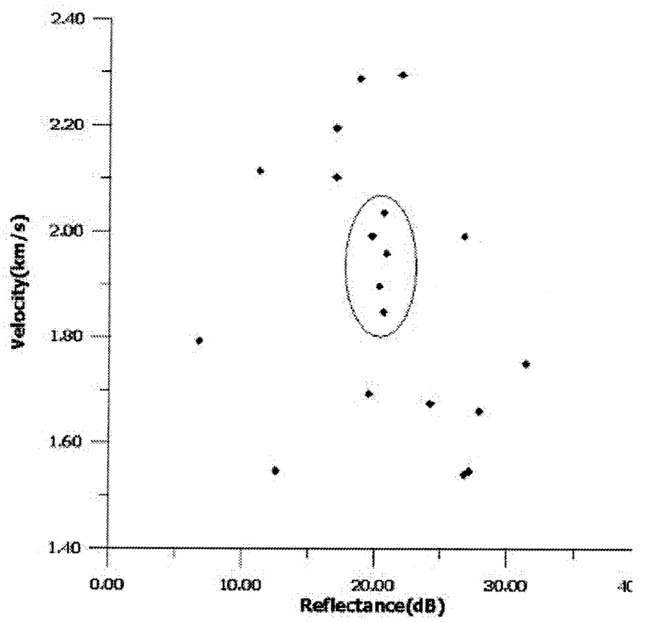

Figure 4. Relation between reflectance (dB) and velocity (km/s).

The zone of blanking is quite prominent and wider for the CDPs 315–320 than for CDPs 495–500 (Figure 3). There is a sharp change in the zone of blanking for CMPs 315–320; it is quite transitional in character for CDPs 495–500. The average amplitude for the section between the water bottom and the BSR is about –32 dB for CDPs 495–500 and about –30 dB for CDPs 315–320. If the amplitude blanking indicates the presence of gas hydrates, then it implies that thicker zone of hydrated sediments occurs near CDP-300 than near CDP-495.

A composite plot is shown in Figure 4 for interval velocity derived from stacking velocity vs mean reflectance. This plot is used to assess the relation between amplitude blanking and interval velocity. Mean reflectance is calculated for a window about 400 ms above the BSR. The maximum amplitude variation for a given interval velocity is about –20 dB at an interval velocity of about 2000 m/s and the interval velocity changes between 1700 and about 2000 m/s for a reflectance of –25 to –35 dB point. One significant result that emerges from the present figure is that the gas hydrate bearing layer has the velocity in the range 1.8 to 2.0 km/s, which is well constrained with smaller scatter (encircled values). Uncertainty in velocity picking may also be a factor that contributes to the large scattering of interval velocity versus reflectance.

The amplitude of seismic reflection within the hydrate zone is generally much lower in the area where there is an observed BSR. Hence, amplitude reduction can be a useful seismic attribute to the presence of gas hydrates.

On the basis of stacking-velocity data, the average interval velocities of sub-bottom sediments between the sea floor and the BSR are similar to the average interval velocity of non hydrate-bearing marine sediments. This implies the small amount of hydrate concentration in this region.

The interval velocity in the part associated with blanking varies from 1600 to 2000 m/s and the reflectance varies from –15–30 dB.

1. Stoll, R. D., Effect of gas hydrates in sediment. In *Nature of Gases in Marine Sediments* (ed. Kaplan, I. R.), Plenum Press, New York, 1974, pp. 235–248.
2. Tucholke, B. E., Bryan, G. M. and Ewing, J. I., Gas hydrate horizons detected in seismic-profile data from the western North Atlantic. *Am. Assoc. Pet. Geol. Bull.*, 1977, **61**, 698–707.
3. Dillon, W. P. and Paull, C. K., Marine gas hydrates, II – Geophysical evidence. In *Natural Gas Hydrates – Properties, Occurrence, and Recovery* (ed. Cox, J. L.), Butterworth Publishers, Boston, 1983, pp. 73–90.
4. Paull, C. K., Ussler, W. III and Dillon, W. P., Is the extent of glaciations limited by marine gas hydrates? *Geophys. Res, Lett.*, 1991, **18**, 432–434.
5. Pearson, C. F., Halleck, P. M., McGulre, P. L., Hermes, R. and Mathews, M., Natural gas hydrates; a review of *in situ* properties. *J. Phys. Chem.*, 1983, **87**, 4180–4185.
6. Lee, M. W. and Hutchinson, D. R., True-amplitude processing technique for Marine, crustal-reflection seismic data. US Geological Survey Bulletins, 1897, 1990, p. 22.
7. Shipley, T. H., Houston, M. H., Buffler, R. T., Shaub, F. J., McMillan, K. J., Ladd, J. W. and Worzel, J. L., Seismic evidence for widespread possible gas hydrate horizons on continental slopes and rises. *Am. Assoc. Pet. Geol. Bull.*, 1979, **63**, 2204–2213.
8. Lee, M. W., Agena, W. F. and Swift, B. A., An analysis of a unique seismic anomaly in Georges Bank basin, Atlantic Continental Margin: US Geological Survey Open-File Report 91-138, 1991, p. 25.
9. Lee, M. W., Hutchinson, D. R., Dillon, W. P., Miller, J. J., Agena, W. F. and Swift, B. A., Use of seismic data in estimating the amount of *in situ* gas hydrates in deep marine sediment: The Future of Energy Gases, US Geological Survey Professional Paper, 1570, pp. 563–581.
10. Reddi, S. I., Thakur, N. K., Ashalatha, B. and Sain, K., Reprocessing multichannel seismic data of the ONGCL for gas hydrate exploration in the offshore Goa. NGRI Technical Report, 2001.

