

The Kombat ore deposit, Otavi Mountainland (Northern Namibia)

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Abstract

The Otavi Mountainland, situated on the Northern Carbonate Platform of the Damara Orogen, underwent a complex deformation during late Proterozoic and early Phanerozoic time. In general the regional structure consists of EW-trending folds, overprinted by a second folding phase producing northward verging recumbent folds. During the orogeny the metamorphism reached lower greenschist to prehnite-pumpellyite facies at some places in the mountainland.

Deposits of the Berg Aukas and Tsumeb type are the main sulphide mineralization types of the Otavi Mountainland.

Kombat is situated on the northern flank of the canoe-shaped Otavi Valley Syncline. The phyllite of the Kombat Fm underlain by the dolostone of the Hüttenberg Fm form the core of the valley. At Kombat the primary sulphide mineralization is similar to the Tsumeb Pipe deposit. The ore bodies comprise an epigenetic, hydrothermal and metasomatic replacement as well as fracture-fill Cu-Pb-(Ag) deposit. Different types of mineralization are described such as the massive/semi-massive sulphides, mineralized net-vein fractures system, Fe-Mn oxide/silicate assemblage and mineralized fracture fillings. The ore mineralization is associated with the second Damara tectono-thermal event.

1 Introduction to the Otavi Mountainland with focus on the Kombat Mine

The Kombat Mine is located about 50 km to the south of Tsumeb within the northern miogeosynclinal shelf of the Damara Orogen (Innes and Chaplin, 1986).

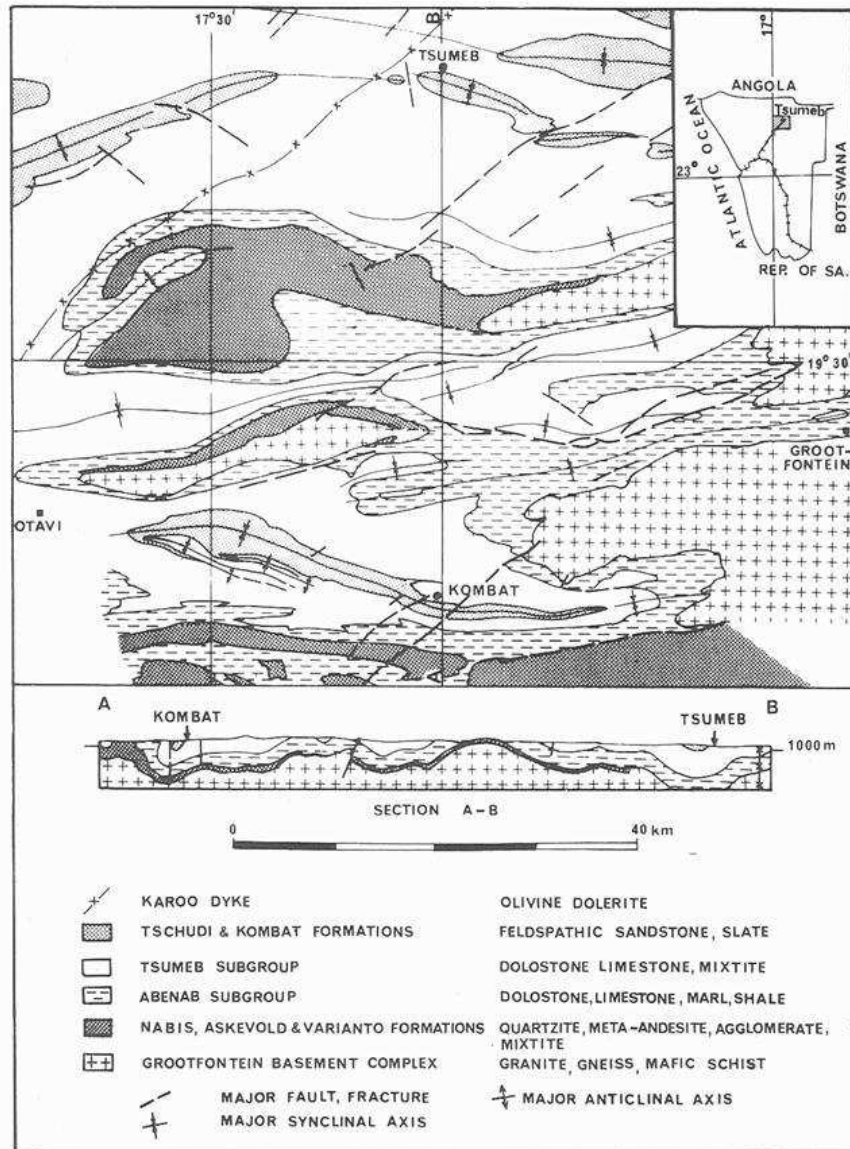


Fig.1. Location plan and regional geology in the Kombat Mine area (Innes and Chaplin, 1986)

1.1 Geology of the Otavi Mountainland

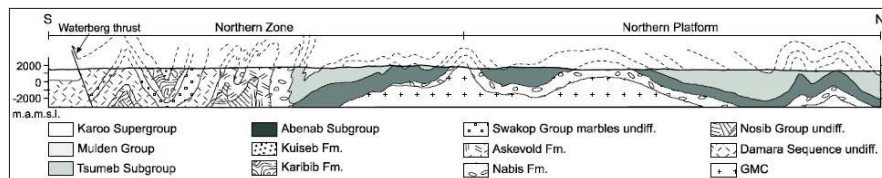


Fig.2. Structural section across the Northern Platform (Laukamp, 2007)

