Dipping Moho in the southern part of Eastern Dharwar Craton, India, as revealed by the coincident seismic reflection and refraction study

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Seismic reflection study along the Kuppam–Bommidi profile in the Southern Granulite Terrain (SGT) shows a south-dipping Moho extending from 10.5 to 14.5 s two-way time in the southern part of the Eastern Dharwar Craton (EDC), which corresponds to a depth ranging from ~34 to ~46 km. A similar Moho feature is also observed from the seismic section of the coincident refraction study. The Moho depth is also constrained by gravity data and other seismic studies of the region. Presence of such an unusual Moho feature in the Archean terrain is due to thermal and tectonic stability of the craton. In contrast, the reflection Moho could not be observed in the Mettur Shear Zone, located further south of the EDC. This may be due to crustal structure developed during the Proterozoic tectonothermal activities in the SGT. However, the refraction study suggests a Moho depth of ~42 km for the SGT along the profile. The Moho seems to be a lithological boundary in the EDC, whereas it is a rheological boundary in the SGT. The present study demonstrates the complimentary nature of reflection and refraction datasets and usefulness of the coincident study.

Keywords: Dipping Moho, Eastern Dharwar Craton, Mettur shear zone, seismic reflection study, Southern Granulite Terrain.

THE Mohorovicic discontinuity, usually referred to as the Moho, is a prominent boundary between the earth's crust and mantle. It is one of the distinct manifestations of a differentiated earth. Moho is a petrological, mineralogical, chemical and rheological boundary, separating different physical properties (velocity, density and composition) on either side. It often exhibits structural and petrological complexity with lateral variability in character and depth. Seismic velocity varies from 6.8–7.4 to 7.8–8.4 km/s and composition changes from mafic to ultramafic across the Moho. The Moho depth varies from 5–8 km for deep oceans to 30–75 km for the continental part, including the recent collisional belts.

High-resolution seismic images of the reflection study provide a realistic picture of the Moho compared with any geophysical data or even the low-resolution refraction profiling. These images have revolutionized our understanding of the Moho and its evolution[1]. In the present study, a seismic reflection profiling along the Kuppam–Bommidi profile is used to investigate the nature of the Moho and its configuration in the southern part of the Archean Eastern Dharwar Craton (EDC). Further, the Moho depth is constrained by the available velocity–depth models of the region and the gravity signature along the profile. A comparison is made between the Moho derived from reflection and coincident refraction studies along the profile.

Reflectivity–seismic methods

The seismic method is an acoustic imaging technique, which identifies the subsurface layers by the amount of energy reflected back to the surface. Reflected energy of seismic waves depends on the physical properties of the subsurface layers and also on the angle of incidence. It is measured with a parameter known as reflection coefficient or reflectivity (R_c).

The reflection coefficient is defined as the ratio of the amplitude of the reflected wave (A_1) to that of incident wave (A_0). For normal incident wave, the reflection coefficient is obtained from the solution of Zoeppritz's equations as:

$$\begin{aligned} R_c &= A_1/A_0 \\ &= d_2V_2 - d_1V_1/d_2V_2 + d_1V_1 \\ &= Z_2 - Z_1/Z_2 + Z_1, \end{aligned}$$

where d_1, V_1, Z_1 and d_2, V_2, Z_2 are the density, P-wave velocity and acoustic impedance in the first and second layers respectively. The product of velocity and density of a rock is referred to as the acoustic impedance. High acoustic impedance contrast at a boundary is manifested in the form of greater reflectivity. Departure from the above simple relationship is small for incident angles less than 15°.

Near-vertical reflections, representing seismic waves with angle of incidence <15°, exhibit a reflection coefficient of the order of 0.1–0.3, whereas wide-angle reflec-

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tions (WAR) with angle of incidence >35° exhibit a value of 0.9. High reflectivity of WAR is due to total internal reflection that takes place for angle of incidence greater than the critical angle, where the entire seismic energy reflects back. The large difference in reflectivity between these two reflection groups makes use of a single-fold WAR study and necessitates multifold near-vertical reflection study.

