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THE KLEIN AUB FAULT ZONE - A WRENCH FAULT SYSTEM IN MIDDLE PROTEROZOIC METASEDIMENTS IN CENTRAL SWA/NAMIBIA

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ABSTRACT

The Klein Aub Fault Zone, situated 180 km south-west of Windhoek, SWA/Namibia, divides a northern, relatively undeformed tilted block from a gently folded southern block. The fault zone is situated near the boundary between coarse clastic red beds and fine-grained psammitic to psephitic rocks, all of late Middle Proterozoic age. It comprises subparallel, en echelon folds and systematically orientated, steeply-dipping normal and reverse faults. Since such interrelated structures are characteristic of major wrench fault systems elsewhere in the world, the Klein Aub Fault Zone is interpreted as a right lateral wrench fault system. The stratabound Cu-Ag deposit at Klein Aub Mine is situated immediately adjacent to the main Klein Aub Fault. The geometry and grade of the ore bodies is partly controlled by subordinate faults of the wrench fault system. Seismic pumping during strike-slip faulting probably moved metal-bearing fluids upwards through permeable zones leading to epigenetic upgrading of earlier, diagenetic mineralisation.

The right lateral Klein Aub Fault can probably be regarded as the northern branch of a positive "flower-structure" with its central part probably 6 km further south. The style and geometry of this fault structure is compared with experimental results of shear deformation and with field observations at the San Andreas Fault, California.

The wrench fault system possibly developed in response to late Damaran convergence of the rigid plates of the Angola and Kalahari Cratons.

1. INTRODUCTION

The area under investigation is situated about 180 km south-west of Windhoek, SWA/Namibia (Fig. 1) where a sequence of late Middle Proterozoic rocks is exposed between Lower and early Middle Proterozoic basement to the north and the younger cover of metasediments of the Late Proterozoic Damara Sequence and the Cambrian Nama Group to the south (Fig.2). The rocks are generally weakly deformed and dip at angles between 45° and 60° to the south.

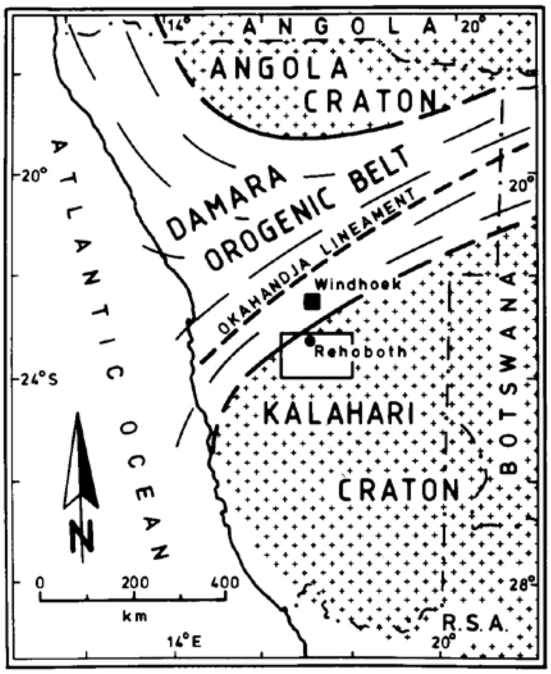


Fig. 1: Geological sketch map of SWA/Namibia, indicating the outline of the cratons and the Damara Orogenic Belt. (after SACS, 1980; Coward, 1983) The area shown in Fig. 2 is marked by a rectangle.

The succession of late Middle Proterozoic metasediments and metavolcanics was deposited in one of several supposedly fault bounded basins extending from central SWA/Namibia into central Botswana (others are found, e.g. in the Dordabis/Witvlei or the Ghanzi/Lake N'Gami areas; they constitute the Kalahari Copper Belt, Borg and Maiden, 1986c). These basins orginated at the margin of the Kalahari Craton by crustal extension in late Middle Proterozoic time. They can be interpreted as rift grabens that developed along a laterally extensive zone of failed continental rifting.

Mapping and sedimentological studies of parts of this area have been carried out by De Kock, 1934; Handley, 1965; Schalk, 1967, 1970, 1973; Tregoning, 1977; Ruxton, 1981, 1986; Maiden *et al.*, 1984; Borg and Maiden, 1986 a,b,c,d).