The Otavi Mountainland is located on the eastern side of the Northern Carbonate Platform of the Damara Orogen. This orogen is considered to be a late-Proterozoic orogenic belt generated during the Pan-African collision of the Sao Francisco-Congo and Kalahari cratons. The Damara Belt is an intracontinental, NE-trending branch of the Damara Orogen and can be divided in three major zones that are separated by the NE-trending lineaments in the Damara Belt. These zones comprise the Northern, the Central and the Southern Zone. The Otavi Mountainland is located at the transition of the Northern Zone to the Northern Platform (see Fig.1.), which consists of Cryogenian and Ediacaran platform carbonates (Laukamp, 2007).

The following steps trace the tectonic evolution of the north-eastern Damara Orogen:

- 1) formation and generation of the Paleoproterozoic basement during the Eburnean orogeny,
- 2) pre Pan-African rifting due to the break-up of Rodina,
- 3) Pan-African orogeny with the formation of the Damara Belt and
- 4) post Pan-African uplift and extension.

During the Pan-African orogeny three deformational events had affected the Otavi Mountainland.

The first deformational event D1 has an early Ediacaran age (~650Ma) and caused an E-W shortening due to accretion of a coastal terrane to the Kaoko Belt in the west, the closure of the proto-Atlantic. It resulted in the formation of large recumbent SE-vergent folds in the Kaoko Belt and gentle N/S-trending open warps in the Otavi Mountainland (Dean, 1995). Northerly directed thrusting has taken place. South of Kombat stratigraphic replication in the Tsumeb Group can be observed. During this period karst structures developed. D1 preceded the deposition of the Mulden Group. Due to the imperfect record of deformation retained in the relatively competent dolostone sequence at Kombat, this early phase of folding, if present, is not recognized (Innes and Chaplin, 1986).

The main deformational event D2 is correlated with a tectonothermal event (~537-550M) due to the collision of the Kalahari and Sao Francisco-Congo Cratons and the closure of the intracontinental arm. It has formed the first macroscopically recognizable folding in Kombat. The deformation resulted in Green-

schist facies metamorphism of the Otavi and Mulden Groups with an increasing grade towards the south. In the northern part of the intracontinental arm relatively high temperature rocks were thrust N-wards onto the lower temperature Mulden rocks. This leads to a complex D2 history in the Kombat environment. At Kombat large-scale, isoclinal, folds can be observed. They trend E-W and are northward-vergent, locally recumbent. Small-scale folds of that deformation event are disharmonic folds with a near-vertical E-W-trending axial planar cleavage S_1 . Mineralization and calcitization are commonly associated with shearing that is parallel S_1 (Dean, 1995). A crenulation cleavage S_2 has been superposed to S_1 into which the sulphides are mobilized (Innes and Chaplin, 1986). D2 can be divided in D2a (late Ediacaran and early Cambrian) where the isoclinal folds were formed and D2b. During late D2b and syn-D3 emplacement of granites in the Damara Belt took place and the Otavi Syncline was ruptured along its synclinal axis.

In addition shear zones can be found that crosscut the Otavi Syncline and therefore they might belong to another deformation event. They may represent zones of shear extensions of attenuated fold hinges (Innes and Chaplin, 1986). Within the shear zones transposition of sedimentary and mineral layering and of sulphide veinlets can be recognized.

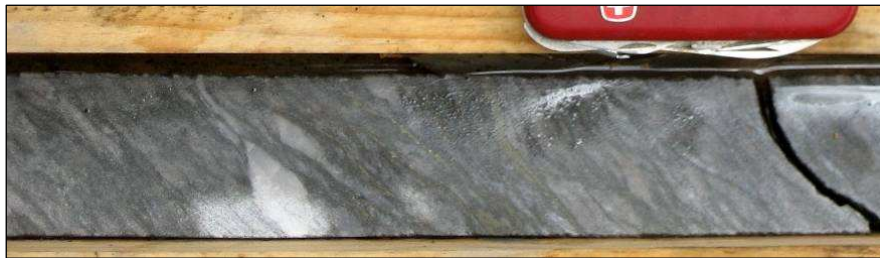


Fig.3. anhedral, flaky pyrite crystals occurring along S_2a surfaces (drill core AU12-247, On-gopolo Mining & Processing LTD)

The third deformational event D3 (~450-457Ma) is also correlated with a tectonothermal event. The early Paleozoic uplift caused the fragmentation of the Otavi Mountainland. Extensional normal faults were formed and NE-trending (e.g. Asis Ost and Kombat West fault) structures were reactivated. In the Otavi Mountainland the deformation resulted in NW-trending open and upright warps (Dean, 1995). As a result of the interference NE-trending cross-warps were formed at Kombat, thus leading to the canoe-like shape of the Otavi Valley.