Reflection coefficient plays an important role in the analysis of reflection phases such as low-velocity layers, crust–mantle boundary, magma chamber, bright spot, oil–gas interface, bottom simulating reflector of gas hydrates, etc.

The seismic study is basically divided into two methods, namely the near-vertical reflections and refraction/WAR studies depending on the angle of incidence (<15° and >35° respectively; Figure 1). Source–receiver geometry of these methods is controlled by the angle of incidence. The refraction/WAR study needs source–receiver offsets ranging from 80 to 150 km and shot-point spacing of ~40 km to delineate the Moho structure (Figure 1). Such studies provide good velocity–depth models, which were used to identify the Moho along various profiles in different parts of the Indian shield[2]. The velocity structure derived from WAR studies provides the depth of various layers up to the Moho and are useful in understanding the composition, degree of metamorphism and material properties of the crust. However, structural resolution from such studies is poor. On the other hand, the near-vertical seismic reflection study provides the highest resolution structural images of the subsurface using multi-fold Common Mid-Point (CMP) technique, where each subsurface reflection point is sampled several times. The dense shot and shot-receiver spacing with much smaller offsets provide multiple coverage of the subsurface. The inherent multiplicity in the CMP reflection data is utilized to increase signal-to-noise (S/N) ratio by the stacking process and to attenuate noise. In such a study, the maximum source–receiver offset is of the order of 3 km in exploration and 12–15 km for crustal and upper mantle studies

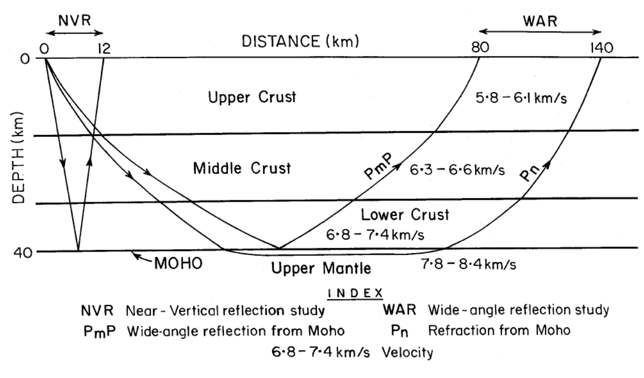

Figure 1. Schematic diagram illustrating crustal seismic refraction/wide-angle reflection and near-vertical reflection experiments.

(Figure 1). Deep seismic reflection studies carried out along various transects were used to understand the crustal and sub-crustal lithospheric structure in different parts of the Indian shield[3,4].

In the present study, coincident seismic reflection and refraction data acquired along the Kuppam–Palani geotransect are used to understand the Moho configuration of the southernmost part of the EDC and a part of the Southern Granulite Terrain (SGT).

Geology and tectonics

The South Indian shield is a mosaic of crustal blocks with varying degrees of metamorphism and age (Figure 2). The low-grade Archean greenstone–granite belt of the Dharwar Craton (DC) is separated from the late Archean high-grade SGT by the E–W trending Moyar-Bhavani Shear Zone (MBSZ) which joins the Mettur Shear Zone (MESZ) in the NE–SW direction. Further, the DC is subdivided into mid-Archean Western and late-Archean Eastern Dharwar cratons (WDC and EDC), which are separated from each other by the Chitradurga schist belt (G. Ramadass *et al.*, unpublished)[5]. The WDC is dominated by tonalite-trondjhenite granodiorite (TTG) gneisses and volcano-sedimentary greenstone belts, whereas the EDC is dominated by late Archean granitic rocks with minor TTG gneisses and thin, narrow elongated greenstone belts. Large amounts of juvenile crustal materials were accreted to the EDC around 2500 Ma, with the formation of Closepet batholith and other calc-alkaline to K-rich granitic plutons[6]. The SGT has experienced several tectono-thermal events ranging from 2500 to 550 Ma and has witnessed episodes of high-grade metamorphism between 2500 and 550 Ma.

