

# Upper-mantle anisotropy beneath the south Indian Shield: Influenced by ancient and recent Earth processes

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## ABSTRACT

We obtained shear-wave splitting parameters from core-refracted phases like SKS, SKKS, and PKS at 75 digital broadband seismic stations almost uniformly spread over the south Indian Shield representing varied geological terrains, including the western Dharwar craton, the eastern Dharwar craton, the Southern granulite terrain, and the continental margins along the west and east coasts. A majority of the stations over the Dharwar craton show delay times of 1–1.6 s, indicative of a 150–200-km-thick anisotropic layer correlating with the lithospheric root, while segments like the Pan-African Southern granulite terrain have delay times of 0.5–0.7 s, suggesting an internally deformed and thin anisotropic layer, possibly due to recent plate-tectonic and geodynamic processes. The average direction of anisotropy is generally ~N30°E, correlating with the present-day plate motion, with local deviations where the direction of anisotropy correlates with the orientation of the regional shear zones. Stations close to the continental margin show large time delays (up to 2 s) with the fast axis parallel to the rift axis. Further, we infer a layered anisotropic lithosphere in the south Indian Shield as revealed in 90° periodicity of the two anisotropy parameters (fast direction and delay time). The upper lithosphere represents the depleted Archean mantle, while the lower lithosphere could be transformed to more fertile mantle due to subsequent deformation. This study suggests that the observed anisotropy over the south Indian Shield is the result of complex interplay between the architecture of an Archean craton and its subsequent deformation in different geological domains due to deep Earth processes.

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## INTRODUCTION

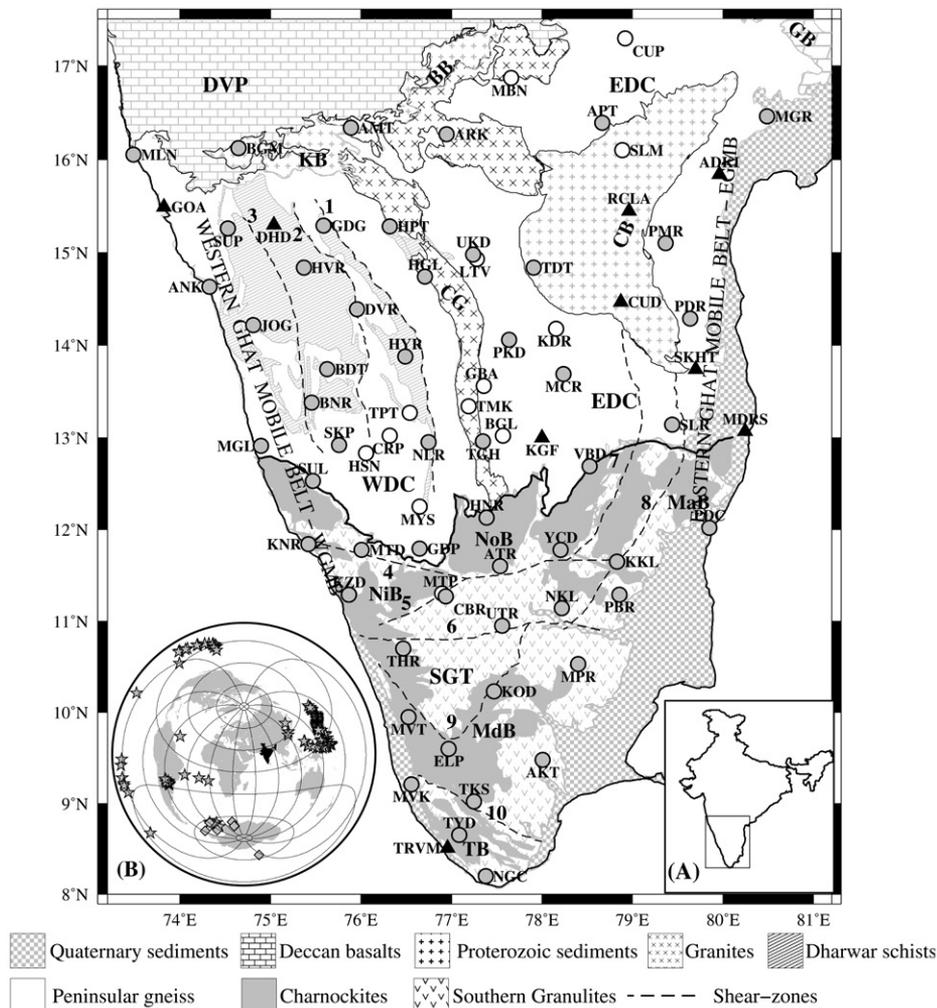
The south Indian Shield is primarily a Precambrian terrain consisting of the Archean Dharwar craton, Proterozoic basins, and a metamorphic (Southern granulite) terrain affected by a Pan-African event at ca. 550 Ma (Fig. 1). The Dharwar craton has been divided into the western Dharwar craton and the eastern Dharwar craton. The western Dharwar craton is composed of tonalite-trondhjemite-granodiorite (TTG)-type peninsular gneisses (older than 3.0 Ga), and greenstone belts (komatiite-basalt volcanic) of two distinct ages (3.35 Ga in south and 2.9 Ga in the north part of the craton). The eastern Dharwar craton is largely composed of 2.7–2.5 Ga TTG and gneisses and 2.6–2.5 Ga plutonic bodies, the most prominent being the N-S-elongated Closepet batholith (Drury et al., 1984; Naqvi and Rogers, 1987; Bouhallier et al., 1995; Chadwick et al., 2000). The western Dharwar craton was cratonized prior to 2.6 Ga, while the eastern Dharwar craton was rejuvenated by massive late Archean magmatism. The eastern Dharwar craton also hosts the Cuddapah Basin, which evolved around 1700 Ma through several episodes of igneous activity (Anand et al., 2003). Regional E-W-trending,

ca. 2400 Ma mafic dike swarms (Kumar et al., 2012) are another important feature of the eastern Dharwar craton that is largely absent in the western Dharwar craton. The western boundary of the Cuddapah Basin is also marked by several kimberlites intruded at ca. 1100 Ma (Rao, 2008; Griffin et al., 2009). Pressure-temperature analysis of kimberlite xenoliths in the region suggests a lithospheric thickness of at least ~185 km during the mid-Proterozoic period (Ganguly and Bhattacharya, 1987). A similar inference was drawn by Griffin et al. (2009) using a geochemical tomography approach.

