JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.97, October 2021, pp.1226-1239

Juvenile Crust Formation in the Precambrian Singhbhum, Dharwar Cratons and the Southern Granulite Terrain, India and Geodynamic Transitions: Evidence from Zircon U-Pb age-Hf Isotope Systematics

T. Vijaya Kumar, Y. J. Bhaskar Rao, E.V.S.S.K. Babu* and B. Sreenivas
LA-MC-ICPMS Facility, CSIR-National Geophysical Research Institute, Uppal Road, Hyderabad - 500 007, India
**E-mail: evsskbabu@ngri.res.in*

ABSTRACT

Zircon age-Hf isotopic data on the Archean Singhbhum and Dharwar cratons and the Archean-Proterozoic Southern Granulite Terrain (SGT) obtained at the CSIR-NGRI and by others elsewhere are in focus here. These data are used to decipher episodes of juvenile crust formation in the protracted (collectively spanning ~3.7 billion years) geologic history of the three terranes in the light of their regional geology, structure and deep-crustal architecture based on recent geophysical experiments as well as current perspectives on early Earth crust forming processes and geodynamics. Our important observations and inferences include: (1) the Hf-isotopic compositions of the Hadean-Eoarchean aged (ca. 4.2-3.6 Ga) zircon grains from the Singhbhum craton have distinctly unradiogenic Hf-isotopic compositions quite similar to the Jack Hills Hadean-Eoarchean detrital zircons, suggesting derivation from TTG-like melts generated by the internal reworking of a long-lived, geochemically enriched mafic reservoir formed around ca. 4.5 Ga; (2) a shift to strongly radiogenic zircon Hf isotope compositions during the early Paleoarchean around ca. 3.6-3.5 Ga (Singhbhum craton) and ca. 3.5-3.4 Ga (Western Dharwar craton) is conspicuous. This may relate to the time of development of depleted mantle reservoirs, the source of the voluminous Paleo-Mesoarchean juvenile felsic magmatism and crust formation events that extended for ca. 400-300 million years; (3) in the entire Dharwar craton and the northern parts of the SGT there is clear evidence for widespread juvenile magmatic episodes during the Neoarchean, around ca. 2.7 Ga and ca. 2.55 Ga, the latter being predominant and widespread; (4) in the southernmost part of the SGT, prominent juvenile magmatic episodes are also evident during the Paleoproterozoic (ca. 2.0 Ga, Trivandrum block) and early Neoproterozoic (ca. 1.0-0.9 Ga, in parts of the Madurai block); (5) onset of plate tectonic processes in the Singhbhum and Western Dharwar cratons during early Paleoarchean (ca. 3.6-3.5 Ga) cannot be ruled out, but there is clear evidence for the operation of plate tectonics, significant crustal growth and terrane amalgamation only after ~3.0 Ga in the Dharwar craton and the SGT and (6) regional dome and basin structural pattern of the pre-3.0 Ga crust attests to the role of internal differentiation processes (Rayleigh-Taylor Inversions) and vertical tectonics for the Paleo-Mesoarchean crust of the Singhbhum and Dharwar cratons. Together with other lines of evidence; changes in bulk crustal composition, deep crustal architecture, zircon age-Hf isotope distribution etc., we infer a transition to plate tectonics around 3.0 Ga in the Singhbhum and Dharwar cratons.

INTRODUCTION

The study of Archean cratons, rare remnants of stable continental crust >2.5 Ga old is paramount to many unresolved problems concerning planetary differentiation processes in general and the evolution of Earth's continental crust in particular. The Singhbhum and Dharwar cratons within the Indian Precambrian shield (Fig. 1) are archetypal granite-greenstone terranes exposing Archean middle – lower crust (reviews by Naqvi, 2005; Ramakrishnan and Vaidyanadhan, 2008; Sarkar and Gupta, 2012). The Southern Granulite Terrain (SGT) is interesting not only for the exposure of Archean deep crust, but also for the section across a series of Proterozoic accreted terranes. Collectively, these terranes provide an opportunity to evaluate episodic crust formation and accretion processes through nearly 3.7 billion years of Earth history (between ca. 4.2 Ga and 0.5 Ga), that encompass the geodynamic transition towards plate tectonics in the Precambrian record of Peninsular India. In recent times, substantive contributions have been made to the geology and regional structure of the Singhbhum and Dharwar cratons and the SGT, together with petrology, geochemistry and age relationships, especially zircon U-Pb age-Hf isotope compositions of the dominant lithounits (recent reviews by Dey 2013; Vijaya Kumar et al., 2017; Jayananda et al., 2018; Olierook et al., 2019; Bhaskar Rao et al., 2020; Chaudhuri, 2020; Dey et al., 2019, 2020; Mukhopadhyay and Matin, 2020; Santosh, 2020). Also, constraints on the structure and rheology of the deep crust and upper mantle of these terranes have been discussed based on geophysical investigations including potential fields, passive and active seismic methods (Biswajit Mandal et al., 2018, 2021; Vasanthi et al., 2021; Prantik Mandal et al., 2021 and references there in). Focusing largely on the *in-situ* U-Pb age-Hf isotope compositions of magmatic (xenocrystic and detrital) zircons from these regions, obtained at the CSIR-NGRI as well as published work by other authors, we discuss here juvenile crust formation and its evolution in the Singhbhum, Dharwar cratons and the SGT in the background of emerging global perspectives on Precambrian geodynamics and lithospheric evolution that are highlighted in the following. *Considering that this article is contextual to the Diamond Jubilee celebrations of CSIR-NGRI, a short note highlighting the development of facilities for geochronology and isotope geochemistry is in order, ahead of the summary on global perspectives on early Earth processes and crustal evolution relevant to this article.*

Development of Analytical Laboratory Facilities for Geochronology and Isotope Geochemistry at CSIR-NGRI: Credits and Salient Achievements in a Fifty-year Legacy

Studies aiming at understanding the structure, composition, dynamics and evolution of the Indian lithosphere assumed great importance right from the inception of the institute. Even 50 years ago, it was appreciated that the Precambrian geological record of Peninsular India preserved in its ancient cratons may extend back in time to at least the Mesoarchean (3200-2800 Ma). However, the spatio-

DOI: 10.1007/s12594-021-1852-6 | 0016-7622/2021-97-10-1226/$ 1.00 © GEOL. SOC. INDIA

temporal relationships within and across the different geological provinces were largely enigmatic owing to the dearth of reliable isotopic age data on the constituent lithounits. A basic laboratory for major and trace element analysis for rocks and minerals was functional by 1970 through efforts by a team led by Dr. S.M. Naqvi and Dr. V. Diwakar Rao. Over the succeeding decades, this laboratory grew in strength incorporating a wide range of modern analytical instruments such as the Atomic Absorption Spectrometer, X-ray Fluorescence Spectrometer, Electron Microprobe and Inductively Coupled Plasma Mass Spectrometer (ICPMS) supporting large research programs in petrology and geochemistry relevant to basic research and mineral exploration programs.

Efforts to initiate a geochronology laboratory at CSIR-NGRI date back to the late 1970s, when Dr. A.K. Baksi commenced work on his **K-Ar geochronology laboratory** with a plan to eventually organize an ^{39}Ar-^{40}Ar facility. A laboratory for conventional K-Ar geochronology was set-up housing AEI MS10 mass spectrometer, connected to bakeable ultrahigh vacuum Argon extraction line for Ar isotopes and K analysis were by flame photometry (Baksi et al., 1978). However, hindered by the lack of indigenous irradiation facilities required for the ^{39}Ar-^{40}Ar dating method, the laboratory was not sustained. A new geochronology laboratory was initiated by Prof. K. Gopalan in 1984. This comprised a state-of-the-art **Thermal Ionization Mass Spectrometer (TIMS, VG-354)** and a basic clean chemistry laboratory. The core group of Dr. Gopalan (Dr. Y.J. Bhaskar Rao, Dr. T.V. Sivaraman, Dr. G.V.C. Pantulu, Dr. Anil Kumar, Dr. A.M. Dayal, Dr. R. Srinivasan, Dr. B. Vijaya Gopal, Dr. S.M. Ahmad among others) comprised a band of motivated scientists with varied expertise and skill sets that included basic mass spectrometry, electronics, software development, analytical chemistry and geology with a deep appreciation of the status and limitations of our understanding of the formation and evolution of Earth's continental lithosphere, which formed the underlying objective of many research programs of the institute. Over the following nearly two decades, this team delivered considerable new information in terms of Rb-Sr, Sm-Nd and Pb-Pb whole rock-mineral isochron ages and isotope systematics of many ancient lithounits of Peninsular India that included Archean metavolcanics, TTG gneisses and granites, metasediments including stromatolitic carbonates, kimberlites, mafic dyke swarms of the Dharwar craton, gabbro-anorthosite plutons, alkali syenite-carbonatite complexes in the EGGT and SGT (see reviews Bhaskar Rao et al., 2008a; 2020) apart from a large dataset of Sm-Nd depleted mantle model ages for charnockite orthogneisses of the SGT. Precise Rb-Sr and Sm-Nd isochron ages for the eucrite Piplia Kalan was reported constraining its formation within a few million years of the earliest condensates of the Solar system (Anil Kumar et al., 1999).

Towards the end of the last century, it was abundantly clear that; (1) the accessary mineral zircon ($ZrSiO_4$) could be the best deep-time archive of Earth's continental crust and U-Pb dating of zircons either by ID-TIMS or by Secondary Ionization Mass Spectrometry (SIMS) methods became the preferred tool to document chronology of magmatism and crustal growth and (2) the Hf-isotopic compositions of magmatic zircons are useful as a proxy to crust-mantle interactions, tectonic setting and in constraining the timing of extraction of the zircon protolith from a mantle reservoir. Remarkably however, the order of Pb-blanks achieved in the TIMS laboratory at CSIR-NGRI precluded ID-TIMS single grain zircon U-Pb dating, while the SIMS facilities abroad were expensive and less accessible. By the turn of the century, technological advancements in terms of a combined use of Laser Ablation probe, Multi Collector-Inductively Coupled Plasma Mass Spectrometry (MC-ICPMS) and Quadruple-ICPMS enabled rapid, precise and cost effective *in situ* U-Pb and Lu-Hf isotope analysis in zircons at spatial resolution suitable for analysis of polymetamorphic multi domain zircons that are common in Precambrian igneous and sedimentary rocks. Taking advantage of this, Dr. Y.J. Bhaskar Rao and team (Dr. B. Vijaya Gopal, Dr. EVSSK Babu, Mr. N.P. Sukumaran, Dr. B. Sreenivas and Dr. T. Vijaya Kumar among others) set up an **LA-MC-ICPMS National facility** around 2007, the first of its kind in India. Over the years, *in situ* zircon U-Pb ages and Hf-isotope compositions were measured on large populations of magmatic and detrital zircons from different lithounits as well as modern stream sediments in parts of Peninsular India, mainly the Dharwar and Singhbhum cratons and the SGT alongside analysis of Sr, Nd, Pb, Hf and Fe isotope measurements and trace elements in a wide variety of materials including marine volcanic glass, marine sediments, deep ocean Fe-Mn crusts and nodules as well as tektites and meteorites. Of late, the earlier Q-ICPMS and LA systems were replaced by an Agilent 7800 Q-ICPMS and 193 nm Excimer Laser System (Resolution, ASI). Considering the importance of the Baddeleyite Pb-Pb method for the dating of mafic/ultramafic rocks, Dr. Anil Kumar implemented a direct thermal extraction method using a Thermo Finnigan, Triton TIMS procured around 2012. Baddeleyite Pb-Pb ages were determined for several Archean and Proterozoic mafic dyke swarms of Peninsular India.

A **stable isotope laboratory** comprising Isotope Ratio Mass Spectrometers (IRMS) VG 602 and VG 602D was set up during late 1970s through efforts by Dr. Balesh Kumar and Dr. A.K. Baksi. In subsequent years, active participation of many colleagues (Dr. A.M. Dayal, Dr. Masood Ahmad, Dr. D.J. Patil, Dr. Das Sarma, Dr. B. Sreenivas, Dr. M.S. Kalpana among others and mentoring by Prof. K. Gopalan for many years) enriched and empowered the R & D activity. The early instruments were of dual inlet and dual collector type. Isotopic analysis of $^{2}H/^{1}H$, $^{13}C/^{12}C$, $^{15}N/^{14}N$, and $^{18}O/^{16}O$ in gaseous mode was initiated in carbonates and water samples. These instruments were further modernized during early 1980s and an upgradation to VG 903 during 1996 alongside assembly of an extraction line for Oxygen from silicates using bromine penta-fluoride (BrF_5). This enabled simultaneous determination of both C and O isotope ratios of carbonate and silicate samples at a higher throughput. Subsequently, augmentation of the laboratory during 2004 with Continuous-Flow IRMS systems (Delta Plus XP and Thermo Finnigan models) and online sample decomposition, gas extraction and purification systems led to new possibilities and applications. A separate facility for stable isotope analysis was set up around 2005 with continuous flow dual-inlet KEIL carbonate system by Dr. S. Masood Ahmad, Dr. V.M. Padmakumari and colleagues. A combination of stable and radiogenic isotope proxies (Sr, Nd, O, C, H isotopes) were used in numerous studies over the last 15 years in R & D projects pertaining to disciplines such as, hydrology, Precambrian sedimentary processes (carbonates, banded-iron formations and magnesite deposits), Phanerozoic marine environments and processes, paleoclimates and climatology including recent variability in monsoon (Bay of Bengal sediments, planktonic and benthic foraminifera, Lakshadweep corals as well as on land cave deposits like stalagmites). Several projects using surface geochemical and biochemical methods for exploration of concealed hydrocarbon deposits were executed funded by the Oil industry.

