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Geology of the Proterozoic Eastern Ghats Belt: Recent Developments and Outstanding Issues

SANKAR BOSE*

Centre of Advanced Study, Department of Geology, Presidency University, Kolkata 700 073, India

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The Eastern Ghats Belt of India has remained a focus for intensive research over three decades. Its unusual rock assemblages, anomalous thermal conditions of metamorphism and consanguinity with the East Antarctica for a considerable geological time has made it a unique case study. This apparently monotonous terrane bears the fingerprint of a complex and fascinating journey of the Indo-Antarctic continental block during Earth's middle age. The paper collates the recent findings from this terrane and presents a status report with yet-to-be resolved issues in the light of current literature.

Introduction

The deeply eroded façade of Proterozoic Eastern Ghats Belt (EGB) attracted the geoscientists of diverse background over last thirty years. It all started with the publication of a major petrological study in the late eighties (Lal *et al.*, 1987) which followed a vast number of data over the years (reviewed in Dasgupta *et al.*, 2017). A majority of this dataset belongs to the petrological issues, yet limited contribution from geochemical, geophysical, structural and isotopic components have also poured in. From these data, several key statements can be made about the geological evolution of EGB. These are (1) a considerable part of EGB experienced the effect of ultrahigh temperature (UHT) metamorphism albeit in two different time spans, (2) the tectonic setting that caused UHT metamorphism, charnockite magmatism, regional extension followed by compression and related features was dominated by subduction-accretion in two important segments of the Proterozoic era, (3) the counter-clockwise pressure-temperature path leading to UHT peak is a hallmark of EGB which matches with the aforementioned tectonic setting, (4) the geological similarities between EGB and parts of East Antarctica that lead to reconstruction of the supercontinents Gondwana, Rodinia and possibly, Columbia, and (5) the evolution of EGB is inseparable

with the evolution of Greater Indian Landmass (GIL). These key issues may be taken as time-tested facts and their implications provided significant knowledge regarding the evolution of Earth during its middle age (ca. 2000-500 Ma). Apart from these, several other important issues have cropped up from the EGB which also provided important clues regarding the chemical and physical changes of lower crust during orogenesis.

The present compilation is a status report on the evolution of EGB and I will be focusing mostly on the data published in last two years (since 2016). An earlier review by Dasgupta *et al.* (2017) described all the major issues outstanding until early 2016 and will not be repeated as far as practicable. However, one important aspect regarding the geological diversity of EGB needs to be mentioned here. Although no detailed geological map is available for this 1000 km long terrane, earlier efforts by the scientists of the Geological Survey of India made it possible to make a broad geological map (Fig. 1a after Ramakrishnan *et al.*, 1998). Based on the broad lithological dispositions (mostly charnockites and khondalites), these authors made longitudinal subdivisions of EGB into four zones with a tacit assumption that these zones represent different time histories of the EGB. Incidentally, the first precision geochronological data from EGB came into light at

*Author for Correspondence: E-mail: sankar.geol@presiuniv.ac.in

Fig. 1: Geological map of the EGB (a) after Ramakrishnan *et al.*, 1998, (b) after Rickers *et al.*, (2001), (c) after Dobmeier and Raith (2003)

the same time (Shaw *et al.*, 1997; Mezger and Cosca, 1999) and it became apparent from these data that there is a considerable time difference of high-grade (including UHT) metamorphism and magmatism between the segment of EGB occurring north and south of the Godavari rift. The idea that EGB is a collage of crustal block got a major fillip with the publication of the first isotopic map of the terrane (Fig. 1b after Rickers *et al.*, 2001). This eventually led to the domain and province-based classification of EGB (Fig. 1c after Dobmeier and Raith, 2003). Therefore, any study made thereafter, considered EGB as a collage of four geological provinces (Krishna, Jeypore, Eastern Ghats and Rengali) within which several crustal domains are joined together. In the present compilation, I am also following the same subdivisions to present the current status. However, the recent data also allowed me to reconsider the rationale behind domain-based classification which I will explain in the later part.

