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by

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ABSTRACT

Subhorizontal gneissosities and lithologies of the granulite-facies terrane of the Okiep Copper District, South Africa, are cut by narrow, discontinuous, easterly trending cusp-like and/or monoclinal structures in which the regional gneissosity has been rotated to subvertical attitudes. The structures are axial planar to upright, large-scale folds which openly refold the 4km-thick granite-gneiss succession of the Okiep Copper District. Closely associated migmatization and charnockitization indicates that these "steep structures" formed during high-grade metamorphic conditions. In this paper the authors present a model which relates the deformational style, strain, and orientation of steep structures to bulk inhomogeneous shortening of the high-grade metamorphic granite-gneiss sequence of the Okiep Copper District. Steep structure development can be described as a progression from initial folding of the gneissose units of the granite-gneiss sequence, via explosive amplification of folds to the progressive obliteration of folds by subvertical, easterly trending, high-strain fabrics, parallel to the axial planes of regional-scale, open folds. This progressive development illustrates the close relationship between buckle folding and the formation of internal, induced anisotropies during deformation of the high-grade metamorphic granitic gneisses which show strongly nonlinear material behaviour. 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 of the ductile granite-gneiss succession, while regional-scale buckle folds are characterized by slow amplification rates.

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INTRODUCTION

High-grade metamorphic granite-gneiss terranes generally show deformational styles which are markedly different from those observed in shallow-crustal, low-grade environments. This is generally attributed to the high ambient temperatures and confining pressures, giving rise to deformation mechanisms which significantly change the rheology and material behaviour of the rocks (Holland and Lambert, 1969; Etheridge, 1983; McLellan, 1984; Dewey, 1986; Weber, 1986; Knipe, 1989).

In this paper the authors report on structural features, locally known as "steep structures", which represent a unique deformation style component of the Proterozoic granulite facies granite-gneiss terrane of the Okiep Copper District in the Namaqualand region of the northwestern Cape Province, South Africa (Fig. 1). The term "steep structure" was coined by geologists in the Okiep Copper District to describe narrow, easterly trending zones of high strain in which the regional subhorizontal gneissosity assumes subvertical attitudes over strike lengths typically several hundred metres in extent. The diverse geometries and variety of structural features associated with steep structures has resulted in diverging views about their origin (Wegmann, 1963; Hälbich, 1978; McIver et al., 1983; Blignault et al., 1983; Venter, 1984). In addition to their academic interest, steep structures play a vital economic role in the Okiep Copper District as they represent the host structures to copper mineralized noritoids of the Koperberg Suite which have been exploited for more than 300 years in the Namaqualand region (Lombaard et al., 1986, Smalberger, 1975).

In this paper the complex geometries and deformation features associated with steep structures are described and discussed, as are the formation mechanisms and significance of steep structures for the deformation of the granite-gneiss sequence of the Okiep Copper District.

REGIONAL GEOLOGY

The granulite-facies terrane of the Okiep Copper District is located in the northwestern Cape Province of South Africa and covers an area of some 2500 km^2 (Fig. 1). The rocks of the region constitute the mid-to-late Proterozoic Namaqualand Metamorphic Complex, forming part of the extensive, WNW-trending Namaqua-Natal mobile belt, which extends from southern Namibia and Namaqualand along the west coast of southern Africa to the Natal Province on the eastern seaboard (Joubert, 1971, 1986a,b) (Fig. 1). This mobile belt records a prolonged history of repeated plutonism and tectonism during Precambrian times, commencing in its western parts with the 1700-2000 Ma Orange River event (Blignault et al., 1983; Reid, 1977) and culminating in the pervasively developed Namaqua tectono-magmatic event at 1000-1200 Ma (Nicolaysen and Burger, 1965; Clifford et al., 1975a; Barton, 1983). In its westernmost parts, the mobile belt was marginally rejuvenated in late-Precambrian-Cambrian times during the Pan-African orogenesis (Allsopp et al., 1979; Joubert, 1986a,b). The Namaqualand Metamorphic Complex consists of lithologically

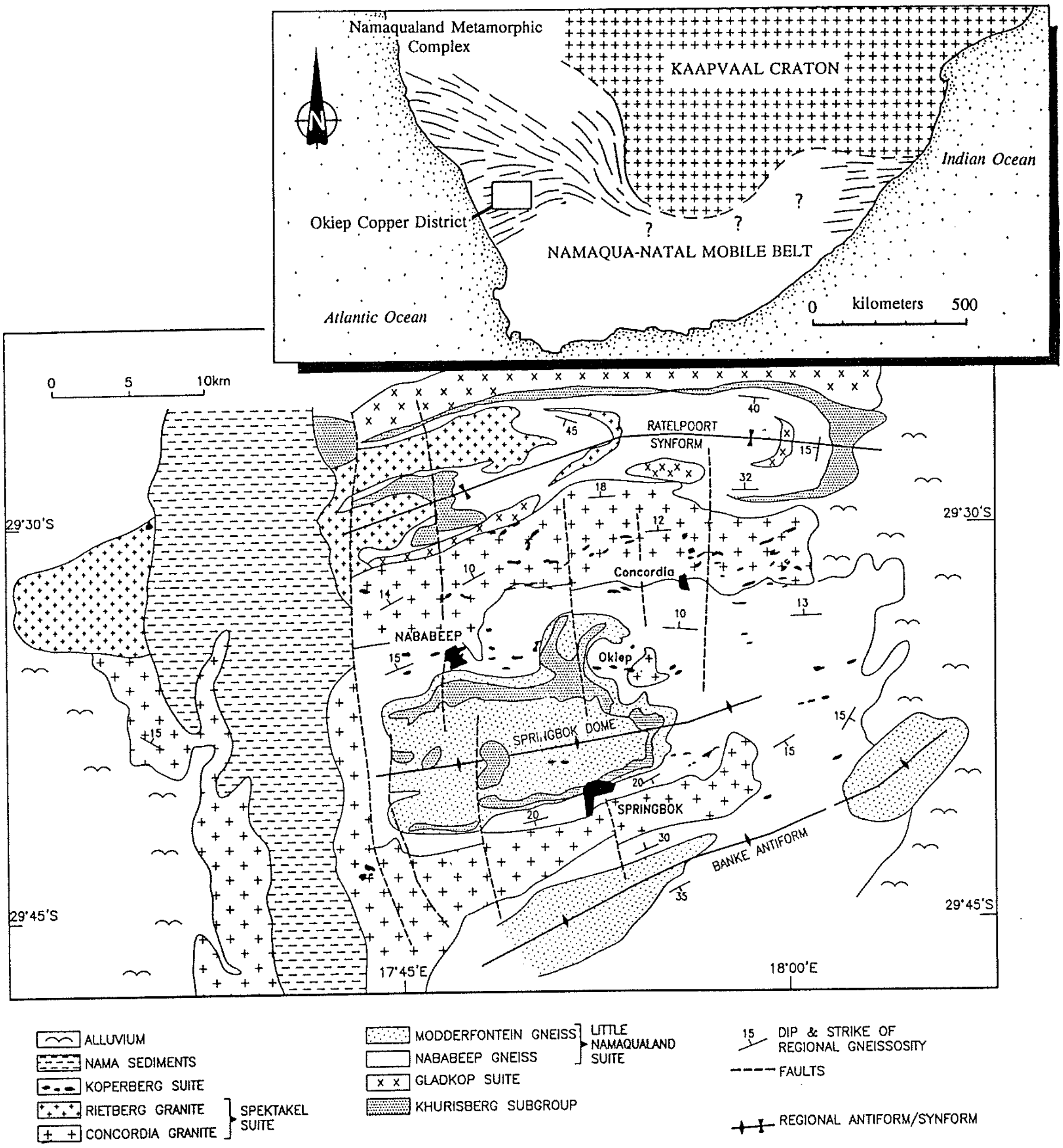


Figure 1: Simplified geological map of the Okiep Copper District (modified after maps of the O'okiep Copper Company). Insert shows the location of the Okiep Copper District within the tectonic framework of southern Africa (modified after Tankard et al., 1982).

distinctive, commonly structurally bounded terranes. These terranes show metamorphic grades ranging from greenschist to upper granulite facies suggesting the juxtaposition of different crustal levels (Joubert, 1971, 1981, 1986a,b; Vajner, 1974; Stowe, 1983, 1986; Blignault et al., 1983; Colliston et al., 1991).

The lithological sequence of the Okiep Copper District comprises a sheeted, subhorizontal assemblage of voluminous, stratified granitic gneisses and granites which intrude an older gneiss and metavolcano-sedimentary supracrustal sequence (Clifford et al., 1975a; Joubert, 1986a,b). These gneisses of the Gladkop Suite and the metavolcano-sedimentary succession of the Khurisberg Subgroup only occur as large rafts and xenoliths within granitic gneisses and later granitic intrusions. The approximately 4km-thick, granite-gneiss sequence of the Okiep Copper District is dominated by augen gneisses of the Little Namaqualand Suite, comprising the widespread lithologies of the Nababeep and Modderfontein Gneiss, and later granites of the Spektakel Suite which is made up of the Concordia, Rietberg, and Kweekfontein Granite. 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 of anorthositic, dioritic, noritic and hypersthenitic composition and are of particular significance since 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 and Schoch, 1986; Cawthorn and Meyer, 1993). In its western parts, the granite-gneiss terrane of the Okiep Copper District is unconformably overlain by weakly deformed, mainly clastic sediments of the late-Proterozoic Nama Group.

