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Review Article

Proterozoic Tectonics and Trans-Indian Mobile Belts: A Status Report

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The Archean cratonic nuclei in India are hemmed by Proterozoic mobile belts or fold belts. These mobile belts reveal the tectonic processes that shaped the then craton margin magmatism, sedimentation, metamorphism and deformation of crustal segments, and suturing of the cratonic blocks embedded within the peninsular Indian shield that remained more or less stable since the Cambrian. A loose spatial connection of the Eastern Ghats belt (EGB) along southeastern margin of India, through Chotanagpur granite gneiss terrain and adjoining North Singhbhum fold belt in eastern India, Central Indian tectonic zone, to Aravalli-Delhi mobile belt in northwestern India constitute the trans-Indian mobile belts with tectonic episodes apparently linked to assembly and dispersal of two major supercontinents in the Proterozoic. Beyond southern extremity of the EGB (Ongole domain), the Nellore schist belt and tectonically juxtaposed Nallamalai fold belt in southern India abuts further south against the Southern granulite terrain (SGT) with remnants of Neoarchean inheritance and Neoproterozic remobilization. SGT is a key element in unravelling trans-continental connections of India during the late Neoproterozoic marked by assembly of the Gondwana supercontinent. Despite the apparent first order connection of these belts developed under largely similar global tectonic framework, individual mobile belts show diverse rock association, metamorphic grade and geologic antiquity. In this status report we briefly review these Indian Proterozoic mobile belts and associated fold belts in the light of recently published work bearing on tectonomagmatic, structural, metamorphic and geochronological data and interpretation.

Keywords: Fold Belt; Indian Shield; Mobile Belt; Proterozoic; Supercontinent

Introduction

The cratonic fragments in India attained sufficient tectonic stability and crustal thickness by 2.5 Ga as evidenced by copious late Neoarchean granite magmatism and the beginning of an era of intracratonic sedimentary basins across the Indian shield (Meert *et al*., 2010; Saha and Mazumder, 2012). This is commensurate with the proliferation of continental passive margin shallow seas in the early Paleoproterozoic, following a global tectonic stasis in the interval 2.6-2.4 Ga (Bradley, 2011; Condie and Aster, 2010). However, the existence of regional fold belts hemming the Indian cratons, namely the Dharwar craton, Bastar craton, Singhbhum craton and Aravalli-Bundelkhand craton, suggests intermittent orogen building activity throughout the Proterozoic. From the story of trans-Indian "Mid-Proterozoic mobile belt" (Radhakrishna and Naqvi, 1986) connecting the Eastern Ghats belt, Central Indian tectonic zone and finally the Delhi-Aravalli fold belt, we have gradually evolved into a state of knowledge where these orogens have been studied in greater detail in the past decade or so to arrive at a better understanding of the Proterozoic shallow and deep crustal processes affecting the Indian shield. We also see a reasoned shift toward application of plate tectonic paradigm in order to realize a comprehensive Earth system process-response-outcome model as relevant to the Indian cratonic blocks and Proterozoic fold belts or mobile belts. In this brief report we review the recent findings on the magmatism, metamorphism and crustal

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deformation affecting mainly the cratonic margins that now exist as deeply exhumed orogens like the Eastern Ghats, and other Proterozoic fold-and-thrust belts, for a state of the art report. Since the Proterozoic sedimentary basins form the subject matter of a separate report (IUGS-INQUA volume), we do not get into their details, except in relation to the tectonic evolution of the Proterozoic orogens.

We deal mainly with the Eastern Ghats belt, North Singhbhum fold belt and Chhotanagpur Granite Gneiss terrain, Central Indian Tectonic zone, Aravalli-Delhi fold (mobile) belt, and Sothern Granulite terrain separately, in this order. All these belts have episodic tectonic history involving multiple deformation, metamorphism and magmatism, spanning for nearly 2 billion years in the Proterozoic. Recognition of ophiolite remnants from the southern India in recent years also propels us to briefly review literature on the Kandra ophiolite complex, Kanigiri ophiolitic mélange and adjoining Nallamalai fold belt occurring along the southeastern margin of the Eastern Dharwar craton, with signatures of accretionary orogenic process. These belts apparently provide spatial connection between the southern Eastern Ghats belt (Ongole domain) and the Southern Granulite terrain (Fig. 1). It may be recalled here that there is growing consensus on the existence of at least two supercontinents assembled from cratonic blocks worldwide, followed respectively by their dispersal at specific intervals in the Proterozoic. As reviewed in this article ancient Indian cratonic blocks and mobile belts suturing them are key elements not only for the assembly and dispersal of Columbia and Rodinia, but also for the Gondwana supercontinent apparently assembled toward the end-Proterozoic.

Eastern Ghats Belt

The Eastern Ghats belt plays a crucial role in understanding the evolution of superhot Proterozoic orogenic system(s) that united and dispersed continental blocks of India and east Antarctica. Recently published data on this belt not only vindicated the existing ideas and hypotheses, but also opened up new possibilities of transcontinental correlation. Independent studies from different groups presented new petrological, structural and precision geochronological data. Salient points of the updated geological history of the belt are enumerated below.

How Many Orogenic Belts within the Eastern Ghats Belt?

An interesting debate emerged recently regarding the multiplicity of orogenic cycle in the Eastern Ghats Belt (EGB). The earlier classifications based on isotopic signatures provide some hints that there are at least two global-scale orogenic imprints preserved the EGB. New petrochronological data clearly show imprints of three distinct orogenic events. The Ongole Domain constituting the southern EGB evolved during the ca. 1.7-1.54 Ga orogenesis (Henderson *et al*., 2014; Dasgupta *et al*., 2013; Sarkar and Schenk, 2014; Sarkar *et al*., 2014; 2015). The Eastern Ghats Province north of the Godavari rift, evolved during the 1.07-0.90 Ga Grenvillian orogenesis (Dasgupta *et al*., 2013; Korhonen *et al*., 2013a). The northern part of the Eastern Ghats Province and adjacent Rengali Province witnessed orogenic events during 0.55-0.50 Ga Pan African orogenesis (Chattopadhyay *et al*., 2015; Bose *et al*., 2016a). With multiple orogenic imprints, the Eastern Ghats Belt has a fascinating history to unveil.

