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Seismic evidence for thick and underplated late Archaean crust of eastern Dharwar craton

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Abstract. The deep crustal structure of eastern Dharwar craton has been investigated through τ-p extremal inversion of P-wave travel times from a network of seismographs recording quarry blasts. Travel times have been observed in the distance range 30–250 km in a laterally homogeneous lithospheric segment. Main features of the inferred velocity-depth relationship include: **(a)** 29 km thick combined upper and middle crust velocity varying from 6 km/s to 7 km/s, with no observable velocity discontinuity in this depth range; **(b)** a lower crust ($\sim$ 29–41 km) with velocity increasing from 7·0 to 7·3 km/s; **(c)** an average upper mantle velocity of 8·1 km/s; and **(d)** presence of a 12 km thick high velocity crustal layer (7·4 – 7·8 km/s) in the depth range 41–53 km, with a distinct velocity gradient marking a velocity increase of 0·4 km/s. The anomalous 53 km thick crust is viewed as a consequence of magmatic underplating at the base of the crust in the process of cratonization of the eastern Dharwar craton during late Archaean. The underplated material reflects here with the velocity of 7·3 to 7·8 km/s below the depth of 40 km. Our proposition of magmatic underplating is also supported by the presence of large scale I-granitoid, a product of partial melting of the upper mantle material.

Keywords. Dharwar craton; Archaean; crust; underplating; travel time inversion.

1. Introduction

Knowledge of the velocity-depth geometry in the crustal segments of the Archaean terrains provides the critical input to study the nature and evolution of the primitive crust. Based on the velocity-depth function from Precambrian terrains across the globe, Durrheim and Mooney (1991, 1994), and Durrheim and Green (1992) have shown that the Proterozoic crust has a thickness of 40–55 km with a substantial high velocity ($>$ 7 km/s) layer at its base while the Archaean crust has a thickness of 27–40 km and absence of basal high velocity layer. This is at a significant variance from the earlier observation of Meissner (1986) that the thickness and average velocity of the continental crust (except the young orogens) is proportional to their age. In this communication we have used travel time data from quarry blasts sources recorded over a network of seismographs in the eastern Dharwar craton to arrive at the extremal bounds on the velocity variation with depth using τ-p inverse formalism (Bessonova *et al* 1974; Kennet 1976). This velocity model has been used to infer the possible tectonic scenario during the early crustal evolution.

2. Geological framework

The Dharwar craton (figure 1) is divided into the western and eastern segments through an NS extending Closepet granite. The western Dharwar craton (WDC) crust is as old

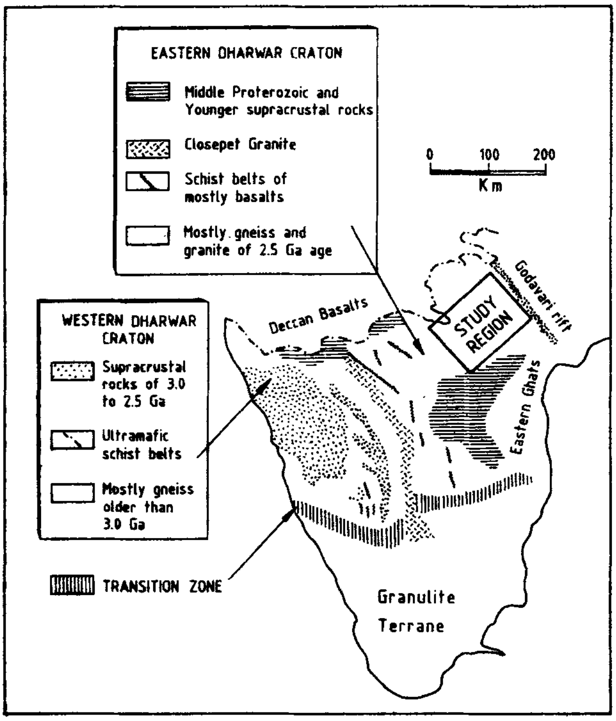

Figure 1. Geological framework of the Dharwar craton, south India (from Rogers and Maulain 1994). The study region is marked in the northern part of the figure.

