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The structural evolution of the Kombat deposits, Otavi Mountainland, Namibia

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The main phase of the Kombat Cu-Pb (Ag) mineralization is interpreted as being stratabound and syntectonic. The ore deposits are located in Hüttenberg Formation carbonates, on the Northern Platform margin of the Damara Province. Mineralization occurs on the contact with the overlying Kombat Formation phyllite. The deposits form a near-linear east-west trend of pendant-shaped ore loci with a strike length of 6 km. Characteristic features are the abundance of sandstone in Damaran-age karsts, Fe-Mn oxide/silicate assemblages, intense faulting, fracturing, shearing and brecciation. A strong calcite alteration halo encompasses the deposits. The calcite alteration is of various ages, and therefore not always related to the mineralizing event. The association of stratiform Fe-Mn oxide/silicate assemblages with the Kombat deposits has led to conflicting ideas regarding the genesis of these deposits. Field evidence, supported by analytical results, has led to the construction of a genetic model for the mineralization and Fe-Mn assemblages. A marine transgression, resulting from late-stage rift tectonism, drowned the southern parts of the Otavi Valley basin. This allowed for deep-seated hydrothermal fluids from the northern graben to migrate up the rift structures, enter the Otavi Valley basin, and deposit Fe and Mn as oxide/silicate assemblages in favourable third-order structures on the platform margin. It is probable that an early phase of Cu mineralization was related to these diagenetic processes. A D_1 age hiatus in deposition over the platform margin resulted in pervasive calcite alteration, and local solution collapse. With further basin drowning, the Kombat Formation transgressed over the carbonate platform margin and karsts developed in the subsurface environment at the intersection of favourable structures at Kombat. During the latter part of D1, and with the onset of D_2, northward directed thrusting exposed basement highs. With subsequent erosion, Otavi Valley sandstone was deposited into the karsts in the subsurface environment. Folding of the Otavi Valley basin formed the east-west trending Otavi Valley syncline with the development of a flexure, the Otavi Valley monocline, along the original platform margin. During late D_2 the Otavi Valley syncline ruptured, forming a complex network of north-northeast trending faults and shear zones. Orogenic brines, expelled from higher temperature metamorphic areas further south, deposited the main phase of Cu mineralization within these karst structures to form the economic Kombat deposits.

Introduction

The Kombat Mine is situated in northern Namibia in a predominantly carbonate-hosted Pb-Zn-Cu (Ag) metallogenic province known as the Otavi Mountainland. The carbonate rocks are of late Proterozoic age, and constitute the Otavi Group of the Damara Sequence.

The mineral potential of the Otavi Mountainland has been exploited since prehistoric times, and there are now over 600 known mineral showings. The majority of these showings consist of uneconomic Pb-Zn and V mineralization, and are often compared to Mississippi Valley-type deposits. The only two currently active mines are Tsumeb and Kombat which host a wide variety of Cu mineralization with variable amounts of Pb, Zn, and Ag. These two mines are situated in the Tsumeb Subgroup of the Otavi Group and share numerous mineralogical, structural and geochemical characteristics.

At Kombat, galena-pyrite-chalcopyrite-bornite- chalcocite mineralization is associated with tectonic and sedimentary breccias, calcitized dolostone, lenses of feldspathic sandstone, and concentrations of Fe-Mn oxides and silicates immediately below the contact between the carbonate rocks and overlying phyllite of the Kombat Formation.

No satisfactory genetic model for the Kombat mineralization exists to date, but theoretically either syngenetic or epigenetic models may be applicable. Non-circumstantial evidence suggests that the Fe-Mn oxide/silicate assemblages represent syngenetic exhalative deposits that accumulated on the disconformity surface from a fumarolic source. Field observations and isotope results support an exclusively epigenetic, hydrothermal and metamorphic model for the Cu mineralization that selectively utilized the phyllite/dolostone contact and various cross cutting structures for emplacement, which could subsequently have been remobilized. A variation of this possibility is an orogenic brine model (Oliver, 1986), with the mineralization related to the Damaran orogeny.

Regional geological setting

Stratigraphy

The Damara orogen is made up of a 400 km-wide northeast-trending intracontinental arm and a north-south trending coastal arm. The intracontinental arm separates the northern Congo Craton from the southern Kalahari Craton (Fig. 1).

The intracontinental arm was dominated by northeast-trending rift faults which probably led to the formation of a narrow ocean in the eastern Khomas trough with later northward-directed subduction. The Northern Rift underwent multiple phases of subsidence but ensialic characteristics never developed. The contact between the Northern Platform and the Northern Rift is marked by an arcuate chain of major basement ridges and domes which extend over 1000 km.

With initial rift evolution the basal formations of the Damara Sequence, the Nosib Group, were deposited. In the Northern Rift these formations are dominated by bimodal volcanics and coarse clastic sediments. On the Northern Platform, in the Otavi Mountainland area, the

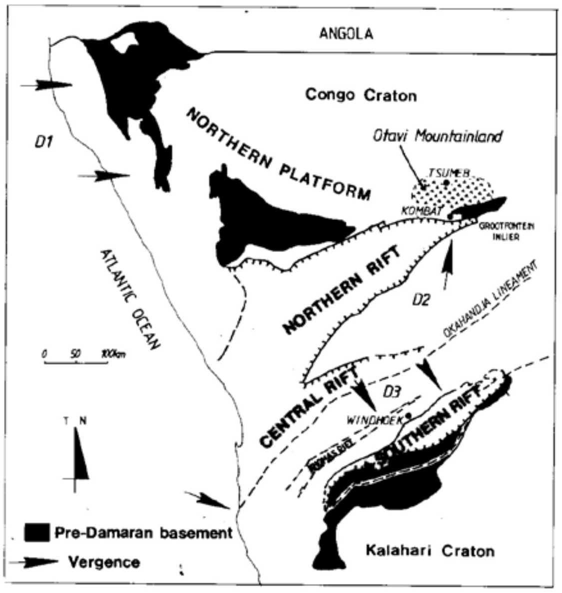

Figure 1: Geological map of the Damara Province showing a: the locality of the Kombat Mine; b: the early rift evolution; c: the dominant structural directions that affected the Kombat area during the Damara orogen; d: the pre-Damara basement inliers. Modified after Miller (1983) and Porada (1985).

