

**THE GEOLOGY AND METALLOGENY OF THE  
OTAVI MOUNTAIN LAND, DAMARA OROGEN, SWA/NAMIBIA,  
WITH PARTICULAR REFERENCE TO THE  
BERG AUKAS Zn-Pb-V DEPOSIT - A MODEL OF ORE GENESIS**

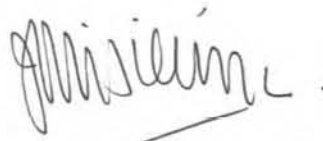
by

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All arguments and interpretations  
presented in this thesis are my own  
except where referenced.

A handwritten signature in cursive script, appearing to read "Misiewicz", with a horizontal line underneath it.

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## ABSTRACT

The Otavi Mountain Land is a 10 000 km<sup>2</sup> mineral province located at the eastern extremity of the exposed Northern Platform of the Damara Pan African orogenic belt. The Otavi Mountain Land is the most important mineral province on the Northern Platform. Exploitation of the Cu-Pb-Zn-V province has been on-going since the possession of the territory by the German colonial authority in 1890. Production has been mostly from four mines which in order of importance are Tsumeb, Kombat, Berg Aukas and Abenab. A second mineral province on the Northern Platform located in the west is centred on Sesfontein where as yet only insignificant mineralization has been noted. Besides these localities, the Northern Platform is conspicuously devoid of notable mineralization.

The aim of this thesis has been to document the Berg Aukas deposit, an important end-member type of mineralization in the Otavi Mountain Land. The basic premise has been to show that the derivation and localization of the mineralization is a consequence of two broad controls which can be simply summarised as features of the basement and of the carbonate sequences.

The geodynamic evolution of the Damara Belt commenced with intra-continental rifting approximately 900 Ma ago. Rift grabens trending north-east were filled by the Nosib Group which comprises mostly clastic lithologies but also some volcanics. The earliest and largest rift is referred to as the Northern Rift. Separation of the Congo, Kalahari, and proto-South American cratons resulted in rifting and rapid downwarping so that an encroaching sea and an Otavi Group carbonate shelf developed along the northern margin of the Northern Rift. Significantly, the carbonates only covered the Northern Rift in the area of the Otavi Mountain Land where a basal dome, referred to as the Grootfontein Basement High, marked the basin edge. In the west, the carbonates covered the less important Sesfontein Rift, and it is only in these two areas where Nosib sequences underlie the carbonate platform.

Carbonate sedimentation was interrupted by a major period of crustal readjustment and the deposition of an extensive mixtite throughout the geosynclinal Swakop Trough and Northern Platform. This is referred to as the Chuos Formation and subdivides the Otavi Group into a lower Abenab and an upper Tsumeb Subgroup. Reversal of spreading lead to plate collision and subduction of the Kalahari craton beneath the Congo craton. It was accompanied by orogenesis which resulted in  $F_1$  folding of the Northern Platform into a series of north-easterly trending intermontane basins into which a  $F_1$  molasse sequence known as the Mulden Group was unconformably deposited. Following this major north-south deformation mild east-west compression initiated  $F_2$  folding and the formation of doubly plunging synclines.

The Berg Aukas Syncline represents a primary depositional basin which was subsequently folded. The original basin was formed by late Nosib rifting when spreading caused the Swakop geosynclinal Trough to form. Carbonates of the basal Berg Aukas Formation were deposited in a lagoonal setting typified by reef and fore-reef facies with peri-platform conditions. Rapid subsidence caused these sediments to be overlain by deep water carbonates of the Gauss Formation.

Two styles of mineralization known as the Tsumeb-type and Berg Aukas-type are stratigraphically, isotopically, and mineralogically distinct. The Tsumeb-type is a cupriferous variety of discordant bodies confined to the upper sequences beneath the Mulden unconformity. The Berg Aukas-type is a Zn-Pb variety confined to the basal unconformity. The Berg Aukas deposit comprises three ore bodies known as the Northern Ore Horizon, the Central Ore Body, and the Hanging Wall Ore Body. Sphalerite and galena constitute the hypogene ore. Willemite, smithsonite, cerussite, and descloizite are important supergene ores.

A review of genetic models concludes that a magmatic origin initially proposed for the Tsumeb deposit is entirely rejected and a basin dewatering model in line with Mississippi Valley-type deposits is proposed. The syntectonic nature of mineralization at Berg Aukas and elsewhere in the Otavi Mountain Land indicates that

syntectonic nature of mineralization at Berg Aukas and elsewhere in the Otavi Mountain Land indicates that orogenesis encouraged dewatering and leaching of metals from a broad mineralizing front along the margin of the Swakop Trough. These were transported by acidic saline brines which migrated along the clastic aquifers and structural conduits provided by the Northern Rift. Fluid inclusion studies indicate that the hydrothermal fluids at Berg Aukas were very saline (23% TDS) and were transported at temperatures ranging between 92<sup>o</sup> to 210<sup>o</sup> C. Hydrothermal fluids which mineralized Berg Aukas-type deposits migrated along the basal unconformity towards the basement high and were responsible for hydrothermally altering the basement granites and gabbros and the Nosib clastic rocks. Tsumeb-type deposits resulted by migration of fluids through the carbonate pile and along north-easterly trending basement geofractures. As a consequence of variation in transport, the Berg Aukas-type and Tsumeb-type fluids leached different sources and therefore derived mineralogically and isotopically separable characteristics.

The localization of the Berg Aukas ores was controlled by the carbonate stratigraphy and structure. Hydrothermal karsting and ore deposition took place on the contact between Massive Grey and Light Grey Dolostones which represents a permeability contrast. The movement of the hydrothermal fluids was controlled by north-south trending vertical fractures caused by F<sub>2</sub> folding which resulted in a periclinal structure. Hydrothermal karsting was accompanied by calcitic, dolomitic and silicic alteration. The heated acidic fluids initiated solution collapse and a variety of breccia types. Supergene processes resulted in oxidation and upgrading of the ore. Vanadium derived indirectly from gabbros in the basement complex were transported as calcium metavanadate complexes and deposited on contact with the oxidizing base metal sulphides.

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## 1. INTRODUCTION

The Berg Aukas Zn-Pb-V deposit is located in the mineral province known as the Otavi Mountain Land which is situated in the north east of South West Africa/Namibia (Figure 1.1). The province covers an approximate area of 10 000 km<sup>2</sup> and is roughly bounded by latitudes 19° 12'S, 19° 50'S and longitudes 17° 15'E, 18° 50'E. The deposit is located in the eastern Mountain Land at latitude 19° 34'12" and longitude 18° 15'36", approximately 20 km north east of Grootfontein, the second largest of three service towns in the province. The largest town is Tsumeb, north west of Grootfontein, and is the site of the largest mineral deposit. The third town, Otavi, is situated in the west. The district is served by a rail network 600 km from Windhoek, the country's capital located to the south, and the port of Walvis Bay located on the Atlantic coast. Railheads are established at the three main towns.

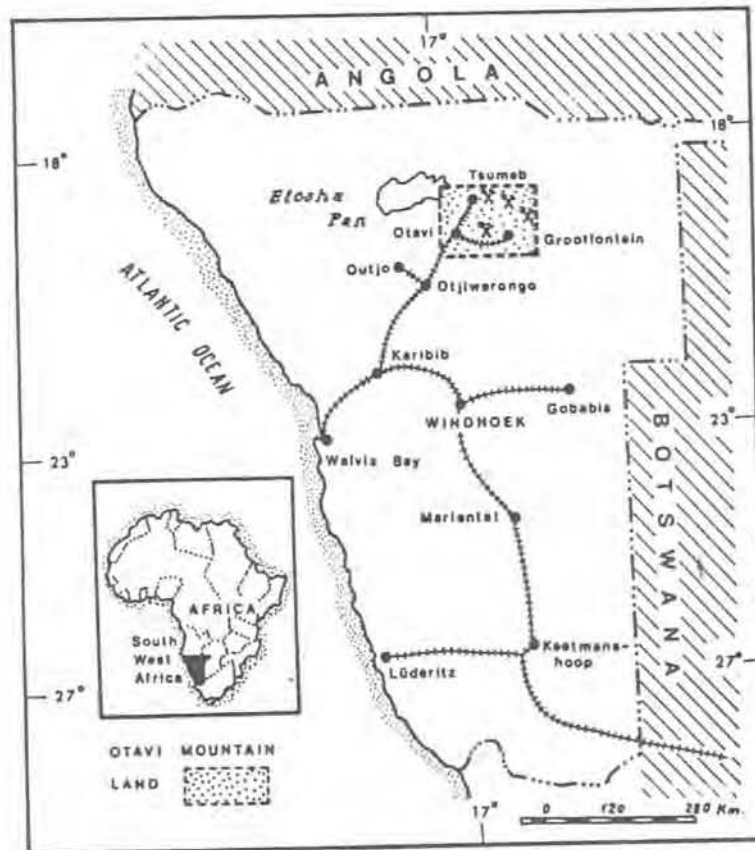


Figure 1.1 : Locality map showing the four mines in the Otavi Mountain Land.

### 1.1 Thesis Objectives

The objective of this study is to document the regional and detailed geology of the Berg Aukas deposit in

the context of its setting within the Otavi Mountain Land which forms part of the Northern Platform of the Pan African Damaran orogen. The basic premise of the study is to show that the ore bodies in the mineral province are a consequence of geological factors which can broadly be separated into two categories. These are, firstly, features of the basement, and secondly, structural and sedimentological characteristics of the carbonates. The study indicates that the Berg Aukas deposit illustrates these controls clearly.

The study is based on a period of 18 months geological exploration conducted by the author at Berg Aukas and throughout the Otavi Mountain Land on behalf of Gold Fields Namibia Limited. The foundation for the study, which has involved mapping and other forms of data collection, has been the collation of invaluable information completed by former South West Africa Company (SWACO) geologists prior to the cessation of mining and exploration activities and the closure of the company.

## 1.2 Discovery, History, Production and Reserves

The history of the Otavi Mountain Land is closely related to the discovery and exploitation of the base metals which exist there. In 1842, Sir Francis Galton, accompanied by a scientist named Anderson, reported the presence of copper smelting by the local population at Tsumeb, the "hill of the frog". In 1890, Germany took possession of the territory and granted a mining concession to the South West Africa Company (SWACO) which was floated in London in 1892. Under this concession, the company was awarded the sole mineral rights for almost the entire northern half of the country. In the same year, an expedition was dispatched to investigate the copper occurrences at Tsumeb, Gross Otavi and Asis in the Otavi Valley. In 1900, a second company with British-German interests known as the Otavi Minen Und Eisenbahn Gesellschaft (OMEG)<sub>2</sub> was formed. An agreement was established whereby SWACO ceded the mineral rights over a 1200 km narrow north-south corridor which included the Tsumeb and Asis occurrences to OMEG in return for the construction of a narrow gauge railway line from Swakopmund to Tsumeb. The work commenced in 1903 and was completed in 1906. Two years later SWACO constructed a branch line from Otavi to Grootfontein.

SWACO's unique mineral rights were lost in 1918 at the end of the First World War but were later renewed over the Otavi Mountain Land by the Union Government. OMEG was confiscated by the Custodian of Enemy Property at the end of the Second World War, was sold and the Tsumeb Corporation Limited (TCL) was formed.

SWACO's main interests were always the vanadium deposits which were found to occur. The first vanadium was reported by Maucher (1908) from Tsumeb where mottramite was found. In 1921, the Abenab vanadiferous breccia pipe was discovered and was exploited until 1947, during which time it was reported to be the largest known occurrence of vanadate ore in the world. Abenab West Mine, which produced oxidized sulphides as well as descloizite and vanadinite, was exploited from 1947 to 1958.

In about 1913 (Schreuder, 1964), a SWACO prospector by the name of W. Joubert, reported the presence of zinc on top of a hill now known as the Berg Aukas Mine Kopje. In the early 1920's, geological investigations revealed limited alluvial descloizite deposits at the base of the hill. In 1940, prospecting work was continued and a narrow interval of fracture filled descloizite from what is now known as the Central Ore Body was found by J.W. Sinclair. The mine was worked on a small scale in 1955 when an extensive diamond drilling programme was started. This successfully led to the discovery of the Northern Ore Horizon and Central Ore Body. Underground development and the establishment of a mine infrastructure commenced in 1958. In 1968, a deep shaft known as N<sup>o</sup> 2 shaft, was sunk and a kiln was constructed to treat the oxidized ore, complementing the gravitation and flotation plant which already existed. Mining operations ceased in 1978 when the price of zinc fell to \$550 per ton causing the operation to run at a loss.

Berg Aukas was a high grade, low tonnage mine with a very small scale of operations, milling only 11 000 tons of ore monthly. It had an average grade of 22% comprising 17% Zn, 5% Pb and 0,6% V<sub>2</sub>O<sub>5</sub> (Table 1.1). It was not uncommon to receive borehole intersections with a grade of up to 70% combined metals over a drilling distance of up to 10 metres. Details of tonnages mined during the early years are sketchy, but it is estimated that total production amounted to 1.6 Mt. The ore reserve at the time of mine closure amounts to 1.651 Mt (Table 1.2).

Table 1.1: Tons and Grade of Ore Hoisted and Milled, Berg Aukas Mine. (Metric tons, grade %)

Year		Tonnage	V <sub>2</sub> O <sub>5</sub>	Pb	Zn
1967	Hoisted	148 660	1,49	5,8	17,1
	Milled	112 990	1,92	7,0	20,3
1968	Hoisted	169 653	0,94	4,2	15,7
	Milled	124 920	1,25	3,2	19,8
1969	Hoisted	178 912	0,72	4,1	17,4
	Milled	127 460	0,97	4,9	22,9
1970	Hoisted	183 300	0,62	3,6	18,5
	Milled	135 900	0,81	4,5	24,4
1971	Hoisted	196 200	0,98	2,5	13,5
	Milled	135 700	1,34	4,7	18,5
1972	Hoisted	169 700	0,83	3,4	16,7
	Milled	130 600	1,04	4,1	21,3
1973	Hoisted	171 200	0,95	3,9	18,2
	Milled	135 600	1,16	4,7	22,2
1974	Hoisted	172 300	1,14	4,7	20,0
	Milled	135 000	1,42	5,7	25,0
1975	Hoisted	209 600	0,70	4,2	13,8
	Milled	123 700	1,10	6,3	21,7

Average grade between 1967 and 1975:

Total hoisted 1 599 528 @ average grade 0,93 4,04 16,77  
 Total milled 1 161 870 @ average grade 1,22 5,23 21,79

Table 1.2: Annual Ore Reserves, Berg Aukas Mine.  
(metric tons, grade %)

Year	Tons	V <sub>2</sub> O <sub>5</sub>	Pb	Zn
1958	825 539	1,65	5,94	36,4
1959	852 755	--- unknown grade ---		
1960	852 755	--- unknown grade ---		
1961	816 467	0,9	5,0	37,0
1962	798 324	1,0	5,0	37,0
1963	907 186	0,7	4,0	36,0
1964	816 467	1,0	5,0	36,0
1965	771 108	0,8	5,0	34,0
1966	1 387 994	0,9	5,0	25,0
1967	1 886 947	0,7	5,0	24,0
1968	1 805 300	0,7	5,0	24,0
1969	1 632 935	0,7	5,0	24,0
1970	1 600 000	0,7	5,0	24,0
1971	1 685 000	0,6	5,0	20,0
1972	1 620 000	0,5	5,0	19,0
1973	1 800 000	0,5	5,0	17,0
1974	1 800 000	0,5	4,0	17,0
1975	1 830 000	0,5	4,0	17,0
1976	-----	unknown	-----	
<u>1977</u>	<u>1 651 000</u>	<u>0,6</u>	<u>5,0</u>	<u>17,0</u>

### 1.3 Previous Work

Relatively few accounts of the regional geology of the Northern Platform have been completed. Much of this work took place between the early 1950's and the late 1960's, and was confined to either the Kaoko Zone or the Otavi Mountain Land. Since then, only one regional synthesis, that of Hedberg (1979), has been completed. Some of the more significant works were contributions from Guj (1970) who completed a study in the southern Kaoko Zone; Frets (1969) who studied the transition between the Northern Platform and Northern Zone in the Khorixas-Outjo area; Sohngé (1957) who documented the regional geology of the Otavi Mountain Land; and Smit (1958) who examined the transitional zone south-east of Otavi.

Probably the most important contribution on the geology of the Otavi Mountain Land was that of Sohngé (*op. cit.*) who collated the results of regional mapping conducted by geologists of the Tsumeb Corporation Limited and SWACO, but this epic account was unfortunately never published since it was written as a company report. Most studies which followed (Grobler, 1961; SACS, 1980; Van der Westhuizen, 1984; this study) have used Sohngé's work as a basis.

Studies of the mineralization of the Otavi Mountain Land have been sporadically published in the literature, with many contributions originating from unpublished company reports. Sohngé (1964) described the Tsumeb deposit, and Verwoerd (1957) published an excellent paper on a study of the Abenab West Mine. Emslie (1979, 1980) completed a regional study of the numerous ore deposits and prospects. The most up to date papers are the detailed accounts on the Tsumeb deposit (Lombaard *et al.*, 1986) and Kombat ore bodies (Innes and Chaplin, 1986) which appear in the recently published Mineral Deposits Volumes of Southern Africa.

No account has ever been published on the geology of the Berg Aukas deposit other than a mention in a brief metallurgical account of the recovery plant (World Mining, October, 1965, 28-32). This was in spite of several excellent company reports which described the geology and the ore mineralogy, and a comprehensive project by Gavine (1979). The better known accounts were those by Weilers (1959), Markham (1958a, 1958b), and Schreuder (1969).

## 2. THE GEOLOGY AND GEODYNAMIC EVOLUTION OF THE DAMARA PROVINCE

The Damara Province is an orogenic belt which forms part of the upper Proterozoic Pan African system (Figure 2.1). The Damara Sequence was deposited on a foundation of granitoid basement and infolded supracrustal formations of pre-Irumide (1.5 to pre 2.0 Ga), and Irumide (0.9 to 1.4 Ga) ages. It is made up of a 400 km wide north-east trending intracontinental arm and two 150 km wide coastal arms meeting at a triple juncture centred off the coastal town of Swakopmund. It evolved as an aulacogen by thinning of sialic crust causing the separation of the Kalahari, Congo and proto-South American cratons, and the deposition of a geosynclinal sequence 900 to 650 Ma ago. The northern coastal arm developed into what is known as the Kaoko Belt and the southern arm into the Gariep Belt which overlies the Richtersveld Subprovince of the Namaqua Metamorphic Complex.

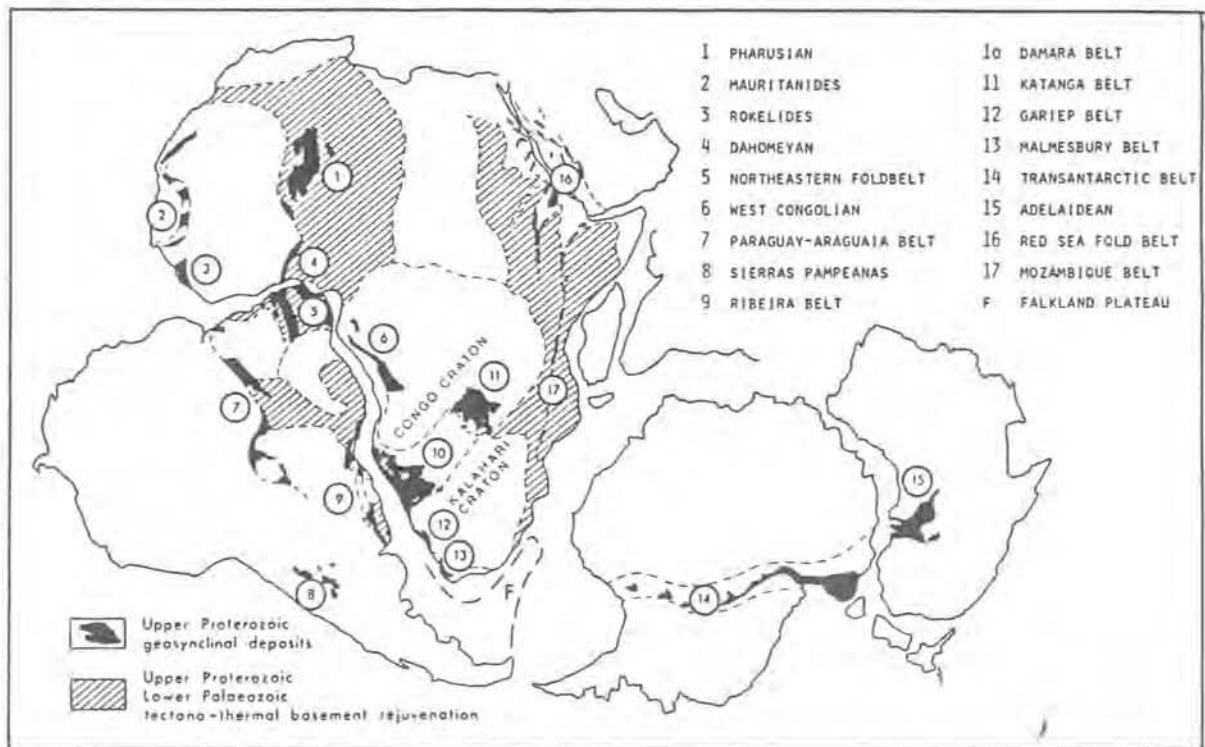


Figure 2.1 : The distribution of the Pan African belts on a reconstruction of the Gondwana continent (from Porada, 1979).

The geology, structure, metamorphism, geochemistry, isotope systematics, geodynamic evolution, and metallogenic aspects of the Damara Province have been subjected to intensive research since 1974. Much of this work was coordinated under the auspices of the International Geodynamics Project, but also includes the results of a number of other independent studies. Some of the more significant contributions include those by Martin and Porada (1977), Porada (1979, 1983, 1985), Miller (1979, 1983), Mason (1981), Martin (1965, 1978, 1983a, 1983b), Hartnady (1978), Miller and Hoffman (1981), and Kroner (1981, 1982). The reader is referred to these authors for more specific subject references.

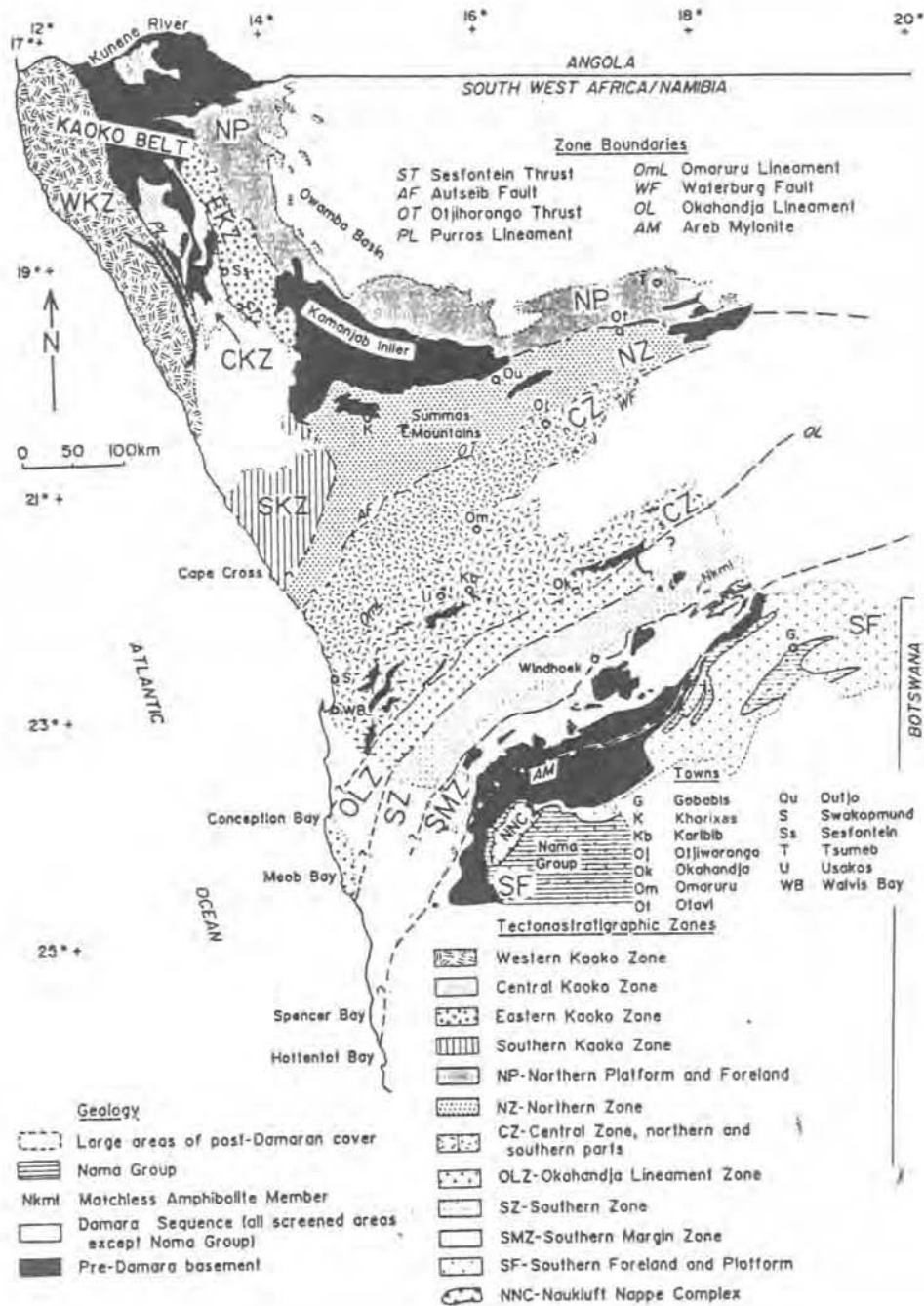


Figure 2.1.1 : Tectonostratigraphic zones of the Damara orogen (from Miller, 1983a).

## 2.1 Tectonostratigraphic Zones of the Damara Orogen

The intracontinental arm of the Damara is divided into several zones (Figure 2.1.1) which are distinguished on the basis of stratigraphy, structure, grade of metamorphism and even aeromagnetic expression (Miller and Hoffman, 1981; Miller, 1983a). From north to south these are referred to as the Northern Platform (NP), Northern Zone (NZ), Central Zone (CZ), Okahandja Lineament Zone (OLZ),

Southern Zone (SZ), and Southern Margin Zone (SMZ). Boundaries between zones are faults (NZ, CZ), major lineaments (CZ-OLZ) or approximate stratigraphic boundaries (SZ-SMZ). The Kaoko Belt is subdivided into the Western, Central, and Eastern Kaoko Zones (WKZ, CKZ, and EKZ).

NORTH				CENTRE				SOUTH				
GROUP	SUBGROUP	FORMATION	LITHOLOGY (WAS THICKNESS)	GROUP	SUBGROUP	FORMATION	LITHOLOGY (WAS THICKNESS)	GROUP	SUBGROUP	FORMATION	LITHOLOGY (WAS THICKNESS)	
MULDEN		OWAKO	Shale, marl, siltstone, sandstone (1000 m)									
		KOMBAT	Shale dolomite lenses									
		ISCHUO	Quartzite, conglomerate, arkose, argillite (2000 m)									
UNCONFORMITY IN NW												
OTAVI	ISUMBE	HUTTENBERG	Dolomite with chert, shale, limestone, stromatolites, oolites (900 m)	KHOMAS		KUSSE	Quartz-biotite schist, biotite-garnet cordierite schist, amphibole schist, quartzite, marble, calcilicite rock (2000 m)	SHOMAS		KUSSE	Biotite schist, biotite-quartzite, graphitic schist, calcilicite rock, amphibole-biotite lamichness member (10000 m)	
		ELAUO	Dolomite with chert, stromatolites (1100 m)			KARIBB	Marble, biotite schist, quartz schist, calcilicite rock (700 m)			KUS	Quartzite, schist, marble, amphibolite, tabirite (1800 m)	
		KARIBB	Dolomite, limestone, slump breccia (250 m)			CHUO	Mylonite, marble, quartzite (700 m)			CHUO	Pebbles schist, mylonite, quartzite schist, isopane, amphibolite, calcilicite rock (1650 m)	
		CHUO	Mylonite, dolomite, limestone, siltstone, tabirite, oolite chert (700 m)									
	LOCAL DISCORDANCE											
	KARIBB	KARIBB	KUSSE	Dolomite, limestone, marl, shale (450 m), stromatolites	UGAR	FOSSING		Marble, quartzite, conglomerate, biotite schist, biotite-hornblende schist, calcilicite rock (700 m)	SHOMAS	SHOMAS	BLAUFRANK	Graphitic schist, quartzite, quartz mica schist, conglomerate, tabirite (700 m)
			KAUS	Dolomite, limestone, oolite chert, sandstone (750 m)								
			BLAUFRANK	Dolomite, limestone, stromatolites, arkose, greywacke (525 m)								
	LOCAL DISCORDANCE											
	NOSIB		KARIBB	Mylonite, full tabirite	NOSIB		KARIBB	Calcilicite rock, amphibole-cordierite gneiss and quartzite (1100 m)	NOSIB		DURU	Phyllite, quartzite, conglomerate, limestone (5000 m)
BLAUFRANK			Rhyolite, tuff, agglomerate, andesite, epiorite, basaltite (6000 m)	ELAUO			Quartzite arkose, conglomerate schist, mylonite (3500 m)	KARIBB			Quartzite, arkose, conglomerate (5700 m)	
ELAUO			Quartzite, arkose, conglomerate									
KARIBB			Quartzite, arkose, conglomerate									
LOCAL DISCORDANCE												

Table 2.2.1 : Regional lithostratigraphy of the Damara orogen (from Miller, 1983a).

The basal sequence of the Damara (Table 2.1.1) is the Nosib Group, a predominantly clastic sequence with minor volcanic rocks and evaporites which were deposited in five north-east trending grabens (Figure 2.1.2) (Porada, 1983, 1985; Kroner, 1981, 1982). These sub-parallel grabens are up to 200 km long and 50-70 km wide, and are separated by palaeo-ridges which are postulated to be fault bounded (Porada, 1983). With the possible exception of the Summas fault in the Northern Rift (Miller, 1980) the faulting associated with the rift margins has not been observed due to later sedimentary overlapping, and the Kaokoveld and Khomas Rifts are hypothetical (Porada, 1983, 1985), totally lacking exposure. It is postulated that graben development commenced with the Northern Rift approximately 900-800 Ma ago. Porada (1985) argues that rifting was initiated by crustal stretching above a passive mantle as opposed to a rising mantle plume as was suggested in an earlier hypothesis (Porada, 1983). The evidence for the location of the rifts has been based on sedimentary facies analysis (Porada and Wittig, 1983a, 1983b) and the location of volcanic sequences which mostly occur in the Northern Rift.

The rifts were predominantly filled by terrestrial sediments composed of fluvial deposits. Local

lacustrine or playa-lake sediments which include evaporite sequences have been recognized in the Duruchaus Formation in the Southern Rift (Behr *et al.*, 1983). Sedimentological studies (Porada and Wittig, 1983a, 1983b) indicate a probable eastward transgression and westward clastic sediment transport expressing a general slope towards the west.

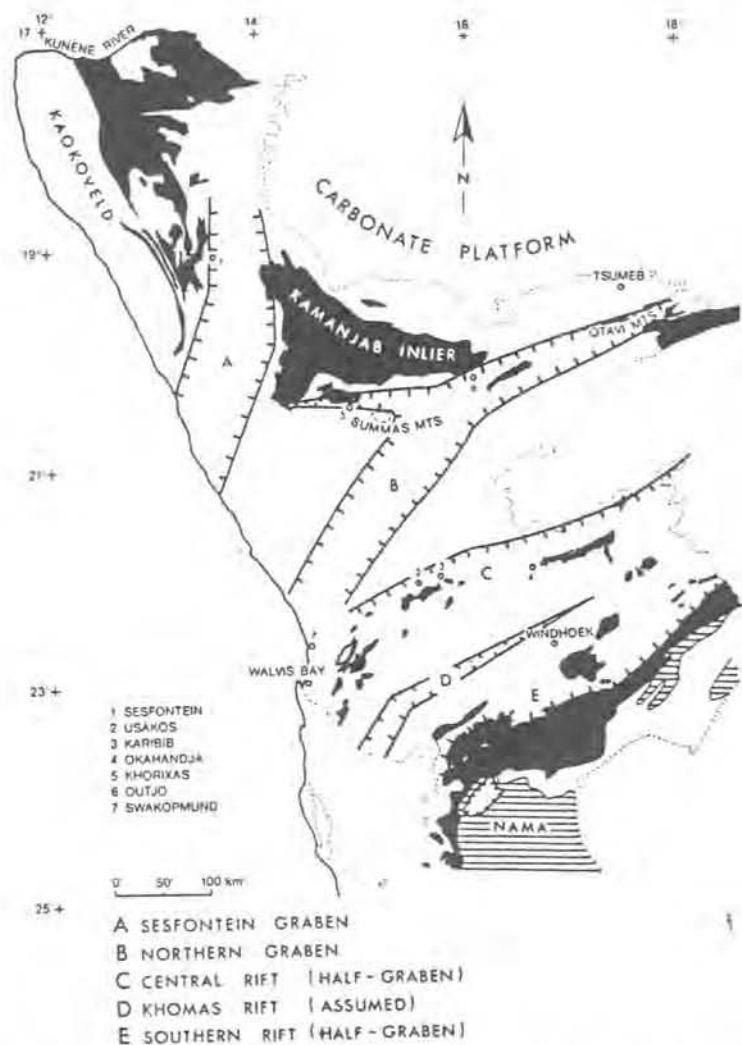


Figure 2.1.2 : Supposed rift systems of the Damara orogen, based on facies analysis. No faults are exposed. (After Porada, 1983.)

Volcanic sequences support the existence of these Nosib rift systems. These are best developed in the Northern Rift where they have been mapped in the Khorixas area (Frets, 1969; Miller, 1974) and in the Otavi district (Smit, 1962). Miller (1983a) and Kroner (1982) indicate that these volcanic rocks are bimodal and are related to continental fault margins. The Austerlitz and Summas Ignimbrite Members in the Khorixas area have respectively been extruded along the Bethanis and Summas faults. They comprise a series of high-soda rhyolites, porphyries, felsites, minor basalts and epidotes. South of the Otavi Mountain Land the Askevold volcanics, comprising a sequence of epidotes with an andesitic composition, were extruded along a supposed rift fault marking the transition from the Northern Zone to

the Northern Platform. The existence of this hinge or fault zone is indicated by large-scale facies changes in the stratigraphic sequence and by post-Otavi east-west faulting (Miller, 1983a).

In the Central Zone, thin high-potassic peralkaline rhyolites are interbedded with Etusis quartzites. They are generally insignificant.

The upper group of the Damara Sequence is divided into two facies. In the southern and central zones, the Swakop facies consists of turbidites, carbonates and siliciclastics, and amphibolitised volcanics with MORB affinity and alkaline basalts typical of continental rifting (Miller, 1983d).

A facies equivalent of the Swakop Group is the Otavi Group, a sedimentary sequence comprising thick carbonates and insignificant interclastic argillaceous layers. Sedimentation occurred on an undulating peneplaned stable platform along the northern margins of the deep Swakop Trough.

Following the terrestrial sedimentation in the Nosib grabens, rapid downwarping along the early graben structures resulted in an encroaching sea. The Swakop Group is largely a turbiditic sequence deposited in the Pan African proto-Atlantic ocean (Miller, 1983a). Marine transgression proceeded from the west to the east, as deduced from overlapping and eastward thinning diachronous sediments. Carbonate sequences at the base of the Swakop Group developed eastwards, matching the rate of transgression. At the same time, siliciclastic sediments were transported westwards, as evidenced by palaeocurrent trends established from the Okonguarri Formation in the Northern Rift (Porada, 1983).

The lower Swakop Group is referred to as the Ugab Subgroup in the Central Zone and as the Kudis Subgroup in the south. It is broadly correlated with the Abenab Subgroup, the lowermost portion of the Otavi Group. The Abenab Subgroup developed on the stable platform along the margins of the early Nosib Northern Rift (Plate 1), and is only known to directly overlie the Northern Rift in the Otavi Mountain Land. Thus, the plan appearance of the Northern Platform is a reflection of the primary basinal configuration of the Damara aulacogen.

The lower and upper parts of the Swakop and Otavi Groups are separated by the Chuos Formation, probably the most important regional marker horizon throughout the Damara Province. The Chuos Formation is an unsorted diamictic assemblage marking a period of widespread crustal disturbance and local erosion of the lower lithologies. The origin remains contentious with hypotheses varying between glaciomarine and deepwater debris flow (Miller, 1983a; Martin, 1983a).

Deposition of the Chuos Formation heralded a period of rapid downwarping resulting in an extensive sea stretching between the Northern Platform and the Southern Foreland. In the Swakop Trough, an extensive carbonate platform, the Karibib Formation, was conformably deposited on the Chuos Formation. On the Northern Otavi Platform, the carbonates of the Tsumeb Subgroup were deposited. Stability of this

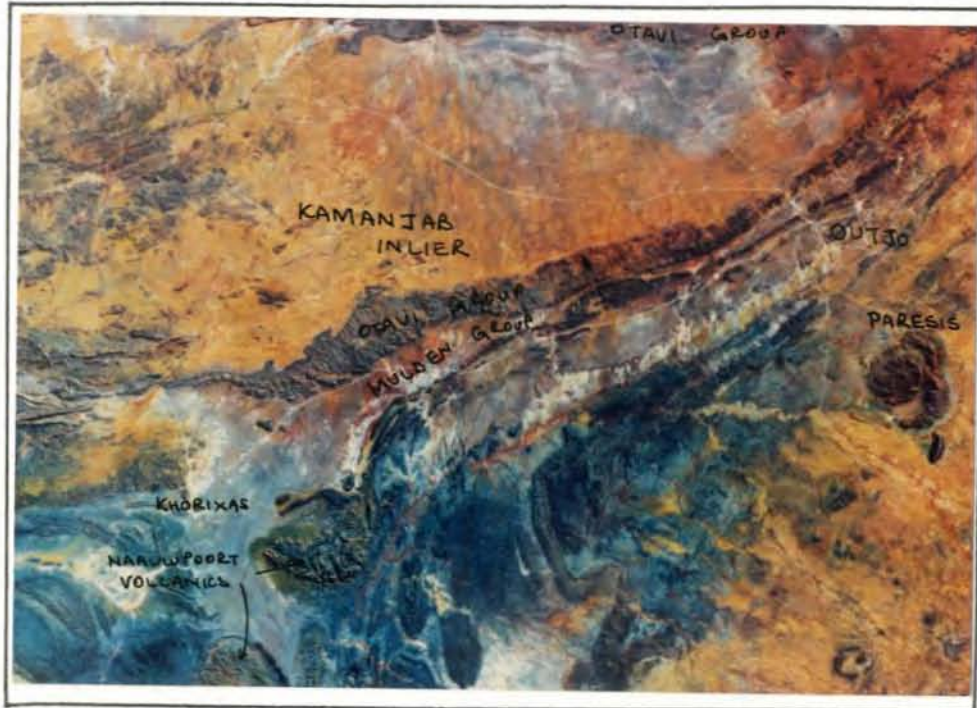


Plate 1 : LANDSAT image of the Northern Platform in the vicinity of Khorixas, Kamanjab and Outjo.

platform continued until Damaran orogenesis commenced. In the Swakop Trough, however, subsidence continued and the carbonate sequences were overlain by the Kuiseb Formation, a time equivalent of the of the upper Otavi Group carbonates. The Kuiseb Formation comprises an almost 10 km thick sequence of graded metapelites and metagreywackes. The source for such an enormous volume of sediment remains conjectural, but the westerly sloping basins (Porada, 1983) indicate an eastern source which could even be the western limits of the Katangan Pan African Belt.

The commencement of orogenesis resulted in deep east-west trending palaeo-valleys on the Northern Platform which were syntectonically filled with intramontane molasse of the Mulden Group. The sediments were localized in two basins of varying type.

- i. A shallow crustal downwarp referred to as the Owamboland basin occurs north of the Kamanjab and Grootfontein basement inliers.
- ii. Deep intermontane basins occur south of the basement inliers.

In the eastern Northern Platform, the Mulden sediments have a disconformable relationship with the underlying carbonates. This disconformity is more strongly developed in the west where the sediments overlap the carbonates to lie on both basement lithologies and Nosib Group rocks.

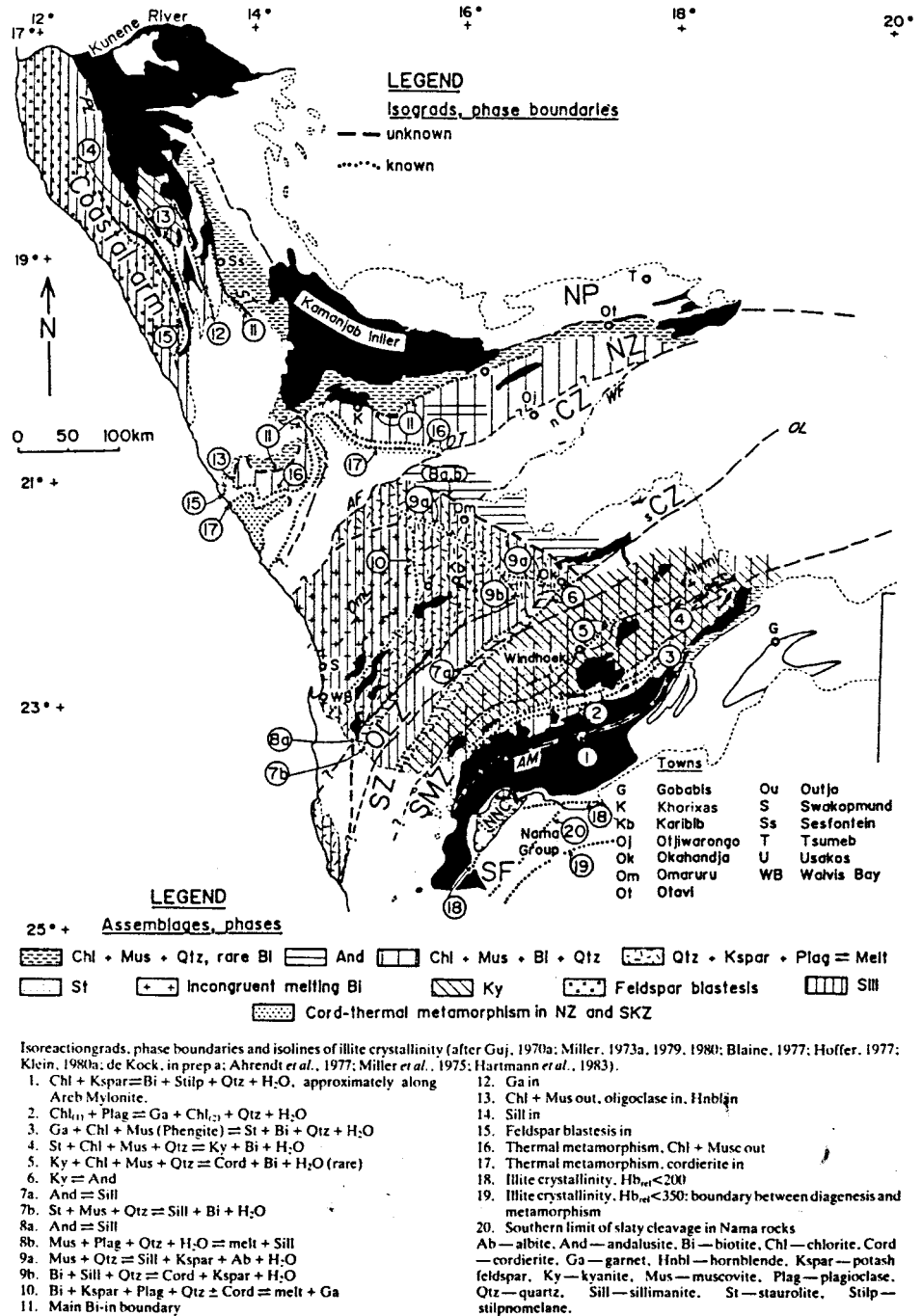


Figure 2.2.1 : Reaction isograds for the Damara orogen (from Miller, 1983a).

## 2.2 Regional Structure and Metamorphism of the Damara Province

The tectonostratigraphic zones of the orogen are characterized by contrasting structural style and intensity of deformation (Miller, 1983a). The Okahandja Lineament Zone is a 500 to 2000m wide monoclinial structure defined by isoclinal folding with steeply inclined axial planar cleavage. To the north of the

lineament, the Central Zone is typified by a dome-and-basin fold pattern with a general north-easterly trend. South of the lineament, the fold pattern is linear. Deformation increased in intensity southwards and the rocks are typified by upright south-east vergent folds which develop into isoclinal structures culminating in overthrusting of the basement along the Southern Margin. Up to five periods of deformation have been recognized (Miller, 1983a; Kasch, 1981). In the Central Zone high temperature - low pressure conditions prevail, while the Southern Zone was metamorphosed at lower temperatures and higher pressures (Martin, 1983a; Jacob, 1974; Kasch, 1978, 1980, 1981, 1983b; Sawyer, 1981).

The Northern Zone and Northern Platform have relatively simple structures which indicate a progressive decrease in intensity towards the north. The Kaoko Belt has complex eastward verging folds, south-easterly directed thrusting, and a decrease in intensity of deformation towards the east (Miller, 1983a).

Reaction isograds established from regional metamorphic studies (Figure 2.2.1) (Jacob, 1974; Kasch, 1981, 1983b; Hartmann *et al.*, 1983) indicate an increase in metamorphic grade towards the triple juncture where anatexis conditions are achieved and uraniumiferous alaskitic granites occur. The question of the metamorphic history remains contentious, and whether a single prograde event or more occurred has not been fully resolved. Hoffer (1983), Martin (1983a), Jacob (1974), and Hartmann *et al.*, (1983) favoured a single diachronous prograde event with the peak of metamorphism post-dating the main deformation events ( $D_1, D_2, D_3$ ). In the Okavango Lineament Zone, Central Zone, and Southern Zone, the peak of metamorphism occurred about 530 Ma ago (Martin, 1983a). A similar age has been established for the Southern Margin Zone, and on the Northern Platform (Kroner and Clauer, 1979). Rb-Sr and K-Ar mineral ages (Kroner, 1982) indicate that metamorphic relaxation was slow, ending at about 440 Ma ago.

Kasch (1983b) argues on the basis of microtextural analysis of petrographic and garnet zonation that two periods of metamorphism occurred. The metamorphic peaks of  $590^{\circ}\text{C}$  (coinciding with  $D_2$ ) and  $570^{\circ}\text{C}$  (post-tectonic) were separated by a late-tectonic  $485^{\circ}\text{C}$  thermal trough (Figure 2.2.2). The  $M_2$  event probably coincides with the approximate 530 Ma event described by the prograde protagonists. Kroner and Clauer (1979) and Kroner (1982) suggest that the 450 Ma thermal event is a third phase of regional metamorphism, but this may be a consequence of uplift (Hawkesworth *et al.*, 1986).

The metamorphic effects on the Northern Platform are restricted to the chlorite + muscovite + quartz assemblage which is best seen in the Nosib schists (for example at Berg Aukas, Section 6.2) and Mulden sequences. The transition from the Northern Platform to the Northern Zone is marked by the biotite reaction isograd (Figure 2.2.1).

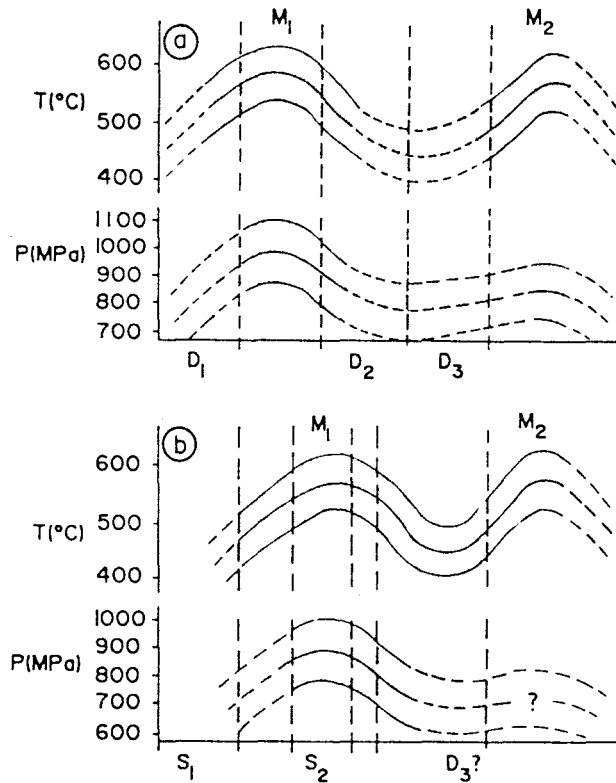


Figure 2.2.2 : Metamorphic and deformation history for the Damara orogen. (a) Omitara area, (b) northern edge of Hakos Mountains (from Kasch, 1983b).