The Klein Aub area is known for its sediment-hosted stratabound copper-silver deposits, exploited by the Klein Aub Mine since 1967. Although the fault is obviously of great importance to the geometry of the ore deposit, no structural interpretation of the area has as yet been undertaken. The object of this paper is to describe the different structural elements of the area and to propose an explanation for the style of deformation.

2. STRUCTURE OF THE KLEIN AUB AREA

An important main structural feature of the study area is the Klein Aub Fault which can be followed for 17 km (Fig. 3). It strikes approximately east-north-east and dips at an angle of 45° to the south. The main fault is generally at a low angle to bedding and is developed in slaty, thinly-bedded, fine-grained metasediments. It

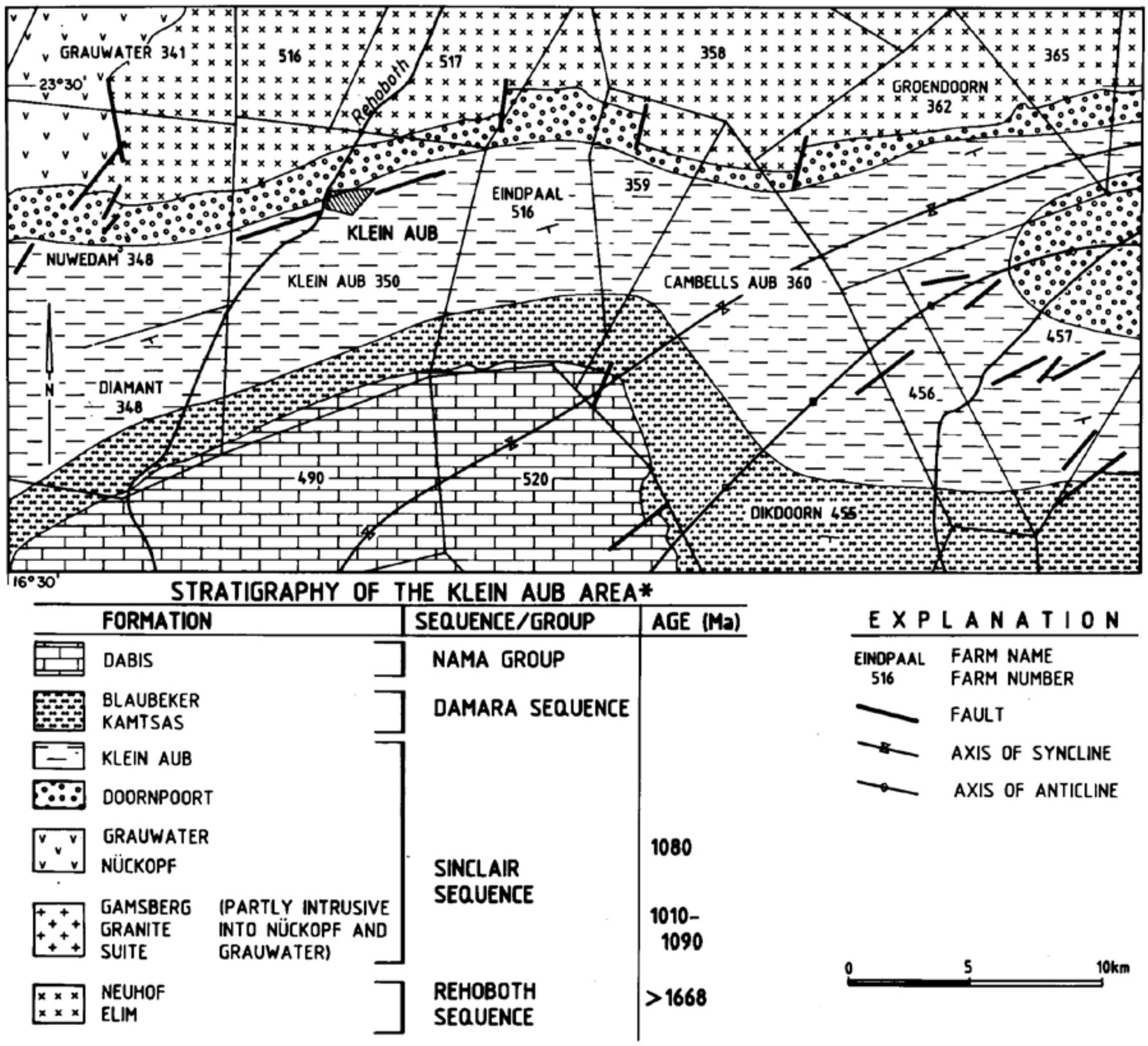


Fig. 2: Simplified geological map (after Schalk, 1970) and local stratigraphy (*after SACS, 1980) of the Klein Aub area. The distribution of the Gamsberg Granite Suite is not displayed on the map.

is recorded from underground workings in the Klein Aub Mine where it folded, displaced and terminated the mineralised beds. Strikeslip movement, as well as vertical movement along the fault, were first recognised by Tregoning (1977).