1.2 Stratigraphy of the Otavi Mountainland

1.2.1 *Igneous and metamorphic rocks of the Paleoproterozoic basement*

The Grootfontein Inlier is presumably the Paleoproterozoic basement of the Otavi Mountainland with an age of approximately 1.946 +299/-333 Ma. It is part of the

southern Congo Craton and can be subdivided in the Grootfontein Metamorphic Complex (mainly alkaline/calc-alkaline granites and granodiorites) and the Grootfontein Mafic Body (anorthosites, gabbros, micaceous biotite gneisses, granites and amphibolites). On a regional scale, the present distribution of basement highs and the unconformably overlying Nosib Group appear to reflect paleotopographic highs that influenced carbonate sedimentation (Beukes, 1986).

1.2.2 Sedimentary successions of the Neoproterozoic Damara Supergroup

The Damara Supergroup with a Neoproterozoic age is divided in the Nosib Group, Otavi Group and the Mulden Group. Further the Nosib Group is divided in the Nabis Fm (shale, phyllite, conglomerate, arkose, and quartzite) and the Askevold Fm (epidosite, agglomerate, chlorite schist, and dolomite). It was deposited in a pre-Pan-African, NE-trending horst-graben-system that developed due to the Cryogenian break-up of Rodinia (Laukamp, 2007). The depositional age for the Nosib Group is approximately 780-740 Ma.

The Otavi Group, deposited as a carbonate platform on the southern margin of the stable crust of the Congo Craton (Laukamp, 2007), consists of the Abenab Subgroup and the Tsumeb Subgroup. These subgroups are separated by the diamictites of the Ghaub Fm (635Ma). The Abenab Subgroup comprises from base to top the Chuos Fm (diamictites), Berg Aukas Fm (cap carbonates), Gauss (massive and bedded dolomites) and Auros Fm (stromatolites and oolites, alternating with bedded limestones and shales).

The Tsumeb Subgroup is subdivided in the Ghaub (T1: diamictites), Maieberg (lower part (T2): cap carbonates; upper part (T3): dolomites of the central Otavi Mountainland), Elandshoek (lower part (T4): dolomites; upper part (T5): bedded dolomites) and Hüttenberg Fm. T3 and T4 represent sedimentary breccia. The ore bodies of Kombat are hosted mainly in the Hüttenberg Fm which can be divided in a lower (T6: bedded dolomites), middle (T7: lagoonal deposits) and upper part (T8: stromatolitic and oolitic dolomites with intercalated cherts). At Kombat the Hüttenberg Fm with a maximum thickness of 700m is restricted to the northern flank of the Otavi Valley syncline. The upper part consists of light to dark grey coloured slumped and partly calciferous dolostone facies. From top to base micritic dolostone with fragments of the underlying members, thin-bedded algal laminated, oolitic (to some extent silicified), stromatolitic, and detrital/pelletal dolostone are found. The latter can display current-bedding, imbrication of clasts and phosphatic replacement of detritus und pellets. T6 are massively bedded, micritic, light to medium grey dolostone with abundant bedded, diagenetic cherts (Innes and Chaplin, 1986).



Fig.4. algal remnants in light grey dolostone (drill core KCN6)



Fig.5. oolitic medium grey dolostone (drill core AU12-193)

The Mulden Group is divided in the Tschudi Fm (conglomerates, sandstones, quartzites and arkoses of NE-/E-trending synclines in the northern Otavi Mountainland) and the Kombat Fm (phyllites). An angular unconformity between the Otavi Group and the Tschudi Fm is represented by the filling of karst depressions by the Tschudi conglomerates and Pan-African thrusting of the carbonates over the siliciclastic rocks (Laukamp, 2007). The Kombat Fm consists of light grey to black laminated feldspar-quartz-muscovite rock, the “Otavi-Valley-Slate”, at Kombat. It contains from top to base 5 to 60 per cent iron sulphides with traces of chalcopyrite, sphalerite and galena over widths of 5m. Also psammitic laminae and at the basal portion graphitic dolostone and marl can be found in the slate.



Fig.6. contact of the sandstone and light to medium grey dolostone (drill core AU12-245)

On the northern flank of the Otavi Valley syncline the Hüttenberg Fm and the Kombat Fm show a complex interfingering as a consequence of repetitive infolding of the Kombat Fm (Innes and Chaplin, 1986). Along these disconformable contact lenses, pods, and stringers of arkose and feldspathic sandstone intrusive into the dolostone occur reaching a maximum size of 250 by 20m in area. The larger bodies show depositional feature like conglomerate interbands, cross-bedding laminae and load casts. Texturally, the feldspathic sandstone is comprised of an aggregate of equigranular, generally well sorted, sub-angular clastic quartz, oligoclase, andesine, and potash feldspar grains in a calcite-kaolinite matrix. The emplacement of the sandstone is controlled partly by bedding, mainly by brecciation, joints, fracture cleavages, and net vein fractures in the dolostone (Innes and Chaplin, 1986). As an intrusive argillaceous equivalent of the sandstone is missing the latter was introduced into dolostone before the more regionally extensive pelites

of the Kombat overlapped onto the Otavi Group during the drowning of parts of an Otavi Valley subbasin (Dean, 1995).

1.2.3 Meso- to Cenozoic sediments and igneous dykes

During the Cretaceous calcalkaline lamprophyres (e.g. kersantites at the Tsumeb Pipe) and other kinds of dyke swarms were formed as well as basalts of the Etendeka Group, relating to the break-up of Gondwana. Tertiary and Quaternary deposits accumulated in post-Damaran karst structures as eolian sands (Kalahari sands) and calcrete cover (Laukamp, 2007).