### 2.3 Damaran Magmatism

Magmatism has played an important role in the geological history of the Damara Province (Pirajno, 1987). Several periods of magmatism reflecting the changing tectonic conditions can be recognized. The early rifting events during Nosib times were accompanied by the bimodal volcanism which occurred especially in the Northern Rift.

In the Southern Zone, the Matchless Amphibolite Belt is located within the Kuiseb pelitic schists and is a 350 km linear feature trending north-east from Gorob and Hope in the west to Steinhausen in the east. It has a MORB composition (Miller, 1983d) and has been interpreted as a complex suture zone resulting from continental collision between two plates. In the Central Zone, amphibolitized basalts are stratigraphically conformable with the underlying Karibib marbles. The basalts have an alkaline chemistry (Miller, 1983d) indicating extrusion from a continental rift setting. They are characterized by pillow structures and associated scoriae.

In the Southern Margin Zone, ultramafic serpentinite bodies with a composition similar to Alpine-type mantle peridotite (Barnes and Sawyer, 1980) are regarded as tectonically emplaced ophiolite bodies.

The Swakop Group was subjected to three periods of granitic emplacement (Miller, 1983a; Pirajno, 1987). These are pre-orogenic alkaline granites emplaced at 650 Ma, syn-orogenic 'S'- and 'T'-type granites emplaced at 550 Ma, and post-orogenic 'S'-type granites referred to as the Donkerhuk Suite which were emplaced 450 Ma ago along the Okahandja Lineament Zone.  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopic evidence indicates that the earlier granites were probably mantle derived, whereas the later granites were derived by partial melting of sediments (Miller, 1983a).

Table 2.4.1 : Geochronological evolution of the Damara orogen (from Kroner, 1982).

~455 - 440 Ma	Uplift and cooling, closure of Rb-Sr isotopic systems
458 ± 8 Ma	Emplacement of uraniferous Rössing alaskitic granite
~510 - 455 Ma	Forth phase of deformation (F <sub>1</sub> ) and strong thermal event, leading to basement mobilization and formation of dome structures, emplacement of late granite, alaskite and pegmatite, partial resetting of Rb-Sr isotopic systems
~520 - 500 Ma	Uplift in central belt, activation of Okahandja Lineament and emplacement of Donkerhoek Granite. Nappe tectonics in southern part of the belt and in the foreland
~550 - 540 Ma	Intrusion of post-F <sub>1</sub> granites, peak of metamorphism
~580 - 550 Ma	Third phase of deformation (F <sub>2</sub> ), intrusion of syntectonic Salem-type granite, folding of Molasse in marginal areas
~640 - 560 Ma	Uplift in central belt, deposition of Molasse, first in the south (Nama Group), then in the north (Mulden Group)
~650 - 620 Ma	Second phase of deformation (F <sub>2</sub> ) and strong metamorphism, generation of regional foliation, intrusion of syntectonic granitoids in central part of the belt, partial resetting of Rb-Sr isotopic systems
750 ± 35 Ma	Emplacement of pre-F <sub>2</sub> diorite in Palmental igneous complex
766 ± 76 Ma	First phase of deformation (F <sub>1</sub> ) of unknown regional significance Intrusion of post-Nosib felsic Abbabis dikes in central part of the belt
~830 - 760 Ma	"Geosynclinal phase": Deposition of Swakop and Otavi Groups, emplacement of Matchless amphibolite belt at about 775 ± 33 Ma
840 ± 13 Ma	Emplacement of pre-tectonic Oas syenite, acid volcanism of upper Nosib Naauwpoort Formation. Probably also mafic volcanism along miogeosynclinal/eugeosynclinal transition zone in the northeast (epidosites of Askeveld Formation)
~1050- 900 Ma	"Early rifting phase": Formation of elongate graben zones, deposition of clastic sediments of lower Nosib Group, minor bimodal volcanism

## 2.4 Geochronological Aspects

Geochronological information for the Damaran igneous and metamorphic rocks have been documented by Miller (1983a), Kroner (1982), and Hawkesworth and Marlow (1983). The chronological evolution spans approximately 400 Ma and is summarized in Table 2.4.1. The earliest rifting is generally thought (Miller, 1983a) to have occurred between 840 Ma and 730 Ma, although Kroner (*op. cit.*) suggests that it may have commenced as early as 1000 Ma ago. A satisfactory age for the Matchless Belt has not been determined, but is correlated with post-rifting spreading. Granite emplacement lasted from 650 to 460 Ma, a 190 Ma period. It is perhaps significant that the syn-orogenic 550 Ma period of granite emplacement corresponds roughly with the same time as ore formation in the Otavi Mountain Land.

## 2.5 Geodynamic Models

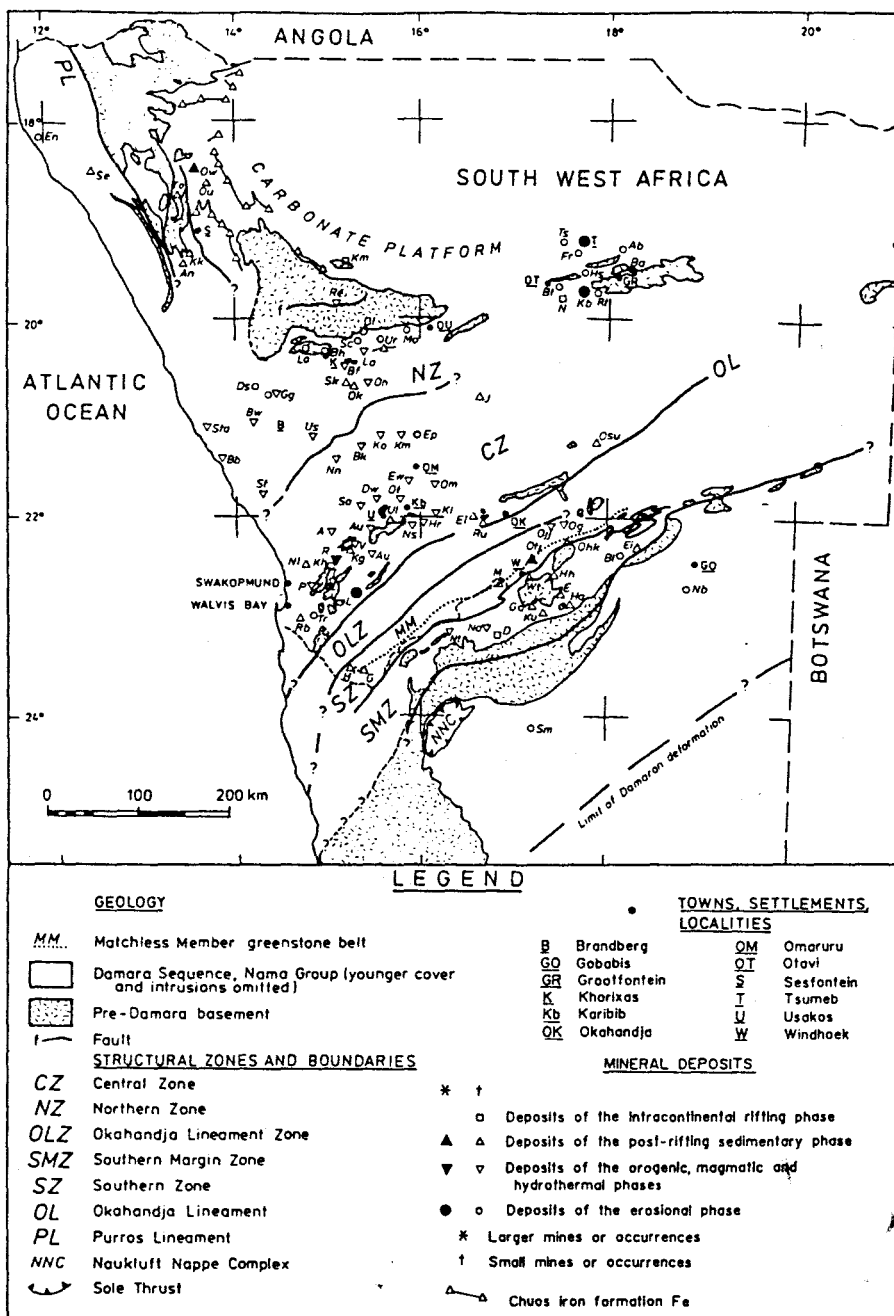
Geodynamic models for the evolution of the intracratonic Damara Belt assume subduction processes of some kind which followed after an initial rifting period. Models vary between those which demand intracratonic processes (Martin and Porada, 1977; Kroner, 1981) and those which invoke some form of ensimatic subduction (Barnes and Sawyer, 1980; Hartnady, 1978; Kasch, 1981, 1983a; Miller, 1983a, 1983b). The earliest models of Martin and Porada (*op. cit.*) were based on aulacogen ensialic processes which suggested that the belt developed as five grabens as a result of gravitational instability between a dense subcontinental lithosphere and the underlying less dense asthenosphere. The Kroner model (1981, 1982), referred to by Martin (1983b) as the "delamination" model, was based on the assumption that the ensialic basin formed by crustal stretching over a mantle plume which was then closed by a process of delamination and followed by continental subduction, crustal underthrusting and interstacking.

A conventional plate tectonic model was initially not favoured because, it was argued, it could not readily explain certain features (Martin, 1983b) such as the paucity of volcanic rocks which would be expected at destructive plate margins, the absence of calc-alkaline volcanics and their tonalitic equivalents, the lack of ophiolites, and the presence of pre-Damara inliers such as the Abbabis Complex in the Central Zone.

Subduction models range between those advocating a limited Wilson-cycle (Kasch, 1983a; Miller, 1983a; 1983b) and those advocating a full Wilson-cycle involving as much as 6600 km of oceanic crust (Hartnady, 1978; Barnes and Sawyer, 1980). These models are based on intracontinental rifting, spreading, reversal of spreading, and plate collision. Block faulting, evaporites, and wedge-shaped clastic deposits are accepted as evidence for intracontinental rifting at the onset of the Pan African Damara cycle. Spreading followed an aulacogen stage and resulted in the development of a narrow Red Sea-like ocean that was flanked by deep water fan deposits and contained basic volcanic rocks of the Matchless Amphibolite Belt with a MORB affinity. Numerous talc serpentinite bodies occurring within the Khomas Trough are regarded as tectonically emplaced ophiolite bodies (Barnes and Sawyer, 1980).

Reversal of spreading led to plate collision, subduction of the Kalahari craton below the Congo craton, and the formation of paired metamorphic belts. The paired belts correspond with the high temperature, medium pressure metamorphic conditions of the Southern Zone.

Continental collision led to overriding of the Kalahari plate by thrust slices, the most famous of which is the Naukluft Nappe Complex. It comprises eight lithostratigraphic units and five major nappes (Hartnady, 1978) which have been moved by as much as 48 km from the north (Miller, 1983c).



A Arandis Sn	Hr Helicon, Rubicon Li, Be	Om Omapyu Sn
Ab Ahenab V, Pb, Zn	Hs Harasib Pb, Zn, V	On Ondundo Au
An Andib, itabirite	I Ida U	Osu Otjosundu Mn
Au Aukas Au	J Joubir Cu, Pb, Zn	Ot Onguati Cu
Ba Berg Aukas V, Pb, Zn	Kb Kombat Cu, Pb	Otj Otjihase, Ongame, Ongombo Cu, pyrite
Bb Bock's Bay W	Kg Kainagchas Cu	Ou Omahu Cu
Bf Braunfels Pb	Kh Khan Cu	Ow Owihende, Ongaba Fe
Bh Buschhöhe Cu, Cr	Kk Khankhah, itabirite	P Palmtenhorst U
Bk Baukuab Sn	Kl Kaliombo, tourmaline	R Rössing U
Bl Bildah Cu	Km Kopermyrn Cu	Rb Rooibank Fe
Bt Baltika V, Pb, Zn, Cu	Ko Kohero Sn	Re Rehderstal Cu
Bw Brandberg West Sn, W	Ku Kudis Cu	Rt Rietfontein Cu, Pb, Zn
D Duruchaus Cu, Au	L Langer Heinrich U	Ru Rüdenu Zn, Cu
DI Dellis, Bothashof Cu, Pb	La Landeck Cu	Su Sandamap Sn
Ds Doros area U	Lo Lofdal, carbonate	Sc Schweickhardtbronn Pb
Dw Davib West Sn	M Matchless Cu	Se Sechomib, itabirite
E Eisenhöhe, itabirite	Mo Moothock Pb, Zn	Sk Schbraskop Fe
Ei Eintracht Cu	N Neuwerk Cu	Sm Schlipmündung Cu
El Elbe Cu	Na Naos Cu	St Strathmore tin Sn
En Engo U	Nb Nabatsaub Cu	Sta Strathmore tantalite Ta, Nb, REE
Ep Epako Au	Nd Nordenburg Au	T Tsumeb Cu, Pb, Zn, Ag, others
Ew Erongo West Sn	Ni Namib Lead Pb, Zn, Ag	To Tsongour-Otjipaka Cu
F Friesenberg V, Pb, Zn	Nn Neineis Sn	Tr Tumas River U
G Gorob Cu	Ns Neu Schwaben, tourmaline	Ts Tschudi Cu
Ga Gross Aub Cu	Nt Natas W, Cu, Au	U Usakos lead Pb, Zn
Gg Goantagab Sn	Og Onganja Cu	Ur Uranus Cu
H Hope Cu	Ohk Otjihokero Cu, Zn	Us Us Sn
Ha Hatsamas Cu, Pb	Ojj Otjosonjati Cu	V Valencia U
Hh Hohewarte Cu, Pb, Zn	Ok Okatjize Fe	W Windhoek Tawnlands, itabirite

Figure 2.6.1 : Mineral occurrences in the Damara orogen (from Miller, 1983a).

## 2.6 Metallogenesis of the Damara Province

The ore deposits of the Damara Province closely reflect the patterns of crustal evolution (Mason, 1981; Misiewicz, 1987), and distinct mineral provinces occur within the orogen (Figure 2.6.1). These include carbonate-hosted massive sulphide deposits of the Otavi Mountain Land on the Northern Platform, turbidite-hosted gold mineralization at Ondundu in the Northern Zone, tin-tungsten mineralization confined to distinct belts in the Central and Northern Zones (Pirajno and Jacob, 1987), massive sulphide mineralization along the Matchless Amphibolite Belt in the Southern Zone, and a uranium province in the zone of anatexis in the Central Zone. Recently, a gold province has been delineated in the Central Zone.

Most Damara mineral deposits are found within the Swakop and Otavi Groups. The basal Nosib Group is surprisingly devoid of mineral deposits despite its favourable setting for mineralization, which include, for example, rift grabens (Porada, 1985), thick evaporite sequences in the Duruchaus Formation (Behret *et al.*, 1983) and characteristics typical of basin dewatering such as palaeo-aquifers and thick sedimentary piles. Mineralized showings do occur, such as at Kainkagchas on the farm Valencia south-west of Usakos in the Central Zone, but these are rare and are generally mere superficial expressions. The Oamites synsedimentary copper deposit located on the Southern Margin of the Damara was incorrectly correlated with Nosib lithologies (Lee and Glenister, 1976). Detailed mapping of the overthrust complexes along the Southern Margin Zone (Hoffmann, 1981) has confirmed Schalk's suspicions (Martin, 1978) that the mineralization is hosted by pre-Damara rocks of the 1800 Ma Rehoboth Sequence. Despite its lack of significant mineralization, the Nosib Group was important in establishing mineralizing processes within the Swakop and Otavi Groups (see later).

Martin (1978) attempted to define the mineralization of the Damara Belt in relation to tectonic setting, and distinguished between geosynclinal and orogenic phases of mineralization. With the exception of the Otavi Mountain Land, the mineralization is confined to the areas of medium- and high-grade metamorphism. Most of the important mineralization such as the carbonate-hosted massive sulphides of the Otavi Mountain Land, the uranium, tin-tungsten, and gold originated during the orogenic phase. The cupriferous pyrite deposits associated with the Matchless Amphibolite Belt are an exception since they formed on the sea floor during intracontinental spreading.

Although the Northern Platform was not severely affected by Damara orogenesis, the mineralization which is located there can be attributed to tectonism, since mineralization occurred syntectonically (refer to later sections). Despite the very extensive development of the Northern Platform (Figure 2.1.1), it is significant that there are only two mineralized areas. These are the Otavi Mountain Land, which is by far the richest, and the Sesfontein-Opuwa area of the Kaoko Zone where there are a number of mineral occurrences (Esterhuizen and Misiewicz, 1986). It is also significant that it is only in these two areas where Nosib sequences in rift grabens underlie the carbonate platform (Figure 2.6.2). Besides these two mineral

provinces, the only other mineralization which has been recorded are insignificant occurrences on the farm Dellis in the Outjo district (P. Harrison and B.D. Coxon, pers. comm.) where the mineralization is attributed to syn- to late-tectonic hydrothermal movement along growth faults in the basement.

In Section 9 it is contended that orogenesis was responsible for dewatering of the Nosib and Swakop Trough sequences along a "mineralizing front" corresponding to the Northern Rift along the Otavi-Swakop transition. The sedimentary pile provided the source of metals which were accumulated by diagenetic leaching. The movement of the fluids was controlled by the plumbing systems which existed in the Nosib rifts. The Northern Rift was the largest and would therefore have encouraged the most extensive hydrothermal brine circulation. The carbonate sequences provided the ideal sites for ore deposition, and since the Otavi Mountain Land directly overlies the Northern Rift, ore deposits either accumulated in satisfactory traps or resulted in numerous insignificant showings. The mineralizing process was probably achieved over a lengthy period which could be as much as 250 000 years (Hanor, 1979).

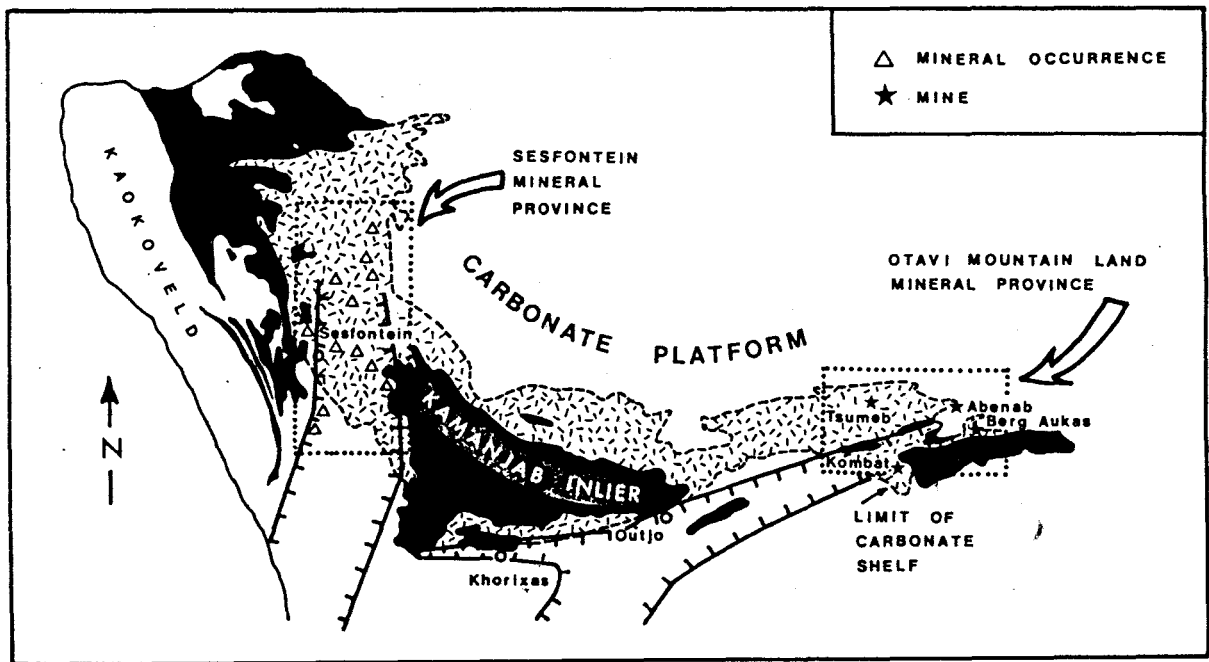


Figure 2.6.2 : Mineral provinces on the Northern Platform of the Damara orogen in relation to the early Nosib rift systems.

### 3. THE GEOLOGY OF THE OTAVI MOUNTAIN LAND

The Otavi Mountain Land is the best known portion of the Northern Platform due to its rich endowment of mineralized occurrences. The dominant lithologies exposed are carbonates of the Otavi Group which were deposited on clastic and metavolcanic sequences of the Nosib Group, and on remnants of lower Proterozoic granites and gabbros which form the basement complex (Table 3.1). The molasse sequences of the Mulden Group unconformably overlie the Otavi Group.

Geographically, the Otavi Mountain Land is a rugged and heavily wooded terrain with its best exposures confined to the carbonates which typically exhibit a karst topography. The basement granites are poorly exposed and are only found outcropping in several areas, but are known from borehole core to be more widely occurrent. Nosib sequences are also poorly exposed and are best known in the Kokasib-Gaikos area, Nosib-Keilberg Anticline, and south of the Otavi Valley where Askevold volcanics are widespread. Unfortunately, large areas of the geology, especially to the north of Tsumeb and east of Grootfontein, are hidden by superficial sand and calcrete cover.

Karoo clastic sequences outcrop to the south, but significantly, there are no Karoo igneous rocks other than a single north-east trending olivine dolerite dyke west of Tsumeb. However, aeromagnetic coverage (Government survey) of the Otavi Mountain Land indicates the existence of several other possible dykes east of Tsumeb which also trend north east. Van der Westhuizen (1984) considers that Karoo clastics must have covered the Mountain Land and were subsequently removed during the African Cycle of Erosion (King, 1963).



Plate 2: LANDSAT image of the Otavi Mountain Land.

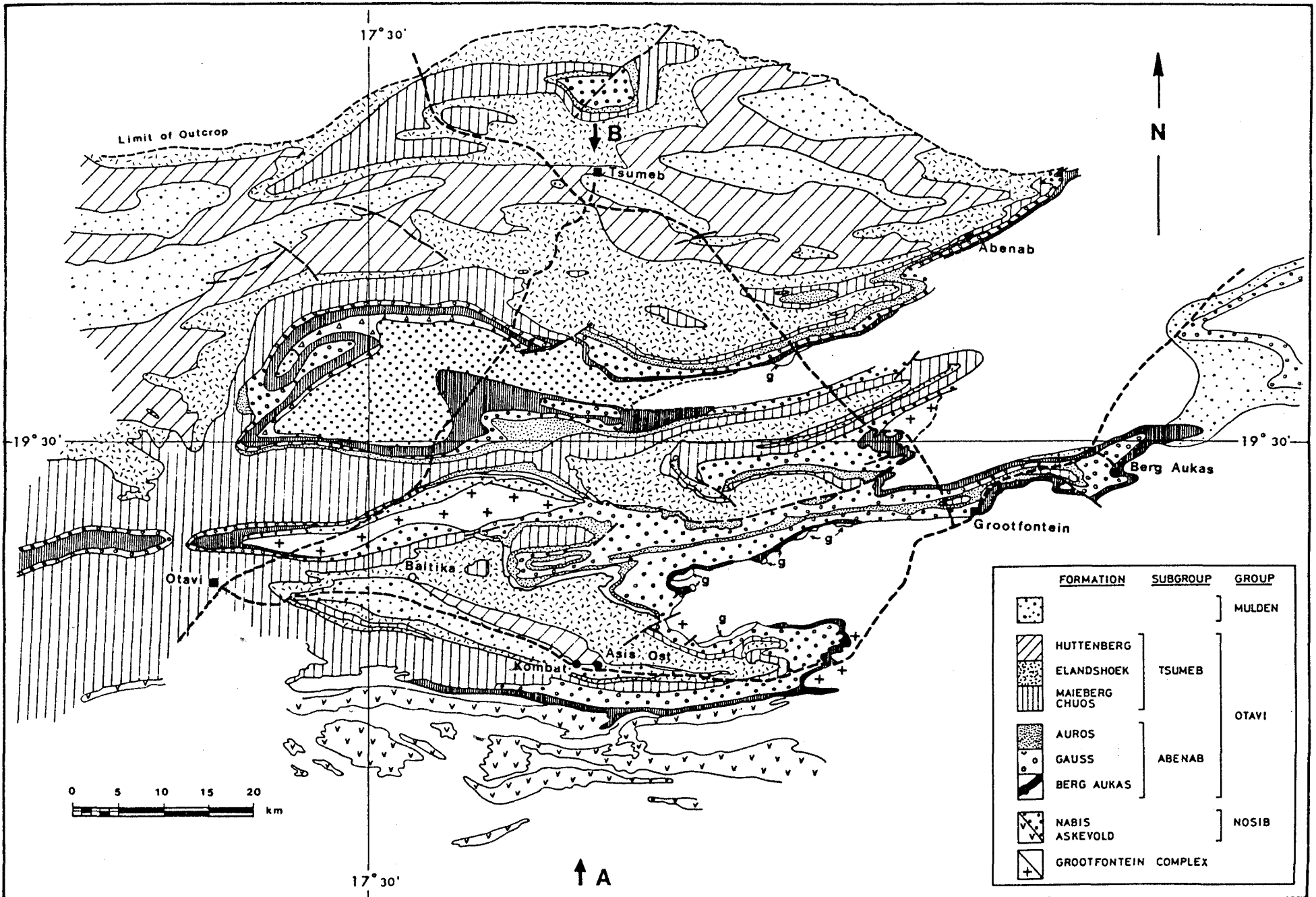


Figure 3.1 : Geology of the Otavi Mountain Land.

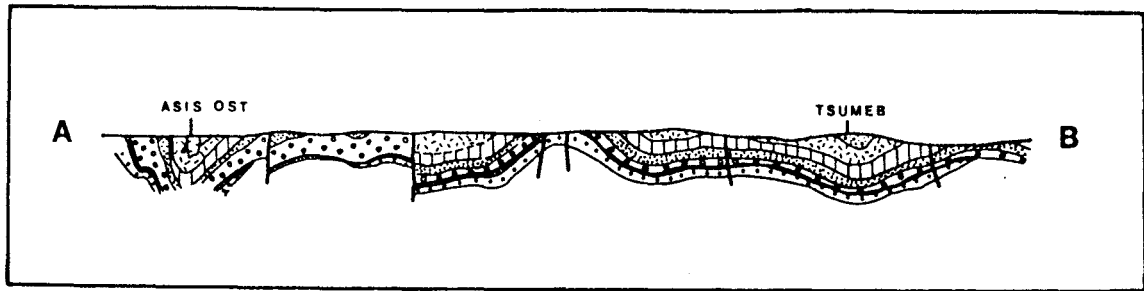


Figure 3.1 (continued): Geological section through the geology of the Otavi Mountain Land.

Table 3.1 : Lithostratigraphy of the Otavi Mountain Land (after SACS, 1980a).

Group	Subgroup	Formation	Lithology	Maximum thickness (m)	Remarks		
MULDEN		Owambo	Red vuggy shale, marl, feldspathic siltstone and sandstone, grey to black shale, limestone and dolomite	1 000	Sesfontein Formation in the Sesfontein area		
		Kombat	Phyllite, dark grey with dolomite lenses				
		Tschudi	Arkose, feldspathic, quartzite, grit, conglomerate, argillite				
PARACONFORMABLE OR UNCONFORMABLE CONTACT							
OTAVI	Tsumeb	Hüttenberg	Grey calcitic dolomite, pisolitic to oolitic chert bands Light grey bedded dolomite with algal markers and chert layers	300	Zone 8 (Söhngé 1958)		
			Alternating dark and light grey dolomite with minor black to grey limestone and thin shale bands. Black "oolitic" chert	290	Zone 7 (Söhngé 1958)		
			Light grey bedded dolomite, algal mats, layers of white chert with ripple marks and cross-bedding Bedded light grey dolomite, numerous silicified stromatolites, three <i>Conophyton</i> marker layers	320	Zone 6 (Söhngé 1958)		
		Elandshoek	Laminated, thin-bedded and massive light grey dolomite, white chert layers	350	Zone 5 (Söhngé 1958)		
			Massive light grey dolomite, stromatolites and oolites near top Silicified and jasperoid zones	750	Zone 4 (Söhngé 1958)		
		Haleberg	Banded, bedded and laminated grey dolomite	200	Zone 3 (Söhngé 1958)		
			Slump breccia Laminated blue-grey limestone Olive-green to brown (argillaceous) limestone Limestone "conglomerate" near base	750	Zone 2 (Söhngé 1958)		
		Chuos	Mixtite with argillaceous and dolomitic matrix, calcareous feldspathic sandstone, oolitic chert, dolomite, limestone, iron formation	200	Zone 1 (Söhngé 1958)		
		PARACONFORMABLE TO UNCONFORMABLE CONTACT					
		Abenab	Auros	Laminated pinkish-white dolomite with "quartz cluster" structures. Laminated limestone/shale and marl Massive grey dolomite with "columnar" stromatolites. Thin-bedded limestone and/or shale Massive grey dolomite with "ringel" stromatolites. Thin-bedded limestone and/or shale Massive grey dolomite with jasperoid bands. Dark limestone, local shale	450	Upper Abenab (Söhngé 1958)	
Light to medium grey, buff and white massive dolomite with colloform textures. Oolitic chert bands near top; local sandstone lenses and black limestone near base	750			Middle Abenab (Söhngé 1958)			
Black banded and laminated dolomite with various stromatolites Light grey laminated and banded dolomite Black limestone, dark grey dolomite, arkose, graywacke	525			Lower Abenab (Söhngé 1958)			
NOSIB		Varianto	Ferruginous mixtite, iron formation				
		Askevoid	Phyllitic agglomerate, tuff; epidosite				
		Nabis	Feldspathic quartzite, arkose, conglomerate				

### 3.1 The Grootfontein Complex

The basement complex to the Damara Sequence comprises the Grootfontein Granite, and various schistose basic rocks (Sohnge, 1957). There are no reliable age determinations for the rocks of the Grootfontein Complex (SACS, 1980b), and the extent and understanding of the Complex remains largely unresolved due to its poor exposure. Consequently, many misnomers have been transcribed in the literature since the original works of Wagner, 1910, Martin, 1965, and Sohngé, 1957 (Figure 3.1.1).

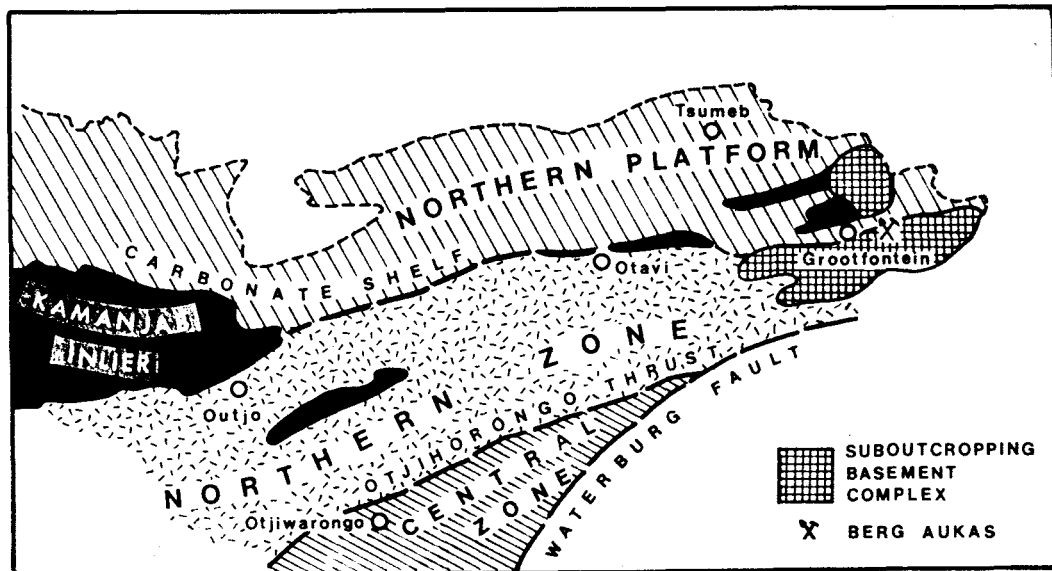


Figure 3.1.1 : The extent of the Basement Complex in the vicinity of the Otavi Mountain Land illustrating the relationship between the basement and tectonostratigraphic zones of the Damara orogen.

The Grootfontein Complex is made up of two main components. The better exposed is the Grootfontein Granite which Martin (1965) correlated with the Abbabis Complex (SACS, 1980b), a basement inlier in the Central Zone comprising ortho- and paragneisses, schists, quartzites, marbles, and calc-silicates. The Grootfontein Granite is best exposed in anticlinal cores that are broadly interpreted as basement highs in the palaeo-topography prior to deposition of the Damara Sequence. The best exposures are in the west at Keilberg 743 - Sumas 746 along the Otavi - Tsumeb main road, and west of Grootfontein in the Hoba Valley where the granite is well exposed along the base of rugged cliffs formed by the Damara Sequence. The best occurrences in the Hoba Valley are at Poolmanskluft 332, Hoba East 13, Johannestal 652, Awagobib 45, Rietfontein 344, Brandwag 41 on the Kombat - Grootfontein road, Farkenfontein 10, and Gemsboklaagte 11. The granite is also well exposed in a road cutting on the main Grootfontein-Tsumeb road on the northern flank of the Nosib Anticline. The unconformable relationship between the basement granite and the Damara Sequence is best seen at Poolmanskluft 332, and at the road cutting along the Nosib Anticline. It was this outcrop which led Martin (pers. comm., 1985) to realize in the early 1960's that the sequences of the Northern Platform post-date the lower Proterozoic basement and therefore had to be a correlative of the Swakop facies. Up until this time, the Otavi sequence had been incorrectly regarded as late Archaean or early

Proterozoic in age and a correlative of the Transvaal Sequence (Sohnge, 1957).

The granite varies between a grey porphyritic variety underlying the town of Grootfontein, and a pinkish gneissic granite in the Hoba valley. The porphyritic variety (Sohnge, 1957) consists of phenocrysts of microperthite, epidotized plagioclase, quartz and subordinate microcline with accessories of dark green biotite, apatite, magnetite and zircon. The gneissic granite on Poolmanskluft 332 (sample JEM 132) is a two-mica granite made up of muscovite and biotite-hornblende. Epidote and carbonate is locally developed as alteration products. Borehole core from Berg Aukas indicates a monzonitic composition (refer to Section 6.1).

The second component constituting the Grootfontein Complex is what Sohnge (1957) refers to as "*schistose basic eruptives of pre-Grootfontein age*". In general, these are very poorly exposed, tending to be covered by calcrete, and are best known from borehole intersections. Outcrops of these basic rocks are found along the southern limb of the Berg Aukas Syncline, where they are recognized as epidotized gabbros, and in the Hoba and Nosib Valleys. Vickers (1975c) reports the basement complex beneath the defunct Nosib mine to be a dioritic hornblende-rich rock intermixed with heterogeneous Grootfontein granite-gneiss. Early magnetic surveys (Sohnge, *op. cit.*) indicate the presence of at least three large basic bodies in the Nosib Valley which are hidden by calcrete. The older formations, which Martin (1965) refers to as micaceous biotite gneiss and amphibolite, are therefore only known from percussion drill holes. The extent of this suboutcropping basement is shown in Figure 3.1.1.

Although Sohnge (1957) suggests that these basic assemblages pre-date the Grootfontein Granite, macroscopic and microscopic examinations indicate considerable interaction of the basic rocks with granitic material as testified by the presence pink gneissic blocks within the basic rocks. The incorporation of gneissic material in the basic rocks suggests that these rocks have an intrusive relationship with the granites. Furthermore, the suboutcropping extent of these rocks (Figure 3.1.1) indicates that they have been emplaced along the Damara regional east-north-east trend. It is apparent that these rocks are more extensive than previously realized. Petrographically, they vary between hornblende-pyroxene gabbros (for example on Farkfontein 10 and Berg Aukas 593), and chlorite-amphibole epidosites (for example on Berg Aukas 593). In the immediate vicinity of the Berg Aukas Syncline phenocrysts of opalescent blue quartz are extremely common. F. Pirajno (pers. comm.) suggests that the opalescent blue quartz together with the variation in mineralogy may be a manifestation of regional hydrothermal alteration and metamorphism.

The gabbroic character of these rocks is similar to the Khankhab gabbroic complex in the Central Kaoko Zone recognized by Guj (1970) to be intruded into the Ugab Subgroup. This unit comprises marbles, pelitic schists, quartz schists, para- and ortho-amphibolite, conglomerate, and dolomite, and is probably a time correlative of the Abenab Subgroup.

In summary, the basement Grootfontein Complex comprises granites and intrusive and extrusive basic rocks

of unknown age and unknown extent. The latter sequences appear to be best developed in the south-east where they broadly adopt a Damara regional trend. They appear to post-date the granites which form a rigid basement palaeo-high.

### 3.2 Nosib Group, Damara Sequence

The Damara Sequence (Table 3.1) is made up of three groups, each of which is separated by a regional unconformity. The lowermost, the Nosib Group, is subdivided into three formations known as the Nabis Formation, a predominantly clastic sequence equivalent to Sohnge's (1957) and Hedberg's (1979) Lower Nosib, a volcanic sequence known as the Askevold Formation, formerly known as the Kombat Suid Formation, and the Varianto Formation, a supposedly glaciogenic sequence. The latter two formations were formerly grouped into the Upper Nosib.

The Nosib Group characteristically varies in thickness from where it is not developed at all to as much as 1200 m thick in the Urupupa 44 and Rietfontein 344 areas. It also varies in geographical development. The Askevold volcanics are confined to the transitional zone between the Otavi Platform lithologies and the Swakop Trough equivalents in a basin homologous with a rift/graben. This coincides with the rift system postulated by Porada (1985). The western limit of the lavas is marked by the Tsumeb West geofracture and the eastern limit by the basic rocks south of Berg Aukas. The Nabis Formation is best developed in depositories directly beneath the platform carbonates.

#### 3.2.1 The Nabis Formation

The Nabis Formation is best developed at Nosib 11, Ghaub 47, and Nabis 587 on the Nosib anticline, in the Urupupa 44 and Rietfontein 344 area where the sediments are up to 1200 m thick, and in the Kokasib-Gaikos synclinal areas east of Grootfontein. These areas occur on opposing sides of the Grootfontein Basement Dome. Thirion (1974) believed that these were two open basins with their sides corresponding to geofractures in the basement. The Grootfontein Basement Dome behaved as a prominent topographic feature throughout Nosib sedimentation and was responsible for the off-lapping unconformable relationship of the Nosib and Otavi lithologies.

The Nabis Formation comprises various interbedded coarse to fine grained arkoses, feldspathic quartzites and well-imbricated conglomerates. The conglomerates contain various sized pebbles up to 30 cm in diameter which tend to be smooth, well rounded and are embedded in a grey to brown feldspathic quartzite matrix. They grade into more massive arenaceous sediments that may be finer grained, laminated, or cross-bedded. The pebbles are largely quartzitic in composition, but may include granite-gneiss, and even magnetite quartzite and chert, epidosite, and chlorite schist, especially where they are developed in the vicinity of

basement granite such as at Rietfontein 344.

Smit (1962) was able to establish that there is a gradual improvement in sorting with a progressive distance from the platform edge. This type of analysis clearly establishes that the conglomerates and associated arenites were deposited under probable fluvial conditions in a continental environment controlled by rift margins. The interbedded conglomerates, cross-bedding, and poorly sorted grits indicate high energy shallow water deposition, suggesting alluvial fan conditions. Vickers (1975) was able to show by detailed mapping at the Nosib Mining Area that the deposition of the Nabis Formation represented a facies thickening towards the west, supporting the existence of a basement high.

### 3.2.2 The Varianto Formation

The Nosib Group in the Nosib-Ghaub-Nabis area is characterized by an upper sequence of iron-rich sediments which have been variably described as a diamictite (Botha, 1960) and a tillite (Schoch, 1956; Simpson, 1957, as quoted by SACS, 1980a), but which is also argued to include a pyroclastic component (Sohnge, 1957). This upper sequence was previously correlated with the Kombat Suid Formation (now Askevold Formation), but is clearly distinguishable due to its geographical, tectonic and genetic characteristics. The formation has a distinct aeromagnetic signature and is currently known as the Varianto Formation. It is interpreted as glaciogenic sediments since it hosts poorly sorted pebble clasts of mixed composition and variable size including quartz, feldspar, arkose, gneiss and chert. The pebbles are often faceted (although disputed by Martin *et al.*, 1985) and are hosted by green feldspathic sandstone and dark brown to *black* ironstone composed mostly of magnetite, hematite specularite and limonite. Another factor is that the Varianto Formation unconformably overlies the Nabis Formation, thus marking an erosional surface.

### 3.2.3 The Askevold Formation

The Askevold Formation is a metamorphosed sequence of basic lavas occurring in two east-north-east trending 1,5 km belts along the southern margin of the Northern Platform (Smit, 1962). The belts are located south of the Otavi Valley between the Askevold and Hartebeestpoort mountain ranges, and south of the Hartebeestpoort range. In terms of tectonic setting, they are similar to the Naauwpoort volcanics in that they appear to be rift-bounded within the Northern Rift. Their most eastern outcrop, is on Deutsche Erde 553, some 16 km south of Otavi.

The basic lavas are characteristically metamorphosed to bright green massive epidiosites with occasional vesicular and amygdaloidal structures. They generally exhibit a schistose fabric and are fairly commonly mineralized with malachite staining.

### 3.3 The Otavi Group, Damara Sequence

The Otavi Group constitutes the thick carbonate sequences deposited under stable platform conditions on the Northern Platform of the Damara Province. The stratigraphy of the Otavi Group (Table 3.1) is conveniently separated by glaciogenic mixites of the Chuos Formation into a lower Abenab Subgroup and an upper Tsumeb Subgroup. The Otavi Group was deposited between 720 Ma and 600 Ma ago and comprises carbonate rocks which are largely dolomitized, calcitized and silicified. Limestone sequences occur in a minority to the dolostones, and clastic sediments, largely argillites, are insignificantly developed in the Berg Aukas, Auros and Maieberg Formations.

The wackestone, mudstone and packstone carbonates of the Otavi Group were deposited on a stable miogeosynclinal platform during the extensional downwarping phase in the orogenic development of the Damara Belt, which caused marine flooding. The carbonates, by modern analogy, were deposited in a very shallow warm, tidal sea strongly favouring algal growth, now evidenced by abundant stromatolitic and oolitic beds. It is likely that biohermal reef structures predominated and that carbonate build-up developed by a progressive shallowing upward process.

Thus, the scenario for the Northern Platform is one where initial Nosib rifting encouraged the development of alluvial fans and braided streams. The separation of the Congo and Kalahari cratons caused subsidence with marine conditions analogous to a narrow Red Sea to develop. As the platform edge flooded, lagoonal conditions prevailed and carbonate accretion equalled relative sea level rise allowing thick sequences to develop. Continued subsidence occurred, during which time carbonate deposition rapidly progressed. Carbonate production and deposition is stimulated by a rise in sea level (Beukes, 1986). Intertidal flats, shallow lagoons and gently dipping continental shelf areas deepening towards the south encouraged extensive horizontal development. A variety of algal stromatolite growths have been described by Schweltnus and le Roux (1944) and Kruger (1969). A schematic section across the Otavi-Swakop transitional zone illustrating the environmental controls on the stratigraphy is depicted in Figure 3.3.1.

#### 3.3.1 Abenab Subgroup

The Abenab Subgroup is best exposed in the eastern Otavi Mountain Land but is also widespread in the central regions where it flanks the Nosib and basement lithologies along the Nosib and Keilberg Anticlines. The Abenab Subgroup is subdivided into three formations known, from the base upwards, as the Berg Aukas, Gauss and Auros Formations. (More specific details of the Abenab Subgroup at Berg Aukas are discussed in Section 6.).

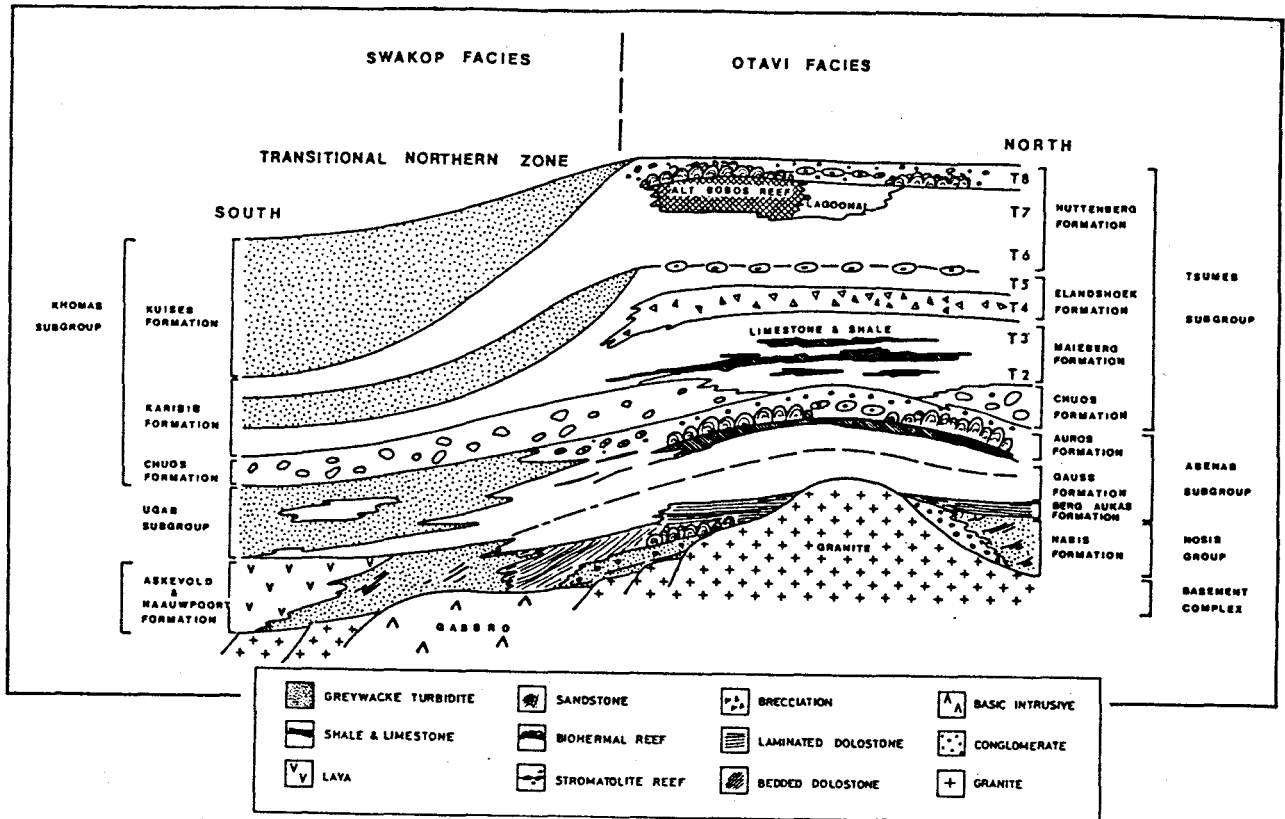


Figure 3.3.1 : Schematic section illustrating the stratigraphic change from the stable conditions of the Northern Platform (Otavi facies) to the geosynclinal conditions of the Swakop Trough (Swakop facies). The section also illustrates the relationship between the Damara Sequence and the basement prior to deposition of the Mulden Group.

The Berg Aukas Formation is a transitional sequence representing the change from the Nosib and basement conditions to a carbonate environment. It comprises various light and dark grey and black laminated dolostones, occasional stromatolitic reefs and interbedded arkoses, greywackes and shales which probably reflect a lagoonal environment. The clastic sediments in the Berg Aukas Formation are particularly well developed at Ghaub 47, north of the Nosib Anticline. The Berg Aukas Formation is characterized by lenticular pinch-outs probably due to the uneven basement topography. The thickness of the unit ranges from zero, such as along the southern flank of the Hoba Valley, to as much as 750 m, but tends to average 300 m (Sohnge, 1957).