Nosib Group is only locally developed.

In the Otavi Mountainland basement highs separated four subsidiary intercontinental rift basins in which the carbonate rocks of the Otavi Group, which overlie the Nosib Group, are preserved in synclinoria. The southern-most of these sub-basins is the Otavi Valley sub-basin in which the Kombat deposits are located. The Otavi Group is divided into two Subgroups, namely a lower Abenab Subgroup and an upper Tsumeb Subgroup. Generally the Pb-Zn Mississippi Valley-type deposits are located in the Abenab Subgroup and the more economical Cu deposits are located in the Tsumeb Subgroup.

A final phase of rift subsidence in the Northern Rift resulted in the drowning of the southern parts of the Otavi Valley sub-basin and the cessation of carbonate deposition. Phyllite of the Kombat Formation was deposited over the Tsumeb Subgroup as an onlap unconformity.

With the onset of the Damaran orogeny the molasse-type Mulden Group was deposited syntectonically. In the Otavi Valley sub-basin the Mulden Group is only found as large sandstone lenses within karst structures developed in the subsurface environment directly under the phyllite/carbonate contact zone. This sandstone is referred to as Otavi Valley sandstone.

Metamorphism and hydrothermal activity

A regional metamorphic grade in the Otavi Valley, based on the mineral assemblage calcite-dolomite-quartz, the absence of talc and tremolite, and by the development of phengitic muscovite and minor chlorite, is regarded as being of lower greenschist facies. Clauer and Kröner (1979) proposed that the Mulden Group in the Etosha Basin comprises zeolite facies to prehnite-pumpellyite facies assemblages (250°C-300°C, up to 2 kb) resulting from two regional tectonothermal events dated at 537 Ma and 457 Ma. Ahrendt *et al.* (1983) relate metamorphism in the Otavi Valley to a tectonothermal event at 450 Ma (Table 1).

Within the Kombat Mine environment mineral assemblages are indicative of higher temperatures. Metamorphic minerals related to the Fe-Mn oxide/silicate assemblages are vesuvianite, actinolite, and magnesio-richterite. Quartz veins within the Kombat Formation phyllite have associated talc and ankerite. The quartz veins are regarded as being the same age as the mineralization. The presence of talc suggests a minimum temperature of 350° C (Trommsdorff and Connolly, 1990). The presence of vesuvianite suggests low $X_{(CO2)}$ values of 0.01, and the absence of anorthite indicates temperatures below 480°C (Frimmel and van Achterberg, in Press). The Kombat ore bodies therefore formed in a temperature range between 350°C and 480°C.

Deformation

Three Damaran deformational events have affected the Otavi Mountainland. D_1 marked the closure of the Proto-Atlantic with the formation of large recumbent southeasterly vergent folds in the Kaoko Belt. This vergence resulted in thrusts moving intensely deformed high grade rocks over the platform carbonates on the southwestern margin of the Congo Craton. In the Otavi Mountainland the effects of this deformation are minimal, and gentle north-south trending, open warps are evident on a large scale. However, the formation of a complex foreland thrust belt to the west may have influenced sedimentary patterns of the Mulden Group within the Otavi Mountainland. The age of D_1 is believed to be approximately 650 Ma (Table 1).

D_2 involved closure of the intracontinental arm and the structures that developed vary in orientation and intensity. Generally this phase involved recumbent shearing with an overthrust sense to the southwest on a low-angle shear zone (Coward, 1983). In the northern parts of the intracontinental arm relatively high temperature rocks were thrust northwards onto the lower temperature Mulden rocks. This resulted in the formation of a complex D_2 history in the Kombat environment, with the development of northwest-. ward-vergent folds and thrusts to form the Otavi Valley syncline. D_2 is correlated with the 537 Ma to 550 Ma tectonothermal event (Table 1).

D_3 involved a change in relative plate movement which led to intense southeast-directed folding and thrusting of the Khomas trough fill onto the Kalahari Craton. In the Otavi Mountainland the deformation was

