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A Review of Paleo- to Neoproterozoic crustal evolution in the Dharwar craton, Southern India and the transition towards a Plate Tectonic regime

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An emerging view is that Earth's geodynamic regime witnessed a fundamental transition towards plate tectonics around 3.0 Ga (billion years). However, the manifestations of this change may have been diachronous and craton-specific. Here, we review geological, geophysical and geochronological data (mainly zircon U-Pb age-Hf isotope compositions) from the Dharwar craton representing over a billion year-long geologic history between ~3.5 and 2.5 Ga. The Archean crust comprises an oblique section of ~12 km from middle to deep crust across low- to medium-grade granite-greenstone terranes, the Western and Eastern Dharwar Cratons (WDC and EDC), and the highgrade Southern Granulite Terrain (SGT). A segment of the WDC preserving Paleo- to Mesoproterozoic gneisses and greenstones is characterised by 'dome and keel' structural pattern related to vertical (sagduction) tectonics. The geology of the regions with dominantly Neoproterozoic ages bears evidence for convergent (plate) tectonics. The zircon U-Pb age-Hf isotope data constrain two major episodes of juvenile crust accretion involving depleted mantle sources at 3.45 to 3.17 Ga and 2.7 to 2.5 Ga with crustal recycling dominating the intervening period. The Dharwar craton records clear evidence for the operation of modern style plate tectonics since ~2.7 Ga.

Introduction

The formation of Earth's continental crust, its growth history and changes in the geodynamic regime with time, especially during the Hadean (4.56 to 4.0 Ga) and Archean (4.0 to 2.5 Ga) Eons remain

equivocal and the subject of an active debate (Harrison et al., 2008, 2017; Kemp et al., 2010, 2015; Cawood et al., 2013; Bédard, 2013; 2018; O'Neill and Debaille 2014; Robert and Spencer 2016; Mueller and Nutman, 2017; Hawkesworth et al., 2017). Granite-greenstone and granulite gneiss terrains within Archean cratons of Precambrian shields archive the geologic record of the early crust (de Wit and Ashwal, 1997; Bleeker, 2003). The specific question; when did plate tectonics begin on Earth? remains unresolved with suggestions ranging from Hadean (e.g., Harrison et al., 2005) to as late as the Neoproterozoic (Stern, 2008; Brown, 2008). Prompted by the observation that the average bulk composition of the continental crust is andesitic, many authors suggest that the continents grew by assembly of subduction generated oceanic arc terranes or maturation of subduction zones into continental arcs (Shirey et al., 2008; Polat, 2012; Arndt, 2013). Subduction-driven accretion of plume-generated oceanic plateaux and subsequent reworking was also proposed for the development of the Archean crust (Benn and Kamber, 2009). Also non-plate tectonic scenarios such as melting at the base of thickened mafic crust and delamination of lower crust were proposed (Smithies et al., 2005; Bédard, 2006). It is widely recognised that the large-scale granite-greenstone structures in the Archean cratons comprise two broad types: the orogenic linear belt type and the dome and keel type. In the former, field structural criteria such as presence of regional scale thrusts, nappes, asymmetric fold forms and shears (allochthonous tectonics) signify operation of convergent-style (horizontal) tectonics - plate tectonics (Percival et al., 2004; Windley and Garde, 2009; Polat et al., 2009). Further evidence comprised: (1) geochemical signatures of calc-alkaline affinities for the magmatic complexes including rare documentation of boninitic and adakitic compositions (e.g., Polat et al., 2009) and (2) seismic evidence of fossil sutures between terranes (Calvert, 1995; Van der Velden and Cook, 2005). On the other hand, the role of vertical (autochthonous) tectonics in granite-greenstone terranes, driven by processes such as sagduction or partial convective overturn have been advocated from several locations based on structural fabrics and shear sense indicators. These dome and keel structures relate to ascent of granitoid domes and coeval development of supracrustal synclines, due to gravity driven Rayleigh-Taylor type instabilities (RTI) (Mareschal and West, 1980; Hickman, 1984; Bouhallier et al., 1993, 1995; Choukroune et al., 1995; Chardon

et al., 1996, 1998; Collins et al., 1998; Thebaud and Rey, 2013; Van Kranendonk et al., 2007, 2015; Wiemer et al., 2018).

It is now widely appreciated that as much as 70% of the present volume of Earth's continental crust may have been extracted from the mantle by the end of the Archean (Belousova et al., 2010; Dhuime et al., 2012; Cawood et al., 2013) and major peaks in the accretion of Archean juvenile crust centred around 3.0 and 2.7 Ga (Condie et al., 2000; Voice et al., 2011). In general, cyclic or episodic geodynamics are suggested by the Archean rock and zircon record, although potential issues concerning a preservational bias exist (Cawood et al., 2013). Several authors (e.g., O'Neil et al., 2007, 2015; Griffin et al., 2014) emphasize a cyclic behaviour during Earth's early history where a stagnant lid regime may be interspersed with major crustal overturn events, thus brief plate tectonic intervals are not precluded during the Hadean-Eoarchean Eras. Nevertheless, subduction and Wilson-cycle type terrane accretion processes dominated since the Archean-Proterozoic transition, 2.5 Ga ago (Taylor, 1987; Cawood et al., 2013; Hawkesworth et al., 2017), but truly modern-style subduction plate tectonics began only since about 0.75 Ga (Brown, 2008 and Stern, 2008). A quasi consensus is that some form of plate tectonics operated at least since ~3.0 Ga (Hawkesworth et al., 2017). Also, around this time, several lines of evidence including field geological observations, paleomagnetic, geochemical, ore deposit studies and global-scale zircon U-Pb age-Hf±O datasets (Cawood et al., 2013; Dhuime et al., 2012; Tang et al., 2016; Hawkesworth et al., 2017 and references therein) support a transition towards plate tectonics around ~3.0 Ga. The transition implies a distinct change in the thermal structure, composition, thickness and growth rate of the continental lithosphere and crust around 3.0 Ga ago. However, such a transition may have been diachronous calling for detailed studies of different cratons.