Continued subsidence and advance of the sea resulted in a thick succession of unstratified light grey dolostones indicating fairly stable, moderately deep waters. The horizon is the 750 m thick Gauss Formation which conformably overlies the Berg Aukas Formation. The dolostone is characteristically massive and fine grained with a primary sucrosic texture having been filled with sparry calcite. Colloform textures are well developed at Berg Aukas and north of Nosib on the farm 682. Typically, the dolostone has undergone some neomorphic recrystallization without completely destroying any primary features. Towards the top of the Formation, bands of oolitic chert have been recorded at Berg Aukas and Ghaub West 590 (Sohnge, 1957).

The dolostones mapped by Smit (1962) in the transitional zone between the Northern Platform and Northern Zone are probable correlatives of the Gauss Formation.

Shallowing of the sea resulted in a series of thin laminated limestones and dolostones with occasional clastic layers, such as at Abenab Mine, being deposited. Stromatolite reefs were prevalent and are particularly well developed at Auros 595. The reefs are believed to have developed adjacent to the cratonic areas prior to the period of crustal disturbance and erosion which brought about the deposition of the Chuos Formation. The lack of dolomitization of the Auros Formation may be a function of the cold waters which are likely to have accompanied Chuos times (C. King, pers. comm.). It is noteworthy that the only significant limestone sequences in the Otavi Group occur on either side of the Chuos Formation.

### 3.2.2 The Tsumeb Subgroup

The Tsumeb Subgroup is a 3000 m thick sequence largely comprising carbonates but also including the Chuos Formation at its base. The carbonates are mostly made up of dolostones but limestone and shales also occur in the lower portion. Stromatolitic reefs are well developed towards the top of the sequence. It is well exposed and is best known from the Tsumeb and Otavi Valley Synclines.

The stratigraphy (Table 3.1) is subdivided into four formations known as the Chuos, Maieberg, Elandshoek and Huttenberg. These are informally subdivided into 8 zones (T1 to T8) on the basis of facies and lithological characteristics.

#### 3.3.2.1. The Chuos Formation

The Chuos Formation (T1) has been variably described as a tillite, a fluvio-glacial deposit, and more recently as a debris flow formed in response to a retreating ice sheet (Sohnge, 1957; Martin *et al.*, 1985; Henry *et al.*, 1986).

The Chuos mixtite is best developed in the central Otavi Mountain Land, and achieves its greatest thickness of up to 1000 m (Sohnge, 1957) in the Otavi area. It does not occur east of the Tsumeb-Grootfontein road with the result that at Abenab the Maieberg Formation rests directly on platy limestones, shales and dolostones of the Auros Formation. The reason for this absence remains unclear, but it is possible that this area represented a palaeo-highland not favouring Chuos deposition. Sohnge (*op. cit.*) has noted that a disconformity exists between the Chuos and the Abenab Subgroup such that it may rest directly on lithologies of the Auros Formation or Gauss Formation. Sohnge (*op. cit.*) suggested that an eastern highland was subjected to scour with mixtite accumulation in basins to the west and south.

The Chuos Formation consists predominantly of diamictites with lenses of dolomite and schist. The clasts consist of dolomite, limestone, quartzite and basement granite and gneiss. Sorting is very poor and individual boulders may have a diameter of one metre or more. The boulders are often faceted clearly indicating their glacial origin. Most of the carbonate fragments display characteristics of having originated from the Abenab Subgroup. The best exposures of this chaotic assemblage are at Keilberg 743, and at Maieberg 790.

Where the diamictite thins out, such as in the vicinity of Nosib Mine, the unit develops into a shaley sequence with more rounded pebbles.

### 3.3.2.2 The Maieberg Formation

The Maieberg Formation (T2 and T3) is a thick (up to 1800 m) well developed carbonate sequence widely established throughout the Otavi Mountain Land. Zone T2 is a sequence comprising laminated limestones and marls with abundant slump breccias and intraformational calcirudite bands consisting of angular blocks and fragments of limestone and dolomite. The lowermost limestone is sometimes referred to as the platy limestone and has successfully been used as a stratigraphic marker horizon, particularly at Abenab Mine and in the Harasib-Olifantsfontein Syncline.

In terms of a palaeo-environmental analysis, the laminated carbonates indicate a platform slope under deepening water conditions. Laminations are typically argillaceous bands indicating a mixed carbonate and clastic influx. Slump brecciation and the rudaceous character of the beds suggests a movement of sediments on a talus slope whilst carbonate deposition resulted by settling of a hemi-pelagic ooze. Sedimentation proceeded immediately after the Chuos mixtite had been deposited, probably in cold water conditions. As in the case of the Auros Formation, this may possibly be the reason why the limestones were not subjected to dolomitization (C. King, pers. comm.).

Zone T3 comprises bedded and finely laminated grey dolostones. They appear to be the dolomitic equivalent of the T2 laminated limestones which they overlie. The lower contact is often brecciated.

Subareal exposure of the limestone sequences has resulted in an extensive karst topography. Subterranean cavities are particularly well developed on Harasib 317.

### 3.3.2.3 The Elandshoek Formation

The Elandshoek Formation (T4 and T5) conformably overlies the Maieberg Formation. It is extensively developed and is mostly responsible for the rugged geomorphological terrain. It is best seen in the Tsumeb Syncline, and the type section is located on Elandshoek 771, approximately 16 km south of Tsumeb. On the

southern flank of the Tsumeb Syncline, a relatively shallow northerly dip combined with a gentle topography has resulted in a 14 km wide outcrop belt.

Zone T4 comprises massive light grey dolostones with occasional oolitic and stromatolitic beds towards the top. It hosts an extensive stratabound zone of brecciation, especially in the central Otavi Mountain Land on Auros 595 and Sommerau 737 north of Kombat, Harasib 317, and Abenab 707 (Carbonate Excursion Guide, 1986). Fracturing and brecciation is typified by a network mosaic of silicified veinlets (Plate 3). Subrounded dolostone blocks occur within a matrix of silica and sparry carbonate with localized calcitization. The brecciation is interpreted (P. Harrison, pers. comm., 1986) as syndepositional features whereby brittle fracturing resulted by creep and slide on a palaeo-slope in response to a tectonic readjustment caused by basement fault activation. These features are similar to those observed in the Baltika Breccia Body which disrupts zones T5, T6, T7, and T8 at the top of the Tsumeb Subgroup.

The brecciation is regionally extensive and is regarded as an important regional aquifer (Carbonate Sedimentology Excursion Guide, 1986) which could have provided dewatering pathways for the passage of hydrothermal brines. The breccia at Sommerau, referred to as the Sommerau breccia zone, hosts disseminated copper, lead and zinc mineralization. At Abenab, the T4 dolostones are known as the Karuchas Zone, a white to light grey siliceous dolostone which is extensively fractured and brecciated. Sparse disseminated Pb and Zn sulphides (not known to exceed 4%) are invariably present.



Plate 3 : Siliceous breccia mosaic in the T4 zone dolostones of the Elandshoek Formation.

The T4 dolostones along the northern flank of the Otavi Valley Syncline are locally referred to as the jasperoidal dolostones. They form a distinct stratigraphic horizon because of their high resistance to weathering. They are intensely jointed which has encouraged siliceous replacement of the carbonate. Progressive removal of the more soluble carbonate has resulted in the formation of very distinctive "cathedral peak" structures. The jasperoid is either in the form of a white friable sugary variety, or as a more bluish chert which may be in laminar masses (Misiewicz, 1986b).

Lithozone T5 is a light grey, thinly bedded siliceous dolostone with occasional oolitic lenses. It is a fairly thin zone averaging 350 m. In the Otavi Valley Syncline, it is not easily distinguishable from the overlying T6 dolostones which are similar in colour and bedding. The lower contact with T4 is generally taken at the commencement of the first jasperoidal dolostones. The upper contact is clearly marked by the ubiquitous and easily identified conophyton stromatolite bed (Plate 4) (Schwellnus and le Roux, 1944; Kruger, 1969).

#### 3.3.2.4 The Huttenberg Formation

The type area for the lithozones T6 to T8 is the Huttenberg ridge, a hilly feature located approximately one kilometre north of the Tsumeb Mine. The Huttenberg Formation conformably overlies the Elandshoek Formation and is itself disconformably overlain by clastic sequences of the Mulden Group. It is most extensively developed in the environs of the Tsumeb Syncline, and although it does not outcrop as extensively, it is also well developed along the northern flank of the Otavi Valley Syncline. Hedberg (1979) reports that the Huttenberg Formation is thinnest in the Tsumeb-Abenab area (450 to 500 m) but tends to thicken in a westerly and southwesterly direction to 760 m. SACS (1980a) indicates a maximum thickness of as much as 900 m.

Lithozone T6 is a light grey bedded dolostone characterized by algal chert lenses and oolitic concentrations towards the top of the sequence. In the type area, three persistent conophyton horizons have been successfully used as stratigraphic markers. These are locally known by Tsumeb Corporation geologists as Tuten 1, Tuten 2, and Tuten 3 after the terminology of Schneiderhohn (1913, as quoted by Lombaard *et al.*, 1986).

Locally developed within the T6 lithozone at Tsumeb is the North Break, a 10 m thick zone of alteration and brecciation conformable with the bedding which is interpreted as a palaeo-aquifer (Lombaard *et al.*, 1986). It has a strike length of some 4 km (3 km west and 1 km east of Tsumeb Mine) and is easily recognized by its ferruginous, manganiferous and calcitic alteration. It has anomalous Cu, Pb, Zn and  $V_2O_5$  geochemical response, and is incorporated in the current genetic model for the Tsumeb ore deposit.

In the Otavi Valley, the T6 lithozone is characterized by a single persistent stromatolite which is used to distinguish the contact between T6 and T5. It is a 30 cm thick conophyton algal bed (Plate 4) that is

occasionally displaced by small dip faults.



Plate 4 : The conophyton stromatolite bed which marks the T5 and T6 contact.

Lithozones T7 and T8 largely comprise lagoonal sequences consisting of algal beds, oolitic and pisolitic facies, and fetid carbonates. They mark the change from a deep water environment seen in the Elandshoek and Maieberg Formations to shallow lagoonal shelves which encouraged algal reefs prior to pre-Mulden uplift and subaerial erosion of the exposed landsurface. At Tsumeb, a prominent marker horizon known as the Augen Marker, comprises calcite nodules interpreted as replaced anhydrite (Lombaard *et al.*, 1986). This indicates that evaporites, possibly in a Sabkha-type setting, were developed in the shallowing environment.

In the Otavi Valley, oolitic and pisolitic beds (Plate 5) are well developed in the T7/T8 zones (Misiewicz, 1986b). These are disrupted at Baltika by a mega breccia body which hosts disseminated mineralization. It is regarded as a slump breccia initiated by tectonism prior to the deposition of the Mulden sediments (Plate 6). The relationship with the overlying Kombat Formation is clearly unconformable at Baltika since the breccia disrupts lithozones T5, T6, and T7/T8, and the Kombat phyllites rest directly on zone T4.



Plate 5 : Oolitic beds in the T7/T8, Huttenberg Formation south of Rohrs Prospect, Otavi Valley.

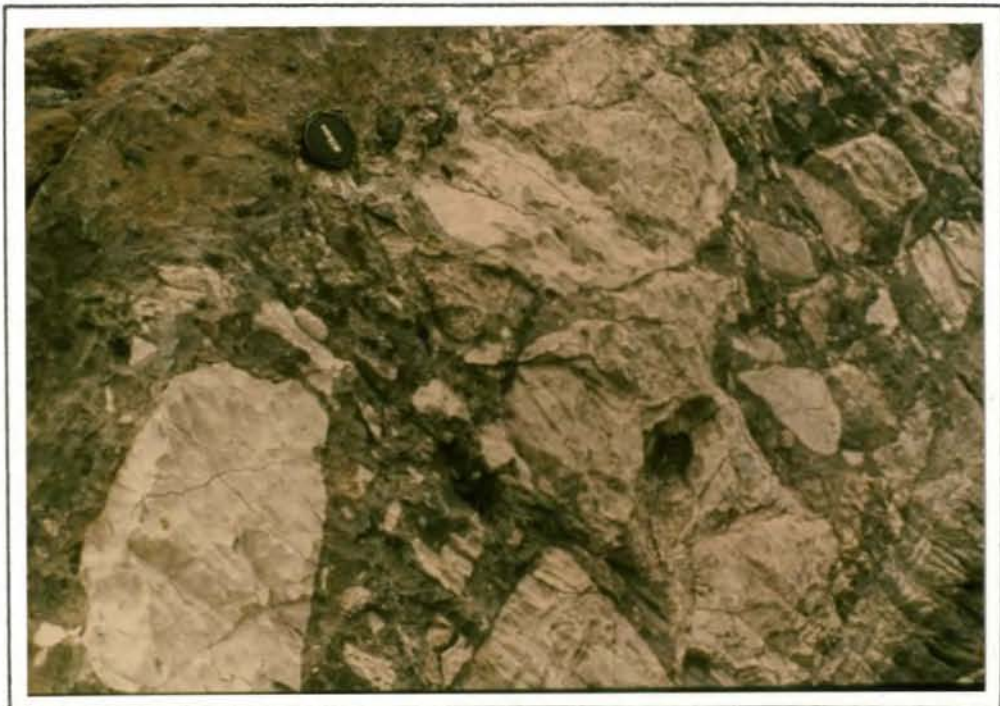


Plate 6 : The uppermost portion of the Baltika Breccia Body illustrating the large blocks of carbonate which resulted by tectonically induced slumping.

### 3.4 The Mulden Group, Damara Sequence

The Mulden Group is a clastic molasse sequence which was deposited syntectonically during the early stages of the Damara orogeny. Miller (1983a) suggests that Mulden sedimentation occurred between the gentle  $D_1$  and the more intense  $D_2$  episodes. As discussed in Section 2.1, the Mulden Group was extensively deposited throughout the Northern Platform, from as far west as Kaokoveld to the Otavi Mountain Land in the east. The Mulden Group marks a drastic change from carbonate sedimentation whereby deposition took place on a stable shelf under lagoonal and shallow platform conditions, to a fluvial and deltaic situation in an intermontane setting. Three formations known as the Owambo, Kombat, and Tschudi, reflect a variation in sedimentary facies as well as geographical accumulation.

In the Otavi Mountain Land, lithologies of the Mulden Group are located in the central portions of regional synclines where they are separated from the Tsumeb Subgroup by an angular unconformity. They are found in the Tsumeb, Tschudi, and Otavi Valley Synclines, and there is no evidence that Mulden sedimentation occurred further to the east such as over the Grootfontein basement high.

In the Tsumeb Syncline, a 30-40 m thick, ill defined unit was formerly known as the Lower Mulden (Sohnge, 1957; Hedberg, 1979; P. Harrison, pers. comm.), but presently has no official status (Miller, 1983a). It forms the basal lithology and consists of a dirty subgreywacke with localized sand supported chert pebble conglomerate. The conglomerates become progressively thicker and coarser towards the Owambo basin in the west. Lenses of argillite, dark shales and siltstones are sporadically intermixed.

Although the Mulden sequences are very poorly exposed, exploration by TCL of the Tschudi sediment-hosted deposit has established that sedimentation took place on an erosional karst surface. Regional seismic surveying conducted by the Etosha Petroleum Company (Hedberg, 1979) indicates a linear reflector extending north-west from Tschudi. P. Harrison (pers. comm.) interprets this as a palaeo-ridge that influenced a thickening of sediments on opposing sides of the feature.

The Tschudi Formation overlies the basal sequence and comprises 1600 m of pale, clean feldspathic arenite and occasional greywackes and intraformational breccias. The arenites are massive to thinly bedded with well developed cross bedding. P. Harrison (pers. comm.) suggests that the Tschudi clastic sequence developed as a delta which built outwards as a fan adjacent to the Tschudi basement high. The lower Mulden was deposited as playa mud flat or shallow lacustrine sediments.

The arenites were deposited by fluvial processes. It is assumed that the sedimentary source originated by denudation of the basement inliers and footwall lithologies in response to basement uplift and erosion. Hedberg (1979) reports that conglomerate clasts are locally derived, which is probably a function of the palaeo-topography. Investigations of the southern intermontane basins (B.D. Coxon, pers. comm.) indicate easterly palaeocurrent directions, which suggests that the earliest sedimentation was from the west, and was

probably derived by denudation of up-domed basement as a consequence of the D<sub>1</sub> event which was more prevalent in the west. However, sedimentary influx from the east exceeded that from the west and the possibility of a source from as far east as the Katangan Belt, as suggested by Porada (1983) cannot be disregarded. Certainly, the vast quantity of sediment input into the Mulden and Khomas Troughs requires a distant sedimentary supply.

An easterly palaeocurrent trend in the southern intermontane basins is a significant observation because it could mean that a depositional facies change from fluvial to deltaic conditions could explain the apparent gradational lateral change from sandstones in the west, such as north of Outjo, to siltstones and greywackes, such as in the Otavi Valley. It is significant that north-north-easterly trending magnetic lineaments intimating basement geofractures, also correspond with the lithological change. It is probable that sedimentation was influenced by these structures. Thus, in summary, the apparent lateral change in sedimentary style was possibly a function of intermixing of sediments from two opposing directions.

In the Otavi Valley Syncline, the Mulden Group represented by the Kombat Formation, an extensive lutite unit which has been metamorphosed to a phyllite or slate. The Kombat Formation is regarded as younger than the Tschudi, and is a possible correlative of the Owambo Formation. Remnant arkosic lenses at the Kombat railway siding (Miller, 1983a) are correlated with the Tschudi Formation. These arkoses attest to the unconformity between the Mulden and Otavi Groups. The unconformity is also well displayed at Baltika Mine where the Baltika Breccia Body disrupts the carbonate stratigraphy, and on top of the Otavi Spitze mountain range. This is a 300 m high range marking the southern limb of the Otavi Valley and is characterized by an extensive layer of phyllite at the top which was unconformably deposited in a parasitic F<sub>1</sub> fold basin.

The sediments of the Kombat Formation are regarded as having been deposited in a deep water environment by deltaic processes.

#### 4. REGIONAL STRUCTURE OF THE OTAVI MOUNTAIN LAND

The Northern Platform is characterized by a relatively simple structure and metamorphism. This was initiated by the orogenic processes brought about by collision following reversal of spreading of the Congo and Kalahari cratons. The intensity of deformation in the Otavi Mountain Land decreases rapidly from the Otavi Valley towards Tsumeb in the north.

Three broad controlling features have been responsible for the structural pattern. These are regional basement highs, basinal depositories which surround the basement highs, and a platform-margin environment south of the Otavi Valley which marks the transition to the Northern Zone. The most important basement high is located between Grootfontein, Kokasib and Abenab. The anticlinal features exposing the basement complex and Nosib Group are a reflection of palaeo-topographic highs which influenced carbonate sedimentation in basins conforming to present day synclinal warps. These are informally referred to as depocentres, and are particularly well developed in the central Otavi Mountain Land.

As discussed in Section 2, the basement topography to the Otavi Mountain Land was characterized by rift grabens formed at the eastern limits of the Northern Rift. With the exception of the Sesfontein Rift, it is the only significant area of the Northern Platform where Nosib sediments accumulated. The Grootfontein-Kokasib-Abenab basement was subjected to rifting, uplift and subsequent subsidence of the basins along its margins. It formed a distinct arch with sedimentary deposits to its west and east. Rifting was accompanied by subsidence and the creation of saucer-shaped basins analogous to the European North Sea basin (Porada, 1985). Into these basins thick clastic sequences were deposited by fluvial-alluvial fan processes and other high energy mass-wasting means.

Continued development of the Northern Rift by reactivation of basement growth faults was most significant in the transitional zone during the later stages of rifting. This resulted in an enhanced subsidence in the transitional zone and a readjustment in the central Mountain Land resulting in uplift and levelling. An uneven erosional surface formed the basement to carbonate sedimentation ahead of an encroaching sea whose deep trough facies was developing to the south.

The later stages of Nosib rifting were characterized by extrusion of the Askeveld volcanics into the subsiding trough created during lithospheric extension. Thus, the Askeveld volcanics are probably coeval with the upper Nabis Formation, and even possibly with the lowermost Abenab Subgroup carbonates since an interfingering relationship has been noted by Smit (1962).

With the initiation of Damaran orogenesis, the land surface was folded into a series of east-west trending steep-sided synclines and anticlines. The intensity of deformation was greatest closest to the platform edge

along the northern margin of the transitional zone. There are two apparent phases of folding ( $F_1$  and  $F_2$ ), the first of which is coeval with the  $D_2$  event recognized by Miller (1983a) in his Damaran synthesis. The  $D_1$  event has not been identified in the Otavi Mountain Land and appears to have been restricted to the Kaoko Zone. The first phase of folding,  $F_1$ , was the most intense, and was governed by compressional forces from the north and south. It commenced after the deposition of the Huttenberg Formation and prior to and concurrently with the deposition of the Mulden Group.

$F_2$  folding, which Miller (1983a) believed to be insignificant, coincides with the 550-530 Ma event of the Central Zone (Haack and Martin, 1983). The  $F_2$  event was the result of a mild compression from the east and west which was normal to the major  $F_2$  episode.  $F_2$  had the effect of creating a series of doubly plunging synclines; an effect which has been important throughout the Northern Platform. Doubly plunging synclines have been recorded from as far east as Berg Aukas and as far west as Outjo (P. Harrison, pers. comm.). Although the  $F_2$  event was mild, for example the Otavi Syncline plunges from the west at approximately  $5^\circ$ , it was sufficient to create very deep structures. Borehole OV 15 drilled by the Tsumeb Corporation some 200 m south of the dolostone-slate contact 15 km east of the fold closure in the Otavi valley was stopped at 772 m when it was still in slate.

In the Otavi Valley,  $F_1$  folding resulted in tight overturned recumbent folding with southward dipping axial planar surfaces. It imparts an  $S_1$  cleavage in the slates of the Kombat Formation (Innes and Chaplin, 1986). Parasitic folding is recognized as "rolls" on each limb. The top of the Otavi Spitze mountains are characterized by a horizon of Mulden phyllites which have been interfolded together with the dolostones. Innes and Chaplin (*op. cit.*) regard this folding as a second phase which occurred prior to the  $F_2$  event referred to in this thesis and would probably correlate with a phase of chevron folding recognized by Innes and Chaplin (*op. cit.*) as an  $F_3$  period of deformation..

There is a general decrease in deformation eastwards and northwards, and the folding becomes more concentric characterized by near vertical axial planar surfaces. A basin-and-doming resulted as a consequence of the interference pattern achieved by the  $F_1$  folding being superimposed on the earlier event.

The stratigraphy of the synclines is not often repeated on opposing limbs. Although this enigmatic problem has not been satisfactorily explained, it is assumed that each syncline corresponds with a primary depocentre and that north-south compression accentuated the structure by forming synclines where depocentres existed. Thus, the inability to correlate stratigraphy across structures could be due to primary facies changes.

The most important synclines or depocentres are informally known as:

1. Otavi Valley Syncline
2. Harasib-Olifantsfontein Syncline
3. Tsumeb Syncline
4. Grootfontein-Berg Aukas Syncline
5. Kokasib Syncline
6. Gaikos Syncline

The principal anticlinal and basement features include:

1. Grootfontein-Abenab-Kokasib Arch
2. Nosib Anticline
3. Keilberg Anticline
4. Hoba Valley Anticline
5. Urupupa Dome

The Grootfontein-Abenab-Kokasib arch divides those structures which plunge to the west such as the Harasib-Olifantsfontein Syncline, and those which plunge to the east such as the Kokasib and Gaikos Synclines. The Grootfontein and Berg Aukas Synclines rest on the southern flank of the arch in the immediate vicinity of the transitional zone with the Northern Zone.

The Mountain Land has been affected by both oblique transverse faults and bedding plane or strike faults. The most significant oblique faults are regarded as reactivated basement fractures which were active during carbonate sedimentation as well as during  $D_2$  deformation. These fractures and faults trend north-east ( $N40^{\circ} E$  to  $N60^{\circ} E$ ) and can be correlated with the major lineaments which occur in the Central Zone of the Damara (R. Gunthorpe, pers. comm., 1986; Carbonate Workshop, 1986). To the west of Tsumeb is a basement fault, referred to in this work as the Tsumeb West geofracture, which can be regarded as a continuation of the Cape Cross-Okarusu Lineament. Anorogenic alkaline magmatism occurred along these deep seated lineaments. Faults of similar trend displace the northern flank of the Otavi Valley at Kombat. It is known as the Kombat Fault and extends for 45 km from the platform into the transitional zone.

$F_2$  folding was accompanied by widespread jointing and fracturing. Fracture traces tend to be fairly straight, lack brecciation, dip steeply, and generally strike north.

Strike and bedding faults are related to the  $F_1$  folding event. At Tsumeb, the North Break is a fracture zone which strikes parallel to bedding. At Abenab, strike faulting hosts the Abenab Breccia Pipe and is associated with the Abenab West ore zone. In the Harasib-Olifantsfontein Syncline, there are a number of strike faults, including the 45 km long Uitsab Fault.

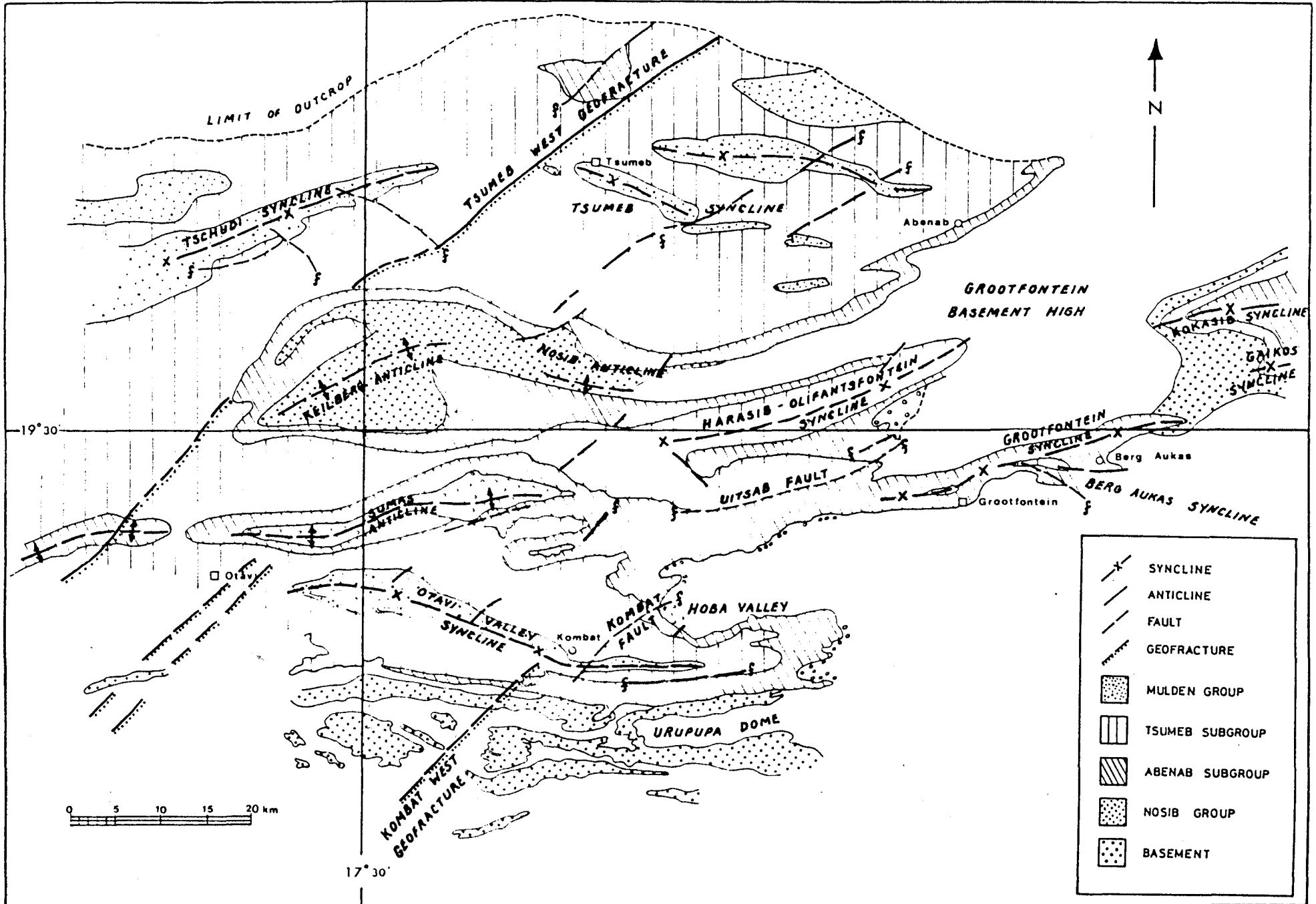


Figure 4.1 : Structural geological features of the Otavi Mountain Land.

## 5. METALLOGENESIS OF THE OTAVI MOUNTAIN LAND

### 5.1 Classification of Mineralization

The Otavi Mountain Land is a richly endowed metallogenic province. It is an area of 10 000 km<sup>2</sup> and is reputed to have some 600 known mineralized showings. There are four major deposits, notably the Tsumeb and Kombat Mines and the defunct Berg Aukas and Abenab Mines. The Tsumeb ore deposit is the largest and the most important. It is world renowned for its exceptional variety and beauty of mineral specimens.

In comparative terms, these ore deposits are not significantly large (Table 5.1), but they are economically rich because they are characterized by polymetallic mineralogies with exceptionally high metal grades. The ore deposits have been producers of copper, lead, zinc, vanadium, silver, gallium, germanium and cadmium.

**Table 5.1: Grade and tonnage for the largest deposits in the Otavi Mountain Land.**

Mine	Tonnage		Grade				
			Cu%	Pb%	Zn%	V <sub>2</sub> O <sub>5</sub> %	Ag g/t
Tsumeb	Tons mined	21 000 613	4,67	12,00	4,35	--	
	Tons reserve	6 170 876	3,31	3,65	1,2	--	
	<u>Total</u>	<u>27 171 489</u>	<u>4,36</u>	<u>10,10</u>	<u>3,66</u>	--	<u>&gt;100</u>
Berg Aukas	Tons mined	1 600 000	--	4,04	16,77	0,93	10
	Tons reserve	1 650 000	--	5,00	17,00	0,60	10
	<u>Total</u>	<u>3 250 000</u>	--	<u>4,52</u>	<u>16,89</u>	<u>0,77</u>	<u>10</u>
Kombat	Tons mined	6 557 992	2,69	1,26	--	--	30
	Tons reserve	3 509 190	2,75	1,76	--	--	23
	<u>Total</u>	<u>10 067 182</u>	<u>2,68</u>	<u>1,93</u>	--	--	<u>26</u>
Abenab	No reliable data available.						

Although each mineral deposit in the Otavi Mountain Land has its own characteristics making each different from the rest, it is possible to distinguish between two broad types in terms of stratigraphy, mineralogy and isotope systematics. These can conveniently be described as **Tsumeb-type** and **Berg Aukas-type**. Their general characteristics are listed as follows:

**A. Tsumeb-Type:**

- i. Confined to the upper portions of the Tsumeb Subgroup, especially zone T8.
- ii. There is a close relationship with the upper unconformity which separates the Tsumeb Subgroup from the Mulden Group.
- iii.  $Cu + Pb > Zn$ . Principally a Cu-type mineralization.
- iv. Ag, Ge and Cd are important economic by-products. They are enriched in As.
- v. No stratabound mineralization.
- vi. Mineralization occurs in fractures, pipes, and solution breccias, but also in replacement bodies at Kombat.
- vii. The most significant deposits are located close to north-east trending fractures and faults regarded as reactivated basement structures.
- viii. The mineralization at Tsumeb and Kombat, where the most important ore bodies of this type are located, are intimately associated with feldspathic sandstone.

**B. Berg Aukas-Type:**

- i. Confined to the lower Abenab Subgroup.
- ii. There is a close relationship with the basal unconformity between the Abenab Subgroup and the Nosib Group or basement. The two principal deposits, Berg Aukas and Abenab, though occurring at different stratigraphic levels, lie equal distances above the basal unconformity.

- iii. Economic minerals are Zn-Pb-V.
- iv. There is no Cu-mineralization.
- v. Sulphides are enriched in Ag, As, Ge, Ga and Cd, although typically less than the Tsumeb-type mineralization (Emslie, 1980).
- vi. Brecciation and palaeo-karsting have been important.
- vii. Mineralization occurs as breccia bodies but may be both stratabound and discordant. Fracture filled mineralization is common.
- viii. There is a close relationship with the Grootfontein basement high.

The concept of a stratigraphic control on ore bodies of the Otavi Mountain Land is not new. Sohngé (1957) attempted to distinguish between those ore bodies located in the Tsumeb Subgroup from those of the Abenab Subgroup. He also noted the apparent mineralogical diversity of deposits in terms of the apparent lack of copper mineralization in the Abenab Subgroup.

Lead isotope studies (Welke *et.al.*, 1983; Allsopp *et.al.*, 1981; Hughes *et.al.*, 1984) on the ubiquitous occurrence of galena in both mineralization types have also established a clear isotopic distinction. High spectrographic resolution (Figures 5.1.1 and 5.1.2) indicates a bimodal separation of the data.

The isotopic data are in general agreement with those collected for Mississippi Valley-type deposits (Canon *et al.*, 1961; Sangster, 1976; Macqueen, 1979). Hughes *et al.*, (1984) have shown that there is a correlation between these data and other deposits in Africa. Tsumeb-type mineralization has a similar isotopic character to mineralization of the Kakontwe basin, Zaire (Kipushi, Lombe, and Kengere). Likewise, the Berg Aukas-type leads show a similarity to the Kabwe deposit (formerly Broken Hill) in Zambia, despite their setting in different fold belts.

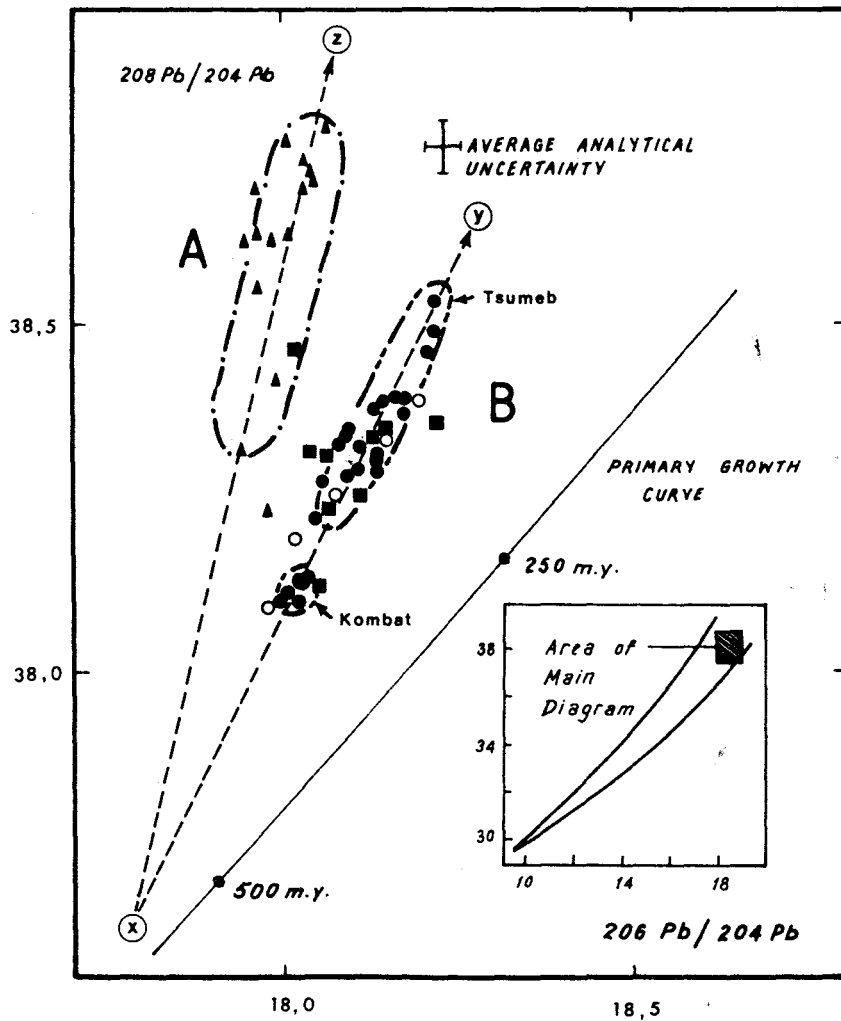
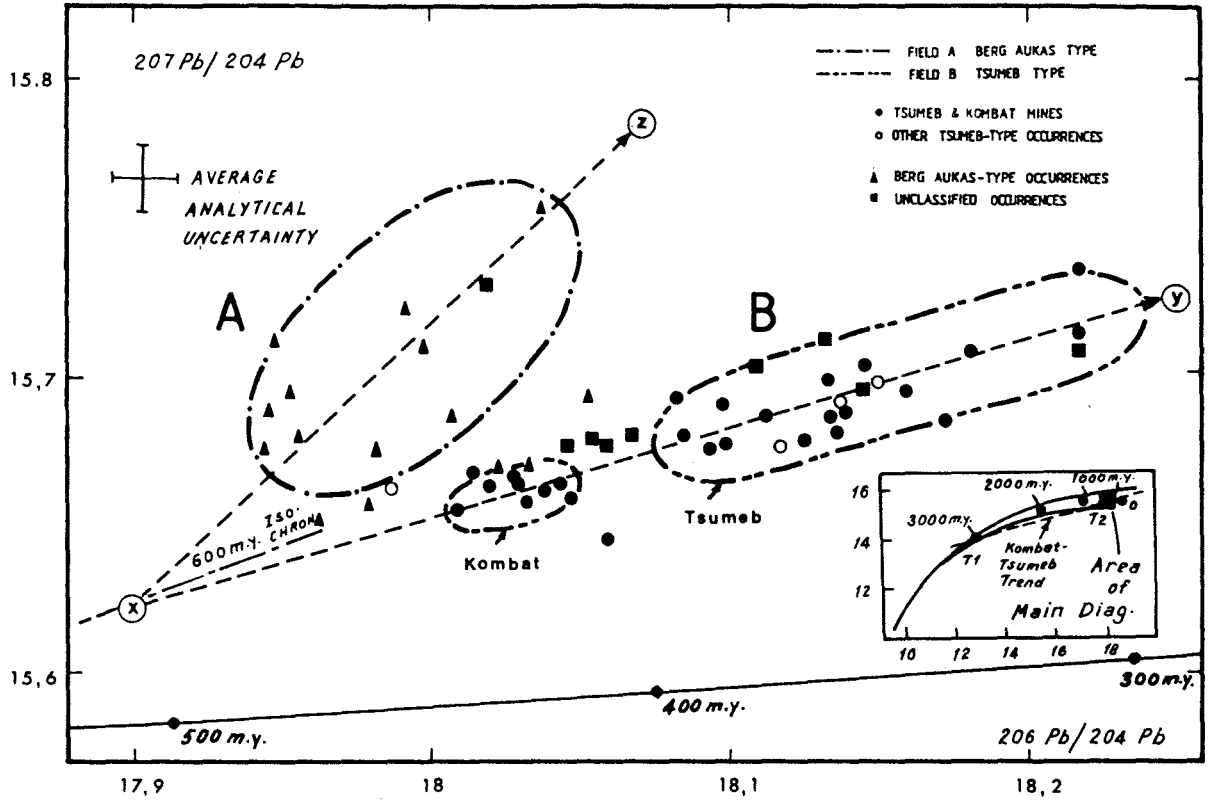


Figure 5.1.1 and Figure 5.1.2 : Experimental lead isotope data from mineral occurrences in the Otavi Mountain Land (from Allsopp *et al.*, 1981).

In general, both Tsumeb-type and Berg Aukas-type mineralization display features which broadly affiliate them to Mississippi Valley-type (MVT) deposits (Ohle, 1959; Beales and Jackson, 1966). These features are enumerated below:

- i. Their occurrence in insignificantly metamorphosed dolostones.
- ii. They have no obvious direct igneous source for ore generation.
- iii. Dominant economic minerals are Pb and Zn sulphides.
- iv. They have a high concentration of trace elements such as As, Cd, Ge, Ga, Co, Ni, Hg, and Ag.
- v. Mineralization is typically coarse grained and classified as open space filling.
- vi. Ore bodies are common in both passive and disturbed structural areas.
- vii. Karsting, solution activity, brecciation, and slump and collapse are important.
- viii. Mineralization has taken place in the vicinity of an apical or basal unconformity.
- ix. They have anomalous Pb-isotope values. In the Otavi Mountain Land these indicate a 3000 Ma source (Allsopp *et al.*, 1981).
- x. They are often located where there is evidence for evaporites.
- xi. Deposits are often found near a basement high, near the margins of basins or on arches between basins.

They differ from Mississippi Valley-type deposits by the notable lack of reef-hosted mineralization. The Cu mineralization of the Tsumeb-type ore bodies is atypical, and they have a higher grade than MVT's (Kyle, 1981). The Pine Point district, for example, averages 8% combined Pb and Zn.

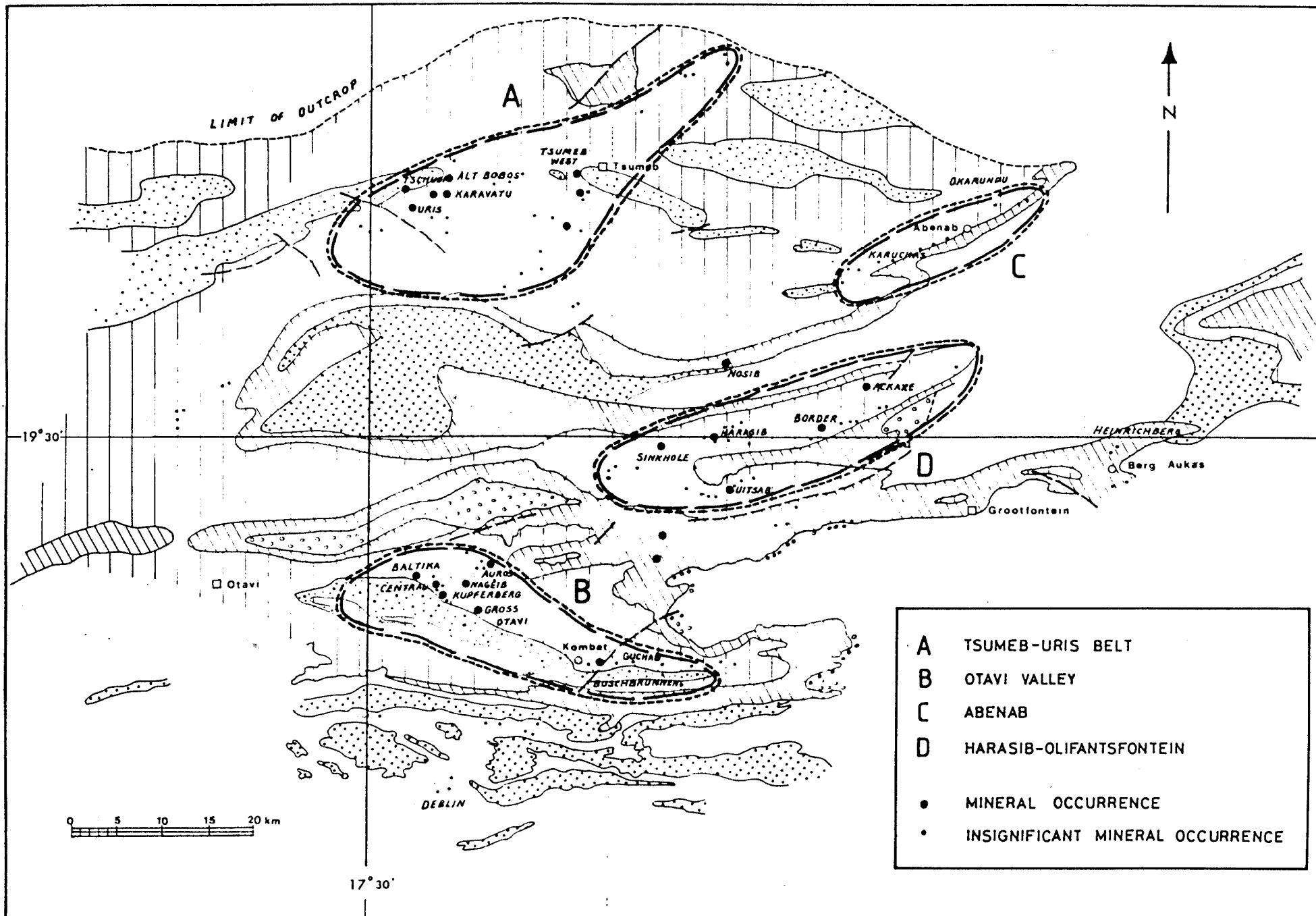


Figure 5.2.1 : Mineral occurrences of the Otavi Mountain Land.

## 5.2 Discussion of Mineralized occurrences

Tsumeb-type mineralization occurs in the Tsumeb - Uris belt and Otavi Valley. Berg Aukas-type mineralization occurs at Abenab and Berg Aukas and also includes the occurrences in the Harasib - Olifantsfontein Syncline. Two mineralized occurrences in the Nosib Group and one in the Mulden Group differ from the carbonate-hosted mineralization and therefore deserve mention.

## 5.3 The Nosib Mining Area

Mineralization at the old Nosib Mine is unusual in that it is best developed along the tectonised contact between clastic sediments of the Nosib Formation and laminated dolostones of the Abenab Subgroup. The defunct Nosib Mine was investigated between 1917 and 1920 using shallow underground development by the Otavi Exploration Syndicate Ltd., a subsidiary of the SWACO Ltd. It is located on the northern flank of the Nosib Anticline close to the Tsumeb-Grootfontein road. The geology is characterized by a transgression of laminated dolostones onto clastic lithologies which pinch out against the Grootfontein basement high in the east (Vickers, 1975c). Diamond drilling has indicated that the granite-Nosib contact increases in depth towards the west. The basement lithologies comprise heterogeneous Grootfontein-granite-gneiss intermixed with a variety of dioritic and hornblende-rich igneous rocks interpreted as gabbros (Vickers, 1975c; Markham, 1958e). Clastic sediments of the Nabis Formation, which comprise arkoses, arenites and conglomerates, unconformably overlie the basement. These in turn are unconformably overlain by the ferruginous mixtite of the Varianto Formation. The Abenab Subgroup comprises argillaceous laminated dolostones with intraformational breccias. Colloform and massive sucrosic dolostones cap the sequence. Diamond drilling has established that the basement-Nosib and Nosib-Abenab contacts are sheared (Schoch, 1958; Brandt, 1955).

The mineralization seems to be confined mainly to the Nosib Group-Abenab Subgroup contact where at least four small deposits of high grade secondary Cu-carbonates, Pb-oxides and Pb-Cu vanadates have accumulated in a highly ferruginous mud. The mineralization also occurs as disseminated pyrite, chalcopyrite, galena, sphalerite, bornite and chalcocite especially within the Varianto diamictite. On surface, the mineralization consists of disseminated malachite, azurite and mottramite in the diamictite, arkoses and conglomerates. Vickers (1975c) suggests that galena, cerussite and anglesite are generally rare and that the lead is probably in the form of lead oxides such as plumboferrite ( $\text{PbO}_2\text{Fe}_2\text{O}_3$ ) and massicot (PbO).

## 5.4 Deblin Mine, Askeveld Volcanics

The disused Deblin Mine situated on the farm Neuwerk 507 is hosted by the Askeveld volcanics. It is possibly

the only mineralized occurrence in the Nosib Group to have been exploited. It is one of three similar occurrences which do not exceed 300 000 tons. Very little is known of the geology, but the nature of this mineralization is regarded as being of indirect importance to the mineralization in the Otavi Mountain Land, particularly since it locates close to the southern extension of the Kombat West geofracture. The mineralization comprises disseminated chalcopyrite and chalcocite, and neodigenite in the supergene portion (Emslie, 1979).

### 5.5 Tsumeb-Type Mineralization in the Tsumeb-Uris Belt

All the known ore bodies and major prospects of the Tsumeb - Uris Belt lie within a zone, about 15 km wide, straddling the Tsumeb-West geofracture (Figure 5.2.1). Northeast and southeast of this fault zone the formations are virtually barren of mineralization, with the nearest ore showings occurring 20 km away at Nosib. The mineralized occurrences (Table 5.2.1) include Tsumeb West, Alt Bobos, Uris, Karavatu, and by virtue of its locality, the Tschudi sandstone-hosted deposit.

