Deformation and metamorphic history of the Singhbhum Craton vis-à-vis peripheral mobile belts, eastern India: implications on Precambrian crustal processes

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The Singhbhum Craton (SC) of eastern India grew and evolved throughout the Precambrian era with a spectacular yet cryptic record of the early Earth processes. An extensive study on geochemistry, metamorphism, deformation, geochronology, and sedimentation of the rocks of the craton produced a large database which is described and synthesized here to build up a deformation and metamorphic history of the craton right from the Eoarchean time. Altogether seven orogenic episodes have been identified from the SC and its margins spanning from Paleoarchean to end-Neoproterozoic. Of these, the earlier two Paleo-Mesoarchean orogenic episodes (~ 3.3 and ~ 3.1 Ga) are confined within the cratonic core and were instrumental in building up the framework of the Archean nucleus in SC. The Neoproterozoic event (~ 2.8 Ga) is marked by thrusting of the granulite-grade lower crust of the SC, the Rengali Province (RP), along its southern margin. Later three Proterozoic orogenic events (~ 1.8, ~ 1.6–1.5, and ~ 1.0 Ga) left imprints along the northern margin of the SC. Among these, the Grenvillian (~ 1.0 Ga) event was most pervasive, which remobilized the northern fringe of the Singhbhum Granite massif developing thick-skinned thrust belt–like structures within the narrow northern belt. Active tectonics later shifted again to the southern margin with the last orogenic event (~ 0.5 Ga) being marked within the RP resulting from oblique docking of the Eastern Ghats Belt (EGB) against the RP–SC. Based on this long and winding history, we also discussed the possible tectonic scenarios that eventually shaped the present configuration of the craton.

Keywords: Singhbhum Craton, Eastern India, Mobile belt, Deformation, Metamorphism

INTRODUCTION

Precambrian cratons bear testimony to the nature of early Earth geodynamic processes in rock records. Though a large part of this record has been erased through later erosion and tectonics, parts of it are still preserved in different cratons and are studied for extracting key information as cratons represent the building blocks of continents. These continents grew incrementally by stitching of smaller blocks to progressively larger volumes via orogenic belts resulting from repeated collision-accretion processes (Cawood et al., 2012) and/or some form of vertical tectonics (Van Kranendonk et al., 2007). The chronological history of the cratonization process is complex due to the polycyclic nature of basin opening-magmatism-deformation-metamorphism that tends to blur the time separated specific growth stages beyond easy recognition. Problems emerge due to paucity of preserved sections, multiple deformation, and metamorphic episodes that obliterate crucial geological relationships and ensues overall tectonic conformity amongst rock units. For such reasons, Archean cratons are proved to be difficult case studies for unravelling early earth history. Despite such uncertainties, deciphering the evolutionary history of the cratons remained one of the most intriguing challenges to the geoscientists. For overcoming such challenges, a multipronged approach has increasingly been practiced involving the careful study of field and microstructures combined with geochronology and geochemistry using robust analytical techniques (Moser et al., 2008; Windley and Garde, 2009; Zhai et al., 2010).
Peninsular India comprises a mosaic of Archean cratons joined through surrounding Proterozoic mobile belts. Amongst these, the Singhbhum Craton (SC) (Fig. 1) in eastern India records prolonged Archean growth history (Saha, 1994; Das et al., 2017; Oliieroook et al., 2019; Upadhyay et al., 2019), which is distinct from the other Indian cratons. The southern margin of SC is composed of high-grade granulites along with medium-grade metasedimentary and metavolcanic rocks (collectively termed as the Rengali Province or RP after Dobmeier and Raith, 2003) that separate the Paleo–Mesoarchean granite–greenstone terrane of the SC (e.g., Saha, 1994; Mukhopadhyay et al., 2001) from the Angul Domain of the Mesoproterozoic Eastern Ghats Belt (EGB; Bose et al., 2011; Das et al., 2011; Dasgupta et al., 2013, 2017a). In the north, the SC is bordered by another Proterozoic mobile belt – the North Singhbhum Mobile Belt (NSMB). In spite of several studies made so far, unravelling the deformation and metamorphic history of the SC were largely neglected and remained incomprensive till date. In this paper, we present an overview of the structural development and metamorphic episodes in the SC and an attempt has been made for correlation of such events with the peripheral mobile belts. Our ultimate goal is to analyze the deformation and metamorphic imprints for understanding the evolution of the SC vis-à-vis Archean tectonic processes.

LITHOTECTONIC UNITS IN THE SINGHBHUM REGION

In the Singhbhum region, an oval–shaped Archean cratonic core is bordered by Proterozoic mobile belt rocks to the north (NSMB) and south (Rengali Province, RP). While the Singhbhum Shear Zone (SSZ) marks the northern boundary of the Archean cratonic core (Fig. 1), its southern boundary with the RP is demarcated by the crustal-scale Sukinda thrust–Barkot Shear Zone (Fig. 2).

The principal components that make up the Archean cratonic core of the Singhbhum region (Fig. 1) are as follows:

1. The gneissic and granitoid suite that include Older Metamorphic Tonalite Gneiss (OMTG), Singhbhum Granite (SBG), Bonai Granite and Mayurbhanj Granite.
2. The older supracrustal sequences comprising the Older (Metamorphic Group (OMG) and the Iron Ore Group (IOG) rocks.
3. Younger supracrustal sequences of the Dhanjori Group and equivalents (Simlipal Group, Mahagiri Formation, and Keonjhar Formation.
4. Intrusive mafic-ultramafic suite represented by Gabro-anorthosite and Newer Dolerite dyke swarm.

The TTG suite of the SC is primarily represented by the OMTG, comprising deformed and metamorphosed tonalite, trondhjemite, and granodiorite (Saha et al., 1984; Saha, 1994; Mukhopadhyay, 2001). The OMTG suite is presumed to have evolved over an extended period, i.e., ~ 3.53–3.40 Ga (Acharya et al., 2010; Nelson et al., 2014; Upadhyay et al., 2014; Pandey et al., 2019; Mitra et al., 2019). Still, older whole–rock geochronological data from the OMTG yielded ~ 3.77 Ga (Basu et al., 1981), 3.66 Ga (Ghosh et al., 1996), and ~ 3.61 Ga (Upadhyay et al., 2014) ages, and range 4.24–4.03 Ga xenocrystic zircon (Chaudhuri et al., 2018) suggesting a mafic Hadean protolith for the OMTG.