These laboratories continue to provide a rare learning opportunity and valuable experience to many young scholars and researches empowering them for research in this important realm of Earth Science, at CSIR-NGRI and at many laboratories in the country, an important measure of success outweighing the hundreds of research papers and scores of Ph.D. dissertations that emanated over the years.

Unlike in the Phanerozoic (<540 Ma) Eon, where the paradigm of plate tectonics and Wilson-cycle processes constitutes a robust and unifying mechanism in which to explain the orogenic processes of crust formation, recycling and preservation, there is yet no consensus on a global geodynamic framework for the early Earth, especially during the Hadean (>4.0 Ga) and Archean (4.0-2.5 Ga) Eons (Cawood et al., 2013; Hawkesworth et al., 2017; Bédard, 2018). This is mainly due to the fragmentary nature of the geological record pertaining to the first one billion years of Earth history. While the Eoarchean (4.0-3.6 Ga) rocks are scarce, the Hadean rock record older than 4.03 Ga is non-existent. Granite-greenstone and high-grade gneiss terrains characterizing Archean cratons within Precambrian shields preserve mostly Paleo- to Neoarchean crust (3.6 and 2.5 Ga). In the absence of an early crustal rock record, much of our understanding of the origin and evolution of the early crust mostly comes from the study of detrital zircon grains entrained in younger (<3.5 Ga) sedimentary rocks, the best example of such an ancient zircon resource is the Jack Hills metaconglomerate, Western Australia (e.g., Wilde et al. 2001; Harrison 2009; Kemp et al. 2010), although Hadean and Eoarchean zircons have also been reported from a few other cratons such as the Slave and Superior cratons, Canada, as well as terrains in W. Greenland and Labrador, South Africa, NE China and the Singhbhum craton, India. In general, critical interrogation of global zircon age-Hafnium (Hf) isotopic datasets have been extremely useful in addressing several long standing questions e.g., rate of crust formation, the onset of modern-style plate tectonics, the relative importance of crust formation vis-à-vis destruction at different times in Earth history (reviews by Harrison, 2009; Kemp et al., 2015; Roberts and Spencer, 2015; Mueller and Nutman, 2017; Hawkesworth et al., 2017 and references there in). An evaluation of the 'juvenile' (the most radiogenic) and 'evolved' (unradiogenic) parts of the Hf-isotope record, is useful in constraining mantle differentiation processes and tectonic settings. However, unlike the Phanerozoic orogens, interpretations of the juvenile Hf isotope signal may not be so straight forward in ancient terranes considering the diversity of the inferred tectonic settings. Recent petrogenetic models on the genesis of tonalite-trondhjemite-granodiorite (TTG) suites that are ubiquitous in the Archean terranes invoke melting of hydrated basalt at garnet-amphibolite, granulite or eclogite facies conditions in different tectonic scenarios. Plate tectonic petrogenetic models include (1) melting of subducted oceanic crust in a hotter mantle and (2) subduction driven accretion of plume generated oceanic plateau crust followed by reworking and terrane collision, while 'no subduction' models involve melting of the base of magmatically or tectonically thickened basaltic crust or delaminated lower crust (reviews by Sizova et al., 2015; Bédard, 2018). Together with numerical models, the U-Pb age-Hf isotope arrays of the ancient zircon grains offer useful insights into the nature of Earth's early crust and geodynamics. The interpretations regarding composition of the Hadean crust vary from dominantly mafic to those with significant felsic components and the inferred geodynamic models include plate tectonics, stagnant lid, heat pipe and plume tectonics. Recent estimates suggest that a large part of the present continental crust (~70% by volume) existed by the end of the Archean (Dhuime et al., 2015), but the chronology of its extraction from the mantle and the mechanism of continental growth remain equivocal. In general, cyclic or episodic crustal growth is suggested by the Archean rock and zircon record, although potential issues concerning a preservational bias exist (Cawood et al., 2013). Currently, a *quasi* consensus is that the planet's geodynamic style witnessed a transition from a dominantly stagnant lid style towards plate tectonics during the Archean (Dhuime et al., 2015; Hawkesworth et al., 2017 and references therein). Several lines of evidence including field geological observations, paleomagnetic, geochemical, ore deposit studies and global-scale zircon U-Pb age-Hf±O datasets support a transition towards plate tectonics around ~3.0 Ga. This implies a distinct change in the thermal structure, composition, thickness and growth rate of the continental lithosphere and crust around 3.0 Ga ago (Hawkesworth et al., 2017). Nevertheless, subduction and Wilson-cycle type terrane accretion processes dominated since the Archean-Proterozoic transition, 2.5 Ga ago, but truly modern-style subduction plate tectonics may have begun only since about 0.75 Ga (Stern, 2008). An important observation is that the purported global geodynamic transition during the Archean may have been diachronous, calling for detailed studies of different Archean cratons. The available data on Singhbhum and Dharwar cratons and the SGT will be evaluated in the light of these perspectives.

REGIONAL GEOLOGY

The crystalline basement of the Singhbhum and Dharwar cratons (Fig. 1) comprises Archean granite-greenstone and granulite gneiss terranes exposing large tracts of low- to medium metamorphic grade rock associations including: 1) grey gneisses, mostly TTG gneisses, 2) supracrustal or greenstone belts, variably migmatised belts and rafts of metavolcanic and metasedimentary rocks and 3) intrusives; granitoids, mafic dyke swarms and variety of ultramafic to mafic bodies. The geology and U-Pb zircon age data for the **Singhbhum Craton** (SC), especially the ellipsoidal Paleo–Mesoarchean granite-greenstone nucleus and the flanking Archean-Proterozoic supracrustal cover sequences (Fig. 2) has been summarized recently by many authors e.g., Dey et al. (2017); Sreenivas et al. (2019); Olierook et al., (2019); Chaudhuri (2020); Mukhopadhyay and Matin (2020). The craton is bound by the Damodar Valley and Mahanadi Valley grabens and the Proterozoic Eastern Ghats Granulite Terrane. The northern and southern limits of the Paleo-Mesoarchean cratonic core comprise prominent thrust/fault zones, the Singhbhum shear zone and the North Singhbhum Mobile Belt to the north and the Sukinda thrust zone to the south. The Archean basement in the cratonic core comprises ca. 3.53-3.29 Ga TTG gneisses referred to as the Older Metamorphic Tonalite Gneiss (OMTG) and over a dozen granitoid plutons collectively known as Singhbhum Granite (SG) with supracrustal rock enclaves, the Older Metamorphic Group (OMG). The central granite-gneiss domain is surrounded by belts of ca. 3.5-3.3 Ga supracrustal rock successions, the Iron Ore Group (IOG). In the cratonic core, phases of granite magmatism have been constrained at ca. 3.47 Ga, 3.35 Ga, and 3.25 Ga (Dey et al., 2017). The Singhbhum granite magmatism is succeeded by the emplacement of gabbro-anorthosite units, A-type granites and ultramafic suites of rocks. Following regional cratonization around 3.0 Ga, the region witnessed widespread emplacement of mafic dyke swarms, the Newer dolerites (ca. 2.80-2.75 Ga, e.g., Anil Kumar et al., 2017) and A-type granites during the late Meso- Neoarchean.

The geology of the **Dharwar craton** and the **SGT** (Figs. 3, 4) has been reviewed recently by many authors, for e.g., Radhakrishna and Naqvi (1986); Bhaskar Rao et al. (2003, 2008a, 2020); Ghosh et al. (2004); Naqvi (2005); Chadwick et al. (2007); Ramakrishnan and Vaidyanadhan (2008); Clark et al. (2015); Santosh (2020); Santosh et al., (2009, 2017); Chardon, et al. (2011); Plavsa et al. (2015); Peucat et al. (2013); Tomson et al. (2013); Chetty and Santosh (2013); Jayananda et al. (2013, 2018); Collins et al. (2014); Vijaya Kumar et al. (2017). The Dharwar craton is divisible into a dominantly Paleo-Mesoarchean Western Dharwar Craton (WDC) and a largely Neoarchean Eastern Dharwar Craton (EDC) based mainly on age and metamorphic criteria. The WDC and EDC are separated by a prominent shear zone along the eastern margin of the Chitradurga greenstone belt. The present exposure constitutes an oblique section of middle to lower crust (~15-30 km paleodepth). From north to south across the WDC and the northern part of SGT, the estimated paleo-pressures in gneissic and mafic lithologies increase from ~3 kbar to 8-9 kbar. An unbroken, prograde metamorphic transition zone (TZ) 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).

Geological and geochronological data on the WDC suggest two prominent orogenic cycles, broadly, the pre-3.0 Ga and post-3.0 Ga (3.0 to 2.5 Ga) tectono-metamorphic superevents. The oldest dated

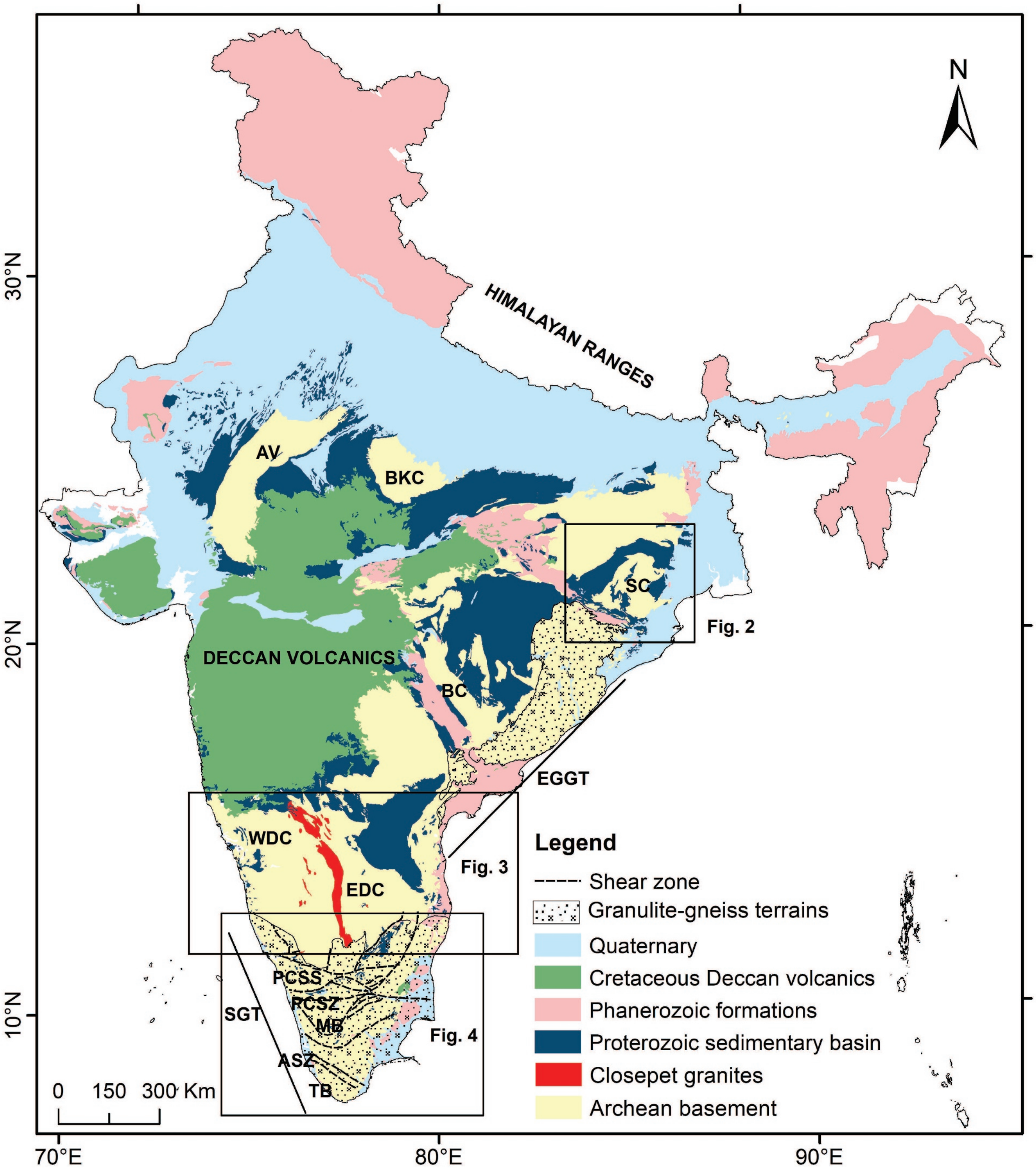

Fig. 1. Simplified geology of Peninsular India modified after Geological Survey of India (1995). Major Precambrian structural/tectonic elements include Western Dharwar Craton-(WDC), Eastern Dharwar Craton-(EDC), Bastar Craton-(BC), Singhbhum Craton-(SC), Bundelkhand Craton-(BKC), Aravalli fold Belt-(AV), Southern Granulite Terrain-(SGT), Madurai Block-(MB), Trivandrum Block-(TB), Palghat Cauvery Shear System-(PCSS), Palghat Cauvery Suture Zone- (PCSZ), Achankovil Shear Zone-(ASZ), Eastern Ghat Granulite Belt-(EGGT). See text for more information.