The Tsumeb ore body is the most important. It is the largest and the best studied (Lombaard *et al.*, 1986), and the interested reader is drawn to the attention of this detailed paper. In summary, it is a polymetallic pipe-like deposit with a total tonnage of 27,2 Mt at an average grade of 10,1% Pb, 4,4% Cu, and 3,7% Zn. In addition, it hosts important quantities of Ag, Cd, Ge, and As. The pipe structure (Figure 5.5.1), which is elliptical in plan, is defined by the distribution of mineralization, dolomite breccia, arcuate fracturing, rock alteration and feldspathic sandstone which was formerly termed the pseudo-aplite (Sohnge, 1964). The origin of the feldspathic sandstone is equated with the arenaceous facies of the Tschudi Formation.

Two breccia-types known as the dark dolomite breccia and dolomite breccia were formed by solution collapse initiated by circulating meteoric waters by way of the North Break, a significant palaeo-aquifer. Lombaard *et al.* (1986) suggest that an early period of folding resulted in a vertical fracture cleavage in the fold axial plane. Heated fluids migrated along this cleavage in the phreatic zone allowing carbonate dissolution to proceed with and the formation of the pipe which broke through into a basin undergoing deposition of arenaceous sediment of the Tschudi Formation. These sediments were washed into the pipe and were later replaced by rising metalliferous brines. The age of mineralization based on galena dating is set at 560 Ma (Lombaard *et al.*, *op. cit.*).

The Tsumeb West pipe is located 3 km west of Tsumeb and has a similar sandstone plug and disseminated mineralization but lacks an ore body. The Alt Bobos prospect situated in the T8 dolostones consists of a stratabound zone of malachite and chalcocite traceable for 2 km (Carbonate Workshop, 1986). The Karavatu prospect comprises an algal reef hosting desclozite-mottramite above hypogene galena and chalcocite. The Uris prospect is located in the T5 dolostones and is made up of karst cavity pockets which were filled with high grade vanadiferous sands.

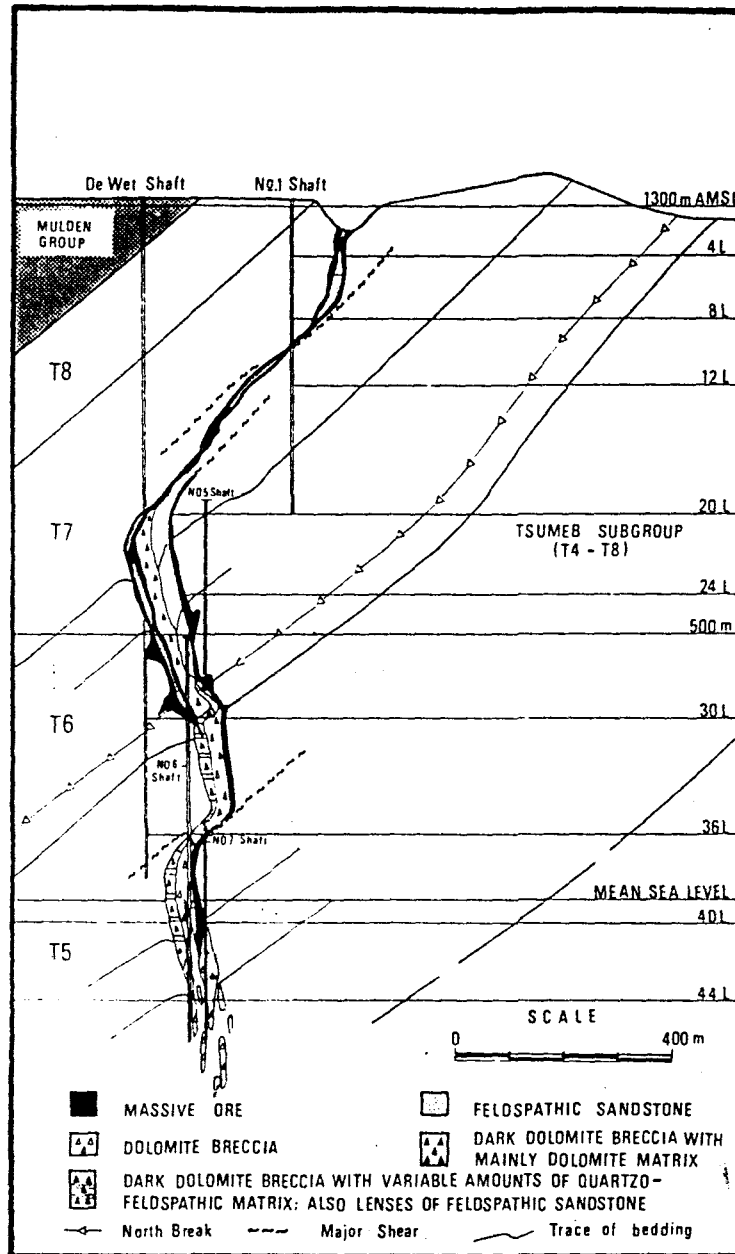


Figure 5.5.1 : Geological section through the Tsumeb Pipe illustrating the principal features of the deposit (from Carbonate sedimentology workshop, 1986).

### 5.6 Tsumeb-Type Mineralized Occurrences in the Otavi Valley

There are over a dozen mineralized occurrences in the Otavi Valley. These are mostly developed on the northern flank of the syncline, with possibly the only exception being the Buschbrunnen prospect which locates on the south limb at the eastern extreme of the Otavi Valley. However, this mineralized occurrence is insignificant and is probably atypical of the type located along the northern flank.

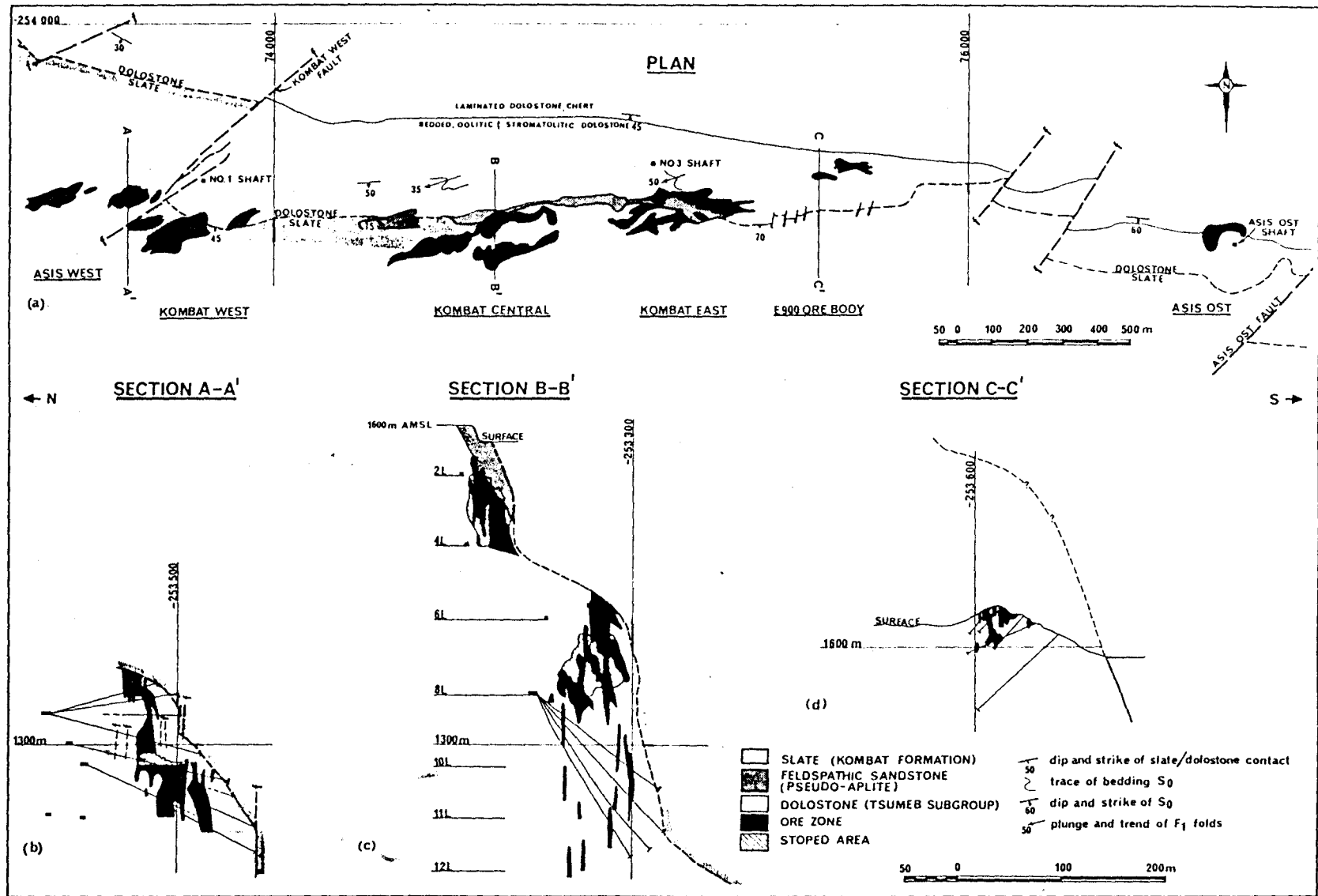


Figure 5.5.2 : (a) Generalized geology and surface projections of the Kombat ore bodies. (b), (c), and (d). Profiles of the Kombat ore bodies illustrating their relation to the contact between the Tsumeb Subgroup and Mulden Group. From Innes and Chaplin, 1986.

The mineralized occurrences include the defunct Baltika Mine, Rohrers/Central prospect, Kupferberg Mine, Auros prospect, Gross Otavi West, Central and East, Schneiderhohn prospect, Nageib, Kombat Mine, Nehlen and Guchab. Five ore bodies are currently being exploited at Kombat, viz. Asis Ost, Kombat East, Kombat Central, Kombat West, and Asis West (Figure 5.6.1).

The Kombat ore bodies (Innes and Chaplin, 1986) are confined to the contact between T8 dolostones and the overlying phyllites. The ore bodies are defined by dolomite breccia bodies with zones of steeply dipping shearing, fracturing, jointing and fracture cleavage. They strike ENE, plunge to the west, and are vertically disposed from monoclinial flexures developed as  $F_1$  parasitic folding along the contact ( $F_2$  of Innes and Chaplin, 1986) (Figure 5.6.1). The mineralization occurs as massive replacement lodes and as a variety of fracture-fill deposits. It is intimately associated with feldspathic pods, lenses, and stringers. The sandstone has been emplaced by way of brecciation and fracturing. Some of this may have been induced by karsting, but may also have been tectonically injected along fractures into areas which display no evidence for karsting (S. Galloway, pers. comm.). The mineralization (bornite - chalcopyrite - pyrite - galena - chalcocite) is intimately associated with breccias which range between synsedimentary, tectonic and karsting in origin. The mineralization is associated with iron-manganese bodies composed of hausmanite, magnetite, hematite, tephroite, barite, and a variety of manganese minerals which are unique to Kombat. The origin of these rocks remains unresolved but Innes and Chaplin (*op. cit.*) and S. Galloway (pers. comm.) draw attention to their similarity with volcanic exhalative deposits.

Alteration is characterized by ubiquitous calcitization, the origin of which is contentious. Innes and Chaplin (1986) regard the calcitization as a hydrothermal product, but this may also be due to solution brecciation. In a synthesis of the Elmwood Zinc District in America, Braun (1983) notes that although alteration is intimately associated with mineralization, the alteration is ubiquitous and there is no unique statistical correlation between alteration and mineralization. A similar conclusion can be applied for the Otavi Mountain Land, and, therefore, caution is necessary in distinguishing between these two varieties.

The mineralization in the Baltika-Kupferberg area (Weilers, 1958; Vickers, 1976; Misiewicz, 1986b) is similar to that at Kombat with the exception that no feldspathic sandstone lodes or iron-manganese bodies have been found with the mineralization. At Kupferberg, copper mineralization is principally tennantite rather than chalcocite, as at Kombat. Baltika Mine and Central/Rohrers prospect host more sphalerite (Markham, 1958c). At Baltika, three types of mineralization are recognized (Weilers, *op. cit.*). These comprise an "opencast" mineralization 100 m long and 200 m wide at the base of the jasperoidal dolostones, north-south trending fracture mineralization (Plate 7), and phyllite-dolostone contact mineralization. Although mineralization is well developed, no ore bodies have been detected.

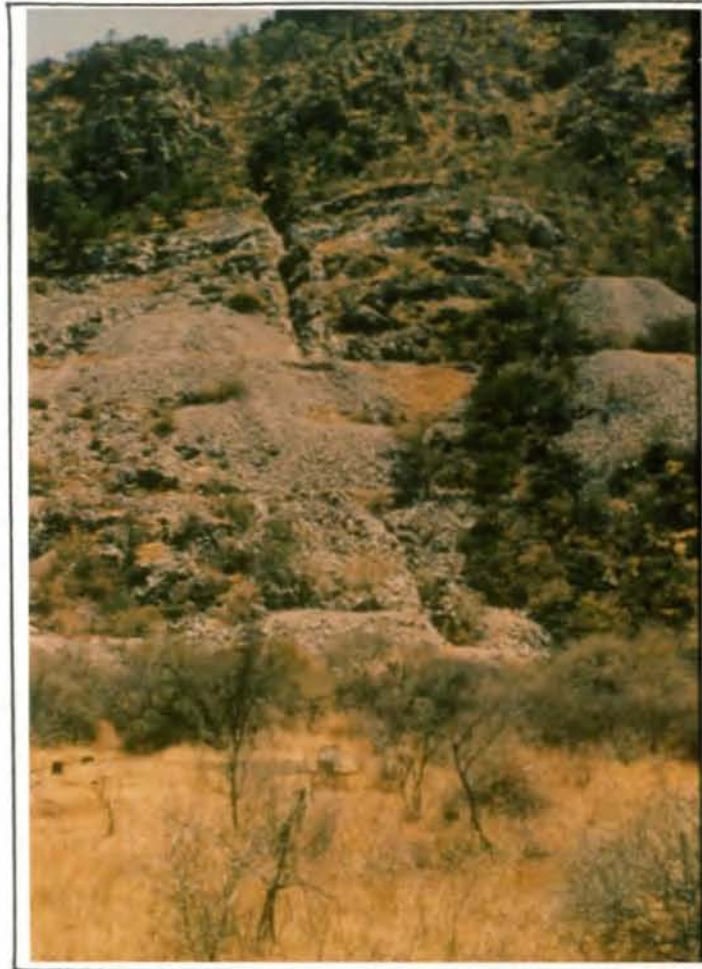


Plate 7 : View of the mined-out fracture mineralization at the defunct Baltika Mine. The fracture ends at the base of the T4 jasperoidal dolostones.

#### 5.7 Berg Aukas-Type Mineralized Occurrences at Abenab

Two ore deposits known as the Abenab Breccia Pipe (Old Abenab) and Abenab West Mines (Figure 5.7.1) were exploited between 1922 and 1958. The Abenab zone of mineralization is located on the south limb of the Tsumeb Syncline. The strata strike roughly east-west and dip between  $60^{\circ}$  to  $80^{\circ}$  NNW. The lithologies comprise the basal and upper members of the Tsumeb and Abenab Subgroups with the exception of the Chuos Formation which is locally absent. The stratigraphy is outlined in Table 5.7.1.

The Abenab Breccia Pipe (Figure 5.7.1; Plate 8) is situated on the Abenab Fault, a bedding fault developed along the massive dolostone/platy limestone contact. The breccia body is circular in plan and is a 250 m deep carrot-shaped structure comprising three forms of breccia (Weilers, 1962). Calcite cement hosts intermixed desclozite and vanadinite mineralization. No sulphide mineralization or oxidized sulphide ore was ever found associated with the pipe. This has fostered speculation that a sulphide body still exists at depth.

The Abenab Fault has a strike length of several kilometres. Tectonic breccias associated with intense shearing on the fault are not mineralized. The Abenab Breccia Pipe is only one of several similar younger breccias,

such as the Okarundu breccia pipes situated along the margin of the fault, but is the only one to be well mineralized.

Table 5.7.1: Stratigraphy at Abenab Mine

Bedded Dolostone T4		Elandshoek	
Karuchas Zone T4 (sil. dol. breccia)		Formation	Tsumeb Subgroup
Massive Grey Dolostone T3		Maieberg	
Platy Limestone T2		Formation	
Upper Pink Dolostone	Abenab		
Cluster Dolostone	West Ore		
<u>Lower Pink Laminated Dolostone</u>	<u>Horizon</u>		Abenab Subgroup
Blue Grey Massive Dolostone		Auros	
Laminated Grey Shale (3rd shale)		Formation	
Grey Siliceous Bedded Dolostone			
<u>Dark Grey Laminated Shale (2nd shale)</u>			

The Abenab West mine comprises a stratabound zone of Pb-Zn-V oxidized muds which were confined to a zone of deformation informally known as the Abenab West Disturbed Zone. It is made up of a "cluster" dolostone enclosed by upper and lower laminated dolostones. Plastic deformation was responsible for anticlinal and synclinal folding coincident with arcuate bedding faults presenting a broadly warped structural feature. The faulting was brought about by the incompetence of the platy limestone and footwall shales which envelop the Abenab West horizon.

The mineralization is confined to the pinch and swelling of the structure as "bedded cave deposits" (Verwoerd, 1957) comprising unconsolidated ferruginous clay enriched in cerussite, galena, willemite, descloizite and vanadinite. Mineralized lenses show a preference for steeper plunging parts of the structure, and tend to peter out where a flattening occurs.

The Karuchas Zone is a stratabound mineralized zone occurring in the upper stratigraphy. It is equated with lithozone T4 and hosts disseminated sphalerite and galena in a fracture mosaic. The mineralization rarely exceeds 4% Pb and Zn and consequently has never been exploited.

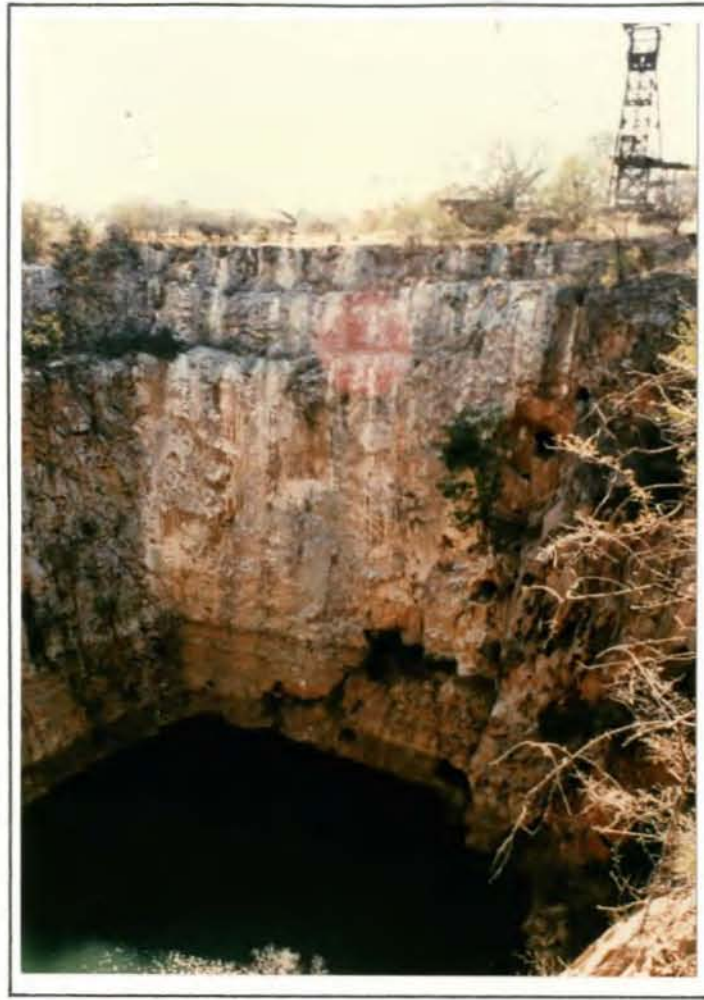


Plate 8: View of the opencast pit at the Abenab Breccia Pipe.

#### 5.8 Berg Aukas-Type Mineralization in the Harasib-Olifantsfontein Area

The Harasib-Olifantsfontein Syncline in the central Otavi Mountain Land hosts approximately a dozen mineralized occurrences with features broadly affiliating them to the Berg Aukas-type. These features include their Pb isotopic character (Allsopp *et al.*, 1981), their simple Pb-Zn mineralization which is often accompanied by descloizite, and their stratigraphic position at the base of the Tsumeb Subgroup which is similar to the Abenab deposits. The better known occurrences are Harasib Sinkhole (Emslie, 1979); Harasib I, Harasib II (Weilers, 1962); Uitsab North, Uitsab East (Vickers, 1975a, 1975b); Border, Olifantsfontein (Tigers Tunnel), Pickaxe, and Driehoek (Ypma, 1984).

Much of the mineralization is of the "Karuchas"-type in that it is associated with lithozone T4 stratabound brecciation attributed to regional slumping. Some of the mineralization, such as at Uitsab North, appears to be fracture-filled vanadiferous muds. The Harasib mineralization is hosted by solution collapse breccias in T5 dolostones.

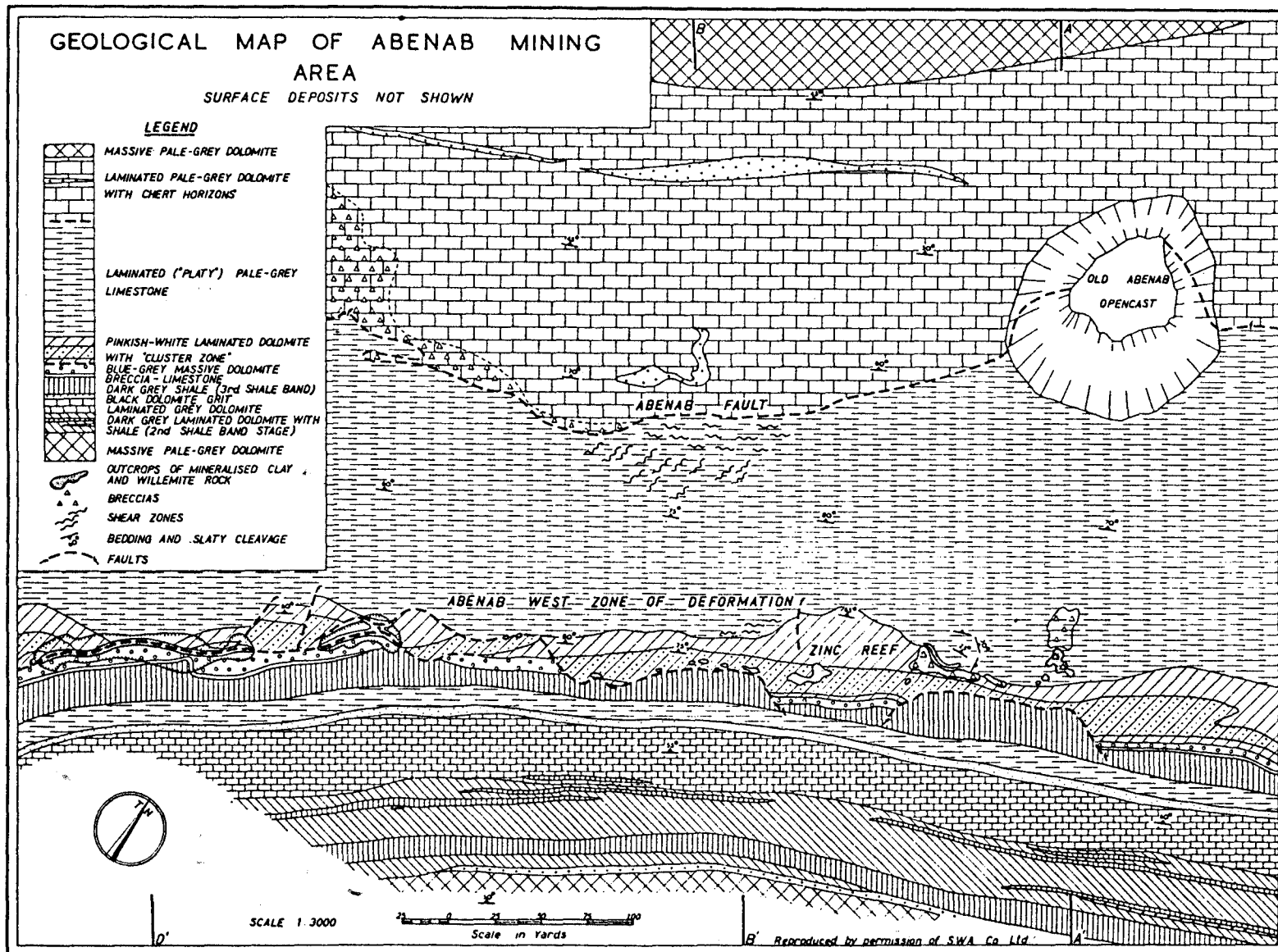


Figure 5.7.1 : From Verwoerd, 1957.

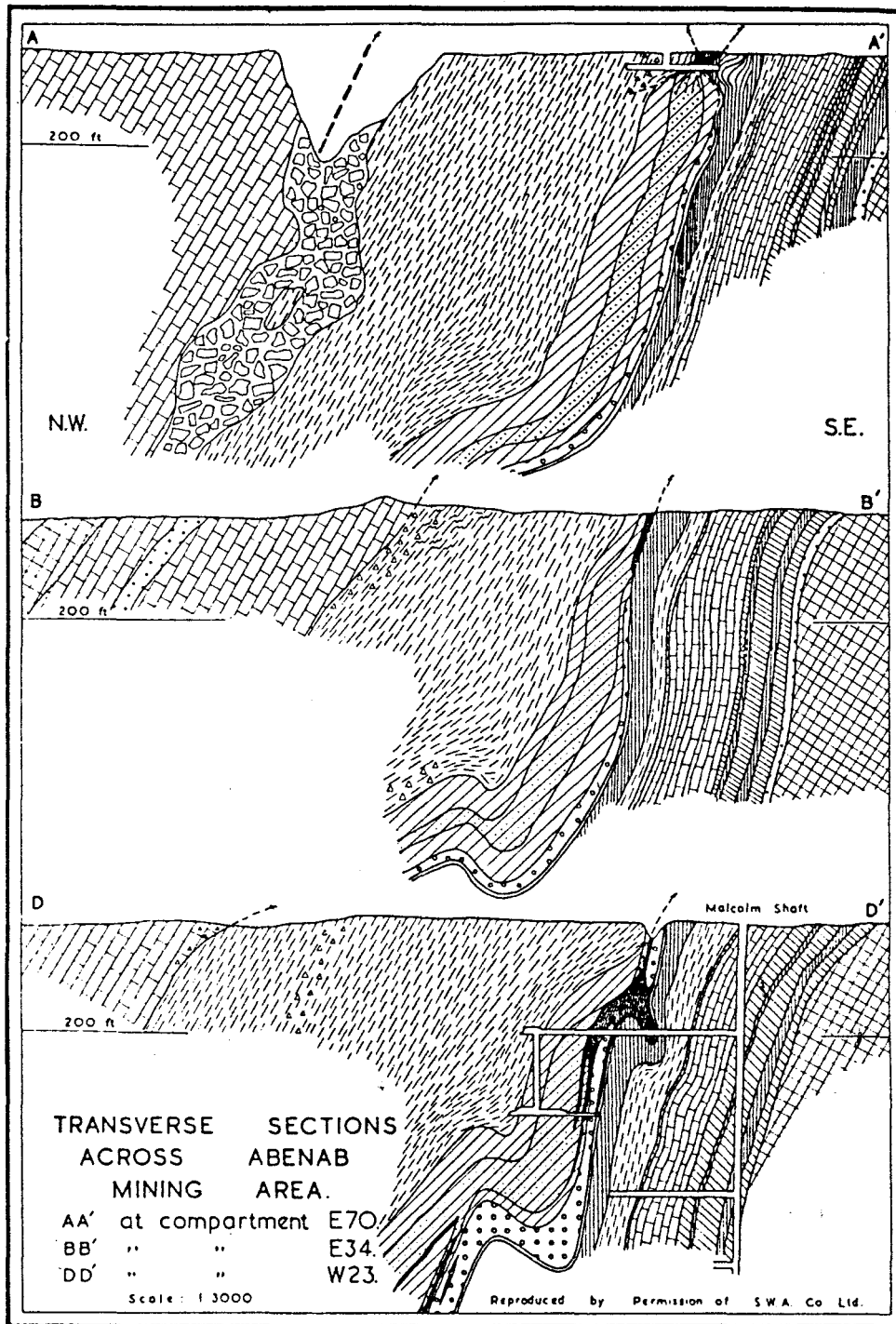


Figure 5.7.2 : From Verwoerd, 1957. Stratigraphic legend as for Figure 5.7.1 or Table 5.7.1.

## 5.9 The Tschudi Sandstone-Hosted Cu-Ag Deposit

An unexploited large tonnage - low grade Cu-Ag deposit is located in the Tschudi Syncline approximately 20 km west of Tsumeb. Disseminated chalcocite which is oxidized to malachite and azurite at surface, is hosted by feldspathic arenites of the Tschudi Formation immediately above the contact with the T8 dolostones. The contact is unconformably marked by a 30-40 m thick ill-defined unit comprising a dirty subgreywacke with a basal sand supported chert pebble conglomerate. Sinkhole depressions in the T8 dolostones attest to a period of subaerial karsting prior to Tschudi sedimentation. The depressions are filled with feldspathic arenite which constitutes the bulk of the Tschudi Formation.

The deposit is a tabular sheet-like body which dips at 30° to the north-west. The karst depressions are characterized by rich accumulations of chalcocite - bornite - chalcopyrite - pyrite. The mineralization is capped by argillite which acted as an impermeable seal. The mineralization displays a vague zoning from chalcocite at the base to bornite - chalcopyrite - pyrite at the top. P. Harrison (pers. comm.) suggests that a localized palaeo-high corresponding to a seismic reflector detected by the Etosha Petroleum Company in the Mulden basin (Hedberg, 1979), could have encouraged both subaerial karsting and the movement of rising hydrothermal fluids. Replacement of diagenetic pyrite in the sandstones is the proposed mechanism for metal precipitation.

Table 5.2.1: A. Tsumeb-type mineralization.

1. Localities in the Tsumeb-Uris belt.

<u>MINERAL OCCURRENCE</u>	<u>LOCATION</u>	<u>STRATIGRAPHIC POSITION</u>	<u>MINERALIZATION</u>
Dairy prospect	0,5 km east of Tsumeb.	Huttenberg Fm, T7	cpy, ma, ga, cc.
Domingo prospect	3 km SSE of Tsumeb on Tsumeb-Gtn road.	Huttenberg Fm, T7	cc.
Domingo Water Tower	South of Tsumeb.	Huttenberb Fm, T7	cu, cc, co.
Friesenberg	Southern slope of Friesenberg 9 km south of Tsumeb.	Elandshoek Fm	Tn, cc, co, ma, ga. Vanadates and sulphides.
Hoepker	Tsumeb Syncline near Otjikoto Lake.	Contact between Huttenberg and Tschudi Fm's.	Ma, cc.
Karavatu	10-15 km west of Tsumeb.	Huttenberg Fm	Ma, cerussite, gn, co, cc, diopase.
Otjikoto II	Tsumeb Syncline 13 km west of Tsumeb.	Huttenberg Fm.	Ma, az, cc, cu, tn, py.
Tsumeb Mine	Tsumeb.	Huttenberg Fm, T7.	Tn, cc, cpy, ga, sp, az, ma.
Tsumeb West	Tsumeb Syncline	Huttenberb Fm, T7.	cc, co.
Uris		Elandshoek Fm, T5.	Mottramite, py, tn, ga, sp.

2. Localities in the Otavi Valley.

<u>MINERAL OCCURRENCE</u>	<u>LOCATION</u>	<u>STRATIGRAPHIC POSITION</u>	<u>MINERALIZATION</u>
Asis Ost	Kombat mine	Huttenberg Fm, T8.	Cc, co, cpy, bo, py.
Auros	6 km north of Kombat.	Maieberg Fm, T3	Ga, sp, tn.
Baltika Mine	Baltika Mining Area, 12 km west of Kombat.	Huttenberg Fm, T6.	Mottramite, sp, wil, ga > tn, ma, cc, py.
Buschbrunnen	South limb, East Otavi Valley.	Elandshoek Fm.	Cc, co.
Central Prospect	Baltika- Kupferberg Reserved Area.	Huttenberg Fm, T6.	Sp, wil, mottramite.
Gross Otavi	5 km west of Kombat.	Huttenberg Fm.	Tn, cpy, bo, cc, co, py, ga.
Guchab	North of Otavi Valley.	Maieberg Fm.	Cc, co, ma, sp.
Kupferberg	Baltika- Kupferberg Reserved Area.	Huttenberg Fm, T7/T8.	Cc, tn, co, cpy, bo, py, sp.
Nehlen	1,5 km east of Asis Ost.	Huttenberg Fm.	Hm, cc, py.
Rodgerberg	Eastern closure Otavi Valley.	Maieberg Fm.	Cc, co, py, hm.
Rohrers Prospect	Baltika- Kupferberg Reserved Area.	Huttenberg Fm, T6.	Mottramite, sp, wil, hm.
Schneiderhohn Prospect.	West of Kombat	Elandshoek Fm.	Cc, co, ma, hm.

B. Berg Aukas-type mineralization.

1. Localities in the Abenab area.

<u>MINERAL OCCURRENCE</u>	<u>LOCATION</u>	<u>STRATIGRAPHIC POSITION</u>	<u>MINERALIZATION</u>
Abenab Pipe	Abenab 111, Tsumeb Syncline	Maieberg Fm/ Auros Fm contact.	Descloizite, vanadinite.
Abenab West	Abenab Tsumeb Syncline	Auros Fm.	Wil, smithsonite, cerussite, ga, sp, descloite.
Karuchas Zone	West of Abenab Mine.	Elandshoek Fm, T4.	Ga, sp.
Okarundu Pipe	East of Abenab Mine.	Maieberg Fm/ Auros Fm contact.	Descloizite.

2. Localities in the Berg Aukas area.

<u>MINERAL OCCURRENCE</u>	<u>LOCATION</u>	<u>STRATIGRAPHIC POSITION</u>	<u>MINERALIZATION</u>
Berg Aukas Mine	Berg Aukas Syncline.	Gauss Fm.	Sp, ga, wil, smithsonite, cerussite, descloizite.
Beacon Kopje	Berg Aukas Syncline.	Gauss Fm.	Ga, sp, wil.
Heinrichberg	Grootfontein Syncline.	Gauss Fm.	Sp
Kopje 1	Berg Auhas Syncline.	Gauss Fm.	Ga, sp.

3. Localities in the Harasib-Olifantsfontein area.

<u>MINERAL OCCURRENCES</u>	<u>LOCATION</u>	<u>STRATIGRAPHIC POSITION</u>	<u>MINERALIZATION</u>
Border	Olifantsfontein	Maieberg Fm zones T3, T4.	Sp, ga, tn.
Gauss Prospect	Harasib Syncline Farm Harasib 648	Gauss Fm.	Ga, sp, tn.
Harasib II	Harasib Syncline Farm Harasib 648.	Elandshoek Fm.	Sp, py, ga, tn.
Harasib Main	Harasib Syncline Farm Harasib 648.	Elandshoek Fm.	Sp, ga, py, tn.
Harasib Sinkhole	Harasib Syncline Farm Harasib 648.	Elandshoek Fm.	Ga.
Odin	South of Hoba Valley. Farm Odin	Berg Aukas Fm.	Ga, sp.
Pickaxe	East of Tsumeb- GTN road. Farm Olifantsfontein	Maieberg Fm zones T3, T4.	Ga, sp, descloizite.
Uitsab Pad	Farm Harasib 648	Elandshoek Fm.	Ga, sp, cerussite.
Uitsab East	Farm Uitsab 654	Elandshoek Fm.	Cc, co, ga, sp.
Uitsab North	Farm Uitsab 654	Maieberg Fm.	Ga, sp, tn, cerussite.
Uitsab Opencast	Farm Uitsab 654	Elandshoek Fm.	Ga, sp, tn, cc, co.
Uitsab Prospect	Farm Uitsab 654	Elandshoek Fm.	Py, sp, tn, cerussite.
Wolkenhaben	Farm Auros 595 5 km north of Kombat.	Auros Fm.	Mottramite- descloite.

## 6. THE GEOLOGY OF THE BERG AUKAS AREA

The Berg Aukas Zn-Pb-V deposit is located 20 km east-north-east of Grootfontein in the Berg Aukas Syncline, a small depocentre linked to the major Grootfontein Syncline (Figure 6.1; Plate 9). The geology of the Berg Aukas deposit is of particular interest because it is located in an area characterized by features which make it ideal for the development of a Mississippi Valley-type deposit. These include palaeo-physiographic features such as basement highs, rift margins, unconformities and structural and stratigraphic controls on ore deposition. The deposit is unique because it is probably the world's largest deposit of willemite and descloizite.



Plate 9 : Vertical aerial view of the Berg Aukas Syncline illustrating some of the pertinent features discussed in the text.

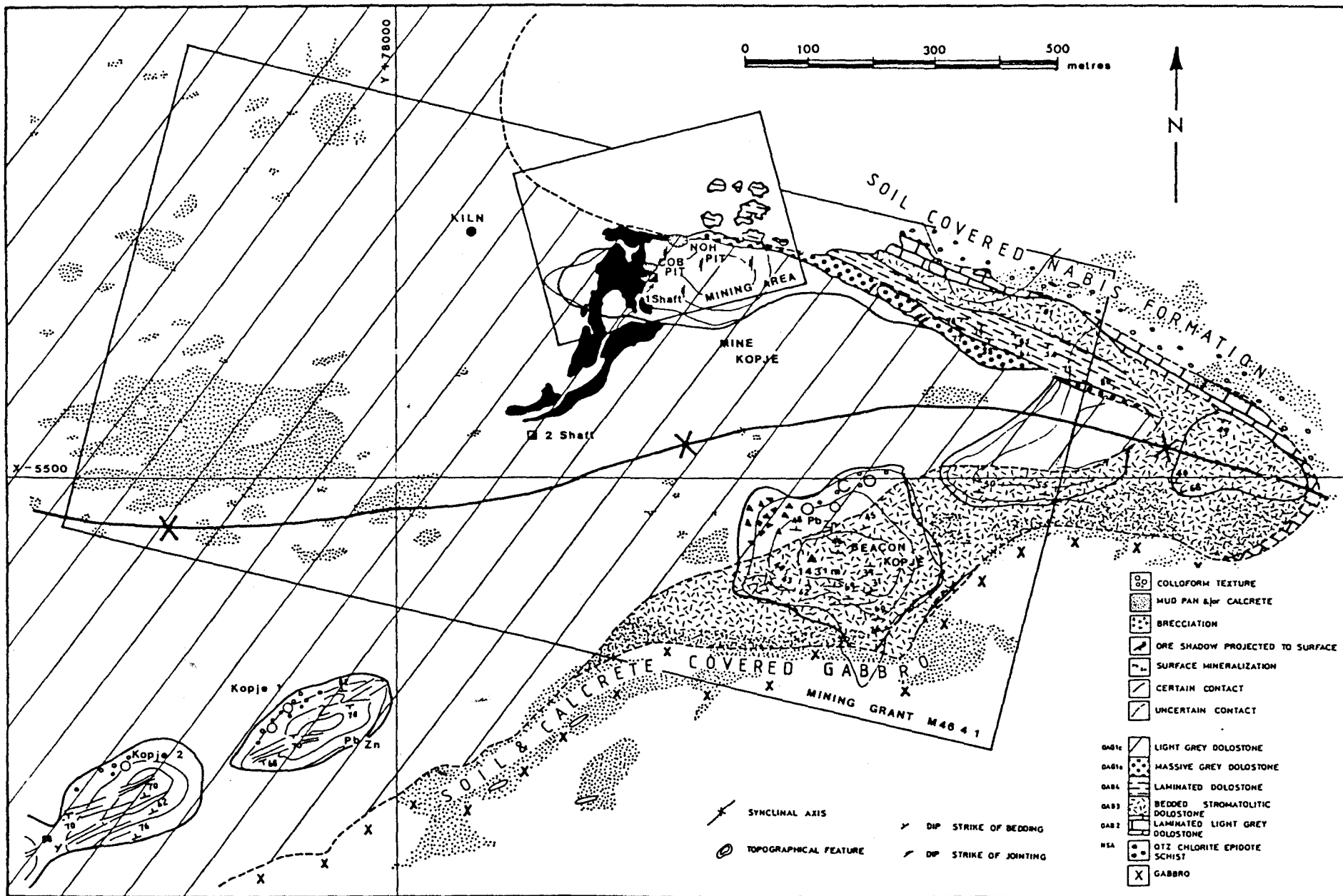


Figure 6.1 : Geology of the Berg Aukas Syncline. Ore body outlines have been projected to surface.

### 6.1 Stratigraphic Relationships

An interesting basement configuration exists beneath the Berg Aukas depocentre because it lies directly on the contact between Grootfontein Granite in the north, and basement basic intrusives to the south (Figure 6.1.1). There are indications that this is a faulted contact along which there has been considerable vertical movement. Petrographic evidence indicates that the rocks have been subjected to deformation. Sohngé (1957) referred to the southern contact as the Grootfontein Contact Fault, the existence of which has been verified by A.E. Lyons (pers. comm., 1987) on the basis of observed shearing and mylonitization. Sohngé believed it to represent a bedding thrust developed as a result of the tight infolding of the carbonates. However, there are indications that movement occurred by downfaulting of the southern block and that only later folding caused resurgence. It is proposed that this contact marks the southern limit of the Northern Platform with the transitional Northern Zone.

	LITHOLOGY	FORMATION	SUB - GROUP	GROUP		
	CALCRETE/SOIL	SUPERFICIAL COVER				
OTSM1	THIN BEDDED LIMESTONE	MAIEBERG	TSUMEB		DAMARA SEQUENCE	
OAA7	LAMINATED LIGHT GREY DOLOMITE	AUROS	ABENAB	OTAVI		
OAA5	BEDDED BROWN LIMESTONE					
OAA4	MASSIVE LIGHT GREY DOLOMITE					
OAA3	BEDDED BROWN LIMESTONE/SHALE					
OAA2	MASSIVE LIGHT GREY DOLOMITE	GAUSS				
OAGlc	GREY COLLOFORM DOLOMITE					
OAGlb	RECRYSTALLIZED GREY DOLOMITE					
OAGla	MASSIVE GREY DOLOMITE	BERG AUKAS				
OAb4	LAMINATED DARK GREY DOLOMITE					
OAb3	BEDDED-STROMATOLITIC LIGHT GREY DOL.					
OAb2	LAMINATED LIGHT GREY DOLOMITE					
OAb1	MASSIVE DARK DOLOMITE	NABIS				NOSIB
NSA	EPIDOSITE, QTZ CHLORITE SCHIST					
NSM1	QUARTZITE, ARKOSE, CONGLOMERATE					
AG2	ALTERED GABBRO				BASEMENT COMPLEX	
AG1	GRANITE	GROOTFONTEIN GRANITE				

Table 6.1.1 : Lithostratigraphy of the Berg Aukas and Grootfontein Synclines.

Clastic sediments of the Nabis Formation (Table 6.1.1) were deposited in grabens flanking the Grootfontein basement high. Alluvial fan and braided stream deposits comprising conglomerates and arenaceous lithologies were well developed east of Berg Aukas in the Gaikos and Kokasib Synclines where quartzite ridges mark the Otjitjika hills. Rift development in the Northern Nosib Rift (Porada, 1985) was accompanied by periodic uplift of the basement. The tectonic development of the Khomas Trough heralded the cessation of Nosib sedimentation, and the downfaulting of the margins of the trough. At Berg Aukas, a rift developed on the flanks of the Grootfontein basement along the contact between the granites and basic rocks. Intensely tectonised smokey black quartz with well developed slickensiding can be observed along the northern contact at the Berg Aukas fold closure. Rifting was more intense along the southern contact of the basement complex approximately 10 km south of Berg Aukas (Wilson, 1987), where a 5 km wide strike-slipped north-easterly

trending belt with a fault bounded south eastern limit has been identified.

As a result of uplift and rifting at Berg Aukas, a chaotic assemblage of Nosib rocks accumulated in the resulting depository by a process of mass wasting. A 100 m thick scarp wedge comprising fragments of conglomerates, arenites, and argillites was deposited along the rift margin of the Grootfontein Granite. This depository formed the depocentre for carbonate sedimentation with a palaeo-shoreline developed to the north and the deeper water environment to the south so that carbonate sedimentation overlapped onto the basic basement rocks.

Damaran orogenesis resulted in uplift of the basic basement and synclinal infolding of the carbonates thereby preserving the original sedimentary configuration. Sheared and fractured dolostones are a feature of the southern contact at Berg Aukas. Figure 6.1.1 schematically illustrates the development of the basin.

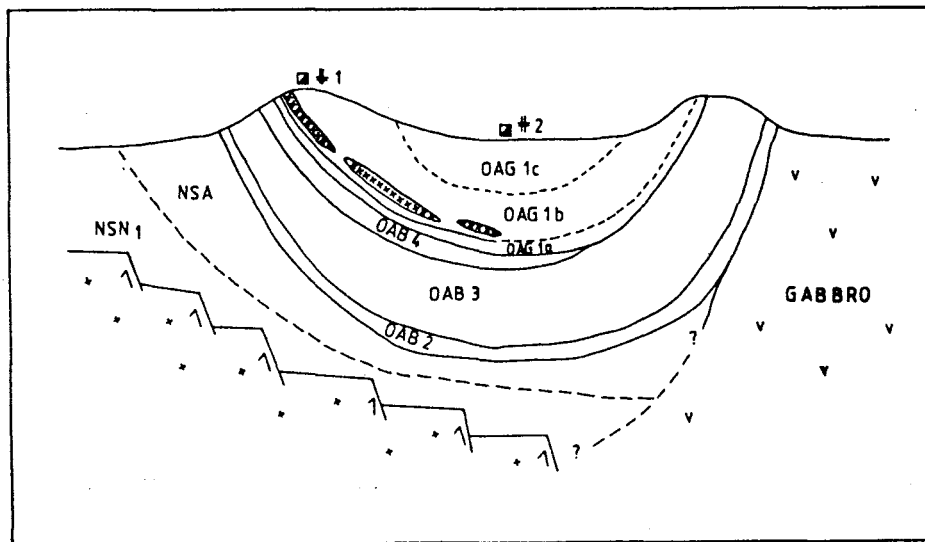


Figure 6.1.1 : Schematic north-south section, looking east, through the Berg Aukas Syncline illustrating the existing stratigraphic relationships.

## 6.2 Basement Complex

The nature of the Grootfontein Granite at Berg Aukas is largely unknown because it does not outcrop. Two diamond drill holes (Boreholes 78 and 98), both of which were drilled along strike on the northern limb of the syncline (Figure 6.1), intersected granite at depths of 434 m and 216 m respectively, below mine datum. This indicates that the Nosib lithologies rest on an uneven granitic palaeosurface which dips steeply to the south. Sohngé (1957) mentioned that the dolostones at Berg Aukas rest directly on granite. However, the author does not have knowledge of such a situation but does not exclude the possibility.

**Table 6.2.1: Volumetric analysis of Grootfontein granite/monzonite at Berg Aukas Mine**

	SAMPLE NUMBERS		
	modal %		
	<u>78/645</u>	<u>78/646</u>	<u>BA 4</u>
K-Feldspar	39	41	29
Plagioclase	29	27	30
Quartz	3	5	3
Hornblende	1	0	1
Biotite	1	0	2
Chlorite	5	2	2
Sericite	9	10	7
Calcite	9	10	7
Opagues	<u>4</u>	<u>5</u>	<u>3</u>
	100	100	100

Petrographic examination of three borehole samples (Borehole 78/645, and 646, and BA 4) indicates a saturated leucocratic medium to coarse grained holocrystalline rock which has been severely altered and deformed. It is composed of K-feldspar, plagioclase, quartz, biotite, hornblende, and zircon, and is classified according to the IUGS system as a (quartz-) monzonite. Secondary minerals include sericite, clay, quartz, carbonate, chlorite and opaques.

The slightly perthitic orthoclase ranges from medium to coarse grained and is typically hypidiomorphic. They have been subjected to intense sericitization (Plate 10) and alteration to clays which is possibly a manifestation of regional hydrothermal alteration. Primary plagioclase was determined to be oligoclase (Ab90-70) by maximum symmetrical extinction angle (MSEA). The oligoclase varies in crystal size from medium to fine grained, and often displays strain-kinking (Plate 11). The oligoclase has been severely altered to albite. The secondary plagioclase is typically a finer grained variety.

