Journal of Structural Geology 33 (2011) 280–291

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Key-ring structure gradients and sheath folds in the Goantagab Domain of NW Namibia

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ARTICLE INFO

Article history:
Received 23 June 2010
Received in revised form
22 November 2010
Accepted 5 December 2010
Available online 24 December 2010

Keywords:
Deformation phase
Sheath fold
Namibia
Foliation

ABSTRACT

The concept of deformation phases is one of the corner stones of structural geology but, despite its simplicity, there are situations where the concept breaks down. In the Goantagab Domain of NW Namibia, structures in an area of complex deformation can be subdivided into at least four sets, attributed to four deformation phases on the basis of overprinting relations. Three of these sets of structures, however, formed during the same tectonic event under similar metamorphic circumstances but slightly different flow conditions. These sets of structures show gradational transitions in space that can be understood by a concept of "key-ring structure gradients", where older D_A structures are reoriented and overprinted by new structures D_{A+1} that have similar orientation, and seem to grade into D_A structures outside the overprinted area. This kind of behaviour may be common in inhomogeneous non-coaxial flow. In the core of the Goantagab Domain, D_2 structures are thus reoriented and overprinted by local D_{2b} folds and foliations that have the same orientation and style as D_2 structures outside the domain core.

1. Introduction

In structural geology, we traditionally organise deformation structures such as foliations, lineations and folds into groups that we attribute to deformation phases (e.g. Ramsay, 1967; Hobbs et al., 1976; Ramsay and Huber, 1987; Marshak and Mitra, 1988; Passchier and Trouw, 2005). In all cases, dating of minerals or intrusions can be attempted to obtain absolute ages, but this should only be done after detailed information on structural relations has been obtained by careful analysis of the relative age and style of structures in the field. The relative age of groups of structures is established through overprinting relations. The deformation phases, thus defined, represent deformation over a certain period of time at any location, although they may be diachronous over a larger area.

Besides overprinting relations, deformation phases are usually characterised by a distinct style of the structures produced, which is an effect of imposed deformation conditions, e.g. metamorphic grade, stress field orientation or flow type: a change in style may mean that imposed deformation conditions locally changed (Hobbs et al., 1976; Ramsay and Huber, 1987; Marshak and Mitra, 1988; Passchier and Trouw, 2005). In some areas, the style of deformation structures may be different enough to be used as a distinguishing criterion in the absence of overprinting relations, although this is less reliable. If deformation phases recognised in a volume of rock are separated by long time intervals without deformation, they may represent tectonic events within orogenies, or even distinct orogenic events (Passchier and Trouw, 2005).

Despite the simplicity of this concept, there are transitional situations where the method cannot be easily applied. Some deformation structures cannot be easily attributed to chronologically distinct phases. For example, shear band cleavage in mylonites represents a second, overprinting foliation that forms during the same mylonitisation process that produced the main mylonitic foliation in the first place. We do not normally label these foliations as S_1 and S_2, belonging to separate deformation phases. Normal crenulation cleavage, however, which may form by small shifts in the orientation of the stress field, is labelled as belonging to a separate phase by most geologists; although there are similar overprinting relations in both cases, the difference is that imposed conditions are considered to have remained the same for shear band cleavage, while crenulation cleavage formed because the external stress frame changed orientation with respect to the fabric.

It is obvious that the distinction structural geologists make between shear band cleavage and crenulation cleavage is rather ambiguous and confusing for students. Where do we start to use different labels, and how can this ambiguity be handled? How can we distinguish structures that form by overprinting of separate

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doi:10.1016/j.jsg.2010.12.005

deformation events separated in time from those that form in the course of one tectonic event? These are the questions that we address in this paper based on a complex structural domain in NW Namibia.

2. The concept of expression

In biology, the shape of an organism is defined by its genes and their 'expression', i.e. the extent to which they produce biological structures; different expression levels mean different final shapes. By analogy, in structural geology we could use the term "expression of a deformation phase" to mean the final geometry of structures locally produced by that phase due to the combination of (1) lithology; (2) previous structure; (3) imposed conditions such as stress orientation and geometry, metamorphic conditions and flow type and (4) accumulation state of the deformation, i.e. local finite strain. The 'expression' of a deformation phase for identical imposed conditions and finite strain can be a continuous schistosity in schist, an open fold and spaced cleavage in sandstone, a crenulation cleavage in previously foliated schist; and no visible structure in a marble. Deformation phase expression can therefore vary strongly over an area even though finite strain, bulk stress orientation and other external deformation conditions were similar. In structural geology, it is tradition to concentrate on a comparison of deformation structures, focussing on the exact nature and geometry of structural expression in each deformation phase. However, this hampers interpretation if no attention is paid to the cause of the differences. Levels of expression are only of significance to understand the tectonic history of an area if they are due to different imposed conditions, not if they are due to differences in lithology or finite strain. In this paper we stress the importance of separating expression gradients that are due to changes in imposed conditions, from those due to these other factors.

3. Handling deformation phases

One of the difficulties in structural geology is to recognise structures of different shape and orientation as being of the same age, i.e. to determine whether different structures are just different expressions of one deformation phase, or of different phases. In our dealing with deformation structures on a regional scale, we have to deal not only with variable expression in any one place, but also with complex spatial gradients and changes in expression with time. The nature of such gradients is best illustrated by an example from biology where similar gradients are common.

Organisms that have evolved in isolation for a long time are clearly distinguishable as different species, while those more closely related are regarded as subspecies. The subdivision of animal groups into species may seem more robust than the geological concept of deformation phases, but it can also break down if considered in adjacent regions. As an example, the European herring gull *Larus Argentatus* is separated in Europe from the Lesser Black-Backed Gull *Larus Graelsii* as separate species, since they do not interbreed in the wild. The former, however, does interbreed with a north American subspecies, which interbreeds with an east Siberian subspecies and so forth, until the last subspecies is interbreeding with *Larus Graelsii*, creating a ring-shaped distribution around the northern hemisphere. Differences between individuals gradually change from east to west until in Europe both gradients produce a full separation of species that do not interbreed (Irwin et al., 2001a). Because of the similarity with a key-ring, species with this characteristic are known in biology as *ring species* (Irwin et al., 2001a,b; Alström, 2006).

In structural geology we are occasionally dealing with similar situations. Within one highly deformed zone, shear sense can grade from well defined and sinistral through a less defined zone into a dextral sense; domains with two overprinting foliations grade into areas with one or three foliations. At present, we know that these gradients may exist, but we lack the proper tools to deal with them in an efficient way. In some cases, gradients in structure may even turn back on themselves in a similar way as that of "ring species" in biology. This paper describes such features, which we name "key-ring structure gradients" in a complex area in NW Namibia, where they can be reconstructed because of the generally excellent outcrop. Such gradients may also exist in other areas, hidden by poor outcrop.

4. Regional geology

The Lower Ugab Domain in Namibia (Hoffman et al., 1994) is the centre of a Neoproterozoic to Cambrian triple junction between the Kaoko, Gariep and Damara Belts, separating the Congo, Kalahari and Rio de la Plata Cratons (Miller, 1983; Goscombe et al., 2003a,b; 2004, 2005; Passchier et al., 2007; Gray et al., 2006, 2008). We concentrate on a dome structure along the east side of this domain, the Goantagab Domain, which shows unusual polyphase deformation of great lateral variability (Fig. 1).

4.1. Stratigraphy

The Lower Ugab Domain (Fig. 1) shows a monotonous stratigraphy of deepwater metaturbidites with very little lateral facies variation from the coast up to the contact with the Goantagab Domain in the east. It consists of five formations with a total minimum thickness of about 1600 m (Swart, 1992; Paciullo et al., 2007; Passchier et al., 2007). The basement is not exposed. Two turbiditic marble deposits, the Brandberg-West and Gemsbok River Formations, separate three formations of pelitic and psammitic metaturbidite (Zebraputz, Brak River and Amis River Formations respectively; Swart, 1992) (Fig. 1). Regional scale mapping suggests that the Brandberg-West and Gemsbok River marbles correspond to cap carbonates which represent the end of the Sturtian and Marinoan glaciations, now dated at ca. 720 and 650 Ma (Kendall et al., 2004; Hoffmann et al., 2004; Hoffman and Halverson, 2008).

