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Steep structure formation in the Okiep Copper District, South Africa: bulk inhomogeneous shortening of a high-grade metamorphic granite-gneiss sequence

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Abstract—Subhorizontal gneissosities and lithologies of the 1200–1000 Ma granulite-facies granite-gneiss terrane of the Okiep Copper District, South Africa, are cut by narrow, discontinuous, E-trending cusp-like and/or monoclinal structures in which the regional gneissosity has been rotated to subvertical attitudes. Closely associated migmatization and charnockitization indicates that these 'steep structures' formed during high-grade metamorphic conditions. In this paper we present a model which relates the deformational style, strain and orientation of the steep structures to bulk inhomogeneous shortening. The development of steep structures can be described as a progression from initial folding, via explosive fold amplification to the progressive obliteration of folds by a subvertical, E-trending, intensely developed transposition fabric. This fabric is parallel to the axial planes of regional-scale, open folds. Shortening in the structures is mainly accommodated by a vertical material extrusion, resulting in the commonly upward-pointing steep structure geometries and volume loss. The strain compatibility with surrounding rocks is maintained by bounding shear zones. The progressive development of steep structures illustrates the close relationship between buckle folding and the formation of internal, induced anisotropies during deformation of the high-grade metamorphic granitic gneisses. The apparent discrepancy between large-scale open folding and simultaneously developed steep structures recording large finite shortening strains is interpreted to be the result of a large component of internal layer-parallel shortening and strain partitioning. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Theoretical and experimental investigations of materials displaying non-linear strain characteristics have established that their deformational behaviour is strongly influenced both by the presence and orientation of pre-existing (intrinsic) anisotropies and by the development of induced anisotropies during deformation (e.g. Latham 1983, 1985a,b). Materials with a strong intrinsic anisotropy, such as layering or a foliation, will favour the development of folds or kinks during layer-parallel plane-strain shortening. In contrast, relatively homogeneous materials which lack an intrinsic anisotropy cannot achieve shortening by buckling and, as a result, are likely to develop induced anisotropies in the form of regularly oriented fabrics or conjugate shear zones or faults (Latham 1985a,b, Price & Cosgrove 1990). Once initiated, induced internal instabilities such as shear zones are likely to be amplified owing to the strain-rate softening effect commonly associated with non-Newtonian materials (Ramsay & Huber 1987).

In this paper, we report on unusual cuspate structures found in a granulite-facies, granite-gneiss terrane in the Okiep Copper District, South Africa, which suggests that: (a) strain behaviour in the high-grade granite-gneisses incorporated both (buckling) folding and the generation and amplification of intense induced anisotropies; and (b) the development of the induced anisotropies was critically dependent on the initial development of the (buckle) folds. We attribute this transitional behaviour to the combined effects of a lack of large-scale variation in the rheology of the granite-gneiss sequence owing to similar mineralogy of the lithologies and the prevailing high-grade metamorphic conditions, and the presence of a well-developed foliation (intrinsic anisotropy) through much of the sequence. The inferred deformation is one of bulk inhomogeneous shortening.

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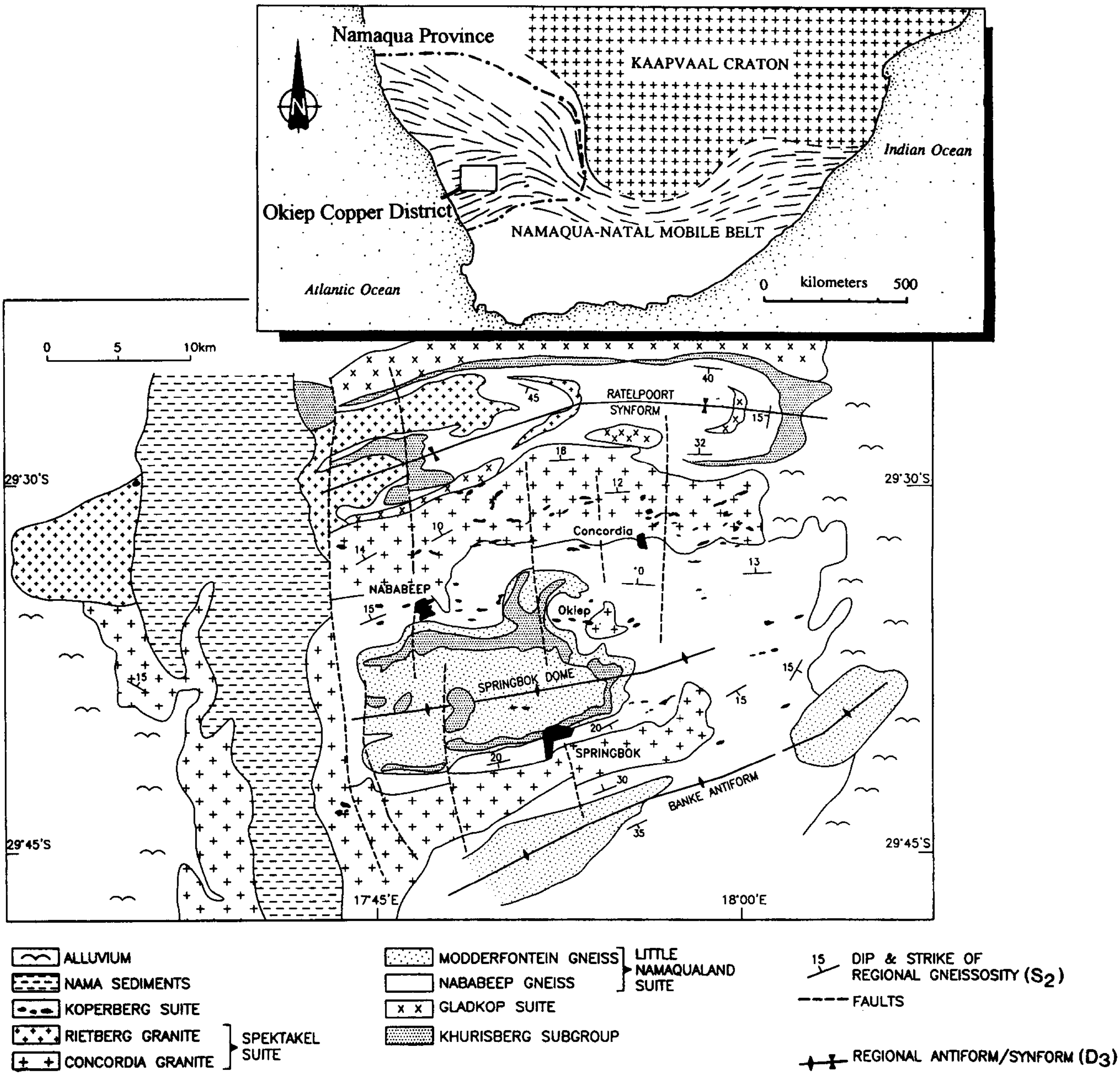


Fig. 1. Simplified geological map of the Okiep Copper District (modified from maps of the O'okiep Copper Company). Inset map shows the location of the Okiep Copper District within the tectonic framework of southern Africa (after Tankard *et al.* 1982).

REGIONAL GEOLOGY

The Okiep Copper District is a well-known copper-mining region, some 2500 km^2 in extent, situated around the town of Springbok in the Northwest Cape Province of South Africa (Fig. 1). Geologically, it is located in the Namaqua Province (Joubert 1971, 1986a,b), which forms part of the extensive Namaqua–Natal orogenic belt bordering the southern and southwestern margins of the Kaapvaal Craton of southern Africa. The Namaqua Province is subdivided into several tectonostratigraphic terranes that experienced a prolonged history of tectonism, metamorphism and plutonism, commencing with the 1700–2000 Ma Orange River event (Reid 1977, Blignault *et al.* 1983) and culminating in the Namaqua event at 1000–1200 Ma (Nicolaysen & Burger 1965, Clifford *et al.* 1975a, Barton 1983) (Fig. 2). The Province was subsequently rejuvenated along its western and southern margins during the late-Precambrian to Cambrian (*ca* 900–500 Ma) Pan-African orogeny (Allsopp *et al.* 1979, Joubert 1986a,b).

The Okiep Copper District is located within the high-grade southwestern portion of the Namaqua Province. Lithologically, it is dominated by an assemblage of compositionally stratified granitic orthogneisses and granites which intrude an older gneiss and supracrustal sequence (Clifford *et al.* 1975a, Joubert 1986a,b) (Fig. 1). The latter consists of the Gladkop Suite and the metavolcanosedimentary Khurisberg Subgroup that occur as large rafts and xenoliths within the younger orthogneisses and granites. The approximately 4-km thick granite-gneiss sequence is dominated by augen gneisses of the *ca* 1200 Ma Little Namaqualand Suite (Nababeep and Modderfontein Gneisses), and the

