Complex shallow mantle beneath the Dharwar Craton inferred from Rayleigh wave inversion

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SUMMARY
The 3-D shear velocity structure beneath South India’s Dharwar Craton determined from fundamental mode Rayleigh waves phase velocities reveals the existence of anomalously high velocity materials in the depth range of 50–100 km. Tomographic analysis of seismograms recorded on a network of 35 broad-band seismographs shows the uppermost mantle shear wave speeds to be as high as 4.9 km s⁻¹ in the northwestern Dharwar Craton, decreasing both towards the south and the east. Below ~100 km, the shear wave speed beneath the Dharwar Craton is close to the global average shear wave speed at these depths. Limitations of usable Rayleigh phase periods, however, have restricted the analysis to depths of 120 km, precluding the delineation of the lithosphere–asthenosphere boundary in this region. However, pressure–temperature analysis of xenoliths in the region suggests a lithospheric thickness of at least ~185 km during the mid-Proterozoic period. The investigations were motivated by a search for seismic indicators in the shallow mantle beneath the distinctly different parts of the Dharwar Craton otherwise distinguished by their lithologies, ages and crustal structure. Since the ages of cratonic crust and of the associated mantle lithosphere around the globe have been found to be broadly similar and their compositions bimodal in time, any distinguishing features of the various parts of the Dharwar shallow mantle could thus shed light on the craton formation process responsible for stabilizing the craton during the Meso- and Neo-Archean.

Key words: Composition of the mantle; Surface waves and free oscillations; Seismic tomography; Cratons; Asia.

1 INTRODUCTION
Cratons are extraordinary areas of continental lithosphere that have exhibited long-term stability against deformation. While the processes of their formation and preservation remain a matter of continuing enquiry, it is clear that their lithospheric structures must be so constituted as to fulfil the following two requirements throughout their history: (i) the ability to maintain a net positive balance between the opposing effects of chemical and thermal buoyancy and (ii) a total yield stress that is greater than those exerted by mantle convection. The latter, in turn, requires a thick root acquired through a cumulative process as well as high viscosity and elevated solidus by expulsion of bound molecular water. Worldwide investigations of mantle xenoliths from cratonic regions have shown that the sub-crustal cratonic mantle lithosphere (SCML) consists primarily of olivine with an unusually high proportion of Mg# minerals and low Ca, Al oxides (Bernstein et al. 1997), even as the high Mg hosts vary from the orthopyroxene-rich harzburgites of the Kaapvaal craton (Boyd & Mertzman 1987) to the refractory dunites of Greenland (Bernstein et al. 1997). However, the particular thermo-mechanical mechanism responsible for sequestering the large amounts of anhydrous lighter derivatives from the parental peridotites to form the cratonic lithosphere is a matter of debate. The two main hypotheses advanced to explain this segregation process, ones that require an efficient melting regime, assume: (i) extensive partial melting with melt and volatiles being extracted under extreme conditions within the head of a hot mantle plume and (ii) repeated reprocessing at subduction margins of the depleted oceanic mantle (Lee 2006; Arndt et al. 2009; Lee et al. 2011) which, in the Archean, would probably have a higher proportion of Forsterite, Fo#91–93. The first of these predicates a zonally differentiated pattern horizontally mediated by the distance to the plume edge and vertically by the distance above the solidus. The latter might be expected to retain the vestiges of the original stratification produced by higher levels of partial melting with decreasing depth, as well as of extensive harzburgite enrichment such as dipping interfaces of stacked oceanic mantle (Bostock 1998; Lavender et al. 2005). This paper presents the results of an experiment designed to discern these features in the shallow cratonic
mantle and to identify dissimilar parts of south India’s Dharwar Craton. To do this, we analyse fundamental mode Rayleigh wave phase velocities to model the shear velocity structure of the region.