We present here an overview of recent research on the Dharwar craton, southern India. The region comprises an extensive (~0.4 x 106 km²) tract of Archean granite-greenstone and granulite gneiss terranes (Swami Nath et al., 1976; Swami Nath and Ramakrishnan, 1981; Radhakrishna and Naqvi, 1986; Naqvi and Rogers, 1987; Ramakrishnan, 2003; Ramakrishnan and Vaidyanadhan, 2008; Naqvi, 2005; Chadwick et al., 2007; Jayananda et al., 2018 and references therein). Building upon the long legacy of nearly 150 years of geological mapping and mineral investigations in the craton (e.g., Bruce Foote, 1888-89, Geological map of Mysore 1² = 8 miles scale after Sampat Iyenger and Smeeth, 1915 and Rama Rao, 1940), multidisciplinary research over last 40 years provides enormous new information bearing upon the crustal and lithospheric properties, structure, radiometric ages constraining events of magmatism, metamorphism and orogeny over a nearly billion year geologic history of the craton. Focusing primarily on change in the tectonic style from Paleo- to Neoproterozoic time, we integrate here geological, geophysical and geochronological data on the craton and discuss its tectonic evolution bearing upon, development of the Paleo-Mesoarchean crust and Neoproterozoic orogeny involving terrane accretion leading to crustal growth in the Dharwar craton.

Regional geological framework of Dharwar craton

The Dharwar craton (Fig.1) represents a large part of the collage of Archean and Proterozoic terranes of peninsular India. The geology

of the craton has been summarised by many authors, e.g., Swami Nath and Ramakrishnan, (1981); Naqvi and Rogers, (1987); Drury et al. (1984); Radhakrishna and Naqvi, (1986); Chadwick et al. (2000, 2007); Naqvi, (2005); Ramakrishnan and Vaidyanadhan, (2008); Bhaskar Rao et al. (2008); Chardon, et al. (2011); Jayananda et al. (2013, 2018); Dey et al. (2018). Regions to the east and south of the craton comprise Proterozoic high-grade metamorphic terranes (the Eastern Ghats Granulite Terrane- EGGT and the Madurai and Trivandrum blocks of the Southern Granulite Terrane-SGT) separated by ductile shear/ suture zones such as the Ediacaran-Cambrian aged Palghat Cauvery Suture Zone (PCSZ, Chetty, 2017). The northern margin of the craton is concealed by Proterozoic and Phanerozoic sedimentary cover and the Cretaceous Deccan lavas. A large part in the east is covered by Paleo- to Neoproterozoic Cuddapah sedimentary basin. A Paleoproterozoic accretionary orogen, the Krishna Orogen (Chatterjee et al., 2016) is located further along the southeastern margin of the EDC. The craton is divisible into a dominantly Paleo-Mesoarchean Western Dharwar Craton (WDC) and a largely Neoproterozoic Eastern Dharwar Craton (EDC) based on age and metamorphic criteria (Rollinson et al., 1981; Swami Nath and Ramakrishnan, 1981). The WDC and EDC are separated by a prominent shear zone along the eastern margin of the Chitradurga greenstone belt, the Chitradurga Eastern Boundary Shear Zone – CEBSZ (Fig. 1, Chadwick et al., 2000, 2007; Ramakrishnan and Vaidyanadhan, 2008; Chardon et al., 2011). In recent years, some authors favoured a further sub-division of the EDC into a Central Dharwar Craton-CDC and Eastern Dharwar Craton-EDC and suggested that the WDC, CDC and EDC represent terranes with distinct thermal records and accretionary histories (Peucat et al., 2013; Jayananda et al., 2014, 2018). For the present purpose however, we adopt here the earlier two-fold subdivision of the craton. The present exposure constitutes an oblique section of middle to lower crust (~15-35 km paleodepth) ascribed to an ~2° northward tilt and differential erosion of southern India during the Phanerozoic (Pichamuthu, 1962; Janardhan et al., 1982; Raith et al., 1982; Raase et al., 1986; Stahle et al., 1987; Newton, 1992). From north to south, the estimated paleo-pressures in gneissic and mafic lithologies increase from ~3 kbar to 8-9 kbar. An unbroken, prograde metamorphic transition zone (TZ, Fig. 1) from amphibolite to granulite grade along the southern part of the craton was established during an end-Archean (~2.5 Ga) craton-wide thermo-metamorphic event(s) (Janardhan et al., 1982; Condie and Allen, 1983; Newton and Hansen, 1986; Friend and Nutman, 1991). The TZ is known for the development of incipient charnockites (orthopyroxene bearing granitoids) in felsic gneisses through dehydration processes, possibly involving CO₂ influx from lower-crustal or mantle sources (Janardhan et al., 1982; Newton, 1992; Friend and Nutman, 1991).

Flanking the WDC and EDC to the south and west of the TZ are high metamorphic grade terranes, constituting the highland charnockite massifs of Coorg, Biligiri Rangan, Malai Mahadeva-Sheveroy, Madras, Nilgiri and Kollimalai hill masses and the interlying low lands occupied by a variety of lithologies; supracrustal rocks, migmatitic quartzofeldspathic gneisses, charnockite-enderbite gneisses and intrusive granitoids (Fig. 1). The geology and age relationships of the high-grade terranes has been summarised by many authors (e.g., Drury et al., 1984; Bhaskar Rao et al., 1996, 2003; Ghosh et al., 2004; Chetty and Bhaskar Rao, 2006; Santosh et al., 2009a; Brandt et al., 2011; Tomson et al., 2006, 2013; Collins et al., 2014; Plavsa et al., 2012, 2015; Amaldev et al., 2016; Vijaya Kumar

Figure 1: A simplified geological map of Dharwar craton, southern India showing major Archean tectonic blocks; WDC, EDC and northern part of the SGT. The EDC and WDC separated by Chitradurga Eastern Boundary Shear Zone (CEBSZ). The Paleo- Mesoarchean crustal domain surrounding the Holenarsipur Supracrustal Belt (HSB) is demarcated by an ovoid bold dash-line. Important greenstone belts in the WDC; Bababudan (Ba), Shimoga (Sh), and Chitradurga (Ch). Closepet Granite (CG). Major charnockite massifs in the Archean granulite gneiss crust include Coorg (Co), BilirigiRangan (BR), MalaiMahadeva – Shevaroy (SH), Nilgiri (NG) and Madras (MD). The dextral Palghat-Cauvery shear system (PCSS) and Palghat-Cauvery suture zone (PCSZ). Insert A is a reconstruction of the crustal blocks across shear systems in the northern part of the PCSS after correction for a 120 km dextral E-W shift and a 9° anticlockwise rotation of the southern block (after Chardon et al., 2008). See text for details.

et al., 2017). An anastomosing network of ductile shear zones, which comprise the crustal-scale Palghat Cauvery shear system-PCSS (referred to as the Cauvery Shear Zone system-CSZ in the earlier literature) constitute a prominent tectonic feature along the southern margin of the craton. The dominant structural trends in the WDC and EDC are related to the end-Archean (2.56 - 2.50 Ga) tectono-metamorphic events associated with the development of regional transcurrent shear zones and high-T low-P metamorphism. The consequent N-S trending structural fabrics preserved in the northern part of the craton are reoriented during the Neoproterozoic into E-W mylonitic fabrics along the dominantly dextral PCSS with an overall

displacement of ~120 km (Drury et al., 1984; Chardon et al., 2008, also see inset Fig.1).

