between the craton and the mobile belt, invoking a new concept of blind thrust resulting from the far-field tectonic stresses.

Regional tectonic setting of the Indian peninsula

A tectonic map of the South Indian shield (Figure 1) has been compiled by bringing together all the available information, mostly based on the author's own interpretation and results[8]. This map basically incorporates structural interpretation of Landsat TM data on 1 : 1 million scale and reconnaissance field traverses in conjunction with the published geological maps. The major geological units in this part of the Indian shield are Archaean granite–greenstone sequence of Dharwar and Bastar cratons, which are skirted by Precambrian mobile belts, namely the EGMB along the east coast of India, and the SGT in the south. These cratons are separated by NW–SE trending Godavari rift filled with coal-bearing Gondwana sediments. Narrow linear belts of high-grade gneisses shoulder the flanks of the Godavari rift on either side. The Mahanadi rift, comprising Gondwana sediments associated with coal seams, separates the Singhbum craton to the north, the Bastar craton to the west and the EGMB to the south. It is observed that the EGMB which trends NE–SW all along, gradually takes a southeasterly trend near Ongole and disappears in the Bay of Bengal. It re-emerges near Madras (Chennai) and forms a part of the SGT. The Proterozoic Cuddapah sedimentary basin overlying the East Dharwar craton, occurs at the bend adjacent to these mobile belts, suggesting its genetic link with the tectonometamorphic history of these mobile belts which are developed likely due to Precambrian continent–continent collisional processes.

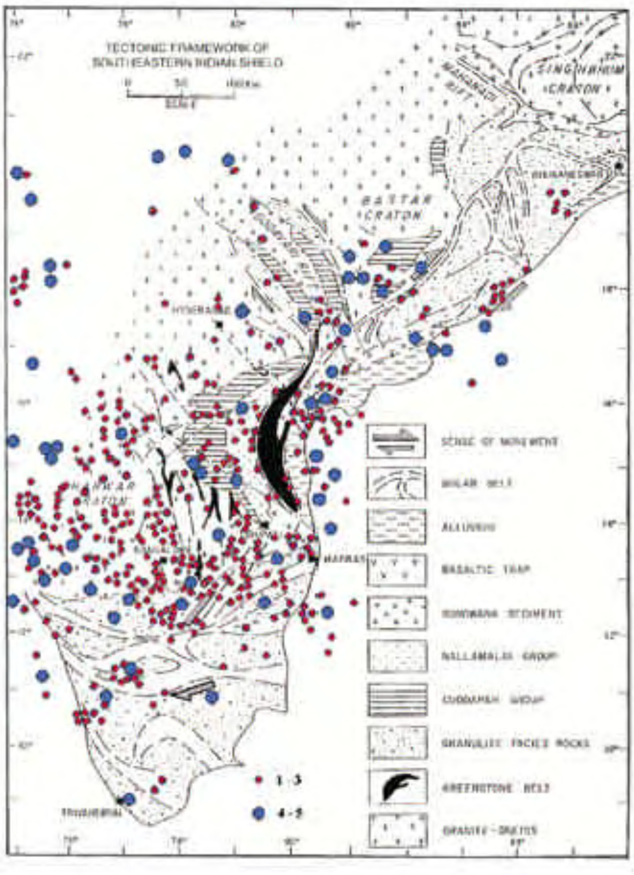

Figure 1. Tectonic map of Precambrian Indian peninsula showing distribution of earthquake epicentral locations. Note the broad correlation of seismicity with major Precambrian geological boundaries, shear zones and graben structures.

The Archaean Dharwar craton, in general, is characterized by two orthogonal systems of shear and fault zones. The former is associated with NW–SE trending linear granite–greenstone belts, particularly at the boundaries, while the latter trends NE–SW, is discontinuous and often filled with mafic dykes. The structural framework obtained by shear systems and fault zones controls the development and evolution of the drainage pattern.

One of the most remarkable features in the Precambrian mobile belts is the presence of a network of Proterozoic shear zones. While the shear zones in the SGT are broadly curvilinear but dominantly striking east-west, the shear zones in the EGMB show varied orientations despite their linear geometry[9,10]. The shear zones in the EGMB are: NE–SW in the southern part, E–W in the northern part, and nearly N–S in the central part, which are nearly orthogonal to the regional trend. The shear zones in the mobile belts vary in their size, geometry and attitude in depth. The recognition of shear zones has resulted in major reinterpretation of structural history, tectonic style and has produced new models providing insights into their crustal evolution[11,12]. It has been well established that several processes like partial melting, mixing with fluids transmitted through shear zones and strain variations combined with rheological properties affect the rocks in the shear zones.

Regional seismic patterns

The Indian peninsular shield region has been considered as a stable land mass and the seismicity is assumed to be low, although micro earthquakes are reported, particularly at its margins[13]. However, historical seismicity and the experience of about 11 earthquakes of magnitude $M > -6.0$ since the 18th century[14], clearly reveal that the Indian shield is not stable as considered earlier. This is particularly evident from recent disastrous to catastrophic earthquakes such as Koyna of 1967, Latur of September 1993, Jabalpur earthquake of 1997, etc. The plot of epicentral data (Figure 1) shows moderately distributed seismicity in the region. The regional distribution appears to be more of cluster nature in the Dharwar craton while it is more diffused in mobile belts such as the EGMB and the SGT. Close examination indicates a fair concentration of events at the contact zone between the Dharwar craton and the SGT. This zone has also been geologically described as the transition zone from amphibolite facies to granulite facies metamorphism. Interestingly, a seismic belt of moderate seismicity has been identified along this zone[15]. Seismicity is also more pronounced along the coastal zones, while it is isolated and clustered and mostly restricted to major shear zone systems within the EGMB and SGT. A broad correlation of seismicity with Precambrian geological boundaries, shear zones and fault patterns seems to be plausible as the sites of reactivation. The reactivation tectonics might have resulted in neotectonic movements, geomorphic rejuvenation, peculiar drainage patterns, anomalous river responses and the observed seismicity pattern[16].