as 3·4 Ga with isotopic indications of LIL enriched sources considerably older (Rogers and Maulain 1994). The WDC was stabilized in an event at $\sim$ 3·0 Ga characterized by matasomatism of the crust. The eastern Dharwar craton (EDC) consists largely of the juvenile crust produced at $\sim$ 2·6–2·5 Ga. Most of the exposed EDC consists of gneisses and granites. The eastern margin of EDC is largely covered by a middle Proterozoic Cuddapah basin. The basin and other rocks of EDC are truncated by the Eastern ghat granulite terrain. The northern end of the EDC is bounded by the middle Proterozoic Godavari rift valley.

3. Travel time observation

The seismic velocity-depth geometry is generally created through the inversion of travel time-distance observation and seismic wave amplitude. The velocity-depth relationship is an average for the structure between seismic source and recording point. To be able to generate a representative model for a particular geological terrain, the study region should be either free from major lateral inhomogeneities or their presence be properly accounted for.

This study is confined to the northern segment of EDC as depicted in figure 1. To analyse the possible presence of lithospheric inhomogeneity in the region we studied the variation in teleseismic travel time residuals and velocity image over this geological segment. The detailed analysis of residual pattern, velocity image and geological correlation is presented in Prakasam and Rai (1996). Since the teleseismic rays impinge the recording station near vertical, the demeaned travel time residual is least contaminated by the heterogeneities far from the station. The teleseismic residual measured over a network of seismic stations provides quick glimpses into the presence of inhomogeneity in the region. The teleseismic residual at a station has been averaged over all the distances and azimuths and is referred as station anomaly. The variation of station anomaly over the region is presented in figure 2. The residual varies between $-0{\cdot}2$ and $-0{\cdot}4$ s in the study region, typical for any Archaean shield (Dziewonski and Anderson 1983). The azimuth independent residual represents travel time response of uppermost 60–70 km of the lithosphere. To examine the velocity inhomogeneity in the representative crustal layer, the per cent velocity variation in the depth range 0–40 km is presented in figure 3. The velocity image has been generated using the arrival time of earthquakes at different teleseismic distances and azimuths recorded at seismic stations in the region. The velocity picture at deeper lithospheric level is presented in Prakasam and Rai (1996). In the study region P-wave velocity varies between 1·3% and 3% in the depth 0–40 km. This observed velocity variation of 1·7% across the study region is not very significant and therefore we conclude that this part of EDC is devoid of any major lateral inhomogeneity.

During the teleseismic tomography experiment, we recorded quarry blasts from the southern fringe of the Godavari basin used for coal mining. We used only large energy explosion that could be recorded properly to a distance of 350 km from the source. These are all near-surface explosions. Their approximate locations were provided by the coal mining authorities. Location of blasts and the recording stations are depicted in figure 4. To record these blasts we used Geotech S-13 short period (1 Hz) vertical sensor and drum recorder operating at 240 mm/min speed and internal clock synchronized twice a day with an external broadcast. The first cycle of the seismogram was $10X$ optically magnified. The inaccuracy in the reading P phase arrival time is generally less than 0·1 s. Using P and S phase data we computed the origin time of these blasts along with their improved location considering a fixed focal depth of 10 m. In order to use the

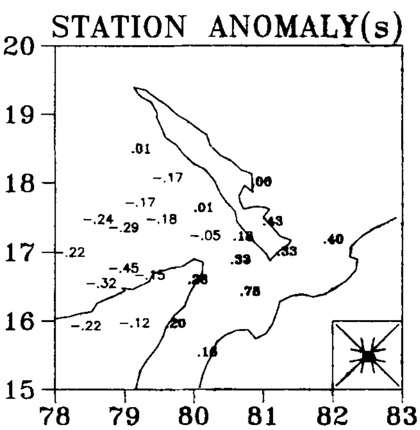

Figure 2. Teleseismic travel time residual (s) averaged over all the azimuths and distance ranges in the northern part of the eastern Dharwar craton. Positive denotes slower and negative represents faster than the average arrival time of teleseismic rays. The media beneath the station accordingly has lower or higher than the average velocity.

