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Proterozoic Orogenesis and Crustal Evolution in The Central Indian Tectonic Zone: Current Understanding from Recent Works

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In the past few years, a huge amount of geological, geochemical and geochronological data have been generated from the southern margin of the Central Indian Tectonic Zone (CITZ) which gives enough clues for understanding the tectonothermal history and Proterozoic orogenesis of the central Indian craton and its implication for the Proterozoic supercontinent assembly. Relevant works published in last four years (2015-2019), with the background geological and tectonic context, are briefly reviewed here. The outstanding geological controversies are also outlined.

Keywords: Central Indian Tectonic Zone; Sausar Group; Granulites; Tectonothermal History; Proterozoic Orogeny

Introduction

The Peninsular Indian landmass is a mosaic of several cratonic nuclei, viz., Bundelkhand craton, Bastar craton, Dharwar craton, Singhbhum craton etc., skirted by a number of prominent mobile belts. It is now generally accepted that the North Indian Block (NIB) comprising the Bundelkhand and Marwar cratons (BKC) and the South Indian Block (SIB), comprising the combined Bastar-Dharwar-Singhbhum cratons (BC) were stitched together in the Proterozoic along a prominent E-W trending crustal scale mobile belt called the Central Indian Tectonic Zone (CITZ) (e.g. Radhakrishna and Naqvi, 1986; Roy and Prasad, 2003; Bhowmik *et al*., 2012 and references therein). CITZ (or its equivalents) has been traced upto Madagascar in the west (Katz and Premoli, 1979) and to the east through Chhotanagpur Gneissic Complex (CGGC) and Shillong Plateau (Acharyya, 2001) upto Western Australia (i.e. Albani-Fraser Orogen) (Harris, 1993). This proposed trans-continental nature of CITZ makes it a potential study area for understanding the crustal evolutionary history in the Proterozoic. In its type area, i.e. in the central Indian craton, the CITZ records a tectonothermal evolutionary history spanning nearly 1000 Myrs from Paleoproterozoic to Neoproterozoic (Acharyya and Roy, 2000; Roy and Prasad, 2003). Thus, the evolution of CITZ overlapped with the assembly and dismemberment of two major supercontinents, viz., Columbia (ca. 2.1-1.8 Ga) (Rogers and Santosh, 2003) and Rodinia (ca. 1.2-0.9 Ga) (Pisarevsky *et al*., 2003). The tectonothermal history of CITZ and its correlation with other major transcontinental mobile belts therefore provides us clues for understanding the Proterozoic supercontinent cycle. A huge amount of work has been carried out on the CITZ (in central India) in the last two decades and a variety of tectonic models have been proposed at different points of time (e.g. Acharyya and Roy, 2000;Roy and Prasad, 2003; Naganjaneyulu and Santosh, 2010; Bhowmik *et al*., 2012; Chattopadhyay *et al*., 2017; Bhowmik, 2019 - to name a few). In this short communication, I shall attempt to review and synthesize the major research works published within the last four years (2015 onward), with necessary references to some of the earlier works for maintaining the geological context. A more detailed, comprehensive review of the geology, geochronology, and tectonics of CITZ is available in a separate publication (to be published in Episodes: IGC 2020 legacy volume).

The Central Indian Tectonic Zone (CITZ)

