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Structural evolution across the Eastern Ghats Mobile Belt–Bastar craton boundary, India: hot over cold thrusting in an ancient collision zone

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Abstract

Along the western margin of the Eastern Ghats Mobile Belt (EGMB), ultrahigh-temperature granulites are thrust westward over hornblende granites and sedimentary rocks of the Bastar craton. Multiply deformed migmatitic gneisses, and porphyritic charnockite of the EGMB unit preserve thrust-related shear fabrics (S_{3M}). In the cratonic foreland, undeformed granites show a progressive decrease in grain-size and increase in penetrative foliation to the east, evolving into orthogneiss near the mylonitized contact zone with charnockite. Foreland fabrics with a consistent top-to-the-west shear sense are conformable with S_{3M} in charnockite and correlate with S_{3B} in polydeformed orthogneisses of cratonic windows. S_{3B} in the windows parallels S_{3M} in overlying EGMB migmatitic gneisses. While S_{3M} accompanied granulite metamorphism in the EGMB, S_{3B} temperature estimates vary from $T > 700$ °C in the windows to $T < 550$ °C in the west. Decreasing temperature and later fabric formation in the west are explained by an evolving thermal profile in the cold craton, which is caused by thrusting against hot lower crustal EGMB rocks.

Based on lithologic, structural and metamorphic variations across the contact, and resemblances between the EGMB and Rayner Complex, the craton–mobile belt boundary is considered a result of Indo-Antarctic collision, leading to the formation of an ancient supercontinent.

Keywords: Craton–mobile belt boundary; Ancient supercontinent; Thermal profile; Cold craton

1. Introduction

Precambrian shields generally comprise a mosaic of crustal segments with differing lithological, structural and metamorphic character. These segments may sometimes bear geological affinity with spatially separated landmasses, suggesting contiguity in ancient 'supercontinents' that subsequently disintegrated (Rogers, 1996). Identification of crustal segments with distinctive geological history, and the nature of their amalgamation in Precambrian shields, are therefore fundamental to understanding the tectonic processes involved in the construction of 'supercontinents'. Of obvious interest in this respect are the contacts between stable Archaean cratons and their bounding mobile belts (Condie, 1989). The pervasive deformation and high grade metamorphism in mobile belts has sometimes been attributed to continental collision processes (e.g. Rivers et al., 1989; Roering et al., 1992). If collision resulted in amalgamation with the craton, deformation and metamorphism in the two units are expected to be correlatable. Additionally, the large (plate-scale) compressive stresses associated with collision may result in crustal/lithospheric-scale thrusting along the craton–mobile belt boundary. Identification of such megathrusts could be critical to any argument favouring Phanerozoic-style tectonics during supercontinent assembly.

In peninsular India, an Archaean nucleus comprising the Bastar and Dharwar cratons is bounded by the Proterozoic Eastern Ghats Mobile Belt (EGMB). The Bastar craton, which lies north of the Godavari rift, consists of 3.5–3.0 Ga hornblende and biotite-bearing granite gneisses (Sarkar et al., 1993) with concordant bands of calc–silicate gneisses, grunerite schists and amphibolites (Crookshank, 1963). Post-tectonic granite intrusive into the gneisses is dated at 2.6–2.1 Ga (Pandey et al., 1989). Unmetamorphosed Proterozoic sediments of the Chhatisgarh Group unconformably overlie the granites (Deb and Chaudhuri, 2002).

The Eastern Ghats Mobile Belt, on the other hand, forms

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an arcuate region of multiply-deformed granulite facies rocks to the east of the craton. Major lithotypes include migmatitic quartzofeldspathic gneisses hosting varied metasedimentary gneisses and mafic granulites, along with early tectonic granitoids, anorthosites and alkaline complexes. The belt has undergone granulite facies metamorphism, in places at ultrahigh temperatures exceeding 900 °C (e.g. Mukhophadhyay and Bhattacharya, 1997; Sengupta et al., 1999; Gupta et al., 2000). South of the Godavari this metamorphism may be older than 1600 Ma (U/Pb monazite; Mezger and Cosca, 1999). The most prominent granulite facies metamorphic imprint in the northern and central parts is, however, considered to be around 980–920 Ma (Shaw et al., 1997; Mezger and Cosca, 1999). These ages are comparable with the ages of granulite facies metamorphism in parts of east Antarctica (the Rayner Complex), which are considered to have been contiguous with the EGMB (Kelly et al., 2002). Based on such reconstructions, it has been suggested that the later metamorphism resulted from the collision between eastern India and a continental fragment that later became part of east Antarctica (Mezger and Cosca, 1999; Kelly et al., 2002). The contact between the EGMB and the Indian cratonic nucleus, therefore, represents the zone along which amalgamation of India into the Precambrian supercontinent was affected.

This paper documents structural evolution across the boundary between the Bastar craton and the EGMB (see Fig. 1, inset). The study has involved extensive lithological and structural mapping over an area of 1500 km^2, south of the terrane boundary delineated in the Deobhog area by Gupta et al. (2000). We examine the response of the cratonic fringe zone to the juxtaposition, and argue that the structures are a consequence of the emplacement of synmetamorphic EGMB granulites onto the craton along a crustal-scale thrust. Finally, we suggest that the incorporation of the peninsular Indian craton into the supercontinent is an outcome of continent–continent collision along this contact.

2. Geologic setting

The western boundary of the EGMB has been suggested to be a faulted margin (Walker, 1902; Fermor, 1936), an 'intrusive' contact (Crookshank, 1938), or even a 'transitional' boundary between granulites of the mobile belt and amphibolites of the craton (Narayanswami, 1975). In the Deobhog area, the western boundary of the Eastern Ghats Belt with the Bastar craton is characterized as a tectonic contact (Gupta et al., 2000), along which mobile belt granulites have been thrust over a cratonic domain comprising largely of variably deformed and metamorphosed granites and gneisses. Although both units experienced polyphase deformation, thrust related fabrics are conformable across the craton–mobile belt contact. Garnet and orthopyroxene-bearing leucosomes in quartzofeldspathic gneisses and mafic granulites are preferentially segregated along this fabric in the EGMB unit, testifying to extremely high prevailing temperatures. Further, temperatures retrieved from metamorphic assemblages overprinting this fabric suggest temperatures in excess of 900 °C, implying ultrahigh-temperatures post-dating juxtaposition. In the underlying craton, metamorphic temperatures show a progressive decrease to the west, with little evidence of thermal rejuvenation just 15 km from the contact (Gupta et al., 2000). Based on these observations, Gupta et al. (2000) suggested that conductive heating from the overthrust EGMB block was responsible for the observed temperature variation in the cratonic fringe.

South of Deobhog (Fig. 1), undeformed and unmetamorphosed hornblende granites and granite gneisses, with sandstones and slates of the overlying Chhatisgarh Group of the Bastar craton, occur in the western part of the study area (Fig. 1), and show a progressive increase in strain towards the contact with the EGMB unit. The strained cratonic zone abuts against a band of porphyritic charnockite. The contact between the two lithologies is marked by a mylonite zone. To the east, migmatitic quartzofeldspathic gneisses of the EGMB host discontinuous bands and lenses of mafic granulites, metapelites, calc–silicates and metagabbros. Orthogneisses of the craton are also exposed in tectonic windows within the EGMB unit around the villages of Ranmal and Sarasmal.