Seismic study along the Kuppam–Bommidi profile

Deep seismic refraction study started in India in 1972 and the reflection study in 1992. However, a systematic coincident reflection and refraction study[7] was carried out for the first time over the Indian shield along a 300 km long Kuppam–Palani geotransect (Figure 3) in the SGT only in 2000. The initial part of the transect between Kuppam and Nagarasampatti traverses the southern part of the EDC and the rest through the SGT across major shear zones of the region. The structure and tectonics of the SGT along the transect have been discussed using various reflectivity patterns and velocity structure in earlier studies[7–9]. However, the nature and characteristic features of the Moho as derived from the coincident study were neither analysed nor discussed. The present study adopts an integrated approach to define, characterize and identify the Moho features across a major tectonic boundary of the region (craton–shear zone) using reflection study and

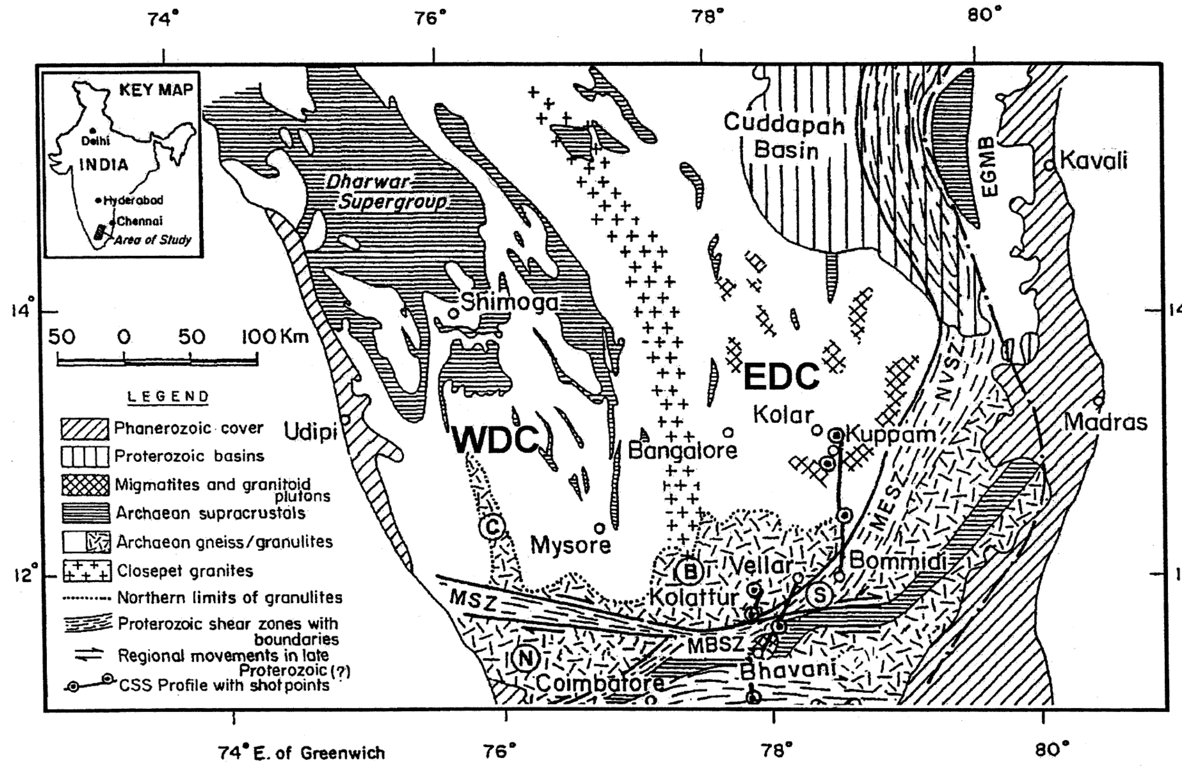

Figure 2. Simplified tectonic map of South India along with the location of Kuppam–Palani geotransect. WDC, Western Dharwar Craton; EDC, Eastern Dharwar Craton. Proterozoic shear zones: MSZ, Moyar Shear Zone; BSZ, Bhavani Shear Zone; MBSZ, Moyar–Bhavani Shear Zone; MESZ, Mettur Shear Zone. Granulite massifs: B, Biligiri Rangan; N, Nilgiri; S, Shevroy.

compare them from those derived from the coincident refraction study. It highlights the importance of coincident reflection and refraction study.