Block rotation tectonics in the East Dharwar craton

The Archaean crust in the East Dharwar craton (EDC), west of the Proterozoic sedimentary basin in the southern part of the Indian peninsula, consists of granite–greenstone–gneiss terrain and is dissected prominently by two major subvertical shear zones and fault systems. They include: NW–SE trending shear zones associated with linear greenstone belts and NE–SW trending brittle shear systems often occupied by mafic dykes, quartz reefs, pegmatites and epidote veins. Besides, the terrain has also witnessed periodic pulses of intense dyke activity (2200–80 Ma) in varied dimensions and orientations, and the emplacement of kimberlites (1100 Ma). Based on the regional structure revealed by Landsat data, and several important structural details, a small region in the central part of the EDC was studied for details. From the aerial photos followed by limited field studies, a tectonic model, i.e. sequence of events with their results, was envisaged broadly in two regimes: first, in the development of mosaic of blocks, and secondly, in the rotation of blocks about the vertical axis[17]. The mechanics of block rotation cause spatial and temporal heterogeneities at the block and domain boundaries, which are intrinsically linked to fault kinematics[18]. The model also implies slow and prolonged tectonic processes, shallow-level internal deformation (~ 10 km depth), local stress variations, fault reactivation and generation of a new set of faults (splays) in the proximity of older faults. Block rotations are interpreted to be responsible for moderate earthquakes as well as recent geomorphological changes. The Indian peninsula has witnessed significant geomorphological changes such as anomalous drainage patterns, river diversions, stream capture, etc.[19]. All these features indicate that the region has been subjected to continuous tectonic activity, resulting in reactivation tectonics in space and time along the pre-existing Precambrian structures, reflecting the crustal deformation and uplift often associated with spatially restricted seismicity.

Block rotation tectonics and the Latur earthquake: an example

The Latur earthquake of 30 September 1993 with magnitude 6.3 on the Richter scale represents a typical example of 'Stable Continental Region' (SCR) earthquakes[20]. The Latur earthquake was one of the eleven SCR events, which generated a surface rupture zone of ~ 500 × 100 m dimension. Geologically, the area occurs in the extended part of the Archaean EDC in the north, covered by the eastern fringes of 65 Ma-old Deccan traps of varying thickness (300–500 m). The seismicity is mainly restricted to the east-west trending part (~ 10 km) of the Tirna river course. Geomorphic features, associated fault patterns and a detailed account of fresh surface deformation are well described by several workers[20,21]. Fault plane solutions indicate thrust faulting along the SW-dipping plane (~ 45°)[20].

Two major sets of lineaments trending NW–SE and ENE–WSW are inferred from satellite data[21] revealing a well-developed mosaic of block structure (Figure 2), similar to that described in the EDC. Orientation of structural and lineament fabrics in the Latur region mimics those of the adjacent pre-Deccan basement regions. It is most probably the reflection of structural inheritance of the basement. The mechanism for this transmission is probably related to movements along the reactivated ancient structures in the basement exerting profound control in generating fractures and small-scale displacements in the overlying basalts. While some of the inferred lineaments terminate against the east-flowing Tirna river course, sinistral strike-slip displacements could be seen along the ENE–WSW lineaments. Gravity maps[22] exhibit many localized gravity highs and lows of 3–5 mgal coinciding with the major NW–SE striking lineaments in the region. The geomorphic features associated with Tirna river[21] indicate that it follows a tectonically active lineament. Further, several archaeological sites along NW–SE trending lineament are also observed along the Tirna river. Rajendran and Rajendran[23] inferred that one ancient earthquake of AD 450 had occurred around one such archaeological site near Thair.

Examination of the Tirna basin and its morphology reveals the shift and migration of the river course in an alternating changing fashion (Figure 3). Migration of the river course is inferred based on the imaginary midline drawn on the basis of the symmetry of the river basin. In the northwestern part, the river course is east-west, and the migration is towards south. The migration direction changes in accordance with the change in direction of the river course. Further, it is also evident that the lineament fabric pattern influenced the river course (Figure 2). Interestingly, the location of the archaeological site at Thair, lies at the intersection of two major lineaments. The topographic profile along the Tirna river (Figure 4) shows steep gradient until the river takes an eastward direction, 10 km west of Killari. The gradient becomes zero near Killari and further east. There is a gradual change not only in the gradient, but also in the regional topography from ~ 700 m in the northwest to 500 m in the east. The main shock and aftershock activities are restricted to the region of lower elevation. Considerable influence of the lineament fabric on the topography, drainage pattern as well as on the river gradient is evident.

In summary, the tectonic fabric of Latur earthquake region presents close similarities to the structural fabric of the exposed granite–gneiss terrain of the EDC. The lineament pattern and fault systems inferred from the satellite data suggest that the area is divided into a number of blocks and that the fault reactivation tectonics played a crucial role in generating the present structural fabric of the terrain[21]. Earthquake data of the region also suggest movement along a NW–SE fracture at depth[24], indicating recent reactivation of NW–SE trending Precambrian crustal weak zones beneath the Deccan traps.

The plot of aftershocks (220) recorded by Gupta *et al.*[25], originated within a depth of 8 km, when plotted, does not define any orientation but is remarkably restricted

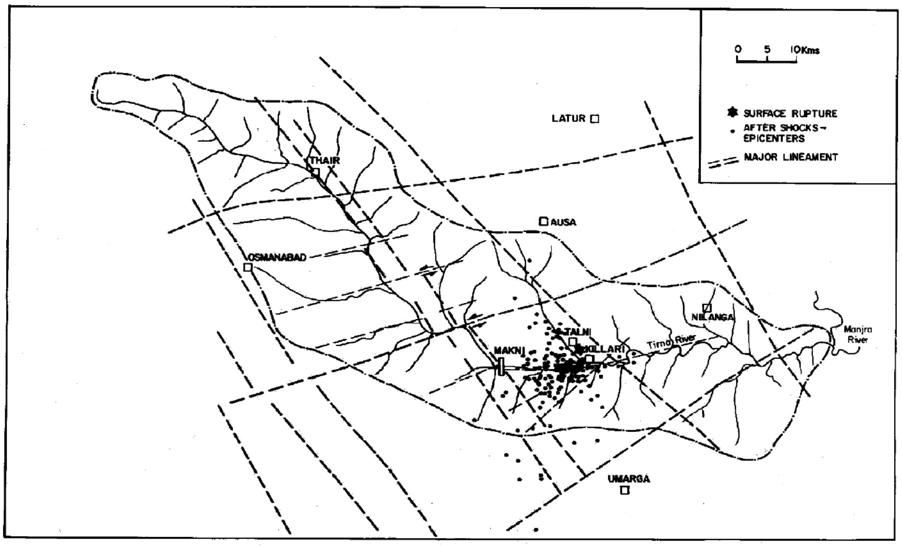

Figure 2. Morphology of Tirna River basin and satellite-derived lineament fabric dividing the area into a mosaic of block structures.