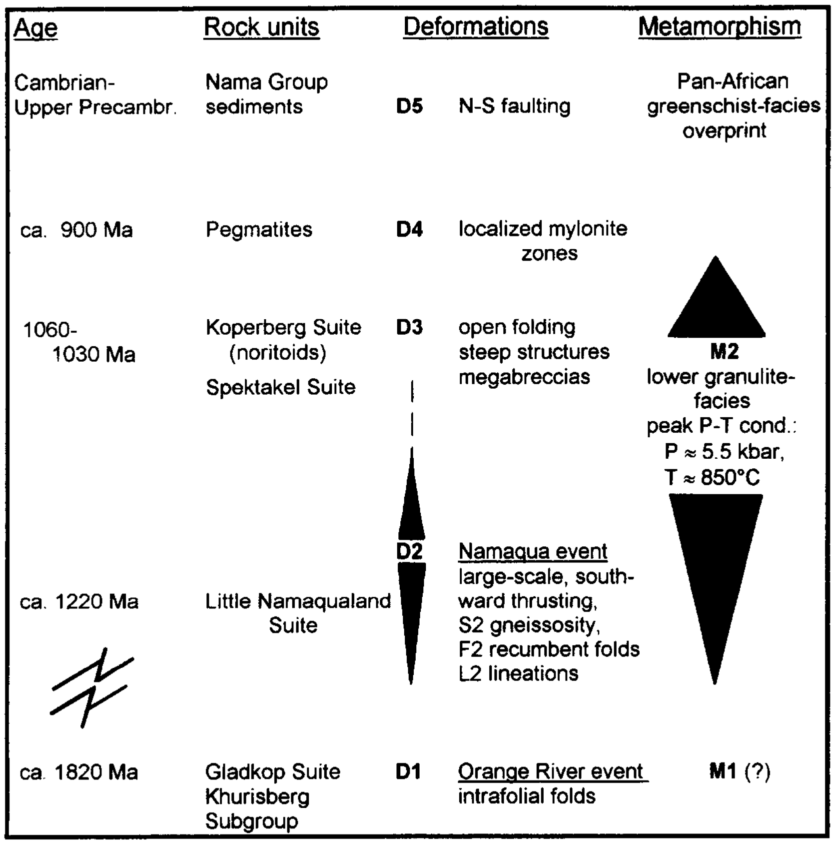


Fig. 2. Summary of the structural and metamorphic events in the Okiep Copper District (compiled from Clifford *et al.* 1975, 1995, Lombaard *et al.* 1986; Robb *et al.* unpublished data).

younger granites of the 1060–1030 Ma (Robb *et al.* unpublished data) Spektakel Suite (Concordia, Rietberg and Kweekfontein Granites). Basic to intermediate rocks of the Koperberg Suite, locally termed 'basic bodies' or 'noritoids', are intrusive into the granitic gneisses. These small, irregular, dyke-, sill- or plug-like bodies are anorthositic, dioritic, noritic and hypersthenitic, and are particularly significant because the more basic members host the copper mineralization in the Copper District (Benedict *et al.* 1964, Stumpfl *et al.* 1976, McIver *et al.* 1983, Lombaard *et al.* 1986, Conradie & Schoch 1986, Cawthorn & Meyer 1993). Robb *et al.* (unpublished data) have obtained SHRIMP zircon ages of 1060–1030 Ma for these rocks. To the west, the granite-gneiss terrane of the Okiep Copper District is unconformably overlain by weakly deformed, mainly clastic sediments of the late-Proterozoic Nama Group (Fig. 1).

Two metamorphic events have been identified in the western parts of the Namaqua Province (Fig. 2). The early metamorphism, termed the M_1 or Orange River event (Blignault *et al.* 1983), is found mainly to the north of the Copper District. It has been largely obscured in the Okiep Copper District by the subsequent granulite-facies M_2 or Namaqua event (Joubert 1971, 1986a,b). Metamorphic conditions during M_2 are constrained by mineral assemblages in pelitic metasediments of the Khurisberg Subgroup and suggest an anticlockwise pressure–temperature (P–T) path during which peak metamorphic temperatures of approximately 850°C were attained at pressures of 5.5–7 kbar (Clifford *et al.* 1975a,b, 1981, Waters & Whales 1984, Waters 1988). This metamorphism gave rise to partial melting and localized intense migmatization and chanockitization of the metasedimentary and granitic gneisses (e.g. Waters 1988, Kisters *et al.* 1992a, Kisters 1993).

The regional structural grain of the Namaqua Province is E–W (Joubert 1971, 1986a,b, Blignault *et al.* 1983, Stowe 1986). Three main phases of deformation have been identified in the rocks of the Okiep Copper District. An early phase comprising tight-to-isoclinal intrafolial folds (the D_1 or Orange River event (Joubert 1971, Lombaard *et al.* 1986)) has been recognized in xenoliths of the Gladkop Suite and Khurisberg Subgroup. The most pervasive deformational phase recorded in the Okiep Copper District is the D_2 or Namaqua event, the main features of which are a pervasively developed, subhorizontal planar fabric (S_2) and a subhorizontal, broadly E-trending mineral lineation (L_2). Large- to small-scale isoclinal, recumbent D_2 folds occur locally in metasediments of the Khurisberg Subgroup. In the granite-gneisses of the Little Namaqualand and lower parts of the Spektakel Suite, the S_2 fabric occurs as a gneissic augen texture or a gneissose compositional banding. It is absent in the upper parts of the Spektakel Suite (upper Concordia Granite and Rietberg and Kweekfontein Granites), implying that these granites were emplaced late- to post-D_2. The D_2-augen textures are defined by a finer-grained quartz–biotite foliation anastomosing around coarser-grained ovoid quartz–feldspar aggregates. Progressive development from the porphyritic textures of the granitic precursors, via foliated augen textures, to strongly foliated and compositionally banded gneissic textures is locally observed on an outcrop scale, indicating that strain was heterogeneous during D_2. The L_2 lineation is defined by the preferred orientation of quartz–feldspar augen and elongated quartz grains.

The D_2 structures have been affected both by large (kilometre-scale), open, upright D_3 folds and by narrow, steeply inclined zones of high strain, known as 'steep structures'. The D_3 folds, which include the Springbok Dome and the Ratelpoort Synform (Fig. 1), are often periclinal and trend ENE. The steep structures, which are the subject of this paper, are described in more detail in the next section.

Conjugate sets of NE- and NW-trending mylonite zones of minor displacement represent the last ductile deformation (D_4) in the Okiep Copper District and are post-dated only by brittle, N-trending, subvertical, normal fault zones that show intense brecciation of country-rock gneisses (D_5) (Fig. 2). These faults also displace the late-Proterozoic Nama sedimentary rocks which unconformably overlie the granulite terrane.

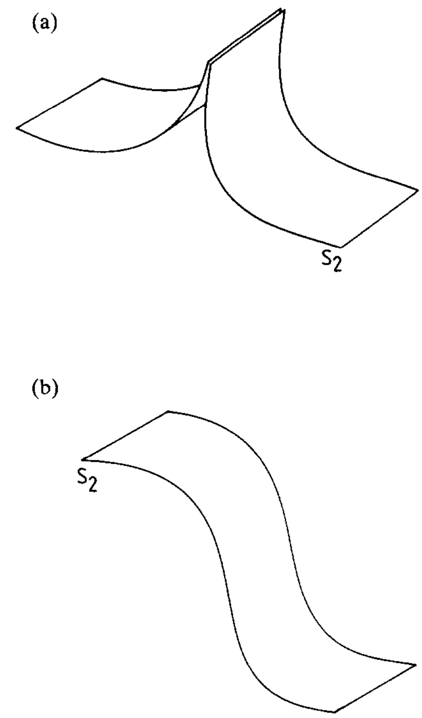


Fig. 3. Schematic illustration of the typical geometries of (a) antiformal steep structures and (b) monoclinal steep structures.

STEEP STRUCTURES

The term 'steep structure' was first used colloquially in the Okiep District to describe narrow zones in which the dominant foliation in the gneisses attained subvertical attitudes. The significance of these zones lay in the frequently observed intimate spatial relationship between them and the copper-bearing basic bodies of the Koperberg Suite (Benedict *et al.* 1964, Lombaard *et al.* 1986, Kisters *et al.* 1994). The development of the steep structures clearly post-dated the D_2 event as the S_2 gneissosity is rotated from its regional subhorizontal orientation to steeper attitudes in the vicinity of these zones. This rotation has resulted in two main geometries (Fig. 3):

(1) an antiformal geometry (Figs. 3a and 4) in which the S_2 gneissosity is steepened symmetrically, producing a cusp-like structure; and

(2) a monoclinal geometry (Fig. 3b), in which the regional gneissosity is monoclinally steepened to subvertical attitudes.

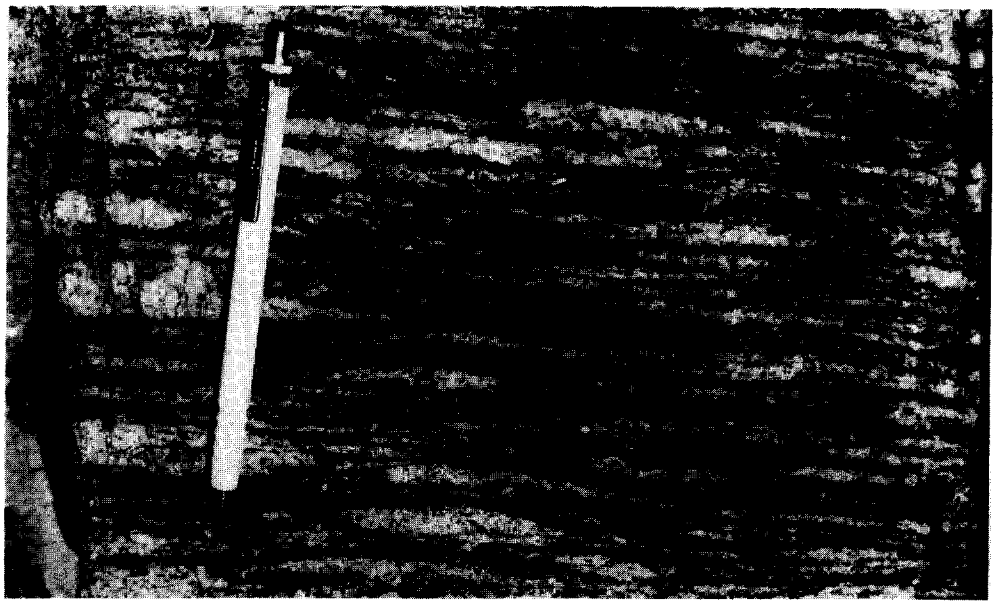
Antiformal steep structures are more common than monoclines. Both types are, however, commonly associated spatially.