rocks in the craton (Paleo-Mesoarchean ages) are from an extensive area encompassing the medium-grade granite-greenstone terrane around the Holenarsipur greenstone belt and the adjacent high-grade terranes of the Coorg and Biligiri Rangan massifs (the HSB domain, Fig. 3). The dominant structural grain comprising NNW-SSE to N-S trending axial planer foliation is related to the end-Archean craton-wide tectono-thermal event (D_2M_2), which realigned the earlier pre-ca. 3.0 Ga deformation fabrics (D_1M_1). The earlier structural fabrics and pristine wholerock isotopic systematics of the Paleo-Mesoarchean lithologies are best preserved in domains of low-D_2M_2 strain, i.e., away from the system of ca. 2.5 Ga regional transcurrent shears. In such domains, U-Pb zircon and Sm-Nd isochron ages record at least two phases of crustal growth; around 3410-3280 Ma and 3230-3200 Ma (Jayananda et al., 2015; Guitreau et al., 2017). The emplacement of syn-kinematic diapiric trondhjemite and granite plutons represents the culmination of the pre-3.0 (D_1M_1) orogenic events. This event of magmatism is constrained closely between 3230 and 3106 Ma based on zircon U-Pb dating (Jayananda et al., 2015; Guitreau et al., 2017).

Flanking the WDC and EDC to the south and west of the TZ are high metamorphic grade terranes of the SGT, constituting the highland charnockite massifs and the interlying low-lands occupied by a variety of lithologies; supracrustal rocks, migmatitic quartzofeldspathic gneisses, charnockite-enderbite gneisses and intrusive granitoids (Fig. 3). The SGT has attracted considerable international attention in studies on structure, rheology and dynamics of lower continental crust;

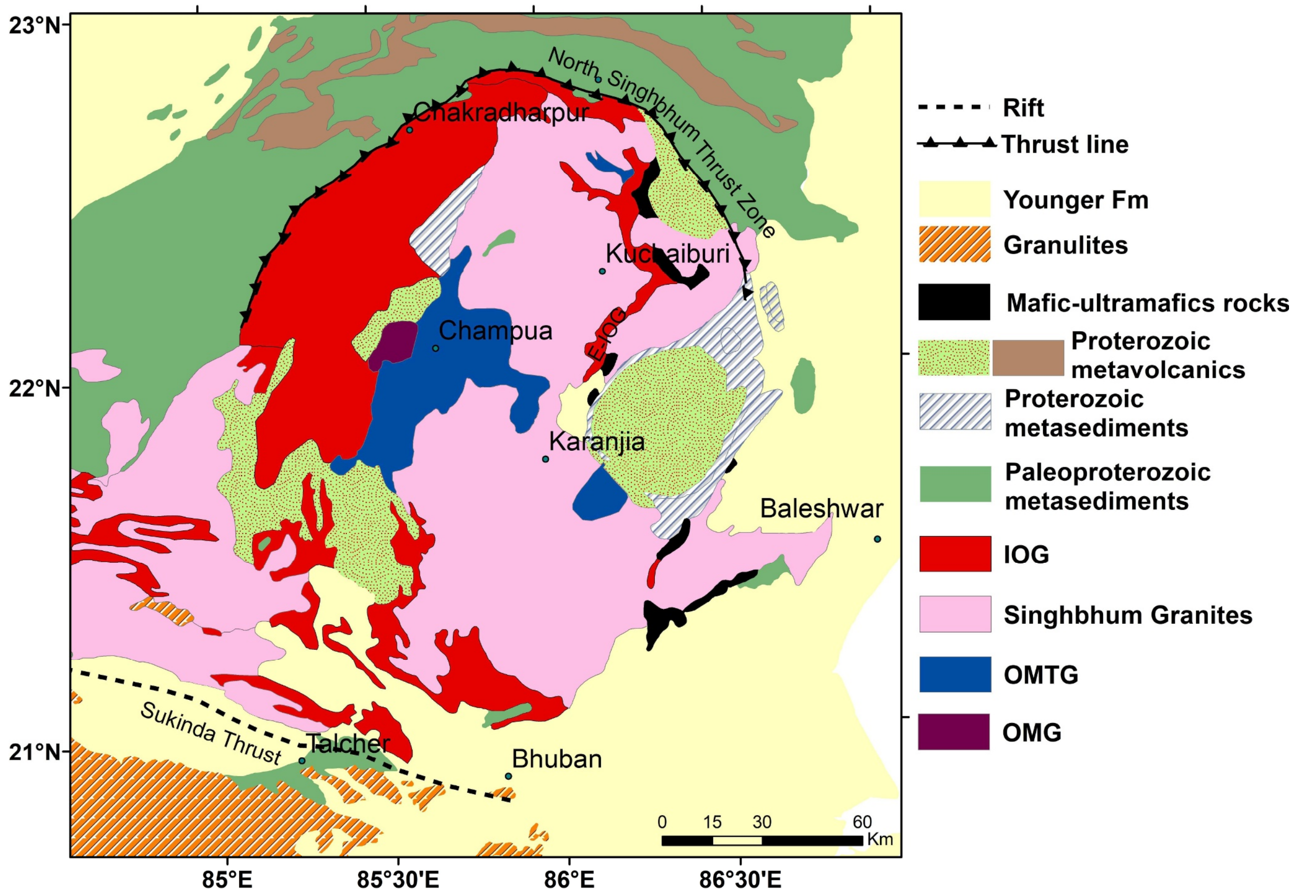

Fig.2. Simplified geology of the Archean Singhbhum Craton (SC) (Sreenivas et al., 2019). OMG: Older Metamorphic Group; OMTG: Older Metamorphic Tonalite Gneiss; IOG: Iron Ore Group (see text for more information).

interaction between mantle and crust; ultra-high temperature and high pressure metamorphic processes and the growth, recycling, assembly and evolution of Supercontinents, especially Rodinia and Gondwana (Collins et al., 2014; Clark et al., 2015; Santosh, 2020 and references therein). The SGT is divisible into temporally distinct Precambrian high-grade terranes separated by crustal-scale ductile shear/suture zones. The most prominent shear zone system in the SGT is described as the Cauvery shear zone or the Palghat-Cauvery shear system (PCSS). Many authors have suggested that the E-W trending Palghat-Cauvery suture zone (PCSZ) at the southern limit of the PCSS, divides the SGT into two temporally distinct granulite blocks with distinct lithologies, age spectra, constraining magmatism and deformation events and most importantly the timing of the last event of regional high-grade metamorphism. Whilst the terranes to the north of the PCSZ, also referred to as the Salem block, record predominantly late Neoarchean to early Paleoproterozoic granulite metamorphism, those to the south described as the Madurai, Trivandrum and Nagercoil blocks are affected by pervasive late Neoproterozoic (Ediacaran) to early Cambrian granulite-facies metamorphic imprints. The Southern Granulite terrane is generally perceived as a key segment of the Gondwana forming orogens, such as the Himalayan-scale collisional orogen, the East African orogen, which lay across the continents of Africa, South America, and Antarctica during the Ediacaran–Cambrian (ca. 600–480 Ma; Collins and Pisarevsky, 2005).

REGIONAL STRUCTURE AND DEEP CRUSTAL ARCHITECTURE

In the Singhbhum craton and the WDC, on a regional scale, the structure of the Paleo-Mesoarchean granite-greenstone terranes are markedly different from those of the Neoarchean. In the Singhbhum cratonic core, there is a general lack of large-scale high strain penetrative deformation fabrics and evidence for thrust/nappe structures (e.g., Prabhakar and Bhattacharya, 2013). The eruptive rocks and associated metasediments of the IOG preserve primary structures (Mukhopadhyay et al., 2008). Geochronological data suggest multiple magmatic pulses within a geographically limited region, where successive magmas representing the granitoid batholiths might have followed the same conduits, such that the older plutonic elements are pushed to the periphery of the ellipsoidal domain. In general, features such as the remarkable longevity of the pulsating magmatism (>300 million years), the regional structural patterns, contemporaneity of the plutonic-volcanic complexes, the geochemistry of igneous rocks (see Dey et al., 2017, 2019, 2020; Chaudhuri et al., 2018; Mitra et al., 2019; Olierook et al., 2019; Sreenivas et al., 2019) of the Paleo-Neoarchean cratonic core of the Eastern Indian Shield is reminiscent of the Archean ‘dome and basin’ structure, best documented in examples such as the eastern Pilbara Craton (Wiemer et al., 2018 and references therein). Recent modelling of the residual gravity field (Vasanthi et al., 2021) and a joint inversion of P-receiver functions and fundamental mode group velocity dispersion data of Rayleigh waves (Prantik Mandal et al., 2021) offer broad constraints on the crust and lithospheric architecture of the Indian Shield. Notwithstanding the differences in the estimated thicknesses by the two methods, a striking observation from the seismic data is that the crust and lithosphere beneath the granitic core of the SC is thinner (by ~4–8 km in crust and ~15–20 km in lithosphere) compared to the peripheral IOG structures, while a prominent high order residual gravity low for the granitic core attests to its unusually large volume and depth extension.

In the pre-3.0 Ga HSB domain of the WDC (Fig. 3), many authors

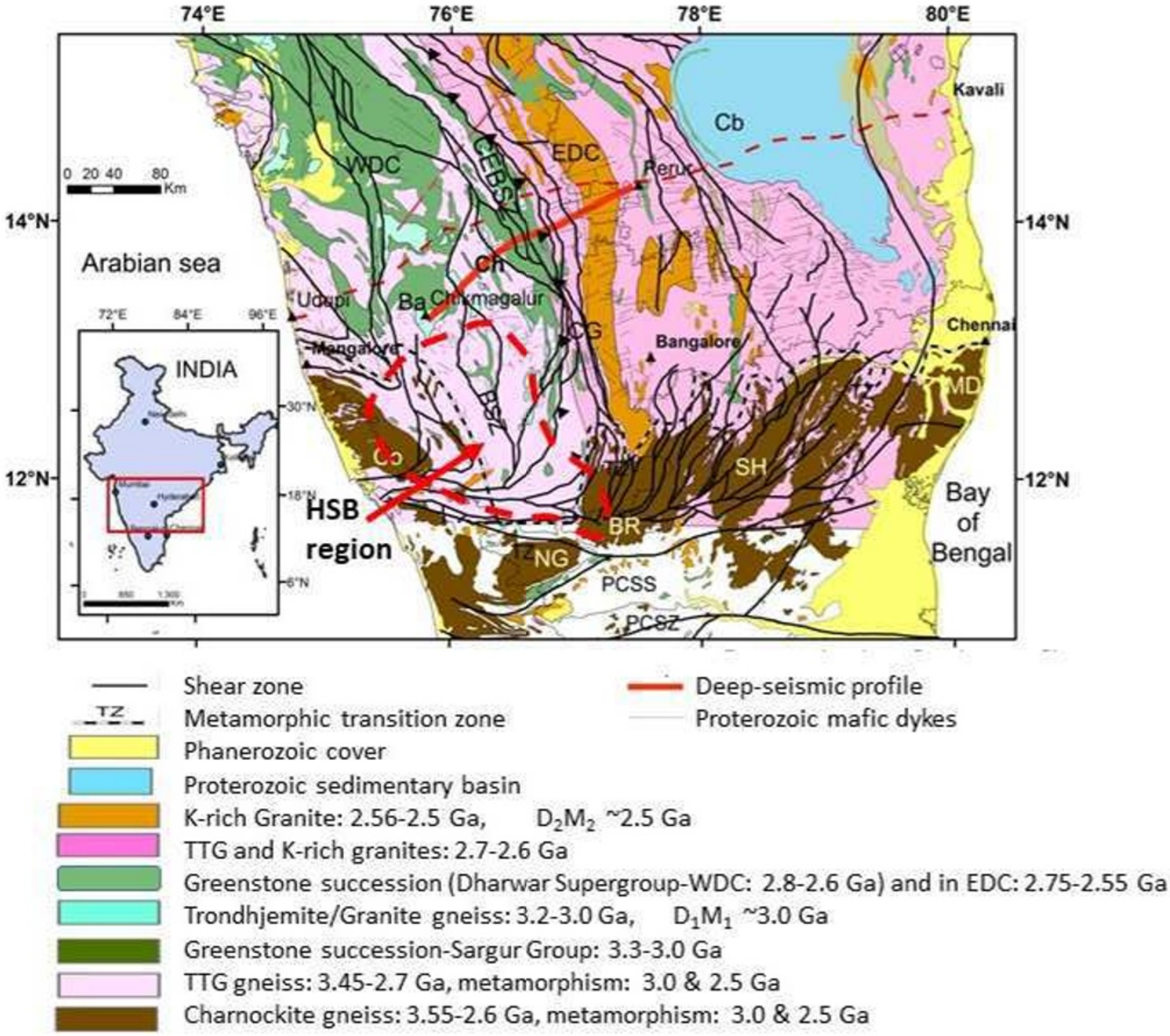

Fig. 3. A simplified geological map of Dharwar craton, southern India (Bhaskar Rao et al., 2020) showing major Archean tectonic blocks; WDC-Western Dharwar craton, EDC-Eastern Dharwar craton and northern (Archean) part of the SGT-Southern Granulite Terrain; CEBSZ-Chitradurga Eastern Boundary Shear Zone. 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).