Ongole Domain and its Connection with Columbia

The tectonic evolution of this domain has been discussed by Dasgupta *et al.* (2013). Some important data have been published subsequently regarding the source of sediment of this domain and identification of a new tectonometamorphic pulse. Metasedimentary rocks of this domain show Paleoproterozoic to Mesoarchean ancestry (Henderson *et al*., 2014; Sarkar *et al*., 2014), but opinions are divided regarding the source of sediments. While one group considered the Dharwar Craton (Sarkar *et al*., 2014), the other preferred Napier Complex (Henderson *et al*., 2014) as source. According to Dasgupta *et al.* (2013), this domain evolved as a part of the accretionary belt of Columbia between the Napier and Dharwar blocks around *ca*.1.8-1.6 Ga. Recent report of a high pressure metamorphism at *ca*. 1.54 Ga (Sarkar and Schenk, 2014; Sarkar *et al*., 2014) has been interpreted to result from the final collision of the Indian and east Antarctic blocks. Since the Ongole domain did not experience any major tectonothermal event subsequently, it is postulated that it was cratonized after *ca*. 1.54 Ga.

Eastern Ghats Province and its Connection with Rodinia

A large number occurrences of pelitic migmatites, mafic granulites and calc-silicate granulites showing UHT metamorphism are reported from the central part of this crustal province (review in Dasgupta *et al*., 2013). The work of Korhonen *et al*. (2013b) vindicates counterclockwise *P-T* evolution for the UHT granulites. However, the existing two-stage evolution of the granulites has been contradicted by Korhonen *et al*. (2013a) who argued for a single long-lived orogenic pulse (*ca*. 1.07-0.90 Ga). This debate is still alive as the other group collated additional textural and geochronological evidences (Sorcar *et al*. submitted). Another debatable issue from this terrain is the stability of osumilite which is inferred from intergrowth textures (Korhonen *et al*., 2013b). The interpreted sustained melt-osumilite interaction eventually eliminated all osumilite from the rock. Similar intergrowth could be explained as product of late-stage melt-solid interaction far away from the UHT conditions. This issue is related to the single cycle vs. multiple cycle evolution of the Eastern Ghats Province. The *ca*. 0.95-0.90 Ga metamorphic events in the Eastern Ghats Province match with the Rayner Province of east Antarctica and these two belts evolved simultaneously as a part of Rodinia (Dasgupta *et al*., 2013). UHT metamorphism in Eastern Ghats is unique and possibly developed in a back arc basin within an accretionary system (Dasgupta *et al*., 2013). The final docking was complete by *ca*. 0.90 Ga when the Eastern Ghats Province was mostly cratonized.

Evidence of Rodinia Break-up and Gondwana Assembly

Rocks of Domain 3 of Eastern Ghats province (Chilka Lake area in Odisha) show discrete rock association, *P-T* evolution and preponderance of Neoproterozoic age data, yet it was considered earlier a part of the Eastern Ghats Province. Recent petrological, fluid and age data from this domain presented a multistage evolutionary history (Bose *et al*., 2016a). The peak UHT metamorphism (900-950ºC, 8.5-9 kbar) at *ca*. 0.98 Ga (with possible clockwise *P-T* path?), was overprinted by three tectonometamorphic events at *ca*. 0.78 Ga (800ºC, 7 kbar), *ca*. 0.75 Ga (700ºC, 6 kbar) and at *ca*. 0.52 Ga (800ºC, 6 kbar). The *ca*. 0.78 Ga event has been correlated with break-up of Rodinia and the *ca*. 0.52 Ga event with Pan African metamorphism. It is argued that the Domain 3 was attached with the Prydz Bay region in east Antarctica within the framework of Rodinia, got separated at *ca*. 0.78 Ga and re-united with rest of India at *ca*. 0.52 Ga as a part of east Gondwana. It appears that the inclusion of Domain 3 within the Eastern Ghats Province is problematic.

Rengali Province and its Connection with Ur

Rengali province was initially considered as a part of Eastern Ghats Belt, albeit with contrasting petrological and geochronological histories (Mahapatro *et al*., 2012; Bose *et al*., 2015, 2016b; Chattopadhyay *et al*., 2015; Ghosh *et al*., 2016). Recent petrological, structural and geochronological investigations have established a late Archean age for the granulite facies metamorphism, which has been correlated with thermal pulses in the Singhbhum craton (Mahapatro *et al*., 2012; Bose *et al*., 2015, 2016b; Chattopadhyay *et al*., 2015; Ghosh *et al*., 2016) refuting the connection between the Rengali Province and the Bastar Craton (Misra and Gupta, 2014). This Archean metamorphism could be connected with the assembly of Ur (Mahapatro *et al*., 2012). In addition, an event of amphibolite facies metamorphism of the supracrustals along a clockwise *P-T* path at *ca*. 0.98 Ga has been reported (Chattopadhyay *et al*., 2015). It is also argued that the Rengali province witnessed regional transpression during *ca*. 0.5 Ga that resulted extrusion of middle crust over upper crust (Ghosh *et al*., 2016). Whether juxtaposition of the Rengali province with the Eastern Ghats occurred during the Grenvillian orogeny (Chattopadhyay *et al*., 2015) or Pan African orogeny (Ghosh *et al*., 2016) is a matter of debate and additional data is needed to resolve it.

Chotanagpur Granite Gneiss Complex (CGGC) and North Singhbhum fold belt (NSFB)

The Chotanagpur Granite Gneiss Complex (CGGC) is a multiply deformed and polymetamorphosed domain in the Eastern Indian shield lying to the north of and in thrust contact along South Puruliya shear zone-SPSZ or Tamar-Porapahar shear zone with the NSFB (review by Sanyal and Sengupta, 2012). Maximum age of tectonic juxtaposition of the CGGC over the NSFB is 0.92 Ga, constrained by the zircon U-Pb SHRIMP age of the alkaline rocks emplaced along SPSZ (Reddy *et al*., 2009). In spite of meagre and not so robust geochronological constraints, and paucity of data from a large tract of the CGGC, Paleoproterozoic antiquity of the belt has been suggested with relicts of high grade rocks preserved mainly in the southern part (Bankura-Santuri-Saltora -BSB sector, West Bengal) with mantles of amphibolite facies rocks of the Bihar Mica belt (BMB) in the north and RK and RT sectors in Chattisgarh bordering the Satpura mobile belt rocks in the west (Sanyal and Sengupta, 2012). The BMB rocks appear to be distinctly younger than granulite facies rocks in the south, as the basal conglomerate in the BMB contain granulite pebbles. The oldest available age for the BSB metapelitic granulites is 1.85-1.7 Ga, constraining the M1 UHT metamorphism (Chatterjee *et al.*, 2010; Maji *et al.*, 2008), while the Bengal anorthosite pluton in Bankura yielded ID-TIMS age of 1.55 Ga and suffered a later phase of metamorphism (around 0.9 Ga) indicating possible Grenvillian imprint on the CGGB (Chatterjee *et al.*, 2008).