The craton progressively transitions in the south to an Archean (2.6 Ga) metamorphic terrain widely known as the Southern granulite terrain. Dissected by a large number of shear zones, the southern part of the granulite terrain was affected by a Pan-African event at ca. 550 Ma (Drury et al., 1984; Collins et al., 2014). The eastern and western coasts of the south Indian Shield have coast-parallel mountain steps (known as Ghats), referred to as the Eastern and Western Ghats. While the Western Ghats were affected by India-Madagascar separation at ca. 85 Ma (Storey et al., 1995), the Eastern Ghats were formed due to processes that operated from ca. 2.6 to 1.2 Ga and have

most recently been affected by India-Antarctica rifting (Naqvi and Rogers, 1987). Other important geodynamic factors include the fast velocity of the Indian plate (Besse and Courtillot, 1988), and the Marion hotspot close to the southernmost part of India, which was responsible for separation of Madagascar from greater India at ca. 85 Ma (Storey et al., 1995).

The geological diversity and tectonic processes described here have made their imprint on the deep structure of the region, as suggested from limited geophysical investigations of the south Indian Shield. Teleseismic delay time tomography using a sparse network of analogue seismic stations indicated the existence of a more than 200-km-thick, high-velocity (1%–2%) layer beneath the western Dharwar craton that progressively thins to ~140 km beneath the Cuddapah Basin and the Eastern Ghats (Srinagesh and Rai, 1996; Prakasam and Rai, 1998). This high-velocity layer is interpreted as the lithosphere. Analysis of the surface wave and also the joint inversion of multiparameter data suggest an ~155–170-km-thick lithosphere beneath the eastern Dharwar craton, thinning to ~120 km beneath the Southern granulite terrain (Shapiro and Ritzwoller, 2002; Mitra et al., 2006; Priestley et



**Figure 1.** Tectonic map of the south Indian Shield showing major tectonic units: DVP—Deccan volcanic province, EDC—eastern Dharwar craton, WDC—western Dharwar craton, KB—Kaladgi Basin, BB—Bhima Basin, CB—Cuddapah Basin, GB—Godavari Basin, CG—Closepet Granite, SGT—Southern granulite terrain, NoB—Northern block, NiB—Nilgiri block, MaB—Madras block, MdB—Madurai block, TB—Trivandrum block. Shear zones: 1—Chitradurga, 2—Bababudan, 3—Balehonnur, 4—Moyar, 5—Bhavani, 6—Palghat-Cauvery, 7—Mettur, 8—Salem-Attur, 9—Karur-Kambam-Painavu-Trichur (KKPT), and 10—Achankovil. The seismic stations are shown as gray (2009–2011) and white (1998–2002) circles. The triangles show the locations of earlier studies (Kumar and Singh, 2008; Roy et al., 2012). Insets: (A) The study region in the map of India; (B) the earthquake distribution used in the study, with SKS/SKKS (stars) and PKS (diamonds) phases.

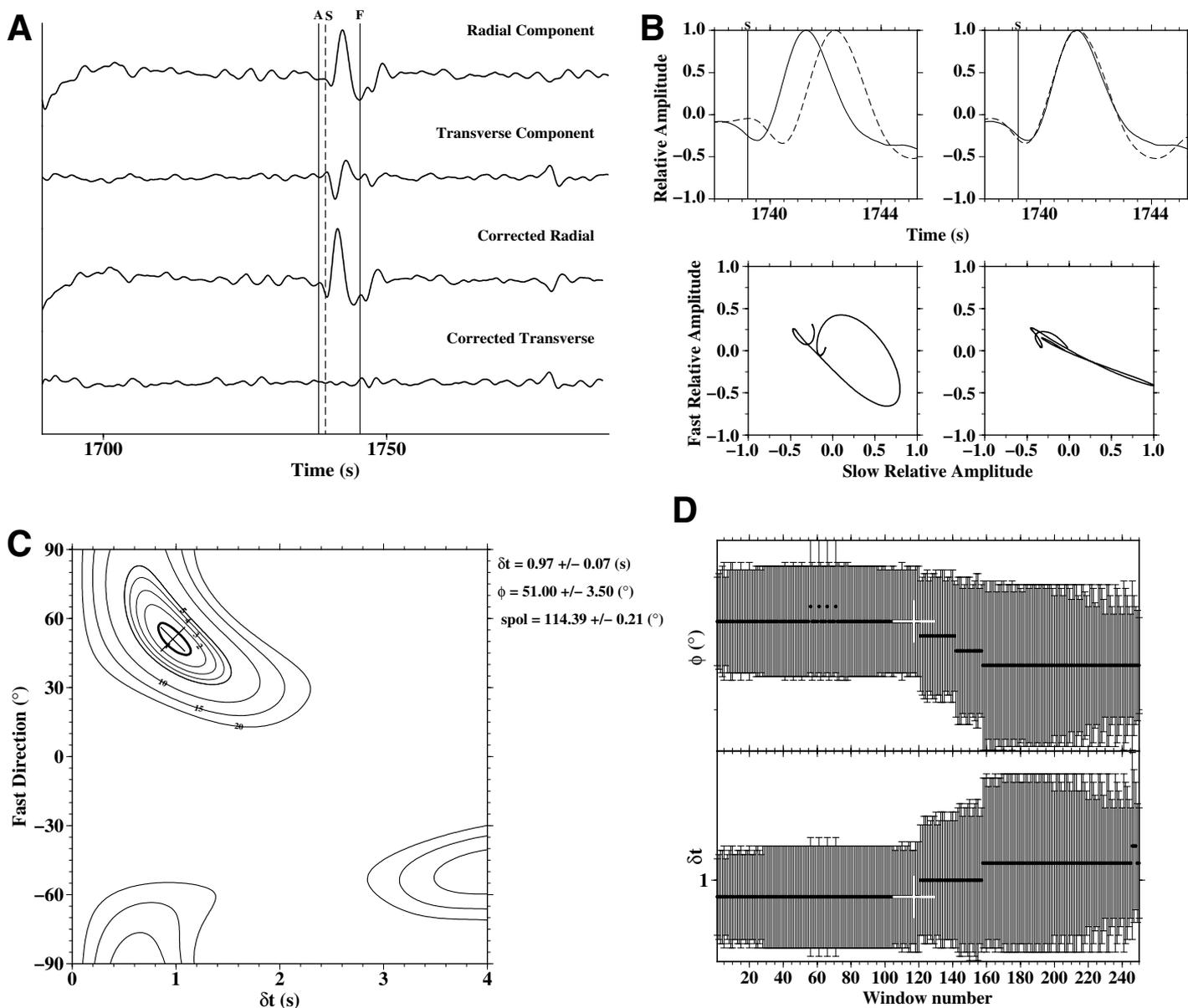
al., 2006; Kumar et al., 2014). Bodin et al. (2014) inferred an ~200-km-thick lithosphere beneath the eastern Dharwar craton and a mid-lithospheric low-velocity region at a depth of ~100 km. An improved surface-wave tomography image of the Dharwar craton reveals a layered lithosphere with a high shear-wave velocity ( $V_s$  ~4.7–4.9 km/s) in the depth range of 40–100 km, followed by a normal mantle velocity of 4.5 km/s (Borah et al., 2014). Presence of an extremely high-velocity shallow layer is argued as indicative of mineralogy/lithology (e.g., dunite that contains olivine and has high seismic anisotropy). Evidence of a