The Krishna Province

The Krishna Province after Dobmeier and Raith (2003) is analogous to the isotopic Domain 1A of Rickers *et al.* (2001). Accordingly, this province is constituted of three crustal domains, namely the

Vinjamuru, the Udaygiri and the Ongole domains (Fig. 1c). Out of these, the first two domains are represented by magmatic (both felsic and mafic) and metamorphic rocks of low to medium grade, whereas the Ongole domain is characterized by broadly granulite facies rocks including the UHT occurrences. The Vinjamuru and Udaygiri domains have known occurrences of extensive schist belts that were known by Nellore and Khammam schist belts in earlier literature. The metasediment-dominated Udaygiri domain is interpreted to have thrust over the metabasalt-dominated Vinjamuru domain along a westerly dipping thrust (Das *et al.*, 2016). This thrusting occurred along dextral strike slip motion during E-W compression. The Vinjamuru metabasalts were formed in an island arc setting coupled with a probable back-arc activity (Das and Shukla, 2017). The tectonic setting of this terrane is controversial as contrasting model for long-lived subduction (Dharma Rao and Santosh, 2011) and collision of India and Napier Complex of East Antarctica (Vijaya Kumar *et al.*, 2011, 2019; Ranjan *et al.*, 2018) exist. In a recent work, Chatterjee *et al.* (2016) proposed a third model based on geochemical study where they proposed a Cordilleran-type accretion involving the East Dharwar Craton (EDC) and North China Craton

(NCC) at ca. 1.78 Ga. These models have both merits and demerits, but the role of presently separated cratonic blocks needs to be verified from more direct evidences like paleomagnetic data. Two important ophiolitic complexes occur in these domains which are of recurrent geologic interest in recent time. The Kandra Ophiolitic Complex (KOC) of ca. 1.9 Ga age represents the suprasubduction zone backarc setting, which was tectonically juxtaposed against the EDC (Saha *et al.*, 2017). These workers demonstrated the stratigraphic succession of the KOC in terms of variation of sedimentary characters of the ocean plate stratigraphy.

The ca. 1.33 Ga Kanigiri Ophiolite (KO), on the other hand, represents the intraoceanic subduction outboard of the EDC which was accreted simultaneously with the Ongole domain and the Nellore schist belt on the margin of the EDC during the breakup of Rodinia (Sain and Saha, 2018). This subduction-accretion process of KO was succeeded by the emplacement of post-orogenic granite at ca. 1.284 Ga (Sain *et al.*, 2017). This process operated simultaneously with development of the Prakasham Igneous Province where mafic magmatism occurred at ca. 1.315 Ga in a broad subduction setting (Subramanyam *et al.*, 2016). Interestingly, trace of a sedimentary basin has recently been identified in-between the Archean basement (EDC) and the Nellore schist belt, based on deep sounding seismic data (Chandrakala *et al.*, 2017). The authors consider that the sediment was deposited in this basin from the eroding orogenic belts formed during the assembly of Columbia and Rodinia. This interpretation is problematic based on the stratigraphic point of view and a more direct evidence is needed to identify the sediment provenance of this buried basin.

The granulite-dominated Ongole domain has an identified UHT metamorphic history (described in detail by Dasgupta *et al.*, 2017). In a recent work, Sarkar and Schenk (2016) demonstrated the geological evolution of this domain involving two separate and contrasting metamorphic cycles. The initial medium-pressure counter-clockwise P-T path culminating in UHT condition resulted from magmatic accretion of the Kondapalle magmatic arc at ca. 1.75–1.60 Ga. Recent zircon U-Pb data (ca. 1.715 Ga) from mafic granulite also validate this time frame (Vijaya Kumar *et al.*, 2019). This was succeeded by

the high-pressure medium temperature clockwise P-T path, which was caused by tectonic crustal thickening at ca. 1.54 Ga. Accordingly, these authors interpreted a protracted evolutionary history of the supercontinent Columbia, a notion which has been disputed in recent time (Bhowmik, 2019).

Emplacement of alkaline rocks at ca. 1.35 Ga (Ranjan *et al.*, 2018) marked a major shift from compressional to extensional tectonic setting with the opening of an ocean basin between India (cratonic India + Ongole domain + Napier Complex) and cratonic East Antarctica (Ruker Province) during disintegration of Columbia. The Ongole domain did not suffer from any high-grade event thereafter.

