Communs geol. Surv. Namibia, **10** *(1995), 109-119*

Metallogenesis of Neoproterozoic basins in Namibia and Botswana

G. Borg

Institute of Geological Sciences, Martin-Luther-University Halle-Wittenberg, Domstr. 5, 06108 Halle, Germany

A Neoproterozoic (1300 Ma - 900 Ma) continental rift, consisting of several volcanosedimentary basins is situated along the Wand NW -margin of the Kalahari Craton. The basins did not develop contemporaneously but show a younging trend from SW to NE. The lithostratigraphy of these basins is similar, comprising a lower succession of bimodal volcanic rocks and continental red beds. In most basins an upper succession contains grey and green, fine-grained, pyrite-bearing siliciclastics and subordinate carbonates. The rocks have been moderately deformed and experienced lower greenschist facies metamorphism during the Damaran orogeny. Both lower and upper successions host copper mineralisation. Minor copper occurrences in altered basalts are erratic and subeconomic. However, sediment-hosted copper-silver mineralisation is widespread at the base of the marine and lacustrine succession. Mineralisation of economic grade occurs at Klein Aub (Namibia, mine closed in 1987) and Lake Ngami (Botswana). At Klein Aub, isotopic age determinations of copper-sulphides, metal and ore mineral zonation patterns and age-sensitive replacement patterns all document a late or post-deformational origin of the orebodies. At Lake Ngami metal and ore mineral zonation patterns and ore replacement textures indicate ascending diagenetic mineralising fluids prior to the main folding event as zonation patterns were folded together with the surrounding strata. A subordinate type of mineralisation is breccia-hosted and postdates the diagenetic phase.

Regional Geological Setting

Neoproterozoic basins of the Sinclair Sequence and equivalents occur as relatively narrow, discontinuous, fault-bounded troughs in southern, central and eastern Namibia extending into western and northern Botswana (Fig. 1). These troughs are volcano sedimentary basins which are aligned along the western, northwestern and northern margin of the Kalahari Craton in the areas of Koras in South Africa, Sinclair, Klein Aub and Dordabis/Witvlei in Namibia and Ghanzi/Lake Ngami, Goha and Shinamba situated in Botswana (Fig. 1) (described and summarised in Borg, 1988b). Features shared by all of these basins are a low metamorphic grade and a moderate degree of deformation. As a result of this, the rocks display their original magmatic or sedimentary textures in great detail. The prefix "meta" has not been added specifically to the original rock names in the following text.

The plate tectonic setting of these basins has been variably interpreted during the last two decades as a magmatic arc (Watters, 1974), an aulacogen (Kröner, 1977) and as a continental rift in an extensional crustal regime (Reeves, 1978; Cahen and Snelling, 1984; Porada, 1985; Borg, 1988b, Hoal *et al.*, 1989, Hoal and Heaman, 1994). Intermediate volcanic rocks occur only as a minor portion in the Sinclair Basin (Borg, 1988b) and are insufficient to support Watters' (1974, 1976) interpretation of a subduction zone. Instead, a continental rift setting is supported by the bimodal volcanism with continental tholeiitic affinity, thick coarse-grained clastic red bed successions and extensional tectonism which can be found in all basins. Diachronous, lateral-rift propagation and a similar thermal, magmatic, tectonic and sedimentological history of the individual basins might explain these seemingly contradictory observations (Borg, 1988b). Such lateral-rift propagation is supported by an overall younging trend (~1200 Ma to ~900 Ma) from S to NNW in Namibia and NE into Botswana. Individual rift basins developed from an initial rift phase of crustal extension and bimodal volcanism through a phase of continued block faulting, erosion of graben shoulders and continental red bed sedimentation to a phase of thermal subsidence with marine or lacustrine environments overstepping the shoulders of the initial rifts.

Age constraints are relatively vague and recently published single crystal zircon age data show that major corrections of age data and their interpretation might be necessary (Hoal and Heaman, 1995, this volume). The overall rift structure probably extended into South Africa in the area of Koras and thus has been named the Koras-Sinclair-Ghanzi rift (KSG rift) (Borg, 1988b). Another extension is to be found in the Goha and Shinamba Hills in northern Botswana (Fig. 1). The Sinclair portion of the KSG rift is located adjacent to the Namaqua (Natal) Mobile Belt situated to the southwest which is interpreted as being contemporaneous but with a distinctly different geological history. A dextral strike-slip component in the Koras-Sinclair branch and a sinistral component in the Klein Aub-Ghanzi branch have been recognised by Borg (1988b), an idea subsequently followed by Jacobs *et al.* (1993) and Thomas *et al.* (1994). The rift basins probably developed as pull-apart structures in response to the oblique magmatic arc-continent collision and the closure of the Tugela-Areachab Ocean as postulated by Thomas and Eglington (1990).

The characteristic metallogenic pattern of these basins is the relative abundance of stratabound copper-silver mineralisation in clastic sedimentary rocks and subordinately in mafic volcanic rocks and the marked lack of other mineral occurrences (Maiden *et al.* 1984; Borg, 1991; Steven, 1992/93).

Individual basins and their metal occurrences

Sinclair Basin

The lithostratigraphic succession of the Sinclair Basin consists of several cycles of bimodal volcanic rocks