1.1 The Dharwar Craton

The Dharwar Craton is the southern constituent of the Indian Shield, thrust against a narrow belt of Eastern Ghats granulites. Stretching from 11° to 18° N, the Dharwar Craton exposes a continuum of crustal rocks bearing low-grade gneisses and greenstone basins that are fringed in the south by a 150-km-wide belt of higher grade granulites (Fig. 1) across a diffused orthopyroxene isograde. Based on age and lithology, the Western part of the Dharwar Craton (WDC) is distinguished from the Eastern (EDC) across the eastern limb of the Chitradurga Schist Belt (CSB; Naqvi & Rogers 1987). The WDC, which hosts a few enclaves of younger 2.5 Ga granites, is composed predominantly of 3.3–3.0 Ga gneisses and greenstones with the oldest (3.6 Ga) in its south-central region. The northern WDC is buried beneath the Deccan basalts but is lined at their boundary by ~2.7 Ga basins created by intermittent volcanic activity under stable conditions (Radhakrishna 1983). The southern half of the WDC shows evidence of an increasing degree of metamorphism southward by exposures of greenschist facies (3–5 Kb and 500° C) at 15° N to granulites (8 Kb and 800° C), corresponding to tectonic uplift and erosion of ~5 and ~20 km, respectively.

The EDC is dominated by the late Archean (3.0–2.7 Ga) calc-alkaline complex of juvenile and anatectic granites, granodiorites and diorites (Drury et al. 1984; Bouhallier et al. 1995; Chadwick et al. 2000) collectively referred to as the Dharwar batholiths. It hosts the spectacular crescent-shaped Cuddappah basin (CB) that evolved around 1700 Ma through several episodes of igneous activity (Anand et al. 2003), and which covers more than a fifth of the area of the EDC. The region southwest of this basin is intensely pierced by east–west trending, ~2400 Ma dyke swarms (Kumar et al. 2012). These mafic dykes tend to fill the entire EDC (Fig. 2), a feature largely absent from the WDC. The western boundary of the CB has also been marked by occurrences of several diamond- and non-diamond-bearing kimberlites and lamproites of Proterozoic age (~1100 Ma; Chalapathi Rao 2008; Griffin et al. 2009).

1.2 Geophysical studies of the Dharwar Craton

There have been limited geophysical investigations of the deep structure of the Dharwar Craton. Teleseismic delay time tomography using a sparse network of analogue seismic stations brought out the existence of a ~200-km-thick lithosphere of significantly higher velocity (1–2 per cent) than the global average beneath the
Layered lithosphere beneath Dharwar Craton

Figure 2. Location of major dyke swarms, kimberlites, lamproites and lamprophyres in the Dharwar Craton.

WDC, thinning to <100 km beneath the Eastern Ghats and the coastal basin (Srinagesh & Rai 1996; Prakasam & Rai 1998). Mitra et al. (2006) presented an $S$-velocity model of the Dharwar Craton determined from interstation Rayleigh wave phase velocity data. Their model showed a $\sim$155-km-thick lithosphere composed of a two-layer crust of 35 km thickness overlying a two-layer mantle lid of 120 km thickness with an average velocity of 4.68 km s$^{-1}$. Their model also showed an increase in the $S$ velocity at 75 km from 4.52 to 4.77 km s$^{-1}$. Using $S$ receiver functions from three broad-band stations in the Dharwar Craton, Kumar et al. (2007, 2013) suggested a velocity inversion at a depth of 80–100 km which they interpreted as the base of the lithosphere, but this result was criticized by Oreshin et al. (2011) and Bodin et al. (2013) as arising from an inappropriate analysis and modelling of the data. In a recent study, Bodin et al. (2013) analysed data from the Geoscope station HYB in the north-central part of the Dharwar Craton using improved inversion methodology. They infer a $\sim$200-km-thick lithosphere beneath the Dharwar Craton and a mid-lithospheric low velocity region at a depth of $\sim$100 km. Kiselev et al. (2008) jointly inverted both $P$ and $S$ receiver functions and teleseismic $P$ and $S$ traveltime residuals to resolve the lithosphere–asthenosphere boundary (LAB) of the Dharwar Craton at 10 seismograph stations. The most conspicuous feature of their study is the absence of a high velocity mantle keel ($V_s \sim 4.7$ km s$^{-1}$), typically observed in other Archean cratons. On the other hand, they found an $S$ velocity close to 4.5 km s$^{-1}$ from the Moho down to a depth of $\sim$250 km. Using $P$ and $S$ receiver functions that predominantly sample the EDC further to its east,

Figure 3. Locations of earthquakes (yellow star) recorded by the Dharwar seismic network (red square).
Ramesh et al. (2010) observed the presence of two distinct westerly dipping interfaces at depths centred at 150 and 200 km, which they interpreted as relics of Precambrian subducted slabs. Most of these studies were based on small sets of data and except for the first, were restricted to isolated geological domains.

