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RESEARCH

Seismological mapping of a geosuture in the Southern Granulite Province of India

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ABSTRACT

The evolution of the Southern Granulite Province of India has remained a contentious issue due to its complex tectonic history and sparsely preserved surface geologic features. This terrain has attracted global attention because of its central role in Gondwanaland tectonics. The crustal structure and composition of this province are examined using passive seismological data recorded by a network of broadband seismic stations sited in the region. Our results clearly show that the composition and seismic structure of the crust across the northeast arm of the Karur-Kambam-Painavu-Trichur shear zone are distinct. This is pronounced even beyond Karur across the eastern and western segments of the Madurai block along its meridional arm as well as across the Namakkal block. These vivid depth images with differing crustal compositions across the blocks, together with occurrence of alkali syenites and other rock types reminiscent of collision, enable us to demarcate the unambiguous presence of a suture in the region.

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INTRODUCTION

The Southern Granulite Province of the Indian Shield constitutes one of the most critical continental fragments of eastern Gondwana. This province therefore assumes global significance from the viewpoint of understanding its (1) tectonic evolution, and (2) paleoposition with respect to other continental counterparts like Antarctica, Madagascar, and Sri Lanka. Because the province has undergone multiple episodes of magmatism and metamorphism spanning over 2 b.y. (Ghosh et al., 2004; Collins et al., 2014), untangling its geotectonic evolution remains a challenging task. Dissection of this region by a large number of prominent crustal-scale deformed zones, designated as shear zones (see Fig. 1), the origin and status of which are enigmatic, further accentuates the complexity associated with the evolution of this geologic province. Although some of these shear zones are argued to be direct products of collision tectonics, the supporting field evidence is ambiguous. Significant shear deformation is reported along the surface outcrops of these shear zones (Drury and Holt, 1980; Ghosh et al., 2004; Cenki and Kriegsman, 2005). A compelling reason to believe that these lineaments form discrete terrane boundaries is the observation that they bound crustal domains of different isotopic character—domains that have different geological histories are juxtaposed along these boundaries (Bhaskar Rao et al., 2003; Collins et al., 2007; Plavsa et al., 2012; Tomson et al., 2013; Collins et al., 2014; Plavsa et al., 2014). Besides geological, geochemical, and isotopic studies, a gamut of geophysical studies, including seismic-reflection, wide-angle refraction, magnetotelluric, and gravity studies, has also been conducted in the terrain (e.g., Reddy et al., 2003; Mahadevan, 2008, and references therein; Patro et al., 2014). However, all these results have not yet yielded a proper understanding of the evolution of this terrain in a meaningful manner. Understandably, therefore, many competing and conflicting models have been proposed (e.g., Raith et al., 1999; Ramakrishnan, 2004; Ghosh et al., 2004; Mahadevan, 2008; Santosh et al., 2013; Brandt et al., 2014). In this context, we acknowledge that in a terrain that is affected by multiple metamorphic events, the field and structural relations are often sparsely preserved. It is therefore difficult to characterize the structural geometry vis-à-vis the tectonic relationships in such a terrain. However, careful design of an experiment can yield valuable insight, as has been documented from the age and petrologic relations of the gneissic and meta-igneous rocks of the Nimrod Group in the Transantarctic Mountains of Antarctica (Goodge et al., 2001).

The thickness (H) and composition (Poisson's ratio, σ) of the crust are the two most crucial parameters that can provide firm constraints to ascertain vital information about the nature of the underlying crust. A comprehensive analysis of the experimental data in this direction analyzed by Christensen (1996) reveals that at confining pressures over 200 MPa, the minerals and their chemical compositions (e.g., composition of plagioclase feldspar as well as the Fe-Mg ratios of pyroxenes and olivine), constituting different rock types, mainly control the Poisson's ratio. He also observed that there exists a good agreement between the Poisson's ratios of monomineralic rocks and those calculated from single-crystal elastic constants. Therefore, integration of σ values with the average crustal composition in terms of SiO_2 content can yield depth-related insights into petrological changes over an area of study. Such information when it becomes available across two different terranes that were amalgamated during the geological past can be used to delineate a terrane boundary.

With this backdrop and realizing that the Southern Granulite Province is geologically complex, a network of broadband seismic stations was installed by the National Geophysical Research Institute (NGRI), Council of Scientific & Industrial Research (CSIR), India, in and across the terrain. Wide areas of this region were covered in this study, so that the proposed prominent shear zones (Fig. 1B) and the associated crustal structures in their vicinity are mapped with a depth connotation. While designing the present network, shown in Figure 1B, due care was taken by way of (1) culling information that is scattered in several key publications (e.g., Ghosh et al., 2004; Leelanandam et al., 2006; Santosh et al., 2009; Ramakrishnan, 2011; Brandt et al., 2011), (2) considering the disposition of earthquake

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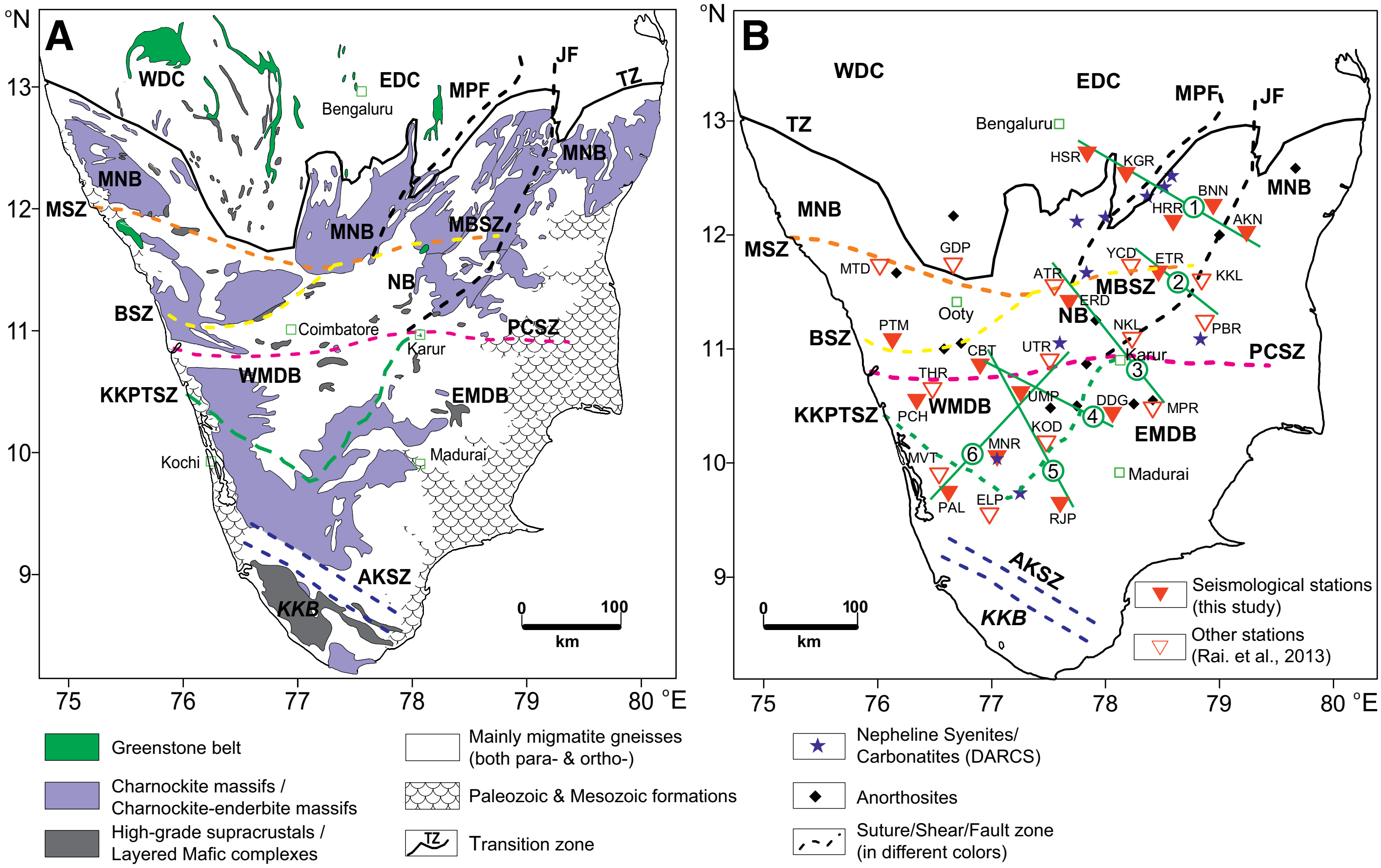