The regional structural trend of the Namaqualand Metamorphic Complex is east-west, but has been modified locally by major crustal shear zones superimposed onto pre-existing structural elements such as gneissosities, lineations, fold axes and thrust zones (Joubert, 1971, 1986a,b; Toogood, 1976; Blignault et al., 1983; Stowe, 1986). Three main deformational phases can be identified for the Okiep Copper District and adjacent terranes. An early deformation phase, the D_1 or Orange River event, can be inferred from tight to isoclinal intrafolial folds within xenoliths of the older metavolcano-sedimentary succession and gneisses which occur within the later granite-gneisses of the Little Namaqualand and Spektakel Suites (Joubert, 1971; Lombaard et al., 1986). The most pervasive deformation phase recorded in the Okiep Copper District is the D_2- or Namaqua- event. In the Okiep Copper District, the main features of the D_2 deformation are a pervasively developed, subhorizontal planar fabric (S_2) and a subhorizontal, predominantly east-trending mineral lineation (L_2). Large-to-small scale isoclinal, often recumbent folds are occasionally found in metasediments of the Khurisberg Subgroup. The S_2 fabric is typically expressed as a gneissic augen texture or gneissose compositional banding in the granite gneisses of the Little Namaqualand and lower Spektakel Suites (lower parts of the Concordia Granite). It is absent in the upper parts of the Spektakel Suite (i.e. upper Concordia Granite and Rietberg and Kweekfontein Granites), suggesting a late-to-post D_2 timing for emplacement of these granites. The regionally widespread augen textures are defined by fine-grained quartz and biotite flakes anastomosing around ovoid quartz-feldspar aggregates. Development from the phenocrystic, granitic textures of the granitic precursors, via foliated augen textures, to strongly foliated and compositionally banded gneissose textures are locally observed on an outcrop scale, indicating heterogeneous strain profiles during fabric development. The L_2 lineation is defined by the preferred orientation of quartz-feldspar augen or elongated quartz grains. The orientation of the D_2 structures is modified by large, open, upright D_3 folds and the development of steep structures. D_3 folds are often periclinal and trend ENE. These include the Springbok Dome and the Ratelpoort Synform (Fig. 1), which are the most conspicuous structural features recognizable on regional maps, determining the disposition of the shallowly dipping gneissose sequence in the Copper District. The timing and origin of the narrow, steeply inclined zones of "steep structures" with respect to the D_3 deformation is a matter of controversy amongst different workers. Clifford et al. (1975a) and Joubert

(1986a), for example, regarded the steep structures as late-D_3 features, while Hälbich (1978) and Lombaard et al.(1986) maintained that they post-date the D_3-event (F_4; Hälbich, 1978). Conjugate sets of northeasterly and northwesterly trending mylonites represent the last ductile deformation to be recorded in the Okiep Copper District and are only post-dated by northerly trending, subvertical, normal fault-zones which show intense brecciation of country-rock gneisses. The displacement of late-Proterozoic Nama sediments along these breccia faults indicates an activation of the normal faults at shallow crustal levels.

Two metamorphic events have been identified in the Namaqualand Metamorphic Complex. 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 overprinted in the Okiep Copper District by a subsequent, high-grade M_2- or Namaqua-event (Joubert, 1971, 1986a,b). Metamorphic conditions during the M_2 event are constrained by mineral assemblages in pelitic metasediments of parts of the Okiep Group and suggest an anticlockwise P-T-t path during which peak metamorphic temperatures of approximately 850°C were attained at pressures of 5.5-7kb (Clifford et al., 1975a,b, 1981; Waters and Whales, 1984; Waters, 1988). These metamorphic conditions, which are characteristic for lower granulite facies grades, have given rise to partial melting and localized intense migmatization of the metasedimentary and granitic gneisses (e.g. Waters, 1988; Kisters et al., 1992a; Kisters, 1993). Post-D_2 prograde mineral growth, identified by Waters (1989), suggests that peak-metamorphic conditions were reached post-D_2 and during D_3.

STEEP STRUCTURES

The subhorizontal regional S_2 gneissosity and sheet-like lithologies of the Okiep Copper District are cut by narrow, upright, easterly trending high-strain zones, locally referred to as "steep structures", in which the regional gneissosity and lithologies have been rotated to subvertical attitudes. The rotation of the country-rock gneissosity to the subvertical occurs in two different ways, such that steep structure geometries are expressed as:
1) antiformal steep structures (Figs. 2 and 3a), which are the most common and dramatic manifestation of steep structure development; and 2) monoclinal steep structures (Fig. 3b), which represent zones in which the regional gneissosity has been monoclinally steepened to subvertical attitudes. Antiformal and monoclinal steep structures are commonly spatially associated. A synformal steep structure has been described by Hälbich (1978), but regional mapping of the area by geologists of the O'okiep Copper Company, through many decades, has provided little evidence for the occurrence of synformal steep structures (Lombaard et al., 1986).

Steep structures show predominantly east-northeasterly trends (Fig. 4). The structures are of limited lateral and vertical extent. Strike lengths of steep structures vary from several metres to 7km. Half-wavelengths range from metres to several hundred metres and vertical extents may exceed 1.5km, but are commonly in the order of 200 to 400 m. Individual structures may initiate and terminate within a single lithology, but they can also cross-cut and "pierce" several gneissose units (Benedict et al., 1964). Steep structures may occur isolated, but are commonly developed as relatively closely and regularly spaced, easterly trending arrays (Fig. 5). Steep structures are also spatially closely associated with transgressing

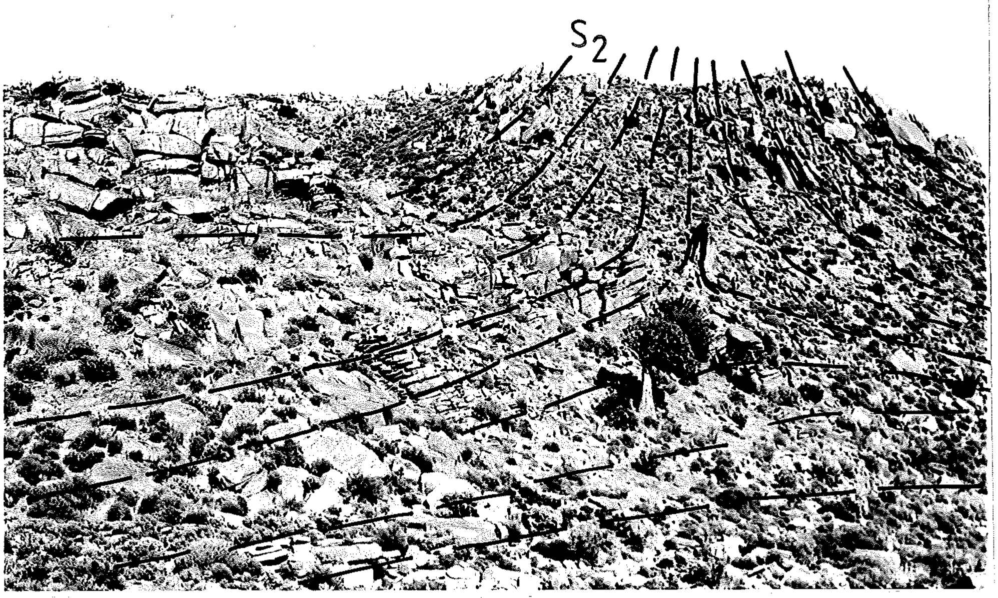


Figure 2: Antiformal steep structure at Narrap NW, viewed to the west, depicting the typical antiformal upwarp of the regional gneissosity (S_2, annotated) developed in and above regionally shallow-dipping Nababeep Gneiss.

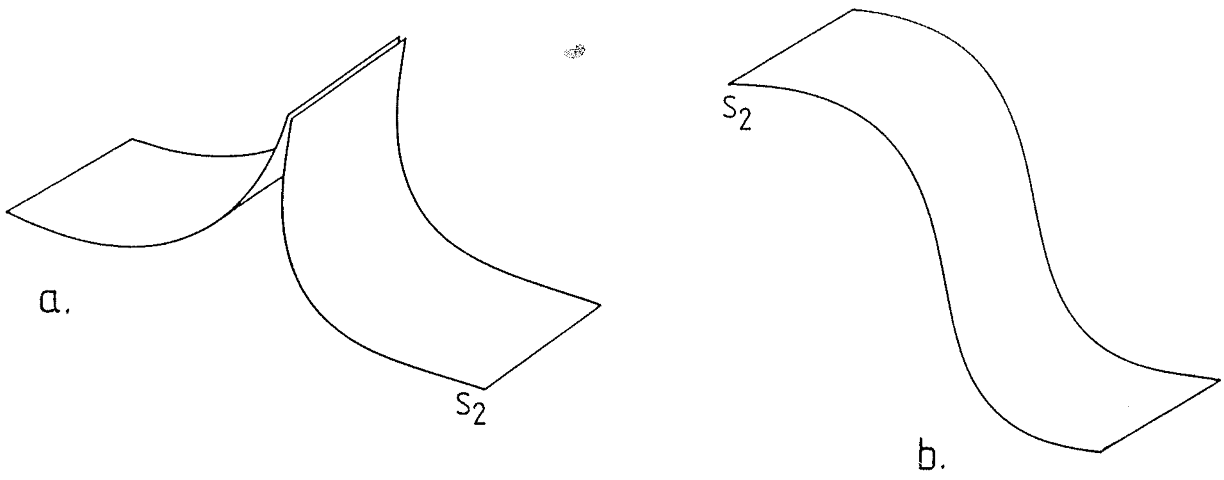


Figure 3: Schematic illustration of the typical geometries of a) antiformal steep structures, and b) monoclinal steep structures.

bodies (Kisters et al., 1992a), locally refered to as "megabreccias" (Lombaard and Schreuder, 1978). The central, subvertical parts of steep structures are, furthermore, commonly intruded by irregular, dyke-like, basic bodies of the Koperberg Suite which host the copper mineralization in the Okiep Copper District (Lombaard et al., 1986; Kisters et al., 1994).