layered lithosphere in the south Indian Shield has also been presented through the analysis of receiver function observations (Jagadeesh and Rai, 2008; Mandal et al., 2012).

Over the past two decades, seismic anisotropy has become a valuable tool in investigating the upper-mantle structure and its mechanical coupling with the crust (Silver, 1996; Savage, 1999). The anisotropic parameters are assumed to be closely related to the crystallographic fabrics developed in the upper mantle due to past and present deformation. Measurement of seismic anisotropy at a seismological station yields two parameters,  $\phi$ —the orientation

of the polarization plane of the faster S wave; and  $\delta t$ —the delay between the arrival times of the fast and slow split waves. The splitting measurements are commonly performed on core-refracted shear waves such as SK(K)S or PK(K)S. These phases are generated due to seismic phase conversion at the core-mantle boundary and are thus polarized along the radial direction as they enter the mantle. Thus, observations of seismic anisotropy can be used to constrain the orientation of the local strain field within the mantle. The SKS-type phases provide lateral resolution of a few tens of kilometers beneath a station. However, they lack vertical resolution, as the observed split time is integrated over the entire depth. Therefore, additional constraint is needed to define the source depth. Recent global tomographic results confirm that on an average, anisotropy is significant only in the uppermost 200–250 km of the upper mantle, and it decreases with depth (Debayle and Ricard, 2013). This study finds no difference in the depth of the anisotropic layer over a fast- or slow-moving continent, except that the fast-moving Archean continent is characterized by higher anisotropy at 100–150 km depths compared to Proterozoic or Phanerozoic terrains. However, geodynamic modeling and anisotropy studies suggest coupling between lithosphere and asthenosphere (Marone and Romanowicz, 2007; Bird et al., 2008; Rafayee et al., 2014). Bormann et al. (1996) investigated the effect of lithosphere-asthenosphere boundary topography on shear-wave splitting measurements. In areas of shallow lithosphere-asthenosphere boundary topography, the measured directions of anisotropy closely follow the direction of the absolute plate motion caused by the basal drag of the moving lithospheric plate, while in areas of deep lithosphere-asthenosphere boundary topography,  $\phi$  will be subparallel to the contour line trends of the lithosphere-asthenosphere boundary. The delay time ( $\delta t$ ) places constraints on the thickness of the anisotropic layer.

Several investigators have addressed the state of seismic anisotropy in the mantle beneath the south Indian Shield. Ramesh et al. (1996) and Heintz et al. (2009) observed that the majority of stations show a NNE-SSW orientation of  $\phi$  over hundreds of kilometers, from Sri Lanka to the northern part of the Dharwar craton. Kumar and Singh (2008) reported, at a few locations, a fast-axis direction subparallel to the strike of the major shear zones in the Southern granulite terrain and Cuddapah Basin. This was inferred to be a signature of anisotropy “frozen” in the lithosphere. Roy et al. (2012) reported that the observed anisotropy over the eastern Dharwar craton has contributions from both lithosphere and asthenosphere. These inferences are based



Station: TDT Event: 2011:093:14:07 Latitude: S17.64 $^{\circ}$  Longitude: W178.59 $^{\circ}$  Depth: 551 km

**Figure 2.** Example of shear-wave splitting measurement performed using the semi-automated code of Teanby et al. (2004) for station TDT. (A) Radial and transverse components before and after correction of anisotropy. Labels A and F represent beginning and end of the shear-wave window, respectively. (B) Waveforms and particle motion of the two quasi-S waves before and after removal of the anisotropy. (C) Contour plot of energy representing fast polarization direction ( $\phi$ ) vs. delay time ( $\delta t$ ). Parameter spol defines source polarization direction. (D) Representation of the  $\phi$  and  $\delta t$  values obtained from the analysis of 250 measurement windows with error bars.

on data from only a few and sparse seismic stations spread over the south Indian Shield. In order to gain insights into the deep deformation processes in the region, we investigated the anisotropic behavior of Earth's crust and upper mantle beneath the south Indian Shield using a well-distributed network of digital broadband seismic stations operated as a part of the India Deep Earth Exploration Program (INDEX; Rai et al., 2013). To improve the lateral resolution,

we also included results from nine stations published from Kumar and Singh (2008) and Roy et al. (2012).