Figure 1. Map of the Southern Granulite Province of India. (A) Generalized geological map of the region (after GSI and ISRO, 1994) and (B) locations of broadband seismic stations with six selected profiles (no. 1 to no. 6) used in Figure 3. The province situated to the south of Archean Dharwar craton has rocks that are metamorphosed to granulite facies (Fermor, 1936). This transition boundary from amphibolite to granulite facies is popularly known as the "Fermor line" and is marked TZ (transition zone) in the figure. Major suture/shear/fault zones (after Tomson et al., 2013) are demarcated using diverse colored broken lines. Various crustal blocks within the Southern Granulite Province are after Drury et al. (1984), Ramakrishnan (2011), and Brandt et al. (2014). Abbreviations used are as follows: AKSZ—Achankovil shear zone, BSZ—Bhavani shear zone, EDC—Eastern Dharwar craton, EMDB—Eastern Madurai block, JF—Jhavadi fault, KKB—Kerala Khondalite block, KKPTSZ—Karur-Kambam-Painavu-Trichur shear zone, MBSZ—Moyar-Bhavani shear zone, MNB—Madras-Nilgiri block, MPF—Mettur-Palakode fault, MSZ—Moyar shear zone, NB—Namakkal block, PCSZ—Palghat-Cauvery shear zone, WDC—Western Dharwar craton, WMDB—Western Madurai block.

source locations with reference to south India, and (3) taking due care not to mix up signals sampling neotectonic blocks such as the Nilgiri Hills with those related to possible Precambrian terrains. The objective of this study is therefore to investigate the crustal structure and determine average composition of a prominent segment of the Southern Granulite Province using passive seismic data (Fig. 1B). Based on the Ps receiver function analyses and *H*-κ stacking results (Zhu and Kanamori, 2000), we demonstrate the presence of a geosuture beneath the investigated area. This significant finding is recorded in terms of differing chemical composition and seismic structure of the crust across certain profiles in the study area. The implications of these seismic results are discussed in the light of the geodynamic setting of the area under investigation.

GEOLOGY AND TECTONICS

The Southern Granulite Province to the south of the Archean Dharwar craton is characterized by high-grade granulite-facies rocks (Fig. 1A; for review, see Collins et al., 2014). The Dharwar craton represents an inclined cross section of the crust such that greenschist-facies rocks are exposed toward the north, followed by amphibolite-facies rocks in the middle, and finally a transition from amphibolite to granulite facies demarcating the northern boundary of the Southern Granulite Province (Peucat et al., 2013; Glorie et al., 2014). This province is characterized by the presence of charnockite massifs (comprising massive charnockites, enderbites, and minor mafic granulite), migmatite gneisses (both orthogneisses and paragneisses), and high-grade supracrustal rocks (GSI and ISRO, 1994; also see Fig. 1A). As noted already, there is a documented presence of a large number of crustal-scale shear zones (see Fig. 1) with diverse structural trends that cut across the Southern Granulite Province, which are believed to have played a crucial role in its tectonic evolution (Ramakrishnan, 2011). Drury et al. (1984) were the first to propose a subdivision of the south Indian Shield into the Northern block and the Southern block, with the Palghat-Cauvery shear zone representing the tectonic boundary between them. In this subdivision, granulites of the Madras-Nilgiri block are included in the Northern block, whereas granulites occurring south of the Palghat-Cauvery shear zone constitute the Southern block. Ramakrishnan (2011) pointed out that subsequent to the work by Drury et al. (1984), many researchers have used individual preferences to name different blocks of the south Indian Shield, leading to confusion among the readers. Presently, a consensus is arrived at (e.g., Ramakrishnan, 2011), where the Southern Granulite Province is divided into four major blocks (see Fig. 1), viz. (1) Madras-Nilgiri block between the Fermor line and the Moyar-Bhavani shear zone; (2) Namakkal block between the Moyar-Bhavani shear zone and the Palghat-Cauvery shear zone; (3) Madurai block between the Palghat-Cauvery shear zone and the Achankovil shear zone; and (4) Kerala Khondalite block (also called the Trivandrum block), lying south of the Achankovil shear zone. Based on recent geochronological and geochemical studies, the Madurai block is further subdivided into western and eastern domains (Brandt et al., 2014). Likewise, the Kerala Khondalite block is also subdivided (not shown in Fig. 1) into the northern Ponmudi block and the southern Nagercoil block (Ramakrishnan, 2011).

It is already pointed out that the Southern Granulite Province is characterized by an unusually complicated tectonic history. The timing and the geodynamic controls for the presence of deep main faults, mega lineaments, major thrusts, crustal scale shear zones and terrane boundaries in the province are not so well understood. Therefore, use of several terms in this study, viz., shear zones, suture zones and geosuture, need better clarification to avoid any confusion. While a shear zone refers to a structural discontinuity arising from a number of processes such as continental accretion, collision, extension, intraplate deformation and subduction related accretion etc., a suture zone is much more than that. Suture is a zone along which separate terranes are joined with the disappearance of intervening ocean. It is a two-dimensional feature observed on the surface, while geosuture has a depth connotation to it. Presence of an ophiolite complex with two diagnostic constituents, namely, the sheeted dykes and plagiogranite are the key indicators of a suture. Full ophiolites are rare in Precambrian terranes; although *ophirags* (ophiolite fragments) and their variants are not uncommon. In the absence of ophiolites, detection of suture zone needs critical scrutiny in terms of variations in lithology, structure, geochronology and metamorphism in the opposing terranes. Under such situations, trace element geochemistry for characterization of tectonic settings may prove to be useful (Abdelsalam and Stern, 1993). Presence of deformed alkaline rocks and carbonatites around the shear zones may be indicative of operation of Wilson cycle (Burke et al., 2003). Geophysical imaging of a suture zone marking distinct crusts across a terrane boundary (e.g., Thomas, 1992; Crosswire and Humphreys, 2003), when integrated with available geological, geochemical and isotopic inputs from a study region can firmly establish the presence of a geosuture.

With this information, it may be worthwhile to note that the radiogenic isotope studies on the rocks of Southern Granulite Province were initiated quite early (e.g., Bühl et al., 1983; Hansen et al., 1985). However, the first systematic Sm-Nd whole-rock and U-Pb zircon dating of samples collected from a number of widely distributed locations south of the transition zone (Fig. 1A) was carried out by Ghosh et al. (2004). They identified that the period between 2.9 Ga and 0.5 Ga recorded imprints of two distinct episodes of metasomatism/charnockitization and at least seven thermo-tectonic events (metamorphism). Subsequent to this, considerable work has been undertaken that has delineated age domains throughout the region and unraveled the metamorphic history. It has been argued that the Cauvery shear zone marks a major boundary between the Paleoproterozoic terrane to the north and the Madurai block to the south (Bhaskar Rao et al., 2003; Collins et al., 2007; Clark et al., 2009; Santosh et al., 2009). The Madurai block itself was initially subdivided by Ghosh et al. (2004), who suggested that the Karur-Kambam-Painavu-Trichur formed a major shear zone. This boundary has recently been highlighted as marking the isotopic subdivision (Plavsa et al., 2012, 2014; Tomson et al., 2013; Brandt et al., 2014) between Neoarchean orthogneiss to the NW (western Madurai block) and younger Proterozoic metasediment-dominated crust to the SE (eastern Madurai block).