The steep structures display a strong ENE trend, parallel to that of the axial traces of the large-scale D_3 folds (Fig. 6). They occur both as isolated features and as en echelon arrays. The axial traces of individual structures may be sinuous and, in some areas, trains of slightly undulating steep structures can be followed for several kilometres along strike. The largest individual structure, at Carolusberg (Fig. 6), has a strike length of 3.5 km and a known vertical extent of at least 1.6 km. In general, however, individual steep structures are of more limited lateral and vertical extent, with strike lengths typically of the order of less than 1 km and vertical extents of 200–400 m (Fig. 7). The width of the cores of the subvertical steep structures ranges from a few metres up to several hundred metres.

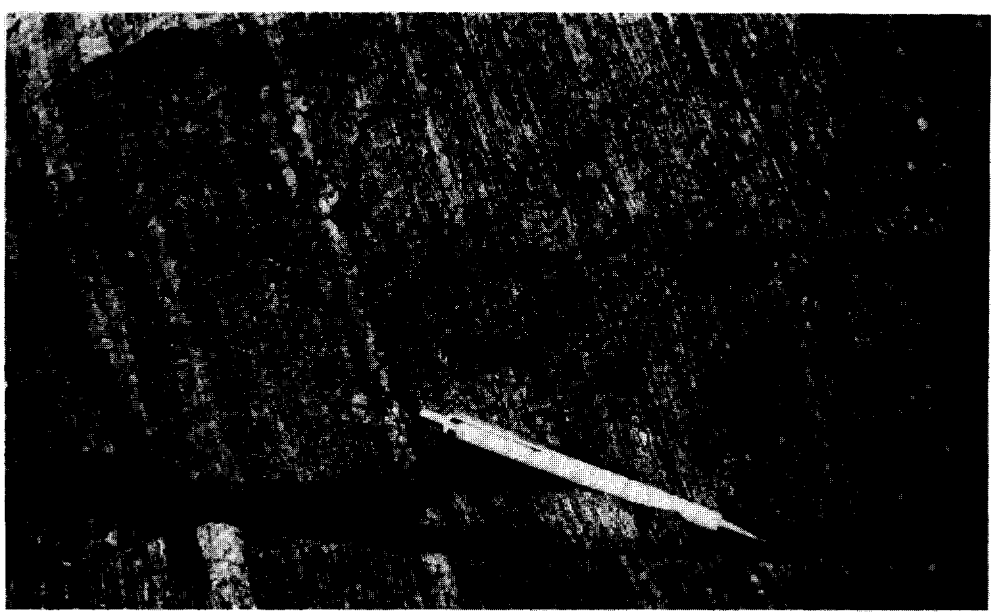
Individual steep structures commonly initiate and terminate within a single lithology, but antiformal structures can also cross-cut and pierce several gneissose units (Benedict *et al.* 1964). The structures are well developed in the foliated, syn-D_2 units of the Little Namaqualand Suite and the lower, gneissose parts of the Concordia Granite. They are, in contrast, poorly expressed or absent in stratigraphically higher, unfoliated, late-to-post D_2 granites comprising most of the Spektakel Suite (Kisters *et al.* 1992b, Kisters 1993).

Steep structures are, in places, spatially associated with transgressing migmatitic bodies (Kisters *et al.* 1992a), locally referred to as megabreccias (Lombaard & Schreuder 1978) and charnockites, indicating that the structures developed under high-grade (granulite-facies) metamorphic conditions. The central, subvertical parts of steep structures are, moreover, commonly intruded by irregular, dyke-like basic bodies of the Koperberg Suite (Lombaard *et al.* 1986). A synkinematic timing for the emplacement of these dykes during steep structure development is indicated by the evidence of: (a) granulite-facies recrystallization textures (McIver *et al.* 1983); and (b) the development of vertical planar fabrics related to steep-structure genesis (Kisters *et al.* 1994) in the dykes.

Fig. 4. Antiformal steep structure at Narrap NW (location in Fig. 6), depicting the typical antiformal upwarp of the regional gneissosity (S_2) in Nababeep Gneiss (viewed facing west).



(a)



(b)

Fig. 5. Photographs of (a) the regionally developed, augen-textured Nababeep Gneiss (S_2) and (b) intensely foliated Nabebeep Gneiss in the centre of the Bloustasie steep structure illustrating the D_3 flattening of regional textures localized within the cores of steep structures.

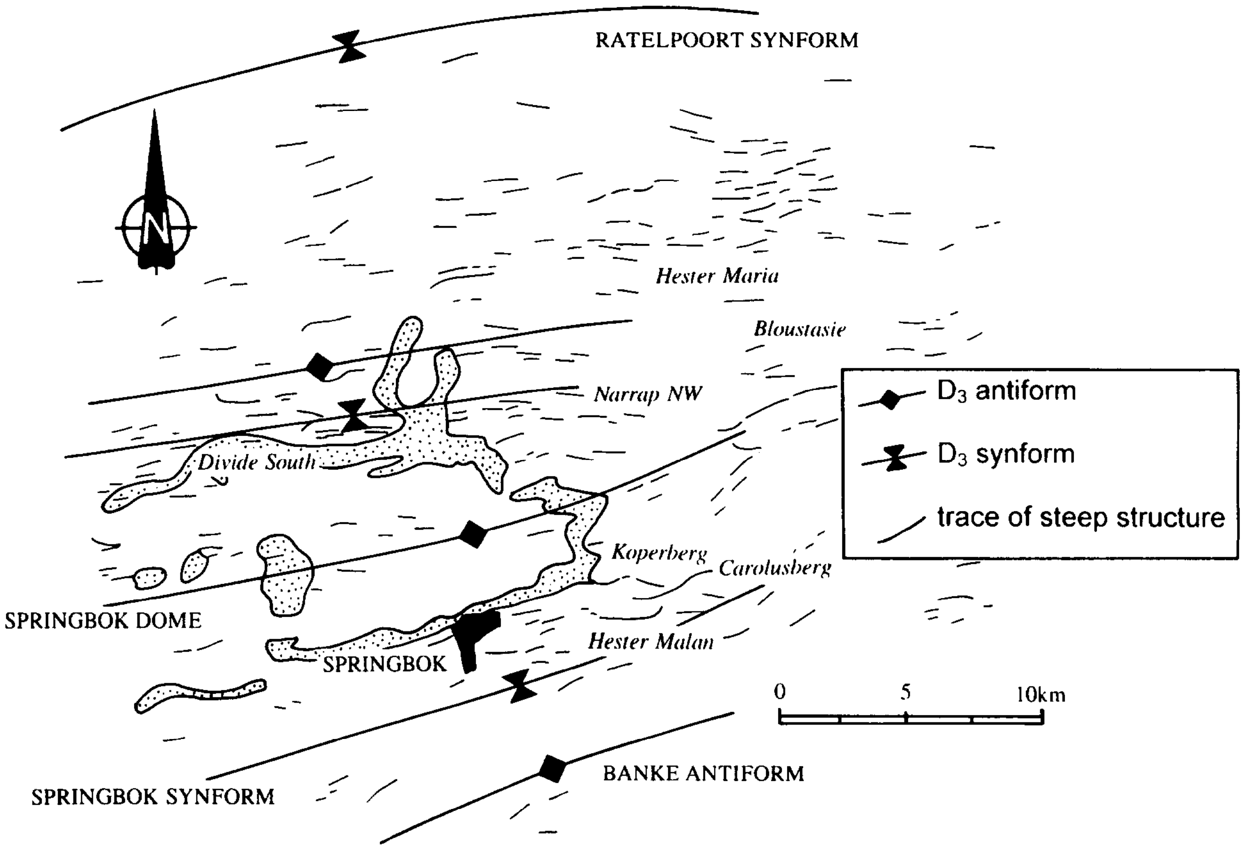


Fig. 6. Map showing prominent steep structures and axial traces of large-scale D_3 folds in the Okiep Copper District. Names depict localities of steep structures discussed in the text. Stippled: metasedimentary rocks of the Khurisberg Subgroup which outline the Springbok Dome.

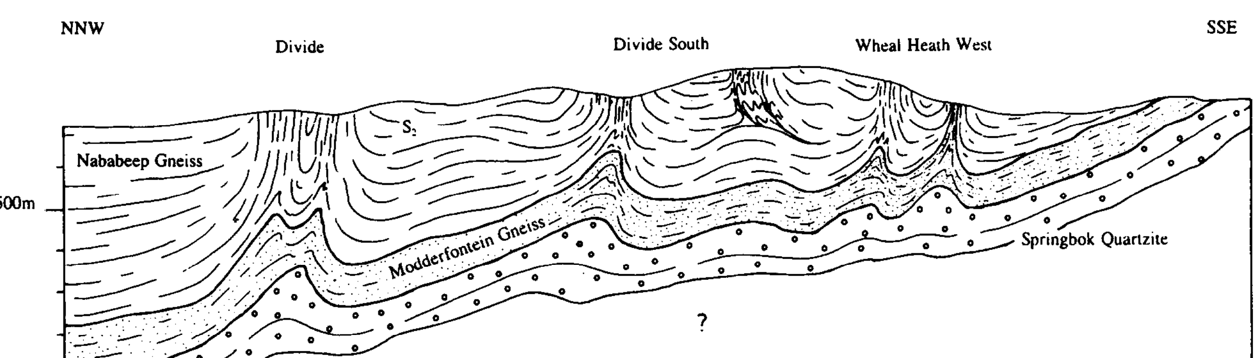


Fig. 7. Simplified cross-section through the Divide area (Fig. 6), illustrating the antiformal upwarp of the regional gneissosity along closely spaced, E-trending steep structures developed in Nababeep Gneiss at Divide, Divide South and Wheal Heath West. The intrusion of basic rocks of the Koperberg Suite into the central zones of the steep structures is not shown (compiled from cross-sections of the O'okiep Copper Company).