The Goantagab Domain adjoins the eastern edge of the Lower Ugab domain (Fig. 1) and is stratigraphically and structurally distinct (Figs. 1 and 2), although local stratigraphy is difficult to reconstruct because of intense deformation. The Amis River Formation is identical in the Lower Ugab and Goantagab Domains, while lower units show significant facies changes (Fig. 1). The highest exposed marble formation is correlated to the Gemsbok River Formation, although of greater thickness than in the west, and containing lenses of marble breccia, conglomerate and diamictite. A pair of lower marble units, separated by micaschist, are correlated to the Brandberg-West Formation in the Lower Ugab Domain (Figs. 1 and 2). The upper unit of this pair is massive while the deepest unit is divided into many thin lenses, possibly in part due to deformation, although no fault rocks have been recognised on the contacts. The equivalents of the Brak- and Zebraputz formations separating the marble formations are recognisable in the Goantagab Domain, but contain numerous discontinuous lenses and layers of coarse, immature brown sandstone and quartzite. In Fig. 2, the Lower Brandberg-West and Zebraputz formation equivalents are presented as a single unit since they are hard to separate at this scale. Diamictite occurs as discontinuous lenses at several levels in the stratigraphy, probably representing local debris flows. A unit of mafic schist probably represents a strongly deformed sill of metadolerite that intruded relatively early since it has undergone all deformation phases in the area (Figs. 2H and 3). The change in stratigraphy from the Lower Ugab Domain to the Goantagab Domain is probably gradual, but the deeper units of both

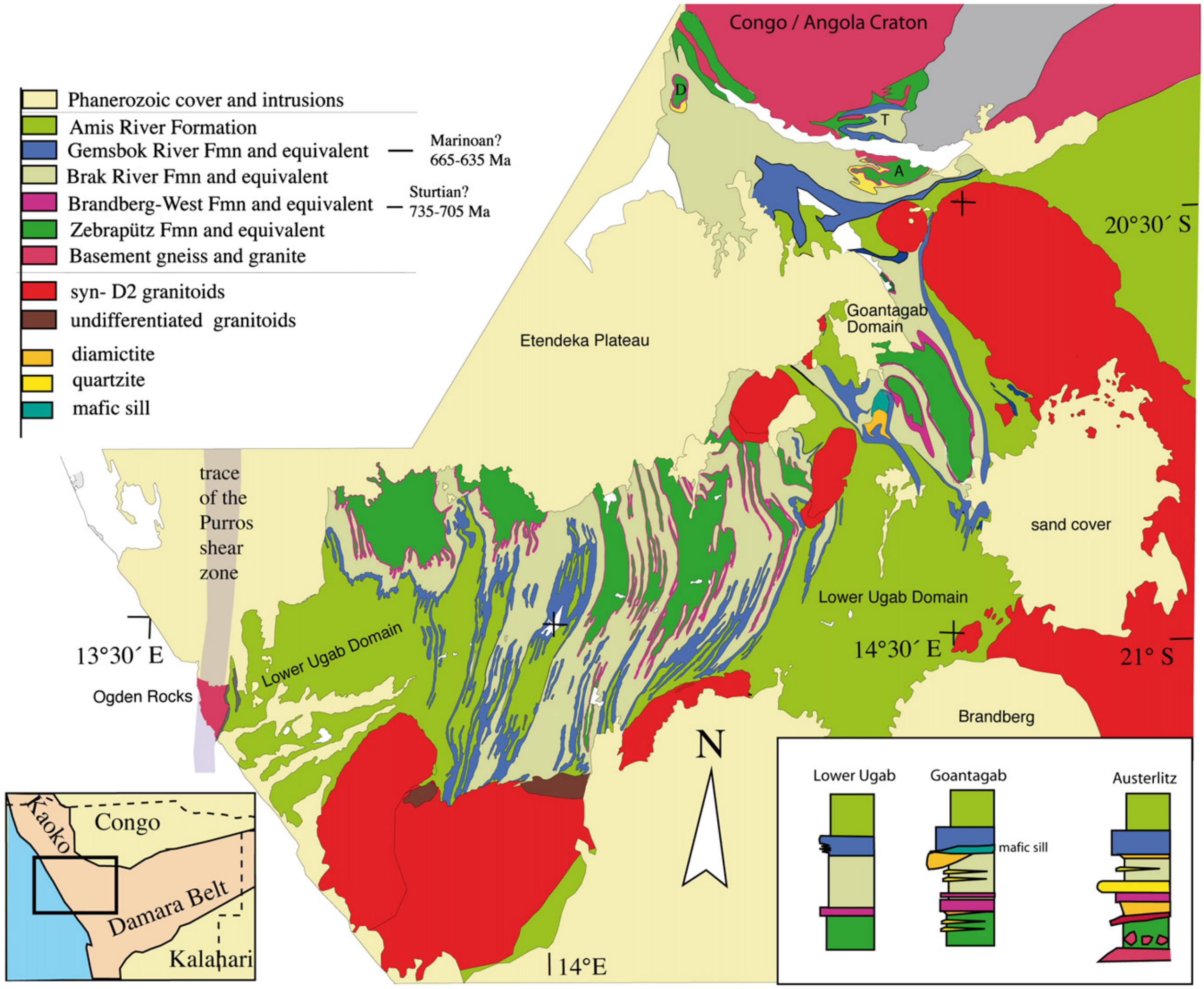

Fig. 1. Simplified geological map of the lower Ugab river catchment, Namibia, partly after the Fransfontein map sheet, published by the Geological Survey of Namibia. The Goantagab Domain discussed in this paper lies at top right. Simplified stratigraphic columns are given at lower right for the Lower Ugab, Goantagab, and Austerlitz areas. Domes in which lower units are exposed in the north are named Austerlitz (A), Donuts (D) and Toekoms (T).

stratigraphies are separated by a 6 km wide syncline of Amis River formation, hiding the transition within these units (Fig. 1).

North of the Goantagab Domain the deeper units, below the Amis River formation, crop out in three domal structures known as the Austerlitz-, Toekoms- and Donuts Domes (Fig. 1; Maloof, 2000; Hoffman and Halverson, 2008) with a different stratigraphy again, including quartzite and several sills of porphyritic volcanics. All formations onlap onto mid-Proterozoic gneisses and granites of the Kamanjab Inlier, related to the Congo/Angola Craton in the north. Clearly, the changes in stratigraphy from west to NE reflect an increasingly proximal setting to the continent and a transition from deepwater to continental slope deposits (Fig. 1).

Major intrusions of syenite and biotite granite occur in the upper formations of the Lower Ugab Domain (Figs. 1 and 2). These include the Voetspoor and Doros plutons in the west (Passchier et al., 2007), the Driekrone and Omangambo plutons in the North and East and several small, unnamed plutons. Thin N–S trending granite veins in the centre of the Goantagab Domain (Fig. 2) may be feeder dykes of granite plutons at higher levels that are now removed by erosion. The Voetspoor and Doros plutons have been dated at approximately 530 Ma (Schmitt et al., submitted for publication), and the other plutons are probably of the same age, judged by their similar composition and relative age with respect to the deformation.

The Gemsbok River Formation marble east of locations P and F in Fig. 2 is strongly thinned, and locally divided into isolated parallel lenses. These effects are not due to ductile deformation, which is not stronger at these sites than elsewhere, but may be due to the action of an early synsedimentary extensional fault (Fig. 2). The exact trace and possible branches of this fault cannot be reconstructed due to intense refolding. The presence of a synsedimentary normal fault could explain the adjacent massive diamictite as a debris flow down the scarp of the normal fault, possibly in a canyon. The fault may also have hosted a feeder dyke for the mafic sill (now greenschist), also localised close to this fault (Fig. 2).

