

Rapid Communication

Cite this article: Deshmukh T and Prabhakar N (2020) Linking collision, slab break-off and subduction polarity reversal in the evolution of the Central Indian Tectonic Zone. *Geological Magazine* **157**: 340–350. <https://doi.org/10.1017/S0016756819001419>

Received: 5 July 2019

Revised: 1 November 2019

Accepted: 1 November 2019

First published online: 7 January 2020

Keywords:

Central Indian Tectonic Zone; slab break-off; North Indian Craton; South Indian Craton; subduction polarity reversal

Author for correspondence:

Tanzil Deshmukh,
Email: tanzil.deshmukh@gmail.com

Linking collision, slab break-off and subduction polarity reversal in the evolution of the Central Indian Tectonic Zone

Tanzil Deshmukh  and N. Prabhakar

Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

Abstract

The Central Indian Tectonic Zone demarcates the zone of amalgamation between the North Indian Craton and the South Indian Craton. Presently, the major controversies in the existing tectonic models of the Central Indian Tectonic Zone revolve around the direction of subduction and the precise timing of accretion between the North Indian Craton and the South Indian Craton. A new model for the tectonic evolution of the Central Indian Tectonic Zone is postulated in this contribution, based on recent geological and geophysical evidence, combined with previously documented tectonic configurations. The present study employs the slab break-off hypothesis and subsequent polarity reversal to explain the tectonic processes involved in the evolution of the Central Indian Tectonic Zone. We propose that the subduction initiated (c. 2.5 Ga) in a S-directed system producing island-arc sequences on the South Indian Craton. The southward subduction regime culminated with slab break-off underneath the South Indian Craton between c. 1.65 Ga and 1.55 Ga, which subsequently induced subduction polarity reversal and set the course for N-directed subduction (<1.55 Ga). The final closure along the Central Indian Tectonic Zone is governed by the collisional regime during the Sausar Orogeny (1.0–0.9 Ga).

1. Introduction

The geological evolution of subduction zones is typically governed by recurrent tectonic and magmatic activities that result in the development of polyphase orogenic belts (Brown, 2009). A detailed tectonothermal history and understanding of temporal relationships between various tectonic domains in an orogen not only provide insights into global tectonic processes but also help in reconstructing the palaeogeography of dispersed crustal fragments within supercontinents (Cawood & Buchan, 2007). The orogenic systems are primarily classified into accretionary and collisional types (cf. Windley, 1992). Accretionary orogens (Fig. 1a) are formed in response to the subduction of oceanic crust along continental margins (Windley, 1992; Condie, 2007), whereas collisional orogens (Fig. 1b) are developed during the orthogonal collision between two or more continental blocks producing a thickened and reworked crust (Windley, 1992; Brown, 2009). Collisional orogens juxtapose different cratons (Fig. 1b) and are always preceded by the development of accretionary orogens (Cawood & Buchan, 2007). Based on kinematics and the resulting structural framework, accretionary orogens are further categorized into retreating and advancing types (Cawood & Buchan, 2007). The growth of retreating orogens is characterized by faster rates of rollback of the subducting plate than the rates of advance of the overriding plate (Elsasser, 1971; Schellart & Lister, 2004), leading to the development of back-arc and intra-arc basins within the overriding plate (Dickinson, 1995; Marsaglia, 1995; Smith & Landis, 1995). On the other hand, advancing orogens develop in zones where the velocity of the overriding plate supersedes that of the subducting slab (Russo & Silver, 1996; Silver *et al.* 1998; Schellart, 2008). Advancing orogens are characterized by crustal thickening, an extensive reworking of the pre-existing crust and the formation of fold and thrust belts (Cawood *et al.* 2009). Despite the significant differences in operating mechanisms, the geodynamic framework and crustal growth along the accretionary margins are manifested through widespread magmatism and crustal thickening during multiple episodes of burial and exhumation (Lister *et al.* 2001; Collins, 2002; Beltrando *et al.* 2007). Further, in some cases, slab break-off has been recognized as a dominant mechanism in the development of orogens during continental collision (Fig. 1c), which is commonly associated with changes in the rate of plate convergence, subduction polarity reversal and slab rollback (Garzanti *et al.* 2018 and references therein).

The Central Indian Tectonic Zone (CITZ; Fig. 1d) in the Indian peninsula, also known as the Satpura Orogen, marks the zone of convergence between the Bundelkhand–Aravalli cratonic mass (North Indian Craton, NIC) and the Dharwar–Bastar–Singhbhum cratonic mass (South Indian Craton, SIC) during Proterozoic time (Radhakrishna & Ramakrishnan, 1988;

© The Author(s), 2020. Published by Cambridge University Press. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted re-use, distribution, and reproduction in any medium, provided the original work is properly cited.

CAMBRIDGE
UNIVERSITY PRESS

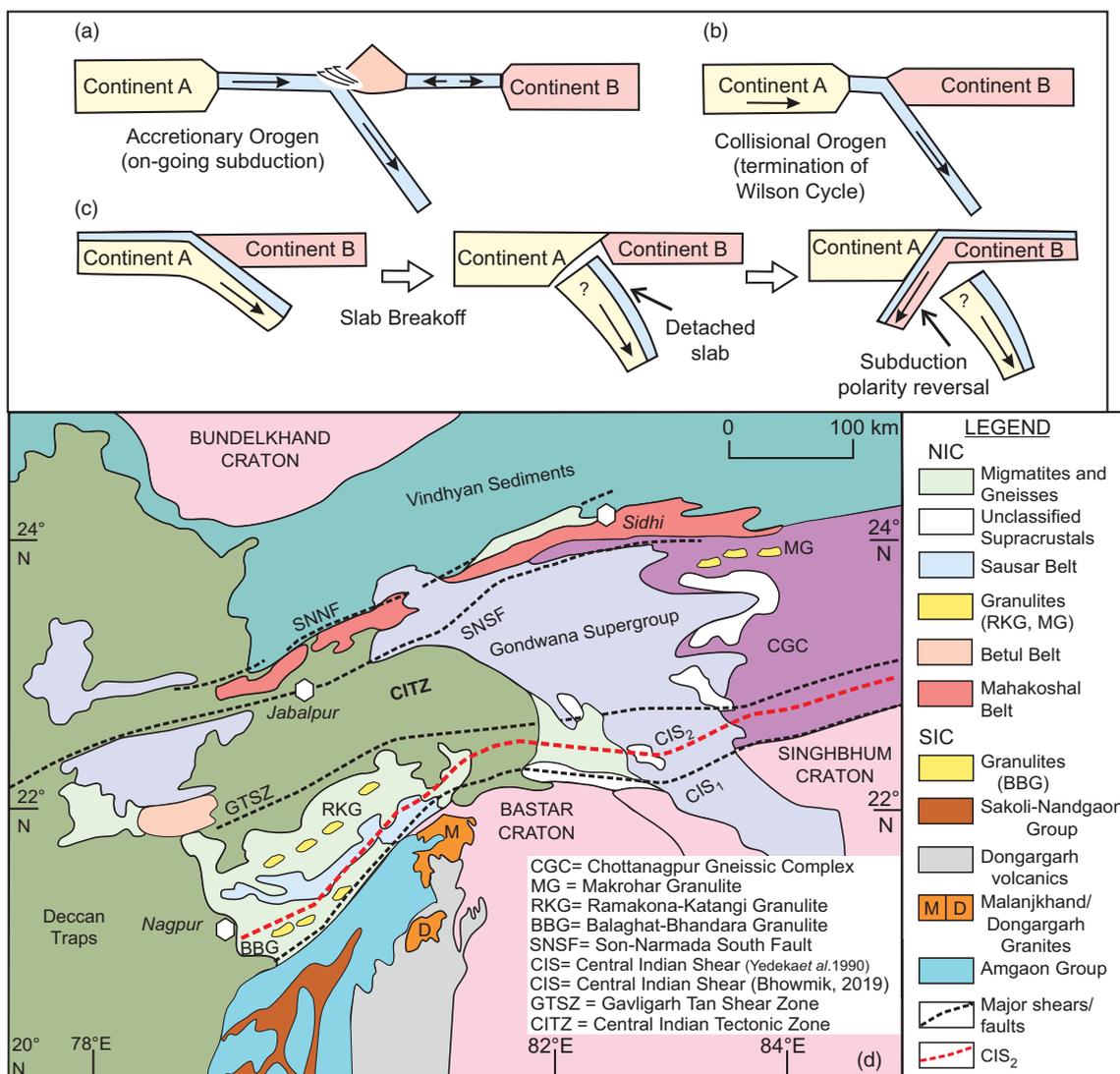


Fig. 1. (Colour online) Sketches illustrate types of orogens and mechanism of slab break-off: (a) accretionary orogen, (b) collisional orogen, and (c) slab break-off along a convergent margin. (d) Geological map of the CITZ (modified after Deshmukh *et al.* 2017; Bhowmik, 2019) showing the spatial distribution of discrete lithological domains in the fold belt.