Primary quartz crystals are very rare, not exceeding 5% of the modal proportions. This establishes the rock to be a saturated variety of the Grootfontein Complex. Abundant secondary quartz recognized by their undulose extinction and ill defined grain boundaries is intermixed with the secondary sericite and clay. Occasional brown biotite has been mostly altered to chlorite and magnetite. Secondary calcite is common, and occurs as coarse and fine grained masses with well developed euhedral form.

The basic basement rocks are very poorly exposed along the south side of the Berg Aukas Syncline. These phaneritic medium grained rocks are green in colour and are highly altered by either the Damara metamorphic event or by a combination with regional hydrothermal alteration. The mineralogy predominantly



Plate 10 : Sericitization of Grootfontein Granite at Berg Aukas. Sample BA 78E/645, XP, 2,5x.



Plate 11 : Kinking of plagioclase feldspar in Grootfontein Granite at Berg Aukas. Sample BA 78E/645, XP, 2,5x.

comprises epidotized and sericitized plagioclase, xenoblastic chlorite and tremolite which are regarded as alteration products after clinopyroxene, acicular apatite needles, and opaque ore (mostly magnetite). Medium grained subidioblastic opalescent blue quartz grains characterized by undulose extinction are regarded as a probable product of regional hydrothermal alteration. Less altered gabbros are rare, but where observed have a troctolitic mineralogy which comprises coarse grained plagioclase, olivine which is commonly nearly completely altered, and pyroxene (Plate 12).

The plagioclase is labradorite, but some albite occurs as an alteration phase. The intensity of epidote and chlorite alteration varies such that the rock may be completely or only partially altered. The mineralogy indicates that the rock has undergone low grade greenschist metamorphism of an original gabbro.

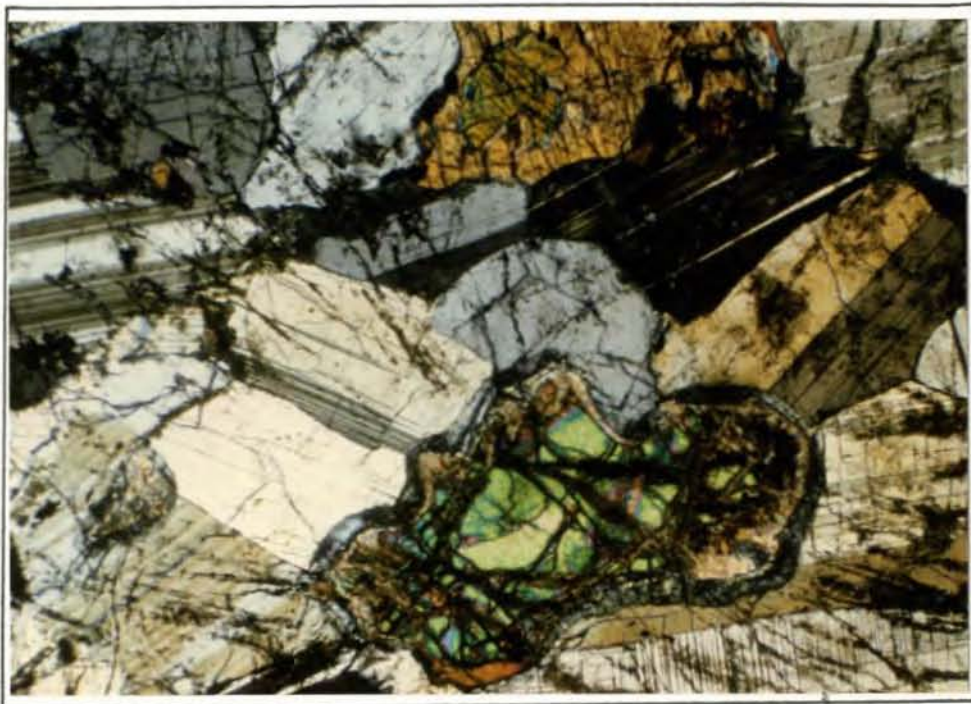


Plate 12 : Altered olivine and feldspar mineralogy of the basic basement rocks at Berg Aukas. Sample JEM 104, XP, 2,5x.

### 6.3 Nosib Group

Thick calcrete and residual soil cover on the outer flanks of the Berg Aukas Syncline are the prime cause for extremely poor bedrock exposure. The lithologies of the Nosib Group sporadically outcrop on the northern flank of the Berg Aukas Syncline. They comprise a chaotic assemblage of epidotized quartzites, conglomerates, arenites and granitic and other rock fragments embedded in a fine grained argillaceous

matrix. This assemblage is interpreted as the product of mass wasting which has been deposited on a localized rift margin. It is only developed along the northern flank of the Berg Aukas Syncline resulting in a localized basal unconformity between the basement complex and the carbonate sequences.

The Nosib sequence at Berg Aukas is broadly correlated with the Nabis Formation which is well developed further east. The clastic sediments were rapidly transported and deposited into a tectonic basin towards the end of Nosib times at the commencement of development of the Swakop Trough.

The rocks are greenish-yellow in colour and vary between phaneritic fine grained and equigranular epidotized quartzites (Plates 13 and 14) and porphyroblastic schists where deformed pebbles and rock fragments are embedded in a strongly foliated lepidoblastic and nematoblastic matrix of fine grained epidote and chlorite. The mineralogy includes quartz, albite, chlorite, epidote, calcite, orthoclase, microcline, sericite, sphene, zircon and opaques, some of which were identified as pyrite. The porphyroblasts are mainly quartz pebbles which have undergone elongate deformation resulting in a flaser structure. Strain or pressure shadows are typically developed (Plate 15), and even some "fish-mouth ends" have been observed. The quartz displays an undulose extinction verifying the deformational history. Other porphyroblasts include albite, microcline, orthoclase and chlorite. Some rock fragments, with a granitic mineralogy are also common, and display some rotation. Chlorite porphyroblasts are often kinked. Pyrite is the only sulphide to have been observed but malachite staining of several outcrop samples was noted. A relatively insignificant residual soil copper anomaly occurs in the Nosib outcrop area.

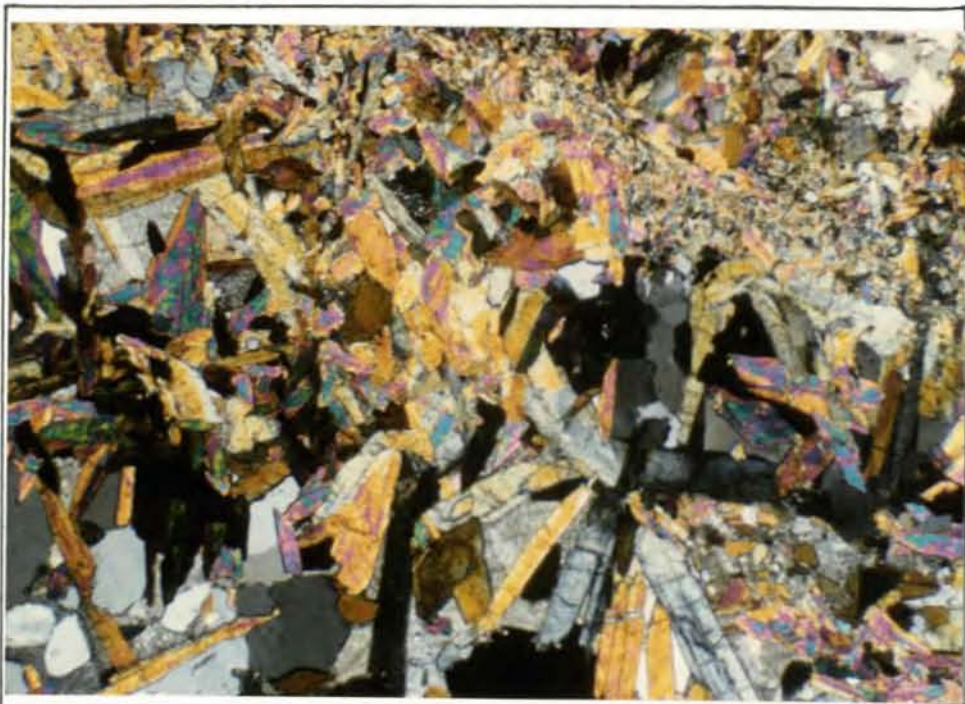


Plate 13 : Acicular epidote (high birefringence) within intensely epidotized and calcitized quartzite of the Nabis Formation at Berg Aukas. Sample JEM 105, XP, 2,5x.



Plate 14 : Acicular epidote (yellow, high relief) with colourless quartz and carbonate constituting epidotized quartzites of the Nabis Formation at Berg Aukas. Sample JEM 105, PPL, 2,5x.



Plate 15 : Deformed conglomerate pebbles of the Nabis Formation at Berg Aukas. The pebbles, comprising quartz with an undulose extinction, are hosted by a schistose matrix consisting of chlorite, epidote, carbonate and quartz. Sample BAD 2/9, XP, 2,5x.

The chlorite-epidote-albite mineralogy is indicative of low grades of metamorphism approximating to the lower greenschist facies. The schistosity of the rock suggests a regional dynamothermal origin. The poorly sorted chaotic assemblages which include original pebbles mixed with granitic rock fragments indicate localised dumping. Deformation and metamorphism is consanguinous with the Damaran event.

#### 6.4 Abenab Subgroup, Berg Aukas Formation

The Berg Aukas Formation is the basal transitional carbonate sequence above the clastic rocks of the Nosib Group. A regional unconformity marks a hiatus between the stabilization of the Northern Platform and the deposition of the carbonate sequences. The carbonates of the Berg Aukas Formation in the Grootfontein Syncline are characterised by a very haphazard distribution which presumably indicates a very irregular pre-Otavi erosional surface. During mine operations the Berg Aukas Formation was referred to by SWACO geologists as the Laminated Dolomite Unit. It comprises a sequence of laminated dolostones and limestones which may be locally argillaceous.

The laminated dolostones were important to the mine because they formed a distinct, easily recognisable marker horizon beneath the light grey dolostones of the Gauss Formation which hosts the ore bodies. They were also important because they are absent from the southern limb of the syncline where no ore bodies are known to exist. Although there is no apparent direct link between the laminated dolostones and the ore bodies, it did foster speculation that there was a relationship.

The Berg Aukas Formation comprises four facies which are clearly defined by composition, fabric and palaeoenvironment although the contacts are gradational and occasionally interfingered. The facies are referred to, from the base up, as the OAB1 to OAB4 members (Otavi Group, Abenab Subgroup, Berg Aukas Formation).

The basal OAB1 facies is locally absent from the Berg Aukas Mine stratigraphy and is not clearly defined. It is apparently well exposed on both flanks of the Grootfontein Syncline (Thirion, 1974) and varies between a very fine grained massive black dolostone and a gritty dark grey bedded limestone subfacies.

The lowermost horizon at Berg Aukas is the OAB2 facies. It is a very clean thinly laminated light grey micritic dolostone of uniform grain size which has undergone neomorphic recrystallization. The laminations are extremely thin, often only several grains thick. Occasional dark grey laminations are possibly indicative of original algal detritus. Some laminations, which tend to be slightly thicker are characterized by the presence of sparry calcite and occasional chert indicates a depositional porosity. The light grey laminated dolostones were deposited in a quiet shallow water environment typified by intertidal algal flats set in a back reef environment.

The OAB2 facies does not usually exceed 10 m in thickness. It is not well exposed, but can be observed on both flanks of the syncline. The best exposures are found along the northern flank, while in the south it is best seen in borehole core where it only persists for a few metres before grading into the overlying dolostones.

Facies OAB3 may be subdivided into two subfacies representing a lateral change in depositional environment. A well developed stromatolitic bed representing an organic "reef" parallels a palaeo-shoreline on the northern flank of the syncline. The stromatolitic reef undergoes a lateral facies change into thickly bedded and laminated dolostones on the southern flank which are more characteristic of a deeper water fore reef environment.

The stromatolitic reef has an exposed strike length of 800 m and a true thickness which varies between 30 m and 45 m. The stromatolites appear to be mainly of the conophyton variety as described elsewhere in the Otavi Mountain Land (Kruger, 1969; Schweltnus and le Roux, 1944). In outcrop (Plates 16 and 17), they rarely achieve individual heights of 30 cm and it is evident that the reef existed in a fairly turbulent environment because broken stromatolitic fragments caught amongst younger growths are common. This imparts a general chaotic appearance to the reef and explains why early mapping referred to the horizon as the "contorted dolomites".



Plate 16 and Plate 17 : Section through a stromatolite hand specimen collected from the northern flank of the Berg Aukas Syncline. Outcropping stromatolite reef along the northern flank of the Berg Aukas Syncline showing its distorted nature.

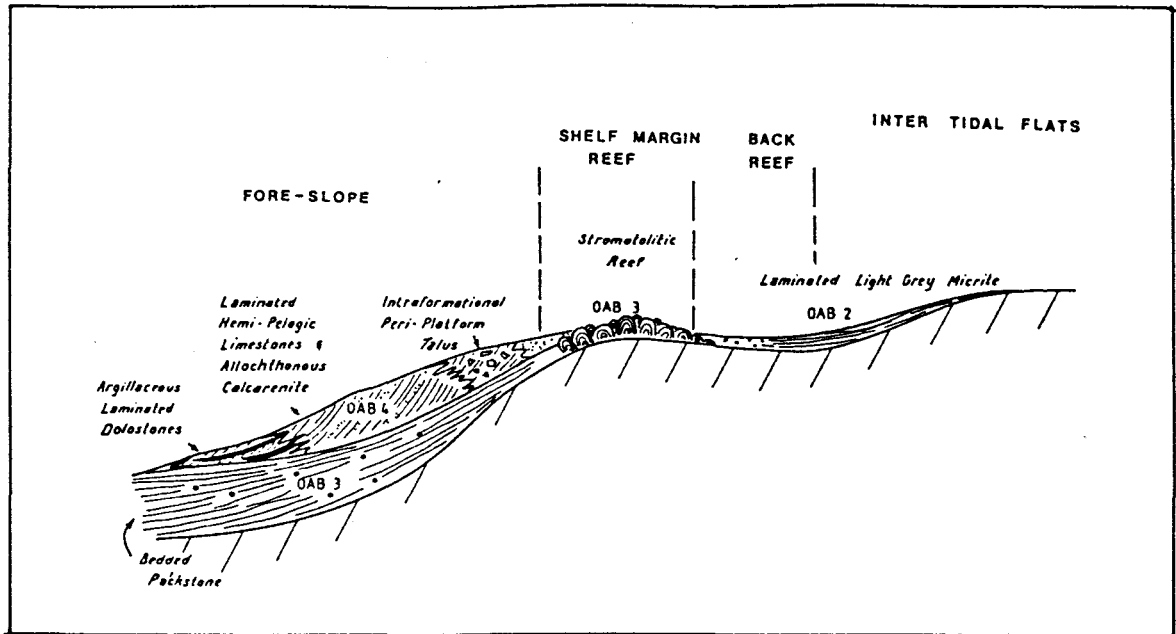


Figure 6.3 : Schematic section illustrating the environment of deposition of the Berg Aukas Formation.

The reef facies is a light grey micritic dolostone exhibiting sparry calcite and chert layers coincident with the stromatolitic layering. Abundant sparry calcite grapestone mosaics are indicative of a diagenetic porosity while the layering is suggestive of a primary depositional porosity. Occasional ghost structures indicate that some replacement has taken place. The fine grained ghost structures are round and can be up to one millimetre in diameter and are probably replaced algal matter.

The micritic matrix is a dense fine calcilitite (0,008 mm-0.016 mm) which has undergone some compaction during diagenetic dissolution. Neomorphism is restricted to a syntaxial overgrowth cement.

The deep water subfacies of the OAB3 member is a well bedded (where laminations exceed 1 cm) and laminated light grey dolostone. It is a locally thick facies and is best developed on the Beacon Kopje along the south eastern synclinal flank where it may achieve a true thickness in excess of 300 m. The dolostone ranges between a coarse silty micrite and a fine silty micrite. It is characterised by abundant ghost structures which are up to 0,5 mm in diameter and are regarded as replaced algal material washed into deeper fore reef waters (Plate 18). Occasional spheroidal ooids averaging 0,25 mm in diameter are fairly common in thin section (Plate 19).

A primary or diagenetic porosity has been totally filled with sparry calcite and occasional chert. The grains comprising the sparry calcite can reach diameters of 0,22 mm.

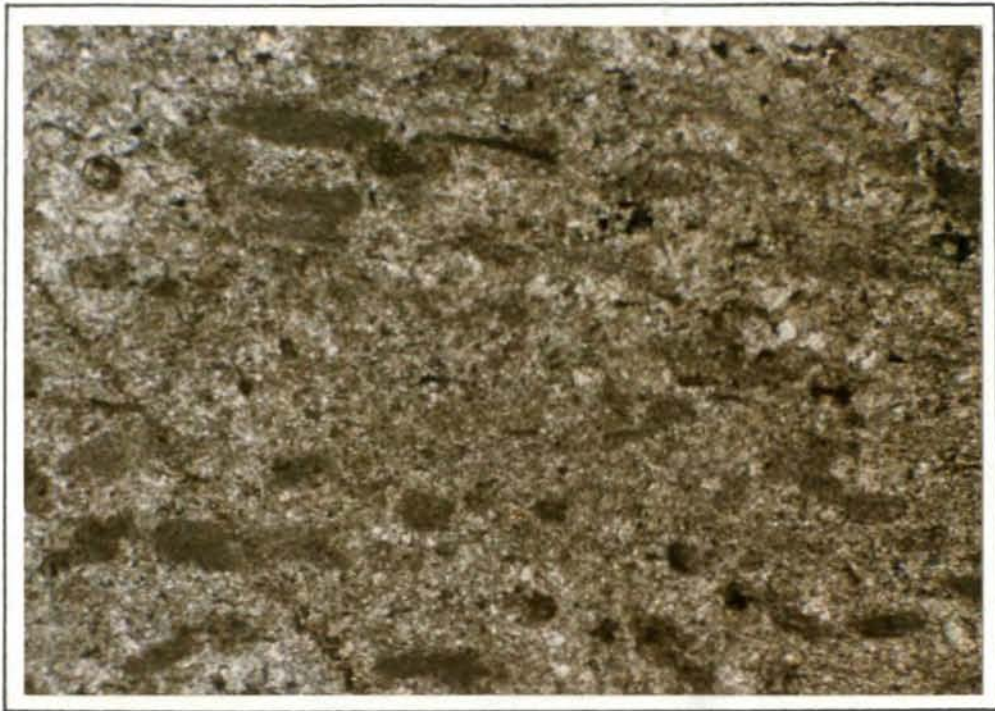


Plate 18 : Photomicrograph of bedded OAB3 dolostone from Beacon Kopje, Berg Aukas, illustrating the abundance of ghost structures and the occasional oolite. Sample JEM 111, XP, 2,5x.

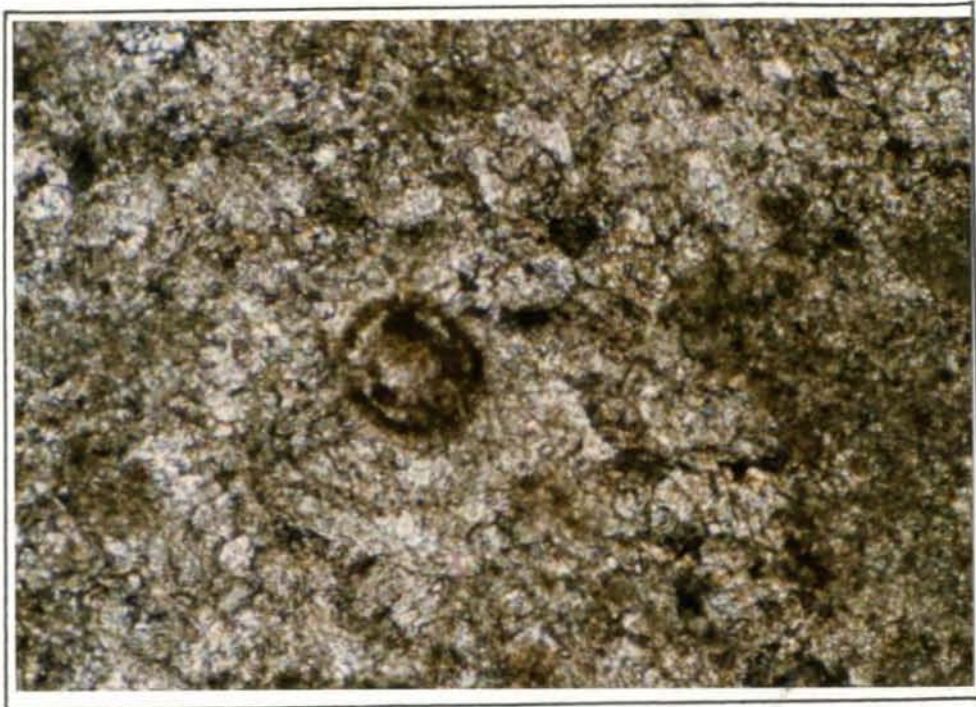


Plate 19 : Photomicrograph of oolite within the OAB3 bedded dolostones from Beacon Kopje, Berg Aukas. Sample JEM 111, XP, 10x.

The uppermost OAB4 facies of the Berg Aukas Formation comprises dirty dark grey and black laminated dolostones (Plate 20) which appear to have been deposited on localized shallow fore-reef slopes. An important aspect of the dark laminated dolostones is that they are not continuous along strike, probably due to a combination of local non deposition brought about by an uneven basement topography and facies change to a deeper water fore-reef slope environment. They have been mapped on both flanks of the Grootfontein Syncline (Thirion, 1974), but in the Berg Aukas syncline are only developed along the northern flank where they have a strike length of approximately 1500 m and thickness of 25 m to 60 m.

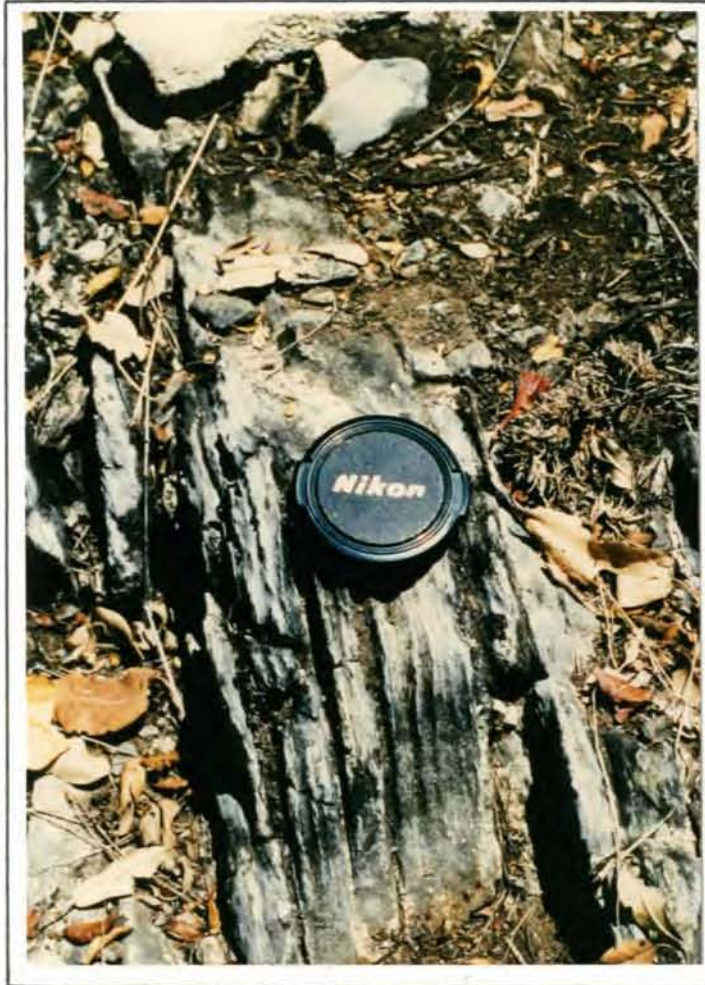


Plate 20 : Outcrop of Laminated Dolostone (OAB4).

The OAB4 facies is characterized by a thinly laminated and poorly sorted micritic packstone (Plate 21) with occasional fore-reef peri-platform talus slope breccias (Plates 22a and 22b). Predominantly dark grey and black laminations are occasionally intercalated with light grey layers. Occasionally coarser grained allochthonous calcarenites (Plate 23) are interlain with the finer grained laminations indicating a seasonal and climatic influence on the sedimentation. Darker laminations due to a high carbonaceous content may be locally developed as calcareous shales.

The breccias are sedimentary (Plate 22a and 22b) and appear to be a mixture of rip-up clasts and other carbonate detritus. They presumably form due to slope instability or storm action, or to a combination of these two factors.

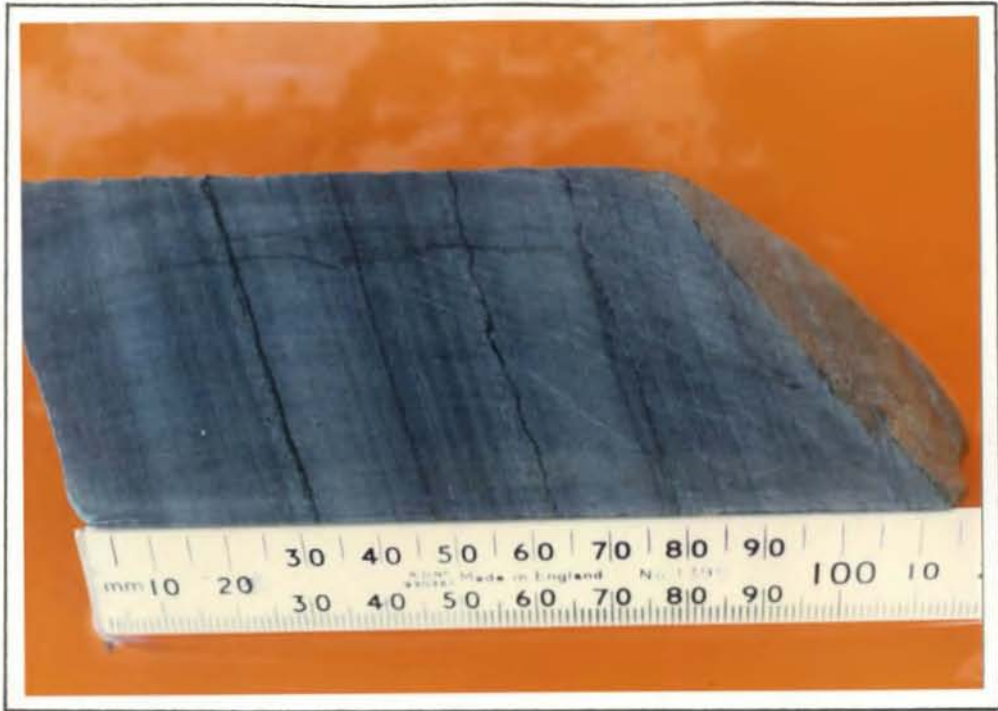


Plate 21 : Borehole section showing the fine grained sedimentary layering constituting the Laminated Dolostones.

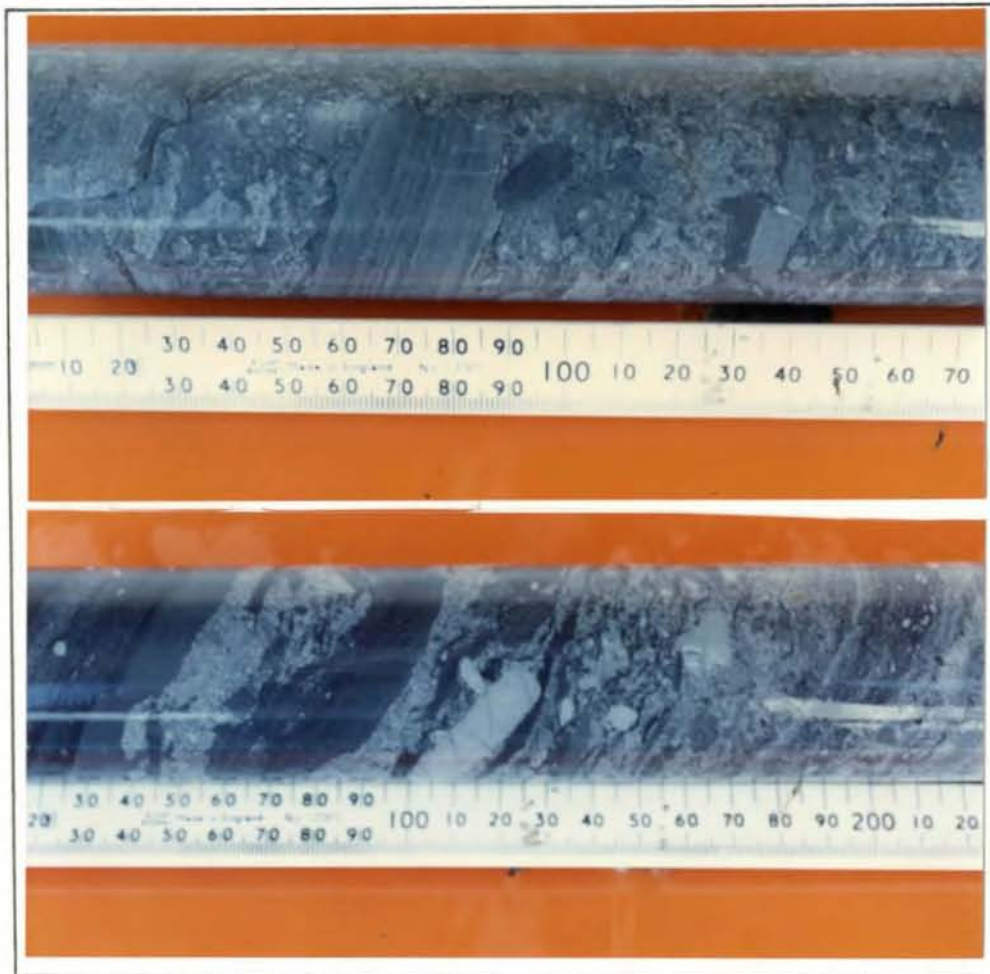


Plate 22a and 22b : Intraformational sedimentary breccias within the laminated dolostones.



Plate 23 : Calcarenite layers within the Laminated Dolostones. The sedimentary nature of the laminations can be clearly seen.

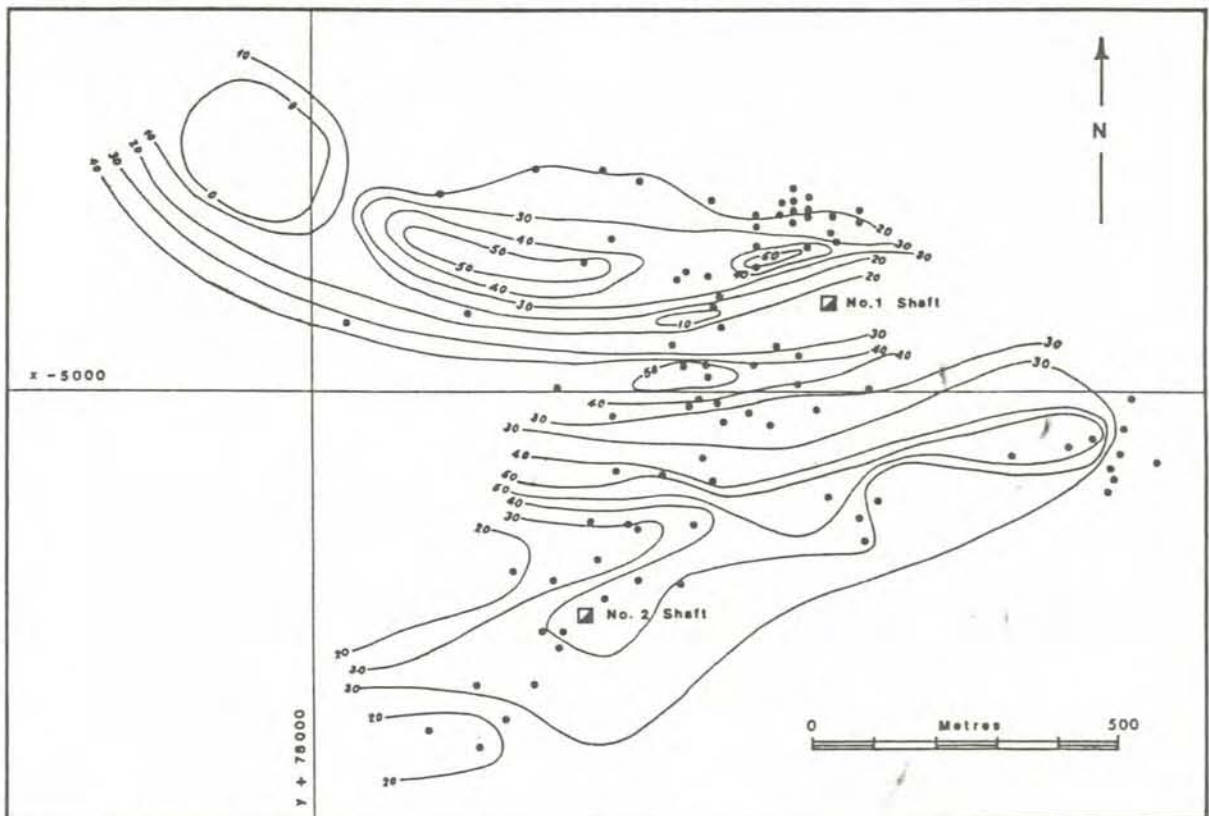


Figure 6.5.1 : Isopach plan of the Massive Grey Dolostone at Berg Aukas Mine.

### 6.5 Abenab Subgroup, Gauss Formation

The transition from The Berg Aukas Formation to the Gauss Formation is marked by a hiatus brought about by rapid subsidence and associated carbonate sedimentation. The subsiding basins adjacent to the cratonic area encouraged a shelf environment where continuous widespread deposits formed in shallow to moderately deep waters corresponding with facies 4 of Wilson (1975, 1983) (The depositional environment for the Berg Aukas Formation at the onset of deposition of the Gauss Formation is illustrated in Figure 6.5.1). These sediments formed in bottom conditions commonly below normal wave base, but above storm wave base.

The Gauss Formation at Berg Aukas was formerly referred to as the Light Grey Dolomite Unit. It comprises three texturally separable subfacies, each of which grades into the other. The basal OAG1a subfacies is known as the Massive Grey Dolostone (Plates 24a and 24b). It is a thin, irregularly thickened light grey



**Plate 24 :** Two examples of Massive Grey Dolostone. a. Surface specimen, b. borehole core.

mudstone and wackestone which in thin section (Plate 25) is seen to have a very low primary porosity. It typically has been well sorted, is well packed and totally lacks sedimentary structures. The lack of pore space suggests that the sediment underwent some compaction prior to diagenesis. Isopach analysis of the Massive Grey Dolostone (Misiewicz, 1985) indicates a regular elongate thinning and thickening pattern parallel to the palaeo-shoreline (Figure 6.5.2). The horizon is generally not thicker than 50 m and is best developed on the northern limb. It is not easily recognized on the south limb and may be characterized by lenticular pinch-outs.

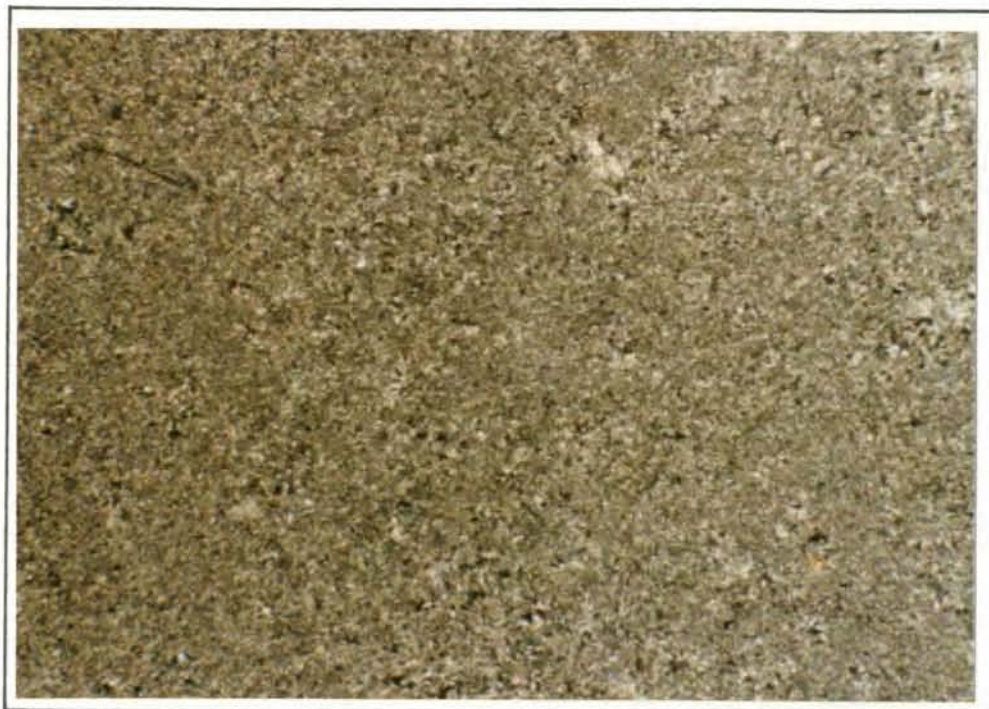


Plate 25 : Photomicrograph of the Massive Grey Dolostone illustrating its dense micritic, neomorphic, and compacted nature with no primary porosity. Sample JEM 14, XP, 2,5x.

The Massive Grey Dolostone grades upwards sharply into the OAG1b subfacies, a light grey packstone which has undergone some neomorphic recrystallization. The OAG1b subfacies was formerly known as the Recrystallized Dolomites, but in this text will be referred to as the Light Grey Dolostone.

The Light Grey Dolostone is a thick carbonate sequence which constitutes the exposed core of the syncline. It is a massive packstone displaying no evidence for bedding. In thin section (Plate 26), it comprises numerous ghost structures which are interpreted as algal detritus, are embedded in a micritic matrix. It is characterized by a primary porosity which has been filled with either sparry calcite cement or chert which may be dominant in localized settings. The Light Grey Dolostone has been subjected to neomorphic recrystallization without totally destroying the primary textures. It is possible that some sparry carbonate crystals are pseudomorphs after replaced anhydrite crystals (sample JEM 4).

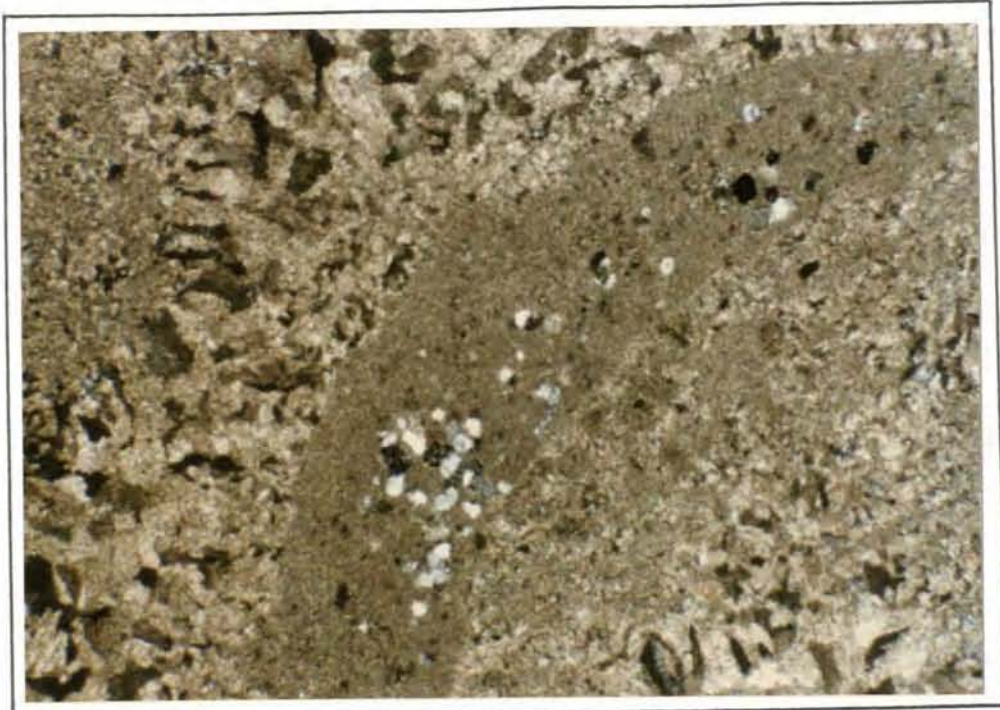


Plate 26 : Replaced algal detritus and sparry calcite filling primary porosity in the Light Grey Dolostones. Sample JEM 4, XP, 2,5x.

The distinguishing feature between the Massive Grey Dolostone and the Light Grey Dolostone is textural, reflecting the primary porosity contrast. The contact between these two horizons, therefore, represents a permeability front which, it is argued, has been exploited by rising hydrothermal fluids.

The uppermost OAG1c subfacies of the Gauss Formation at Berg Aukas does not represent a primary facies change but is a diagenetic feature which was formed in the subaerial environment. The subfacies is referred to as the Colloform Dolostone, and represents light grey dolostone which has undergone dissolution and colloformal precipitation. The colloform textures are spherical features comprising radial growths of siliceous carbonate around what must have been a suspended particle (still often discernable) in solution within an open space (Plate 27). Much of the colloform growth has been replaced by silica. The colloform structures vary in size, and may become very large, sometimes exceeding 30 cm in diameter.

Groundwater movement in the vicinity of a subaerial exposure initiated dissolution of sparry calcite from primary pore-spaces. Particles of dolostone are frequently seen in the centre of a spherical colloform feature, and implies that siliceous carbonate grew radially outwards until the entire space was filled.

Colloform Dolostone is well developed along the southern limb of the Berg Aukas Syncline, particularly along the north western flank of Beacon Kopje. A large slump breccia on the northern side of the kopje has

extensively undergone dissolution and colloform growth.

Other subaerial features include recent developments of caliche pockets. The caliche is a carbonate sand similar to calcrete but which has accumulated by carbonate dissolution in subaerial karst pockets.

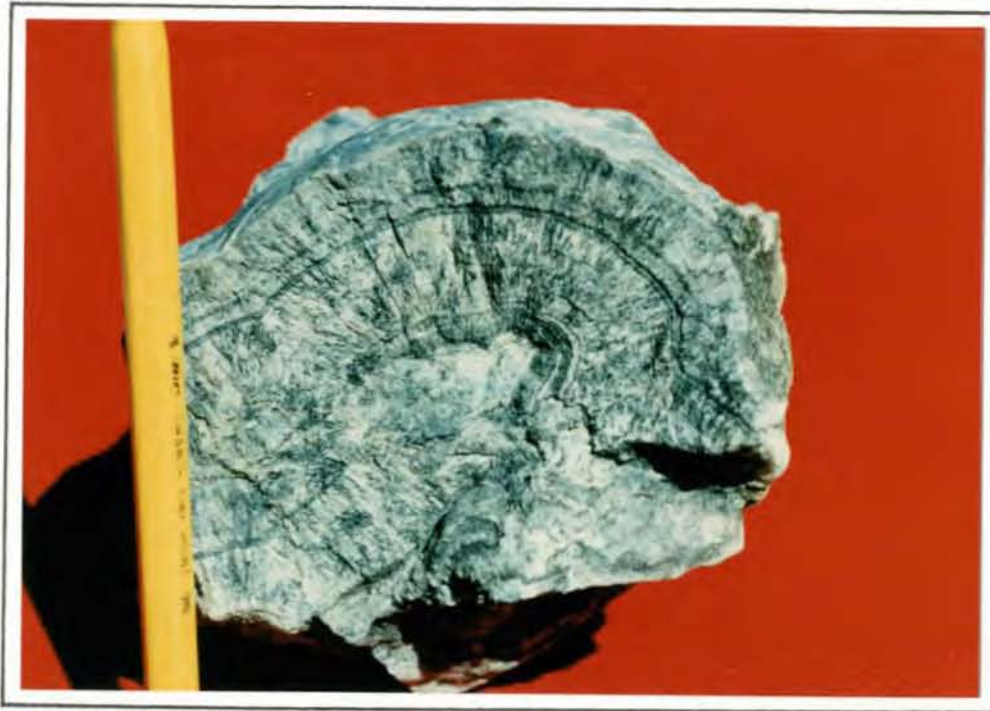


Plate 27 : Colloform Dolostone exhibiting concentric carbonate growth around a central large fragment. The sample is completely spheroidal.

#### 6.6 Abenab Subgroup, Auros Formation

The Auros Formation is exposed approximately 2500 m west of the Berg Aukas Syncline. It is a massive light grey dolostone with subordinate limestone and shale horizons, bedded limestone with subordinate dolostone, and laminated light grey dolostone. Columnar stromatolites are abundant, and the carbonate sequence indicates that sedimentation occurred in the intertidal environment.

#### 6.7 Structure

The north south trending Berg Aukas ore bodies are developed on the northern flank of the Berg Aukas Syncline, a 25° westerly plunging structure off the major Grootfontein Syncline. The Berg Aukas Syncline is approximately 6000 m in length and less than 2000 m at its widest. The structure represents an F<sub>1</sub> deformational event whereby north-south compression mostly resulted in steep limbed open folds. The limbs of the syncline form topographically dominant features clearly seen on aerial photographs (Plate 9).

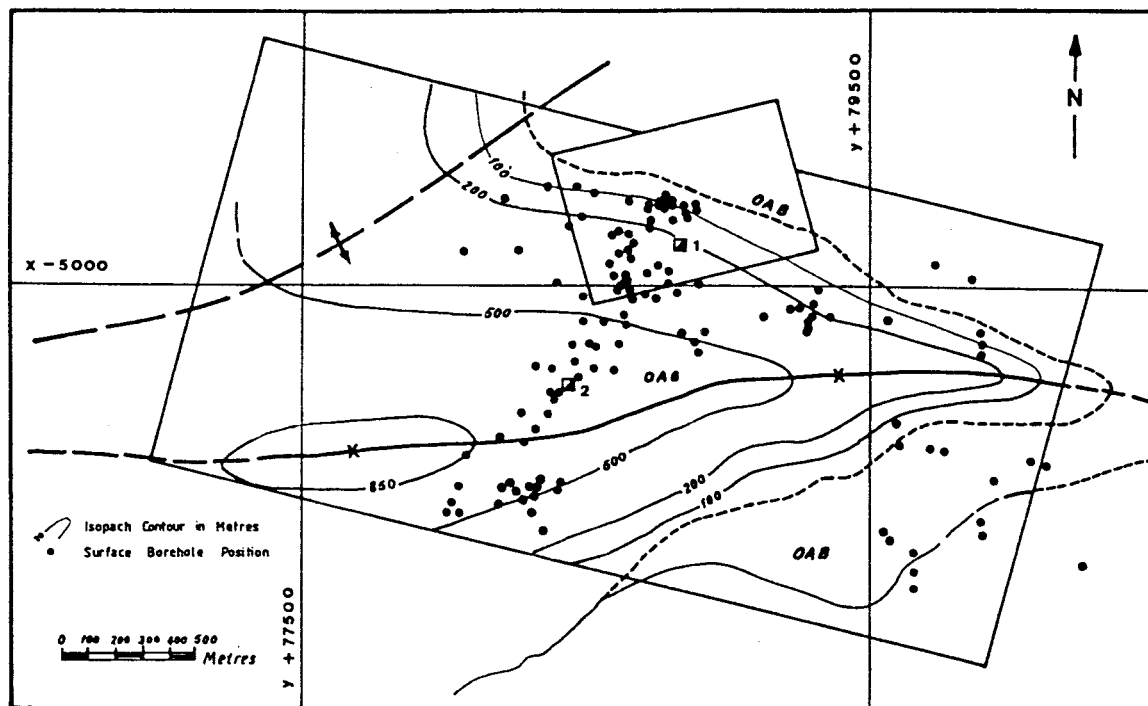


Figure 6.7.1 : Structural contours for the base of the Gauss Formation at Berg Aukas Mine.

The Berg Aukas fold structure is asymmetric about an approximately east-west striking fold axial plane. The north limb has a generally uniform dip approximating closely to  $70^{\circ}$  S, whilst the south limb has a variable attitude. In the vicinity of Beacon Kopje the bedding dips between  $70^{\circ}$  S and  $90^{\circ}$  but on Kopje 1 it tends towards a vertical dip and in some instances is overturned.