3. Structure

3.1. Structural development in the Eastern Ghats Unit

The structural development of the Eastern Ghats Unit is broadly compatible with observations in other parts of the EGMB (e.g. Halden et al., 1982; Bhattacharya, 1996; Gupta et al., 2000). The migmatitic quartzofeldspathic gneiss, the dominant lithologic component of the EGMB, is an intensely sheared unit within which early structural features are largely obliterated. However, infrequent low strain domains preserve a record of repeated deformation. The primary fabric within these gneisses (S_{1M}), which is a segregation into hornblende and biotite-bearing mafic layers, and quartz, plagioclase and orthoclase-rich leucocratic layers, is attributed to an early deformation event D_{1M}. Isoclinal folding (D_{2M}) of these layers transposes the entire foliation parallel to F_{2M} axial planes, but with little associated fabric formation. The third and most prominent event (D_{3M}) is characterized by pervasive shearing; the resulting shear foliation (S_{3M}) is the dominant fabric in the entire unit. The S_{1M} foliation is, in most places, indistinguishable from S_{3M}, but locally is observed curving into parallelism with the shear plane. The movement sense is invariably top-to-the-west. In low shear strain zones, F_{2M} isoclinal folds, having a reclined geometry with steeply plunging axes, are coaxially refolded into tight, asymmetrical

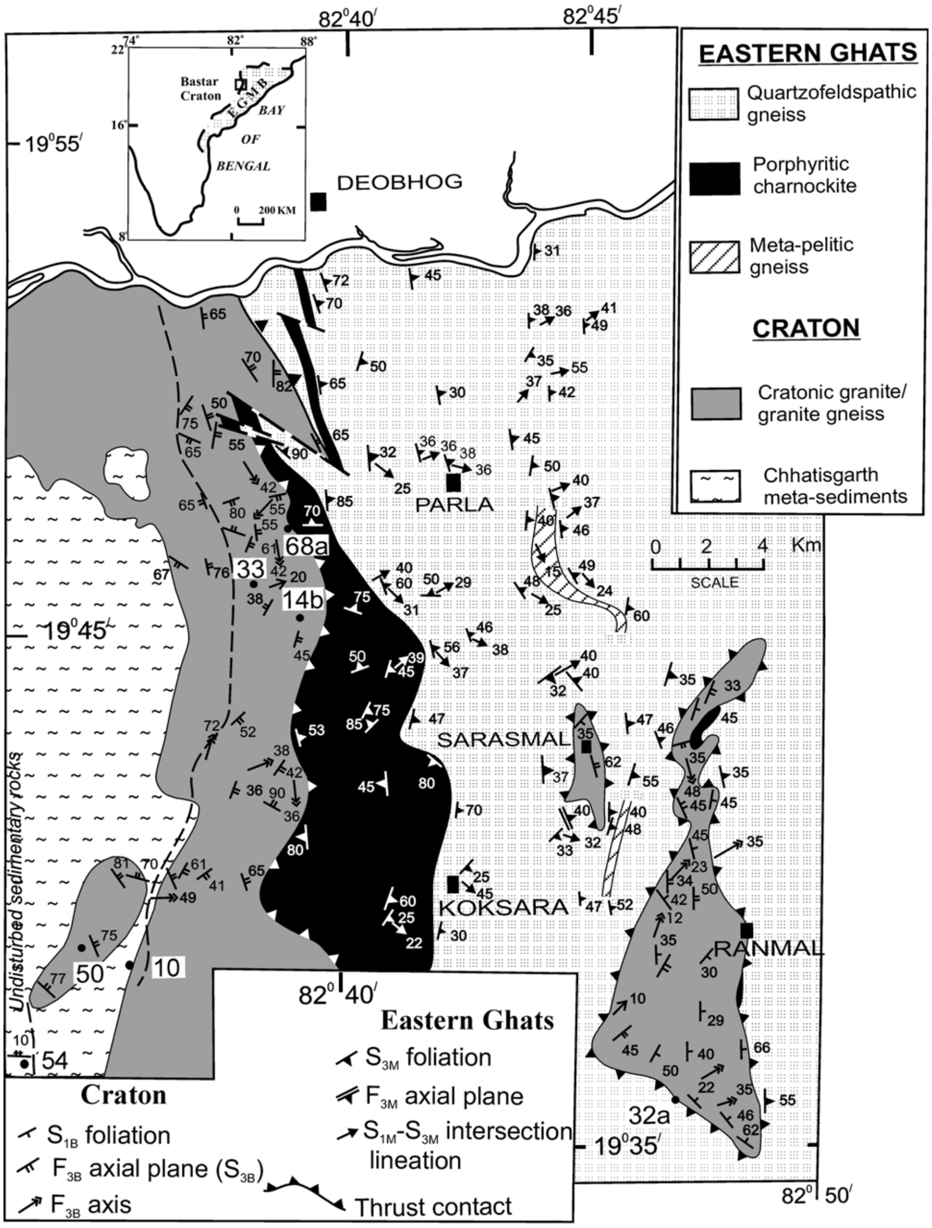

Fig. 1. Simplified map across the Eastern Ghats Belt–Bastar craton contact south of Deobhog. The craton-mobile belt boundary is indicated as a thrust. Note the cratonic windows around Ranmal and Sarasmal. The dashed line in the craton separates the zone of penetrative foliation development from undeformed granites in the craton. The location of samples mentioned in the text is indicated. Inset map shows location of the study area with respect to the Eastern Ghats Mobile Belt (EGMB).

folds (F_{3M}); the axial planes of these folds are parallel to the shear fabric S_{3M}. In places, S_{3M} is itself refolded along near-coincident axes, implying that an element of buckling accompanied D_{3M} shearing. Pervasively developed leucosomes (quartz + feldspar-bearing veins containing garnet + orthopyroxene and rimmed by biotite selvages) are parallel to S_{1M} and S_{3M}, reflecting the high-grade conditions prevailing during deformation.

π-pole plots to the S_{3M} shear foliation in the entire unit shows a point concentration, with a maxima of 350°/41°E (Fig. 2a). The S_{1M}/S_{3M} intersection lineation (L_{3M}) shows a girdle distribution (354°/43°E) (Fig. 2b) which closely approximates the attitude of the S_{3M} foliation maxima. The symmetrical spread of L_{3M} on the shear foliation reflects widespread rotation of the lineation towards the down-dip movement direction on the shear plane, consistent with high strain during progressive simple shear deformation (e.g. Escher and Watterson, 1974; Cobbold and Quinquis, 1980; Goscombe, 1991). Similar lineation patterns, and the implied megasheath geometry have been reported earlier from other parts of the EGMB (Biswal et al., 1998).