The geophysical studies in the region include controlled deep seismic-reflection and refraction/wide-angle reflection, magnetotelluric, gravity, and magnetic measurements (e.g., Reddy et al., 2003; Vijaya Rao et al., 2006; Mahadevan, 2008, and references therein; Patro et al., 2014). However, unambiguous detection or demarcation of subsurface features associated with collision tectonics could not be established by these studies. It may be pointed out that usually measurements using active sources are much better at imaging the shallow portions of sutures, provided the seismic profile is appropriately oriented (e.g., Hauser et al., 2008). However, such care was not taken while planning active source experiments in the Southern Granulite Province of India. All the geophysical data, be it seismic profiles, magnetotelluric profiles, or gravity, were planned and executed based on geological structural information derived mainly from interpreted geological maps with little inputs from actual field mapping. Although some plausible interpretations are discussed in these studies (e.g., Raith et al., 1999; Ramakrishnan, 2004; Ghosh et al., 2004; Mahadevan, 2008; Ramakrishnan, 2011; Plavsa et al., 2012; Santosh et al., 2013), a broad understanding of the evolution of this terrain is yet to emerge.

DATA AND METHODS

A semipermanent network of 14 broadband stations was installed in south India by our research group in two time windows. Among the first group of 10 broadband instruments installed during 2011, two stations, DDG and HSR, were discontinued in 2012 due to unforeseen problems, and eight stations are still operational. The remaining four stations were sited during early 2013 and continue to remain in operation since then. Seismological data from these 14 stations and a permanent broadband station PCH operated by CSIR-NGRI are utilized in this study. These 15 stations (filled inverted triangles) are shown in Figure 1B, and their corresponding latitudes and longitudes, along with other details, are presented in Table 1.

It is well known that a large velocity contrast across a discontinuity (e.g., Moho, 410 km discontinuity, or 660 km discontinuity) causes a part of the steeply incident teleseismic P wave to convert into an SV wave (Burdick and Langston, 1977; Vinnik, 1977). Besides the direct conversions Ps, there are also many multiple reflections and conversions (Burdick and Langston, 1977; Vinnik, 1977) that occur between the surface and the interface (e.g., Moho). While the P wave and its multiples dominate the vertical component, Ps conversion and its multiples are prominently registered on the horizontal component (SV). Therefore, an appropriate component rotation into a ray coordinate system isolates the Ps energy from that of P. The effects related to source, mantle propagation, and instrument response are suppressed by deconvolving the P waveform from the SV component, to obtain what are called the receiver functions. The crustal multiples, designated as Pps and Pss, together with the direct conversion from the Moho boundary (Pms) contain a wealth of information concerning the average crustal properties, such as the Moho thickness (H) and Vp/Vs value (related to Poisson ratio σ), in a well-constrained manner, and these are therefore utilized in this study.

Teleseismic events with magnitudes (Ms) greater than 5.5 and within the epicentral distance range of 30°–90° were used. Seismograms with clear P-wave registrations recorded at each station were selected for the receiver function analysis. A high-pass filter with corner frequency 0.02 Hz was applied to the data. Radial and tangential components were obtained by rotating the horizontal components of the seismogram

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TABLE 1. LOCATIONS OF 15 NETWORK BROADBAND SEISMIC STATIONS DEPLOYED IN THE SOUTHERN GRANULITE PROVINCE OF INDIA

Station code	Latitude (°N)	Longitude (°E)	Starting date	No. of RFs	H (km)	Vp/Vs
AKN	12.00	79.24	01/2013	107	33.0 ± 0.19	1.69 ± 0.007
BNN	12.24	78.95	01/2013	94	29.4 ± 0.14	1.70 ± 0.008
CBT	10.84	76.90	02/2011	189	42.9 ± 0.30	1.75 ± 0.005
DDG	10.43	78.03	02/2011–09/2012	199	42.1 ± 0.17	1.71 ± 0.004
ERD	11.40	77.68	02/2011	247	43.4 ± 0.17	1.77 ± 0.005
ETR	11.66	78.47	01/2013	97	46.6 ± 0.30	1.71 ± 0.006
HRR	12.10	78.59	02/2011	354	42.6 ± 0.15	1.75 ± 0.003
HSR	12.70	77.84	02/2011–02/2012	155	31.6 ± 0.10	1.75 ± 0.003
KGR	12.52	78.18	01/2013	117	33.0 ± 0.18	1.82 ± 0.010
MNR	10.04	77.05	02/2011	157	39.7 ± 0.15	1.75 ± 0.004
PAL	09.73	76.61	02/2011	208	35.4 ± 0.11	1.79 ± 0.005
PCH	10.53	76.35	01/2011–12/2012	222	38.5 ± 0.11	1.77 ± 0.005
PTM	11.06	76.13	02/2011	324	40.8 ± 0.16	1.77 ± 0.005
RJP	09.62	77.60	07/2011	249	38.3 ± 0.20	1.74 ± 0.006
UMP	10.52	77.26	02/2011	287	41.0 ± 0.15	1.77 ± 0.006

Note: Period of operation, number of receiver functions (RFs) analyzed at each station, the Moho depth (crustal thickness, H), and Vp/Vs ratio estimated using method of Zhu and Kanamori (2000) are also included.

by their corresponding back-azimuths. Receiver functions were computed from the radial and vertical components by using the time domain iterative deconvolution procedure of Ligorria and Ammon (1999). To obtain better resolution of crustal layers, a Gaussian filter of width 4 was chosen during the iterative deconvolution. The receiver functions that produced at least 70% fit with the vertical traces, when convolved with the radial traces, were selected. These receiver functions were visually inspected, and any conspicuously bad traces were discarded. The number of receiver functions finally used for each station in further analysis is noted in Table 1.

The H-κ stacking method (Zhu and Kanamori, 2000) was adopted to estimate the crustal thickness (H) and the Vp/Vs ratio (κ) beneath each individual station. This method significantly reduces the ambiguity arising from the trade-off between H and κ as compared to the simple stack procedure (Zhu and Kanamori, 2000). Unlike the simple stack method, there is no need to pick arrival times of various converted phases, and hence large amounts of data can be processed quite conveniently. Since the receiver functions at most of the stations in the study area show clear Pms conversions and Pps and Pss crustal multiples (Fig. 2), the H-κ stacking method is well suited for estimation of the crustal thickness and Vp/Vs ratio.

Assuming a homogeneous P-wave velocity in the crust, the stacking technique sums the receiver function amplitudes at the predicted arrival times of the crustal phases, Pms, Pps, and Pss, for a combination of crustal thickness (H) and Vp/Vs values. A grid search is performed over several values of Moho depth H and Vp/Vs ratio. The values of H and κ for which all the three phases stack coherently, and the stack reaches a maximum value, are taken to be the estimates of the crustal thickness and Vp/Vs ratio. In the present study, a Vp of 6.3 km/s is used, and a grid search was performed over the H and κ ranges of 20–50 km and 1.6–2.0 with increments of 0.1 km and 0.01, respectively. The standard bootstrap technique was used to estimate the uncertainty in the H and Vp/Vs values. In this approach, data sets are constituted by randomly picking samples with repetition from the original data pool, and these are subjected to the grid search analysis for determination of H and Vp/Vs values. This operation was repeated 200 times for each station.