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Lateral and vertical crustal velocity and density variations in the Southwestern Cuddapah Basin and adjoining Eastern Dharwar Craton

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Seismic, gravity and aeromagnetic data are reviewed to understand the complex nature of the structure of the Cuddapah basin. Deep Seismic Sounding analogue data acquired along Kavali–Udipi profile, covering middle

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and western parts of Cuddapah basin and adjoining granitic gneissic terrain of Eastern Dharwar Craton have been primarily used for this study. We have derived a two-dimensional crustal velocity structure by reprocessing of refraction and wide-angle reflection data acquired along the profile. Derived basement and sub-basement crustal structure has brought out finer structural details. Two layers are present above the upper crust. The first layer has a velocity of 5.2 to 5.4 km/s and the basement has a velocity of 5.95 to 6.00 km/s. The upper crust has a velocity of 6.4 km/s, mid crustal velocity is 6.6 to 6.8 km/s, whereas the lower crustal velocity is 7.4 km/s. Moho-1 is observed at an average depth of 37 km with a derived velocity of 7.8 km/s. A deeper Moho-2 is also observed at a depth of 45 km with a Pn velocity of 8.4 km/s. A low-velocity layer (6.5 km/s) separates the two Moho discontinuities. In addition, the analysis has brought out finer crustal velocity–depth details of the region, including presence of regionally extending upper crustal domal features. The study has also revealed the presence of deep-seated faults near Parnapalle, Tonduru and Malepadu. Gravity modelling of the seismic structure further substantiated the results and brought into focus the good correlation of datasets.

DEEP Seismic Sounding (DSS) studies were carried out[1], as an Indo-Soviet collaboration programme, during 1972–74 along a 600 km long profile, from Kavali on the east coast to Udipi on the west coast. This profile cuts across various geological formations in the Dharwar craton and the Proterozoic Cuddapah basin and as such has been considered as unique in many ways. As one velocity–depth function for the entire stretch of 600 km does not bring to light the lateral and vertical velocity structural details of different important tectonic segments, the data have been processed region-wise. Details of reprocessing, covering middle and western segments of Cuddapah basin and a part of Eastern Dharwar Craton (EDC), are presented here. For the present study we have considered 250 km of the 600 km long profile. Data from shot points, sps 360, 320, 280, 240, 165 and 120 have been utilized (Figure 1 *a* and *b*), as this stretch of the Kavali–Udipi profile brings into focus the prominent geologic and tectonic segments of the southwestern Cuddapah basin and adjoining EDC. We discuss here some of the significant results that are useful in understanding the structural evolution of Cuddapah basin and adjoining gneissic EDC.

Greenstone belts dominated by volcanic rocks and intrusive granitoids and characterized by low-pressure regional metamorphism typify EDC. The Cuddapah basin is surrounded by granitic and gneissic terrain, including thin, linear, N–S trending, K-granitic plutons and greenstone belts towards north, west, and south. The rocks in the Cuddapah basin originally were deposited in a broad trough, part of which has remained comparatively stationary, while the middle and northern parts of the eastern half have been crushed, folded and faulted along the eastern margin[2].

The Cuddapah basin resting on the Precambrian crystallines has sediments that are essentially nonmagnetic in nature, mostly arenaceous, argillaceous and calcareous. Papaghni and Chitravathi groups of rocks are associated with large-scale volcanism in the form of ash fall tuffs, ignimbrites, and basic sills and flows, which outcrop in an arc-concentric form paralling the western margin of the basin. The eastern part of the basin is occupied by the Kurnool group of rocks, which are highly disturbed, folded and faulted. The basin filled with Precambrian rocks of the Cuddapah and Kurnool groups, comprises mainly shales, limestones and quartzites with basic sills in the southwestern part. A remarkable tectonic feature in the Cuddapah basin is the presence of a belt of domal upwarp along an axis trending NE–SW across the middle of the basin. This region of domal upwarp also marks the zone where the fold axis of the basin swerves from NW-SE to NE–SW. The zone of upwarp is probably the result of some vertical tectonic compressional force following the nearly right-angled swerve in the axis of the basin.

Data acquired across southwestern segment of Cuddapah basin and a part of adjoining EDC of Kavali–Udipi DSS profile have been utilized for the present study. Data were acquired by continuous profiling using two seismic units of Russian made POISK-I-40 with frequency range of 5 to 30 Hz. Open cast gelignite explosive was used as the energy source with shot point spacing of 10–40 km for shallow to deep crustal studies. The travel times of first and some later arrivals were picked from analogue records of six shot points, sps 360, 320, 280, 240, 165 and 120. Since the data were recorded in analogue form, no amplitude information is available. The first arrival data have been plotted in the form of time versus distance curves for each shot point and used to derive 1D velocity models. These 1D models have been used to construct the refined 2D model using RAYAMP program (developed by McGill University in 1986). Some prominent reflectors that are consistently observed on the seismograms of all the major shot points were also used in building up the final 2D crustal model.

A seismic study gives detailed information regarding the basement configuration and sub-basement crustal structure. Efforts were made to get a crustal seismic velocity structure of western segment of Cuddapah basin and eastern segment of EDC. The present study has provided finer crustal velocity–structure of the crust and upper parts of subcrustal lithosphere compared to the models of Kaila *et al.*[1] and Tewari and co-workers[3–5]. The present study has brought out significant structural variations in all the six layers from surface to Moho-II, including disposition of deep faults (in the zone of sp 165 and Malepadu and adjacent to Parnapalle).