recorded evidence for superposed deformation of the Paleo-Mesoarchean supracrustal rocks and gneisses that involved two main phases of folding (Naha et al., 1990; Bhaskar Rao et al., 2020 and references therein). Detailed structural mapping by Bouhallier et al. (1993) demonstrated that the regional structural pattern around the HSB conform to dome and basin structures bearing evidence for vertical tectonics prior to 3.0 Ga. Dome and basin structures were also mapped around Gundlupet and JC Pura to the south and east of HSB and were inferred over a wider region around HSB (see Bhaskar Rao et al., 2020). By contrast, structural studies in the post-3.0 Ga Archean terranes in the WDC, EDC and SGT emphasize the role of convergent tectonics (e.g., Chadwick et al., 2007; Chardon et al., 2011; Peucat et al., 2013). For example, in the region around the Chitradurga greenstone belt, 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 was sustained for about 150 Ma. Both pre- and syn-tectonic granites were emplaced as steep orogen parallel NW-SE sheets along listric faults that are believed to sole from a mid-crustal detachment. Chardon et al. (2011) interpreted the Neoarchean 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, in the middle-lower crustal levels with modern analogs in the Himalaya-Tibet wide hot orogen. The LCF combines orogen-normal shortening, orogen-parallel stretching and transtension.

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 (Vp and Vs) 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 (Vs >4.0 km/s and Vp >7.0 km/s) mafic lower crustal layer, while the EDC shows a much thinner mafic layer. This implies that the crust evolved from mafic to intermediate average composition with a decrease in crustal thickness

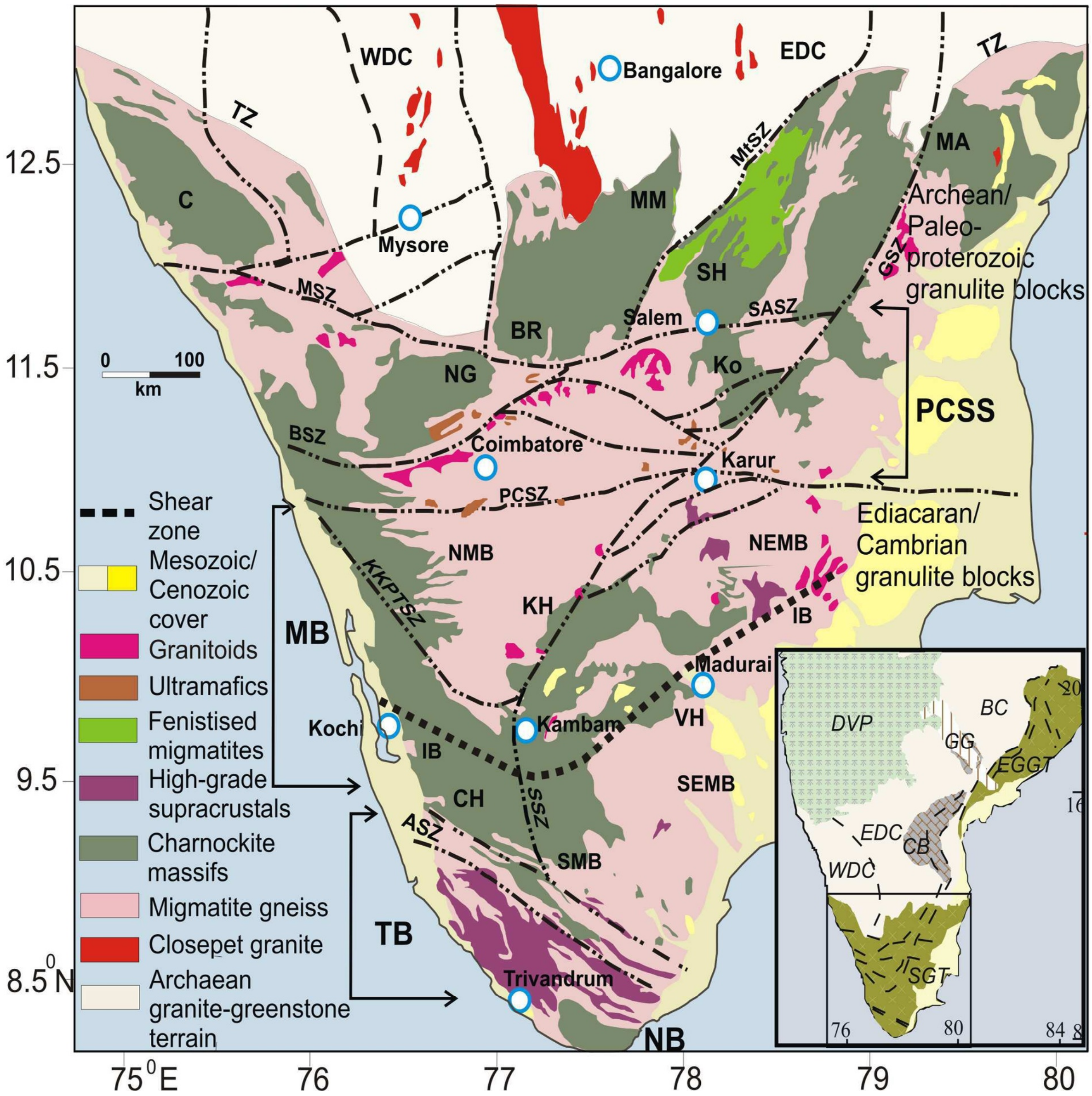

Fig. 4. Simplified geological sketch of southern India showing the Southern Granulite terrane (SGT), and the western and eastern parts of Dharwar craton (WDC and EDC) located to the north of the Southern Granulite terrane across the metamorphic transition zone (TZ), modified from Vijaya Kumar et al. (2017). The sketch shows sample locations and the Neoarchean and Neoproterozoic (more specifically, Ediacaran–early Cambrian) granulite blocks. The latter include the Madurai block (MB, where NMB—northern Madurai block, SMB—southern Madurai block), Trivandrum block (TB), and Nagercoil block (NB). Prominent charnockite highland massifs referred to in the text include: Coorg (C), Nilgiri (NG), Biligiri Rangan (BR), Male Mahadeshwara (MM), Shevaroy (SH), Kollimalai (Ko), Madras (MA), Kodaikanal (KH), Varusanadu(VH), Cardamom (CH), and Nagercoil (NH). Major shear zones include: Moyar shear zone (MSZ), Bhavani shear zone (BSZ), Mettur shear zone (MtSZ), Salem-Attur shear zone (SASZ), Gangavalli shear zone (GSZ), Palghat-Cauvery shear system (PCSS), Palghat–Cauvery shear zone (PCSZ), Karur–Kambam–Painavu– Trichur shear zone (KKPTSZ), Suruli shear zone (SSZ), and Achankovil shear zone (ASZ). Also shown is an isotopic boundary (IB) separating the northeastern Madurai block (NEMB) and southeastern Madurai block (SEMB). The inset shows a part of Peninsular India: BC—Bastar craton; CB—Cuddapah basin; EGGT— Eastern Ghats Granulite terrane; DVP—Deccan volcanic province; GG—Godavari graben, See text for more details.

accompanied by a partial loss of lower crust. Interpretation of seismic reflection and wide-angle refraction data along profiles across the WDC-EDC boundary (Vijaya Rao et al., 2015; Biswajit Mandal et al., 2018), across the PCSS (Reddy et al., 2003) and across the Achankovil Shear zone separating the Madurai and Trivandrum blocks of the SGT support collision tectonics during the Neoarchean and late Neoproterozoic. 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 was likely related to subduction processes.

ZIRCON U-Pb AGE-Hf ISOTOPES AND EPISODES OF JUVENILE FELSIC CRUST FORMATION

The Singhbhum Craton

The zircon ages and Hf-isotopic compositions are summarised in Fig. 5a. Sensitive High Resolution Ion Microprobe (SHRIMP) zircon U-Pb ages of 4241±4 Ma and 4239±4 Ma for a grain within a ca. 3400 Ma tonalitic gneiss representing the OMTG suite around Champua mark the oldest dated zircon from Peninsular India thus far (Chaudhuri et al., 2018). These authors also reported four other Hadean spot ages on two xenocrystic zircons with ages ranging between 4057 and 4010 Ma. Detrital zircon grain from a river sand sample in the area yielded U-Pb age of 4015±9 Ma (Miller et al., 2018). Twelve detrital grains separated from the Mesoarchean Mahagiri quartzite analysed by SHRIMP and LA-ICPMS (6 grains each) yielded Eoarchean ages ranging between ca. 3950 and 3661 Ma (Sreenivas et al., 2019). Several other authors also reported Eoarchean xenocrystic and/or detrital zircons from samples of the craton (Goswami et al., 1995; Upadhyay et al., 2014; Miller et al., 2018; Olierook et al., 2019; Chaudhuri, 2020). In Fig. 5a, barring a lone grain of detrital zircon from river sand dated at ca. 3619 Ma, which shows ε_{Hf}(t) of +5.23, the entire population of the Hadean and Eoarchean zircons from the craton show negative ε_{Hf}(t) between -9.75 and -2.39 (also see Chaudhuri, 2020). In this regard, the Singhbhum Hadean zircons are similar to those of the Jack Hills detrital zircon population that generally have unradiogenic Hf-isotope compositions. An interpretation of age-Hf isotopic data on the Jack Hills Hadean zircons holds that a geochemically enriched silicate reservoir with a ^{176}Lu/^{177}Hf as low as ~0.01 developed very early in the Earth history, by ca. 4.5 Ga ago (Iizuka et al., 2017 and references therein). This reservoir may have significantly contributed to the crustal magmatism during the Hadean and Eoarchean through continuous reworking until about 4.0 Ga and disappeared following the onset of Eoarchean crust generation processes (Kemp et al., 2010; 2015).

Ion Probe ^{207}Pb/^{206}Pb ages for detrital zircons from three different samples of the OMG yield range of ages between 3628 and 3375 Ma (Goswami et al., 1995; Mishra et al., 1999; Nelson et al., 2014) constraining the minimum age of deposition of OMG at ca. 3375 Ma. Both high- and low-Al variants of TTG gneisses are known from the OMTG suite that generally exhibit fractionated REE patterns with strong LREE and moderate HREE enrichment with no Eu-anomaly. Their genesis has been modelled in terms of partial melting of amphibolites or hydrated mafic crust at different depths with or without garnet in the residue (Dey et al., 2017 and references therein). For the xenolith host rocks (OMTG gneisses), zircon ages up to 3471±24 Ma have been reported (Dey et al., 2017 and references there in) apart from a younger age of 3380±11 Ma (Nelson et al., 2014) although the rocks are known to carry much older (Hadean-Eoarchean) aged xenocrystic zircons as stated above. In general, consistently near zero to positive values of ε_{Hf}(t) +0.1 to +5.9 have been reported for the OMTG (Dey et al., 2017; Upadhyay et al., 2019) indicating an essentially juvenile origin for these rocks. However, marginally negative zircon ε_{Hf}(t) values of -2.8 to -2.1 were reported for ca. 3.4 Ga gneisses (Chaudhuri et al., 2018). Compositionally both tholeiitic and calc-alkaline affinities were attributed to the S-IOG volcanics. Rarely komatiites inter-layered with these volcanics has been noted. The oldest greenstone unit of the craton is constrained by Ion Probe ^{207}Pb/^{206}Pb concordia upper intercept ages 3507±2 Ma, 3505.5±0.5 Ma for magmatic zircons in a felsic volcanic unit in the basal section of the southern IOG (Mukhopadhyay et al., 2008; Sreenivas et al., 2019), while an Ion Probe ^{207}Pb/^{206}Pb age of 3392±29 Ma was reported for the felsic tuff from the western IOG (Basu et al., 2008). The zircon grains from the 3.51 Ga dacite from the S-IOG have strikingly positive values ε_{Hf}(t) ranging from +0.5 to +7.8, mostly plotting close to the DM curve attesting to the juvenile character of the volcanic suite (Sreenivas et al., 2019).