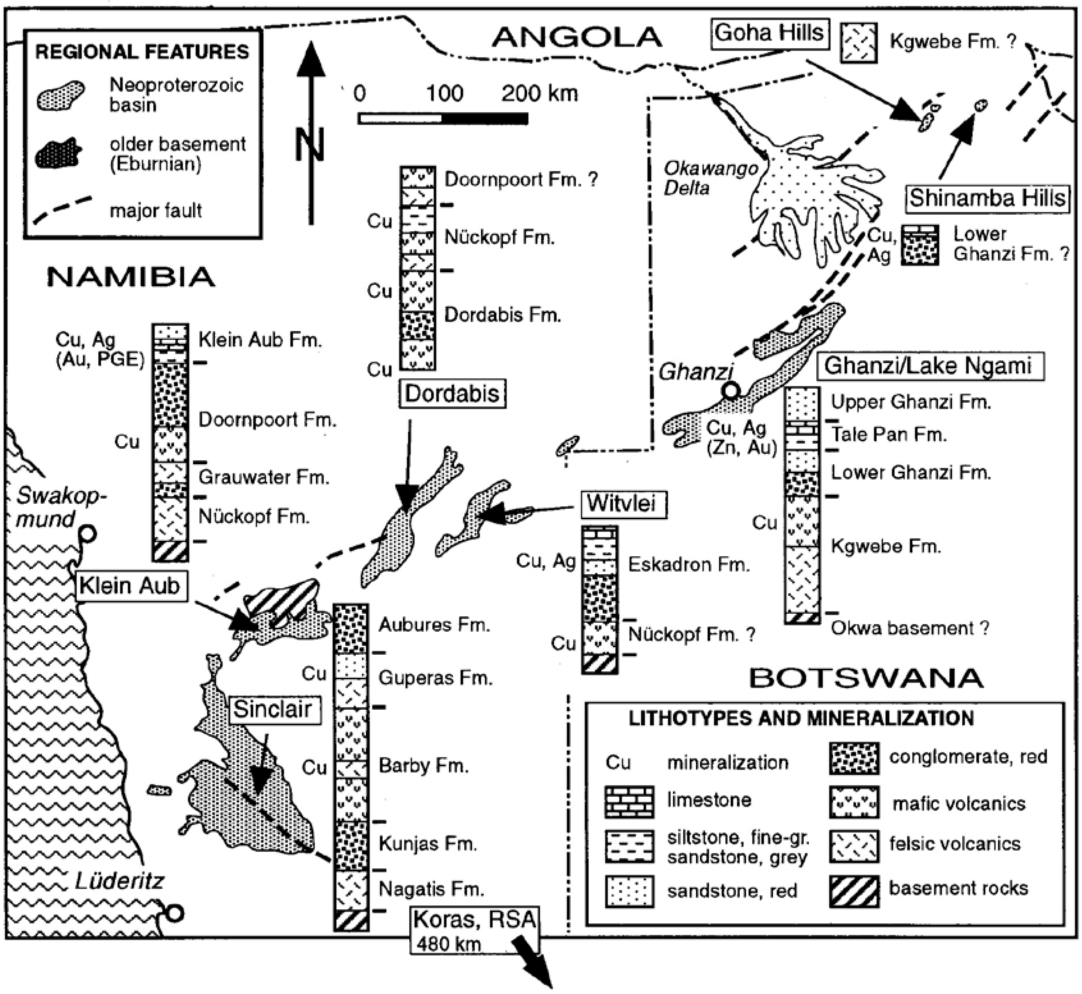


Figure 1: Regional distribution, stratigraphic subdivision and principal lithotypes of the Neoproterozoic basins in Namibia and Botswana and stratigraphic position and metal association of known copper deposits.

and oxic continental clastic sedimentary rocks as described by Watters (1974, 1976, 1977) (Fig. 1). The rocks are bordered to the west and southwest partly by overlying sediments of the Namib Desert and by rocks of the contemporaneous Namaqua Belt and the younger Gariep Belt.

To the east the Sinclair Sequence is unconformably overlain by sedimentary rocks of the Nama Group. The lithostratigraphy of the area differs from that of all other basins in that no shallow marine or lacustrine, chemically reduced sediments were deposited.

To date the only mineral occurrence of some significance within the Sinclair succession is the copper mineralisation at Sinclair Mine (Fig. 1). The former Sinclair Mine is situated some 60 km NW of Helmeringhausen. The mine operated from 1913 to 1914 and from 1927 to 1932. Mining produced several hundred tons of hand-picked ore with relatively high copper grades (16%-40%) which was shipped to Europe. Since then only limited exploration has been carried out without significant success (Söhnge, 1958; Martin, 1965). These investigations indicated reserves of some 15 800 t of copper ore with a grade of 3% Cu and 15 g/t Ag (Fuchter, 1964).

Mineralisation is restricted to several cupriferous quartz veins and subordinately to some mineralised patches within altered mafic lavas of the Barby Formation (Figs 1 and 2). The mafic lava flows occur intercalated with volcanic rocks of rhyolitic and andesitic composition and all show strong chlorite-epidote alteration where in contact with the quartz veins. The area has been intruded by the Nubib Granite some two kilometres to the west of the mine. The majority of the quartz veins have formed as extensional veins with either fibrous quartz growing perpendicular to the wall rocks or displaying symmetrical banding and idiomorphic quartz crystals growing into open spaces. Copper-sulphides such as chalcocite and minor bornite and chalcopyrite occur as irregular patches, as aggregates several centimetres in diameter and as thin layers within the banded quartz veins. Minor mineralisation is hosted as irregular aggregates in fractures and amygdales within the altered basalt and andesite. Generally the extensional quartz veins are located within or at the margin of the rhyolite, probably due to its more brittle rheological behaviour.

All evidence points to a late, epigenetic origin of the copper mineralisation, derived locally from the alteration of adjacent mafic and intermediate volcanic rocks. Traces of copper-sulphides were also trapped within vugs of the altered wall rocks but the main portion of the mineralisation was precipitated in extensional quartz veins. Mineralisation at this location is both too erratic and too small for any further systematic exploration.

Klein Aub Basin

Rocks of the Klein Aub Basin are exposed between the Naukluft Nappe Complex in the west and the sand cover of the Kalahari Desert to the east. To the north, the rocks are generally in undisturbed contact with basement rocks of the Marienhof and Elim Formation, which are part of the Rehoboth Sequence (1600 Ma). The exposure is limited to the south by the cover of unconformably overlying Nama Group sedimentary rocks. The sequence can be subdivided into a lower part, the Nückopf and Grauwater Formations, and an upper part, the Doornpoort and Klein Aub Formations (Fig. 1). The former two consist mainly of rhyolitic volcanic rocks and subordinate conglomerate and minor basalt (Borg, 1988a, b). The Doornpoort Formation comprises continental, partly evaporitic red beds with intercalated, subaerially extruded, tholeiitic basalt. The overlying fine clastic sedimentary rocks and minor carbonate (Klein Aub Formation) are chemically reduced, contrasting markedly with the underlying red beds and have been deposited in an intratidal to subtidal environment.

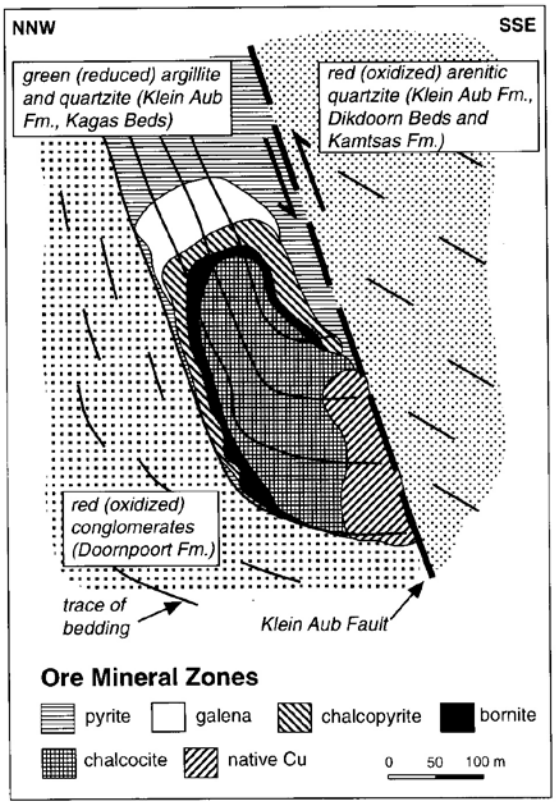


Figure 3: Schematic cross section (NNW-SSE) through the Maria shaft orebody at Klein Aub Mine, showing the zonation pattern of ore minerals. The orebody extends to a maximum depth of 800 m below surface.