North Singhbhum Fold Belt

Sandwiched between the Archean Singhbhum craton in the South and the Chotonagpur granite gneissic complex (CGGC) in the north, North Singhbhum fold belt (NSFB) is an important tectonic element in the evolution of the Eastern Indian shield. The E-W trending curvilinear belt is in apparent easterly continuation of the Satpura mobile belt (Fig. 1). Although direct geochronological constraints on the age of constituent units of the NSFB are only a few, the older volcanosedimentary successions (Dhanjori Group and Singhbhum Group) north of the Singhbhum shear zone possibly represent Paleoproterozoic sedimentation (Mazumder *et al.*, 2012). The rhyolites from the Chandil Formation lying north of the Dalma volcanics and in thrust contact with the CGGC along the South Puruliya shear zone (Tamar-Porapahar shear zone) has yielded zircon U-Pb SHRIMP age of 1623 Ma (Reddy *et al*., 2009 quoted in Chatterjee *et al.* 2013). Although the geochemical data from Dalma volcanics was earlier interpreted to represent a back arc setting, the deformation and greenschist to amphibolite facies metamorphism within the NSFB is interpreted in recent years as due to collision related orogenic thickening, with age of metamorphism in the interval 1.5-1.3 Ga (Mahato *et al.* 2008). North dipping

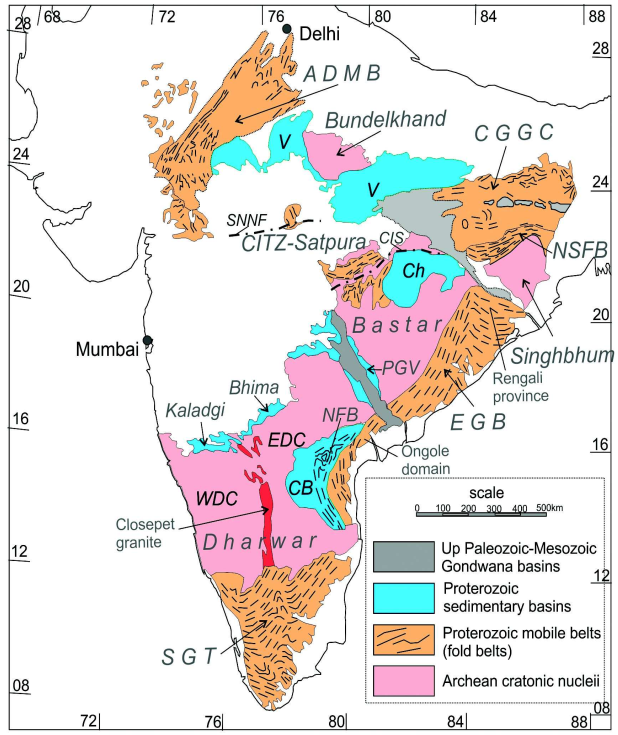

Fig. 1: Simplified geological map showing Archean cratonic nuclei and Proterozoic mobile belts in peninsular India (after map collated from various sources by Ramakrishnan and Vaidyanadhan, 2008). Tertiary and younger cover rocks are omitted. SGT = Southern granulite terrain, EGB = Eastern Ghats belt, CITZ = Central Indian tectonic zone, EDC = Eastern Dharwar craton, WDC = Western Dharwar craton, ADMB = Aravalli-Delhi mobile belt, CGGC = Chotanagpur granite gneiss complex, NSFB = North Singhbhum fold belt, PGV = Pranhita-Godavari basin, NFB = Nallamalai fold belt, CB = Cuddapah basin, Ch = Chattisgarh basin, V = Vindhyan basin

imbricate thrusts in the NSFB and internal folds and cleavages within the Singhbhum Group and absence of basement rocks resemble structures of a collisional orogeny (thin skinned tectonics). However, the tectonic model of imbricate thrusts with kyanite-staurolite grade metasediments of the central part of the NSFB thrusted over the muscovite biotite grade metasedimentary rocks further south representing foreland, needs to be reconciled with apparent northward younging of age of the volcanosedimentary successions. Further, it is still unresolved how Dalma volcanics belt and amphibolite to granulite facies rocks at the southern border of the CGGC fit in this model of collisional orogenesis.

Central Indian Tectonic Zone

The E-W to ENE-WSW trending Central Indian Tectonic Zone (CITZ), bounded by the Son-Narmada North Fault (SNNF) to the North and the Central Indian Shear (CIS) zone to the south, and lying between the North and South Indian Cratonic Blocks (NIB and SIB respectively) records >800 My of protracted Proterozoic tectono-thermal and tectono-magmatic history from Paleoproterozoic to Early Neoproterozoic. The tectonic evolution of the CITZ overlaps with two supercontinent assembly events (cf. Columbia, between 2.1 and 1.8 Ga and Rodinia, between 1.2 and 0.9 Ga). These tectono-thermal and tectono-magmatic events have been documented from the three supracrustal belts of the CITZ, which from the north to south are Mahakoshal belt, Betul belt and the Sausar Mobile Belt (SMB).

Mahakoshal Belt

The earliest of these events is marked by emplacement of late to post-tectonic granitoid bodies and associated mafic microgranular enclaves (MME) within the Mahakoshal supracrustals. The timing of magmatic emplacement of some of these granitoid bodies (e.g. Jhirgadandi Pluton) and the MMEs have been dated between 1.76 and 1.75 Ga from U-Pb Sensitive High Resolution Ion Micro-probe (SHRIMP) zircon $^{206}Pb/^{238}U$ ages (Bora *et al.*, 2013). While this Paleoproterozoic felsic plutonism has been correlated with continental collision during the assembly of Columbia (Bora and Kumar, 2015), there are also suggestions of mantle plume-activated lithospheric thinning and rifting of the Mahakoshal belt, which is tentatively constrained at ca. 1.6 Ga (Srivastava, 2013). The extension event led to the intrusion of dykes and plugs of mafic, ultramafic, alkaline and carbonatitic rocks within the Mahakoshal supracrustal belt (Srivastava, 2013). The existence of a Late Paleoproterozoic to Early Mesoproterozoic metasomatized mantle in the west-central part of the CITZ has been recently advocated based on geochemical studies of the Padhar mafic-ultramafic complex of the Betul belt (Chakraborty and Roy, 2015).