The Singhbhum granites comprise different plutonic suites covering a range of compositions from trondhjemite / tonalite through granodiorite to granite, considered to have emplaced in three phases, each showing different enclave geology, bulk composition and age. Based on field relationships and age data for the granite and supracrustal succession, a polycyclic history between ca 3.38 Ga and 3.25 Ga has been proposed across the cratonic core (Ghosh et al., 1996; Upadhyay et al., 2014; Dey et al., 2017, 2019). Xenocrystic zircons were dated at 3467-3495 Ma and 3471 Ma in the TTG gneiss enclaves within the Singhbhum granites. Overall, ε_{Hf}(t) values in zircons from Singhbhum granites of different ages comprise a range of values between +3.6 and -2.9 (Dey et al., 2017; Pandey et al., 2019; Chandhuri, 2020) indicating significant juvenile character. Several discrete intrusive granite bodies are known outside the Paleoarchean core of the craton. These granites have Mesoarchean and Neoarchean ages, the former overlapping with the youngest phase of the Singhbhum granite, for example, the Bonai granite and Mayurbhuj granite-gabbro suite (not shown in Fig.2). Dated at 3163±126 Ma (wholerock Pb-Pb isochron), the Bonai granite has tonalitic gneiss xenoliths dated at ca. 3380 Ma and 3369 Ma. Xenocrystic zircons from these xenoliths yielded ID-TIMS age of 3448±22 Ma (Sengupta et al., 1991). Zircon U-Pb ages for the Mayurbhunj granite fall in a narrow interval between 3092 and 3063 Ma (Mishra et al., 1999; Nelson et al., 2014; Upadhyay et al., 2019).

A few other Meso-Neoarchean igneous intrusions and sedimentary stacks have been dated, these include the Sukinda-Nuasahi layered mafic-ultramafic body. Zircon ages of 3123±7 Ma and 3119±6 Ma have been reported (Augé et al., 2003). Although no Hf-isotopic data are reported, it is likely that some of these magmatic suites may have had juvenile protoliths. The Mahagiri Formation unconformably overlies the S-IOG and the younger phase of the SG (Sreenivas et al., 2019 and references therein). The Eoarchean detrital zircons from a sample of the Mahagiri quartzite have been described in the foregoing. Apart from this, a few other samples from this unit, along the basal section show a spectrum of ages ranging from ~3661 Ma to 2909 Ma, while the Paleo- and Mesoarchean ages predominate. These zircons analyse a wide range of ε_{Hf}(t) from -9.75 to +9.4 indicating a heterogenous provenance that might include juvenile felsic suites (Sreenivas et al., 2019). Further manifestation of widespread juvenile magmatism during the Neoarchean is implicit as the Singhbhum craton witnessed extensive multiphase emplacement of dyke swarms and other mafic-ultramafic bodies and granites. For e.g., the Newer Dolerite dyke swarm intruding the Paleo- to Mesoarchean granite-greenstone terrane yielded Pb-Pb baddeleyite ages between 2800 Ma and 2752 Ma (Anil Kumar et al., 2017), which could mark a younger time limit to regional cratonization. Several anorogenic granite-felsic volcanic suites also mark Neoarchean granite activity, generally dated around 2.8 Ga, e.g., the Tamperkola granite (Bandyopadhyay et al., 2001).

The Dharwar Craton and the Southern Granulite Terrain

Crust formation in the Dharwar craton involved multiple episodes of juvenile crust accretion. For example, Jayananda et al. (2018) inferred five episodes of felsic magmatism in the intervals of ca. 3450–3300 Ma, 3230–3150 Ma, 3000–2960 Ma, 2700–2600 Ma, and 2560–2520 Ma. Chronostratigraphic models for development/deposition of greenstone successions of the WDC recognise two major cycles; the older (>3.0 Ga) Sargur Group and the younger (ca. 2.9-2.6 Ga) Dharwar Supergroup. Each of these cycles culminate with the emplacement of potassic granites dated respectively at ca. 3.0 Ga and 2.6 Ga (Bhaskar Rao et al., 2008a; Jayananda et al., 2015, 2018). The two early episodes of crust formation, between 3450 and 3200 Ma, correspond to the emplacement of the oldest TTG suites mainly in the region around Holenarsipur Schist Belt (HSB), WDC. These suites are pene-contemperaneous with volcanism and sedimentation of the older greenstone cycle. Both high and low-Al_2O_3 TTG magmas have been described in the region suggesting melting of shallow and deep sections of amphibolite / mafic crust that may have formed during the Eoarchean to Paleoarchean as indicated by their bulk geochemistry, wholerock Sm-Nd and zircon Lu-Hf model ages for the TTG suites

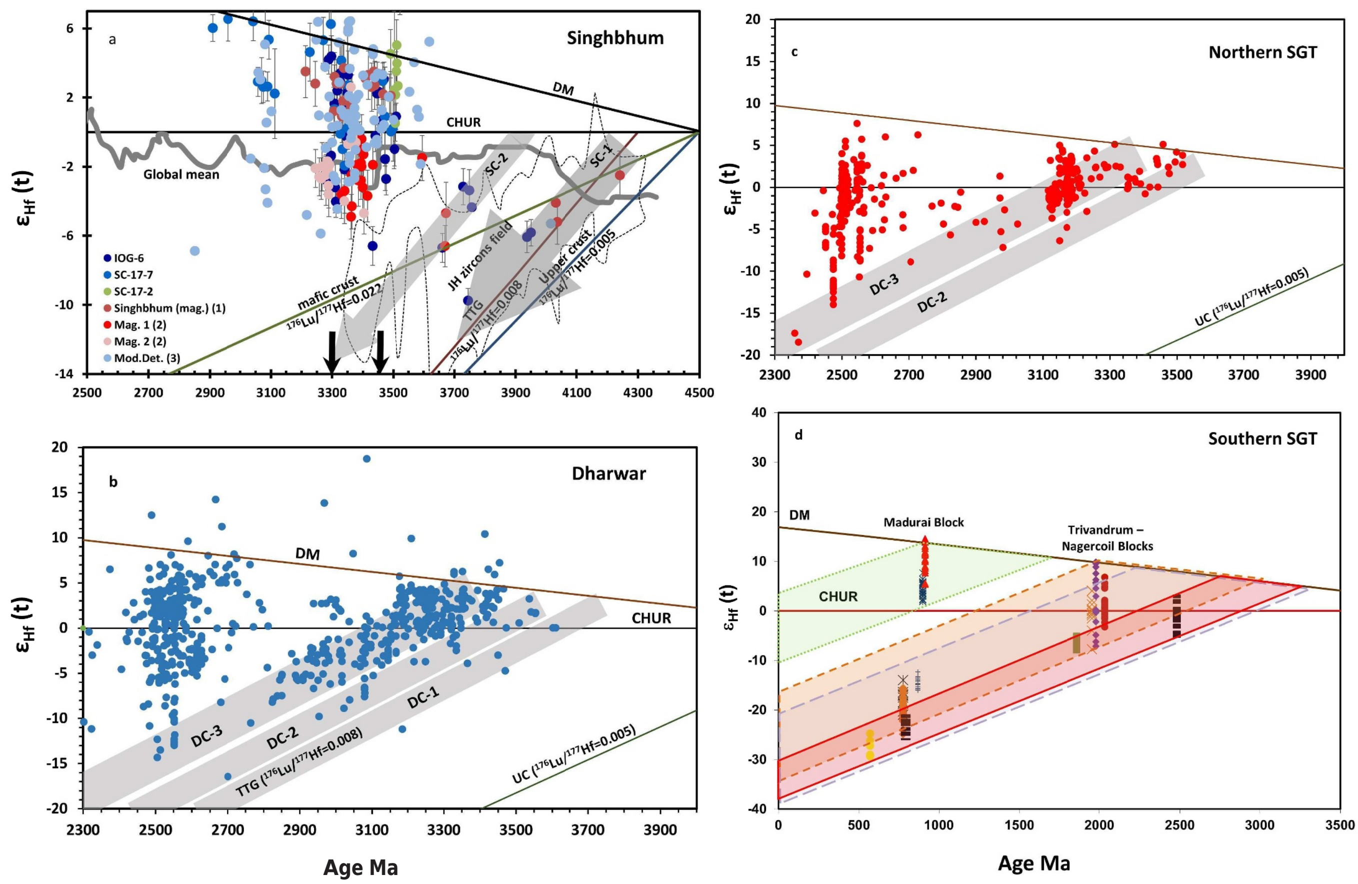

Fig. 5. The age vs. ε_{Hf}(t) ($\varepsilon_{Hf} = ((^{176}Hf/^{177}Hf_{sample})/(^{176}Hf/^{177}Hf_{chondrite}) - 1) \times 10^4$) plot of magmatic and detrital zircons **(a)** for Singhbhum craton (data from Dey et al., 2017; Chaudhuri et al., 2018; Miller et al., 2018; Sreenivas et al., 2019); **(b)** for Western Dharwar craton and Eastern Dharwar craton; **(c)** for northern part of the SGT (data from Mohan et al., 2014; Santosh et al., 2016; Yang and Santosh, 2015; Collins et al., 2015; Lancaster et al., 2015; Amaldev et al., 2016; Maibam et al., 2016; Ratheesh Kumar et al., 2016; Bhaskar Rao et al., 2017, 2020; Guitreau et al., 2017; Santosh and Shan-Shan Li, 2018; Shan-Shan Li et al., 2018); **(d)** for charnockite orthogneiss samples from different terranes in the Madurai, Trivandrum, and Nagercoil blocks of the SGT (data from Vijaya Kumar et al., 2017). CHUR - chondritic uniform reservoir, DM - depleted mantle, JH-Jack Hills zircons (Kemp et al., 2010; Bell et al., 2014). The global mean curve is from Roberts and Spencer (2015). See text for details.

(Jayananda et al., 2018; Bhaskar Rao et al., 2020 and references therein). The possibility of older crust (the Eoarchean - early Paleoarchean) is reflected by the record of $^{207}Pb/^{206}Pb$ ages of xenocrystic and detrital zircons from gneisses and metasediments as well as from modern stream sediments (Bhaskar Rao et al., 2008a, b; Sarma et al., 2012; Lancaster et al., 2015; Maibam et al., 2016; Santosh et al., 2016; Guitreau et al., 2017), as well as Pb isotope systematics in wholerocks and Sm-Nd and Lu-Hf depleted mantle model ages of wholerocks and zircon respectively (Jayananda et al., 2018 and references therein).

In the EDC, the greenstone successions are predominantly Neoarchean (2.7 to 2.5 Ga). However, some ca. 3.38–3.0 Ga zircon U-Pb ages have been reported from 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., 2013; Maibam et al., 2016; Shan-Shan Li et al., 2018). 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) all across the EDC around 2.72-2.67 Ga and 2.58-2.54 Ga (Balakrishnan et al., 1999; Jayananda et al., 2013, 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 region, that is about 300 km northwest of the exposed basement in the EDC, also yield ages between 2.7 and 2.5 Ga. The initial $^{176}Hf/^{177}Hf$ values lie in a narrow range corresponding to ε_{Hf}(t) values of +3.7 to +8.0 indicating that the magmatic precursors of the gneisses within the basement represent juvenile magmatism around 2700 Ma (Bhaskar Rao et al., 2017 and Fig. 5b). Similar ages (2.6-2.55 Ga) have been recorded for charnockites in the Karimnagar Granulite Terrain (unpubl. data with authors) indicating the extant of Neoarchean crust of the EDC in the northern part of the Dharwar craton.

Flanking the WDC, Paleo- to Neoarchean (3.55-2.6 Ga) high-grade supracrustals and felsic gneisses (charnockite-enderbite) have been described from the Coorg, BR Hills and the Wynad region of the SGT. In the Coorg massif, U-Pb zircon age data for meta igneous rocks define magmatic events at 3.5 Ga, 3.2 Ga, 2.7 Ga and 2.5-2.4 Ga, while metasedimentary rocks indicate discrete zircon age populations between 3.4 and 1.3 Ga (Santosh et al., 2015, 2016; Amaldev et al., 2016). In the Biligiri Rangan massif, TTG 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 ε_{Hf}(t) between +4.1 and -2.5 for tonalitic gneisses. In the Wynad region, Qiong-Yan Yang et al. (2016) reported metaultramafic 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 (Fig. 5b and Bhaskar Rao et al., 2020 and references therein).