The derived 2D velocity–depth section is shown in Figure 2. A thin sedimentary layer of velocity 5.2–5.4 km/s was deposited over the Cuddapah basin, between shotpoints sp 120 and sp 165. The thickness of lower Cuddapah and Kurnool sediments varies from about 900 to 1200 m. Our model

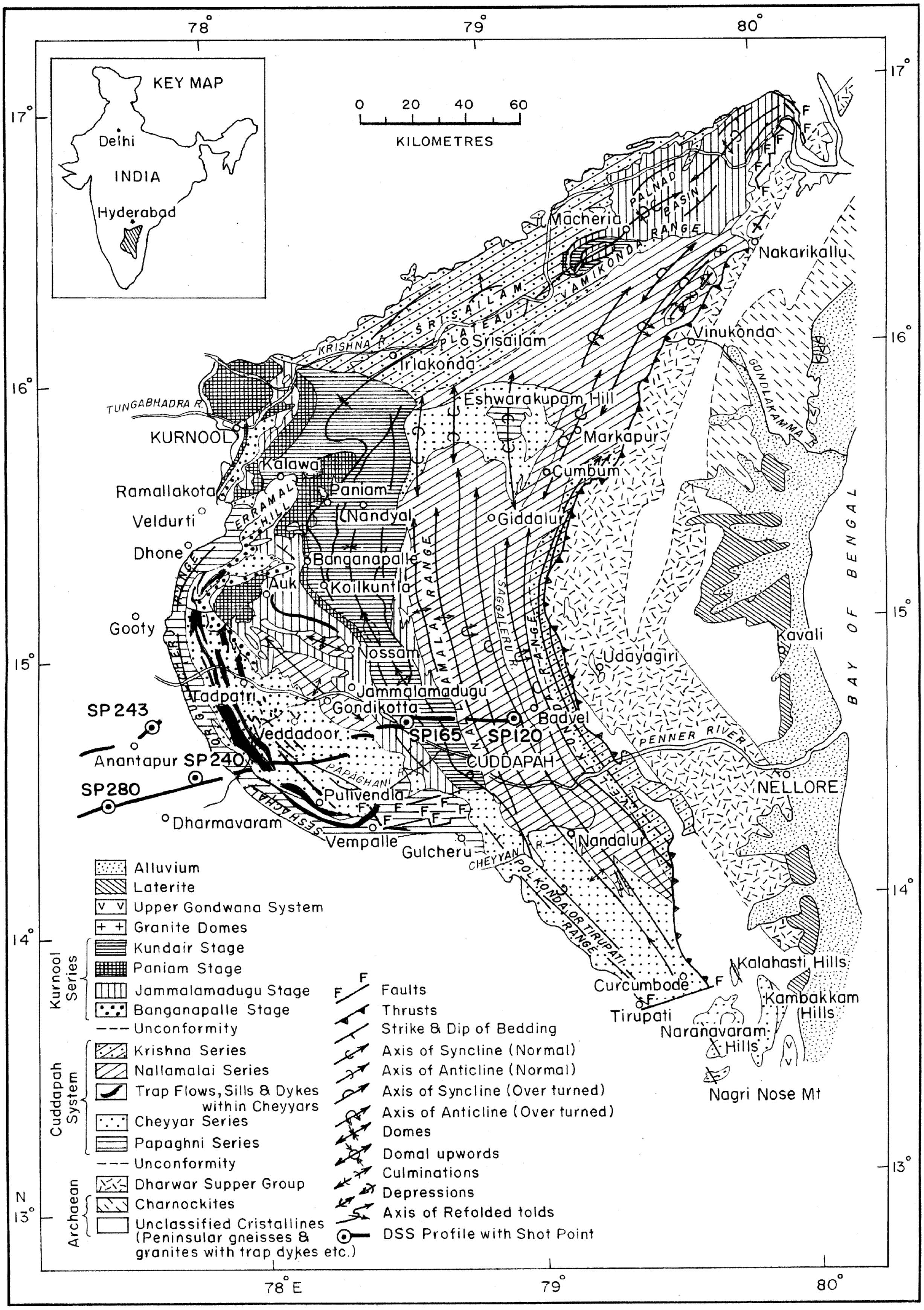

Figure 1 ***a.*** Geological and tectonic map of Cuddapah basin.

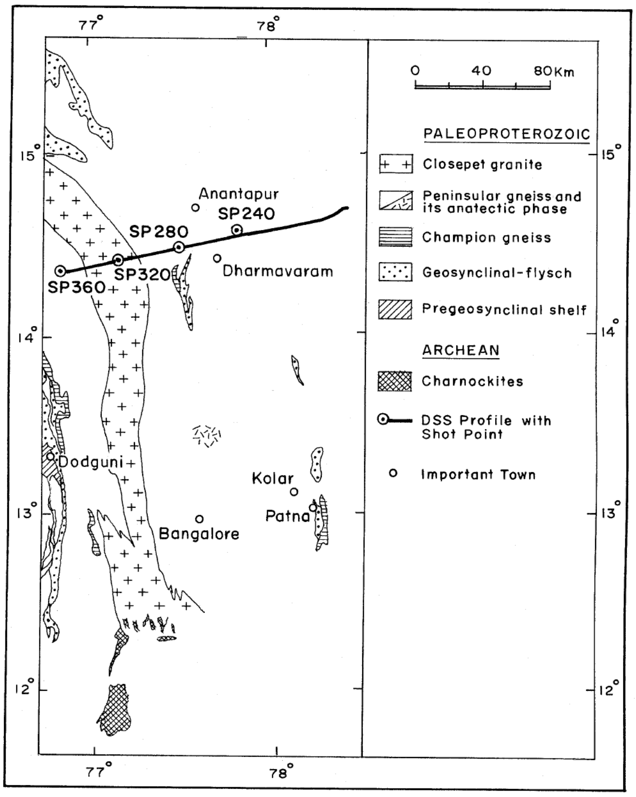

Figure 1 *b*. Ajoining Eastern Dharwar Craton along with DSS coverage details (modified after Kaila *et al.*[1]).