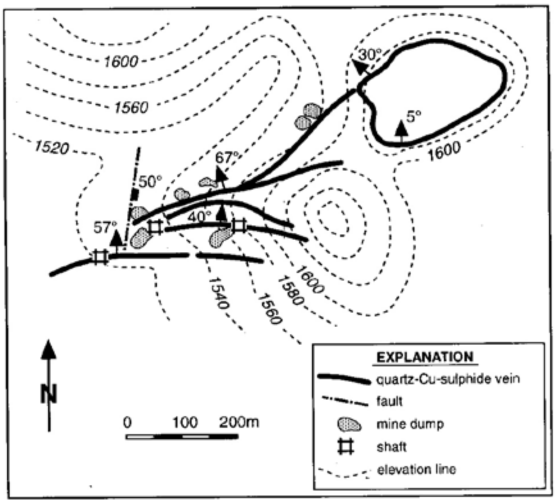


Figure 2: Spatial distribution of quartz-copper-sulphide veins at the abandoned Sinclair Mine (after Söhnge, 1958). The map area is located on the southwestern slope of a hill some 5 km northwest of the farmhouse on farm Sinclair Mine 2.

The rocks dip at moderate angles to the south and have been deformed into several open folds. The Klein Aub Formation is overlain by oxidised arkosic quartzites which are regarded as being equivalent to the Kamtsas Formation of the Damara Sequence (Schalk, 1970). A prominent bedding-parallel fault in the Klein Aub Formation displays a reverse oblique-slip (dextral) sense of movement (Borg *et al.*, 1987). The overall structure has been interpreted by these authors as a positive flower structure. The fault has dragged and fractured the rocks of the Klein Aub Formation and controls the shape, size and grade of the orebodies at Klein Aub Mine (Borg, 1988a).

Copper mineralisation is hosted by both basalt (mainly Doornpoort Formation) and pyritic green mudstone and siltstone (Klein Aub Formation). The basalt of the Doornpoort Formation is generally altered and copper-depleted (Borg and Maiden, 1987; Borg, 1988a) but locally hosts small amounts of native copper and cuprite in and adjacent to amygdales and quartz veins. However, the more striking metallogenic feature of the Klein Aub Basin is the laterally extensive occurrence of copper anomalies which follow the stratigraphic redox contact between continental red beds and overlying

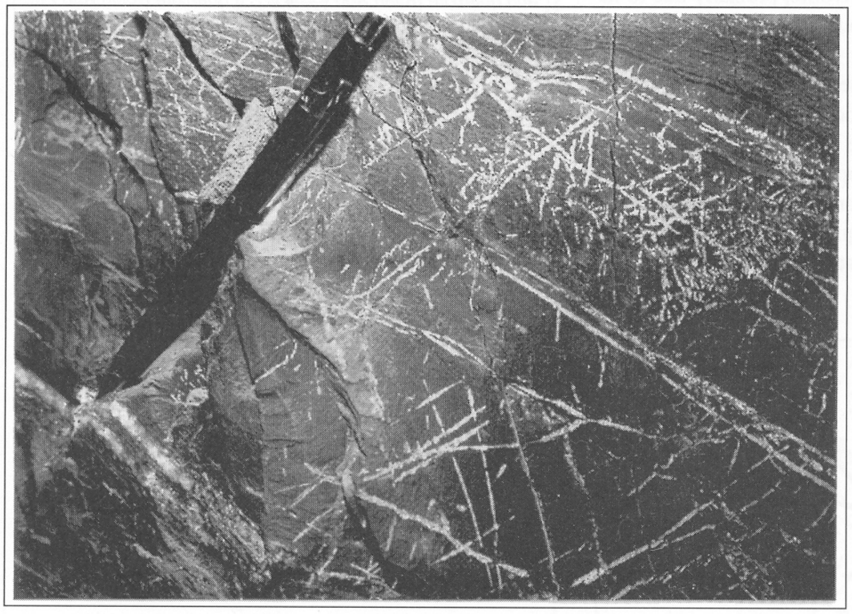


Figure 4: Underground photograph of high-grade ore (8 % Cu) at Klein Aub Mine, comprising both fracture-hosted and disseminated (not visible) chalcocite mineralisation. The weathering products of the sulphides suggest a greater width of the fractures which were originally less than 1 mm across.

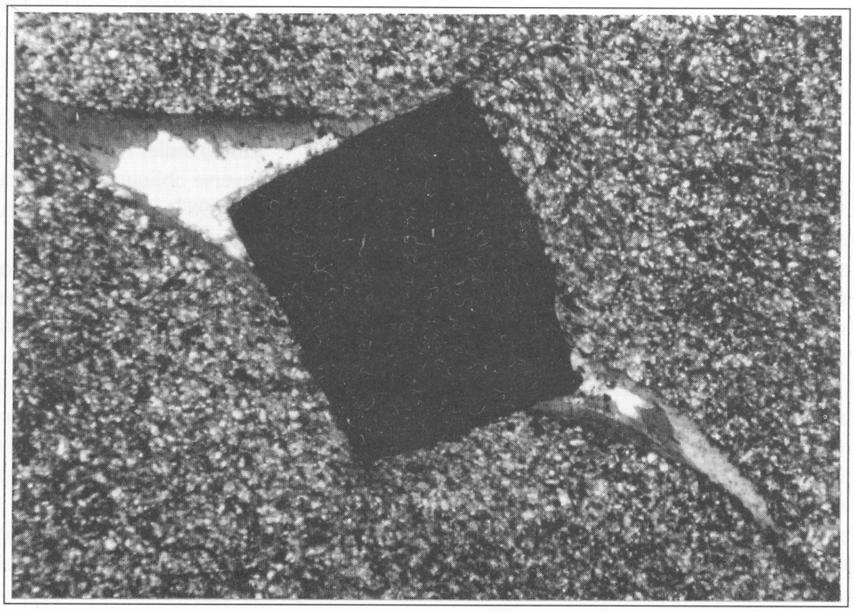


Figure 5: Microphotograph showing a diagenetic pyrite cube with pressure shadows filled by quartz and chlorite in an unmineralised quartzite from Klein Aub Mine. Long axis of field of view is 6 mm. See Fig. 7 for comparison.