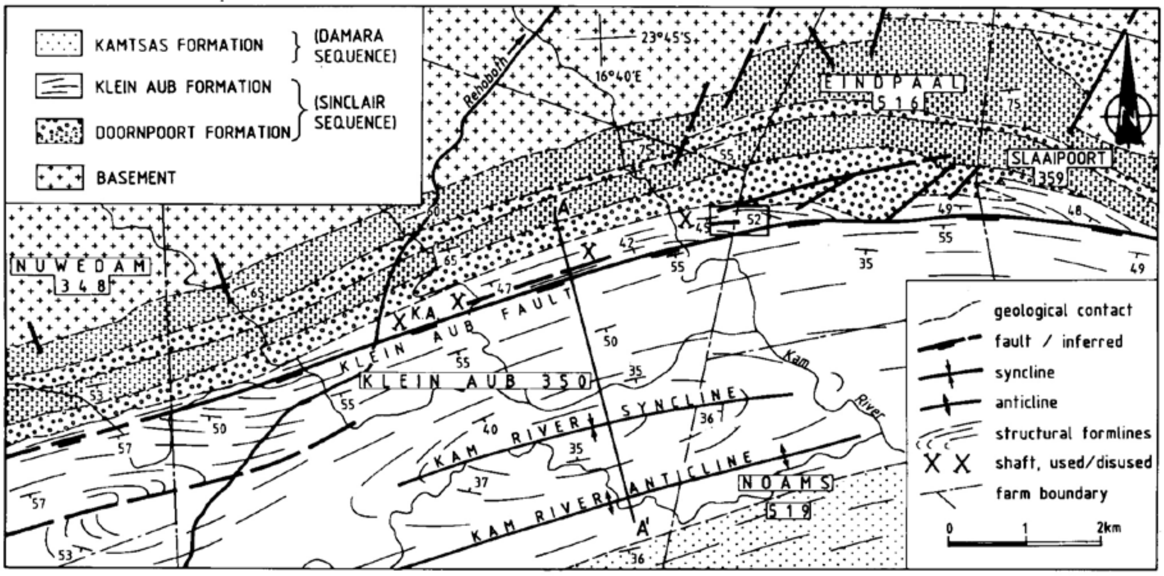
Surface expression of the main fault is limited to a dark maroon, strongly hematitic fault breccia that crops out spo-radically over several kilometres. Several other shears and faults, parallel to the main fault, are exposed in mine workings but surface exposure is insufficient to allow detailed mapping of these subordinate faults. Deformation of the fine-clastic wall rocks increases approaching the fault, resulting in a narrow zone of stronger brittle fracturing and intense ductile deformation. Regionally however, the deformation of the metasediments is only moderate and sedimentological structures are preserved.

The block situated north of the fault consists of a tilted succession of interbedded metaconglomerate and metasandstone of the Doornpoort Formation and the lower part of the Klein Aub Formation. This block appears to be rather undeformed. The statistical comparison of pebble elongation measured in several conglomerate horizons at various distances from the Klein Aub Fault zone revealed no significant increase in deformation towards the fault zone. The southern block is gently folded and forms a shallow syncline (Kam River Syncline) and an anticline (Kam River Anticline) 3 km south of Klein Aub (Fig. 3).

2.1 Structures mapped in mine workings

The main fault is generally bedding-parallel, but on deeper levels of the mine (500-700m) the footwall beds are dragged upward and strongly deformed. Here the deformed and mineralised beds are cut off by the fault and are not found in the hanging wall. This might imply a vertical component of displacement of at least 700 m.

En echelon normal faults, dipping 75°-85° towards



Fi.g 3: Geological and structural map of the Klein Aub area; KA = Klein Aub village. The location of the area shown in Fig. 4 is indicated by a rectangle.