In recent literature, the shear zone system along the southern part of the PCSS has been identified as a relict suture zone between the Dharwar Craton and other Precambrian terranes that were amalgamated to the craton during the Ediacaran-Cambrian collisional orogeny. In this model, the PCSZ forms a part of the East African Orogen (EAO, Fig. 2) (Collins and Pisarevsky, 2005; Santosh et al., 2009; Fritz et al., 2013; Collins et al., 2014; Plavsa et al., 2015; Vijaya Kumar et al., 2017).

A narrow, but extensive tract of Neoproterozoic crust (~2.7-2.5 Ga)

Figure 2: A schematic of correlation of SGT and EGGT with Grenvillian age and Pan-African mobile belts in E. Gondwana (modified after Collins and Windley, 2002). AKSZ-Achankovil Shear Zone, CSZ-Cauvery Shear Zone (described in the text as PCSS), DML-Dronning Maud Land, EGGT-Eastern Ghats Granulite Terrain, LG-Lambert Graben, LVC-Lutzu-Holm Complex, MG-Mahanadi Graben, NC-Napier Complex, RC-Rayner Complex, SGT-Southern Granulite Terrain, RSZ-Ranotsara Shear Zone, LVB-Lurio-Vijayan Block.

with a high temperature low pressure granulite facies metamorphism around 2.5 Ga is located along the northeastern margin of the EDC, the Karimnagar granulite terrane (KGT, Rajesham et al., 1993; Divya Prakash et al., 2017). The lithological association resembles that of the EDC.

Lithology and major orogenic (tectono-metamorphic) events

The lithological associations of the Archaean basement of the WDC and EDC include polyphase and multiple deformed TTG gneisses, tracts and xenolithic screens of volcano-sedimentary successions ('greenstone' or 'supracrustal' or 'schist belts') and dominantly calc-alkaline high-K granitoid plutons (Fig. 1). Geological and geochronological data on the WDC support involvement of at least two prominent orogenic cycles grouped here as the pre-3.0 Ga and post-3.0 Ga (3.0 to 2.5 Ga) events (Fig. 2). The oldest dated rocks in the craton (Paleo-Mesoarchean ages) are from an extensive area encompassing the medium-grade granite-greenstone terrane around the Holenarsipur, Nuggihalli, Krishnarajpet and Sargur greenstone belts and the high-grade terrane in the adjacent parts of the Coorg

and Biligiri Rangan massifs (the HSB domain, Fig. 1). The geology of the HSB domain has been summarised by many authors (Ramakrishnan et al., 1976; Hussain and Naqvi, 1983; Bhaskar Rao et al., 1983; Naqvi et al., 1983; Monrad et al., 1983; Strogh et al., 1983; Drury et al., 1984; Bouhallier et al., 1993). The lithology is dominated by a trimodal association of; (1) ultramafic-mafic schists, (2) quartzite, Alrich metapelite, carbonates and BIFs and (3) quartzofeldspathic gneisses and schists. These rocks occur as macro-layered structurally concordant units intruded by trondhjemite and granite plutons. In general, the geological maps grossly understate the volumetric proportion of maficultramafic rocks, the predominance of which (upto ~ 45 volume %) on a regional scale is evident from observations along the extensive network of irrigation canals (Bhaskar Rao et al., 1983, 1986; Naqvi et al., 1983). U-Pb zircon and Sm-Nd isochron ages record atleast two phases of crustal growth; around 3410-3280 Ma and 3230-3200 Ma (Bhaskar Rao et al., 2000, 2008b; Jayananda et al., 2015; Guitreau et al., 2017). The emplacement of syn-kinematic diapiric trondhjemite and granite plutons (e.g., such as Halekote trondhjemite and Chickmagalur granite) represents the culmination of the pre-3.0 (D_1M_1) orogenic events. This event of magmatism is constrained between 3230 and 3106 Ma based on zircon U-Pb dating (Jayananda et al., 2015; Guitreau et al., 2017), which refines the chronological scheme based on Rb-Sr and Pb-Pb isochron ages (Beckinsale et al., 1982; Strogh et al., 1983; Taylor et al., 1984; Rogers and Callahan, 1989; Meen et al., 1992; Peucat et al., 1993). This stage is associated with medium grade metamorphism, wide spread metasomatism and resetting of Rb-Sr and Pb-Pb isotopic systems in rocks (Bhaskar Rao et al., 1983; Rogers and Callahan, 1989) and succeed by brief stage of cratonization.

The post-3.0 Ga geologic history of the WDC is marked by the deposition of the 'Dharwar Supergroup' (DS) greenstone successions (2.9-2.6 Ga). The Dharwar Supergroup is divisible into the lower Bababudan and upper Chitradurga Groups. U-Pb zircon ages of felsic volcanics and syn- to late kinematic high-K granite plutons bracket the deposition of DS between 2.75-2.60 Ga (Trendall et al., 2007a, b; Dey et al., 2018; Jayananda et al., 2018 and references there in), which was likely followed by a second stage of cratonization in the WDC (Swami Nath et al., 1981; Taylor et al., 1984; Bhaskar Rao et al., 1992; Anil Kumar et al., 1996; Chadwick et al., 2000; Jayananda et al., 2013b; Hokada et al., 2012; Mohan et al., 2014; Maibam et al., 2016). By contrast, in the EDC, the ca. 3.38-3.0 Ga ages are limited to gneissic and supracrustal inclusions within essentially ca. 2.90-2.56 Ga granitoid basement along the western part of the EDC as well as inherited cores of zircon in these granitoids (Chardon et al., 2011; Jayananda et al., 2013a; Maibam et al., 2016; Shan-Shan Li et al., 2017). Barring these, there is evidence for a diachronous development of greenstone successions and nearly coeval granite plutonism (juvenile and anatectic TTG and high-K granitoids including sanukitoids) in the EDC around 2.72-2.67 Ga and 2.58-2.54 Ga (Balakrishnan et al., 1990, 1999; Manikyamba and Kerrich, 2012; Jayananda et al., 2013a, 2018; Qiong-Yan Yang et al., 2015 and references therein). U-Pb zircon ages of granitoids underlying ~ 1000 m thick stack of Deccan lavas around Koyna, that is about 300 km northwest of the exposed basement, also yield ages between 2.7 and 2.5 Ga (Bhaskar Rao et al., 2017). Similar ages have been recorded for charnockites in the KGT indicating the extant of Neoproterozoic crust of the EDC.