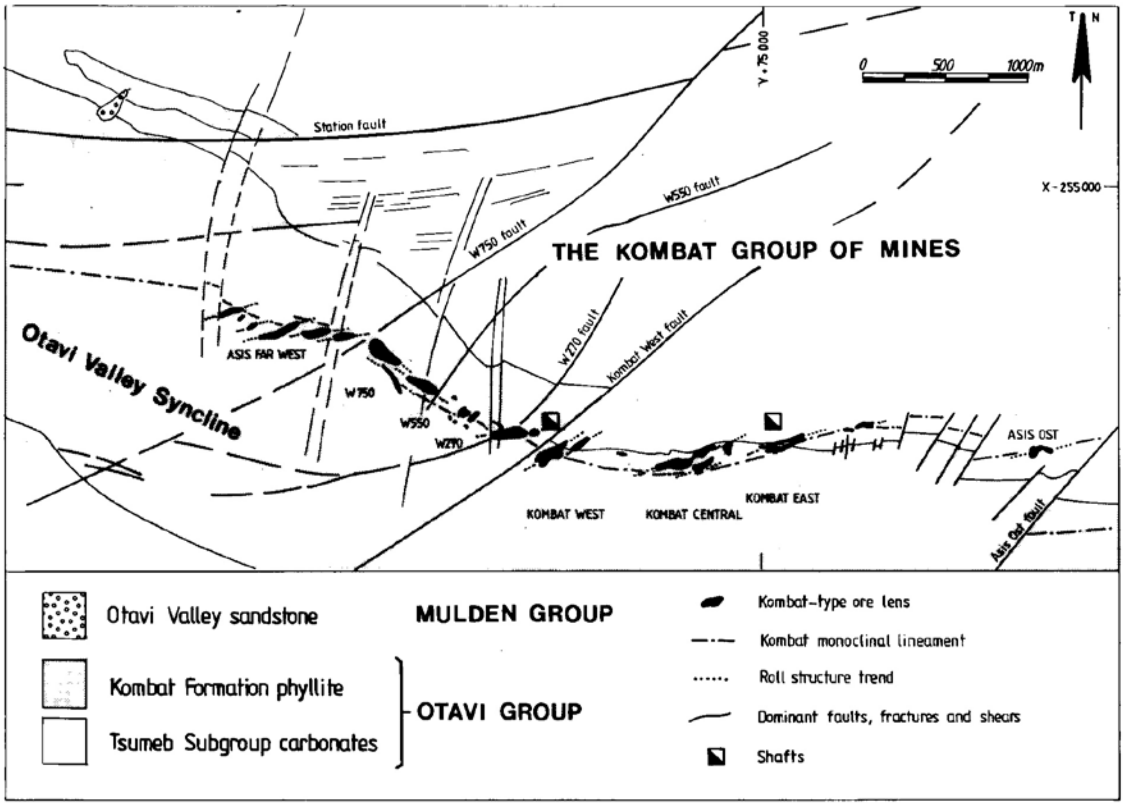

Figure 2: The Geology of the Kombat Area showing a: the important surface structures and b: the surface vertical projection of the Kombat monocline and the ore lenses.

less intense resulting in northwest-trending open, upright warps. D_3 is correlated with the 450 Ma to 457 Ma tectonothermal event (Table 1).

Structural analysis of the Kombat Environment

Syn-sedimentary tectonics

The oldest recognizable structural fabric is an S_{0a} bedding-parallel cleavage in the Kombat Formation phyllite. This is related to burial effects.

Table 1: Age constraints on the regional tectonothermal events.

Age (Ma)	Clauer and Kröner 1979	Ahrendt *et al.* 1983
450 457	Mulden Group, Etosha Area	Otavi Mountainland Kaoko Belt, Central Zone
537 550	Mulden Group, Etosha area	Kaoko Belt, Central Zone
650		Central Zone

The most distinguishable structure associated with the early phase of basin tectonism is the north-northeast trending, subvertical, Asis Ost fault of which the Kombat West fault zone represents a branch structure within this fault zone (Figure 2).

Evidence on the southern limb of the Otavi Valley syncline suggests that these early faults have been deformed by the Damaran orogeny. The Asis Ost fault system probably represents transform faulting associated with the Northern Rift. These faults have been reactivated during late Karoo times.

Damaran orogenic tectonics

The local Damaran deformational events at Kombat can be correlated with the three regional Damaran deformational events defined by Miller (1983) for the Northern Zone. The first regional Damaran deformational event, D_1, affects the sedimentation on the Northern Platform. Geological mapping west of the Otavi Valley (Hedberg, 1979) indicates that folding of the Otavi Group preceded deposition of the Mulden Group.

During D_1 times most parts of the Otavi Mountainland underwent a period of non-deposition which lasted up to 20 Ma (Hoffmann, 1989), and numerous karst structures developed in favourable loci such as at Kombat and Tsumeb Mines. The main phase of the Mulden Group sedimentation occurred during the early regional D_2 deformation when basement structures in the Otavi Mountainland became exposed. This is in contrast to the Mulden deposition in the Kaoko Belt which peaked during the regional D_1. The topography during the Mulden deposition was probably of low relief, as basal conglomerates are poorly developed and karst-fill commonly consists of immature sediment.

The earliest Damaran-age ductile deformational structures at Kombat occur to the south of the Kombat Mine where stratigraphic replication of the Tsumeb Subgroup has taken place. The rocks along the disconformity are strongly foliated, and the foliation is bedding-parallel with no observable lineation associated with it. Quartzites are commonly intensely mylonitized along this contact zone producing an S_1 fabric. Microscale tight to isoclinal, recumbent F_1 folds with sheared limbs are noted in thin section. All these observations suggest that northerly directed thrusting has taken place. These structures represent D_1.

The D_2 can be correlated with the 550 Ma tectonothermal event of Ahrendt *et al.* (1983) for the Kaoko Belt and Central Zone. Clauer and Kröner (1979) recognized a tectonothermal event at 537 Ma in the Etosha area which is also a D_2 age (Table 1). Further, a best estimate age date for the Tsumeb Mine and Kombat Mine mineralization based on Pb isotope work (Hughs, 1987) is 600 Ma.

