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Preserved and modified mid-Archean crustal blocks in Dharwar craton: Seismological evidence

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ABSTRACT

We report significant lateral variability in shear wave velocity and Moho depth in the Archean crust, beneath the Dharwar craton, using earthquake waveform data recorded over 50 broadband seismographs. The craton is a continuously exposed Archean continental fragment divided into the west Dharwar craton (WDC) of age 2.7–3.36 Ga, and the east Dharwar craton (EDC) of age, dominantly, 2.5 Ga. The craton progressively transitions into the Southern Granulite Terrain (SGT) with age of metamorphism around 2.6 Ga.

The inversion and modeling of receiver function data reveal significant variation of Moho depth, viz., 38–54 km in the WDC, and 40–46 km in the SGT and 32–38 km in the EDC. The average shear wave velocity (Vs) of crust beneath the WDC is ∼3.85 km/s as compared to ∼3.6 km/s in the EDC. We infer highly variable thickness (16–30 km) of mafic cumulate (Vs ≥ 4.0 km/s and Vp ≥ 7.0 km/s) beneath the WDC, in contrast with a thin one (<5 km) beneath the late Archean EDC. The 3.36 Ga greenstone belt in the WDC has maximum basal layer thickness of ∼30 km. These results suggest the intermediate-mafic composition and exceptional thickness of crust beneath the WDC (>50 km) as compared to felsic to intermediate composition for the EDC crust with almost flat Moho (down to ∼38 km). These results suggest preserved mafic crustal root beneath the middle Archean terrain in the WDC that has remained inert since then. On the other hand, felsic to intermediate composition of crust with a nearly flat Moho beneath the late Archean EDC could be a consequence of regional delamination of lower crust. The preserved distinct Moho topography across the Archean terrains suggests it as compositional boundary. Considering the surface exposure of 15–20 km crust, based on P–T condition, in the granulite segment of the WDC, we speculate a Himalaya-like crustal thickness (50–70 km) beneath the middle Archean crust pointing toward a plate tectonic-like scenario at ∼3.0 Ga.

1. Introduction

Zircon chronology on minerals suggests existence of continental crust as far back as 4.2 Ga (Compston and Pidgeon, 1986; Bowring et al., 1989). However, most of our knowledge of the crustal characteristics and its evolution mechanism is restricted to continental crust younger than ∼3.3 Ga, due to large-scale thermal modifications prior to this age. Two prominent continental crust forming events, at ∼3.3 Ga and 2.7 Ga, have been reported during the Archean (De Wit et al., 1992; Rudnick, 1995; Condie, 2005; Hawkesworth and Kemp, 2006; Van Kranendonk, 2011; Dhuime et al., 2012). Based on geochemical analysis of rocks and minerals, and supported by geophysical signatures, various geodynamic models have been proposed for the evolution of the Archean continental crust. These include the formation of crust in the late Archean (3.0–2.5 Ga) through accretion of volcanic arc (Lowe, 1994; Kusky and Polet, 1999), and interaction of mantle plume with the arcs (Choukroune et al., 1997). Estimates of the beginning of plate tectonics vary from about 800 Ma to close to 4.2 Ga (Stern, 2005; Hopkins et al., 2008), with a clear preference for the end of the Archean (Calvert et al., 1995; White et al., 2003; Arndt, 2013). More recent papers place the start even earlier, around or before 3.0 Ga (Bastow et al., 2011; Arndt, 2013). Middle Archean terrains (3.6–3.0 Ga), however, lack most of the features associated with convergent plate boundaries and could possibly have evolved through melting of thick mafic crust (De Wit, 1998; Zegers and van Keken, 2001; Nagel et al., 2012). Scientific opinion, however, remains divided on the processes responsible for the formation and evolution of the early and middle Archean continental crust. For better identification of the crust evolution process during Archean,

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there is need for further constraining the composition of the crust and nature of the crust–mantle interaction in geological blocks with diverse ages.