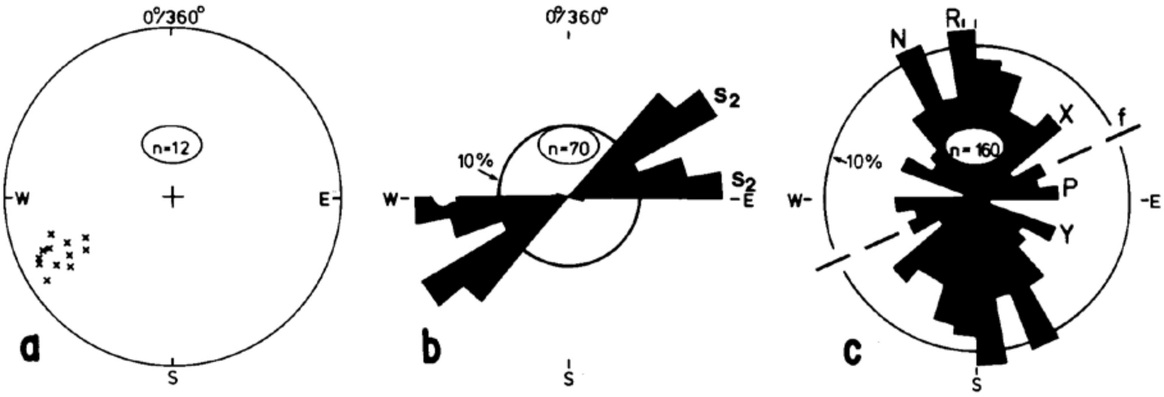


Fig. 4: (a) Diagrammatic projection of fold axes.
(b) Strike direction of the regional cleavage (S_1) and the locally developed axial planar cleavage (S_2). Compare orientation of cleavages with photograph of Fig. 7a.
(c) Orientation of fold axes (f), normal faults (N), conjugate shears (R') and fracture pattern from underground and surface. For comparison and explanation of other characters see Fig. 8.

west-south-west (strike: 340°) are commonly observed, Sets of quartz-carbonate filled extension fractures and waterbearing fissures show the same orientation as the normal faults (N in Fig. 4c). Due to the extensional character of the fissures they commonly act as conduits for groundwater, causing serious mining problems.

A Further set of faults, developed at an oblique angle to the main fault, strike at 1100 (Y in Fig. 4c). In conjunction with the normal faults these faults confine the mineralised ore horizons laterally and down dip (Fig. 5).

Small-scale en echelon folds with a wavelength of 10 to 100 em and amplitudes of 10 to 60 em are developed in the finer grained metasediments. The fold axes plunge towards south-west (Fig. 4a). Slickensides are commonly developed on bedding planes and suggest movement also parallel to bedding planes, or thrusting, in addition to that indicated by the visible fault displacement. The orientation of these slickensides is either horizontal (south-west to north-east), steeply south-plunging or pitching at an angle of 45° (on south-dipping bedding planes).

2.2 Structures mapped on surface

Mapping of some well-exposed areas, close to the main Klein Aub Fault, located en echelon folds (wave length appro. 100 m, amplitude appro. 120 m) with fold axes plunging at 10° to 40° towards 220° to 230° (Fig. 4a, 6). The folds are developed in metasandstone! metasiltstone with intercalated layers of recrystallised detrital and algal limestone. A second cleavage (S_2) is developed sub-parallel to the axial planes of the fold axes (Fig. 4b, 7b). This cleavage is superimposed on

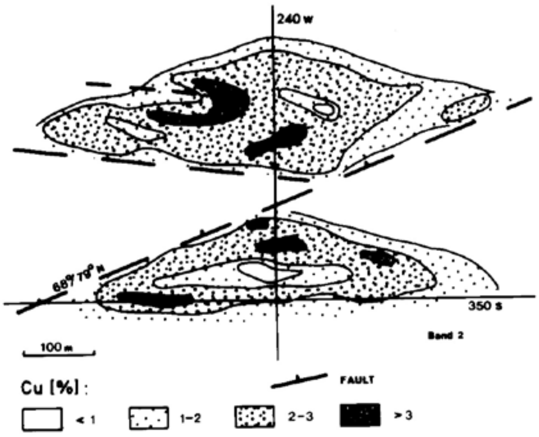


Fig. 5: Reef plan of ore-band 2 at Klein Aub Mine (Maria Shaft ore body, 550 level, 240 west). The mineralised band has been set off by a right lateral strike slip fault. Note the locally decreasing metal contents away from the faults, indicating epigenetic upgrading of earlier, diagenetic mineralisation.

