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Downward-facing structures in the Khomas Trough of the Damara Orogen, Namibia

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The Khomas Trough of the southern Damara Orogen comprises Upper Proterozoic Kuiseb Formation schists which have undergone prograde regional metamorphism and polyphase deformation. Bedding is easily identifiable and graded units allow younging to be readily determined. Three phases of deformation have been distinguished. Downward-facing D2 structures are documented from three localities about 5 km north of the Matchless Member amphibolite. Both synformal anticlines and antiformal synclines are recorded based on bedding - cleavage relationships. This contrasts with the usual upward-facing structures recognized elsewhere in the Khomas Trough. The downward-facing sequence appears to be related to a major thrust zone, which indicates that thrusting was pre- and syn-D_2 phase in this area. Additional evidence for a D_1 phase of deformation occurs in the form of an s_1 metamorphic banding cleavage and early quartz-veins and calc-silicate layers are folded by D_2. The occurrence of the D_1 deformation event implies a protracted deformational history in this part of the Khomas Trough which can be correlated with the D_2 event in the Central Zone represented by recumbent, south-easterly verging and locally downward-facing D_2 folds.

Introduction

The Khomas Trough (Fig. 1) of the Damara Orogen is characterized by meta-sedimentary sequences, several kilometres thick, which have undergone polyphase deformation (Blaine, 1977; Hälbich, 1977; Miller, 1979; Sawyer, 1981) and upper greenschist to amphibolite facies regional metamorphism (Hoffer, 1977). The succession exhibits extreme lateral persistence of structural and lithological markers over strike lengths of several hundred kilometres (Kukla *et al*., 1988b). These include major sedimentary cycles, graphitic and scapolitic schists and the Matchless Member amphibolites.

While studying the late Proterozoic Kuiseb Formation schists in the Khomas Trough, downward-facing structures were detected for the first time in this part of the orogen (Kukla *et al*., 1988b). It is the aim of this paper to document these structures in more detail and to discuss their formation and implications for the regional tectonics.

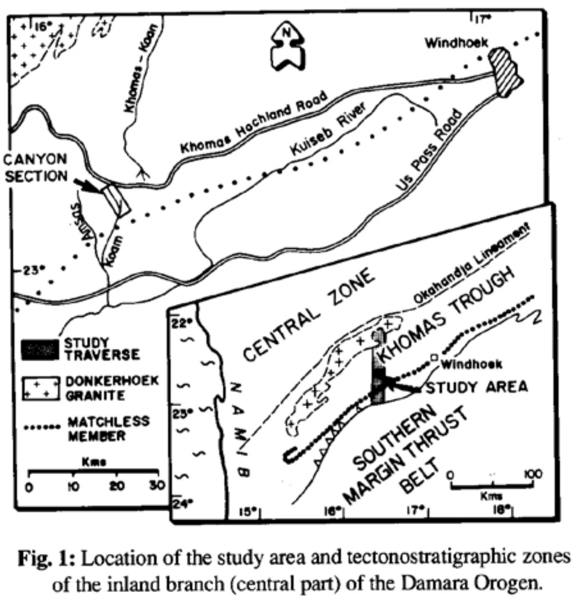

Fig. 1: Location of the study area and tectonostratigraphic zones of the inland branch (central part) of the Damara Orogen.

Geology of the canyon section

The investigated area forms part of a north-south trending traverse along the Khomas Hochland escarpment, 120 km west of Windhoek (Fig. 1) and is situated within a 6 km .long, north-west trending canyon along the upper course of the Koam River on the farm Annelie 412 (Fig. 2).

Petrology and sedimentology

The rock types represented in the canyon section are typical for Kuiseb Formation meta-sediments in the southern Khomas Trough namely: quartz-plagioclase-mica schists (psammites); mica- (chlorite-muscovite-biotite) quartz-plagioclase schists (pelites); minor graphitic schists (Fig. 2); and calc-silicate rocks in the form of spindle-shaped concretions.

The metamorphic grade is characterized by the paragenesis biotite + chlorite + muscovite + garnet in pelitic rocks. The rare occurrence of staurolite and kyanite in rocks of suitable bulk compositions indicates amphibolite-grade metamorphism.