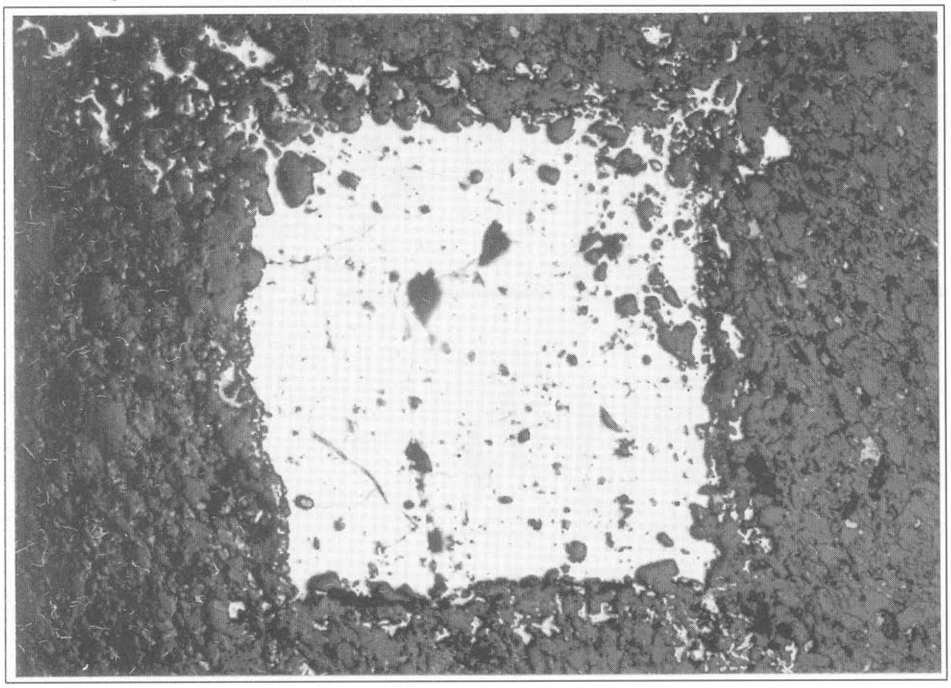


Figure 6: Microphotograph showing a chalcocite cube pseudomorph after pyrite, from the Maria shaft orebody, Klein Aub Mine. The replacement must postdate main deformation as a relatively soft chalcocite cube would have been severely distorted during deformation. Long axis of field of view is 6 mm. See Fig. 8 for comparison.

pyritic sedimentary rocks. The grade of these copper showings is generally between 0.1-1.0% Cu.

At Klein Aub Mine, three orebodies were identified and mined between 1966 and 1987, producing 5.5 million tons of ore at 2% Cu, 50 g/t Ag (total pre-mining reserves 7.5 million t). High-grade parts of the orebodies contain up to 8 % Cu and 170 g/t Ag as well as traces of gold and platinum (155 ppb Pt, 118 ppb Au in ore concentrates; Borg *et al.*, 1987). The most abundant ore mineral is chalcocite with minor bornite and chalcopyrite occurring as a narrow fringe zone that encloses the chalcocite orebodies (Fig. 3). Mineralisation at Klein Aub Mine occurs as finely disseminated chalcocite and minor chalcopyrite and bornite in the coarser-grained strata of mm-scale laminated siltstone and sandstone, interpreted to be of marine intratidal origin, and subordinately in subtidal sandstone (Borg and Maiden, 1989). Some parts of the ore bodies contain rich fracture-hosted chalcocite mineralisation (Fig. 4) in rocks that are also mineralised with disseminated ore. Concentrations of other base metals are low (pb <30 ppm, Zn <100 ppm, Co <40 ppm) and no economically significant lead or zinc zones have been identified. However, isolated lead concentrations of up to 700 ppm and traces of galena on fractures in pyrite cubes, situated distal to the chalcocite ore zone and the enclosing bornite/chalcocite fringe, suggest the presence of a weakly developed lead zone.

The ore mineral and metal zonation pattern of the orebodies is related systematically to the Klein Aub Fault in the shape of concentric lobes with their source close to the deeper part of the fault (Fig. 3). The zonation pattern is elongated along the bedding of the northerly rising green sedimentary rocks. A zone of native copper grades outward and upward into the chalcocite zone (main ore zone) which is enclosed by the bornite and chalcopyrite fringe zone. This fringe zone grades into a sparse galena-bearing pyrite zone and finally into rocks containing unmineralised diagenetic pyrite, that is the unaffected host rock. This zonation pattern is an indicator for the migration direction of the mineralising fluids. The ore fluids migrated upward along the fault zone, through oxidised red beds until they encountered the favourable host rock of the pyritic green sedimentary rocks. From the fault the fluids utilised permeable coarser grained sedimentary layers and fractures to ascend further, at the same time precipitating the metals in the order of their solubility. Zinc, as the most soluble, was either carried even further and became eroded or was not a major constituent of the ore fluids, although the latter possibility is rather unlikely.

Further evidence for a post-deformational origin of the mineralisation is given by especially indicative replacement textures. Massive sandstone, containing large (®1 cm diameter) pyrite cubes with pronounced pressure shadows, has been mineralised in several locations. The pyrite displays undeformed cube shapes and generally shows no signs of cataclasis (Fig. 5). The pressure shadows are filled by quartz, chlorite and minor calcite. Locally these pyrite cubes have been replaced by chalcocite and here the chalcocite has re-

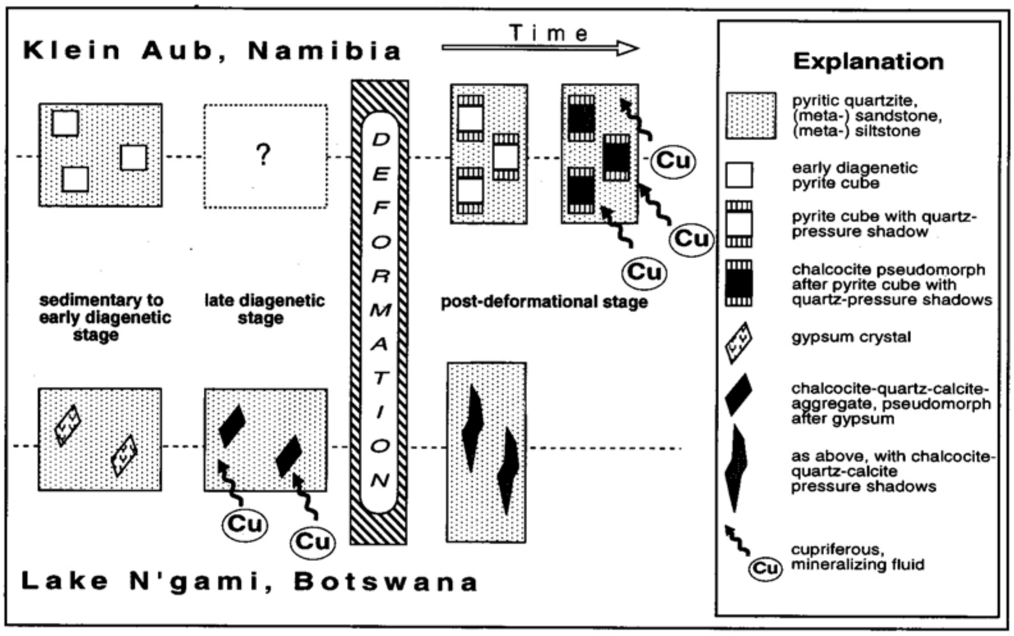


Figure 7: Sketch diagram illustrating different types of ore replacement textures found at Klein Aub (post-deformational) and Lake Ngami (pre-deformational). See Figs 5, 6 and 10 for comparison.

tained the cube-shape.of the former pyrite (Fig. 6). Such textures give evidence for the post-deformational origin of the mineralisation since pre-deformational relatively ductile chalcocite cubes would have become elongated, flattened or squeezed during the main folding and stretching event that produced the pronounced cleavage and the pressure shadows (Fig. 7).