Radhakrishna, 1989; Roy & Prasad, 2003). The diverse lithological domains in this orogen preserve crucial evidence of the subduction, collision and accretion between the NIC and SIC (Yedekar *et al.* 1990; Acharyya, 2003; Roy & Prasad, 2003). The evolutionary history of the CITZ is thought to be a product of multiple orogenic events between Palaeoproterozoic and early Neoproterozoic times. The majority of the Palaeoproterozoic tectonic events are best preserved along the northern segment of the CITZ, while the late Mesoproterozoic – early Neoproterozoic events are mainly recognized within the southern parts of the CITZ (Deshmukh & Prabhakar, 2019). However, the direction of subduction and the initial timing of accretion between the NIC and the SIC remain disputed (Bhowmik *et al.* 2012 and references therein). Based on existing models, some researchers believe that the SIC subducted northward beneath the NIC (Roy & Prasad, 2003; Mall *et al.* 2008; Mandal *et al.* 2013; Chattopadhyay *et al.* 2017), while some have argued in favour of southward subduction of the NIC beneath the SIC (Yedekar *et al.* 1990; Acharyya, 2003; Bora, 2015; Bhowmik & Chakraborty, 2017). In both cases, the final closure of the ocean basin and the cessation of tectonic activity between the NIC and SIC is postulated at *c.* 1.0–0.9 Ga (Bhowmik *et al.* 2012 and references

therein). These events have a significant bearing on the geological evolution and transition of the tectonic regime from the initial to the final stages of the CITZ development. Spatially and temporally, the prominent tectonic episodes of the CITZ broadly coincide with the assembly and break-up of the Columbia and Rodinia supercontinents (Fig. 2; Bhowmik, 2019 and references therein).

In this contribution, we integrate our recent tectonothermal findings from the Mahakoshal Belt (MB; Fig. 2) with the existing data available from the CITZ and present a model for basin formation, sedimentation, metamorphism and magmatism associated with Proterozoic accretion along the fold belt. In combination with arguments made by earlier researchers, our hypothesis highlights the significance of recent geochronological and geophysical studies while describing the important tectonic events in the CITZ. We propose that the subduction polarity reversal between the NIC and SIC is responsible for the crustal growth and present tectonic framework of the CITZ, which involves an initial (Palaeo- to Mesoproterozoic) southward subduction of the NIC followed by the flipping of subduction polarity between late Mesoproterozoic and early Neoproterozoic times.

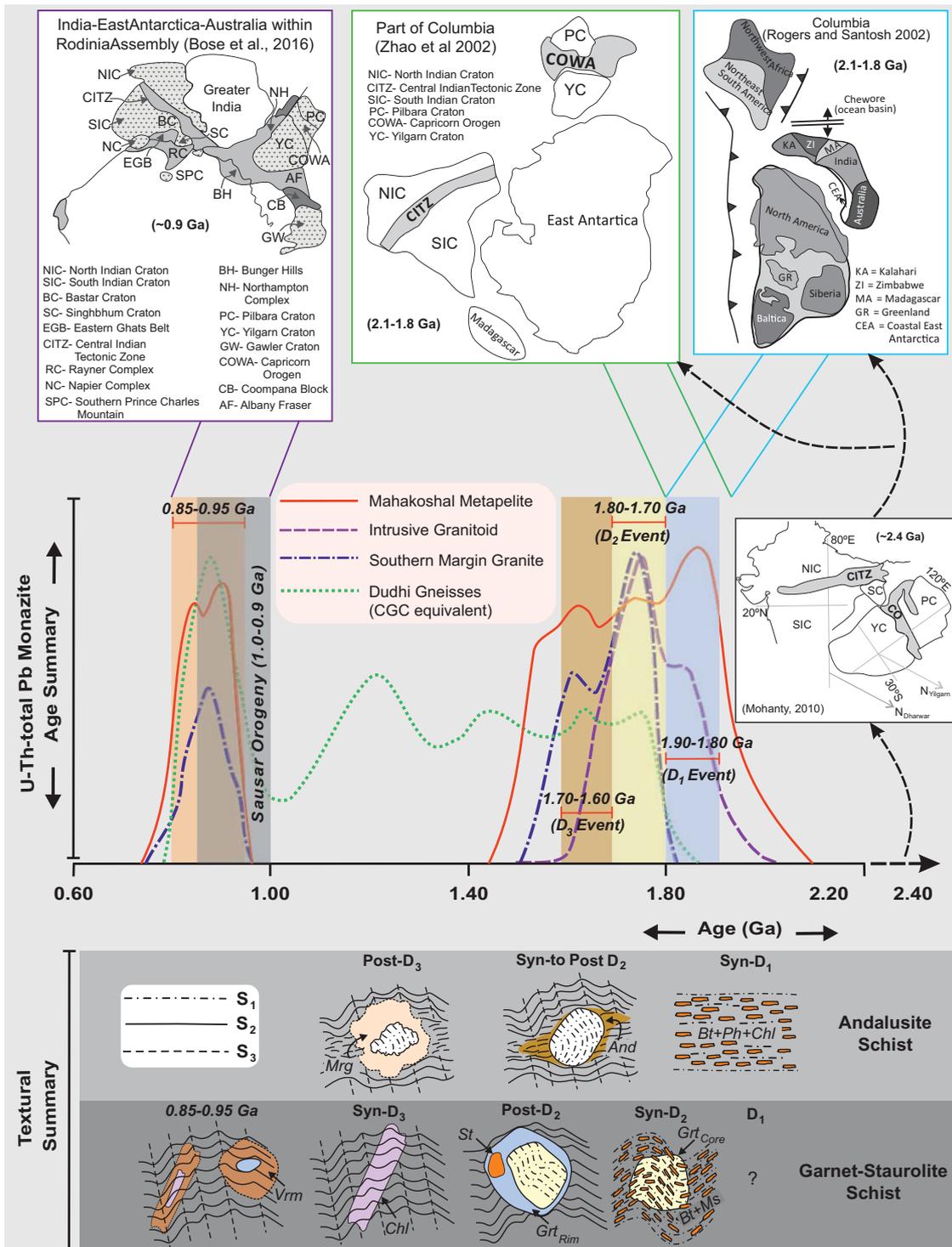


Fig. 2. (Colour online) Relative probability plots of monazite ages of Mahakoshal Belt (MB) pelites and associated litho-units (modified after Deshmukh *et al.* 2017 and Deshmukh & Prabhakar, 2019). The sketches in the lower panel demonstrate the time-constrained deformation textures and associated mineral assemblages in andalusite and garnet-stauroilite schists, where S₁, S₂ and S₃ are denoted by dashed-dotted, solid and dashed lines, respectively. All mineral abbreviations are after Whitney & Evans (2010). The tectonothermal events identified from the MB largely coincide with the timing of formation and subsequent dispersal of Columbia and Rodinia supercontinent assemblies (top panel).

2. Tectonic framework of the CITZ

The E-W-trending CITZ (Fig. 1d) is a collage of granulite facies para/ortho-gneisses and greenschist- to amphibolite-facies volcano-sedimentary supracrustal sequences with distinct geological histories (Bhowmik *et al.* 1999; Roy & Prasad, 2003; Roy *et al.* 2006). Other lithological units associated with these

belts include the Tirodi Biotite Gneisses (TBG), Chottanagpur Gneissic Complex and sporadic granitoid intrusions. The Son-Narmada North Fault and the Central Indian Shear (CIS) represent the northern and southern boundaries of the CITZ, respectively (Fig. 1d) (Radhakrishna & Ramakrishnan, 1988; Ramakrishnan & Vaidyanadhan, 2010).