In the western part of the SGT, south of WDC, Paleo- to Neoproterozoic (3.55-2.6 Ga) high-grade supracrustals and felsic gneisses

have been described from the Coorg, BR Hills and the Wynad region within the PCSS. In the Coorg massif, U-Pb zircon age data for meta igneous rocks (granitoids, charnockites, diorites and metavolcanic rocks) define magmatic events at 3.5, 3.2, 2.7 and 2.5–2.4 Ga, while metasedimentary rocks (quartzite, ferruginous quartzite, banded iron formation and calcareous / pelitic schists) indicate discrete zircon age populations between 3.4 and 1.3 Ga (Santosh et al., 2014, 2015, 2016; Amaldev et al., 2016). In the Biligiri Rangan massif, TTG orthogneisses and charnockites reveal zircon U-Pb ages of ca. 3362–3315 Ma, 3207–3100 Ma and 2985–2972 Ma marking successive stages of accretion (Peucat et al., 2013; Ratheesh Kumar et al., 2016). Along the western flank of BR hills, Vijaya Kumar et al. (2013) obtained zircon U-Pb ages between 3391 and 3309 Ma, with $\epsilon\text{Hf}_{(t)}$ between +4.1 and -2.5 for tonalitic orthogneisses. In the Wynad region, Qiong-Yan Yang et al. (2016) reported meta ultramafic rocks that contain magmatic zircon grains with crystallization ages of 3.3–3.0 Ga and 2.5 Ga, the Mesoarchean ages being similar to those in the Coorg massif (Santosh et al., 2016). Elsewhere in the SGT, much of the crustal growth is ascribed to Neoarchean (ca. 2.70–2.50 Ga) accretionary processes, broadly contemporaneous with those in the WDC and EDC (Praveen Kumar et al., 2014; Ratheesh Kumar et al., 2016; Santosh et al., 2016; Shan-Shan Li et al., 2018). The entire Dharwar craton (WDC, EDC and the northern parts of the SGT) was finally shaped by the end Archean thermo-tectonic event(s) (D_2M_2) around ca. 2.56–2.50 Ga. The latter events that are associated with terrane accretion and collision, for instance, between WDC and EDC, include: 1) widespread partial melting of lower-middle crust, syn-kinematic juvenile granite magmatism, especially in the EDC and SGT; 2) the development of a craton-wide (and across the entire crustal column) homogenous strain pattern of arcuate transcurrent shear zones and 3) regional high temperature-low pressure (HT-LP) metamorphism, where the high-grade domains show prominent isobaric cooling P-Tt paths suggesting prolonged thermal buffering of the lower and middle crust (Chardon et al., 2011; Peucat et al., 2013; Jayananda et al., 2018).

Eoarchean zircon ages

From the Coorg block and the Mercara shear zone region, Santosh et al., (2016) reported Eoarchean Lu-Hf model ages between 3.8 and 3.5 Ga for magmatic and detrital zircons from Mesoarchean orthogneiss and metasediments. One detrital zircon grain from a ferruginous quartzite sample yielded Hf T_{DM}^C age of 4031 Ma, an indication of a late Hadean protolith in the provenance of the Coorg metasediments (Santosh et al., 2016). Paleo-Eoarchean context (3.64–3.52 Ga ages) is also reflected in the HSB region (as well as younger greenstone successions of the WDC) by a limited set of detrital (magmatic) zircon grains extracted from Sargur and Dharwar Supergroup metasediments deposited between ~3.3 and 2.7 Ga as well as modern river sand from around Holenarasipur (Nutman et al., 1992; Bhaskar Rao et al., 2008b; Hokada et al., 2013; Lancaster et al., 2014; Maibam et al., 2016; Guitreau et al., 2017). Detrital zircons from the quartz pebble conglomerate quartzite unit at the base of the Bababudan group, near Chikmagalur (unconformably overlying the greenstone gneiss basement around the HSB) yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages upto 3636 ± 7 Ma (1s) with $\epsilon\text{Hf}_{(t)} = +0.31$. Two other zircon grains with ages of 3632 and 3605 Ma have $\epsilon\text{Hf}_{(t)}$ of -1.08 and -1.34 (Bhaskar Rao et al. 2008b) suggesting older crust in their provenance. The interpretations are also consistent with wholerock Sm-Nd isotopic

systematics and model ages (Jayananda et al., 2015; Dey et al., 2015 for review) and whole rock Pb-Pb isotope systematics of the 3.33 Ga TTGs (Meen et al., 1992).

Zircon age-Hf isotope constraints on episodic crust accretion and reworking events

A plot of published zircon U-Pb ages (SIMS and LA-ICPMS methods) and Hf-isotopic compositions ($\epsilon\text{Hf}(t)$ using LA-MC-ICPMS) is shown in Fig. 3. The data from the low- to medium-grade terranes (WDC and EDC) and the high-grade (SGT) terranes are plotted separately (Figs. 3a and 3b respectively) and their data sources

Figure 3: A plot of zircon age vs. initial Hf isotopic compositions normalised to CHUR value and represented as $\epsilon\text{Hf}_{(t)}$, (3a) data from WDC and EDC, (3b) data from SGT. Data Sources: Mohan et al., 2014; Praveen Kumar et al., 2014; Yang and Santosh, 2015; Collins et al., 2015; Lancaster et al., 2015; Amaldev et al., 2016; Maibam et al., 2016, 2017; Ratheesh Kumar et al., 2016; Bhaskar Rao et al., 2017; Guitreau et al., 2017; Santosh et al., 2015b, 2016; Santosh and Shan-Shan Li, 2018; Shan-Shan Li et al., 2018. See text for details.