The OMG supracrustals consist of metasedimentary rocks with interlayered ortho-amphibolites, the latter rocks showing tholeiitic affinity, near-chondritic εNd (0.9–0.7), light rare earth element (LREE) enrichment, and yield a whole–rock Sm–Nd isochron age of 3305 ± 60 Ma (Sharma et al., 1994). The metasedimentary units are represented by muscovite–biotite–sillimanite–garnet schists, quartz–sericite schists, quartz–magnetite–cummingtonite schists, quartzites, and banded para-amphibolites. Detrital zircon grains from quartzite yielded ages ranging from ~ 3.20 to ~ 3.63 Ga (Basu et al., 1993; Misra et al., 1999), with continuing debate on maximum depositional age of these sediments, i.e., ~ 3.50 Ga (Goswami et al., 1995) and ~ 3.38 Ga (Nelson et al., 2014).

Contrasting views also exist regarding the OMTG–OMG mutual relationship. Most of the earlier workers believed that the OMTG is intrusive into the OMG supracrustal sequence (e.g., Saha et al., 1984; Saha, 1994; Mukhopadhyay, 2001) while some later workers opined OMG sequence was deposited upon the older OMTG gneisses (Prabhatkar and Bhattacharya, 2013; Nelson et al., 2014; Mitra et al., 2019).

The SBG and its variants occupy the major part of the Singhbhum cratonic core (Fig. 1) and are considered to be emplaced in two (Nelson et al., 2014; Upadhyay et al., 2014; Dey et al., 2017; Upadhyay et al., 2019) or three phases (Saha, 1994; Misra et al., 1999; Misra, 2006; Tait et al., 2011). The SBG massif is composite in nature and comprises biotite granite, granodiorite, adamellite and of minor TTG components. 207Pb/206Pb whole–rock isotopic ages reported from SBG phase–I and phase–II are 3.44 and 3.29 Ga, respectively (Ghosh et al., 1996). 207Pb/206Pb date of zircon grains from SBG phase–II yielded an age of 3.32 Ga (Misra et al., 1999). SBG phase–III had yielded a 207Pb/206Pb isochron age of 3.05 Ga (Ghosh et al., 1996). Hence, the older phases of SBG was as old as the OMTG while the youngest phase (III) was of ~ 3.1 Ga age, which is also the age of the
Figure 1. Generalized geological map of the Singhbhum region (modified after Saha, 1994). Inset shows the position of the Singhbhum craton in the map of India. Blue dotted lines indicate presence of major thrusts in the Singhbhum region (see text for details). White dash lines represent other major fault planes. Iron Ore Group basins are denoted as WIOG, EIOG, SIOG (see text for details). (T), Tikra Formation; (K), Keonjhar Formation; (P), PalLahara geniss; (B), Bonai Granite; RP, Rengali Province; EGB, Eastern Ghats Belt; NSMB, North Singhbhum Mobile Belt; SSZ, Singhbhum Shear Zone; BSZ, Barkot Shear Zone.
Mayurbhanj Granitoid body (Misra et al., 1999, 2002; Acharyya et al., 2010; Chakrabarti et al., 2019) and of the Bonai Granite (Sengupta et al., 1991). However, later workers argued that the SBG granitoids were emplaced in two pulses at ~ 3.45–3.44 Ga and 3.35–3.25 Ga (Nelson et al., 2014; Upadhyay et al., 2014; Dey et al., 2017; Chaudhuri et al., 2018; Upadhyay et al., 2019; Pandey et al., 2019; Olierook et al., 2019; Mitra et al., 2019).

The IOG rocks occur peripheral to the ovoid SBG massif in three successions (Fig. 1), in the west (Western IOG or WIOG), south (Southern IOG or SIOG), and east (Eastern IOG or EIOG), are represented by low-grade metasedimentary rocks interlayered with mafic and minor felsic volcanic rocks (Acharyya, 1993; Saha, 1994; Mukhopadhyay, 2001). The SBG massif depicts an intrusive relationship to the IOG rocks wherever the contact is discernible in the outcrop scale (Saha, 1994; Ghosh et al., 2015). Dacitic lava flows interlayered with sediments in the SIOG belt have been dated at 3.51 Ga (U–Pb zircon) by Mukhopadhyay et al. (2008). Basu et al. (2008) reported a 3.39 Ga U–Pb concordant age of zircons collected from tuffs in the WIOG belt. The ~ 3.1 Ga aged Mayurbhanj Granite bears a clear intrusive relationship with the EIOG rocks (Saha, 1994; Acharyya et al., 2010). A metasedimentary sequence from the EIOG yielded a maximum age of 3.29 Ga estimated from the youngest zircon population in the sequence (Ghosh et al., 2019). The age of the EIOG basin is further constrained by a cross-cutting granite at the center of the basin yielding an age of 3.33 Ga (Nelson et al., 2014). Thus, these dates point tentatively towards a Paleo- to Mesoarchean age range (~ 3.51–3.35 Ga) for the IOG rocks of the three belts.

The younger Dhanjori Group, dominated by mafic lava in the upper part and siliciclastics at the base, developed in a basin along the north-northeast boundary of the SBG massif (Fig. 1) and overlays unconformably the SBG body (Gupta et al., 1985; Mazumder et al., 2012). No reliable age data are available from the Dhanjori Group and these are tentatively put in the ~ 2.9–2.1 Ga

Figure 2: Generalized geological map of the Rengali Province and its surrounding geological terranes (modified after Crowe et al., 2003). The black rectangles represent the position of Figures 3 and 4 in the Rengali Province where detailed geological maps are shown.
age bracket (Misra and Johnson, 2005; Acharyya et al., 2010). In contrast, the dominantly siliciclastic Mahagiri Formation and Keonjhar Formation rocks were deposited in a passive margin setting along the southern and south-western margin of the SBG massif respectively at ~ 3.02 Ga (Mukhopadhyay et al., 2014; Fig. 1), which are considered as Dhanjori equivalents in this study. Similar Dhanjori equivalent rocks of the Achu Formation (cf. Ghosh et al., 2015) crop out along the north-western margin of the SBG massif (Fig. 1).