2 PRESENT STUDY

2.1 Data analysis

Waveform data were generated at 35 broad-band seismic sites across the Dharwar Craton between 2009 February and 2011 February (Fig. 1). The spacing of the stations ranged from \(\sim 55\) to \(\sim 210\) km. The seismograph systems consisted of a Guralp CMG3T or 3ESP broad-band sensor recorded on a REFTEK 130 data acquisition system sampling at a frequency of 50 Hz. Seismograms for all events of \(M > 5.5\) in the epicentral distance range 30° to 95° were examined for their signal-to-noise ratio, and of these, only the well-recorded (high signal-to-noise ratio) events shallower than 200 km were retained for further analysis. Most of the 113 events (Fig. 3) selected had focal depths less than 100 km, providing strong fundamental mode surface wave signals. The network produced a reasonably good azimuthal distribution of earthquakes despite most of the events occurring to the east of India (Fig. 3). The resulting ray path coverage (Fig. 4) allowed us to extract the lateral variation in the fundamental mode Rayleigh wave signals.

Rayleigh waveforms were isolated at eight periods from 20 to 80 s, after we first removed the instrument response, the trend and mean of the vertical component time-series and filtered them with a 10 mHz wide, fourth-order, double pass Butterworth filter centred...
2.2 Inversion for phase velocities

The determination of surface wave phase velocity assumes that the wave propagates along a great circle path and that the advancing wave front is planar across the array. This assumption is violated if velocity heterogeneities intervene this path. Non-planar energy caused by scattering or multipathing is ubiquitous and can significantly perturb the Rayleigh wave field recorded by a regional seismic network (Friederich 1999). Several approaches have been proposed to account for ray-path deviation from the idealized great circle (Friederich & Wielandt 1995; Forsyth et al. 1998). Forsyth et al. (1998) modelled the non-planar energy propagation by treating the incoming Rayleigh wavefield as a sum of two interfering plane waves with different initial phase, propagation directions and amplitudes:

\[ U_z(\omega) = A_1(\omega) \exp[-i(k_1x - \omega t)] + A_2(\omega) \exp[i(k_2x - \omega t)], \]

(1)

where \( U_z \) is the vertical displacement, \( A_i \) the amplitude of each incoming plane wave, \( k_i \) the horizontal wave number vectors, \( x \) the

at the frequency of interest. The filtered records were then windowed to isolate fundamental mode Rayleigh wave signals from other phases using window widths that captured the Rayleigh wave dispersion around the central frequency. The filtered Rayleigh wave signals were examined individually for their clarity and the selected suites were Fourier analysed to obtain their respective amplitudes and phases. An example of the original and filtered Rayleigh wave signals is shown in Fig. 5. Fig. 6 shows the effective ‘sensing’ depth of Rayleigh waves at the frequencies of our study.
position vector and \( t \) the time. For each event, the Rayleigh wave phases and amplitudes at all stations are normalized with respect to the station recording the largest amplitude values, assuming this is a point of constructive interference. As the wave field is represented by the sum of two plane waves with unknown amplitudes, phases and propagation directions, six parameters are required to describe the incoming wave field at each frequency.

The amplitude and phase of a Rayleigh wave at each site is determined by Fourier analysis of the filtered seismogram and the two best-fitting plane waves solved for by a simulated annealing search (Forsyth et al. 1998). In the second step, the data are inverted using the derived plane wave parameters and a starting phase velocity model to obtain a phase velocity model at individual grid nodes using the Bayesian inverse:

\[
\Delta m = \left( G^T C_{dd}^{-1} G + C_{mm}^{-1} \right)^{-1} \left[ G^T C_{dd}^{-1} \Delta d - C_{mm}^{-1} (m - m_0) \right],
\]

where \( m \) is the current model, \( m_0 \) the original starting model, \( \Delta m \) the change to the model, \( \Delta d \) the difference between the observed and the predicted data for the current model, \( G \) the partial derivative or sensitivity matrix relating predicted changes in \( d \) to perturbation in \( m \) and \( C_{dd} \) and \( C_{mm} \) are the \textit{a priori} data and model covariance matrices, respectively.