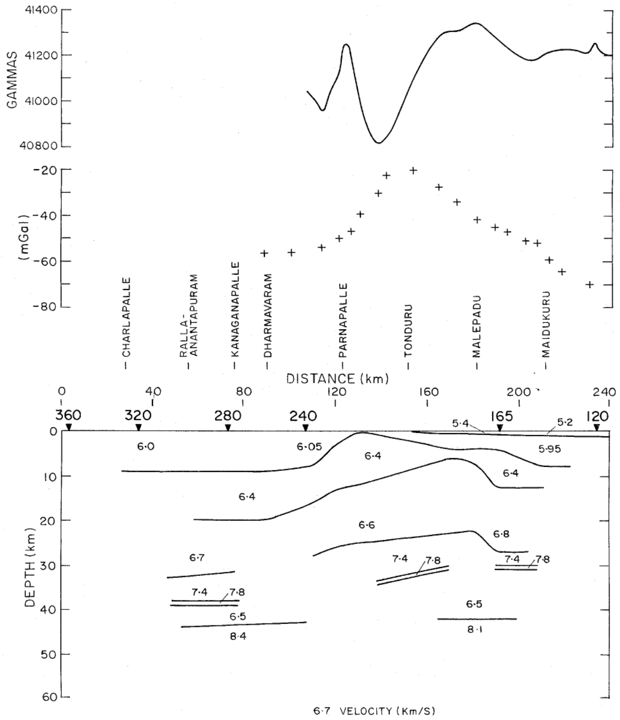

Figure 2. 2D crustal velocity structure of middle and western segments of Cuddapah basin and adjoining EDC along with data on observed gravity and magnetic total intensity anomaly.

shows that the shallowest depth to the base of the crystalline basement is around 200 m near Parnapalle. Crystalline basement (velocity 5.95–6.05 km/s) extends to a depth of 10 km in the eastern segment of the EDC and around 8 km near Maidakuru. The upper crustal layer of about 10 km thick (below the granitic basement) having a velocity of 6.4 km/s, is found to have extended to a depth of 20 km in the eastern segment of the EDC. This layer thins out to 2–5 km between Malepadu to Maidakuru. It is thickest (11–12 km) east of Parnapalle. Midcrustal refractor velocity varies from 6.6 to 6.8 km/s. Rock types consistent with this velocity include amphibolites, gabbros or granulite[6]. The next layer, the lower crust, is found to be at an average depth of 34 km, with velocity varying between 7.4 and 7.6 km/s. This segment of the crust is more or less horizontal in the EDC and shows up dip only towards east of the Cuddapah basin. According to Steven *et al.*[7], high velocity in the lower crust corresponds to granulite facies metapelite or pyroxenite and in the middle crust the velocity matches with that of greenschist-facies metagabbro.

A thin layer of 7.8 km/s with thickness ~ 1 km would be difficult to be noticed as a first arrival phase. However, the manifestation of this as a seismic phase is observed as a post-critical Moho reflection (PmP). We consider this as the Moho-1. The Moho-1 (PmP) depth varies from 30 km in the Cuddapah basin to 38 km in the EDC. Our model shows the presence of a low-velocity layer of velocity 6.5 km/s below the Moho-1 at a depth of 31 km under the Cuddapah basin and about 39 km under the EDC. The low velocity layer (LVL) seems to be thickening towards the Cuddapah basin. Below this LVL we have noticed the presence of Moho-2 at a depth of about 45 km. This is more prominent compared to Moho-1 and has a boundary velocity of 8.4 km/s (Pn). This Moho-2 is up-dipping towards east in the Cuddapah basin with a velocity of 8.1 km/s at an average depth of about 41 km.

To fill the gaps in the seismic model, a two-dimensional gravity model was derived using the software 'Saki'. Bouguer gravity anomaly values along the profile are taken from Mishra *et al*[8]. To compute the gravity response of the derived seismic depth section, a gravity profile of 148 km length connecting Parnapalle and Maidakuru has been modelled. Since the western and eastern extremities of the gravity profile reach to the background level, it is assumed that no serious edge effects will be introduced in gravity modelling.

During the computation of gravity response, density values for the derived seismic structure are assigned based on the empirical relationship between density and seismic velocity as suggested by Woolard[9], and Nafe and Drake[10]. Deviation of the computed gravity response from the observed anomalies is then minimized by adjusting the density values of different blocks of the subsurface within permissible limits[11,12] and the final model is shown in Figure 3.

Extensive geophysical studies over the Cuddapah Basin have been carried out to understand the structure and evolution of the basin. Chekunov *et al.*[13] revised the cross-section given by Kaila *et al.*[1], especially in its upper portion. The velocity structure interpreted by Chekunov *et al.*[13] provides a high velocity layer of 6.5–6.9 km/s at a depth of 3–15 km. According to Kaila *et al.*[1], the basement lies in the region between Maidakuru and Malepadu at a depth of 9–10 km. From the present study this seems to lie at a depth of 4–8 km.