Monoclinal steep structures

Monoclinal steep structures are less common than antiformal steep structures, although the two are frequently closely associated (Kisters *et al.* in press). The monoclines are defined by sinusoidal deflections of the subhorizontal S_2 gneissosity and lithological layering into subvertical attitudes (Fig. 3b). They display both south-down and north-down senses of displacement, with the former occurring on S-dipping limbs of the large-scale D_3 folds and the latter occurring on their N-dipping limbs. Their easterly trend and systematic arrangement with respect to the regional-scale folds suggests that their formation was related to the D_3 event.

Figure 8 shows a small monoclinal steep structure which illustrates the salient features that are observed on a larger scale. The structure occurs as a S-facing monoclinal flexure in the Nababeep Gneiss. While the hanging-wall contact with the regional, subhorizontal S_2 gneissosity is gradational, the footwall contact is sharp, giving the appearance of a detachment zone. Country-rock

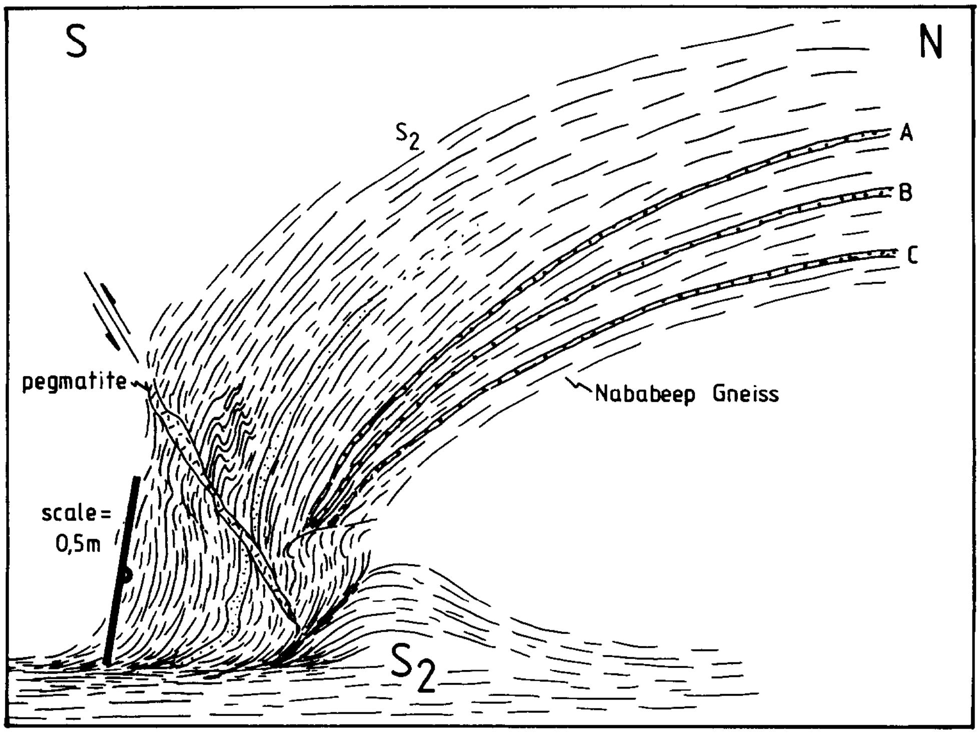


Fig. 8. Sketch from a photograph of a small monoclinal flexure in Nababeep Gneiss, looking west. Lower bounding surface (bottom of clino-rule) is represented by intense, subhorizontal gneissosity. The monoclinal steepening of S_2 is associated with the formation of smaller folds (centre of the sketch) superimposed on the monoclinal flexure. The convergence of three marker bands (A, B and C) traced into the monoclinal flexure indicates the increase in strain.

gneisses in the footwall are highly strained and are markedly darker than adjacent Nababeep Gneiss, reflecting an enrichment in less soluble mafic minerals such as biotite and hypersthene and dissolution of leucocratic minerals in this zone. The rotation of the gneissosity to steeper attitudes is associated with a marked increase in strain, which is indicated by the attenuation of augen textures, a decrease in grain size, the convergence of marker bands contained in S_2 (Fig. 8) and apparent volume loss. Small-scale, upright folds of S_2 (Fig. 8) indicate a foliation-parallel shear and imply that some strain is accommodated by flexural-slip.

In many of the larger monoclines, a subvertical, E-trending axial-planar fabric is defined by elongate quartz grains, called S_3, because of above-established genetic link with D_3. The S_3 quartz foliation is best developed in antiformal steep structures and it will be discussed in more detail below.

Antiformal steep structures

Antiformal steep structures show a complex three-dimensional geometry, as indicated in Fig. 9. In profile, antiformal steep structures are geometrically best described as tight, upward pointing cusps flanked by broad synforms. Significantly, no synformal steep structures have been found. Hälbich (1978, fig. 18.23) described what he interpreted as a synformal steep structure; however, we believe that this feature can be better explained as the product of complex deformation that accompanied the development of a monoclinal and antiformal steep structure.

In profile, the structures comprise: (a) two symmetrical, concave-upward limbs in which the regional, subhorizontal gneissosity is steepened (Figs. 3a, 4, 7 and 9); and (b) an inner, E-trending core characterized by an intensely developed, subvertical, E-trending foliation. The outer limits of the steep structures are defined both by marginal synformal structures, which may be up to 300 m wide, and by the distribution of a subvertical, E-trending quartz-mineral foliation, defined by flattened quartz ribbons, that resembles the S_3 fabric associated with the monoclinal structures. This quartz foliation is, accordingly, denoted S_3 here. The S_3 foliation is most easily identified on the limbs of the steep structures where it is highly discordant with respect to S_2. Towards the cores of the steep structures, however, it is more difficult to distinguish from S_2 owing to the rotation of S_2 to steep attitudes, and the development of subvertical high-strain fabrics (see below).

In detail, the steepening of the S_2 gneissosity from subhorizontal to subvertical attitudes is discontinuous, occurring in a step-wise fashion (Fig. 10). Limbs of steep structures are commonly cut by narrow, steeply inclined zones of intense foliation development that converge upwards. Individual shear zones vary from sharply defined discontinuities to zones in which S_2 undergoes more subtle steepening. The S_2 gneissosity is sigmoidally folded between these zones, giving the appearance of macrolithons bounded by zones of shearing. The gentle to tight folds in the macrolithons show shallow easterly and/or westerly plunges, parallel to the main antiformal structure with which they are associated. The folds display a progressive increase in amplitude and decrease

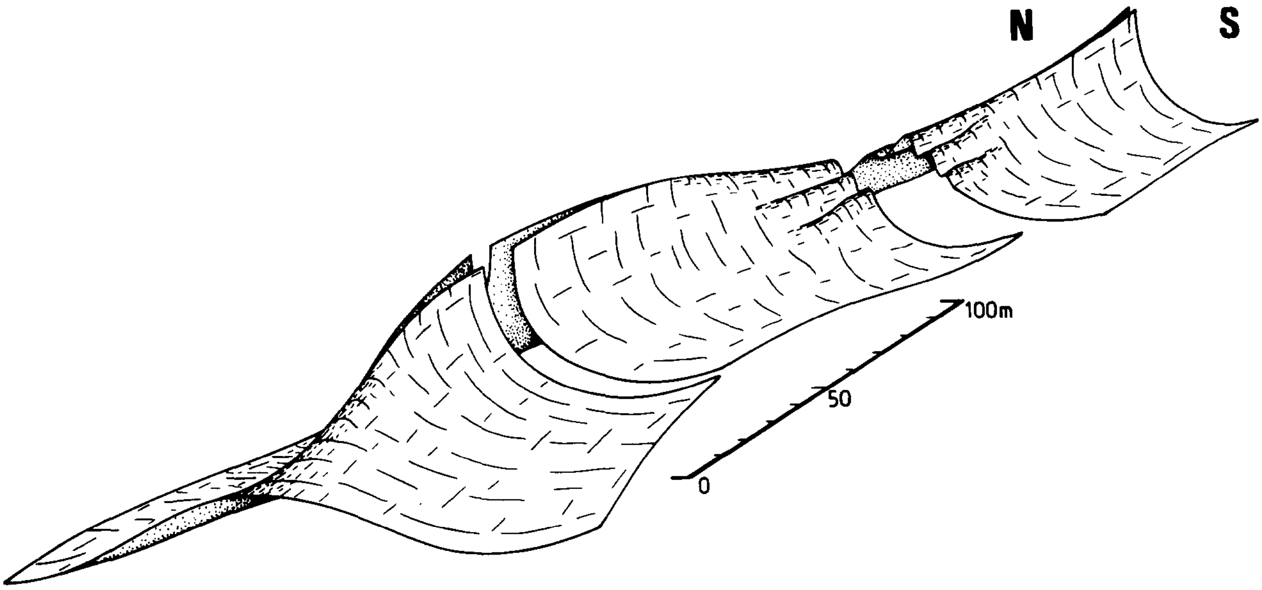


Fig. 9. Schematic illustration of the variation of structural development along the Hester Maria steep structure (Fig. 6). Tightening and amplification of folds alternates with open warps of the regional gneissosity along strike.