2.a. Granulite belts

The CITZ is composed of three major granulite terranes: the Makrohar Granulite (MG) belt to the north, the Balaghat–Bhandara Granulite (BBG) belt to the south and the Ramakona–Katangi Granulite (RKG) belt in the central part (Fig. 1d). These granulite belts comprise a variety of lithodemic units that preserve protracted Proterozoic tectonothermal histories (Roy & Prasad, 2003; Roy *et al.* 2006; Bhowmik *et al.* 2014) and are spatially associated with low- to medium-grade supracrustal rocks (Fig. 1d). According to Roy & Prasad (2003), the MG belt comprises intercalations of mafic and felsic lithologies (mafic granulite, banded iron formation and calc-silicates), which are abundantly exposed around the Makrohar area. Owing to the absence of direct geochronological data, the age of granulite metamorphism in the MG belt has been inferred at 1.8–1.7 Ga (Fig. 3), using the results obtained from Rb–Sr dating of the host granitoid (Sarkar *et al.* 1990; Acharyya, 2001). The BBG belt, located in the southern part of the Sausar Belt (Fig. 1d), is widely composed of quartzofeldspathic gneisses and mafic granulites. This belt witnessed three distinct high-grade metamorphic events (M_1 , M_2 and M_3), which are illustrated by looping P – T paths, most likely indicating repeated cycles of slab rollback and advancements of the oceanic crust that was subducting beneath the SIC (Bhowmik *et al.* 2011; Bhowmik & Chakraborty, 2017). Monazite and zircon ages obtained for BBG lithologies suggest that the high-grade metamorphic events are bracketed between 1.62 and 1.54 Ga (Bhowmik *et al.* 2011, 2014; Fig. 3). Furthermore, the occurrence of U–Pb zircon ages of 3.5–2.5 Ga reveal that the BBG belt contains vestiges of older reworked crust possibly derived from the Bastar Craton (Ramachandra & Roy, 2001; Bhowmik *et al.* 2011). The RKG belt is exposed in the central part of the CITZ, and is dominated by migmatitic gneisses, mafic granulites, cordierite gneisses and garnet-bearing metadolerites (Bhowmik *et al.* 1999). Previous studies have noticed that these rocks exhibit a clockwise P – T trajectory path, with the peak metamorphism at *c.* 1.04 Ga, followed by a decompression event at *c.* 0.95 Ga (Bhowmik *et al.* 2012; Fig. 3). Together, it is evident that the timing of high-grade metamorphism of the RKG belt is distinct from that of the MG and BBG belts.

2.b. Low- to medium-grade supracrustal belts

The greenschist- to amphibolite-facies supracrustal belts in the CITZ are represented by the Mahakoshal Belt (MB) in the north, the Betul Belt in the central part and the Sausar Belt in the south (Fig. 1d). Spatially, these belts are distributed parallel to the high-grade belts, and other minor lithologies within the CITZ (Fig. 1d). The E–W-trending MB is regarded as the oldest (*c.* 2.2 Ga) supracrustal belt in the CITZ (Nair *et al.* 1995; Pandey *et al.* 1998), and is composed of phyllites, garnet–staurolite schists, andalusite schists and quartzites. The prominent metamorphic events (M_1 , M_2 and M_3) in the belt are dated between 1.9 Ga and 1.6 Ga (Figs 2, 3), where the peak metamorphism (M_2) occurred at *c.* 1.7 Ga (Deshmukh *et al.* 2017; Deshmukh & Prabhakar, 2019). This peak metamorphism likely took place at *c.* 1.7 Ga, as indicated by the coeval emplacement of granitoids along the southern margin of the MB (Deshmukh & Prabhakar, 2019) and the intrusion of the Jhirkadandi pluton within the MB (Bora *et al.* 2013). The Betul Belt, located in the central part of the CITZ, shares tectonic contact with the Gavligarh–Tan Shear Zone (GTSZ) along its southern margin (Fig. 1d), and is characterized by phyllites with

intercalated mica schists. Based on early geochronological studies, the upper age of the Betul Belt is constrained at *c.* 1.50 Ga (Fig. 3; Raut & Mahakud, 2002) using Rb–Sr ages of syntectonic granite that are unlikely to represent the age of crystallization. Despite the limited petrological and geochronological data from the Mahakoshal and Betul belts, Roy & Prasad (2003) postulated that both the basins opened simultaneously at *c.* 2.2 Ga, with prolonged sedimentation between *c.* 2.2 Ga and 1.9 Ga (Fig. 4a). The Sausar supracrustals, along with the surrounding RKG and BBG belts, are together referred to as the Sausar Mobile Belt (SMB) (Roy *et al.* 2006). Nevertheless, these lithologies, with their variable metamorphic grade, are considered to be associated with the undifferentiated TBG (1.62 Ga) that forms the basement for the Sausar Group of rocks (Bhowmik *et al.* 1999, 2011). The SMB underwent extensive reworking and amphibolite-facies metamorphism during the Sausar Orogeny at 1.0–0.9 Ga (Fig. 2; Bhowmik *et al.* 2011, 2012). Initially, this Grenvillian event was believed to have affected lithologies within the southernmost part of the CITZ, but recent monazite dating indicates a northward extension of the Neoproterozoic tectonic front towards the MB and associated granitoids (Figs 2, 3; Deshmukh *et al.* 2017; Deshmukh & Prabhakar, 2019).

2.c. Magmatic arc sequences in the SIC

The lithological units of the southern cratonic nuclei are dominated by tonalite–trondhjemite–granodiorite (TTG) basement gneisses, volcano-sedimentary supracrustal rocks (*viz.*, Amgaon and Sakoli–Nandgaon groups; Manikyamba *et al.* 2016) and associated granitoids (*viz.*, Malanjkhanda Granite and Dongargarh Granite; Pandit & Panigrahi, 2012 and references therein). The Malanjkhanda Granite, located along the northern margin of the Bastar Craton, is known for a giant porphyry-style Cu–Mo–Au mineral deposit, and is considered to be associated with the subduction of the NIC beneath the SIC (Yedekar *et al.* 1990). Re–Os dating of molybdenite samples from the Malanjkhanda Granite yielded a crystallization age of 2490 ± 8 Ma (Stein *et al.* 2004). Stein *et al.* (2006) suggested that the deformation in the central parts of the Malanjkhanda Granite ceased before *c.* 2465 Ma, given the occurrence of undeformed molybdenite spindles in the Devgaon area. However, the authors emphasized that the precipitation and mineralization in the northwestern parts of the batholith continued until *c.* 2450 Ma owing to the intense metamorphic reworking. Based on geochemical and isotopic studies, the Malanjkhanda Granite is classified as calc-alkaline, metaluminous (I-type) to peraluminous (S-type) (Arya *et al.* 2019 and references therein), with an island-arc affinity (Yedekar *et al.* 1990; Stein *et al.* 2004). This interpretation is supported by the presence of microgranular enclaves in the Malanjkhanda Granite, produced owing to the mixing and mingling of coeval mafic and felsic magmas (Kumar & Rino, 2006). All these observations indicate that the Malanjkhanda Granite was emplaced along an active continental margin and eventually embedded along the northern margin of the SIC during the early development of the CITZ.

The Dongargarh Granite, located to the south of the Malanjkhanda Granite, is typically associated with bimodal volcanic rocks of the Sakoli–Nandgaon Group. Geochemically, bimodal volcanic rocks are interpreted to have developed in an island-arc/back-arc tectonic setting, whereas the granitoids are classified as potassic and within-plate A-type granites (Pandit & Panigrahi, 2012; Manikyamba *et al.* 2016). U–Pb zircon dating