The one-dimensional velocity–depth models for the EDC, at the boundary of Cuddapah basin and inside the basin are presented in Figure 4. There are significant lateral variations in velocity throughout the upper crust. A thick upper crustal column exists beneath the eastern segment of the EDC. This is found to be thinning inside the basin. The upper and lower crustal layers appear to be more or less laterally homogenous within the granitic gneissic terrain of the EDC. The upper (6.0–6.4 km/s), middle (6.6–6.8 km/s) and lower crust (7.4 km/s) show a layered structure in the eastern part of the EDC. Derived crustal structure of the Cuddapah basin displays lateral velocity variations from the top of the basement to the middle crust. The base of the granitic crystalline basement, which lies at a depth of about 10 km in the EDC shows an upwarping trend, attaining a depth of about 200 m at Parnapalle (western contact with the basin). All the layers in the Cuddapah basin from the top of the basement to the lower crust, and even the Moho show an up-dipping trend towards east. This is significant from the point of view of evolution of the basin. A close look into the seismic model clearly indicates the presence of deep faults, disturbing an entire crustal column, below sp 165–Malepadu zone and adjacent to Parnapalle. These two fault systems seem to have played a major role in the structural disposition of Cuddapah basin between Maidakuru and Parnapalle. Kaila *et al.*[1] have also brought out the presence of deep faults at Malepadu and Parnapalle, mainly from the shifts in the Moho topography and some indirect evidences, introducing an amount of subjectivity compared to the present exposition, wherein one can notice the clear fault disposition from near surface depths to subcrustal levels.

The crustal velocity models[4,5] have not brought out any specific information about the crustal velocity structure, except for showing shallow crustal high-velocity zone (interpreted as due to top of a body with lower crustal densities that has intruded the upper crust).

Gravity and airborne magnetic surveys were carried out in this region by NGRI, Hyderabad. For the present study, we have taken observed gravity and magnetic total intensity anomaly data over the Cuddapah basin. Data are plotted over the seismic depth section (Figure 2). The total intensity aeromagnetic anomaly in the present study has been reproduced from Krishna Brahmam *et al.*[14] (figure 14). This anomaly has an amplitude of more than 500 nT and covers entirely the high-density mafic dyke-like body within the basement under the Papaghani and Chitravati group of rocks. The estimated depth to the top of this body is around 7.9 km[15] near Muddanuru. This estimate is slightly on the higher side of the sediment thickness (of 6.5 km), suggesting a possible source within the basement. Chatterjee and Bhattacharji[16] suggested deep mantle perturbation, currently manifested by a lopolithic cupola-like intrusion under the southwestern part of the basin. According to them, xenolith-bearing sills occur at the periphery of the lopolithic body. They compared the tholeiites both inside and outside the basin to mid-oceanic ridge basalts. According to Glazner and William Ussler III[17], midcrustal magma

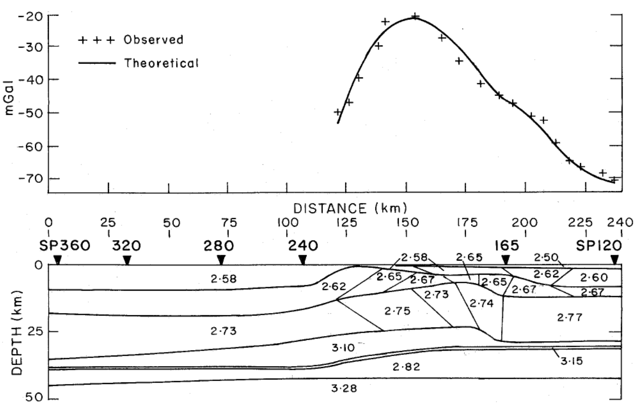

Figure 3. Gravity modelling of derived 2D crustal seismic velocity structure of the region.

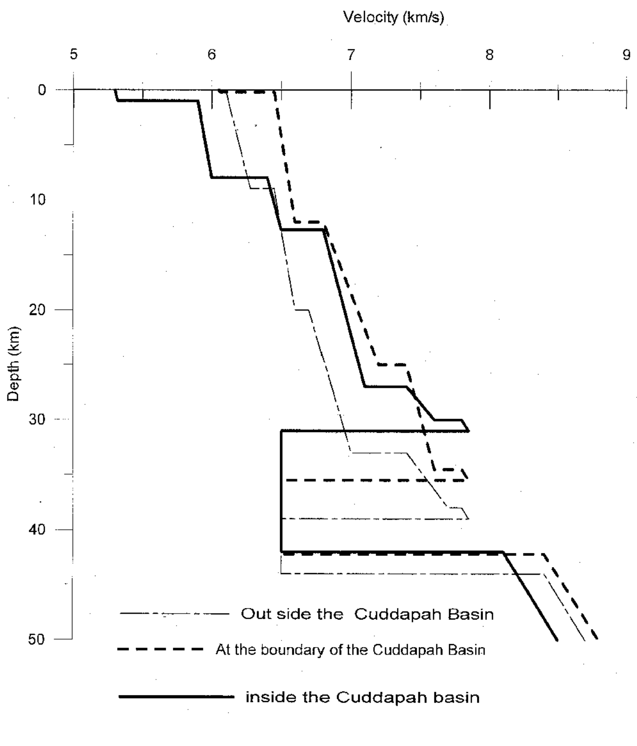

Figure 4. 1D velocity–depth model for eastern part of EDC, at the western boundary of the Cuddapah basin and inside the basin, to bring into focus the lateral and vertical structural variations.

bodies are present in the basin and range province of the western United States. According to Clemens and Vielzenf[18], most of the crust-derived magmas, as melting is due to heat sources transferred from the underlying mantle, are often basaltic intrusions. Structural and compositional trends show that the present seismic model agrees well with the above findings.

The variation in seismic velocity and density throughout the upper crust all along the section is consistent with the variations in composition. Highest density occurs beneath the basin and is probably due to a combination of relatively dense metamorphic rocks (hornblende–biotite gneiss). However, Qureshy *et al.*[19] noticed that the presence of granitic intrusions in different parts of the basin has locally reduced the density of an originally heavier upper crust.

