6. STRUCTURAL GEOLOGY OF THE KLEIN AUB AREA

The Sinclair Sequence in the Klein Aub area has been affected by three different phases of deformation. The first phase (D1), pre-dated and accompanied the deposition of the Nickopf, Grauwiters and Doornpoort Formations. This earliest phase produced only normal faults in the underlying basement and the early formations of the Sinclair Sequence (Figs.3.1, 6.1). The faulting also controlled sedimentary facies distribution in these early Sinclair formations and this deformational phase will be described in Chapter 6.1. A second deformational phase (D2), described in Chapter 6.2, was associated with the development of large, dome-like, open folds with wavelengths of several kilometres (Fig.3.1) and a distinct regional cleavage. The third phase of deformation (D3) produced en echelon folds with an associated axial planar cleavage and a variety of faults and thrusts.

Where discrete structural elements could be related to the different deformational phases, the following terminology was applied:

- \text{Deformational phase:} D_1 \quad D_2 \quad D_3
- \text{Folds:} F_2 \quad F_3
- \text{Cleavage:} S_2 \quad S_3

The description of structural elements in this chapter is subdivided into three groups according to the separate phases of deformation. Section 6.4, following the descriptive part, is an interpretation of the data presented. Section 6.5 compares the characteristic structural style of the Klein Aub area with other fault zones where similar arrangements of tectonic elements have been described. Finally in section 6.6 of this chapter, an attempt is made to determine the timing of tectonic events, with an emphasis on the relationship to the Damara Orogeny.

First Phase of Deformation (D1)

This first deformational phase affected the basement rocks underlying the Sinclair Sequence and to a lesser extent, units of the Nickopf and Grauwiters Formations. Deformation during this phase produced normal faults that bounded horst blocks, graben- and half-graben structures but was not associated with folding. These fault-bounded troughs subsequently became depositional sites for the volcano-sedimentary sequence where syndepositional faults controlled the distribution of the lithofacies in the lower part of the Sinclair Sequence (described in Chapter 5).

- **Faults:**

  The normal faults, now striking at angles of 110° and 205° (Fig.6.1), intersect the basement and the fault part of the Doornpoort Formation which, in the vicinity of Klein Aub Mine, immediately overlies a local basement. Vertical displacement on these steep faults is in the order of hundreds of metres. The apparent lateral sense of movement on these faults, suggested in map-view, is a result of Late Rotation during deformation, and the present erosion surface produced a section-like exposure of the basement-sediment contact. This contact is especially well-documented from Farm Eindpaal close to Klein Aub Mine which has been discussed in more detail in Chapter 5 (Fig.5.7). Elsewhere in the basin, where the Nickopf and Grauwiters Formations are preserved in deep grabens and half-grabens, the normal faults bounding these grabens and basement highs, are even more abundant and vertical displacement locally exceeds 1000 m (Fig 5.2).

Second Phase of Deformation (D2)

Large-scale folds and a regionally developed cleavage are attributed to this second phase of deformation (D2). It can not be excluded that some of the faults within the area also have originated from this deformational phase. However, such an interpretation is not unambiguous, since later reactivation of these tectonic elements probably destroyed any evidence for a D2 event.
Folds:

This deformational phase produced pronounced, large-scale open folds (F2) which do not show any vergence. In this respect the Klein Aub area differs from other areas of the Kalahari Copperbelt in SWA/Namibia where folds tend to show a typical southerly directed vergence, produced by the Damaran Orogeny. The F2 folds with a km-scale wavelength plunge at 5°-10° to the west. The Klein Aub Mine is situated on the southern limb of one major fold which generally dips 40° to 80° south (Figs. 3.1, 6.1).

Cleavage

The regional S2-cleavage is more distinctly developed in fine-grained rocks, were it defines a weak planar texture, due to the alignment of chlorite and muscovite (Plate 6.1A). A distinct lineation (L1), plunging 70° north, is recognizable in lenses of recrystallized siliceous limestone, where it is defined by the orientation of elongated calcite crystals (Plate 6.1B). This S2-cleavage strikes approximately parallel to bedding, but dips at some 70° to the north (Plate 6.1C; Fig. 6.2).

