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ORIGINAL PAPER

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Emplacement of Proterozoic massif-type anorthosite during regional shortening: evidence from the Bolangir anorthosite complex (Eastern Ghats Province, India)

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Abstract A study of the 933 ± 32-Ma-old Bolangir massif-type anorthosite complex (Eastern Ghats Province, India) yielded strong evidence for anorthosite emplacement during regional shortening, and thereby new insights in massif-type anorthosite formation. Several lines of evidence strongly suggest synchronism of plutonism and regional deformation. First, structures in the country rocks, which imply N–S-directed shortening accompanied by E–W extension, are mirrored by a E–W trending post-magmatic foliation and N–S trending shear zones in the anorthosite complex. Near the intrusion, the foliation in the country rocks becomes parallel to the contact and an internal marginal foliation, and foliation triple points occur in the country rocks. Second, synshortening dikes inside and outside the anorthosite complex are filled with pluton-related melts. Third, ferrodiorites, which are considered late-stage differentiates of the anorthositic pluton, concentrate in tectonic voids at the pluton margin. Some of these occurrences have been affected by the last increments of the regional deformation, but others transect the same structures. Ascent mechanism and significance of the adjacent terrane boundary of the Eastern Ghats Belt for ascent and emplacement of the Bolangir anorthosite complex are discussed. The results of this study imply that emplacement of Proterozoic massif-type anorthosite is not restricted to extensional settings.

Keywords Massif-type anorthosite · Diapir · Pluton emplacement · Eastern Ghats · India

Introduction

Massif-type anorthosites constitute a distinct component of many Proterozoic crustal provinces, which usually is accompanied by contemporaneous intermediate to felsic igneous rocks. In consequence, the terms anorthosite–adamellite complex (Emslie 1978), respectively, anorthosite–mangerite–charnockite–granite suite (Emslie and Hunt 1990) were introduced. The observed bimodality of magmatism led many workers to assume the formation and emplacement of massif-type anorthosite in a rift-like anorogenic setting (summarized in Ashwal 1993). However, recent investigations in the Grenville province, where numerous anorthosites occur, concluded that anorthosite magmatism was induced by orogenic processes (McLelland et al. 1996; Corrigan and Hanmer 1997). According to McLelland et al. (1996), anorthositic complexes formed after crustal thickening and subsequent delamination of the subcontinental lithosphere during orogen collapse. Corrigan and Hanmer (1997) envisaged the formation of anorthosite complexes in extensional domains of the orogen core while the orogen was still in an overall converging setting, and invoqued convective removal of the lithosphere as a potential mechanism to generate the necessary heat in the upper mantle. Likewise, Scoates and Chamberlain (1997) proposed emplacement of the Horse Creek anorthosite complex (Wyoming, USA) during late- to post-orogenic transtension.

The present study, however, provides evidence for the emplacement of massif-type anorthosite during regional compressive deformation in the Proterozoic Eastern Ghats Province of India. This has important implications for massif-type anorthosite formation as it rules out that anorthosite emplacement was restricted to extensional environments.

Geological setting

The Eastern Ghats Province

The Eastern Ghats Province (Dobmeier and Raith 2003) is an anorthosite-bearing granulite terrane that borders

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several Archean crustal segments of peninsular India (Fig. 1). The Archean crust was consolidated by 2.5 Ga (Sarkar et al. 1993; Chadwick et al. 2000; Kovach et al. 2001), whereas Nd-model ages from different lithologies of the Eastern Ghats Province imply that its crust formed in Proterozoic time (Rickers et al. 2001). Lithological similarities (Katz 1989), a similar crustal evolution (Mezger and Cosca 1999; Rickers et al. 2001), and combined tectonic and petrologic studies at the contact with the Bhandara craton (Gupta et al. 2000) strongly suggest that the Eastern Ghats Province and East Antarctica formed one crustal terrane that collided with proto-India during the global Grenvillian orogeny (Mezger and Cosca 1999; Gupta et al. 2000). The present-day surface expression of the tectonic terrane boundary is the Eastern Ghats Boundary Fault (Ramakrishnan et al. 1998).

High-precision U–Pb age data from zircon, monazite and titanite (Mezger and Cosca 1999 and references therein; Jarick 1999; Krause et al. 2001) and EPMA-dating of monazite (Simmat and Raith 1998; Dobmeier and Simmat 2002) disclosed a prolonged tectonometamorphic evolution of the Eastern Ghats Province. The reproducible part of the geological evolution started with an event of ultra-high temperature metamorphism (summarized in Sengupta et al. 1999), which may have occurred at c.1.1 Ga (Jarick 1999). The dominant orogenic event was an early Neoproterozoic orogeny at ca. 960–945 Ma (“Late Grenvillian”; Simmat and Raith 1998; Mezger and Cosca 1999 and references therein). A Neoproterozoic (790–660 Ma) period of crustal instability left its imprints only in the northeastern coastal area, which was within the stability field of granulite facies parageneses at that time (Simmat and Raith 1998; Dobmeier and Raith 2000; Krause et al. 2001; Dobmeier and Simmat 2002). Finally, most parts of the Eastern Ghats Province were affected by a Late Pan-African (~520 Ma) thermal event that reached upper amphibolite facies conditions (Mezger and Cosca 1999 and references therein, Dobmeier and Simmat 2002).

To date, massif-type anorthosite complexes are known only in the northern part of the Eastern Ghats Belt (Fig. 1). In comparison with the prominent anorthosite complexes of the Grenville orogen, a few confirmed occurrences of the Eastern Ghats Province are small. Three of them are situated close to the northwestern terrane boundary. A discordant U–Pb zircon age of 933 ± 32 Ma (2Φ) has been determined for the largest anorthosite complex at Bolangir (Krause et al. 2001). No isotope data exist for the neighbouring anorthosite occurrences at Turkel and Jugasaypatna (Fig. 1), but field relations indicate that both massifs