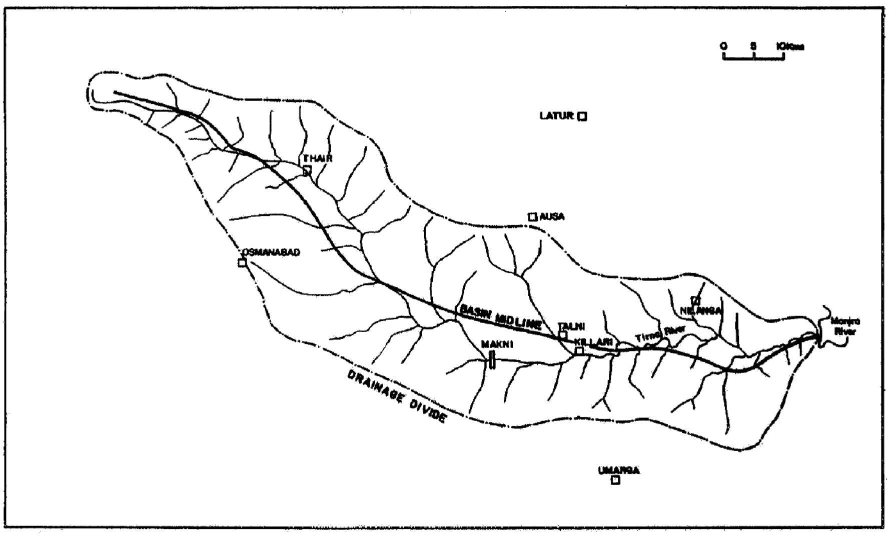

Figure 3. Drainage morphology of Tirna river basin showing the migration of river course.

to a block structure bound by lineaments (Figure 2). Several workers[20] recorded aftershocks during a limited period for an area of 5 × 15 km and inferred a narrow zone of hypocentres dipping 45°SW. However, the scattered data-points were interpreted as the growth of the aftershock zone[23]. Based on geomorphic characteristics of Tirna river and locations of archaeological sites, complex surface deformational features and the shallow focal depth consideration, we suggest that block rotation tectonics about the vertical axis seems to have played a crucial role in causing such a deadly earthquake of magnitude 6.3. The block structure of the basalts also shows considerable influence on the behaviour of seismic waves across the block boundaries. The seismic energy might have been channelled along the boundaries and interfaces amongst different compositional flows. We opine that the block rotation model for the basement tectonics could be responsible for the continued tectonic activity in EDC and in turn the inherited structural fabric and reactivation tectonics in the overlying Deccan traps.

Tectonic framework of the SGT

The high-grade terrain occurring at the southern tip of India, popularly known as the SGT, consists mainly of late Archaean charnockites, quartzo-feldspathic gneisses, high-grade supracrustals and a variety of younger intrusions such as alkaline-anorthositic rocks and a variety of granitoids (~ 700 Ma). The SGT is considered as an ensemble of fragmented and imbricated crustal blocks separated by east-west trending crustal-scale shear-zone systems, which include the CSZ and the Achankovil shear zone. Details of lithology, structure, geochemistry and various geophysical datasets along a north-south corridor (Kuppam–Palani) across a major part of the SGT, have been recently presented by Ramakrishnan[26].

Structural interpretation of Landsat TM data covering the SGT, on 1 : 1 million scale reveals large-scale geological features which include broad lithologies, shear zones, regional fold forms and a variety of lineaments depicting shear planes, foliation trends, etc. (Figure 5). The shear zones, remarkably well displayed on the images include: (i) Moyar–Bhavani–Mettur; (ii) Salem–Attur and (iii) Chennimalai–Noyil–Cauvery, which are together considered here as the CSZ, and (iv) the Achankovil shear zone. The prominent E–W trending CSZ (60 × 350 km) separates the Archaean Dharwar craton to the north and the precambrian SGT to the south. They are expressed in variable bright tonal characteristics, probably representing different lithologies and different depths of erosion. Major river courses follow mainly the shear zones. The disposition, regional geometry, remarkable variation in foliation trajectories, consistent dextral kinematic patterns and the contemporaneity of mylonitic fabrics suggest that the shear zone network in the CSZ could represent a crustal-scale ‘flower structure’[4]. These features are consistent with the model of regional late Neoproterozoic transpressional tectonics in a convergent regime. However, Quaternary movements are also reported along these shear zones, as is evident from the displacements of alluvial tract in the east coast.