RESULTS AND DISCUSSION

Several researchers have used results obtained from receiver function analyses to study the crust and upper mantle of the Indian subcontinent (e.g., Gaur and Priestley, 1996; Saul et al., 2000; Ramesh et al., 2010; Rai et al., 2013, and references therein). Many of these studies were also carried out in south India, including the Southern Granulite Province. The main emphasis of all these studies was to assess the average crustal composition and velocity structures beneath the Indian landmass, with the exception of one study by Ramesh et al. (2010), where images of possible fossil collision structures beneath the Eastern Dharwar craton and Eastern Ghats belt of India were presented. In this work, we have analyzed data pertaining to 15 stations sited by us (Table 1) and used published results from 13 stations of Rai et al. (2013) that cover the region of our study (Fig. 1B). Thus, results related to a total of 28 stations are utilized and interpreted in this study. Our aim is to obtain crustal thickness and average crustal composition of the region under study with special emphasis on the geodynamic implications of these results.

Receiver Function Stack Sections and Related Observations

Figure 2 presents Ps receiver function distance stack sections corresponding to representative broadband seismic stations. The first positive arrival for each trace at zero time is the direct P arrival, and the next-highest-amplitude positive arrival is the converted wave (Pms) signal from the Moho. The sum traces record large variations in delay times of the Pms arrivals, reaching up to 1 s or more. To gain better insight into our observations, we therefore combined the Ps results from present study with those of Rai et al. (2013). The station locations of this latter study are shown as unfilled inverted triangles in Figure 1B. In Figure 3, we present the sum traces culled from stations corresponding to six select profiles shown in Figure 1B. A major observation from Figure 3 is that the sum traces record large variations in the delay times of the Pms arrival, which are documented by stations sited by us as well as those reported recently by Rai et al. (2013). Significant offset in the Pms (conversion from the Moho) delay times is characteristic of the study region. A traverse along six select profiles from the eastern segment into regions comprising the western segment encompassing the Namakkal and Madurai blocks reveals a clear downward step in the Pms arrivals of ~0.3–1.4 s (corresponding step in Moho depth on the order 2.5–10 km) across these blocks (Figs. 1B and 3). These results, documenting a strong variation in Moho depth across the western and eastern domains comprising different segments of the Madurai and Namakkal blocks within the Southern Granulite Province of India, are first of their kind reported from the study region. Based on deep seismic profiling experiments in the regions covering northwestern Europe and the western Canadian Shield (Cook et al., 1999; Balling, 2000), it has been argued that subduction and collision tectonics of the geologic past can produce local topography on the Moho boundary similar to that observed in the present study. In addition to the Moho topography, such processes can also generate additional layering within the upper mantle that may get preserved for a long time (Bostock, 1998; Ramesh et al., 2010; Das Sharma and Ramesh, 2013). Alternately, a step in the Moho can also be induced due to operation of vertical tectonics or could result from terrane accretion. The implication of this significant result for a plausible model for the tectonic evolution of the shear zones in the study region is discussed later herein.

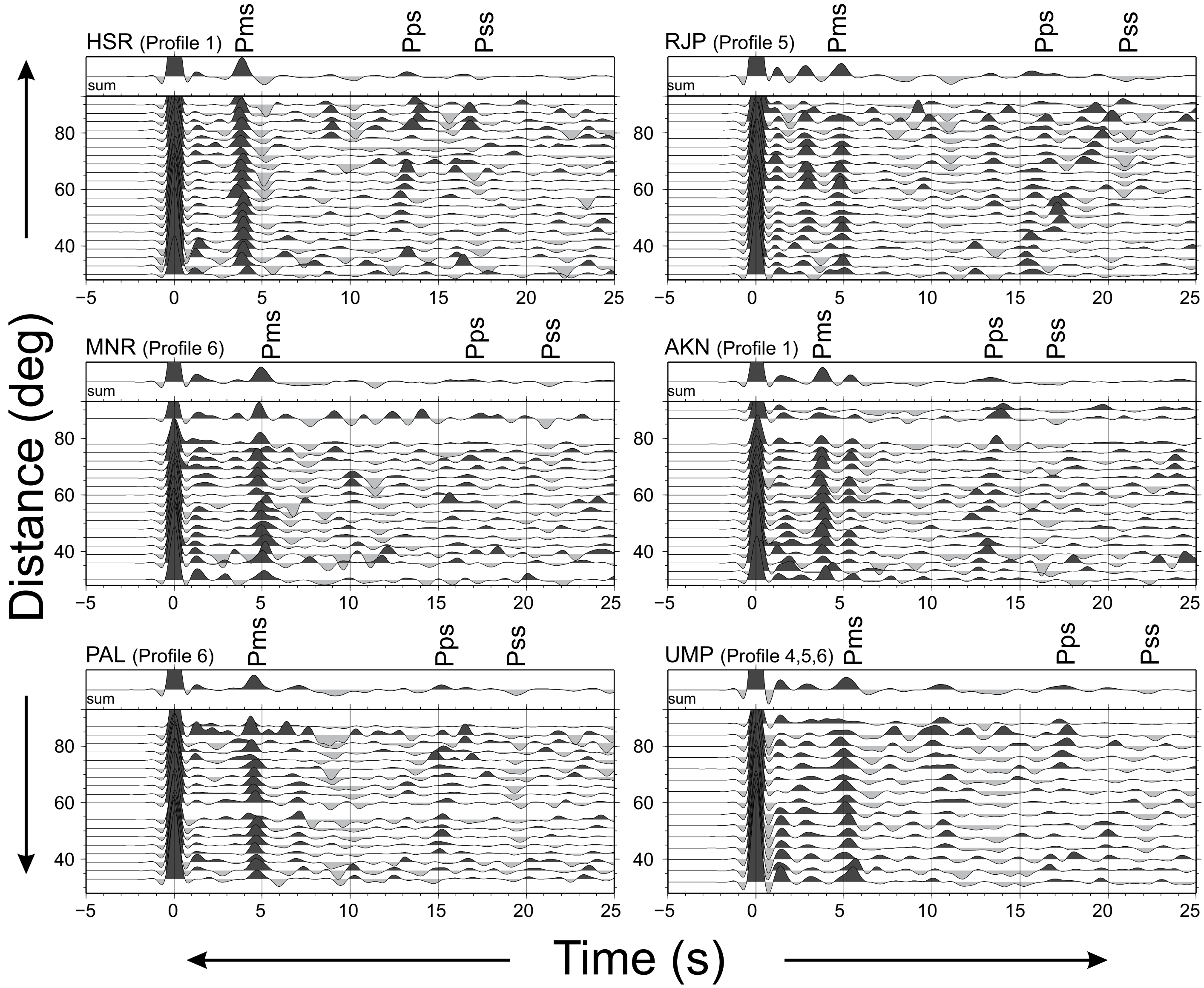

Figure 2. Examples of P-to-S (Ps) stacked radial receiver functions. Results pertaining to six representative stations from the Southern Granulite Province of India are shown. Note that for each station, the profile number shown in Figure 1B is also mentioned.

Crustal Elastic Properties of the Study Region

Most of the information built into the popular models of crustal evolution is largely abstracted from seismic-refraction or seismic-reflection experiments that provide accurate estimates of the depth to the Moho and compression wave velocities (Vp). Though attractive, these models suffer from a lack of constraints on shear wave velocities (Vs) in the crust. Measurement of Vs becomes particularly important while discriminating the rock types with similar Vp values, because the ratio Vp/Vs is sensitive to the composition, and hence is a better discriminant (Christensen, 1996). It is important to recognize that interpretation of Vp/Vs, however, is not straightforward enough to reduce the ambiguity regarding crustal composition. We therefore attempt to interpret the measured Vp/Vs values mainly in terms of composition constrained by other geological factors relevant to the study region. It therefore seems crucial to accurately determine the Moho depth (H) and Vp/Vs to understand the tectonic evolution of the region through geological times.