In this paper, we study the nature of mantle anisotropy beneath the geologically diverse south Indian Shield, which has been affected by deep Earth processes from 3.35 Ga to the present. The plate motion is almost uniform over the study region (Paul et al., 2001), and so we expect the contribution from basal drag to be

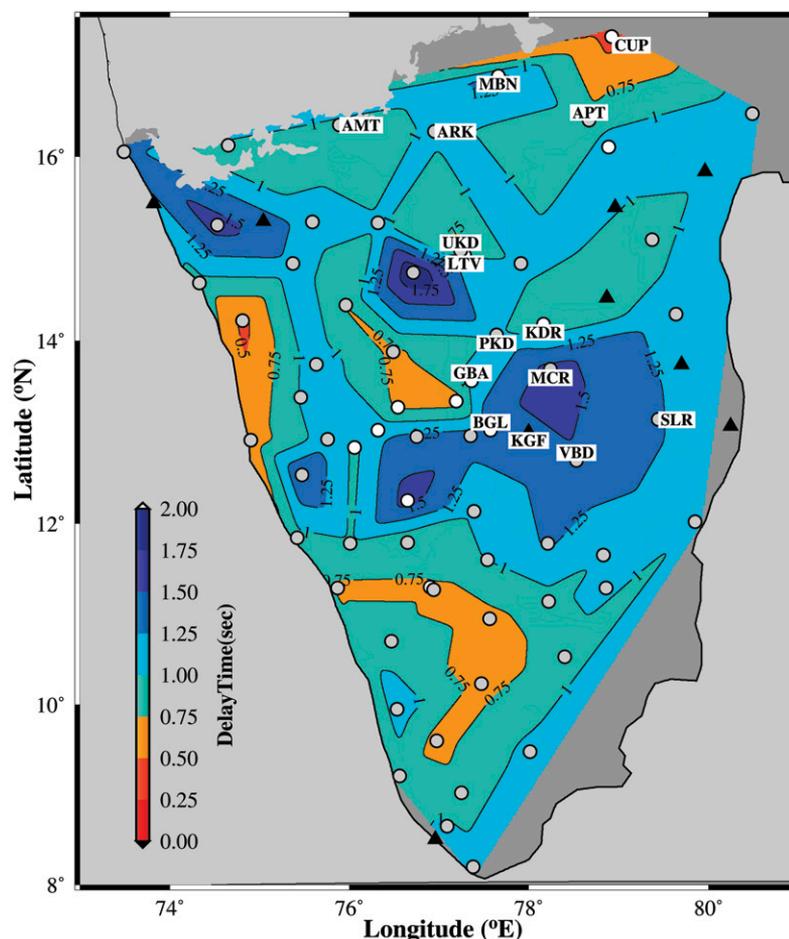
nearly the same. The observed lateral anisotropy, therefore, should have a contribution from the fossil lithosphere fabric. The present network of broadband seismographs and the tectonic setup in south India provide an excellent opportunity to study the factors that contribute to the observed mantle anisotropy: lithosphere or lithosphere-asthenosphere coupling. We also investigated the possible signature of lithospheric layering and contribution of preferred

orientation of dikes and/or shear zones to the anisotropy measurements.

## SHEAR-WAVE SPLITTING MEASUREMENTS

We select core-refracted shear waves (SK[K]S and PKS) recorded at 66 digital broadband seismological stations in the south Indian Shield (Fig. 1). Of these, 51 seismographs were operated between 2009 and 2011 (Rai et al., 2013) and the remaining were operated during 1998–2002 (Gupta et al., 2003). The operation period for these instruments varied from 6 to 24 months (GSA Data Repository Table DR1<sup>1</sup>). Shear-wave splitting measurements were performed using the semi-automated approach of Teanby et al. (2004), which is based on the shear-wave splitting method of Silver and Chan (1988). Splitting parameters  $\phi$  and  $\delta t$  are determined through a grid search procedure by correcting the observed components for the anisotropy effect, so as to minimize the energy on the transverse component associated with the arrival of the core-refracted phase on the radial component (Fig. 2A). The advantage of using a semi-automated version lies in consistency of splitting parameters over completely manual window picking (Heintz et al., 2009). We used 250 windows for this study. A reliable solution is characterized by a plateau for  $\phi$  and  $\delta t$  associated with small error bars (Fig. 2D). Stable regions are then identified through a cluster analysis. Each measurement is manually checked and sorted into three categories, “good,” “fair,” and “null,” with the following criteria: (1) waveform signal-to-noise ratio, (2) elliptical particle motion when anisotropy is present, (3) linear particle motion after removing anisotropy, (4) similarity between the fast and slow split shear waves, and (5) stability of the measurements over shear-wave windows. The measurements satisfying all the criteria are grouped as “good,” and those satisfying only three criteria are labeled “fair.” Figure 2 gives an example of splitting measurements from the station TDT. We analyzed 149 high-quality events with magnitude  $\geq 5.5$  in the epicentral distance range of  $85^\circ$  and  $140^\circ$ , recorded over the network. Observation of SKS, SKKS, and PKS phases yielded 576 valid shear-wave splitting results (good + fair + null). Individual results from different tectonic units are given in the GSA Data Repository (Table DR2 [see footnote 1]).

<sup>1</sup>GSA Data Repository Item 2015046, Tables DR1 and DR2 and Figures DR1–DR6, is available at [www.geosociety.org/pubs/ft2015.htm](http://www.geosociety.org/pubs/ft2015.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org), Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.



**Figure 3.** Delay time ( $\delta t$ ) contour map for the south Indian Shield computed from good splitting measurements. Circles and triangles represent the seismic stations. Stations marked in the eastern Dharwar craton are used to compute azimuthal variation of splitting parameters as shown in Figure 5.