are in figure caption. Data on magmatic zircon grains separated directly from metaigneous rock samples and detrital zircon grains from metasedimentary rocks as well as from modern river sand samples are plotted here with reference to Chondritic Uniform Reservoir (CHUR), Depleted Mantle (DM) evolution curves and the evolutionary trends corresponding to TTG melts (DC 1–3) with $^{176}\text{Lu}/^{177}\text{Hf} = 0.008$. An important observation is that there is a clear similarity in the distribution of data from the low and high-grade

terrane. The Eoarchean (ages around 3600 Ma) zircon grains, restricted to the low- medium-grade terranes show chondritic Hf-isotopic compositions. These zircons together with a few grains of ages between ~3.5 and 3.17 Ga lie within the array, DC-1. The T_{DM} ages of these zircons correspond to melt extraction either from depleted mantle reservoir between 3.8 and 3.7 Ga or from CHUR like reservoir at 3.6 Ga. A shift in $\epsilon Hf_{(t)}$ values from chondritic to super-chondritic at ~3.5 Ga is apparent signifying the earliest unambiguous establishment of depleted mantle reservoir. In the low-medium and high grade regions alike, a large population of zircon grains with ages between ~3450 and 3170 Ma show dominantly radiogenic $\epsilon Hf_{(t)}$ values plotting close to the DM curve, implying continuous involvement of depleted mantle reservoir in generation of felsic magmas for nearly 300 million years. A small proportion of zircon grains within this time window (and extending up to ~2.7 Ga) show unradiogenic $\epsilon Hf_{(t)}$ values that define the array, DC-2. This array would correspond to recycling of older TTGs (~3.6-3.5 Ga). This 3.45 to 3.17 Ga phase of juvenile magmatism is succeeded by a protracted interval between ~3.1 and 2.8 Ga, where a majority of zircon grains have sub-chondritic $\epsilon Hf_{(t)}$ values and lie in the array, DC-3, that relate to the recycling of the older TTG crust that accreted during the prominent juvenile crust forming episode between 3.45 and 3.17 Ga. The zircon grains with ages of ~2.7 Ga and younger up to 2.48 Ga show large variations in their $\epsilon Hf_{(t)}$ values ranging between +11 and -14. Most of the zircon grains in this population are of the ages from 2.64 to 2.48 Ga. The unradiogenic $\epsilon Hf_{(t)}$ values in this zircon population plot along the DC-3 array suggesting recycling of 3.45 to 3.17 Ga TTGs. Some of the lower $\epsilon Hf_{(t)}$ values correspond to anatexic melting involving mixing with synchronous juvenile felsic magmas generated during this period.

Temporal and lateral variations in the properties of deep crust; constraints from geophysical data

The WDC, EDC and SGT have been studied by a large number of passive and active seismic experiments with interpretations combining potential field data (Kaila et al., 1979; Chowdhury and Hargraves, 1981; Kaila and Krishna, 1992; Saul et al., 2000; Reddy et al., 2003; Gupta et al., 2003; Sarkar et al., 2003; Rai et al., 2003; Borah et al., 2014; Vijaya Rao et al., 2015a, b; Mandal et al., 2018; Halder et al., 2018; Ravi Kumar et al., 2018). Using receiver function analysis of broadband seismic data, Borah et al. (2014) and Ravi Kumar et al. (2018) reported a wide lateral variation in P and S-wave velocities (V_p and V_s) and depth to Moho (crustal thickness) across the craton, viz., 38–54 km in the WDC, 32–38 km in the EDC and 40–46 km in the SGT. Significantly, the WDC is characterised by 16–30 km thick high velocity ($V_s \geq 4.0$ km/s and $V_p \geq 7.0$ km/s) mafic lower crustal layer, while the EDC shows a much thinner mafic layer (<5 km) at its lower crust. The thickest part of the crust with its thick lower crustal mafic layer is around the southwestern part of the HSB close to its margin with the Coorg and Wynad regions. A thick mafic lower crust in the WDC is quite unusual among Archean cratons (Abbott et al., 2013; Borah et al., 2014) and its tectonic significance is ambiguous; ascribed to underplating of mafic magmas during the Mesoarchean (Borah et al., 2014) or post-Neoproterozoic mafic underplating (Vijaya Rao et al., 2015a). Halder et al. (2018) observed a positive correlation between the age and nature of the Archean crust

in terms of both thickness and Poisson's ratio (V_p/V_s) – i.e., a thicker and older crust has higher V_p/V_s ratio. This implies that the crust changed from mafic to intermediate average composition with a decrease in crustal thickness through time accompanied by a partial loss of lower crust. Ravi Kumar et al. (2018) also inferred thick (>38 km) mafic crust (Poisson's ratio >0.25) beneath the SGT and suggested that the crustal thickening along the southern margin of the WDC may relate to subduction processes.

Contrasting structural styles

Paleo-Mesoarchean crust; the dome and keel structural pattern

Aerial photo interpretation by Bhaskar Rao et al. (1986) indicated that over an extensive region encompassing the HSB, variably migmatized greenstone successions define an anastomosing network enclosing oval/elongated domains comprising dominantly felsic gneisses that resemble gneissic domal structures. Further, a series of NNW-SSE or N-S sinistral transcurrent shear zones deform the latter structures resulting in variable elongation of the domal features (Fig. 4a). Several authors recorded evidence for superposed deformation commonly two-three phases of folding (Chadwick et al., 1978; Drury et al., 1984; Mukhopadhyay, 1986; Naha et al., 1990; Bouhallier et al., 1993; 1995). In general, superposition of the earlier foliation (S_1 , related to D_1M_1) by younger (S_2) planar fabrics related to D_2M_2 is common. The shear zones are loci of non-co-axial deformation and retrogression of mineral assemblages (e.g., along the eastern margin of the HSB and the western margin of Krishnarajpet belts). Wholerock and wholerock-garnet Sm-Nd isochron ages constrain the D_2M_2 event between 2530 and 2500 Ma (Drury et al., 1982; Bouhallier et al., 1995; Bhaskar Rao et al., 2000; Jayananda et al., 2013b). The oldest crustal components are best preserved in domains of low- D_2 strain, where low- and high-Al TTG gneisses and migmatites constitute the gneissic domes and ultramafic-mafic komatiites and tholeiites predominate the greenstone belts apart from pelitic, arenitic, carbonate and iron-rich sediments (BIF). Detailed structural mapping around HSB region by Bouhallier et al. (1993) demonstrated that the regional foliation trajectories outline elliptical domes of gneissic material, which are separated and surrounded by supracrustal rocks (Fig. 4b). The foliation trends also define triple junctions where linear vertical tectonites are observed, some of which are marked by superimposed structures such as folds with vertical axis. Stretching lineations are generally vertical except in narrow N-S shear zones, where foliations (S_2) are vertical and the lineations are horizontal. The regional structural pattern comprises evidence for dome and keel tectonics prior to 3.0 Ga (Bouhallier et al., 1993, 1995; Choukroune et al., 1997), also see discussion in Arndt et al. (2013). Similar structural pattern also characterizes the regions around Gundlupet, further south of the Holenaripur (Bouhallier et al., 1995; Choukroune et al., 1997) and JC Pura to its east (Chardon et al., 1996). The emplacement of the diapiric plutons between 3230–3150 Ma sets the younger age limit to the development of the regional dome and keel structures.