The Newer Dolerite Dyke swarm is disposed in a conjugate NW–SE and NE–SW pattern transgressing cratonic rocks and emplaced episodically over a large time span ranging from Neoarchean to Paleoproterozoic (Shankar et al., 2014; Kumar et al., 2017). Whereas, the Kolhan Group deposited in a separate basin along the north-western boundary of the SBG massif marks the only Proterozoic equivalent in this dominantly Archean milieu (Saha, 1994; Mukhopadhyay et al., 2006; Fig. 1).

Mobile Belts

The arcuate NSMB comprises multiply-deformed greenschist-amphibolite facies phyllites and schists flanking the centrally-located belt of the meta-igneous suite of rocks, known as the Dalma Group (Fig. 1). The Dalma Group comprises multiply folded greenschist-to-amphibolite-facies metamorphosed mafic and ultramafic rocks containing serpentinites and horizons of pillow lava, interbanded with deep-sea euxinic sediments (Bhattacharyya and Bhattacharyya, 1970) and flanked in the south by the rocks of the Singhbhum Group (Naha, 1965; Sarkar, 1982; Fig. 1). The Singhbhum Group metasediments are intercalated with mafic volcanic rocks and lensoid granite–granodiorite plutons and are classified into a lower Chaibasa Formation and an upper Dhalbhum Formation (Sarkar et al., 1985; Saha, 1994). To the north of the Dalma Group occurs a thick sequence of phyllite and schist interbanded with quartzite, quartz-schist, graphite-phyllite, and chert of the Chandil Formation (Fig. 1). Detrital zircon data from the Dhalbhum and Chandil Formations suggest ages of ~ 2.8–2.6, ~ 2.55–2.43, ~ 2.15–1.95, and ~ 1.75 Ga (Olierook et al., 2019). These ages are surprisingly similar to those obtained from the supracrustal sequences occurring south of the SC (Das et al., 2017). A further constraint came from the 1.63 Ga age rhyolite flows in the lower Chandil Formation (Olierook et al., 2019). Prominent ductile shear zones separate the NSMB from the SC in the south (SSZ), and the suite of granulite-amphibolite facies gneisses and foliated granites of the Chhotanagpur Gneissic Complex (CGGC) to the north (Tamar-Porapahar Shear Zone; Fig. 1).

The RP, occurring south of the SC (Fig. 2), was identified as a separate crustal province which might have genetic relations with the southerly-placed Proterozoic Eastern Ghats Belt (EGB; Crowe et al., 2001, 2003; Dobmeier and Raith, 2003). Because of its position, this terrane is crucial in understanding the timing of the suturing of the EGB with the SC. It was later recognized as a southern extension of the SC preserving vastly exposed granitic basement (Pallahara Gneiss) with granulite enclaves and supracrustal sequences (Mahapatro et al., 2012; Bose et al., 2015; Chattopadhyay et al., 2015; Ghosh et al., 2016; Das et al., 2017). The major lithounits in its central part comprise a median granulite-gneissic belt flanked by Pallahara Gneiss-younger BIF-bearing supracrustal sequences (Devgarh–Malaygiri basins; Saha, 1994) in the north, and a belt of siliciclastic dominated supracrustals (Tikra Formation; Mahalik, 1994) in the south.

DEFORMATION PATTERNS AND METAMORPHIC SIGNATURES

Structural and metamorphic data are relatively scarce from the central part of the cratonic core comprising OMG–OMTG–SBG–EIOG sequences. In comparison, deformation analyses and metamorphic studies from the western, southern and northern cratonic margins and adjoining mobile belts are more in number. However, no proper attempt in erecting a comprehensive structural framework and metamorphic history of the entire terrane has been made from the available data to date.

The Archean cratonic core including EIOG

The OMG–OMTG enclave suites (Prabakar and Bhattacharya, 2013; Saha, 1994; Nelson et al., 2014; Upadhyay et al., 2019) make up a few map-scale discontinuous outcrops scattered through the central part of the terrane (Fig. 1). According to Saha (1994), the OMG–OMTG suites were co-folded in two stages, first about a steep NE-plunging axis (D1C) and later about a moderate to steep SE plunging axis (D2C) with development of an early gneissic foliation S1c, which was later folded by S2c developing axial planar to these folds. In contrast, Prabakar and Bhattacharya (2013) documented four-phase deformation structures from the OMG–OMTG suites with the dominant trend of deformation structures varying between NNW to NNE with later E–W cross folding transposing the earlier structures.

Upadhyay et al. (2014) reported a concordant U–Pb age of 3.31 Ga from metamorphic rutile in mica-schist of OMG which indicates amphibolite-facies metamorphism of the OMG rocks in late Paleoarchean. This corroborates
the earlier reported Ar-Ar and K-Ar cooling ages of 3.20–3.30 Ga from metamorphic hornblende and biotite (Sarkar et al., 1969; Baksi et al., 1987) in OMG rocks. Upadhyay et al. (2014) also documented ~ 3.30–3.28, ~ 3.19–3.12, and ~ 3.02–2.96 Ga deformation/metamorphic imprints from the OMTG granitoids.

Foliation in the SBG massif characteristically shows small-circle girdle pattern about sub-vertical axes in structurally homogeneous sectors (Saha, 1994) from which the predominant foliation was interpreted to be of primary in origin (S0). However, Prabhakar and Bhattacharya (2013) described presence of a penetrative N-NE trending steep tectonic foliation from the SBG around Champa–Rairangpur, where the granites have been dated to be of ~ 3.32–3.25 Ga age (Nelson et al., 2014; Upadhyay et al., 2014; Dey et al., 2017; Upadhyay et al., 2019). Penetrative NW–WNW trending northerly dipping foliation S1G had been described from the north-northwestern boundary of the SBG massif in between Saraikela-Bisrampur (Fig. 1; Ghosh et al., 2015). Microfabric studies indicated the penetrative foliation to be of mylonitic character depicting top-to-sense of ductile shearing (correlated with D2N of northern craton margin as described later) which has been linked with the development of WNW–ESE trending thrust planes along the granite-metasediment contact (Ghosh et al., 2015). The ~ 3.1 Ga Mayurbhanj Granite at the eastern flank of the SC locally records N-S trending gneissic to mylonitic fabric (Chakraborti et al., 2019) implying post- to syn-emplacement deformation. Similar deformation structures had been reported from the 3.1 Ga age Bonai Granite by Sengupta et al. (1991) from the western flank of the SC. According to Chakraborti et al. (2019), the Mayurbhanj Granite and Bonai Granite together represent a major phase of post-to syn-collisional granitic activity in the SC indicating crustal stabilization. It is worthwhile mentioning here that the well-constrained monazite chemical age data from the metasedimentary sequences within and around the Mayurbhanj Granite near Bangripasi yielded ~ 3.0–2.9 and 0.9–1.0 Ga age peaks, which was ascribed to two separate metamorphic event affecting the rock volume (Prabhakar et al., 2014). Among these, the older age range of ~ 3.0–2.9 Ga coincides roughly with the time of emplacement of the Mayurbhanj Granite.