Photogeological interpretation indicates that the 30 km long Grootfontein Syncline is a doubly plunging structure with its broadest dimension west of Berg Aukas where it has a width of 6000 m. The curvi-linear Grootfontein axial plane is partly due to the basement configuration, but also to the mild  $F_2$  folding which initiated the doubly plunging structures.  $F_2$  compression also influenced the Berg Aukas Syncline, developing a periclinal canoe-shaped basin but not exposing its western closure (Figure 6.7.1). P.D.F. Vickers (pers. comm.) reports that during mining activities at Berg Aukas, water input increased with mining depth until at 14 level (400 m below surface) the water input stabilized and became constant regardless of any increase in mine depth. The  $F_1$  folding was responsible for a pronounced S shear cleavage dipping  $60^{\circ}$  to the north which is best seen in the argillaceous dolostones (Weilers, 1959) of the OAB4 subfacies.

The  $F_2$  compressional event, although mild, was a significant deformational event in the history of the Berg Aukas deposit. The  $F_2$  axial planar trend broadly corresponds with the direction of the Berg Aukas ore

bodies. Disharmonic  $F_2$  folding on the north limb of the Berg Aukas syncline resulted in occasional north-south trending anticlinal-synclinal warping (Weilers, 1959; Schreuder, 1969).

$F_2$  deformation was responsible for extensive north-south dip fracturing and jointing, but no faulting has been observed. Three fracture directions exist, although the first predominates:

$N10^{\circ} W$ , dip  $80^{\circ} - 90^{\circ} W$

$N30^{\circ} E$ , dip  $80^{\circ} - 90^{\circ} NW$

$N95^{\circ} E$ , dip  $80^{\circ} N$

$N70^{\circ} E$ , dip  $25^{\circ} N$

The  $N30^{\circ} E$  axial planar fracturing is the important ore control. On 19 level the fracturing swings southeasterly  $S55^{\circ} W$  and appears to be drawn into the  $F_1$  fold axial plane. Schreuder (*op. cit.*) draws attention to the coincidence of north-south fracturing, probably  $S_2$  fracture cleavage, and the  $F_2$  folding. It is clear that these two structures are related and where they occurred in the keel of the  $F_2$  fold axial plane influenced the movement of hydrothermal fluids.

Several other important structural features require mention. The southern basal carbonate contact south of Beacon Kopje is marked by a major basement inflection with the appearance of a fold structure. The nature of this structure has not been fully resolved (Misiewicz, 1986a) but is most likely a reflection of the uneven basement topography.

No faulting in the carbonate sequences has been noted, but the basal contact has been subjected to bedding plane movement and is known as the Grootfontein Contact Fault (Sohnge, 1957). Shearing along this contact is best observed in borehole core (A.E. Lyons, pers. comm.) and is reported to be developed for up to 17 km west of Berg Aukas (Sohnge, *op. cit.*). The contact fault is an important water aquifer and has been investigated in a number of places for this resource by the Department of Water Affairs.

LANDSAT imagery indicates extensive northwest striking faults in the basement complex which terminate against the carbonate sequences. The most prominent lineation is marked by swampy ground and calcrete development, intersecting the Berg Aukas Syncline in the vicinity of Beacon Kopje, but shows no evidence for displacement of these sequences. At the Strydfontein beacon, 7 km west of Berg Aukas, a high angle fault displaces the contact in the vicinity of where a basement LANDSAT northwest trending fault has been detected.

### 7. GEOLOGY OF THE BERG AUKAS ORE DEPOSIT

The Berg Aukas Zn-Pb-V deposit is hosted by the Light Grey Dolostones of the Gauss Formation. In the context of this discussion, an ore body connotes a mineable zone of economic ore which may be a continuously mineable zone or a series of lenses with sufficient unifying criteria to be described jointly. An ore deposit refers to an area encompassing a number of ore bodies.

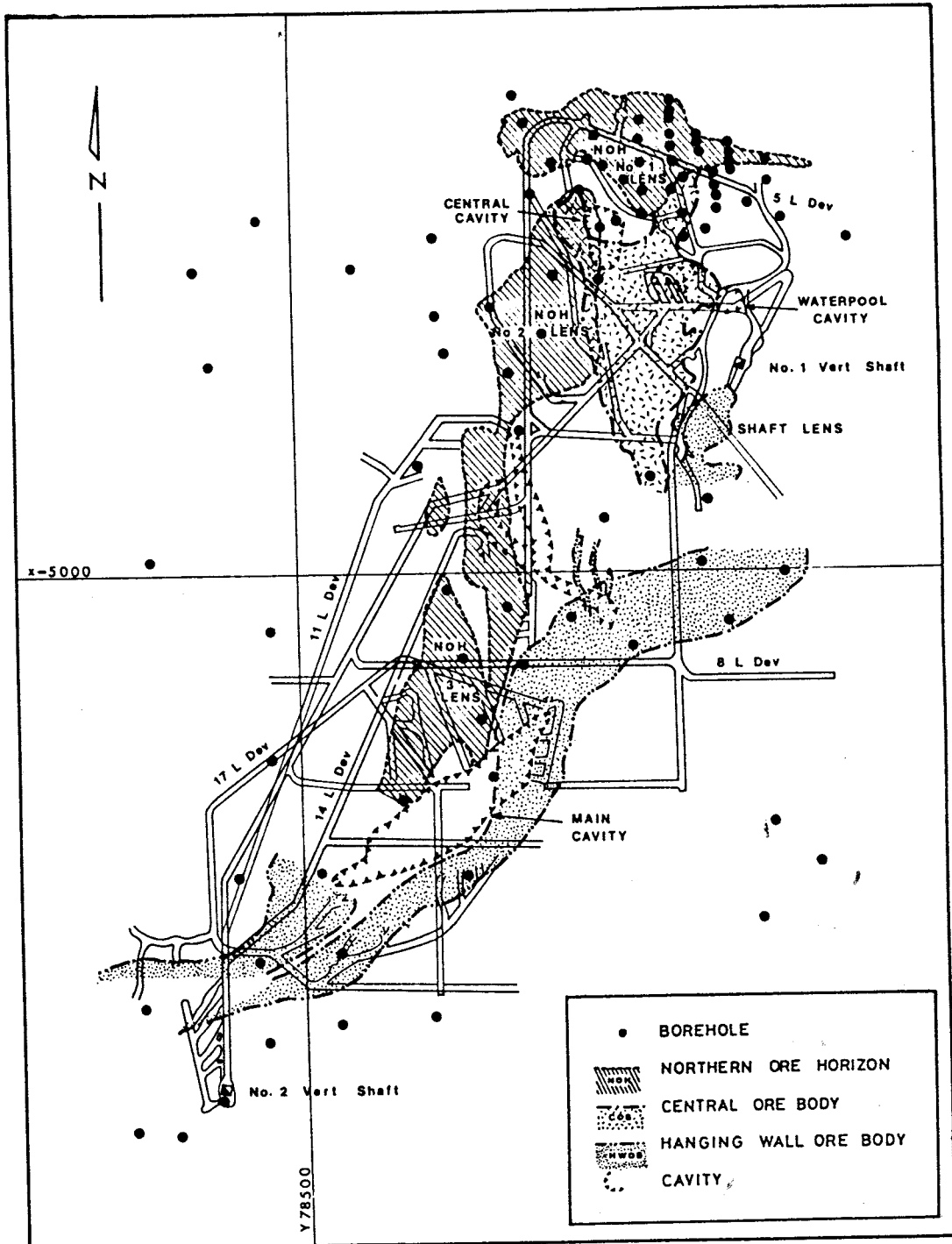


Figure 7.1 : Composite underground plan of the Berg Aukas deposit. Ore shadows have been projected to surface.

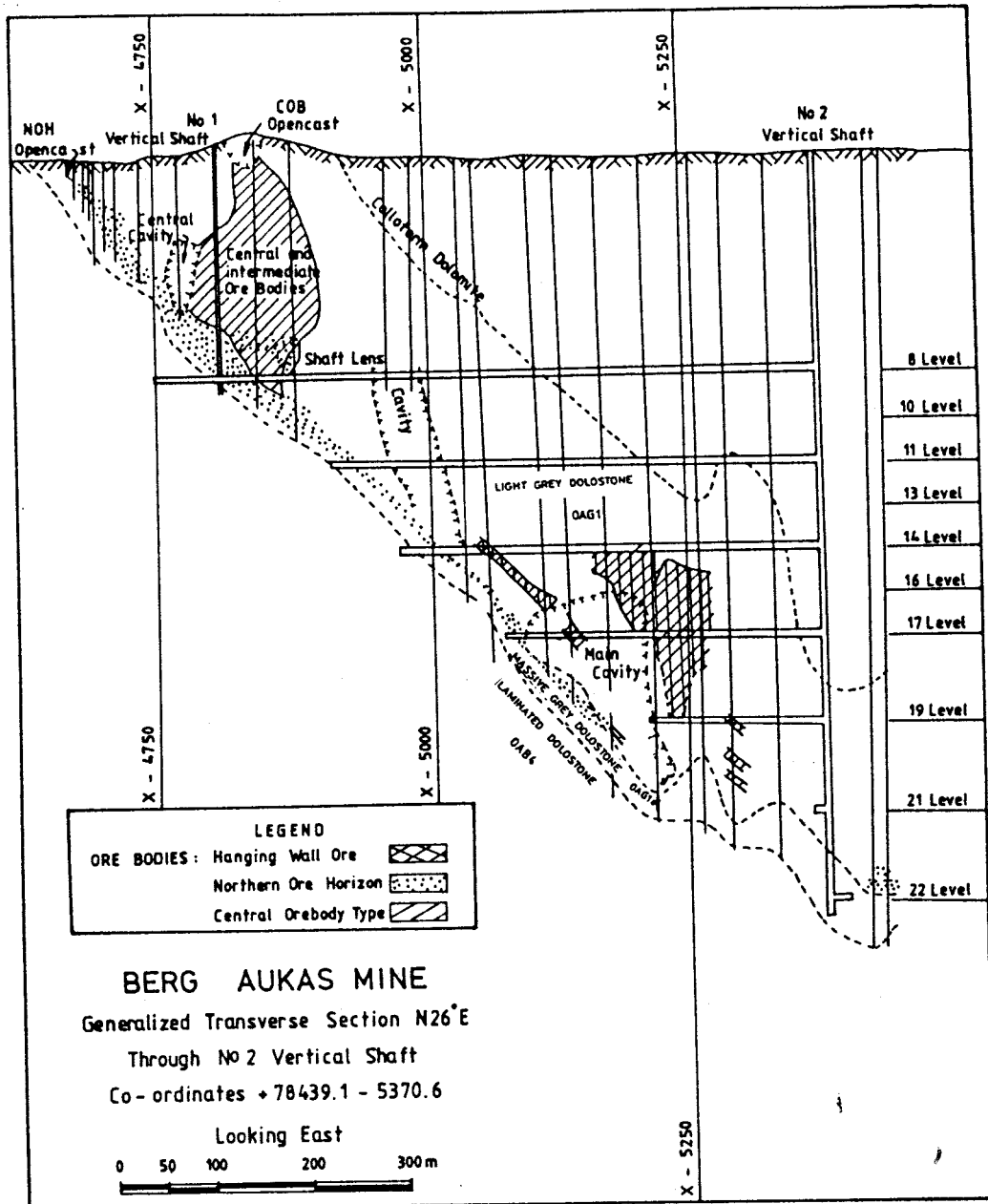


Figure 7.2 : Simplified north-south cross section (looking east) through the Berg Aukas deposit.

Three distinct types of ore body were exploited at Berg Aukas. These were a stratabound Northern Ore Horizon (NOH), a discordant Central Ore Body (COB), and a stratabound Hanging Wall Ore Horizon (HW-ore). The ore bodies are confined to a distinct north-south trend on the northern limb of the syncline (Figure 7.1). Their positions are stratigraphically and structurally controlled, although the latter is not obvious. The ore bodies are known to persist to the keel of the  $F_1$  fold axis, coinciding with the 23 level or approximately 750 m below surface, but they have only been subjected to limited mining to the 19 level, approximately 600 m below surface (Figure 7.2).

Mineralization was deposited as open space filling created by karsting formed by rising hydrothermal fluids along  $S_2$  fracture planar cleavage in the keel of the  $F_2$  fold axial plane. The mineralization comprises massive sulphides of primarily sphalerite and galena. The Berg Aukas deposit is the only sphalerite deposit of significant size in the Otavi Mountain Land. Circulating meteoric waters during later karsting episodes extensively oxidized the sulphide minerals forming large deposits of secondary mineralization which includes willemite ( $Zn_2SiO_4$ ), smithsonite ( $ZnCO_3$ ), and cerussite ( $PbCO_3$ ). Late stage descloizite ( $PbZn(VO_4)OH$ ) mineralization took place by introduction of metavanadate solutions along north-south trending vertical fractures.

The mineralization is essentially a breccia-hosted-type and there is an intimate relationship between the ore bodies and an extensive cavity system which is developed to the lowest levels. Mineralized muds or caliche form a rich component of the deposit.

### 7.1 The Northern Ore Horizon

The Northern Ore Horizon comprises three lenses of stratabound, largely oxidized sulphides, lying on the contact between the Massive Grey Dolostone and the Light Grey Dolostone. The control on mineralization is a combination of structure and stratigraphy. Mineralizing fluids have penetrated the Light Grey Dolostones by way of fracturing but mineral concentration was preferentially developed on the lithological boundary. Consequently, the mineralization of the Northern Ore Horizon characteristically strikes east-west and dips steeply to the south in conformity with the bedding. Surface exposure was negligible, not exceeding a 10 m x 40 m area.

The mineralization has a depositional preference for the steep slopes of synclinal warps on the stratigraphic contact (Weilers, 1959). The mineralized lenses which precipitated have been subjected to considerable oxidation and secondary brecciation. A typical lens (Figure 7.1.1) comprises a massive sulphide component at the base which consists of coarse grained sphalerite and galena in variable quantities but usually in ratios of 3,4:1. The upper portion of the massive sulphide is usually oxidized into mostly willemite, and lesser smithsonite and cerussite. The ore lens is typically capped by dolomite breccia enriched in descloizite at its base. Limonite and goethite pseudomorphs are common after pyrite and willemite, and quartz and dolomite frequently accompanies the descloizite (Weilers, 1959).

The ore lenses are characterized by a sharp contact with the host dolostone and usually incorporate cavities of varying dimension within the confines of, or adjacent to the ore, but more generally towards the hanging wall contact. Caliche sand and mud enriched in descloizite and ore fill these cavities.

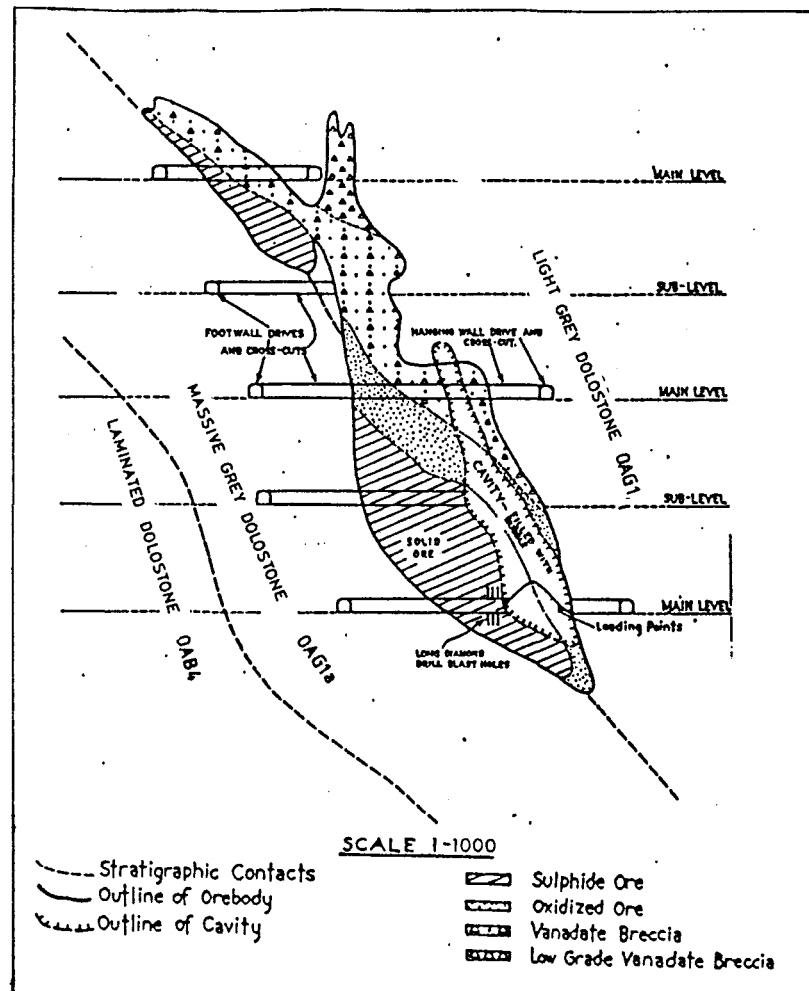


Figure 7.1.1 : Idealised north-south section (looking east) through a lens of the Northern Ore Horizon showing geology and mining layout.

## 7.2 The Central Ore Body

The Central Ore Body was a term used for a discordant brecciated pipe-like body which extended vertically from the Massive Grey Dolostone contact into the hanging wall (Plate 28). It is similar to the Hanging Wall ore bodies but represented a more concentrated development of ore.

The Central Ore Body was exposed on surface as a series of mineralized mud-filled fractures, but was not more extensive than 40 x 10 metres. Below surface it developed into an elliptical body due to the concentration of a complex network of steeply dipping north-south fractures.

The ore was extensively oxidized and particularly enriched in vanadiferous muds and breccia. It comprised a breccia with blocks of barren dolostone and partially oxidized sphalerite and galena intermixed with vanadiferous caliche. Associated cavities were frequently lined with solid willemite or descloizite.

The Central Ore Body included two satellite bodies to the north-east and were known respectively as the Intermediate and Eastern Ore Bodies.

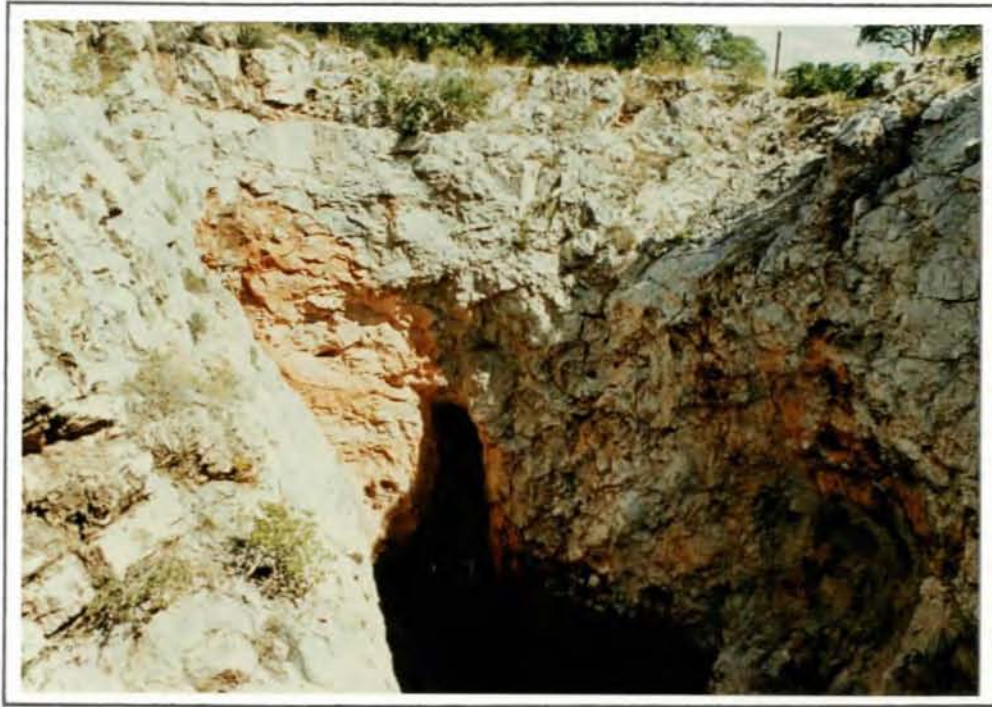
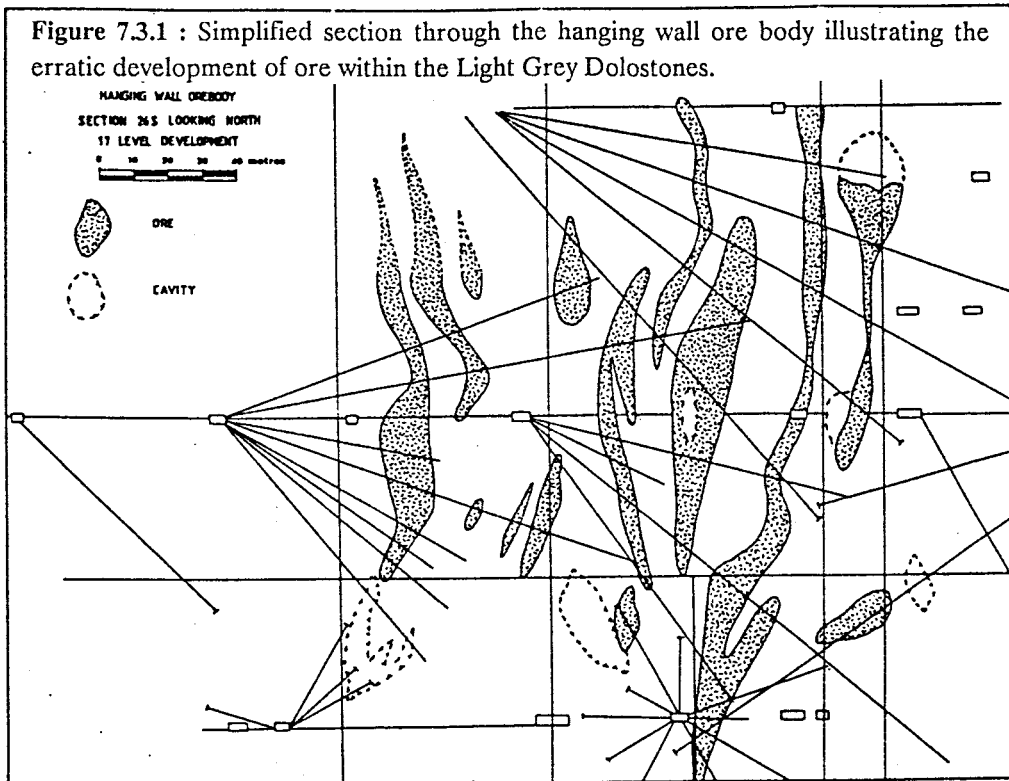


Plate 28 : View of the Central Ore Body illustrating the sharp contact between non-economic karst breccia and the Light Grey Dolostones.

### 7.3 The Hanging Wall Ore Body

Hanging wall ore refers to north-south trending lenses of steeply dipping ore-filled fractures which were developed in the Light Grey Dolostones stratigraphically above the Northern Ore Horizon. The Hanging Wall Ore is found along the extent of the ore zone (Figure 7.1), but is best developed between 14 and 23 levels (Figure 7.2). It differs from the Northern Ore Horizon in that it has NE-SW strike and vertical dip. This is a consequence of a lack of stratigraphic control on the localization of mineralization. The effect of this was that although grade was similar to the Northern Ore Horizon, its development was more erratic (Figure 7.3.1). This feature made the Hanging Wall Ore less favourable for mining and much of the remaining ore reserve is this type of ore.



#### 7.4 Hypogene Mineralization

The hypogene ores of the Berg Aukas deposit are relatively simple with sphalerite, galena and small amounts of pyrite constituting the only macroscopically visible sulphides. The mineralogy of the Berg Aukas hypogene ores were described by Markham (1958a) and Emslie (1979).

A reflected light study of polished briquettes indicates that the dominant hypogene mineralogy includes a variety of accessory sulphide minerals.

**Table 7.4.1: Hypogene Mineralogy of the Berg Aukas deposit:**

Sphalerite	ZnS
Galena	PbS
Pyrite	FeS <sub>2</sub>
Tennantite	Cu <sub>12</sub> As <sub>4</sub> S <sub>13</sub>
Jordanite	Pb <sub>14</sub> As <sub>7</sub> S <sub>24</sub>
Enargite	Cu <sub>3</sub> As <sub>4</sub> S <sub>4</sub>
Chalcopyrite	CuFeS <sub>2</sub>
Renierite	Zn <sub>3</sub> (AsO <sub>3</sub> ) <sub>2</sub>
Dolomite	CaMg(CO <sub>3</sub> ) <sub>2</sub>
Calcite	CaCO <sub>3</sub>
Quartz	SiO <sub>2</sub>

*Sphalerite*,  $ZnS$ , is the dominant ore mineral and varies between an iron-rich, fine grained (<1 mm), red-black variety and a more common iron-poor, honey coloured variety which is coarse grained. Grain size varies but often exceeds 2 mm and it is not uncommon to find crystals greater than 10 mm in length. In polished section, the honey coloured sphalerite have beautiful bright yellow internal reflections (Plate 29). The sphalerite tends to be massive with only occasional inclusions and interstitial sulphide development. Inclusions are mostly tennantite and pyrite and interstitial sulphide is usually galena but does not often exceed quantities of 5%. Gangue minerals are dominantly dolomite with lesser calcite and very infrequent quartz.

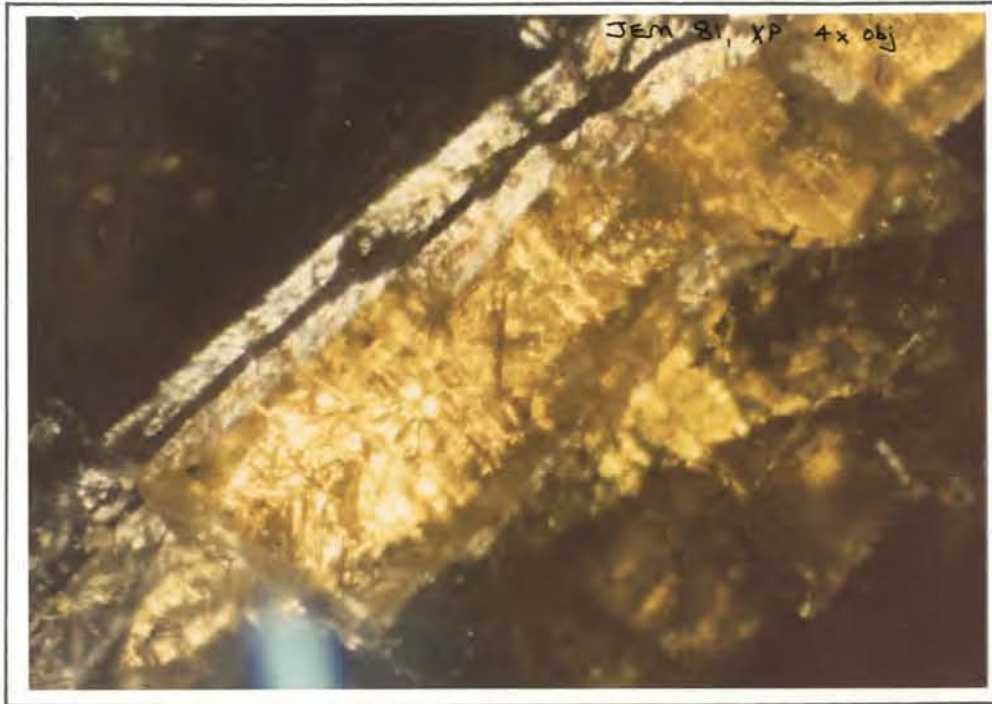


Plate 29 : Yellow internal reflections reflected from polished section of sphalerite.

Analyses of the Berg Aukas sphalerites (Markham, 1958a) indicates that they are a very poor iron type, with the iron usually not exceeding 1% in composition. This indicates that there is a strong agreement between colour and composition. Other important trace elements include Cd and Ge. The Cd has an average concentration of 0,15% (Emslie, 1980) but may be present to levels of 0,47%, and Ge, which was never recovered, was recorded at levels of 0,015%. Emslie (1980) noted that Cd levels at Berg Aukas are lower than other deposits in the Mountain Land.

*Galena*,  $PbS$ , is present in varying amounts, but in comparison to the sphalerite is much more sporadically developed. It occurs in two forms and displays no evidence for deformation as described for Abenab West (Verwoerd, 1957). The conclusion is that the mineralization is syn- to late-tectonic. Coarsely crystalline massive galena typified by an equigranular texture occasionally occurs as massive blocks within the sulphide ore. A more common interstitial variety of galena is intimately intergrown with the sphalerite ore indicating a co-precipitation. The galena is enriched in silver (A.E. Lyons, pers. comm.). Lombard (1981) reports that

silver was recovered from lead concentrate at grades of 210 g/ton indicating an average grade throughout the deposit of 10 g/ton.

Markham (*op. cit.*) draws attention to the common association between galena and secondary zinc and lead minerals. This galena is a fine grained variety with indications for recrystallization and is probably supergene in nature.

Pyrite,  $Fes_2$ , contributes only 1 to 10% of the sulphide mineralogy. It occurs as mostly subhedral crystals in sphalerite and galena with grain size usually not exceeding 0,3 mm.

The most common accessory mineral is *tennantite*, occurring as anhedral inclusions within sphalerite and galena (Plate 30). It is the only common copper sulphide as chalcopyrite was noted in only one sample in this investigation. The tennantite is typically very fine grained but may achieve a diameter of 0,2 mm. The tennantite is the primary source for arsenic within the deposit. Rare quantities of *enargite* were noted in this study, and Markham (1958a) reports the presence of *reneirite* and *jordanite*.

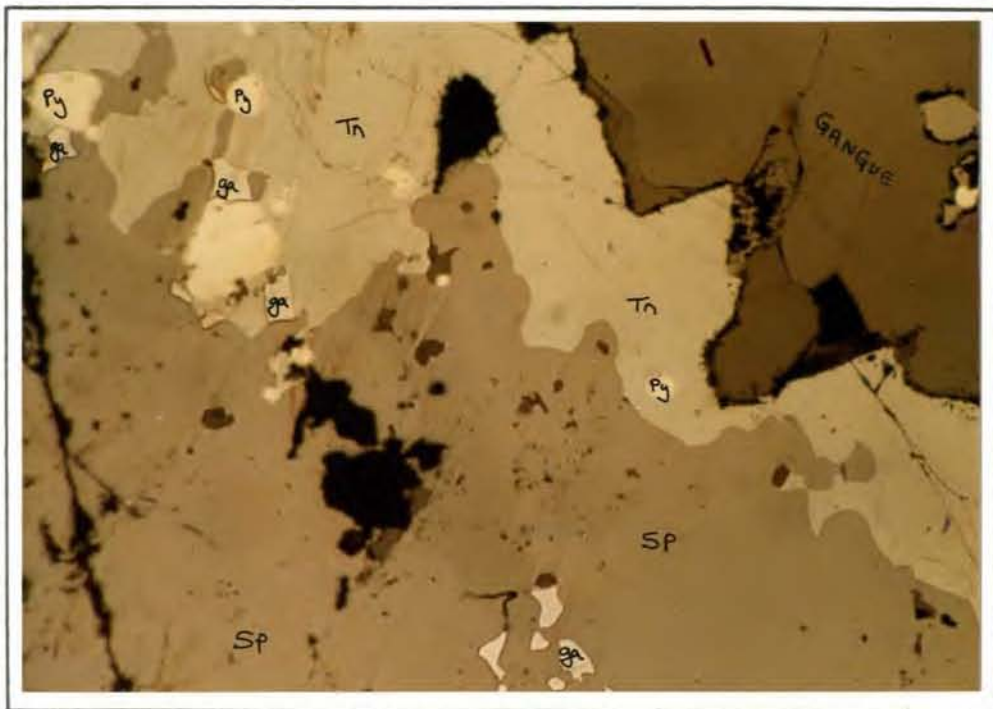


Plate 30 : Tennantite, pyrite, galena, sphalerite in polished section of hypogene ore.

## 7.5 Supergene Mineralization

The Berg Aukas deposit has been subjected to extensive supergene enrichment with the supergene ores contributing substantially to the total reserve. The mineralogy is varied and is a particularly interesting aspect

of the deposit. It has been described in two unpublished reports by Markham (1958b) and von Rahden (1963). Petrographic studies in this investigation have not advanced beyond a mineral reconnaissance, and aspects such as the geochemistry of the supergene ores are an exciting subject matter for a more specialized study.

**Table 7.5.1: Supergene Mineralogy of the Berg Aukas deposit:**

Galena	PbS
Chalcocite	$\text{Cu}_2\text{S}$
Covellite	CuS
Greenockite	CdS
Willemite	$\text{Zn}_2\text{SiO}_4$
Smithsonite	$\text{ZnCO}_3$
Cerussite	$\text{PbCO}_3$
Calcite	$\text{CaCO}_3$
Dolomite	$\text{CaMg}(\text{CO}_3)_2$
Quartz	SiO <sub>2</sub>
Aragonite	$\text{CaCO}_3$
Goethite	$\text{FeO}(\text{OH})$
Hematite	$\text{Fe}_2\text{O}_3$
Descloizite	$\text{PbZn}(\text{VO})_4\text{OH}$
Malachite	$\text{Cu}_2(\text{CO}_3)(\text{OH})_2$

*Chalcocite*, *covellite* and *greenockite* are secondary sulphides which have formed by the breakdown of tennantite and sphalerite. The covellite may be found as rare inclusions within either sphalerite or galena (Plate 31), but it is often found in direct association with chalcocite. The greenockite is an extremely rare alteration product of sphalerite. Its presence was recorded by Markham (*op. cit.*) but not by Emslie (1980). It was only observed in one sample in this study, and was found to be developed along fracture cleavage and is recognized by its bright yellow internal reflections. Without this diagnostic criterion it is easily confused with tennantite as they are both similar in green-grey colour and anisotropy.

*Willemite*,  $\text{Zn}_2\text{SiO}_4$ , is the most important and most widely distributed supergene mineral. It occurs in all parts of the mine and it has been estimated (P.J. Schreuder, pers. comm.) that up to 40% of the total zinc occurs in this form. This unique feature possibly makes the Berg Aukas deposit the worlds largest willemite resource. Willemite is a rare ortho-silicate mineral often found in trace quantities in the supergene environment above massive zinc sulphide deposits. It has been described from various parts of the world (Spencer, 1927; Pough, 1941; Ingerson and Tuttle, 1947; Ingerson *et al.*, 1948; Verwoerd, 1957; Taylor, 1962; Muller, 1977; Metcalf-Johansen, 1977) but is best known from Franklin, New Jersey; Beltana, South Australia; Kabwe (formerly Broken Hill), Zambia; Berg Aukas and Abenab in the Otavi Mountain Land.

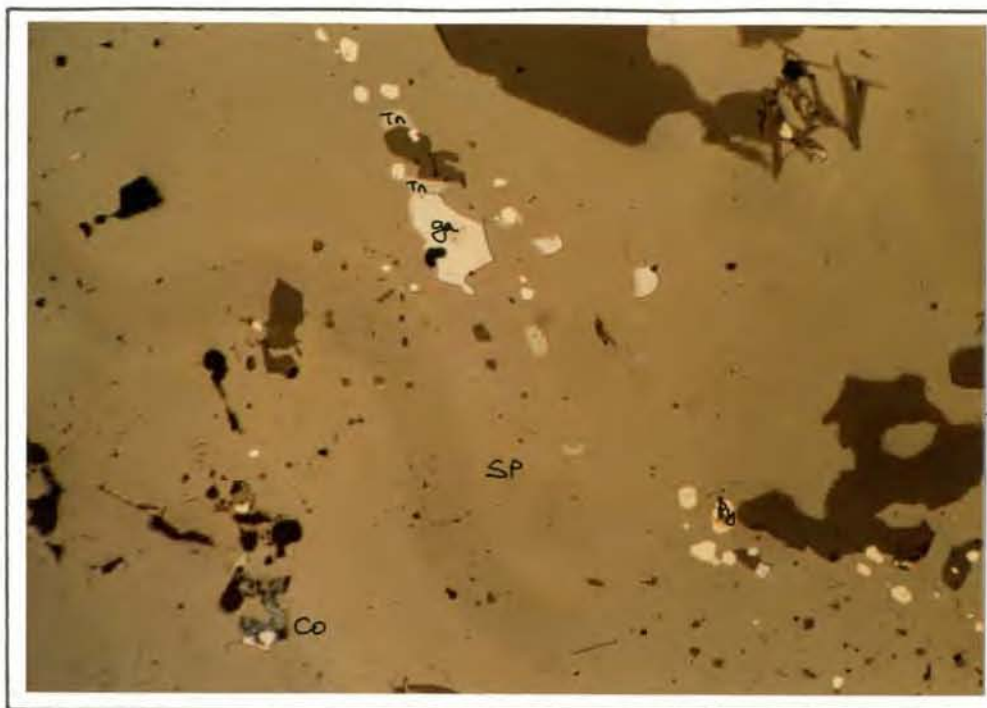


Plate 31 : Accessory covellite hosted by massive sphalerite.

In hand specimen, massive willemite ore is fine grained and granular. It varies in colour from yellowish-white to red-brown-black depending on the amount of associated ferruginization. It typically has a vuggy appearance with drusy willemite encasing the open spaces.

In thin section, the willemite occurs in two main forms. It may have a well packed granular habit or a coalescing assemblage of radiating prismatic needles. The granular willemite comprises closely-packed, subhedral, hexagonal grains with a variable grain size ranging from 0,005 mm to 0,015 mm (Plates 32 and 33). The radiating, prismatic willemite most typically forms spherical rosettes (Plates 34 and 35), but they also result in parallel and interlocking assemblages. The needles are slender with an elongation ratio ranging between 1:10 to 1:20 (Markham, 1958b). Markham (*op. cit.*) noted that the prismatic variety was the most common form, but the results of this study suggest that the two forms are found in equal proportions.

Willemite is easily identified by its optical properties. It is colourless with a moderate to high relief and has easily recognisable prismatic or granular hexagonal crystal habit. Its second order birefringence ( $n_{1,719} - n_{1,69} = 0,028$ ; Phillips and Griffen, 1981) and uniaxial positive optic figure are diagnostic. The Berg Aukas willemite, in conformity with those studied at Abenab West (Verwoerd, 1957), show no evidence for fluorescence in ultra-violet light. This is atypical for other world occurrences (Spencer, 1927) and is probably a function of composition. Ingersen and Tuttle (1947) attributed the yellow-green fluorescence of willemite to critical amounts of manganese in the crystal lattice which probably means that this element is apparently

lacking from the Berg Aukas mineral.

The origin of the willemite is ascribed to direct replacement of sphalerite since the two minerals can often be intimately observed in thin section (Plates 36 and 37). The oxidation process is accompanied by the liberation of considerable amounts of iron which accounts for the ferruginous nature of massive willemite ore. Willemite is also usually associated with smithsonite which forms as a simultaneous replacement of the sphalerite together with willemite or as a later replacement of the willemite. However, the mineral relationships in thin section suggest that the smithsonite was formed well after the willemite.

Von Rahden (1963) completed a limited spectrographic analysis of the willemite noting an enrichment in arsenic and vanadium. The origin of the arsenic is largely attributed to the breakdown of tennantite, but probably also jordanite, enargite, and renierite. The incorporation of vanadium is significant because it implies that metavanadate solutions were already involved with the oxidation process from its inception. The zinc content is notably higher than the value of 58,6% Zn in willemite quoted by Spencer (1927) for the Franklin deposit, New Jersey.

**Table 7.5.2: Chemical composition  
for Berg Aukas Hexagonal Willemite (after von Rahden, 1963)**

ZnO	72,95%
SiO <sub>2</sub>	26,71%
V <sub>2</sub> O <sub>5</sub>	0,13%
As <sub>2</sub> O <sub>5</sub>	0,21%
Total	100,00%

*Smithsonite*, ZnCO<sub>3</sub>, is an important ore mineral at Berg Aukas, but is not as extensively developed as willemite. Markham (1958b) notes that it was more common in the upper portions of the Central Ore Body. The smithsonite is an alteration product formed by the replacement of sphalerite, but unlike willemite, precipitation does not commonly occur *in situ* and may develop some distance away.

The petrographic identification of the smithsonite may be confused by its broad optical similarities to the other carbonate minerals such as calcite, dolomite and cerussite. All four minerals are characterized by an extreme birefringence ( $n - n_o = >0,172$ ), and all are uniaxial negative except for cerussite which is biaxial negative with a very small optic angle ( $2V = 9^\circ$ ). However, despite these shortcomings, there are optical characteristics which allow an identification of the mineral. Smithsonite at Berg Aukas is characteristically coarse grained (0,5 to 1,0 mm), and is typified by a botryoidal crystal form lacking twinning. It often occurs as sheaf like aggregates giving an imperfect extinction which may cause confusion with aragonite. However, aragonite can normally be identified by its cleavage which is not usually well developed in the smithsonite (Plate 38).

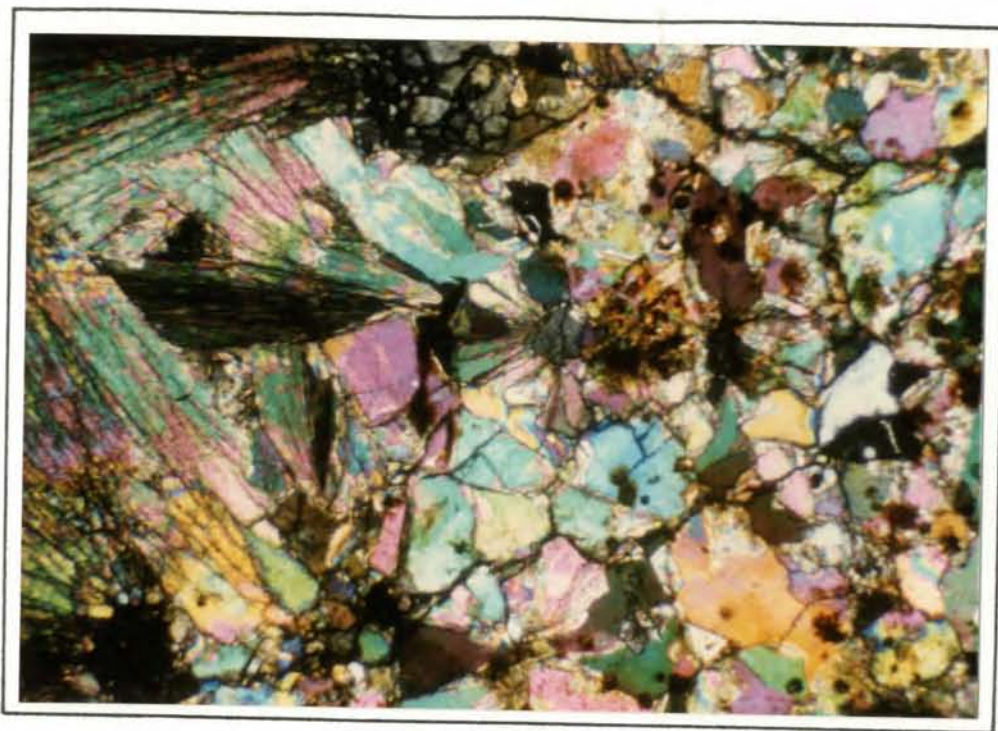


Plate 32 : Granular and acicular willemite (high birefringence). Sample BA 323, XP, 2,5x.

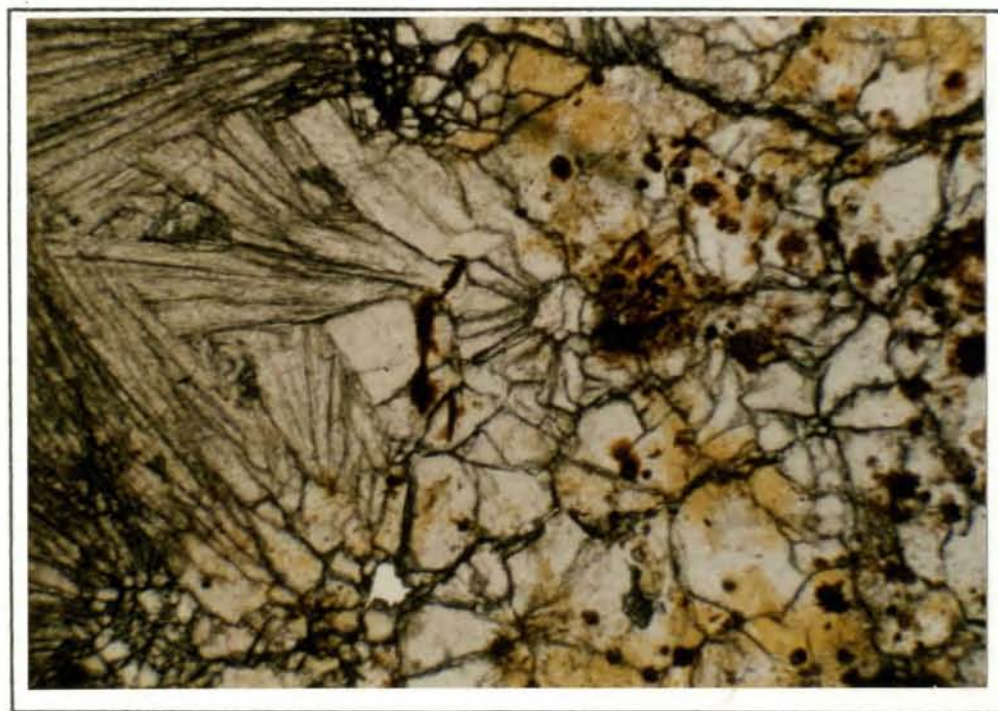


Plate 33 : Granular and acicular willemite (colourless, high relief). Sample BA 323, PPL, 2,5x.

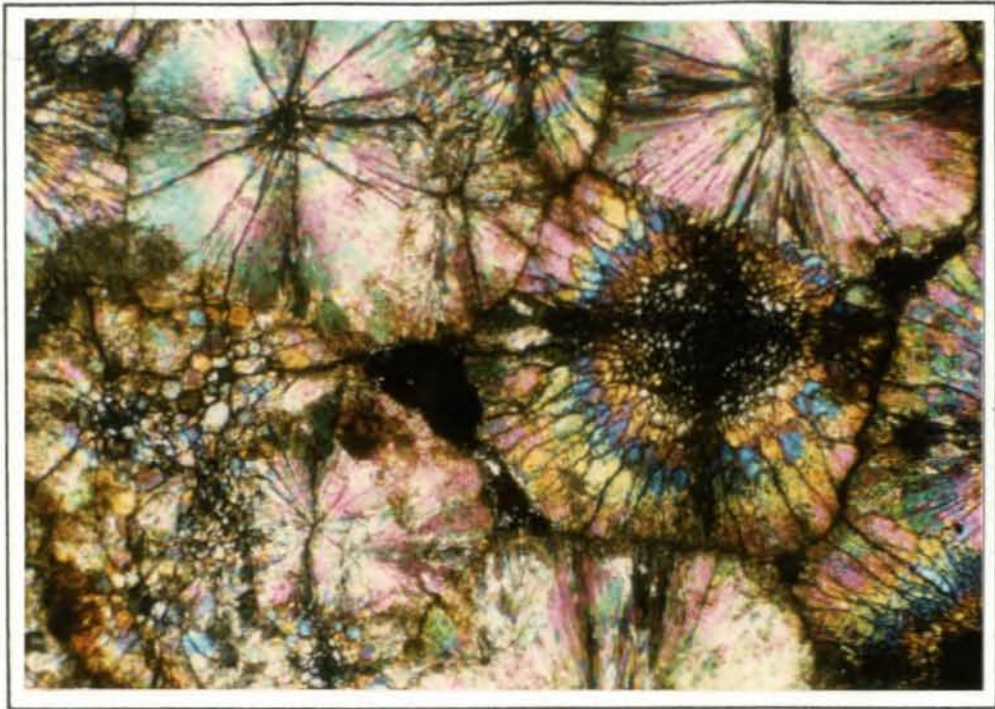


Plate 34 : Prismatic willemite developed as rosettes. Sample BA 59/27, XP, 2,5x.