Most of the existing information on the nature of the Precambrian continental crust is directed to understand the distinction between Archean and Proterozoic crustal domains, where thickness and composition (inferred from seismic wave velocities) are used as key parameters. Apart from individual velocity (Vp, Vs), the ratio of two velocities (Vp/Vs) or Poisson's ratio (σ) value is also used as diagnostic to understand the petrological nature of the Earth's crust. For the common igneous and metamorphic rocks, composition is controlled by the relative presence of quartz (Vp/Vs ~ 1.49) and plagioclase (Vp/Vs ~ 1.87). For example, granite rock has a characteristic Vp/Vs ratio of 1.71, while diorite ~1.78, and gabbro ~1.87. This has been used to characterize the average crust composition as felsic to intermediate (1.65 < Vp/Vs < 1.78), or mafic (Vp/Vs > 1.78).

One of the models of crustal evolution based on global compilation of seismological measurements suggests that the mean velocity and crustal thickness (or Moho depth), except for young orogens, are proportional to its age, with ancient crust being the thickest (Smithson et al., 1981; Meissner, 1986; Jarchow and Thompson, 1989). A more recent global review of seismic structure, however, indicates that the Proterozoic crust has a thickness of 40–50 km and a substantial high velocity layer (also called basal layer, with Vp > 7.0 km/s) at its base, while Archean crust is only 27–40 km thick, and lacks the basal layer (Durrheim and Mooney, 1994; Abbott et al., 2013). Thickening of the crust is hypothesized by repeated episodes of basaltic underplating (Nelson, 1991). This view is not supported by Rudnick and Fountain (1995) and Tugume et al. (2012), who proposed that both Archean and Proterozoic crusts have similar crustal thickness (37–45 km). Chevrot and van der Hilst (2000), using broadband receiver function measurements from Australia, found no significant variation in Vp/Vs ratio between the Archean and Proterozoic crust. However, thickness of the crust shows remarkable variability from thinner Archean crust (~35 km) to a thicker Proterozoic crust (~45 km). Detailed analysis of observations from a South African seismic experiment (Nguuri et al., 2001; Nair et al., 2006) bring out some very interesting results: the undisturbed Archean terrains (Zimbabwe and Kaapvaal cratons) have thinner crust (38 km) with lower Vp/Vs ratio (1.73), compared to a thicker crust (~43 km) with higher Vp/Vs ratio (~1.78) for a disturbed Archean terrain (Bushveld mafic complex). The Limpopo belt formed because of collision at 2.7 Ga, has lower Vp/Vs ratio (1.73) in spite of increased crustal thickness. Seismological measurements from the Canadian shield (Thompson et al., 2010) suggest transparent and felsic (Vp/Vs ~ 1.73) crust with sharp Moho at 35–40 km depth beneath the middle (3.2–3.6 Ga) and late (2.5–2.8 Ga) Archean crustal domains.

Analysis of limited seismological observations (maximum 15 locations) from Precambrian terrain of South India (Kumar et al., 2001; Rai et al., 2003; Gupta et al., 2003a,b) using receiver function (RF) approach, suggest the average crustal Vp/Vs ratio varying in a narrow range of 1.70–1.75 for crustal domains from middle Archean to Proterozoic age. This characterizes average crust with felsic-intermediate composition. The late Archean and Proterozoic terrains are conspicuous with thinner crust (36–41 km), in contrast with a thicker middle Archean crust (48–54 km). Due to limited data availability, it remains speculative whether both the late- and middle-Archean crusts have similar crustal structure considering that the crustal evolution process were different because of the distinct thermal regime (Foley et al., 2003).