1.3 Base metal mineralization in the Otavi Mountainland

The economically most important types are the Tsumeb-type occurring in the upper Tsumeb Subgroup and the Berg Aukas-type predominantly in the upper Abenab and lower to middle Tsumeb Subgroup.

Both types comprise sulphide mineralization. Nonsulphide mineralization like Zn-silicates and vanadates of the Otavi Mountainland are not further described in this paper.

	Berg Aukas-type	Tsumeb-type
Host-rock	Abenab Subgroup and lower Tsumeb Subgroup	Elandshoek and Hüttenberg Formations (dolomites), T4 through T8 zones
Shape of orebody	Stratiform lenses, discordant breccias	Discordant pipe, filled with breccia and sandstone; structural control
Ore mineralogy	Sphalerite, galena (pyrite, chalcocopyrite, tennantite)	Tennantite, galena, sphalerite, pyrite, bornite, chalcocopyrite, germanite
Ore geochemistry	Zn>Pb; low Cu, Ag, As, Ge, Ga, Cd	Pb>Cu=Zn, Considerable As, Ag, Cd, Ge, Ga, W
Fluid inclusions	ca. 23 wt.% NaCl eq., 137 to 255°C	22.3 wt.% NaCl eq., >212°C (dolomite III)
Fluid source	Basinal brines	Orogenic fluids
Age	635 to 750 Ma ?	460 to 530 Ma?

Table 1. Major Types of base metal mineralization of the Otavi Mountainland (Laukamp, 2007)

1.3.1 Berg Aukas-type

Within the type locality, the Berg Aukas mine is located 20 km northeast of Grootfontein in large scale folded dolomites of the Abenab Subgroup (Gauss Fm), resting on the basement high of the Grootfontein Inlier and separated by a thin layer of the Nosib Group. Berg Aukas belongs to the Mississippi Valley-type deposits. Other deposits of this type can be found in the central to eastern Otavi Mountainland (e.g. in the area of the Maieberg Anticline, Keilberg Anticline, and

Gauss Anticline). The spatial distribution of the ore at Berg Aukas is stratigraphically and structurally controlled. Enrichment took place along a bedding parallel fault breccia and in collapse breccias. The hypogene ore is dominated by Zn-Pb sulphides.

Three types of ore bodies were mined at Berg Aukas:

- (1) the Northern Ore Horizon consisting of three stratabound lenses that were subjected to oxidation and brecciation (the brecciated dolomite is enriched in descloizite capes of the lenses),
- (2) the discordant Central Ore Body is a brecciated pipe-like body consisting of oxidized extensively enriched in vanadiferous muds and breccia,
- and (3) the stratabound Hanging Ore Horizon located above the Northern Horizon and characterized by N-S-trending, steeply dipping lenses of ore-filled fractures.

In karst areas the mineralization occurs as space filling. The late-stage descloizite mineralization took place when calcium metavanadate solutions were introduced into the deposit along vertical fractures forming breccia-type deposits (Cairncross, 1997).

Two models are suggested for the formation of Berg Aukas-type deposits: 1) MVT-style mineralization prior to the Pan-African orogeny due to basin dewatering processes and 2) syn Pan-African emplacement (Laukamp, 2007).

The operation of the Berg Aukas Mine ceased in 1978. On average 11,000 tons were milled per month, grading 17% Zn, 5% Pb and 0.6% V₂O₅.

1.3.2 Tsumeb-type

The discordant, basically elliptical shaped ore pipe is confined to the upper portions of the Tsumeb Subgroup. Prior to syn-D2 folding and shearing dissolution by meteoric water and hydrothermal alteration during syn- and post-D2 have affected the carbonate host rocks. The collapse brecciation progressed upward until the influx of siliciclastic material (feldspathic sandstone) of the Tschudi Fm took place. Another theory assumes the feldspathic sandstone as intruded quartzofeldspathic sediments from lower formations that were mobilized by deep seated igneous activity (Gilbert, 1986).

According to Laukamp (2007), the following base metal mineralization types can be distinguished:

- (1) horseshoe-shaped massive peripheral ores replacing the feldspathic sandstone and extending laterally into a dolomite breccia,
- (2) manto ores comprising massive sulphides, extending from the margin of the breccia pipe into the country rocks at the lower T6 and being controlled by structures which developed prior to the formation of the karst pipe,
- (3) disseminated and stringer ores comprising a variety of sulphide mineralization (e.g. disseminated replacements of feldspar and Cu-rich veins in the feldspathic sandstone, massive sulphides as vugfilling and irregular blebs to discontinuous veins associated with altered breccia bodies and steep fractures),
- and (4) secondary ores of two oxidation zones.

The emplacement of base metal mineralization is related to the ascent of metal-bearing hydrothermal fluids generated during prograde metamorphism of the Pan-

African orogeny. Thus a significant enhancement of permeability could be due to the main deformational event. A formation temperature of 405°C have been calculated for Tsumeb-type mineralization in the Kombat Mine. The paragenetic sequence of the hypogene mineralization started with early pyrite and followed by the main mineralization with Cu-Fe-Ge(-Zn) sulphosalts as well as sulphides. Commencing sulphide mineralization was dominated by Zn-Cu sulphides, which was finally displaced by galena.