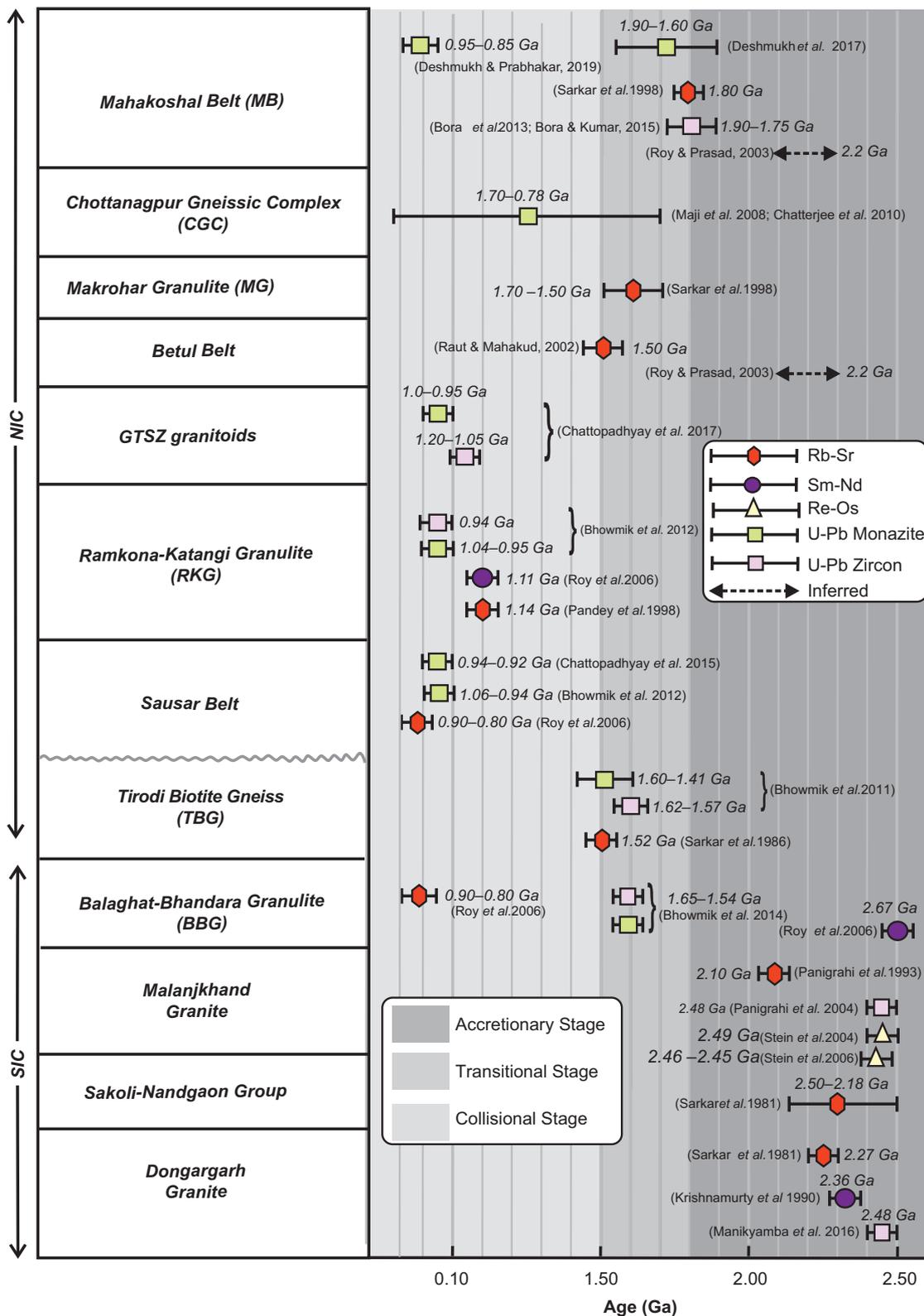


Fig. 3. (Colour online) Summary of available age data, acquired using various geochronological techniques from different domains of the CITZ. Abbreviations for litho-units are in accordance with Figure 1.

of the Dongargarh Granite yielded a crystallization age of 2.48 Ga (Manikyamba *et al.* 2016) while earlier studies inferred a Rb–Sr age of *c.* 2.27 Ga (Sarkar *et al.* 1981) and Sm–Nd age of *c.* 2.36 Ga (Krishnamurthy *et al.* 1990) (Fig. 3). Furthermore,

zircons obtained from basaltic and rhyolitic samples (volcanic units) confirm the age of crystallization at 2471 ± 7 Ma and 2479 ± 15 Ma (Manikyamba *et al.* 2016). These zircons display variable $\epsilon_{\text{Hf}}(t)$ values of -10.0 to -6.4 (model ages, T_{DM}^{C} :

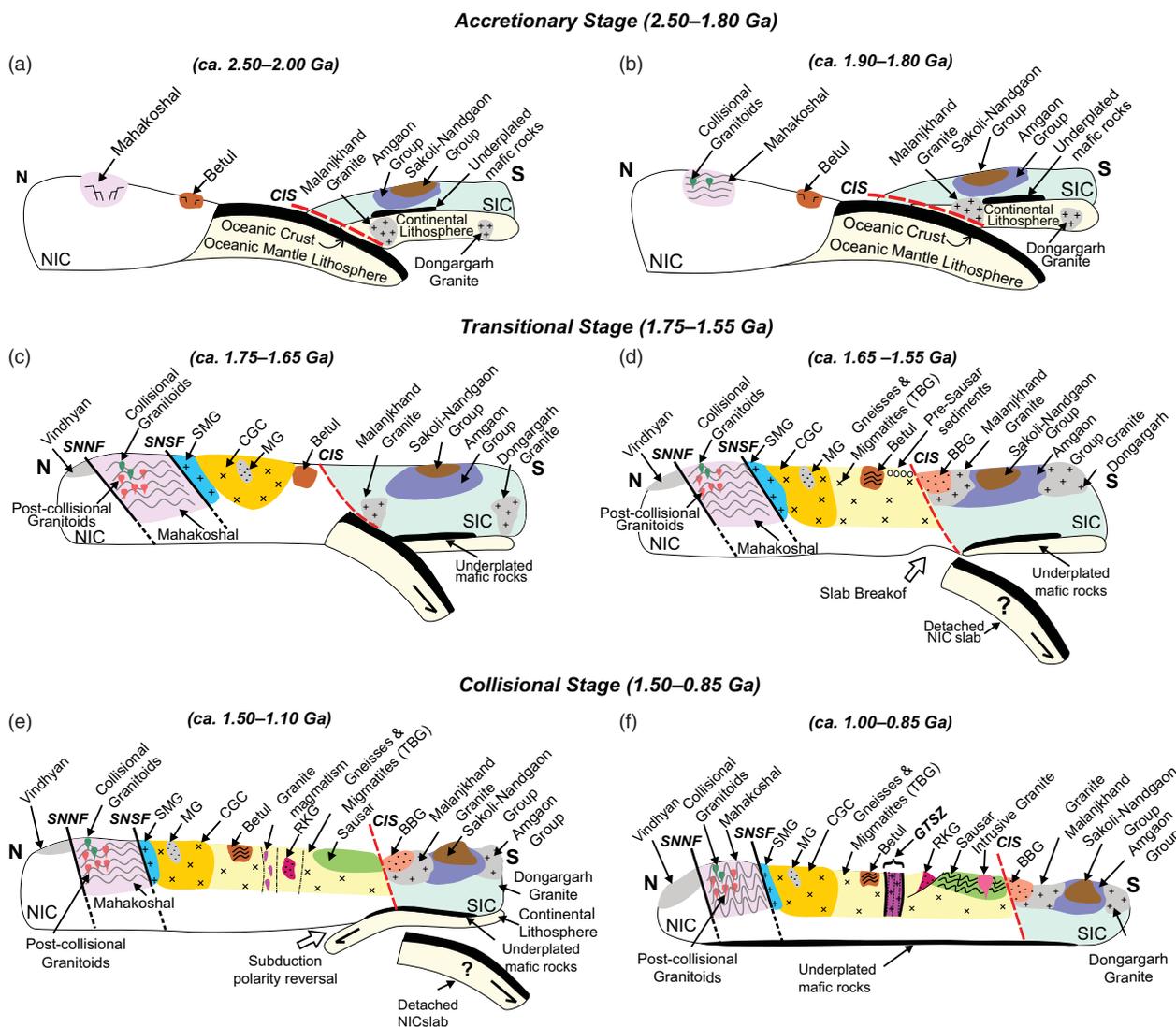


Fig. 4. (Colour online) Schematic diagram (not to scale) illustrating the accretion and evolution of various lithological domains within the CITZ. (a, b) Accretionary stage (2.50–1.80 Ga): Initiation of S-directed subduction system (c. 2.5 Ga) and the development of island-arc magmatism (c. 2.48 Ga) on the SIC, followed by the closing of the Mahakoshal basin (1.90–1.80 Ga; D₁ event) with the emplacement of syntectonic granites. (c, d) Transitional stage (1.75–1.55 Ga): Continued deformation within the evolving domains of the CITZ and high-grade metamorphism (BBG) on account of asthenospheric upwelling produced in response to slab break-off (1.65–1.55 Ga) underneath the SIC. (e, f) Collisional stage (1.50–0.85 Ga): Subduction polarity reversal (< 1.55 Ga) leading to the N-directed subduction of the SIC beneath the NIC followed by the development and tightening of ENE–WSW fabric within the CITZ during the Sausar Orogeny (c. 1.0–0.9 Ga). Abbreviations for litho-units are in accordance with Figure 1.

3.38–3.60 Ga) and –8.8 to –4.3 (model ages, T_{DM}^C : 3.27–3.54 Ga) for volcanic units and granitoids, respectively, indicating a Palaeoarchaean crustal source (Manikyamba *et al.* 2016), likely in a continental margin setting. On the basis of bulk-rock geochemistry and Hf–Nd systematics, the Dongargarh volcanic rocks represent an Andean-type magmatic arc developed along the northern part of the Bastar Craton (Khanna *et al.* 2018).

In summary, the northern margin of the SIC witnessed abundant magmatism during early Palaeoproterozoic times (c. 2.50–2.45 Ga), which was dominated by contemporaneously evolved volcanogenic basalts and rhyolites (Sakoli–Nandgaon Group), and granite plutons (viz. Malanjhand and Dongargarh granites). Notably, the Malanjhand Granite is represented by a porphyry Cu–Mo–Au deposit, which is typically associated with arc-related subduction zone magmas (cf. Richards, 2003). In other words, according to geochemical–isotopic characteristics, various magmatic rocks were emplaced in a subduction–

collision-type tectonic setting (Stein *et al.* 2004; Manikyamba *et al.* 2016), and their crystallization ages provide a limit for attenuation of subduction-related magmatism in the SIC.