In the frontal part of the thrust sheet, the S_{3M} foliation in

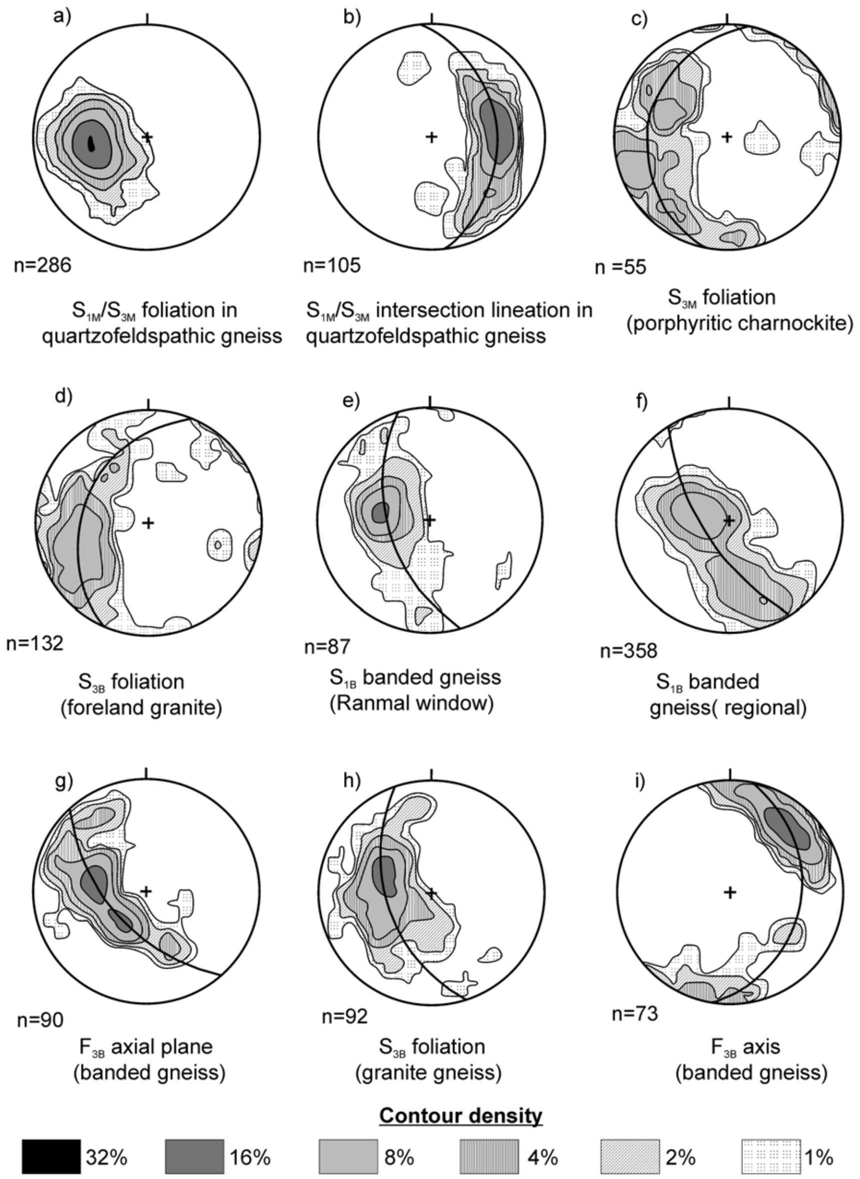

Fig. 2. Stereographic projections of different structural elements. (a) Plot of S_{1M}/S_{3M} composite foliation in quartzofeldspathic gneiss. Contour intervals at: 1, 2, 4, 8, 16 and 32%, preferred direction 350°/41°E. (b) Plot of L_{3M} axis (S_{1M}/S_{3M} intersection lineation) distribution in quartzofeldspathic gneiss. Contour intervals at: 1, 2, 4, 8 and 16%, girdle distribution 354°/43°E. (c) Plot of foliation in porphyritic charnockite. Contour intervals at: 1, 2, 4 and 8%, preferred direction 349°/61°E. (d) Plot of augen defined foliation in the granite west of the porphyritic charnockite body. Contour intervals at: 1, 2, 4 and 8%, preferred direction 343°/56°E. (e) Plot of augen defined foliation S_{1B} in banded gneiss, Ranmal window. Contour intervals at: 1, 2, 4, 8 and 16%, preferred direction 09°/32°E. (f) Plot of S_{1B} in banded gneiss within the entire cratonic unit. Contour intervals at: 1, 2, 4 and 8%, preferred direction 313°/20°N. (g) F_{3B} axial plane plot in banded gneiss. Contour intervals at: 1, 2, 4, 8 and 16%, preferred direction 1°/35°E. (h) Plot of the augen defined foliation (synchronous with S_{3B} in banded gneiss) in sheared granite gneiss. Contour intervals at: 1, 2, 4, 8 and 16%, preferred direction 3°/35°E. (i) Plot of F_{3B} axis distribution in banded gneiss. Contour interval at: 1, 2, 4, 8 and 16%, preferred direction 18°/35°E.

migmatitic gneisses is concordant with the segregation layering in the porphyritic charnockite band, defined by pyroxene-bearing mafic and quartzofeldspathic felsic layers. This foliation is therefore correlated with the D_{3M} event. The charnockite band contains no leucosomes and is itself folded (Fig. 1), with the foliation showing a corresponding girdle distribution (Fig. 2c). Unlike the migmatitic gneisses, new axial planar foliation development on the S_{3M} fabric is not observed in the charnockite.

3.2. Structural development in the cratonic foreland

The cratonic foreland in the western part of the area is dominated by a coarse-grained hornblende-biotite granite with no penetrative fabric, overlain by sediments of the Proterozoic Chhatisgarh Group. Coarse-grained plagioclase, microcline (>4 cm), hornblende (>3 cm) and biotite in the granite show no preferred orientation and define a hypidiomorphic granular texture (Fig. 3a). Quartz shows

