# 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 ($D_1$), pre-dated and accompanied the deposition of the Nückopf, Grauwater 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 ($D_2$), 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 ($D_3$) 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:

| | | | |
|---|---|---|---|
| Deformational phase: | $D_1$ | $D_2$ | $D_3$ |
| Folds: | | $F_2$ | $F_3$ |
| Cleavage: | | $S_2$ | $S_3$ |

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 emphasize on the relationship to the Damaran Orogeny.

## First Phase of Deformation ($D_1$)

This first deformational phase affected the basement rocks underlying the Sinclair Sequence and to a lesser extent, units of the Nückopf and Grauwater 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 basalt part of the Doornpoort Formation which, in the vicinity of Klein Aub Mine, immediately overlies a local baseme[illegible]a. 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 later rotation during deformation, and the present erosion surface produced a section-like exposure of the basement-cover 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 Nückopf and Grauwater 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).

## 6.2 Second Phase of Deformation ($D_2$)

Large-scale folds and a regionally developed cleavage are attributed to this second phase of deformation ($D_2$). 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 $D_2$ event.

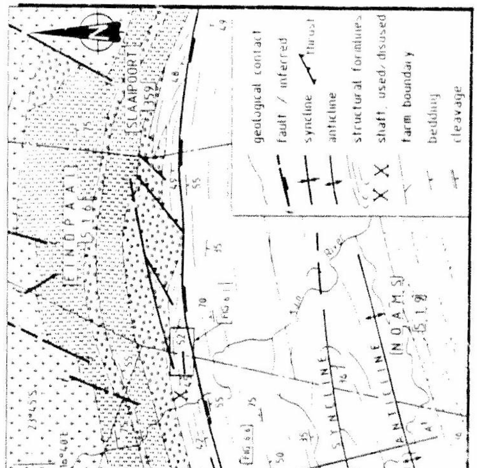



**Fig.6.1.** Geological and structural map of the vicinity of Klein Aub Mine (K.A.). The positions of the sections of Figs 6.6 and 6.12.A, and the more detailed m[illegible] of Fig 6.3 are indicated.

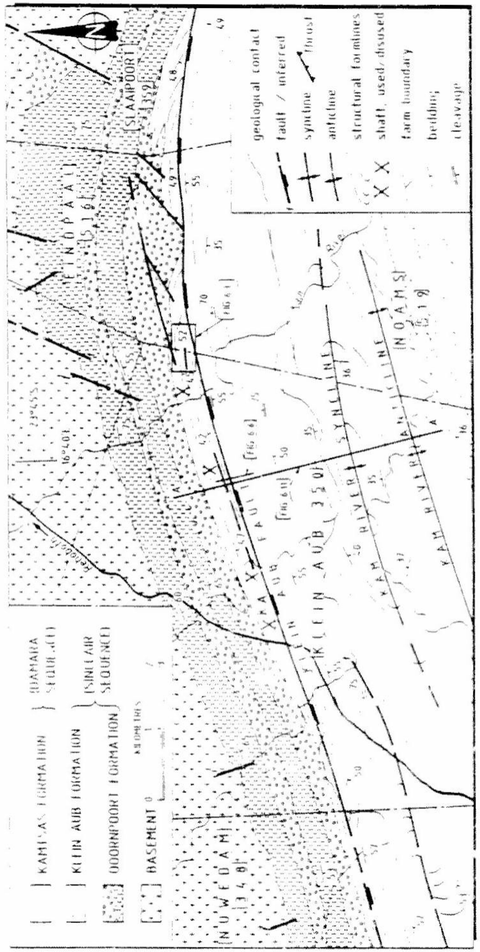



**Fig.6.1**: Geological and structural map of the vicinity of Klein Aub Mine (K.A.). The positions of the sections of Figs.6.6 and 6.12,A, and the more detailed map of Fig.6.3 are indicated.

*Folds:*

This deformational phase produced pronounced, large-scale open folds ($F_2$) 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 $F_2$-folds with a km-scale wavelength plunge at 5°-10° to the west. The Klein Aub Mine, is situated on the so ern limb of one major fold which generally dips 40° to 60° south (Figs.3.1, 6.1).

*Cleavage:*

The regional $S_2$-cleavage is more distinctly developed in fine-clastic rocks, were it defines a weak planar texture, due to the alignment of chlorite and muscovite (Plate 6.1,A). A distinct lineation ($L_2$), plunging 70° north, is recognizable in lenses of recrystallized siliceous limestone, where it is defined by the orientation of elongated calcite crystals (Plate 6.1,B). This $S_2$-cleavage strikes approximately parallel to bedding, but dips at some 70° to the north (Plate 6.1,C; Fig.6.2).