Published zircon U-Pb ages and Hf-isotopic compositions for the Dharwar craton and the Archean domains of the SGT are plotted separately in Figs. 5b and c respectively, where data on magmatic zircon grains separated from metaigneous rock samples and detrital zircon grains from metasedimentary rocks as well as from modern river sand samples are plotted. Zircon populations in the Paleo-Mesoarchean TTG suites generally have radiogenic initial Hf-isotopic compositions, plotting close to the DM and CHUR curves indicating a predominantly juvenile character of protoliths. In the Neoarchean samples, the zircons of ca. 2700 Ma ages have a predominantly juvenile signatures, while the ca. 2.5 Ga group show a wide range of initial $\varepsilon_{Hf}(t)$ values indicating both juvenile and evolved magmatic protoliths consistent with petrological and geochemical evidence for the involvement of both calc-alkaline and anatectic magma types, well established in the EDC (see foregoing section). There is a striking similarity in the distribution of data from the low- and high-grade terranes (Figs. 5b and 5c). We interpret that the Archean zircon populations from WDC, EDC and the northern part of the SGT represent multiple episodes of juvenile crust accretion that fall into two major time intervals. The older interval comprised a protracted period between 3.45 to 3.17 Ga, while the younger, relatively short interval is constrained between 2.7 to 2.5 Ga. Recycling of older (Paleo-Mesoarchean) crust dominated the intervening time span. Most interestingly, the Neoarchean crustal growth processes in the entire region (WDC, EDC and the Archean parts of the SGT) culminated in the end-Archean thermo-tectonic event(s) (D_2M_2) around ca. 2.56–2.50 Ga. These events are associated with terrane accretion and collision(s), for instance, between WDC and EDC and 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-T-t paths suggesting prolonged thermal buffering of the lower and middle crust (Chardon et al., 2011; Peucat et al., 2013; Jayananda et al., 2018). The distribution of Hf-isotopic compositions in zircons from the Neoarchean crustal domains attest to the end-Archean orogenic processes that underpin the present crustal configuration of the craton.

Over last 15 years, wholerock Sm-Nd and zircon U-Pb dating in the Madurai, Trivandrum and Nagercoil blocks of the SGT (Fig. 4) have led to resolution of individual terranes with distinct ages, which accreted to the southern margin of the Dharwar craton during the global Pan-African Orogeny (e.g., Ghosh et al., 2004; Clark et al., 2015; Collins et al., 2014; Plavsa et al., 2015; Vijaya Kumar et al., 2017; Santosh, 2020). As summarised by Vijaya Kumar et al., (2017) the new zircon U-Pb ages for charnockite orthogneisses in these terranes provide evidence for four distinct magmatic episodes, which include; ca. 2.62–2.46 Ga in the northern Madurai block, ca. 2.05–1.84 Ga in the Trivandrum and Nagercoil blocks, ca. 1.0–0.9 Ga in the southern Madurai block, southeast of the Suruli shear zone, and ca. 0.80–0.76 Ga widespread in the southern and eastern Madurai block. Based on zircon age-Hf isotopes and wholerock Sm-Nd isotopic systematics (Fig. 5d), the protoliths of the Paleoproterozoic gneisses in the Trivandrum-Nagercoil blocks and those of the earliest Neoproterozoic in the southern Madurai block can be characterised as juvenile calc-alkaline magmas. The magma generation during the other two episodes (ca. 2.62-2.46 Ga and 0.80-0.76 Ga) involved ancient crustal components up to ca. 3.1 Ga.

DISCUSSION AND SUMMARY

A Glimpse of the Hadean Protocrust

An important observation concerns the remarkable similarity of the Singhbhum and Jack Hills Hadean-Eoarchean zircon populations in terms of their Hf-isotope systematics. In the context of the debate on time scales and mechanisms of Earth's early silicate differentiation and the nature of primitive crust, it is instructive to recall that the earlier studies on the Jack Hills detrital zircons suggested their origin in felsic crust at ~4.4 Ga and interaction with liquid water (Wilde et al., 2001; Valley et al., 2002) and that the Hf isotope evolution diagrams (e.g., Harrison, 2009; Kemp et al., 2010) showed a highly scattered distribution from extreme values ranging between +16 and -14 $\varepsilon_{Hf}(t)$ units. Interpretations based on concurrent Pb-Hf isotope analysis with reference to Chondritic Uniform Reservoir (CHUR) model suggested that the magmatic sources of nearly all zircons were geochemically enriched ($^{176}Lu/^{177}Hf \sim 0.01$) suggesting extraction from a primitive mantle as early as 4.5 Ga and such an enriched reservoir contributed to the felsic melts until ca. 3.8 Ga that were parental to the Jack Hills zircons (Iizuka et al., 2017 and references therein). A majority of the Singhbhum ancient zircons can be related to TTG melts produced around 4.3-4.2 Ga and 3.95 Ga (Chaudhuri et al., 2018; Sreenivas et al., 2019). In some Archean cratons, e.g., Isua greenstone belt, Greenland, the 3.8 Ga age has been interpreted as the time at which solidification of the magma ocean may have been completed and the tectonic regime changed from stagnant-lid to mobile-lid (e.g., Furmes et al., 2007). At this Hadean-Eoarchean transition, several gneissic suites (e.g., Acasta, Itsaq and Anshan) show near chondritic $\varepsilon_{Hf}(t)$ values (Kemp et al., 2015). This suggests limited or no involvement of Hadean crustal sources in the generation of many Eoarchean felsic crustal rock components. In the Singhbhum and Dharwar cratons, the earliest appearance of strongly radiogenic zircon $\varepsilon_{Hf}(t)$ values are noted in the age intervals between 3.6-3.5 Ga (Singhbhum) and 3.5-3.4 Ga (WDC), suggesting the time of earliest mantle depleting events in these cratons. This is similar to what is recorded in cratons such as Wyoming, which also records a drastic shift in $\varepsilon_{Hf}(t)$ values at 3.6-3.5 Ga (Mueller and Wooden, 2012). In the Singhbhum and Dharwar cratons, there is evidence for extended periods (about 400-300 million years) of magmatism from depleted mantle sources during the Paleo-Mesoarchean. Such a feature suggest that large volumes of felsic crust may have been extracted from the mantle sources of these cratons prior to ca. 3.6-3.5 Ga although there is no direct evidence for this in the geologic record. The overall range of $\varepsilon_{Hf}(t)$ values however suggests variable involvement of older crust in the magma genesis, but clearly no older than 3.7 Ga, also implying no involvement or complete decoupling from the Hadean-type enriched mantle reservoir. Potential scenarios to explain such drastic shifts in $\varepsilon_{Hf}(t)$ from unradiogenic to radiogenic values include: (i) subduction-like processes involving destruction of older crust and addition of new crust (Næraa et al., 2012) and (ii) major mantle overturn events that may lead to establishment of thick mafic plateaux (Griffin et al., 2014).

The Transition to Plate Tectonics

The pre-3.0 Ga crusts in both Singhbhum and Dharwar cratons share several common features, which include: longevity (>300 million years) of essentially continuous juvenile magmatism, dome and basin structural style, contemporaneity between plutonic and supracrustal cycles within the cratons, presence of both Al-depleted and enriched TTGs. Thermo-mechanical and fluid dynamic considerations to explain the Archean dome and basin structures invoke chiefly Rayleigh-Taylor Instabilities (RTIs) that develop at the interface between the gravitationally unstable less dense and buoyant felsic juvenile crust and the overlying dense mafic crust (Wiemer et al., 2018 and references therein). Emphasis is on the role of gravitational reorganization of hot and reversely stratified crust that forms in situations like wholesale mantle overturns or mantle upwellings/mantle plumes effecting global-scale mantle dynamics. In this context, generation of the voluminous TTGs that occupy the granitic domal structures is directly linked to polybaric infra-crustal magma differentiation and partial melting at the base of thick mafic–ultramafic edifices such as at oceanic plateaux under conditions of high thermal gradients related to mantle plumes. Several authors observed similarity between the Singhbhum and Pilbara cratons on many counts: depositional and magmatic histories of Paleo-Mesoarchean granites and greenstones, the deformation episodes, proximity of the two cratons in terms of paleo-positions of nearly co-eval ca. 2.8 to 2.7 Ga intrusive dyke swarms (also see Chaudhuri, 2020), while the Dharwar craton also draws a broad analogy in terms of the structural pattern. Such considerations prompt the relevance of autochthonous tectonic models involving within plate magmatism and melting at the base of a thickened oceanic plateau possibly affected by recurrent mantle plumes accounting for the generation of TTGs (Prabhakar and Bhattacharya, 2013; Dey et al., 2017; Sreenivas et al., 2019; Bhaskar Rao et al., 2020). On the other hand, the operation of some form of plate tectonics since ca. 3.6-3.5 Ga in the Singhbhum and Dharwar cratons cannot be precluded based on the presence of some zircons with unradiogenic $\varepsilon_{Hf}(t)$ values (Fig. 5b) and the calc-alkaline affinity of the igneous rocks. This could imply the relevance of episodic short lived subduction tectonics alternating with mantle plume/cyclic gravitational overturns through the Paleo-Mesoarchean period. This mode of concurrent juvenile felsic and mafic crust generation with associated delamination of residual mafic crust could characterize the pre-plate tectonic scenario prior to ca. 3.2-3.0 Ga period (Hawkesworth et al., 2017) that may correspond to 'lid breaking' event(s) (Bell et al., 2018). Indeed, plate tectonic models, some involving formation and subduction of oceanic plateaux were proposed by several authors (Mukhopadhyay et al., 2008; Jayananda et al., 2015, 2018; Santosh et al., 2016; Sreenivas et al., 2019) for the Paleo-Mesoarchean crustal growth in the Singhbhum and Dharwar cratons.

The global compilations of U-Pb zircon ages for orogenic granitoids (e.g., Condie and Aster, 2010 and references therein) indicate a predominant peak around 2.7 Ga suggesting that the Neoarchean represents, by far the most productive and dynamic phase in the growth of continental crust. At the present stage, the Neoarchean of the Singhbhum craton has been rather poorly explored in terms of zircon age-Hf isotopic systematics. By contrast, the Neoarchean crust is widespread in the WDC, EDC and the northern part of SGT and relatively well-studied. Interestingly however, major Neoarchean 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 juvenile 2.7 Ga crust in the Dharwar craton is rather subdued compared to many other cratons (e.g., Condie and Aster, 2010; Cawood et al., 2013) which might reflect a data gap or due to poor preservation owing to extensive reworking/melting *shortly* after formation. Indeed, most of the dated ca. 2.7 Ga juvenile TTGs in the EDC occur as enclaves in the ca. 2.55 Ga intrusive granitoids that also include a dominant juvenile magmatic component as stated above. The development of the Neoarchean crust of the Dharwar craton have been explained in terms of plate tectonic models in many studies. For instance, the EDC was visualised as a wide-hot orogen involving a Lateral Constrictional Flow (LCF) mode of EDC, while the WDC acted as an indenter. Several authors proposed involvement of continental and oceanic arcs generating both juvenile and recycled crustal material between ~2.75 and 2.55 Ga (Dey et al., 2016; Jayananda et al., 2018; Bhaskar Rao et al., 2020 and references therein). 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. We consider that the geological and seismic data for the Dharwar craton offer a rare perspective to the global Neoarchean 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.

In the SGT, the two prominent periods of juvenile crust addition during late Paleoproterozoic around ca. 2.0-1.9 Ga and early Neoproterozoic around 1.0-0.9 Ga have been ascribed to arc magmatism and terrane accretion (Vijaya Kumar et al., 2017). The recognition of these juvenile crust forming episodes is significant to the evolving models that attempt to reconstruct the position of southern India in the Gondwana Supercontinent.

Acknowledgements: We thank Dr. V.M. Tiwari, Director, CSIR-NGRI for continued support and the editorial board for inviting us to contribute an article for the special volume coinciding with diamond jubilee celebration of CSIR-NGRI. We acknowledge financial support initially from CSIR, NGRI, NIO and DST and of late from MoES for establishment of LA-MC-ICPMS facility. We appreciate the contributions especially Dr. B. Vijaya Gopal in this regard. The authors are grateful to Dr. V. Ravikant and Dr. Sukanta Dey for their critical review, valuable suggestions and comments.

References

Amaldev, T., Santosh, M., Tang, L., Baiju, K. R., Tsunogae, T. and Satyanarayanan, M. (2016) Mesoarchean convergent margin processes and crustal evolution: Petrologic, geochemical and zircon U–Pb and Lu–Hf data from the Mercara Suture Zone, southern India. Gondwana Res., v.37, pp.182-204.

Anil Kumar., Gopalan, K. and Bhandari, N. (1999) $^{147}Sm/^{143}Nd$ and $^{87}Rb/^{87}Sr$ ages of the eucrite Piplia Kalan. Geochim. Cosmochim. Acta, v.63, pp.3997-4001.

Anil Kumar, Parashuramulu, V., Shankar, R. and Besse, J. (2017) Evidence for a Neoarchean LIP in the Singhbhum craton, eastern India: implications to Vaalbara supercontinent. Precambrian Res., v.292, pp.163-174.