Finally, Pb-Pb isotopic age dating of the mineralisation produced a homogeneous age for both disseminated and fracture-hosted chalcocite mineralisation (Walraven and Borg, 1992). Ore samples yielded an age of 586+62/-65 Ma which is equivalent to the age of Damara metamorphism (Ahrendt *et al.*, 1978). No direct age can be given for the enclosing host rocks of the Klein Aub Formation but an age bracket between 1000 and 800 Ma must be assumed for the Klein Aub Formation. Underlying Grauwater volcanic rocks yielded an age of 1069 ± 70 Ma (Hugo and Schalk, 1974) and the age of the overlying Kamtsas Formation is constrained by the age of the basal (Naauwpoort) volcanic rocks at 748 ± 3 Ma (Hoffman *et al.*, 1994). Thus the age difference between host rock deposition and ore formation must be at least some 250 Ma. In the past, the regionally stratabound nature of the mineralisation led some authors to consider the mineralisation as syngenetic (e.g., Martin, 1965; Ruxton, 1986). However, at Klein Aub Mine the ore mineral and metal zonation patterns, indicative replacement textures, and Pb-Pb isotopic age dating of the mineralisation do not support such an interpretation. Instead, an epigenetic, post- or late-deformational origin of the ores, structurally controlled by the Klein Aub Fault is supported by observational and isotopic data.

Dordabis/Witvlei Basin

The Dordabis/Witvlei Basin (Fig. 1) consists of a number of almond-shaped thrust slices and fault blocks between Damaran rocks to the north and Nama Group sedimentary rocks to the south. The lithostratigraphy comprises tholeiitic, subaerially extruded basalt, quartz-feldspar porphyry, interflow sedimentary rocks such as conglomerate and aeolian sandstone and minor siltstone which are locally pyritic and/or evaporitic (Fey, 1976; Williams-Jones and Marsh, 1985; Ruxton and Clemmey, 1986).

Copper mineralisation is widespread and occurs in a wide range of volcanic and sedimentary rock types (Fig. 8). Altered basalt in the Dordabis area contains numerous copper occurrences, mainly in the form of native copper in amygdales. Locally, brecciated flow tops contain networks of copper-filled vugs and amygdales. Individual lumps of native copper can be up to more than one ton in weight but copper occurrences are very erratic. Overall, the basalts have been leached of their copper content during metamorphic alteration (Borg and Maiden, 1987; Borg, 1988a).

Sediment-hosted mineralisation in the Witvlei area occurs in various rock types such as sandstone, limestone, poorly sorted conglomerate, evaporitic and pyritic siltstone (Anhaeusser and Button, 1973; Hilke, 1986; Ruxton and Clemmey, 1986). Twelve sediment-hosted copper occurrences have been identified, five of which contain between 0.5 and 6 million tons of ore at grades of 1.5-2.3% Cu and up to 10 g/t Ag (Schneider, 1992). The main ore mineral is chalcocite (55%), followed by bornite (20%), chalcopyrite (20%) and minor covellite

(5%) (Anhaeusser and Button, 1973). Mineralisation occurs finely disseminated, as small aggregates (pseudomorphs after evaporite minerals?) and on fractures and cleavage planes. A major structural feature of the local geology, which also constrains the economical viability (size) of the orebodies is the abundance of closely spaced faults and thrusts.

Ruxton and Clemmey (1986) established a sedimentological model for the Witvlei area in which a local basement high surrounded and controlled the distribution of proximal alluvial fan conglomerates, distal lacustrine and playa lake sediments (Fig. 8). These authors suggested a synsedimentary ore genesis model with copper-sulphides derived detritally from the local basement with fixation near delta (fan) margins and also distally to these in cupriferous playas. To date, no detailed information on zonation patterns, replacement textures or on isotopic dating of the mineralisation is available. However, features such as the variety of mineralised lithotypes, the host rock permeability as a major controlling factor, the subordinate occurrence of mineralisation in pyritic, pelagic sedimentary rocks, the proximity to both a basement high and late tectonic faults and thrusts, all point away from a simple syngenetic origin of the mineralisation. A diagenetic and in some cases a syn- or post -tectonic origin of the mineralisation appears to better fit the geological observations.

Ghanzi/Lake Ngami Basin

Exposure of rocks of the Ghanzi/Lake Ngami Basin (Fig. 1) is largely obscured by a cover of Kalahari sediments. These Neoproterozoic rocks are flanked to the NNW by units of the Damara Sequence which is thrusted to the SE. To the S and SE the volcanosedimentary sequence is situated adjacent to the unexposed, younger Passarge Basin with an inferred sedimentary thickness of 15 km (Reeves, 1979). An isolated outcrop of older basement, the Okwa basement inlier, is located some 90 km to the SE of the exposed rocks (Aldiss and Carney, 1992).

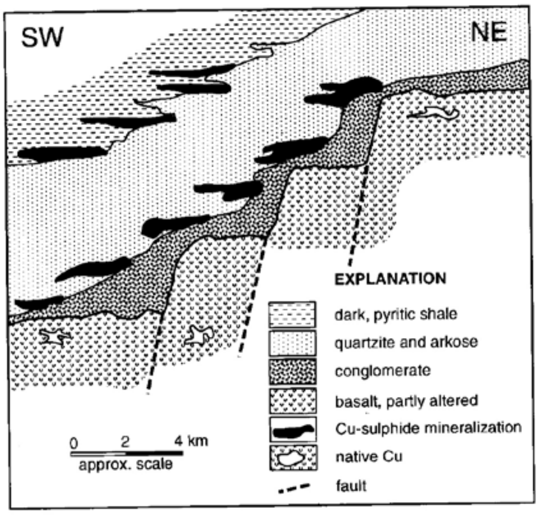


Figure 8: Simplified cross section through the Witvlei area (modified from Ruxton and Clemmey, 1986) showing the mineralisation in different host rocks on the flank of a fault-bounded basement high. The cross section runs approximately NNE-SSW, across the farms Okatjepuiko 154 and Okatjirute West 324. Vertical scale is enlarged by two.

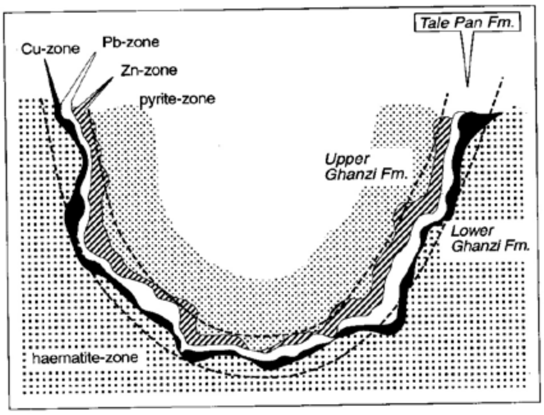


Figure 9: Schematic compilation of the typical metal zonation pattern in Neoproterozoic rocks which form a syncline, characteristic for the Lake Ngami area. Note that the diagenetic, mineral redox front does not coincide with the original redox boundary at the base of the Tale Pan Formation. The zonation suggest an ascending ore fluid flow during diagenesis with later folding of both rocks and metal zones. Diagram is not to scale but synclines are up to 5 km across and the Tale Pan Formation might extend to 5 km depth according to geophysical data.

