Tectonophysics 612–613 (2014) 128–133

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Thin lithosphere–asthenosphere boundary beneath Eastern Indian craton

Shalivahan [a,*], Bimalendu B. Bhattacharya [b], N.V. Chalapathi Rao [c], V.P. Maurya [a]

[a] Department of Applied Geophysics, Centre of Advanced Study, Indian School of Mines, Dhanbad 826004, India
[b] Department of Theoretical Studies, S.N. Bose National Centre for Basic Sciences, Salt Lake, Kolkata 700098, India
[c] Department of Geology, Centre of Advanced Study, Banaras Hindu University, Varanasi 221005, India

ARTICLE INFO

Article history:
Received 3 October 2013
Received in revised form 19 November 2013
Accepted 29 November 2013
Available online 4 December 2013

Keywords:
LAB
Magnetotelluric
Craton
Archean

ABSTRACT

The lithosphere–asthenosphere boundary (LAB) separates the hard and rigid outer layer of the earth (lithosphere) and the weaker, hotter, and deeper part of the upper mantle (asthenosphere) and plays a pivotal role in plate tectonics. However, its definitive detection, especially beneath the cratons, is proving elusive. One of the geophysical tools used to map the LAB beneath the cratons is through magnetotelluric (MT) observations. The resistivity at boundary falls in the range of 5–25 Ω-m and can be explained by the presence of a small amount of water in the asthenosphere, possibly inducing partial melt. Here, we report thickness of the LAB in one of the oldest dated ancient cratons of India—Eastern Indian Craton (EIC) of ~3.3 Gyr, from MT studies. The two prominent phase-sensitive strike directions, one each for crust and mantle, and the presence of resistive continental lower crust act as a window to mantle in resolving deeper electrical conductivity structures beneath EIC. Our results show that the LAB beneath the EIC is at 95 km. The region is interesting as the electrical properties of the crust and mantle and the Moho depth are similar to those of the Slave Craton, Canada (~4.0 Gyr) but the depth of the LAB beneath the EIC is half that of the Slave craton. As cratonic signatures, depicted by ultrapotassic rocks from Gondwana coal fields close to EIC, are preserved at least till early Cretaceous (117 Ma) it is likely that Himalayan orogeny could have played a major role in delamination of the lithospheric roots of the EIC in addition to attendant seismicity.

1. Introduction

Lithosphere, the hard and rigid outer layer of the earth, includes the crust and the uppermost mantle and is underlain by the asthenosphere, the weaker, hotter, and deeper part of the upper mantle. The boundary between the lithosphere and the underlying asthenosphere is defined by a difference in response to stress: the lithosphere remains rigid for very long periods of geologic time in which it deforms elastically and through brittle failure, while the asthenosphere deforms viscously and accommodates strain through plastic deformation. The term lithosphere is commonly understood as describing Earth's rigid outer shell floating on a viscous asthenosphere. Lithosphere–asthenosphere boundary (LAB) has been explained in a mechanical sense using post-glacial rebound phenomenon (Barrell, 1914), as well as thermal, chemical and seismic (Anderson, 1995) and electrical phenomenon (Eaton et al., 2009).

The LABs have been identified on geological evidences such as xenolith and xenocryst record entrained in deep mantle derived magmas such as kimberlites, lamproites and lamprophyres. The thermobarometric techniques developed for xenoliths have validated stratigraphies for cratonic lithosphere that extends to almost 250 km depth. Such stratigraphies commonly exhibit coarse-textured peridotites that equilibrated near conductive pressure–temperature conditions and are replaced at depth by high-temperature, dynamically recrystallized peridotites with finer-grained "sheared" textures (Finnerty and Boyd, 1987). The LABs have also have been identified using rheological lithosphere. The differential motion between tectonic plates and the asthenosphere is accommodated at the LAB by one of two primary creep mechanisms (Karato and Wu, 1993). The seismological lithosphere beneath cratonic regions is commonly characterized as a lid of anomalously high shear-wave velocity from the Moho to ~100–300 km depth. Its base is difficult to identify using surface waves, due to the integrating properties of the technique. Although surface waves have good sensitivity to absolute seismic velocity over a given depth range, related to the sensitivity kernels of the phases at different periods, they are relatively insensitive to the nature of the boundaries between high and low velocities. Thus a sharp velocity contrast at the base of the seismological lithosphere is generally indistinguishable from a gradual velocity gradient.