Sausar Mobile Belt (SMB)

The SMB at the southern margin of the CITZ records two orogenic events at ca. 1.66-1.54 Ga and ca. 1.06-0.93 Ga (Bhandari *et al.*, 2011; Bhowmik *et al.*, 2011, 2012, 2014; Chattopadhyay *et al.*, 2015). The latest Paleoproterozoic to early Mesoproterozoic event is linked with accretionary orogenesis that led to voluminous arc magmatism (cf. Tirodi biotite gneiss-TBG) at 1.62 Ga from partial melting of Paleoproterozoic, near juvenile source (Bhowmik *et al.*, 2011), and near-coeval, episodic short-lived granulite facies metamorphism, namely pre-BM_1 at 1.66 Ga and BM_1-BM_2-BM_3 metamorphic cycles between 1.6 and 1.54 Ga, where B refers to Bhandara-Balaghat granulite (BBG) terrain (Bhowmik *et al.*, 2014). This pulsating granulite facies metamorphism, locally reaching lower crustal ultra-high temperature (UHT) metamorphic conditions (BM_1 peak T ~950-1000°C at 8-9 kbar) and marking alternating crustal extension and compression, when evaluated with co-eval TBG felsic plutonism indicates a geodynamic setting of periodic back-arc extensions of the BBG terrain and its final closure due to collision between arc and back-arc systems along the presently disposed CIS (Bhowmik *et al.*, 2011, 2014). There are also suggestions that this latest Paleoproterozoic to early Mesoproterozoic accretionary orogenesis led to the growth of a Proto-Greater Indian landmass by 1.54 Ga (Bhowmik *et al.*, 2014). In the context of the continuing debate on the nature of Proterozoic tectonics between the two supercontinent assembly events (Paleoproterozoic Columbia and late Mesoproterozoic to early Neoproterozoic Rodinia), these findings from the BBG terrain provide new insight into two aspects: (a) ca. 1.6 Ga orogenesis is a globally significant crustal amalgamation event, hitherto unrecognized and (b) the event, nearly 200 My younger than the main period of Paleoproterozoic supercontinent assembly is unlikely to be the continuation of Columbia tectonics.

Suturing of Southern and Northern Indian Blocks

The Proto-Greater Indian landmass remained largely stable until the onset of renewed crustal extension and the development of the Sausar Basin (cf. Sausar Group of rocks in central and northern Ramakona-Katangi granulite (RKG) domains of the SMB) on the northern margin of the composite South Indian Block and the BBG crust with the TBG basement between 1.54 and 1.06 Ga (Bhowmik *et al.*, 2012; Bhowmik *et al.*, 2014). Metamorphic and chronological constraints from the central and RKG domains of the SMB reveal that the Sausar basin closed during the continent–continent collisional orogeny between 1.06 and 0.93 Ga (Bhowmik *et al.*, 2012; Chattopadhyay *et al.*, 2015) due to the underthrusting of the SIB beneath the North Indian Block (NIB). This orogenic event having age comparable with that of Grenville orogeny led to the final suturing of the SIB and NIB, producing the Greater Indian landmass.

Additional structural constraints for the collisional event emanate from the documentation of an oblique collision and transpressional deformation in granitoids along the Gavilgarh-Tan shear zone, at the northern margin of the SMB (Chattopadhyay and Khasdeo, 2011).

Paleoproterozoic Glaciation in Central India?

Two recent studies in the central domain of Sausar Group of rocks have presented evidence for Paleoproterozoic glaciation based on the identification of a cap carbonate horizon (presently dolomitic marble) with a strong negative $\delta^{13}C$ excursion (Mohanty *et al.*, 2015) and a Paleoproterozoic paleosol horizon at the base of the Sausar Group (Mohanty and Nanda, 2015). In both these studies, the depositional age of the Sausar Group of rocks is considered by the authors to be of earliest Paleproterozoic, which is debatable (e.g. Chattopadhyay, 2015) and not consistent with previous studies (e.g. Bhowmik *et al.*, 2011) and geological setting of the terrain. Thus the granitoid basement over which the Paleoproterozoic paleosol is said to have developed is recently dated to be of ca. 950 Ma age (Chattopadhyay *et al.*, 2015).

Aravalli-Delhi Fold Delt or Mobile Belt (ADMB)

North of the CITZ and west of the Bundelkhand cratonic basement, the ~700km long, NNE-SSW trending ADMB has evolved over protracted geologic time overlapping with formation of the Columbia (c. 1.9-1.8 Ga) and Rodinia (1.0-0.9 Ga) supercontinents. Early suggestions of the Banded Gneissic Complex (BGC) as representing the Archean foundation on which successively younger Aravalli Supergroup and Delhi Supergroup have evolved in the Proterozoic saw considerable modifications as the stratigraphic framework have been refined over decades based on newer data, particularly those bearing on structural, magmatic and metamorphic, and metallogenic history constrained by geochronology (Bhowmik and Dasgupta, 2012; Saha and Mazumder, 2012 and references therein). It has been shown that though BGC in central Rajasthan contains Archean slivers as old as 3.3-3.2 Ga, this TTG gneiss-migmatite-intrusive granitoid-amphibolite ensemble with supracrustals has diverse rock association, metamorphic grade and geologic antiquity. Cratonization of the block hosting BGC and the Bundelkhand granite was completed by 2.5 Ga as evidenced by dates from the Berach granite and Bundelkhand granite (e.g. Meert *et al.*, 2010 and references therein). Based on newer data, various authors have tried to synthesize the tectonic evolution of the 2.1-1.8 Ga old Aravalli Supergroup together with granulitic rocks of Sandmata complex, and Mangalwar complex constituting the bulk of the eastern half of the ADMB. However, some workers suggest that Mangalwar gneissic complex may have components of Archean protolith as indicated by inherited zircon ^{207}Pb–^{206}Pb ages of 2698 ± 49 Ma and 2750 ± 44 Ma interpreted to represent Neoarchean metamorphic event (e.g. Dharma Rao *et al.*, 2011a).