At Kombat D_2 produced the first large-scale fold phase, which is an east-west (120°) trending, isoclinal (F_2) phase which produced the Otavi Valley syncline (Fig. 4). D_2 is subdivided into two stages: D_{2a} produced the northward-vergent, locally recumbent F_2 folds, and D_{2b} resulted in rupturing of the Otavi Valley syncline along its synclinal axis.

The Otavi Valley syncline is an isoclinal fold with its southern limb locally overfolded. The amplitude of this fold is not known, and diamond drilling to depths of 1200 m has not intersected the phyllite/carbonate contact.

The most frequent small-scale folds at Kombat are disharmonic-style F_2 folds with a near-vertical east-west trending axial planar cleavage (S_{2a}). Mineralization and calcitization are commonly associated with shearing that parallels this cleavage. Within quartzites south of Kombat Mine, a strong axial planar foliation (S_{2b}) is associated with F_2 folds. A prominent crenulation lineation (L_{2a}) is also observed in these quartzites representing the intersection lineation between S_{0a}/S_1 and S_{2b} fabrics. The lineation parallels the F_2 fold axes.

Within drill cores of the Kombat Formation phyllite, two foliations are commonly observed in areas of quartz vein development. Pressure fringes of quartz associated with deformed pyrite define a lineation (L_{2b}) on both S_1 and S_{2a} surfaces. Anhedral, flaky pyrite megacrysts also occur along S_{2a} surfaces, and pyrrhotite is virtually restricted to the deformationally derived S_{2a} surfaces where it develops spindle-like lamellae. In areas of intense F_2 folding, chert nodules and oölites have become extremely elongated (L_{2c}) parallel to the fold axes.

Field evidence, supported by aerial photographic observations and aeromagnetic interpretation, indicate that eastwest rupturing of the Otavi Valley syncline has taken place (D_{2b}). The aeromagnetic survey points towards the stratigraphy south of the rupture being upthrown by a few hundred meters. North of the western closure of the Otavi Valley syncline, numerous large drag folds with amplitudes up to 200 m are present along the rupture. These drag folds represent a component of left-lateral shear. Due south of Kombat Mine the rupture outcrops as a series of high-angle reverse faults, or imbricate structures. A strong vertical foliation (S_{2c}) is observed with S_0 and S_{0a} fabrics being locally transposed into this foliation. The foliation is defined by a mylonitic fabric produced within phyllite bands.

Approximately 1 km west of Kombat Mine the rupture branches out to form the Station fault. This fault is an east-northeast trending reverse fault with a right-lateral component producing horizontal displacements of up to 1.5 km. Although a strong transposition of bedding in a vertical sense is observed, the amount of vertical displacement is not known.

Intensely foliated, steep, northeast- to east-trending zones of deformation occur at many centres of mineralization within the vicinity of the Kombat Mine. Innes and Chaplin (1986) have suggested that these zones represent sheared extensions of attenuated fold hinges. The shear zones contain boudings of quartz, chert, sandstone, and dolostone displaying transposition of both sedimentary and mineral layering and of sulphide veinlets. A steeply plunging mineral lineation (L_{2d}) is developed within the shear zones. The shear zones crosscut the Otavi Valley syncline at a low angle, suggesting that they are not of the same deformational event as the folding which produced the Otavi Valley syncline.

The Otavi Valley syncline is doubly plunging and "canoe shaped". This unusual shape is caused by northeast-trending cross-warps, which are F_3 interference folds. This is regarded as representing D_3. On a regional scale two major warps have affected the Otavi Valley syncline, of which one hinge passes through Kombat. A late north- to northeast-trending fracture cleavage (S_3), which is non-penetrative in the phyllite on a mesoscopic scale, is axial-planar to chevron-style F_3 folds and kink bands associated with the cross-warping.

The Asis Ost fault system, of which the Kombat West faults are related, has been reactivated during Karoo times. The faults are commonly subvertical structures with downthrow to the west. Horizontal displacements of up to 400 m and vertical displacements of up to 200 m on the orebodies have been recorded on this fault system (Innes and Chaplin, 1986). These faults are of a different orientation to the Station fault. Both normal and reverse movements are recorded on the faults.

Table 2: Structural history of the Kombat Environment.

Deformation event	Surfaces (S)	Folds (F)	Lineations (L)	Faults and shears
rifting	(s_0+s_{0a})	-	-	Asis Ost fault
D_1	S_1	F_1	absent	thrusts
D_{2a}	S_{2a}+S_{2b}	F_2	l_{2a}+l_{2b}+l_{2c}	E-W shears
D_{2b}	S_{2c}	-	L_{2d}	O.V. rupture Station fault ENE shearing
D_3	S_3	F_3	-	-
Karoo -	-	-		Kombat West fault
Post Karoo	-	-	-	N-S faults

Crosscutting the Kombat West faults are vertical, north-south trending faults, being of post-Karoo age. These are tension faults which have given rise to horst and graben structures.

Mineralization

The Kombat group of mines can be divided from east to west into seven distinct zones of mineralization separated by barren dolostone (Fig. 2). Mining activities at Kombat are directed at the more shallow eastern ore bodies, with present development being in the W270 prospect area. Some 35,000 tons of ore are milled per month, and at the end of 1991 8.8 million tons of ore had been produced with mill head grades of 2,74% Cu, 1,69% Pb, and 22 g/t Ag.

