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Status Report

Proterozoic Tectonics: An Indian Perspective

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Significant advances have been achieved over the last five years in our understanding of the nature of Proterozoic tectonothermal events in India. This was possible because of (a) proper understanding of the pressure-temperature paths of evolution (both prograde and retrograde) of metamorphic rocks and better constraint on peak thermal and baric conditions of metamorphism, (b) better understanding of the correlation of P-T paths with tectonics, and thereby obtaining information on crustal evolution, (c) availability of well-constrained geochronological data on metamorphic and magmatic events, (d) availability of geophysical and structural data, and, (e) development of new ideas on transcontinental correlation of orogenic belts and formation/break-up of supercontinents.

One of the key aspects of Proterozoic tectonics is the assembly and growth of two supercontinents, when most of the world's landmasses were joined together. These are namely, Columbia/Nuna in the Palaeoproterozoic and Rodinia in Late Mesoproterozoic. Significant progress has been made over the years in understanding the assembly, configuration and basic components of these supercontinents. There is an increasing body of new information that indicates that orogenic events in the time period 1.75 to 1.5 Ga, in between the two supercontinent formation events were widespread in different mobile belts around the world.

This report deals primarily with the published work of Indian geoscientists with or without the involvements of their foreign collaborators. However, we acknowledge the contributions of several groups of foreign scientists working independent of Indian counterparts. At the outset, it must be pointed out that this report is not complete, as time constraint did not allow us to compile and synthesize the work carried out in the Southern Granulite Terrain. We are, therefore, constrained to develop this report on the themes related to assembly and break-up history of Columbia and Rodinia synthesizing available data from three critical mobile belts belonging to the so-called North Indian Block.

Broadly, the Indian peninsula bears evidence of the following tectonothermal events in the Proterozoic:

The Early Palaeoproterozoic Tectonothermal Event (Ca. 2500-1800 Ma)

The Palaeoproterozoic to Early Mesoproterozoic Tectonothermal Event (Ca. 1800-1500 Ma)

The Late Mesoproterozoic and "Grenvillian" Tectonothermal Event (Ca. 1300-900 Ma)

The Neoproterozoic Pan-African Tectonothermal Event (Ca. 650-500 Ma)

We will first document the results obtained from several key Proterozoic mobile belts, such as the Central Indian Tectonic Zone (CITZ), Eastern Ghats Mobile belt (EGMB) and the Aravalli-Delhi mobile belt (ADMB), and subsequently, we will summarize the results in the context of Columbia and Rodinia. Instead of referencing, we will present a bibliography of the work done by the Indian geoscientists and their collaborators.

Key Words : Proterozoic Mobile Belts; Collisional and Accretionary Orogenesis; Supercontinent Assembly Events

The Central Indian Tectonic Zone (CITZ)

Figure 1 summarizes the geochronological data on Proterozoic tectonothermal events recorded in several mobile belts in India.

1. The Sausar Mobile Belt at the southern margin of the Central Indian Tectonic Zone records two distinct orogenic events at 1.62-1.42 Ga and 1.06-0.94 Ga. While the southern Bhandara-Balaghat Granulite (BBG) domain records only the latest

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Palaeoproterozoic to early Mesoproterozoic orogeny, the central and northern Ramakana-Katangi Granulite (RKG) domains additionally show evidence for a Grenville-aged orogenic event, which reworked 1.62-Ga crust. The metamorphism in the central and northern domains (CW P-T path, peak metamorphism at 1.06 to 1.04 Ga) was not time-equivalent to that in the southern domain (CCW P-T path, peak granulite facies metamorphism at 1.6 Ga). This requires a re-evaluation of the model of paired metamorphic belts in the CITZ.