Systematic deformation studies from the EIOG basin is limited (Acharyya, 1993; Saha, 1994; Mukhopadhyay, 2001; Ghosh et al., 2019). A few studies on the EIOG rocks showed a set of early D1E N to NNE trending low-plunging overturned folds being refolded (D2E) by WNW–ESE trending cross folds about a steep axis, where the second folding was mostly represented in mesoscopic scale (Saha, 1994).

WIOG and western cratonic margin

The WIOG basin depicts two phases of folding and related cleavage development (D1W–D2W) (Ghosh and Mukhopadhyay, 2007; Ghosh et al., 2010a). The NNE-SSW trending fold and cleavage set (D1W) is interpreted to be the earlier developed one as it often gets bent and warped against the E-W trending later fold–cleavage set (D2W). Though the two phases of folds are present with equal intensity in the mesoscopic scale, the regional fold structures are dominated by the NNE-SSW trending (F1W) fold set (Fig. 1). The map and structural section of the WIOG basin reveal that the outcrop pattern of the IOG rocks is controlled by the NNE trending regional horseshoe synclinorium structure (Fig. 1) consisting of a pair of a narrow syncline in the west and a broad asymmetric anticline in the east (Ghosh and Mukhopadhyay, 2007).

Along the western margin of the basin, the D1W deformation is mostly represented by asymmetric easterly verging folds (F1W), westerly dipping tension gash structures and reverse faults (our unpublished data). Shear sense deduced from these structures consistently points towards top-to-the east movement. This thrust sense along the western margin has been clubbed with the D1W deformation of the WIOG rocks as the fold–thrust structures formed under a similar E-W compressive kinematic framework. Few D1W phase reverse faults have been described from the eastern margin of the basin (G. Ghosh, unpublished data), which could be probable equivalents of the thrust structures from the western margin.

SIOG and southern cratonic margin

The northern and southern margin of the SIOG sequence is demarcated by two E-W trending regional scale faults, the Sukinda Thrust in the south and the Dholakmundai fault in the north (Fig. 3; Ghosh et al., 2010b). Detailed structural analysis establishes that the D1S phase of deformation represents E-W trending fold–thrust structures with early reclined folds within the SIOG rocks. The unconformably overlying Mahagiri Quartzite was deposited over already folded and thrust (D1S) sequence of the SIOG–ultramafics (Ghosh et al., 2010b). Detrital zircon ages obtained from the Mahagiri Quartzite constraint the establishment of a post-D1S passive margin setting along SC margin at ~ 3.0 Ga (Mukhopadhyay et al., 2014). The depositional age of the Mahagiri Quartzite thus pinpoints the D1S orogeny in the SIOG rocks at ~ 3.1–3.0 Ga, which is in conformity with the ages obtained from syn- to post-tectonic (D1S) gabbroic intrusive within the deformed ultramafics (Augé et al., 2003).
Figure 3. Geological map of the southern margin of the Singhbhum Craton (modified after Bose et al., 2015) showing relative disposition of the SIOG, RP, and EGB. Major structural elements of the different rock sequences are also displayed in the map (see text for details).
The deformation of the Mahagiri Quartzite and co-folding of the SIOG rocks-ultramafics occurred subsequently (D_{2S}) with development of E-W trending fold and fault structures. The near-parallel orientation of the map-scale F_{1S} and F_{2S} fold axial traces and non-cylindricity of the large F_{2S} folds have been viewed as a result of the D_{2S} thrusting event (Ghosh et al., 2010b). The part of the SIOG sequence bounded between the Sukinda Thrust and the Dholakmundi fault and traversed by several intermittent map-scale D_{2S} faults were remobilized during D_{2S} thrusting. To the north of the Dholakmundi fault, the attitude of dominant structural grain within the SIOG rocks changed to NW–SE from the dominant E–W trend south of the fault (Fig. 3). Thus, the swing in structural trend within the SIOG rocks north and south of the Dholakmundi fault has been viewed as an effect of the D_{2S} deformation front. The S_{2S} foliation in the SIOG rocks and the equivalent foliation in the granulite belt of the Rengali Province are considered correlatable confirming that the later part of the deformational history (D_{2S}) was shared by the two terranes (Ghosh et al., 2010b).

**Rengali Province**

In its narrow eastern part, the northern boundary of the RP is marked by the Sukinda Thrust characterized by southerly dipping mylonitic foliation. It separates the high-grade charnockite–enderbite suite of the RP in the south from the SC rocks to the north (Fig. 3). The occurrence of pervasively deformed granite bodies near the SC–RP contact zone has been viewed in terms of granite emplacement concomitant with the early shearing event D_{1R} within RP. The sense of shear deduced from S–C fabrics in the contact zone is consistently top-to-the north (Ghosh et al., 2010b). It implies northward thrust transport of the granulite grade rocks of the RP over the crustal footwall along the Sukinda Thrust during the main tectonic event in the RP – the Rengali orogeny (D_{1R}) at ~2.83–2.78 Ga (Mahapatro et al., 2012; Bose et al., 2016).