The Eastern Ghats Province

A major part of EGB occurring north of the Godavari rift and a small triangular segment south of it is brought into this province. The Eastern and Western Khondalite Zone, as well as the Central Migmatite Zone of Ramakrishnan *et al.* (1998) belong to this, while the isotopic Domain 2, 3 and part of Domain 4 of Rickers *et al.* (2001) can be accommodated in this province (Fig. 2). Most of the UHT occurrences were reported from this province where the characteristic P-T path is counter-clockwise and the major tectonothermal events occurred at ca. 1.0–0.9 Ga (reviewed in Dasgupta *et al.*, 2017). Notwithstanding this mostly accepted metamorphic history, there are major disagreements on several issues. It was postulated in earlier studies that sediments were deposited with the opening of ocean basin at ca. 1.4–1.2 Ga (Upadhyay *et al.*, 2008). Recent studies indicate a major phase of granitic basement formation at ca. 1.17 Ga (Ganguly *et al.*, 2018). On the other hand, Kelsey *et al.* (2017) reported mafic magmatic emplacement at ca. 1.58 Ga which implies crustal formation was complete in some parts of the province, a notion which is not reflected in any detrital zircon study carried out earlier (Upadhyay *et al.*, 2009). Mafic granulite from the Vishakhapatnam-Koraput area recorded fluctuation of fluid regime (in terms of fO_2) during metamorphism which is reflected in complex oxide-silicate-sulphide-sulphate mineralogy (Mondal and Bose, 2019). There is still an ongoing debate on the timing of UHT metamorphism. Although it is more or less agreed upon that the time frame is ca. 1050–990 Ma (Dasgupta *et al.*, 2017;

Fig. 2: Metamorphic, magmatic and deformation histories of different domains and provinces of EGB and its adjoining cratons (after Ganguly, 2019)

Mitchell *et al.*, 2018), Das *et al.* (2017) reported ca. 1.17 Ga UHT event based on monazite data. Strangely, this latter age coincides with the granitic emplacement age at Phulbani area (Ganguly *et al.*, 2017, 2018). The latter area (cited as Phulbani domain), remained largely uncharacterized until recent times, gained international focus due to its reported occurrence of ca. 0.99 Ga UHT rocks which were intruded by porphyritic charnockite at ca. 0.97 Ga (Ganguly *et al.*, 2018). The P-T-t history of this domain is quite similar to the adjacent Visakhapatnam domain despite the presence of the Nagavalli-Vamshadhara shear zones in-between. No new petrological data came from the Angul, Tikarpara and Rampur domains. Based on the structural data, Bose and Gupta (2018) proposed dextral strike slip movement along the Mahanadi shear zone, which presumably occurred at ca. 0.5 Ga as determined by earlier studies (Lisker and Fachman, 2001; Crowe *et*

al., 2001). The Chilka domain has a complex history dominated by ca. 0.99 Ga UHT metamorphism, followed by cooling, ca. 0.78 Ga decompression and reworking at ca. 0.53 Ga (Bose *et al.*, 2016a). New geochronological data have been presented from the Koraput Alkaline Complex, which lies at the junction of the Khariar domain and the Jeypore Province. While Nanda *et al.* (2018) argued that the alkaline complex intruded the EGP at ca. 850 Ma, Ranjan *et al.* (2018) reported the intrusion age of the same complex as ca. 1387 Ma. The younger age could be related to the fragmentation of Rodinia, but the older age matches with the fragmentation of Columbia. It is intriguing how fragmentation history of two supercontinents can be preserved in the same rock suite. Nanda *et al.* (2018) also reported the age of granulite metamorphism of the alkaline complex as 0.7 Ga which was preceded by a thrusting event of the EGP over the Jeypore Province. On the other

hand, new geochronological data from the southwestern part of the Khariar domain suggest two separate thrusting (cum metamorphism) event where the rocks of the EGP were initially thrust on the Bastar Craton at ca. 0.9 Ga followed by another thrusting at ca. 0.5 Ga (Chatterjee *et al.*, 2017a, b). These authors further proposed that the thrusting continued until the Cambrian time.