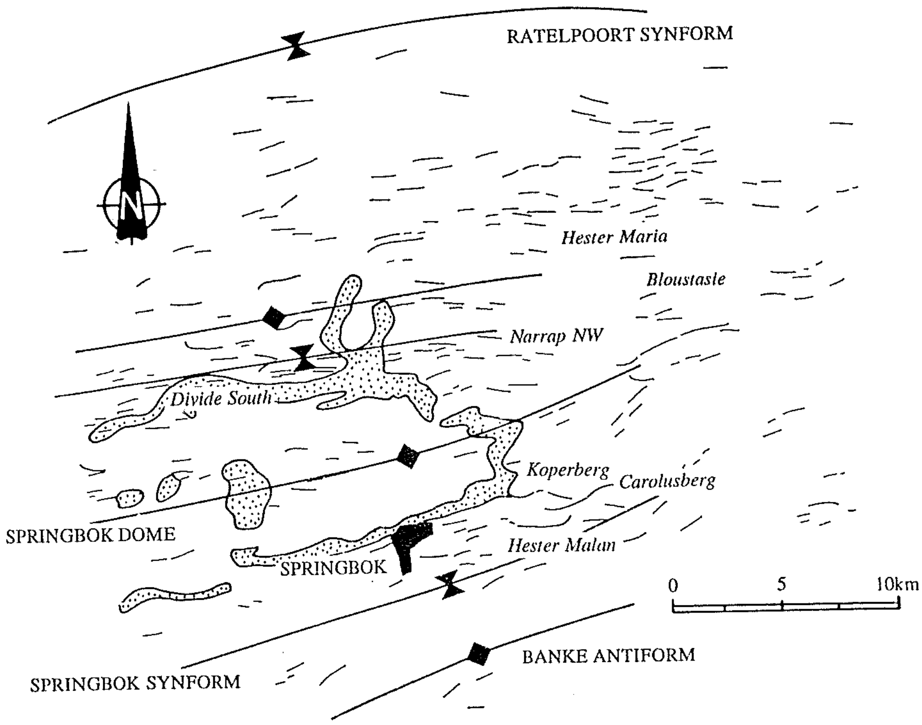


Figure 4: Occurrence of prominent steep structures and axial traces of large-scale D_3 folds in the Okiep Copper District. Names depict localities of steep structures discussed in the text. Stippled: occurrence of metasediments outlining the Springbok Dome.

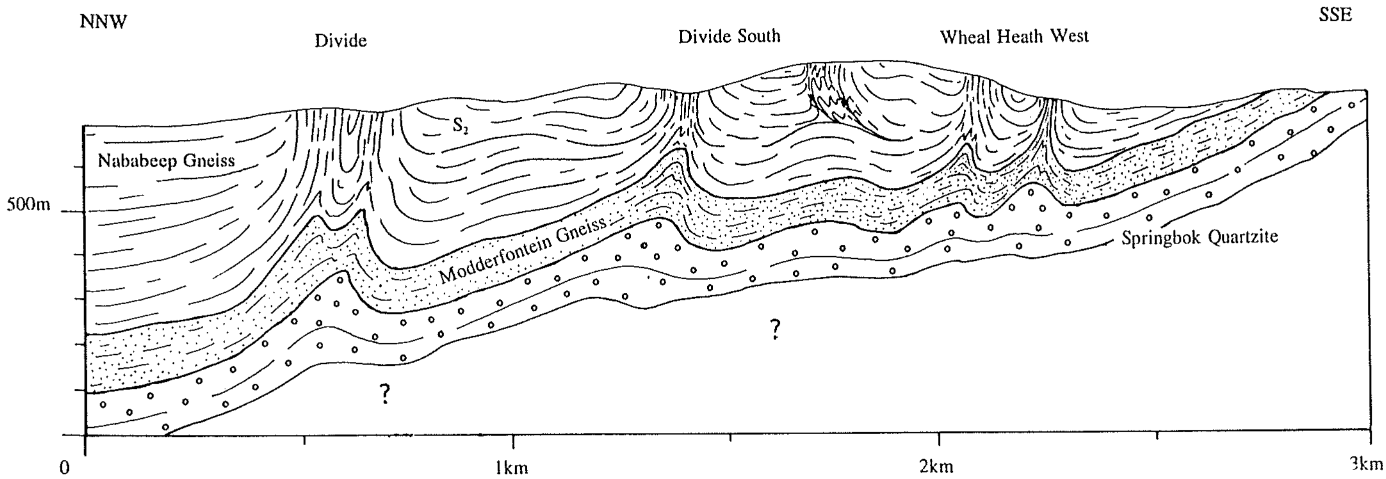


Figure 5: Simplified cross-section through the Divide area (Fig. 4), illustrating the antiformal upwarp of the regional gneissosity along closely spaced, easterly trending steep structures developed in Nababeep Gneiss at Divide, Divide South and Wheal Heath West. The intrusion of basic rocks of the Koperberg Suite into the central zones of the steep structures is not shown (compiled from cross-sections of the O'okiep Copper Company).

The lack of synformal steep structures in the Copper District, the development of a high strain fabric in the central parts of the structures and the emplacement of syn-tectonic intrusions of the Koperberg Suite into or close to the axial planes of the structures are difficult to reconcile with a fold-like origin for the steep structures. This has led to diverse interpretations on the origin and formation mechanisms of these structures. Hälbich (1978), following Wegmann (1963), in attempting to reconcile the emplacement of basic dykes of the Koperberg Suite into steep structures, envisaged the structures to represent mega-boudin necks, i.e. to be extensional features. The high-strain fabric associated with steep structures led Kröner et al. (1973), McIver et al. (1983), and Blignault et al. (1983), amongst others, to interpret steep structures as being shear zones. Local geologists, however, have repeatedly emphasized the fold-like geometries of steep structures, describing them as "cusps" or "piercement folds", although the actual formation mechanisms have remained enigmatic (Benedict et al., 1964; Lombaard and Schreuder, 1978).

The variety of interpretations and tectonic models proposed for the formation of steep structures, as well as their unique occurrence in the Okiep Copper District, underscores their complexity and enigmatic origin despite decades of mapping and research. Because steep structures vary considerably in character the following represents a synthesis of their development style compiled from the detailed mapping and structural analysis of a number of selected examples in the Okiep Copper District. Individual steep structures investigated in detail for this study are indicated in Figure 4.

Structural development of steep structures

Steep structures can be considered in terms of two end-members comprising antiformal and monoclinal steep structures. The close spatial association between the two types suggests a close genetic relationship.

Antiformal steep structures

Antiformal steep structures are geometrically best described as upward pointing cusps (Figs. 2, 3a, 5). The structures consist of an inner, easterly trending core characterized by subvertical and highly strained country-rock gneisses and two symmetrical limbs adjacent to the parallel-sided core, along which the regional, subhorizontal gneissosity is steepened. Vertical and lateral terminations of steep structures are commonly very abrupt and antiformal steep structures may terminate as 1) open antiforms, which gently grade into the regional subhorizontal gneissosity (Figs. 6 and 7); 2) monoclinal warps in which the gneissosity assumes progressively shallower attitudes (Lombaard et al., 1986; Kisters, 1993); or 3) a series of closely spaced cusps, abruptly grading into overlying subhorizontal gneissosities (Fig. 8).

The development of antiformal steep structures can be described as a progression from gentle and open folding of the S_2 gneissosity, via rapid tightening of fold shapes, to typically developed cusp-like geometries (Figs. 6 and 7). Tightening of folds from open fold shapes to tight and isoclinal fold geometries can occur within tens of metres both in plan as well as in profile section of a steep structure, suggesting highly heterogeneous strain profiles. The resulting non-cylindrical nature of folds is shown schematically for the Hester Maria steep

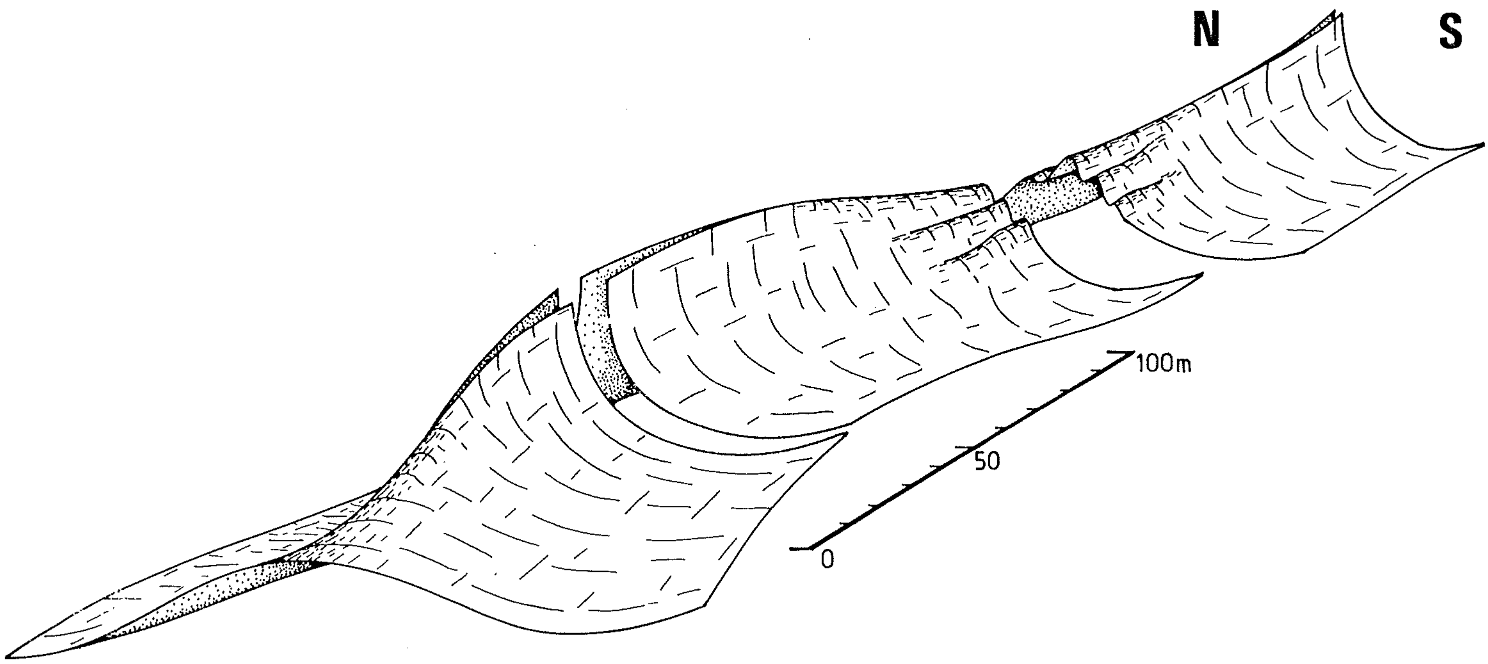


Figure 6: Schematic illustration of the variation of structural development along the Hester Maria steep structure (Fig. 4). Note the tightening and amplification of fold geometries alternating with open to gentle warps of the regional gneissosity along strike of the steep structure.

structure (Fig.6). Open folding of the S_2 gneissosity is characterized by rounded hinges showing shallow easterly and westerly plunges. The rapid tightening of folds along strike is associated with a drastic amplification of the overall structure which is most pronounced in the central parts where the typical subvertical high-strain fabric is developed. As a consequence of the tightening the curvature of the developing fold changes to give typical cusp-like forms. The amplification of the cores of steep structures commonly leads to a strong attenuation and disruption of overlying lithological units and steep structures may ultimately even pierce through their external boundary layers, as has been demonstrated for several steep structures in the Okiep Copper District (e.g. Benedict et al., 1964; Lombaard and Schreuder, 1978). The Narrap NW steep structure (Figs. 2 and 4), which is exposed on a steep flank of a hill, can be mapped over a vertical distance of some 150-200m and illustrates the tightening of fold shapes in profile (Fig. 7; levels I-VIII). The steep structure is underlain by shallow southerly dipping Nababeep Gneiss (Fig. 7, I). Steep structure development at the base of the structure is initially expressed as a gentle, west-northwesterly plunging antiformal warp of the gneissosity (Fig. 7a, II), developing upwards into open-to-close, upright, shallowly plunging folds (Fig. 7b, III) which become rapidly tightened. Tightening of the folds is associated with a dramatic amplification of fold structures yielding upright, isoclinal folds with strongly attenuated limbs (Fig. 7, IV). Ultimately, isoclinal fold closures are progressively transposed leading to the subvertical, high strain gneissosities which are characteristic of steep structure cores (Fig. 7, V).