The estimated Vp/Vs ratios, adopting the approach of Zhu and Kanamori (2000), vary from 1.69 to 1.82 for the 15 stations presented in this report (see Table 1). The Vp/Vs ratios reported by Rai et al. (2013) at other locations within our study region vary between 1.69 and 1.77. Thus, as the ranges of Vp/Vs measurements obtained from both the studies (totaling to 28 stations) are comparable, these results are henceforth jointly discussed. Zandt and Ammon (1995) and Christensen (1996) showed that the average Vp/Vs ratio of a predominantly felsic crust is around 1.73, while for intermediate and mafic crusts, these values are greater than 1.73. The Vp/Vs values from the 28 stations in the study region clearly delineate that the eastern segment is predominantly felsic in nature, while its western counterpart is different in terms of Vp/Vs ratio, with values suggesting an inter-

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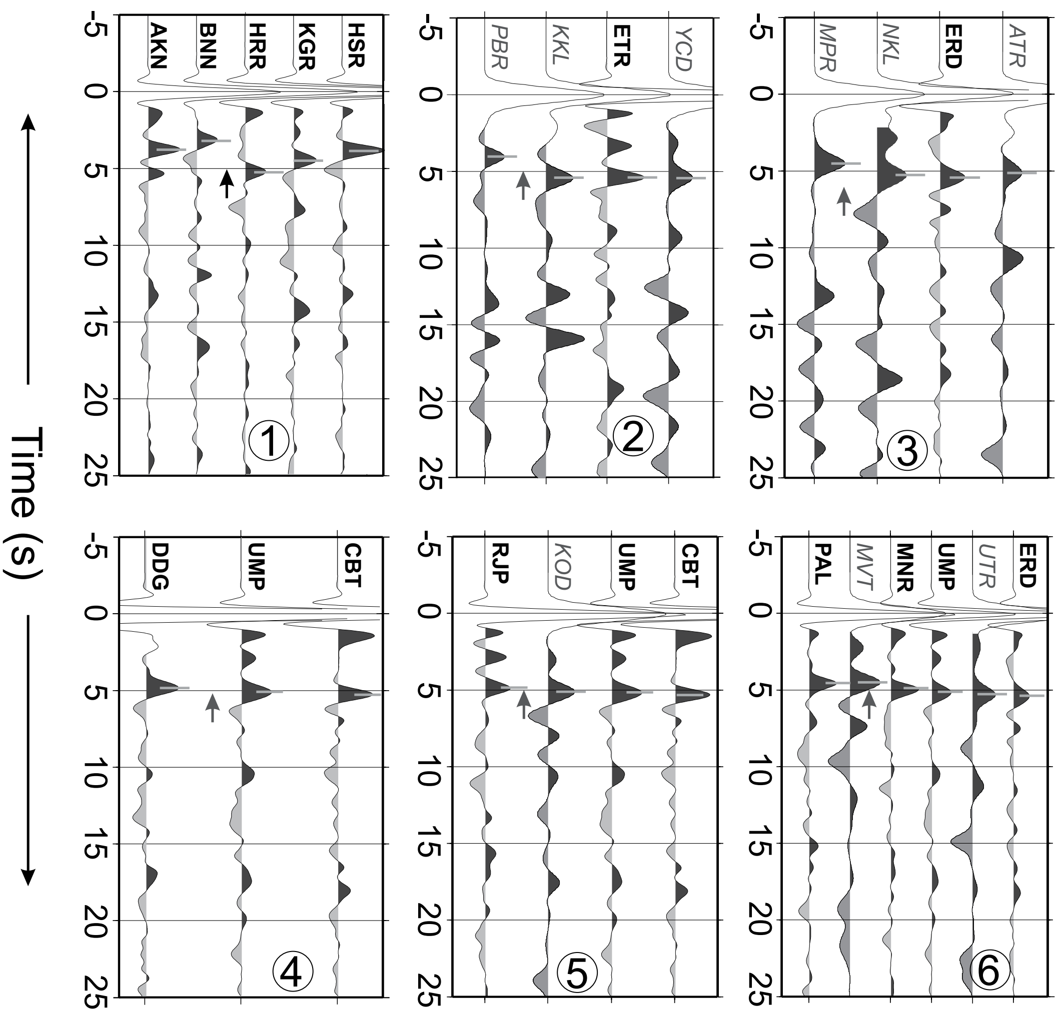

Figure 3. Receiver function sum traces along six different profiles. These profiles, along with station names, are mentioned in Figure 1B. Seismic station names of Rai et al. (2013) are shown in italics. Consistency in Pms arrivals can be noted between stations sited by us and those of Rai et al. (2013). A clear step (i.e., offset indicated by arrow) in Pms arrivals (Moho depth) along each profile can be observed. This offset is more pronounced across the Namakkal as well as Eastern and Western Madurai blocks. We infer that convergence between these two discrete segments during the Neoproterozoic period resulted in the observed Moho disposition across the selected profiles (see also Figs. 7A and 7B and text for details).

mediate crust composition (Fig. 4). Therefore, distinct eastern and western segments in terms of their average crustal compositions seem to exist within the study area. This finding is in conformity with our earlier observation on the presence of distinct eastern and western regions based on Ps delay times across them that document a large offset/step in the Moho boundary. Figure 5 shows H-κ stacking results at representative stations, while Table 1 lists corresponding parameters with error bounds.

It is important to note that the northeast arm of a major geologic feature in the study region, viz. Karur-Kambam-Painavu-Trichur shear zone, which manifests on the surface, is characterized by the presence of seismically dissimilar crustal materials at depth (Fig. 4). Moreover, such distinct crustal characteristics are also documented beyond Karur, in and around the regions across the Jhavadi fault and north of the Moyar-Bhavani shear zone as well (Fig. 4). While the surface disposition of the Moyar-Bhavani shear zone is predominantly E-W, that of the Karur-Kambam-Painavu-Trichur shear zone and Jhavadi fault is chiefly NE-SW (Fig. 1B). The selected six different profiles, which are near perpendicular to these shear/fault zones (see Fig. 1B), document a clear offset/step in the depth to the Moho boundary from east to west (Fig. 3), especially across the meridional arm of the Karur-Kambam-Painavu-Trichur shear zone and beyond.

Integration of Moho Offset Results with Estimated Average Composition of the Crust

It was mentioned earlier that the average chemical composition and nature of the crust can be inferred on the basis of fundamental work carried out by Christensen (1996), who pointed out that there exists a good agreement between the Poisson's ratios of monomineralic rocks and those calculated from single-crystal elastic constants. For igneous and metamorphic rocks, he observed that the Poisson's ratios correlate qualitatively with mineralogical changes. The overall trend is nonlinear (Christensen, 1996) in the binary plot between weight percent SiO_2 and Poisson's ratio (σ). However, σ increases with decreasing SiO_2 content and exhibits a linear correlation between 55 and 75 wt% SiO_2. Based on such an analysis, Christensen (1996) proposed that measurements of Poisson's ratio might provide valuable information on crustal chemistry of a region. Subsequently, numerous studies were conducted using different seismological techniques where the validity of such a relationship was tested to evaluate crustal characteristics of widely diverse geology and antiquity (e.g., Egorkin, 1998; Chevrot and van der Hilst, 2000; Morozov et al., 2003; Mechie et al., 2005).