There is a recent discrepancy regarding the nature of P-T loop for the Eastern Ghats Province. The existing counter-clockwise P-T path (Dasgupta *et al.*, 2017) which has been validated in the study of Kelsey *et al.* (2017) from the Visakhapatnam domain has been contradicted by Mitchell *et al.* (2018) from the same domain. The latter study also refuted the model of short-lived two-cycle orogeny for this province (ca. 1.03-0.99 Ga and 0.95-0.90 Ga by Bose *et al.*, 2011; Das *et al.*, 2011, cited in Dasgupta *et al.*, 2017) and proposed a monocycle long-lived orogeny. In the case of two-cycle orogenesis, a major phase of isothermal decompression occurred as recorded in the study of Kelsey *et al.* (2017). Mitchell *et al.* (2018) ruled out this decompression event but reserved comments on how the hot lower crustal granulites resided in the middle crust up to ca. 0.55 Ga before exhumation. The latter age represents amphibolite facies (Dasgupta *et al.*, 2017; Kelsey *et al.*, 2017) to locally granulite facies (Mitchell *et al.*, 2018) reworking of the cooled granulites during the Pan African orogeny.

The Chilka domain has a unique lithological association, but its boundaries are not well-defined. A review of the literature on metamorphic evolution of the rocks of this domain shows convergence in opinion about one phase of UHT metamorphism at ca. 1.0 Ga (Bose *et al.*, 2016a). Tectonothermal reworking of UHT granulites has been constrained within the time frame 0.8-0.5 Ga (Bose *et al.*, 2016a). These later events are similar to those deduced by Mitchell *et al.* (2018) from the Visakhapatnam domain. While the event at 0.8 Ga coincides with the known time of disintegration of the supercontinent Rodinia, documentation of high grade (granulite facies) re-metamorphism at ca. 0.5 Ga in both the domains (Mitchell *et al.*, 2018; Bose *et al.*, 2016a respectively) has important implications in the assembly of East Gondwana and correlation of parts of the EGB with east Antarctica.

The Jeypore Province

The Jeypore Province is equivalent to the isotopic Domain 1B of Rickers *et al.* (2001) and dominantly composed of mafic granulite and charnockite which are bounded by major shear zones against the Bastar Craton. Despite the importance of crustal amalgamation, rocks of this province are least studied regarding the nature and timing of metamorphism as well as the structural and tectonic history. Apart from recent data of Nanda *et al.* (2018) in the alkaline complex, the timing of thrusting between the craton and mobile belt is also unclear. Monazite chemical age data from Koraput anorthosite yield three groups, at ca. 0.94 Ga, ca. 0.88-0.75 Ga and ca. 0.57 Ga (Saikia *et al.*, 2018). The authors suggest that the oldest age reflects emplacement of the anorthosite magma, while the intermediate age reflects the breakup of Rodinia and the youngest one is the timing of assembly of Gondwana. No metamorphic imprint older than ca. 1.5 Ga is reported from this province, and clearly a lot of work needs to be done in future.

The Rengali Province

This province of Dobmeier and Raith (2003) is equivalent to the isotopic Domain 4 of Rickers *et al.* (2001) and is separated from the Eastern Ghats Province by a strip of Gondwana sediments (Fig. 1c). The rocks of this province have greenschist to granulite facies metamorphic signatures, which is starkly different from the northerly occurring Singhbhum Craton and the southerly occurring Eastern Ghats Province. The gneissic basement of this province is composed of granitoids (A. Dasgupta *et al.*, 2017) showing amphibolite to granulite facies metamorphism that occurred during ca. 3.0-2.5 Ga (Bose *et al.*, 2016b and references therein). The supracrustal sequences that lie over the basement show greenschist facies metamorphism and represent multiple cycles of basin development during the Neoproterozoic-Mesoproterozoic time frame (K. Das *et al.*, 2017). Alkaline rocks from this province were emplaced at ca. 1.35 Ga (Ranjan *et al.*, 2018). Geological data suggest that this province is a deeper section of the Singhbhum Craton which was structurally emplaced in the shallow level by a transpression-dominated tectonic setting at ca. 0.5 Ga (Ghosh *et al.*, 2016 and others cited in Bose and Dasgupta, 2018). Barring a single occurrence of ca.

1.0 Ga metamorphism (Chattopadhyay *et al.*, 2015), no clear indication of Grenville-age metamorphism which is characteristic of the Eastern Ghats Province, is recorded from here. In an alternative model, the Rengali Province represents a part of the Bastar Craton which was transported over the Eastern Ghats Province by a dextral strike slip movement at ca. 0.5 Ga (Sawant *et al.*, 2017 and references therein). The latter workers correlated the Eastern Ghats-Rengali contact zone and the Rauer Group of East Antarctica that also evolved as a ca. 0.5 Ga strike-slip shear zone. Thus, more geological data are required to delineate the ancestry of Rengali Province.