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dissects the Indian landmass in an E-W to ENE-WSW direction, and has a maximum width of about 200 km in central India. Three major supracrustal belts, viz., Mahakoshal, Betul and Sausar belts occur within the CITZ from north to south. These belts are set in a vast country of unclassified gneiss-migmatite-granitic rocks, locally named as Tirodi Biotite Gneiss, Amgaon Gneiss, Betul Gneissic Complex etc. The CITZ is traversed by a few major tectonic lineaments parallel to its length, viz. Son-Narmada North Fault (SNNF), Son-Narmada South Fault (SNSF), Gavilgarh-Tan Shear Zone (GTSZ) and Central Indian Suture/Shear (CIS) from north to south (Fig. 1). While the Mahakoshal supracrustal belt is confined between SNNF and SNSF, GTSZ separates the Betul belt from the Sausar Belt and CIS is considered as the southern limit of the CITZ, south of which N-S structural grain of the Bastar craton is observed. Three granulite belts are identified within CITZ, viz., Makrohar granulite (MG) in the south of the Mahakoshal belt, Ramakona-Katangi granulite (RKG) along the northern margin of the Sausar belt, and Balaghat-Bhandara granulite (BBG) along the CIS (Fig. 1). Geological information from the Makrohar granulite is limited, but a lot of information is now available on the tectonothermal evolution of the RKG and BBG belts (Bhowmik 2019 and references therein). In the last four years (2015-2019), maximum work has been carried out in the southern part of CITZ i.e. on the Sausar Fold Belt (SFB), the associated granulites (RKG and BBG belts), and the GTSZ, and a cogent picture on the Proterozoic orogenesis in the CITZ is gradually emerging. Therefore, only this part of the CITZ is taken up in the present review.

Sausar Fold Belt and Ramakona-Katangi (RKG) Granulites

The 300 km long and 70 km wide arcuate (southward convex) Sausar Fold Belt (SFB) is the southernmost supracrustal belt of the CITZ, lying between the GTSZ and the CIS (Fig. 1). SFB consists of the metasedimentary Sausar Group (SSG) - a typical platformal assemblage of metamorphosed quartzite-pelite-carbonate with stratabound Mn-ore, which structurally overlies a vast expanse of gneissic rocks (dominantly TTG, migmatites and granite gneiss) known as the Tirodi Biotite Gneiss (TBG). TBG is presently considered as the basement to the Sausar Group (Bhowmik *et al*., 1999; Chattopadhyay *et al*., 2015), whereas some workers (e.g. Mohanty, 2010, and references therein) have argued that migmatization of Sausar sediments has generated TBG. Four phases of deformation – an early phase of southward thrusting and associated recumbent/reclined folding (D_1/F_1), followed by E-W trending upright/steeply inclined folding (F_2) of the thrust allochthon ('Deolapar Nappe') characterize the deformation of the Sausar Group. Minor F_3 folds, locally distorting the F_2 hinges, and late F_4 cross-folds are also observed (Chattopadhyay *et al*., 2003a,b). The Sausar Group rocks have undergone Barrovian-type regional metamorphism, varying in grade from low greenschist facies in the south and southeast to upper amphibolite facies (T_{Max}~675°C at P~7 kbar) in the northwest (near the contact with RKG domain) (Bhowmik *et al*., 1999). Sausar Group metasediments show a clockwise metamorphic P-T path of evolution indicating a continental collisional set-up during orogenesis (Bhowmik *et al*., 2012). Similarly, four phases of deformation and three phases of metamorphism have been established from metabasic granulites of the RKG domain (Bhowmik and Roy, 2003). The peak metamorphic condition reached P~9-10kbar, T~750°-800°C, followed by isothermal decompression at about 7 kbar/775°C and a later near-isobaric cooling at 6 kbar/650°C, recording a clockwise P-T path. A similar P-T path was established from pelitic granulites also (Bhowmik and Spiering 2004), indicating an overall collisional setting for the RKG granulites (Bhowmik, 2019 and references therein).

In the last few years, the work on Sausar Fold belt (including RKG) mostly concentrated on the timing of the tectonothermal events. While a late Mesoproterozoic to early Neoproterozoic (ca. 1063-993 Ma) age of prograde and retrograde metamorphism respectively has been established by Electron Microprobe (EMP) dating of monazites from Sausar Group metasediments, the metapelitic granulites from RKG belt yielded weighted mean monazite age of ca.1043 Ma and 955 Ma for peak and retrograde metamorphism. SHRIMP U-Pb zircon age of magmatic charnockite from the RKG domain has yielded an age of ca. 938 Ma (Bhowmik *et al*., 2012). Chattopadhyay *et al*. (2015) have reported EMP monazite ages of ca. 945 Ma from syntectonic (syn-D_2) granites and ca. 928 Ma from post-tectonic granites intrusive into the Sausar Group. From the similarity of peak (syn-D_2) metamorphism of SSG and