6.3 Third Phase of Deformation (D3)

This D3 deformational event produced a wide variety of deformational features, characterized by en echelon folds, a cleavage, faults, thrusts and various types of veins.

Folds

The rocks display F3-fold structures on all scales, both on surface and underground. A set of en echelon folds is exposed km east-northeast of Klein Aub, adjacent to the main fault (Fig. 6.3). Thin, discontinuous lenses of detrital and algal limestones interbedded with quartzite and...
Plate 6.1: Structural elements from the Klein Aub area.

(A) Interlaminated mudstone and very fine-grained sandstone from the Kagas Beds of the Klein Aub Formation. The mudstone layer displays a weakly developed S3 cleavage (c-c').

(B) L3 lineation in recrystallized detrital limestone from the Kagas Bed of the Klein Aub Formation.

(C) Photograph from a river section, 4 km east of Klein Aub, showing the dip of the strata to the south (here right) and the regional S3 cleavage which strikes parallel to bedding but dips steeply to the north (left); hammer is 38 cm long.

(D) Photograph of weathered quartz arenite which displays the axial planar S3 cleavage superposed over the regional S2 cleavage which is bedding parallel; hammer is 38 cm long.

(E) Vertical quartz vein (132°/60°) showing right lateral displacement. Maria shaft ore body, 450 m level, 600 west, south facing wall of main haulage way; hammer head is 18 cm long.

(F) En echelon set of quartz-filled Piedmont shears, indicating right lateral movement. Maria shaft ore body, 550 m level, 400 west, south facing wall of main haulage way; length of arrows is approximately 15 cm.

(G) Small-scale F1 fold in interlaminated siltstone and mudstone in river section (discovery outcrop, 200 m east of Van Zyl shaft). The fold axis plunges at a shallow angle to the southeast; lens cap is 5.5 cm in diameter.

(H) Lensoid quartz-chlorite feldspar vein, exposed in an underground pillar wall. Maria shaft ore body, 450 m level, 600 west, east facing wall of highly fractured and mineralized pillar; hammer head is 18 cm long.
Siltstone, form open and tight folds with a wave length of some 100 m and an amplitude of approximately 120 m. The fold axes plunge 10°-40° on 225° (Fig. 6.4).

Open and tight upright folds, plunging at shallow angles or sub-horizontally on 225°, are developed on a decimetre- to metre-scale on surface and in underground workings (Plate 6.1.1). These folds are similar in orientation to the ones described above and structural data describing their orientation as well as associated structures are shown in the stereographic plot of Figure 6.4. Another prominent deformation feature in the Klein Aub area is the Kam River Syncline, situated some 3 km south-east of Klein Aub (Fig. 6.1). It is a shallow, doubly plunging syncline with its curved longer axis striking approximately N30°. Only several hundred metres south, the strata dip south again (dip 36°). Thus an anticlinal structure, the Kam River Anticline is inferred (Fig. 6.1). Dis-folding of the strata adjacent to both, the Klein Aub Fault and the inferred fault on Farm Nwedum, is known from surface mapping and interpretation of aerial photographs (Fig. 6.1). Whereas open synforms are developed in the footwall of both faults, antiforms appear in the hanging wall strata. The fold structures on both sides of the faults plunge at angles between 10° and 40° towards the southwest. This type of lateral dis-folding is shown in the simplified sketch of Figure 6.5.
Fig. 6.4: Structural data from underground workings of the Maria shaft ore body (450 m level, 240-600 m west).

Fig. 6.5: Normal sketch map, illustrating the sense of drag folding of the strata adjacent to the main Klein Aub fault, which suggests right-lateral strike-slip movement along the fault structure.
Cleavage:
A distinct axial planar cleavage (S3), associated with the southwest-plunging F3 folds, is exposed on surface and underground (Figs. 6.2, 6.3, 6.4). Whereas the regional, S2-cleavage strikes sub-parallel to bedding (strike: 085°) the axial planar cleavage (S3; strike: 050°) shows an angular relationship to the strike of the beds (Plate 6.1D; Figs. 6.2, 6.4). Poles to the axial planes of the F3 folds plot immediately adjacent to the poles of the axial planar (S3) cleavage.