Outstanding Issues of the EGB

Domains and Provinces

In the published literature, present configuration of EGB is conceived as an amalgam of discrete provinces and domains. These provinces and domains are believed to have juxtaposed by boundary ductile shear zones assuming these are true terrane boundaries. With growing evidences, it is now time to rethink about this classification. Considering the lithological continuity across the shear zones and the timing(s) of the activation of some of the shear zones, it is clear that majority of the crustal domains of the Eastern Ghats Province evolved as a single entity (Fig. 2 after Ganguly, 2019). Although geological histories of the Eastern Ghats Province and the Ongole domain are significantly different in time frame, there is no unambiguous evidence to consider the fact that the individual domains in the former evolved differently. The status of the Jeypore Province or domain 1B is unclear as no recent data are available. This could be a separate terrane comprising the exhumed deeper margin of the Bastar Craton analogous to the Rengali Province, which is the exhumed deeper margin of the Singhbhum Craton. Careful orchestration of petrological and isotope investigations is required to resolve these issues.

EGB and Rodinia

It is generally agreed upon that different segment (domains and/or provinces) of the EGB evolved during the accretionary growth of Proterozoic supercontinents (Dasgupta *et al.*, 2013, 2017; Bose and Dasgupta, 2018). The metamorphic age provinces of EGB show a strong dominance of the

ca. 1000-900 Ma and ca. 1800-1600 Ma events with sporadic presence of ca. 500 Ma events along the shear zones (Fig. 3). The Ongole domain evolved along with the Napier Complex of East Antarctica during the growth of Columbia (references as above). On the other hand, the evolution of the Eastern Ghats Province could be linked with the evolution of Rodinia. Recent studies from the Rayner Complex also support this (Tong *et al.*, 2017). Although the position of India within Rodinia is a matter of conjecture (reviewed in Dasgupta *et al.*, 2017; Bose and Dasgupta, 2018; Mitchell *et al.*, 2018), it is accepted that the Eastern Ghats Province formed a composite orogen with the Rayner Province (R-EG orogen of Morissey *et al.*, 2015, 2016) at ca. 1.0-0.9 Ga possibly as a part of Rodinia. Paleomagnetic tools can directly resolve the issue, but the deformed and intensely metamorphosed rocks of EGB are not ideally suited for this purpose. Whether part of Rodinia or not, it is however, agreed upon that the evolution of R-EG resulted from subduction-dominated accretionary tectonics involving cratonic India and East Antarctica (Van Leeuwen *et al.*, 2019). It is now important to identify which part of the Eastern Ghats Province can be matched with which part of the Rayner Province. It is already proposed that the Chilka lake domain was a part of the Prydz Bay area of the Rayner Province (Bose *et al.*, 2016a). With more petrological and geochronological inputs from both sides of the great divide, one can precisely fit the Grenville-age crustal fragments in the India-Antarctica frame. Based on the geochronological evidence, records of assembly of the East Gondwana supercontinent has also been proposed from the EGB in recent time (Mitchell *et al.*, 2018). It is intriguing to note how a single orogenic belt underwent two (or three) supercontinent cycles during the Proterozoic era.

Style and Duration of Orogenic Cycle in the Eastern Ghats Province

Although the occurrence of UHT metamorphism is well-documented, debate is still going on to explain the anomalous thermal perturbation that was experienced by the Eastern Ghats Province at ca. 1.0 Ga. Models predicting back arc tectonic setting to truncated hot orogen with contributions from high concentrations of heat producing elements and slab break-off/lithospheric delamination have been invoked to explain UHT metamorphism in this belt

Fig. 3: Metamorphic age provinces of EGB compiled from data presented in the text