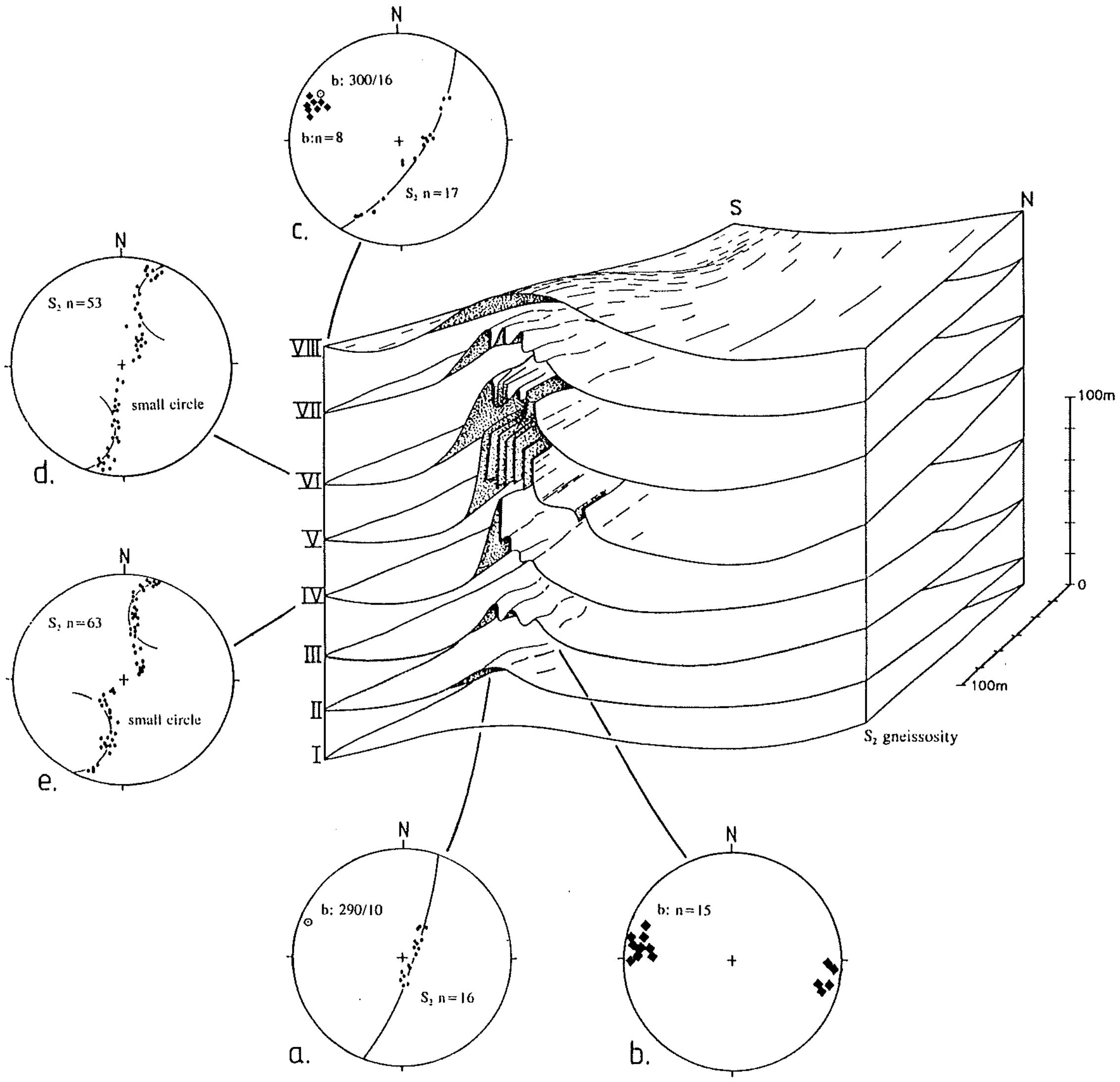


Figure 7: Schematic sketch of steep structure development at Narrap NW (Figs. 2 and 4).
a: Lower hemisphere equal area projection of poles to S_2, illustrating the open, westerly plunging fold (290/10) developed in the footwall of Narrap NW.
b : Lower hemisphere equal area projection of minor fold axes associated with the antiformal upwarp of the gneissosity in the footwall of Narrap NW.
c : Lower hemisphere equal area projection of 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: Lower hemisphere equal area projections of poles to S_2 illustrating the asymmetric, sigmoidal girdle distribution of poles to S_2 during the advanced stages of steep structure formation.

This progressive steep structure development is also reflected in stereographic projections recording the successive stages of steep structure formation. The initial gentle-to-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 (Fig. 7, a and c).

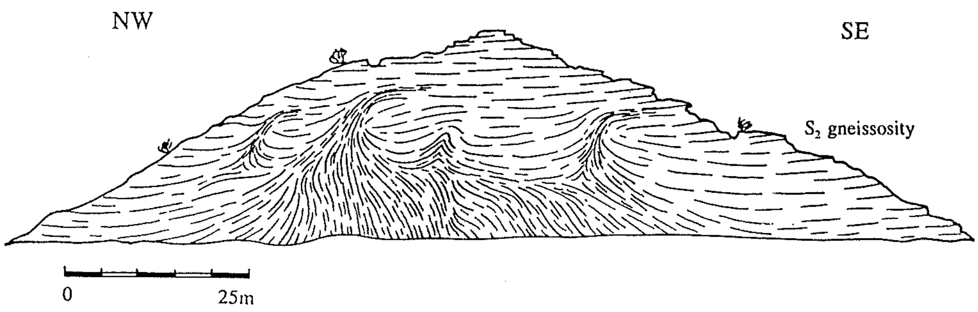


Figure 8: Cross-section through the antiformal steep structure at Bloustasie (Fig. 4) illustrating its vertical termination. Note the abrupt transition from highly strained, subvertical gneissosities to shallowly dipping, regional gneissosities in the hangingwall of the structure.

Stereographic projections of poles to S_2 during the advanced stages of steep structure formation deviate from this great circle distribution, resulting in a somewhat sigmoidal form of the girdle (Fig. 7, d and e). The sigmoidal form of the distribution of poles to S_2 is caused by steep to subvertical gneissosities in steep structure centres which fall on segments of a small circle (Fig. 7, d and e).

The steepening of the regional gneissosity into antiformal steep structures occurs symmetrically along two concave limbs which gives the structures their cusp-like geometry (Figs. 2, 5, 6, and 7). In detail, however, the actual steepening of the S_2 gneissosity, from subhorizontal to subvertical attitudes, is not continuous, but occurs in a step-wise fashion (Fig. 9). Limbs of steep structures are commonly transected by narrow, steep-to-subvertically inclined zones of high strain, which generally converge upwards. Individual shear discontinuities can be well defined, but may also be expressed simply as a subtle steepening of the gneissosity. The regional gneissosity (S_2) is sigmoidally folded between these zones, giving the appearance of macrolithons bounded by zones of shearing. The gentle-to-tight folds show shallow easterly and/or westerly plunges, parallel to the main steep structure with which they are associated. The spacing of these zones may be as much as several tens of metres, but generally decreases towards the centre of the structure, and is accompanied by progressively tighter folding and decreasing wavelength: amplitude ratios of the folds. Larger macrolithons are transected, in places, by small-scale, closely spaced shears (2-25cm apart), which are subparallel to the larger-scale shear discontinuities and which result in a crenulation-type deformation of macrolithons (Fig. 9, a and b). Wavelengths of crenulation folds thus produced decrease dramatically towards steep structure centres, grading from open fold shapes (Fig. 9a) to tight and isoclinal fold geometries (Fig. 9b), indicating an increase in strain towards the centre of the steep structure.

The regional lineation, L_2, which is expressed by elongated quartz-feldspar augen contained within S_2, is, together with the regional gneissosity, reoriented into parallelism with the steep structure (Fig. 10a). However, approaching the centre of the structure, L_2 is progressively obliterated by a subhorizontal, easterly trending intersection lineation, L_i (Fig. 10b), 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 gneissosity, S_2, and a

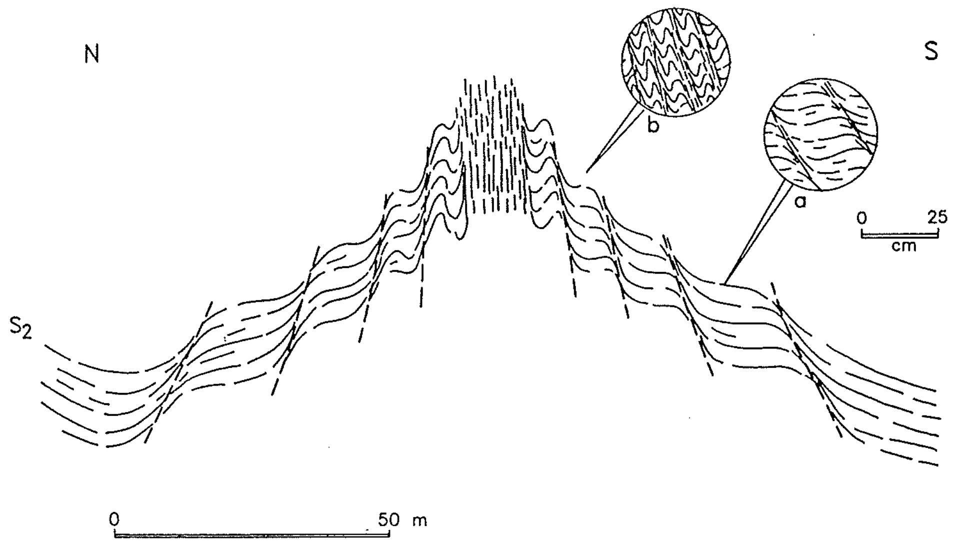


Figure 9: Diagrammatic illustration of the upwarp of the gneissosity (S_2) into the subvertical centre of steep structures, showing the sigmoidal folding of the limbs along shear discontinuities. Inserts a and b illustrate small-scale folding within macrolithons.

secondary, subvertical, easterly trending foliation, S_3 (Fig. 10b). S_3 is expressed by flattened quartz grains and is axial planar to steep structures (Fig. 10b). The development of S_3 is most apparent on the limbs of the structures, but is difficult to ascertain in the core zones because of the subparallelism between S_2 and S_3. S_3 is variably developed in individual steep structures and can locally be traced several hundred metres from steep structures into undisturbed country-rock gneisses.