3. Existing tectonic models

Tectonic conditions for the evolution of the CITZ have been discussed and debated for nearly three decades (Yedekar *et al.* 1990; Acharyya, 2003; Roy & Prasad, 2003; Bhowmik & Chakraborty, 2017). Among these various models, Yedekar *et al.* (1990) proposed the first hypothesis, which merged datasets from structural, geochemical and deep continental studies. This model advocates S-directed subduction of the NIC underneath the SIC along the CIS located south of the BBG (Yedekar *et al.* 2000; 2003). This early Mesoproterozoic suture zone, extending over 500 km along-strike, is represented by mylonites and phyllonites (Yedekar *et al.* 2000, 2003). Based on lithological

associations and structural differences, the migmatites and gneisses to the north and south of the CIS are designated as the Tirodi and Amgaon gneisses, respectively (Jain *et al.* 1991). The Tirodi gneisses and the granulite belts represent the high-grade gneissic terrane of the NIC, whereas the Malanjhand Granite, Dongargarh Granite and Sakoli–Nandgaon supracrustals represent the island-arc sequences on the overriding SIC (Yedekar *et al.* 1990; Jain *et al.* 1991, 1995). In this setting, the BBG is interpreted to represent remnants of exhumed oceanic crust (Yedekar *et al.* 1990). However, this model was criticized as it failed to provide evidence for the presence of an ophiolite sequence, deep-sea sediments and high-pressure metamorphic rocks (Bandyopadhyay *et al.* 1995). Furthermore, recent geochemical (Ramachandra & Roy, 2001) and geochronological (Bhowmik *et al.* 2014) studies disproved the status of the BBG as exhumed oceanic crust, and subsequently moved the possible zone of accretion (i.e. CIS) to the north of the BBG (Bhowmik, 2019).

Acharyya (2003) proposed a tectonic model in which the Indian subcontinent is divided into southern and northern crustal provinces along the CITZ. The model assumes the MB as a major lithological domain along the northern fringe of the CITZ that possibly corresponds to a continental rift zone. The closure of the Mahakoshal basin owing to S-directed subduction marks the earliest tectonic event within the CITZ, consequently producing calc-alkaline magmatism along the southern margin of the belt (1.8–1.7 Ga). On the other hand, the southern part of the CITZ is predominated by the SMB along with the Chottanagpur Gneissic Complex and Betul supracrustal belt. These crustal domains evolved during two major tectonic events, the collisional event at 1.6–1.5 Ga and the Sausar Orogeny (1.0–0.9 Ga). Although this model supports the S-directed subduction of the NIC, it fails to delineate and demonstrate the presence of island-arc systems formed during the subduction process.

In a diametrically opposite scenario, Roy & Prasad (2003) preferred the N-directed subduction of the SIC lithosphere beneath the NIC. This model emphasizes the opposite sense in the subduction direction based on northward younging of metasedimentary sequences in the Sausar basin, suggesting the derivation of Sausar sediments from the Bastar Craton. This interpretation is consistent with the structural vergence of the Sausar basin, where the proposed hinterland is located in the northern part of the basin. The authors demonstrated that the final closure of the subduction between the NIC and SIC occurred at 1.5 Ga and resulted in the formation of the RKG belt in the vicinity of the accretionary zone. Despite these observations, N-directed subduction cannot explain the presence of island-arc-related magmatic sequences on the SIC and the corresponding absence of those features within the NIC (Yedekar *et al.* 1990; Bora, 2015).

Recently, Bhowmik & Chakraborty (2017) interpreted the subduction settings along the southern margin of the CITZ based on metamorphic evolution, diffusion kinetics and geochronological results of high-grade rocks in the BBG, including the development of the TBG. This study applies diffusion chronometry to reconstruct the burial and exhumation rates of short-lived metamorphic episodes, which are critical in illustrating the tectonic style for a single orogenic process. Considering the various short-lived metamorphic events in the BBG (viz., M₁: 1.62–1.59 Ga; M₂: 1.57 Ga; M₃: 1.56–1.54 Ga), the authors attempted to explain the predominance of lithospheric extension versus compression during multiple cycles of slab

rollback and advancement. Furthermore, the BBG is assumed to represent the leading edge of the SIC on account of its Palaeoarchean ages, while the position of the CIS has been relocated to the north of the BBG based on contrasting protoliths for the high-grade rocks on either side of the shear zone (Bhowmik *et al.* 2011; Bhowmik, 2019).

4. Discussion

4.a. Drawbacks of existing models and scope for new hypothesis

Based on the analysis of the tectonic models discussed above, we infer that the models of Yedekar *et al.* (1990), Acharyya (2003) and Roy & Prasad (2003) are mostly based on field observations and provenance studies while giving little weight to geophysical evidence. On the other hand, the observations of Bhowmik & Chakraborty (2017) are restricted to the domains around the CIS (i.e. BBG and TBG) while ignoring the presence of subduction-related arc-magmatism within the SIC. Nevertheless, the major controversies in existing models revolve around the direction of subduction and the precise constraints on the timing of accretion between the NIC and the SIC.

Recently, deep seismic reflection studies have identified the presence of two distinct fabric domains with opposing dip directions to the north and south of the CIS (Mall *et al.* 2008; Mandal *et al.* 2013), which allows re-evaluation of the tectonic regime within the CITZ. The seismic reflection data obtained by Mandal *et al.* (2013) have been processed using the common reflection surface (CRS) method. The results obtained using the CRS technique are of superior quality compared to other conventional techniques (e.g. common mid-point and common reflection point methods), and yield valuable information on deep crustal structures of Precambrian shield areas across the globe (cf. Mandal *et al.* 2014, 2017 and references therein). According to Mandal *et al.* (2013), the reflection from 16.0 s two-way time (TWT) indicates the Moho at a depth of 48 km in the vicinity of the CIS. The deep continental geological features identified by Mandal *et al.* (2013) and available seismic characteristics (Mall *et al.* 2008; Naganjaneyulu & Santosh, 2010) across the CIS are attributed to the collision between different proto-continent. Therefore, the imaged crustal structures acquired with the CRS method not only represent the upper crustal features but also outline seismic patterns present up to the Moho boundary interface.

In this context, and to improve our understanding of the convergence between the SIC and NIC, it is necessary to integrate geological evidence with inferences made by geophysical studies. The present model suggests that the geological setting of the CITZ is governed by three distinct stages: an accretionary stage (2.5–1.8 Ga), transitional stage (1.75–1.55 Ga) and collisional stage (1.50–0.85 Ga).

4.b. Accretionary stage (2.5–1.8 Ga): formation and deformation of Palaeoproterozoic magmatic arc

In the present model, the Sakoli–Nandgaon volcanic rocks and associated Malanjhand and Dongargarh granites are together termed as a reworked magmatic arc of the Bastar Craton (Yedekar *et al.* 1990; Stein *et al.* 2004). It is postulated that the early tectonic cycle (c. 2.5 Ga; Stein *et al.* 2004) within the CITZ initiated with the subduction of the oceanic crust attached to the NIC beneath the SIC (Fig. 4a, b). This southward polarity of

the subduction is consistent with the presence of calc-alkaline type Malanjhand Granite with giant porphyry Cu–Mo–Au deposits (c. 2.5 Ga; Stein *et al.* 2004, 2006) and bimodal volcanic rocks of the Sakoli–Nandgaon Group including the Dongargarh Granite (c. 2.5 Ga; Manikyamba *et al.* 2016 and references therein). These geological observations suggest the presence of a remnant magmatic arc that formed along the northernmost portion of the SIC.

In contrast, Bhowmik & Roy (2003) argued that the characteristic N–S-trending fabric in the Malanjhand Granite is discordant with the ENE–WSW-striking CITZ fabric, and therefore this calc-alkaline magmatism cannot represent a product of the subduction between the SIC and NIC. Recent microstructural studies and anisotropy of magnetic susceptibility data, however, suggest syntectonic fabric development in the Malanjhand Granite (Majumder & Mamtani, 2009). The authors concluded the presence of pervasive magmatic foliation that was syntectonic with the evolution of the CITZ and the emplacement of the Malanjhand Granite. This N–S-trending synmagmatic fabric reoriented to a NE–SW-directed fabric, proximal to the CIS, synchronous with WNW–ESE-directed convergence between the NIC and SIC in a transpressional regime (Majumder & Mamtani, 2009). Furthermore, geochemical and isotopic data from the Kotri–Dongargarh belt, located south of the Malanjhand Granite, show an affinity towards an island-arc setting (Manikyamba *et al.* 2016). The above-stated evidence, in addition to the lack of early Palaeoproterozoic subduction-related magmatic activity within the NIC, emphasizes southward subduction of the NIC beneath the SIC (Bora, 2015).

Contemporaneously (Fig. 4a), the accretionary phase within the NIC is characterized by the opening of the Mahakoshal and Betul basins at c. 2.2 Ga (inferred age of basin opening; Roy & Prasad, 2003). As the accretion progressed, the metasedimentary sequences of the MB were overprinted with multiple episodes of deformations (D₁ to D₃), which represent three distinct metamorphic events (M₁ to M₃) between 1.90 Ga and 1.60 Ga (Figs 2, 4b–d; Deshmukh *et al.* 2017; Deshmukh & Prabhakar, 2019). These events coincide with the timing of syn- to post-tectonic granite magmatism along the southern and northern margins of the belt, respectively (Bora *et al.* 2013; Bora & Kumar, 2015; Deshmukh & Prabhakar, 2019).