The gneissic basement of the RP, the Pallahara Gneiss and equivalents, contain pockets of mafic, pelitic, and ultramafic granulites. Contrasting metamorphic peaks were reported from mafic granulite (10–12 kbar, 860 °C) and pelitic granulite (6–6.5 kbar, 730 °C) enclaves with structural characteristics indicating that these rock suites were juxtaposed by thrusting (Bose et al., 2015). Zircon U–Pb age data suggest emplacement of charnockite magma at ~3.05–2.86 Ga, high-grade metamorphism at ~2.84–2.82 Ga and emplacement of felsic magma at ~2.83–2.78 Ga (Mahapatro et al., 2012; Bose et al., 2016). From this data, Mahapatro et al. (2012) and Bose et al. (2016) contended that the Pallahara gneiss and equivalent gneissic rocks in RP represent thrusted deep crustal section of the SC which resulted from the D_{1R} event at ~2.8 Ga.

The central part of the RP (Fig. 4) is dominated by the ~2.8 Ga age Pallahara gneiss (Misra et al., 2000; Crowe et al., 2001; Mahapatro et al., 2012; Bose et al., 2015) mantled by thick packages of metasedimentary and metavolcanic rocks (Tikra, Malaygiri and Devgarh Assemblages; Mahalik, 1994) along its northern and southern margins forming two spatially separated low-to-medium grade (greenschist–lower amphibolite facies) supracrustal belts (Fig. 4). Detrital zircon study from the supracrustal belts reveals multiple cycles of basin development during the Neoarchean–Mesoproterozoic time (Das et al., 2017). Alkaline magmatism at ~1.35 Ga in this province marks the last magmatic event recorded so far (Ranjan et al., 2018). At the southern part of the province, amphibolite–facies metamorphism in the supracrustals along a clockwise P–T path occurred at ~0.98 Ga, which was followed by further tectonothermal events at ~0.85–0.80 and ~0.62–0.50 Ga (Chattopadhyay et al., 2015). The central RP is bounded between two major E–W trending shear zones, i.e., the Barkot Shear Zone in the north and the Kerajang Fault Zone in the south, also bounded by the NE–SW trending Riamol Shear Zone and the NW–SE trending Akul Fault Zone represent large-scale sinistral and dextral shear zones, respectively (Fig. 4). The central RP has been shown to be pervasively deformed in the form of fold–fault and foliation–lineation development in a major transpressive deformation event D_{2R} resulting from oblique docking of the EGB against SC (Fig. 4) in end Neoproterozoic time (Ghosh et al., 2016). The overall architecture of the belt defines a regional–scale positive flower structure (Ghosh et al., 2016) with significant vertical extrusion and emplacement of the mid–level basement crustal segments over upper crustal parts occurred through emanation of oppositely–verging thrust sheets from the steep central root zone of the transpressional belt at ~0.5 Ga (Ghosh et al., 2016). An alternative model, however, exists in which the RP represents a septum of the Bastar Craton which was transported over the EGB by a dextral strike–slip movement at ~0.5 Ga (Bhattacharya et al., 2016; Sawant et al., 2017).

**Northern cratonic margin**

Contrary to the narrow northern margin of the SBG massif, the northeast and southwest margins are marked respectively by westerly and easterly opening wedge-shaped and variably deformed supracrustal packages (Fig. 5a). The Dhanjori basin, developed unconformably over the northeast margin of the SBG body (Fig. 5a), shows
heterogeneous development of E–W trending fold–thrust structures along its northern margin in proximity to the SSZ (Joy and Saha, 1998) while the major part of the basin-fill sediments in south remain undeformed (Gupta et al., 1985; Mazumder and Sarkar, 2004; Mazumder, 2005). The northwest margin in between SSZ and Kolhan basin also presents variably deformed sequences, which include IOG equivalents and Dhanjori equivalent rocks (Ghosh et al., 2015; R. Ghosh et al., 2019).

The IOG equivalents that occur in the northern craton margin, invariably present an early E–W trending schistosity S_{1N} which gets transposed by a northerly dipping later shear foliation S_{2N} related with D_{2N} deformation. Presence of large-scale D_{2N} thrusts with a top–to–south sense of movement has been reported from the northern margin of the SBG body resulting in basement granitoid slices within deformed supracrustals (Mukhopadhyay et al., 1980; Ghosh et al., 2015). These workers established that the northern margin of the SBG body, between Saraikela and Bisrampur, was involved in thick-skinned style thrust–related deformation (D_{2N}) where some of the thrust splays emanating from the SSZ footwall reached up to the rigid SBG basement and produced basement wedges within the adjoining metasediments (Fig. 5a). The younger Dhanjori and equivalent units outcropping in this deformed zone depict the shear related later structures (D_{2N}) only. The regional folds present in IOG equivalent rocks in the northwest margin have been demonstrated to be F_{2N} folds (developed on early bedding parallel S_{1N}) by Mukhopadhyay et al. (1990) showing eye–shaped to reclined geometry with increasing proximity to the SSZ. It clearly depicts that the F_{1N} regional folds within the IOG rocks from the WIOG were rotated and transformed into F_{2N} structures by this later fold–thrust belt shearing (D_{2N}).

Ghosh et al. (2015) showed that the effect of the D_{2N} deformation can be traced till the north–western boundary of the Kolhan basin in the form of a major thrust, the
Chaibasa Thrust, with top-to-south sense of displacement which emplaced the older IOG equivalent successions over the younger Kolhan rocks (Fig. 5a). Several thrust slices have been identified between the SSZ and the Chaibasa thrust in this region (Fig. 5a). These thrust sheets had been envisaged as a foreland-vergent thrust system at the footwall of the SSZ resulting from D2N deformation in a similar manner as the northerly placed NSMB by earlier workers (Ghosh and Sengupta, 1990; Blackburn and Srivastava, 1994; Mahato et al., 2008; Rekha et al., 2011). In recent times, Ghosh et al. (2019) described two internal thrusts (Bamebasa Thrust and Jhinkpani Thrust; Fig. 5b) from the Kolhan basin on the basis of SPO–CPO magnetic fabric (AMS data) analyses and linked their development with the craton-margin D2N deformation. These are evidently the subsidiary thrusts that splayed upward from the basal decollement connecting the Chaibasa Thrust (Fig. 5b) and form a part of the same D2N imbricate thrust system described from north of the Kolhan basin (Ghosh et al., 2015), the SSZ being the hinterland ward distal member of the system.