In the present study, near-vertical seismic reflection data acquired using the CMP technique, along the Kuppam–Bommidi profile were reprocessed to enhance the weak reflections observed in the earlier sections and analysed to understand the nature of the crustal blocks. The reflectivity image of the subsurface as derived from the reflection stack section representing the southern part of the EDC is presented in Figure 4. The seismic section is similar to a geological cross-section. A line drawing of the prominent reflections from the stack section is shown in Figure 5. Significance of some of the prominent reflection bands has been analysed in the context of tectonic scenario of the region. The important features of the seismic section as shown in Figure 5 are the bright south-dipping reflection from 10.5 s two-way time (TWT) at Kuppam that deepens to a depth of 14.5 s TWT near Nagarasampatti. Further south, it was not observed in the shear zone region. The entire northern block (EDC) seems dipping southwards. No prominent reflections were found further deep beyond the 10.5–14.5 s TWT reflection band, indicating transparency in the deeper part at least up to 20 s TWT.

The velocity structure along the Kuppam–Bommidi profile derived from refraction data[7] was modified using the constraints from reflection study (Figure 6).

Discussion and conclusions

The amplitude of a reflection generally depends on the reflection coefficient. Large energy is reflected from a subsurface layer with high reflection coefficient (greater acoustic impedance contrast). In general, the reflection coefficient of the Moho boundary is high due to compositional changes from mafic to ultramafic, which manifests a large velocity and density changes at this boundary compared with other sub-basement crustal layers. Velocity of the seismic wave in any medium is given by

$$V = \sqrt{E/d},$$

where E is the elastic modulus and d the density of the medium.

The above relationship suggests that manifestation of the Moho boundary between the crust and mantle in the near-vertical seismic reflection section is more due to higher elastic coefficients of the upper mantle than the increase in its density compared to the rocks of the crust. Though the density of the upper mantle is greater than that of the crustal rocks, the increase in seismic velocity is mainly due to large increase in the value of elastic constants.

The above-mentioned facts suggest that the Moho boundary reflects maximum energy compared with other sub-basement reflectors. Thus, the base of the deepest,