Augé, T., Cocherie, A., Genna, A., Armstrong, R., Guerrot, C., Mukherjee, M.M. and Patra, R. N. (2003) Age of the Baula PGE mineralization (Orissa, India) and its implications concerning the Singhbhum Archaean nucleus. Precambrian Res., v.121(1-2), pp.85-101.

Baksi, A.K. (1978) Use of an AEI MSIOS Mass Spectrometer for $^{40}Ar/^{39}Ar$ dating. Proc. Mass. Spec. Conf., BARC, Bombay.

Balakrishnan, S., Rajamani, V. and Hanson, G.N. (1999) U-Pb ages for zircon and Titanite from the Ramagiri area, southern India: Evidence for accretionary origin of the eastern Dharwar craton during the late Archaean. Jour. Geol., v.107, pp.69-86.

Bandyopadhyay, P.K., Chakrabarti, A.K., Deomurari, M.P. and Misra, S. (2001) 2.8 Ga old anorogenic granite-acid volcanics association from western margin of the Singhbhum-Orissa Craton, eastern India. Gondwana Res., v.4(3), pp.465-475.

Basu, A.R., Bandyopadhyay, P.K., Chakrabarti, R. and Zou, H. (2008) Large 3.4 Ga algoma-type BIF in the Eastern Indian Craton. Geochim. Cosmochim. Acta, Supplement., v.72(12), p.A59.

Bédard, J.H. (2018) Stagnant lids and mantle overturns: implications for Archaean tectonics, magma genesis, crustal growth, mantle evolution, and the start of plate tectonics. Geosci. Front., v.9, pp.19–49.

Bell, E.A., Harrison, T.M., Issaku, E.K. and Young, E.D. (2014) Eoarchean crustal evolution of the Jack Hills zircon source and loss of Hadean crust. Geochim. Cosmochim. Acta, v.146, pp.27-42.

Bhaskar Rao, Y.J., Janardhan, A.S., Vijaya Kumar, T., Narayana, B.L., Dayal, A.M., Taylor, P.N. and Chetty, T.R.K. (2003) Sm-Nd model ages and Rb-Sr isotopic systematics of charnockite gneisses across the Cauvery Shear Zone, southern India: Implications to the Archaean - Neoproterozoic terrane boundary in the Southern Granulite Terrain. *In:* M. Ramakrishnan (Ed.), Mem. Geol. Soc. India, no.50, pp.297-317.

Bhaskar Rao, Y.J., Vijaya Kumar, T., Krishna, K.V.S.S. and Tomson, J.K. (2008a) The Emerging Pattern of Crust-formation and Recycling History in the Precambrian Dharwar Craton and the Southern Granulite Terrain, Southern India: Constraints from Recent Geochronological and Isotopic Results. Mem. Geol. Soc. India, no.74, pp.147-168.

Bhaskar Rao, Y.J., Griffin, W.L., Ketchum, J., Pearson, N.J., Beyer, E. and O'Reilly, S.Y. (2008b) An outline of juvenile crust formation and recycling history in the Archaean western Dharwar craton, from zircon *in situ* U–Pb dating and Hf-isotopic compositions. Goldschmidt conference. Geochim. Cosmochim. Acta, v.72, A81.

Bhaskar Rao, Y.J., Sreenivas, B., Vijaya Kumar, T., Namrata Khadke, Kesava Krishna, A. and Babu, E.V.S.S.K. (2017) Evidence for Neoarchean basement for the Deccan volcanic flows around Koyna-Warna region, western India: zircon U-Pb age and Hf isotopic results. Jour. Geol. Soc. India, v.90, pp.752-760.

Bhaskar Rao, Y.J., Vijaya Kumar, T., Sreenivas, B. and Babu, E.V.S.S.K. (2020). A Review of Paleo- to Neoarchean crustal evolution in the Dharwar craton, Southern India and the transition towards a Plate Tectonic regime. Episodes, v.43(1), p.51-68.

Biswajit Mandal., Rao, VV., Sarkar, D., Bhaskar Rao, Y.J., Raju, S., Karuppannan, P. and Sen, M.K. (2018) Deep crustal seismic reflection images from the Dharwar craton, Southern India—evidence for the Neoarchean subduction. Geophys. Jour. Internat., v.212(2), pp.777-794.

Borah, K., Rai, S.S., Prakasam, K.S., Gupta, S., Priestley, K. and Gaur, V.K. (2014) Seismic imaging of crust beneath the Dharwar Craton, India, from ambient noise and teleseismic receiver function modelling. Geophys. Jour. Internat., v.197(2), pp.748-767.

Bouhallier, H., Choukroune, P. and Ballèvre, M. (1993) Diapirism, bulk homogeneous shorteningnd transcurrent shearing in the Archaean Dharwar craton: the Holenarsipur area, southern India. Precambrian Res., v.63, pp.43–58.

Cawood, P.A., Hawkesworth C.J. and Dhuime B. (2013), The continental record and the generation of continental crust. Geol. Soc. Amer. Bull., v.125(1–2), pp.14–32.

Chadwick, B., Vasudev, V., Hegde, G.V. and Nutman, A.P. (2007) Structure and SHRIMP U/Pb zircon ages of granites adjacent to the Chitradurga schist belt: implications for Neoarchean convergence in the Dharwar craton, southern India. Jour. Geol. Soc. India, v.69, pp.5–24.

Chardon, D., Jayananda, M. and Peucat, J.J. (2011) Lateral constructional flow of hot orogenic crust: insights from the Neoarchean of South India, geological and geophysical implications for orogenic plateaux. Geochemistry, Geophysics, Geosystems, v.12, Q02005.

Chaudhuri, T. (2020) A review of Hadean to Neoarchean crust generation in the Singhbhum Craton, India and possible connection with Pilbara Craton, Australia: The geochronological perspective. Earth Sci. Rev., v.202, 103085.

Chaudhuri, T., Wan, Y., Mazumder, R., Ma, M. and Liu, D. (2018) Evidence of enriched, Hadean mantle reservoir from 4.2-4.0 Ga zircon xenocrysts from Paleoarchean TTGs of the Singhbhum Craton, Eastern India. Scientific reports, v.8(1), pp.1-12.

Chetty, T.R.K. and Santosh, M. (2013) Proterozoic orogens in southern Peninsular India: contiguities and complexities. Jour. Asian Earth Sci., v.78, pp.39-53.

Clark, C., Healy, D., Johnson, T., Collins, A.S., Taylor, R.J., Santosh, M. and Timms, N.E. (2015) Hot orogens and supercontinent amalgamation: A Gondwanan example from southern India. Gondwana Res., v.28(4), pp.1310-1328.

Collins, A.S. and Pisarevsky, S.A. (2005) Amalgamating eastern Gondwana, the evolution of the circum-Indian orogens. Earth Sci. Rev., v.71, pp.229–270.

Collins, A.S., Clark, C. and Plavsa, D. (2014) Peninsular India in Gondwana: The tectonothermal evolution of the Southern Granulite terrane and its Gondwanan counterparts. Gondwana Res., v.25, pp.190–203.

Condie, K.C. and Aster, R.C. (2010) Episodic zircon age spectra of orogenic granitoids: the supercontinent connection and crustal growth. Precambrian Res., v.180, pp.227–236.

Dey, S (2013) Evolution of Archean crust in the Dharwar craton: the Nd isotope record. Precambrian Res., v.227, pp.227-246.

Dey, S., Topno, A., Liu, Y. and Zong, K. (2017) Generation and evolution of Paleoarchean continental crust in the central part of the Singhbhum craton, eastern India. Precambrian Res., v.298, pp.268-291.

Dey, S., Mitra, A., Nandy, J., Mondal, S., Topno, A., Liu, Y. and Zong, K. (2019) Early crustal evolution as recorded in the granitoids of the Singhbhum and Western Dharwar cratons. Earth's Oldest Rocks, pp.741-792.

Dey, S., Nayak, S.K., Mitra, A., Zong, K. and Liu, Y (2020) Mechanism of Paleoarchean continental crust formation as archived in granitioids from the northern part of Singhbhum craton, eastern india. Geol. Soc., London, Spec. Publ., v.489(1), pp.189-214.

Dhuime, B., Wuestefeld, A. and Hawkesworth, C.J. (2015) Emergence of modern continental crust about 3 billion years ago. Nature Geosci., v.8(7), pp.552-555.

Furnes, H., de Witt, M., Staudigel, H., Rosing, M. and Muehlenbachs, K. (2007) A vestige of Earth's oldest ophiolite. Science, v. 315, pp.1704–1707.

Ghosh, J.G., de Wit, M.J. and Zartman, R.E. (2004) Age and tectonic evolution of Neoproterozoic ductile shear zones in the Southern Granulite Terrane of India, with implications for Gondwana studies. Tectonics, v.23(3), pp.TC3006.

Goswami, J.N., Misra, S., Wiedenbeck, M., Ray, S.L. and Saha, A.K. (1995) 207Pb/206Pb ages from the OMG, the oldest recognized rock unit from Singhbhum–Orissa Iron Ore craton, E. India. Curr. Sci., v.69, pp.1008–1012.

Griffin, W.L., Belousova, E.A., O'Neill, C., O'Reilly, S.Y., Malkovets, V. and Pearson, N.J. (2014) The world turns over: Hadean-Archean crust-mantle evolution. Lithos, v.189, pp.2-15

GSI (1995) Geological and Mineral map of Tamil Nadu and Pondicherry (scale 1:0.5 million), Geol. Surv. India, Kolkata.

Guitreau, M., Mukasa, S.B., Loudin, L. and Krishnan, S. (2017) New constraints on the early formation of the Western Dharwar Craton (India) from igneous zircon U-Pb and Lu-Hf isotopes. Precambrian Res., v302, pp.33-49.

Harrison, T.M. (2009) The Hadean crust: evidence from > 4 Ga zircons. Annual Rev. Earth Planet. Sci., v.37, pp.479-505.

Hawkesworth, C.J., Cawood, P.A., Dhuime, B. and Kemp, A.I.S. (2017) Earth's continental lithosphere through time. Annual Rev. Earth Planet. Sci., v.45, pp.169-198.

Iizuka, T., Takao Yamaguchi, Keita Itano and Kazue Suzuki (2017) What Hf isotopes in zircon tell is about crust-mantle evolution. Lithos, v.274-275, pp.304-327.

Jayananda, M., Peucat, J.-J., Chardon, D., Krishna Rao, B. and Corfu, F. (2013) Neoarchean greenstone volcanism, Dharwar craton, Southern India: Constraints from SIMS zircon geochronology and Nd isotopes. Precambrian Res., v.227, pp.55–76.

Jayananda, M., Gireesh, R.V., Sekhamo, Kowete-u and Miyazaki, T. (2014) Coeval Felsic and Mafic Magmas in Neoarchean Calcalkaline Magmatic Arcs, Dharwar Craton, Southern India: Field and Petrographic Evidence from Mafic to Hybrid Magmatic Enclaves and Synplutonic Mafic Dykes. Jour. Geol. Soc. India, v.84(1) pp.5–28.

Jayananda, M., Chardon, D., Peucat, -J.-J. and Fanning, C.M. (2015) Paleo- to Mesoarchean TTG accretion and continental growth, western Dharwar craton, southern India: SHRIMP U-Pb zircon geochronology, whole-rock geochemistry and Nd-Sr isotopes. Precambrian Res., v.268, pp.295–322.

Jayananda, M., Santosh, M. and Aadhiseshan, K.R. (2018) Formation of Archean (3600–2500 Ma) continental crust in the Dharwar Craton, southern India. Earth Sci. Rev., v.181, pp.12-42.

Kemp, A.I.S., Wilde, S.A., Hawkesworth, C.J., Coath, C.D., Nemchin, A., Pidgeon, R.T., Vervoort, J.D. and DuFrane, S.A. (2010) Hadean crustal evolution revisited: new constraints from Pb-Hf isotope systematics of the Jack Hills zircons. Earth Planet. Sci. Lett., v.296, pp.45-56.

Kemp, A.I.S., Hickman, A.H., Kirkland, C.L. and Vervoort, J.D. (2015) Hf isotopes in detrital and inherited zircons of the Pilbara Craton provide no evidence for Hadean continents. Precambrian Res., v.261, pp.112-126.

Lancaster, P.J., Dey, S., Storey, C.D., Mitra, A.M. and Bhunia, R.K. (2015) Contrasting crustal evolution processes in the Dharwar craton: Insights from detrital zircon U–Pb and Hf isotopes. Gondwana Res., v.28, pp.1361–1372.

Maibam, B., Gerdes, A. and Goswami, J.N. (2016) U-Pb and Hf isotope records in detrital and magmatic zircon from eastern and western Dharwar craton, southern India: evidence for coeval Archaean crustal evolution.