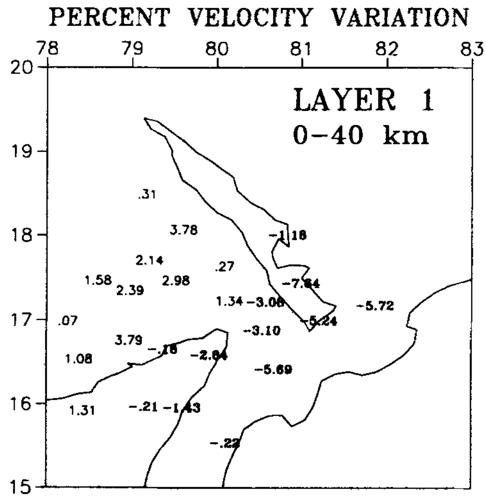

Figure 3. *P*-wave velocity variation in the depth 0–40 km inverted from inversion of teleseismic travel times over the network (from Prakasam and Rai 1996).

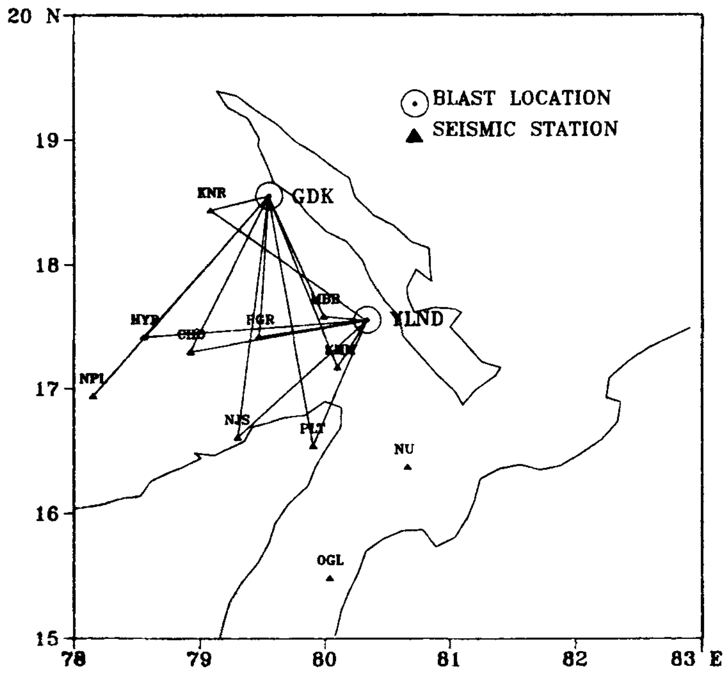

Figure 4. Location of quarry blasts and recording stations. Source-reveiver pairs used in creating travel time distance graph are line joined.

travel time data exclusively from EDC, we used the observations restricted over the study region marked in figure 1. Scatter in the travel time data (figure 5a) basically arises from source mislocation ($<0{\cdot}5$ km) and origin time error. The reduced travel time plots for the eastern Dharwar craton is presented in figure 5(b).

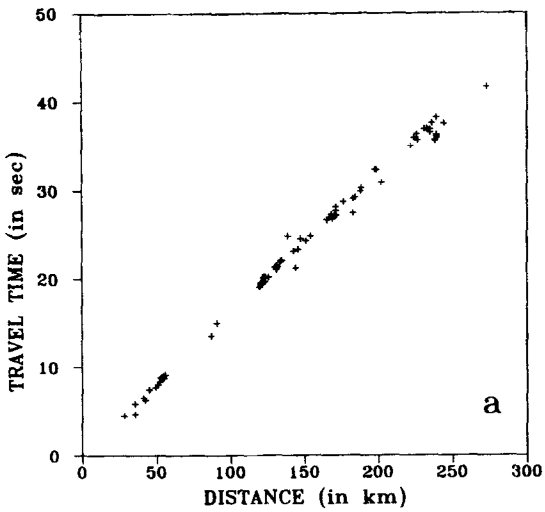

Figure 5(a). Travel time distance graph for the eastern Dharwar craton.