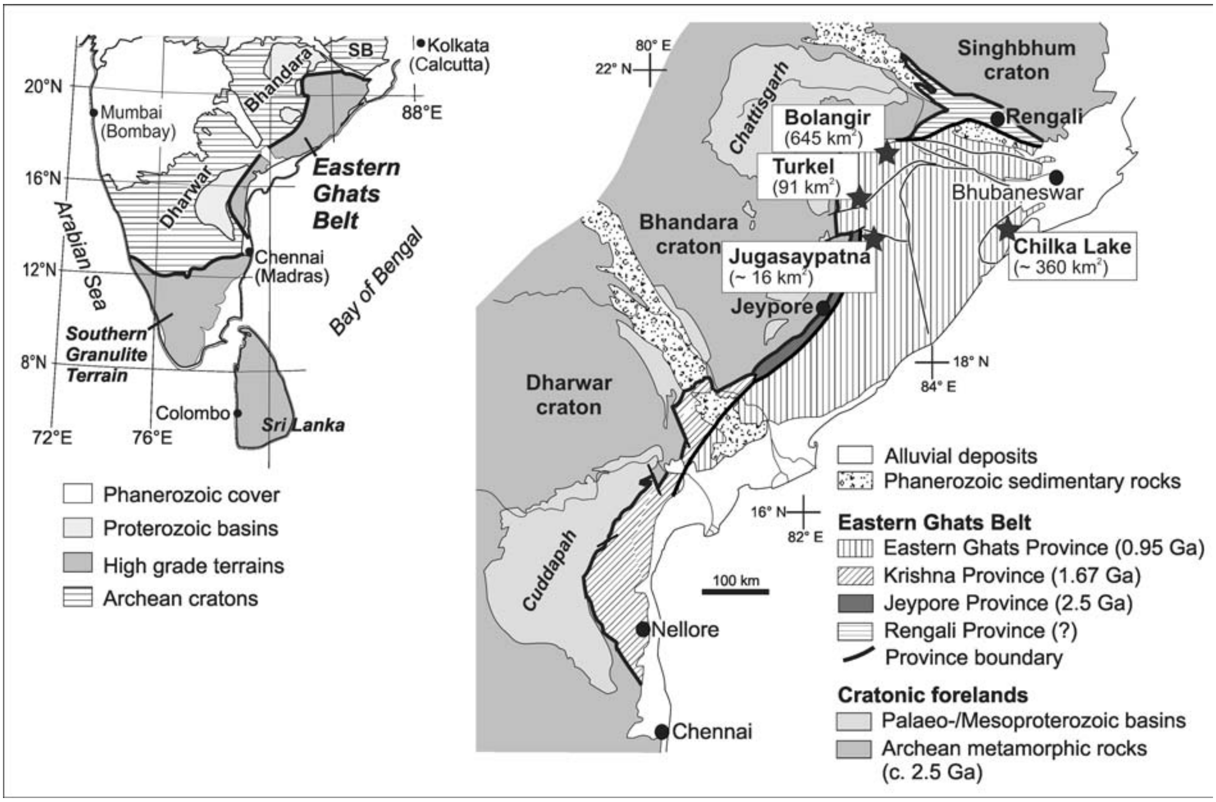

Fig. 1 Geological outline of peninsular India and internal crustal configuration of the Eastern Ghats granulite terrain following Dobmeier and Raith (2003) with age of dominant metamorphism (data compilation see text and Dobmeier and Raith 2003). *Black stars* indicate position of massif-type anorthosites

were emplaced during the Grenvillian orogeny (Maji et al. 1997; Nanda and Panda 2000). Emplacement of the solitary Chilka Lake anorthosite occurred much later at 792 ± 2 Ma (2Φ) (Krause et al. 2001).

The massif-type anorthosite complex of Bolangir

The presence of anorthositic rocks in the vicinity of Bolangir was first reported by Tak et al. (1966). Subsequent investigations largely concentrated on petrological, geochemical or geochronological aspects (Tak 1972, 1983; Mukherjee et al. 1986, 1999; Mukherjee 1989; Raith et al. 1997; Bhattacharya et al. 1998; Krause et al. 2001), although some publications briefly describe and discuss structures in the anorthosite massif and neighbouring country rocks. In contrast, the present contribution is only concerned with structural and tectonic aspects.

The fish-shaped massif covers some 645 km^2 to the east of the city of Bolangir and only 5–10 km away from the Eastern Ghats Boundary Fault, i.e. from the present terrane boundary (Figs. 1, 2, 3). It is composed of metaanorthosite and metaleuconorite. Unusual Zr and REE-rich ferrodioritic gneisses, the protoliths of which are considered late-stage differentiates of the anorthosite pluton (Raith et al. 1997; Bhattacharya et al. 1998), concentrate largely at the interface between the massif and its country rocks and constitute less than 2% of the exposed area. Ferromonzodioritic varieties probably evolved by mixing of the Fe-rich residual magmas with bordering felsic melts (Bhattacharya et al. 1998). Within the anorthosite, ferrodiorite forms dikes up to 4 m wide and 100 m long. A distinct alkali feldspar and garnet-bearing charnockitic rock ("garnetiferous granite" of Bhattacharya et al. 1998), 0.5–1 km wide, rims the anorthosite pluton entirely. This rock shows an inhomogeneous composition with local variations, such as a highly porphyritic texture or an increased garnet content. Contacts with country rocks are usually sharp, but a gradual transition into migmatitic gneisses has been observed in one locality. Locally, the garnetiferous granite is transected by a dense network of monzonitic dikes, which at places (esp. SE corner of anorthosite pluton) extend into neighbouring anorthositic rocks. Bhattacharya et al. (1998) concluded from bulk rock and isotope geochemistry that the peraluminous garnetiferous granites represent crustal melts which formed by advective heating and partial melting of country rocks bordering the anorthosite pluton. Due to this genetic linkage the garnetiferous granite is considered a component of the Bolangir massif-type anorthosite complex.

Garnet-bearing quartzites and garnet + sillimanite enriched layers ("khondalites") indicate that at least parts of the migmatitic quartzofeldspathic gneisses, that make up the majority of the country rocks, are derived from supracrustal rocks. This is corroborated by the presence of calc-silicate gneisses. Rocks with magmatic precursors (basic granulite layers and small lenses of megacrystic granite) are rare.

Deformation

Structures in the country rocks and the garnetiferous granite

The oldest planar element in the quartzofeldspathic gneisses is a migmatitic layering traced by potassium feldspar-bearing leucosomes or by restite layers in otherwise homogenized felsic gneisses (Fig. 2c, d). A pronounced compositional layering is defined by the alternation of centimetre-wide scapolite and clinopyroxene-rich layers in calc-silicate gneisses (Fig. 2a, b), which form 5–50 m wide bands that can be followed-up for several kilometres (Figs. 3, 4a), and by plagioclase- and pyroxene-rich layers in basic granulites. Sporadic intrafolial folds prove that the compositional foliation is secondary in nature. As both secondary foliations register an identic tectonic overprint wherever found together in one outcrop, they will be jointly termed as S_1 in the following. S_1 was multiplely folded during progressive regional shortening (Figs. 2, 3, 4a). The axial planar foliations (termed S_2 and S_3 for better clarity) of the close to isoclinal inclined folds are subparallel to S_1 and dip moderately to steeply to the south (Fig. 3). S_2 and S_3 formed only locally and mainly in fold hinges, and replace S_1 as pervasive foliation only in areas of increased deformation (Fig. 2c), although minerals in fold hinges are mostly aligned in the axial planar foliation. In areas under extension, the newly generated foliations and associated conjugate shears were used as sites for the emplacement of leucocratic melts in the quartzofeldspathic gneisses (Fig. 2d) respectively the deposition of mobilisates in calc-silicate gneisses (Fig. 2a) and quartzites. Near the boundary with the anorthosite complex the subparallel foliations contour the margin of the complex and dip steeply away from the margin. Similarly, a composite foliation, $S_{1\text{-}2}$, in the garnetiferous granite trends parallel to the boundary. This foliation is defined by leucosomes, aggregates of ferromagnesian silicates, trails of centimetric alkali feldspar porphyroclasts, and ribbon quartz. It is termed as composite foliation as the generally subparallel foliations, S_1 and S_2, are undistinguishable at most areas where usually tightly to isoclinally folded leucosomes are absent, and in strongly porphyritic portions, in which no folds were found at all. The long axes of the alkali feldspar porphyroclasts are mostly subparallel to the dip direction of the foliation. A weak and irregularly spaced foliation, S_4, which transects all other foliations, is axial planar to open to close folds, F_4, with E–W trending axial planes (Figs. 2a, 5). This sporadically occurring foliation can be separated from earlier foliations only in the garnetiferous granite and in country rocks near the anorthosite complex, where the orientation of earlier foliations deviates strongly from the regional trend (E–W). Especially at the contact between garnetiferous granite and country rocks, leucocratic felsic melt frequently crystallized in S_4-parallel veins (Fig. 5b).