The relation between Poisson's ratio (σ) and Vp/Vs can be expressed as

$$\frac{Vp}{Vs} = \sqrt{\frac{2(\sigma - 1)}{(2\sigma - 1)}}.$$

This was utilized by Christensen (1996) to transform the experimentally determined Vp/Vs values of the samples into Poisson's ratio (σ) and then establish a relation with wt% SiO_2 to finally calculate the silica content in the suite of rocks. We, however, explored the relationship between

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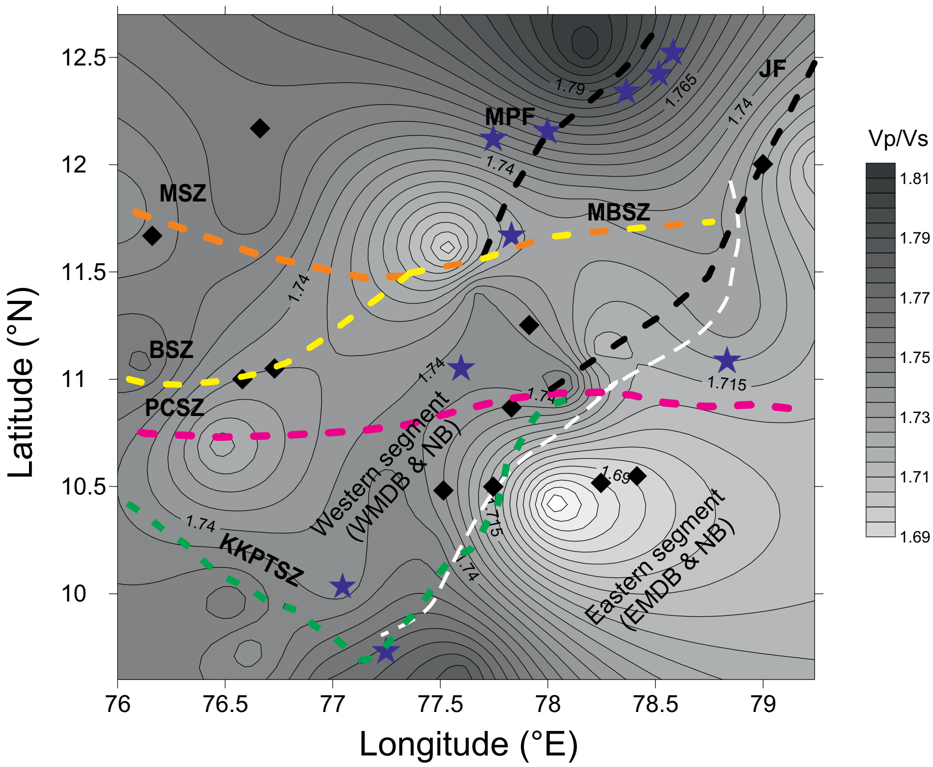

Figure 4. Distribution of Vp/Vs values of the Southern Granulite Province. These values across the designated eastern and western segments are distinct. The distributions of alkaline rocks and carbonatites (star) and anorthosites (diamonds) are shown. Broken lines in different colors represent major shear/fault zones in the region. A tentative geosuture is demarcated by the white dashed line based on a jump in the Moho depth across station locations corresponding to six profiles of Figure 3. Note its broad agreement with the Karur-Kambam-Painavu-Trichur shear zone (KKPTSZ) and Jhavadi fault (JF) mapped on the surface. Each degree in the diagram corresponds to ~111 km. Abbreviations used are same as in Figure 1.

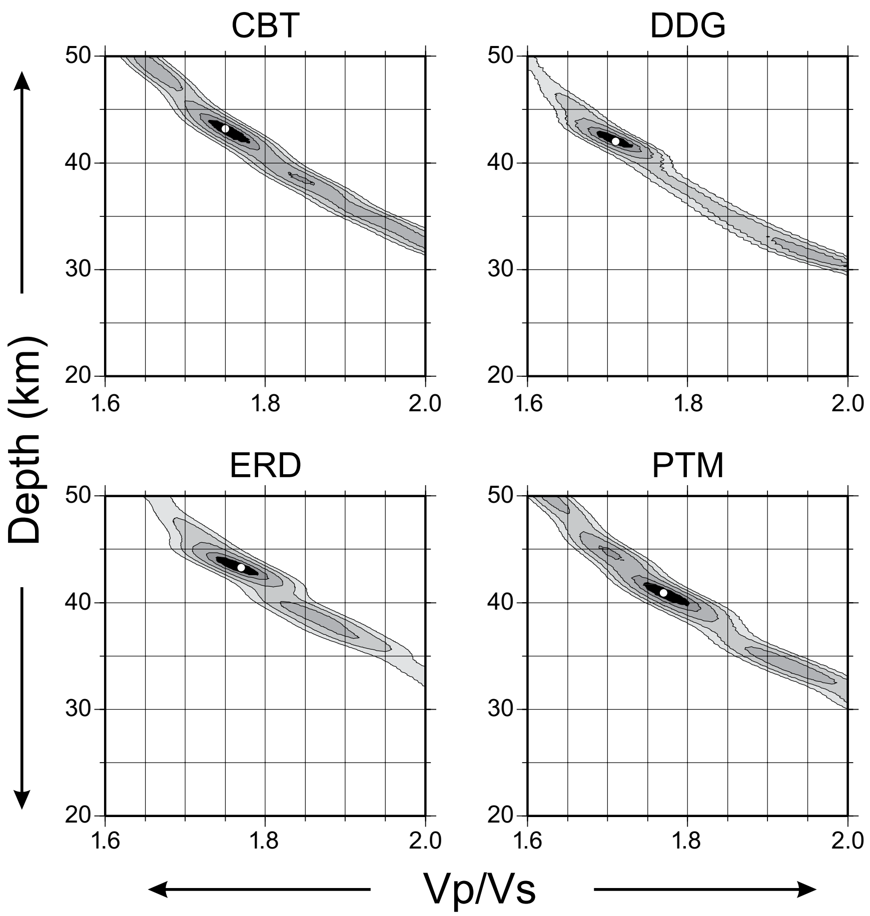

Figure 5. The *H*-κ stacking results for representative stations. The optimum values of *H* and κ are marked by white dots. See also Figure 4 and text for more details.

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wt% SiO_2 and Vp/Vs directly, using the data given in Christensen (1996) for 18 different rock types of metasedimentary and igneous origins, such as quartzite, slate, metagraywacke, paragranulite, felsic and mafic granulites, granite, basalt, diorite, and anorthosite. These rock types essentially comprise the important constituents of crustal geology. It is interesting to note that, contrary to the observed nonlinear binary relation between wt% SiO_2 and σ by Christensen (1996), we obtained a linear relationship of the form $y = -mx + c$ between wt% SiO_2 and Vp/Vs with a high correlation coefficient of $R^2 = 0.88$ (see Fig. 6). Such a good correlation is in concert with the documented decrease in compressional wave velocities with concomitant increase in shear wave velocities as a function of SiO_2 content (Christensen, 1996). The estimated linear relation was used to compute the average crustal wt% SiO_2 beneath each station shown in Figure 1B within the Southern Granulite Province of India. It was found that the average SiO_2 content of this province ranges from ~62 to 73 wt%, with the eastern segment in general being more felsic (>68 wt% SiO_2) than the average continental crust (~61.8 wt% SiO_2) reported from elsewhere in the world (e.g., Christensen and Mooney, 1995).

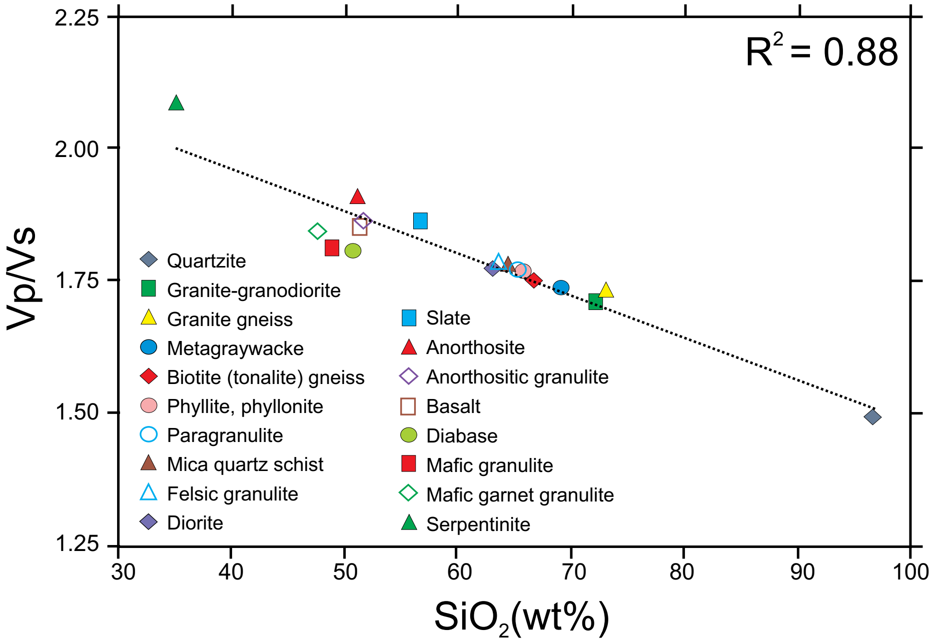

Figure 6. Relationship between average SiO_2 contents and corresponding Vp/Vs ratios. All common rock types are shown in the diagram (data from Christensen, 1996). Excellent linear correlation ($R^2 = 0.88$) can be observed between the plotted parameters. This diagram forms the basis of Figure 7C.