Faults:
A major structural feature is the Klein Aub fault which can be traced for at least 17 km (Fig. 6.1). It strikes approximately 080° (sub-parallel to bedding) and dips 45° to the south (Fig. 6.6). The Klein Aub fault separates dark grey siltstone and quartzite of the Kagas Beds in the footwall from brownish-red arkose of the Dikdoorn Beds in the hangingwall.

Fig. 6.6: Geological cross-section through the Maria shaft - body of Klein Aub Mine, illustrating the relationship between unmineralized (light stippled bands) and mineralized (darker stippled bands) siltstone/mudstone units and the main Klein Aub fault. The position of the section is indicated in Fig. 6.1.
Fig. 6.7: Cross-section and plan view of a crosscut into the Maria shaft ore body (450 m level, 240 west). The plan view was mapped on the floor level of the cross-cut.

The fault is marked, both on surface and in underground workings by a 0.5 m thick, hematitic fault breccia, which is strongly silicified and locally mylonitised. Surface weathering emphasizes the matrix-supported nature of the breccia, with single rounded breccia clasts in a dark maroon, mylonitised matrix. The fault dragged, displaced and terminated beds of the Klein Aub Formation and the contained ore bodies (Figs. 6.6, 6.7). Bedding within the footwall block, north of the fault, dips 40° to 70° south southeast with only minor lateral variation. The strata in the hangingwall block are gently folded and form the Kam River Syncline and Kam River Anticline (Fig. 6.1), described in section 6.2.

A subordinate fault, locally termed "Vliegveld shear", is only exposed in underground workings. It is developed parallel to the Klein Aub fault and has displaced the strata up to 40 m with a normal sense of movement (Fig. 6.6). Thus, the units bounded by the normal Vliegveld shear zone and the reverse Klein Aub fault have been rotated. A 0.5 m wide breccia zone, similar to the one associated with the previously described Klein Aub fault, is also developed along the Vliegveld shear zone. The fault has not been identified above the 300 m level. Here, the strata appears to be more brecciated and folded in a flexure-like fashion. Numerous small-scale, normal- and reverse faults (strike: 0°-90°), with a vertical displacement less than 1 m, commonly occur in the vicinity of the two major faults. A set of sub-vertical faults (striking at 110°) defines the rhomboid shape of many of the ore bodies together with the faults described above, truncating them both laterally and vertically (Fig. 6.8).

Another set of reverse faults is also arranged en echelon, striking 170°, dipping 75°-85° west. On surface, the Klein Aub fault is flanked by several other faults and shear zones and has been termed the Klein Aub Fault Zone (Borg et al., 1987). The subordinate faults are arranged either parallel to the Klein Aub fault or "branching off" at angles of approximately 40° to the main fault (Figs. 6.1, 6.4). Surface expression is generally limited to a dark maroon, silicified fault breccia but the faults appear as distinct linear features on aerial photographs. In an area some 4 km east-northeast of Klein Aub (indicated by a rectangle in Fig. 6.1), essentially two separate fault directions are developed, striking approximately 060° and 105° (Fig. 6.3). The faults that strike 060° have displaced the other set (striking 105°), thus postdating this set. The orientation of the faults on surface is approximately the same as underground (070°-085° and 110°). In surface exposure these faults define blocks, several hundred metres across, which
Fig. 6.8: Reef plan (plan view, projected normal to the mineralized horizon) of ore band 2 at Klein Aub Mine, Maria shaft ore body, 550 m level, 240° west.

have been displaced and rotated clockwise (Fig. 6.3). The blocks appear to have remained internally unaffected by the rotation. Striking on a bearing of approximately 050° (dip 25°), thrusts intersect the conglomerate of an alluvial fan lobe which underlies the slaty sediments some 4 km north-east of Klein Aub (Fig. 6.3; compare Fig. 5.4). The thrusts are arranged en echelon between the Klein Aub fault and a subordinate, parallel fault which is developed approximately 500 m north of the former, on Farm Eindspaal. A further, laterally extensive fault is inferred from interpretation of aerial photographs. On Farm Notched, some 7 km south-west of Klein Aub, structural form lines, clearly identified on aerial photographs (defined by the intersection of the sedimentary layering with the present surface), are displaced along a prominent linear feature, striking 050° (Fig. 6.4). Slickensides, commonly developed on faults and subordinately on bedding planes are orientated either horizontal (strike east-west), south plunging or pitching at an angle of 45° (on south dipping faults and bedding planes) (Fig. 6.4).