Up to its closure in 1996 the Tsumeb Mine produced about 30 Mt of ore grading 10% Pb, 4.3% Cu and 3.5% Zn.

Other Tsumeb-type deposits in the Otavi Mountainland are represented by the Kombat, Khusib Springs and several occurrences in the north-western Otavi Mountainland.

1.3.3 Other Types

The Nosib-type comprises disseminated Cu-Pb(-Zn) mineralization in the Nosib Group, close to the tectonic contact with overlying Abenab Subgroup. Sulphides like pyrite, chalcocite, galena, sphalerite and bornite as well as secondary minerals (Cu carbonates, Pb oxides and Pb-Cu vanadates) are recorded.

The Tschudi-type is located in the north-western Otavi Mountainland. Its low-grade Cu mineralization impregnates sandstones and conglomerates at the base of the Mulden Group. The mineral content of the stratiform ore body comprises chalcocite as the main sulphide, bornite, chalcopyrite and pyrite. Metal precipitation by replacement of diagenetic pyrite has been suggested for this type.

VMS-type ores occur in the southernmost Otavi Mountainland, which is part of the Northern Zone of the Damara Belt. The low grade Cu-Ag-Au mineralization is associated with metavolcanics and chlorite schists, containing magnetite and pyrite of the Askevold Fm which are intercalated in clastic rocks of the Nabis Fm and dolomitic marbles. The primary sulphides comprise chalcopyrite, chalcocite and bornite, whereas supergene sulphides are represented by chalcocite and neodigenite (Laukamp, 2007).

Several other mineralized areas could be mentioned here but that might be not important for the purpose of this paper.

2 Ore Bodies of the Kombat Mine

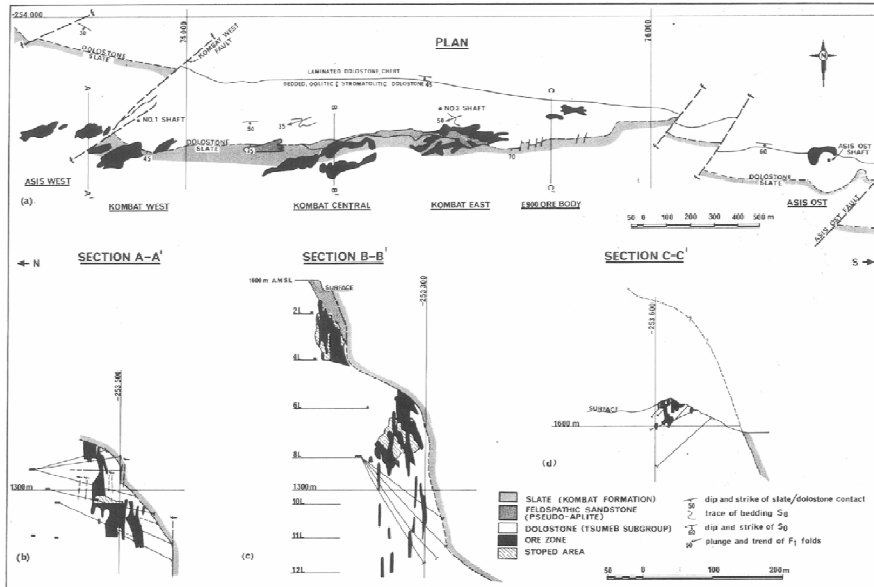


Fig.7. generalized surface geology of the Kombat Mine area and profiles of the contact (Innes and Chaplin, 1986)

2.1 Geological setting of the ore bodies

The ore bodies are situated on the northern limb of the double plunging, canoe-shaped Otavi Valley syncline with its northern limb dipping south at 20° to 75° and an overturned southern limb. Several NE- and E-trending normal and strike-slip faults cross-cut this syncline. The fold of the Otavi Valley has a tight character in contrast to the rest of the Otavi Mountainland where the folds are more open. Seven distinct zones of mineralization separated by barren dolostone strung out over a distance of 6km along the so-called Kombat monoclinial lineament. All zones have surface expression except for Asis West where the ore body is down-faulted along the Kombat West Fault (see Fig.6.).

Hosted by the dolostone of the Hüttenberg Fm, the ore occurs below monoclinial flexures on the contact between the Kombat Fm and the Hüttenberg Fm. This affinity for the contact is not obvious at the Asis Ost and E900 as the ore bodies are truncated here by erosion. The amplitude of the flexures varies from 75 to 100m and the wavelength ranges from 150 to 250m. In general the ore loci are defined by breccia bodies in dolostone and a variety of structural controls (e.g. steeply-dipping zones of shearing, net-vein fractures, joints, and fracture cleavages). These planar structures are sub-parallel within the ore bodies and diverge from the contact, hence imparting an échelon pattern to the ore and a crosscutting relationship with the contact (Innes and Chaplin, 1986; Dean, 1995). They are in-

terpreted as D2b structures into which the Pb- and Cu-sulphides were remobilised. The country rock above the ore bodies is sheared and fractured what is described by the term “roll structures”. A relation between the ore bodies and the feldspathic sandstone is also indicated.

The ore lenses abut against the contact and hang like pendants beneath the flexures. They are steep in orientation and transgressive to stratigraphy. With depth the massive sulphides horsetail and merge into thready, stringer type until they become disseminated in calcitized zones of net-vein fractures.