4.c. Transitional stage (1.75–1.55 Ga): slab break-off beneath the SIC and associated slab rollback

The continued accretion and subduction between the NIC and SIC produced mantle melting, accompanied by the formation of the TBG (1.62 Ga; Fig. 4d) at the expense of pre-existing tonalite–granodiorite–granite crust (Bhowmik *et al.* 2011; Bhowmik, 2019). Subsequently, the accretionary front experienced several cycles of slab advancement and rollback during 1.62–1.54 Ga (Bhowmik *et al.* 2011; Bhowmik & Chakraborty, 2017), resulting in the formation of the BBG in association with high-grade metamorphism. This c. 1.65–1.55 Ga metamorphism that affected most of the lithological units probably indicates the final tectonothermal event in the S-directed subduction regime. In particular, outcrops of the BBG have been identified with high-gravity values and corresponding dome-shaped seismic reflection patterns, representing an upward-thrusted block from the lower crust (Mishra *et al.* 2000). According to Naganjaneyulu & Santosh (2010), such domal structures with metamorphic cores are produced as a consequence of slab break-off. This event, referred to as slab break-off, resulted in the detachment of the downgoing

NIC, which successively sank into the deeper mantle (Fig. 4d), thus creating a window for N-directed subduction of the SIC lithosphere (Fig. 4e).

The slab break-off is predicted to have initiated along the CIS, where the SIC began its northward advance (Fig. 4e). The slab break-off process is generally coupled with asthenospheric upwelling, which results in a high heat flow and exhumation rate (Barr & Dahlen, 1989; Teng *et al.* 2000). These geological features are preserved within high-grade sequences of the BBG belt, where the thermally uplifted domains were subjected to crustal extension. The period of extension associated with the M₂ phase of metamorphism (c. 1.57 Ga; Bhowmik & Chakraborty, 2017) of the BBG domain is representative of the crustal extension experienced by the granulite belt on account of gravitational collapse owing to slab break-off (1.65–1.55 Ga). This slab break-off (1.65–1.55 Ga; Fig. 4d) induced a reversal in the direction of subduction (<1.55 Ga); thus setting the course for a N-directed subduction system (Fig. 4e).

4.d. Collisional stage (1.50–0.85 Ga): subduction polarity reversal, Sausar Orogeny and final amalgamation

The subduction polarity reversal (<1.55 Ga; Fig. 4e) was followed by a period of tectonic quiescence during 1.55–1.20 Ga, which might have been associated with relatively flat-subduction of the SIC lithosphere. Lithological domains around the CIS were subjected to intense contractional deformation owing to this flat-subduction. As a result, the orogen experienced emplacement of syntectonic calc-alkaline granites (1.20–1.05 Ga) along the GTSZ (Chattopadhyay & Khasdeo, 2011; Chattopadhyay *et al.* 2017). Subsequently, the CIS reactivated during the Sausar Orogeny at 1.0–0.9 Ga (Bhowmik *et al.* 2012; Fig. 4f). The intensity of the Sausar event is highest in the vicinity of the CIS where it has resulted in amphibolite-facies metamorphism of the SMB (Roy *et al.* 2006) and deformation of granitoids along the GTSZ (Chattopadhyay & Khasdeo, 2011; Chattopadhyay *et al.* 2017). The effect of this event lessens towards the northern margin of the CITZ, where it causes tightening of the pre-existing fabric (Fig. 2; Deshmukh *et al.* 2017; Deshmukh & Prabhakar, 2019). Further, geophysical evidence suggests that the Sausar Orogeny produced a bivergent reflection fabric in the vicinity of the CIS (Mall *et al.* 2008; Mandal *et al.* 2013), implying a northward vergence for the SIC lithosphere during early Neoproterozoic times.

In conclusion, the slab break-off process proposed underneath the NIC is a consequence of ocean closure and is considered to be the driving mechanism for polarity reversal in subduction zones (Davies & von Blanckenburg, 1995; Hildebrand & Bowring, 1999; Teng *et al.* 2000). Although geophysical exploration of the Earth's interior is yet to confirm the case in favour or against the slab break-off hypothesis (Garzanti *et al.* 2018), the present model seems to provide a plausible explanation for the presence of Palaeoproterozoic island-arc sequences on the SIC while simultaneously incorporating the subsurface features observed across the CIS. Previously documented seismic studies (Mall *et al.* 2008; Naganjaneyulu & Santosh, 2010; Mandal *et al.* 2013 and references therein) within the CITZ are limited to the Moho boundary, whereas gravity modelling studies are yet to recognize the remnants of detached slab beneath the SIC. Therefore, further studies using advanced geophysical techniques (e.g. seismic tomography) are awaited to delineate the presence of a detached crustal segment of the NIC underneath the SIC.

5. Conclusions

- The Palaeoproterozoic evolution of the CITZ is characterized by island-arc magmatism (c. 2.5–2.4 Ga) in the Bastar Craton (i.e. Malanjhand Granite, Dongargarh Granite and Sakoli–Nandgaon volcanic rocks) implying S-directed subduction of the NIC oceanic crust beneath the SIC at c. 2.5 Ga.
- The S-directed subduction and deformation process continued until slab break-off beneath the SIC at c. 1.65–1.55 Ga. The protracted accretion during this period (c. 2.50–1.55 Ga) was dominated by the following tectonic events: (i) emplacement and deformation of felsic and mafic suites on the SIC, (ii) opening of rift basins followed by sedimentation and deformation (i.e. Mahakoshal and Betul) on the NIC, (iii) evolution of high-grade crystalline rocks such as Tirodi Biotite Gneiss, Makrohar and Balaghat–Bhandara granulites, and (vi) activation of the ENE–WSW-trending Son-Narmada North Fault and Son-Narmada South Fault on the northern margin and CIS along the southern margin, respectively.
- The slab break-off process induced polarity reversal that resulted in the flipping of the subduction direction (<1.55 Ga). The detached segment of the NIC created an opening for the lateral movement of the SIC, eventually setting the course for N-directed subduction. This event coincides with the reworking of the BBG unit, which was subjected to crustal extension as a result of slab break-off. The tectonic events that occurred at this stage (c. 1.50–1.10 Ga) are characterized by the 1.20 Ga granite magmatism along the GTSZ and the formation of the RKG.
- The final stage of accretion (c. 1.00–0.85 Ga) is dominated by the Sausar Orogeny, which resulted in the development of an ENE–WSW-trending fabric coupled with reworking along the southern margin (i.e. SMB, GTSZ) of the CITZ. The effect of this event diminishes towards the northern margin, where it is manifested by the tightening of the pre-existing fabric.

Acknowledgements. This study was financially supported by the IRCC project (13IRCCSG025) of the Indian Institute of Bombay, India. TD acknowledges the financial support provided by the CSIR research fellowship (File No: 09/087(0813)/2015-EMR-I). We acknowledge the Science and Engineering Research Board (Govt. of India) funded EPMA national facility in the Department of Earth Sciences at IIT Bombay. The comments by Dr. Holly Stein and two anonymous reviewers considerably improved the clarity and presentation of the manuscript. Editorial handling of the manuscript by Prof. Oliver Lacombe is gratefully appreciated. We acknowledge the discussions with G. Mohan, M. Radhakrishna and B. Sekhar on the possible interpretations of various geophysical data. We also thank P.U. Naveen for his help with interpretation of gravity anomaly measurements from Central India.