Interference between antiformal steep structures and the regional, subhorizontal gneissosity results in the formation of a synform adjacent to the steep structures (Fig. 11). The orientation and plunge of the interference synform, with respect to the associated steep structure, is directly related to the regional dip of S_2, i.e. the obliquity between the regional gneissosity and easterly trending steep structure lines.

The transition between the limbs and the central parts of the antiformal steep structure is gradational as the limbs curve asymptotically into the cores of the steep structure (Figs. 2, 5, 7, and 9). The widths of the parallel-sided cores of steep structures may range from $\leq$5m to $>$100m and show good correlation with the overall size of the structure, i.e. the wider the core, the larger the amplitude and half-wavelength of the steep structure. These central or core zones of steep structures are characterized by subvertical, easterly trending, typically high-strain fabrics developed in the country-rock gneisses. The increase in strain towards the subvertical centres of steep structures is most prominently expressed by the flattening of regionally developed augen-textures within the phenocrystic granite gneisses, leading to banded textures in the core of the structures (Fig. 12). Rotation of clasts within the gneisses (e.g. feldspar-augen) during steepening of the gneissosity into steep structures is rarely observed, and the attenuation of feldspar augen and development of banded textures in steep structure centres appears to be largely due to an approximately N-S directed flattening strain. Microscopically, strain increase is manifested by a drastic grain-size reduction and recrystallization of the coarse country-rock gneisses. Feldspar phenocrysts

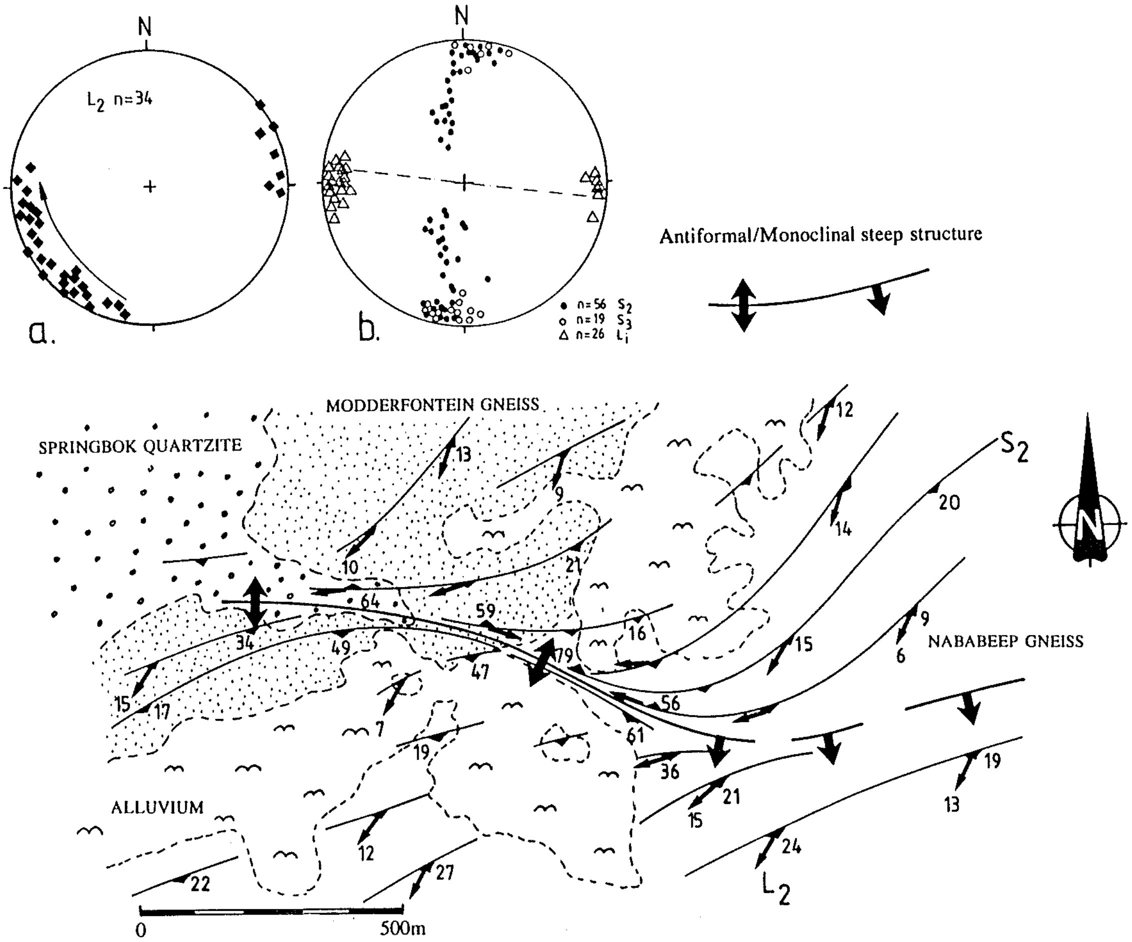


Figure 10: Simplified geological map of the Koperberg steep structure (West Extension) (see Fig. 4 for location). Note the drag and the antiformal steepening of the regional gneissosity into the steep structure. a: Lower hemisphere equal area projection of poles to S_2 and S_3, and the intersection lineation L_i. Note the asymmetric girdle distribution of poles to S_2. Dashed line represents the trend of the steep structure; b: Lower hemisphere equal area projection of the regional feldspar lineation, L_2 illustrating the rotation of L_2 into parallelism with the easterly trend of the steep structure.

develop subgrain boundaries and the initial marginal recrystallization of feldspars results, ultimately, in the formation of a fine-grained quartz-feldspar matrix. Recrystallized polygonal quartz occurs as a fine-grained groundmass or as largely undulose equidimensional quartz-grains. Strongly undulose quartz-ribbons are steeply inclined and orientated parallel to the core of the structure defining the S_3 foliation. Seams of biotite and accessory orthopyroxene define a foliation which alternates with more leucocratic portions rich in quartz, K-feldspar and plagioclase. Myrmekitic intergrowths of quartz and feldspar are common.

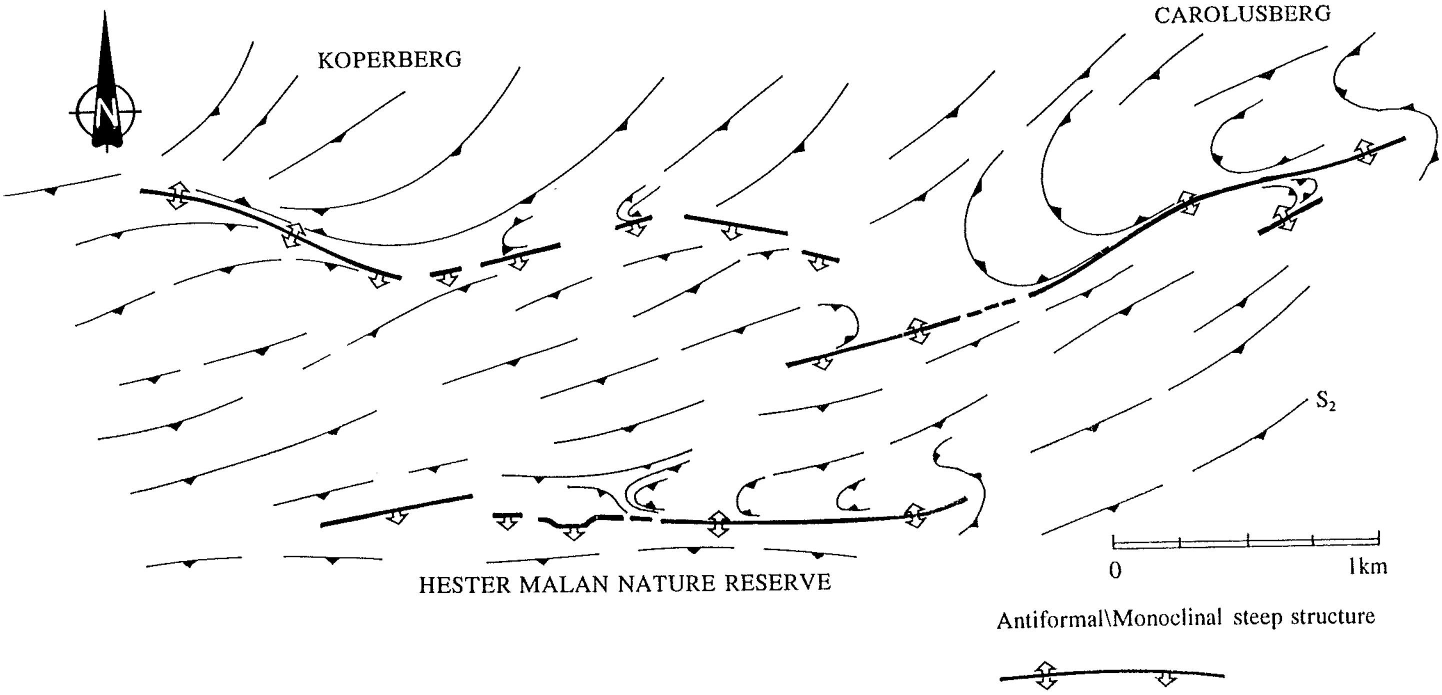


Figure 11: Trajectories of the regional, shallow, southeasterly to southerly dipping S_2 gneissosity in the Koperberg-Carolusberg area. Note the easterly undulating trend of monoclinal and antiformal steep structures as well as the adjacent interference synforms.