2.2 Alteration

The alteration is promoted by presence of sedimentary and tectonic breccia and particularly by development of net-vein fracturing. It precedes the deposition of the ore. Also a later episode associated with post-ore faults is reported.

The alteration process starts with decolourising of dolostone due to outward migration of argillaceous and carbonaceous inclusions concomitant with a slight increase of grain size. Increasing alteration causes broadening of bleached zones until calcitization and associated Mn alteration took place. Broad zones, ranging from 200m to 300m in width of calcitization, flank the ore lenses. These zones have a fine to medium grained, saccharoidal texture. The Mn alteration comprises pink to intense rouge-coloured magnanoan calcite with nodules and detritic growth of black manganese (mostly pyrolusite). It is often associated with intense calcitization in areas proximal to ore.

Hydrothermal silicification is only prominent in some sandstone lenses. This alteration facies comprises the association quartz-sericite-pyrite(-chalcopyrite), chlorite-hematite and kaolinite-pyrophyllite. Traces of epidote in silicified sandstone are found.

Metasomatized zones in the dolostone occur adjacent to lenses of Fe-Mn ores. Within these zones mica and amphiboles like magnesio-richterite and subordinate actinolite have been formed.



Fig.8. intense alteration within light grey dolostone (drill core AU12-248)

2.3 Mineralization

The ore bodies consist of an epigenetic, hydrothermal, and metasomatic replacement and fracture-fill Cu-Pb-(Ag) deposit. Common for all types of mineralization is the small quantity of associated hydrothermal gangue minerals such as calcite, quartz, dolomite, and seldom barite. The degree of oxidation of massive sulphides is independent of the depth, it is controlled by the proximity of the ores to the water-bearing faults and steeply foliated sandstone aquifers.

2.3.1 Massive and semi-massive sulphides

They are elongated, foliated zones of mineralized dolostone related to centres of tectonic and sedimentary brecciation in dolostone stratigraphy. The replacement ore is best developed in breccia matrices, lenses of feldspathic sandstone, in pervasively calcitized dolostone and particularly in oölitic, pelletal/detrital units closest to the slate contact. At least four breccia types can be distinguished. These are firstly the syn-depositional sedimentary breccia with angular dolostone clasts in a micritic and often calcitic matrix and secondly the stylobreccia with an anastomosing or quadrangular meshwork of net-vein fractures. The fault breccia (associated with post-ore fractures) and the solution collapse breccia (associated with karsting and localized by N-E trending fault) have little volumetric extent and no control on hypogene mineralization (Innes and Chaplin, 1986).

A foliation is frequently superimposed where breccia grades into transposition breccia in which clasts are attenuated and boudinaged.

High grade mineralization extends away from the centres of brecciation along zone of recrystallized dolostone. All gradations of mineralization from finely disseminated sulphides to completely replaced rock exist in the sandstone and in the dolostone.



Fig.9. massive ore comprising bornite, chalcopyrite and malachite (drill core KCN7)

The following five assemblages are mentioned by Innes and Chaplin (1986) for this type of mineralization:

- *bornite + chalcopyrite (galena, sphalerite, tennantite)*

It is the most abundant and widely distributed assemblage of hypogene ores. Coarse-grained exsolution flames, lenses and trellis-like lamellae of chalcopyrite in bornite, and vice versa are typical textures. Also indications of deformation and recrystallization can be observed. The subordinate tennantite occurs as exsolution blebs in bornite.

- *galena*
- *pyrite + galena*
Pyrite occurs as loose packed aggregates of euhedral/anhedral grains and spheroids. Galena contains erratic, economically insignificant concentration of sphalerite.
- *chalcopyrite + pyrite* in carbonaceous host
- supergene assemblage: *chalcocite + digenite + malachite (covellite, cuprite, Cu, Ag)*
This assemblage is localized at the water-bearing Kombat West Fault. At Asis West (E140-11) cerussite, anglesite, leadhillite, pyromorphite and wulfenite crystals were described.

2.3.2 Net-vein fracture system

A reticulate or anastomosing mesh of mineralized calcitic micro-fractures is developed adjacent to shears, faults and broad zones of pervasive calcitization below massive sulphides. It is therefore regarded as the “root zones” of the massive ore (Dean, 1995). With increasing deformation it grades into sutured stylolites. The stylolites contain magnetite, bornite, galena and chalcopyrite. In oxidized zones chalcocite, malachite, Cu and hematite are found. It is common for mineralization of this type to merge into alteration breccias and massive replacement Cu-Pb ores (Innes and Chaplin, 1986).

2.3.3 Galena-rich alteration breccias

This type of mineralization is confined to Kombat East ore bodies where steep breccia bodies of pipe-like configuration exist. An unaltered core of close-packed angular dolostone blocks is surrounded by a bleached, calcitized fringe induced by hydraulic fracturing which permitted increased fluid flow along the fracture system. The mineral assemblage comprises galena, pyrite and subordinate chalcopyrite.

2.3.4 Pyrite-sericite association

It is an alteration facies of the feldspathic sandstone affected by penetrative deformation and therefore formed early in the mineralizing process. Fine-grained, euhedral pyrite is disseminated in a generally strongly foliated sericite-quartz matrix. Ore minerals are seldom present.