The other important constraint, crucial to understand the formation and evolution of lithosphere is the knowledge of structure and physical property of the crust–mantle transition. Though the crust–mantle transition and the Moho have been used interchangeably, more recent geological and geophysical data sets suggest that they may not be the same (Eaton, 2006; Cook et al., 2010; Artemieva and Meissner, 2012). Petrological model for Moho suggests it as: (1) compositional change from mafic (mafic granulite and gabbro) to peridotitic rocks, (2) a phase transition from mafic granulite to eclogitic rocks. These two categories would correspond to a sharp and transitional Moho, respectively. Geophysically, transition is primarily delineated using seismic P- and S-wave velocities, Vp/Vs and associated density increase that is a measure of a rapid change in bulk composition. In a recent global review of the Archean crusts, Abbott et al. (2013) suggest that virtually all (>99%) of the Archean terrains that stabilized prior to 2.9 Ga and 67–74% of the Archean terrains that stabilized from 2.8 to 2.5 Ga have a sharp Moho. This, however, requires more critical evaluation with larger data sample from diverse geological terrains across the globe.

We report here significant difference in the Moho depth and the shear wave velocity (Vs), and the nature of crust–mantle transition between the late Archean and the contiguous middle Archean terrains of the Dharwar craton using the receiver function approach. Data includes teleseismic waveforms recorded on fifty broadband seismographs mostly operated for a period of 12–24 months. These variations are found to have close linkage with the surface geology and the age of the crust formation.

2. Geological framework of Dharwar craton

The Dharwar craton (Fig. 1), in southern India, is an amalgamation of a series of terrains evolved from mantle over the period >3.4 to ~2.5 Ga and could be considered as a natural laboratory to investigate the nature of Archean crust (Naqvi and Rogers, 1987; Naqvi, 2008). With an average elevation of 500–800 m, the craton comprises of three distinct lithological units: peninsular gneisses of tonalite–trondhjemite–granodiorite composition (TTG) dated between 3.36 and 2.7 Ga, volcano-sedimentary greenstone belt of two distinct ages 3.3–3.1 Ga and 3.0–2.7 Ga. Based on the ages and lithologies, the craton is divided into the west Dharwar craton (WDC) and the east Dharwar craton (EDC). The boundary between these two is a narrow north–south shear zone referred to as Chitradurga schist belt (CSB) (Drury et al., 1984). The WDC crust with two distinct ages: 2.7–3.0 Ga in the north, and 3.0–3.4 Ga in the south, is an Archean continental fragment with a continuously – exposed crustal section from low-grade gneisses and greenstone basins in north, to granulites in the south. The average P/T condition suggests 2.6–3.8 Kbar/520–620 °C in the north and 4.5–5.0 Kbar/690–700 °C in the south. This corresponds to surface exposure of rocks of 7 km and ~15–20 km, respectively (Drury et al., 1984). Southern part of the WDC consists of one of the oldest (3.36 Ga) crustal nuclei in form of the greenstone belt (Taylor et al., 1984; Peucat et al., 1995). Several other minor occurrences of greenstone belts have been reported in the WDC and the EDC, apart from those discussed above (Jayananda et al., 2013 and Fig. 2). The WDC in the north is covered by Proterozoic Kaladgi basin (KB), Bhima basin (BB), and Deccan volcanics (DVP). The western part of the WDC is bounded by the western Ghat – an escarpment formed during separation of India from Madagascar at ~90 Ma. The EDC crust with largely granodioritic composition evolved around 2.5 Ga, is argued as an Archean batholith (Chadwick et al., 1997). The major tectonic feature of the EDC is a north–south trending horst of K-rich granitoid plutons and migmatite (Closepet granite, CG). The EDC is in thrusted contact with the Proterozoic (1.8–0.7 Ga) Cuddapah basin (CB) and the eastern Ghat granulite terrain (Eastern Ghat) (2.5–1.1 Ga). Several diamond and non-diamond bearing kimberlites, and lamproites of Proterozoic age (~1100 Ma) have been discovered in the EDC and CB (Chalapathi Rao, 2008; Griffin et al., 2009; Smith et al., 2013). Also, the region of the EDC and CB has