The high-strain gneissosity in the central parts of steep structures is characterized by the presence of secondary structures which provide clues as to the state of strain within the steep structures. Although the high-strain gneissosity in steep structure centres generally displays easterly to east-northeasterly trends, it can be shown to undulate on the scale of metres and tens of metres, both along strike and in the vertical. Undulations can be very subtle, but deviations from the general subvertical, easterly trending attitudes can be as much as 30°, which is also reflected in the fairly wide scatter of poles to steep and subvertical foliations in stereographic projections (Fig. 10a).

Conjugate shear bands commonly occur in N-S cross-sections of steep structures. Shear bands are confined to the central subvertical and highly anisotropic core zones of steep structures and may range from centimetres to several metres in extent. They may occur isolated within the foliation, but can also be developed as multiple, closely spaced sets obliterating the subvertical gneissosity which is openly sigmoidally folded between shear bands. Although morphologically very similar, shear bands can be grouped into two categories, based on their orientation with respect to the subvertical, easterly trending gneissosity in the steep structures. These include 1) shear bands with orientations $\leq 45°$ (max. 30-45°) with respect to the gneissosity (type I shear bands), and 2) shear bands showing orientation $>45°$ (max. 65-85°) to the subvertical foliation (type II shear bands). While type I shear bands are best described in terms of a "symmetric extensional crenulation cleavage" or "foliation boudinage" (after Platt and Vissers, 1980; Lacassin, 1988), type II

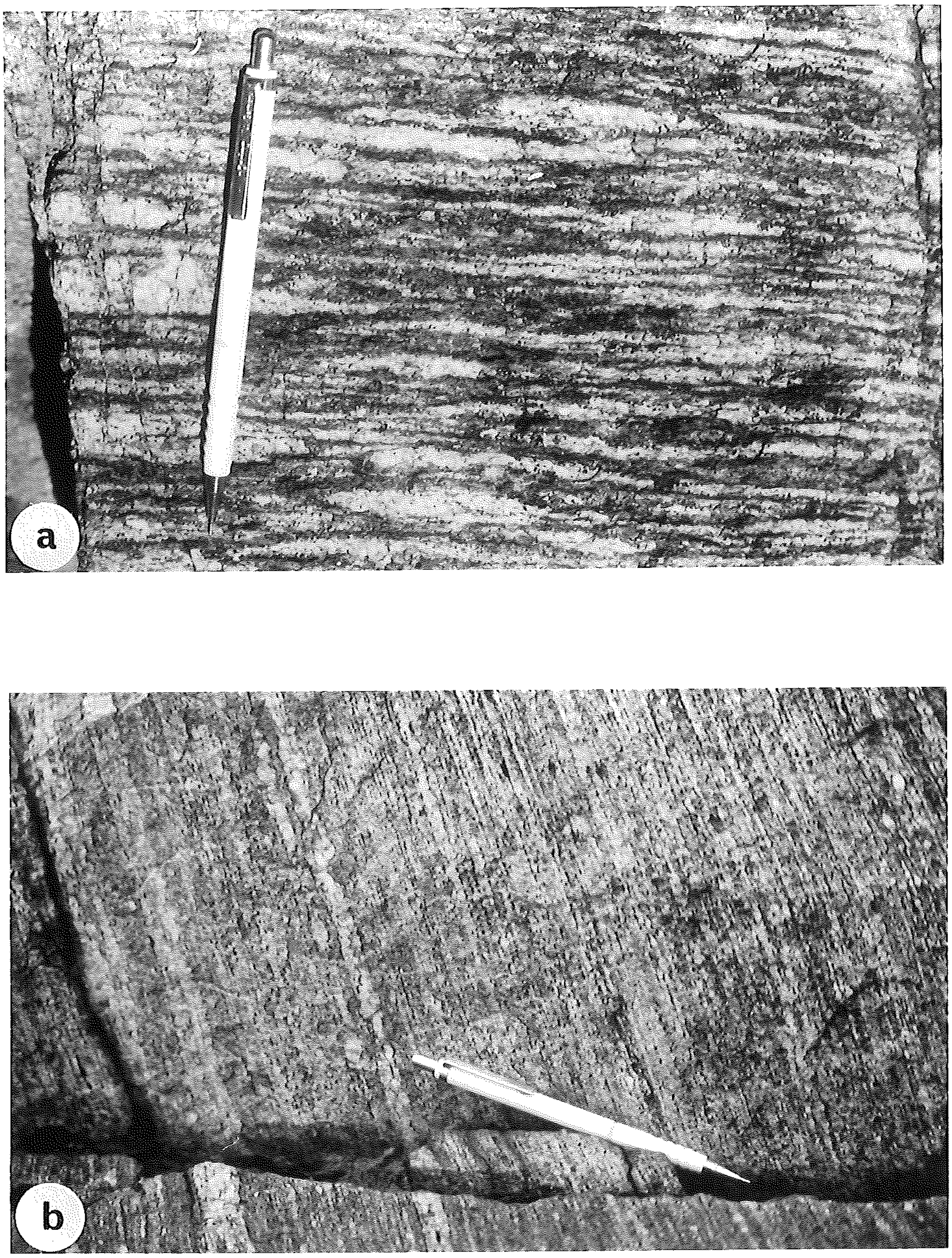


Figure 12: Photographs of the regionally developed, augen-textured Nababeep Gneiss (a), and highly strained Nababeep Gneiss in the centre of the Bloustasie steep structure (b), illustrating the flattening of regional textures and strain increase in the cores of steep structures.

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 (Burg and Harris, 1982; Nadai, 1963). Hence, the orientation and shear sense of both the type I and type II shear bands are consistent with a N-S directed, coaxial shortening normal to the subvertical, easterly trending gneissosity in steep structure centres and 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 type II shear bands or at the intersection of the conjugate shear band populations.

A variably developed mineral stretching lineation is most prominently expressed along the lateral terminations of steep structures. The subvertically plunging extension lineation is defined by elongated mineral aggregates such as quartz-feldspar augen, quartz and biotite.

Boudinage has affected both country-rock gneisses and noritoids of the Koperberg Suite in the cores of steep structures. Homogeneous country-rock gneisses in the centre of steep structures are occasionally boudinaged without showing any sign of a presumed competence contrast between the boudinaged portion and the enveloping gneisses of the same composition. The generally noritic intrusions of the Koperberg Suite display, in places, pinch-and-swell structures and/or boudinage. The necking of boudins is initiated along conjugate shears and a pegmatitic quartz-feldspar-biotite phase is commonly developed at the intersection of the shears or boudin necks respectively. Intermediate axes of boudins invariably show easterly trends, parallel to the strike of steep structures, suggesting a subhorizontal, east-westerly direction of extension.

The formation of asymmetric shear foliations in the central parts of steep structures are best described, in terms of Platt and Vissers (1980), as an "asymmetric extensional crenulation cleavage". Shear bands can be closely spaced, in which case a somewhat curviplanar appearance of the subvertical, easterly trending gneissosity 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 the easterly trending gneissosity indicate a dextral strike-slip component of movement along steep structures.

The subvertical, high-strain gneissosity in steep structure cores is locally refolded by small-scale, intrafolial, symmetric 'S'- and 'Z'- folds. Folds show predominantly shallow easterly plunges parallel to the steep structure. The folds are interpreted to have originated due to a shear component along the subvertical gneissosity during the later or advanced stages of steep structure formation.

Although textures and secondary structures in country-rock gneisses record a dramatic strain increase towards steep structure centres, the increase in strain is rarely uniform and is heterogeneous both parallel and normal to the strike of the steep structures. This is indicated by the occasional presence of lozenge-shaped areas in which the primary, phenocrystic augen textures and tight-to-isoclinal folding of the S_2 in country-rock gneisses is still observed. Low-strain zones in the cores of steep structures may be several metres wide and the commonly easterly strike length parallel to steep structures can exceed 10m, but are usually very localized. These areas become progressively obliterated by closely spaced, anastomosing high-strain zones which transpose the low-strain augen textures of the granitic augen-gneisses into the high-strain fabric of steep structure cores. Fold hinges developed during the early stages of steep structure formation and preserved in low strain areas become similarly transposed into the highly strained gneissosity of steep structure centres. The transposition of fold hinges during advanced stages of fabric development is facilitated by the lack of confining lithological layer boundaries in the gneisses, also making a recognition of the actual obliteration of hinge zones difficult.

Monoclinal steep structures

Monoclinal or sinusoidal deflections of the regional, shallowly dipping gneissosity to commonly subvertical attitudes are the typical manifestation of monoclinal steep structures (Fig. 3b). The resulting geometry is that of large-scale, monoclinal, reverse kink bands with rounded kink-band boundaries. Monoclinal steep structures trend easterly, parallel to antiformal steep structures with which they are spatially closely associated. Amplitudes of monoclinal steep structures vary considerably, ranging from 2 m to > 1.5 km in the Carolusberg monoclinal structure, the largest known steep structure.

Due to the obviously diverse geometries of monoclinal and antiformal steep structures, the structural development of monoclines differs somewhat from that of antiforms. Figure 13 illustrates a small monoclinal steep structure, exemplifying the salient features of the formation mechanisms of monoclinal steep structures, which are also observed on a large-scale. The structure occurs as a south-facing monoclinal flexure in Nababeep Gneiss, in which the regionally south-dipping gneissosity is monoclinally steepened. The monoclinal flexure is contained within S_2, i.e. the upper and lower bounding surfaces of the structure are defined by the subhorizontal regional gneissosity. While the hanging wall contact is gradational, the footwall contact is sharp, giving the appearance of a detachment zone. Country-rock gneisses in the footwall are highly strained and are markedly darker than adjacent Nababeep Gneiss, reflecting an enrichment of less soluble mafic minerals such as biotite and hypersthene in this zone. The anticlockwise rotation of the gneissosity to steeper attitudes is associated with a marked increase in strain, which is indicated by the attenuation of augen textures and decreasing grain size, as well as evidence of volume loss. An indication of the amount of dissolution of material can be obtained from the spacing of three concordant, leucocratic marker bands within the structure (Fig. 13). Traced from outside the monoclinal flexure into the steepened gneissosity, the bands show a convergence of about 70%, which can be taken as a crude approximation of the amount of material being dissolved during fabric development in the structure. Small-scale, upright folds of S_2 in the structure (Fig. 13) suggest a dextral foliation-parallel shear. This is opposite to the bulk anticlockwise (sinistral) rotation of S_2 and suggests that some strain is accommodated by a flexural-slip type mechanism such as is occasionally observed in kink folds (Dewey, 1965).