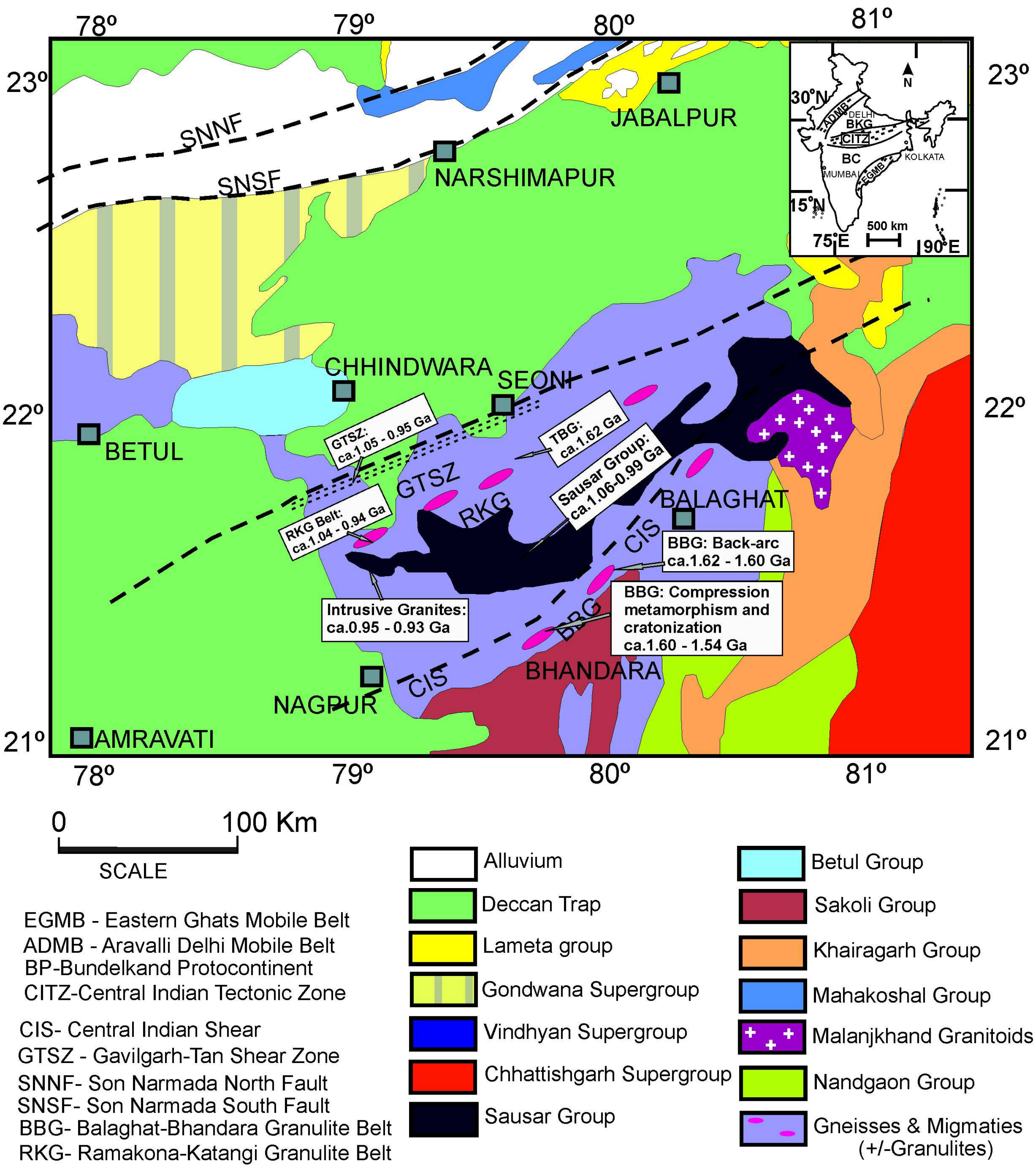

Fig. 1: Simplified geological map of the CITZ in central India showing all the supracrustal belts and tectonic lineaments. Selected geochronological data from different parts of CITZ are shown in the boxes (modified after Yedekar et al. 1990; Acharyya and Roy 2000; Chattopadhyay and Khasdeo 2011). Geochronological data taken from Bhowmik et al. (2012), Bhowmik (2019), Chattopadhyay et al. (2015), Chattopadhyay et al. (2017). See the text for more details

age of retrograde metamorphism in RKG, they argued for a slightly younger tectonothermal history of the SSG than that of the RKG.