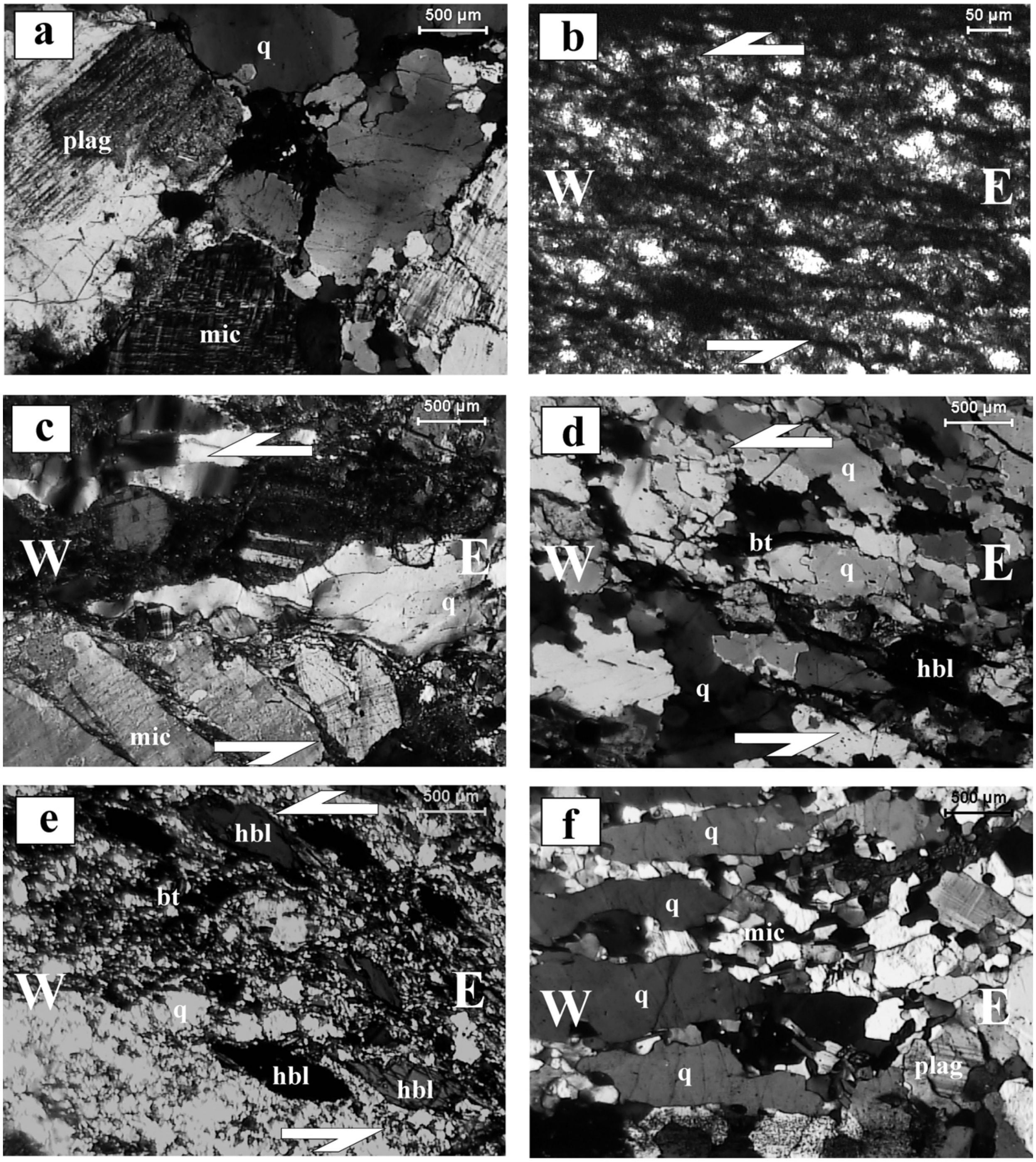

Fig. 3. Photomicrographs of showing shear sense and deformation of cratonic rocks. (a) Undeformed granite with large microcline, plagioclase and unrecrystallized quartz (Sample 50). (b) Slaty cleavage in sedimentary rock, with S–C fabrics showing top-to-the-west shear sense (Sample 10). (c) Flattened, plastically deformed ribbons of quartz wrapped around fractured microcline clasts showing book-shelf structure. Shear sense is top-to-the-west (Sample 33). (d) Serrated grain boundaries in recrystallizing quartz grains, testifying to grain boundary migration recrystallization. Recrystallized biotite flakes show S–C fabrics with top-to-the-west shear sense (Sample 14b). (e) Lenticular amphibole clasts showing top-to-the-west shear sense in mylonite zone. Note acute grain-size reduction of quartz (Sample 68a). (f) Coarse-grained, strain-free quartz grains are segregated into elongate ribbons parallel to the lineation. Feldspars define an equigranular granoblastic mosaic (Sample 32a).

strained extinction without recrystallization while feldspar is essentially undeformed. Occasional microshears dissecting amphibole grains form locales for the stabilization of biotite, chlorite and epidote. Locally, the granite is mylonitized within infrequent, narrow high strain zones, with a foliation defined by flattened quartz ribbons, chlorite and biotite. Feldspar is invariably deformed by brittle fracture. Sandstones and shales of the Chhatisgarh Group overlying the granites in the west are undeformed and show shallow dips (see Loc. 50, Fig. 1). Along the exposed eastern margin of the sequence, however, the sedimentary rocks preserve isoclinal to tight asymmetric folds, with an axial planar slaty cleavage that is parallel to the mylonitic foliation in high strain zones of the granites. S–C fabrics in the slates also show a top-to-the-west sense (Fig. 3b). The deformation of the sedimentary rocks is therefore correlated with the event that affected high strain zones in the underlying granite.

Mesoscopically, an increase in strain in the granite is manifested by an increase in the foliation intensity. From about 6 km west of the contact, the granite is penetratively foliated, with a corresponding reduction in grain-size. Hornblende grains show brittle failure into fragments which are still ~1 cm in length, while quartz shows extreme flattening into ribbons with only incipient marginal recrystallization. Porphyroclasts of microcline survive as augen (~1 cm) that deformed primarily by cataclasis. Quartz ribbons defining the foliation envelop hornblende and feldspar clasts forming bookshelf structures (Fig. 3c) with a consistent top-to-the-west sense of movement.

Within 2 km of the contact with the porphyritic charnockite the granite progressively changes into an orthogneiss. The segregation banding comprises predominantly hornblende and biotite-bearing mafic layers and discrete quartz and feldspar-bearing layers. A characteristic feature in this area is the appearance of mesoscopic-scale folds in the layering; broad, open folds in the west become increasingly tight and asymmetric to the east, though axial planar foliation development is absent. Quartz in the segregated domains has highly serrated boundaries characteristic of grain boundary migration recrystallization (Fig. 3d). Occasional relict microcline grains show sweeping extinction, while most feldspars show size reduction to a medium-grained equidimensional mosaic (~300 microns). Triple junctions are rare, and there is little evidence of annealing recrystallization.

A narrow (5–10 m) zone of intensely mylonitised granite marks the contact between the porphyritic charnockite and the cratonic foreland. The rock is dark-coloured and intensely foliated. On the regional, mesoscopic and microscopic scale the mylonitic foliation shows tight, asymmetric folds; the foliation parallels the contact with the porphyritic charnockite. Asymmetric lenticular relicts of the original igneous amphibole, with a top-to-the-west movement sense (Fig. 3e), are wrapped by recrystallized biotite flakes that parallel the segregation banding. These biotites commonly describe S–C fabrics. In the felsic layers K-feldspar shows evidence of dynamic recrystallization in the form of ‘core-mantle’ structures. Quartz, on the other hand, is recrystallized to a strain-free equigranular mosaic.

The mylonitic foliation in the granite at the contact is conformable with the syn-D_{3M} foliation in the adjacent porphyritic charnockites. Poles to all measured foliations (Fig. 2d) in the foreland granites show a cylindrical dispersion, reflecting folding after fabric formation. The distribution is closely comparable with the foliation pole girdle in the porphyritic charnockite. Consequently, the fabric and the subsequent folding in the porphyritic charnockite and the cratonic footwall are considered to be contemporaneous (syn-D_{3M}). The S_{3M} foliation in the EGMB unit is correlatable with S_{3B} in cratonic orthogneisses in the windows; the foliation in the foreland is therefore also designated S_{3B}.

3.3. Structural development in the cratonic windows

Orthogneisses in the cratonic windows are structurally more complex than those in the foreland, preserving evidence of repeated folding and axial planar fabric formation on an earlier K-feldspar augen-defined foliation. Structurally, two major components, designated banded gneiss and sheared granite gneiss can be distinguished, the latter having suffered fewer folding events. Banded gneisses are restricted to the contact with the EGMB, and their boundaries with the sheared granite gneisses vary from diffuse to sharp and are not persistent along strike. Quartz and feldspar in orthogneisses of the windows are segregated into distinct domains with quartz occurring in elongate lenticles and ribbons parallel to the foliation (Fig. 3f). Within the ribbons quartz is completely strain-free and relatively coarse-grained. K-feldspar and plagioclase define an equigranular granoblastic mosaic with perfectly developed triple junctions. Medium-grained hornblende and biotite are also recrystallized and aligned along the fabric. Quartzofeldspathic layers rimmed by biotite selvages, that may represent leucosomes, occur frequently within the banded gneiss. In the sheared granite gneiss leucosomes are rare.