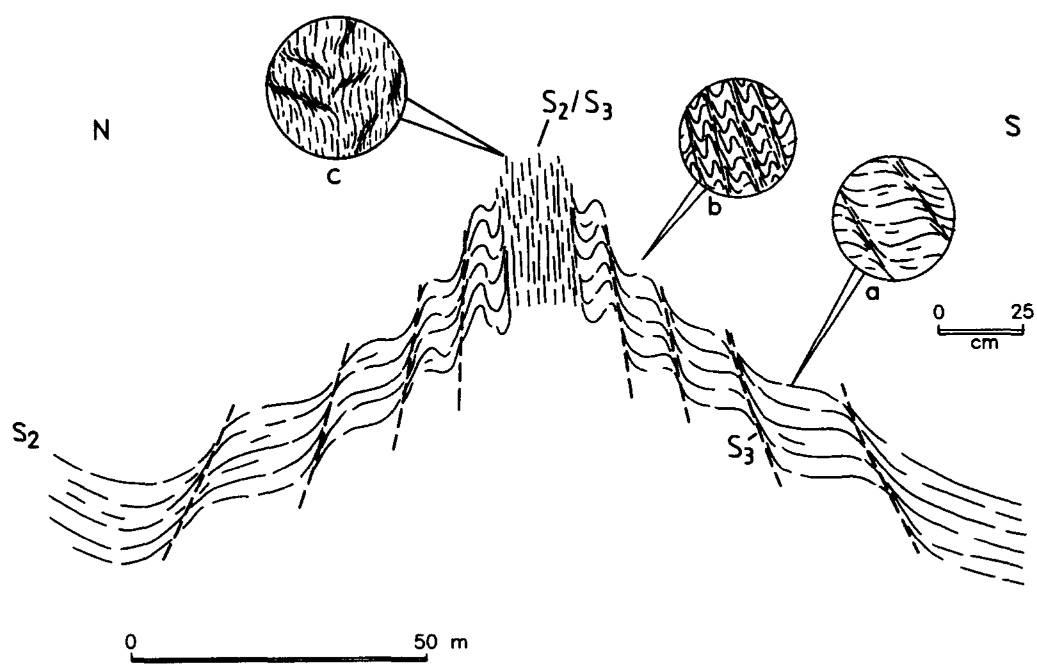


Fig. 10. Diagrammatic illustration of the upwarp of the gneissosity (S_2) into the subvertical centre of steep structures, showing the sigmoidal folding of the limbs along shear discontinuities. Insets (a) and (b) illustrate small-scale folding within macrolithons; inset (c) illustrates the formation of high-angle shear bands superimposed on the S_2/S_3 transposition fabric in the cores of the structures.

in wavelength towards the steep structure core (Fig. 10). The spacing of the shear discontinuities may be as great as several tens of metres, but generally it decreases towards the core of the structure. Larger macrolithons are transected, in places, by small-scale, closely spaced shears (2–25 cm apart), which are subparallel to the larger-scale shear discontinuities and which result in a crenulation-type deformation of macrolithons (Figs. 10a & b). The crenulation foliation is subparallel to the S_3 quartz fabric (Fig. 10). The wavelength of these crenulations decreases sharply towards the core of the steep structure. The gradation from open (Fig. 10a) to tight and isoclinal fold forms (Fig. 10b), which mimics the pattern observed in the larger-scale macrolithon folds, indicates an increase in strain towards the centre of the steep structure.

In their central parts, the steep structures are dominated by an intense, subvertical, E-trending gneissose banding derived by flattening and attenuation of the S_2 augen textures (Figs. 5a & b). This foliation is parallel to, but differs morphologically from, the more widespread quartz-ribbon foliation described above. The presence of rare, relic fold hinges within this foliation testifies to its development by transposition of S_2 so that it is denoted S_2/S_3. Remnants of upright F_3 folds also occur in larger (several metres to more than 10 m wide)

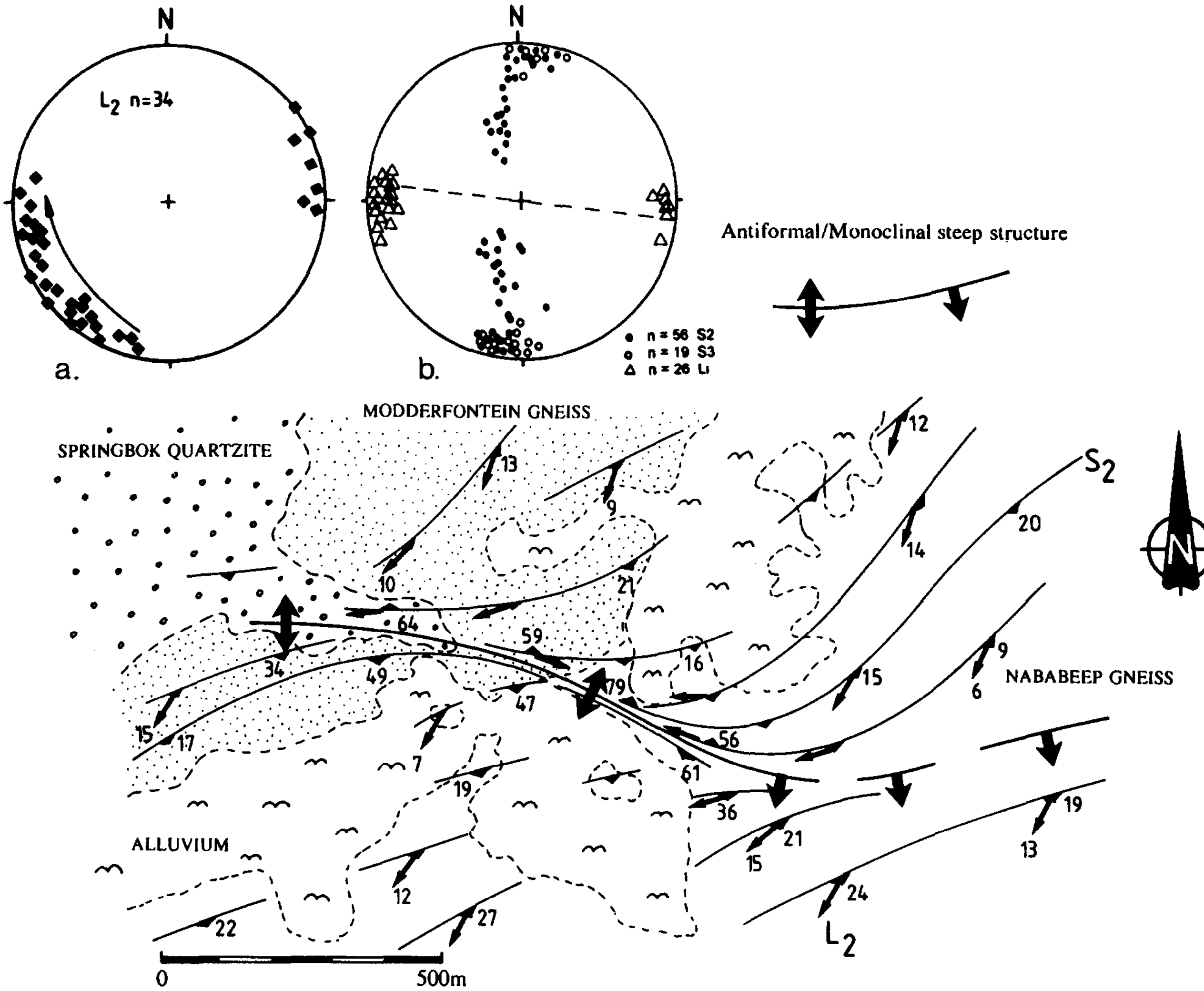


Fig. 11. Simplified geological map of the western extension of the Koperberg steep structure (see Fig. 6 for location). Note the drag and the antiformal steepening of the regional gneissosity into the steep structure. Lower-hemisphere equal-area projections of: (a) the regional feldspar lineation, L_2, illustrating the rotation of L_2 into parallelism with the easterly trend of the steep structure; and (b) poles to S_2 and S_3, and the intersection lineation L_i. Note the asymmetric girdle distribution of poles to S_2. Dashed line represents the average trend of the steep structure.

lozenge-shaped zones in which lower-strain S_2-augen textures are still present indicating that the strain distribution in the cores is heterogeneous. Towards the margins of these lozenge-shaped zones, the S_2 foliation is progressively obliterated by anastomozing high-strain zones into the S_2/S_3 transposition fabric. The foliation in the resulting undulating patterns deviates from a few degrees to as much as 30° from the main foliation, and this is reflected in the scatter of poles to foliations on stereographic projections (Fig. 11b). The banding in the high-strain S_2/S_3 zones is defined by seams of biotite and accessory orthopyroxene alternating with more leucocratic bands of quartz, K-feldspar and plagioclase.

Evidence for the rotation of clasts within the gneisses (e.g. feldspar augen) during steepening of the gneissosity is rarely observed. Microscopically, the banded gneisses display significant grain-size reduction and recrystallization relative to the coarse country-rock gneisses. Feldspar megacrysts are characterized by subgrain development and the marginal recrystallization of feldspars results in the formation of a fine-grained quartz–feldspar matrix. Recrystallized polygonal quartz occurs as a fine-grained groundmass or as largely equidimensional grains. Myrmekitic intergrowths of quartz and feldspar are common.