To remove the influence of events that are not well described by the two-plane wave approximation, each inversion is performed in

Figure 10. Rayleigh wave phase velocity maps (a, c, e, g, i, k) and standard error (b, d, f, h, j, l) with reference velocity (\( V_{\text{ref}} \)) for 20, 25, 30, 40, 60 and 80 s periods. Black triangles mark station locations. The bottom left colour scale is for the phase velocity plots and the bottom right colour scale is for the error plots.
two stages. First, the entire set of observations are assigned equal variance and the data covariance matrix is assumed to be diagonal. A typical misfit to the normalized real and imaginary terms is of order 0.1, which we chose as the initial, *a priori* estimate of standard deviation in the first set. The inversion is terminated after 10 iterations. At this point the *a posteriori* standard deviation of the data is estimated for the individual earthquakes. In the second stage, an *a priori* standard deviation to the observations is assigned, based on the *a posteriori* standard deviations found for each event after the first set of iterations.

There is always a trade-off between resolution and variance of inverted models, that is, between the range of admissible models and misfit to the data. In the inversion for phase velocity, the resolution or regularization is governed by a combination of the smoothing length ($L_w$) and the *a priori* model covariance. In this study, a smoothing length of $3\lambda/4$ was used to obtain the maximum resolution, where $\lambda$ is the wavelength. We also tested smoothing lengths of $\lambda$ and $3\lambda/2$. Decreasing the $L_w$ increases both the variance of the model parameters and the amplitude of the short length scale velocity variation. Regularization is provided in the form of an *a priori* model covariance which is set to 0.1 km s$^{-1}$.

For constructing 2-D images, the study area was pararnetrized by 1856 grid nodes (Fig. 7) at 0.5° intervals. An *a priori* model covariance equal to 0.1 and smoothing length of $(3\lambda/4)$ was assigned at each node. The surface wave phase velocity $C$ in an isotropic medium depends only on the frequency $\omega$ and is equal to $B_0(\omega)$, where $B_0$ is the azimuthally averaged phase velocity (i.e. the isotropic component). For constructing a 2-D velocity image of the region, we first derived the best-fitting average phase velocity variation with period. For these inversions, the initial value of $B_0$ was
taken from the phase velocity for the ak135 (Kennett et al. 1995) velocity model. This average phase velocity model was then used as an initial value for generating the 2-D phase velocity image of the region.

2.3 Inversion for shear wave velocity

Rayleigh wave phase velocity is primarily sensitive to shear wave velocity (Vs) and much less influenced by the compressional wave velocity (Vp) and density (ρ). During the inversion the Vp/Vs value was held constant and the P-wave velocity updated accordingly while the density was calculated using the Nafe–Drake relation (Ludwig et al. 1970; Brocher 2005). Because of the large trade-off between the Moho depth and the seismic velocity structure adjacent to the Moho discontinuity, the a priori crustal thickness for the 1-D inversion was selected from the results of earlier investigations. Early wide-angle reflection and refraction records across the central part of this craton suggest that the crust is broken into blocks with distinct Moho depths varying from 34 km in the east to 41 km in the west (Kaila et al. 1979; Roy Chowdhury & Hargraves 1981). Receiver function studies (Gupta et al. 2003; Rai et al. 2013; Borah et al. 2014a,b) show significant variations in the Moho depth beneath the Dharwar Craton: ~34–38 km in the EDC, ~38–46 km in the Eastern and Western Ghats, and 40–50 km beneath the Southern Granulite Terrain (SGT). Below the WDC, the Moho depth increases from ~38–46 km in the north to ~44–52 km in the south. Fig. 8 shows the Moho variability beneath the Dharwar Craton. An average Moho depth of 40 km was, therefore, selected as an initial crustal thickness for the 1-D shear wave velocity inversion. The model consists of a stack of 5 km-thick layers composed of 20 km of upper crust (Vs = 3.49 km s⁻¹) and four layers of lower crust (shear wave velocities: 3.65, 3.8, 3.95 and 4.15 km s⁻¹) overlying the reference velocity model ak135 from 40 km (Moho) to 200 km depth. The average phase velocity data were inverted in terms of a 1-D shear wave velocity model was subsequently used as an initial model to generate the Vs-depth profile at different locations in the region. These 1-D shear wave velocity models were eventually gathered to construct a 3-D shear wave velocity model.