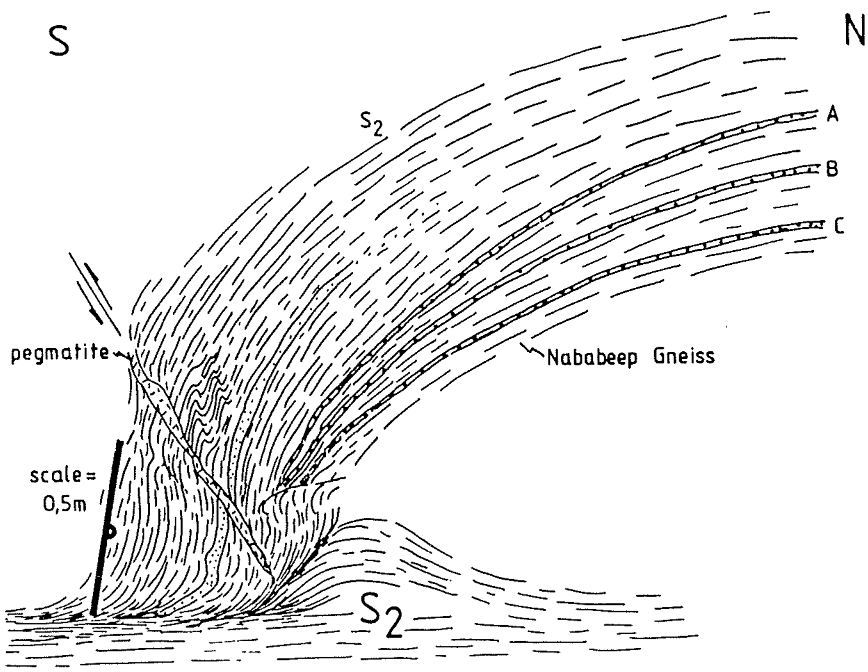


Figure 13: Schematic sketch of a small monoclinal flexure in Nababeep Gneiss, looking west. Lower bounding surface (bottom of clino-rule) is represented by highly strained, subhorizontal gneissosity. The monoclinal steepening of S_2 is associated with the formation of smaller antiforms (centre of the sketch) superimposed onto the monoclinal flexure. The convergence of three marker bands (A, B and C) traced into the monoclinal flexure indicates a volume loss by dissolution of material.

Regional disposition of steep structures

The subvertical gneissosity in steep structures trends predominantly east-northeast, parallel to the axial traces of large-scale D_3 folds such as the Springbok Dome and the Ratelpoort Synform (Fig. 4). Steep structures may form en-échelon arrays with both left- and right-stepping off-sets being observed (Fig. 11). The axial traces of the structures may themselves be sinuous, and trains of composite, slightly undulating steep structure lines can be followed for several kilometres along their strike (Fig. 11). Adjacent steep structures may be separated by only gently folded country-rock gneisses, but rapid tightening and amplification of folds leads into zones of typical steep structure development.

Steep structure development varies throughout the sequence of granites and granite-gneisses of the Okiep Copper District. The structures are well-developed in the lower, foliated, gneissose units of the Okiep Copper District sequence (i.e. gneisses 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, porphyritic granites comprising most of the Spektakel Suite (Kisters et al., 1992b; Kisters, 1993).

Strain in steep structures

Various fold geometries associated with individual steep structures reflect the highly heterogeneous strain as well as different types of strains formed along steep structures during their progressive development.

The initial stages of steep structure formation are largely characterized by a component of non-coaxial deformation, namely a layer-parallel shear along the subhorizontal S_2 gneissosity which acts a detachment (Fig. 13). As the S_2 gneissosity attains steeper attitudes in steep structures, non-coaxial deformation becomes less evident. Once the steep structure has developed into its typical upright position, it appears to lock-up, and lateral propagation of the structure is no longer observed. Instead a component of vertical amplification and propagation along strike prevails under a largely N-S directed, subhorizontal flattening strain. The XY-plane of the finite strain ellipsoid for these advanced stages of steep structure formation can be approximated by the orientation of the subvertical, easterly trending, high-strain gneissosity in the steep structures. A principal direction of extension in the subvertical is indicated by the subvertically plunging mineral stretching lineation, as well as the orientation and shear sense of secondary shear bands and Lüder's bands. On the other hand, easterly trending intermediate boudin axes developed in country-rock gneisses and competent, dyke-like intrusions of the Koperberg Suite suggest a subhorizontal, east-west trending direction of principal extension. It thus appears that the finite strain ellipsoid in the central zones of steep structures is of an oblate (flattening) type ($X \approx Y > Z$) recording a N-S directed shortening strain perpendicular to the easterly trend of the steep structures (see also Venter, 1984). A component of non-coaxial deformation is, however, recorded by 1) refolding of the high-strain gneissosity of the steep structure cores, and 2) an asymmetric extensional crenulation cleavage, documenting a strike-slip component along steep structures.

DISCUSSION

Progressive steep structure development

Steep structure development can be described as a progression from open, upright, shallowly plunging folds and/or monoclinal warps, via upright, high-amplitude isoclinal folds to subvertical, high-strain, easterly trending gneissosities in which the initial folds have been largely obliterated. This sequence of progressive steep structure development departs markedly from the classical models of buckle-fold development raising questions as to the mechanism involved in their formation.

As was demonstrated previously steep structures develop progressively as open folds or monoclinal warps exclusively in well foliated gneissose units of the Okiep Copper District granite-gneiss sequence. Further development is characterized by the explosive amplification and progressive obliteration of earlier folds and the formation of subvertically inclined high-strain fabrics. Latham (1985a,b), in his treatment on the folding behaviour of non-linear materials, emphasized the close relationship and continuum between folding, kinking and shearing. The properties and deformational behaviour of non-linear materials are strongly influenced by the presence and orientation of a pre-existing, or intrinsic anisotropy and the development of induced anisotropies. Rocks with strongly intrinsic anisotropies, such as a layering or foliation, will favour the development of folds or kinks during layer-parallel plane-strain shortening. The development of induced anisotropies, by contrast, occurs preferentially in relatively homogeneous materials in which shortening of the rock mass can not be achieved by buckling, due to homogeneity and the lack of competence contrasts within the rock. Induced anisotropies can be represented by regularly orientated fabrics throughout the sequence (e.g. cleavages or schistosities) or by conjugate shear zones or faults (Latham, 1985a,b; Price and Cosgrove, 1990). Once initiated, induced internal instabilities, like shear zones,are likely to be amplified due to the strain softening effect commonly associated with non-Newtonian materials (Ramsay and Huber, 1987).

In country-rock gneisses of the Okiep Copper District folding is initiated by the buckling of the pre-existing gneissosity, outlining the significance of the S_2 gneissosity as an intrinsic anisotropy for the nucleation of steep structures. Further development, however, is characterized by the formation of highly strained fabrics obliterating earlier folding, suggesting that the amplification and advanced stages of steep structure development record an induced anisotropy. This changeover, from early-stage folding acting as a nucleus for progressive heterogeneous shortening and shearing, reflects the combination of geometrical and mechanical properties of the granitic gneisses in the Okiep Copper District. An intrinsic anisotropy favouring the formation of folds is provided by the S_2 gneissosity developed in the gneissose units where steep structures are preferentially developed. On a bulk scale, however, the compositionally homogeneous granite-gneiss sequence of the Okiep Copper District can be regarded as a unit where intrinsic anisotropies are negligible, rather promoting the development and amplification of internally induced anisotropies. Latham (1985a,b) pointed out, however, that induced anisotropies should develop conjugate sets of shear zones and/or faults inclined to the bulk shortening strain and recording a largely non-coaxial deformation. The fact that steep structures are approximately normal to the bulk shortening direction and record a large component of co-axial shortening can be attributed to the very low strength of the partially molten granitic gneisses during the high-grade metamorphism.

The actual displacement field occurring in steep structures is best described as an extrusion of the central parts of the structures under an approximately N-S directed, bulk heterogeneous pure shear (Fig. 14). Bulk shortening strains are inevitably associated with a strain incompatibility or 'space problem' (Ramsay, 1967; Bell, 1981; Ramsay and Huber, 1987). This potential strain incompatibility along steep structures is accommodated by a variety of mechanisms reflecting a partitioning of the bulk strain into differential shortening components normal and parallel to the steep structure. These include: 1) a subvertical and lateral material flow accompanying the N-S directed shortening which is most dramatically documented by the attenuation and piercing of external material layer boundaries. A component of gravitationally induced instability during steep structure development is suggested by the lack of synformal steep structure geometries and the amplification of anti-formal steep structures. Subvertical material flow is, furthermore, supported by the presence of a subvertical mineral extension lineation, as well as the orientation and shear sense of shear bands (type I and II) and a late-stage refolding of the high-strain gneissosity; 2) shear discontinuities on the limbs of steep structures (Fig. 9) which reflect shear strains that are induced in order to accommodate strain heterogeneities and the heterogeneous vertical ampli-