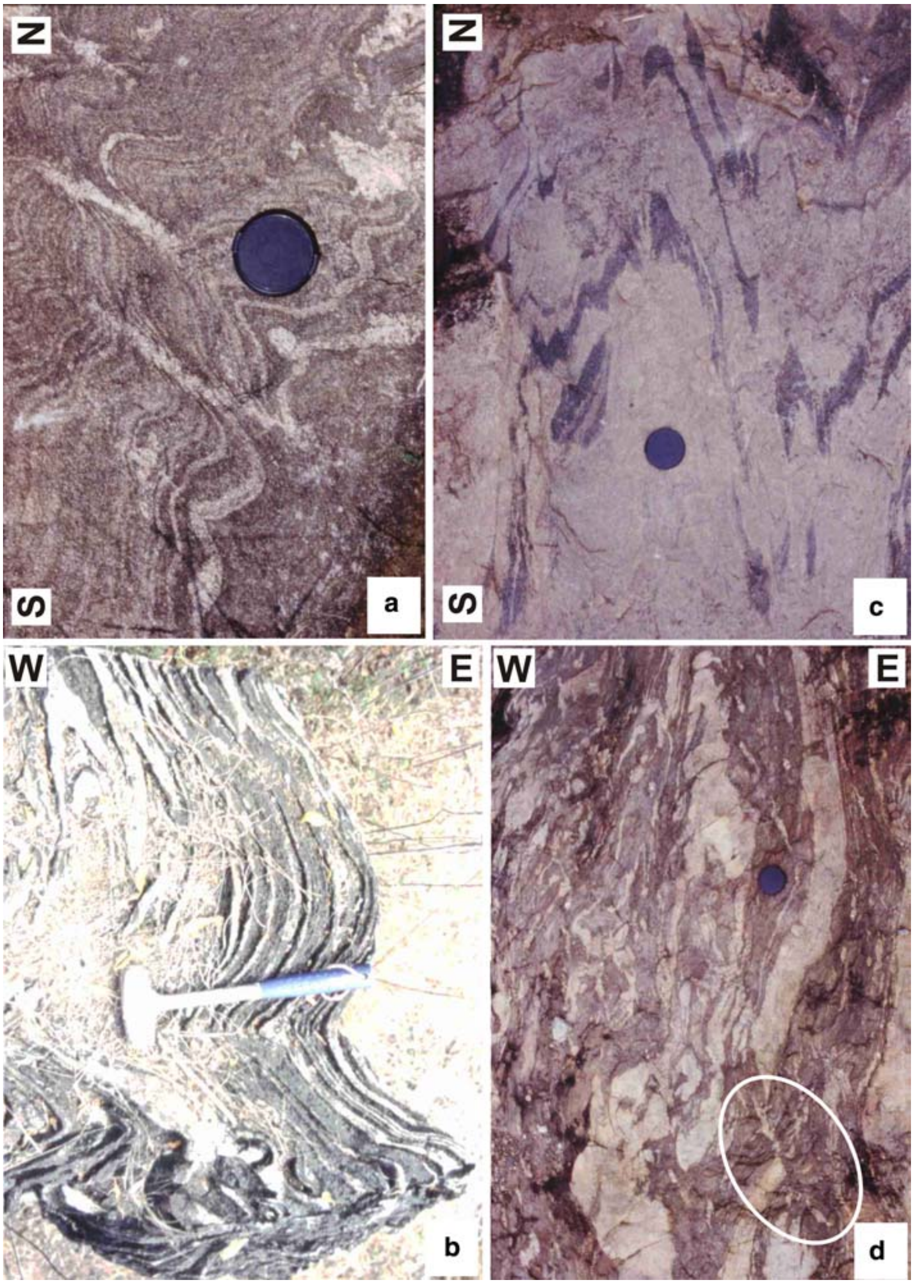

Fig. 2 Structures in the country rocks. **a** Close folding of compositional layering in calc-silicate gneisses. A steep E–W trending axial planar foliation is marked by wollastonite-rich veinlets. Side view, diameter of lens cap is 6.6 cm. **b** Open refolding with steep fold axes and E–W trending axial planes of tightly folded compositional layering in calc-silicate gneisses. Plan view, length of hammer is 30 cm. **c** Granitic gneiss containing isoclinally folded restite layers. Development of a pervasive axial planar foliation is notable in limb areas. Plan view, diameter of lens cap is 6.6 cm. **d** Intensely deformed leucosomes in migmatitic gneiss. Note renewed emplacement of leucocratic melt in areas under extension (*encircled*). Plan view, diameter of lens cap is 6.6 cm. The localities from which the photographs were taken are indicated with *black stars* in Fig. 3

Two foliation triple points are present in the country rocks about 2.5 km away from the contact with the garnetiferous granite. Although they occur in multiplely folded rocks, they cannot result from superposed folding of S_1 in the above-described environment of progressive fold tightening and coaxial refolding (compare interference pattern in Ramsay and Huber 1987). In addition, S_2 and S_3 are also reoriented. Further, all structural elements progressively steepen and become subvertical towards the centre of the western triple point (Fig. 4b; poor exposure prohibited detailed mapping of the eastern triple point). This observation is in accordance with theoretical considerations and numerical modelling of Brun and Pons (1981) who showed that the axis of finite extension is vertical in ideal triple points. In consequence, the triple points are interpreted as expressions of the interaction of regional and emplacement-related strain (Brun and Pons 1981).

To the north of the anorthosite complex, large-scale folds are missing (Fig. 3). Instead, the country rocks contain indicators of increased deformation (e.g. rootless folds, strongly flattened porphyroclasts) and the sense of shear, deduced from the asymmetry of porphyroclasts and from quartz-c-axis patterns, uniformly indicate transport of the hanging wall to the north. Probably the stronger deformation in this area relates to the proximate margin of the Eastern Ghats Province, which had to accomodate substantial deformation during thrusting of the Eastern Ghats Province on the Archean cratons of peninsular India (compare Gupta et al. 2000).