2. New geophysical, petrological, geochronological and zircon Hf-isotopic data confirm the previous predictions that the Central Indian Shear/Suture (CIS) marks a Proterozoic suture, the location of which was traditionally placed at the boundary between the South Indian Block (SIB) and the BBG domain. The Hf-isotopic constraint, on the other hand favours that the location of the CIS to be placed at the boundary between the BBG and central domains. New data favour two-stage amalgamations along the CITZ leading to the growth of the Greater India Landmass. The earliest amalgamation event occurred between 1.57 and 1.42 Ga, leading to the suturing of arc (cf. Tirodi biotite gneiss units of the central and RKG domains) and back-arc (cf. BBG domain) systems along the presently disposed CIS. The landmass produced by the early Mesoproterozoic collision remained largely stable until the onset of crustal extension and the development of the Sausar Basin (cf. central domain) on the northern margin of the composite South Indian Block and the BBG crust. The basin closed during the continent–continent collisional orogeny between 1.06 and 0.94 Ga due to the underthrusting of the SIB beneath the North Indian Block (NIB).

3. Collisional event at the northern margin of Sausar Mobile Belt (SMB) is also supported by the finding of Meso-Neoproterozoic oblique collision and transpressional deformation of granitoids along the Gavilgarh-Tan shear zone, which lies about 10-15-km north of type SMB.

4. Recent petrological and geochronological investigations from the Proterozoic mobile belts adjoining the CITZ indicate that geological events in the time period 1.7 to 1.5 Ga and 1.05-0.9 Ga can be traced right across India, further supporting two-stage amalgamation model for the growth of the Greater Indian Landmass. One important consequences of the reconstruction of a Proto-Greater Indian Landmass between 1.65 and 1.5 Ga is the recognition of a globally significant collisional orogeny in the Early Mesoproterozoic, hitherto unrecognized, and which would require a revision of current models of assembly of continental blocks in the Proterozoic.

The Eastern Ghats Mobile Belt (EGMB)

Several isotopic and petrological studies have indicated that the EGMB is a collage of several isotopic domains (or provinces) that amalgamated during the Grenvillian orogeny. We describe two such provinces separately – the Ongole Domain to the south and the Eastern Ghats Province and the Jeypore Province to the north.

The southern Eastern Ghats

A 1760-Ma UHT metamorphic event followed by granulite facies metamorphism and partial melting at 1600 Ma were identified, which were correlated with the accretion of the supercontinent Columbia in the Palaeo- to Mesoproterozoic. A number of studies, based primarily on the geochemistry of the igneous precursors to mafic igneous rocks, have suggested an initial phase of rifting, followed by convergent tectonics that culminated ultimately in collision within Columbia. Magmatism related to rifting started in the Cuddapah basin and southern Bastar craton at around 1.9 Ga and culminated in convergence and emplacement of reported ophiolites around 1.85 Ga. Another phase of rifting followed, that is correlated with the break-up of Columbia. This evolved once again into an arc-type environment with addition of new continental crust in the Mesoproterozoic and renewed emplacement of ophiolites. The process culminated in Grenvillian-age collision during the formation of Rodinia; emplacement of gabbro-anorthosites along dilational jogs within a dextral transpressive regime has been suggested at this time, based on structural and AMS studies .

Northern Eastern Ghats

An important thermal pulse within the basement possibly occurred during ca. 1.76-1.70 Ga. A rift basin was opened within a continent or a continental amalgamation within Columbia. Subsequently, the basin evolved through accretionary process with subduction, formation of island arc and accretionary prism between India and East Antarctic cratons. Possibly the subduction took place towards the Indian side. Sediments were metamorphosed and deformed with development of fold-thrust belt at the western margin against the Bastar Craton. This phase of evolution occurred at advancing accretionary mode according to the theory of accretionary orogeny. The mode switched to the retreating one with subduction rollback and development of a back-arc basin and the basin was opened up due to rifting with the emplacement of alkaline magma at ca. 1.48 Ga and mafic magma at ca. 1.45 Ga. Sediments deposited within