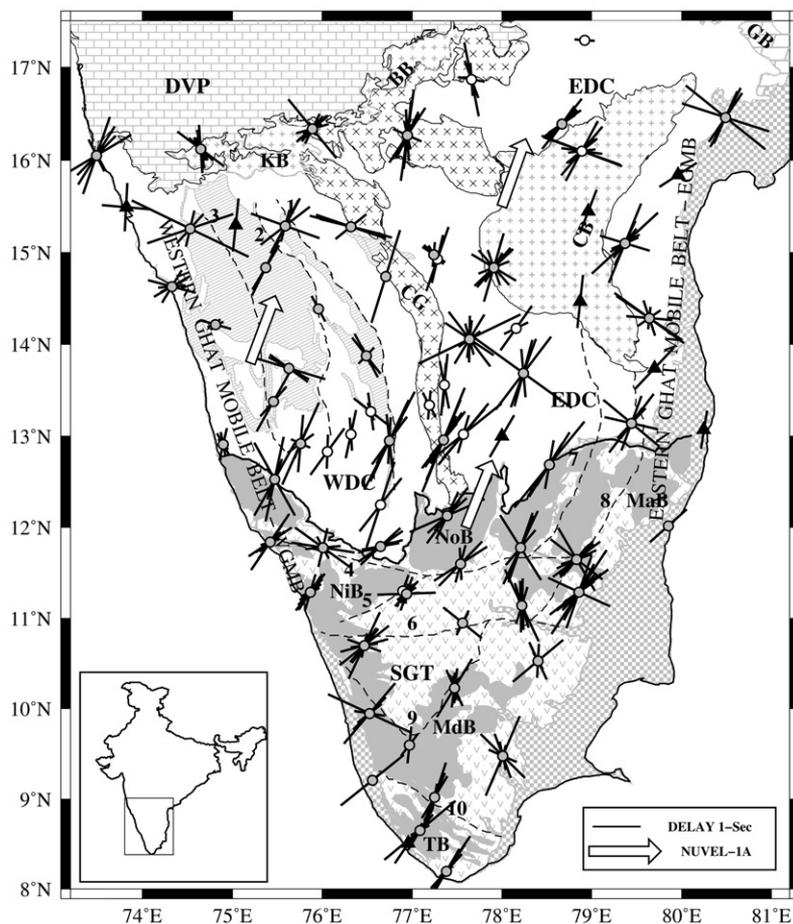
## RESULTS

We use the “good” data sets to present a contoured plot of average shear-wave splitting time (Fig. 3) and a plot of fast polarization direction and the corresponding delay time for individual stations (Fig. 4). Detailed statistical analysis of “good” measurements from 75 stations depicting (1) the delay time  $\delta t$  and associated error  $\delta(\delta t)$ , and (2) fast polarization direction  $\phi$  and associated error  $\delta\phi$  for the eastern Dharwar craton, western Dharwar craton, and Southern granulite terrain are presented in Figures DR1, DR2, and DR3 (see footnote 1). Some of the general characteristics of splitting parameters over the south Indian Shield are presented next.

### Split Time

Delay time ( $\delta t$ ) between fast and slow polarized shear waves at stations from the

south Indian Shield shows significant variation: dominantly between 0.4 and 1.8 s, with an average of 1.0 s (Fig. 3; Figs. DR1–DR3 [see footnote 1]). The delay time has a contribution from the crust, subcrustal lithosphere, and asthenosphere mantle. The observed values are too large to be accounted for by the crustal contribution. In the south Indian Shield, the contribution from crust to anisotropy is  $0.3 \pm 0.1$  s (Rai et al., 2008), with a dominantly NW–SE direction. Globally, average delay times of more than 1.0 s have been observed over Archean cratons (Vinnik et al., 1995; James and Assumpção, 1996; Silver, 1996; Barruol et al., 1997). Considering vertically propagating waves like SK(K)S, the delay time of 1.0 s between fast and slow shear waves would result from an  $\sim 100$ – $150$ -km-thick anisotropic layer, assuming velocity anisotropy of 4%–3%, respectively, consistent with laboratory measurements on mantle xenoliths (Mainprice and Silver, 1993).



**Figure 4.** Map showing the individual good measurements at 75 stations in the south Indian Shield. The length of each line is proportional to the delay time between the fast and slow S waves. Arrow represents the direction of the Indian plate motion as defined by the NUVEL-1A plate model (DeMets et al., 1990). Abbreviations are given in Figure 1. The small circles and triangles are the seismic stations as mentioned in Figure 1.

### Stratified Anisotropy

We discuss briefly the spatial and azimuthal variation of split time and its correlation with the geological structures and the regional geodynamics. Though a majority of stations over the south Indian Shield show a fast axis subparallel to the plate motion direction, significant numbers of stations deviate from it (Fig. 4). To establish the variability of  $\delta t$  and  $\phi$  with back-azimuth in individual geological domains (western Dharwar craton, eastern Dharwar craton, Southern granulite terrain, Eastern and Western Ghats, Cuddapah Basin), observations from individual stations in the respective domain are combined. As an example, we present the  $\delta t$  and  $\phi$  variation for the eastern Dharwar craton in Figure 5. Stations representing the eastern Dharwar craton are shown in Figure 3. For the other geological blocks, the azimuthal variations of  $\delta t$  and  $\phi$  are presented in supplementary Fig-

ures DR4 and DR5 (see footnote 1). It is clearly evident from Figure 5 that the splitting parameters show periodicity of  $\sim 90^\circ$ . Similar inference could be drawn for other terrains, as shown in the supplemental information (Figs. DR4 and DR5 [see footnote 1]). Variations in splitting parameters as a function of back-azimuth could be due to an inclined axis of symmetry (Hartog and Schwartz, 2000) or multiple layers of anisotropy (Silver and Savage, 1994). In the latter case, the apparent splitting parameters exhibit a distinctive  $90^\circ$  periodicity as a function of incoming polarization direction.

### Null Anisotropy

We observe that many stations (for a few events) show a small value of split time despite good signal-to-noise ratio (S/N) of the waveform. These stations and the corresponding events are listed in the GSA Data Repository