Another major controversy has recently surfaced, regarding the glaciogenic origin of Sausar rocks. This issue is also intertwined with the

Paleoproterozoic *vis-a-vis* Meso-Neoproterozoic age of the Sausar Group. Mohanty *et al*. (2015) have argued that a major diamictite horizon present in the lower part of the Sausar Group (Nayakund Formation), and the presence of 'dropstones' and rock fragments within dolomitic marble (Potgowari Formation) characterize it as a glacial deposit with a cap-carbonate horizon. Isotopic analyses ($\delta^{13}C$ and $\delta^{18}O$) of the cap carbonate indicates strong negative $\delta^{13}C$ excursion, similar to other Paleoproterozoic glacial deposits of USA, Australia and Canada. On the basis of this, Mohanty *et al*. (2015) have reinterpreted all the reported ages and structural-metamorphic studies of the earlier workers, and have suggested that the Sausar Group was formed as a glacial deposit in the early Paleoproterozoic and was subsequently deformed and metamorphosed through Palaeo- and Mesoproterozoic (1900-1800 Ma and 1500-1400 Ma) while the last 'minor thermal event' occurred at ca. 1000-900 Ma. However, many of these interpretations seemingly contradict the basic field relationships and radiometric age data obtained from the Sausar Group and associated granulites in recent times, and are therefore open to questions (Chattopadhyay, 2015; Bhowmik, 2019). Mohanty and Nanda (2016) have reported a paleosol horizon at the contact of the Sausar Group and the Tirodi Gneiss, showing several evidences of pedogenesis, e.g. stress corrosion cracks, core stone weathering, nodular rocks etc. Different major element ratios in the paleosol indicate base loss through hydrolysis. According to these authors, flat Ce and Eu anomalies, low ΣREE, and high $(La/Yb)_N$ indicate a reducing environment during the paleosol formation in a oxygen-deficient environment near the Archaean-Paleoproterozoic transition. More recently Sarangi *et al*. (2017) has inferred anoxic depositional conditions of the Sausar basin during the interglacial periods of the Paleoproterozoic (Huronian) glaciation from the REE characteristics of the cap carbonate rock, e.g. conspicuous Ce anomaly, and enrichment of Fe, Mn, Zn and U among others.

Gavilgarh-Tan Shear Zone (GTSZ)

An ENE-WSW-trending, more than 300 km long and 2-3 km wide, brittle-ductile shear/fault zone runs through the unclassified gneisses exposed between the Betul and the Sausar Supracrustal belts (Fig. 1) (Golani *et al*., 2001; Chattopadhyay and Khasdeo, 2011). The eastern part of this linear structure is expressed as a ductile shear zone comprising sheared Precambrian gneisses and granitoids, while the western part is mainly observed as a brittle fault zone affecting Gondwana sandstone and Deccan Trap basalt flows, within which slivers of the sheared gneissic basement rocks are also found. Repeated reactivation of the fault/shear zone from Proterozoic to Quaternary has been established (Bhattacharjee *et al*., 2016; Chattopadhyay and Bhattacharjee, 2019). The ductile shear zone is best exposed in the Kanhan River and its tributaries as a series of outcrops of mylonitized granitoids ranging in composition from granite to granodiorite and quartz monzonite. Sheet-like intrusions of the granitoids into the shear zone, mutually cross-cutting relationship between different types of granitic rocks, and the presence of Pre-full crystallization (PFC) deformation fabric indicate syn-kinematic intrusion of granites into the GTSZ (Chattopadhyay and Khasdeo, 2011). Spectacular shear zone structures, e.g. tails of mantled porphyroclast, S-C-C′ structure, mineral fish, core-and-mantle microstructure etc. indicate sinistral strike-slip shearing at a depth of 15 km or more (Chattopadhyay *et al*., 2008). Kinematical vorticity analysis of the mylonites has demonstrated 'partitioned' transpression along the GTSZ where the central part is dominated by simple shear and the marginal part has largely accommodated pure shear. This was considered as a result of oblique collision between continental (or continent and arc) fragments within the CITZ (Chattopadhyay and Khasdeo, 2011).