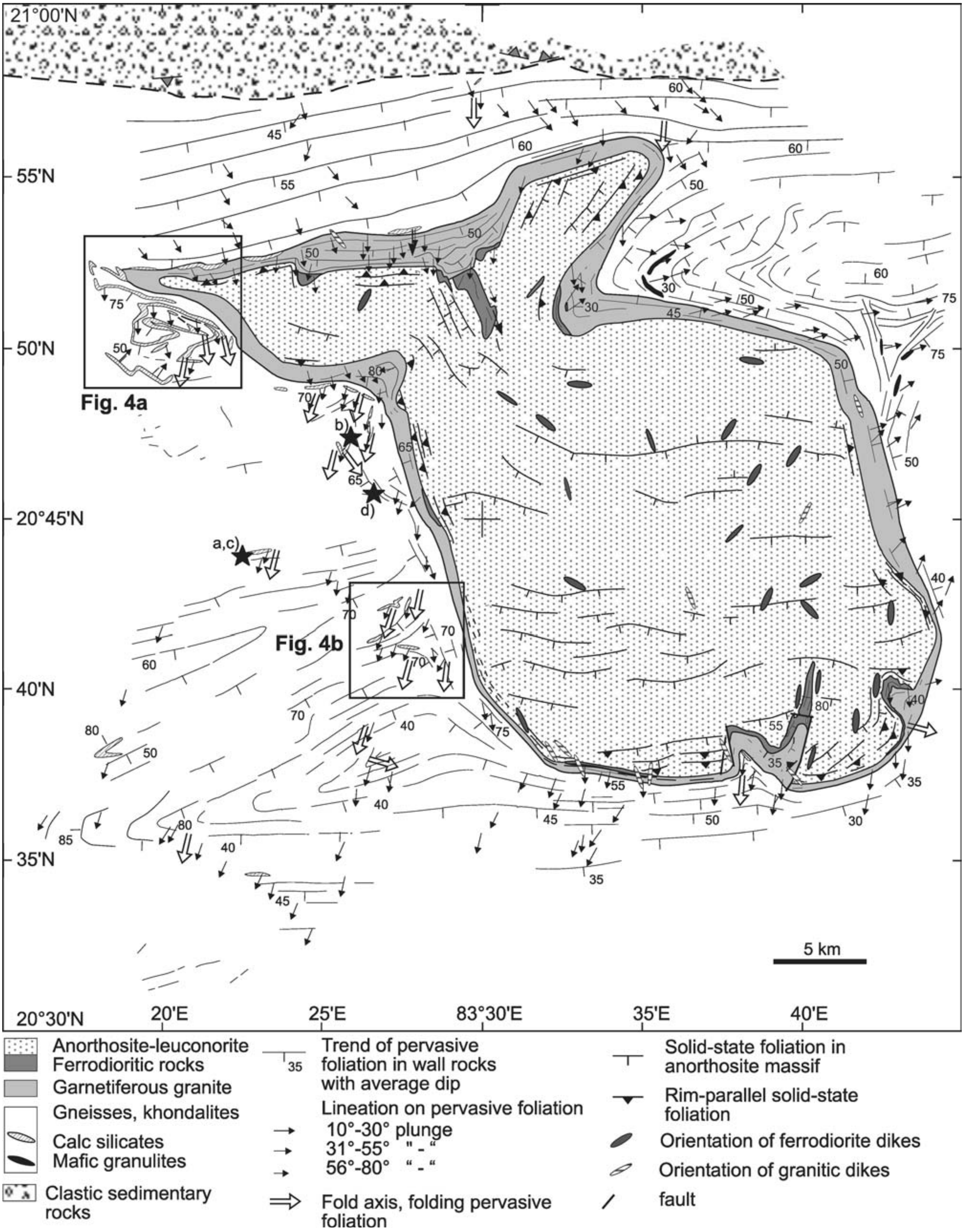

Fig. 3 Structures formed during regional deformation in and around the massif-type anorthosite complex of Bolangir. *Boxes* indicate positions of Fig. 4a, b. *Black stars* indicate localities from which photographs of Fig. 2 are taken

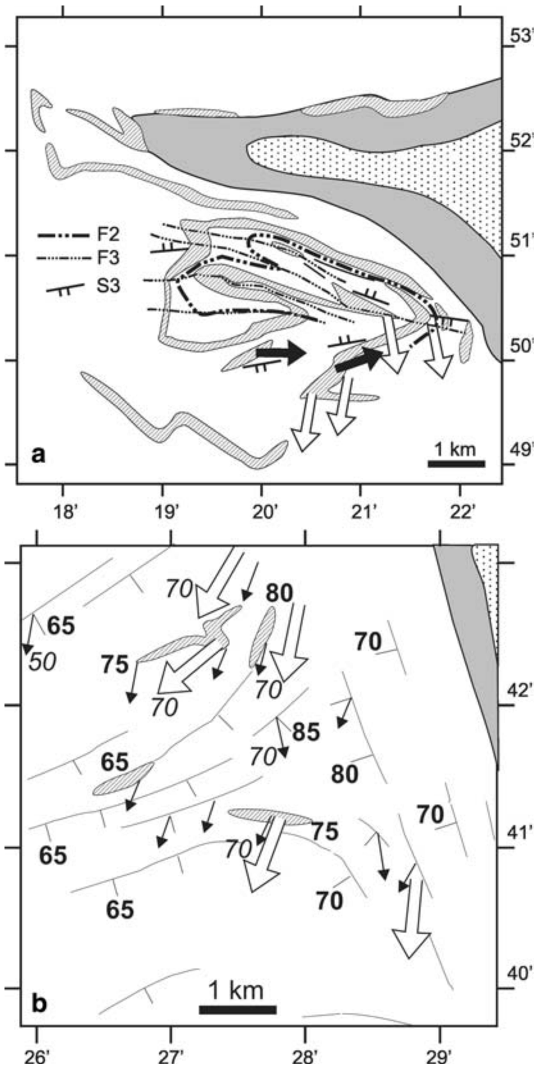

Fig. 4 Detail maps highlighting important map-scale structures. For map key see Fig. 3. **a** Calc-silicate layer exemplifying progressive fold tightening and coaxial refolding. *Black arrow* intrafolial folds, *F2* trace of axial plane of early isoclinal fold, *F3* trace of axial planes of folds which isoclinally refold the calc-silicate layer and *F2, S3* axial planar foliation of F3-folds. **b** Western triple point. Pervasive foliation and lineation are steepening towards the centre of the triple point

Most fold axes are parallel or slightly oblique to the mineral lineation present on the pervasive foliation in the country rocks. Exception to this is to the E-plunging intrafolial folds (F1) in calc-silicate gneisses (Fig. 4b) while the lineation is almost down dip. Generally, the southward or eastward plunging mineral lineation (Fig. 3) is defined by long axes of orthopyroxene, sillimanite, and garnet grains or alkali feldspar porphyroclasts.

Structures in the anorthosite complex

The principal structure in the anorthosite complex is an igneous layering shown by alternating, isomodal or modally graded, anorthosite and leuconorite layers. Rare occurrences of channel scours and truncated layers (Fig. 6a) indicate some synmagmatic disruption, or pre-consolidation deformation. Locally, settled blocks of earlier-formed anorthosite or norite disturb layering in leuconorite. The complex orientation pattern of the igneous layering (Fig. 7) is difficult to interpret. The different shapes and internal geometries of the two domal areas and the obliquity between compositional layering and the contact of the cells argue against models of a simple two-cell convection system in a rising diapir (e.g. Schmeling et al. 1988). Indeed, layering is nearly perpendicular to the contact in places and a triple point structure appears to have developed southeast of Mehermunda (Fig. 7). A more plausible explanation would be the existence of two individual plutons which were emplaced sucessively (e.g. Wiebe 1992). However, this hypothesis is difficult to test as the two domal areas do not show distinct bulk chemical compositions or structural differences. In this context it has to be pointed out that the apparent higher frequency of ferrodiorite dikes in the southeastern dome (Fig. 7) likely results from better exposure conditions.

The alignment of orthopyroxene aggregates and trails of dynamically recrystallized plagioclase aggregates define a weak, internal, post-magmatic foliation that predominantly trends E–W and dips towards S (Figs. 3, 5, 6b). Locally, a subparallel system of anastomosing small-scale shear zones (2–40 cm width) evolved. Therein, the grain size of feldspar and orthopyroxene was considerably reduced (from several centimetre down to less than 100 m) and an equigranular fabric evolved. The dynamic recrystallization of the ternary primary feldspars (mantled porphyroclasts) under decreasing temperature led to exsolution of the potassium component and the formation of small alkali feldspar grains. Long axes of rare antiperthite porphyroclasts and orthopyroxene grains, and trails of biotite flakes indicate N–S-directed elongation in relation to the shear zones.