The Aravalli basin likely opened up at 2.2-2.1 Ga over the stable Aravalli-Bundelkhand craton, and hosted a volcanosedimentary succession with a preponderance of meta-lava, meta-tuff mixed with dolomites in lower-middle part and unique development of extensive dolomitic limestone and stromatolitic phosphorite, together representing shallow shelf sedimentation. Possible deep water sedimentation is recorded in the Jharol belt, occurring to the west of a linear belt of serpentinites. The basin was closed by westward subduction at around 1.8 Ga (e.g. Bhowmik and Dasgupta, 2012). The early deformation in the ADMB linked with the Aravalli orogeny is constrained by Anasagar granite gneiss embedded within the supracrustal rocks of the south Delhi fold belt (SDFB) at around 1.8 Ga (Chattopadhyay *et al.*, 2012 and references therein). Combined metamorphic and geochronologic studies suggest that the Sandmata complex with granulite facies rocks as well as the Mangalwar gneissic complex are polymetamorphic with an early medium-pressure (7.5-8 kbar at 800ºC) granulite facies metamorphism with partial melting at 1.74-1.72 Ga (coeval with orthopyroxene-bearing granitoid magmatism), followed by partial melt segregation, and re-metamorphism (M2) along a clockwise P-T trajectory at greater depth (maximum pressure of 14-15 kbar and T 800-850ºC) at 0.95–0.88 Ga. The clockwise P-T trajectory is suggested to have links with continent-continent collision and crustal thickening (Bhowmik *et al.*, 2010; Bhowmik and Dasgupta, 2012). In contrast, the Mangalwar metasedimentary complex is claimed to have suffered only the M2 metamorphism. The 0.95-0.8 Ga event is comparable with amphibolite facies metamorphism and tectonothermal development of Sendra arc terrain along the eastern margin of the Delhi fold belt. Based on geochemistry of calcalkaline pegmatites intrusive into Delhi Supergroup metasediments from Ajmer in SDFB, a case for subduction related volcanic arc magmatism has been made (Joshi *et al.*, 2014).

Traditionally, the Delhi Supergroup in the North Delhi fold belt (NDFB) is divided into younger largely arenaceous Alwar Series (group), and older, dominantly argillaceous Ajabgarh Series (group), while the position of the Rialo Series with dolomite-quartzite association, as an intermediate unit between Ajabgarh and Alwar successions has been debated (Saha and Mazumder, 2012 and references therein). A two-fold classification of SDFB metasedimentary successions into Gogunda and Kumbhalgarh groups corresponding respectively to Alwar and Ajabgarh groups of NDFB, needs further scrutiny, as the above classification may represent only fault bound adjoining successions. High resolution stratigraphic detail in each of these belts together with robust geochronologic and isotopic studies may lead to better tectono-stragraphic model in these Proterozoic fold belts. Of particular interest here is the age of the Ranakpur Diorite (1012±78Ma, Sm-Nd) and that of Sendra granite (1.0 Ga). The former occurs in the Phulad shear zone in the western margin of the SDFB; the Phulad ophiolite suite occurring along ~300km long stretch following this margin is a possible indicator of subduction related Delhi orogeny (e.g. Pandit *et al.*, 2011 and references therein). Significant Neoproterozoic events west of the Delhi fold belt are represented by the Malani rhyolite (0.8-0.7 Ga) and the unconformably overlying late Precambrian-early Cambrian Marwar Supergroup. Geochronologic and paleomagnetic studies from the Malani igneous suite consisting of voluminous felsic lavas, subordinate mafic lavas and late felsic plutons, and mafic and felsic dykes, led to critical reevaluation of the models of dispersal of the Rodinia supercontinent and assembly of the Gondwana supercontinent in the late Neoproterozoic (e.g. Gregory *et al.*, 2009).

Pending availability of more robust geochronologic, petrologic, and even field data on basic structure and detailed stratigraphy, emanating from various sectors of the ADMB having diverse rock association and structural complexity, a two stage subduction-collision roughly coinciding with timing respectively of Columbia and Rodinia supercontinents is apparent from the extant data and interpretation. Additional support for the subduction-collision models comes from interpretation of geophysical data, particularly deep seismic sounding profile (DSS) across the ADMB. Oppositely dipping features in seismic reflection fabrics along the Nagaur-Nandsi DSS profile is interpreted to reflect collisional shortening across the Arvalli-Delhi fold belts. It has been postulated that geophysical signatures of oppositely dipping crustal layers, thickening of the crust (~45 km) across the ADMB, and domal reflectors from the lower crust indicate rifting as well as subduction related processes during the Aravalli orogeny and the Delhi orogeny (e.g. Mishra and Ravikumar, 2014 and references therein).

Fold-and-Thrust Belts and Southeastern Margin of the Indian Craton

West of the high grade Eastern Ghats belt, the southern peninsular India hosts a number of Proterozoic sedimentary basins, the largest of which is the Cuddapah basin. Other important basins are the Chattisgarh basin, Pranhita-Godavari (P-G) basin, Indravati basin sitting on Bastar and Dharwar cratons. Of these, the Cuddapah basin and the P-G basin merit recounting here as these have deformed Proterozoic sedimentary successions bordering flat lying to weakly deformed successions typical of intracratonic basins in India. The Nallamalai fold belt (NFB) constituting the eastern part of the Cuddapah basin, and the eastern and southern parts of the P-G basin have received focused attention in recent years (see review by Saha and Mazumder, 2012, Saha and Patranbis-Deb, 2014).