It has been inferred previously that the psammites were deposited by turbidity currents because of their graded character (Miller, 1979; Sawyer, 1981; Downing, 1983; Preussinger *et al*., 1987). The discovery of Bouma sequences has proved the turbidite nature of the psammites and these have been interpreted as having been deposited within an elongate submarine fan system (Kukla *et al*., 1988a). This interpretation is based on the recognition of original sedimentary structures, the organization of the sedimentary sequence into cyclic successions of progradational and retrogradational character and the distribution of facies (Kukla *et al*., in press). The canyon section represents a prograding

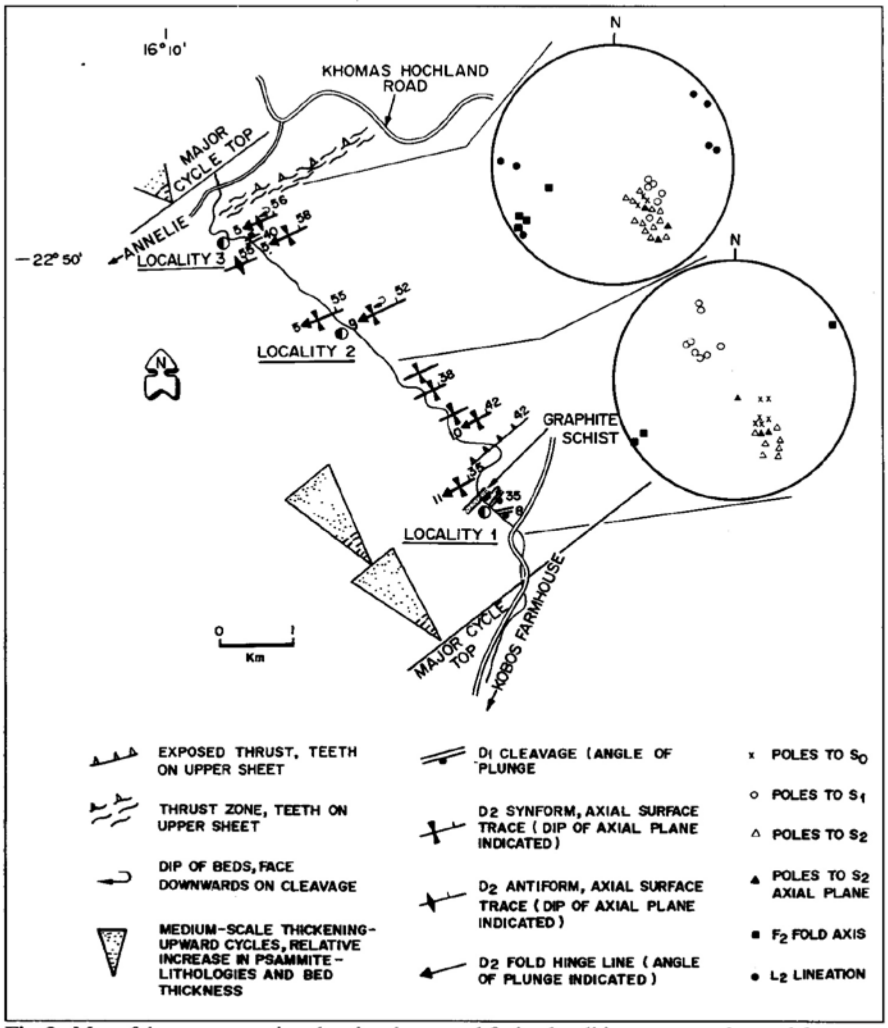

Fig. 2: Map of the canyon section showing downward-facing localities, stereonet data and the extent of sedimentary cycles.