Aggregates of orthopyroxene, plagioclase and biotite enveloping garnet and occasionally clinopyroxene grains (Fig. 6c), and centimetric to decimetric ellipsoidal orthopyroxene–plagioclase symplectites mark a strong marginal, post-magmatic foliation which contours the margin of the anorthosite pluton.

A set of N–S trending, subvertical, anastomosing, small-scale shear zones (Fig. 6d) crosscuts igneous layering and internal solid-state foliation everywhere inside the pluton. The asymmetry of mantled antiperthite ?-porphyroclasts and a subvertical mineral lineation, marked by orthopyroxene and biotite, identifies them as normal shear zones. Further, the shape of the porphyroclasts and the orientation of their long axes relative to the mineral lineation imply a component of transcurrent shear (Fig. 6d). However, these narrow shear zones are most likely the imprint of reactivation of much wider shear belts (width ca. 10 m), which are characterized by strongly aligned centimetric mafic ellipsoidal domains consisting of garnet and clinopyroxene porphyroblasts

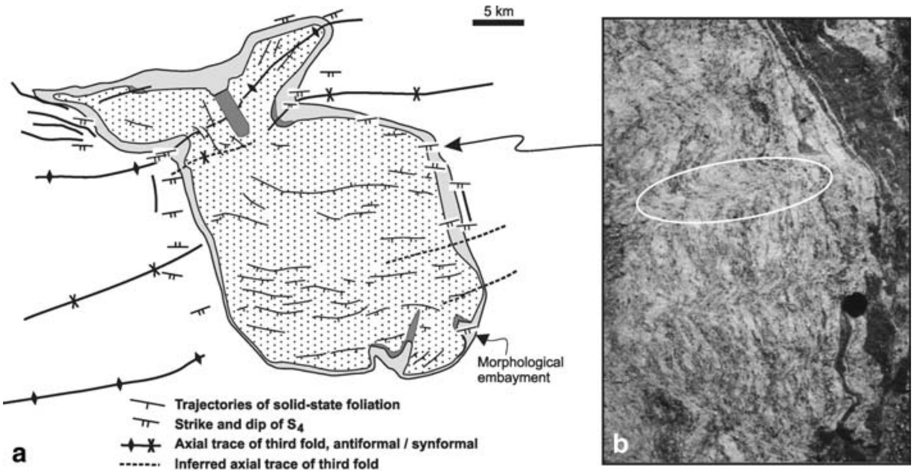

Fig. 5 **a** Trace of axial planes of large-scale late folds shown against traces of pluton-intern solid-state foliation and orientation of a weak late foliation, S_4. **b** S_4, the axial planar foliation of latest folds in garnetiferous granite, is frequently marked by leucocratic veins probably representing a melt (*encircled*). Note, that compositional banding in screens of migmatitic country rocks is parallel to the pervasive composite foliation, $S_{1\text{-}2}$, in porphyritic garnetiferous granite. Plan view, diameter of lens cap is 6.6 cm

with symplectitic rims of orthopyroxene and plagioclase. Conventional Fe–Mg exchange thermometry for garnet and clinopyroxene (Pattison and Newton 1989) yielded apparent temperatures of ca. 925–950°C. Considering the high mobility of these elements at high temperatures, even higher temperatures can be expected. Reintegration of antiperthite suggests temperatures in excess of 1,100°C for the crystallization of the original ternary feldspar. The formation of the orthopyroxene + plagioclase symplectites occurred at temperatures of c. 800°C and 0.75 GPa (deduced from calculations using TWQ 2.02, Berman 1997). The application of the two-feldspar thermometer of Kroll et al. (1993) for exsolved alkalifeldspar and host plagioclase of the narrow shear zone indicates temperatures of c. 625°C during exsolution.

Usually 40 cm to several metres wide ferrodiorite dikes within the massif trend dominantly NNE–SSW or NW–SE, at low angles to the N–S-oriented shear zones (Fig. 3). A weak foliation defined by aligned opaques and mafic minerals trends subparallel to the post-magmatic foliation in the neighbouring anorthositic rocks. Close to the margin, the marginal post-magmatic foliation is either transected by the ferrodiorite dikes or it defines the axial planar foliation of isoclinally folded ferrodiorite dikes. This clearly documents synchroneity of deformation and dike emplacement.

Ferrodiorites at the boundary exhibit a variable planar fabric that contours the contact. In the two large occurrences, which extend parallel to shear zones for several kilometres into the anorthosite (A and B in Fig. 7), the pronounced preferred orientation of plagioclase porphyroclasts and an anastomosing foliation marked by mafic minerals define a LS fabric. Deformation concentrated in rare, centimetre-wide, shear zones with drawn out and recrystallized plagioclase grains that are parallel to the foliation. Outside these occurrences, in thin ferrodiorite sheets that are intercalated between anorthosite and the garnetiferous granite, the grain size of plagioclase was considerably reduced and a compositional layering formed, which was subsequently isoclinally folded. The weaker deformation of ferrodioritic rocks in the large occurrences most likely results from their protected position within the anorthosite.

Timing of deformation and plutonism

The consistently N–S trending monzonitic dikes, which occur in anorthosite and garnetiferous granite, transect igneous layering in the pluton respectively the composite foliation, $S_{1\text{-}2}$, of the garnetiferous granite but contain the solid-state foliation respectively S_2 and are locally folded by F_2-folds in the garnetiferous granite. This indicates dike formation late during N–S shortening and thus the presence of pluton-related melt during late deformation (Table 1).

In the wedge-shaped ferrodiorite occurrence in the southeastern anorthosite complex (“A” in Fig. 7), ferromonzodioritic varieties concentrate on the eastern margin, and anorthosite sheets occur close to the western margin. This compositional asymmetry argues against the fold character of the occurrence proposed by Bhattacharya et al. (1998). As the eastern and western margins of the occurrence trend parallel to shear zones in anorthosite, it seems more probable that this occurrence represents the filling of a megascopic tectonic void that opened in response to N–S shortening.

Similarly, the large occurrence of ferrodioritic rocks at the northern pluton margin (“B” in Fig. 7) is interpreted as filling of a tectonic void that opened during late regional folding as it transects the axial trace of a F_3 antiform at almost right angles (Fig. 5). The concentration of ferrodiorites in hinges of F_3-synforms (“C” and “D” in Figs. 7, 5) additionally points to the emplacement of the ferrodioritic melts during F_3. Thus, the position of ferrodioritic rocks in the northern sector of the anorthosite complex, which is considerably affected by F_3 (Figs. 4, 5), suggests synchronism of ferrodiorite emplacement and F_3 in the country rocks.