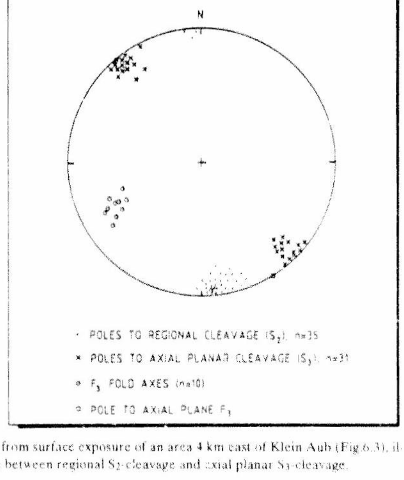



**Fig.6.2:** Structural data from surface exposure of an area 4 km east of Klein Aub (Fig.6.3), illustrating the difference between regional $S_2$-cleavage and axial planar $S_3$-cleavage.

## 6.3 Third Phase of Deformation ($D_3$)

This $D_3$-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 $F_3$-fold structures on all scales, both on surface and underground. A set of *en echelon* folds is exposed 4 km east-northeast of Klein Aub, adjacent to the main fault (Fig.6.3). Thin, discontinuous lenses of detrital and algal limestone, 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 $S_2$ cleavage (c-c').

**(B)** $L_2$ 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 $S_2$ 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 $S_3$-cleavage superimposed over the regional $S_2$-cleavage which is bedding parallel; hammer is 38 cm long.

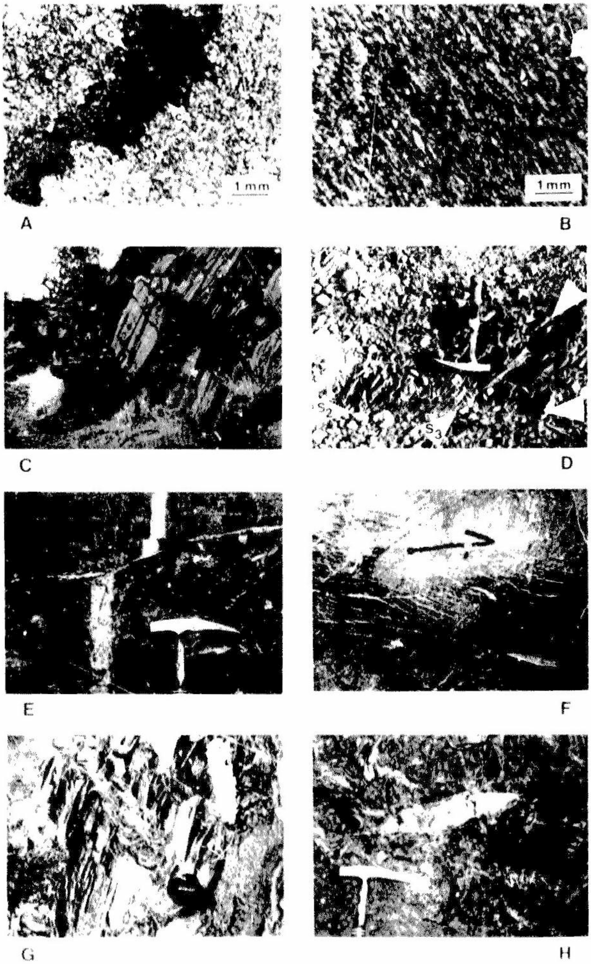
**(E)** Vertical quartz vein (172°/90°) showing right lateral displacement. Maria shaft ore body, 450 m level, 600 west, south facing wall of main haulage way; hammer head is 18 cm long.

**(F)** *En echelon* set of quartz-filled Riedel shears, indicating right lateral movement. Maria shaft ore body, 550 m level, 480 west, south facing wall of main haulage way; length of arrows is approximately 15 cm.

**(G)** Small-scale $F_3$ 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; lense 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.

Plate 6.1



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° (Figs.6.3, 6.4).

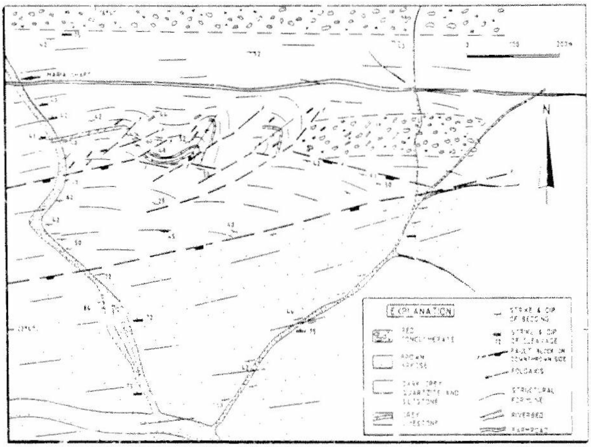



**Fig.6.3:** Detailed structural map of an area adjacent to the main Klein Aub fault (position indicated in Fig.6.1).

Open and tight upright folds, plunging at shallow angles or sub-horizontally on 230°, are developed on a decimetre- to metre-scale on surface and in underground workings (Plate 6.1,G). 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 plots of Figure 6.4. Another prominent deformational feature in the Klein Aub area is the Kam River Syncline, situated some 3 km southeast of Klein Aub (Fig.6.1). It is a shallow, doubly plunging syncline with its curved longer axis striking approximately 75°. 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). $D_3$-folding of the strata adjacent to both, the Klein Aub fault and the inferred fault on Farm Nuwedam, 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 hangingwall strata. The fold structures on both sides of the faults plunge at angles between 10° and 40° towards the southwest. This type of lateral drag folding is shown in the simplified sketch of Figure 6.5.