In the Ranmal window, the dominant foliation in high strain zones of banded gneiss is very consistent, with a maxima around (009°/32°E) (Fig. 2e). Low strain zones, however, preserve evidence for repeated folding and transposition. The early augen-defined foliation, S_{1B}, is isoclinally folded (F_{2B}), and then refolded around tight, asymmetric folds (F_{3B}) verging to the west. A fabric (S_{3B}) is invariably well developed parallel to F_{3B} axial planes; this fabric is defined by reoriented feldspar augen (Fig. 4a) and is largely a transposed S_{1B} fabric. In high strain zones, F_{3B} axial planes are extremely close-spaced and earlier structures are almost completely obliterated. On a regional scale, the S_{1B} foliation pole distribution is cylindrical, defining a girdle with a northeasterly plunging β-axis (Fig. 2f). F_{3B} axial plane data also show a spread similar to S_{1B} (Fig. 2g). A later cross-folding event (F_{4B}) is observed on outcrop-scale (Fig. 5), where the S_{1B} foliation describes an elongate, closed pattern. F_{3B} folds in the outcrop are characteristically tight and asymmetric, but the axis plunge varies from shallow northerly, through horizontal, to shallow southerly from the northern to the southern end of the outcrop (Fig. 5b).

The foliation in the sheared granite gneiss parallels F_{3B} axial planes in the banded gneiss, and is consequently

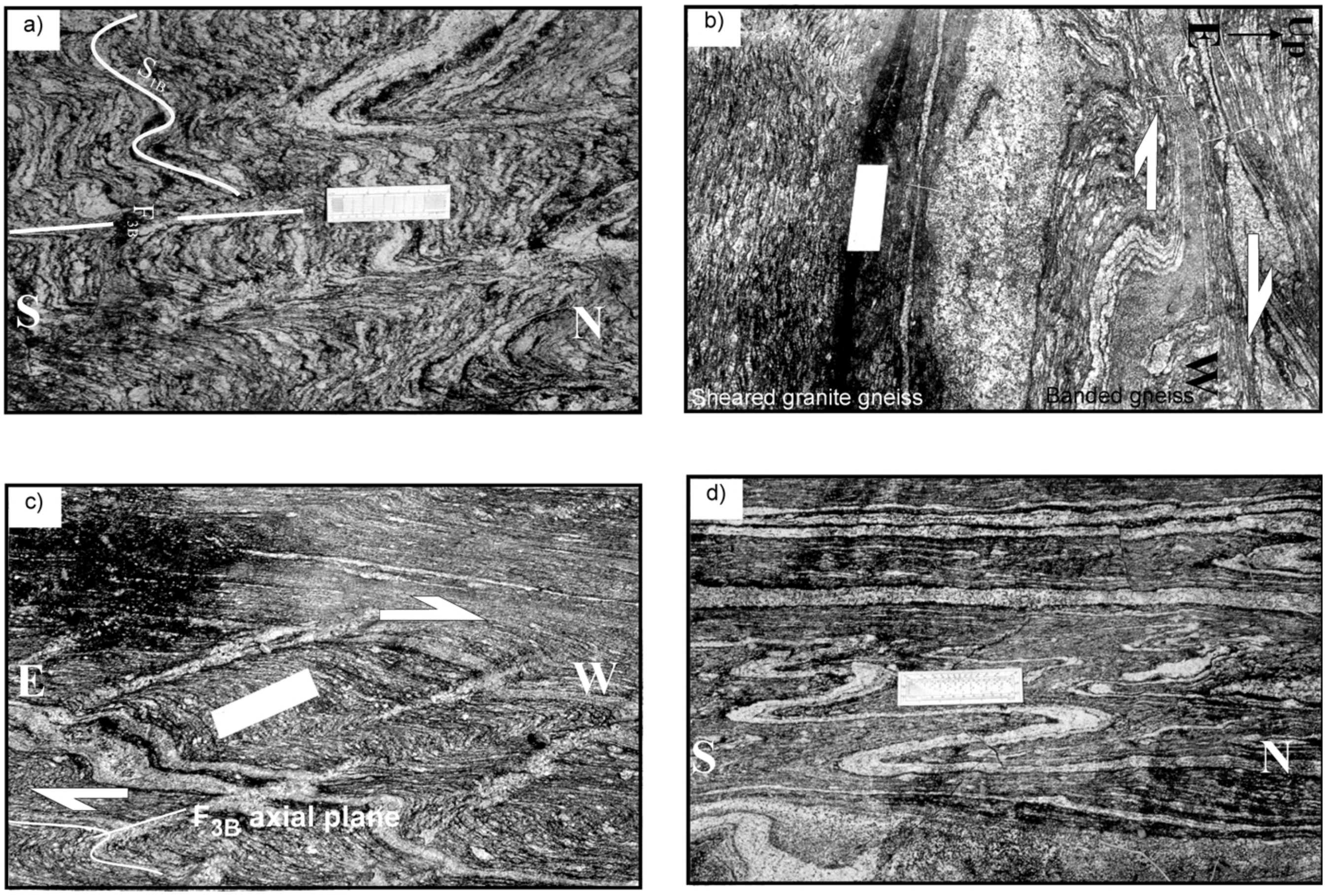

Fig. 4. Field photographs showing (a) transposition of early augen-defined foliation S_{1B} within high strain zones parallel to F_{3B} axial plane in banded gneiss. (b) Banded gneiss and sheared granite in mutual contact, with asymmetric F_{3B} folds in the former paralleling the augen-defined foliation in the latter. (c) Pre- and syn-F_{3B} leucosomes in low-strain zones in banded gneiss aligned along F_{3B} axial planes. Note that the folds have a westerly vergence. (d) Near isoclinally folded pre-F_{3B} leucosomes in high-strain zones within banded gneiss. The diagonal scale is 15 cm long.

considered equivalent to S_{3B} (Fig. 4b). Asymmetric mesoscopic-scale folding on S_{3B} is locally common, with the foliation pole girdle indicating a northeasterly plunging axis (Fig. 2h). Poles to the axial planes of these folds also define a similar girdle, comparable with the S_{1B} and S_{3B} foliation girdles in banded gneiss. The vergence of all asymmetric folds, both within the banded gneiss and the sheared granites is consistently top-to-the-west (Figs. 4c and 5c). Similarity of S_{1B} and S_{3B} foliation girdles in the banded gneiss and sheared granite indicate a consistency in kinematic framework, and are interpreted as products of a single continuous or progressive event (e.g. Tobisch and Paterson, 1988; Holdsworth, 1990; Connors and Lister, 1995). This implies that, during the same progressive event, foliation developed earlier in cratonic zones immediately adjacent to the contact.

The regional scale distribution of F_{3B} fold axes (Fig. 2i), which plunge at shallow angles to the north and south, is similar to that observed on outcrop-scale (Fig. 5b). This lineation distribution is distinctly different from that in the EGMB unit, and on the basis of outcrop-scale observations, can be attributed to the superposition of later cross-folds. However, sub-parallelism of the S_{3M} fabric maxima in the migmatitic quartzofeldspathic gneisses of the EGMB, and S_{3B} foliation maxima in the banded gneiss indicates that the same shearing process affected both units. The top-to-the-west shear senses, and the vergence of all asymmetric folds are consistent with westerly transport of the overlying EGMB unit.