(see reviews in Dasgupta *et al.*, 2017; Mitchell *et al.*, 2018; Bose and Dasgupta, 2018). This seems to be the only viable model so far, but opinions are still divergent on the time scale of this accretionary growth history. While some workers are of the opinion that the entire process went to completion at one go with existence of a long-lived hot orogen (Korhonen *et al.*, 2013a), others argue for short-lived repeated orogenesis (Dasgupta *et al.*, 2013, 2017; Bose and Dasgupta, 2018). One important approach to resolve this issue could be kinetic modelling as a recent study showed that multiple episodes of ‘short-lived’ orogenies could be traced back from the complexly evolved Proterozoic orogenic system (Bhowmik and Chakraborty, 2017). This is an important distinction to be made to explain the tectonic setting in the Proterozoic era. It is a fact that, the EGB as an entirety experienced at least one phase of UHT metamorphism at mid- lower crustal depths, but at

different times in various segments. Therefore, apart from the cause of UHT metamorphism, it is important to evaluate whether tectonic settings were similar or different, and why these were recurrent in time. The timing of supercontinent assembly cannot be just coincidental without a secular change in plate tectonic style (Brown and Johnson, 2018).

Exhumation of Deep Crust and the Shear Zones

One key issue which remains untouched for decades is how the isobarically cooled deep crust of the EGB got exhumed at shallower level. Excepting a few cases, the UHT granulites do not exhibit a decompression-dominated P-T path, which implies large-scale exhumation at high temperature did not occur. It is prudent to conceive the crisscrossing ductile shear zones as the principal conduits for exhumation of deeper crust (tectonic exhumation) at

later time. Very little work has been done on this issue and the kinematics of the major shear zones remain poorly characterized so far. The assumption that the ductile shear zones are terrane boundaries is not valid for many cases. For example, the N-S trending Nagavalli-Vamshadhara Shear Zone (NVSZ) was originally considered as a terrane boundary suturing the Vishakhapatnam and Phulbani domains. In a recent study, it is shown that the rocks exposed on both sides of the NVSZ show similar metamorphic and geochronological histories. The activation of such shear zones must be younger in age, but could not be dated using precision geochronological tools. While data (K-Ar, Ar-Ar) from the Mahanadi and Ranipathar shear zone indicate a Pan-African age, the age of others remain still uncertain. It is also possible that a majority of these shear zones are intracrustal in nature and formed due to far field stress (Ravikant, 2019; Ganguly *et al.*, 2019).

Juxtaposition of EGB with Cratonic India

Timing of juxtaposition of EGB with cratonic India is still a debated topic. While there are models suggesting thrusting of EGB over the Bastar Craton at ca. 1.0-0.9 Ga (Ranjan *et al.*, 2018 and references therein), the alternate model suggests a Pan-African (ca. 0.55-0.50 Ga) thrusting (Nasipuri *et al.*, 2018). It is, however, possible that there exist two thrusting events and the earlier thrusts are buried under the younger thrusts, which was conceived earlier (Upadhyay, 2008). In recent work, Chatterjee *et al.* (2017b) identified two different age domains (ca. 1.0-0.9 Ga and ca. 0.55-0.50 Ga) from the EGB-Bastar contact. While it is understood that the identification of possible counterparts of the EGB in east Antarctica will be speculative, detail petrological, isotopic and structural investigations are required along the contacts of EGB with the three cratonic blocks to ascertain whether the cratonization of the EGB was completed by ca. 1.0 Ga or at ca. 0.5 Ga to define the present crustal architecture of India.

The missing Grenvillian-age Suture

The nature and location of the proposed Grenvillian-age (~ 0.9 Ga) suture between India and East Antarctica is “missing” information in the reconstruction hypothesis. The western boundary of EGB has long been thought of as a suture although no unambiguous evidence of ocean closure like presence of ophiolite is identified. This has been elaborated recently in Bose and Dasgupta (2018) and they proposed that the true continental suture could be located in the interior part of the Prydz Bay region of East Antarctica. Therefore, the absence of such a suture at the western margin of EGB is not surprising.

Recent geophysical data across the EGB and adjoining Singhbhum and Bastar Cratons provide some interesting clues. The seismic profiles identified prominent Moho offsets which are interpreted as the evidence of collisional tectonics (Singh and Singh, 2019; Jana *et al.*, 2019). However, the amount of Moho offset is small (~ 5 km) which can be interpreted by accretionary tectonics (Dasgupta *et al.*, 2013). This is also vindicated by the fact that no significant crustal thickening has been noted near the proposed suture (Singh and Singh, 2019). These geophysical signatures need to be correlated with the petrological, geochronological and structural data for unambiguous interpretations.

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