Generally the stratigraphy consists of felsic, mafic and subordinate intermediate volcanic rocks at the base of the sequence, named the Kgwebe Formation (Fig. 1), and fine-grained clastic sedimentary rocks and carbonates making up the upper part of the succession, the Ghanzi Formation. The volcanic-dominated Kgwebe Formation shows an increase of mafic material towards the top. Around Lake Ngami, the Ghanzi Formation can be subdivided further into three principal units. The Lower Ghanzi Formation consists mainly of oxidised immature clastic sedimentary rocks, deposited in tidal and fluviatile environments with a sediment source area to the NW. The overlying Tale Pan Formation consists of grey-green pyritic, laminated siltstone and sandstone with intercalations of carbonate and minor tuffaceous units. These rocks represent a shallow marine transgression from the E and locally lagoons might have developed. The overlying Upper Ghanzi Formation comprises more clastic and carbonate units, generally oxidised and deposited in marginal marine and lagoonal environments. The sequence is folded into open (Ghanzi area) and tight, almost isoclinal (Lake Ngami area) synclines and anticlines with fold axes striking ENE-WSW. The synclines in the Lake Ngami area are between 1 km and 5 km deep, according to geophysical investigations, and display steeply-dipping flanks (65-80°).

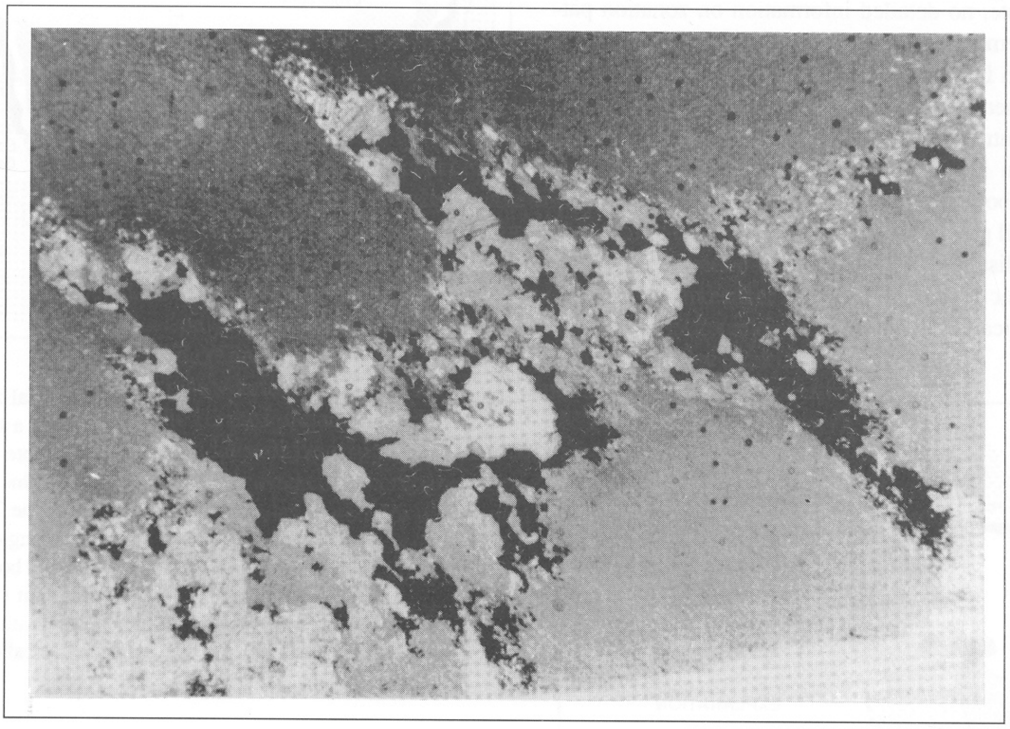
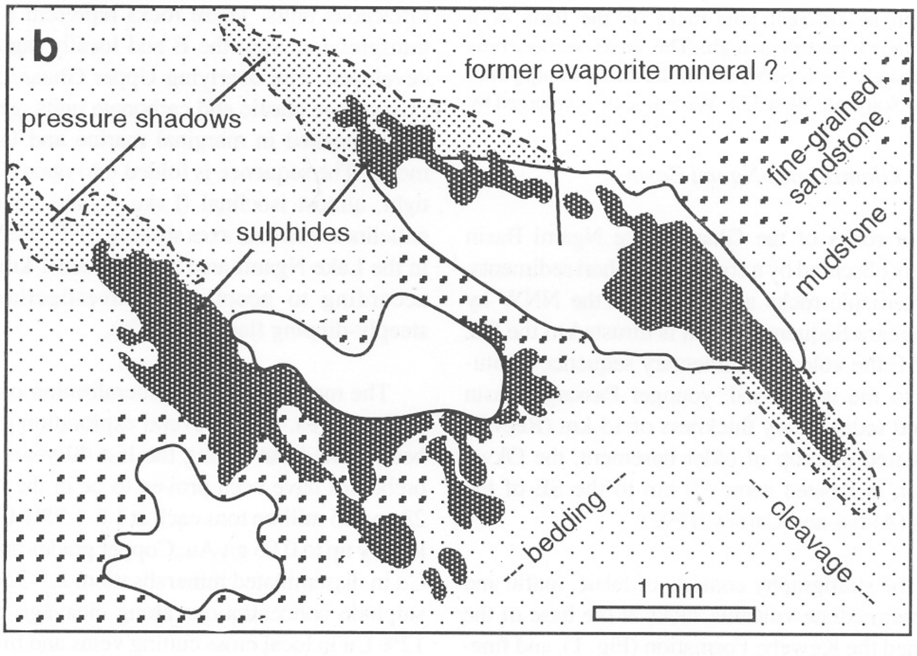


Figure 10: Transmitted-light photomicrograph (a) and interpretation (b) of petrographic and structural elements in mineralised, laminated mudstone and fine-grained sandstone with sulphide-quartz-carbonate aggregates occurring perpendicular to bedding. The aggregates are possibly after former evaporite minerals (gypsum?) which formed preferably in the coarser laminae due to enhanced fluid and element migration in these layers. Mineralisation occurs in both the former evaporite minerals and in pressure shadows, developed adjacent to the original (evaporite?) minerals, suggesting a pre-deformational origin of the copper mineralisation. See Fig. 8 for explanation of mineralising process.



The most prominent mineralisation occurs in the Lake N'Gami area, where several exploration programmes have been carried out during the last 40 years. Three potential orebodies have been proven to be in the order of between 28 and 45 million tons each at 1.8-1.95% Cu, 67 g/t Ag with locally up to 0.05 g/t Au. Copper grades are between 0.52% Cu in disseminated mineralisation, 2.5-3.5% Cu in copper-sulphide concentrations along cleavage planes and up to 12% Cu in local cross cutting veins and breccias. The latter are restricted to mineralised strata and are surrounded by unmineralised, bleached halos, suggesting an origin by lateral secretion.