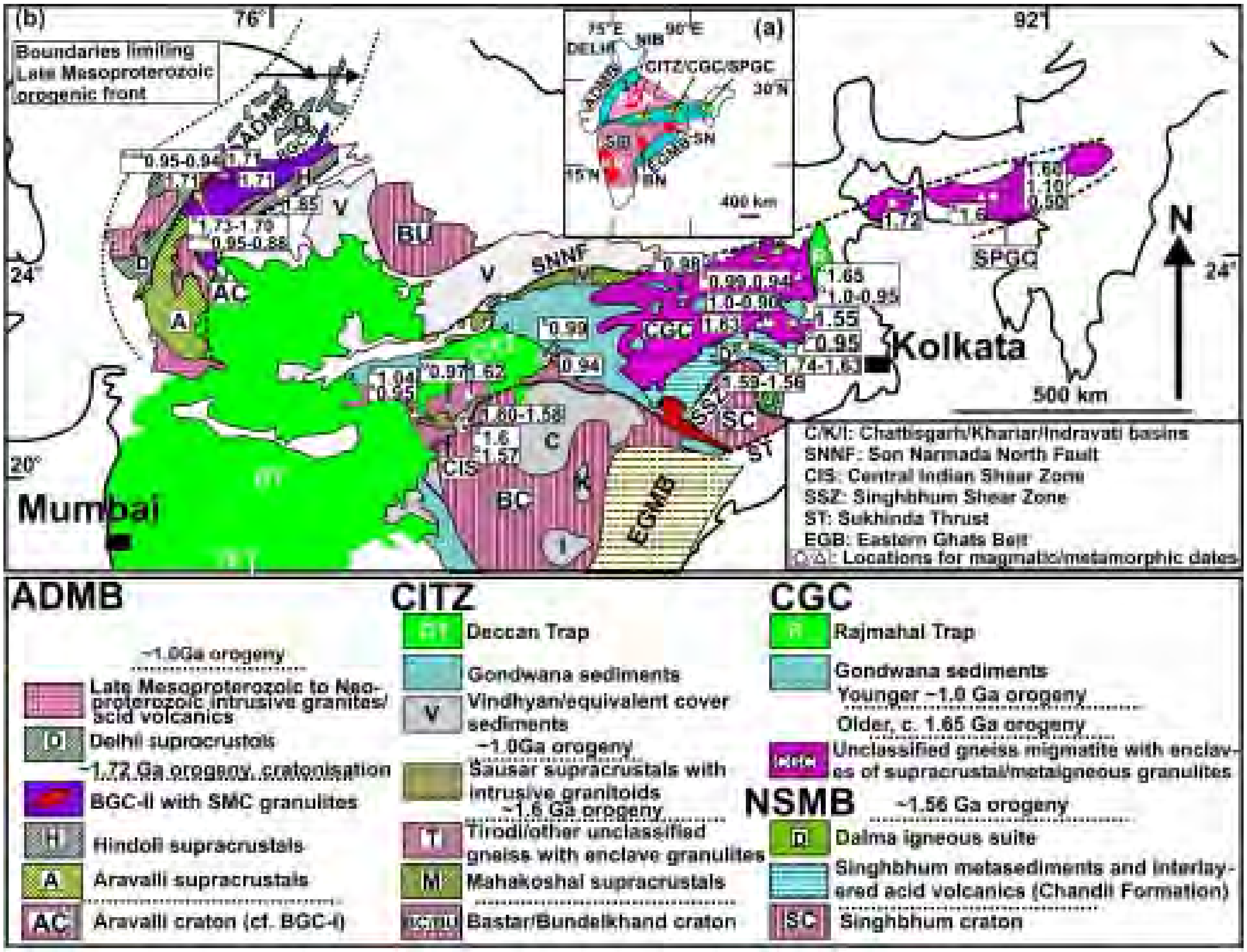

Fig. 1: (a) Simplified tectonic map of India showing Archaean crotonic blocks (orth and South Indian Blocks, NIB and SIB) and Proterozoic mobile belts (after Bhowmik *et al*., 2011, 2012). The SIB contains the Archaean nuclei of Singhbhum (SN), Bastar (BN) and Karnataka (KN), while the NIB includes the Bundelkhand (BKN) nucleus. (b) Distribution of Proterozoic mobile belts of Peninsular India with timing of magnetic and metamorphic events in Ga (after Bhowmik *et al*., 2012): the Aravalli-Delhi Mobile Belt (ADMB) in the west; the Central Indian Tectonic Zone (CITZ) in the center; the composite Chhotanagpur Gneissic Complex (CGC)-North Singhbhum Mobile Belt (NSMB) in the east; the Shillong Plateau Gneissic Complex (SPGC) in the northeast and the Eastern Ghats Belt (EGB) in the southeast. Number(s) in white boxes refer to the metamorphic age data and are as follows: G/UA/A: Granulite/upper amphibolite/ amphibolite facies. The extent of the Late Mesoproterozoic orogenic front in the ADMB is after Bhowmik *et al*., (2010).