The deposits form a near-linear structure some 6 km long referred to as the Kombat monoclinallineament (Fig. 2). The monoclinal flexure occurs on the northern limb of the Otavi Valley on the Otavi Group/Kombat Formation contact. The "pivot point", or hinge of this flexure is usually greater than 1000. The individual ore loci are located within this hinge zone (Figure 3).

The ore loci are generally defined by various types of brecciation in the dolostone, as well as a variety of structural controls which include northeast-trending steeply-dipping zones of shearing and net-vein fracturing. These structures are interpreted as being of D_{2b} age. Their crosscutting relationship with the contact between the Otavi Group and the Kombat Formation accounts for the en echelon pattern to the ore bodies.

The zones of shearing and fracturing have resulted in the development of "roll structures", a term that describes the folded and sheared nature of the Otavi Group/Kombat Formation contact above ore loci. These "roll structures" parallel the zones of intense shearing and brecciation. In profile, the individual ore lenses abut against the contact and hang like pendants beneath the "roll structures" (Fig. 3).

The ore lenses (or roll structures) are commonly

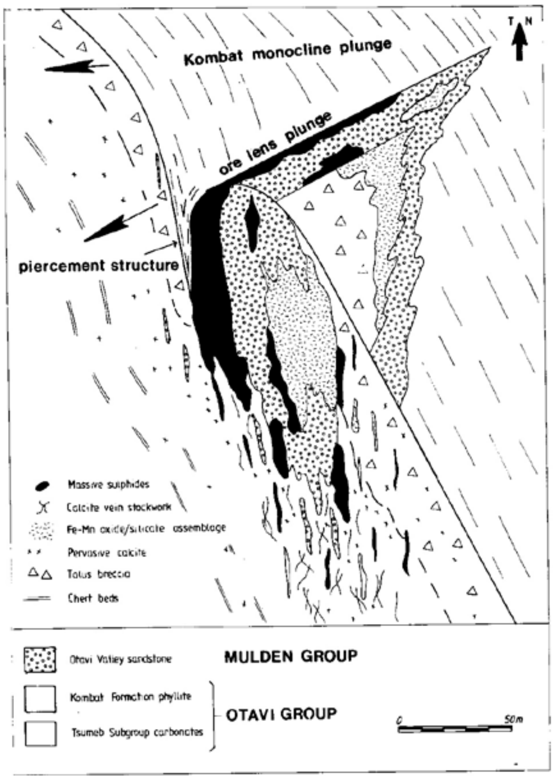

Figure 3: A schematic section of a typical Kombat-type ore lens, with the phyllite stripped away on the contact zone.

steep, crosscut stratigraphy, and dip at between -85°N and -80°S. At depth, the lenses generally "bottom out" and become stringer-type disseminated mineralization occurring in calcitized zones and net-vein calcite fractures. The amplitude of individual "roll structures" is usually about 100 m, and they commonly have a shallow, westerly plunge. The vertical height of the individual ore lenses is usually less than 250m.

The Kombat Central, Kombat West and Asis West deposits characterize Kombat-type ore lenses. Four types of ore associations are identified:

(i) Massive and semi-massive sulphides.
(ii) Mineralized net-vein fracture systems.
(iii) A Fe-Mn oxide/silicate assemblage.
(iv) Mineralized fracture fillings.

The massive and semi-massive sulphides are spatially related to areas of hydraulic brecciation, with the ore best developed in the breccia matrices, in lenses of Otavi Valley sandstone, and associated with calcitization. The brecciation is a result of intense north-northeast faulting. Mineralization has replaced the Otavi Valley sandstone to varying degrees from finely-disseminated sulphides forming the sandstone matrix, to total replacement of the sandstone.

Annealed textures in chalcopyrite, kinking of twin lamellae, piercements of massive sulphide intruding the country rock on the peripheries of orebodies, and the folding of chalcopyrite stringers in the phyllite, all suggest that recrystallization and deformation of most of the ore has occurred. There is, however, little evidence of folded massive ore lenses, although folded calcite veins hosting massive bornite and chalcopyrite are present.

The net-vein fracture systems occur below the massive sulphides (Fig. 3). These fracture systems consist of anastomosing, predominantly coarse white calcite veins associated with shear and fault zones. The host dolostone below these massive ore lenses is also commonly intensely calcitized. The calcite veins can be barren or mineralized (coarse bornite, chalcopyrite and galena). These net-vein fracture systems are often regarded as the "root zones" to the massive ore.

The Fe-Mn oxide/silicate assemblages are usually compositionally texturally layered (Innes and Chaplin, 1986) and form an integral part of the orebodies at Asis West, Kombat Central and Kombat East. These assemblages occur at intervals along the Kombat lineament and are always associated with feldspathic sandstone and mineralization. At least six such bodies have been recorded along the Kombat lineament. The Fe-Mn bodies range in size up to 50 m long and are commonly located within "roll structures" (Fig. 3).

Mineralogically, the banded ores are characterized by the presence of magnetite, hematite, barite, calcite, tephroite, alleghanyite, and pyrochroite with small amounts of jasperoidal rock. Other minor constituents include manganosite, jacobsite, galaxite, spessarite, vesuvianite, native Cu, barysilite, rhodonite, kutnahorite and several as yet unnamed minerals (Innes and Chaplin, 1986). Metasomatism has affected the adjacent dolostone and marl producing amphibolite-mica assemblages (magnesio-richterite and actinolite).

The Mn ores are fine to medium grained with a well-defined mineral banding. Typically, layers of hausmannite alternate with leucophoenicite, tephroite, native Cu, kutnahorite, barite and barysilite in bands that are between 1 to 6 mm wide.