Post 3.0 Ga crust: the Neoproterozoic orogeny

In general, the WDC, EDC and SGT show a remarkable contemporaneity in the Neoproterozoic (post-3.0 Ga) crust formation and reworking events. In the EDC two episodes of magmatism are

Figure 4: An example of dome-keel structural pattern in the HSB domain (see Fig. 1). (a) Schematic from aerial photo interpretation of the region around Holenarsipur supracrustal belt showing dominantly gneissic domains and supracrustals (described in Bhaskar Rao et al., 1986); (b) A structural map around the Holenarsipur supracrustal belt (shaded area) showing foliation trajectories, the triangles represent tectonites with vertical lineation (Bouhallier et al., 1993); (c) shows a cross sectional schematic across the region, Fig. 3b (ibid).

represented by emplacement of TTG gneisses and K-rich granites during 2750-2600 Ma and 2560-2520 Ma, essentially coeval with calc-alkaline volcanism in the greenstone belts. In the WDC, Neoproterozoic felsic crust is represented by granitoids dated at ~3.0 Ga and 2.6 Ga (see data compilation by Jayananda et al., 2018; Dey et al., 2018). Also in the SGT, felsic orthogneisses (charnockite gneiss) from the Sheveroy or Salem block yield U-Pb zircon ages of ca. 2.76-2.53 Ga (Clark et al., 2009; Peucat et al., 2013; Glorie et al., 2014; Shan-Shan Li et al., 2018). Shan-Shan Li et al. (2018) summarised evidence for episodic juvenile crust formation between 3.3 and 2.7 Ga followed by crustal reworking and high-grade metamorphism in a continental arc around 2.5-2.46 Ga. In the SGT, many authors interpreted the shear zone systems as Neoproterozoic sutures marked by relict suprasubduction rock suites including mafic-ultramafic rocks and layered meta-anorthosite complexes as dismembered Paleoproterozoic ophiolite complexes (Yellappa et al., 2012; Santosh

et al., 2012, 2013b, 2016; Mohan et al., 2013b; Collins et al., 2014b; Praveen et al., 2014; Plavsa et al., 2015; Qiong-Yan Yang et al., 2016; Yano et al., 2016).

The tectonic interpretations of 2.75-2.5 Ga crust accretion and reworking episodes in the Dharwar craton have been controversial, best illustrated by the conflicting models proposed for the Neoproterozoic accretion of EDC and WDC (Chadwick et al., 2007; Chardon et al., 2011; Jayananda et al., 2013a). The structure of the CEBSZ, separating WDC and EDC, has been mapped as an ~400 km long east-dipping, crust-penetrating fault in the earlier geological and geophysical studies (Kaila et al., 1979; Chadwick et al., 2007; Chardon et al., 2011; Gokarn et al., 2004). This boundary shear zone has also been central to a recent experiment of deep-seismic wide-angle refraction and coincident reflection profile between Chickmagalur and Perur (Fig. 1, Vijaya Rao et al., 2015b; Mandal et al., 2018). This data offers a new insight into the assembly of EDC and WDC together with recent results from modelling of gravity, magnetic and magnetotellurics data along the profile (Kumar et al., 2013; Pratap et al., 2018).

Consistent with the regional deformation pattern, the diatexite gneisses and greenstone belts along the Chickmagalur-Perur seismic profile record two stages of deformation: 1) early shallowly east dipping foliations and synchronous granitic sills related to pure shear deformation and synchronous melting and 2) reworking along system of conjugate strike slip shears producing steep easterly dipping foliation and down-dip lineation (Figs. 1 and 5b). Geological descriptions of CEBSZ include; on an average ~0.5 km wide belt of mylonites within a much wider west-verging fold-thrust belt encompassing adjacent parts of the WDC and EDC (Chadwick et al., 2007) and a part of a regional zone of constrictional deformation and reworking of pre-2.56 Ga structures in the Chitradurga greenstone belt and the gneissic terrane to its east (Fig. 5a; Chardon et al., 2011). These studies emphasized NE-SW shortening across the craton during the Neoproterozoic. For instance, Chadwick et al. (2007) interpreted the structural pattern along a ~250 km section across the WDC-EDC join as a SW-verging imbricate fold-thrust zone developed during NE-SW oblique convergence related to far-field subduction that sustained for about 150 Ma (Fig. 5a). Both pre- and syn-tectonic granites were emplaced as steep orogen parallel NWSE sheets along listric faults that are believed to sole from a midcrustal detachment at ~18-23 km depth (Fig. 5a). On the other hand, Chardon et al., (2011) interpreted the Neoproterozoic accretionary orogen of the EDC as an ancient field example of a type Ultra-hot orogen that preserves the deformation fabrics and pluton emplacement features related to a 3-D syn-convergence (NE-SW) Lateral Constrictional Flow (LCF) mode with modern analogs in the Himalaya-Tibet wide hot orogen (Fig. 5c). The LCF combines orogen-normal shortening, orogen-parallel stretching and transtension (Fig. 5c).