Although the kinematics of the Gavilgar-Tan shear zone has been well studied, its temporal tectonic correlation with other units of CITZ (e.g. Sausar/Betul belts) was largely unknown due to the lack of proper radiometric ages of these sheared granites. Recently Chattopadhyay *et al*. (2017) have carried out U-Pb zircon (by LA-ICPMS) and U-Th-total Pb monazite dating (by EPMA) of these granitoids. From the geochronological data, they have interpreted that the granitoids intruded the shear zone syntectonically between ca.1.2 Ga and 0.95 Ga. The age of transpression and mylonitization was more tightly bracketed between ca. 1.05 Ga and 0.95 Ga. This suggests an early Neoproterozoic age of transpression and granite magmatism in GTSZ, which closely matches with the collision events (ca 1.06-0.93 Ga) recorded in the adjacent Sausar Fold belt (see

Chattopadhyay *et al*., 2017 for details).

Balaghat-Bhandara Granulite (BBG) Belt

The Balaghat-Bhandara granulite (BBG) domain is represented by detached, lensoidal (~500-1000 meter long and ~50-200 meter wide) bodies of a variety of pelitic, psammo-pelitic granulites, Banded Iron Formation (BIF, including quartzite) and two-pyroxene (cf. gabbro-norite suite) granulites within highly tectonised felsic gneisses along the southern margin of the Sausar Belt (Ramchandra and Roy, 2001; Bhowmik *et al*., 2005, 2014; Alam *et al*., 2017). Combined metamorphic and geochronological (SHRIMP U-Pb zircon and EMP monazite dating) studies have revealed lower crustal, ultra-high-temperature (UHT) granulite facies metamorphic conditions at ca. 1.6 Ga in the central segments of the BBG belt and a medium-pressure/medium temperature granulite facies metamorphism farther east and northeast (see Bhowmik, 2019 for a comprehensive review). The UHT domain in the BBG belt is polyphase metamorphosed with three distinct cycles of metamorphism between 1.6 and 1.54 Ga: BM_1-BM_2-BM_3 (where B refers to the BBG belt) (Bhowmik *et al*., 2014).

Recently Bhowmik and Chakraborty (2017) have developed a tool based on diffusion kinetics to reconstruct sequences of short-lived metamorphic events in very old, hot orogens. Application of the method to the ultra-hot ca.1.6 Ga orogenic domain (i.e. BBG belt) has shown that pulses of advance and roll-back of colliding plates preceded the final closure and collision. These authors have demonstrated that cooling from ultra-high temperature metamorphic conditions in the orogen took place in multiple pulses that occurred with a periodicity of about 10 Myr at rates that varied between 100's to 10's of °C/Myr, and burial-and/or exhumation-rates that varied between 30 and 2 km/Myr, respectively. Recurring short-lived heating/cooling and burial/exhumation cycles of ultra-hot (T>900ºC) to hot (700<T<800ºC) thermal pulses at lower to middle crustal levels within one orogenic event of ~50 Myrs duration, and implying episodic mantle-scale thermal perturbations at 1.6-1.54 Ga is, therefore, a characteristic feature of the BBG belt, and distinguishes it from other metamorphic belts of the CITZ (Bhowmik *et al*., 2014; Bhowmik& Chakraborty, 2017).

Discussion

It is evident from the above discussion that the southern part of the CITZ records two separate orogenic events at ca. 1.62-1.54 Ga and ca. 1.06-0.94 Ga. The older orogenic imprint is best observed in the BBG terrain and the Tirodi Biotite Gneiss (TBG), whereas the later (Meso-Neoproterozoic) orogenic signatures are best recorded in the northern part (i.e. Sausar Group, RKG and GTSZ). Recent works in the southern part of CITZ, as discussed in the preceding sections, suggest the following crustal evolutionary history (for more details see Bhowmik, 2019):

1) An active continental margin developed at ca 1.62 Ga at the southern margin of the CITZ and led to the growth of an aerially extensive magmatic arc, now represented by the Tirodi biotite gneiss.