In the Fe-rich ores, magnetite is interbedded with specular hematite and sandstone. All the Fe-Mn bodies contain interfoliated sandstone slivers with large, commonly unfoliated sandstone bodies lying juxtaposed to the assemblages (Innes and Chaplin, 1986).

The Fe-Mn bodies occur typically, but not immediately, in the footwall of the phyllite and are always "transposed" into the dolostone. This gives the appearance that they crosscut stratigraphy. An estimation of the undeformed size of these larger lenses is 50 m in length by 10 m thick. The larger lenses consist commonly of Fe-rich ores in juxtaposition with Mn-rich ores, with no clear observable intermixing.

The mineralized fracture fillings commonly develop adjacent to the massive sulphides and are associated with strong shearing. The mineralization constitutes bornite, chalcopyrite, pyrite, chalcocite, and rare galena.

The nature of the mineralizing fluids

Carbon, oxygen and strontium isotope analyses carried out by Deane (1993) on the calcite alteration, and fluid inclusion work conducted by Ypma (1978) on the sulphides, have constrained and characterized the nature of the mineralizing fluids. The isotope data disputes a magmatic source, and the apparent high $\delta^{18}O$ value of +17‰ supports a metamorphic origin for the fluids. $^{87}Sr/^{86}Sr$ values (between 0.711 and 0.713) are indicative of late diagenetic to metamorphic signatures for these fluids.

The high $\delta^{18}O$ value for the fluid (calculated from fractionation curves of Bottinga, 1968), and the negative mixing curve on the $^{87}Sr/^{86}Sr$ versus Sr (ppm^{-1}) plot suggests isotopic non-equilibrium between the host carbonate and mineralizing fluid. This is interpreted as being a result of rapid, channelized fluid flow rather than due to low fluid/rock ratios. Further, the large spread in all isotope ratios suggests a prolonged mineralization period.

With the onset of the Damaran orogeny, large volumes of evolved connate water (brines), carrying dissolved salts and metals leached from the sedimentary pile, would have been expelled. The progressive dewatering of sediments can continue to a depth of approximately 6000 m. Zones of structural deformation, such as the D_2 high-angle reverse faults and shear zones, would act as ideal channelways for the migration of these fluids.

Although compactional waters are capable of transporting ore constituents, the quantities of fluids required to produce significant ore bodies necessitate strong focusing of fluid flow such as observed at Kombat. In the Kombat deposits the karsts provide a perfect locus for precipitation (Fig. 4).

The presence of abundant algal beds and stromatolite horizons in the Tsumeb Subgroup suggest that H_2S, originating from bacterial action, probably aided in the precipitation of the base metals. The locus of brecciation and karstification in the Kombat area would have created spaces to concentrate H_2S rich fluids. H_2S that is produced in sandstone-shale sequences is commonly precipitated with Fe to form pyrite which in turn can form a geochemical barrier and cause precipitation of sulphides at a later stage (Emslie, 1980).

Discussion

The Kombat environment was the focus for various structural events which prepared the ground for the formation of the Kombat ore deposits. The earliest structures were synsedimentary and resulted in the development of karsts at Kombat, which led to the deposition and preservation of the Otavi Valley sandstone. These early faults and fractures are northeast -trending and are associated with the Asis Ost fault system, they include the W270, W550, W750 and Kombat West faults.

The faulting imposed two important controls on the

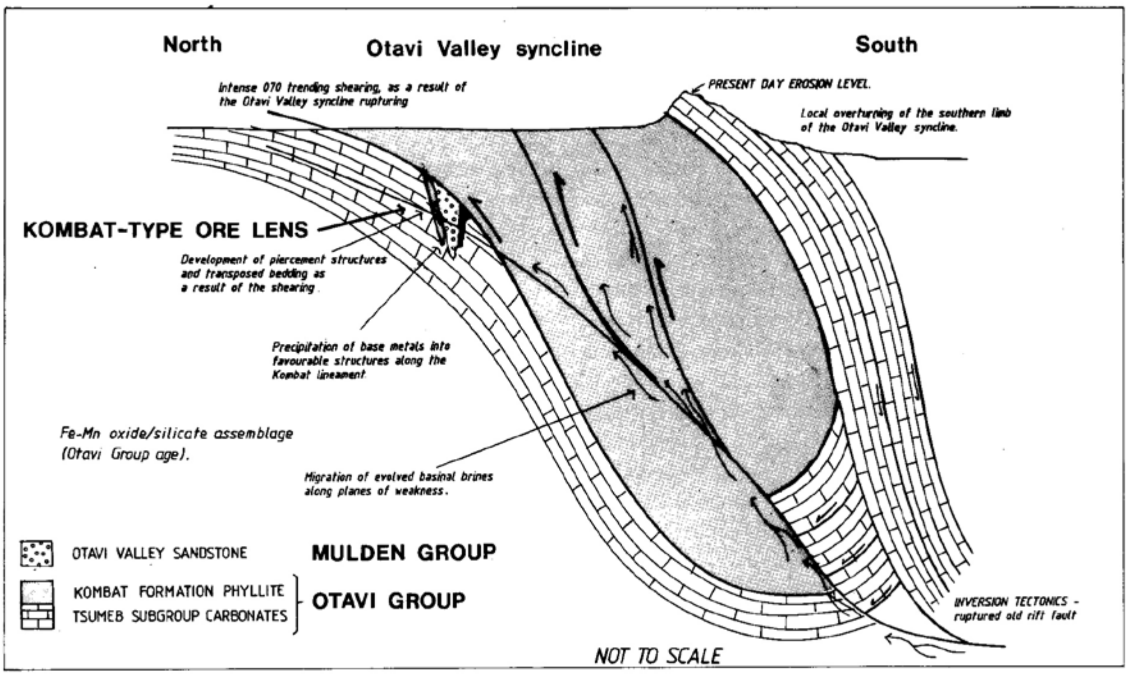

Figure 4: D_{2b} rupturing of the Otavi Valley syncline with the expulsion of orogenic (metamorphic) brines to produce the Kombat deposits.