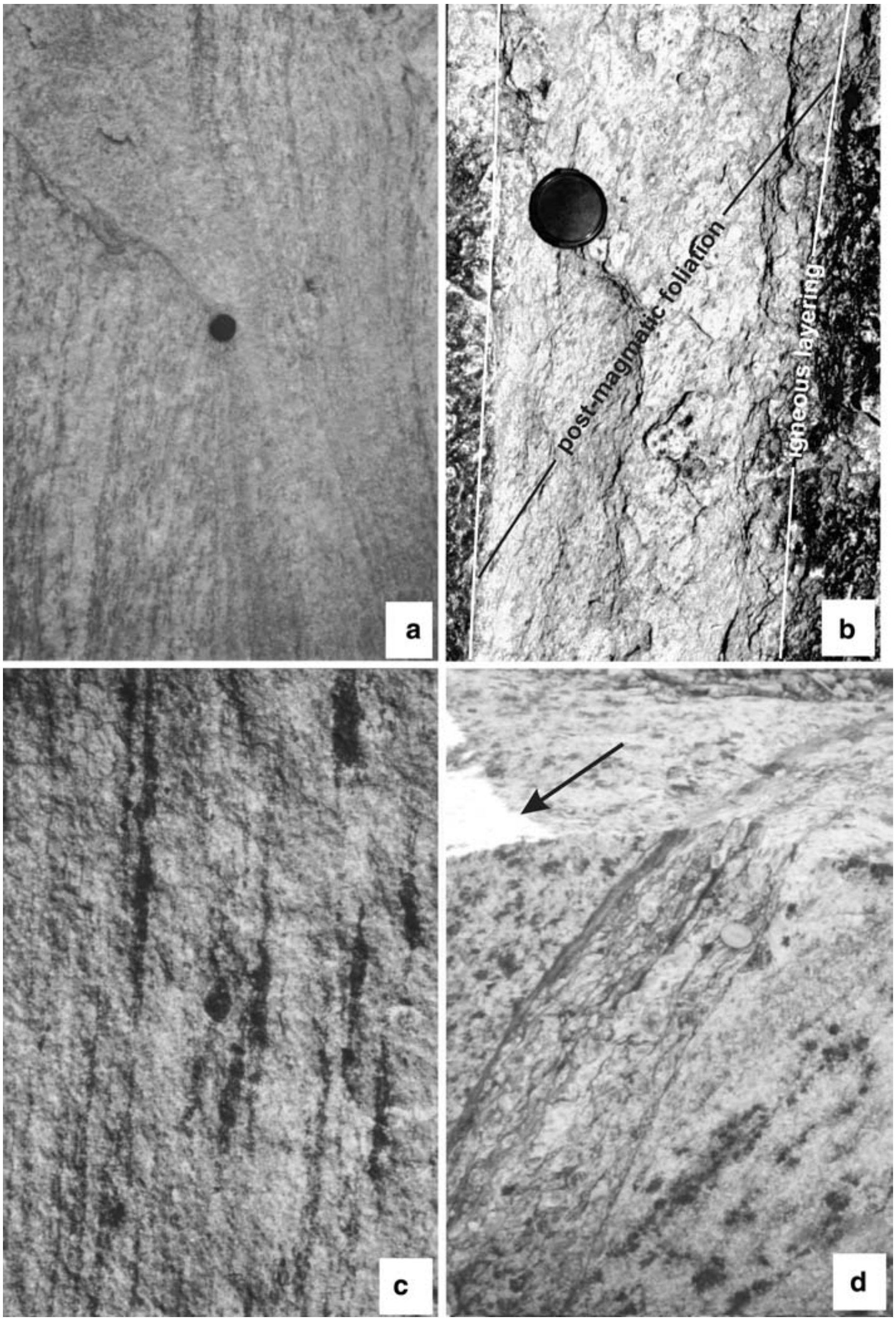

Fig. 6 Structural elements in the Bolangir anorthosite. **a** Igneous structures like channel scours indicate syndepositional disruption or pre-consolidation deformation. Plan view, diameter of lens cap is 6.6 cm. **b** An internal post-magmatic foliation is defined, among others, by the alignment of long axes of orthopyroxene grains, which are locally at high angles to the igneous layering. Diameter of lens cap is 6.6 cm. **c** Aggregates of orthopyroxene and biotite enveloping garnet grains define a rim-parallel post-magmatic foliation in the anorthosite margin. Diameter of garnet in the centre is ~1.5 cm. **d** N–S trending oblique normal shear zone in anorthosite. Diameter of coin is 2.5 cm, *arrow* indicates north direction. The localities from which the photographs were taken are indicated with *white stars* in Fig.7

In conclusion, relationships between ferrodiorites and structural elements in the anorthosite complex and the country rocks indicate emplacement of the Fe-rich residual melts preferably in extensional shears during final stages of the regional deformation (Table 1).

The association of the ferrodioritic rocks, which are late-stage differences of the anorthosite pluton, with late-stage structural elements implies emplacement of the anorthosite pluton during preceding stages of the progressive deformation. This is corroborated by the presence of a post-magmatic foliation in the anorthositic rocks which trends parallel to the regional trend of the pervasive foliation in the country rocks. Furthermore, parallelism of the marginal post-magmatic foliation in the pluton and pervasive foliations in garnetiferous granite and country rocks as well as the presence of foliation triple points suggest interaction of regional and emplacement-related strain (Brun and Pons 1981). The late, open folding of all foliations contouring the interface between anorthosite pluton and wall rock suggests that regional deformation outlasted the emplacement process. However, a later deformational event cannot be excluded.

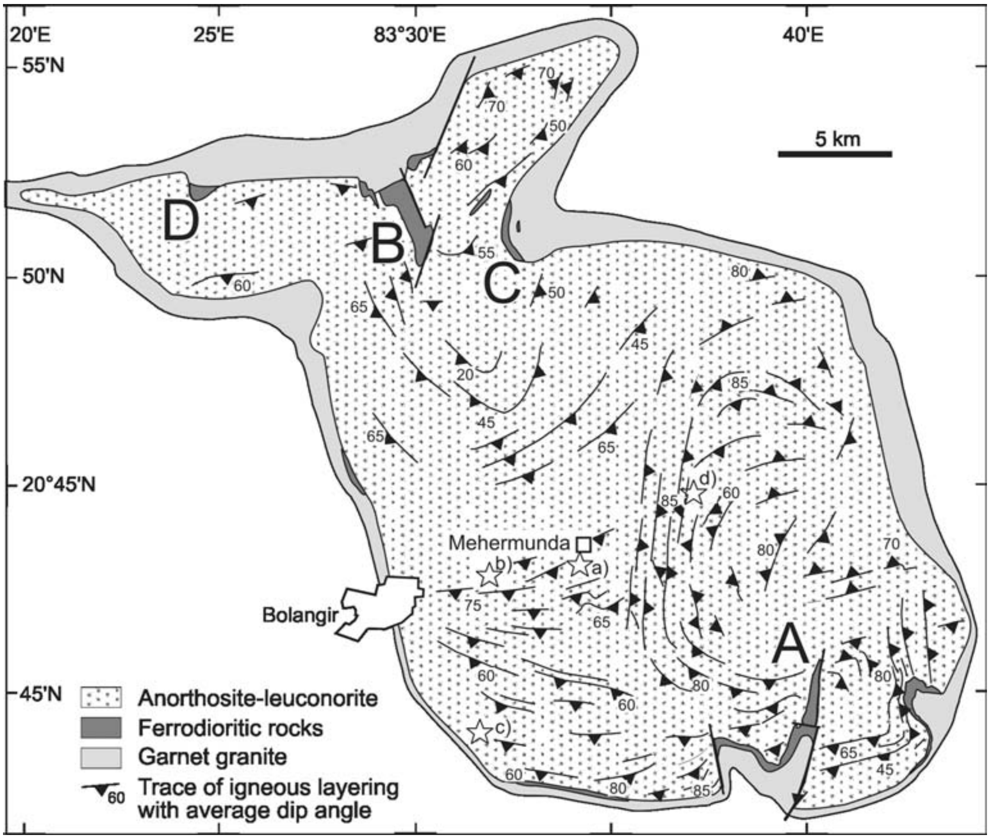

Fig. 7 Map of igneous layering in the Bolangir massif-type anorthosite complex. *A, B, C, D* Ferrodiorite occurrences mentioned in the text. *White stars* mark positions of outcrops from which photographs shown in Fig. 6 are taken

Inferences on the ascent mechanism

It is well accepted for granitic plutons that their ascent and emplacement is often controlled by crustal shear zones (Pitcher 1997; Castro et al. 1999). A similar relationship has been proposed by Scoates and Chamberlain (1997) and Duchesne et al. (1999) for individual Proterozoic anorthosites. Therefore, the proximity of the Bolangir anorthosite complex to the margin of the Eastern Ghats Belt deserves attention.