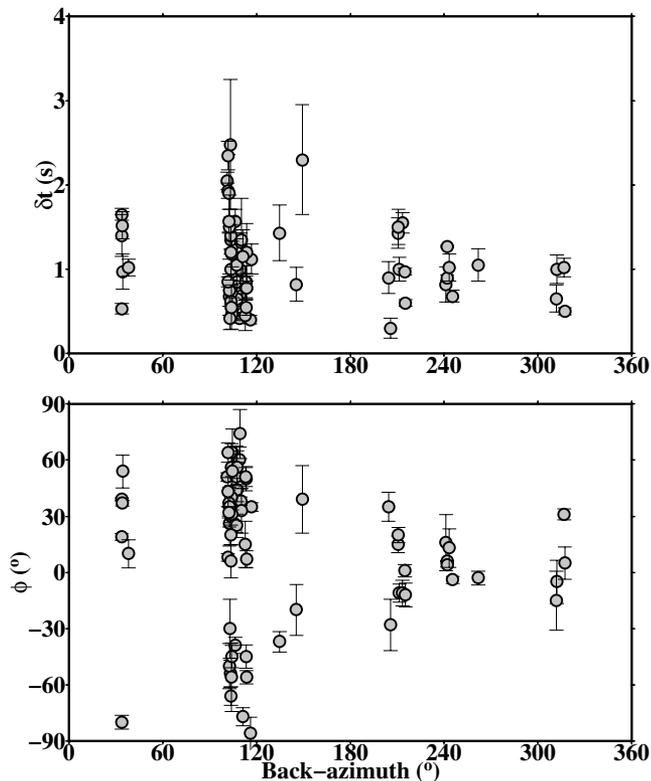
(Table DR2 [see footnote 1]). Individual null results computed at individual seismological station are presented in the GSA Data Repository (Fig. DR6 [see footnote 1]) and are consistent with the results of Heintz et al. (2009). The possible explanation for a null result could be the following. Plastic deformation of peridotites usually results in the alignment of the  $a$  axis of olivine parallel to the flow direction (e.g., Zhang and Karato, 1995; Bystricky et al., 2000; Tommasi et al., 2000). This results in anisotropy subparallel to the plate motion. However, for olivine crystallographic orientations that have axial  $b$  patterns, a null split can emerge from horizontal flow field patterns (Vauchez et al., 2005; Bascou et al., 2008). The other possibility for null observations could be due to a two-layered velocity model with orthogonal directions (e.g., Barruol and Hoffman, 1999).

### Anisotropy Characteristics of Different Geological Domains

Next, we briefly discuss our measurements from different geological blocks in the south Indian Shield.

#### Eastern Dharwar Craton

The 125 good shear-wave splitting measurements from 23 stations in the eastern Dharwar craton (Fig. 4; GSA Data Repository Table DR2 [see footnote 1]) show that almost half of the stations have a delay time of more than 1.2 s and a NE direction of fast polarization, which is close to the motion of the Indian plate (i.e., NNE-SSW) as defined through the NUVEL-1A model considering a fixed Eurasia (DeMets et al., 1990). The southern eastern Dharwar craton stations have delay times of 1.0–1.6 s, as compared to 0.4–1.0 s in the north eastern Dharwar craton. Stations GBA and TMK, located in proximity to the NNW- to N-S-trending Closepet Granite, show  $\phi$  between  $N-28^\circ$  and  $N6^\circ$ , parallel to the trend of the Closepet Granite. In contrast, stations AMT and HPT show two fast polarization directions, one between  $N-28^\circ$  and  $N-76^\circ$ , parallel to the trend of the Closepet Granite, and the other one between  $N14^\circ$  and  $N60^\circ$ , subparallel to the motion of the Indian plate. Similarly, at stations PKD and MCR, located SE of the Closepet Granite, the measured  $\phi$  has two potential directions  $N-5^\circ$  to  $N-56^\circ$  and  $N1^\circ$  to  $N64^\circ$ . For the station HGL, we obtained only one good measurement with fast polarization direction parallel to the plate motion direction and a delay time of 2 s. Stations in the Proterozoic Cuddapah Basin (SLM, RCLA, CUD, and TDT) have fast polarization direction in two potential directions,  $N16^\circ$  to  $N68^\circ$  and  $N-59^\circ$  to  $N-79^\circ$ . The fact that more



**Figure 5. Azimuthal variation of splitting time (top) and the fast direction (bottom) in the eastern Dharwar craton for stations shown in Figure 3.**

than two fast polarization directions were observed in eastern Dharwar craton and Cudapah Basin is due to the back-azimuthal dependence of the splitting parameters (Figs. DR4 and DR5 [see footnote 1]).

#### **Western Dharwar Craton**

In this cratonic block, there are 80 good splitting measurements from 20 locations. The western Dharwar craton stations show large time delays of 1.0–1.6 s, similar to those observed beneath the southern eastern Dharwar craton. The seismic stations GDG, HYR, TPT, NLR, and MYS show a fast polarization direction varying from N–52° to N52° (NNW to NNE), correlating well with NW–SE structural trend of shear zone 1 (Fig. 4). This shear zone is a proposed contact between the eastern Dharwar craton and western Dharwar craton. The fast polarization direction in the southern part of the western Dharwar craton (at GDP) is subparallel to the direction of plate motion. At seismic stations HVR, DVR, BDT, BNR, CRP, HSN, and SKP in and around the NNW- to N–S–trending shear zones 2 and 3 (Fig. 4), the fast polarization direction is subparallel to the trend of these shear zones ( $\phi$  between N–73° and N54°). The back-azimuth variations of splitting parameters for the entire set of western Dharwar craton stations are plotted in the GSA Data Repository (Figs. DR4 and DR5 [see footnote 1]).

#### **Southern Granulite Terrain**

In the Southern granulite terrain, 133 good splitting measurements were obtained from 23 seismograph locations (Fig. 4; GSA Data Repository Table DR2 [see footnote 1]). The delay time is ~0.8 s, with most of the stations showing a fast polarization direction between N16° to N65°, which correlates with the direction of Indian plate motion. A few splitting measurements in the Southern granulite terrain are subparallel to the trend of shear zones 4–6 (Moyar, Bhavani, and Palghat-Cauvery) in the north Southern granulite terrain, and a few measurements are parallel to the shear zone 10 (Achankovil) in the south Southern granulite terrain (Fig. 4). Like other geological provinces discussed earlier, for the Southern granulite terrain, we observe a similar back-azimuthal dependence of splitting measurements (Figs. DR4 and DR5 [see footnote 1]).

#### **Rifted Margins**

The Eastern Ghats mobile belt, represented by seismic stations MGR, PMR, PDR, and SLR, has two dominant fast axes, N–6° to N–85° and N6° to N67°, depending on the azimuth of the incoming wave. For the Western Ghats, all the stations (MLN, SUP, ANK, JOG, GOA, MGL, and SUL) show a NNW to NNE and WNW to ESE trend of fast polarization direction that is subparallel to the trend of the mobile belt. Sta-

tion SUP recorded the largest delay time of up to 2.7 s. A clear azimuthal dependence of splitting parameters is observed with  $\pi/2$  periodicity for the two rifted margins.