karst process. Firstly, the intersection of the faults with the Otavi Group carbonate platform margin probably provided the loci for karst development. There is a close spatial relationship between these faults and the east-west extent of the karsts. Secondly, they provided the ideal channelways for sand transportation. These fracture systems trend north-eastwards towards the Grootfontein inlier which was probably the source area for the sandstone.

It must be noted that these faults also displace ore bodies, therefore they have been reactivated at later (Karoo) times. This later reactivation has no control on the genesis of the ore deposits.

The Kombat monoclinal structure represents a flexure on the Otavi Group/Kombat Formation contact zone within the vicinity of the Kombat ore bodies. The monoclinal structure represents the flexure of the northern limb of the Otavi Valley syncline around the area incorporating the massive "Fe-Mn assemblages and the sandstone along the Kombat lineament (Fig. 4).

The generally accepted idea for the genesis of the ore at Kombat is that the D_{2b}-age northeast to east -northeast trending shear zones and fractures were the feeders for the Kombat ore. This becomes evident underground where ore occurs dominantly in zones of intense faulting, fracturing and tectonic brecciation associated with these structures.

West of Kombat Mine the Otavi Valley rupture has branched-out to form the Station fault and numerous north-northeast trending vertical shear zones and faults. Surface mapping suggests that the zone of most intense shearing is between the Station fault and the Asis Ost orebody. Numerous large ductile shear zones with left-lateral displacement subparallel the fault. These shear zones display vertical plunging, elongated (L_2) fabrics such as stretched oölites.

The D_{2b} rupturing of the Otavi Valley has been cited as the important structural control on the development of the Otavi Valley "roll structures". Mapping by S. Galloway, (pers. comm., 1989) west of Kombat Mine reveals the intensity of left-lateral shear movement along north-northeast-trending structures that parallel the Station fault. Large oolitic blocks up to 2 m in diameter are found along these shear zones some 200 m from the oölite marker horizon. The width of individual shear zones is commonly small (1-2 m), however the whole area south of the Station fault is dominated by fractures and shear zones which all developed during the D_{2b} event.

A study of these shear zones within the Kombat Mine shows the close association of "roll structures" with the shearing, and the possibility that the shearing has produced the "roll structures". This idea was first suggested by S. and C. Galloway in the late 1980s but has never been fully appreciated. The roll structures are interpreted as "pseudo" folds produced by shearing in zones which intersect the Kombat lineament.

An important observation is the identification of both brittle and ductile deformation within these shear zones, which is a result of the competency difference between the massive carbonate and the other lithological units (sandstone, Fe-Mn assemblages and phyllite). Commonly, where the D_{2b} shear zones intersect the phyllite/dolostone contact, numerous structures are observed.

These include tight isoclinal infolding of the phyllite into the dolostone forming "cusp" structures along the dolostone phyllite contact. "Cusps" can progress into "piercement" structures which attain vertical lengths of up to 60 m (Fig. 3). The sandstone has in many places been "injected" into the shear direction, suggesting that some of it may have been only partly lithified at the time of deformation. Within the phyllite units chalcopyrite stringers are commonly isoclinally folded, suggesting some of the mineralization was pre-D_{2b} deformation.

Brittle structures are confined to the massive dolostones of the Hüttenberg Formation, where the rock has been tectonically fractured and brecciated. These zones of brecciation parallel the local shear direction. Mineralization within these breccias generally forms matrix infill. Coarse white calcite veins have also invaded these fractured zones forming the net-vein fracture systems.

To further complicate the structural history, late, post-Damaran age north-south block faulting has produced "compartments" within the Kombat orebodies.

Conclusions

The Otavi Valley sub-basin is classified as a subsidiary intracontinental rift basin to the northern rift, situated on the Congo Craton. The environment during the formation of the Kombat ore deposits was tectonically active, being the final stages of rift tectonism, and the main phase of the Damaran orogeny.

Both field and geochemical evidence suggest that the mineralization event at Kombat was complex, probably occurring over a long timespan. At least two phases of mineralization are evident at Kombat. In the Otavi Valley, the emplacement of the Fe-Mn oxide/silicate assemblages on the carbonate platform margin took place during a final rifting stage, and shortly thereafter the Kombat Formation transgressed over the platform margin area. It is probable that an early phase of Cu mineralization is related to fluids of a similar source as those which brought the Fe and Mn. This mineralization can be regarded as stratiform in appearance, as it forms thin layers parallel to relic bedding within the phyllite.

Jowett (1989) stated that: "statiform Cu-Ag deposits are closely associated with continental rifts (including failed rifts and aulacogens with continental sediments) and are controlled by rift-related volcanic rocks and basement highs." He suggested that the underlying rift environment provided the metal source, formational brines, channel-ways, and topography necessary for ore formation and that it was the primary control in determining the location of these deposits. Metalliferous hydrothermal solutions associated with the early rifting can rise through the section and mineralize the host rock syngenetic ally or during early diagenesis.