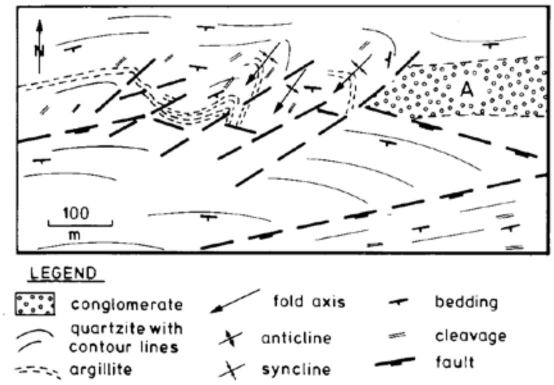
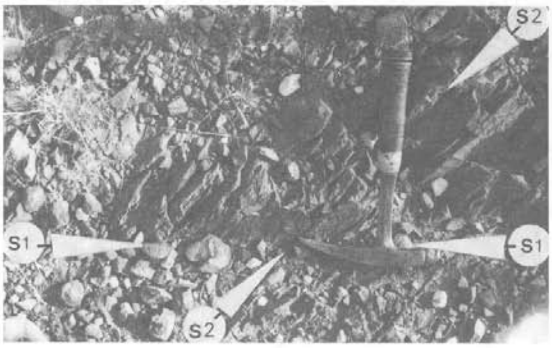
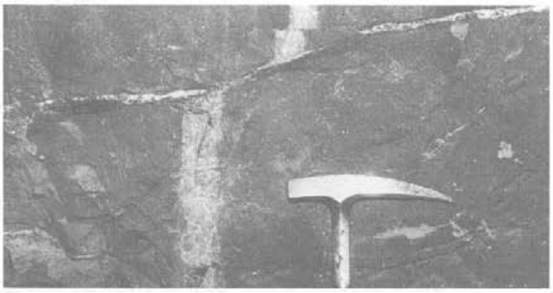


Fig. 6: Detailed structural map of an area 3 km north-east of Klein Aub village. Right lateral strike slip faulting has caused dragging and folding of the beds and the clockwise rotation of fault bounded blocks.

Fig. 7: (a) Regional cleavage (S_1), dipping orthogonal to bedding, in laminated slate and quartzite in the vicinity of Klein Aub.



(b) Locally developed axial planar cleavage (S2) superimposed over regional cleavage (S1) which strikes parallel to bedding (E-W).



(c) Vertical quatz vein (172°/90°) showing right lateral displacement. Maria shaft ore body, 450 level, 600 west, south facing wall of main haulage way.

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

the regional, east-west orientated slaty cleavage (S_2) (Fig. 4b, 7a). The folds are truncated by later faults and blocks several hundred metres across have been displaced and rotated clockwise (Fig. 6). Two distinct fault directions are developed, striking approximately 60° and 105° (Fig. 6).

Striking at an angle of approximately 50°, thrusts intersect and cut off the conglomerate of an alluvial fan lobe which underlies the slaty sediments some 3 km north-east of Klein Aub (Fig. 6). Exposure does not allow the determination of the dip of the thrust planes. These thrusts occur between the main Klein Aub Fault and a subordinate, parallel fault which is developed approximately 500 m north of it. These two faults show a right lateral sense of movement.

Dragging and rotation of the beds is found in the opposing fault blocks (Fig. 3). At the eastern end of the fault structure, the beds of the northern block are dragged in a clockwise sense and folded into a shallow syncline, plunging steeply south-west. The beds of the southern block are dragged anticlockwise and folded but form an anticline at the western extremity of the fault zone. Both the syncline and the anticline have the same plunge direction.

The structure of the area shown in Fig. 6 has been complicated by the extreme difference in competency of the deformed rocks. In this area, a block of metaconglomerate (A in Fig. 6), with pebbles of up to 1 m in diameter, collided with the layered, slaty metasediments to the west. The different response to stress in different rock types has enhanced and complicated the folding and faulting in this area.

3. INTERPRETATION AND RELATION TO MINERALISATION

Hancock (1985) has given an explicit summary of all possible en echelon structures found in strike-slip fault zones (Fig. 8). The principal features which are also found in the Klein Aub Fault Zone are en echelon folds, an axial-planar cleavage, normal- and reverse faults, thrusts, extension joints and fissures.