The gravity anomaly over the Cuddapah basin shows a rapid increase from about – 60 mgal to – 20 mgal. The large negative anomaly on the basement side of the present profile may however be related to domal features. The gravity anomaly varies from a minimum of – 60 mgal to a maximum of – 20 mgal in regions between Parnapalle and Tonduru. This could be related to upwarping of the crust at shallow depths. The gravity anomaly again decreases from a maximum of – 20 mgal to – 80 mgal. This decrease in anomaly is not uniform. A low-amplitude gravity anomaly is observed at sp 165 (Malepadu and Maidakuru region). This anomaly could be due to deep fault-related structural disposition, wherein the eastern block is down faulted with respect to the western block. According to Balakrishna *et al.*[20], high gravity feature can be attributed to block uplift involving the crust. Due to this block uplift, the sediments in the eastern part of the basin might have been subjected to folding and faulting leaving the lower Cuddapahs less affected. The southwestern gravity high could be related to the feeder dike responsible for the igneous activity. The presence of hidden domal features between Dharmavaram and Tonduru as also between Malepadu and Maidakuru, has been explicitly brought out in the present study. They seem to be low-amplitude gravity features. These features correlate well with the findings of Narayanaswami[21], who found a belt of domal upwarp along an axis trending NE–SW across the middle of the basin. According to Valdiya[22], the gravity lows in the Cuddapah basin imply a great accumulation of sediments. Actually the decrease is rather unexpected, because sediments in the Cuddapah basin have densities higher than or equal to the surrounding granite rocks[19]. According to Kaila and Bhatia[23], the occurrence of numerous igneous dykes and sills in the western half of the Cuddapah basin is associated with a general upwarping of the crustal column in the region and thickening of the basaltic crustal layer. It is possible that the thickening of the basaltic crustal layer and lower Cuddapah sedimentation took place simultaneously. This is evidenced from contemporaneous doleritic traps and felsites resulting in overall increase of velocity/density compared to the known upper crustal velocities at those depths. Tewari and Rao[4] interpreted shallow structural high velocity zone (velocity of 6.9 km/s) as an intruded body of lower crustal densities. Our present exercise of explaining the Bouguer gravity anomaly with the derived seismic velocity structure does not suggest the presence of a lower crustal-derived high-density body of specific dimensions to explain the gravity anomaly. The gravity anomaly is well explained by the very nature of lateral and vertical structural disposition of various layers, including the presence of two domal features and two fault zones and an overall upwarping of intracrustal layers in the zone between Parnapalle and Tonduru, as revealed by the seismic section.

Drury *et al.*[24] have proposed that the pattern of orientation of dyke swarms indicates that the Archean crust in the vicinity of the Cuddapah basin was thermally warped into an elongated dome with a roughly E–W axis under varying tectonic stresses. Thermal relaxation and erosion of this dome preceded sedimentation in the basin, with its deepest part located to the SW of its present outcrop. Eastern geosyncline, an eastern depression lying between Rallaanantapuram and Parnapalle has a thinner section of Dharwars when compared to the Western Dharwaa Craton (WDC). Lower Cuddapah formations were deposited between Maidakuru and Parnapalle. After the close of the Cuddapah period, Kurnool sediments were deposited between Maidakuru and Malepadu. All these structural and evolutionary signatures brought out by well-known geologists are fairly well corroborated by the present seismic velocity model. Our study in addition has brought into focus specific finer structural details of all the intra crustal layers and presence of a low velocity layer sandwiched between the two Mohos. Presence of LVL at this depth probably indicates two crustal domains. If the entire M1 and M2 zone is considered as a crust–mantle boundary, then such a transition suggests a strong orogenic phenomenon wherein certain lateral or vertical and possible chaotic movement of the Moho may occur[25].

According to Furlong and Fountain[26], high velocity (7.1–7.4 km/s) can be explained either as the result of the underplating of mafic and ultra mafic magmas or the presence of high-grade metamorphic rocks of supracrustal origin (metapelite). According to Nelson[27], the crust is thickened by repeated episodes of basaltic underplating. Durrheim and Mooney[28] mentioned that thickening of the Proterozoic crust occurred by the extrusion of flood basalts and underplating, the latter forming the high-velocity basal layer. According to Durrheim and Mooney[29], the Archean crust is significantly thinner than the Proterozoic crust and lacks a high velocity (> 7 km/s) basal layer. According to Nelson[27], the ubiquitous overlapping mafic dyke swarms of the Precambrian shields is the surface manifestation of these episodic underplating events. The earlier[1] and present studies clearly indicate the presence of the lower crust having velocity greater than 7 km/s. Also, the thickness of the eastern segment of the EDC seems to be more compared to the Proterozoic western and middle parts of the Cuddapah basin.

Seismic depth section (Figure 2) shows a LVL of 6.5 km/s lying at a depth of 31–39 km between the two Moho layers, having velocities varying from 7.8 to 8.4 km/s (Pn). This LVL is thinning towards the eastern segment of the EDC. LVLs arise due to various reasons. They can be either due to increased pore pressure/presence of fluids, or high temperature. The basic question is whether this is a LVL or fragments of the lower crust, which were trapped in the Moho. According to Frederick *et al.*[30] such layers can be reconstructed to synform as a fold. Then the anticline of this layer may be present above the Moho or it could be relict of subcrustal layer.

It is also interesting to note that such a LVL is not present below the least disturbed WDC. This LVL could be associated with the lower viscosity and higher mobility of the mantle material. As this LVL is of significant thickness (5 to 10 km), one needs to invoke an evolutionary mechanism that can explain its presence. This could probably indicate either the presence of a deep magma chamber (source of magmatic activity noticed at the western flank of the Cuddapah basin) or fluid impregnated, porous or fractured rocks or an oceanic crust. With the present study it is difficult to give a more definite interpretation.