Seismicity patterns in the SGT

The distribution of epicentral data of historical seismicity[15] shows random nature (Figure 5), irrespective of the magnitude of the earthquake events. However, they are certainly more densely distributed in the northern parts, north of 12°N, particularly in the central region. The striking feature is the absence of magnitude 5 and above in the region except the one that is located in the proximity of the Bhavani shear zone. The other events with less magnitude, although scattered, are mostly confined to the vicinity of the shear zones. For instance, they are seen in the northeastern extremity of Achankovil shear zone; southern foothills of Kodaikanal Hills, a major thrust plane, southwest of Madurai, northwestern part of Moyar shear zone, and along the Salem–Attur shear zone. In general, all the events seem to have spatial association with some shear zone or the other, suggesting their recent reactivation. The northward-directed thrust movement must have transferred partially as strike-slip displacement along the reactivated shear zones and/or fault

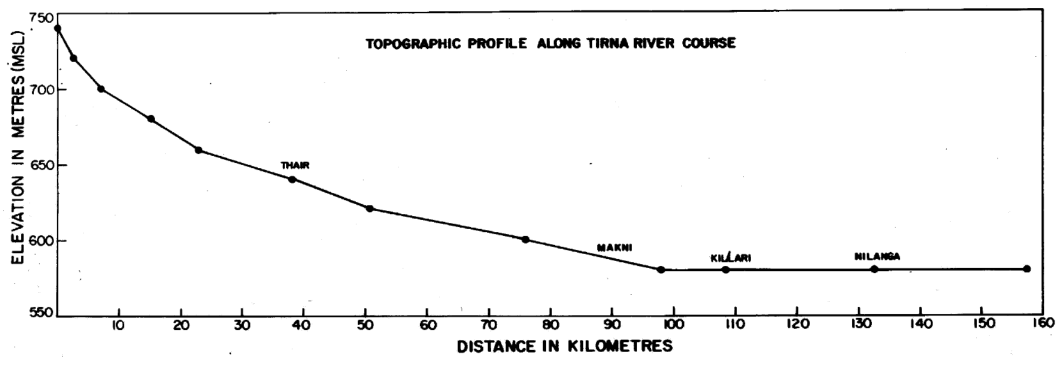

Figure 4. Topographic profile along Tirna river showing steep gradient before becoming flat.

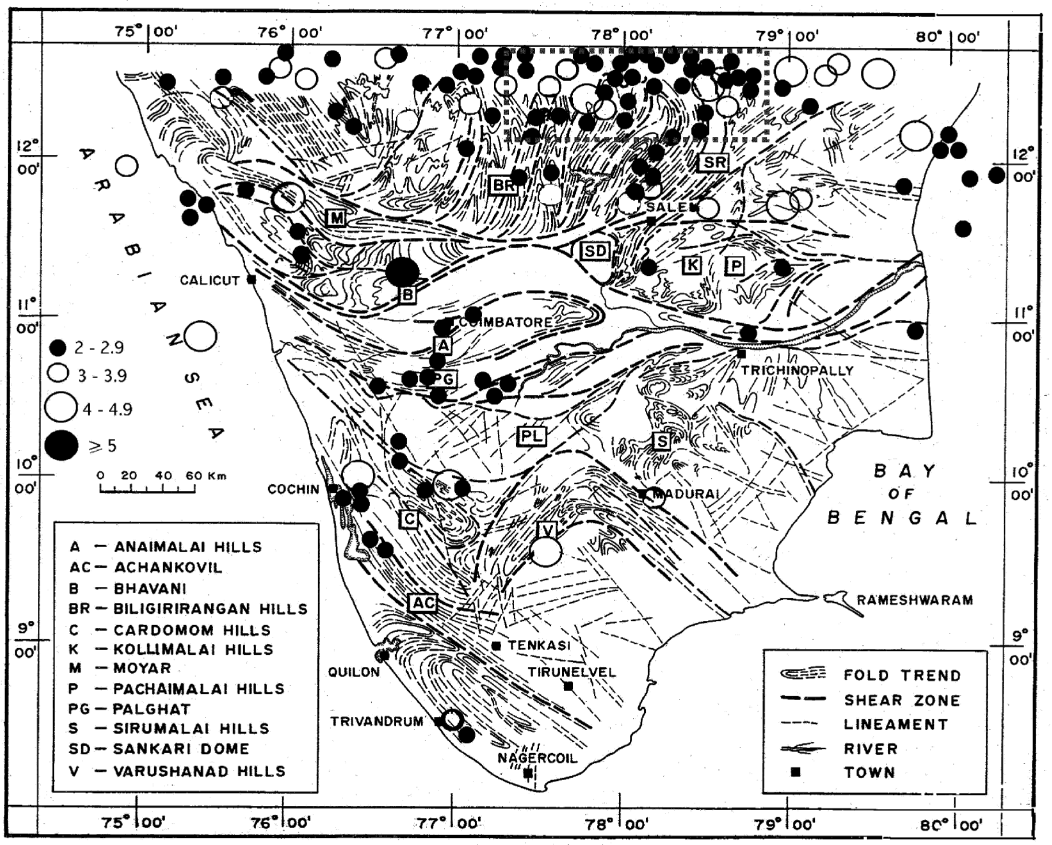

Figure 5. Structural interpretation of Landsat TM data over the Southern Granulite Terrain showing shear zones, fold forms, lineaments and associated seismicity. The block indicated by dotted line on top of the figure is enlarged in Figure 6.

zones of Precambrian antiquity. It is also interesting to note the occurrence of epicentres in the western part of the SGT along the west coast (Kerala region), which seems to be associated with pre-existing faults and shear zones[27].

More detailed analysis of tectonic elements and associated seismicity in a part of the transition zone is depicted in Figure 6 (for location see Figure 5). The region is considered to be at the junction of the Dharwar craton and the SGT. The important rock types include the presence of Archaean Kolar greenstone belt in association with east-west trending mafic dykes surrounded by younger plutons of granite. The other features in the northern part of the NE–SW trending Mettur shear zone are marked by extensive alkaline magmatism in the form of a chain of plutons (~ 780 Ma) associated with dextral sense of movements and late Neoproterozoic reactivation. Seismic activity, as observed from epicentral data, is moderately pronounced along this shear zone. The deep seismic studies show southerly dipping reflection fabrics across the southern part of shear zone and suggest that it represents the contact zone between the craton and the SGT[28]. Based on structural studies, it was also envisaged that the granulite facies rocks that occur in this part were emplaced on to the craton by northward over-thrusting (Figure 7). These granulite facies rocks are now seen as isolated erosional remnant outcrops of highly sheared, migmatized and retrogressed granulite facies rocks. This is further supported by the presence of east-west fold trends. Another important feature in the western part is the concentration of earthquake events along the Closepet granite, which is considered as the contact zone between the Western and Eastern Dharwar cratons.