5. Structure

In the Lower Ugab Domain, three deformation phases have been recognised (Fig. 1; Passchier et al., 2007; Maeder et al., 2007). D_1 folds are asymmetric open to tight folds with N–S trending axes and associated S_1 axial planar foliation, which is the dominant foliation here (Fig. 1). The fold asymmetry is west-vergent in the west and

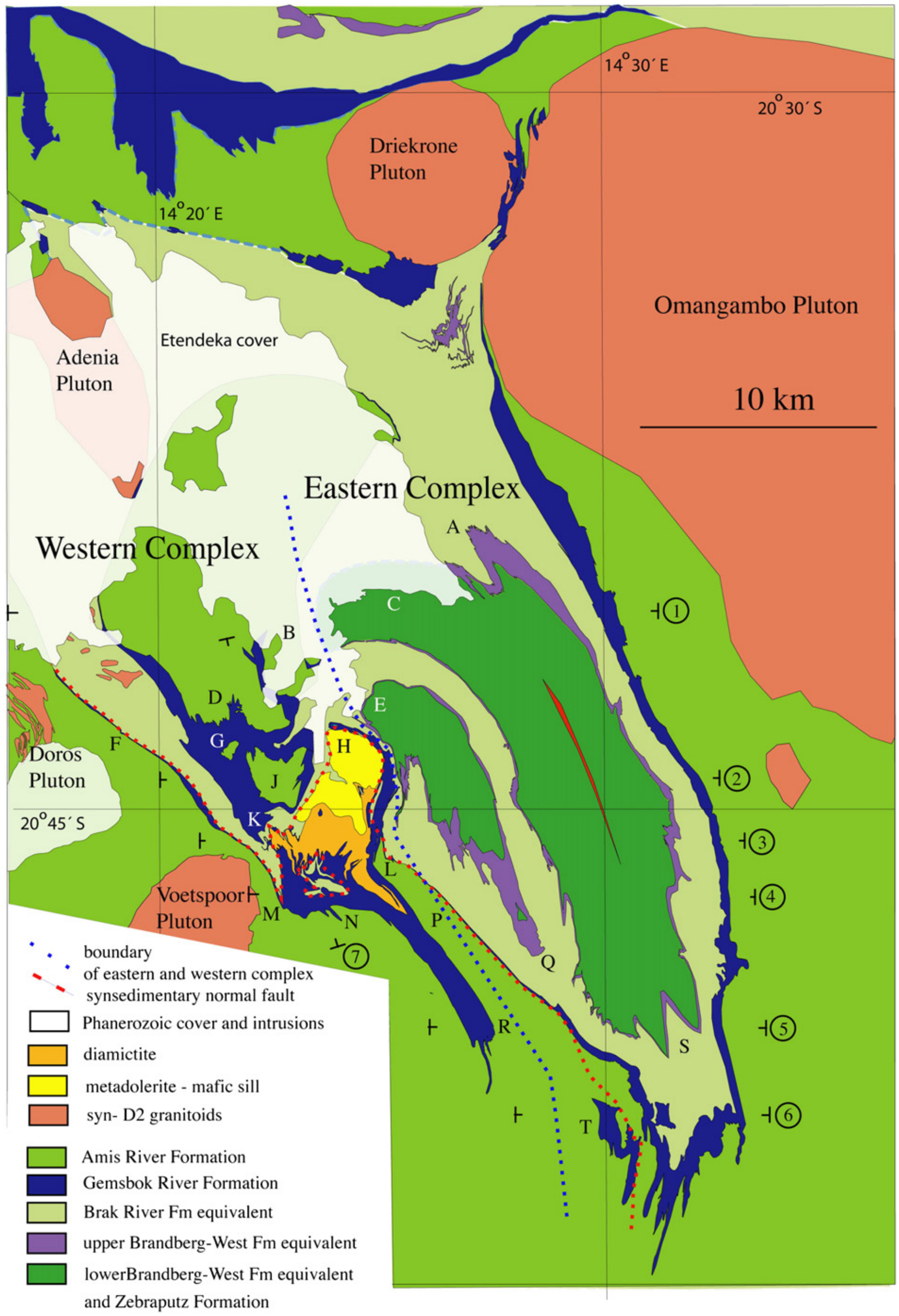

Fig. 2. Simplified geological map of the Goantagab Domain. Capital letters indicate locations discussed in the text. Numbers refer to sections in Fig. 3.

symmetric or east-vergent in the east, close to the Goantagab Domain. D_2 structures occur locally as open folds of S_0 and S_1 with axes parallel to D_1 axes, but with axial planes oblique or perpendicular to S_1. S_2 developed locally as a crenulation cleavage, especially where an earlier post-S_1 vein-related flame foliation (Maeder et al., 2007) is present. D_3 is expressed throughout the area as open folds and local development of an S_3 crenulation cleavage. S_3 is mostly steep and E-W or NE–SW trending and wraps around the syenite/granite plutons, which cut D_1 structures and intruded during formation of D_2 structures (Passchier et al., 2007).

The Goantagab Domain is a complex series of N–S trending domes and subdomes on the western edge of the large Omangambo pluton (Figs. 2 and 3). The NW limit of the structure cannot be determined since it is hidden below Palaeozoic and younger undeformed cover (Karroo and Etendeka deposits; Fig. 1). In the Goantagab Domain, four generations of small-scale structures can be recognised, mostly foliations but also associated folds and lineations (Figs. 2–5). These structures are expressions of deformation phases or sub-phases labelled D_1, D_2, D_{2b}, and D_3. Three of these phases, D_1, D_2 and D_3 can be traced without interruption to the Lower Ugab Domain, whereas the fourth, D_{2b}, is only expressed in the Goantagab Domain up to the Austerlitz Dome (Figs. 1 and 2). All deformation structures formed at similar metamorphic conditions in the middle to upper greenschist facies (biotite zone, low pressure; Passchier et al., 2002), although D_3 may have formed during retrogression; biotite recrystallised in structures of D_1, D_2 and D_{2b} age, but only

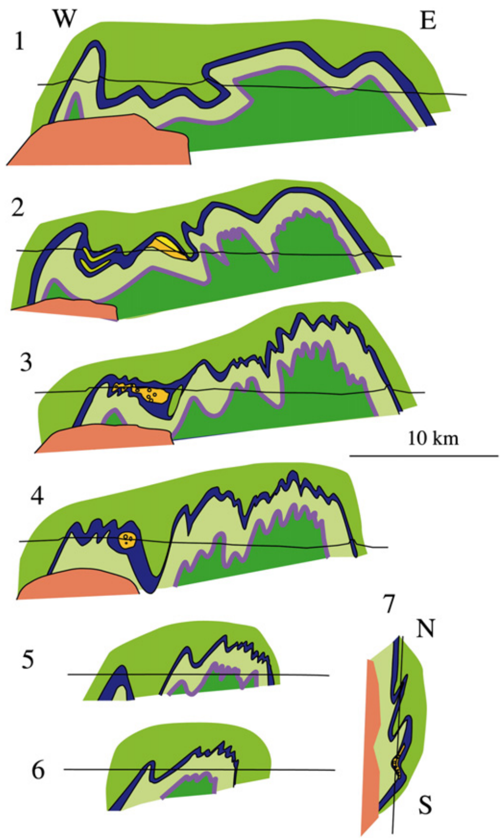

Fig. 3. Schematic geological sections through the Goantagab Domain, locations shown in Fig. 2. The inferred presence of granite at depth in the left half of some sections is a possible explanation for the development of sheath folds in the west.

rarely in structures of D_3 age. D_3 folds commonly have a slightly different, more angular style from earlier structures. D_3 structures occur locally in the Goantagab Domain on a microscopic to km-scale as open folds or as a crenulation cleavage. D_3 folding locally leads to reorientation of older structures visible on the map, for example at L and in the southern part of the Dome at T (Fig. 2), where it gives rise to D_2-D_3 Type 3 dome-and-basin fold interference (Ramsay, 1967; Figs. 4 and 5). However, D_3 does not play a major role in structural development of the Goantagab Domain, and is not further discussed in detail below.

The structure of the Goantagab Domain is not easy to reconstruct in the field since all four phases of deformation can express foliations and lineations. There are hardly any outcrops in the Goantagab Domain, however, where all four foliations with associated lineations and folds are expressed in the same outcrop; pairs of S_1-S_2, S_2-S_{2b}, S_1-S_3 etc. are commonly found. The expression of foliations is highly variable, and is in some cases even different on both sides of the same fold (Fig. 6b). Since all structures formed at similar metamorphic conditions, they have very similar styles, and cannot be distinguished by their geometry or mineral content. We found that the only way to solve the internal structure and structural evolution of the Goantagab Domain was to identify outcrops with multiple overprinting structures, determine which deformation phases were expressed and by what structures, and to trace lateral continuity of each of the deformation structures by detailed mapping, plotting them onto structural contour maps (Figs. 4 and 5). Based on this mapping, the Goantagab Domain could be subdivided into an Eastern and Western Complex, separated by the blue dotted line in Fig. 2. In the following text, capital letters shown in Fig. 2 are used to refer to specific areas within the Goantagab dome.