4. Discussion

4.1. The craton-mobile belt contact—a thrust zone

The contact between the EGMB unit and the cratonic footwall is tectonic, represented by the easterly dipping mylonite zone between the porphyritic charnockite band and strained orthogneisses of the cratonic foreland. The sense of movement along the easterly dipping mylonite zone is top-to-the-west; this implies westward transport of the EGMB unit over the cratonic footwall. West of the mylonitic contact zone, orthogneisses with a prominent planar fabric grade into weakly deformed, coarse-grained

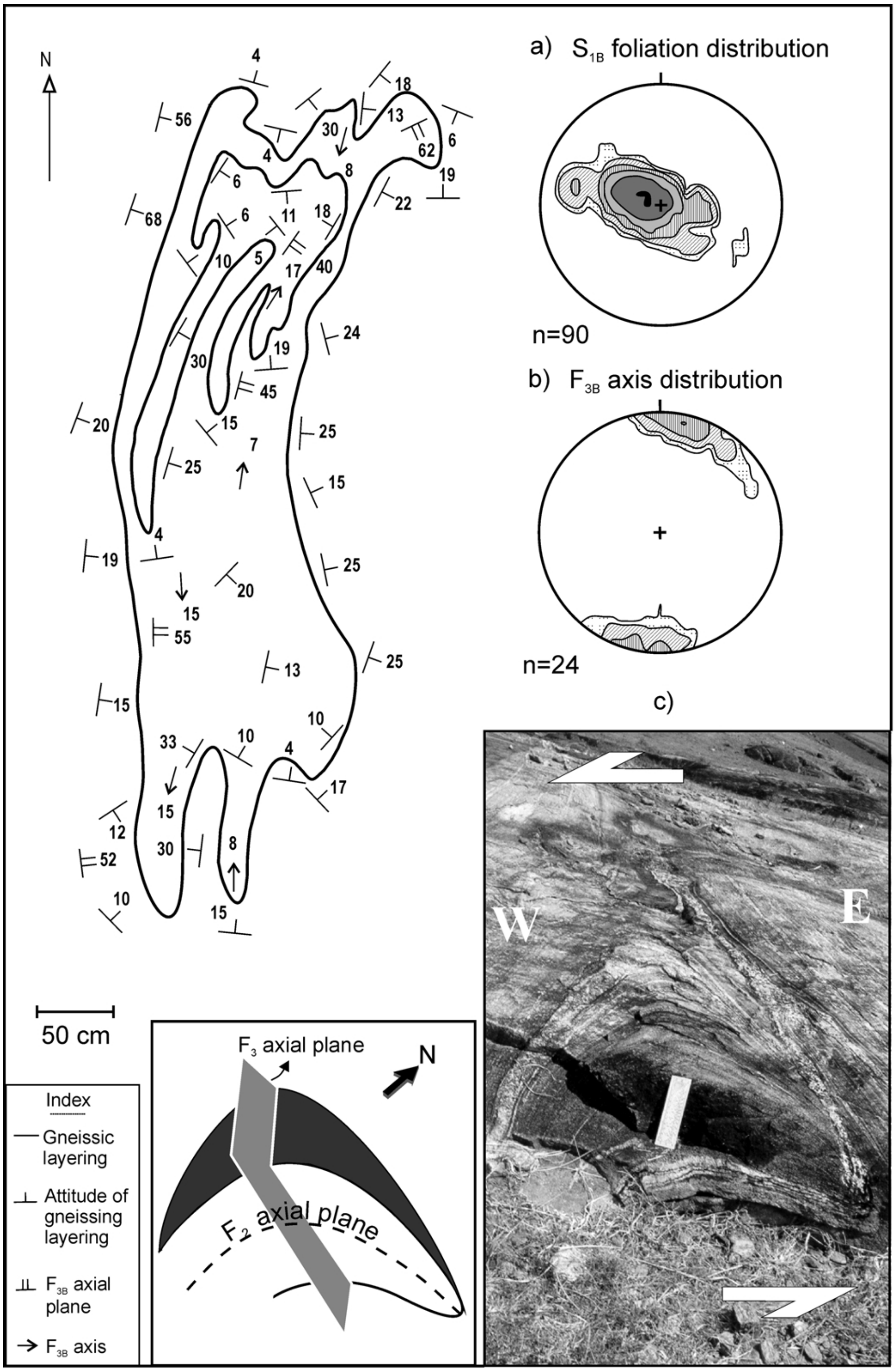

Fig. 5. Detailed outcrop-scale map of banded gneiss in Ranmal window. Stereographic projection of the (a) attitude of the S_{1B} augen-defined foliation. Contour intervals at: 1, 2, 4, 8, 16 and 32%, preferred direction 18°/12°E. (b) F_{3B} axis distribution. Contour intervals at: 1, 2, 4, 8, 16 and 32%, preferred direction 3° → 14°. Shades on contour intervals the same as in Fig. 2. (c) Field photograph showing refolding (F_{3B} folding) of an earlier isoclinal fold in banded gneiss. Schematic diagram showing F_{2B}, F_{3B} fold style and relative orientation of the respective axial planes.

hornblende-biotite granite. This planar fabric is defined by quartz grains flattened by plastic deformation. Corresponding grain-size reduction in feldspars takes place either by cataclasis or by dynamic recrystallization. The increasing intensity of the planar fabric, and the decreasing grain-size in the granite from west to east are therefore correlated with an increase in strain. The sense of shear deduced from S–C fabrics in the zone of penetrative foliation development, and also in infrequent high strain zones further westward, are consistently top-to-the-west. This strain pattern in granites of the cratonic foreland is therefore correlated with the thrusting of the EGMB over the craton. Cylindrical folding of this fabric suggests continued shortening; similarity of the foliation dispersion girdle with that for the porphyritic charnockite unit indicates a shared history subsequent to juxtaposition.

Orthogneisses preserving evidence of repeated folding, similar to those within the cratonic windows, are present in the foreland west of the contact in Deobhog (Gupta et al., 2000). Shear senses in east-dipping S_{3B} shear bands in the banded gneisses of Deobhog suggest westward transport of the overlying EGMB unit. This is corroborated by the consistent westerly vergence of all F_{3B} asymmetric folds in cratonic window orthogneisses. Attitudes of F_{3B} axial planes are concordant with S_{3M} shear foliations in adjacent migmatitic gneisses of the EGMB, with comparable maxima in foliation pole diagrams. As in the Deobhog area, the S_{3M} foliation in the EGMB, and the S_{3B} foliation in the banded gneiss are therefore considered correlatable, confirming that the latter part of the deformation history was shared by the two units.

Asymmetry of porphyroclasts and S–C fabrics associated with the foliation in the craton indicate that a major part of the strain was non-coaxial (e.g. Berthé et al., 1979). Shear strain decreased in magnitude to the west, as evidenced by the increasing size of porphyroclasts and weakening of foliation intensity. Additionally, buckle folding of this foliation suggests the involvement of a component of layer parallel shortening. Since the frequency, tightness and axial planar foliation development of these folds increases from orthogneisses of the foreland to the windows, the shortening component is also inferred to increase in magnitude towards the contact. The spatial association of the shortening and shearing components with the EGMB contact suggests that both relate to the thrusting event and operated simultaneously. This is consistent with the formation and folding of cleavage in a single, progressive event, as observed in orthogneisses of the windows (e.g. Ghosh, 2001), which can otherwise not be reconciled with simple shear deformation alone.

The foliation girdle for the cratonic foreland does not coincide with that in the windows. This suggests a variation in the orientation of the strain field during the final stages of transport of the EGMB thrust sheet westward to its present location, with concomitant shortening. A non-cylindrical component of shortening is inferred to have been superposed on earlier coaxial folds in banded gneisses, which become oppositely plunging, with closed outcrop patterns. This mimics the shape of the cratonic windows. Such overprinting relationships in progressive deformation have been related to changes in principal stress directions with respect to early formed structures (Helmstaedt and Dixon, 1980), and may have resulted from a change in the transport direction.