Geomorphic feature along 13°N latitude parallel and associated seismicity

A zone of major geomorphic expression in the form of an east-west trending ~ 100 km wide Quaternary regional arch occurs along 13°N latitude-parallel passing through Mangalore–Bangalore–Chennai (MBC). The MBC geomorphic ridge occurs at the transition zone between the Dharwar craton and the SGT. The axis of the ridge is a major water divide separating the northeast and southeast-flowing drainage patterns. Subramanya[29] described details about the nature and origin of this geomorphic ridge and its tectonic implications. The MBC ridge exhibits interesting geophysical characteristics. The free-air anomaly map[30] shows a positive signature and Bouguer anomaly indicates relatively high over this region. Further, a thin crust is inferred based on regional gravity modelling[31]. These features reveal that the Moho occurs at shallow depth, implying the involvement of lithospheric deformation. The region is marked by a large number of micro to moderate earthquakes[15] ranging from $M2$ to $M5$. Especially, the prominent distribution of epicentres in the region is distinct along the Mettur shear zone (Figure 6).

Geomorphic ridge and its linkage with the CSZ

A north-south structural section across the MBC-geomorphic-ridge and its close association with the CSZ clearly reveals the geometric details of the 'flower structure' and the inferred north verging basement thrust (Figures 7 and 8). The seismicity observed in the region can be correlated with the exposed part of the basement thrust or floor thrust. Available geophysical data such as seismic, magnetotellurics, gravity and magnetic data[28,32,33] corroborate the disposition and geometry of the shear zones described here and suggest their extensions, at places, to mantle depths. Considering this tectonic scenario and with a view to explaining the seismicity along the MBC-ridge, we invoke a new causative mechanism involving tectonic stresses in the form of a buried north-verging 'blind thrust' emanating from the deeper levels of the CSZ (Figure 9), giving rise to the crustal upwarp implying that the northward compression is still active.

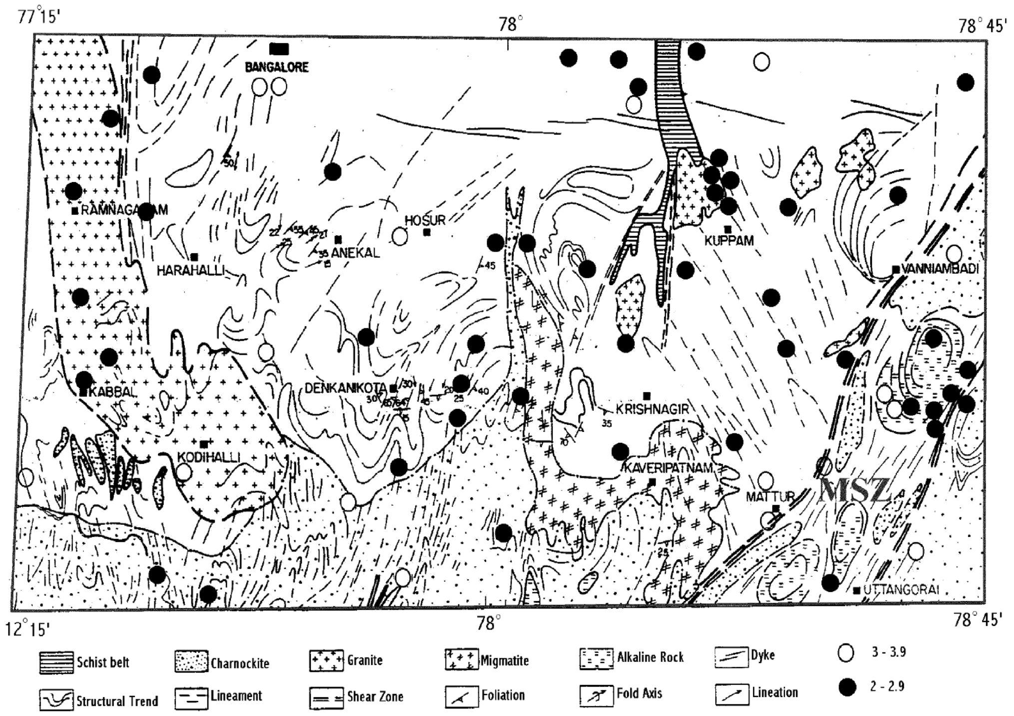

Figure 6. Structural architecture of the transition zone around 13°N lat. interpreted from Landsat TM data and epicentral locations. Note the NE–SW trending Mettur shear zone and associated Neoproterozoic alkaline plutons (~ 780 Ma).

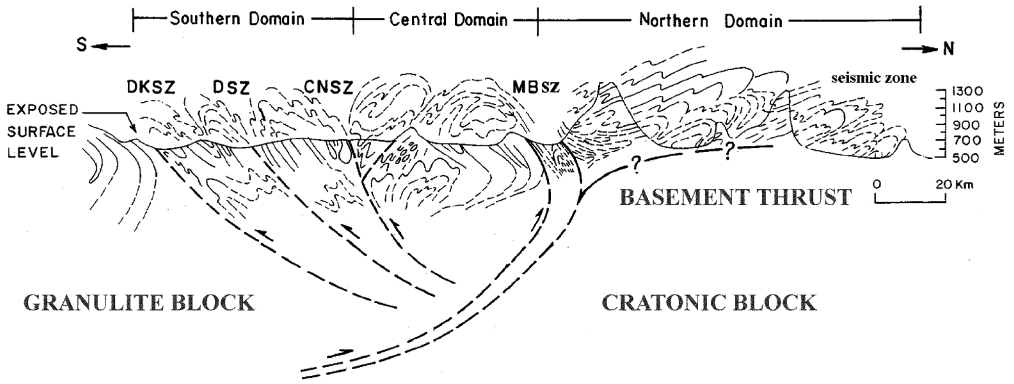

Figure 7. Structural cross-section showing overthrusted granulite facies rocks on the Dharwar craton. Shear zones: MBSZ, Moyar–Bhavani; CNSZ, Chennimalai–Noyil; DSZ, Dharapuram; DKSZ, Devattur–Kallemandeum. Note the presence of seismicity in the transition zone and exposed north verging basement thrust.