The subvertical foliation in the core is locally affected by conjugate shear bands (Fig. 10c). These shear bands, which are confined to the strongly banded high-strain zones within the core, range from centimetres to several metres in strike length. They occur as isolated bands within the foliation and as multiple, closely spaced sets. Both modify the subvertical S_2/S_3 gneissosity which is deformed into open sigmoidal folds between shear bands. Shear bands can be grouped into two categories, based on their orientation with respect to the subvertical, E-trending gneissosity: (1) those (type I shear bands) having orientations ≤45° (max. 30–45°) with respect to the gneissosity; and (2) those (type II shear bands) oriented >45° (max. 65–85°) to the subvertical foliation. Whereas type I shear bands are best described in terms of a 'symmetric extensional crenulation cleavage' or 'foliation boudinage' (after Platt & Vissers 1980, Lacassin 1988), type II shear bands resemble Lüder's bands which form at high angles to the principal direction of extension, akin to ductile necking in response to boudinage (Nadai 1963, Burg & Harris 1982). The orientations and shear senses of both the type I and II shear bands are consistent with a N–S-directed, horizontal shortening normal to the S_2/S_3 gneissosity, together with a component of subvertical extension along this foliation. A leucocratic, quartz–K-feldspar–plagioclase ± orthopyroxene ± biotite-bearing granitic charnockitic phase is locally developed along both type I and II shear bands and at the intersection of the conjugate shear bands. The presence of these leucosomes indicates that the shear bands formed under high-grade metamorphic conditions. Additional asymmetric shear foliations are observed in plan view in the cores of steep structures. They are best described, in terms of Platt & Vissers (1980), as an 'asymmetric extensional crenulation cleavage'. These shear bands can be closely spaced, in which case a somewhat curviplanar appearance of S_2/S_3 results. Oblique shear foliations may also occur on a metre-scale as single, isolated shear bands. In all observed cases, the orientation and shear sense of oblique shear bands with respect to S_2/S_3 indicates a dextral strike-slip component of movement along the steep structures.

Boudinage occurs in both the country-rock gneisses and in the noritoids of the Koperberg Suite in the cores of the steep structures. Boudin orientations indicate subhorizontal E–W-directed extension.

The subvertical gneissosity in steep-structure cores may, itself, be locally refolded. These folds are small scale and tight-to-isoclinal. They show shallow easterly plunges and display both 'S'- and 'Z'-asymmetries. They are interpreted as drag folds generated by a shearing component along the S_2 gneissosity that is progressively steepened during the advanced stages of steep structure formation.

The regional lineation, L_2, which is defined by elongated quartz–feldspar augen contained within S_2 is, together with the regional gneissosity, reoriented into parallelism with the steep structure (Fig. 11a). Near the centre of the structure, L_2 is progressively obliterated by a subhorizontal, E-trending intersection lineation, L_i (Fig. 11b), which locally causes the development of a pencil structure in the country rock gneisses. The development of L_i is the result of the intersection of the regional S_2 gneissosity with the subvertical, E-trending S_3 foliation (Fig. 11b). In addition to L_i and the rotated L_2 in steep structures, a variably developed mineral stretching lineation (L_m) is most prominent near the lateral terminations of the structures. This subvertically plunging extensional lineation is defined by elongate mineral aggregates of quartz and biotite and by quartz–feldspar augen.

In contrast to the N–S profile, the vertical terminations of steep structures are relatively abrupt. The structures may terminate as: (1) open antiforms, which grade imperceptibly into the regional subhorizontal gneissosity (Figs. 9 and 12); (2) a series of closely spaced cusps, abruptly grading into overlying subhorizontal gneissosities (Fig. 13); (3) monoclinal warps in which the gneissosity assumes progressively shallower attitudes (Lombaard *et al.* 1986, Kisters 1993); or (4) along a lower detachment zone in the footwall of the structures which is represented by the S_2 gneissosity (Fig. 12) or shallowly dipping thrust zones (Fig. 14).

A profile through the Narrap northwest steep structure, which is exposed on the steep flank of a hill for a vertical distance of some 150–200 m is shown in Fig. 12. The steep structure is underlain by shallow S-dipping Nababeep Gneiss (Fig. 12, level I). The base of the structure is expressed as a gentle, WNW-plunging antiformal warp of the S_2 gneissosity (Fig. 12a, level II). At higher levels the structure consists of open to close, upright, shallowly plunging folds (Fig. 12b, level III) that abruptly tighten upward. Tightening of the folds is associated with a dramatic amplification of fold structures yielding upright, isoclinal folds with strongly attenuated limbs (Fig. 12, level IV). Isoclinal fold closures are progressively transposed to the subvertical, intensely developed S_2/S_3 fabric in the core of the steep structure (Fig. 12, level V). The initial open folding of the gneissosity as well as the upper termination of steep structures are characterized by concentric folds, i.e. poles to S_2 describe a great circle (Figs. 12a & c). Stereographic projections of poles to the S_2/S_3 fabric in the steeper parts of the structure deviate from this great circle distribution, resulting in a somewhat sigmoidal form of girdle (Figs. 12d & e). The 'sigmoidal girdle' is caused by the steep to subvertical S_2/S_3 foliations falling on segments of small circles.

Along strike, the steep structures terminate as gentle antiformal and/or monoclinal warps which grade into the regional, subhorizontal gneissosity (Figs. 9 and 12, levels VII and VIII).

Strain in steep structures

The development of planar and linear fabrics and the orientation and sense of shear associated with secondary structures have been used for estimates of the finite-strain. The orientation of the X- and Y-axes of the finite strain ellipsoid ($X \geq Y \geq Z$) in steep structures is indicated by: (1) the subvertical mineral stretching lineation that is locally recognized in the centre of the structures; and (2) the orientation and shear sense of secondary shear bands and Lüder's bands. Both indicate a principal direction of extension in the vertical. However, the boudinage of country-rock gneisses and competent, noritic intrusions of the Koperberg Suite parallel to the easterly trend of steep structures indicates also a component of subhorizontal, E–W extension. It thus appears that the finite-strain ellipsoid is of an oblate (flattening) type ($X \approx Y > Z$) and records a N–S-directed shortening perpendicular to the easterly trend of steep structures (see also Venter 1984).

Bulk shortening strains are inevitably associated with a strain incompatibility or 'space problem' (Ramsay 1967, Bell 1981, Ramsay & Huber 1987). This potential

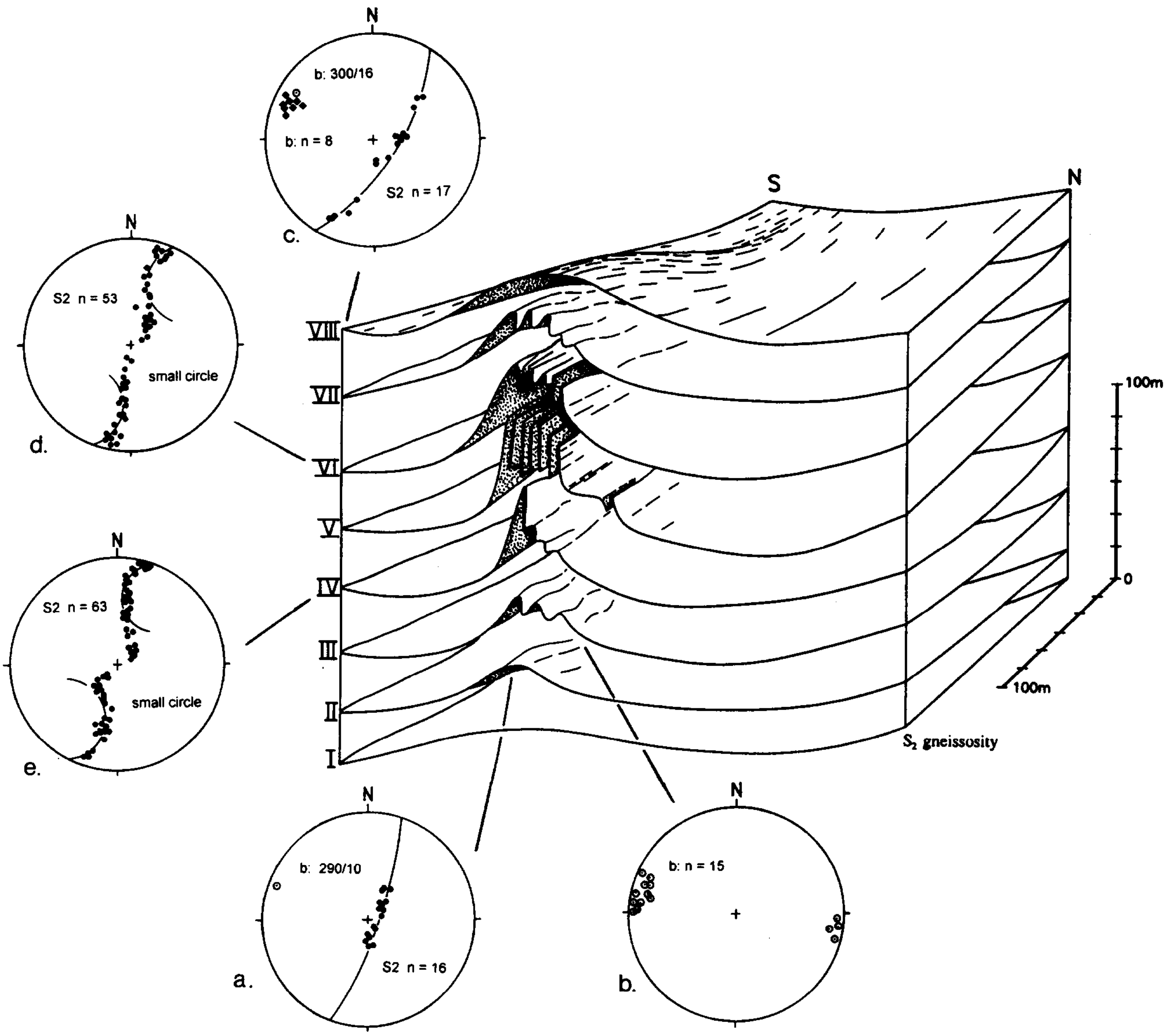


Fig. 12. Schematic sketch of steep structure development at Narrap NW (Figs. 4 and 6). Lower-hemisphere equal-area projections of: (a) poles to S_2, illustrating the open, W-plunging fold (290/10) developed in the footwall of Narrap NW; (b) minor fold axes associated with the antiformal upwarp of the gneissosity in the footwall of Narrap NW; (c) poles to S_2, illustrating the cylindrical, westerly plunging fold in the hangingwall of Narrap NW. Diamonds: plunges of minor folds; overall fold plunges 300/16; (d) & (e) poles to S_2, illustrating the asymmetric, sigmoidal girdle distribution reflecting the advanced stages of steep structure formation. (*n*: Number of measurements.)