2.3.5 Iron-manganese oxide/silicate association

This compositionally and texturally layered Fe- and Mn-assemblage is always associated with feldspathic sandstone and discrete steeply orientated zones of tectonic deformation. It forms an integral part of the ore bodies of Asis West, Kombat Central and Kombat East. Larger bodies, with an estimated undeformed size of 50m in length by 10m thick comprise hematite and magnetite in juxtaposition to

layered Mn-oxides and -silicates within a zone of transposition. There is no intra-layer admixture of magnetite and Mn ores. All Mn-Fe ore bodies contain interfoliated sandstone sliver and lenticles. The main banded ore minerals are magnetite, hausmannite, hematite, barite, calcite, tephroite, alleghanyite, pyrochroite, and small amounts of pinkish jasperoid rock. Sulphides such as pyrite, chalcopyrite, and galena are present in small amounts.

Mn-ores are fine grained and polymineralic aggregates with a well defined internal mineral banding (band width: 1 to 6 mm) of magnetite alternate with the assemblage leucophoenicite-tephroite-Cu and kutnahorite-barite-barysilite. They occur only in zones of tectonic transposition. In Fe-rich ores, granular magnetite is interlayered with schistose specular hematite and sandstone (Dean, 1995).

The layered Fe-Mn bodies are confined to the Kombat Mine and predate the sulphide formation. Fe-rich metasomatism of the dolostone could be expected to produce large amounts of Ca- and Mg amphiboles, epidote, diopside-hedenbergite, and andradite but only an amphibole(-mica) association with small amounts of epidote has been formed in the dolostone. Shortly before the deposition of the Kombat Fm, the emplacement of Fe- and Mn-carbonates/-hydrous oxides on the carbonate platform margin together with the feldspathic sandstone could have taken place during a rifting phase (Dean, 1995). The analogy between the layered Fe-Mn bodies of Kombat and volcanic exhalative class of Fe-Mn ore is described by Innes and Chaplin (1986).

2.3.6 Mineralized fracture fillings

Dilation features are developed in predictable geometric relationship to S_3 shears and a joint pattern is superimposed on altered net-vein fractures and mineralized dolostone. Early shear type fractures adjacent to steeply dipping, foliated zones of massive replacement sulphides contain blebby, disseminated bornite, chalcopyrite, pyrite, chalcocite und rare galena. Post-ore shears, characterized by peripheral, en echelon, sigmoidal gash veins are infilled by sparry calcite, quartz, and dolomite.



Fig.10. sparry calcite vein with speckles of chalcocite (drill core KCN7)

2.3.7 Epithermal association

This association commonly comprises transgressive vuggy veins containing euhedral calcite, quartz, and chalcopyrite. It postdates the main period of mineralization. In addition, a number of narrow veins containing galena, sparry rhodochrosite, helvite, and barite cross-cut the lenses of Fe-Mn oxides/silicates and adjacent bodies of massive galena-chalcopyrite (Innes and Chaplin, 1986).

2.4 Paragenesis and geochemistry of the ore

The hypogene ore was formed syntectonic with exception of the epithermal ones. In spite of this, the paragenetic sequence, beginning with pyrite followed by the deposition of sphalerite, bornite, tennantite, chalcopyrite and galena, is regarded as a primary one. Sulphide formation postdates the formation of Fe/Mn ores as it is indicated by pyrite rimming and replacing euhedra of magnetite. Layers of hausmannite or magnetite are observed outlining mesoscopic folds and this layering may predate tectonism (Innes and Chaplin, 1986) whereas specular hematite seems to have been grown syntectonic. The growth of amphiboles and some other Mn-silicates is also inferred to have been syntectonic.

	Tsumeb Pb>Cu>Zn (Lombaard et al., 1986)	Kombat Cu, Zn, Pb, Ag (Innes & Chaplin, 1986) (Deane, 1995)	Khusib Cu>Pb>Zn (Melcher et al., 2006)
D3	<p>Cu-(Zn) ger, ren, gn, ten, pyr</p> <p>Pb gn</p> <p>Zn-Cu sp, ena, ten, bn</p>	<p>gn ↑ ccp ↑ ten ↑ bn ↑ sp</p> <p>main Cu-sulphides</p>	<p>Late-stage Cu-Ag Cu-Ag-Zn-sulphide, dg, tel, pss-pol</p> <p>Early-stage Cu-(Ge) ten, ena, gn, Ge-col</p> <p>replacement ↑ Cu-Fe-Zn sp, pyr ↑ ccp, bn</p>
D2b	<p>Cu-Fe-Ge-(Zn) ccp, ger, sp, ren</p>		
D2a			
prä-v syn-D1	<p>Fe pyr</p>	<p>Fe pyr</p> <p>Fe-Mn-bodies</p>	

Table 2. Paragenetic sequence of major Tsumeb-type deposits in the Otavi Mountainland (Laukamp, 2007)

Geochemically, the Kombat ores comprises Cu-Pb mineralization with major concentrations in Fe and Mn and lower, but consistent and widely distributed values of Zn, Ag, Ba, and As (Innes and Chaplin, 1986). Cr, Mo, and Cl are widespread in the ore reaching concentrations of 100 to 500 ppm. Hypogene sulphides contain Ag in solid solution (galena with 20ppm to 240ppm Ag, bornite with 230ppm to 770ppm Ag). The major elements of the Fe/Mn ore bodies are Mn, Fe, Si, Ba, Pb, Cl, Mg, Ca, Na, ±Cu, ±As and minor elements are P, Ag, Ni, Co, Ti, K, Sr, Y, Zr, B, Be, Li. Compared to Tsumeb, Kombat ore is enriched in Fe, Mn, Ba and depleted in As, Zn, Ag, Ge.