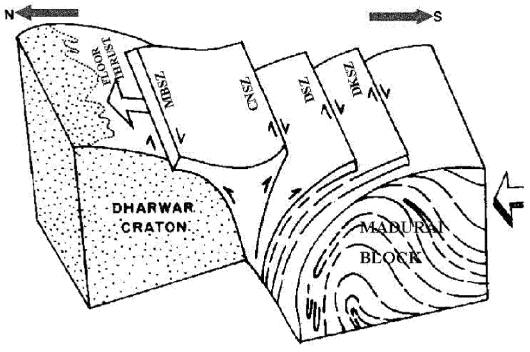

Figure 8. Schematic block diagram showing crustal-scale 'flower structure' and north verging floor thrust. Shear zones are termed as in Figure 7.

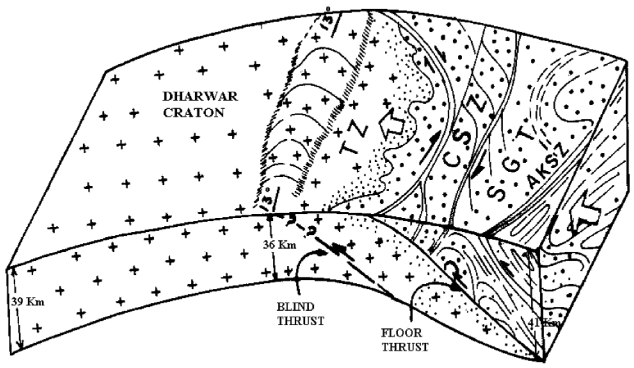

Figure 9. Schematic three-dimensional block diagram showing transition zone together with the Southern Granulite Terrain showing north verging 'blind thrust', emanating from the deeper levels of the Cauvery Shear Zone. TZ, Transition Zone; CSZ, Cauvery Shear Zone; SGT, Southern Granulite Terrain; AKSZ, Achankovil Shear Zone.

The consistency among various geological, geomorphological and geophysical datasets suggests that a still active compressional migrating belt may control the topography in the 13°N latitude-parallel. Seismological and geodetic evidences together with southerly dipping low-velocity zone suggest that the crustal deformation may be driven by the passive sinking of the lithosphere. This driving mechanism is evident from the geomorphology through northward migration of significant exhumation rates and the close correspondence of highest elevations, drainage divide and changes in river courses. The drainage system evolving through structural network is consistent in association with the uplifting of the Indian peninsula along 13°N latitude.

Discussion and conclusion

The epicentral distribution of low to moderate earthquakes in the Indian peninsula shows a broad correlation with major geological boundaries, shear zones, rifts and other geological structures. This indicates that the pre-existing shear zones, faults and other structures in terms of reactivation tectonics, significantly control the occurrence of seismicity. It is also fairly well established that the northward movement of the Indian plate causes reactivation of pre-existing structures as a common source of continued neotectonic activity and seismicity in the Precambrian terrains of India[34]. In general, the larger earthquakes seem to be related to the periodic release of accumulated regional stresses in crustal-scale features such as shear zones, rift structures and suture zones, suggesting that these features reflect the common crustal precursors rather than the development of new fracture system. They have also emphasized the importance of regions of the lithosphere where pre-existing extension has covered permanent reduction in strength, which would lead to the accumulation of strain in the overlying brittle crust. Talwani[35] noted the role of intersecting faults for the generation and localization of earthquakes. According to him, faulting usually starts along one of the fault planes, which in turn perturbs the neighbouring stress field and triggers movement on the adjacent fault. This model of intersecting faults in the upper crust provides a location for stress accumulation in continental interiors, often accompanied by uplifts. In the light of the above, the source mechanism of the Latur earthquake is now examined. Reactivation of pre-existing basement structures was proposed by Chetty and Rao[21], while Kayal[36] opined that the Latur earthquake could be due to interactions of two shallow crustal faults. However, in the present study, we propose an alternative explanation in terms of block rotation tectonics as a plausible mechanism for the Latur earthquake and the details are described below.

Block rotation is a significant mode of deformation in the earth's crust[37–39]. Based on the structural fabric in the EDC, as derived from satellite data as well as aerial photos, and the unusual shapes, sizes and geometry of mafic dykes and distinct fault systems, block rotation tectonics with clockwise rotations were inferred from the deformational system of the EDC. Similar block rotations were also described in another part of the EDC based on the results derived from aeromagnetic data[40]. Such block rotations can be attributed to local stress variations, fault reactivation and alternate zones of transtention and transpression associated with small amounts of internal deformation. While the correlation of seismicity and reactivation tectonics of pre-existing structures is apparent on a regional scale, the applicability of the block rotation model for the Latur earthquake region is examined further.

The Latur region lies in the proximity of the Kurudwadi lineament, first described by Brahmam and Negi[41] as a subtrappean rift on the basis of gravity anomalies. Based on geomorphic studies using satellite data and aerial photos, Peshwa and Kale[42] concluded that this is a Precambrian deep crustal-scale shear zone comprising an array of NW–SW trending faults along which dextral sense of movements have taken place, even during the Quaternary period. This is evident from the parallelism of the drainage network with the Kurudwadi lineament, suggesting the control of basement structures in their development. These movements based on the presence of sheared segments of the Archaean gneisses were also responsible for the secondary development of east-west trending faults identified by gravity studies. Structural architecture of the Latur earthquake region presented in this study favours the block rotation model, which could be a part of dextral sense of shear along the NW–SE trending lineaments.

Block rotation is considered as a manifestation of large-scale shearing in the brittle layer of the upper crust, the lateral motions being the result of rotations about the vertical axes. The applicability of this model to the cratonic part of the Indian peninsula could be due to the combined effects of remnant collisional processes both from south and east, and the lithospheric deformation since the Precambrian times. Recent seismicity and block rotation tectonics could be accounted for by the northward movement of the Indian subcontinent, further supported by the direction of the *in situ* stress inferred as northeast[43]. In Greece, block rotations initially proposed on the basis of seismicity and palaeomagnetic studies, were confirmed by GPS observations[44]. Block rotation defines an apparent zone of shear and the boundary faults of the blocks are likely to be responsible for moderate earthquakes. In the light of the above, we suggest that block rotation could be a possible mechanism for the Latur earthquake. Our observations suggest that the block rotation tectonics in the cratonic region of peninsular India may be a structural response to the lithospheric plate movements of India to the north. Neotectonic studies from different parts of the Indian peninsula clearly brought out the reactivation tectonics of the pre-existing structures[34]. Tectonic stresses resulting from NNEward movement of the Indian plate caused the reactivation.