#### **DISCUSSION**

We present evidence for significant spatially and azimuthally varying seismic anisotropy beneath the south Indian Shield. Splitting parameters were obtained by core-refracted phases that represent the integrated effect of anisotropy in a vertical column beneath each seismic station. We assume a single homogeneous anisotropic layer with a horizontal symmetry axis to explain the observed SK(K)S and PKS waveform data using a semi-automated version of shear-wave splitting analysis. Under this assumption,  $\phi$  and  $\delta t$  measured from SKS/PKS waves arriving from different back-azimuths are expected to have the same values. A plot of back-azimuth versus  $\phi$  and  $\delta t$  is presented in the GSA Data Repository (Figs. DR4 and DR5 [see footnote 1]). Here we include data from all the stations in each geological province. We observe a clear back-azimuthal variation of  $\phi$  and  $\delta t$  with  $\pi/2$  periodicity. The observed complexity can arise from a dipping symmetry axis or the presence of multiple layers of anisotropy, which have been found in many continental regions (e.g., Savage and Silver, 1993; Silver and Savage, 1994).

Generally, two competing hypotheses are proposed to account for the observed seismic anisotropy in continental regions. Firstly,  $\phi$  over cratons is parallel to past geological features and reflects the fossil lattice-preferred orientation of olivine minerals within the Precambrian continental lithosphere (Silver and Chan, 1991; Silver, 1996). The other hypothesis assumes that the observed  $\phi$  is directed parallel to the present-day absolute plate motion and reflects lattice-preferred orientation associated with asthenospheric shear (Vinnik et al., 1992, 1995; Wolfe et al., 1999). Silver (1996) presented an extensive compilation of continental splitting results, showing that several cratons (e.g., Canadian Shield, Brazilian craton, and Kaapvaal craton) display  $\phi$  parallel to ancient geological structures, consistent with anisotropy caused by vertically coherent deformation of the crust and mantle during Precambrian orogenies. A recent review on continental anisotropy can be found in Fouch and Rondenay (2006). Next, we examine the following two hypotheses that may contribute to the observed anisotropy in the study area: (1) asthenospheric flow related to present-day absolute plate motion, and/or (2) “frozen” mantle deformation associated with the evolution of the craton or regional extension that occurred in late Mesozoic and Cenozoic time.

## Anisotropy Direction

We first examine the hypothesis of whether the observed seismic anisotropy is dominated by large-scale asthenospheric flow associated with absolute plate motion. NUVEL-1A (DeMets et al., 1990) is a global model of current relative plate velocities, assuming constant velocities over the past 3 m.y. The N10°–22°E direction of the Indian plate, with respect to fixed Eurasia obtained through NUVEL-1A, is in good agreement with several studies dealing with geodetic measurements (Paul et al., 2001) accounting for current tectonic motions between India and Eurasia. On the basis of the NUVEL-1A model, the absolute plate motion for our study region is N21°E (location: 12°N, 77.6°E) with a velocity of 4.8 cm/yr. The absolute plate motion related to anisotropy should have a regional character. A majority of measurements show a fast-axis direction almost parallel to the plate motion. In such a situation, the splitting parameters will have significant contribution from the asthenosphere (Conrad et al., 2007). The plate motion will facilitate the mineral to orient in the direction of the infinite strain axes, and, therefore, the fast direction will be parallel to either the plate motion or the mantle flow direction (Karato et al., 2008; Huang et al., 2011). Also, we find noticeable variations in fast-axis direction as well as in splitting time that exist in both regional and local length scales, suggesting that other mechanisms might also be partly, if not entirely, involved in producing the observed seismic anisotropy (Li and Niu, 2010). Notable geological locations where anisotropy exists in the lithosphere are mountain belts, major fault zones, rift zones, and continental margins (Silver, 1996).

As previously stated, we observe a small number of fast split shear-wave polarization planes correlating with the NW-SE and N-S structural trends of shear zones and major features like the Closepet Granite in the western Dharwar craton and eastern Dharwar craton. We report similar observations for the Southern granulite terrain also, where the fast split direction correlates with the strike of shear zones. However, the number of such observations is small. Many of these shear zones have been interpreted in terms of terrain boundaries inherited from past collisional or rifting events. Earlier geophysical observations suggest that these shear zones in the Dharwar craton are crustal-scale fault systems (Roy Chowdhury and Hargraves, 1981). Coherence between crustal structures of all ages and seismic anisotropy data suggests that the signature of texture-induced anisotropy may be long-lived.

Further, we examine the observed anisotropy along the rifted margin of the south Indian Shield. Rifting between southwestern India and eastern Madagascar occurred during the Late Cretaceous and was associated with Marion hotspot volcanism (Storey et al., 1995). Similarly, the eastern margin of India rifted from Antarctica at ca. 100 Ma. On the basis of laboratory study and geological observations, in an extensional or rifting environment, mineral foliation planes tend to be horizontal, and the stretching lineation is likely parallel to the extension direction (Gao et al., 1997). We thus infer that the observed seismic anisotropy beneath the rifted margins of the south Indian Shield reflects extensional deformation in the lithosphere being frozen since Late Cretaceous time (Li and Niu, 2010).

## Shear-Wave Split Time and the Fresnel Zone

Average delay time contours from the “good” shear-wave phases from the south Indian Shield show delay times of 1.0 s, which are close to the global average for continental shield regions (Fig. 3). The observed time delays of 1–1.6 s over the majority of stations in the south eastern Dharwar craton, most of western Dharwar craton, and the northern part of the Southern granulite terrain depict the regional distribution of an Archean cratonic root. The majority of stations in the southern part of the Southern granulite terrain have small delay times (less than 0.7 s) with fast polarization directions nearly parallel to the plate motion. It may be noted that the southern part of the Southern granulite terrain has been affected by Pan-African tectonics at 550 Ma and more recently due to India-Madagascar rifting at ca. 85 Ma. This is reflected in high surface heat flow (50 mWm<sup>-2</sup>), almost 30%–40% higher than that over the western Dharwar craton and eastern Dharwar craton (Ray et al., 2003). Also, the region is characterized by thinner (100–120 km) lithosphere compared to the western and eastern Dharwar craton (Kumar et al., 2014).