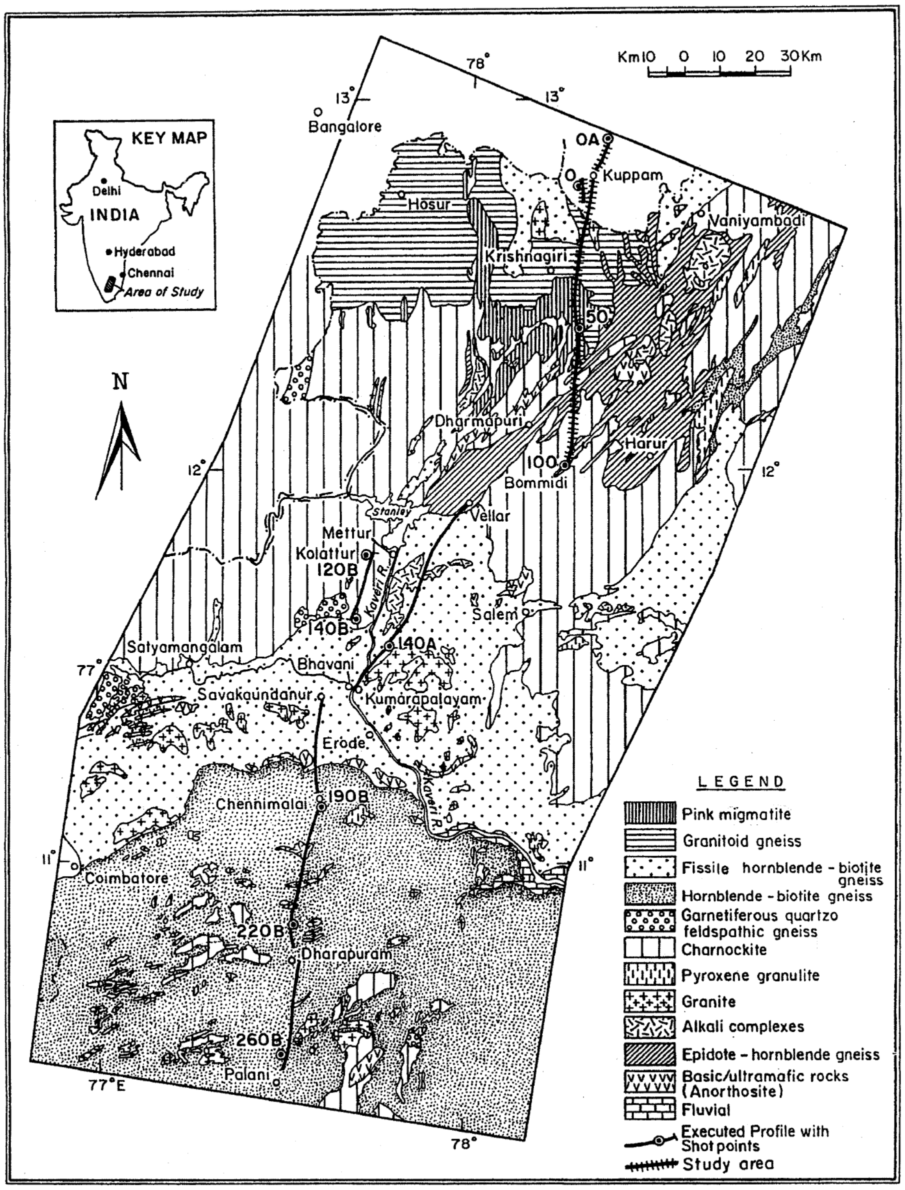

Figure 3. Geological map of the Southern Granulite Terrain along with the Kuppam–Palani profile.

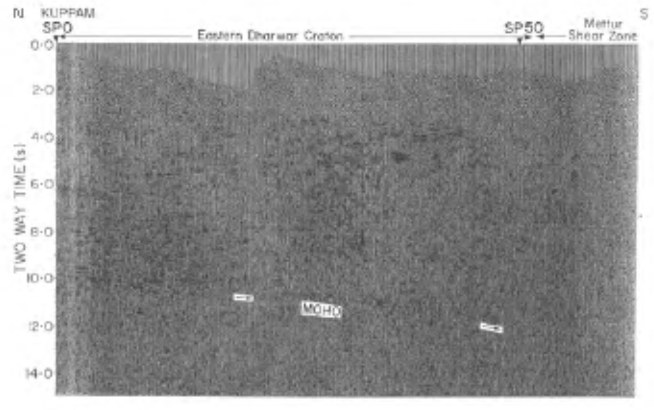

Figure 4. Seismic section along the Kuppam–Bommidi profile covering the southern part of the EDC and the MESZ.

high amplitude, laterally extensive reflection band in the crust represents the Moho. In the present study, termination of the deepest gently dipping bright reflection band from 10.5 to 14.5 s TWT from Kuppam–Nagarasampatti (Figure 5) is interpreted to represent the Moho of the region. Such a characteristic feature is used to identify the Moho from reflection studies in various parts of the world[1,10]. The transparent subsurface further deep in the seismic section represents the upper mantle. The dipping Moho feature is observed to a distance of 50 km (up to SP50). It is for the first time that a dipping Moho has been imaged over the Indian shield. The dipping Moho observed in the southern part of the EDC is an unusual feature of an Archean terrain and provides important clues to understand the tectonic evolution of the region.