Nallamalai Fold Belt (NFB)

In contrast to the traditional view of the NFB rock successions (Nallamalai Group) being an integral part of the Cuddapah Supergroup, Saha and Tripathy (2012) have shown the fold-and-thrust belt with regional bounding thrusts on its eastern and western boundaries probably represents an allochthonus terrain accreted to the Eastern Dharwar craton (EDC) margin. Paleostress reconstruction from the western Cuddapah basin and its interpretation point to PanAfrican reactivation of intra-basinal faults, possibly linked to thrust transport of the NFB (Tripathy and Saha, 2013; 2015). This interpretation fits well with the overall scheme of growth of the EDC and amalgamation of the other adjoining fold-and-thrust belts like components of the Nellore schist belt which include ophiolitic slices like the Kandra ophiolite complex and the Kanigiri ophiolitic mélange (Vijaya Kumar *et al.*, 2010; Saha, 2011; Dharma Rao *et al.*, 2011b; Saha *et al.*, 2015). The interpreted maximum age of deposition of the Nallamalai Group is 1659±22 Ma as obtained from U-Pb SHRIMP ages of detrital zircons (Collins *et al.*, 2015) and the internal deformation of NFB was complete by ~1300 Ma as evidenced by the age of the Chelima lamproites or Racherla Syenite (e.g. Chalapathi Rao *et al.*, 2012). In contrast to the passive margin sequences of the Paleoproterozoic Papaghni and Chitravati Groups constituting the little deformed western Cuddapah basin (Saha and Tripathy, 2012; Patranabis-Deb *et al.*, 2012), some authors consider the Nallamalai fold belt has evolved as a foreland basin developed as a consequence of the Krishna orogeny at 1.68-1.6 Ga (Collins *et al.*, 2015; Hendeson *et al.*, 2014, see also Chandrakala *et al.*, 2013; Matin, 2015). However, the detrital zircon data (Collins *et al.*, 2015) as well as paleocurrent data (Saha and Tripathy, 2012) from the Nallamalai Group indicating Eastern Dharwar as the likely main provenance needs to be reconciled with the interpretation of NFB as a proximal foreland basin.

Nellore Schist Belt and Proterozoic Ophiolitic Remnants

South of the Pranhita-Godavari graben, the southern Eastern Ghats belt (Ongole domain) is mantled on its west by the Nellore schist belt which have been traditionally compared with the Dharwar schist belt. However, recent work clearly shows that the NSB consists of geologically and geochemically distinct tracts of multiply deformed volcanosedimentary successions: the Vinjamuru Group, the Kandra ophiolite complex (KOC), the Kanigiri ophiolitic mélange (KOM) and the Udaigiri Group, tentatively arranged in relative order of younging (Saha *et al.*, 2015). While the Vinjamuru Group have signatures of Archean protolith (Ravikant, 2010), the available age data indicate amalgamation of bulk of the Vinjamuru Group showing amphibolite facies metamorphism, and the KOC later than 1900 Ma (Vijaya Kumar *et al.*, 2010; Saha, 2011). The deformation and emplacement of syntectonic granites within the Vinjamuru Group occurring on the hanging wall of the Vellikonda thrust at the eastern boundary of the NFB, is constrained by the Vinukonda granite dated at 1589 Ma (Dobmeier *et al.*, 2006). The 1.9 Ga old KOC consisting of imbricate thrust slices representing dismembered ocean plate stratigraphy is interpreted to have originated under supra-subduction zone setting (Vijaya Kumar *et al.*, 2010; Saha, 2011). The 1334 Ma old KOM is also interpreted as of supra-subduction setting (Dharma Rao *et al.*, 2011b) attesting to Mesoproterozoic subduction and convergence outboard of the Eastern Dharwar craton margin (Saha *et al.*, 2015). Late granites, apparently clubbed with the Prakasam alkaline province plutons emplaced in the northern NSB have been interpreted to represent a Mesoproterozoic rifting episode in this domain, but their status is not altogether well settled (e.g. Sesha Sai, 2013).

Repeated subduction-related ocean closures outboard and east of the Dharwar Craton, evidenced by the KOC and KOM, possibly had links with the assembly of Columbia and its final dispersal, respectively (Saha *et al.*, 2015). New zircon Hf data from the metapelites of the Ongole domain also signifies that while the provenance of the Paleoproterozoic as well as Neoproterozoic sedimentary successions of the western Cuddapah basin is directly linked to the Eastern Dharwar craton, Ongole domain metapelites have Hf isotopic signatures remarkably overlapping with those from the NFB (Henderson *et al.*, 2014; Collins *et al.*, 2015). Thus the tectonic evolution of the NFB is more closely linked with the Ongole domain (Krishna orogeny) with a core of the granulite facies metapelites and metaigneous rocks, dated around 1700 Ma and a mantle of the tectonically juxtaposed NSB and NFB terranes.

Deformed Proterozoic Successions of the Pranhita-Godavari Valley Basin

In the Pranhita-Godavari valley basin at the join of the Dharwar and Bastar cratons, the Mesoproterozoic to Neoproterozoic rock successions form two NW-SE trending linear belts separated by an axial outcrop of the Upper Paleozoic – Mesozoic Gondwana succession. While the western Proterozoic belt with generally flat lying successions of the Pakhal and Penganga Groups have been studied for stratigraphic and sedimentologic analysis for decades, it is only in recent times that a robust stratigraphic framework constrained by geochronologic dates are emerging for both the western and eastern belts (Conrad *et al.*, 2011; Chaudhuri *et al.*, 2012). With bordering granulite terranes, namely the Bhopalpatnam and Karimnagar granulite belts) yielding Mesoarchean to Neoarchean age, the regional stratigraphic correlation, and the broader tectonic framework of basin evolution and deformation of the eastern belt (Somanpalli Group) and the southern extremity (Yellandu and Borgampad area) of the P-G basin have received attention only in recent years (e.g. Conrad *et al.*, 2011; Saha and Patranbis-Deb, 2014; Joy *et al.*, 2015). While some workers consider influence of amalgamation of the Eastern Ghats belt (EGB) on to the Bastar craton margin responsible for deformation and metamorphism in the Yellandu area, the ca. 1626 Ma old Somanpalli Group was deformed prior to the deposition of the unconformably overlying Albaka Group (Saha and Patranabis-Deb, 2014), attesting to early Mesoproterozoic deformation in this region prior to the tectonic accretion of the northern EGB. To our understanding, the new data and analysis do not fully support the idea that the P-G basin successions represent a foreland type basin proximal to the EGB, as the final docking of the EGB on to the Bastar craton margin is likely related to a late Neoproterozoic event much younger than the bulk of the P-G valley successions, namely Pakhal Supergroup and Somanpalli group (Chaudhuri *et al.*, 2012). However, the Late Neoproterozoic succession represented by the Sullavai Group has yielded SHRIMP U-Pb zircon ages of ca.700 Ma, and some authors tentatively relate provenance of the Sullavai Group to the Eastern Ghats after its docking at the Bastar craton margin (Joy *et al.*, 2015).