The interpretation of time-migrated post-CRS (Common Reflection Surface) stack section of the 200 km long Chickmagalur-Perur deep-seismic reflection profile across the CEBSZ (Fig. 6a; Mandal et al., 2018), nearly orthogonal to the predominant (D2) structural grain offers some useful insights into the deep crustal structure of the craton across the WDC-EDC join. It is noted that, the middle and lower crust all along the profile is generally reflective, but the pattern of reflectors in the WDC and EDC is different. Mandal et al. (2018) argued that the reflectivity pattern across CEBSZ supports the model of plate convergence and collision during the Neoproterozoic. The accretion of EDC to the eastern margin of the WDC was interpreted in terms of two stages of westward subduction of successive

Figure 5: (a) The Neoarchean thrust tectonic model illustrated by the SW-NE structural cross section across the Chitradurga greenstone belt and the adjacent granitic regions (Chadwick *et al.*, 2007); (b) a schematic crustal cross section along WSW-ENE across WDC and EDC showing the architecture of transcurrent shear zones and trend of foliation (Jayananda *et al.*, 2006); (c) Schematic tectonic model for the Neoarchean (2.56 to 2.50 Ga) orogeny and collision of EDC against WDC related to a westward dipping subduction at the eastern margin of EDC. The figure shows development of a distributed shear systems, orogen parallel extension and the LCF mode of crustal flow (Chardon *et al.*, 2011).

oceanic arcs beneath the WDC at 2.7 and 2.5 Ga, much similar to the models proposed by Jayananda *et al.* (2013, 2018).

Discussion and Summary

This review of geological, geochronological and geophysical information on the Dharwar craton brings to fore the striking similarity in the chronology of major crust forming and reworking episodes recorded in the Archean low- to medium-grade granite-greenstone terranes of WDC and EDC and the flanking high-grade gneiss terranes

of the SGT. This inference is consistent with the time honoured observation of a late Neoarchean metamorphic gradation across the terranes. Thus, it is unlikely that the SGT consists of exotic Archean terranes accreted to the southern margin of WDC and EDC.

Evolution of the pre-3.0 Ga crust

The strongly positive $\epsilon\text{Hf}_{(t)}$ values since ~3.5 Ga evident in the age- Hf plot (Fig. 3) of zircons constrain the timing of establishment of depleted mantle reservoir in the Dharwar craton. This would require significant extraction of felsic magmas from CHUR-like mantle reservoir prior to 3.5 Ga, for which there is no direct crustal rock record in the craton. Nevertheless, the data suggest unambiguously that depleted mantle sources contributed to magma genesis in the Dharwar craton since about 3.5 Ga and in the subsequent nearly 300 million years (from ~3450 to 3150 Ma), the craton records a continuum of juvenile TTG magmatism and crustal growth. This may be related to either (a) subduction like processes associated with addition of voluminous juvenile crust and destruction of older crust (e.g., Næraa *et al.*, 2012; Nutman *et al.*, 2013; Bell *et al.*, 2014) or (b) a major episode of mantle overturn events leading to establishment of thick mafic plateau, which would source the TTG magmas (Griffin *et al.*, 2014). We speculate that the seismic evidence for an uncommonly thick (15-30 km) of a mafic lower crustal layer above the Moho in the oldest cratonic nucleus (the HSB domain) may be a relict ancient feature inherited from Paleo-Mesoarchean accretionary processes. We further speculate the relevance of processes such as mantle plumes in the initial accretion of a mafic-ultramafic crust (komatiitic) and its further processing in at least two short events of

melting. Indeed, the Paleo- Mesoarchean tectonics in the Dharwar craton was explained in terms of a plume-arc model involving accretion of a thick plume generated mafic plateau, formation of island arc and melting at different depths during subduction (Jayananda *et al.*, 2008; 2015; 2018). In this respect, the Dharwar craton is similar to few other cratons such as the Singhbhum and North China (Sreenivas *et al.*, 2019; Wu *et al.*, 2008; Wan *et al.*, 2015) cratons as well as the Barberton region (Zeh *et al.*, 2013). In contrast however, the 3.5 to 3.0 Ga crustal history of other ancient cratons such as the Limpopo belt (Zeh *et al.*, 2014), Minnesota River Valley gneisses (Satkoski *et al.*

Figure 6: Figure summarising the seismic reflection results along the Chikmagalur-Perur deep seismic reflection profile across the EDC and WDC: (a) interpretation of Mandal et al., 2017 and (b) a schematic based on a reinterpretation of the reflectivity pattern by the present authors; The limits for Bababudan, Kibbanahalli and Chitradurga greenstone belts (Ba, Ka, Ch), and Closepet granite (CG) are shown for reference. See text for details.

al., 2013) and Greenland (Næraa et al., 2012) is dominated by recycling of largely Eo- to Paleoproterozoic crustal components. On the other hand, the field evidence for dome and keel structures in the pre-3.0 Ga domains of the craton underpin the significance of vertical tectonics. The zircon age spectra suggesting two peaks of TTG formation 3450-3300 Ma and 3200-3150 Ma in the HSB region may relate to melting within the thick mafic plateau at different depths producing the compositional variability in the coeval TTG suites. Thus, intra crustal differentiation mainly through RTI and sagduction tectonics may account for the dome and keel structural pattern and a change in the bulk composition of the crust from mafic to intermediate.

Recent models on TTG genesis invoke melting of hydrated basalt at garnet-amphibolite, granulite or eclogite facies conditions in different tectonic scenarios. Plate tectonic models include (1) melting of subducted oceanic crust in a hotter mantle (e.g., Rapp et al., 1991; Martin, 1993) and (2) subduction driven accretion of plume-generated oceanic plateau crust followed by reworking and terrane collision (Hill et al., 1992; Abbott et al., 1997; Benn and Kamber, 2009), while 'no subduction' models involve melting of the base of magmatically or tectonically thickened basaltic crust or delaminated lower crust (Campbell and Hill, 1988; Van Thienen et al., 2004; Smithies et al., 2005; Bédard, 2006; Sizova et al., 2015). In the present case, the latter scenario may be relevant to the Dharwar craton considering the lack of field geological evidence for large scale thrust-nappe tectonics and preservation of dome and keel structural pattern in the WDC, especially during the 3.3 to 3.15 Ga time interval. Interestingly, manifestation of similar tectonic models has been favoured for the

Paleo- to Mesoproterozoic terrains such as the Singhbhum, Pilbara, Kaapvaal and Wyoming province (Sreenivas et al., 2019; Smithies et al., 2009; Johnson et al., 2017; Sandiford et al., 2004; Prabhakar and Bhattacharya, 2013; Dey et al., 2017). These terranes attest to the importance of vertical tectonics in accretion of large volumes of continental crust during the Paleoproterozoic to Mesoproterozoic time interval.

In the interval between 3.1 and 2.7 Ga, crust formation in the Dharwar craton predominantly involved recycling of older crust in the 3.45-3.15 Ga stage and to a limited extent older crust that formed between 3.6-3.5 Ga.