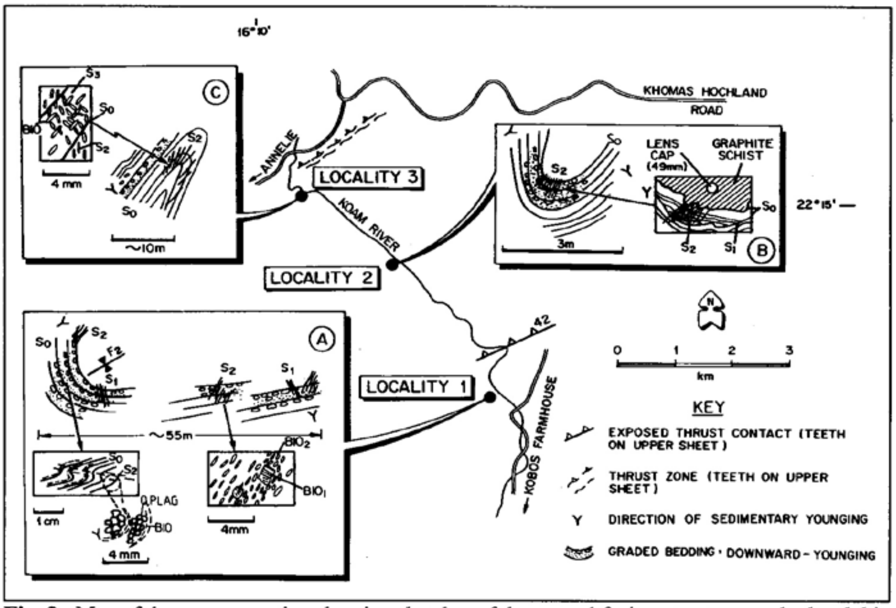

Fig. 3: Map of the canyon section showing sketches of downward-facing structures and related thin section information. Note particularly the direction of sedimentary younging with respect to the s_2 axial planar cleavage, which indicates downward-facing. Abbreviaitons: Q, quartz; PLAG, plagioclase; BIO, biotite.

sequence of nested thickening-upward cycles with a major cycle top developed at its southern and northern limits (Fig. 2). This is expressed by reduced bed thicknesses and high pelite contents in the south, culminating in the upper canyon with psammitic sequences with layer thick-nesses of up to 5 metres.

Structural setting

Within the study area three phases of deformation (D_1, D_2 and D_3) are recognized. As with most of the Khomas Trough, the distribution of strain is extremely heterogeneous, characterized by superimposed folding and thrusting. The northern end of the canyon section coincides with a structural discontinuity originally detected by Kukla *et al*. (l988b). This is defined by a change from complete open asymmetric folds on the north side of the discontinuity to folds on the south side in which the bedding/cleavage (s_0/s_2) relationships confirm the presence of antiforms in which overturned limbs have been eliminated. These antiforms pass southward into tight to isoclinal overturned folds. The horizontal attitude of the D_2 fold hinges, the steep northwest dipping axial planes and the south-easterly vergence of the D_2 structures indicate that the discontinuity is a thrust zone.

The characteristic features of original layering and fabric elements are as follows.

Layering s_0

Layering is well preserved with bed thicknesses ranging from a few centimetres to several metres. The primary nature of the layering is evident from the preservation of graded units and it strikes generally north-east (050°) and dips moderately (30°-50°) to the north-west. Folding of layering is mainly visible in hinge areas of medium-scale tight to isoclinal D_2 folds. In thin section, graded layers are more quartz- and feldspar-rich at the base and more mica-rich at the top, representing a metamorphosed compositional grading. Biotites are aligned parallel with the bedding planes and also define s_1 and s_2 (Fig. 3A).

D_1 deformation

An early s_1 fabric is clearly evident as a metamorphic banding cleavage with alternating quartz-rich and mica-rich layers orientated obliquely to bedding (Fig. 4). Because of later refolding there is no consistency in the orientation of s_1 which dips south-east in locality 1 (Fig. 2) and dips north-west in localities 2 and 3. In thin section, the s_1 fabric is characterized by an early generation of biotites which may be enclosed and wrapped-around by later biotites developed in s_2 (Fig. 3A). Further evidence for D_1 comes from early quartz veins and calc-silicate units which are folded by D_2.

D_2 deformation

Examples of D_2 folds with wavelengths of 15-20 metres and amplitudes of tens of metres are well-exposed along the canyon (Fig. 2). These folds are tight to isoclinal, inclined, and horizontal to shallow plunging in attitude. Axial planes dip between 40°-60° towards the north-west (310°) and fold axes plunge at low angles both towards 235° and 050° -060° (Fig. 2). A strong, pervasive s_2 metamorphic banding cleavage dips moderately (40°-60°) to the north-west and occurs as an axial planar foliation. Fanning of the cleavage and refraction at psammite - pelite contacts is common (Fig. 5). An l_2 intersection lineation between s_0 and s_2 plunges subhorizontally towards both the north-east and the southwest (Fig. 2). Large-scale synforms and antiforms are clearly indicated from bedding - cleavage relationships on fold limbs. In thin section, s_2 is defined by the preferred alignment of biotite and chlorite. In an area just south of the canyon, s_2 is further characterized by the syn- to post-kinematic growth of staurolite and garnet.