Tak (1983) concluded from a satellite imagery that "the anorthosite body is confined within two major lineaments, viz. the NE–SW trending Tel lineament and E–W trending Ong lineament" (p. 69). However, own field surveys could not confirm the Tel lineament which may be a photolineament without tectonic significance. On the other hand, the Ong lineament, which coincides with the Eastern Ghats Boundary Fault (Ramakrishnan et al. 1998), demarcates the contact of the Eastern Ghats Belt with the Archean gneisses of the Bastar craton, although a narrow and elongate sedimentary basin covers the contact (Fig. 3). The age of the non-metamorphosed clastic deposits is not constrained by fossils or radiometric data, but a Late Carboniferous age was assumed by comparison with similar rocks from the base of a coal-bearing sedimentary sequence in the Mahanadi rift (Tak 1983). The presence of the elongate basin on or at the margin of the Eastern Ghats Belt strongly suggests a period of tectonic activity in Phanerozoic time, and it is reasonable to assume that the actual contact is a Phanerozoic fault. But the strong deformation of the granulite facies country rocks (compared to the same lithologies situated further south) and the prevalent top-to-the-north shear sense in the area to the north of the Bolangir anorthosite indicate that the terrane boundary was a (several kilometres?) wide granulite facies shear zone during the Late Grenvillian orogeny. In all probability, the Phanerozoic fault results from brittle reactivation of this shear zone or part of it.

It has to be emphazized, however, that the anorthosite most likely was not emplaced in the high-strain zone, but a few kilometres away from it. In consequence, a direct control of ascent and emplacement of the anorthosite by a shear zone is not imperative. Instead, the presence of the narrow garnetiferous granite that completely encircles the anorthositic rocks permits to propose diapirism as mode of magma ascent, as the granitic melt provides a zone of highly reduced viscosity. The concomittant presence of granitic and pluton-related melts is highlighted by the formation of ferromonzonitic rocks (Bhattacharya et al. 1998).

According to Marsh (1982), the successful diapiric rise of a magma batch, which is driven by a density contrast with the country rocks, requires considerable reduction of the wall rock viscosity near the margins of a diapir. Longhi et al. (1993) inferred from the aluminium content of high-alumina orthopyroxene megacrysts that

Table 1 Structural evolution of the Bolangir area

	Country rocks	Garnetiferous granite	Anorthosite + ferrodiorite
Primary structures (not related to the regional deformation)			
	–	–	Igneous layering; syn-depositional disruption or pre-consolidation deformation indicated
Structures related to the progressive regional deformation (D1–D4)			
D1	Compositional layering (S_{CL}) and migmatitic foliation (S_1); extensive leucosome formation	–	–
D2–D3	Repeated isoclinal to open folding during N-directed thrusting accompanied by W-E extension; pervasive foliation trends W-E (regional strain) but contact-parallel near the garnetiferous granite (emplacement-related strain); formation of foliation triple points; lineation pattern resembles patterns around syn-kinematic gneiss domes	Generation/emplacement; composite $S_{1\text{-}2}$, contours the contact with the anorthosite (emplacement-related strain);Late emplacement of monzonitic dikes which propagade into anorthositeMixing of granitic and ferrodioritic magmas	Emplacement of anorthosite; post-magmatic foliation trending W–E in the interior (regional strain) but parallel to the contact near the margin (emplacement-related strain); NNE–SSW/NW–SE trending oblique normal shear zones;Emplacement of ferrodiorite at margin and in anorthosite
Late D3	Folding of interfaces between country rocks and garnetiferous granite respectively garnetiferous granite and anorthosite massif; Emplacement of ferrodiorite in fold hinges at the anorthosite margin and in dilational sites in anorthosite (Figs. 3, 7)		
D4	W–E trending weak foliation, locally melt-filled		–

Proterozoic anorthosites crystallize at temperatures of 1,100–1,275°C. (This temperature is corroborated by the composition of reintegrated alkali feldspar epipedes and plagioclase hosts to one ternary feldspar for the studied anorthosite complex.) Hence it is expected that anorthositic plutons contain sufficient excess heat to cause softening of the country rocks even at granulite facies conditions. The very high temperature of an anorthositic pluton very likely initiates partial melting of the innermost zone of the thermal aureole, thus providing a zone of highly reduced viscosity.

In the case of the Bolangir anorthosite, the width of the garnetiferous granite, which amounts to ~7% of the pluton radius (measured along the connecting line of the triple points), is in good agreement with theoretical considerations on the width of the zone of highly reduced viscosity (Marsh 1982). Thus, the garnetiferous granite is interpreted as a diapir-enclosing zone of highly reduced viscosity, in which material can flow from above the diapir downwards to fill the volume vacated by the rising diapir (“mass transfer zone” cf. Paterson and Vernon 1995) while the diapir occupies the newly gained volume atop its previous position. The fact that shear sense indicators in the garnetiferous granite do not exclusively indicate downward flow is explained by subsequent folding due to flattening of the garnetiferous granite during emplacement of the anorthosite complex.

The envisaged model of zonal melting ahead of a rising diapir combined with downward transport of the mobilized wall rocks ensures volume permanence, i.e. no volume problem arises. This continuous process ceases only when (1) isostacy is achieved, (2) the temperature difference between diapir and country rocks no longer allows partial melting of the latter, or (3) the diapir stops to behave as a rheologic liquid.

The mean density of the Bolangir anorthosite was calculated from modal rock composition averages for anorthosite, leuconorite and ferrodiorite, albeit for mineral densities at 0.001 kb and 25°C (taken from Tröger 1982). The volumetric proportions of anorthosite, leuconorite and ferrodiorite (49/49/2 vol%) were estimated from field observation. Rock densities for country rocks were calculated in the same way. The calculations yield a mean density of 2.82 g cm^{-3} for the anorthositic pluton (including ferrodiorites) and mean densities of 2.86–3.05 g cm^{-3} for different types of quartzofeldspathic country rocks. The high densities of the country rocks result from their restitic character and considerable contents of hypersthene, Fe-rich garnet and sillimanite. The present leucosomes (5–15 vol%) with a mean density of ~2.60 g m^{-3} reduce the mean density of the mostly migmatitic country rocks only slightly (~0.03 g m^{-3}). The calculated data, which agree well with measured data drawn from the literature (Feininger 1993), imply that the anorthositic pluton was still slightly buoyant at its emplacement level. As the mean density of a basic lower crustal (gabbronorite, Duchesne et al. 1999) or uppermost mantle (high-Al tholeiite, Ashwal 1993; Bhattacharya et al. 1998) source rock is considerably higher (> 3.15 g m^{-3}), diapirism aided by thermally reduced viscosity in the wall rocks closest to the diapir seems to be a very efficient ascent mechanism. The strength of the covering rock should be considerably reduced by latent heat of the anorthositic pluton.