The second phase of Cu mineralization was syntectonic, being directly related to the collision of the Congo Craton and Kalahari Craton during the Damaran orogeny. This phase has almost totally destroyed the first generation of mineralization, and is stratabound rather than stratiform.

Tectonism following rifting adds dynamic and thermal components to the environment that could promote ore forming processes (Kirkham, 1989). The closure of the intracontinental arm during the collision phase of the Damaran orogeny resulted in dewatering of these Damaran basins causing evolved basinal brines to deposit Cu-rich sulphides under the Otavi Group/Kombat Formation unconformity.

References

Ahrendt, H., Behr, H.-J., Clauer, N., Hunziker, J.C., Porada, H.and Weber, K. 1983. The Northern Branch: Depositional Development and Timing of the Structural and Metamorphic Evolution within the Framework of the Damara Orogen. *In*: H. Martin and F. W. Eder (Eds), *Intracontinental Fold Belts*.

Allsopp, H.L., Welke. H.J. and Hughes, M.J. 1981. Op Jag met isotope. *Kernaktief*, **24**, 8-12.

Bottinga, Y. 1968. Calculation of fractionation factors for carbon and oxygen exchange in the system calcite-carbon dioxide-water. *J. Phys. Chem*., **72**, 800-808.

Clauer, N. and Kröner, A. 1979. Strontium and argon isotopic homogenization of pelitic sediments during low-grade regional metamorphism: the Pan African Upper Damara sequence of northern Namibia (South West Africa). *Earth Planet. Sci. Lett*., **43**, 117-131.

Coward, M.P. 1983. The tectonic history of the Damara Belt. *In*: R.McG. Miller (Ed.), *Evolution of the Damara Orogen of South West Africa/Namibia*. Spec. Publ. Geol. Soc. S. Afr., **11**, 409-421.

Deane, J.G. 1993. *The Controls on "Contact-type" Cu-Pb (Ag) Mineralization within the Tsumeb Subgroup of the Otavi Valley syncline*. Unpubl. MSc thesis, Univ. Cape Town, 240pp.

Emslie, D.P. 1980. *The mineralogy and geochemistry of the copper, lead, zinc sulphides of the Otavi Mountainland*. Unpubl. Rep. National Institute for Metallugy, Johannesburg, South Africa, No. 2056, 45pp.

Frimmel, H.E. and Van Achterbergh, E. (in press). Metamorphism of calc-silicate and associated rocks in the Pan-African Kaaimans Group, Saldania Belt, South Africa. *Mineral. Petrol*.

Hedberg, R.M. 1979. Stratigraphy of the Owamboland Basin, South West Africa. *Bull. Precambr. Res. Unit, Univ. Cape Town*, **24**, 325pp.

Hoffmann, K.H. 1989. New aspects of lithostratigraphic subdivision and correlation of late Proterozoic to early Cambrian rocks of the southern Damara Belt and their correlation with the central and northern Damara Belt and the Gariep Belt. *Communs geol. Surv. Namibia*, **5**, 59-67.

Hughs, M.J. 1987. *The Tsumeb ore body, Namibia, and related dolostone-hosted base metal ore deposits of Central Africa*. Unpubl. D.Sc. thesis Univ. Witwatersrand, 448pp.

Innes, J. and Chaplin, R.C. 1986. Ore bodies of the Kombat Mine, South West Africa/Namibia, 1789-1805. *In*: C. Anhausser and S. Maske (Eds), *Mineral Deposits of Southern Africa*, **2**, Geol. Soc. S. Afr., Johannesburg, .

Jowett, E.C. 1989. Effects of Continental Rifting on the Location and Genesis of Stratiform Copper-Silver Deposits. *In*: R.W. Boyle, A.C. Brown, C.W. Jefferson, E.C. Jowett and R.V. Kirkham (Eds), *Sediment-hosted Stratiform Copper Deposits*. Spec. Paper Geol. Assoc. Can., **36**, 53-66.

Kirkham, R.V. 1989. Distribution, settings, and genesis of sediment-hosted stratiform copper deposits. *In*: R.W., Boyle, A.C., Brown, C.W., Jefferson, E.C., Jowett and R.V., Kirkham (Eds), *Sediment-hosted Stratiform Copper Deposits*. Spec. Paper Geol. Assoc. Can., **36**, 53-66.

Miller, R.McG. 1983. The Pan-African Damara Orogen of South West Africa/Namibia. *In*: R.McG. Miller (Ed.). *Evolution of the Damara Orogen of South West Africa/Namibia*. Spec. Publ. Geol. Soc. S. Afr., **11**, 431-515.

Oliver, J. 1986. Fluids expelled tectonically from orogenic belts: Their role in hydrocarbon migration and other geologic phenomena. *Geology*, **14**, 99-102.

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

Söhnge, P.G. 1974. *Exploration in the Otavi Valley*. Unpubl. rep. Tsumeb Corp. Ltd., Tsumeb, Namibia.

Trommsdorff, V. and Connolly, A.D. 1990. Constraints on phase diagram topology for the system CaO-MgO-SiO_2-CO_2-H_2O. *Contrib. Mineral. Petrol*., **104**, 1-7.

Ypma, P.J.M. 1978. *Fluid inclusions and ore genesis in the Otavi Mountains, South West Africa - Part 1 - Geothermometry and Barometry*. Unpubl. Rep. Tsumeb Corp. Ltd. Tsumeb, Namibia, 33pp.