Southern Granulite Terrain

Southern India is known to be an amalgam of continental crustal blocks that are demarcated or divided by several shear zones. Northern part of the southern Indian crust is the Archean Dharwar Craton, which is divided into Western and Eastern Dharwar Cratons — WDC and EDC respectively. The Dharwar craton stabilized by *ca*. 2.5 Ga is separated from the crustal block further south by a crustal scale shear zone referred to as the Palghat-Cauvery shear zone (PCSZ). In this section we deal with this southern block named as the Southern Granulite Terrain (SGT) (alternatively Pandian mobile belt) with a dominant E-W structural trend in contrast to the dominant N-S trend of the Dharwar craton (Fig. 1). A transitional zone between the Dharwar craton in the north and the SGT in the south, roughly demarcated by the Salem-Attur shear zone (continuing in Moyar shear zone) in the north and PCSZ in the south, show a complex tectono-magmatic history dominated by Archean granite gneisses and charnockite including the type area charnockite of St. Thomas mount, near Chennai.

A collage of various shear zones, referred to as Palghat-Cauvery shear system represents a broad swathe including the western Archean Nilgiri Block bounded by the Moyar Shear Zone (MoSZ) to the north and the Bhavani Shear Zone to the south, and the charnockite massifs to the east (Samuel *et al.*, 2014 and references therein). The E-W trending PCSZ bounds in the south granulite facies rocks with complex folding and shearing structures (e.g., Mohanty and Chetty, 2014).

The Nilgiri Block: Neoarchean Inheritence

Major rock types of the Nilgiri Block are charnockite, two-pyroxene granulite, hornblende gneiss, amphibolite, mafic granulite, and websterite (dated *ca* 2.55 Ga, Samuel *et al.*, 2014). Earlier *P-T* estimates indicating sedimentary protolith and *P-T* gradient of 6-10 kbar and 700-800º C, from south to north indicating collisional orogeny is counterpoised by recent suggestions of Niligiri block as a magmatic arc, related to Archean 'supracrustal subduction' (Samuel *et al.*, 2014, 2015).

Palghat Cauvery Shear Zone (PCSZ): Archean Remnants and Proterozoic Reworking

Earlier studies based on lineament mapping from satellite imagery regarded PCSZ as a post-Archean dextral shear zone, reinterpreted later as the central part of a mobile belt (Pandyan mobile belt). Early geochronologic work using Sm-Nd whole rock and mineral isochron ages yielded *ca.* 2.9 Ga and 0.8 Ga ages of granulites from the Sittampundi layered complex indicating Neoproterozoic reworking of the Archean crust. Later structural studies considered PCSZ as a dextral transpressive shear zone exhibiting 'flower structure'. The suggestion that PCSZ represents a Cambrian suture zone (Collins and Pisarevsky, 2005) was later elaborated in 'Pacific type orogeny model' with two-sided subduction – beneath southern margin of Dharwar Craton and the Madurai Block – during Gondwana amalgamation (Santosh *et al.,* 2009). Subduction related magmatism and metamorphism close to the Archean-Proterozoic boundary was also supported by later work on the charnockites from the Salem block yielding ages between 2.52 Ga and 2.48 Ga (Clarke *et al.*, 2009). Reports of eclogites indicating *P-T* condition of 20 kbar and 1020°C, from the layered anorthosite complex of Sittampundi is supplemented by recent metamorphic age of *ca.* 2.4 Ga (Sajeev *et al.,* 2009 and unpublished data). Geochronological studies (Sato *et al.,* 2011a; Saitoh *et al.,* 2011) on granulites from Kanjamalai region near Salem, within the Salem-Attur Shear Zone further confirmed magmatism and metamorphism during the late Archean. Ultramafic-mafic sequence from the Manamedu area located within the Cauvery Shear Zone (CSZ), interpreted as an ophiolite complex (Yellapa *et al*., 2010; Chetty *et al*., 2011) has been dated at 790 Ma from U-Pb zircon dating of associated plagiogranite (Santosh *et al.,* 2012), the latter work postulating remnants of the Mozambique Ocean in this belt, which supposedly existed before the amalgamation of Gondwana supercontinent around *ca.* 0.55 Ga. Devannur ophiolite from the southern margin of the CSZ, dated (U-Pb zircon) at *ca*. 2.52 Ga from trondhjemite sample, has been interpreted as an ophiolite complex formed in an accretionary prism setting during collision and continental growth (Yellappa *et al.,* 2012). Ram Mohan *et al.* (2013) reported new U-Pb zircon age of anorthosite of Sittampundi, with magmatic age pegged at *ca*. 2.53 Ga and granulite metamorphism *ca*. 2450 Ma. Geochronological studies from Kanjamalai on high-pressure granulites also underscored Archean crustal formation and the metamorphism in the Paleoproterozoic (Noack *et al.,* 2013; Anderson *et al.,* 2012). Anderson *et al.* (2012) dated kyanite-garnet bearing granulite and inferred that the high-pressure texture grew at *ca*. 2.49 Ga with *P-T* conditions 14-16 kbar and 820-860° C, vindicating earlier work. Noack *et al.* (2013) however, dated the garnetiferous mafic granulite from the region using Lu-Hf systematic from garnet and found that the peak metamorphism occurred in the early Paleoproterozoic around 2.48 Ga.

The southern part of the PCSZ with the presence of Mg-Al rich rocks and granites, has been shown to have suffered Neoproterozoic metamorphism. West of Cauvery Shear Zone, massive granite plutons (Sankagiri granite) intrusive into the hornblende gneiss at Sankagiri-Tiruchengode region, has been recently dated at *ca.* 0.55 Ga (Brandt *et al.,* 2014). However, there are reports of *ca.* 0.8 Ga granites too (Sato *et al.,* 2011b). Earlier reports of UHT metamorphism within garnet-gedrite-kyanite-sapphirine-corundum granulite and gedrite-kyanite-sapphirine-corundum granulite of the CSZ was however questioned by Raith *et al.* (2010) based on interpretation of presence of corundum as due to dehydration of muscovite at around 800°C. However the possibilities of a hyper aluminous melt produced during UHT metamorphism was not considered in this interpretation. Summarizing, recent work presents the PCSZ as a crustal segment undergoing two-stage evolution – by the end of Archean and later during the Neoproterozoic.