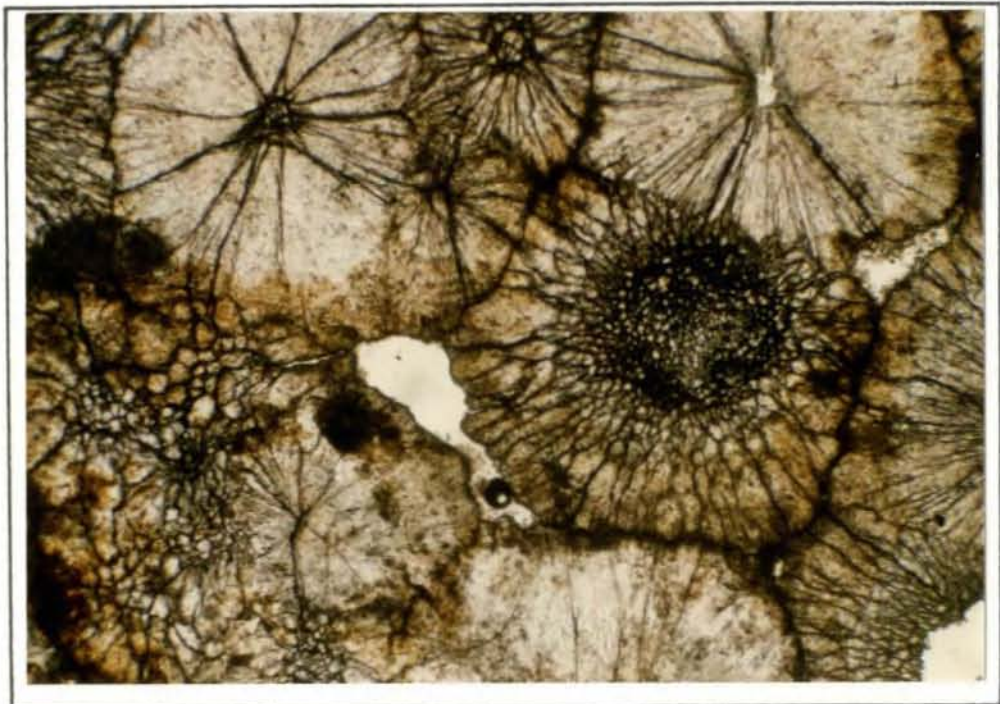


Plate 35 : Willemite rosettes. Sample BA 59/27, PPL, 2,5x.

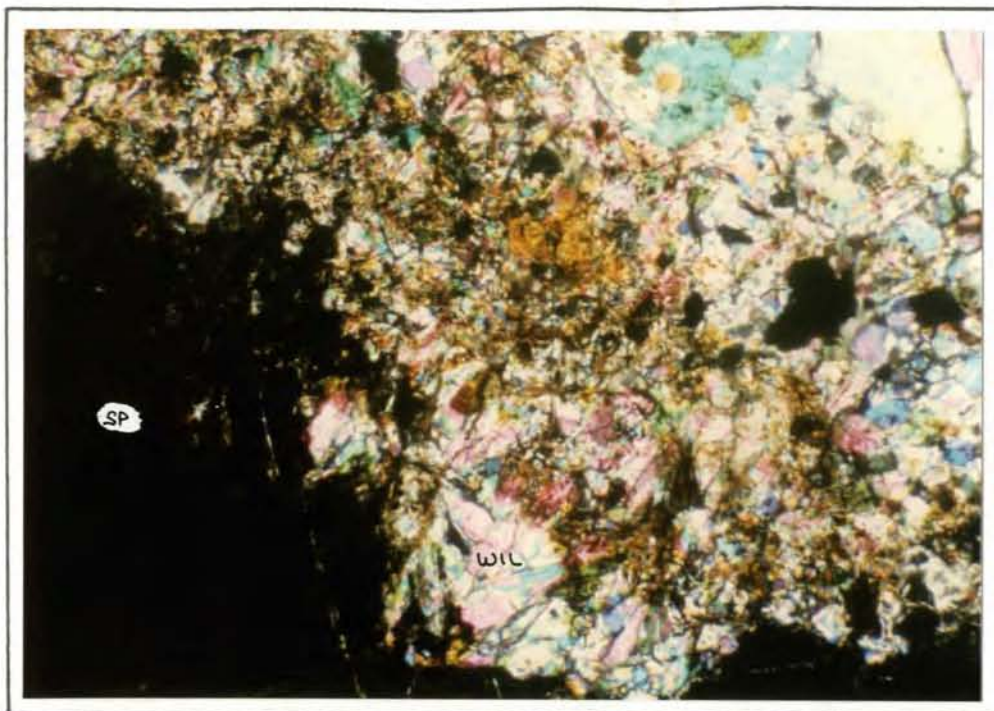


Plate 36 : Replacement of sphalerite (opaque) by willemite (high birefringence).  
Sample BA 283/133, XP, 2,5x.

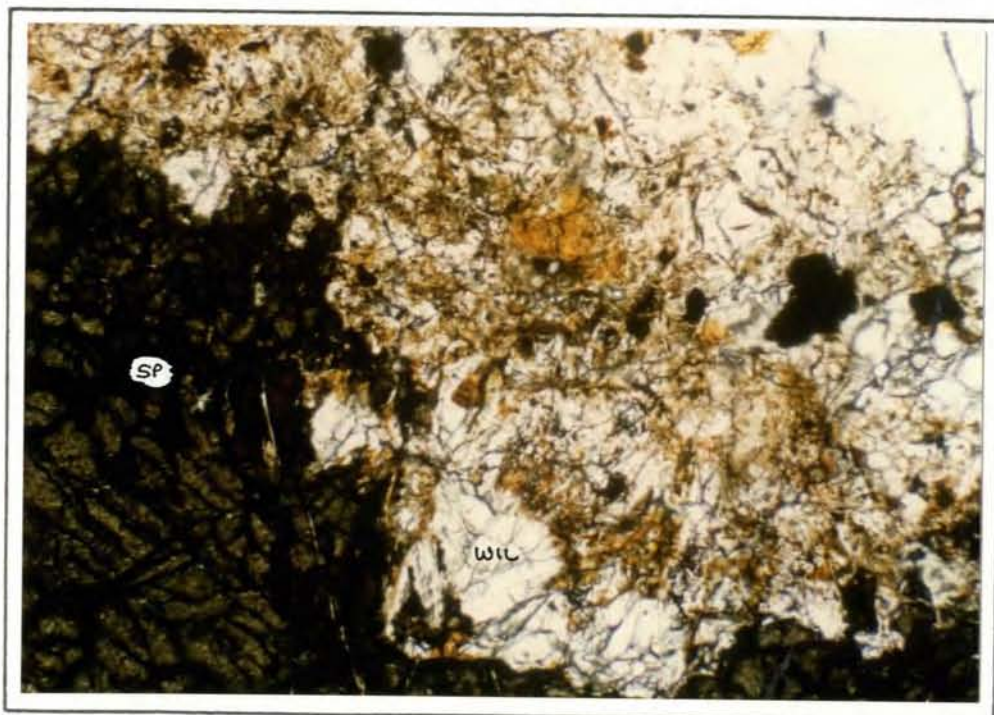


Plate 37 : Replacement of sphalerite (brown-yellow, high relief) by willemite  
(colourless, high relief). Sample BA 283/133, PPL, 2,5x.



Plate 38 : Botryoidal smithsonite developed around a grain of descloizite. Sample BA 52, XP, 2,5x.

*Cerussite*,  $PbCO_3$ , is not a well developed phase, amounting to less than 1% of the ore minerals. It forms by replacement of galena (Plates 39 and 40) which is often resistant to oxidation and is often found within the supergene ores. Anglesite is not developed at Berg Aukas which is a probable indication of high pH and low Eh conditions during oxidation (Reynolds, 1987).

The cerussite is recognized by its mineral association (cerussite-willemite and cerussite-smithsonite), and by its distinctive {110} and {021} cleavage, its extreme birefringence which is the highest amongst the carbonates ( $n_{2,074} - n_{1,803} = 0,273$ ), and higher relief.

The gangue mineralogy comprises *calcite*, *dolomite* and *quartz*. They are relatively rare constituents, but several varieties have been noted. Hydrothermal hypogene calcite and dolomite are recognized when they are completely enclosed by sphalerite. The calcite is pure white with no impurities and the dolomite is often a pink colour probably due to manganese and iron in the crystal lattice. The hydrothermal crystals are often coarse grained and euhedral. Primary quartz can occasionally be seen associated with a sphalerite-carbonate association, but is extremely rare.

Secondary calcite and quartz is abundant in the supergene breccias, especially where descloizite is well developed. This quartz is anhedral and distinguished from the chert in the country rock dolostones by its coarser grain size and uniform extinction. The cherts typically display an undulose extinction. Aragonite occurs in large masses in association with descloizite. The association is due to open space crystal growth.

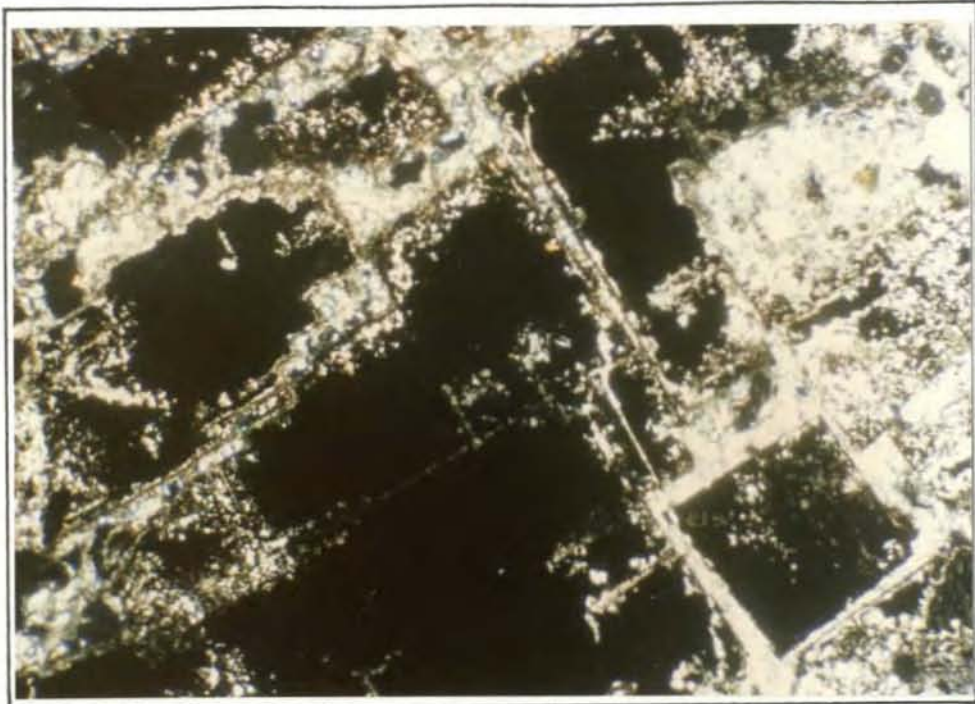


Plate 39 : Replacement of galena (opaque) by cerussite (high birefringence) along the margins of galena boxworks. Sample BA 416, XP, 2,5x.

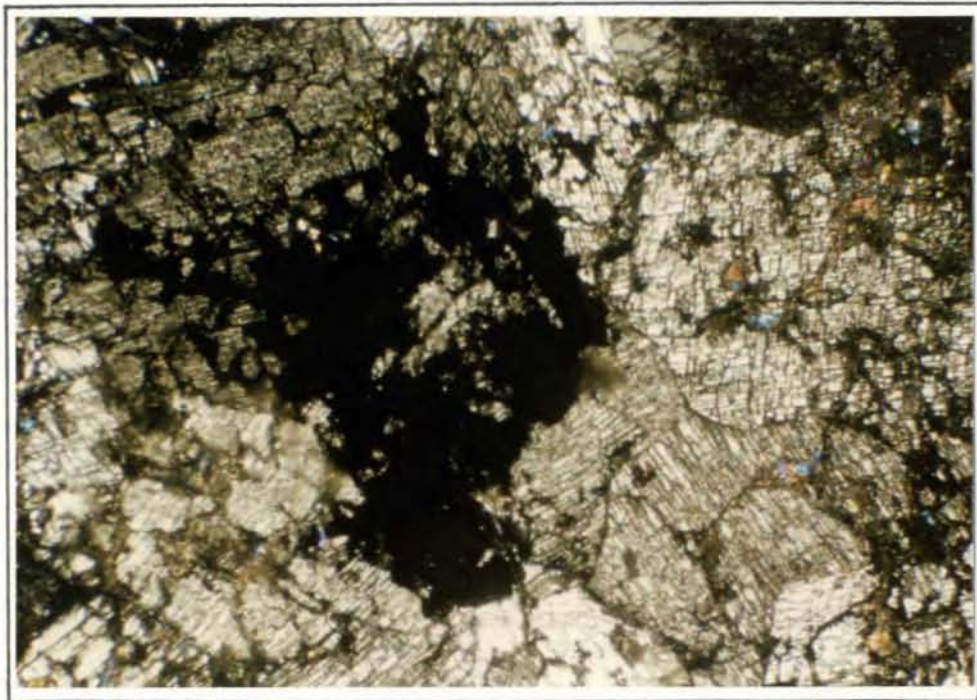


Plate 40 : Complete replacement of galena by cerussite which has a well developed cleavage and a high birefringence. Opaque mineral is sphalerite. Sample BA 184, XP, 2,5x.

*Descloizite*,  $PbZn(VO_4)OH$ , is probably the most famous mineral to have been exploited at Berg Aukas, and is probably the world's largest accumulation of this mineral. It occurs throughout the supergene fraction of the deposit, to the lowest levels, but was better developed in the upper portions of the mine. Berg Aukas is the largest vanadiferous deposit amongst many known occurrences in the Otavi Mountain Land. General and specific descriptions of the vanadiferous occurrences have been given by Wagner (1922); Clark (1931); Schwellnus (1945); Verwoerd (1957); Markham (1958b); von Rahden (1963); von Rahden and Dicks (1967) and van der Westhuizen (1984). The mineral association (Zn-Pb-V) is rare, but is known from other occurrences in Africa. The Kabwe (formerly Broken Hill) deposit in Zambia is very similar and has been described by Pelletier (1930), and Spencer (1908). Similar mineralization sporadically developed in the carbonates around the Bushveld Complex have also been noted (Imperial Institute on Mineral Resources, 1924; Willemse *et al.*, 1944). The chemistry of descloizite -mottramite from Mines Lo Lucca in Angola has been described by Millman (1960).

**Table 7.5.3: Analysis of Descloizite**

(1,2,3,4 from Markham, 1958b, and 5,6,7,8 from Von Rahden, 1963; Von Rahden and Dicks, 1967).

	1	2	3	4	5	6	7	8
PbO	54.78	54.98	55.26	56.62	54.66	54.77	54.73	54.22
ZnO	19.19	19.42	18.77	19.10	19.60	19.48	18.99	19.40
CuO	1.19	0.62	0.60	0.42	0.45	0.49	0.74	0.60
FeO	na	na	na	na	tr	tr	tr	tr
MnO	na	na	na	na	tr	tr	tr	tr
$V_2O_5$	21.00	22.27	22.76	21.19	20.94	21.20	21.64	21.36
$As_2O_5$	0.20	0.51	0.41	0.47	1.08	0.63	0.52	1.10
$P_2O_5$	nd	tr	tr	tr	na	na	na	na
$H_2O$	3.64*	2.20*	2.20*	2.20*	2.43	2.37	2.50	2.52
Totals	100.00	100.00	100.00	100.00	99.16	98.94	99.12	99.20

na = not analysed, nd = not detected, tr = below detection limits, \* = normalised

The descloizite at Berg Aukas is found in a variety of forms, including spectacular drusy aggregates comprising pyramidal crystals generally less than a centimetre in length (Plate 41). The crystals are typically acicular prisms, but may be a botryoidal or even cubic form (Plate 42). The mineral varies in colour between orange-brown, green-black, and metallic black. Larger crystals are usually black, but delicate bright red crystals are also common. Calcite and aragonite are the most common minerals associated with the descloizite, but it is also occasionally developed with willemite and smithsonite. It is a common constituent of

the breccia ores, (Plates 43 and 44) but the best crystals were developed along cavity walls.

The descloizite is easily recognized under the microscope. It is strongly pleochroic in shades of yellow ( $b = c$ ) and brown-yellow ( $a$ ) and is characteristically zoned (Plate 45). Despite the variation in colour, the chemical composition (Table 7.5.3) is fairly consistent. This indicates a negligible copper content, reflecting a copper-poor hypogene source, and an enrichment in arsenic which is attributed to the breakdown of tennantite and associated minerals.

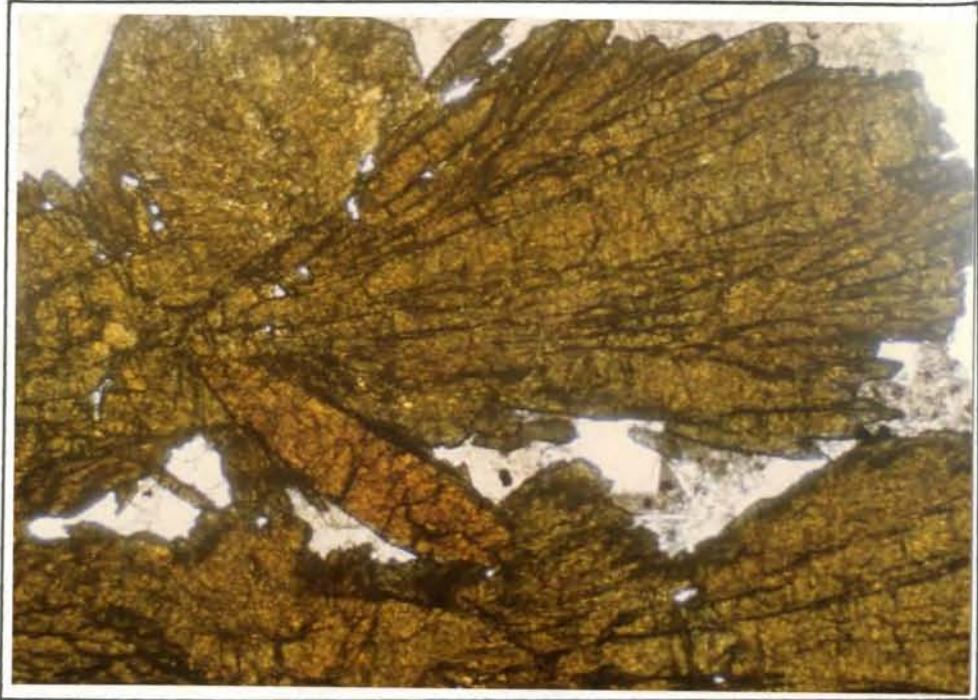


Plate 41 : Prismatic descloizite. Sample BA 241, PPL, 2,5x.

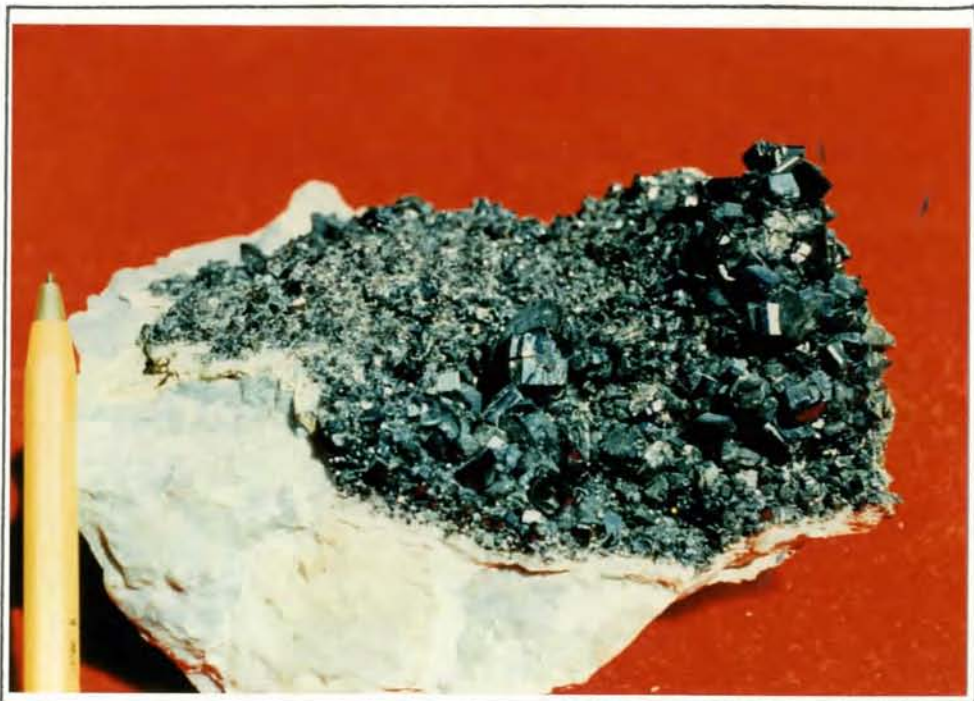


Plate 42 : Well developed descloizite crystals with an unusual cubic habit.

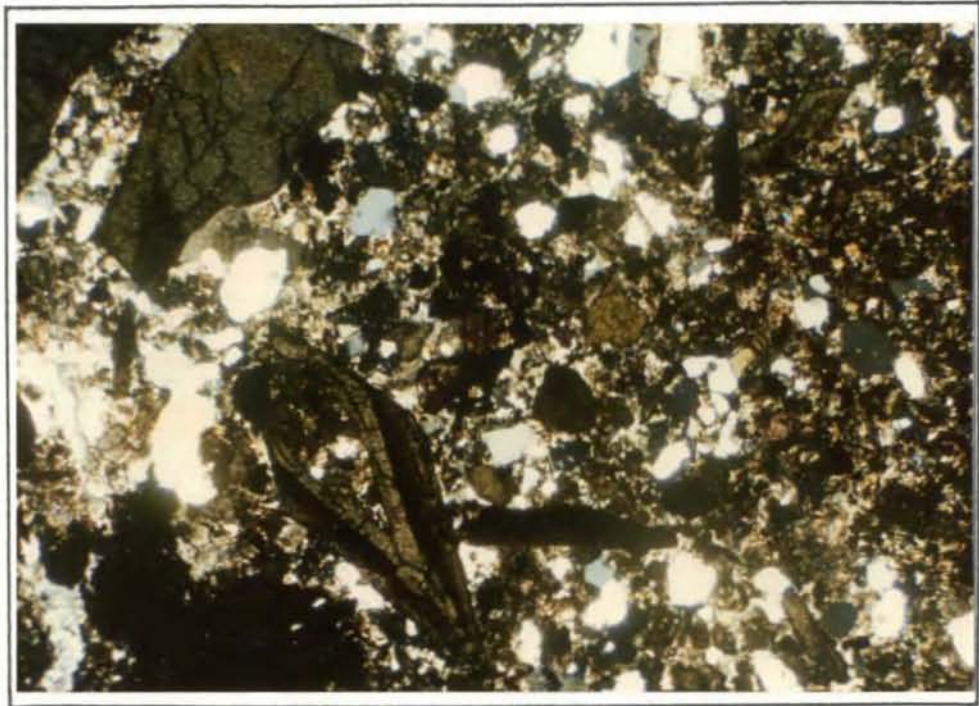


Plate 43 : Vanadiferous breccia ore. Sample BA 339, XP, 2,5x.

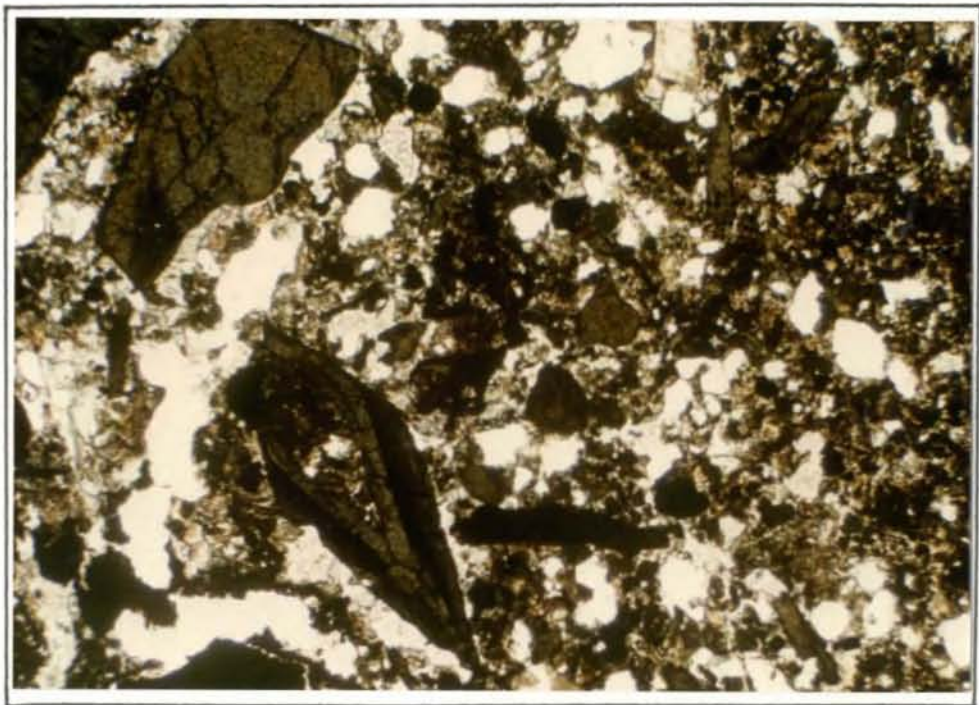


Plate 44 : Vanadiferous breccia ore. Sample BA 339, PPL, 2,5x.

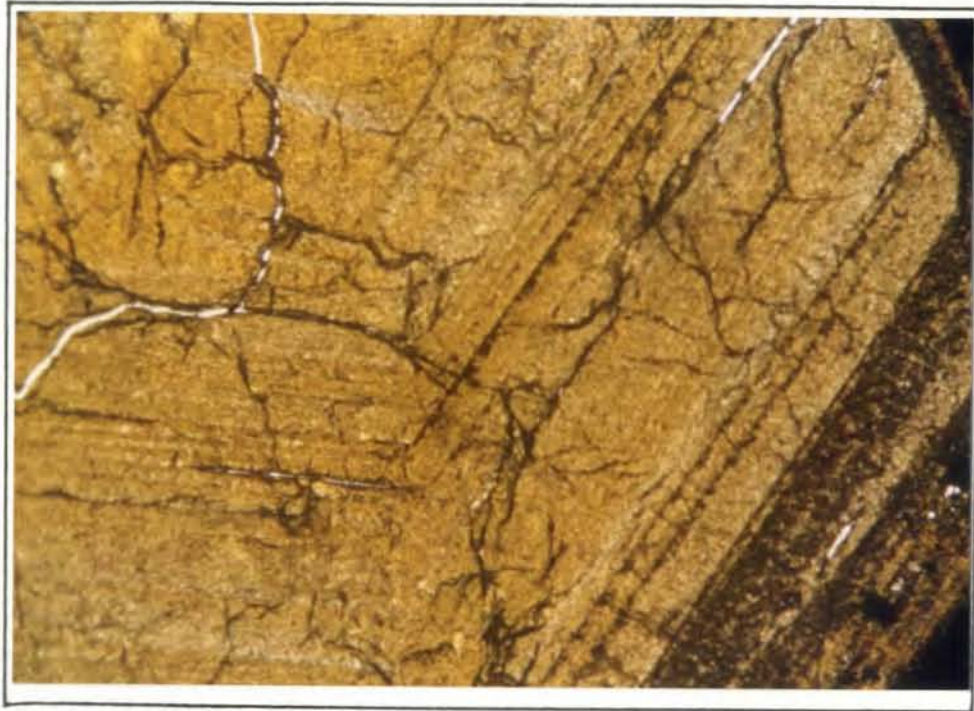


Plate 45 : Zoned descloizite crystal. Sample BA 58, PPL, 1,2x.

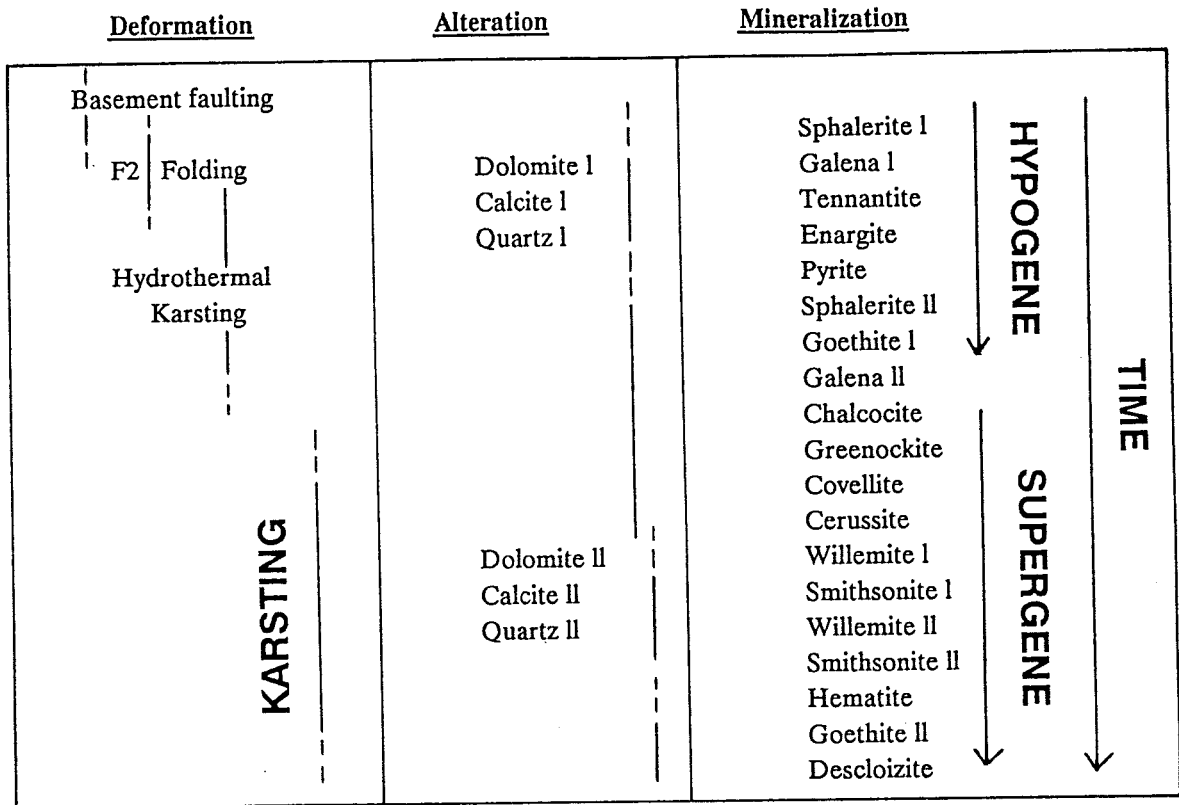
#### 7.6 Mineral Paragenesis

The paragenesis is depicted in Figure 7.6.1. The exact timing of the mineralization relative to the deformational history is not conclusive due to secondary modification. However, the primary sulphide minerals do not display any extensive deformational features and it is concluded that mineralization was syn- to late-tectonic, possibly following immediately after the  $F_2$  deformational event.

#### 7.7 Alteration

Hydrothermal alteration in the Otavi Mountain Land is particularly well displayed at Baltika, Kupferberg, and Kombat where calcitization and silicification are ubiquitous (Vickers, 1974; Misiewicz, 1986b; Innes and Chaplin, 1986). This style of hydrothermal alteration is similar to that described for other Mississippi Valley-type deposits throughout the world (Siems, 1984). However, there is an exception since hydrothermal dolomitization of the country carbonates has not been observed. Guilbert and Park (1986) note that dolomitization commonly accompanies Mississippi Valley-type deposits. The absence of this form of alteration in the Otavi Mountain Land is probably due to it not having been recognized as a consequence of mineralization post-dating diagenetic dolomitization.

Figure 7.6.1: Mineral Paragenesis for the Berg Aukas Deposit



The alteration associated with the ore bodies at Berg Aukas is not extensive and calcitization is more commonly found associated with the breccias. Hydrothermal calcitization and silicification have been noted with the hypogene ores in accessory amounts, and is better developed with the hydrothermal breccia. Goethite and hematite, formed during the replacement of sphalerite and the oxidation of pyrite, cause extensive ferruginized haloes to the mineralization. This secondary alteration was a useful diagnostic feature in assessing potential ore-bearing ground during the life of the mine.

A more regional manifestation of hydrothermal alteration is seen in the basal lithologies to the carbonates. The granites display evidence for sericitization; the gabbros have been propylitized and in the immediate vicinity of Berg Aukas are characterized by opalescent blue quartz phenocrysts; and the clastic rocks of the Nabis Formation have been intensely epidotized.

### 7.8 Brecciation

Three types of breccia are associated with the deposit (Gavine, 1978). A *collapse breccia* comprising a varied assortment of breccia blocks cemented by a calcite and descloizite matrix occur along the floors of the cavities. It is a late features formed by secondary karsting processes. *Dolostone breccia* comprising

unmineralized and unaltered blocks, is developed in the hanging wall light grey dolostones. The blocks lie within a ferruginous matrix within which ubiquitous pyrite rimmed by goethite occurs.

The only primary hydrothermal breccia was referred to as *replacement breccia*. It was characterized by varying degrees of calcitization of the Light Grey Dolostone. Disseminated sphalerite and oxidized pyrite are common constituents of this breccia.

## 7.9 Fluid Inclusion Studies

Freezing and heating experiments using a Linkam T<sub>H</sub> 600 stage were carried out on fluid inclusions in doubly-polished sphalerite plates. The scarcity of good inclusions provided only 30 good determinations, but the consistency of the results with support from 4 determinations in dolomite gangue allow a satisfactory assessment of the results (Table 7.9.1). The best inclusions were found hosted by honey coloured sphalerite which is in contrast to a study conducted by Ypma (1984), whose observations indicated that dark red sphalerite was a more frequent host.

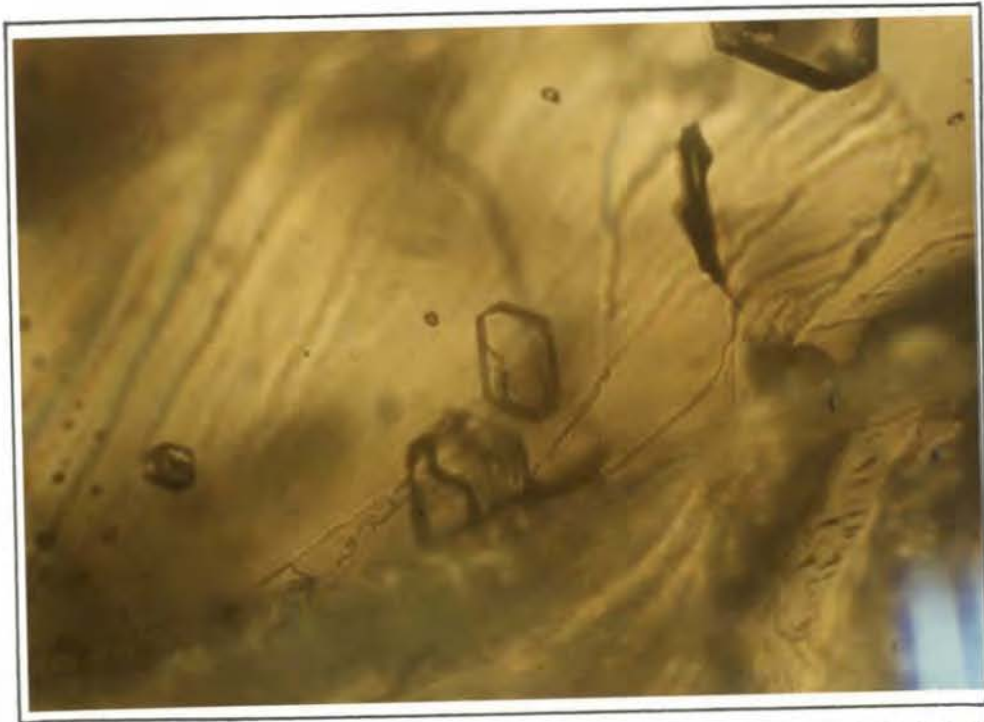


Plate 46 : Euhedral fluid inclusion in sphalerite with vapor bubble. Sample JEM 131, PPL, 40x.

The inclusions are generally not greater than 30 microns in diameter, and are often dark in colour, possibly reflecting the compositional nature of the liquid. The best inclusions were noted to have a well developed euhedral crystal shape (Plate 46) and commonly occurred in clusters. Vapor bubbles are not always present, but where observed, they are generally very small, usually not exceeding 1-2 microns. No daughter crystals were observed in the inclusions examined.

Homogenization temperatures (TH) for primary fluid inclusions range from 97<sup>o</sup> to 205<sup>o</sup> C in sphalerite and 92<sup>o</sup> to 210<sup>o</sup> C in dolomite. These results are lower than those obtained by Ypma (1984) whose results from sphalerite determinations range from 230<sup>o</sup> to 250<sup>o</sup> C. Freezing experiments yielded an average initial or eutectic melting temperature (Te) of -37,5<sup>o</sup> C indicating that the total dissolved salts (TDS) have a complex composition. One interpretation is a mixed four component brine composition (NaCl - CaCl<sub>2</sub> - MgCl<sub>2</sub> - H<sub>2</sub>O). An eutectic temperature (Te) of -20,8<sup>o</sup> C is diagnostic of the NaCl - H<sub>2</sub>O system (Crawford, 1981), and is only depressed by the addition of other components, particularly CaCl<sub>2</sub> and MgCl<sub>2</sub>. Phase equilibria (Figure 7.9.1; Crawford, 1981) for a -37,6<sup>o</sup> C eutectic indicates a liquid composition comprising 75% H<sub>2</sub>O, 5% NaCl, and 20% CaCl<sub>2</sub> - MgCl<sub>2</sub>. However, it must be stressed that this is based on only one possible phase equilibria.

The final melt or temperature of melting (Tm) yielded an average of -20,7<sup>o</sup> C over a narrow range of -18<sup>o</sup> to -25<sup>o</sup> C. This establishes the salinity of the system to be 23 weight %, based on a two component NaCl - H<sub>2</sub>O system (Figure 7.9.2; Crawford, 1981).

Assuming a mixed hydrostatic - lithostatic pressure load of 1500 m, the homogenization temperatures can be corrected for pressures of 0,5 Kb using the curves of Potter (1977). These indicate a correction temperature of 45<sup>o</sup> C should be added establishing an initial trapping temperature range of 137<sup>o</sup> to 255<sup>o</sup> C.

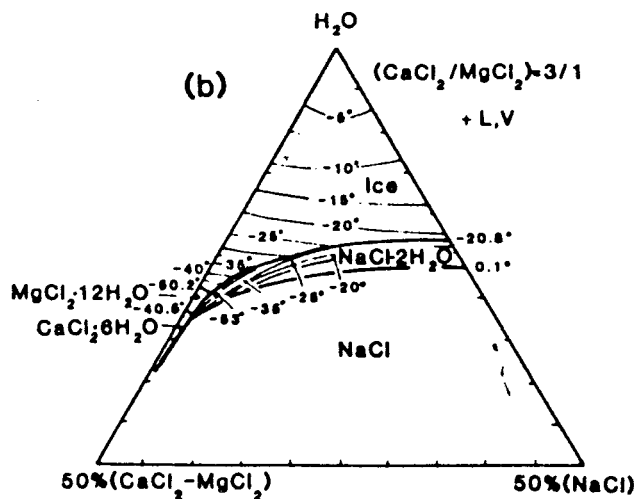


Figure 7.9.1 : NaCl - CaCl<sub>2</sub> - MgCl<sub>2</sub> - H<sub>2</sub>O system at a CaCl<sub>2</sub>/MgCl<sub>2</sub> ratio of 3:1. Liquidus fields are labelled and separated by heavy lines (from Crawford, 1981).

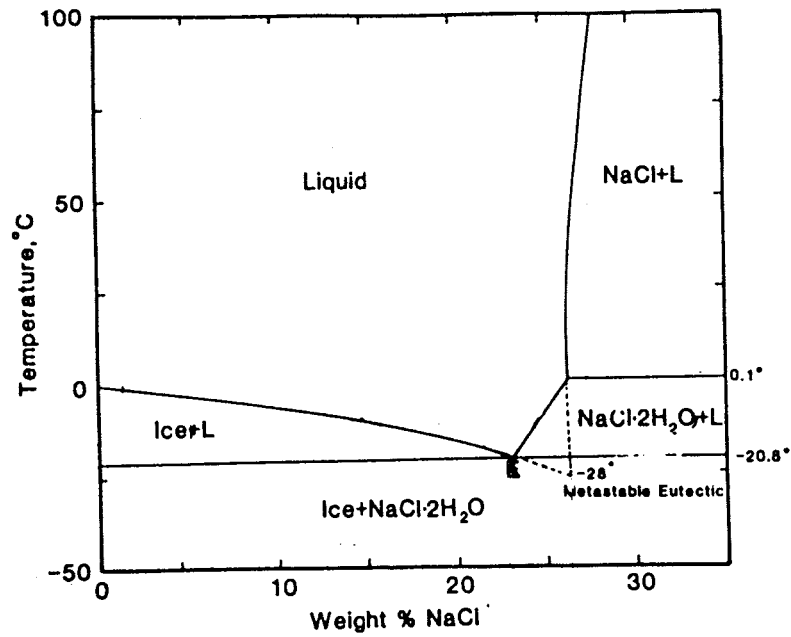


Figure 7.9.2 : NaCl - H<sub>2</sub>O system, temperature - composition diagram at 1 bar. From Crawford, 1981.

Table 7.9.1: Results of Fluid Inclusion Experiments (T<sup>0</sup>C)

	1	2	3	4	5	6	7	8
Freezing	-74	-79	-80	-81	-74	-85	-69	-73
1st Melt (Te)	-35	-38	-42	-36	-41	-36	-35	-
2nd Melt (Tm)	-22,2	-22,3	-22,0	-22,5	-22,9	-18,9	-21,2	-20,2
Homogenization (TH)	125	124,4	126	154	151	150	163	97,3
Mineral Phase	sp	sp	sp	sp	sp	sp	sp	sp
	9	10	11	12	13	14	15	16
Freezing	-74	-73,7	-74,6	-	-69	-80	-66	-58
1st Melt (Te)	-	-35	-	-	-34	-29	-37	-36
2nd Melt (Tm)	-17,8	-20,2	-18,8	-18,8	-22,5	-18,5	-20,1	-20,7
Homogenization (TH)	150	151	-	-	155	210	102	92
Mineral Phase	sp	sp	sp	sp	sp	dol	dol	dol
	17	18	19	20	21	22	23	24
Freezing	-65	-72	-65,6	-68,6	-70,5	-71	-71,5	-72,6
1st Melt (Te)	-36	-37	-41	-40,4	-40,1	-36	-37	-36,5
2nd Melt (Tm)	-19,7	-19,7	-19,7	-19,7	-20,1	-20,2	-19,9	-20,1
Homogenization (TH)	129	201	205	205	203	201	189	188
Mineral Phase	dol	sp	sp	sp	sp	sp	sp	sp

Table 7.9.1 (continued):

Results of Fluid Inclusion Experiments ( $T^0$ ).

	25	26	27	28	29	30	31	32
Freezing	-64	-40	-90	-90	-71	-46	-64,2	-64,1
1st Melt ( $T_e$ )	-40,4	-38	-42	-43	-43	-35	-33	-39,6
2nd Melt ( $T_m$ )	-22,2	-19,9	-19,8	-20,8	-25	-19,8	-23,6	-24,3
Homogenization (TH)	188	188	150	120	120	129	133	130
Mineral Phase	sp	sp	sp	sp	sp	sp	sp	sp

	33	34
Freezing	-64	-46
1st Melt ( $T_e$ )	-40,1	-36
2nd Melt ( $T_m$ )	-23,1	-22,5
Homogenization (TH)	139	146
Mineral Phase	sp	sp

## 8. THE CONTROLS ON MINERALIZATION

There are two fundamental reasons for the establishment of a mineral province in the Otavi Mountain Land. They are: a.) ideal basement conditions which encouraged the supply and movement of mineralizing fluids, and b.) the carbonates which provided the suitable sites for ore deposition. Basement conditions include rift-grabens, growth faults, clastic aquifers, and palaeo-physiographic features such as basement highs and unconformities. Features in the carbonates include a possible sulphur source, and structural, stratigraphic and sedimentological controls which influenced the depositional sites..

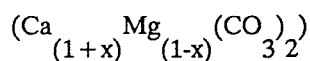
The fundamental prerequisite for the formation of an ore body in carbonate rocks is the effective porosity and permeability of those rocks. The host rock must be permeable to allow movement of metal-bearing solutions (Anderson and Macqueen, 1982; Garven, 1985) and to supply the necessary open spaces into which the ore minerals can be deposited. It follows, therefore, that the controls on mineralization will be intimately related to those factors which influence the porosity of the rocks and permeability pathways within them. Porosity may be a primary sedimentary feature or a diagenetic feature, or could be induced by secondary processes such as dolomitization, palaeophysiology, carbonate structure (folding, faulting, jointing or fracturing), basement structure, and karst tectonics. All these factors have to a lesser or greater degree influenced the localization of the mineralized occurrences in the Otavi Mountain Land.

The nature of porosity in carbonate rocks is rarely homogenous and although dolomitization can enhance porosity, neomorphism and compaction tend to reduce it. Likewise, impermeable horizons within a sequence may behave as barriers to fluid movement. These factors are important with respect to ground preparation for ore deposition and Beales and Jackson (1966) have argued that permeability trends may be geologically predictable.

### 8.1 Dolomite and Dolomitization as a Control on Mineralization

An understanding of the dolomitization process is important because a characteristic feature of Mississippi Valley-type deposits is that they are hosted by carbonate lithologies, principally dolostones. There are some exceptions such as the Old Lead Belt in south eastern Missouri (Snyder and Gerdemann, 1968) where the mineralization occurs in a variety of lithotypes including sandstones and conglomerates, but this is rare and strictly atypical.

The term *dolomite* refers to the mineral species dolomite with the general formula:

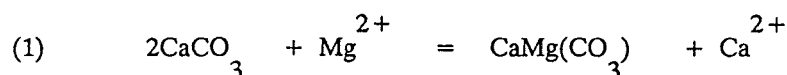


A rock with greater than 50% dolomite is referred to as a *dolostone*.

Dolomites in nature tend to be non-stoichiometric (Beukes, 1986; Morrow, 1982a) with a degree of mixing

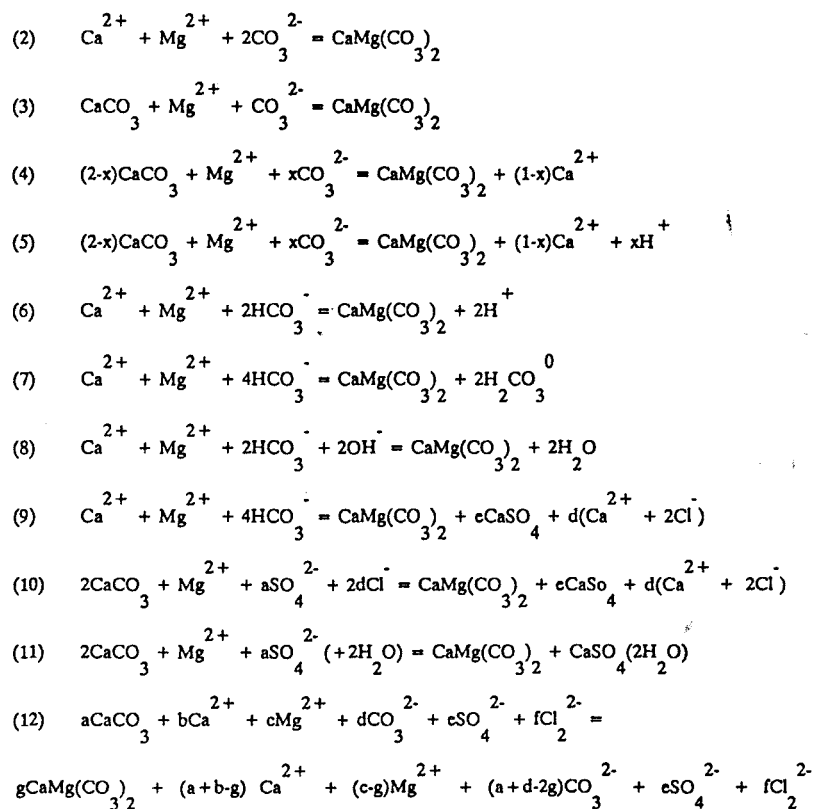
of calcium and magnesium between cation layers. Exotic cations such as Fe, Sr, Na and Mg may substitute for calcium in the crystal lattice. Although dolomite is thermodynamically stable, it is extremely rare for it to directly precipitate from sea water, and it is more typical for lime muds comprising Mg-calcite and aragonite to be deposited which may then be dolomitized. Three major kinetic barriers impede the direct precipitation of dolomite. (a) Saline solutions encourage rapid crystallization resulting in disordered Ca-Mg carbonates. (b) The hydration behaviour of the constituent ions of dolomite promotes calcium-rich phases. (c) A low  $\text{CO}_3^{2-}$  concentration inhibits Mg-carbonate precipitation.