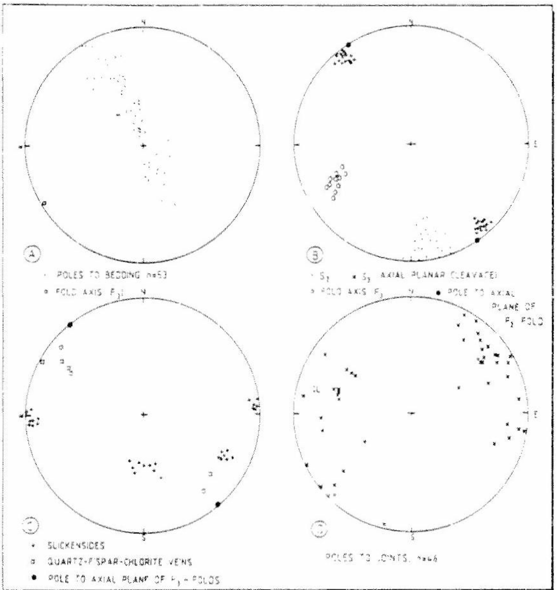



**Fig.6.4:** Structural data from underground workings of the Maria shaft ore body (450 m level, 240-600 m west).

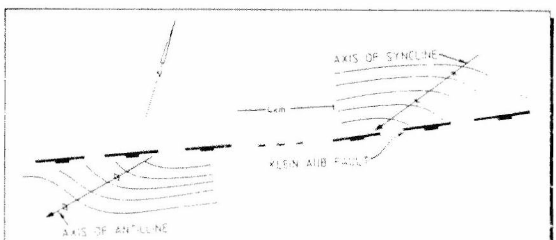



**Fig.6.5:** Simplified sketch map, illustrating the sense of drag-folding of the strata adjacent to the main Klein Aub fault, which suggests right-lateral strike-slip movement along the fault structure.

*Cleavage:*
A distinct axial planar cleavage ($S_3$), associated with the southwest-plunging $F_3$-folds, is exposed on surface and underground (Figs.6.2, 6.3, 6.4). Whereas the regional, $S_2$-cleavage strikes sub-parallel to bedding (strike: 085°) the axial planar cleavage ($S_3$; strike: 050°) shows an angular relationship to the strike of the beds (Plate 6.1,D; Figs. 6.2, 6.4). Poles to the axial planes of the $F_3$-folds plot immediately adjacent to the poles of the axial planar ($S_3$-)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.

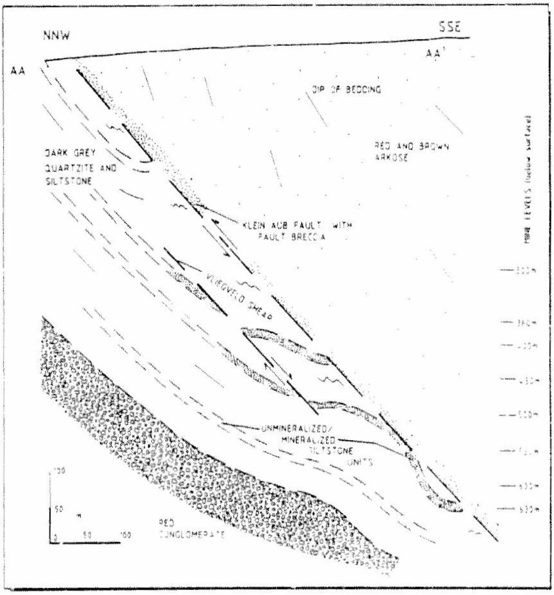



**Fig.6.6:** Geological cross-section through the Maria shaft ore body of Klein Aub Mine, illustrating the relationship between unmineralized (light stippled bands) and mineralized (darker stippled bands) siltstone/mudstone units and the main Klein Aub fault. The position of the section is indicated in Fig 6.1.