Electrical conductivity provides an important constraint on mantle structure that is independent of those obtained using seismological, or other geophysical, techniques. The bulk conductivity of the mantle is primarily controlled by temperature and composition (Xu et al., 2000), but can be dramatically enhanced by the presence of an

* Corresponding author. Tel.: +91 3262235475; fax: +91 3262296618.
E-mail address: svismagp@yahoo.co.in (Shalivahan).

0040-1951/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tecto.2013.11.036

interconnected conducting phase such as melt or graphite, which is typically a minor constituent of the rock matrix. For these reasons, conductivity in the mantle lends itself to the identification of key upper upper-mantle boundaries, both vertically and laterally. The magnetotelluric (MT) method is well suited to the problem of inferring Earth structure at mantle depths (Jones, 1999). The lithospheric mantle represents a relatively resistive layer (1000 to 10,000 Ω-m) beneath a (typically) conductive lower crust.

Determination of mantle resistivity directly below the Moho to depths of about 100 km is hampered by pervasive highly-conductive lower crust that acts as a screen. In such a case the MT data provides conductance of the conducting lower crust uniquely but thickness may be determined with lower and upper bound only. Thus, any depth determination below the conducting lower crust is ambiguous. Resistive continental lower crusts (CLC) have been reported only underneath the Eastern Indian Craton (EIC) (Bhattacharya and Shalivahan, 2002) and the Slave craton, Canada (Jones and Ferguson, 2001). The resistive CLC beneath the EIC acts as "window" through which the lithospheric mantle resistivity–depth profile can be reasonably well resolved and an anisotropic layer at a depth of 175 km is seen (Shalivahan and Bhattacharya, 2005). Both the resistivity and velocity decreases at the LAB. This can possibly be explained by the presence of hydrous olivine (Eaton et al., 2009). Globally, comparisons with seismic data have shown that the electrical asthenosphere accords well spatially and in depth with the seismically-defined asthenosphere (Praus et al., 1990). Typical values quoted for the resistivity of the electrical asthenosphere are in the range of 5–25 Ω-m, whereas at depths of 200–250 km a dry mantle mineralogy on an adiabat will yield a resistivity of hundreds of ohm-m (Xu et al., 2000).

Global view of the LAB on the basis of analysis of 15 years of global seismic data using P-to-S (Ps) converted phases imaged an interface that correlates with tectonic environment (Rychert and Shearer, 2009). The LAB beneath three well studied Archean regions: the Kaapvaal craton, the Slave craton and the Fennoscandian Shield has been found to elusive (Eaton et al., 2009). The lithospheric roots in South Africa, Australia and Antarctica are between 180 and 300 km deep, whereas its Gondwanic counterpart of the Indian lithosphere extends only about 100 km deep (Kumar et al., 2007). It has been inferred that the plume that partitioned Gondwanaland may have also melted the lower half of the Indian lithosphere, thus permitting faster motion due to ridge push or slab pull (Kumar et al., 2007).

In this paper we report the thickness of the LAB in, one of the oldest dated cratons of India, EIC (~3.3 Gyr) in a region of window to mantle as evident from the MT studies. Subsequently, we discuss the geological signatures in support of the LAB thickness as obtained by MT studies and explore its geodynamic implications.

2. Geology of the Eastern Indian Craton

The eastern Indian shield comprises the Singhbhum craton, the Chhotanagpur Gneissic Terrain (CGT) and the Shillong plateau. The exact relationship between the Singhbhum craton and the CGT is uncertain and debatable; while some workers regard CGT to be a mobile belt constituting a distinct terrane (Ghose, 1983; Ghose et al., 2005; Ghose and Chatterjee, 2008; Mahadevan, 2002; Mukhopadhyay, 1988), others consider it to be a cratonized mobile belt (Kumar and Ahmad, 2007; Naqvi and Rogers, 1987; Sharma, 2009; Srivastava et al., 2009, 2012). The cratonic nature of CGT appears to be more favorable due to the facts that:(i) it has an Archean antiquity whose convergence with the Singhbhum craton in the south gave rise to the Singhbhum mobile belt and medium-grade enclaves of metasediments and basic rocks exclude its mobile belt nature; (ii) discovery of spinifex textured komatiite within the CGT, near Daltonganj which are characteristic of Archean cratons (Bhattacharya et al., 2010); (iii) the presence of ultrapotassic intrusives with petrological and geochemical affinities to predominantly cratonic magmas such as orangeites, lamproites and aillikites- and (iv) Mesoproterozoic metabasite rocks and amphibolites dykes respectively exposed south and north of the Damodar valley show their emplacement in an extensional tectonic regime of intracratonic setting (Kumar and Ahmad, 2007; Srivastava et al., 2009).