Precambrian Res., v.275, pp.496–512.
Miller, S.R., Mueller, P.A., Meert, J.G., Kamenov, G.D., Pivarunas, A.F., Sinha, A.K. and Pandit, M.K. (2018) Detrital zircons reveal evidence of Hadean crust in the Singhbhum craton, India. Jour. Geol., v.126, pp.541-552.
Misra, S., Deomurari, M.P., Wiedenbeck, M., Goswami, J.N., Ray, S. and Saha, A.K. (1999) $^{207}Pb/^{206}Pb$ zircon ages and the evolution of the Singhbhum craton, eastern India: an ion microprobe study. Precambrian Res., v.93, pp.139-151.
Mitra, A., Dey, S., Zong, K. and Liu, Y. (2019) Building the core of a Paleoarchean continent: evidence from granitoids of Singhbhum craton, eastern India. Precambrian Res., v.335, 105436.
Mohan, M.R., Satyanarayanan, M., Santosh, M., Sylvester, P.J., Tubrett, M., and Lam, R. (2013) Neoarchean suprasubduction zone arc magmatism in southern India. Geochemistry and U-Pb geochronology and Hf isotopes of Sittampundi anorthosite complex. Gondwana Res., v. 23, pp.539–557.
Mueller, P.A. and Nutman, A.P. (2017) The Archean-Hadean Earth: modern paradigms and ancient processes. The Web of Geological Sciences Advances Impacts and Interactions II, v.523, pp.175-237.
Mueller, P.A. and Wooden, J.L. (2012) Trace element and Lu-Hf systematics in hadean-archean detrital zircons: implications for crustal evolution. Jour. Geol., v.120, pp.15-29.
Mukhopadhyay, D. and Matin, A. (2020) The architecture and evolution of the Singhbhum Craton. Episodes, v.43(1), pp.19-50.
Mukhopadhyay, J., Beukes, N.J., Armstrong, R.A., Zimmermann, U., Ghosh, G. and Medda, R.A. (2008) Dating the oldest greenstone in India: a 3.51-Ga precise U-Pb SHRIMP zircon age for dacitic lava of the Southern Iron Ore Group, Singhbhum craton. Jour. Geol., v.116, pp.449-461.
Næraa, T., Schersten, A., Rosing, M.T., Kemp, A.I.S., Hoffmann, J.E., Kokfelt, T.F. and Whitehouse, M.J. (2012) Hafnium isotope evidence for a transition in the dynamics of continental growth 3.2 Gyr ago. Nature, v.485, pp.627-630.
Naha, K., Srinivasan, R. and Jayaram, S. (1990) Structural evolution of the peninsular gneiss—An early Precambrian migmatitic complex from South India. Geologische Rundschau, v.79(1), pp.99-109.
Naqvi, S.M. (2005) Geology and Evolution of the Indian Plate (From Hadean to Holocene: 4 Ga to 4 Ka). Capital Publishing, New Delhi, 450p.
Nelson, D., Bhattacharya, H.N., Thern, E.R. and Altermann, W. (2014) Geochemical and ion-microprobe U-Pb zircon constraints on the Archean evolution of Singhbhum Craton, eastern India. Precambrian Res., v.255, pp.412-432.
Olierook, H.K., Clark, C., Reddy, S.M., Mazumder, R., Jourdan, F. and Evans, N.J. (2019) Evolution of the Singhbhum Craton and supracrustal provinces from age, isotopic and chemical constraints. Earth Sci. Rev., v.193, pp.237-259.
Pandey, O.P., Mezger, K., Ranjan, S., Upadhyay, D., Villa, I.M., Nägler, T.F. and Vollstaedt, H. (2019) Genesis of the Singhbhum Craton, eastern India; implications for Archean crust-mantle evolution of the Earth. Chemical Geol., v.512, pp.85-106.
Peucat, J.J., Jayananda, M, Chardon, D, Capdevila, R, Fanning, M. M. and Paquette J.L. (2013) The lower crust of the Dharwar Craton, Southern India: Patchwork of Archean granulitic domains. Precambrian Res., v.227, pp.4-28.
Plavsa, D., Collins, A.S., Payne, J.L., Foden, J.D., Clark, C. and Santosh, M. (2014) Detrital zircons in basement metasedimentary protoliths unveil the origins of southern India. Geol. Soc.Amer. Bull., v.126, no.5–6, pp.791–811.
Prabhakar, N. and Bhattacharya, A., (2013) Paleoarchean thrust-and-fold belt tectonics in the Singhbhum craton, eastern India. Precambrian Res., v.231, pp.106-121.
Prantik Mandal, Kumar, P., Sreenivas, B., Babu, E.V.S.S.K. and Bhaskar Rao, Y.J. (2021) Variations in crustal and lithospheric structure across the Eastern Indian Shield from passive seismic source imaging: Implications to changes in the tectonic regimes and crustal accretion through the Precambrian. Precambrian Res., v.360, pp.106-207.
Qiong-Yan Yang and Santosh, M. (2015) Zircon U-Pb geochronology and Lu–Hf isotopes from the Kolar greenstone belt, Dharwar Craton, India: implications for crustal evolution in an ocean trench continent transect. Jour. Asian Earth Sci., v.113, pp.797–811.
Qiong-Yan Yang, Santosh, M., Ganguly, S., Arun-Gokul, J., Dev, S.G.D., Tsunogae, T., Shaji, E., Dong, Y.P. and Manikyamba, C. (2016) Melt-fluid infiltration in Archean suprasubduction zone mantle wedge: evidence from geochemistry, zircon U-Pb geochronology and Lu–Hf isotopes from Wynad, southern India. Precambrian Res., v.281, pp.101–127.
Radhakrishna, B.P. and Naqvi, S.M. (1986) Precambrian continental crust of India and its evolution. Jour. Geol., v.94, pp.145-166.
Ramakrishnan, M. and Vaidyanadhan, R. (2008) Geology of India. (vol. I) Geological Society of India, Bangalore, 556p.
Ratheesh Kumar, R.T., Santosh, M., Yang, Q.-Y., Iswar Kumar, C., Chen, N.S. and Sajeev, K. (2016) Archean tectonics and crustal evolution of the Biligiri Rangan block, southern India. Precambrian Res., v.275, pp.406–428.
Ravi Kumar, M., Arun Singh, Bhaskar Rao, Y.J., Srijayanthi, G., Satyanarayana, H.V. and Sarkar, D. (2018) Vestiges of Precambrian subduction in the south Indian shield? – A seismological perspective. Tectonophysics, v.740-741, pp.27-41.
Reddy, P.R., Rajendra Prasad, B., Vijaya Rao, V., Sain, K., Prasada Rao, P., Khare, P. and Reddy, M.S. (2003) Deep seismic reflection and refraction/wide angle reflection studies along Kuppam–Palani transect in the southern granulite terrain of India. *In:* Ramakrishnan, M. (Ed.), Tectonics of SouthernGranulite Terrain, Kuppam– Palani Geotransect. Mem. Geol. Soc. India, v.50, pp.79–106.
Roberts, N.M.W. and Spencer, C.J. (2015) The zircon archive of continent formation through time. In: Roberts, N.M.W., Van Kranendonk, M., Parman, S., Shirey, S., Clift, P.D. (Eds.), Continent Formation through Time. Geol. Soc., London, Spec. Publ., v.389, pp.197–225.
Santosh, M. (2020) The Southern Granulite Terrane: A synopsis. Episodes, v.43(1), pp.109-123.
Santosh, M., Maruyama, S. and Sato, K. (2009) Anatomy of a Cambrian suture in Gondwana: Pacific-type orogeny in southern India? Gondwana Res., v.16, pp.321–341,
Santosh, M., Yang, Q.Y., Shaji, E., Mohan, M.R., Tsunogae, T. and Satyanarayanan, M. (2016) Oldest rocks from Peninsular India: evidence for Hadean to Neoarchean crustal evolution. Gondwana Res., v.29(1), pp.105-135.
Sarkar, S.C. and Gupta, A. (2012) Crustal Evolution and Metallogeny in India. Cambridge University Press, Cambridge, p.840.
Sarma, D.S., McNaughton, N.J., Belusova, E., Ram Mohan, M. and Fletcher, I.R. (2012) Detrital zircon U–Pb ages and Hf-isotope systematics from the Gadag Greenstone Belt: Archean crustal growth in the western Dharwar Craton, India. Gondwana Res., v. 22, pp.843–854.
Sengupta, S., Paul, D.K., De Laeter, J.R., McNaughton, N.J., Bandopadhyay, P.K. and De Smeth, J.B. (1991) Mid-Archaean evolution of the eastern Indian craton: geochemical and isotopic evidence from the Bonai pluton. Precambrian Res., v.49(1-2), pp.23-37.
Shan-Shan Li, M. Santosh, Sohini Ganguly, P.V. Thanooja, K. Sajeev, Arijit Pahari, and C. Manikyamba, (2018) Neoarchean microblock amalgamation in southern India: Evidence from the Nallamalai Suture Zone. Precambrian Res., v.314, pp.1–27.
Sizova, E., Gerya, T., Stüwe, K. and Brown, M. (2015) Generation of felsic crust in the Archean: a geodynamic modeling perspective. Precambrian Res., v.271, pp.198-224.
Sreenivas, B., Dey, S., Bhaskar Rao, Y.J., Vijaya Kumar, T., Babu, E.V.S.S.K. and Williams, I.S. (2019) A new cache of Eoarchaean detrital zircons from the Singhbhum craton, eastern India and constraints on early Earth geodynamics. Geosci. Front., v.10(4), pp.1359-1370.
Stern, R.J. (2008) Modern-style plate tectonics began in Neoproterozoic time: An alternate interpretation of Earth tectonic history. In: Condie, K, and Pease, V. (eds.) When did plate tectonics begin? Geol. Soc. Amer., Special Papers, v.440, pp.265-280.
Tomson, J.K., Bhaskar Rao, Y.J., Vijaya Kumar, T. and Choudhary, A.K. (2013) Geochemistry and neodymium model ages of Precambrian charnockites, Southern Granulite Terrane, India: Constraints on terrane assembly. Precambrian Res., v.227, pp.295–315.
Upadhyay, D., Chattopadhyay, S., Kooijman, E., Mezger, K. and Berndt, J. (2014) Magmatic and metamorphic history of Paleoarchean tonalite-trondhjemite-granodiorite (TTG) suite from the Singhbhum craton, eastern India. Precambrian Res., v.252, pp.180-190.
Upadhyay, D., Chattopadhyay, S. and Mezger, K. (2019) Formation of Paleoarchean-Mesoarchean Na-rich (TTG) and K-rich granitoid crust of the Singhbhum craton, eastern India: constraints from major and trace element geochemistry and Sr-Nd-Hf isotope composition. Precambrian Res., v.327, pp.255-272.

Valley, J.W., Peck, W.H., King, E.M. and Wilde, S.A. (2002) A cool early Earth. Geology, v.30(4), pp.351-354.

Vasanthi, A., Singh, A.P., Niraj Kumar, Nageswara Rao, B., Satyakumar, A.V., Santosh, M. (2021) Crust-mantle structure and lithospheric destruction of the oldest craton in the Indian shield. Precambrian Res., v.362, 106280.

Vijaya Kumar, T., Bhaskar Rao, Y.J., Clark, C., Taylor, R., Tomson, J.K., Sreenivas, B., Babu, E. and Vijaya Gopal, B. (2013) Zircon U–Pb ages and Hf–isotopic compositions of Late Archean charnockites from the Biligiri Rangan, Nilgiri, Vythiri and Coorg granulite massifs, the Southern Granulite Terrain, India: constraints on terrane assembly and charnockite precursors. *In:* Fitzsimons, I., Clark, C. (Eds.), Granulites & Granulites 2013 - Hyderabad, 16-20, January, 2013, p.63.

Vijaya Kumar, T., Bhaskar Rao, Y.J., Diana Plavsa., Collins, A.S., Tomson, J.K., Vijaya Gopal, B. and Babu, E.V.S.S.K. (2017) Zircon U-Pb ages and Hf isotopic systematics of Proterozoic charnockite gneisses, southern India: constraints on crust foration, recycling and Gondwana correlations. Geol. Soc. Amer. Bull., v.129(5-6), pp.625-648.

Vijaya Rao, V., Murty, A.S.N., Dipankar Sarkar, Bhaskar Rao, Y.J., Prakash Khare, Prasad, A.S.S.S.R.S., Sridher, V., Raju, S., Rao, G.S.P., Karuppannan, Prem Kumar, N. and Mrinal K. Sen, (2015) Crustal velocity structure of the Neoarchean convergence zone between the eastern and western blocks of Dharwar Craton, India from seismic wide-angle studies, Precambrian Res., v.266, pp.282–295

Wiemer, D., Schrank, C.E., Murphy, D.T., Wenham, L. and Allen, C.M. (2018) Earth's oldest stable crust in the Pilbara Craton formed by cyclic gravitational overturns. Nature Geosci., v.11(5), pp.357-361.

Wilde, S.A., Valley, J.W., Peck, W.H. and Graham, C.M. (2001) Evidence from detritical zircons or the existence of continental crust and oceans on the Earth 4.4 Gyr ago. Nature, v.409, pp.75-178.

(Received: 18 June 2021; Revised form accepted: 15 July 2021)