Here we summarize some of the key insights:

The granitic basement with velocity of 5.9–6.1 km/s is found to extend to a depth of about 10 km in the eastern part of the EDC. However, near Parnapalle, the granitic basement extends only to a depth of 200 m.

There are considerable variations in the thickness of the granitic and the basaltic layers under the Cuddapah basin. Granitic layer thickness increases from west to east of the Cuddapah basin, whereas the basaltic layer in general, thickens from east to west.

Hidden domal features are well reflected in seismic section.

Low amplitude gravity high observed near Malepadu and Maidakuru could be associated with the deep fault at sp 165-Malepadu.

Thin Moho-1 (PmP-derived) is observed at a depth of 30 km under the basin and at an average depth of 37 km beneath the eastern part of the EDC (velocity of 7.8 km/s). This Moho seems to be up-dipping towards east.

A prominent second Moho-2 (Pn-derived) is observed at a depth of 42 km with a velocity of 8.1 km/s beneath the Cuddapah basin. Moho-2 lies at a deeper depth in the eastern part of the EDC (with a velocity of 8.4 km/s at a depth of 45 km).

A LVL with a velocity of 6.5 km/s is observed between Moho-1 (derived velocity of 7.8 km/s) and Moho-2 (derived velocity of 8.4 km/s). This layer thickens towards the Cuddapah basin. This LVL could probably indicate either the presence of a deep magma chamber or fluid-impregnated porous or fractured rocks or an oceanic crust.

1. Kaila, K. L. *et al.*, Crustal structure along Kavali–Udipi profile in the Indian peninsular shield from deep seismic sounding. *J. Geol. Soc. India*, 1979, **20**, 307–333.
2. King, W., The Kadapah and Karnul formations in the Madras presidency. *Mem. Geol. Surv. India*, 1872, **8**, 1–346.
3. Tewari, H. C., Rao, V. K. and Kaila, K. L., A model of the crust beneath the Cuddapah basin from Deep Seismic Soundings and gravity. Proceedings of the International Symposium on Deep Seismic Sounding Traverses (AEG) 1985, pp. 11–16.
4. Tewari, H. C. and Rao, V. K., A high velocity intrusive body in the upper crust in the southwestern Cuddapah basin as delineated by deep seismic soundings and gravity modelling. *Mem. Geol. Soc. India*, 1987, **6**, 349–356.
5. Tewari, H. C. and Rao, V. K., Crustal velocity model in the eastern part of the Indian peninsular shield. *J. Geol. Soc. India*, 1990, **36**, 475–483.
6. Kern, H. and Richter, A., Temperature derivatives of compressional and shear wave velocities in crustal and mantle rocks at 6 kb confining pressure. *J. Geophys.*, 1981, **49**, 47–56.
7. Steven, H. W., Mooney, W. D. and Christensen, N. I., The seismic velocity structure of the deep continental crust. *Continental Lower Crust* (eds Fountain, D. M., Arculus, R. and Kay, R. W.), *Developments in Geotechnics 23*, Elsevier, 1992, pp. 1–43.
8. Mishra, D. C. and Prajapati, S. K., A plausible model for evolution of schist belts and granite plutons of Dharwar Craton, India and Madagascar during 3.0–2.5 Ga: Insight from gravity modeling constrained in part from seismic studies. *Gondwana Res.*, 2003, **6**, 501–511.
9. Woolard, G. P., Crustal structure from gravity anomaly and seismic measurements, *J. Geophys. Res.*, 1959, **69**, 1524–1544.
10. Nafe, J. E. and Drake, C. L., Physical properties of marine sediments, In *The Sea* (ed. Hill, M. N.), Wiley, New York, 1963, vol. 3, pp. 794–8150.
11. Barton, P. J., The relationship between seismic velocity and density in the continental crust – a useful constraint? *Geophys. J. R. Astron. Soc.*, 1986, **87**, 195–208.
12. Reddi, A. G. B., Mathew, P. M. and Kailasam, L. N., Proc. Symp. Upper Mantle Project, Natl. Geophys. Res. Inst. India, 1967, pp. 286–302.
13. Chekunov, V., Sollogub, V. B., Starotenko, Kharechko, G. E., Rusakov, O. M., Kozlenko, G. and Kostyukevich, A. S., Structure of the earth's crust and upper mantle below Hindustan and the northern part of the Indian Ocean from geophysical data. *Tectonophysics*, 1984, **101**, 63–73.
14. Krishna Brahmam, N., Sarma, J. R. K., Aravamadhu, P. S. and Subba Rao, D. V., Bouguer Gravity Anomaly Map of Cuddapah Basin (India), (NGRI/GPH-6), 1986.
15. Babu Rao, V., Geological significance of magnetic depth estimates over western part of Cuddapah basin. *J. Geol. Soc. India*, 1991, **38**, 605–614.
16. Chatterjee, N. and Bhattacharji, S., Petrology, geochemistry and tectonic settings of the mafic dikes and sills associated with evolution of the Proterozoic Cuddapah basin of South India. *Proc. Indian Acad. Sci. Earth Planet. Sci.*, 2001, **110**, 433–453.
17. Glazner, A. F. and William Ussler, III., Trapping of magma at mid-crustal density discontinuities. *Geophys. Res. Lett.*, 1988, **15**, 673–675.
18. Clemens, J. D. and Vielzeuf, Constraints on melting magma production in the crust. *Earth Planet. Sci. Lett.*, 1987, **6**, 287–306.
19. Qureshy, M. N., Krishna Brahamam, N., Aravamadhu, P. S. and Naqvi, S. M., Role of granitic intrusion in reducing the density of the crust and other related problems as illustrated from a gravity study of the Cuddapah basin, India. *Proc. Geol. Soc. Sm.*, 1968, **304**, 449–465.
20. Balakrishna, S., Christopher, G. and Ramana Rao, A. V., Regional magnetic and gravity studies over the Cuddpah basin. Proc. Symp. Upper Mantle Project, NGRI, Hyderabad, 1967, pp. 303–319.