the back-arc basin were metamorphosed to UHT conditions at ~1020-990 Ma producing an anomalously hot orogen. This was immediately followed by emplacement of voluminous charnockite-enderbite magma (0.98-0.96 Ga). The back arc as well as the open ocean basin gradually contracted due to closeness between the Indian and East Antarctic cratons. This finally caused closure of the basin through a series of accretion collision process at ~0.9 Ga, coinciding with the formation of Rodinia.

Several studies in recent years on the Koraput alkaline complex have provided important constraints on the geological relationship between the Jeypore Province and the Eastern Ghats Province. The Koraput alkaline complex is metamorphosed (along with other complexes aligned along the western margin of the EGB) with a prograde heating + loading trajectory. Since this intrusion cuts across earlier granulite facies fabrics, this late tectonothermal event is considered to be intracontinental. These observations have been integrated into a comprehensive geodynamic model, and visualized the craton-mobile belt contact as the site of a Grenvillian suture reworked during intracontinental Pan-African deformation, during which the granulites were thrust further inland over the craton after the initial juxtaposition following Grenvillian collision.

It is evident that no single tectonic model can act as a proto-type of tectonic evolution of the entire EGB. For both the provinces Wilson Cycle begins with continental rifting and opening of ocean basins at the margins of India, but at different times: ca.1.9 Ga in the southern domain and ca.1.5 Ga in the central domain. Oceanic subduction, arc magmatism, metamorphism at lower crustal levels, accretion and subsequent collision in the southern domain culminated at ca.1.6 Ga, and this part became part of proto-India – Napier amalgamation. A high-grade tectonothermal/magmatic event either at the source or at the basement of the northern province occurred during ca.1.76-1.7 Ga. However, rifting and consequent ocean opening and sedimentation in this domain started only around 1.5 Ga. Accretionary orogenesis, ultrahigh temperature metamorphism (inferred to be due to slab detachment), arc magmatism and collisional orogenesis in this domain culminated at ca. 0.9 Ga, when final docking of other microplates took place as an integral part of the formation of Rodinia.

The Aravalli-Delhi Mobile Belt (ADMB)

The Precambrian crust in this segment of Peninsular India records a protracted sedimentational, tectono-magmatic and tectono-metamorphic history over a period of > 1 Ga from c.2.2-2.1 Ga to 0.95-0.88 Ga. Following the stability of the Archaean craton at ~2.5 Ga, the Aravalli basin opened up by ~2.2-2.1 Ga on a tonalite-trondhjemite-granodiorite-amphibolite basement, and closed at ~1.8-1.9 Ga due to westward subduction of the Aravalli crust during the Aravalli orogeny. A-type granite magmatism in the North-Delhi Fold Belt at 1.7 Ga and the formation of granulites, synchronous with mafic and felsic magmatism at ~ 1.74-1.72 Ga in the Sandmata Metamorphic Complex (SMC) are related to a switching of tectonic style from subduction to extension. The supracrustal and metaigneous granulites of the SMC and the A-type granites of the North-Delhi Fold Belt acted as basement for the opening up of two Mesoproterozoic sedimentary basins: the Delhi Basin to the west and the Mangalwar Basin to the east. These basins were closed with the onset of a continent-continent collisional orogeny at ~0.95-0.88 Ga (cf. Grenvillian orogeny), producing an extensive, amalgamated crustal domain.