The en echelon folds identified both underground and on surface are a typical feature of wrench fault systems. As shown in experiments by Wilcox *et al.* (1973) they form during an early stage of simple shear deformation. Fig. 6 shows that these folds have been truncated by faults. Although differences exist in composition of rocks and shape of folds between structures studied on the surface of underground respectively, the direction of plunge is common to both sets.

Areas of convergence, high stress domains and small areas of divergence have developed between subparallel, right lateral, strike-slip faults. The fracture pattern shown in Fig. 4c comprises structures associated with both divergent and convergent right lateral wrench fault systems. The different structures have possibly formed during different phases of the development of the Klein Aub Fault zone. In addition to the strike-slip movement the Klein Aub Fault has a considerable vertical throw. Along the Klein Aub Fault, sensu stricto, oblique slip has occurred.

The analysis of the geometrical arrangement of structures allows the definition of the main stress directions. In case of the Klein Aub Fault Zone, the principal stress (δ1) was directed in a north-westerly direction while north-east was the direction of extension (δ3). Although horizontal shear was predominant, local uplift of the basement occurred as a result of compression between two convergently and laterally slipping rigid crustal blocks. Due to the combination of horizontal and vertical movement, displacement resulted in oblique slip. The lack of marker beds prevents exact determination of lateral displacement but it is possibly in the range of several kilometres.

In areas of more intense faulting and brittle fracturing the ore grade tends to be higher than in relatively undisturbed parts of the ore-bearing horizons. In the high-grade zones up to 60 percent of the mineralisation (chalcocite ore) is hosted by brittle fractures. Based on studies of ore textures, Borg and Maiden (1986d) proposed an epigenetic phase of syn- or post-deformational metal emplacement. Epigenetic upgrading of earlier, diagenetic mineralisation close to subordinate faults of the wrench fault system is common at Klein Aub Mine (Fig. 5).

Sibson *et al.* (1975) proposed "seismic pumping" as a transport mechanism for large quantities of fluid within wrench fault systems, a model illustrated in Fig. 9.

The rapid transport of fluid upward, in the direction of easiest pressure relief, is common with strike-slip and normal faults. Here strongest compression is horizontal and fractures and fault planes are orientated vertically

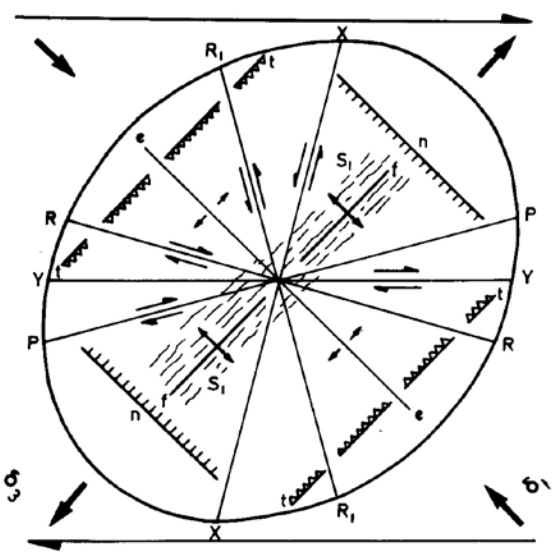


Fig. 8: Compilation diagram, illustrating en echelon structures characteristic of strike slip fault zones, evolving during simple shear. R and R', Riedel and conjugate Riedel shears; P, X and Y, P-, X-, and Y-shears; e, extension joints, fissures or veins; n, normal faults; t, thrusts, f, folds; S', cleavage or other foliation. After Harding, 1974; Bartlett *et al.*, 1981 and Hancock, 1985.

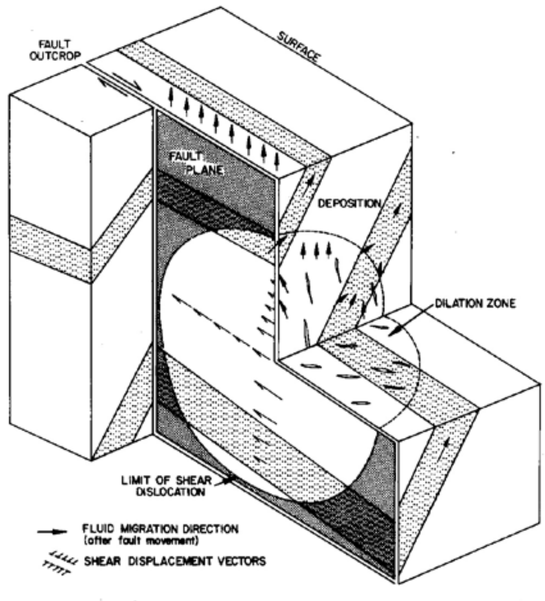


Fig. 9: Simplistic model of seismic pumping around a vertical, right lateral wrench fault (modified from Sibson *et al.*, 1975). The expulsion of fluids follows the collapse of a dilatant zone. Fluids are pumped upwards through fault planes, fractures and permeable horizons (dotted layer).