The mineralisation is not stratiform, neither on a regional nor on a macroscopic or microscopic scale, and occurs both considerably below and above the base of the Tale Pan Formation (Fig. 9). Copper-silver mineralisation occurs in a wide variety of predominantly siliciclastic rock types. Differing from mineralisation in the other basins, the Lake Ngami area displays subeconomic but geochemically distinct lead and zinc zones with macroscopically visible galena and sphalerite. An ore mineral zonation on a metre scale can be documented in drill core. The zonation grades from oxidised haematitic sedimentary rocks in the footwall to a copper zone and a lead and zinc zone, perpendicular to the sedimentary layering (Fig. 9). The redox boundary occurs in some places below and above the datum line of the base of the Tale Pan Formation and locally originally pyrite-bearing laminated tidal sedimentary rocks and carbonates have been oxidised. Both the zonation pattern and the ore grades are poorly developed where clay-rich intercalations occur at the base of the Tale Pan Formation. The zonation pattern is developed in a quasi-symmetrical fashion directed towards the axial planes of the synclines (Fig. 9). Such a pattern is consistent with diagenetic ore fluids that have ascended through the rocks approximately perpendicular to sedimentary layering after deposition of at least the lower part of the Upper Ghanzi Formation. The ore mineral zones have apparently been folded together with the host rocks in a symmetrical fashion. The deposit with its zonation pattern must have formed after sedimentation but prior to deformation, indicating a diagenetic to late diagenetic origin of the orebodies. Ore textures include diagenetic pyrite cubes being replaced by chalcopyrite, at the distal fringe of the copper zone. More indicative replacement textures are former evaporite minerals (gypsum?) which have been replaced by chalcocite quartz-carbonate aggregates (Fig. 10). These evaporite minerals show pressure shadows which are also filled by the same ore-gangue association (Borg and Maiden, 1989), suggesting a mobilisation into the pressure shadows during deformation thus supporting ore formation during diagenesis (Figs. 7 and 10). The vein-type mineral occurrences appear to be the result of a later tectonothermal event, probably the Damaran orogeny, which caused the development of lateral secretion veins and mineralised breccias.

Discussion of Regional Controls and Timing of Metal Emplacement

The copper mineralisations of the Neoproterozoic basins in Namibia and Botswana show overall similarities regarding the lithology of host rocks and their metal association. Virtually all basins host erratic, subeconomic occurrences of copper in altered mafic volcanic rocks. Sediment-hosted mineralisation is stratabound on a broad scale, associated with redox interfaces, but on a more detailed scale transgresses the stratigraphy at shallow to steep angles. This type of mineralisation is not developed where chemically reduced fine-grained clastic sedimentary rocks are lacking, for example, in the Sinclair Basin. Geochemically the mineralisation is characterised by Cu >>> Pb >Zn and contains silver in appreciable amounts plus minor gold and platinum group elements. The distribution of the precious metals is still poorly documented and understood. A great variety of host rocks are mineralised and a common feature of the larger copper occurrences is their strong permeability control. The mineralising systems appear to have been relatively sulphur-poor, utilising sulphur from diagenetic pyrite and subordinately from evaporite minerals within the host rocks. A further control is given by structural features such as bounding faults to basement highs (for diagenetic mineralisation) and late tectonic fault and thrust structures (for epigenetic mineralisation). Ore mineral and metal zonation patterns can be documented in some places and give evidence for at least two major mineralising events that have affected the basins. Both diagenetic (~900-800 Ma?) and epigenetic (~600-550 Ma) mineralising processes have operated, possibly in each basin but to differing extents. Predominantly diagenetic mineralisation occurs at Lake Ngami whereas the mineralisation at Klein Aub is mainly of epigenetic origin. Mineralisation at Dordabis/Witvlei shows evidence of both diagenetic and epigenetic metal emplacement. Evidence for later redistribution of pre-existing mineralisation is scarce and generally most mineralisation seems to be the result of metal introduction from extraformational sources. Altered and leached basalts appear to be the most likely metal sources (Borg and Maiden, 1987; Borg, 1991), but basement rocks and possibly the red beds might have contributed some metals. The effect of Damaran faulting and thrusting on the Klein Aub Basin has been controlled partly by the position of the Rehoboth basement inlier (Fig. 1). This basin has been "protected" from Dordabis/Witvlei-style thrusting by the buttress of the Rehoboth basement. This might be one reason why here a relatively isolated fault structure (Klein Aub Fault) was closely related to the Klein Aub orebodies. In contrast, significant copper mineralisation and fault and thrust structures are far more abundant in the Dordabis/Witvlei area. However, isolated fault structures might have a stronger focusing effect on mineralising fluids whereas a greater abundance of tectonically induced channel-ways might have a "dispersing" effect, producing numerous small copper occurrences of subeconomic size and grade. Careful re-examination of existing exploration data, in the light of the controlling mechanisms outlined above, should help to delineate target areas that might have a potential for economic copper-silver (plus gold and platinum group element) mineralisation within the central Namibian and Botswana basins.

Acknowledgements

The present review paper is partly based on a Ph.D. thesis (1988) at the University of the Witwatersrand, Johannesburg which was funded by the Geological Survey of Nambia. The author is grateful to KJ. Maiden, R.Y. Kirkham, I. Plimer, Roy McG Miller, D. Groves, N. Phillips, G. Palmer and C. Smyth, for numerous fruitful and exciting discussions on the topic of syngenesis, diagenesis and epigenesis. My sincere thanks are due to Anglo American Corporation for permission to utilise information from the Lake Ngami area. Two referees, R.Y. Kirkham and M.J. Tomkinson, are gratefully acknowledged for their helpful comments which improved the final version of the manuscript.

References

Ahrendt, H., Hunziker, J.C. and Weber, K. 1978. Age and degree of metamorphism and time of nappe emplacement along the southern margin of the Damara Orogen. *Geol. Rundsch*., **67**, 716-742.

Aldiss, D.T. and Carney, J.N. 1992. The geology and regional correlation of the Proterozoic Okwa Inlier. *Precambr. Res*., **56**, 255-274.

Anhaeusser, C.R. and Button, A. 1973. A petrographic and mineragraphic study of the copper-bearing formations of the Witvlei area, South West Africa. *Trans. geol. Soc. S. Afr.*, **76**, 279-299.

Borg, G. 1988a. *Controls on stratabound copper mineralisation at Klein Aub Mine and similar deposits within the Kalahari Copperbelt of South West Africa/Namibia and Botswana*. Unpubl. Ph.D. thesis, Univ. Witwatersrand, Johannesburg, 107 p.

Borg, G. 1988b. The Koras-Sinclair-Ghanzi Rift in Southern Africa. Volcanism, Sedimentation, Age Relationships and Geophysical Signature of a late Middle Proterozoic Rift System. *Precambr. Res*., **38**, 75-90.

Borg, G. 1991. The significance of Rotliegend volcanic rocks for the metal provinces of the Kupferschiefer Basin. *Geol. Palaont*., **1991**, (4), Teill, 123-137.

Borg, G. and Maiden, K.J. 1987. Alteration of late middle Proterozoic volcanics and its relation to stratabound copper-silver - gold mineralization along the margin of the Kalahari Craton in SWA/Namibia and Botswana, 347-354. *In*: Pharaoh, T.C., Beckinsale, R.D. and Rickards, D.T. (Eds), *Geochemistry and mineralisation of Proterozoic volcanic suites*. Spec. publ. geol. Soc. London, **33**.

Borg, G. and Maiden, K.J. 1989. The Middle Proterozoic Kalahari Copper Belt of Namibia and Botswana, 525-540. *In*: Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C. and Kirkham, R.V. (Eds), *Sediment-hosted Stratiform Copper Deposits*, Spec. Paper Geol. Ass. of Canada, **36**.