The geomorphic ridge along 13°N latitude-parallel is characterized by: (i) positive free-air anomaly, (ii) Bouguer gravity high, (iii) relatively thinner crust, (iv) shallow Moho and possible involvement of lithospheric deformation, (v) major water divide, and (vi) occurrence of micro-to-moderate earthquakes. The development of this upwarp is essentially attributed to the compressive stress regime as a result of continued sea-floor spreading in the Indian Ocean[29]. However, we invoke hypothesis of north verging 'blind thrust', emanating from the floor thrust of the crustal-scale CSZ (Figure 9) with continued compressive forces, in order to explain the crustal upwarp and associated seismicity. This could also be a northern extension of the low-velocity zone obtained from DSS studies across the CSZ. Our interpretation implies that the contemporary stress field is reactivating the deeply buried thrust. Prevalence of compressional features, including the geomorphic ridge and positive structural features seen in the form of 'flower structure' across the CSZ are consistent with the intensified compression dominated by transpressional tectonic regime.

Our observations in the present study suggest that each deforming geologic system in the Indian peninsular shield, while complex into itself, can be considered only as a single sample within a continuum of how the crust could deform given a range of rheologies, boundary conditions and applied stresses. Therefore, a comprehensive multidisciplinary study of the deformational systems and their integration are important to map fault connectivity and related deformation in more detail, to assess seismic hazard in the Precambrian Indian peninsular region. This is possible through the following: (i) Characterization of structures in the upper crust and a better understanding of their relationship to such factors as topography and tectonic geomorphology, through an integrated approach of geological and geophysical studies involving high-resolution satellite data and GIS. (ii) Understanding of the driving forces, rate and episodic nature of deformation and their mechanisms controlling these factors. (iii) Characterization of physical and chemical properties of rocks in the seismogenic zone and architecture of faults in different lithospheric and tectonic settings. The main conclusions derived from the present study are: (i) the pre-existing Precambrian deformational structures and their reactivation tectonics are adequately correlated with the seismic patterns in the Indian peninsula; (ii) block rotation is a possible cause to explain the mechanism for the Latur earthquake and could be a part of dextral sense of shear along the Kurudwadi lineament, a basement tectonic feature beneath the Deccan traps; (iii) a new hypothesis is proposed postulating a north verging 'blind thrust' emanating from the floor thrust of the CSZ, resulting in crustal upwarp and the lithospheric deformation to give rise to the 13°N latitude-parallel geomorphic ridge and the ongoing neotectonic activity and associated seismicity. (iv) It is essential to map the fault connectivity and related deformation in more detail to understand crustal geodynamics and to assess seismic hazard in the region.

1. Dewey, J. F., Hempton, M. R., Kidd, W. S. F., Sargolu, F. and Sengor, A. M. C., *Shortening of Continental Lithosphere: The Neotectonics of Eastern Anatolia – A Young Collision Zone* (eds Coward, M. P. and Ries, A. C.), Geol. Soc. Spl. Publications, 1986, vol. 19, pp. 3–36.
2. Holdsworth, R. E., Butler, C. A. and Roberts, A. M., The recognition of reactivation during continental deformation. *J. Geol. Soc. London*, 1997, **154**, 73–78.
3. Naqvi, S. M. and Rogers, J. J. W., *Precambrian Geology of India*, Oxford University Press, Oxford, 1987, p. 223.
4. Chetty, T. R. K., Bhaskar Rao, Y. J. and Narayana, B. L., A structural cross section along Krishnagiri–Palani corridor, southern granulite terrain. *J. Geol. Soc. India*, 2003, **50**, 255–277.
5. Chandra, U., Earthquakes of peninsular India: a seismotectonic study. *Bull. Seismol. Soc. Am.*, 1997, **76**, 1387–1413.
6. Rao, B. R. and Rao, S., Historical seismicity of peninsular India. *Bull. Seismol. Soc. Am.*, 1984, **74**, 2519–2533.
7. Johnston, A. C., Intraplate not always stable. *Nature*, 1992, **355**, 213–214.
8. Chetty, T. R. K., Some observations on the tectonic framework of southeastern Indian shield. *Gondwana Res.*, 1999, **2**, 651–653.