However, the extent of the PCSZ and the Archean crust has been debated (e.g., Collins *et al.,* 2014). Earlier work suggested that the Archean crust extends through the northern part of Madurai block till the Karur-Kambam-Painav-Trichur (KKPT) shear zone (e.g., Tomson *et al.,* 2013 and references therein) based on the results from geochronological studies from the northern part of Madurai block with Archean ages (Brandt *et al.,* 2014; Plavsa *et al.,* 2012; Plavsa *et al.,* 2014). However, report of Cryogenian age (*ca.* 0.8 Ga) from layered complex in Madurai Block (Brandt *et al.,* 2014; Teale *et al.,* 2011) are cited as evidences for amalgamation of Gondwana supercontinent in the Cryogenian (Santosh *et al.,* 2012; Santosh *et al.,* 2014; George *et al.,* 2015). Geophysical evidence also suggests that the PCSZ is a deep crustal feature with indications of Moho-offset, marking PCSZ as a crustal block independent from the Madurai block (e.g., Naganjaneyulu and Chetty, 2010).

The Madurai Block and Neoproterozoic UHT Metamorphism

The Madurai block is the largest and most studied crustal block of the Southern Granulite Terrain and is bounded by the PCSZ in the north and Achankovil shear zone in the south (Rajesh *et al.,* 2013). The major rock types of this block are granitic gneiss, charnockite and granite, with reports of UHT rocks from the central part indicating complex evolutionary history. Based on the U-Pb ages from zircon a two-fold division of the Madurai block into northern and southern blocks separated by KKPT lineament and having different evolutionary history has been proposed (Plavsa *et al.*, 2012). However, Brandt *et al.* (2014) hypothesized that a belt of UHT granulites divides the block into Eastern and Western domains with different evolutionary history.

Ultrahigh-temperature (UHT) (~1000ºC, 10-11 kbar) granulite facies metamorphic rocks have also been reported from several localities in central region of this block (e.g., Collins *et al.,* 2014 and references therein). The UHT assemblages reported so far include sapphirine-quartz, spinel-quartz (Shazia *et al*., 2015 and references therein) and orthopyroxene-sapphirine-cordierite (Shazia *et al.,* 2012). The 0.55 Ga U-Pb zircon ages of the UHT rocks have been put forward to indicate regional metamorphism during the Gondwana amalgamation (e.g., Collins *et al.*, 2014). However, the heat sources for the UHT rocks are yet to be understood.

Teale *et al.* (2011) also reported magmatism at 0.8 Ga from Kadavur anorthosite complex, which lies to the east of the Madurai block, leading to the suggestion of Cryogenian magmatic imprints within the Madurai block, possibly due to the southward subduction during the closing stages of Gondwana assembly. Reports of association of granite and charnockite formed by the Cryogenian magmatism from the southern part of the block near Rajapalayam also exist (George *et al.*, 2015). The granite-charnockite association and incipient charnockite formation are also seen widely in the Munnar region as reported by Bhattacharya *et al.* (2014).

The Trivandrum Block, Peak Metamorphism during the Ediacaran and Provenance

Wide range of metamorphic zircon growth during the Neoproterozoic has been reported from the Trivandrum Block (Kerala Khondalite Belt) and Achankovil Zone. While earlier estimates of peak metamorphism ranges between 0.59 Ga and 0.53 Ga, through studies of a detailed texturally controlled zircon age results, Harley and Nandakumar (2014) have suggested that peak metamorphism occurred earlier than 545 Ma, Taylor *et al.* (2014) proposed from studies of monazite growth that peak metamorphism was shortly after ca. 585 Ma and demonstrated later zircon growth at ca. 0.523 Ga. Achankovil Zone situated to the north of Trivandrum Block experienced relatively younger peak metamorphism (ca. 545-512 Ma) and sediment source age ranging from 0.65-1.1 Ga (Taylor *et al.*, 2015). The southern tip of Trivandrum Block, also known as Nagercoil Block shows relatively older peak-metamorphic age at *ca.* 0.56 Ga (Johnson *et al.*, 2015) with a prograde age of *ca.* 0.57 Ga and retrogression at *ca.* 0.535 Ga.

That several stages of zircon growth and dissolution occurred during high-temperature metamorphic evolution in the Trivandrum block is clear from the results quoted above. It must be noted that Mg-Al rich UHT granulites are not yet identified from the Trivandrum Block, however there are unpublished reports on Zn-rich spinel + quartz assemblage similar to that of southern Wanni Complex, Sri Lanka. Kröner *et al.* (2015) reported that granitic rocks of the Trivandrum and Nagercoil blocks were emplaced between 1.765-2.1 Ga, and were intercalated with meta-sedimentary rocks that must be older than 2.1 Ga. However, Taylor *et al.* (2014) obtained 1.8-1.7 Ga detrital zircon ages from meta-sedimentary rocks of Trivandrum Block, meaning that the sedimentary protoliths must be *ca.* 1.8 Ga or younger. Further studies are required for resolving the issues related to provenance and deformation histories of the Trivandrum Block.

Concluding Remarks

Tectonomagmatic, metamorphic history of the Proterozoic mobile belts and associated fold belts in the Indian shield show diverse and protracted development, in some cases with Neoarchean inheritence. Recent publications bearing on geochronology and isotopic studies, combined with studies on metamorphism in deeply exhumed orogens and deformation in associated fold-and-thrust belts show a growing trend towards a more holistic approach in our understanding of the Proterozoic tectonics as applied to the Proterozoic mobile belts in India. We also see a trend toward integrating interpretations based on Indian crustal evolution with global tectonic processes of Proterozoic supercontinent assembly and dispersal. While significant data and newer interpretation for some belts like the Eastern Ghats or even the Southern granulite terrain are forthcoming, other regions like the Chotanagpur granite gneiss complex, Satpura mobile belt even parts of Arvalli-Delhi mobile belt show paucity of good quality geochronologic and isotopic data, even basic tctonostratigraphic detail for comprehensive understanding, validation of models based on plate tectonic framework, and regional and global correlation.

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