The dolomitization reaction may proceed in a number of ways (Table 8.1.1) but is usually presented in a simplified form:



This reaction involves a loss in volume by as much as 6-13% (Morrow, 1982a) which improves the porosity of the rock. However, the process may proceed without influencing the porosity which is evident where primary sedimentary features such as algal mats are preserved.

**Table 8.1.1: Selection of stoichiometric dolomitization reactions**  
(From Beukes, 1986).



For the dolomitization process to proceed, the kinetic requirements, especially  $Mg^{2+}/Ca^{2+}$  ratio, need to be met. A number of models have been developed which usually incorporate a means of  $Mg^{2+}$  concentration and a mechanism to deliver the  $Mg^{2+}$  to the dolomitizing site (Morrow, 1982b). These include the Hypersaline Lagoon and Reflux model, the Burial Compaction model, the Coorong model, the Sabkha model, and the Mixed Water (Dorag) or Dilution model. An in-depth review of these models is beyond the scope of this dissertation and the interested reader is referred to the literature for more details. A critical appraisal of these models (Hardie, 1987) indicates that none have been completely satisfactory, but despite this, the dolomitization process is possibly important for mineralization.

The preference for dolostones as the favoured host rocks for low temperature lead-zinc ore deposits can only be partly due to dolostone porosity since other lithologies such as sandstones tend to have a more enhanced permeability. A primary source of sulphur in the dolostones may be an important controlling factor. The Hypersaline Lagoon or the Evaporative Reflux Model for dolomitization incorporates evaporation of sea water and precipitation of gypsum ( $CaSO_4 \cdot 2H_2O$ ), removing  $Ca^{2+}$  from the water thereby raising the  $Mg^{2+}/Ca^{2+}$  ratio. Evaporation also has the effect of creating denser water which would provide a mechanism for it to sink through earlier deposited unconsolidated lime mud, flushing a high  $Mg^{2+}/Ca^{2+}$  solution. Beales and Hardy (1980) have studied a number of MVT deposits with the conclusion that anhydrite and/or gypsum were originally present in dolostone host rocks and which were later removed by solution. In the Tsumeb-Uris belt, the Augen Marker in the T7 Huttenberg Formation comprises "augens" of secondary calcite which are interpreted as pseudomorphs after nodular anhydrite (Lombaard *et al.*, 1986). Beales and Hardy (*op. cit.*) argue that evaporite sequences in carbonate environments are easily lost due to intrastratal solution by either meteoric or formation waters, and pseudomorphs after evaporites may be difficult to recognize, particularly where they occur as irregular clumps that range from paramorphic (pelmicrites or intraoosparites) to neomorphic in texture.

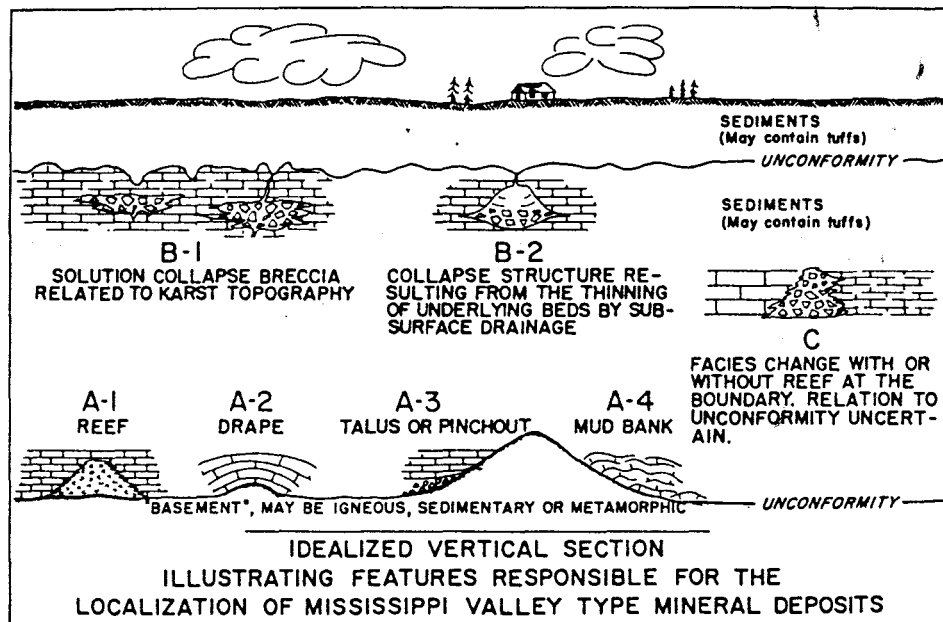


Figure 8.2.1 : Palaeo-physiographic controls in carbonates on localization of Mississippi Valley-type deposits. From Callahan, 1977b.

## 8.2 Palaeo-physiography

The significance of palaeo-physiography in the localization of MVT deposits has been successfully applied to the discovery of the Elmwood zinc deposit in Middle Tennessee (Callahan, 1964, 1977a, 1977b; Braun, 1983). Palaeo-physiographic features of importance include basin morphology, palaeo-topographic highs, erosional surfaces expressed as unconformities, palaeo-aquifers and primary permeable sedimentary features such as carbonate reef complexes (Figure 8.2.1).

Mississippi Valley-type deposits tend to develop along the margins of depositional basins, usually along the edge of basement palaeo-highs. This is particularly well exemplified by the St. Francois Mountains in Southeastern Missouri (Kisvarsanyi, 1977) (Figure 8.2.2), and by the Ozark Dome in the Tristate area of the central USA, around which mineral deposits have been concentrated. This is in contrast to carbonate-hosted oil deposits which in general tend to concentrate in the central portions of depositional basins. It is probable that the Grootfontein basement high marked the basinal edge during sedimentation, and therefore influenced the regional migration of metalliferous brines.

Callahan (1977a, 1977b) has classified the possible sites where MVT deposits are likely to develop relative to erosional surfaces. Sites developed above an unconformity favour stratabound mineralization and are strongly influenced by sedimentary/biogenic features along palaeoshorelines. These include pinchouts, breccias, talus slopes, reefs, mud banks, facies boundaries, or a combination of these features. Those sites developed below an unconformity are subsurface erosional features such as crevices, caverns, collapse breccias, chimneys or pipes or a combination of these.

The ore deposits in the Otavi Mountain Land are related to the two principle unconformities. Berg Aukas-type deposits are developed above the basal Abenab unconformity, and Tsumeb-type deposits developed below the Tsumeb unconformity.

Primary permeable sedimentary features such as carbonate reef complexes have traditionally been regarded as important environmental loci for stratabound MVT deposits (Callahan, 1977a). However, regional studies demonstrate that actual reef hosted deposits are in a minority to other settings. Deposits are closely controlled by the prior development of porosity, and thus may be located in platformal carbonates of biostromal character, or back-reef or fore-reef settings (Anderson and Macqueen, 1983; Skall, 1975; Kyle, 1981). In the Otavi Mountain Land, no reef-hosted deposits have been found despite the wide development of such features. Only the Alt Bobos reef west of Tsumeb hosts disseminated malachite mineralization.



Karst has been defined as "a diagenetic facies, an overprint in subaerially exposed rocks, produced and controlled by dissolution and migration of calcium carbonate in meteoric waters, occurring in a variety of climatic and tectonic settings, generating a recognizable landscape" (Esteban and Klappa, 1983). Traditionally, karst processes are believed to operate in the vadose zone (Figure 8.3.1) where the action of aggressive aqueous solutions of any origin and temperature form structures and deposits referred to as speleothems. In the genesis of Mississippi Valley-type deposits, dissolution of carbonate may have been achieved in the phreatic zone by hot waters, possibly basinal brines rather than by groundwater, and it has been proposed that the term hydrothermal karst (Ohle, 1985) be adopted. The concept has been fully adopted in Poland where the solution, collapse and brecciation of the Silesian deposits (Sass-Gustkiewicz, *et al.*, 1982) is wholly attributed to the action of hydrothermal ore solutions.

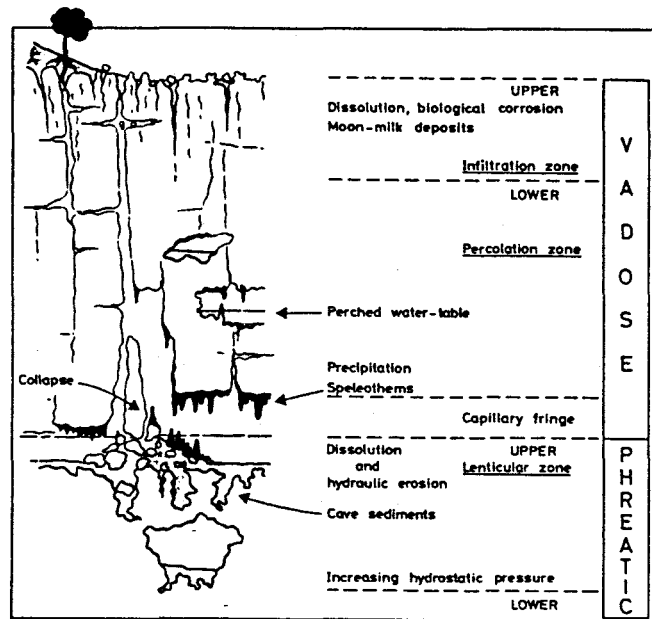


Figure 8.3.1 : Idealized authigenic karst profile (from Esteban and Klappa, 1983).

Typically, the carbonate hosted ore consists of brecciated country rock with sulphides and associated gangue contributing to the breccia matrix. The origin of these breccias has always attracted controversy, and in large part was attributed to tectonic processes. However, it is generally conceded that localized carbonate solution brecciation is the preferred mechanism (Ohle, 1985; Lombaard *et al.*, 1986; Misiewicz, 1985).

*Gravity induced collapse breccias* are the most visible manifestation of karst tectonics, but Ohle (1985) has noted that irregularities such as the size and shape of breccia fragments, and the size and shape of some of the breccia bodies suggests that other mechanisms were also responsible. Sass-Gustkiewicz *et al.* (1982) have proposed that under phreatic conditions dissolution openings and rock deformations result from stress redistribution which in turn results from solutional removal of soluble rocks (Figure 8.3.2a). They

have coined the term karst tectonics for the process, whilst Ohle (1985, after Sawkins, 1969) terms it **chemical brecciation**. Thus, the concept suggests that gravity induced collapse breccias are initiated in the phreatic zone by karst tectonic processes. *Agmatic breccias* result by an increase in fluid pressure brought about by the force of crystallization, and it promotes and extends fracturing (Figure 8.3.2b).

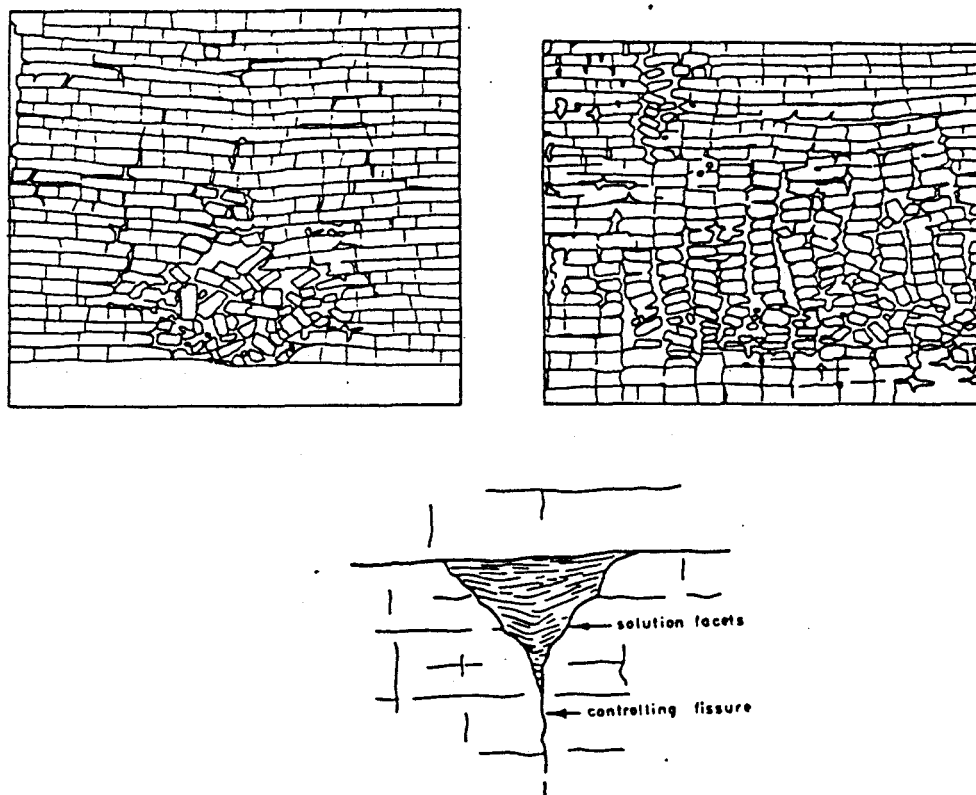


Figure 8.3.2 : (a) Experimental collapse breccias produced under phreatic conditions by flow of water through bedded and fractured model aquifer. (b) Agmatic brecciation and fracturing of limestone resulting from changes in fluid pressure. From Sass-Gustkiewicz *et al.*, 1982.

The Otavi Mountain Land is a terrain which is actively undergoing karsting. During severe rainfall there is little or no surface run-off as water is rapidly absorbed and transmitted by structural and karst conduits. The Mountain Land abounds in karst features, many of which have been documented by Van der Westhuizen (1984). It is apparent that the Mountain Land has been subjected to several periods of karsting. The first two were the shortest, possibly lasting no longer than 40 Ma, but were the most important with regard to mineralization.

### 8.3.1 Karst Episode                    1: Post Huttenberg Formation and pre-Mulden Group

In the Tsumeb Syncline, there is evidence for a palaeo-karst surface which was active during the hiatus before Mulden sedimentation commenced. The origin of the Tsumeb pipe is interpreted as a solution

chimney (Hughes, 1983) which was formed by dissolution of carbonate

Table 8.3.1: Karsting episodes in the Otavi Mountain Land

<u>KARST EPISODE</u>	<u>PERIOD</u>	<u>REMARKS</u>
III	Post-Damara	Responsible for the oxidation and reconcentration of ore. Movement of late stage fluids into fractures as superficial enrichment. eg Kupferberg, Uris.
II	Syntectonic	Faulting at Abenab and fracturing at Berg Aukas provide the loci for hydrothermal karsting.
I	Post-Huttenberg	Uplift prior to Mulden initiates hydrothermal karsting at Tsumeb Pipe and karsting of the exposed subaerial topography.

at the intersection of the North Break palaeoaquifer and the ore body fold zone, the earliest tectonism to have been operative (Lombaard *et al.*, 1986). If the Tsumeb pipe is projected to its original configuration by the unfolding of the stratigraphy, it may be concluded that solution collapse of the pipe occurred in the phreatic zone. This could have been induced by agmatic brecciation or even by evaporite solution collapse since pseudomorphs after anhydrite have been recognized in the stratigraphy, but hydrothermal karsting was probably also active. Lombaard *et al.* (1986) propose that the solution collapse process was activated by a geothermal gradient related to the prominent north east geofracture passing through the Tsumeb-Uris belt. Isopach studies undertaken by Lombaard *et al.* (*op. cit.*) indicate that the geofracture was active during deposition of the Otavi Group. A galena age of 560 Ma for the Tsumeb mineralization establishes that karsting was probably active between 600 Ma and 560 Ma.

It is evident that karsting in the vadose zone was also active during this period. A palaeokarst surface has been identified between the T8 horizon and the base of the clastic sequence at the Tschudi disseminated copper deposit (P. Harrison, pers. comm.). Van der Westhuizen (1984) notes that excavations at the Tsumeb West prospect have revealed a palaeo-grike infilled by Tschudi sandstone. Uplift at the cessation

of platform conditions prior to orogenesis and clastic Mulden sedimentation was probably responsible for the subaerial conditions necessary for karsting.

### 8.3.2 Karst Episode            II: Syntectonic Karsting at Abenab and Berg Aukas

The age and nature of karsting at Abenab and Berg Aukas is not easily resolved, but appears to have been influenced by the advent of orogenesis. The Abenab Breccia Pipe is located on the Abenab Fault, a bedding plane thrust along the contact of massive dolostone and platy limestone. The breccia pipe is one of several along the fault which post date the structure, but it is the only one to be well mineralized. This leads to the conclusion that solution brecciation followed the tectonism and that, as in the case of the Tsumeb-Uris Belt, a karst chimney formed by solution collapse prior to the entry of mineralizing fluids.

Although there is no evidence to support dissolution in the phreatic or vadose zones, it is probable that orogenic uplift was accompanied by movement of meteoric waters along the Abenab Fault leading to the karsting. Mineralizing fluids generated by basin dewatering moved above the basal unconformity towards the Grootfontein basement high where metal precipitation occurred in the open spaces of the pipe structure.

At Berg Aukas, palaeokarst features include cavities and speleothems of various shape and size. The largest was the Main Cavity (Gavine, 1979) situated between 14-70 sublevel and 19 level. It had dimensions of approximately 200 m E-W, 100 m N-S and 120 m in height. Various breccia types, viz. collapse breccia, dolomite breccia and replacement breccia suggest that karsting could have been influenced by solution collapse in the vadose zone, but could also have resulted by hydrothermal or chemical brecciation in the phreatic zone. The interpretation of the origin of the replacement breccia as hydrothermal together with the depth of the cavities (base of Main Cavity is 600 m below surface) suggests that hydrothermal karsting was operative. Weilers (1959) noted two varieties of cavity in the upper levels. The first is lined with mineralization and probably has a hydrothermal origin. The second only hosts vanadiferous muds and was probably formed by meteoric dissolution.

The close relationship between dolomite breccia and ore strongly suggests that breccia formation and the emplacement of sulphide ores were part of the same formative process. This is especially evident where dolomite breccia blocks are completely encased in ore. The genetic model is similar to that suggested for Abenab.

Since the karsting at Abenab and Berg Aukas pre-dates or is contemporaneous with mineralization, it can be concluded that the karsting episode occurred at approximately 600 Ma the approximate age of mineralization established by lead isotope systematics (Allsopp *et al.*, 1981). As in the case of Tsumeb, the episode is tentatively correlated with a period of uplift.

8.3.3 Karst Episode      III:      Post-Damara Karsting

Karsting has continued to be active during periods of subaerial exposure since the demise of Damara orogenesis. The last karsting period post-dates Karoo times and was responsible for the present day topography and speleothems, especially at Harasib where there are extensive subterranean cavities and lakes.

Post-Damara groundwater movement was responsible for the transport of calcium metavanadate complexes (Van der Westhuizen, 1984) and the oxidation and vanadium enrichment of the sulphide ores. At the same time, continued karsting and supergene processes were responsible for upgrading and concentrating the ores.

**8.4 Structure as a Control on Mineralization**

Structure has played a fundamental role in the localization of mineralization in the Otavi Mountain Land. The Tsumeb-West basement geofracture demarcates the western limits of economically significant mineralization. It has been postulated that this feature provided the means for mineralizing fluids to penetrate the Tsumeb pipe (Lombaard *et al.*, 1986; R. Gunthorpe, pers. comm., 1986). The Kombat ore bodies are located in the vicinity of the Kombat Fault, a major north-north easterly trending basement fault which extends from north of the Otavi Valley into the transitional Northern Zone where it disrupts the Askevold volcanics.

Sohnge (1957) noted that most deposits are located on the steep sides of regional synclines. This observation is also valid for local depositional sites within individual ore bodies. Abenab West and the Northern Ore Horizon at Berg Aukas display a preference for ore deposition along steeper parts of the structure. Where there is a levelling out, ore tends to diminish. Lombaard *et al (op. cit.)* have established at Tsumeb that it was the ore body fold zone which was responsible for the axial planar fracture cleavage along which solution collapse occurred. At Abenab, the breccia pipe is located on the Abenab bedding plane fault, and at Kombat (Innes and Chaplin, 1986), structural breaks in the dolostone-slate contact are regarded as important loci for mineralization.

At Berg Aukas, the relationship between structure and the ore bodies is less clear. There is no obvious structural control to the trend of mineralization. However, vanadium-base metal enriched muds filling fractures can be clearly seen in the south adit on the Mine Kopje. The surface expression of the Central Ore Body, which can still clearly be seen, was in the form of descloizite and galena mineralization along steeply dipping north-south fracturing. Schreuder (1969) made the significant observation that the

Northern Ore Horizon coincides with a north-south trending anticlinal crossfold seen as a major inflection in the Massive Grey Dolostone-Light Grey Dolostone contact. Air photo interpretation and structural synthesis (Misiewicz, 1985; 1986a) indicate that this broadly corresponds with the axial trend of the mild  $F_2$  folding event which caused the doubly plunging syncline. Steeply dipping north-south fractures were developed as a consequence of the secondary cross folding and hydrothermal karsting was preferentially initiated along this trend. Although fracturing was also developed throughout the syncline, the ore trend broadly corresponds with the keel of the  $F_2$  fold axial plane suggesting that this was the controlling factor in directing the hydrothermal fluids.

Fracture-filled mineralization is also well developed in the Otavi Mountain Land at Kombat, Kupferberg, Rohrsers/Central prospect and Baltika (Misiewicz, 1986a; 1986b; Vickers, 1976; Innes and Chaplin, 1986). At Abenab West, anticlinal and synclinal warping within the mineralized zone has been an important control. It is informally known as the Abenab West Disturbed Zone. Verwoerd (1957) noted that some massive galena displays some deformation establishing that the mineralizing event was syntectonic.

## 9. ORE GENESIS

The origin of the carbonate-hosted deposits in the Otavi Mountain Land has been a debated subject for many years. The prime reasons for this were based on the misunderstanding and misinterpretation of the so-called pseudo-aplite at Tsumeb and Kombat. The nature of the feldspathic sandstone (pseudo-aplite) was argued to be igneous (Schneiderhohn, 1919, as quoted by Lombaard *et al.*, 1986; Botha, 1960; Sohnge, 1964), and consequently, most early models were based on a magmatic origin with the result that a correlation with Mississippi Valley-type deposits was disregarded. This misnomer also influenced some of the genetic models which had been proposed for the Berg Aukas-type deposits, but this was largely confounded by the lack of literature on these deposits. For example, Mason (1981) noted the existence of pseudo-aplite at Berg Aukas which is incorrect because the feldspathic sandstone associated with the mineralization is only found with Tsumeb-type mineralization since it originates from the Tschudi Formation.

Whichever genetic model is proposed, it should offer a satisfactory explanation for a source of base metals and vanadium, a means of transport, the nature of the hydrothermal solution, the means by which the solution was moved, and a mechanism for ore deposition. The model should adequately incorporate a number of basic aspects common to the Mountain Land which include:

- i. The influence of a granitic basement dome.
- ii. The role, if any, played by a basic intrusive counterpart in the basement complex.
- iii. The relationship of the rift grabens with the overlying carbonates.
- iv. The influence of the carbonates on metal precipitation and on the sites of ore deposition.
- v. The anomalous ore isotope behaviour.
- vi. The nature of the vanadium mineralization.

### 9.1 A Review of Genetic Models

#### 9.1.1 A Magmatic Origin

Magmatic genetic hypotheses were largely developed for the Tsumeb deposit because the basis for these

models was the supposed evidence of the pseudo-aplite being an igneous rock. The concept (as reviewed by Lombaard *et al.*, 1986) was originally proposed in 1929 by Schneiderhohn, favoured by Sohnge (1957, 1964), and supported by Botha (1960). The model suggests that the metals were derived from a magmatic source related to the emplacement of igneous bodies intruded at depth beneath the Otavi Mountains. Magmatic waters transported the ore to the site of deposition.

The models have been generally rejected for a number of reasons. Firstly, there has been agreement that the pseudo-aplite is indeed a feldspathic sandstone originating from the Tschudi Formation, and secondly, that hypogene mineralization post-dates the sandstone emplacement.

On Pb-isotope evidence, Allsopp *et al.* (1981) argue that if a two-stage evolution (implying a magmatic origin), is used to explain the linear trend of the observed Tsumeb-Kombat data (Figure 5.1.1), then the conclusion is that mineralization took place some 600 Ma ago and that it was derived from an approximate 3000 Ma source. Since no rocks in the area of such an age occur, a magmatic origin is ruled out.

Another theory based on a magmatic theme (Sohnge, 1964; Allsopp and Ferguson, 1970), proposed that the calcitic alteration at Tsumeb might have a carbonatitic origin since it and the Tsumeb West pipe lie almost directly on the Tsumeb West geofracture. This is the east-north-east extension of the Cape Cross-Okarusu lineament along which a number of alkaline and carbonatitic complexes have been emplaced. Allsopp and Ferguson (*op. cit.*) tested the theory with Sr-isotope and La and Ce trace element analyses. Their results concluded that the rocks had  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (mean = 0.712) which do not correlate with those typical of carbonatites (mean = 0.7035). They also obtained low La and Ce values and therefore concluded that there is no evidence to support a carbonatitic origin. The concept is rejected also on the grounds of age since the mineralization at Tsumeb has been established to be 560 Ma whereas the complexes located on the Cape Cross-Okarusu lineament are Karoo-aged (Marsh, 1973).

Despite the overwhelming evidence in favour of rejecting a magmatic origin, there remain some aspects which might involve an igneous component. The Kombat ores are anomalously enriched in Li, Be, and B which strongly suggest that magmatism did influence mineralization in some way. Since the mineralization is syntectonic, it has been postulated that this is linked to the Damaran tectono-thermal event (Innes and Chaplin, 1986).

The resolution of a sedimentary origin for the pseudo-aplite has only been achieved in recent years (Lombaard *et al.*, 1986). Emslie (1980) accepted a volcanic origin for this enigmatic rock and invoked a dual model for the mineralization of the Otavi Mountain Land by proposing a separate origin for the Cu-rich Tsumeb-type ores to the Pb-Zn-rich ores of the Berg Aukas-type. He suggested that the Pb-Zn ores were derived from basinal brines analogous to Mississippi Valley-type deposits and that the As-rich Cu ores are an indication of volcanic activity and linked to the pseudo-aplite. However, this disregards the evidence of inconsistent age relationships between the hypogene ores and the feldspathic sandstone, and the fact that

tennantite is also a very common accessory constituent of the Berg Aukas ores indicating that there is some agreement between the two end members.

### 9.1.2 A Basin Dewatering Model

A basin dewatering model has been proposed by Emslie (1980) and Misiewicz (1985) and is based on the ore genetic models proposed for Mississippi Valley-type deposits which were largely established at Pine Point in Canada (Beales and Jackson, 1966; Kyle 1981; Anderson and Macqueen, 1982; Garven, 1985). The model incorporates the evolution of hydrothermal brines in a deep geosynclinal trough due to compaction and diagenesis. It involves leaching of metals from the sedimentary pile and the movement of highly saline metalliferous fluids at temperatures ranging between 100 °C and 250 °C via rift-grabens, growth faults, unconformities, and other basement fractures to the carbonate environment at the basin margin. The mineralization was preferentially deposited in the carbonates in sites produced by solution and collapse during hydrothermal karsting. Depositional sites were controlled by the basement structure and the palaeo-physiography.

*Source of metals:* A thick sedimentary pile is a necessary requirement when considering a source of metals from a non-magmatic parent. A sub-surface circulating brine model requires large volumes of sedimentary rock and/or basement which can be leached of base metals. Emslie (1980) has estimated that only 3 ppm of Cu, Pb, and Zn need to be removed from a source area with a volume of 100 km<sup>3</sup> to produce an ore body containing one million tons of metal.

There is no consensus on an ideal lithological source for the leaching of base metals for Mississippi Valley-type deposits (Kyle, 1981). Shales tend to contain more Pb and Zn than other sedimentary rocks, and have been postulated as satisfactory source material (Macqueen, 1976), especially at depths of up to three kilometres which falls in the 75 °C to 175 °C range. The turbidite sequences, such as the Okonguarri Formation in the Northern Zone, could then be an ideal base metal source horizon. Shales have been disregarded at Pine Point because of their conspicuous absence from the stratigraphy.

In the Southeastern Missouri district, USA, the coarse clastic sediments of the Lamotte Sandstone have been suggested as a possible source for the metals on the grounds that there is a correlation in Pb-isotope composition (Doe and Delvaux, 1972). In the Otavi Mountain Land, anomalous copper mineralization in the sandstones of the Nabis Formation were unsuccessfully investigated in the Gaikoš and Kokasib Synclines in the early 1970's by a French exploration company. At Berg Aukas, the clastic lithologies of the Nabis Formation on the northern flank of the syncline has an anomalous residual soil copper geochemistry, and malachite staining of the rocks has been observed.

At Pine Point (Kyle, 1981), the carbonate host rocks are the favoured source horizons. However, in the Otavi

Mountain Land, the carbonates generally have a low copper content (< 20 ppm; Van der Westhuizen, 1984), and these rocks are not regarded as the important source horizon. The lavas of the Askevold volcanics, however, have a number of occurrences such as at Deblin Mine where copper mineralization is notable. These rocks are therefore a possible copper source.

In summary, the lithological sequences of the Swakop Trough provide a variety of source horizons in sufficient quantities and at ideal depths, in tectonic settings which could have been leached by hydrothermal brines generated by compaction, diagenesis, and orogenesis. The turbidite sequences such as the Okonguarri Formation could have provided a Pb-Zn source, and the Askevold volcanics could have been a proto-copper source. Such a dual source could be a plausible explanation for the bimodal Pb-isotope systematics.

*Hydrothermal brines:* The nature of hydrothermal brines associated with Mississippi Valley-type deposits in the USA are largely known from fluid inclusion studies. They typically have a high salinity (> 15% NaCl), and have a hydrocarbon component. Although there has been no analytical confirmation of the fluid composition, the salinity and homogenization temperatures deduced from fluid inclusion studies (Section 7.9) indicates that the hydrothermal fluids which deposited metals in the Otavi Mountain Land are remarkably similar.

The nature of the hydrothermal brine is derived as a function of the sedimentary basin. Salinity increases with depth due to the ionic filtration of clays (Anderson, 1973; Kyle, 1981). Temperature also increases with depth and the result of an increased temperature and salinity is that base metal solubility increases due to the improved metal-chloride complexing. Furthermore, increasing temperature at depth has an effect on lowering the pH which facilitates the release of metals (Ellis, 1979). Also with depth, liquid viscosity decreases which favours the rapid transmission of heavy brines when there are suitable permeability pathways (Hanor, 1979).

*Dewatering and leaching of metals:* Dewatering of sediments is a normal diagenetic process where approximately 75% of contained water is lost within the first 100 m of burial (Hanor, 1979). With continued compaction, interstitial water is continually expelled by diffusion. These fluids are heated, increase their salinity, derive a low pH and therefore are able to dissolve and transport base metals. It is estimated that the optimal depth for generation of metalliferous brines, based on fluid inclusion temperatures, is at approximately three kilometres. Anderson and Macqueen (1982) suggest that sediment porosity varies between 0 to 20% at a depth of 3000 m. However, Emslie (1980) notes that dewatering can continue to a depth of 6100 m, depending on the porosity nature of the sediments.

*Movement of fluids:* The Northern Rift represents an extensive "mineralizing front" because as the base metals were leached from the Swakop Trough, they were moved into the rift where they were directed along the rift margins. The coarse alluvial fan and related coarse clastic wedges of the Nabis Formation also provided an extensive lateral permeable aquifer. The Grootfontein Basement Dome marks the margin of the basin and is characterized by a pinching out of the Nabis sediments against its flanks. The mineralization in the Nosib sediments along the contact between the Nosib Group and Abenab Subgroup in the Nosib Mining Area

attests to the movement of hydrothermal fluids through these sediments, probably in response to the hydraulic gradient, towards the basement dome.

*Sulphide precipitation and concentration:* The hydrothermal fluids were directed along the clastic aquifers to where they pinch out. The fluids entered the carbonates through structural features and initiated "hydrothermal karsting". Base metals were deposited in the resulting receptacles where a sulphur source was intercepted. Although the nature of this sulphur is conjectural, it is suggested that the sulphur was made available either directly from evaporite sequences in the carbonates, or was derived as a product of the dolomitization process (as discussed in the evaporative reflux model in Section 8.1).

*Timing of mineralization:* The narrow range in age of mineralization (560 Ma to 600 Ma) which is contemporaneous with the major  $D_2$  period of orogenesis indicates that this event was probably responsible for accelerating the dewatering process. The tectonism was also responsible for the structural conduits in the carbonates, such as the  $F_2$  folding and  $S_2$  fracture cleavage at Berg Aukas.

### 9.1.3 A Mixing Model

A variation of the dewatering model, termed the "mixing model", was proposed by Allsopp *et al.* (1981) to explain the difference in anomalous Pb-isotope data which exists between the Tsumeb-type and Berg Aukas-type ores. The model, which also attempts to account for a copper supply, proposes that Pb leached from two different sources would generate two ores with distinctly different isotopic character. Similarly, it is reasonable to accept that as the hydrothermal fluid migrates, it will adopt a *mixed* isotopic character due to percolation through the sedimentary rocks it encounters. Thus, the isotopic distinction between Tsumeb-type and Berg Aukas-type ores is not necessarily only a function of widely different source, but also of the different migration routes. These in turn are a function of the palaeo-physiography.

Allsopp *et al.* (1981) proposed that the character of the Tsumeb-type ores was derived by percolation of fluids through the relatively permeable Mulden sandstones and the underlying karst surface before penetrating the breccia pipe at Tsumeb. Hughes *et al.* (1984) argue that copper mineralization originates from stratiform copper deposits hosted by the Mulden sediments since Pb-isotopes associated with pyrite in this stratiform copper mineralization has a similar isotopic composition to the ore at Tsumeb. The model proposed by these researchers, therefore, suggests that the origin of the copper is probably similar to the Zambian and Zaire Copper Belts. This would account for the apparent isotopic similarity which exists between the Tsumeb-type mineralization and these ores.

The model, however, disregards the evidence that the mineralization at Tsumeb and Kombot post-dates the feldspathic sandstone emplacement, and ignores the evidence of the high fluid inclusion homogenization temperatures (up to 250 °C) derived by Ypma (1984) for the Tsumeb ores. It is more likely, therefore, that

hydrothermal fluids penetrated upwards into the Mulden basin and mineralized the sandstones at Tschudi. This would result in the similar isotopic character which has been observed as well as the higher grade ore in the karst depressions found at Tschudi. However, this would not explain the apparent isotope correlation that exists with the Zambian Copper Belt.

#### 9.1.4 Genetic Models Accounting for the Vanadium Ores

There is general consensus amongst geologists working in the Otavi Mountain Land that the ubiquitous vanadium mineralization post-dates the emplacement of the base metal hypogene sulphides. The source of the vanadium, however, has not been adequately resolved and remains a contentious issue. Thus, a two-stage mineralizing process is advocated whereby the base metals were deposited before undergoing oxidation and supergene concentration of vanadium which was accumulated by leaching of the country rocks by meteoric waters. The issues are well reviewed by Verwoerd (1957).

The base metal sulphides are ruled out as a primary vanadium source since analyses of the sulphides indicates a negligible content (Verwoerd, 1957; Von Rahden and Dicks, 1967). The vanadium ores tend to be confined to the oxidized portions, usually breccias, of the ore bodies. Likewise, a primary hydrothermal source for the vanadium has acquired no credence, as was originally suggested by Newhouse (1934), mostly because there is no apparent direct link between the vanadium ores and the hypogene minerals and their gangue. It is generally concluded, therefore, that the vanadium was leached from a local source after the deposition of the base metals which during oxidation behaved as precipitation barriers for any vanadium that was transported by meteoric waters. Van der Westhuizen (1984) suggests that the vanadium was transported as calcium metavanadate solutions. At Berg Aukas, willemite ore has an anomalous enrichment in vanadium which indicates that meteoric waters with a high vanadiferous content were present from the onset of oxidation.

Thus, it may be summarised that the vanadium ores (descloizite-mottramite-vanadinite) had a symbiotic relationship with the base metals in that vanadium ores precipitated only where there were oxidizing metals. The composition of the base metals influenced the vanadium mineralogy. For example, mottramite, the Cu-rich variety, is more common at Tsumeb, and descloizite is dominant at Berg Aukas where there is limited copper. The concept may also be regarded from the point of view that where vanadium minerals are found, there should be a hypogene base metal source at depth. This did apply in the case of the Central Ore Body at Berg Aukas, but not at the Abenab Breccia Pipe. This led to speculation that such a body still exists but has not yet been found.

The debates regarding the source of vanadium all concluded that sediments of the Otavi Mountain Land could have been leached for their vanadium content (Schwellnus, 1945; Verwoerd, 1957; Van der Westhuizen, 1984). These researchers have shown that all the sediments, and in particular the shales of the Maieberg Formation, have a supply of trace amounts of vanadium. Verwoerd (1957) and Schwellnus (1945) favoured a

shale source, whilst Van der Westhuizen (1984) argued in favour of the carbonates. Despite these accounts, there has yet not been a satisfactory suggestion for a proto-vanadium source. All previous workers have ignored the intrusive basic rocks which form part of the Grootfontein Complex. These rocks tend to have a high magnetite content and are likely to be enriched in vanadium (no analyses have been obtained for these rocks). It is therefore postulated that these basic rocks are the proto-source for the vanadium in the carbonate and clastic sequences and in the ore bodies such as Berg Aukas and Abenab.

## 9.2 Conclusion: A Genetic Model for the Berg Aukas Zn-Pb-V Deposit

The following pertinent points summarise the main features of the Berg Aukas deposit:

- i. The deposit is located within the Berg Aukas Syncline which occurs along the southern margin of the Grootfontein Granite.
- ii. The syncline is regarded as a localized doubly plunging periclinal structure formed by plastic deformation of a primary depositional basin.
- iii. The basement configuration to the syncline is such that the  $F_1$  fold axial plane parallels the contact between Grootfontein granite in the north and intrusive gabbros in the south. This contact is tectonised and is therefore interpreted as a rift margin and it is proposed that this marks the change from the stable Northern Platform to the transitional Northern Zone.
- iv. Carbonate deposition occurred against a wedge of clastic rocks deposited during Nosib times by a process of mass wasting which was induced by movement along the rift margin. The carbonate sedimentology indicates that initial sedimentation occurred in a localized lagoonal setting with a palaeo-shoreline along the north. Shallow water intertidal conditions developed into an organic reef paralleling a peri-platform slope to the south. Rapid subsidence during Gauss Formation times was responsible for a rapid rise in carbonate deposition. The lowermost lithology of the Gauss Formation was a lime mud which underwent compaction and neomorphism. This formed an impermeable horizon now known as the Massive Grey Dolostone.
- v. Three ore bodies are located only on the northern flank of the syncline. They have a linear trend broadly corresponding to the  $F_2$  fold axial plane.
- vi. The ore bodies are hosted by the Light Grey Dolostones of the Gauss Formation and mineralization is best developed along the contact between the Massive Grey and Light Grey Dolostones. There is a relationship between  $S_2$  north-south trending vertical fracture cleavage and the mineralization. The  $S_2$  fracture cleavage is well developed along the ore trend as a

result of  $F_2$  anticlinal warping on the northern flank of the  $F_1$  fold structure.

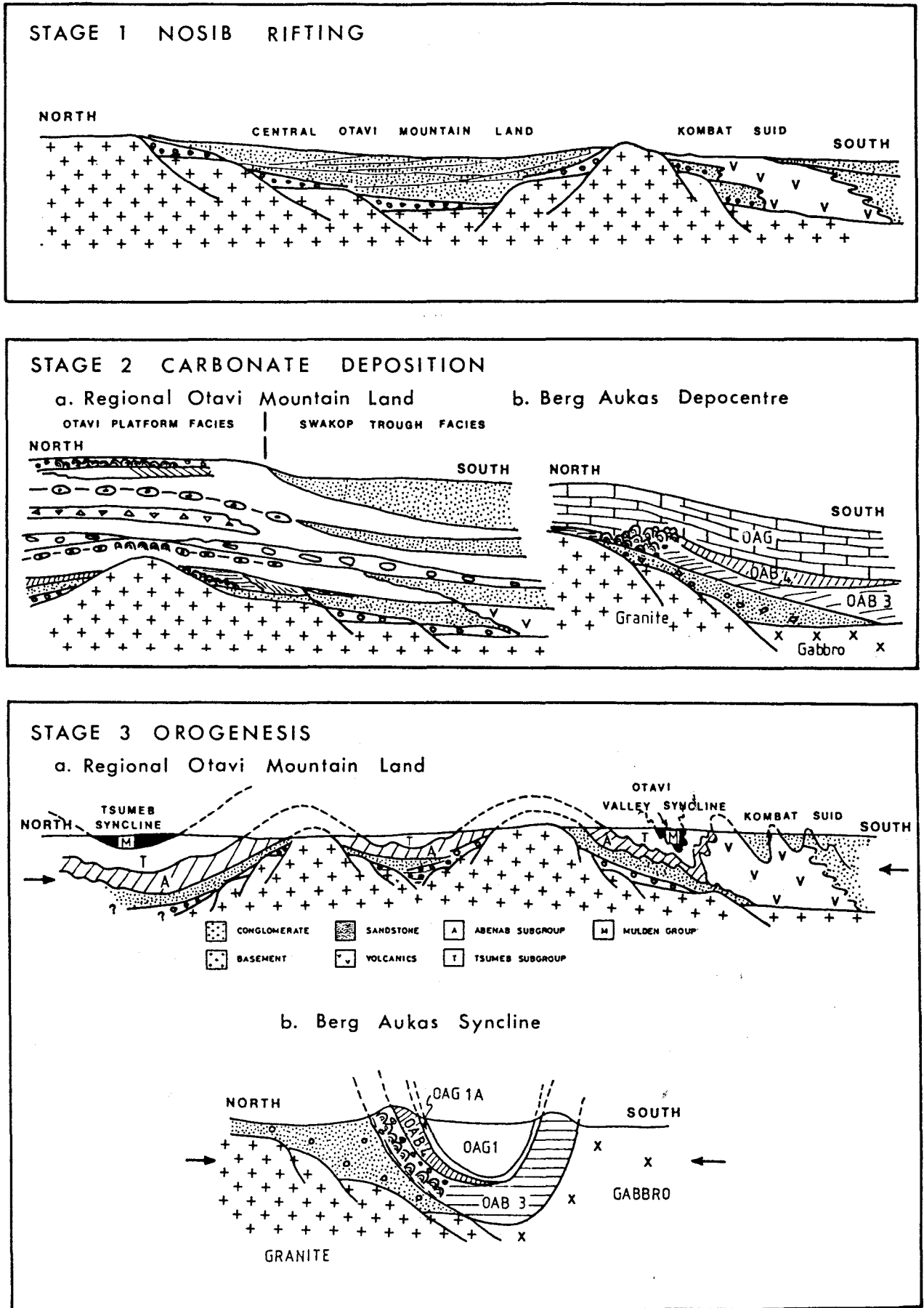
- vii. Mineralization is intimately associated with an intricate karst network, and the ore is hosted by breccia bodies. Supergene enrichment has been responsible for a varied ore mineralogy which includes descloizite, willemite, smithsonite, cerussite, sphalerite, and galena. Hydrothermal alteration was limited to minor calcitization and silicification, and more extensive ferruginization.

The sequence of events leading to the formation of the Berg Aukas deposit (Figure 9.1) commenced with the deposition of the Nosib clastic wedge and the subsequent deposition of carbonates in the localized basin. This resulted in a combination of factors which ultimately had an important bearing on the localization of mineralization. The basement granite dome and its structural features which included regional fracturing, influenced the pattern of sedimentation by generating a number of unconformities beneath the carbonates, and also within these lithologies themselves. Sedimentation was also responsible for the formation of an impermeable stratigraphic horizon within the carbonates above a facies change characterized by isolated deposition of laminated dolostones.

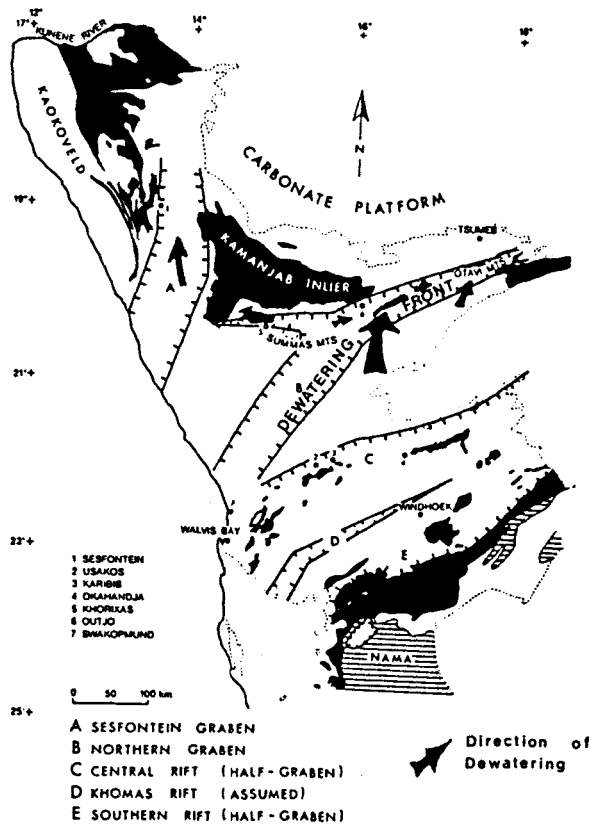
Orogenesis was responsible for providing structural conduits which helped to direct the movement of hydrothermal fluids. Basin dewatering of the Swakop Trough along a mineralizing front which could have been several hundreds of kilometres in length, was accelerated by orogenesis. Hydrothermal fluids moved in response to the hydraulic gradient along clastic aquifers in the Northern Rift towards the basin margin which was represented by the Grootfontein Granite Dome. The basal unconformity behaved as an aquiclude surface to guide the brines toward the structurally, lithologically, and chemically favourable traps in the overlying porous and permeable carbonates. The  $F_2$  fold axial plane provided a broad channel towards the basement dome and the  $S_2$  fracture cleavage allowed the fluids to penetrate the Berg Aukas Syncline. The fluids utilized the permeability relationship along the Massive Grey Dolostone and Light Grey Dolostone contact to initiate karsting and deposit ore. The Light Grey Dolostones were apparently the preferred horizon for precipitation which is postulated to have occurred due to interception with a sulphur source. Regional hydrothermal alteration resulted in sericitization of the Grootfontein Granite and propylitization of the basement gabbros and Nosib clastic rocks. Opalescent blue quartz in the gabbros in the immediate vicinity of the Berg Aukas Syncline are identified as the products of hydrothermal alteration. Hydrothermal alteration associated with the ore deposit was restricted to calcitization and silicification. Dolomitization is recognized only with the hypogene ores and cannot be distinguished in host rocks probably due to early diagenetic dolomitization.

Subsequent oxidation by circulating meteoric waters upgraded the ore body and deposited vanadium which was transported as calcium metavanadate complexes. The vanadium was derived either from the weathered components of the gabbros in the basement complex, or from sediments which were derived from the basement.

Figure 9.0 : A schematic summary illustrating the geological events leading to the genesis of the Berg Aukas deposit.

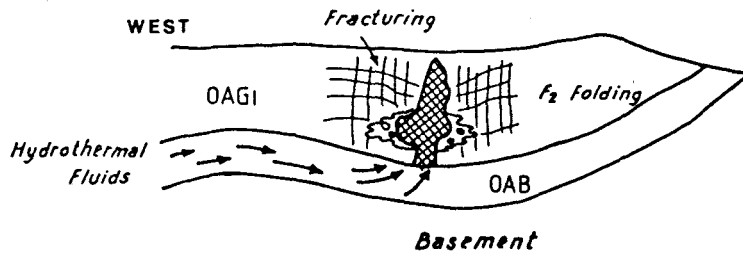


STAGE 4 a. DEWATERING & HYDROTHERMAL MINERALIZATION

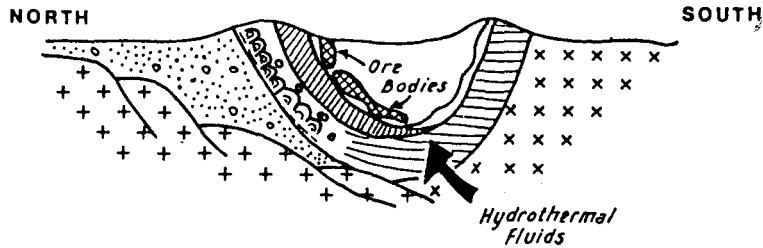


b. Berg Aukas Syncline

East-West Section Illustrating Structural Control on Hydrothermal Karsting along F<sub>2</sub> Trend



North-South Section Illustrating the Stratigraphic Control on Localization of the Ore Bodies



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