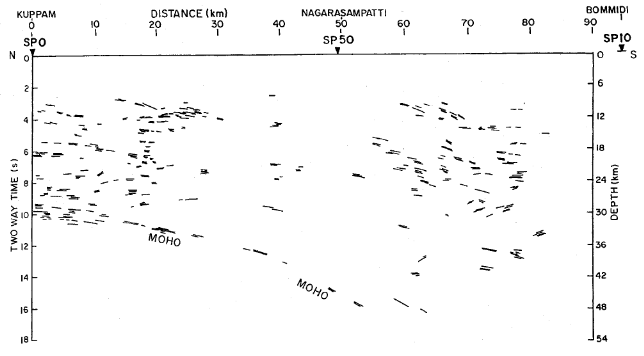

Figure 5. Line drawing of the seismic stack section derived from reflection study along the Kuppam–Bommidi profile (after Reddy *et al.*[7]).

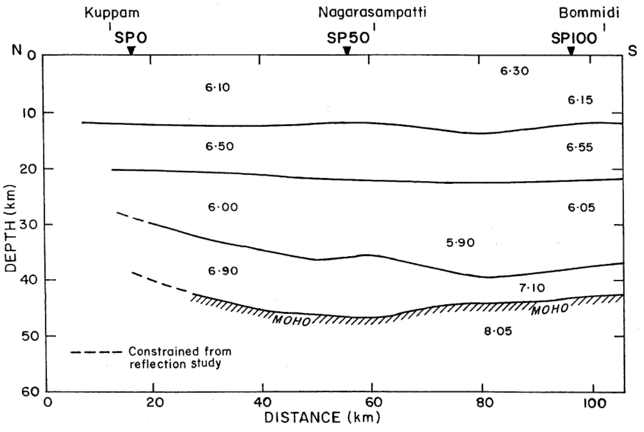

Figure 6. Velocity structure derived from the coincident seismic refraction study along the Kuppam–Bommidi profile (modified after Reddy *et al.*[7]).

While analysing the reflection Moho, it is essential to compare the amplitude standout of the lower crustal reflection band in relation with other reflections of the seismic section. The line drawing of the seismic reflection section south of Nagarasampatti (Figure 5) does not show the typical characteristic, bright, continuous, reflection band in the lower part of the crust representing the Moho, which is contrary to the one observed to its north. All reflections in this part exhibit the same amplitude irrespective of their depth. Absence of typical characteristic Moho signature inhibits its identification in the southern part of the profile from the reflection study. The notable break in the lateral continuity of the reflection Moho along the profile clearly indicates the presence of a fault/shear zone which demarcates the boundary of the EDC. The geologically envisaged MESZ coincides with this boundary. Absence of reflection Moho in the MESZ could be due to the structure of the shear zone or crustal reworking and vertical intrusions of alkaline and granitic plutons during the Proterozoic tectono-magmatic activities. A large number of Neoproterozoic alkaline and granitic plutons observed all along the MESZ in the NE–SW direction (Figure 3) might have obliterated the earlier structural features. It is generally observed that identification of the Moho boundary in seismic reflection section over any shear zone is never a certainty, least in a shear that occurred during the Proterozoic period.

The physical nature of the Moho discontinuity at the boundary of the crust and upper mantle depends mainly on the thermal state of the latter. If the upper mantle is relatively cool, the Moho boundary is usually a lithological boundary and it is possible to obtain seismic reflections from this boundary, as has been mapped in various seismic sections from different parts of the world[1]. On the other hand, if the upper mantle is rather hot, the Moho boundary tends to be a rheological boundary and the seismic section expectedly devoid of characteristic Moho reflections. The heat-flow study in the present study area indicates lower mantle heat flow values for the EDC compared to the SGT, which are of the order of 16–18 and 32–36 mW/m^2 respectively[11]. Magnetic data suggest that the Curie temperature is reached at a shallow depth of a mere 22 km in the SGT[12], indicating higher heat flow in the SGT compared to the EDC. These independent studies further constrain the presence and absence of Moho reflections in the EDC and SGT, as revealed by the seismic reflection study. Thus, we interpret that the Moho in the EDC is a lithological boundary, whereas it is a rheological boundary in the SGT.