3 RESULTS

3.1 Phase velocity computation

Only a few paths have phase velocity measurements with high signal-to-noise ratio for periods greater than 80 s and we restrict our study to this maximum period. Below 30 s period, surface waves are primarily influenced by crustal structure and at 40 s period they begin to ‘sense’ the upper mantle structure. We first create a mean phase velocity curve for the Dharwar Craton from the first stage of the two-plane wave inversion. The mean phase velocities vary from 3.69 km s⁻¹ at 20 s to 4.16 km s⁻¹ at 80 s, with standard deviations between 0.004 and 0.018 km s⁻¹ (Fig. 9). Fig. 9 also compares the fundamental mode average phase velocity curve for the Dharwar Craton with those from other shields. Dispersion values for the Dharwar Craton are higher than those for the Siberian (Priestley & Debayle 2003) and South African Shields (Priestley 1999), but lower than the Canadian Shield (Brune & Dorman 1963). The lower phase velocities for the Siberian Shield compared to those of other shields is probably due to the thicker crust (45 km) of the Siberian Shield compared to the other shields. A small variation is observed in the dispersion curve at 50–60 s between our mean curve for the Dharwar Craton and the results of Mitra et al. (2006), but this is probably due to the wider region covered by our study.

Using the average phase velocity as a starting point, we computed the phase velocity dispersion curves at each grid node (0.5° × 0.5°; Fig. 7), keeping the damping (0.1) and smoothing length (3λ/4) the same as in the 2-D inversion. Variations of phase velocities at periods from 20 to 80 s are shown in Fig. 10 (left-hand panel) along with their associated errors (right-hand panel) estimated from...
Figure 12. Average shear velocity anomaly in different depths ranges (a) 0–20 km, (b) 20–40 km, (c) 40–60 km, (d) 60–80 km, (e) 80–100 km and (f) 100–120 km. Stations are marked by red triangles.

model covariance matrices and the weighting function. The colour code has been shifted after 30 s period to account for the phase velocity variation. All error maps (right-hand panel in Fig. 10) show a similar pattern, with increasing error values from the centre to the edge of the study area. Due to overlapping sampling depths, the phase velocity maps show gradual changes among adjacent periods. At 20 s period, which primarily senses the crust, the southern part of WDC and SGT show low phase velocities, ones that are visible at all periods but in diminishing degree with increasing periods. This could be a consequence of the thickened crust that has been mapped using receiver functions (Gupta et al. 2003; Rai et al. 2013; Borah et al. 2014a,b). At longer periods a significant high velocity anomaly is observed in the northern WDC; this section of the WDC also contains prominent deposits of iron and manganese ores. Most parts of the EDC show a small positive anomaly for all periods without any characteristic features. The results are tested by repeating the $V_s$ inversions with varying smoothing length of $\lambda$ and $3\lambda/2$. Tomographic results obtained for those values were found to be of similar geometry to those obtained for a smoothing length of $3\lambda/4$ but with a change in amplitude.
3.2 3-D shear velocity model

We then invert the average phase velocity for the region (Figs 9 and 11a) for an average upper mantle velocity model of the Dharwar Craton (Fig. 11b). This model has a high velocity upper mantle lid (4.6–4.7 km s⁻¹) extending to ~100 km depth. We then used the phase velocity values determined at individual grid points to invert for the lateral variation in shear velocity (Vₛ), depth, using the average shear velocity for the Dharwar Craton (Fig. 11b) as a starting point. A 3-D shear velocity model for the region was then created by gathering all 1-D shear velocities from 0.5° gridpoints (Fig. 7).

The shear wave velocity in different depth ranges (Fig. 12) relative to the average 1-D wave velocity reveals lateral inhomogeneities (~2 per cent to 8 per cent) beneath the Moho to a depth of 100 km, the most remarkable being the high +8 per cent (Vₛ ~4.9 km s⁻¹) shear wave anomaly in the northern WDC. This feature is also prominent in the phase velocity map. In this same depth range, however, the southern part of the WDC shows lower wave speeds. At levels deeper than 100 km, the lateral inhomogeneity is significantly reduced (±1 per cent). However, the shallower mantle velocity in the EDC is close to the average for the region.