5.1. Eastern Complex

The Eastern Complex has a relatively simple structure and is therefore discussed first. It contains two subdomes of folded Brandberg-West Formation marbles attributed to D_2 (Figs. 2 and 3). Isoclinal recumbent D_1 folds in bedding with NW–SE trending axes are refolded by upright D_2 folds, also with NW–SE trending axes (Fig. 6a), although there is usually a small difference in orientation between both. Type 3 fold interference patterns (Ramsay, 1967) are common. There is a transition from east-vergent closed D_1 folds in the Lower Ugab Domain west of F-M-R in Fig. 2 to tight and isoclinal D_1 folds in the Goantagab Domain (Fig. 6a). S_1 is commonly transposed and only found in thin sections as a remnant crenulated slaty cleavage. S_2 is the dominant foliation in the Eastern Complex, in some localities as a tight crenulation cleavage and in other places as a transposed new slaty cleavage (Figs. 4 and 5). D_2 fold axes are south-plunging in the south, and gently north-plunging in the NE parallel to stretching lineations discussed below (Figs. 2 and 4a). D_1 and D_2 folds both occur on a mm–km scale.

D_2 structures are overprinted by D_{2b}, expressed as a phase of open to tight mm-m scale folds (Figs. 4 and 5). D_{2b} axial planes are steeply east-dipping in most of the Eastern Complex, but more gentle dips and even subhorizontal orientations are attained to the west along the line H-L (Figs. 2 and 4c). The intensity of D_{2b} increases eastward and S_{2b} is most frequently and most strongly expressed in the eastern part of the complex, where it can be the dominant foliation, usually as a tight crenulation cleavage (Figs. 4 and 5). Where intersection lineations L_{22b} are steep, S_{2b} is more NE trending than S_2 in any outcrop (Fig. 5). This gives rise to S_{2b} cleavage-transected D_2 folds (Fig. 6d). Aggregate (stretching) lineations (Piazolo and Passchier, 2002) of variable age are found in all suitable lithologies of the Goantagab Domain (Fig. 4a), but they disappear towards the Lower Ugab Domain; in fact, the presence of these lineations is a main characteristic of the Goantagab Domain (Fig. 4a). They are easily confused with intersection lineations, but the prolate shape of pebbles and breccia fragments identifies them as stretching lineations.

5.2. Western Complex

Whereas the eastern part of the Goantagab Domain is mostly a simple D_2 domal overprint of D_1 folds, slightly modified by D_{2b}, the Western Complex is more complicated. Unfortunately, outcrop conditions are poor in some critical areas. The following unusual features were noticed:

1 Where stretching lineations are strong, cm–m scale sheath folds with axes parallel to the lineations are common in marble. The lineations are of D_1 or early D_2 age and are folded by D_2 folds and younger structures, as explained below.
2 The distribution of stretching lineations in the Goantagab Domain is unusual (Fig. 4a). In the SE of the Eastern Complex, lineations are generally parallel to D_2 fold axes and gently south-plunging, in agreement with the general south-plunge of the axis of the antiformal structure of the Goantagab Domain as a whole. To the casual observer, the same seems to apply along the west side of the Western Complex; stretching lineations retain a south-plunge from F through M and N to R and from D through G to K (Figs. 2 and 4a). In the centre of the Goantagab Domain, however, lineation attitude changes from south-plunging through horizontal to north-plunging and locally reaches a vertical orientation and even steep south plunges; this is shown in Fig. 4a with 30° spaced contours of lineation plunge. The orientation distribution of D_2 fold axes, and of intersection lineations L_{02} and L_{12} is identical to that of stretching lineations, showing that the change in orientation of

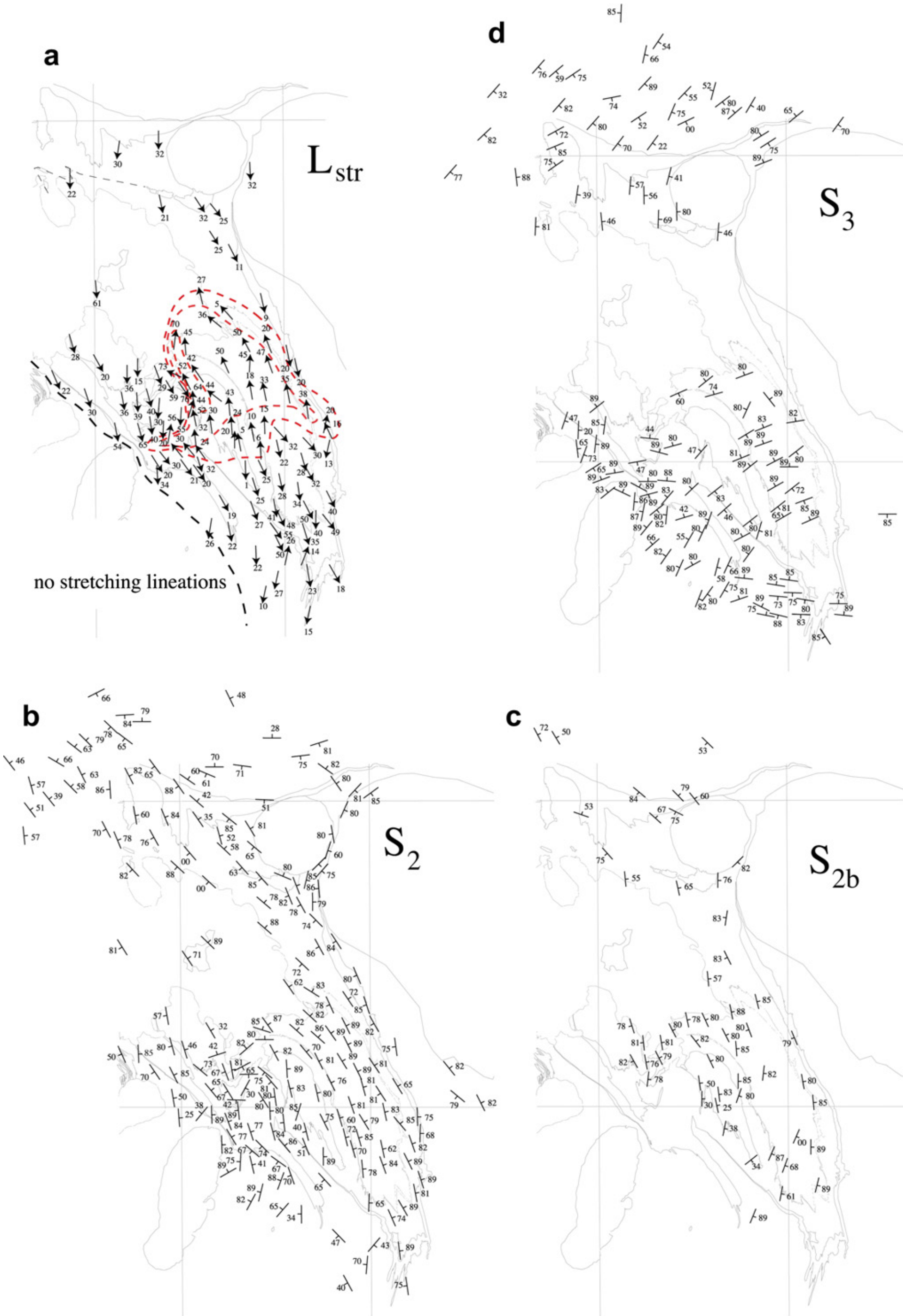

Fig. 4. Structural data for the Goantagab Domain, separated into diagrams for (a) stretching lineations; (b) S_2; (c) S_{2b} and (d) S_3. Notice the gradual change in plunge of stretching lineations, indicated by contour lines in (a).

lineations is associated with reorientation of the major D_2 folds in subdomes Q-E and S-C-A (Fig. 2); it also explains the change in map pattern of the "sperm-whale shaped" subdome Q-E from an elongate profile at Q where D_2 axes and intersection lineations are gently south-plunging, to a stunted map outline at E where they are vertical (Figs. 2, 4a and 7b).