The post-3.0 Ga crust: Plate tectonics and terrane assembly

As stated earlier, several authors advocated plate tectonics and terrane assembly models (Drury et al., 1984; Chadwick et al., 2002, 2007; Reddy et al., 2003; Chardon et al., 2011; Jayananda et al., 2013a; Vijaya Rao et al., 2015a; Qiong-Yan Yang et al., 2015; Santosh et al., 2015; Mandal et al., 2018; Shan-Shan Li et al., 2018; Jayananda et al., 2018 among others). Some authors suggested mixed mode (plume and plate) tectonic mechanisms for the Neoproterozoic crustal evolution of the craton (Chardon et al., 1998; Harish Kumar et al., 2003; Jayananda et al., 2000; Manikyamba and Kerrich, 2012). There is no consensus on the subduction polarity. The wide range of $\epsilon\text{Hf}_{\text{t}}$ values (11 to -14, Fig. 3) characterizing the Neoproterozoic (2.7-2.5 Ga) episode is consistent with the geological, petrological and geochemical data on granitoids from the craton. Interestingly however, major

Neoproterozoic accretionary processes in the craton span a narrow time window between 2.6 and 2.5 Ga during which there is evidence for voluminous granitoid magmatism including juvenile K-rich granites and sanukitoids as well as nearly synchronous anatectic granites formed by recycling of older crust, the 2.7 Ga juvenile crust. Involvement of even older (3.45–3.1 Ga) crust is significant in the WDC and along the western margin of the EDC. Apparently, the record of 2.7 Ga crust in the Dharwar craton is quite muted and less prominent compared to many other cratons and the well-established global peak of juvenile crust accretion (e.g., Condie and Aster, 2010; Voice et al., 2011; Cawood et al., 2013).

In the context of the suggestion that the EDC represents a 'widehot' orogen involving a Lateral Constrictional Flow (LCF) mode of EDC, while the WDC acted as an indenter (Chardon et al., 2011), our interpretation of the Chikmagalur – Perur deep seismic profile (Fig. 6b) offers the following observations. The seismic profile shows that the middle and lower crust of the WDC and the lower crust in the EDC are not only reworked but clearly decoupled from the upper mantle (Fig. 6b). In analogy to a few ancient and younger terranes (Van der Velden and Cook, 2005; Eaton, 2006), the features such as nearly uniform crustal thickness, flat Moho and its decoupling from the mantle may be ascribed to a range of mechanical and thermal scenarios such as (1) shearing and extensional deformation, where the lower crust behaves like a decollement, (2) lithospheric delamination and (3) a rheologically weak lithosphere leading to crustal channel flow (Van der Velden and Cook, 2005; Eaton, 2006). The common planar penetrative fabrics of the granulites (Chardon and Jayananda, 2008; Chardon et al., 2011) and sub-horizontal reflectivity pattern of the lower crust of the Dharwar craton is similar to the lower crustal reflectivity characterizing many accretionary and collisional orogens of all ages including the Himalaya, Pyrenees, the Trans-Hudson and collisional orogens in many Archean cratons (Beaumont et al., 2011; Chardon et al., 2011; Hajnal et al., 2005; Ross et al., 2004; Meissner et al., 2006; Cook et al., 2010; Chardon and Jayananda, 2008; Royden et al., 2008; Dumond et al., 2010). The characteristic deformation feature of the latter; large areas of monotonous strain patterns, HT-LP granulites showing isobaric P-T-t paths and extensive magmatism contributing to crustal growth are consistent with the hypothesis that these orogens formed above a relatively hotter mantle than that in the modern orogens and remained hot and mechanically weak during deformation over extended periods of time (Cagnard et al., 2006; Chardon et al., 2011; Eaton, 2006; Chardon and Jayananda, 2008; Dumond et al., 2010). Thermo-mechanical and numerical experiments (Chardon et al., 2011; Sizova et al., 2014; Chardon and Jayananda, 2008), indicate that convergence related deformation of hot and buoyant lithosphere produces distributed patterns of strain, lower topographic relief and high- and/or ultrahigh temperature granulites (Cagnard et al., 2006; Eaton, 2006; Harris et al., 2012; Sizova et al., 2014). Our preferred tectonic model for the Neoproterozoic Dharwar craton envisages the combined role of continental and oceanic arcs generating both juvenile and recycled crustal material between ~2.75 and 2.55 Ga. The prolonged NE-SW convergence culminated in the collision of EDC and WDC accompanied by some process of lithospheric erosion that triggered significant advection of heat from the asthenosphere into the lower crust. The seismic reflection results summarized in Fig. 6b corroborate the first order field geological relationships and the LCF model for the ultra-hot orogen of EDC (Chardon and Jayananda, 2008; Chardon et al., 2011). Further, the results suggest that not only the allochthonous

hanging wall of the EDC, but also the foot wall substrate of WDC shows high-temperature viscous flow implying that at least during the advanced stage of collision, the middle and lower crust of WDC ceased to be an indenter. We believe that the geological and seismic data for the Dharwar craton offer a rare perspective to the global Neoproterozoic orogeny, especially in the case of orogens where the lower crust may have surpassed a certain temperature threshold (>750°C), involved in syn-orogenic ductile flow and substantial 3-D re-homogenization of the middle-lower crust.

Conclusions

- Recent data on the geology, age relationships (mainly zircon U-Pb ages and Hf-isotopic compositions) and geophysics (active and passive seismic experiments) indicate that the Archean crust in the Dharwar craton exposed along a 12–15 km oblique section of middle to lower crust, archives geologic history spanning over a billion years from the Paleoproterozoic to Neoproterozoic Eras (3.5–2.5 Ga).
- Two major episodes of juvenile crust accretion are evident in the craton; between ~3.45–3.15 Ga and 2.6–2.5 Ga and a minor event around 2.7 Ga. The craton records protracted phase of crustal reworking between 3.1 and 2.7 Ga.
- From a dominantly vertical tectonic regime in the Paleoproterozoic-Mesoproterozoic (sagduction processes) that produced a dome and keel structural pattern, a clear shift to a plate tectonic regime is evident around 2.75 Ga. The latter orogeny is associated with accretion and collision processes culminating with the development of craton wide homogeneous strain pattern and high temperature low pressure regional metamorphism.
- With regard to the emerging view that on a global scale Earth's continental crust may record a transition towards a plate tectonic regime around 3.0 Ga, we observe that a clear evidence for the operation of plate tectonics in the Dharwar craton is discernible since around 2.75 Ga.

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