Veins:
Quartz-carbonate-filled fractures strike at 170° (Plate 6.1,E). The fractures contain an unzoned, crudely intergrown mosaic of 3-5 mm large anhedral quartz and calcite crystals, and are locally displaced by south dipping faults (085°/45°) with a right lateral sense of movement (Plate 6.1,E). Horizontal sets of en echelon arranged sigmoidal fractures with a right lateral sense of shear are commonly found underground (Plate 6.1,F). Generally, these fractures are filled with quartz and calcite, similar to the previous fractures. Where sets of these sigmoidal fractures occur within mineralized horizons the filling often consists of chlorite. Quartz-feldspar-chlorite veins occur which are locally oriented parallel to the axial plane of F-folds or arranged in a radial fashion within these folds (Plate 6.1,H). The veins are of lensoid shape, 10-30 cm wide, 50-100 cm high, 30-100 cm long, and often show signs of deformation and rotation. They display emulsion aggregates. Anhedral quartz and feldspar which is intergrown with coarse fibrous chlorite. Locally the chlorite forms massive, very fine-grained, black-green aggregates of cm-size. These veins are associated with both mineralized and unmineralized horizons and do not contain any ore minerals.
6.4 Interpretation of Structural Data

The earliest, the D1-deformation, was a phase of extensional faulting. The area underwent compression during the regional D2-deformation which was accompanied by the development of large-scale folds and a regional S2-cleavage. The principal D3-features which are found in the Klein Aub Fault Zone, are tension folds, an axial-planar cleavage, normal- and reverse faults, thrusts and extensional fissures. The dragging of footwall strata to the Klein Aub fault can be explained in two different ways and these are:

(a) Although footwall beds have been forced upward in the vicinity of the Klein Aub fault, the overall movement of the hangingwall strata might have been upward relative to the footwall. Thus the Klein Aub fault would have an apparent reverse sense of movement, due to crustal shortening and local uplift of the southern block, as indicated by the upward dragging of the footwall strata. Such a process is illustrated in Figure 6.9 A and B. If this process was operative, any stratigraphic markers across the fault should now be situated at a higher level in the hangingwall of the fault (relative to the footwall). The vertical throw, if reverse faulting is assumed, might exceed 700 m since neither on higher mine levels nor on surface any of the truncated ore bands have been found in the hangingwall of the fault.

(b) Another possible explanation is the development of a transpressional zone due to the oblique convergence of two rigid blocks (Harland 1971; Sanderson and Marchini, 1984; Fig 6.9 A, C). Such a zone would be characterized by compressional features, such as folds and would also involve the internal rotation of the zone.

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Fig.6.9 Sketch diagram, illustrating two different explanations for the dragging features in the footwall of the main Klein Aub fault.

(A) An idealised block (square) with an inclined marker horizon (similar to the ore bands at Klein Aub) is situated between two rigid blocks.

(B) Reverse faulting produced the upward dragging of the footwall strata.

(C) A similar drag-like appearance of the footwall strata developed as a result of transpressive deformation and internal rotation of the deformed block. Note the contrasting hangingwall position of the marker horizon in both models (A and C modified after Sanderson and Marchini, 1984).
Here a stratigraphic marker would be found further down in the hangingwall of the fault, with respect to the footwall, indicative for normal faulting.

However, the lack of structural data from the hanging wall block of the Klein Aub fault (especially underground) prevents a decision on this matter.

Fig. 6. The Compilations shown of
(A): directions of strike of en echelon structures and
(B): interpretation of the same features, from the Klein Aub area in a deformation ellipsoid.
(C): Characteristic orientation of en echelon structures from strike-slip fault zones (adapted after Harding, 1974; Bartlett et al., 1981 and Hancock, 1985)

The en echelon folds, identified both underground and on surface, are a typical feature of strike-slip faulting. Oblique-slip movement along the Klein Aub fault has first been postulated by Tregoning (1977). Hancock (1985) has given an explicit summary of all en echelon structures found in strike-slip fault belts (Fig. 6.10.11). Since Hancock's diagram displays and emphasizes
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