4.2. Pressure–temperature conditions across the contact

In the Deobhog area, a discontinuity between the EGMB and cratonic units coincides with a sharp difference in metamorphic assemblages and peak P–T conditions, though the contact zone is not exposed. Lithologies and mineral assemblages in this area are near-identical. As in Deobhog, the S_{3M} foliation in migmatitic gneisses is overprinted by granoblastic, equigranular orthopyroxene-bearing domains (‘patchy charnockite’) characteristic of the granulite facies. Mafic granulites are characterized by post-S_{3M}, granoblastic Opx–Cpx–Plag–Hbl assemblages with coronal garnet (on plagioclase), while high Mg–Al metapelites contain sapphirine–orthopyroxene–cordierite assemblages overprinting S_{3M} fabrics. Geothermometry on mafic granulites in the Deobhog area indicate temperatures of the order of 920–940 °C, at pressures of around 9 kbar. Again, as in Deobhog, mafic granulites of the area contain syn-D_{3M} Gt-/Cpx-bearing leucosomes suggesting peak temperatures higher than 1000 °C (Rapp and Watson, 1995).

Metamorphic assemblages and microstructures in the craton are also similar to those in Deobhog. K-feldspar and plagioclase in orthogneisses of the windows are recrystallized, while hornblende and biotite are aligned along the S_{3B} fabric. Hornblende–plagioclase thermometry (Holland and Blundy, 1994) in similar rocks (banded gneisses) in the Deobhog foreland record temperatures in excess of 700 °C (Gupta et al., 2000), further supported by the proliferation of syn-D_{3B} leucosomes in both areas. Dynamically recrystallized K-feldspar in the mylonite zone at the contact suggest temperatures in excess of 600 °C (Tullis, 1983), while in orthogneisses to the west, brittle fracture of feldspars and ductile flow of quartz indicate temperatures in the range 350–550 °C (e.g. Pryer, 1993). Stabilization of chlorite at the expense of hornblende in weakly deformed granites, and the slaty cleavage in overlying sedimentary rocks testifies to greenschist facies conditions. As in Deobhog, there is a marked decrease in metamorphic temperature from multiply folded orthogneisses in the windows to the weakly deformed granite in the west.

During the process of thrusting and juxtaposition, therefore, the EGMB unit was extremely hot, while temperatures in the craton decreased progressively from the contact to the west. The Deobhog model can also be applied to the present area—that an initially ‘cold’ cratonic footwall was rejuvenated at the contact owing to the overthrusting of ‘hot’ granulites. The latter were last equilibrated in lower crustal domains, indicating rapid uplift leading to juxtaposition against shallow crustal levels of the footwall.

4.3. Consequences of 'hot' over 'cold' thrusting

Continental underthrusting involving rapid transport of hot lower crustal rocks to comparatively colder, shallower levels, leads to a bending of isotherms towards the foreland (Vannay and Grasemann, 2001). The isotherms tend to be subparallel to the trend of lithotectonic boundaries (Štípská et al., 2000), but may dip towards or away from the foreland; the latter case reflects an inversion of the geothermal gradient. At high convergence rates, it is theoretically possible to cause such a transient 'inverted' thermal gradient in the footwall (e.g. Jain and Manickavasagam, 1993). However, two-dimensional numerical thermal models predict that geologically reasonable convergence rates of around 2 cm/yr are inadequate to induce such a gradient (e.g. Shi and Wang, 1987), and would remain unlikely even if rates were enhanced to unrealistic values of 5 cm/yr (Grasemann, 1993). Consequently, the qualitative model suggested below assumes foreland-dipping isotherms.

The model (Fig. 6) attempts to explain how fabrics evolve in the footwall as a function of the interplay between strain and migrating isotherms in the course of thrusting. The strain involves shearing across the thrust contact, with concomitant shortening of both blocks. We envisage a situation where thrusting leads to rapid uplift of 'hot' lower crustal hanging wall rocks into juxtaposition with 'cold', upper crustal rocks of the footwall. Consequently, heat from the lower crust is advected with the hanging wall during uplift, and is subsequently conducted into the footwall across the contact. Immediately after thrusting, therefore, isotherms in the hanging wall block dip towards the foreland, and progressively lower temperatures are encountered to the west. Continuing movement along the thrust causes progressive westward shift of the isotherms. At any point within the cratonic foreland, temperature would therefore increase with time. Ductile strain in the craton

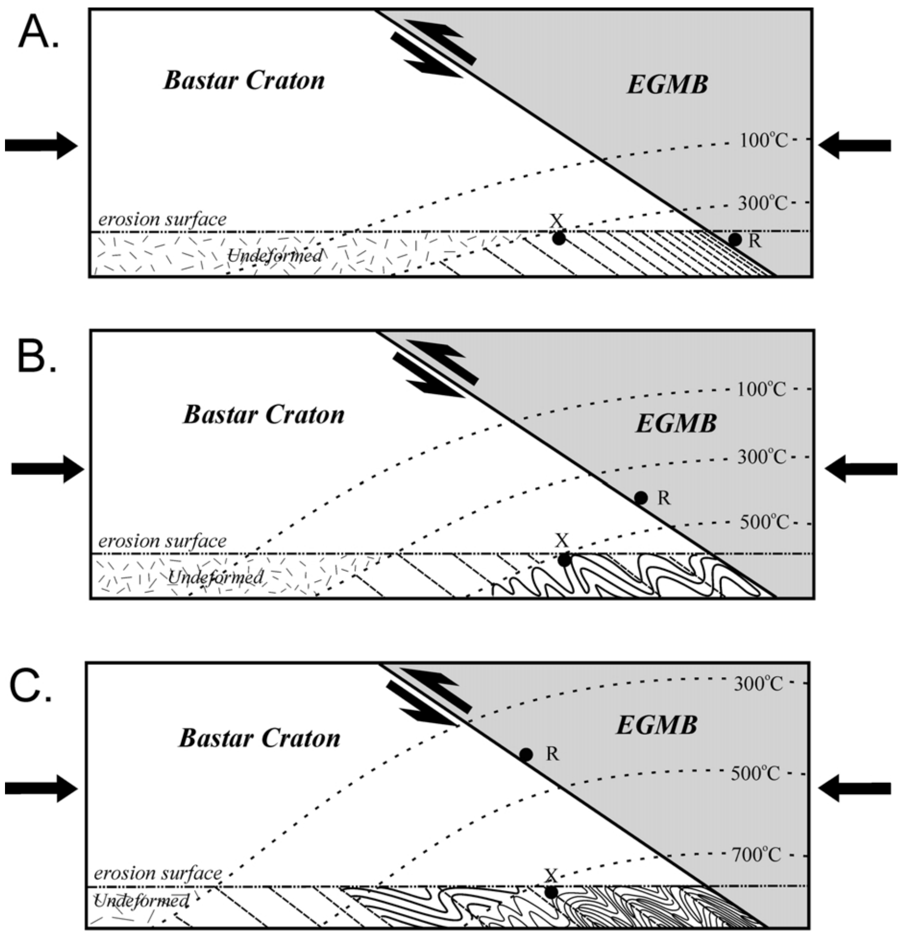

Fig. 6. Schematic representation of the evolving structure of the craton with progressive movement on the thrust (A–C). The strain involves shearing (arrows along the thrust plane) with concomitant shortening (horizontal arrows) of the block. Isotherms in the craton dip towards the foreland (see text), and migrate westward with continued thrusting. Points R and X are reference points in the EGMB and Bastar craton, respectively. While fabrics related to thrusting tend to form parallel to the contact, foliations in the craton physically develop only in domains where temperatures exceed 300 °C, above which quartz deforms plastically. The deformation has components of both pure and simple shear, resulting in folding of the shear fabric after formation. Note that the temperature at point X in the craton increases with movement on the thrust plane.

commences with the plastic flow of quartz at 300 °C, and so, fabrics start forming at any point in the craton as soon as this temperature is crossed. Since the 300 °C isotherm also migrates westward with movement on the thrust, foliation development in the cratonic interior is correspondingly late. Concomitant with the westward migration of isotherms, cratonic domains in the proximity of the EGMB unit experience increasing temperatures. The easternmost orthogneisses in the windows, which preserve the earliest fabrics in the craton, therefore also record the highest metamorphic temperatures. It appears that migration of thermal fronts (in this case, the 300 °C isotherm) with movement on the thrust plane leads to later fabric formation in the internal parts of the footwall. This isotherm therefore acts as a 'deformation front' (Gray and Mitra, 1993), a conceptual instantaneous spatial boundary between rocks undergoing different stages of deformation. Migration of such deformation fronts may be a characteristic feature of footwall evolution during hot over cold thrusting.