3 At D (Fig. 2), the Gemsbok River Formation lies on top of the Amis River Formation with a contact that dips gently south (Figs. 2 and 3 section 7); the entire stratigraphy is therefore inverted here. Stretching lineations in the marble are south plunging. The main foliation in the Amis River Formation is gently dipping or subhorizontal, overprints an older foliation, and is therefore interpreted as S_2. This is in contrast with the Eastern Complex where S_2 is steeply dipping and N-S trending. S_2 at D is overprinted by open N-S trending folds with steep axial planes which we interpret as D_{2b}, since rare D_3 folds are still younger, crosscutting both foliations (Figs. 5 and 6c). This is remarkable, since the couple S_2-S_{2b} at D has a very similar style and orientation to the couple S_1-S_2 in the Eastern Complex, e.g. at S and Q.

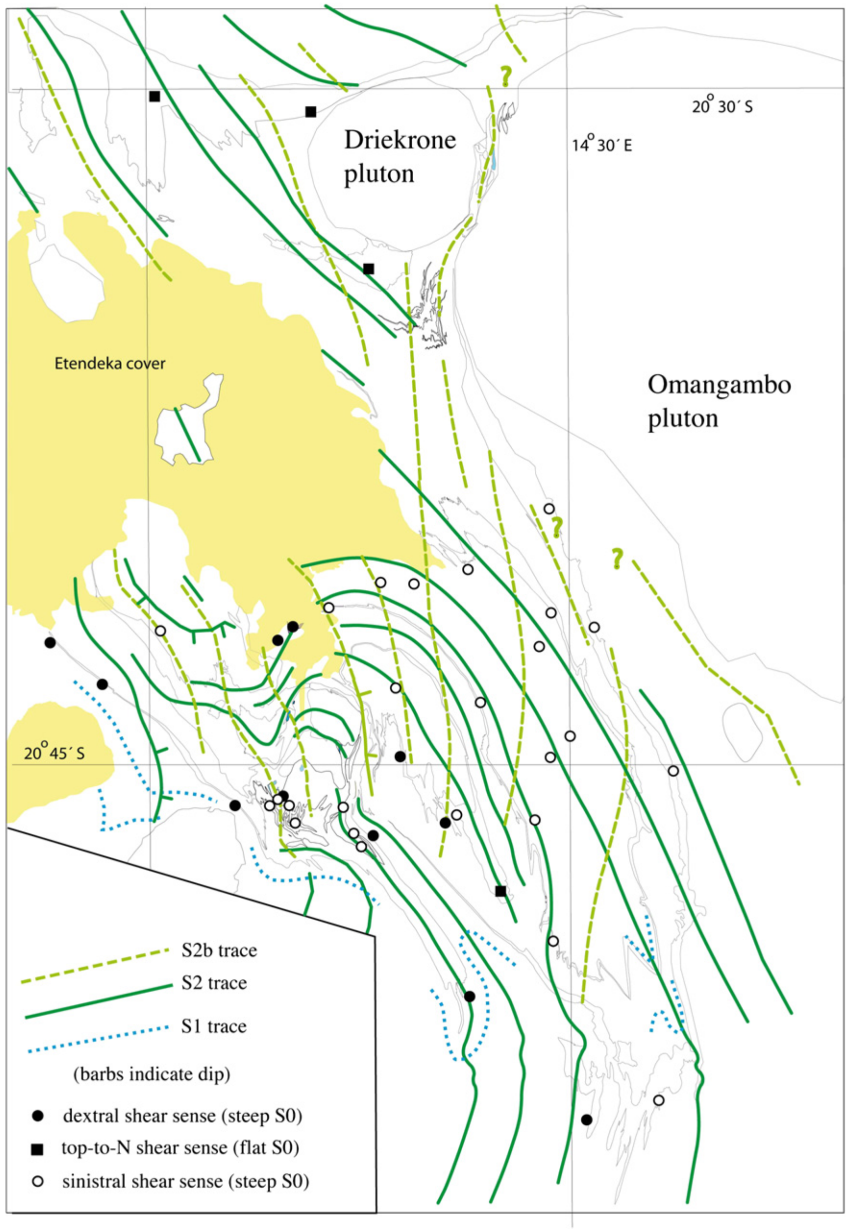

Fig. 5. Schematic representation of the trace of foliations in the Goantagab Domain, based on measurements as shown in Fig. 4. Open and closed circles and squares represent locations where shear sense could be determined based on sigmoids and asymmetric deformed pebbles.

4 The fold closure at J (Fig. 2) is a north-vergent D_2 Amis River Formation synform, refolded by a north-south trending upright D_{2b} synform into a km-scale sheath fold with Type 2 fold interference geometry (Ramsay, 1967). Stretching lineations are gently south-plunging. The southern, upper limb of this structure is overturned in a similar way as the structure at D, since it is covered by the Gemsbok River Formation (Fig. 3 section 7). The window of Amis River Formation at G is a similar sheath fold with south-plunging stretching lineations, also with an overturned upper limb.

5.3. *Relation of Western and Eastern Complexes*

In the Eastern Complex, gentle plunges of stretching lineations and D_1 and D_2 fold axes at S and Q gradually change to horizontal and then to steep plunges at C and E (Fig. 4a). Although partly obscured by poor outcrop, there also seems to be a gradient in plunge of lineations from E to H to D-J from a vertical to a south-plunging orientation again (Fig. 4a). We interpret this to mean that the stretching lineations, together with D_1 and D_2 fold axes, have been folded over more than 150° along the lines Q-E-H-R and S-C-B-D. Between S and the large D_2 fold at A (Fig. 4a), the stretching lineation and D_1-D_2 fold axes in the Brandberg-West Formation change plunge from south to north over 70° while in the strip of Gemsbok River Formation that forms the eastern edge of the Goantagab Domain, east of S and A, the transition is approximately 50° (Fig. 4a). The intensity of refolding of stretching lineations therefore gradually decreases from west to east.

Along the line R-P-L-H (Fig. 2), a gradual change in attitude of stretching lineations, and of L_{12} and L_{01} lineations is visible in Amis River Formation micaschists from gently south plunging to a vertical orientation. Outcrops in the L-H region contain a gently