Documentation of a step in Moho depth or Moho-step (Fig. 3) and compositionally distinct crust in the study area (Fig. 4) need better integration in order to appreciate their subsurface manifestation, which in turn would be helpful to understand the geodynamic implications of these results. We therefore present in Figures 7A and 7B the crustal thickness variations (Pms arrivals and *H*, respectively) across the meridional arm of the Karur-Kambam-Painavu-Trichur shear zone, which show a 2.5–10 km step in the Moho depth. Also, discernible differences in the silica content up to 6 wt% (see Fig. 7C) across this prominent geologic feature are evident. Importantly, such sharp demarcation coincides with the northeast (NE) arm of Karur-Kambam-Painavu-Trichur shear zone and the Jhavadi fault on the surface. These findings, originating from two independent and yet similar measurements (this study and those from Rai et al., 2013), when viewed collectively are significant. Incidentally, the Karur-Kambam-Painavu-Trichur shear zone was delineated on the surface based on structural mapping and geochronological studies (Ghosh et al., 2004). It is significant to note from our results that the divergent nature of the underlying crust extends ~200 km beyond Karur in the northeast direction (see Fig. 7).

Geotectonic Interpretations

The geotectonic implications of our results are presented here in the backdrop of the regional geology of the study region. First, we point out that in several geologic and geodynamic settings of the globe, juxtaposition of distinct crustal blocks, as observed in our study region, is often viewed as a consequence of suturing between two geologically diverse terranes (Thomas, 1992; Crosswhite and Humphreys, 2003; Grad et al., 2003a, 2003b; Wilde-Piórko et al., 2010; Brennan et al., 2011). For example, receiver function crustal images across the Proterozoic Cheyenne belt in the United States revealed a zone of very thick crust south of the Cheyenne belt embedded with a south-dipping set of conversions together with a step in the crustal thickness. The thick crust is inferred to be a remnant from the original 1.8 Ga suturing event (Crosswhite and Humphreys, 2003). Likewise, ancient collision-related continental margins were recognized in the Canadian Shield, where deep crustal breaks along boundaries between two distinct provinces with differences in crustal thickness on either side were detected. Such breaks were interpreted to represent collisional sutures (Thomas, 1992). With the help of massive international cooperation, several seismic experiments such as POLONAISE'97, CELEBRATION 2000, ALP 2002, and SUDETES 2003 were launched to image the crust and lithosphere of Central Europe. From these studies, it emerged that the Polish landmass is of prime importance in understanding the tectonic evolution of the whole European continent. Three major European tectonic units, viz. the Precambrian platform of Eastern Europe (also called the East European craton), the Paleozoic Platform of Central and Western Europe, and the youngest Alpine orogenic belt (represented in Poland by the Carpathians), converge at this location. Based on distinct Moho depths and velocity structures, the contact zone between the East European craton and the Paleozoic Platform is argued to represent a suture zone (the Trans-European suture zone). This suture zone is more than 2000 km long and traverses the entire European continent (Grad et al., 2003a, 2003b; Wilde-Piórko et al., 2010). In a recent study, Brennan et al. (2011) presented results from receiver function analyses along different transects across the central Alaska Range. They identified three distinct crustal sections based on differing crustal thickness and Vp/Vs ratios, besides the presence of intracrustal discontinuities. The documented variability in the crust across the Alaska Range was interpreted to represent amalgamation between a former continental margin and allochthonous oceanic terrane with the intermediate zone characterizing the suture zone.

Taking cue from all these studies, we prefer to interpret the observed distinct crusts across the NE-SW arm of the Karur-Kambam-Painavu-Trichur shear zone and beyond (Fig. 7) to constitute a terrane boundary. In this context, it is pertinent to mention the recent results obtained by Brandt et al. (2014) from laser ablation–inductively coupled plasma–mass spectrometry U-Pb zircon and U-Th-Pb monazite ages of fel-