The final phase of deformation, characterized by folding across the trends of earlier axes in orthogneisses of the windows, is attributed to a change in the movement direction during the final stages of thrusting. This would also account for the differing foliation distribution pattern in the foreland. A schematic cross-section, representing the structural development in the craton with progressive movement on the thrust, is shown in Fig. 7.

4.4. Geodynamic setting and the Antarctica connection

A major conclusion from this study is that the EGMB–Bastar craton contact is tectonic, represented by a ductile shear zone that transported hot granulites from the lower crust and juxtaposed them against upper crustal rocks of the craton. The discontinuity must therefore extend through the entire crust. Across the discontinuity, the two units differ in lithology, structure and P–T-deformation history, in keeping with earlier suspicions of the contact being a suture zone (Gupta et al., 2000). The EGMB–Bastar craton boundary is therefore interpreted as the site of an ancient continent–continent collision.

The 980–920 Ma ages in the EGMB have been attributed to the collision of India with a fragment of the Antarctica, following the closure of an ocean basin located to the south of the northern Prince Charles Mountains in east Antarctica (Kelly et al., 2002). An assumption of this model is that the Eastern Ghats, along with the Napier and Rayner Complexes of the Antarctic, had already accreted to the Indian craton prior to the Grenvillian orogeny. This earlier accretion may correspond to the 1600 Ma granulite event.

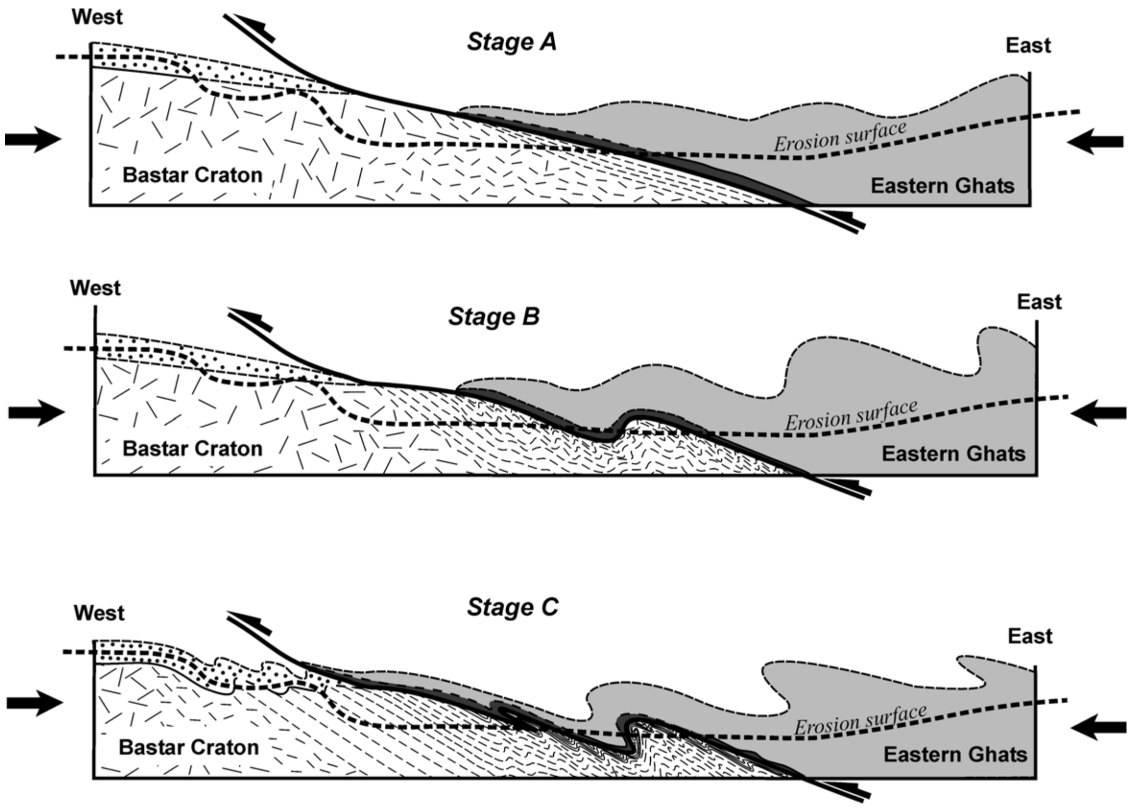

Fig. 7. Cartoon depicting the structural evolution of the footwall (Bastar Craton) with continued movement of the thrust sheet (Eastern Ghats Unit). Emplacement (Stage A) and folding (Stage B) of the thrust sheet lead to early fabric formation and folding close to the contact while the interior is undeformed. Stage C represents continued westward translation of the thrust sheet into the craton with a change in movement direction, during which fabric-formation takes place in the interior while earlier fabrics are cross-folded.

However, the deformation of Chhatisgarh Supergroup sedimentary rocks during this event precludes such a possibility. K–Ar dating of authigenic glauconitic minerals from sandstones in the basal part of this succession yield ages of 700–750 Ma (Kreuzer et al., 1977). Deformation of these rocks must then be Neoproterozoic. In this context, it is worthwhile to recall that a Pan-African thermal disturbance (Shaw et al., 1997; Mezger and Cosca, 1999; Rickers et al., 2001) is also recorded in the EGMB. This age has yet to be correlated with any specific tectonic event. If this corresponds to a collision with the craton, then it must correlate with a granulite facies metamorphic event, which can only be confirmed through radiometric dating of the EGMB unit and the cratonic fringe zone of the present area. If verified, this would suggest that amalgamation of the Indian craton into the Indo-Antarctic supercontinent took place considerably later than previously assumed.

5. Conclusions

The contact between the EGMB and upper crustal rocks of the Bastar craton is an easterly dipping thrust with a top-to-the-west sense that emplaced hanging wall granulites onto the cratonic footwall. The process was synchronous with granulite facies metamorphism in the EGMB, implying that the discontinuity extended through the entire crust and that crustal-scale stresses operated during amalgamation. Fabrics in the craton developed progressively later in the west as isotherms migrated into the foreland with continued movement on the thrust. This sequential fabric formation in the footwall is interpreted as an outcome of 'hot over cold' thrusting, and may represent a general criterion characteristic of the phenomenon. Precise radiometric dates for the region are not available, but deformation of possibly Neoproterozoic Chhatisgarh Supergroup sediments in the cratonic foreland suggests that incorporation of the craton into the Indo-Antarctic supercontinent took place in the Pan-African.

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