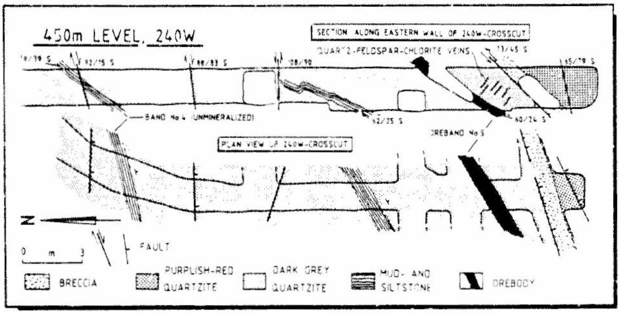



**Fig.6.7:** Cross-section and plan view of a crosscut into the Maria shaft ore body (450 m level, 240 west). The plan view was mapped on the floor level of the cross cut.

The fault is marked, both on surface and in underground workings by a 0.5-1 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 southern (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: 070°-085°), 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 normal 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

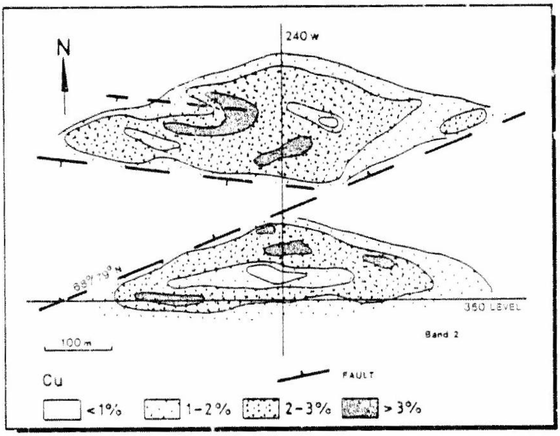



**Fig.6.8:** Reef plan (plan view, projected normal to the mineralized horizon) of ore band 2 at Klein Aub Mine; Maria shaft ore body, 550 m level, 240 west.

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 Eindpaal. A further, laterally extensive fault is inferred from interpretation of aerial photographs. On Farm Nuwedam, 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 075° (Fig.6.1). Slickensides, commonly developed on fault- and subordinately on bedding-planes are orientated either horizontal (strike: east-west) or south-plunging or pitching at an angle of 45° (on south-dipping faults and bedding planes) (Fig.6.4,C).

*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°S) 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 fissures. Where sets of these sigmoidal fractures occur within mineralized horizons the filling often consists of chalcocite. Quartz-feldspar-chlorite veins occur which are locally oriented parallel to the axial plane of $F_1$-folds or arranged in a radial fashion within these folds (Plate 6.1,H). The veins are of lenticular shape, 10-30 cm wide, 30-50 cm high, 80-100 cm long, and often show signs of deformation and rotation. They display cm-size aggregates of 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 $D_1$-deformation, was a phase of extensional faulting. The area underwent compression during the regional $D_2$-deformation which was accompanied by the development of large-scale folds and a regional $S_2$-cleavage. The principal $D_3$-features which are found in the Klein Aub Fault Zone, are *en echelon* 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.

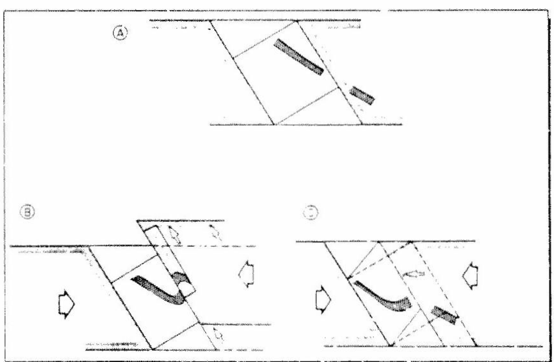



**Fig.6.9**: Sketch diagram, illustrating two different explanations for the dragging features in the footwall of the main Klein Aub fault.
**(A)** An idealised block (square) with an inclined marker horizon (similar to the ore bands at Klein Aub)is situated between two rigid blocks.
**(B)** Reverse 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.

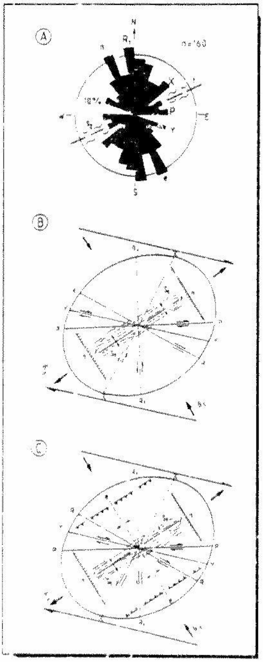



**Fig.6.10:** Compilation diagram of
**(A)** directions of strike of *en echelon* structures and
**(B)** interpretation of the same features, from the Klein Aub area in a deformation ellipsoid.
**(C)** Characteristic orientation of *en echelon* structures from strike-slip fault zones (adapted after Harding, 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 zones (Fig 6.10.C). Since Hancock's diagram displays and emphasizes