Homogenization temperatures of 300°C are measured for inclusions in carbonate and quartz gangue associated with early formed galena. For the main chalcopyrite-bornite mineralization the temperatures range from 230 to 280°C. According to Dean (1995) the Kombat ore bodies formed in a temperature range between 350°C (presence of talc) and 480°C (absence of anorthite).

2.5 Conclusion

No satisfactory genetic model for the Kombat mineralization exists to date, but theoretically either syngenetic or epigenetic models may be applicable (Dean, 1995).

Further indication for Berg Aukas type mineralization formed during D1 (stage I of Pan-African mineralization), in the Tsumeb-type deposits were obliterated by the following stages of mineralization (Laukamp, 2007). Dean (1995) mentioned that probably an early phase of Cu mineralization is related to fluids of a similar source as those which brought the Fe and Mn. Then the syntectonic second phase of Cu-mineralization, being directly related to the collision of the Congo Craton and Kalahari Craton, has almost destroyed the first generation of mineralization, and is stratabound rather than stratiform.

According to Laukamp (2007) the main sulphide depositions at the Khusib, Kombat and Tsumeb Mine were formed during the stage II when hydrothermal fluids were triggered by the regional metamorphism. In stage III the primary ore was remobilised. The remobilised material and probably further element, added by fluids from the central regions of the Damara Belt were transported along sedimentary and tectonic structures such as extensional faults into D2 structures and formed the so called "Kombat-type" deposit. The driving force for the hydrothermal fluids could have been the second regional metamorphism in the Otavi Mountainland which accompanied D3 (Laukamp, 2007). At this time migmatization and granite emplacement took place in the Central Zone.

The two nonsulphide mineralizations that are mentioned for the Otavi Mountainland are the Zn-silicate-mineralization (stage IV) and vanadates-mineralization (stage V).

The genetic relationship of the Kombat deposit and the Tsumeb-type deposits is supported by high amount of Cu sulphosalts (e.g. tennantite) and a similar paragenetic sequence of base metal sulphide ores and carbonate generations (Laukamp, 2007). At Kombat the mineralization event took place in a tectonically active environment over a long time span. According to Dean (1995) isotope data suggest a magmatic source, high $\delta^{18}\text{O}$ value a metamorphic origin and $^{87}\text{Sr}/^{88}\text{Sr}$ a late diagenetic to metamorphic source for the mineralizing fluids. The derived isotopic non-equilibrium between the host carbonate and the mineralizing fluids is interpreted as result of a rapid, channelized fluid flow. Metal reservoirs for the hydrothermal event might be the basement gneiss and the volcanic suite of the Askevold Formation. According to Innes and Chaplin (1986), the involvement of a magmatic component in the mineralization finds not only support in the sulphur

isotope data but also in the association of certain lithophile elements in the Kombat ores (Li, Be, B).

The onset of Damara orogeny and the closure of the intracontinental arm during collision resulted in the dewatering of the Damara basins. Large volumes of brines with dissolved salts and metals were produced and transported along D2b high-angle reverse faults and shear zones. Karst structures along earliest faults and brecciation spaces in which H_2S might have concentrated could have formed the locus of precipitation. Probably H_2S originated from bacterial action as there are algal beds and stromatolite horizons in Tsumeb Subgroup. The hanging wall phyllites and shales of the Kombat Fm along the contact might have acted as a seal for ascending metalliferous fluids.

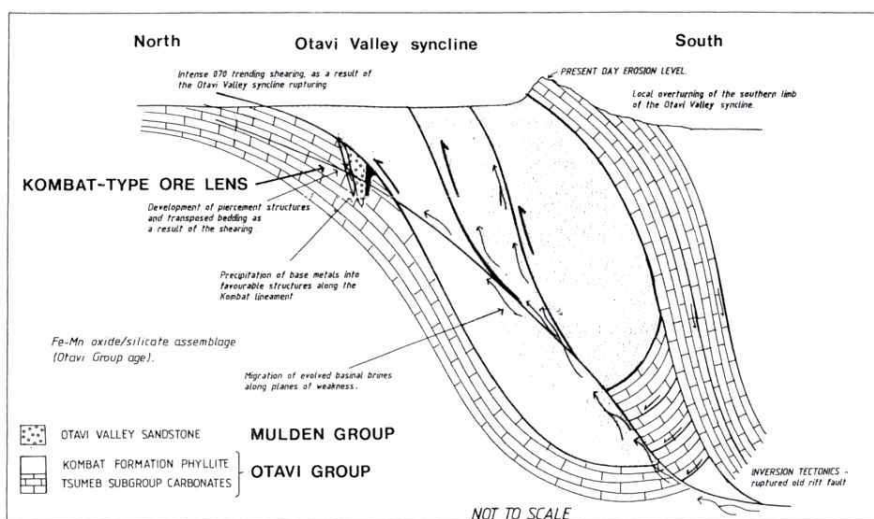


Fig.11. rupturing of the Otavi Valley syncline with the expulsion of brines (Dean, 1995)

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