Mafic dykes of Precambrian and early- to late-Cretaceous age and early Cretaceous-ultrapotassic dykes age are also very conspicuous in the CGT apart from the Deccan Traps and the Rajmahal volcanics. Thus, the CGT is the only geological domain in the entire Indian shield which hosts the early Cretaceous Rajmahal- as well as the Late-Cretaceous Deccan-igneous activities (Srivastava et al., 2013 and the references therein). Whereas the early-Cretaceous volcanics, mafic and ultrapotassic dykes are linked to the Kerguelen hotspot (Ghatak and Basu, 2013; Kent et al., 2002; Mahoney et al., 1983), the late-Cretaceous (Deccan) igneous activity is related to the Reunion hotspot (Paul, 2005).

3. MT survey

Remote reference (RR) MT measurements were made over the transect AB over a part of EIC (Fig. 1). The measurements were made in the frequency range of 320 Hz to 0.0055 Hz (Bhattacharya and Shalivahan, 2002). The dipole length was of 100 m. The acquired data was processed using extra-hybrid processing technique (Shalivahan et al., 2006). The average phase-sensitive regional strike changes from N45°W for frequency >1 Hz to N25°W for frequency <0.1 Hz. 2-D geoelectric model (in between 320 and 0.1 Hz) along transect AB beneath the EIC shows a 38 km thick electrically homogeneous granitic crustal layer of very high resistivity of about 40,000 Ω-m (Bhattacharya and Shalivahan, 2002) (Fig. 2). The model fit the data to within 2.8° in phase and 0.0217 in log ρ_a. A uniform layer of 8 km thickness below the granitic crust with relatively lower resistivity is found at a depth of 38 km. The resistivity of this layer is as high as 8500 Ω-m instead of typically conductive lower crust globally encountered. Keeping in view the outcrops of charnockites along the southern fringes of the Singhbhum craton north of the Sukhinda thrust and of khondalites (graphite-bearing) to the south of the Sukhinda thrust, these rocks may be candidates for the 8500 Ω-m layer. This implies a greater crustal thickness, i.e., 46 ± 2.1 km below the craton. The resistivity of the upper mantle at a depth of 46 ± 2.1 km (Bhattacharya and Shalivahan, 2002) is about 750 Ω-m showing a decrease in resistivity by an order from that of the resistive lower crust of about 8500 Ω-m encountered in this region. Shalivahan and Bhattacharya (2005) reported that the olivines below EIC are hydrous. In the south-eastern end of the profile, the thickness of the granitic crust remains 38 km (Fig. 2). The conductivity of 0.00012 S/m for CLC under EIC (Bhattacharya and Shalivahan, 2002) and are in broad agreement with the experimental results (Olhoeft, 1981). A possible explanation for the resistive CLC below EIC is the absence of imbrications of sedimentary material and underplating of mafic crust related to subduction processes. About 8 km thick lower crustal layer occurring at a depth of 38 km and extending horizontally for more than 40 km as revealed by this MT study will be difficult to explain by sub-horizontal disposition along a thrust. Near subduction boundary the down going slab usually becomes steeper. Plume magmatism can potentially explain the horizontal disposition and layered pattern of the crustal structure of the region. Indeed Nd-isotope studies of the TTG-amphibolites of Older Metamorphic Group of rocks strongly suggest their derivation from a depleted plume source (Sharma et al., 1994). The obtained electrical properties beneath EIC for crust, upper mantle and the Moho are comparable to Slave Craton (~4.0 GYr) (Jones and Ferguson, 2001).

4. Results and discussion

Two prominent phase-sensitive strike directions (Fig. 3) for higher and lower frequencies indicate that the direction of the conductivity structure in the crust does not coincide with the mantle structure.