9. Chetty, T. R. K., A correlation of shear zones between Eastern Ghats, India and Enderby Land, East Antarctica, based on Landsat imagery. In *India and Antarctica during the Precambrian* (eds Yoshida, M. and Santosh, M.), Mem. Geol. Soc. India, 1995, vol. 34, pp. 205–220.
10. Chetty, T. R. K., Proterozoic shear zones in Southern granulite terrain, India, In *The Archean and Proterozoic Terrains of Southern India within East Gondwana* (eds Santosh, M. and Yoshida, M.), Gondwana Research Group Mem., 1996, vol. 3, pp. 77–89.
11. Drury, S. A., Harris, N. B. W., Holt, Reves-Smith, G. J. and Wightman, R. T., Precambrian tectonics and crustal evolution in South India. *J. Geol.*, 1984, **92**, 3–20.
12. Chetty, T. R. K. and Murthy, D. S. N., Regional tectonic framework of the Eastern Ghat Mobile Belt: A new interpretation. *Geol. Surv. India Spl. Publ.*, 1998, **44**, 39–50.
13. Krishnan, M. S., *Geology of India and Burma*, Higginbothams, Madras, 1968, p. 604.
14. Ramlingeswara Rao, B., Historical seismicity and deformation rates in the Indian peninsular shield. *J. Seismol.*, 2000, **4**, 247–258.
15. Ramlingeswara Rao, B., Seismicity and geodynamics of the low-to high-grade transition zone of peninsular India. *Tectonophysics*, 1992, **201**, 175–185.
16. Valdiya, K. S., Late Quaternary movements and landscape rejuvenation in Southeastern Karnataka and adjoining Tamil Nadu in southern Indian shield. *J. Geol. Soc. India*, 1998, **51**, 139–166.
17. Chetty, T. R. K., Significance of the Block Rotation Model in tectonics and mineralisation in Precambrian terrains. An example from the south Indian shield. *J. Geodyn.*, 1995, **20**, 255–266.
18. Nur, A., Ron, H. and Scotti, O., Fault mechanics and the kinematics of block rotation. *Geology*, 1986, **15**, 740–749.
19. Radhakrishna, B. P., Cauvery – its geological past. *J. Geol. Soc. India*, 1992, **40**, 1–12.
20. Seeber, L., Ekstrom, G., Jain, S. K., Murthy, C. V. R., Chandak, N. and Armbruster, J. G., The 1993 killari earthquake in central India: a new fault in Mesozoic basalt flows? *J. Geophys. Res.*, 1996, **101**, 8543–8560.
21. Chetty, T. R. K. and Rao, M. N., Latur earthquake of September 30, 1993: Surface deformation and lineament pattern. *Mem. Geol. Soc. India*, 1994, **35**, 65–73.
22. Mishra, D. C., Tiwari, V. M., Gupta, S. B. and Rao, Y. M. B. S., Anomalous mass distribution in the epicentral area of Latur earthquake, India. *Curr. Sci.*, 1998, **74**, 469–472.
23. Rajendran, K. and Rajendran, C. P., Characteristics of the 1997 Jabalpur earthquake and their bearing on its mechanism. *Curr. Sci.*, 1998, **74**, 168–174.
24. Baumbach, M. *et al.*, Study of foreshocks and aftershocks of the Intraplate Latur earthquake of September 30, 1993, India. *Mem. Geol. Soc. India*, 1994, **35**, 33–63.
25. Gupta, H. K., Rastogi, B. K., Mohan, I., Rao, C. V. R. K., Sarma, S. V. S. and Rao, R. U. M., An Investigation of the Latur earthquake of September 29, 1993 in southern India. *Tectonophysics*, 1998, **287**, 299–318.
26. Ramakrishnan, M., Craton-mobile belt relations in southern granulite terrain. *J. Geol. Soc. India*, 2003, **50**, 1–24.
27. Rajendran, K., Rajendran, C. P. and Kesavan, S. K., Mild tremors near Thalasseri (November, 2003): Evidence for a seismic source in North Kerala. *J. Geol. Soc. India*, 2004, **64**, 233–236.
28. Reddy, P. R. *et al.*, Deep seismic reflection and refraction/wide-angle reflection studies along Kuppam–Palani Transect in the southern granulite terrain of India. *Geol. Soc. India Mem.*, 2003, **50**, 79–106.
29. Subramanya, K. R., Active intraplate deformation on South India. *Tectonophysics*, 1996, **262**, 231–241.
30. NGRI, *Free-Air and Bouguer Anomaly Maps of India*, National Geophysical Research Institute, Hyderabad, 1974.
31. Subba Rao, D. V., *Regional Gravity Modeling NGRI*, Annual Report, 1987, pp. 16–17.
32. Harinarayana, T. *et al.*, Magnetotelluric investigations along Kuppam–Palani Geotransect, South India – 2D modeling results. *J. Geol. Soc. India*, 2003, **50**, 107–124.
33. Singh, A. P., Mishra, D. C., Vijay Kumar, V. and Vyaghreswara Rao, M. B. S., Gravity–magnetic signatures and crustal architecture along Kuppam–Palani Geotransect, South India. *J. Geol. Soc. India*, 2003, **50**, 139–163.
34. Valdiya, K. S., Tectonic resurgence of the Mysore plateau and surrounding regions in cratonic southern India. *Curr. Sci.*, 2001, **81**, 1068–1089.
35. Talwani, P., Fault geometry and earthquakes in continental interiors. *Tectonophysics*, 1999, **305**, 371–379.
36. Kayal, J. R., Seismotectonic study of the recent SCR earthquake in central India. *J. Geol. Soc. India*, 2000, **55**, 123–138.
37. Freund, R., Kinematics of transform and transcurrent faults. *Tectonophysics*, 1970, **21**, 93–134.
38. Kissel, C. and Laj, C., *Palaeomagnetic Rotations and Continental Deformation*, Kluwer, The Netherlands, 1989, p. 513.
39. McKenzie, D. and Jackson, J., A block model of distributed deformation by faulting. *J. Geol. Soc. London*, 1986, **143**, 349–353.
40. Rama Rao, Ch., Bhaskar Rao, D. S. and Atchuta Rao, D., Block rotation in a part of eastern Dharwar craton of south India – A suggestion from aeromagnetic data interpretation. *Curr. Sci.*, 1997, **72**, 337–341.
41. Brahmam, N. K. and Negi, J. G., Rift valleys beneath Deccan Traps (India). *Geophys. Res. Bull.*, 1973, **11**, 207.
42. Peshwa, V. V. and Kale, V. S., Neotectonics of the Deccan Traps Province : Focus on the Kurduwadi Lineament. *J. Geophys.*, 1997, **1**, 77–86.
43. Gowd, T. N., Srirama Rao, S. V. and Gaur, V. K., Tectonic stress field in the Indian sub-continent. *J. Geophys. Res.*, 1992, **97**, 11879–11888.
44. Billiris, H. *et al.*, Geodetic deformation of the strain of Greece in the interval 1900 to 1988. *EOS*, 1989, **90**, 719.

ACKNOWLEDGEMENTS. I thank Dr V. P. Dimri, Director, NGRI, Hyderabad for support and permission to publish this work. I also thank Dr C. Subramanyam for his critical and helpful suggestions on an earlier version of the manuscript. The anonymous reviewer is acknowledged for helpful suggestions. This paper is dedicated to Sri. T. M. Mahadevan, Kochi, on the occasion of his 80th birthday.

Received 27 May 2005; revised accepted 7 December 2005