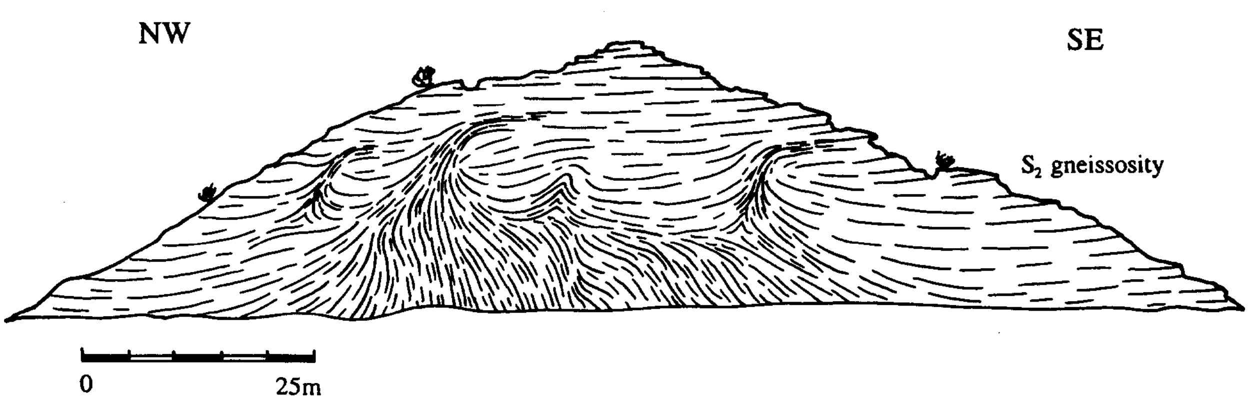


Fig. 13. Cross-section through the antiformal steep structure at Bloustasie Hill (Fig. 6) illustrating its vertical termination. Note the abrupt transition from highly strained, subvertical gneissosities to shallow-dipping, regional gneissosities in the hangingwall of the structure.

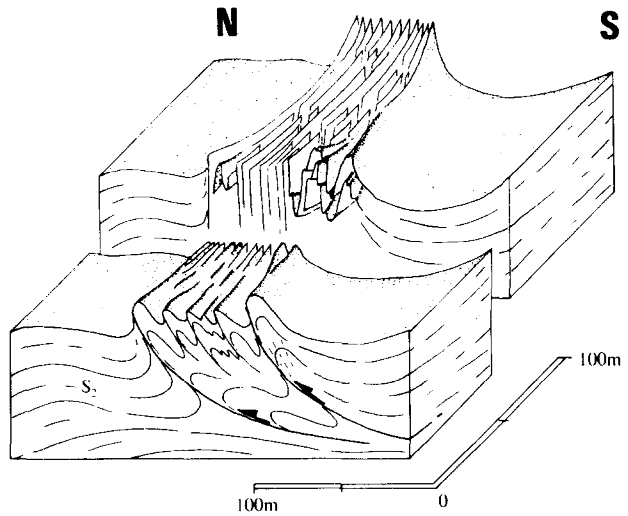


Fig. 14. Block diagram illustrating the progressive development of a steep structure at Divide South from shallow-dipping thrust zones, via upright folding into the subvertical steep structure fabric.

strain incompatibility along steep structures is accommodated by a variety of mechanisms in which the bulk strain is partitioned into differential shortening components normal and parallel to the steep structure. These include the following mechanisms.

(1) Bounding shear discontinuities on the limbs (Fig. 10) and at the base of the steep structures (Figs. 12 and 14). These shear discontinuities reflect shear strains that are induced in order to maintain strain compatibility with the surrounding gneisses and to accommodate strain heterogeneities that are associated with the heterogeneous vertical amplification across steep structures. The intensification of the subhorizontal S_2 gneissosity (Figs. 8 and 14) during the development of the subvertical S_2/S_3 fabric in steep structures indicates that they were active at the same time.

(2) A subvertical and lateral material flow accompanying the N–S-directed shortening. Subvertical material flow is evidenced by the presence of a subvertical mineral extension lineation, as well as by the orientation and shear sense of shear bands (types I and II). Vertical material extrusion is most dramatically documented by the attenuation and piercing of external material layer boundaries (Fig. 7) (Lombaard & Schreuder 1978, Kisters 1993).

(3) Volume loss by dissolution of material in the cores of steep structures (Kisters *et al.* in press).

The amplification of monoclinal steep structures is characterized by a steepening of the monoclinal limb to subvertical attitudes and the development of an intense fabric. The bulk N–S shortening strain and rotation of the regional S_2 gneissosity is accommodated by flexural-slip along the gneissosity, frequently resulting in the superimposition of antiformal upwarps on to monoclines, as well as by volume loss during fabric development.

DISCUSSION

It is clear from the descriptions presented earlier that the steep structures in the Okiep District display highly unusual three-dimensional geometries that appear to have no known analogues in other deformed metamorphic terranes. Previous studies have concentrated largely on the more common (and more spectacular) antiformal steep structures, for which various mechanisms have been proposed:

(1) Kröner *et al.* (1973), Blignault *et al.* (1983) and McIver *et al.* (1983) suggested that the highly attenuated fabrics in the antiformal steep structure cores indicate that they developed in response to shearing and that the steep structures themselves represent shear zones;

(2) Hälbich (1978), following Wegmann (1963), concluded (from the orientation of syn-steep structure basic dykes of the Koperberg Suite) that the antiformal structures formed as extensional features, corresponding to mega-boudin necks; and

(3) Benedict *et al.* (1964), Lombaard & Schreuder (1978) and Lombaard *et al.* (1986) emphasized the fold-like geometries of the antiformal structures, describing them as 'cusps' or 'piercement folds', although they did not suggest a mechanism.

The problem with these models lies in the fact that no single model accounts adequately for all the features observed in the steep structures. For instance, the fold model, while recognizing the overall antiformal geometry of the antiformal steep structures, fails to explain how the extreme high-strain axial-planar fabrics came to be developed in the hinges of the folds, in apparent contradiction of typical fold–cleavage relationships. A second problem with this model is the absence of synformal structures displaying similar geometries. Third, although the antiformal steep structures bear a superficial resemblance to large-scale cuspate–lobate folds, their distribution is not dependent on the existence of lithologies with a high competence contrast. The shear zone model, on the other hand, cannot adequately explain the symmetrical rotation of the regional gneissosity into the antiformal structures. Finally, the boudinage model fails to explain both the lack of similar synformal structures and why the steep structures are distributed throughout a relatively homogeneous granite-gneiss sequence rather than at the interface between rocks with strongly contrasting competencies, nor do the proponents of this model attempt to explain the development of the monoclinal structures.

A further criticism of the previously proposed models is that they have not attempted to reconcile the two steep structure geometries — antiformal and monoclinal — despite the close spatial links between the two, their similar timing (post-D_2, synchronous with high-grade and anatectic conditions) and orientation and the similarity of structural features, such as the S_3 quartz-ribbon foliation. In the following sections we develop a general model to account for both the antiformal and monoclinal steep structures, first by establishing their relationship to the large-scale D_3 folds in the Okiep District, and then by considering the likely rheological behaviour.

Timing of steep structures

The timing of steep structures is a matter of controversy amongst different workers. While Clifford *et al.* (1975a) and Joubert (1986a) regarded the steep structures as late-D_3 features, Hälbich (1978) and Clifford *et al.* (1995) maintained that they post-dated the D_3 event. It is clear, from Fig. 6, that the ENE strike of the steep structures is parallel to the trend of the regional D_3 folds such as the Springbok Dome and Ratelpoort Synform. Furthermore, the subvertical orientation of the S_3 quartz-ribbon fabric in both the monoclinal and antiformal steep structures, and the S_2/S_3 transposition foliation in the antiformal cores, is axial planar to the regional folds, indicating a similar orientation of the strain axes for both sets of structures. Moreover, the closely associated migmatitic megabreccias and charnockitization in steep structures indicate that the steep structures have formed under peak-metamorphic conditions in the Okiep Copper District. The peak of metamorphism was placed by Waters (1988, 1990) as post-D_2 and syn-D_3. In addition, the monoclinal steep structures show a systematic relationship with respect to the large-scale D_3 folds, with structures showing a south-down sense of displacement occurring on the S-dipping limbs of the D_3 folds, and those with north-down displacement occurring on the N-dipping limbs. Although the monoclinal structures clearly cannot be interpreted as parasitic folds on the larger-scale D_3 folds (their 'vergence' is wrong, nor do they appear to have formed by the same mechanism that produced the larger folds), we believe that this relationship, together with their orientation, fabric development and their origin during peak metamorphism, points to a temporal link between the steep structures and the regional D_3 folds. The steep structures are thus interpreted as products of the D_3 event.