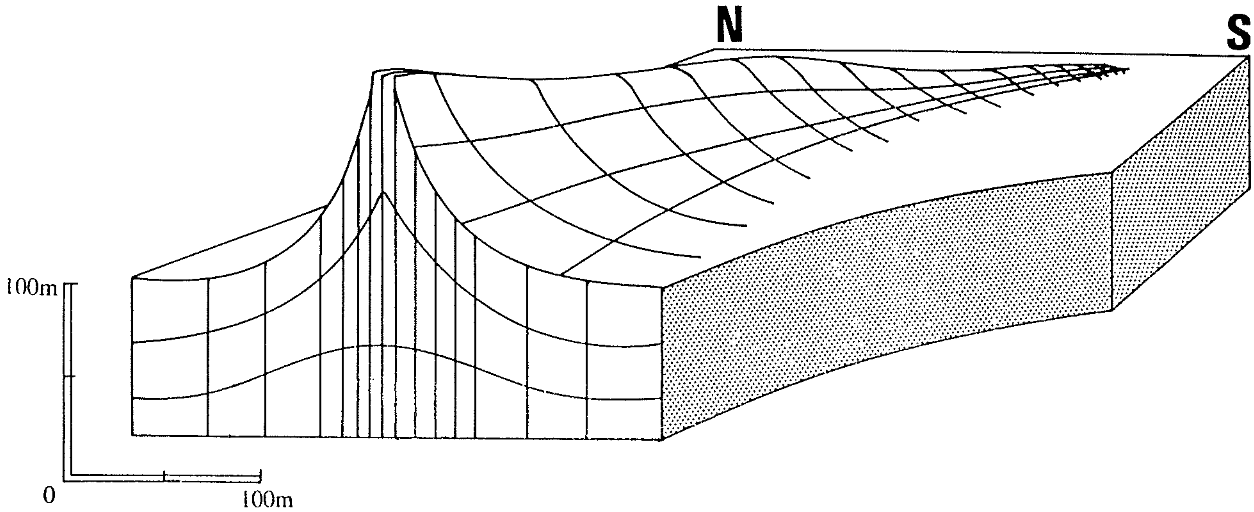


Figure 14: Simplified displacement field for a steep structure formed under largely heterogeneous pure shear, illustrating the amplification of the central parts of steep structures and progressively more open fold shapes grading into undeformed material (modified after Bell, 1981; Ramsay and Huber, 1987).

fication across steep structures; and 3) volume loss by dissolution of material in the cores of steep structures.

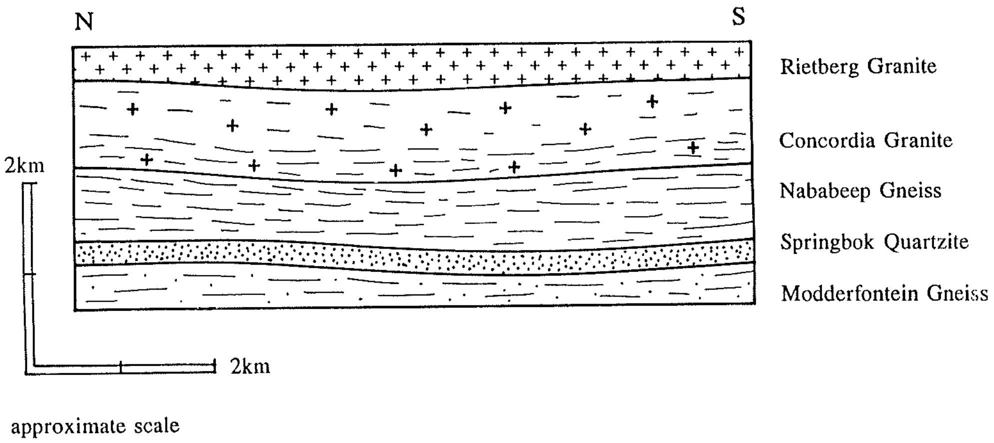
The amplification of monoclinal steep structures is characterized by a steepening of the monoclinal limb to subvertical attitudes which is, as it is the case for antiformal steep structures, associated with an intense fabric development. The bulk N-S shortening strain and external rotation of the regional subhorizontal gneissosity is accommodated by a subvertically directed flexural slip along the subvertical gneissosity, frequently resulting in the superimposition of antiformal upwarps onto monoclines, as well as volume loss during fabric development.

Significance of steep structures for the deformation of the Okiep Copper District

The most prominent manifestation of the D_3 deformation is the formation of ENE-trending, large-scale, upright, often periclinal folds such as the Springbok Dome and the Ratelpoort Synform. The large-scale folds show wavelengths in the order of 4 to > 10km and openly refold the flat lying lithologies and gneissosities of the granitic gneisses. A D_3 origin of steep structures coeval with large-scale folding of the granite-gneiss sequence in the Okiep Copper District is suggested by their geometries and orientation, including the parallelism between steep structure trends and the axial planes of upright, regional-scale folds (Fig. 4). In addition, the orientation of the finite strain ellipsoid in steep structures coincides with the approximately N-S directed, compressional D_3-event, and is also responsible for the development of D_3-folds.

The amount of shortening recorded by the open buckling of the gneissose strata in regional-scale D_3 folds is small. Tight-to-isoclinal fold geometries in steep structures, indicate, however, a considerably greater amount of shortening than that recorded for large-scale D_3 folds. Considerable volume loss in steep structures suggests that shortening is even greater than is indicated by the geometries of the structures. This apparent discrepancy reflects the response of the relatively homogeneous lithological granite-gneiss sequence of the Okiep Copper District to D_3 folding, i.e. N-S shortening. The lack of any marked competence contrasts between individual lithologies is likely to have resulted in predominantly layer parallel shortening during the D_3 deformation (e.g. Biot, 1961; Ramsay, 1967; Sherwin and Chapple, 1968). The amplification rates of regional-scale buckle folding will be low. The bulk homogeneous strain-induced by layer parallel shortening resulted in 1) the development of strain-induced fabrics, showing a regular orientation throughout the granite-gneiss sequence and accommodating the N-S directed shortening strain, and 2) a crustal thickening at the level of the Okiep Copper District (Fig. 15).

a.



b.

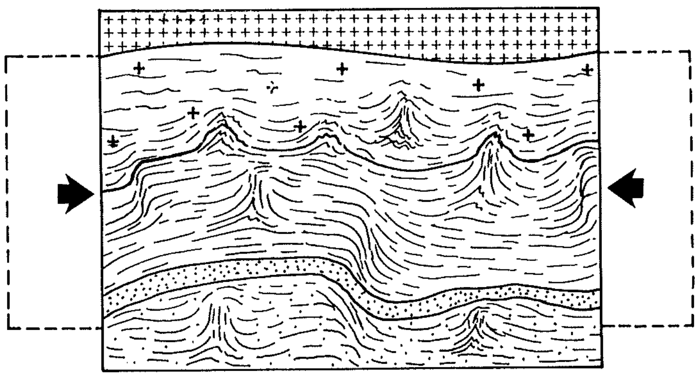


Figure 15: (a) Schematic cross-section through the Okiep Copper District depicting the after effects of the fabric-forming D_2 event. (b): Sketch showing that the co-axial shortening, developed during D_3, is largely accommodated by layer parallel shortening and consequent crustal thickening rather than by buckle folding of the granite-gneiss sequence. Layer parallel shortening is associated with the developent of induced internal instabilities, i.e. steep structure formation. Note that the amount of layer parallel shortening is only presented qualitatively.

On a bulk scale, cores of antiformal steep structures are essentially parallel to the axial planes of regional-scale D_3 folds suggesting that the structures have partly assumed the function of an axial planar cleavage being subparallel to the XY-plane of the bulk strain ellipsoid (Williams, 1976, 1977). Bell (1981) has emphasized the anastomosing nature of foliations formed under predominantly bulk inhomogeneous shortening and which is reflected in the often undulating strike of the steep structures.

The pervasive fabric development and concentration of strain in the central zones of the steep structures, compared to the relatively unstrained enveloping country-rock gneisses, suggests strain softening during progressive deformation. Strain softening is likely to be enhanced by the presence of partial melts and the dissolution of material during fabric development. The presence of partial melts may increase strain rates by orders of magnitude (e.g. Pharr and Ashby, 1983) and deformation processes are likely to change from dominantly dislocation creep to melt-assisted dislocation creep and boundary melt migration (e.g. Dell'Angelo and Tullis, 1988; Cooper and Kohlstedt, 1986), promoting the pervasive fabric development in steep structures.

Crustal thickening of the Okiep Copper District during high-grade metamorphism and deformation is suggested by the anticlockwise P-T-t path of the terrane (Waters and Whales, 1984; Waters, 1986; 1988; 1990). Although crustal thickening has largely been attributed to the addition of granitic magmas at the level of the Copper District, a component of tectonic thickening cannot be neglected. Layer-parallel shortening and crustal thickening was assisted by the material flow and geometries of both antiformal and monoclinal steep structures. Monoclinal steep structures showing S-down as well as N-down deflections of the regional gneissosity describe a conjugate pattern on the larger scale of the Okiep Copper District as a whole. The geometry of this conjugate set of reverse monoclinal structures suggests the accommodation of a N-S directed shortening parallel to the lithological layering and subhorizontal fabrics of the granite-gneiss sequence. Crustal thickening, assisted by antiformal steep structures, is accomplished by the predominantly vertical material flow within the structures, as well as their antiformal geometries.

CONCLUSIONS

A genetic relationship exists between regional-scale, upright, easterly trending, open D_3 folding of the high-grade metamorphic granite-gneisses of the Okiep Copper District and steep structure formation. The regularly orientated, easterly trending, upright steep structures are axial planar to large-scale folds and represent strain-induced anisotropies that formed in response to N-S directed bulk inhomogeneous shortening during the D_3 deformation. Initiation of steep structures occurred by buckling of the pre-existing, subhorizontal gneissosity, S_2, within the gneissose units of the Copper District sequence. Because of the homogeneity, on a bulk scale, of these granitic gneisses, progressive shortening resulted only in the slow amplification of large-scale buckle folding of the sequence as a whole (i.e. D_3 regional folding) and was largely accommodated by layer parallel shortening. Although steep structures initiate by buckle folding of the pre-existing gneissosity as a plane of anisotropy, further development, on a larger scale, is determined by the homogeneous, non-linear behaviour of country-rock gneisses, which inhibits further response to deformation by buckling. Early-stage folding in steep structures represents the nucleus for further steep structure development, but is progressively obliterated by strain induced high-strain zones, favoured by the material properties of the high-grade metamorphic gneisses. These high-strain zones form parallel to the XY-plane of the bulk strain ellipsoid, now acting as an axial planar foliation. Easterly trending, reverse 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 monoclinal steep structures, are likely to have resulted in a tectonic crustal thickening of the Okiep Copper District. The prevailing antiformal geometries of steep structures and their frequent association with anatectic migmatites point, furthermore, to the significance of gravitationally induced instabilities for their formation. These aspects, involving the role of gravity in the formation of steep structures, will be discussed in a follow-up paper (Kisters et al., in prep.).

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