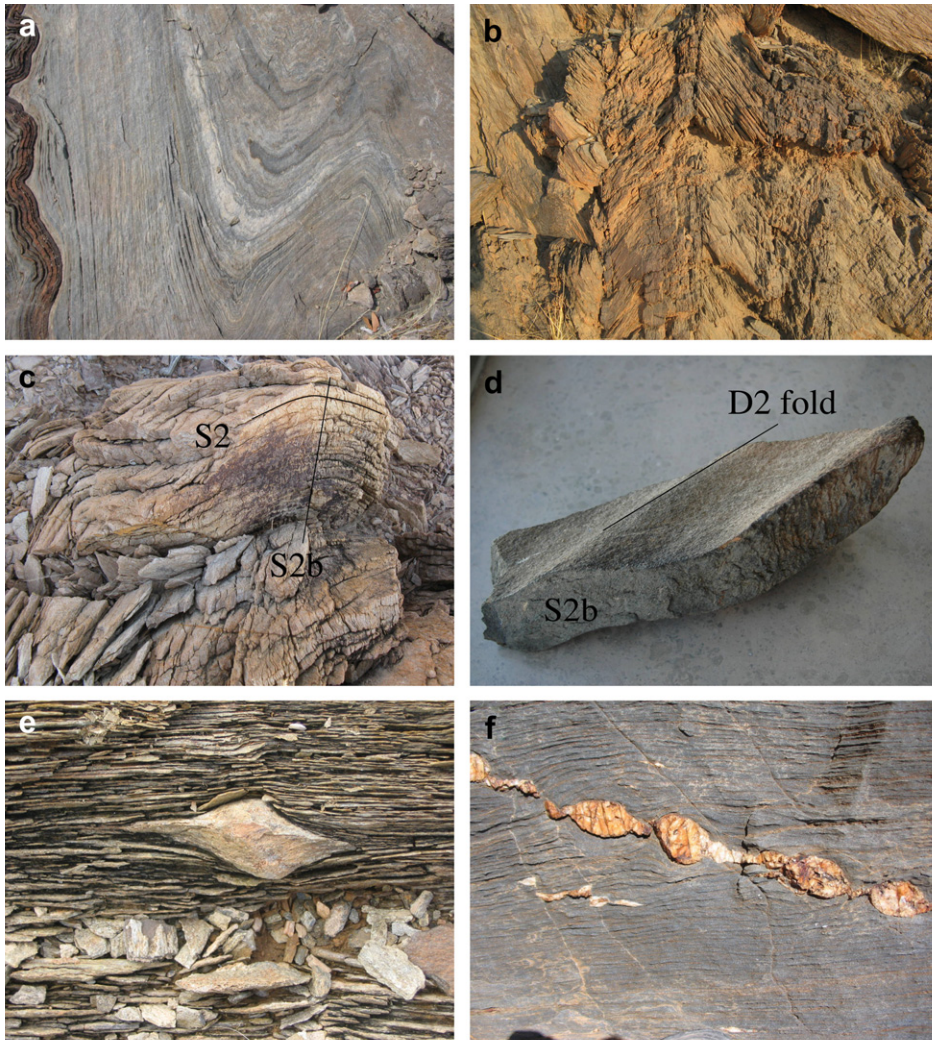

Fig. 6. (a) Gemsbok River Fm Marble, with isoclinal D_1 folds, refolded by upright D_2 folds in Type 3 fold interference. Weak D_{2b} folds affect a schist band at left. 4 km NE of A in Fig. 2. Width of view 1.2 m (b) S_1 foliation in Amis River Fm micaschist, folded by D_2 folds. S_2 crenulation cleavage is only developed in the short limbs (left dipping S_1). 5 km west of Driekrone Pluton, vertical outcrop, looking SE. Width of view 0.8 m. (c) Subhorizontal S_2 crenulation cleavage with folded S_1 in the microlithons, refolded by steep S_{2b}. View looking north, Brak River Fm, west of H in Fig. 2. Width of view 60 cm. (d) Brak River Fm micaschist with S_{2b} foliation transecting D_2 folds at an angle of 40°. 2 km north of A in Fig. 2. Length of sample 35 cm (e) asymmetric dropstone in diamictite, indicating sinistral shear sense. Diamictite outcrop west of L in Fig. 2. Width of view 40 cm. (f) Brandberg-West Fm marble with asymmetric quartz "beads" indicating sinistral shear sense. At C in Fig. 2. Width of view 1.2 m.

dipping crenulation cleavage that predates S_3 and can be associated with D_{2b} folds. It produces a subhorizontal L_{22b}intersection lineation with S_2. Stretching lineations, L_{12} and L_{01} vary strongly in orientation from outcrop to outcrop at L, while L_{22b} is constant in orientation, implying that the former are refolded here. Refolding of the lineations and of D_1 and D_2 folds in the Western Complex can therefore be locally dated to belong to the D_{2b} forming phase. Summarising these observations, D_1 and D_2 structures in the northern part of the Western Complex were locally refolded during development of D_{2b} structures to an overturned orientation.

5.4. Sheath folding

From the map pattern (Fig. 2), the fold structure P-L which contains Amis River Formation in the core and which closes at L, between R and Q seems to be a simple south-plunging syncline between a small Gemsbok River Formation anticline R and the massive Eastern Domain antiform. However, detailed mapping of minor limestone bands in the Amis River Formation at L shows that this Formation plunges *below* the Gemsbok River Formation north of L in a gently north-plunging *antiform*. As described above, stretching lineations change from south-plunges in the south at R and Q to gently north-plunging in the antiform closure at L, and then to steep orientations north of L, similar to what happens in the anticline Q-E (Figs. 2 and 4a). The P-L fold is therefore not a simple syncline, and is hard to explain by cylindrical folding since gently south-plunging anticlines lie at R and Q. A similar problematic relationship exists between diamictite and Gemsbok River Formation marble in the extensive marble domain west of L; the major, western part of the diamictite lies on top of the Gemsbok River Formation in an open E-W trending D_3 synform (Fig. 3), but the south-closing diamictite west of P in the core of anticline R plunges *below* the Gemsbok River Formation. Again, this kind of structure is hard to explain by cylindrical folding or by fold interference. The most likely explanation seems to be the geometry of sheath folds (Fig. 7). In fact, metre-scale sheath folds are common in the Gemsbok River Formation marbles throughout this part of the area. Therefore, we consider the structures in the domain M-L-P-R to be part of a complex, km-scale sheath fold structure with axes parallel to the stretching lineation (Figs. 3 and 7).

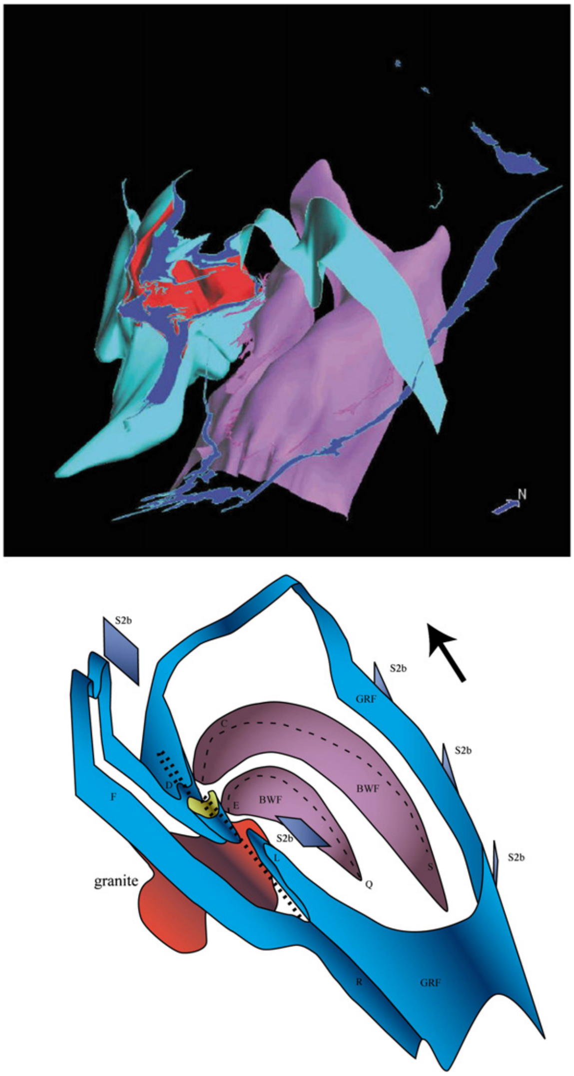

Fig. 7. (a) Computer reconstruction of the main structure of the Goantagab Domain. Blue indicates Gemsbok River Formation, pink the upper marble band of the Brandberg-West Formation. The inside of the sheath folds of the western domain is highlighted in red. In (b), the structure has been simplified to show main features. The two subsidiary D_2 domes in the centre of the Goantagab Domain were refolded to an E-W orientation in the North, and in the western Domain, km-scale sheath folds developed. Postulated granite below the western domain is indicated in orange. Capital letters indicate locations mentioned in the text, and shown in Fig. 2. Further explanation in text.

5.5. Reworked shear sense indicators

Two sets of veins are found in blue and grey graphite-bearing marbles throughout the area: early fine-grained white calcite veins and younger "beady" quartz veins of irregular thickness, which cut the calcite veins (Fig. 6f). Both develop into isolated asymmetric sigmoids that can serve as shear sense markers. In diamictite, pebbles have commonly also obtained an asymmetric sigmoidal shape (Fig. 6e). Monoclinic symmetry axes of these structures are mostly normal to the local stretching lineations. The carbonate vein sigmoids show alternating shear sense in the southwest of the Goantagab Domain, sinistral on east-limbs of major D_2 folds, and dextral on west limbs (Figs. 2 and 5), all with symmetry axes normal to the D_2 fold axes and in the plane of the bedding.

In the north of the Goantagab Domain, north of the Etendeka cover and west of the Driekrone pluton (Figs. 1, 2 and 5), D_2 is weak and is mostly expressed by open folds. Here, stretching lineations are north-south trending (Fig. 4a) and shear sense indicators in marble all indicate thrusting to the north, with north-south trending vertical vorticity profile plane (Robin and Cruden, 1994). Since D_2 and D_{2b} deformation is weak here, this set-up may have been the initial structural arrangement for the southern part of the dome as well (Fig. 5). The stretching lineations and asymmetric shear sense markers formed late during D_1 or early during D_2. The alternating shear sense in the southern part of the dome can therefore be explained if these markers developed before the onset of D_2 folding (Goscombe and Trouw, 1999), or if they formed by preferential top-to-the-north shear in gently D_2-folded marble layers. Consequently, the vorticity profile plane, the plane normal to the inferred vorticity vector of flow (Robin and Cruden, 1994) seems to have been vertical north-south trending, and has been refolded by D_2, although the shear sense indicators may have formed when open D_2 folds were already present.