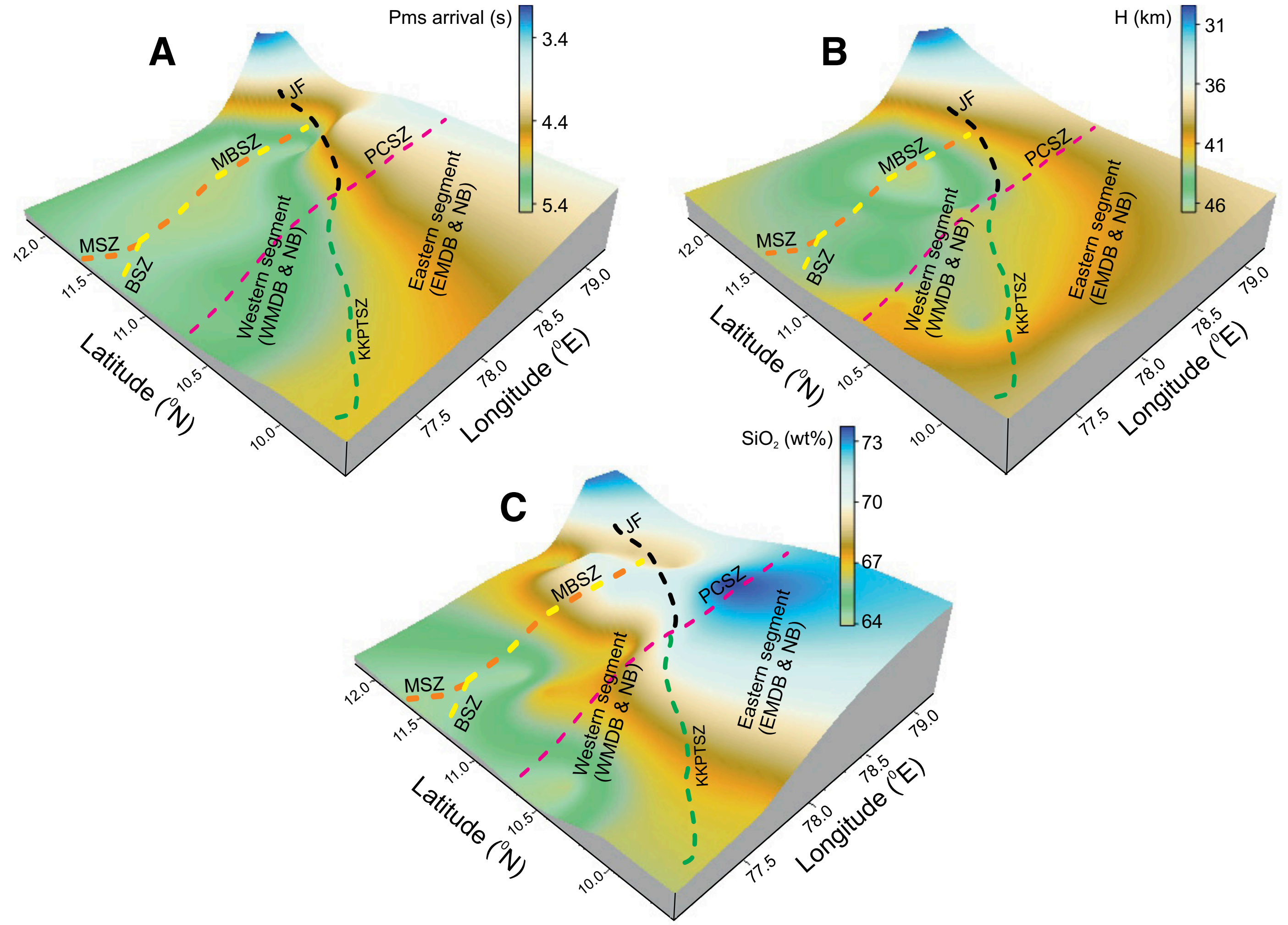

Figure 7. Comparison of crustal parameters presented in three-dimensional perspective views. (A) Pms arrivals (P-to-s mode conversion from the Moho boundary), (B) Moho depth, *H* (Zhu and Kanamori, 2000), and (C) average SiO_2 contents corresponding to stations across which we observe Moho offsets (Figs. 1B and 3) and distinct crustal Vp/Vs ratios (Fig. 4). Approximate surface dispositions of major shear/fault zones within the region are displayed using colored broken lines. Note that distinct crustal characteristics are evident between the eastern and western segments roughly across the NE arm of the Karur-Kambam-Painavu-Trichur shear zone and Jhavadi fault. Observed distinction of crustal parameters in the study region together with other surface geological evidences for operation of a Wilson cycle lend unambiguous support to convergence between the discrete eastern and western segments (see text for details). Each degree in the diagram corresponds to ~111 km. Abbreviations used are same as in Figure 1.

sic orthogneisses and granites from the Southern Granulite Province of India encompassing the Cauvery shear zone and Madurai Province. Together, with support from geochemical characterization of the rocks in the study area, their results could establish two distinct crustal domains within the Madurai Province. The western domain of the Madurai Province is typically characterized by late Neoarchean (2.53–2.46 Ga) subduction-related, magnesian charno-enderbites in a magmatic arc setting, while the eastern part is typified by a vast supracrustal sequence that was deposited on a 1.74–1.62 Ga basement of magnesian charnockites and hornblende-biotite gneisses, which were produced as a consequence of reworking of the underlying Archean rocks. Further, it is also documented that both eastern and western domains of the Madurai Province were intruded subsequently by A-type charnockites and felsic orthogneisses during 0.83–0.79 Ga. Suturing of these two domains took place along a SSW-NNE–trending zone of high strain, giving rise to ultrahigh-temperature metamorphic rocks exposed in the area (Brandt et al., 2014). This SSW-NNE zone approximates the Karur-Kambam-Painavu-Trichur shear zone, across which the distinct nature of the crust is delineated from our receiver function measurements. Importantly, we also document presence of such distinct crust beyond the Karur area, approximately tracking the Jhavadi fault on the surface. In view of these significant findings, it becomes necessary to critically evaluate the nomenclature of different blocks based on presence of crustal-scale shear zones alone (e.g., Drury et al., 1984; Ramakrishnan, 2011).

The tectonic significance of the presence of alkali syenites and related rocks that occur in the vicinity of the Moyar-Bhavani and Karur-Kambam-Painavu-Trichur shear zones within the Southern Granulite Province (see Fig. 1B) has been elaborated earlier by Gopalakrishnan (2003, and references therein) and Leelanandam et al. (2006). While the former relates the occurrence of alkali plutons in the region to abortive (unsuccessful) rifting, Leelanandam et al. (2006) attributed the presence of alkaline rocks and carbonatites and their deformed variants to an unmistakable operation of rifting and collision processes in the region. They mapped deformed alkaline rocks and carbonatites as linear occurrences to postulate a suture trending NE-SW (akin to the Karur-Kambam-Painavu-Trichur shear zone) within the Southern Granulite Province. Further, association of deformed alkaline rocks and carbonatites with ultramafic/mafic igneous bodies was also noted by them. It is also pertinent to mention that Santosh et al. (2010) reported the occurrence of diopsidite dikes and veins within altered gabbroic rocks from various locations in the vicinity of the Karur area. Based on the major, trace, and rare earth element compositions of diopside crystals, they interpreted the formation of these crystals in a subduction zone environment. Further, the Manamedu complex, which is also located near the Karur area, is interpreted as a dismembered mid-Neoproterozoic ophiolite (Yellappa et al., 2010; Sato et al., 2011; Santosh et al., 2012).

All these results, originating from independent lines of evidences (seismological, geological, geochemical, and geochronological), when viewed collectively are significant and lend unambiguous support to convergence between the discrete eastern and western segments encompassing the Madurai block along the NE arm of the Karur-Kambam-Painavu-Trichur shear zone and the Namakkal block beyond Karur (Figs. 4 and 7). The timing of this collision event can be placed as during the Neoproterozoic (Brandt et al., 2014). The charnockite gneisses in the delineated eastern segment exhibit geochemical affinity akin to calc-alkaline magmas yielding Sm-Nd model ages of ca. 2.5–1.2 Ga (early Proterozoic to Neoproterozoic; Tomson et al., 2013), which are older compared to their crystallization age. This is directly suggestive of mixing of Neoproterozoic arc magmas and older crustal components (Ghosh et al., 2004; Tomson et al., 2013) and lends support to a collision event possibly during the late Neoproterozoic (Brandt et al., 2014).

Notwithstanding this significant finding, it may also be noted that Gopalakrishnan (2003) proposed a model of amalgamation of microterranes to describe the evolution of the Southern Granulite Province based on an overview of the reconstruction of Precambrian assemblages of Gondwanaland. It is therefore possible that in addition to the geosuture delineated in this study, there could be other fragments that collided with the Southern Granulite Province through geological time during its evolutionary path. Close-spaced crustal mapping of the entire region is essential to examine this complex terrain and unravel more details.

CONCLUSIONS

In this study, the depth to Moho and average crustal composition are obtained from a network of seismological stations in the Southern Granulite Province of India. Results from this passive seismic experiment, when integrated with the available geological, geochemical, and geochronological information, provide fresh insights into the tectonic evolution of the Southern Granulite Province. Several geologic and seismological evidences lend unambiguous support to a collision event possibly during the late Neoproterozoic along the NE arm of the Karur-Kambam-Painavu-Trichur shear zone and Jhavadi fault. In the following, we present other highlights from this study.

(1) Across the eastern and western segments of the study region covering the Namakkal and Madurai blocks within the Southern Granulite Province of India, a step in the Moho depth (2.5–10 km) accompanied by a compositionally distinct crust is observed.

(2) When superimposed on the seismic results, the shear zones and faults observed on the surface in the study area suggest the presence of distinct crust across the Jhavadi fault and the meridional arm of the Karur-Kambam-Painavu-Trichur shear zone within the Namakkal block and the Madurai block, respectively. Similar results from other parts of the globe are interpreted in terms of a terrane boundary between such distinct crustal domains.

(3) The seismic results, when integrated with the surface geological evidences together with available geochemical and geochronological data, also support such an interpretation.

(4) These results clearly point to the fact that the nomenclature of different blocks within the Southern Granulite Province, based on the presence of crustal-scale shear zones alone, may not be valid and hence require a critical evaluation.

(5) Seismological results of similar nature accruing from other high-grade terrains of Gondwanaland, when available, would add an element of certainty to the subsurface extension, average petrological character, and depth disposition of various surface geological features of the deformed zones mapped across different crustal fragments. This would enable evaluation of their status/role as continental-scale megasutures during supercontinent amalgamation.

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