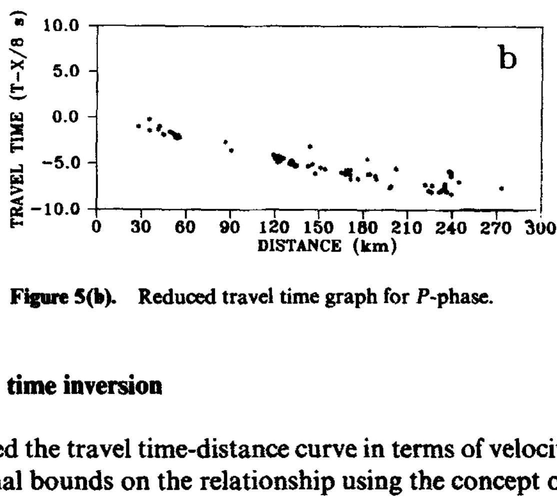

Figure 5(b). Reduced travel time graph for P-phase.

4. Travel time inversion

We inverted the travel time-distance curve in terms of velocity-depth function providing extremal bounds on the relationship using the concept of delay times $\tau(p) = T(p)-\tau X(p)$ for a ray parameter p, travel time T and distance X. Details of the methodology is presented by Bessonova *et al* (1974) and Kennet (1976). The delay time $\tau(p)$ is a single valued function associated with travel time and represents the intercept on the time axis of a tangent to the travel time curve at a point where the slope is p. To compute $\tau(p)$ we interpolated the travel time curves with a smoothed spline accounting for the data error by weighting each point by inverse of its error. The estimates of ray parameter p are obtained by differentiating the spline. Using the interpolated value of T and X we estimated τ from the above relationship. The resulting τ-p graph for the travel time curve is presented in figure 6. Following Bessonova *et al* (1974), we computed the velocity-depth functions. These bounds are presented in figure 7 along with an average of all the velocity models.

The following salient features of the velocity depth function for the EDC are observed:

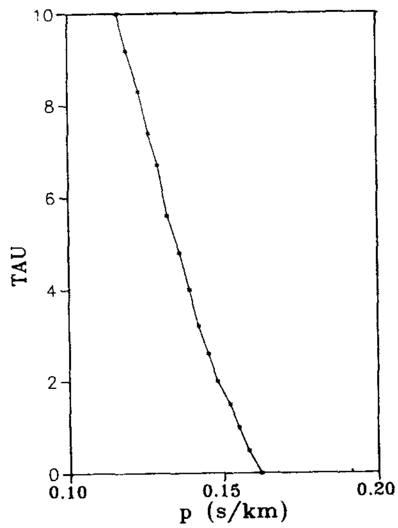

Figure 6. τ-p relationship obtained from travel time-distance observation.

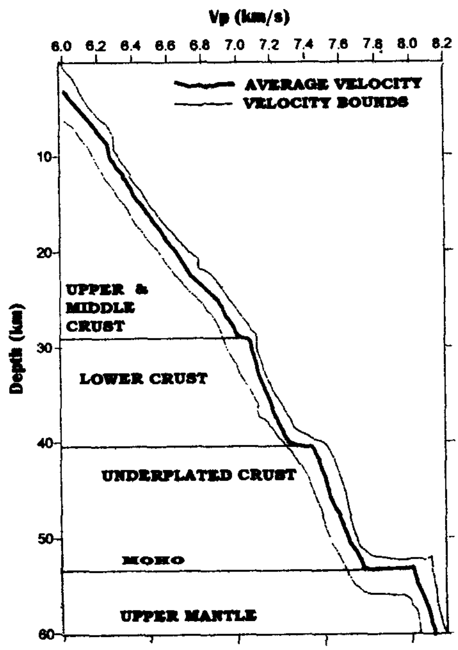

Figure 7. Extremal bounds on the velocity-depth relation derived from the inversion of $\tau(p)$ measurements. The averaged velocity-depth graph is also presented.