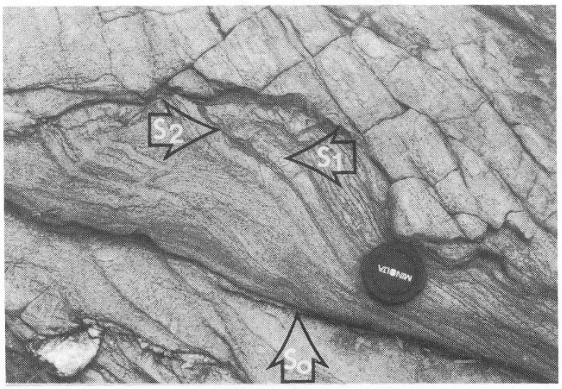

Fig. 4: Layering (s_0) and transposition of s_1 within the s_2 metamorphic banding cleavage (indicated by arrows) at locality 1. Sedimentary younging indicated by graded layering is towards the bottom of the photograph.

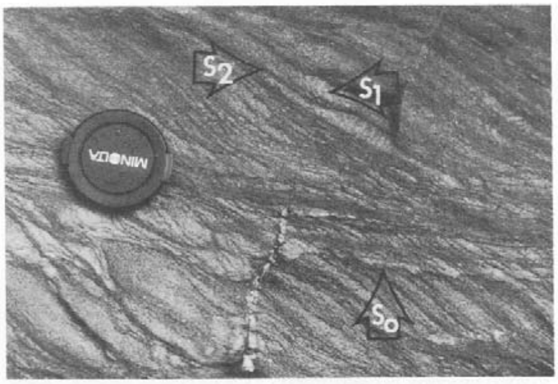

Fig. 5: Transposition of s_1 and refraction of s_2 at lithological contacts s_0 (indicated by arrows) at locality 1. Sedimentary younging indicated by graded layering is towards the bottom of the photograph.

D_3 deformation

The third deformation event is represented by an s_3 penetrative cleavage which strikes north-east and dips moderately to the north-west. D_3 folds are asymmetric, have subhorizontal fold hinges and axial planes which also dip moderately to the north-west. These folds occur only on a centimetre- to metre-scale mostly within and subparallel to narrow shear zones which developed in less competent zones. The fabric is characterized in thin section by a biotite generation which encloses the s_2 fabric (Fig. 3C).

Downward-facing structures

The term "downward-facing" is used here in the sense of Shackleton (1956) who extended the application of "facing" from strata to structures. It is therefore essential for the recognition of downward-facing that younging criteria are combined with fabric elements. Two lines of evidence were used in the canyon section to define downward-facing: (i) sedimentary younging indicated by graded bedding and (ii) bedding - cleavage relationships with respect to D_2 folds. Downward-facing was detected in three localities of the canyon profile; these are described below.

Locality 1, southern canyon

This locality exhibits a synformal D_2 structure with an s_2 axial planar cleavage which dips at moderate angles to the north-west (Figs 2, 3A, 4, 5). Thin- to medium-bedded psammitic and pelitic layers are mostly graded and upside down. The relationship of overturned graded layering and the s_2 cleavage which fans around the D_2 synform is evidence that this structure represents a synformal anticline. Small-scale tight to isoclinal D_2 intrafolial folds occur together with an s_1 metamorphic banding cleavage which dips between 26°-60° towards 135°-157° (Fig. 2).

Locality 2 central canyon

This locality comprises a small D_2 synform (Fig. 3B). Thin-bedded graded units are clearly recognizable in an upside-down position with psammites above grading into graphitic petites below (Fig. 3B). S_1 is subparallel to so and both fabric elements are folded by D_2. In relation to the s_2 axial planar cleavage the grading indicates that this structure is a synformal anticline. Adjacent rock units are ungraded massive psammites.

Locality 3, northern canyon

The northern locality exhibits an antiformal syncline. This is evident on the northern limb of the antiform where graded layering is overturned. This indicates together with the orientation of the s_2 axial planar cleavage (Fig. 3C) that the structure is downward-facing. Judging from the orientation of bedding and s_2 at this locality a major antiformal D_2 structure is situated to the south. The lack of younging indicators in this northern part of the canyon inhibits further recognition of downward-facing.

Discussion and conclusions

Downward-facing structures could have originated in four structural settings: (i) refolding of recumbent folds (Shackleton, 1956; Hobbs *et al*., 1976; Ramsay and Huber, 1987), (ii) refolding of upright to overturned D_1 folds due to progressive unidirectional stress perpendicular to the axial surface, (iii) refolding of overturned limbs associated with thrusting and (iv) refolding caused by an intruding pluton (Shackleton, 1956).