Geothermobarometric data have been published only for ferrodiorites (Raith et al 1997; Bhattacharya et al. 1998). Accordingly, these rocks were equilibrated at 750–800°C and 7–8 kb after their emplacement. Own data for samples from the garnetiferous granite and anorthosite samples containing garnet with orthopyroxene + plagioclase symplectites yielded similar p,T-conditions for post-kinematic reequilibration. Migmatization of the country rocks took place largely during initial stages of the regional deformation (syn-S_1 and S_2), but late leucosomes (syn-S_4) formed especially near the contact with the garnetiferous granite. The presence of foliated monzonitic dikes, which transect the margin of the anorthosite undisturbed, implies that the anorthositic pluton was stationary during closing stages of the deformation, although partial melting of garnetiferous granite and adjacent country rocks was still possible. From this and the density calculations, it is concluded that further ascent was inhibited when the diapir was largely solidified. As stated earlier, a prerequisite of diapirism is the existence of a thin continuous layer of molten country rocks at the diapir margin. This layer is maintained as long as sufficient heat of the diapir is transported to its margin. Advanced solidification of the diapir, however, prevents internal convection, which is the most efficient mechanism for heat transport in igneous diapirs. The inefficiency of the remaining conductive heat transport leads to solidification of the country rocks at the diapir margin which ultimately inhibits further ascent of the diapir.

Although diapirism has been strongly criticized, it has to be pointed out, again, that the temperature of an anorthositic melt is in excess of at least 1,100°C, depending on the plagioclase composition (Longhi et al. 1993). If such a melt was transferred to mid-crustal levels, a severe imprint on the country rocks had to be observed, e.g. the presence of ultra-high temperature assemblages like spinell + quartz or sapphirin + quartz. Further, it can be expected that plagioclase crystallization from the melt during ascent results in zoned crystals. However, plagioclase is generally unzoned in Proterozoic massif-type anorthosites (Ashwal 1993). This observation in combination with the required ultra-high temperatures led petrologists to conclude that (a) this type of anorthosite formed as cumulates at the crust–mantle boundary or within the lowermost crust and (b) their ascent started only after crystallization (Ashwal 1993).

At present, granites serve as a model case for the ascent of magmas. Unfortunately, little work has been done on anorthosites. Royse and Park (2000) numerically modelled the ascent of anorthosite in self-propagating dikes and found that it was well possible to transport anorthosite in narrow conduits. However, they assumed a partially molten system, which is in contrast to petrological evidence. Barnichon et al. (1999) concluded from their numerical modelling, which was based on a field study of the Egersund-Ogna anorthosite massif in South Norway, that diapirism is a viable ascent mechanism.

The main problem with Proterozoic massif-type anorthosites is that they are largely solid during ascent. The melt fraction, as estimated from the modal amount of mafic minerals, varies considerably from pluton to pluton and can be close to nil, but generally does not exceed 25%. However, some of the mafics, the so-called high-alumina orthopyroxene megacrysts (e.g. Barnichon et al. 1999), crystallized together with plagioclase at great depth. Current models for magma propagation require much higher melt fractions, although the existence of a rheologically critical melt proportion (Arzi 1978) is disputed (Rosenberg and Handy 2005).

Still, the question remains, how a largely solid diapir can ascent as internal convection is required for heat transport to the margins. A key to understand the process may be the heterogeneous distribution of the mafics within a pluton. In Bolangir, orthopyroxene often concentrates at the contacts of modaly distinct layers, thus forming several centimetre-wide melanorite to pyroxenite layers. These layers are interpreted as layer-parallel melt "films", which enabled pluton-internal movements. At the same time, temperatures are high enough to allow dynamic recrystallization of plagioclase.

Discussion and conclusions

New tectonic models for the Grenville orogen explain the presence of impressive volumes of mantle-derived magmas in the internal collision zone by large-scale delamination of both lower crust and mantle lithosphere (McLelland et al. 1996) respectively convective removal of the mantle lithosphere (Corrigan and Hanmer 1997) of the overthickened orogen and heating of the newly exposed crust base through influx of hot asthenosphere. This leads to regionally extensive ponding of high-Al tholeiitic magmas and, after fractional crystallization, formation of plagioclase-rich (anorthositic) plutons which subsequently ascent and intrude the middle crust in extensional domains of the orogen. The ponding of the high-Al tholeiitic magmas at the crust–mantle boundary causes partial melting in the lowermost crust and the formation of voluminous felsic plutons that ascent together with the anorthositic plutons. This results in the formation of enormous anorthosite–mangerite–charnockite–granite complexes which consist of several anorthositic and granitic intrusions. Such complexes cover ~20% of the interior magmatic belt of the Grenville orogen. The non-anorthositic proportion exceeds 30% in some complexes.

The data obtained in this study, however, provide evidence that the Bolangir anorthosite complex was emplaced synkinematically in a compressive deformation regime near the terrane boundary. This is concluded from the obvious contemporaneity of magmatism and deformation. Further more, massif-type anorthosites in the Eastern Ghats Belt occupy less than 1% of the total area, and are not accompanied by voluminous felsic intrusives. These important differences stand against the transferability of the models for anorthosite formation in the Grenville orogen on the anorthosite complexes of the Eastern Ghats Province.

The proximity of the Bolangir anorthosite complex to the margin of the Eastern Ghats Province corroborates observations from other anorthosite provinces in which anorthosites are frequently associated with terrane boundaries and other crustal discontinuities (Scoates and Chamberlain 1997; Duchesne et al. 1999). Based on this relationship and extensive research on the Rogaland anorthosites, South Norway, Duchesne et al. (1999) proposed the crustal tongue-melting model. Accordingly, the generation of the parental melts took place in the tapering bottom part of a mafic lower crustal wedge which resulted from lithospheric accretionary wedging and crustal imbrication during collision, and a crustal- or lithosperic-scale shear zone channelled the ascending anorthosites.

Unfortunately, knowledge of the deep structure of the Eastern Ghats is very limited and deep seismic sounding has mainly been undertaken across the contacts with the Phanerozoic rifts (Nayak et al. 1998). However, gravity models for the southern and northern segments of the Eastern Ghats predict a wedge-shaped and upwards tapering high-density layer which terminates in the Eastern Ghats Boundary Fault (Kaila and Bhatia 1981; Nayak et al. 1998). If this gravity anomaly is interpreted as a remnant mantle wedge, a tectonic setting similar to the setting proposed by Duchesne et al. (1999) for the Rogaland anorthosites can be assumed for the anorthosite complex at Bolangir, with the difference that formation of the parental melts is expected in the upper portion of a lithospheric mantle wedge. In view of the continued discussion of the source area of the parental melts, production of the parental melts by adiabatic partial melting in an obducting mantle wedge remains a feasible alternative.

The significance of the Mid-Proterozoic terrane boundary shear zone (which may not be confused with the Eastern Ghats Boundary Fault which results from, most probably repeated, reactivation of the original terrane boundary in Neoproterozoic to Phanerozoic time) for the ascent of the Bolangir anorthosite complex remains undecided in the absence of appropriate geological, geophysical and geochronological data.

The presented observations and discussions are summarized as follows:

1. The emplacement of the Bolangir anorthosite complex occurred close to the tectonic terrane boundary of the Eastern Ghats Belt during regional shortening.
2. The model of Duchesne et al. (1999) for the Rogaland anorthosites is favoured as scenario for the ascent and emplacement of the Bolangir anorthosite.
3. Diapirism is proposed as ascent mechanism.

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