A model for steep structure development

Given a D_3 timing for steep structure development, any model proposed to explain the genesis of these structures must reconcile the following features:

(1) the development of zones of locally intense strain (the steep structures) in an environment undergoing relatively minor bulk strain (indicated by the gentle regional-scale D_3 folds);

(2) the restriction of the steep structures to the strongly foliated parts of the granite-gneiss sequence;

(3) the apparently sporadic distribution of the steep structures, both vertically and laterally in the sequence exposed in the Okiep District;

(4) the unusual geometry of the steep structures, with the predominance of antiformal structures and the lack of synformal steep structures.

The lithological succession of the Okiep Copper District can be viewed on two different scales: (1) as a sequence with layering/stratification on a broad scale (i.e. stratified granite-gneisses interlayered with metasediments); and (2) as a sequence with small-scale layering (i.e. the S_2 gneissosity in the orthogneisses of the Little Namaqualand Suite and the lower Spektakel Suite).

Latham (1983, 1985a,b), in his treatment of the folding behaviour of non-linear materials, emphasized the close relationship between folding, kinking and shearing. Materials which display a strong intrinsic anisotropy will develop folds and/or kinks. Conversely, more homogeneous materials are likely to develop shear discontinuities (induced anisotropies). Significantly, Latham (1983, 1985a,b) demonstrated a continuum between the strain responses.

The large-scale layering in the granite-gneiss sequence and, in particular, the presence of the massive unit of the Springbok Quartzite, have probably played a dominant role in determining the character of the open, regional-scale folds. However, the high-grade metamorphic conditions and associated partial melting are likely to result in a mechanical homogenization of the granite-gneisses, despite the stratification of the sequence. The lack of marked competence contrasts inhibits the formation of well-developed regional-scale buckle folds, and shortening is more likely to be accommodated by a component of layer-parallel shortening during D_3. The amplification of regional-scale folds would be correspondingly low, as it is expressed by the open fold geometries of D_3 folds.

The development of the smaller-scale steep structures is determined by the presence of the pre-existing S_2 gneissosity, i.e. by the initial buckling of a small-scale anisotropy developed in the gneissose units of the granite-gneiss sequence (i.e. the Little Namaqualand Suite and lower parts of the Concordia Granite). However, the mechanically homogeneous nature of the granulite-facies granite-gneisses will favour the formation of strain-induced fabrics rather than the amplification of folds. This transitional behaviour is recorded in steep structures by the changeover from early-stage folding (at lower strains) to heterogeneous shortening and the development of high-strain fabrics (i.e. during the advanced stages of steep structure formation) (Figs. 9, 12 and 14). The N–S shortening strain normal to the S_2/S_3 fabric is accommodated by predominantly vertical material extrusion. Since material flow follows hydraulic gradients, it is likely to be directed towards a free surface (i.e. the Earth's surface). This upward-directed material flow results in the antiformal geometries of the steep structures and the lack of synformal (downward-pointing) steep structures in the Okiep Copper District (e.g. Fig. 7). The intense foliation development and concentration of strain in the central zones of the steep structures, compared to the relatively unstrained enveloping country-rock gneisses, indicates strain partitioning and strain-rate softening during progressive deformation. Strain-rate softening is likely to be enhanced by the presence of partial melts and the dissolution of material during fabric development which may increase

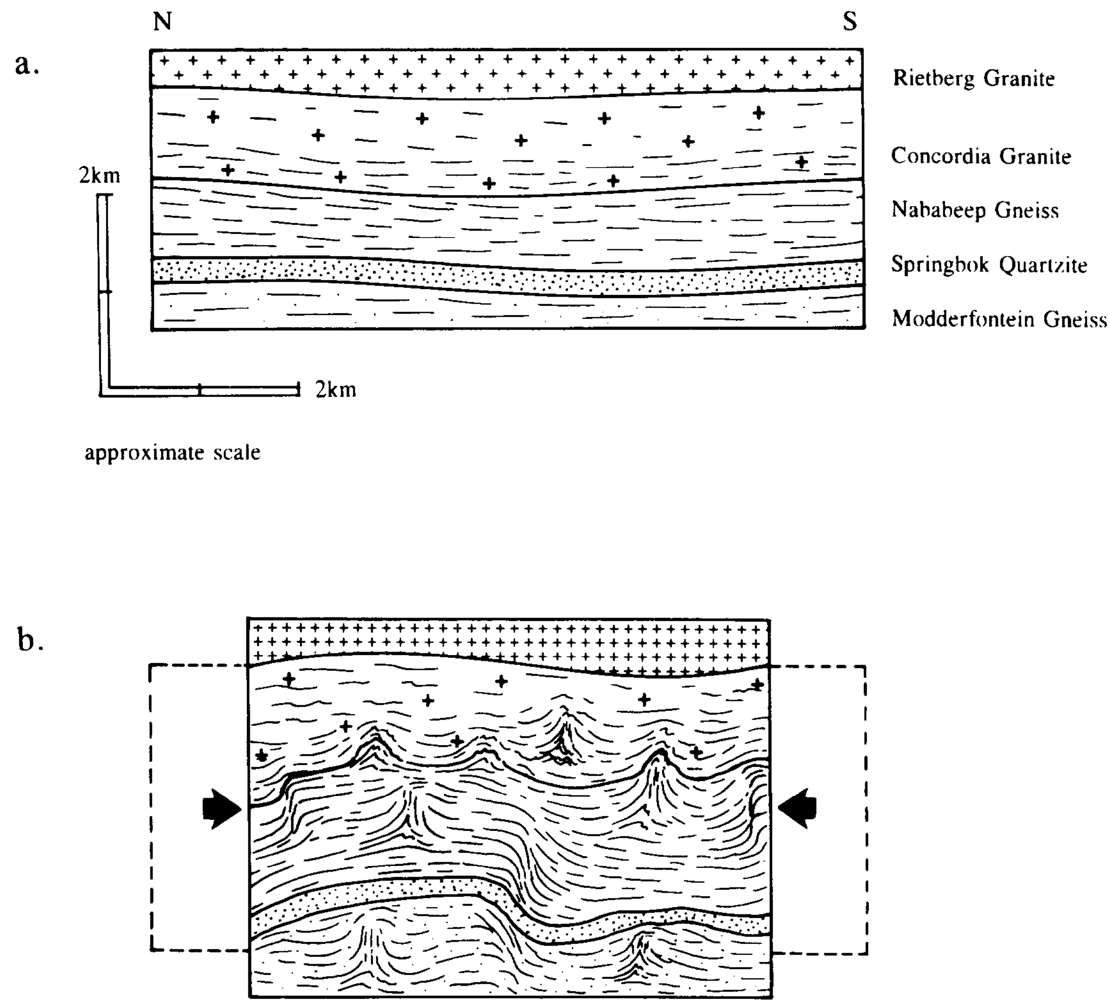


Fig. 15. Schematic cross-section through the Okiep Copper District (a) prior to D_3 and (b) after D_3. Coaxial shortening during D_3 was largely accommodated by layer-parallel shortening. Steep structures represent induced internal instabilities during layer-parallel shortening. The relative amount of layer-parallel shortening is only presented qualitatively.

strain rates by orders of magnitude (Pharr & Ashby 1983, Dell'Angelo & Tullis 1988). In the steep structures, partial melting is most dramatically documented by the presence of megabreccias (i.e. anatectic migmatites) that are associated with the structures. Strain compatibility with the surrounding wall rocks is maintained by bounding shear zones.

Crustal thickening of the Okiep Copper District during high-grade metamorphism and deformation is implied by the anticlockwise *P–T-t* path (Waters & Whales 1984, Waters 1986, 1988, 1990). These authors attribute crustal thickening to the addition of granitic magmas at the level of the Copper District. This study, however, indicates that a component of tectonic thickening cannot be neglected. Crustal thickening at the level of the Okiep Copper District is induced by the large component of layer-parallel shortening and was assisted by the mainly vertical material flow and the geometries of both antiformal and monoclinal steep structures (Fig. 15).

CONCLUSIONS

A genetic relationship exists between regional-scale, upright, E-trending, open D_3 folding of the high-grade metamorphic granite-gneisses of the Okiep Copper District and steep structure formation. The steep structures are axial-planar to large-scale D_3 folds and represent localized zones of high strain that formed in response to the N–S-directed bulk inhomogeneous shortening during the D_3 event. Because of the regional bulk homogeneity of the granitic gneisses, progressive shortening during D_3 resulted in only open, large-scale folding and was largely accommodated by layer-parallel shortening. Initiation of steep structures occurred by folding of the pre-existing, subhorizontal gneissosity, S_2, within the gneissic units of the Copper District sequence to provide the nucleii for further steep structure development. The early-stage folding in steep structures was progressively obliterated by the development of strain-induced high-strain fabrics. These high-strain zones formed parallel to the XY-plane of the bulk strain ellipsoid during D_3. The prevailing antiformal geometries of steep structures illustrate the vertical material extrusion of the high-grade metamorphic gneisses during coaxial shortening. Strain compatibility with adjacent country-rock gneisses was maintained along a lower detachment and bounding shear zones and also by volume loss in steep structures. Easterly-trending, reverse-sense monoclinal steep structures are, on the scale of the Okiep Copper District, conjugate and, as such, also formed in order to accommodate the N–S-directed shortening strain. Layer-parallel shortening and resulting internal deformation, the predominantly subvertical material flow in antiformal steep structures and the conjugate arrangement of reverse-sense monoclinal structures are likely to have resulted in a tectonic crustal thickening of the Okiep Copper District.

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