2) Back-arc extension occurred between ca.1.62 and 1.60 Ga, producing an extremely high heat flow at the base of the attenuated back-arc crust (cf. BBG supracrustal sequence). Between ca. 1.60 and 1.59 Ga, a compressional event led to the collision between the SIB and the arc crust, closure of the back-arc basin and a lower crustal UHT metamorphism along a CCW *P–T* path in the BBG belt. Polyphase deformation and metamorphism of BBG rocks continued between ca. 1.57 and 1.54 Ga.Large-scale cratonization of the BBG belt took place at ca. 1.54 Ga, due to final suturing of arc-back arc systems along the southern margin of the CITZ.

3) The Sausar basin opened up in Mesoproterozoic - between ca.1.54 and 1.06 Ga, and most likely coincided with the ca. 1.45 Ga extension in the adjoining Chhotanagpur Gneissic Complex.

4) Under-thrusting of the amalgamated BBG and SIB crust beneath the combined Mahakoshal and NIB crust took place between ca. 1.06 and 0.93 Ga. The collision event led to the closure of the Sausar basin and produced high-pressure upper amphibolite to granulite facies rocks in the RKG domain.

5) The north-directed (SIB beneath NIB) subduction and collision led to the final suturing between the NIB and SIB, and the oblique collision was partly adjusted by transpressional

deformation and granite magmatism (ca. 1.05-0.95 Ga) along the Gavilgarh-Tan shear.

6) The position of the 'suture' between NIB and SIB is not well constrained. The Central Indian Shear (CIS) has been traditionally considered as a major suture formed by collision of SIB and NIB (or BC and BKC in other words) (Yedekar *et al*., 1990). However, the current analysis reveals that the CIS marks a boundary between the arc and the back-arc systems in the Sausar Mobile Belt (SMB), and not between the NIB and SIB sensustricto. CIS is better placed at the northern boundary of the BBG belt (Bhowmik 2019). On the other hand, a north-directed subduction of SIB (+BBG+TBG) under NIB led to the closure of Sausar basin, and continued northward subduction resulted in an oblique continental collision along the RKG and/or GTSZ which finally stitched the NIB and SIB (Bhowmik *et al*., 2012; Chattopadhyay *et al*., 2017). The northern suture may therefore be placed along (or close to) the Tan shear lineament (i.e. GTSZ), as is also suggested by recent geophysical studies (Azeez *et al*., 2017).

7) One major outstanding problem at present is the origin and sedimentation age of the Sausar Group, as discussed above. The recently suggested glaciogenic origin of the Sausar Group sediments, isotopic analyses of carbonates showing strong negative $\delta^{13}C$ excursion, and anoxic condition of deposition (Mohanty *et al*., 2015; Sarangi *et al*., 2017), opens up interesting new research issues. But their proposition that Sausar Group is Paleoproterozoic in age, and is correlatable with the Huronian glaciations of Canada, is very much doubtful as the huge amount of structural, metamorphic and geochronological data, described above, point to a Meso-Neoproterozoic age of the Sausar Group rocks and the associated granulites (Chattopadhyay, 2015; Bhowmik, 2019).

Recent work has suggested that the Late Paleoproterozoic to Early Mesoproterozoic orogenesis is a globally significant amalgamation event separate from the Columbia Supercontinent assembly and gave rise to the first nucleus of a proto-Greater Indian Landmass. The Late Mesoproterozoic-Early Neoproterozoic (i.e. broadly Grenville-age) continental collision tectonics observed in the Sausar Belt, RKG and GTSZ, is also recorded from the adjoining Proterozoic mobile belts in eastern and north-western India, involving at least three micro-continental blocks (e.g. North and South Indian Blocks and the Marwar Block). These cratonic blocks were amalgamated at ca. 1.0 Ga to produce the final configuration of the Greater Indian Landmass (see Bhowmik, 2019 and references therein).

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