Summary and Remarks

We present two summary diagrams to highlight the major conclusions of this article. Fig. 1 gives a comprehensive account of geochronological data on the major tectonothermal events in all the mobile belts in the North Indian Block. Figure 2 depicts the growth of the Greater Indian Landmass during the Grenvillian orogeny.

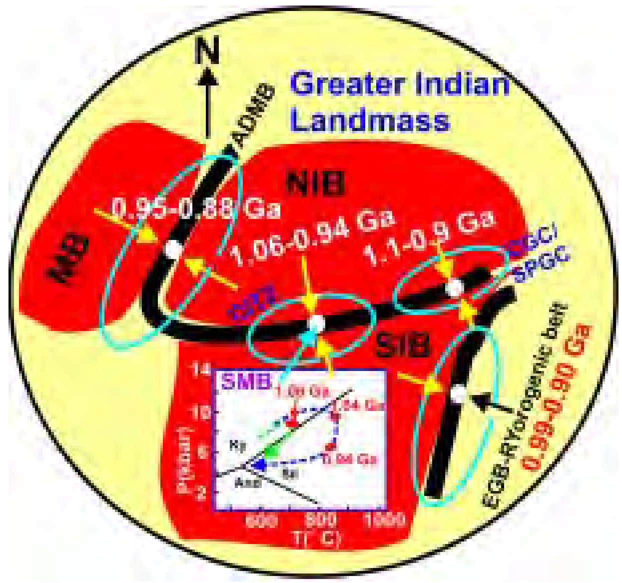

Fig 2: Cartoon diagram showing the pre-1.0 Ga architecture of the Greater Indian Landmass that consisted of three separate cratonic blocks, namely the North Indian Block (NIB), the South Indian Block (SIB) and the Marwar Block (MB) (after Bhowmik *et al*., 2012). The final amalgamation of the three micro-continents, leading to the growth of the Greater Indian Landmass, was due to broadly coeval collisional tectonics at c.1.0 Ga along the Aravalli-Delhi Mobile Belt (ADMB), Central Indian Tectonic Zone (CITZ), the Chhotanagpur Gneissic Complex (CGC), Shillong Plateau Gneissic Complex (SPGC) and the Eastern Ghats Belt-Rayner Complex (EGB-RC) orogenic domains

The supercontinent Columbia is supposed to have originated between ~2.1-1.8 Ga. In the Indian continent, the growth of the supercontinent is poorly recorded, but for some events in the ADMB. Unambiguous evidence for a late Palaeoproterozoic ultrahigh temperature metamorphism at lower crustal depths is available from parts of the Central Indian Tectonic Zone (~1.6 Ga), Chhotanagpur Gneissic Complex (CGC)(~1.72 Ga) , and in the southern part of the Eastern Ghats Belt (EGB)(~1.76 Ga). In the CGC and south EGB, a second granulite facies overprint occurred at ~1.6 Ga, and in the former massive anorthosite intruded at 1.55 Ga. In the Aravalli-Delhi Mobile Belt (ADMB), an early high temperature granulite facies metamorphism at ~1.72 Ga is recorded. The southern part of the EGB bears evidence of accretionary growth of Columbia through a transition from arc-continent collision to continent-continent collision (Pacific type) over the period ~1.8-1.6 Ga. The Grenvillian age orogeny left its strong imprint in the ADMB (high-pressure granulite metamorphism in a collisional setting), CGC (amphibolite-granulite transition facies, ~1.2-0.95 Ga), NE India, CITZ

(Sausar orogeny) and the EGB (granulite facies metamorphism along a clockwise P-T path followed by isothermal decompression). Recent data shows that in the central part of EGB the granulite facies event at 0.95-0.9 Ga was preceded by an UHT metamorphism along a counterclockwise P-T trajectory at ~1.03-0.98 Ga. Recent postulation of the existence of an “Eastern India Tectonic Zone” (EITZ) that extends from the CGC through the Chilka Lake area of the northern EGB and the Rayner Complex in east Antarctica , and formed at 0.87-0.78 Ga indicates that India did not break from Rodinia before ~0.78 Ga.

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A caveat

We apologize for any inadvertent ommision – Authors.