- The first observable change in the velocity gradient occurs at a depth of 29 km. The velocity varies from 6 km/s near surface to 6·9–7·1 km/s at the base. Since no other discontinuity is observed in this depth range, we interpret the 29 km thick column to be a combined upper and middle crust of the EDC.

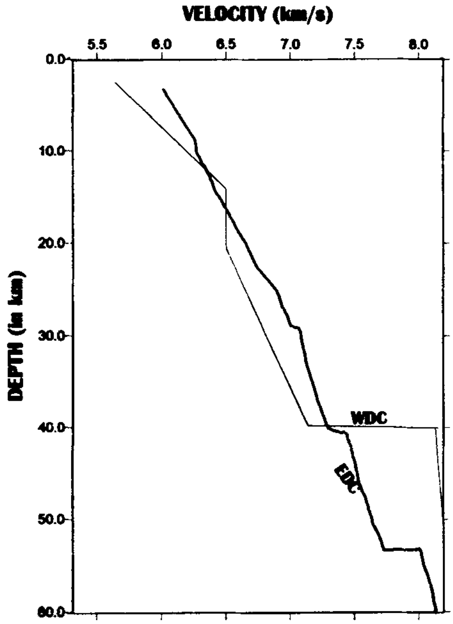

Figure 8. The velocity-depth relationship inferred from refraction seismic experiment in the western Dharwar craton (Kaila *et al* 1979) is compared with the averaged velocity-depth from eastern Dharwar craton (present study).

- The lower crust (29–41 km) has seismic velocity in the range 7·0 to 7·3 km/s.
- Moho is typically identified with the depth where Vp exceeds 7·8 km/s. We observe a sharp velocity increase to 8·1 km/s at a depth of 53 km and interpret this to be the depth of Moho.
- Between the lower crust and 53 km discontinuity a thick layer of 12 km (41–53 km) with velocity ranging 7·4 to 7·8 km/s is observed.

The above observations point to an anomalous 53 km thickness of the Archaean crust. We compare our velocity model with an earlier refraction seismic result (Kaila *et al* 1979) in the western Dharwar craton (figure 8).

5. Implications to Archaean crustal growth

Velocity-depth modeling of the travel time data in the eastern and western Dharwar cratons depicts significant differences in the crustal velocity signatures specifically below the depth of 40 km. Beyond this depth upper mantle velocity (8·1 km/s) is observed in WDC whereas in EDC a similar velocity is observed at ~ 53 km. Between 41–53 km a high velocity layer (7·4 to 7·8 km/s) has been observed beneath the EDC. The Moho is generally linked to observation of seismic velocity > 7·8 km/s. With this in view, we observe around 53 km thick crust in the EDC in contrast to a normal 40 km thickness in WDC. The most important inference from this study is the observation of the 7·4–7·8 km/s layer at the base of the lower crust beneath the EDC. This we consider as the response of the underplated material. The most likely candidate for this high velocity is the magma generated by partial melting of upper mantle (Furlong and Fountain 1986; Nelson 1991) that is usually mafic or ultra mafic in character. This material would generally settle in the lower level of the crust (Herzberg *et al* 1983) and lead to elevated velocity in lower crust along with deepening of the crust/mantle boundary (Drummond and Collins 1986). The presence of this higher velocity is viewed as a consequence of either continuous or episodic addition of material at the base of the crust during the cratonization of EDC.

Our above inference on the magmatic underplating of the eastern Dharwar craton crust finds support from geological evidences. The EDC has wide spread I-type granitoids (Naqvi and Rogers 1987; Jayananda *et al* 1995) originated through the partial melting of the upper mantle material. Such mantle-derived crustal material added over 10 km to the thickness of the crust. The absence of similar underplating in WDC is probably due to the absence of I-type granite generation event in the region.

Acknowledgements

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