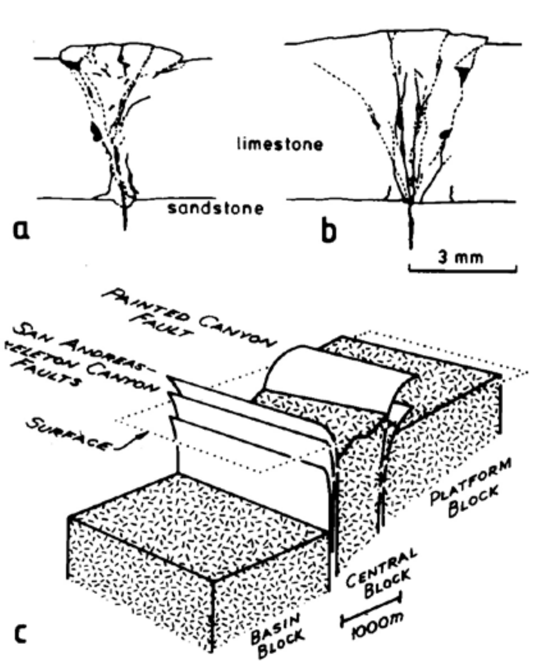


Fig. 10: (a,b) Cross section through right lateral shear zone in limestone (after Bartlett *et al.*, 1981).

or subvertically. Sibson's description of this process applies precisely to the setting within the Klein Aub Wrench Fault System: "Upflow from the collapsing dilatant zone must take place through the fault, adjacent fractures and all permeable layers ..." (Sibson- *et al.*, 1975). Metal-bearing fluids, driven by the mechanism described above, were funneled through the layers of massive, relatively permeable footwall metasandstone underlying the mineralised metapelite bands. Due to insufficient sulphur supply only some diagenetic pyrite cubes have been replaced by chalcocite but no significant mineralisation occurs in these horizons. From these aquifers the fluids penetrated the pyritic metapelite and mineralised permeable layers, brittle fractures and cleavage planes.

4. SIMILARITIES WITH KNOWN STRIKE-SLIP FAULT ZONES

Strike-slip fault zones are generally more steeply disposed than the main "Klein Aub Fault" described here, but shallow dips are not uncommon in wrench fault systems (Harding, 1985). Experiments by Bartlett *et al.* (1979) as well as field observations and geophysical interpretations (Harding and Lowell, 1979) have shown that the inclination of some faults within wrench fault systems tends to become shallower in the upper and outer regions of the system. Such structures are known as "flower structures" (Harding and lowell, 1979). Harding's characterisation of these structures (Harding, 1985) applies to the structural pattern observed in the Klein Aub Fault Zone. "A positive flower structure is defined as a linear antiform that is bounded longitudinally along its flanks by the upward and outward diverging strands of a wrench fault that have mostly reverse separations. The antiform" (Kam River Anticline, Fig. 3) "is subparallel to the principal strike- slip zone and thereby differs from the oblique orientation of en echelon folds that can form external to the zone. The formation of positive flower structures is promoted by a component of convergence normal to the wrench fault, by increased strike-slip displacements, and by the presence of a thick and ductile sedimentary section" (Harding, 1985). Fig. 10a and bare adapted from Bartlett *et al.* (1981) and show shear zone fractures in sections through samples of artificially deformed limestone. In Fig. 10c a block model illustrates the "flower structure" arrangement of the Painted Canvon Fault and the San Andreas Fault (after Sylvester and Smit, 1976). The shallow dip of the Klein Aub Fault and the gentle folding of the southern fault block (Fig. 3 and 11a) is comparable with the structures described from the San Andreas Fault region. Tectonic "transgression", defined by Harland (1971) as lateral and convergent slip along wrench faults, has caused the buckling and folding of the block west of the Painted Canvon Fault, a 20 km long fault within the San Andreas Fault System (Fig. 10c and 11b), producing faults and folds with a similar geometric arrangement as in the Klein Aub area.