**Singhbhum Shear Zone**

The SSZ occurs at the contact between the SC on the south and the NSMB on the north (Fig. 1). The shear zone in general cuts across the Singhbhum Group rocks belonging to the NSMB and the Dhanjori Group–Iron Ore Group and equivalents of the SC. The deformed, metamorphosed and hydrothermally altered rocks of the SSZ are represented largely by biotite schist, chlorite schist, sericite schist, meta-conglomerate, quartzite, tourmalinite and feldspathic schist/soda granite. Using the reaction textures and mineral chemical data of tourmaline-bearing metamorphic assemblages, Sengupta et al. (2005) opined that the rocks were affected by two sets of folding and ductile shearing, the earlier (D1SZ) of which occurred during ~ 1.60–1.80 Ga. The early prograde metamorphic
(M₁SZ) event culminated at 480 ± 40 °C, 6.4 ± 0.4 kbar while the second metamorphic event (M₂SZ) caused regression of the M₁ assemblages by infiltration of boron-rich fluid from a deep-seated magma. Pal and Rhede (2013) used U-Th-Pb chemical ages from uraninite in SSZ to demonstrate that the uranium mineralization occurred at ~1.90–1.80 Ga, followed by a HREE metamatism at ~1.66 Ga. They further argued that the timing of the latest hydrothermal and related deformation events (D₂SZ) that affected the SSZ was ~1.0 Ga, which is coeval with the last stage of tectono-thermal event in NSMB (Sarkar et al., 1969; Bose, 2009; Acharyya et al., 2010; Rekha et al., 2011; Chakraborty et al., 2019). This is further corroborated by recent muscovite ⁴⁰Ar/³⁹Ar age of 970 ± 8 Ma (Olierook et al., 2019).

**North Singhbhum Mobile Belt**

The metamorphosed volcanosedimentary rocks of the NSMB (schist, phyllite, and amphibolite) and the felsic intrusives experienced at least three phases of deformation (D₁NSMB-3SMB) and metamorphism (M₁NSMB-3SMB: Mahato et al., 2008). The M₂SMB $P$-$T$ condition increases from greenschist or low-$P$ amphibolite facies (~5–6 kbar; 500-600 °C; Lal and Singh, 1978; Lal et al., 1987; Sen-gupta et al., 2005) in the southern parts of the S-NSMB, to higher-$P$ (~10 kbar; ~620 °C) close to the Dalma Group (Mahato et al., 2008). Throughout the southern NSMB, the M₃SMB metamorphism shows greenschist facies mineral assemblages. U-Th-Pb chemical ages of monazite indicate post-peak ($P_{M3SMB}$) metamorphism occurred between 1.72 Ga (D₁SMB) (Chatterjee et al., 2010) and 1.55 Ga (D₂SMB) (Mahato et al., 2008). These workers correlated the greenschist facies M₁ metamorphism with 1.3 Ga monazite ages, with similar ages (1.3–1.2 Ga) from monazite rims in schists from the southern NSMB. Monazite spot ages from metapelites in the northern domain of the NSMB yielded an age of 957 ± 17 Ma (D₂SMB) (Rekha et al., 2011). The overall metamorphic grade of the Singhbhum Group is reported to greenschist facies, which increases to garnet-, staurolite-, and kyanite-bearing amphibolite facies schists close to the Tamar–Porapahar Shear Zone at the contact with the CGGC. The increase in metamorphic grade is restricted to <1 km wide zone adjacent to the Tamar–Porapahar Shear Zone along the southern fringe of the CGGC. Mahato et al. (2008) estimated the prograde $P$-$T$ conditions for the shear zone-hosted syn-tectonic garnet-staurolite schist to be 620 ± 50 °C, 7 ± 1 kbar. Petrological and geochronological data from rocks lying at the western fringe of the NSMB (Gangpur Schist Belt) are recent additions to this evolutionary history (Chakraborty et al., 2019). The first metamorphic event was reported to have reached peak amphibolite facies conditions of 5.7 ± 0.1 kbar and 623 ± 10 °C. The second metamorphism ensued along a counter-clockwise $P$-$T$ path with peak conditions of ~8.3 kbar and 730 °C. Monazite data yielded 1.55 and 1.44 Ga chemical ages for these two events, respectively. The rocks were later affected by a major metamorphic overprint along a clockwise $P$-$T$ trajectory with peak conditions of ~4.7 kbar and 610 °C at 0.96 Ga.

**DISCUSSION**

**Correlation of events and regional structural framework**

A major hindrance in building the regional structural framework from the cratonic core is the lack of deformation studies from the SBG massif and equivalent granitoids, which volumetrically constitute the major part of the craton. The WIOG and EIOG basins, though spatially separated by the intervening SBG massif, share some similarity in deformation pattern, having similar low-grade metamorphic (greenschist facies) traits. In both the basins, the outcrop pattern is controlled by N-NNE trending regional F₁ folds developed on primary bedding surfaces with an axial planar S₁ cleavage dipping steeply due west. From the dominance of easterly verging asymmetric F₁ folds, fold-fault relations and microstructural observations, a case for top-to-the-east thrusting (D₁WS) have been advocated from the western margin of the WIOG belt (our unpublished data). This shearing episode is manifested in N-S trending, W-dipping basin boundary reverse faults from the eastern margin along which the folded IOG rocks had been thrust over the younger supracrustal sequences. Though N-S and E-W trending faults have been documented from the EIOG basin (Saha, 1994), their kinematics is still not well-constrained for correlation. Thus, an episode of E-W compression and easterly-directed thrusting is the major deformation event (D₁WS-D₁EE) inferred for the IOG rocks. This deformation event (D₁WS-D₁EE) had been labelled as the IOG orogeny after Saha (1994). However, as commented earlier, the effect of this IOG orogeny on the SBG massif is largely undocumented till date.

The cratonic core was overprinted by later south-directed thrusting (D₂) along its northern margin. The dominant N-NNE trend of regional F₁ folds in both the WIOG and EIOG basins got modified due north near the SSZ. In the WIOG basin, the regional structural trend rotated clockwise to ENE, while in EIOG, an anticlockwise sense
of rotation of structural trends to NW from NNE had been observed (Saha, 1994; Mukhopadhyay, 2001; Ghosh et al., 2015). Outcrop scale $F_{2W}$–$F_{2E}$ folds are prominent in SSZ footwall those transpose the earlier $F_{2W}$–$F_{2E}$ folds with development of an E–W trending steep northerly–dipping axial planar cleavage ($S_{2W}$–$S_{2E}$). While the IOG and IOG equivalents share both the deformation fabric ($D_{1S}$–$S_{2}$; $D_{1N}$–$S_{2}$), the younger Dhanjori equivalents characteristically display the later fabric only ($D_{2S}$; $D_{2N}$).