References

- Acharyya SK** (2001) Geodynamic setting of Central Indian Tectonic Zone in Central, Eastern and Northeastern India. *Geological Survey of India Special Publication* **64**, 17–35.
- Acharyya SK** (2003) The nature of Mesoproterozoic Central Indian Tectonic Zone with exhumed and reworked older granulites. *Gondwana Research* **6**, 197–214.
- Arya D, Kumar G, Gupta S, Kumar S, Panwar KS, Deepti GL and Khan RM** (2019) Geochemistry and petrogenesis of mafic dykes in Paleoproterozoic (Cu ± Mo ± Au) hosting granitoids at Malanjhand Mine Area, Central India. *Journal of Geoscience Research* **3**, 121–32.
- Bandyopadhyay BK, Roy A and Huin AK** (1995) Structure and tectonics of a part of the Central Indian shield. *Geological Society of India Memoir* **31**, 433–67.
- Barr TD and Dahlen FA** (1989) Brittle frictional mountain building: 2. Thermal structure and heat budget. *Journal of Geophysical Research: Solid Earth* **94**, 3923–47.
- Beltrando M, Hermann J, Lister G and Compagnoni R** (2007) On the evolution of orogens: pressure cycles and deformation mode switches. *Earth and Planetary Science Letters* **256**, 372–88.
- Bhowmik SK** (2019) The current status of orogenesis in the Central Indian Tectonic Zone: a view from its southern margin. *Geological Journal* **54**, 2912–34.
- Bhowmik SK and Chakraborty S** (2017) Sequential kinetic modelling: a new tool decodes pulsed tectonic patterns in early hot orogens of Earth. *Earth and Planetary Science Letters* **460**, 171–9.
- Bhowmik SK, Pal T, Pant N and Shome S** (1999) Evidence for Pre-Grenvillian high-pressure metamorphism from the northern margin of the Sausar mobile belt in Central India. *Journal of Geological Society of India* **33**, 385–99.
- Bhowmik SK and Roy A** (2003) Garnetiferous metabasites from the Sausar Mobile Belt: petrology, P–T path and implications for the tectonothermal evolution of the Central Indian Tectonic Zone. *Journal of Petrology* **44**, 387–420.
- Bhowmik SK, Wilde SA and Bhandari A** (2011) Zircon U–Pb/Lu–Hf and monazite chemical dating of the Tirodi biotite gneiss: implication for latest Palaeoproterozoic to Early Mesoproterozoic orogenesis in the Central Indian Tectonic Zone. *Geological Journal* **46**, 574–96.
- Bhowmik SK, Wilde SA, Bhandari A, Pal T and Pant NC** (2012) Growth of the Greater Indian Landmass and its assembly in Rodinia: geochronological evidence from the Central Indian Tectonic Zone. *Gondwana Research* **22**, 54–72.
- Bhowmik SK, Wilde SA, Bhandari A and Sarbadhikari AB** (2014) Zoned monazite and zircon as monitors for the thermal history of granulite terranes: an example from the Central Indian Tectonic Zone. *Journal of Petrology* **55**, 585–621.
- Bora S** (2015) *Mineralogy, geochemistry and geochronology of granitoid plutons of Dudhi Gneissic Complex, Mahakoshal Belt, Central India*. Ph.D. thesis, Kumaun University, Nainital, India. Published thesis. <http://hdl.handle.net/10603/74688>.
- Bora S and Kumar S** (2015) Geochemistry of biotites and host granitoid plutons from the Proterozoic Mahakoshal Belt, central India tectonic zone: implication for nature and tectonic setting of magmatism. *International Geology Review* **57**, 1686–706.
- Bora S, Kumar S, Yi K, Kim N and Lee TH** (2013) Geochemistry and U–Pb SHRIMP zircon chronology of granitoids and microgranular enclaves from Jhirdagandi pluton of Mahakoshal Belt, Central India Tectonic Zone, India. *Journal of Asian Earth Sciences* **70**, 99–114.
- Bose S, Das K, Torimoto J, Arima M and Dunkley DJ** (2016) Evolution of the Chilka Lake granulite complex, northern Eastern Ghats Belt, India: first evidence of ~780 Ma decompression of the deep crust and its implication on the India–Antarctica correlation. *Lithos* **263**, 161–89.
- Brown M** (2009) Metamorphic patterns in orogenic systems and the geological record. In *Earth Accretionary Systems in Space and Time* (eds PA Cawood and A Kröner), pp. 37–74. Geological Society of London, Special Publication no. 318.
- Cawood PA and Buchan C** (2007) Linking accretionary orogenesis with supercontinent assembly. *Earth-Science Reviews* **82**, 217–56.
- Cawood PA, Kröner A, Collins WJ, Kusky TM, Mooney WD and Windley BF** (2009) Accretionary orogens through Earth history. In *Earth Accretionary Systems in Space and Time* (eds PA Cawood and A Kröner), pp. 1–36. Geological Society of London, Special Publication no. 318.
- Chatterjee N, Banerjee M, Bhattacharya A and Maji AK** (2010) Monazite chronology, metamorphism–anatexis and tectonic relevance of the mid-Neoproterozoic Eastern Indian Tectonic Zone. *Precambrian Research* **179**, 99–120.
- Chattopadhyay A, Chatterjee A, Das K and Sarkar A** (2017) Neoproterozoic transpression and granite magmatism in the Gavilgarh–Tan Shear Zone, central India: tectonic significance of U–Pb zircon and U–Th-total Pb monazite ages. *Journal of Asian Earth Sciences* **147**, 485–501.
- Chattopadhyay A, Das K, Hayasaka Y and Sarkar A** (2015) Syn- and post-tectonic granite plutonism in the Sausar Fold Belt, central India: age constraints and tectonic implications. *Journal of Asian Earth Sciences* **107**, 110–21.