3.2.1 Velocity sections

Cross-sections of the absolute shear wave velocity model along N–S and W–E profiles are shown in Figs 13 and 14, respectively. Along the N–S section AA’, the shear wave speed at ~50–80 km depth varies from 4.9 km s⁻¹ below the northern part of the WDC to 4.6 km s⁻¹ below the southern part of the WDC. At deeper depths beneath the whole of the WDC, the wave speed is ~4.5 km s⁻¹, close to the global average at these depths. Beneath the EDC (section BB’), a high velocity lid with a shear wave speed of ~4.6–4.7 km s⁻¹ occurs. Along the E-W profile CC’, a 50-km-thick high shear wave speed layer exists below the Moho from the WDC to the EDC with the wave speed decreasing from west to east. Along profile DD’ a high wave speed (~4.6 km s⁻¹) layer occurs down to a depth of ~110 km in the southern WDC which becomes shallow eastward in the southern EDC to ~90 km. These results show that a high velocity lid with varying velocity and thickness exists beneath the whole of the craton.

3.2.2 Average shear velocity model for the EDC and the WDC

We identify three distinct regions within the Dharwar Craton: the northern WDC, the southern WDC and the EDC. We calculated the mean phase velocity curves for these blocks and inverted them for their shear wave speed structure. The mean phase velocities for each block were determined by averaging the values at the grid points in each of the blocks as follows:

\[ V_{ew} = \frac{\sum_i V_i / E_i}{\sum_i 1 / E_i}, \]

where \( V_{ew} \) is the error-weighted phase velocity for the jth period, \( V_i \) the phase velocity for the jth dispersion curve and the jth period and \( E_i \) the associated phase velocity error. We then computed the ±1 standard deviation bounds for the average phase velocity at each period (Fig. 15a). We used the average 1-D shear velocity model for the Dharwar Craton but with average Moho depths for the three regions determined by receiver function analysis (35 km for the EDC, 40 km for the northern WDC, 50 km for the southern WDC) for an initial model and inverted the dispersion data for the shear wave speed structure down to a depth of ~120 km (Fig. 15b). The dispersion curves computed from these models provide an excellent fit to the observed dispersion data (Fig. 15c).

We compare the phase velocities for three blocks and the phase velocity for global models PEM-C (Dziewonski et al. 1975) and ak135 in Fig. 16(a). Dispersion curves for the three blocks of the Dharwar Craton show significant variations between 20 and 40 s periods. Beyond 40 s, they are similar but much higher than those
Figure 15. Average phase velocities and average shear velocity models for the EDC, north WDC and south WDC. (a) Error weighted phase velocities with error bounds (black line). Grey lines are the dispersion curves in the block. (b) Vs model which fit the dispersion curve. (c) Computed phase velocity dispersion curve (red line) and the observed one (black line).
of the global average. Phase velocities at all periods for the northern WDC and the EDC blocks are significantly higher than the dispersion for PEM-C and ak135. For the southern WDC, they are similar to the dispersion of PEM-C and ak135 up to 30 s period but increase significantly at higher periods. Shear velocity models for the three blocks along with that for PEM-C and ak135 model are compared in Fig. 16(b). These show that below the Moho down to a depth of ∼100 km, Vs in the Dharwar Craton is significantly higher (by 0.2–0.4 km s⁻¹) compared to the Vs of the global average models but similar at deeper levels.

To establish the reliability of the shear velocity model, that is, the existence of a high velocity layer (4.7–4.9 km s⁻¹) in the shallow mantle followed by velocity reduction (4.5 km s⁻¹) in the three blocks (EDC, north WDC and south WDC), we tested various forward models. We find that the inverted shear velocity model (with Moho at 35 km) for the EDC block (red line in Fig. 17b) fits the dispersion curve rather well (red line in Fig. 17a). Changing shear velocity values in the shallow mantle to 4.53 and 4.7 km s⁻¹, leads to dispersion values significantly lower and higher than in the observed phase velocities. Similar tests for the other two blocks show the same result.