These comparisons suggest that the Klein Aub Fault is only the northernmost expression of a much bigger wrench fault system, with its central part approximately 6 km Further south. The fault system can have either a symmetrical or an asymmetrical pattern. This interpretation might be supported by a structure which could represent another similar fault zone (right lateral strike-slip) which can be recognised on air photographs and

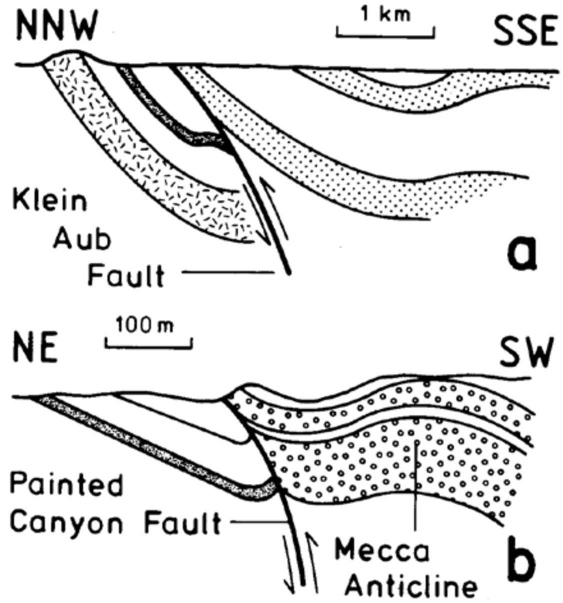


Fig. 11: Idealized, cross sectional geometries of a: the Klein Aub Fault, SWA/Namibia and b: the Painted Canyon Fault, California. The sense of movement is in both cases right lateral (b after Sylvester and Smith, 1976).

from field observations 3 km south-west of Klein Aub (Fig. 3).

5. RELATION TO DAMARAN DEFORMATION

The Klein Aub wrench fault system developed at a late stage of, or after, the main regional deformation event, as the local cleavage cuts across the regional, east-west striking, slaty cleavage (Fig. 4b, 7a). The development of a second cleavage (S_2), striking at 50°, was not limited to the immediate vicinity of the Klein Aub Fault Zone but has been observed on farm Schlip 473, 60 km towards the south-west (H. Ahrendt, pers. comm., 1987). The age of the peak of metamorphism and deformation has been determined at 530± 10 Ma (Ahrendt *et al*, 1977), which indicates a Damaran age. This main deformation event tilted the succession to the south and produced a regional, slaty cleavage, dipping approximately 70° to the north and strikes approximately parallel to bedding (Fig. 7a).

Within the tectonic framework of southern Africa the Klein Aub area is situated on the margin of the stable Kalahari Craton, adjacent to the Damaran Orogenic Belt (Fig. 1). The Klein Aub Fault Zone possibly developed in response to convergence of the Angola and the Kalahari Cratons during a late stage of the Damara Orogeny (Coward, 1983). Another expression of this collision is sinistral strike-slip movement along the Okahandja Lineament (Fig. 1), produced by simple shear deformation (Coward, 1983; Downing and Coward, 1981).

6. CONCLUSIONS

The Klein Aub Fault Zone is a right lateral wrench fault system which developed in metasediments of the Middle Proterozoic Doornpoort and Klein Aub Formations.

Detailed field and underground mapping has revealed a number of structural features that are commonly associated with wrench faults, namely:

i) the bedding-parallel main fault and a number of subparallel, minor faults (strike 80°)
ii) en echelon folds (plunging 10° - 40° on 220° - 230°)
iii) axial planar cleavage (strike 40° - 60°)
iv) en echelon normal faults (strike 330° - 340°)
v) extensional fractures (strike 330° - 360°) vi) thrusts (strike 50° - 60°)
viii) dragging of beds at opposite ends of the fault structure.

These structures form the principal pattern which delineates the right lateral character of this strike-slip fault zone. The relatively shallow angle of the Klein Aub Fault probably reflects the position of this area in the northern, outer zone of a "flower structure". The axial planar cleavage, superimposed on the regional cleavage indicates that the wrench fault developed either later than the main deformation event or at a very late stage of it. Convergence of the rigid plates of the Angola and Kalahari Craton possibly caused the development of the Klein Aub Fault Zone during the late Damara Orogeny. Seismic pumping during wrench faulting probably provided the driving mechanism for epigenetic, mineralising fluids which upgraded earlier, diagenetic mineralisation.

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