These possibilities can be constrained when the geological setting of the Canyon section is considered. Significantly the Kuiseb schists in this part and in fact most of the traverse through the Khomas Trough (Fig. 1) are upward facing with respect to D_2 folds. This would not be the case if settings (i) and (ii) applied. Plutonic intrusions are not a factor in this part of the Khomas Trough which precludes setting (iv). The downward-facing se-

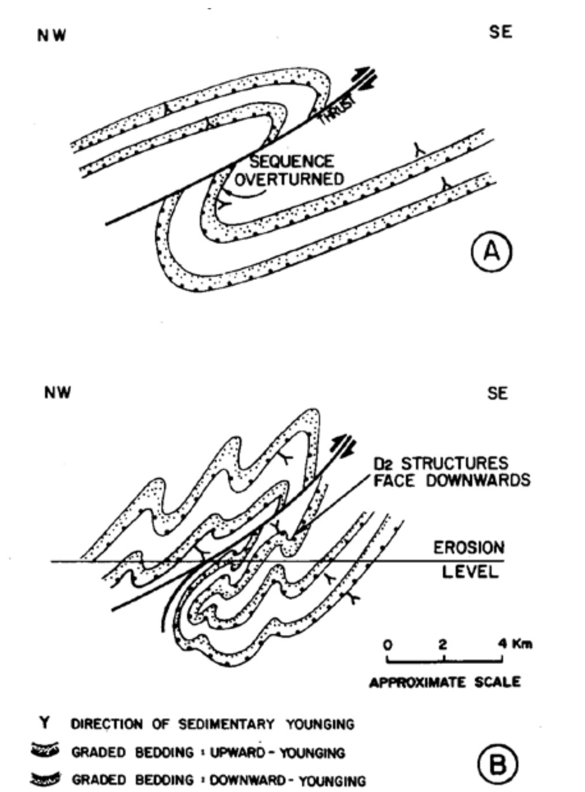

Fig. 6: Schematic diagram of the model for the development of downward-facing structures along the canyon section.
(A) Early (D_1) folding and thrusting, creating overturned limbs.
(B) D_2 folding, rejuvenated thrusting and subsequent development of downward-facing structures. Note folds produced in the overturned sequence are downward-facing.

quence is a local feature which represents a heterogeneity related to the major thrust zone at the northern end of the canyon, shown in Fig. 2 and described earlier. This accords with setting (iii) outlined above.

Figure 6 is a schematic diagram showing how the downward-facing structures were probably formed. The thrust is interpreted as having a pre-D_2 history which produced initial overturning of the stratigraphy. The superposition of the D_2 folds on the overturned sequence developed the downward-facing structures. This model is supported by the presence of a layer-parallel zone of brecciation and silicification which is crosscut by the s_2 fabric and may represent a minor thrust component of the earlier deformation in the canyon (Fig. 3, between localities 1 and 2).

The recognition of early D_1 structural elements and inferred major D_1 folds in this study is important in unravelling the early tectonic history and development of the Khomas Trough. An early. deformation phase has also been demonstrated by Sawyer (1981) and Preussinger (1987) in the Gorob area. The exact correlation and timing of these pre-D_2 deformation phases throughout the Khomas Trough requires, however, further examination. Elsewhere it appears that evidence for major D_1 structures is not widespread. The lack of recognition of D_1 might be attributed to transposition during the regional D_2 phase. In other medium-grade metamorphic terrains, transposition and obscuring of D_1 fold closures by later phases of deformation has been widely documented (Turner and Weiss, 1963; Hobbs *et al*, 1976).

We correlate D_2 of this paper with the first phase of deformation described by Hälbich (1977) from the Okahandja - Windhoek profile. Both his s_1 and our s_2 are metamorphic banding cleavages which are axial planar to folds developed prominently on a regional scale. In contrast, the D_1 fabric which we describe has a partially transposed intrafolial character.

Our D_2 event therefore correlates with D_3 of Blaine (1977) in the Central Zone following the correlations of Miller and Hoffmann (1981). The establishment of an early D_1 fabric in the southern Khomas Trough would imply that this fabric might correlate with the D_2 phase of Blaine (1977) in the Central Zone. The latter deformation is characterized by recumbent, southeasterly verging folds, which have been refolded to produce downward-facing structures (Coward, 1983). Furthermore, the deformational phases of the Southern Margin Thrust Belt have so far been regarded as time-equivalent with those of the Khomas Trough (Miller and Hoffmann, 1981; Miller, 1983). The recognition of deformation in the southern Khomas Trough implies that this area has experienced early deformation prior to the development of the thrust sheets in the Southern Margin Thrust Belt.

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