Borg, G., Graf, N. and Maiden, K.J. 1987. The Klein Aub Fault Zone. A Wrench Fault system in Middle Proterozoic Metasediments in Central SWA/Namibia. *Communs geol. Surv. SWA/Namibia*, **3**, 91-98.

Borg, G., Tredoux, M., Maiden, K.J., Sellschop, J.P.F. and Wayward, O.F.D. 1987. PGE and Au-distribution in rift-related volcanics, sediments and stratabound Cu/Ag ores of Middle Proterozoic age in central SW A/Namibia, 303-318. *In*: Prichard, H.M., Potts, P.J., Bowles, J.F.W. and Cribb, S.J.(Eds), *Ceo-Platinum '87*, Elsevier Applied Science.

Cahen, L. and Snelling, N.J. 1984. The Geochronology and Evolution of Africa. Clarendon Press, Oxford, 512 pp.

Fey, P. 1976. The geology of the Witvlei-Omitara area, South West Africa. *Trans. geol. Soc. S. Afr*., **78**, 349-357.

Fuchter, J.H.G. 1964. *Report on Sinclair Mine South West Africa, Grant. No M46/3/110*. Unpubl. rep., Falconbridge Exploration (Pty) Ltd., 10 pp.

Hilke, C. 1986. *Petrographie, Cenese, Erzmineralogie und Strukturgeologie der Eskadron Formation sudwestlich Witvlei, SWA/Namibia*. Unpubl. diplomathesis, Univ. Münster, 151 pp.

Hoal, B.G., Harmer, R.E. and Eglington, B.M. 1989. Isotopic evolution of the Middle to Late Proterozoic Awasib Mountain Terrane in southern Namibia. *Precambr. Res.*, **45**, 175-189.

Hoal, E.G. and Heaman, L.M. 1994. The Sinclair Sequence: U-Pb age constraints. *Abstr. Proterozoic crustal and metallogenic evolution*, Geol. Surv. and geol. Soc. Namibia, 29.

Hoffman, P.F, Bowring, S.A. and Isachsen, C.E. 1994. New U-Pb zircon ages for the early Damaran Oas Syenite (Welwitschia Inlier) and upper Naauwpoort volcanics (Summas Mts.), Namibia. *Abstr. Proterzoic crustal and metallogenic evolution*, geol. Surv. and geol. Soc. Namibia, 32.

Hugo, P.J. and Schalk, K.E.L. 1974. The isotopic ages of certain granites and acid lavas in the Rehoboth and Maltahöhe districts, South West Africa. *Ann. geol. Surv. S. Afr*., **9**, 103-105.

Jacobs, J., Thomas, R.J. and Weber, K. 1993. Accretion and indentation tectonics at the southern edge of the Kaapvaal craton during the Kibaran (Grenville) orogeny. *Geology*, **21**, 203-206.

Kröner, A. 1977. The Sinclair aulacogen, a late Proterozoic volcanosedimentary association along the

Namib Desert of southern Namibia (SWA). *9th Colloquium Afr. Geol.*, Göttingen, 82-83.

Maiden, K.J., Innes, A.H., King, M.J., Master, S. and Pettit, I. 1984. Regional controls on the localisation of stratabound copper deposits: Proterozoic examples from southern Africa and South Australia. *Precambr. Res.*, **25**, 99-118.

Martin, H. 1965. The Precambrian geology of South West Africa and Namaqualand. *Precambr. Res. Unit, Univ. Cape Town*, 159 pp.

Porada, H. 1985. Stratigraphy and facies in the Upper Proterozoic Damara Orogen, Namibia, based on a geodynamic model. *Precambr. Res.*, **29**, 235-264.

Reeves, C.V. 1978. A failed Gondwana spreading axis in Southern Africa. *Nature*, **273**, 222-223.

Reeves, C.V. 1979. The Reconnaissance Aeromagnetic Survey of Botswana, 69-92. *In*: McEvan, G. (Ed.), *The Proceedings of a seminar on geophysics and the exploration of the Kalahari*. Bull. Geol. Surv. Botswana, **22**.

Ruxton, P.A. 1986. Sedimentology, isotopic signature and ore genesis of the Klein Aub Copper Mine, SW A/Namibia, 1725-1738. *In*: Anhaeusser, C.R. and Maske, S.(Eds), *Mineral Deposits of Southern Africa*.

Ruxton, P.A. and Clemmey, H. 1986. Late Proterozoic stratabound red bed copper deposits of the Witvlei Area, SWA/Namibia, 1739-1754. *In*: Anhaeusser, C.R. and Maske, S.(Eds), *Mineral Deposits of Southern Africa*, Vol. **2**. geol. Soc. S. Afr., Johannesburg.

South African Committee for Stratigraphy (SACS),l980. Stratigraphy of South Africa. Part I (Camp. L.E. Kent). Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republics of Bophuthatswana, Transkei and Venda: *Handb. geol. Surv. S. Afr.*, **8**.

Schalk, K.E.L. 1970. Some Late Precambrian Formations in central South West Africa. *Ann. geol. Surv. S. Afr.*, **8**, 29-47.

Schneider, G.I.C. 1992. *The Mineral Resources of Namibia*. Geological Survey of Namibia, Windhoek.

Söhnge, P.G. 1958. The environment of copper deposits in South West Africa. *CCTA Publ. Leopoldville*, **44**, 231-248.

Steven, N.M. 1992/93. The potential for stratabound copper(silver-platinum) mineralisation in the Rehoboth-Dordabis-Witvlei area, central Namibia: a new approach. *Communs geol. Surv. Namibia*, **8**, 151-154.

Thomas, R.I. and Eglington, B.M. 1990. A Rb-SR, Sm-Nd and U-Pb zircon isotopic study of the Mzumbe Suite, the oldest intrusive granitoid in southern Natal, South Africa. *S. Afr. J. Geol.*, **93**, 761-765.

Thomas, R.J., Agenbacht, A.L.D., Cornell, D.H. and Moore, J.M. 1994. The Kioaran of southern Africa: Tectonic evolution and metallogeny. *Ore Geol. Rev.*, **9**, 131-160.

Walraven, F. and Borg, G. 1992. Lead isotopic signatures at the Klein Aub Mine, Namibia Implications for mineralisation models. *Miner. Deposita*, **27**, 115-121.

Watters, B.R. 1974. Stratigraphy, igneous petrology and evolution of the Sinclair Group in southern South West Africa. *Bull. Precambr. Res. Unit, Univ. Cape Town*, **16**, 235 pp.

Watters, B.R. 1976. A possible Late Precambrian subduction zone in South West Africa. *Nature*, **257**, 471-473.

Watters, B.R. 1977. The Sinclair Group: definition and regional correlation. *Trans. Geol. Soc. S. Afr.*, **80**, 9-16.

Williams-Jones, I.E. and Marsh, J.S. 1985. The geochemistry of basic volcanics of the Dordabis Formation northeast of Dordabis and their significance for correlations within, and evolution of, the Rehoboth Magmatic Arc. *Communs geol. Surv. SWA/Namibia*, **1**, 63-67.