The 10.5 and 14.5 s TWT, representing the Moho, when converted to depth using the average velocity of the region[7] corresponds to ~34 and 46 km depth respectively. Thus, the reflection data indicate a crustal thickness of 34 km at Kuppam (situated in the EDC) and a maximum value of 46 km at the EDC–MESZ boundary. Reddy *et al.*[7], from the coincident refraction/WAR studies, have identified a gradual increase of crustal thickness from Kuppam in the EDC, reaching a value of 46 km at the EDC–MESZ boundary, which decreases to 42–40 km after this boundary in the shear zone region (Figure 6). Comparison of the Moho derived from both the reflection and refraction studies indicates good correspondence between them. However, the refraction/WAR study could not delineate the crustal thickness in the northernmost part of the profile near Kuppam due to limitations of the method and the adopted source–receiver geometry, unlike the reflection profiling. This is due to the fact that the refraction/WAR study samples the subsurface Moho location which is always separated from the source as well as receiver by a large distance of the order of 40–50 km, unlike in the near-vertical reflection study, where the subsurface is sampled nearer (6 km) to both the source and receiver (Figure 1).

Velocity structure derived from the refraction data[7] shows only two prominent layers between 20 and 40 km depth, suggesting a poor indicator of the fine structure of the area (Figure 6). Further, it shows a gently dipping Moho in the EDC. On the other hand, the reflection section and line drawing (Figures 4 and 5) show prominent reflection band from 6 to 10.5 s TWT. Most of these layers, including the Moho dip towards south from Kuppam, resolve the fine structure of the lower crust and the Moho. One can observe the difference in the dip of the Moho derived from both datasets. The information content of two types of seismic datasets is variable, which can be used to derive the true nature of the Moho. These two sections of the same subsurface provide different resolutions. Even though the reflection profiling provides an accurate picture of the Moho, it could not identify the Moho in the tectonically disturbed MESZ of the SGT, whereas the refraction data suggest average crustal velocity structure and identified the Moho. The refraction data consist of prominent WARs which are generated mainly due to the velocity contrast at the Moho boundary. They are always present even in areas of complex structure and display simplistic Moho structure which is laterally continuous and appears to exist virtually everywhere as the basement of crust, irrespective of the Moho structure. On the other hand, reflection data are more sensitive to fine structure of the Moho because of its high frequency content. Therefore, the Moho derived from reflection study is laterally variable or discontinuous or even completely absent at some places depending on the structure of the lower crustal transition zone, which is formed due to igneous/metamorphic layering during the crust–mantle interaction process. The observed difference in the reflection and refraction Moho signature in the region is mainly due to the difference in their causative factors. Thus, a unified approach using the results of both datasets, which are complementary to each other, will provide the most complete, highest resolution and least ambiguous nature of the Moho. The coincident reflection and refraction study provided important constraints on depth, geometry, thickness and internal structure of the Moho of the SGT.

Gravity study along the seismic profile[13] shows decrease in the Bouguer gravity values from –45 mGal at Kuppam to –75 mGal at the EDC–MESZ boundary (Figure 7), indicating a gradual increase in crustal thickness. Increase of the gravity values further south in the shear zone indicates crustal thinning as indicated by the velocity–depth model (Figure 6). Thus, a good correlation is found between seismic and gravity studies. The controlled source and tomographic studies[14–17] indicate a crustal thickness of 33–36 km for the EDC (Figure 8). Good correspondence is observed between the crustal thickness inferred from the present reflection study and earlier seismic studies for the EDC. The crustal thickness derived from the present reflection study is in agreement with the global average[18] of 35 km.