21. Narayanaswami, S., Tectonics of Cuddapah basin. *J. Geol. Soc. India*, 1966, **7**, 33–50.
22. Valdiya, K. S., Tectonic framework of India – A review and interpretation of recent structural and tectonic studies. *Geophys. Res. Bull.*, 1973, **11**, 79–114.
23. Kaila, K. L. and Bhatia, S. C., Gravity study along the Kavali–Udipi deep seismic sounding profile in the Indian peninsular shield: some inferences about the origin of anorthosites and the Eastern Ghats orogeny. *Tectonophysics*, 1981, **9**, 29–143.
24. Drury, S. A., Harris, B. W., Holt, R. W, Reeves-Smith and Wightman, R. T., Precambrian tectonics and crustal evolution in south India. *J. Geol.*, 1984, **92**, 20.
25. Meissener, R., The 'MOHO' as a transition zone. *Geophys. Surv.*, 1973, **1**, 195–216.
26. Furlong, K. P. and Fountain, D. M., Continental crustal underplating: Thermal considerations and seismic petrologic consequences. *J. Geophys. Res.*, 1986, **91**, 8285–8294.
27. Nelson, K. D., A unified view of craton evolution motivated by recent deep seismic reflection and refraction results. *Geophys. J. Int.*, 1991, **105**, 25–35.
28. Durrheim, R. J. and Mooney, W. D., Evolution of the Precambrian lithosphere: Seismological and geochemical constraints. *J. Geophys. Res.*, 1994, **99**, 15,359–15,374.
29. Durrheim, R. J. and Mooney, W. D., Archean and Proterozoic crustal evolution: Evidence from crustal seismology, *Geology*, 1991, **19**, 606–609.
30. Frederick, A. Cook and Kris Vasudevan, Are there relict crustal fragments beneath the Moho? *Tectonics*, 2003, **32**, 1026.

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The Pangidi Anorthosite Complex, Eastern Ghats Granulite Belt, India: Mesoproterozoic Sm–Nd isochron age and evidence for significant crustal contamination

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The Pangidi Anorthosite Complex (PAC) is a small, magmatically layered body emplaced into high-grade supracrustal rocks and metamorphosed together with the host rocks in the southern sector of the Eastern Ghats Granulite Belt, South India. It is dominated by coarse-grained anorthosite and leuconorite, minor leucogabbronorite and ultramafics with chromitites. The anorthositic rocks contain plagioclase (An_{55-70}) + orthopyroxene (En_{50-60}) + augite + amphibole + ilmenite + magnetite with accessory olivine, biotite, apatite and rarely coronal garnet related to metamorphic reconstitution. Despite a less calcic plagioclase composition in the anorthosites, the major and trace element distributions are akin to comparable litho types (at similar SiO_2 wt%) of the Kondapalli layered anorthosite complex in close proximity. However, the PAC shows distinct effects of metamorphism and significant modal volume of secondary hydrous mineral phases unlike the latter. A five-point whole-rock Sm–Nd isochron gives 1739 ± 220 million years (Ma) (2σ) age for the complex, which constraints the younger limit to its intrusion and probably metamorphism under amphibolite to granulite facies conditions. The PAC is characterized by strikingly low $\varepsilon_{Nd\ (at\ 1750\ Ma)}$ of –14.4 ± 3.7, indicating the importance of crustal contamination in its genesis possibly involving significantly older (Late Archaean) crustal components.

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ANORTHOSITE is a less abundant but fascinating rock composed almost entirely of calcic-plagioclase. Terrestrial anorthosite occurrences fall into a few genetic 'types' or 'associations' such as: (i) Archaean (> 2500 million years (Ma)) megacrystic, (ii) Proterozoic (2500–500 Ma) massif-type and (iii) components of layered mafic and ultramafic igneous plutons. The genesis of anorthosite complexes involves essentially a two-stage process of mantle magmatism (accumulation of typically Fe and Al-rich basaltic parental magmas at sub-crustal cites), followed by magma differentiation and emplacement of plagioclase-rich mushes into the crust at different tectonic settings[1,2]. Implicit in this model is assimilation of continental crust by the parental melts of the anorthosite intrusives primarily during differentiation and/or emplacement, so much so that their geochemical and isotopic signatures are being used not only to characterize their parental magmas and the mantle source, but also as a tracer of composition of the deep-crust, which they assimilate[1–3]. The Proterozoic Eastern Ghats Granulite Belt (EGGB) exposes several large and small anorthosite complexes most of which are 'massif-type'. However, examples of 'layered-type' anorthosite complexes like the Kondapalli anorthosite complex from the southern sector (south of the Godavari graben) are also well known[4]. The Pangidi Anorthosite Complex (PAC)[5], N16°41′: E80°32.5′, Krishna District, Andhra Pradesh is a small and less known, deformed and metamorphosed layered intrusion[5–10] (Figure 1). It is emplaced into the high-grade gneisses of the EGGB and was considered a part of the Kondapalli complex, which is located in close proximity[4,6]. However, it appears to be petrographically distinct from the Kondapalli complex because of its distinctly higher content of hydrous minerals and coarse pegmatoidal texture. The host rocks of PAC include multiple deformed