We now compare the nature of deformation and metamorphism suffered by the OMG–OMTG suites in the backdrop of the IOG deformation to get a comprehensive picture. Though two or more generation of folding (Saha, 1994; Prabhakar and Bhattacharya, 2013) have been reported from the OMG–OMTG suites, the deformation pattern is distinct from the IOG rocks by its higher metamorphic grade (amphibolite facies) and dominant NW–SE trending structural grain. The variation could be a result of time separated diachronous development of the two suites representing two distinct stages in the overall growth history of the craton. Alternatively, the distinctly lesser volumetric proportion of the OMG–OMTG suite and its spatial position at the center of the cratonic core engulfed by the SBG massif might indicate that this suite represents the higher grade orogenic core of the IOG orogeny that co-deformed the two, now spatially separated, IOG belts. The NW–SE structural trend in the latter scenario could result from rotation of the NNE–SSW IOG fabric during post-to–syn- tectonic granitoid emplacement subsequent to deformation and metamorphism of the IOG orogeny. Lack of precise data focusing on structural and metamorphic aspects of the OMG–OMTG suite and SBG body till date hinders us to choose between these alternatives.

**Chronology of Archean crustal evolution vis-à-vis deformation, metamorphism and tectonics**

A brief overview of the depositional and magmatic events from the SC and the marginal mobile belts is presented in Figure 6. Recent age data tend to converge to the idea that the OMTG body and the OMG–IOG enclave suites were contemporaneous at ~ 3.51–3.37 Ga (Chaudhuri et al., 2018; Olierook et al., 2019). The SBG massif and equivalent granitoids were clearly intrusive within this early cratonic core in between ~ 3.45–3.1 Ga (Saha, 1994; Misra, 2006; Upadhyay et al., 2014; Dey et al., 2017; Upadhyay et al., 2019) and were instrumental in building up of the major part of the craton. The last phase of major granite emplacement at ~ 2.8 Ga in SC was localized along the southern margin, i.e. Pallahara gneiss and equivalent granitoids in the RP (Misra et al., 2000; Dasgupta et al., 2017b; Topno et al., 2018). Some acidic volcanics (Nelson et al., 2014) and a component of the mafic dyke swarm (Newer Dolerites; Kumar et al., 2017) also lie within the same age bracket indicating near contemporaneous felsic to mafic additions to the cratonic mass. The craton attained stability in pulses at ~ 3.3,
3.1, and 2.8 Ga and it paved the way to the younger Neoarchean to Palaeoproterozoic basin developments at different parts of the craton, which are diachronous but have been broadly clubbed here as Dhanjori Group equivalents. An episode of Newer Dolerite dyke swarm also testifies to this phase of basin opening episode (Shankar et al., 2014). The Mesoproterozoic to Neoproterozoic Kolhan Group (Mukhopadhyay et al., 2006) is the only basin to have developed and/or now preserved (?) along the north–western margin of the SBG massif. The marginal mobile belts (both NSMB and RP), however, amply demonstrate evidence for Proterozoic volcanism and sedimentation (Fig. 6).

In this backdrop, we now discuss the time-separated orogenic episodes that left robust signatures in rock records and were ultimately instrumental behind the composite shape of the craton and the peripheral mobile belts (Fig. 7). Saha (1994) recognized three orogenic pulses from the cratonic core of which the earlier two were from the OMG–OMTG suite while the last one was more pervasive and affected the IOG rocks as well. Recent data presumes that the OMTG granitoids were deformed/metamorphosed at 3.30–3.28, 3.19–3.12, and 3.02–2.96 Ga (Upadhyay et al., 2014, 2019) implying an earlier ~ 3.3 Ga orogeny from the OMG–OMTG suite. The later widely recognized orogenic event from the cratonic core is the IOG orogeny. The folding and low-grade metamorphism of the WIOG basin was fixed at ~ 3.1 Ga (Saha, 1994; Misra et al., 1999; Acharyya et al., 2010) due to well-preserved intrusive relation shown by the 3.1 Ga age last phase of the SBG massif within folded IOG rocks along the marginal parts of the WIOG basin (Saha, 1994; Mukhopadhyay, 2001). For the EIOG basin, the 3.1 Ga age Mayurbhanj Granite displays similar intrusive relationship with the folded IOG rocks. Moreover, a well-constrained ~ 3.0–2.9 Ga age metamorphic imprint has been documented from rocks occurring within the supracrustals surrounding the Mayurbhanj Granite (Prabhakar et al., 2014). The SIOG rocks also bear a similar time-frame for the first phase of deformation (D1s). It is manifested by the depositional age of the Mahagiri Quartzite (~ 3.02 Ga; Mukhopadhyay et al., 2014) that lies unconformably over the deformed ultramafics (Augé et al., 2003) of the SIOG sequence.

Zircon U–Pb age data indicate syn–orogenic metamorphism and magmatism in RP at ~ 2.83–2.78 Ga (Rengali orogeny ~ D1R, Bose et al., 2016). Petrological data suggest that the RP represents the deeper section of the SC which was structurally emplaced at a shallower level over the low–grade cratonic rocks of the SIOG along the Sukinda Thrust by this ~ 2.80 Ga Rengali orogeny (D1R). The record of such switch–over from passive to active margin after a gap of ~ 200–300 million years has a far-reaching implication with regard to Archean geodynam-
ics. Similar repeated accretion along the margins of cratons, as witnessed along the southern margin of the SC, is believed to be a hallmark of Phanerozoic accretionary systems (Isozaki et al., 2010). The entire belt presents a final pervasive deformation imprint (D2R) at ~ 0.49–0.52 Ga (Ghosh et al., 2016), which represents a transpression-dominated tectonic setting (Ghosh et al., 2016; Bose and Dasgupta, 2018) resulting from oblique-docking of the Eastern Ghats Belt at ~ 0.50 Ga against the SC.