In general, reflections from 5.5 to 10.5 s TWT from Kuppam dip towards south forming a crustal fabric are generally observed at the palaeo-subduction zones. The gradual increase in crustal thickness (from 34 to 46 km) towards the EDC–MESZ boundary and the nature of the Moho indicate that the crustal fabric might have formed during subduction of oceanic crust or under thrusting of continental crust in the collision zone[8]. Subduction and collision might be responsible for the evolution of granulites in the region[9]. Dipping Moho feature is also observed at the subduction zones of the Baltic shield[19] and the Archean Superior Province of the Canadian shield[20].

From the Neoproterozoic alkaline and granitic magmatism observed in the region, Mahadevan[21,22] suggested that dipping reflections, including the Moho, might have resulted from the crust that is isothermally and differentially exhumed from mid- to lower crustal levels due to distension. He further stated that the evolutionary models based on collision and subduction may be misleading. However, crustal thinning due to distension is generally manifested as a subhorizontal Moho fabric in different parts of the globe and is also observed beneath the Mangalwar Complex of the Aravalli–Delhi fold belt of the NW Indian shield[1,23]. The distension process as observed over the Basin and Range Province, USA exhibits a subhorizontal Moho geometry[10]. Whether distension can produce a dipping Moho characteristic of the observed magnitude at lower crustal depth (from 10.5–14.5 s TWT) is not certain, because the lower crust is ductile. However, such structures can survive in the lower crust of subduction and collision zones due to different environments and strain hardening processes that act at these places[24]. Thus,

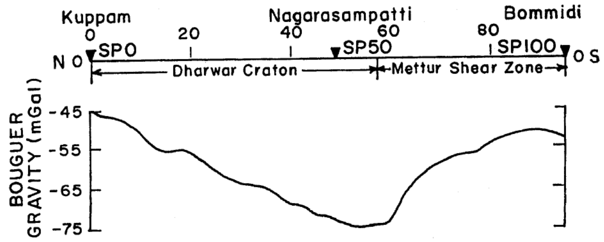

Figure 7. Gravity signature along the Kuppam–Bommidi seismic profile (after Singh *et al.*[13]).

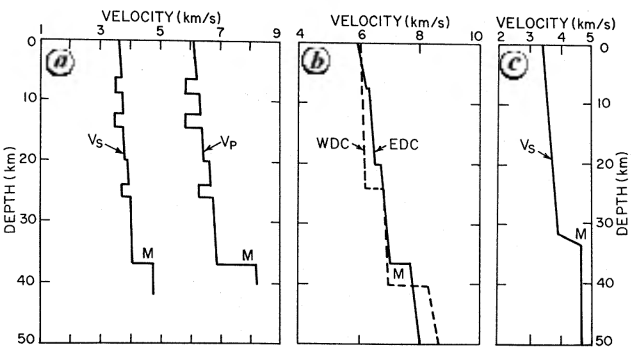

Figure 8. One-dimensional velocity models for various parts of the Eastern Dharwar Craton. (***a***) Velocity models (V_p and V_s) from earthquake data for the Latur region (redrawn after Krishna *et al.*[14]). (***b***) Along the Kavali–Udipi profile from controlled source seismic studies (after Reddy *et al.*[15]). (***c***) Shear wave velocity model derived from receiver function studies for Hyderabad (redrawn after Sarkar *et al.*[16]).

we believe that the dipping nature of the Moho is related to earlier compression rather than later Neoproterozoic distension.

Generally, it is observed that the post-collisional extensional processes modify the original Moho configuration and are exhibited by flat, subhorizontal reflection geometry at the Moho and lower crustal level[25,26]. However, preservation of original dipping Moho characteristics in the EDC indicates the tectonic and thermal stability of the DC since late Archean collision at ~2500 Ma. The lithospheric thickness and mantle heat flow for the DC and the SGT were of the order of 160–140 km, 16–18 mW/m^2, and 100 km, 32–36 mW/m^2 respectively[10,27]. Such a distinct change in geophysical properties may be responsible for the observed differences in the Moho characteristics of both these regions. The lithospheric roots and heat flow values also support the tectonic stability of the DC. The stability of the region has helped to retain the palaeo-signatures of the Precambrian tectonics.

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