In the east of the Goantagab Domain, both calcite and younger quartz veins are developed to sinistral sigmoids on both limbs of D_2 folds (Fig. 5), with vertical symmetry axes. The geometry of these shear sense markers is identical to those described above. The sigmoids are overprinted by D_{2b} folds and foliation, and by so-called hog-vein structures (Coelho et al., 2005), indicative of a sinistral shear sense. In the Eastern Complex, between and east of A and S (Fig. 2), S_{2b} is strong, overprints S_2 and is locally the dominant foliation (Figs. 4c and 5). Towards the west, S_{2b} gradually disappears and D_{2b} is only expressed as a crenulation lineation on S_2 or S_1, and open folds without a foliation, and without influence on earlier shear sense indicators. Together, this indicates strong sinistral shear with horizontal vorticity profile plane during D_{2b} in the east of the Goantagab Domain. This deformation may have locally erased or modified earlier top-to-the north shear sense markers described above that formed early during D_2. Similar looking shear sense indicators are therefore probably of different relative age in the west and east: early D_2 versus syn-D_{2b}. For the same reason, stretching lineations must also be of different relative age in different part of the Goantagab Domain, even though they are similar in orientation and style.

In the Western Complex of the Goantagab Domain in the D-G-J area (Fig. 2), no shear sense indicators have been found in the marbles. In diamictite, pebbles are locally asymmetric here, but no consistent pattern of shear sense was found. This absence of consistent shear sense indicators can be attributed to local complex flow conditions leading to sheath folding, as explained below.

6. Interpretation of D_2-D_{2b} in the Goantagab Domain

The unusual arrangement of D_2 and D_{2b} structures in the eastern Goantagab Domain seems to be an effect of rotation of D_2 folds into the shortening domain of local flow and overprinting by a new set of structures, while D_2 development and tightening with north-south axes and steep axial planes continued in other parts of the area. Along the contact with the basement, north of the Driekrone Pluton (Fig. 1), north-south trending lateral ramp structures and stretching lineations are interpreted to be an effect of thrusting to the north. These structures are overprinted by upright D_2 folds with E-W trending axes, indicating that locally thrusting was pre to syn D_2 (Fig. 1). Further south, in the Eastern Complex, D_1 folds were also formed during or first overprinted by deformation which expressed north-south trending stretching lineations and shear sense indicators, indicative of north-directed thrusting. Shortly afterwards D_2 folds developed because of an increasing component of E-W shortening and increasingly constrictional flow conditions. In the east, close to the Omangambo pluton, the E-W shortening component was dominant and became associated with a subhorizontal vorticity profile causing overprinting of D_2 structures by D_{2b}. Between the Driekrone and Omangambo plutons, both D_2 and D_{2b} have an unusual orientation because of tightening between the two plutons (Figs. 2 and 5).

The complex flow conditions and changes therein which are responsible for D_2 and the D_{2b} overprint of D_2 are probably associated with the presence of granite plutons that intruded during D_2, and especially by the large Omangambo pluton (Figs. 2 and 5). On the map (Figs. 1 and 2), granite plutons lie in an arc around the Goantagab Domain, because granite plutons mostly intruded into the Amis River Formation along the contact with lower units. Consequently, parts of the Omangambo pluton, or independent granite intrusions may have been present above the Goantagab Domain as well (Fig. 8); the presence of feeder dykes (Fig. 2) mentioned above makes this likely. Although the contact of the Omangambo pluton with surrounding schist is mostly steep in outcrop, the intrusion contacts may have been flattened upwards to an overal wedge-shaped geometry, as has been suggested for the Voetspoor pluton west of the Goantagab Domain, and many other granite plutons (Passchier et al., 2007). North-directed motion of a hanging wall of Amis River Formation, possibly with granite plutons or gently dipping offshoots of the Omangambo pluton over the top of the dome, can explain the observed D_1-D_2 deformation pattern. Relative motion of the steep-sided part of the Omangambo pluton to the north past the Goantagab Domain at the present erosion level, may first have caused D_2 folding, then D_{2b} overprinting accompanied by sinistral shear where S_2 was rotated into the shortening field of local flow (Fig. 8).

In the Western Complex of the Goantagab Domain, D_2 folds and older structures were not only overprinted by D_{2b} folds and a new S_{2b} foliation like in the east, but refolded into sheath fold-like structures on a km-scale with refolding of stretching lineations over more than 150° (Figs. 7 and 8). This kind of behaviour would be expected if some type of horizontal rigid indenter were present in the sequence below the present topography, pinning the lower part of the western limb of the Goantagab dome during north-directed motion of the eastern part of the dome. The Voetspoor and Doros plutons (Fig. 2) are likely part of one large planar but refolded intrusion (Passchier et al., 2007), and are possibly connected to the Adenai pluton as well (Fig. 2). If such a large pluton intruded in the Western Complex below the present erosion level and solidified rapidly after intrusion during D_2, it may have pinned parts of the structure during ongoing north-directed thrusting causing them to be overridden, and causing the isoclinal D_{2b} refolding and sheath fold development (Fig. 8).

7. Sequence of events

Deformation of the stratigraphy in the Goantagab Domain can now be reconstructed as follows, based on the observations described above (Fig. 8). Early during deposition of the Gemsbok River Formation, the western part of the Western Complex was possibly affected by a NW-SE trending normal fault which dropped older formations down to the SW; the massive diamictite between K and L in Fig. 2 formed as a massive debris flow dropping off the plateau towards the SW, while magma at H intruded along the fault plane to form the dolerite sill. Subsequently, the area was covered by the main body of the Gemsbok River Formation and by the Amis River Formation.

During the onset of ductile deformation, N-S trending D_1 folds and foliations of variable dip formed in the Lower Ugab and Goantagab Domains. The structures formed in a transpressional system that is associated with sinistral shear along the Purros shear zone west of the Lower Ugab Domain (Fig. 1; Passchier et al., 2002, 2007). This movement has been attributed to SE-directed docking

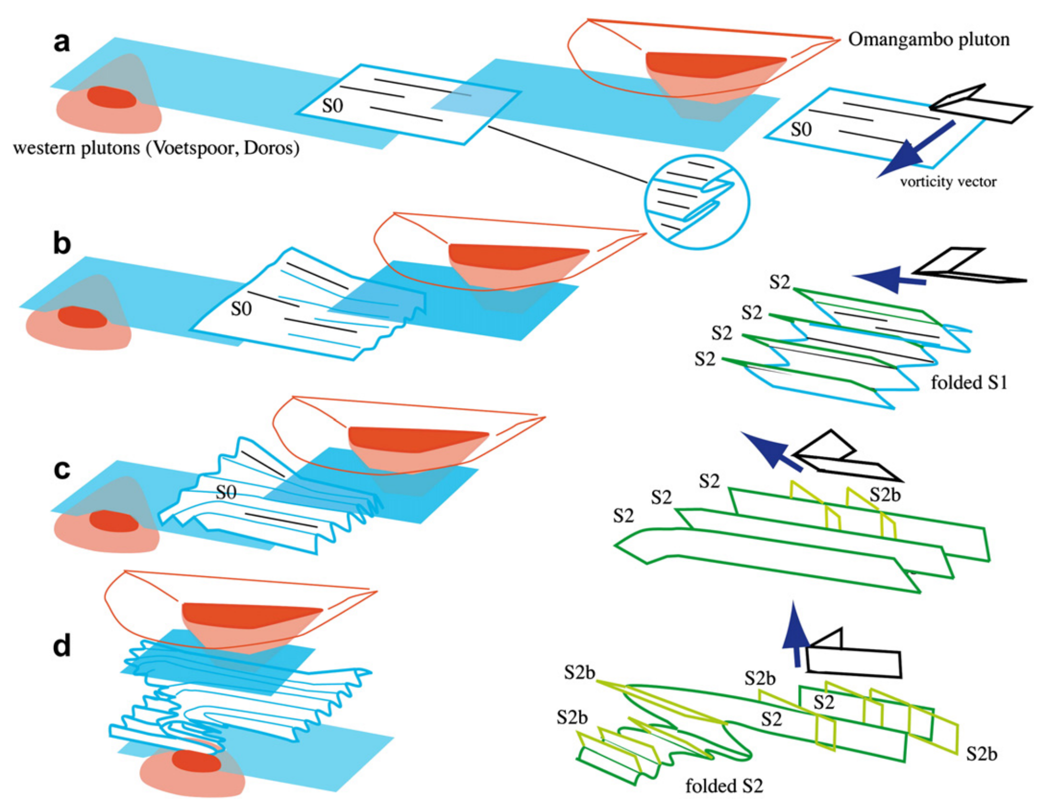

Fig. 8. Schematic diagram showing the development of foliations in the Goantagab Domain in response to thrusting to the North and relative motion of granite plutons that intruded during D_2. Further explanation in text.