We further demonstrate the robustness of shear velocity result due to change in crustal thickness or velocity contrast at the Moho. We varied the Moho depth by ±5 km with reference to the initial model of Moho depth 40 km and inverted the shear velocity model for north WDC. The resulting inversion results for the three Moho models show similar results (Fig. 18a). Similarly, we varied the velocity contrast at Moho by ±4 per cent compared to the initial model and inverted the velocity model for north WDC (Fig. 18b). We observe very small difference in the resulting velocity models.

4 DISCUSSIONS AND CONCLUSIONS

The shear wave velocity model of the Dharwar Craton determined from the inversion of fundamental mode Rayleigh wave phase velocities distinguishes an upper ∼50-km-thick high wave speed upper mantle lid of shear wave velocity 4.6–4.9 km s⁻¹ overlying a deeper layer of shear wave velocity ∼4.5 km s⁻¹, which is near the global average shear wave velocity at these depths. Although the frequency range of our data limits our investigation to depths of ∼120 km, this lower layer probably continues deeper to the LAB, which is about 170 km in southern India (Mitra et al. 2006; Priestley & McKenzie 2013).

Shear wave velocities in the Earth vary with temperature and composition. A 100 K change in temperature leads to ∼5 per cent change in shear velocity, while differences in composition are generally responsible for 1 per cent velocity variation (Priestley & McKenzie 2006, 2013; Schutt & Lesher 2006). From a geotherm based on xenolith data from EDC, Roy & Mareschal (2011) calculated mantle shear velocities and found these to be less than the global model values (Shapiro & Ritzwoller 2002). This result emphasizes the significance of compositional variations in explaining the observed anomalies and their implications to craton formation processes.

The mantle stratification delineated by the Vs anomalies at ∼100 km depth beneath the Dharwar Craton is consistent with the isopycnic lithosphere proposed by Jordan (1988) who argued that the continued preservation of a cratonic lithosphere against convective stresses through a temporarily cooling Earth of increasing viscosity required the compositional and thermal buoyancy to be balanced at every depth in the lithosphere. The lower lithosphere is at nearly the same temperature as the surrounding asthenosphere,
Figure 17. Reliability check for the shear velocity models of the Dharwar Craton. Figure shows, dispersion curve (a) computed for different velocity models (b). Black circles are the observed phase velocity dispersion with ±1σ error bounds.
and would, therefore, resist foundering, even with the marginal compositional buoyancy as that offered by the less-depleted lherzolite residues at the base of a melting column.

However, the range and lateral distribution of the positive anomalies in the Dharwar upper mantle are remarkable. While being positive nearly everywhere, this high velocity marks the northwestern craton with an unusually high anomaly of 8 percent that is an extremely high shear wave velocity of 4.9 km s$^{-1}$. The existence of higher velocity, lighter refractory materials in the upper cratonic mantle, is of course, a necessary condition for its longevity, as borne out by the prevalence of positive velocity anomalies throughout the craton between 50 and 100 km depth. But, the existence of an extraordinarily depleted region of $\sim 100$ km radius suggests that it evolved in the highest column of an intensively melting plume.

Two notable features of this anomalous upper mantle are the wide variation in the magnitude of the anomalies and a very sparse distribution of moderately conspicuous anomalies. Furthermore, there is little coherence in their geographical patterns, suggesting that the craton was finally assembled from individually evolved units of lateral extents comparable to their depths. Yet, this raises tantalizing questions about the processes that mediated their amalgamation by the late Archean. One could, for example, model the possible compositions of the northwestern cratonic upper mantle distinguished by its high anomaly to test whether or not its origin is compatible with the result of plume melting. This should, in turn, provide constraints on the dimensions of a plume sustainable by an Archean mantle. The latter, with a nearly flat Moho, is underlain by a shallow mantle of relatively more homogeneous and lower Vs, $\sim 4.5-4.7$ km s$^{-1}$, suggesting that it was most likely homogenized by tectono-thermal event(s) subsequent to its cratonization. Several prominent surface features of the EDC are more likely associated with such a hypothetical event (Fig. 2). However, much more research is required to consolidate these observations of the various cratonic columns into a plausible, testable hypothesis.

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