Determination of the depth of the anisotropic layer using the shear-wave splitting method is still highly subjective, because of the steep angle of incidence of SK(K)S raypaths. This leads to good lateral resolution but poor vertical resolution. The most common method used to estimate the depth of a horizontal anisotropic layer is the intersecting Fresnel zone (radius of influence) approach (Alsina and Snieder, 1995). This study shows that for a vertically incident shear-wave front passing through an anisotropic layer, the Fresnel zone varies as a function of anisotropic layer thickness and the dominant period of the incoming phase. Because of

finite frequencies of the waveform, the ray can be treated as a tube defined by its first Fresnel zone. For a dominant period of 8 s, the radius of the Fresnel zone is ~35 km at the surface, increasing to 50 km at 100 km depth and 70 km at 200 km depth (Rümpker and Ryberg, 2000). Alsina and Snieder (1995) proposed that if an SKS event produces different splitting parameters at two stations, the anisotropic layer must be shallower than the depth at which the two tubes intersect. For this study, the average station separation is between 55 and 100 km, and split times at most locations vary from 0.75 to 1.5 s. Following the Fresnel zone concept, we speculate that the depth of anisotropy varies from ~100 km beneath the Southern granulite terrain to ~200 km over the southern eastern Dharwar craton and western Dharwar craton. These depths correlate well with the previously discussed lithospheric thickness estimates of these geological domains.

## Layered Anisotropy

A notable observation from this study is the distinct 90° periodicity observed for the two apparent splitting parameters ( $\phi$  and  $\delta t$ ) as a function of incoming polarization direction. This observation could be indicative of the presence of a layered anisotropic structure beneath the south Indian Shield. Seismological observations indicate the presence of a layered lithospheric mantle beneath south India, where the shallower lithosphere has higher shear-wave velocity ( $V_s \sim 4.7$  km/s), followed by a normal velocity of 4.5 km/s in its deeper part (Borah et al., 2014; Kiselev et al., 2008). The thickness of the 4.7 km/s layer varies from ~100 km beneath the western Dharwar craton to ~80 km beneath the eastern Dharwar craton. In the absence of any detailed modeling, the depth of this layer is not well constrained in the Southern granulite terrain. However, Rai et al. (2013) reported a midlithospheric low velocity at a depth of ~70 km beneath the Southern granulite terrain. The mantle stratification delineated by the  $V_s$  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 temporally cooling Earth of increasing viscosity requires 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 and would, therefore, resist foundering, even with the marginal compositional buoyancy of a less-depleted lherzolite residue at the base of a melting column. Griffin et al. (1999)

and Djomani et al. (2001) argued that such a buoyant Archean mantle lithosphere would survive a rifting and collision event, but it would be transformed to more fertile composition in its deeper part (lower lithosphere) with marginally reduced velocity.

We suggest that the upper lithosphere layer with its distinct high velocity and anisotropy represents a depleted primitive mantle with higher content of olivine, whereas the distinct lower lithosphere in individual geological segments could be due to (1) a part of the cratonization process at 2.6 Ga beneath the western Dharwar craton, (2) a partially modified lithosphere due to Proterozoic kimberlite magmatism at 1.2 Ga in the eastern Dharwar craton, or (3) a partially modified lower lithosphere due to the effect of a Pan-African event at ca. 550 Ma and India-Madagascar rifting at 85 Ma in the Southern granulite terrain.

## CONCLUSION

The shear-wave splitting parameters from core-refracted phases (SK[K]S and PKS) were measured at 75 digital broadband stations in the south Indian Shield consisting of Archean cratons (western Dharwar craton, eastern Dharwar craton), Southern granulite terrain, and continental margins. The western Dharwar craton evolved between 3.35 and 2.6 Ga, while the eastern Dharwar craton evolved ca. 2.5 Ga and was subjected to large-scale Proterozoic kimberlite magmatism and basin evolution. The metamorphic Southern granulite terrain evolved at ca. 2.6 Ga and was further affected by the Pan-African event at ca. 550 Ma. The continental margins on the east and west coasts of India were shaped as a consequence of rifting at ca. 110 and ca. 85 Ma, respectively. A majority of stations in the eastern and western Dharwar craton have split times of  $\sim 1$ –1.6 s, in contrast to a smaller delay time of  $\sim 0.5$ –0.7 s beneath the Southern granulite terrain. The average fast S-wave polarization direction in the south Indian Shield correlates with the plate motion of the Indian plate. Significant numbers of data values, particularly from the western Dharwar craton and Southern granulite terrain, show the fast polarization direction subparallel to the structural trend of major shear zones. Assuming an average 3% anisotropy in the crust and mantle, and an average delay time of 1.0 s, 1.5 s, and 0.7 s in the eastern Dharwar craton, western Dharwar craton, and Southern granulite terrain, respectively, we infer an anisotropic layer thickness of 150, 200, and 120 km beneath these terrains, respectively, which correlate well with the mapped lithosphere thickness (Srinagesh and Rai, 1996; Prakasam and Rai, 1998; Shapiro

and Ritzwoller, 2002; Mitra et al., 2006; Priestley et al., 2006; Kumar et al., 2014). However, the large time delay of more than 1.0 s beneath the rifted margins suggests that the anisotropy has a contribution from both the lithosphere and asthenosphere.

We observe a clear back-azimuthal variation of anisotropy parameters ( $\phi$  and  $\delta t$ ) with  $\pi/2$  periodicity, suggesting a layered anisotropic lithosphere in the south Indian Shield. This is also suggested by shear velocity models, where upper lithosphere is interpreted as Archean depleted mantle, while lower lithosphere possibly represents a modification due to subsequent geodynamic events. The anisotropy direction in the two lithospheric layers remains to be resolved.

These results indicate that the observed anisotropy fast direction and splitting times from the south Indian Shield are due to a complex interplay of Archean craton-forming processes and subsequent lithospheric deformation. In certain geological domains like the Southern granulite terrain and western Dharwar craton, anisotropy is influenced by the asthenosphere and/or regional structures (e.g., shear zones). To further quantify the depth and the direction of anisotropy, other imaging approaches (e.g., surface waves) will be used in the future.

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