- Chattopadhyay A and Khasdeo L** (2011) Structural evolution of Gavilgarh-Tan Shear Zone, central India: a possible case of partitioned transpression during Mesoproterozoic oblique collision within Central Indian Tectonic Zone. *Precambrian Research* **186**, 70–88.
- Collins WJ** (2002) Hot orogens, tectonic switching, and creation of continental crust. *Geology* **30**, 535–8.
- Condie KC** (2007) Accretionary orogens in space and time. In 4-D Framework of Continental Crust (eds RD Hatcher Jr., MP Carlson, JH McBride and JR Martínez Catalán), pp. 145–58. The Geological Society of America Memoirs no. 200.
- Davies JH and von Blanckenburg F** (1995) Slab breakoff: a model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens. *Earth and Planetary Science Letters* **129**, 85–102.
- Deshmukh T and Prabhakar N** (2019) Tectonic evolution of the Mahakoshal Belt, Central India: insights from phase equilibria modelling and monazite geochronology. *Goldschmidt Abstracts* **2019**, 785.
- Deshmukh T, Prabhakar N, Bhattacharya A and Madhavan K** (2017) Late Paleoproterozoic clockwise *P–T* history in the Mahakoshal Belt, Central Indian Tectonic Zone: implications for Columbia supercontinent assembly. *Precambrian Research* **298**, 56–78.
- Dickinson WR** (1995) Forearc basins. In *Tectonics of Sedimentary Basins* (eds CJ Busby, RV Ingersoll and D Burbank), pp. 221–61. Oxford: Blackwell Science.
- Elsasser WM** (1971) Sea-floor spreading as thermal convection. *Journal of Geophysical Research* **76**, 1101–12.
- Garzanti E, Rade G and Malusà MG** (2018) Slab breakoff: a critical appraisal of a geological theory as applied in space and time. *Earth-Science Reviews* **177**, 303–19.
- Hildebrand RS and Bowring SA** (1999) Crustal recycling by slab failure. *Geology* **27**, 11–4.
- Jain SC, Nair KKK and Yedekar DB** (1995) Geology of the Son-Narmada-Tapti lineament zone in central India. *Geological Survey of India Special Publications* **10**, 1–154.
- Jain SC, Yedekar DB and Nair KKK** (1991) Central Indian Shear Zone – a major Precambrian crustal boundary. *Journal of the Geological Society of India* **37**, 521–31.
- Khanna TC, Bizimis M, Barbeau DL, Krishna AK and Sai VVS** (2018) Evolution of ca. 2.5 Ga Dongargarh volcano-sedimentary Supergroup, Bastar craton, Central India: constraints from zircon U–Pb geochronology, bulk-rock geochemistry and Hf–Nd isotope systematics. *Earth-Science Reviews* **190**, 273–309.
- Krishnamurthy P, Sinha DK, Rai AK, Seth DK and Singh DK** (1990) Magmatic rocks of the Dongargarh Supergroup, Central India – their petrological evolution and implications on metallogeny. *Geological Survey of India Special Publications* **28**, 303–19.
- Kumar S and Rino V** (2006) Mineralogy and geochemistry of microgranular enclaves in Palaeoproterozoic Malanjkhanda granitoids, central India: evidence of magma mixing, mingling, and chemical equilibration. *Contributions to Mineralogy and Petrology* **152**, 591.
- Lister GS, Forster MA and Rawling TJ** (2001) Episodicity during orogenesis. In *Continental Reactivation and Reworking* (eds JA Miller, RE Holdsworth, IS Buick and M Hand), pp. 89–113. Geological Society of London, Special Publication no. 184.
- Maji AK, Goon S, Bhattacharya A, Mishra B, Mahato S and Bernhardt HJ** (2008) Proterozoic polyphase metamorphism in the Chhotanagpur Gneissic Complex (India), and implication for trans-continental Gondwanaland correlation. *Precambrian Research* **162**, 385–402.
- Majumder S and Mamtani MA** (2009) Magnetic fabric in the Malanjkhanda Granite (central India)—implications for regional tectonics and Proterozoic suturing of the Indian shield. *Physics of the Earth and Planetary Interiors* **172**, 310–23.
- Mall DM, Reddy PR and Mooney WD** (2008) Collision tectonics of the Central Indian Suture zone as inferred from a deep seismic sounding study. *Tectonophysics* **460**, 116–23.
- Mandal B, Rao VV, Sarkar D, Bhaskar Rao YJ, Raju S, Karuppanan P and Sen MK** (2017) Deep crustal seismic reflection images from the Dharwar craton, Southern India—evidence for the Neoproterozoic subduction. *Geophysical Journal International* **212**, 777–94.
- Mandal B, Sen MK, Vaidya VR and Mann J** (2014) Deep seismic image enhancement with the common reflection surface (CRS) stack method: evidence from the Aravalli – Delhi fold belt of northwestern India. *Geophysical Journal International* **196**, 902–17.
- Mandal B, Sen MK and Vijaya Rao V** (2013) New seismic images of the Central Indian Suture Zone and their tectonic implications. *Tectonics* **32**, 908–21.
- Manikymba C, Santosh M, Kumar BC, Rambabu S, Tang L, Saha A, Khelen AC, Ganguly S, Dhanakumar T and Rao DVS** (2016) Zircon U–Pb geochronology, Lu–Hf isotope systematics, and geochemistry of bimodal volcanic rocks and associated granitoids from Kotri Belt, Central India: implications for Neoproterozoic – Paleoproterozoic crustal growth. *Gondwana Research* **38**, 313–33.
- Marsaglia KM** (1995) Interarc and backarc basins. In *Tectonics of Sedimentary Basins* (eds CJ Busby, RV Ingersoll and D Burbank), pp. 299–329. Oxford: Blackwell Science.
- Mishra DC, Singh B, Tiwari VM, Gupta SB and Rao M** (2000) Two cases of continental collisions and related tectonics during the Proterozoic period in India—insights from gravity modelling constrained by seismic and magnetotelluric studies. *Precambrian Research* **99**, 149–69.
- Mohanty S** (2010) An Archaean supercontinent “SIWA”: spatio-temporal and palaeomagnetic evidence. In *Fifth International Archaean Symposium Abstracts* (eds IM Tyler and CM Knox-Robinson), pp. 194–5. Geological Survey of Western Australia, Record 18.
- Naganjaneyulu K and Santosh M** (2010) The Central India Tectonic Zone: a geophysical perspective on continental amalgamation along a Mesoproterozoic suture. *Gondwana Research* **18**, 547–64.
- Nair KKK, Jain SC and Yedekar DB** (1995) Stratigraphy, structure and geochemistry of the Mahakoshal Greenstone Belt. *Memoir of the Geological Society of India* **31**, 403–32.
- Pandey BK, Krishna V and Chabria T** (1998) An overview of Chhotanagpur gneiss–granulite complex and adjoining sedimentary sequences, eastern and central India. In *International Seminar on Precambrian Crust in Eastern and Central India. Abstract volume UNESCO-IUGS-IGCP 368*, 131–5.
- Pandit D and Panigrahi MK** (2012) Comparative petrogenesis and tectonics of Paleoproterozoic Malanjkhanda and Dongargarh granitoids, Central India. *Journal of Asian Earth Sciences* **50**, 14–26.
- Panigrahi MK, Bream BR, Misra KC and Naik RK** (2004) Age of granitic activity associated with copper–molybdenum mineralization at Malanjkhanda, Central India. *Mineralium Deposita* **39**, 670–7.
- Panigrahi MK, Mookherjee A, Pantulu GVC and Gopalan K** (1993) Granitoids around the Malanjkhanda copper deposit: types and age relationships. *Proceedings of Indian Academy of Sciences (Earth and Planetary Sciences)* **102**, 399–413.
- Radhakrishna BP** (1989) Suspect tectono-stratigraphic terrane elements in the Indian subcontinent. *Journal of the Geological Society of India* **34**, 1–24.
- Radhakrishna BP and Ramakrishnan M** (1988) Archaean–Proterozoic boundary in India. *Journal of the Geological Society of India* **32**, 263–78.
- Ramachandra HM and Roy A** (2001) Evolution of the Bhandara-Balaghat granulite belt along the southern margin of the Sausar mobile belt of Central India. *Proceedings of the Indian Academy of Sciences (Earth and Planetary Sciences)* **110**, 351–68.
- Ramakrishnan M and Vaidyanadhan R** (2010) *Geology of India, Vol. 1*. Bangalore: Geological Society of India, 556 pp.
- Raut PK and Mahakud SP** (2002) Geology, geochemistry and tectonic setting of volcano-sedimentary sequence of Betul Belt, Madhya Pradesh and ore genesis of related zinc and copper sulphide mineralization. In *Proceedings of the National Seminar on Mineral Exploration and Resource Surveys, Geological Survey of India, Jaipur*.
- Richards JP** (2003) Tectono-magmatic precursors for porphyry Cu–(Mo–Au) deposit formation. *Economic Geology* **98**, 1515–33.
- Rogers JJW and Santosh M** (2002) Configuration of Columbia, a Mesoproterozoic supercontinent. *Gondwana Research* **5**, 5–22.
- Roy A, Kagami H, Yoshida M, Roy A, Bandyopadhyay BK, Chattopadhyay A, Khan AS, Huin AK and Pal T** (2006) Rb–Sr and Sm–Nd dating of different metamorphic events from the Sausar Mobile Belt, central India: implications for Proterozoic crustal evolution. *Journal of Asian Earth Sciences* **26**, 61–76.

- Roy A and Prasad MH** (2003) Tectonothermal events in Central Indian Tectonic Zone (CITZ) and its implications in Rodinian crustal assembly. *Journal of Asian Earth Sciences* **22**, 115–29.
- Russo RM and Silver PG** (1996) Cordillera formation, mantle dynamics, and the Wilson cycle. *Geology* **24**, 511–4.
- Sarkar A, Boda MS, Kundu HK, Mamgain VV and Shankar R** (1998) Geochronology and geochemistry of Mesoproterozoic intrusive plutonites from the eastern segment of the Mahakoshal greenstone belt, Central India. In *IGCP-368 Seminar on Precambrian Crust in Eastern and Central India, Bhubaneshwar, Abstract*, Abstract, pp. 82–5.
- Sarkar SN, Gopalan K and Trivedi JR** (1981) New data on the geochronology of the Precambrian of Bhandara–Drug, central India. *Indian Journal of Earth Science* **8**, 131–51.
- Sarkar A, Sarkar G, Paul DK and Mitra ND** (1990) Precambrian geochronology of the Central Indian Shield – a review. *Geological Survey of India Special Publication* **20**, 453–82.
- Sarkar N, Trivedi JR and Gopalan K** (1986) Rb–Sr whole-rock and mineral isochron age of the Tirodi gneiss, Sausar Group, Bhandara district, Maharashtra. *Journal of the Geological Society of India* **27**, 30–7.
- Schellart WP** (2008) Overriding plate shortening and extension above subduction zones: a parametric study to explain formation of the Andes Mountains. *Geological Society of America Bulletin* **120**, 1441–54.
- Schellart WP and Lister GS** (2004) Tectonic models for the formation of arc-shaped convergent zones and back-arc basins. In *Orogenic Curvature: Integrating Paleomagnetic and Structural Analyses* (eds AJ Sussman and AB Weil), pp. 237–58. Geological Society of America Special Paper 383.
- Silver PG, Russo RM and Lithgow-Bertelloni C** (1998) Coupling of South American and African plate motion and plate deformation. *Science* **279**, 60–3.
- Smith GA and Landis CA** (1995) Intra-arc basins. In *Tectonics of Sedimentary Basins* (eds CJ Busby, RV Ingersoll and D Burbank), pp. 263–98. Oxford: Blackwell Science.
- Stein H, Hannah J, Zimmerman A and Markey R** (2006) Mineralization and deformation of the Malanjhand terrane (2,490–2,440 Ma) along the southern margin of the Central Indian Tectonic Zone. *Mineralium Deposita* **40**, 755–65.
- Stein HJ, Hannah JL, Zimmerman A, Markey RJ, Sarkar SC and Pal AB** (2004) A 2.5 Ga porphyry Cu–Mo–Au deposit at Malanjhand, central India: implications for Late Archean continental assembly. *Precambrian Research* **134**, 189–226.
- Teng LS, Lee CT, Tsai YB and Hsiao LY** (2000) Slab breakoff as a mechanism for flipping of subduction polarity in Taiwan. *Geology* **28**, 155–8.
- Whitney DL and Evans BW** (2010) Abbreviations for names of rock-forming minerals. *American Mineralogist* **95**, 185–7.
- Windley B** (1992) Proterozoic collisional and accretionary orogens. *Developments in Precambrian Geology* **10**, 419–46.
- Yedekar DB, Jain SC, Nair KKK and Dutta KK** (1990) The Central Indian collision suture. Precambrian of Central India. *Geological Survey of India Special Publication* **28**, 1–37.
- Yedekar D, Karmalkar NR and Pawar NJ** (2003) Tectonomagmatic evolution of Central Indian Terrain. *Geological Survey of India Special Publication* **7**, 67–88.
- Yedekar D, Reddy PR and Rao D** (2000) Deep continental studies in Central India. In *Research Highlights in Earth System Science* (eds OP Varma and TM Mahadevan), pp. 55–75. Indian Geological Congress Special Volume 1.
- Zhao GC, Cawood PA, Wilde SA and Sun M** (2002) Review of global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent. *Earth-Science Reviews* **59**, 125–62.