of a terrane along the Kaoko Belt (Passchier et al., 2007). This event was followed by intrusion of the syenite and granite plutons around 530 Ma. This includes granite veins in the central Goantagab Domain, which may have acted as feeder dykes for a pluton at a higher crustal level above the present erosion level of the dome structures. Intrusion of the plutons is associated with the formation of the first D_2 structures. The Goantagab Domain was then overridden by parts of the lower Ugab stratigraphy including some of the plutons. D_1 folds were tightened to an isoclinal geometry and N-S trending stretching lineations developed in the Goantagab Domain. Early shear sense markers in the SW and northern Goantagab Domain indicate top-to-the-north transport. D_2 folding overprints these early shear sense markers, and is itself overprinted by D_{2b} folding and foliations; both sets of folding are probably related to the relative transport of the Omangambo pluton past the Goantagab Domain towards the north. The presence of granite plutons along the western edge of the Goantagab domain may have impeded northward motion of the Western Complex, causing large scale refolding of D_2 and older structures, and development of sheath folding. Finally, D_3, with steep axial planes trending SW–NE to E-W, can be attributed to minor N-S shortening in the entire pile leading to local development of foliations and folds. On a regional scale, D_3 structures have been attributed to shortening in the NE–SW trending Damara belt (Goscombe et al., 2003a). Because of the associated north-directed thrusting, D_2 and D_{2b} structures are most likely due to early phases of shortening in the Damara Belt, and not associated with the Kaoko Belt and D_1. The age of 530 Ma for the syn-D_2 Voetspoor and Doros plutons (Schmitt et al., submitted for publication) is consistent with this reconstruction.

8. D_2-D_{2b} "key-ring gradient"

The Goantagab Domain shows examples of gradual transition in expression of sets of structures as described in the introduction of this paper. Although there is a clear overprinting sequence of structures in any outcrop of the area, the sequence D_2-D_{2b}-D_3 seems to have formed during one continuous tectonic event with gradually and locally changing flow geometry. D_3 structures can usually be recognised since they formed at slightly lower metamorphic conditions as earlier phases, and commonly have a different style. However, although D_2 and D_{2b} structures can usually be distinguished and labelled sequentially in any one outcrop, this cannot be maintained over the entire area (cf. Bell et al., 1992).

An apparent geometrical contradiction exists when one compares the structure at D in Fig. 2 - gently dipping S_2 overprinted by vertical north-south trending D_{2b} folds - with the structure in the southern and eastern Goantagab Domain(R-Q-S-A in Fig. 2). At S and Q, gently dipping bedding and S_1 are refolded by vertical north-south trending D_2 folds, and there is no break in continuity towards R, (Figs. 2, 4 and 5). Following the structure from R to the north, however, one runs into D_{2b} folds at J of the same orientation and geometry as D_2 folds at S and Q: apparently, D_{2b} and D_2 structure cannot be distinguished here, and grade spatially into each other. On the other hand, D_2 and D_{2b} structures can be distinguished by clear overprinting relations at A and C, and can be followed towards D. D_2 and D_{2b} structures may in fact have formed contemporaneously, and the development of D_{2b} folds at A can have taken place during tightening of the D_2 anticline at Q (Figs. 2 and 9b). This kind of structure can be regarded as the geological equivalent of a "ring-species" described in the introduction, and by analogy we could speak of a "D_2-D_{2b} key-ring gradient".

Localised refolding and overprinting occurs on a mm–m scale in many mylonites when sheath folds develop (Marques and Cobbold, 1995; Alsop and Holdsworth, 2004, 2006; Alsop et al., 2007) and on a metre-scale in some slate belts (Powell and Richard, 1985). Here, an example is shown of the same phenomenon on a km-scale and of two distinct types; in the east, the main foliation S_2 simply rotated into the shortening field along the vorticity axis, and was overprinted by S_{2b} of the same orientation as the non-rotated S_2, with steep intersection lineations L_{22b}. In the west, near D, the original foliation was rotated into the shortening field but approximately normal to the vorticity axis, resulting in a gently plunging L_{22b}. The presence of both types of "key-ring gradients" is a strong indication that D_2 and D_{2b} structures formed diachronously in a relative short period of time.

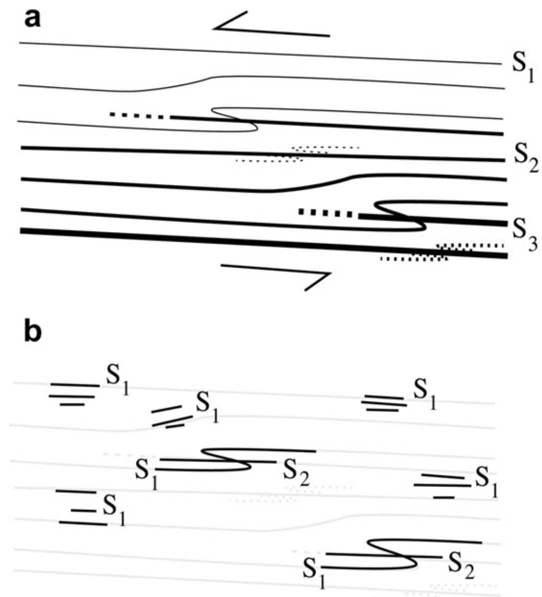

Fig. 9. Diagram illustrating the concept of key-ring structure gradients. (a) Foliations are folded to produce progressive new foliations towards the bottom of the schematic map. These new foliations have the same orientation and grade into the older foliation outside the folded domain. (b) if outcrop is poor, the structure gradients shown in (a) can be misinterpreted and complexity is underestimated.

9. Conclusion

The deformation pattern in the Goantagab Domain is complex and unusual, but is probably not unique. The excellent local outcrop conditions make a full detailed analysis possible, but it is likely that similar "key-ring gradients" associated with complex shear zone deformation and development of sheath folds occur elsewhere. Fig. 9 summarises the simplest way in which such structures can form, comparable to developments in the eastern Goantagab Domain. Whenever a foliation and related structures develop in a highly vortical flow such as simple shear, they may locally rotate into the shortening domain, usually by a slight temporary change in stress field orientation or a local pulsating kinematic vorticity number, temporarily exceeding 1 (Passchier, 1998). In this way, folds and second foliations can form and the old structures will be locally erased (Fig. 9a). Continuous outcrop will allow a recognition of the transitions and will reveal the local polyphase nature of deformation, although labelling the phases in a consistent way may still be problematic: however, in fragmentary outcrop conditions, a much simpler deformation pattern may be erroneously reconstructed which misses the complex cyclic and polyphase nature of the deformation history (Fig. 9b). If all foliations formed at similar metamorphic conditions and in the same materials, their expression would be identical at similar strain magnitude. It is therefore important in areas with evidence of non-coaxial progressive deformation history to closely investigate domains adjacent to sites with folded foliations to see if gradients in deformation phase from an earlier to a younger phase exist, and the possibility of key-ring gradients must be considered.

Acknowledgements

We thank the Dutch Schürmann Foundation for several grants to finance the fieldwork for this study. We thank Neil Mancktelow and Bernard Graseman for fruitful discussion in the field about the labelling of local deformation phases, especially about "2b, or not 2b". The students Martine Vernooij, Janneke Salemans, Hazel Goethart, Eveline Vermeer, Mathijs Boden, Hugo Beentje and Suzanne Lint mapped in the Goantagab area for undergraduate projects and helped to collect the data on which this paper is based. Cees van Staal and Mark Jessell are thanked for constructive reviews. This paper is dedicated to Paul Williams who taught me structural geology.

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