The overall deformation history is markedly different at the northern cratonic margin where two early orogenic pulses are recorded at ~ 1.83 Ga (D1SMB; D1SZ) and 1.66 Ga (D2SMB; D2SZ) followed by a final major event (D3SMB; D3SZ) at ~ 1.00–0.90 Ga (Mahato et al., 2008; Pal et al., 2011; Rekha et al., 2011; Pal and Rhede, 2013). The last event was the most intense tectonothermal event at the northern margin, which resulted in the final accretion of the NSMB to the SC. This Grenvillian-age tectonic event was strong enough to activate pre-existing thrust systems and initiate new ones even in the deeper parts of the SC and is correlatable with the ~ 1.0 Ga Sausar orogeny from the Central Indian Tectonic Zone (Roy and Hanuma Prasad, 2003; Bhowmik et al., 2005). A matching deformation history has been reported from the western flank of the NSMB from within the Gangpur Group rocks (Chakraborty et al., 2019) where continent-continent collision at ~ 0.96 Ga is proposed between CGGC and SC-Gangpur Group. It is important to note here that no Pan-African tectono-thermal event (~ 0.5 Ga) has yet been confirmed from the tectonic milieu of the SSZ or the NSMB (Fig. 7).

Thus, altogether seven distinct orogenic episodes have been recorded from the SC spanning from Paleo-archean (~ 3.3 Ga) to end-Neoproterozoic (~ 0.5 Ga; Fig. 7). Of these, the earlier two Paleo-Mesoarchean orogenic episodes (OMG, ~ 3.3 Ga and IOG, ~ 3.1 Ga) are exclusively confined within the rocks of the cratonic core and were instrumental in building up of the framework of the Archean nucleus in SC. The younger IOG orogeny also marks cratization of the SC with emplacement of the post-tectonic SBG III–Mayurbhanj Granite–Bonai Granite masses. Following the ~ 2.8 Ga event along the northern margin, tectonic activity was mostly concentrated along the northern margin of the SC. Three successive phases of Proterozoic orogenic events (~ 1.83, ~ 1.66, and ~ 1.0–0.90 Ga) affected the northern margin of which the youngest Grenvillian-age event was the most pervasive. It remobilized the northern fringe of the SBG massif developing thick-skinned thrust belt structures within the narrow northern belt. However, active tectonics again shifted to the southern margin with the last orogenic event (~ 0.50 Ga) being marked within the RP resulting from oblique docking of the EGB terrane against the RP-SC.

A number of tectonic models have been proposed in recent times explaining the structural architecture and evolution of the SC. The apparent curving of the N–NNE IOG trend around the oval-shaped SBG massif had been explained by molding of the supracrustals round a rigid basement during later deformation (Mukhopadhyay, 2001) or were perceived to have resulted from deformation in narrow keels of the IOG basins in between rising granitoid plutons depicting a case of vertical tectonics (Van Kranendonk et al., 2007; Prabhakar and Bhattacharya, 2013; Dey et al., 2017; Upadhyay et al., 2019; Srinivas et al., 2019). Prabhakar and Bhattacharya (2013) conceived ascent of the basement derived anatectic melt in the form of SBG body within the cover sequence made up of OMGT–IOG rocks with simultaneous sinking (‘dripduction’ by van Kranendonk, 2011) of the latter along steep extensional shear planes to be the causative mechanism to produce the varied structures and observed disposition of the lithounits at the ‘SC’ cratonic core. The spread in the εNd and εH values in the OMTG suite led Upadhyay et al. (2019) to conclude that some form of the burial of colder crustal material occurred to produce the observed variation in the nature of the isotopic signatures in the rocks. They also conceived a “dripduction” type geodynamic setting where gravitational instabilities at the base of the thickened felsic crust led to large-scale delamination and sinking of the proto-crust with concomitant melting and ascent of the mafic lower crust. Simultaneous occurrence of high–HREE and low–HREE type TTGs in SC was explained by Dey et al. (2017) by invoking extensive melting of the mafic crust of the oceanic plateaus (produced through plume activity) at a range of depths. Dey et al. (2017) linked different episodes of felsic magmatism in the SC with distinct mantle plume events, which led to a soft and ductile middle to lower crust inducing sagging of the overlying denser greenstone sequences forming keels and rise of granitic bodies producing overall domal structures and thought this to be a major process of crust formation in Paleo–Mesoarchean time in SC. Arguing in a similar line Srinivas et al. (2019) proposed a combination of plate and plume tectonic processes to account for the Paleo–Mesoarchean crust formation in the SC.

In the present case, we have tried to argue through disentangling of successive orogenic events that their eventual superposition led to the growth of the oval-shaped SC through successive accretionary events. Amongst these, the earlier orogenic events (~ 3.3–3.1 Ga) affected the cratonic core (OMG–OMGT–IOG–SBG) while the later phases (~ 2.8–0.5 Ga) were concen-
trated along its southern and northern margins. It was not a case of double-sided subduction and accretion along the northern and southern margins, which is frequently advocated as an alternative tectonic mode in Archean (Singh et al., 2019), but a case of punctuated accretion at its core and along the two opposite margins. Establishment of successive diachronous fold-thrust related deformation structures along the southern, western and northern SC margins, as presented in this study, strongly negates the contention of vertical tectonics in which synchronicity of the gradually curving orogenic trend is an essential feature. The observed swing in IOG structural grain around the SBG massif has been convincingly shown in this study to be an effect of successive orogenic events along the SC margins that eventually shaped the overall architecture of the craton. Though Prabhakar and Bhattacharya (2013) tried to argue for a supracrustal down–granitoid up movement along granitoid-supracrustal contacts in the SC, well-constrained data on deformation kinematics (Ghosh et al., 2010a, 2010b, 2015, 2016) from the western, northern and southern margins of the central granitoid complex (SBG–OMTG) unequivocally establishes the granitoid-supracrustal contacts as thrust contacts with supracrustal up movement. The established deformation kinematics thus again strongly negates the idea of supracrustal down–granitoid up notion, which is a prerequisite for vertical tectonics. However, it must be mentioned here that though successive accretion appears more logical option in view of the present database, more precise, preferably geochronologically constrained, kinematic data from the central granitoid belt and its eastern margin is an essential prerequisite to have a clear understanding on the nature and mechanism of the tectonics processes that ultimately shaped the present configuration of the craton and for better constraining the geodynamic model in vogue during Archean.

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