

Chapter 1

Introduction to the Kombat Mine Setting

1.1 Introduction

The Kombat Mining Complex (KMC) is situated on the northern limb of the Otavi Valley synclinorium, located approximately 400km northeast of Windhoek, the capital of the Republic of Namibia, also approximately 100km south of Tsumeb, another well known mining town, 42km east of Otavi and 49km west of the biggest army military base in Namibia, Grootfontein (Fig. 1.1a). Figure 1.1b shows an aerial view of the Kombat Mining Complex. It is linked to all these centers with a major surfaced road, locally called B8 and a railway line connected to the national railway network. B8 road is a major road (part of the Trans Caprivi Highway) linking up Namibia with Botswana, Zambia and Zimbabwe to the east and the port of Walvis Bay (Atlantic Ocean) to the southwest. The nearest airport is situated in the town of Grootfontein (Fig. 1.1a). Whilst Namibia is generally a dry country, the Kombat area receives ~610mm rainfall annually (SRK, 1992) generally falling in the period December to May.

The KMC hosts 7 known ore loci; Asis Ost, E900, Kombat East, Kombat Central, Kombat West, Asis West and Asis Far West as depicted in Figure 1.2. These mineralized mining localities are hosts to Cu, Pb, Ag and minor Zn occurring in variable quantities and distribution as described in later chapters and are operated by Weatherly Mining Namibia – a subsidiary of Weatherly International (www.weatherlyplc.com), an AIM – quoted integrated base metal producer with Copper Mining and Smelting operations in Namibia.

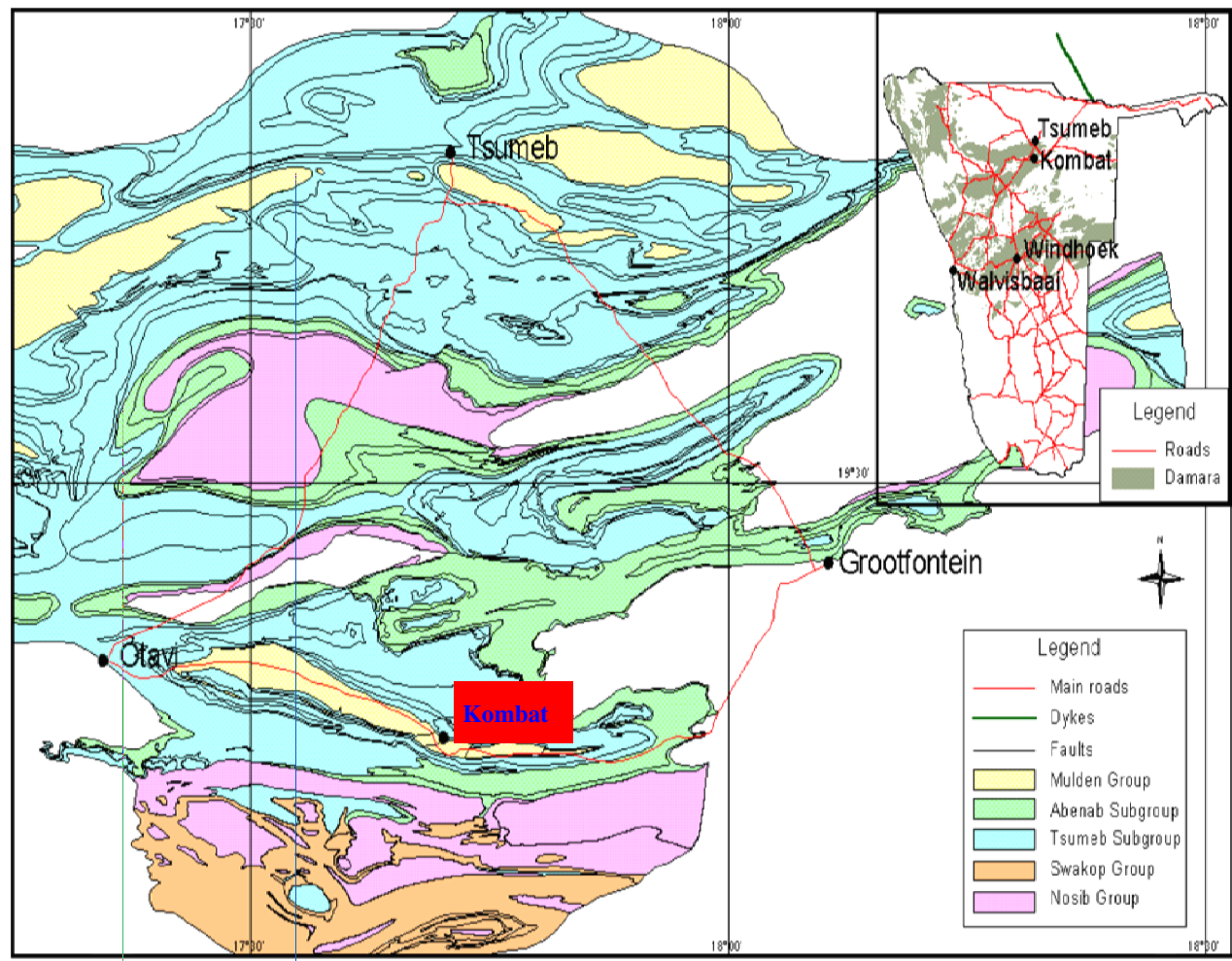


Figure 1.1a: Location Map and Regional Geology of the Kombat Mining Complex, at scale 1: 840 000. (modified from mapping by Hedberg (1979) and Tsumeb Corporation Limited).



Figure 1.1b: Aerial view of the Kombat Mining Complex showing the Mine Township, road network, railway and general landuse.

Mineralization at Kombat mines was first reported by Francis Galton in 1851 and mining operations commenced in 1911 by the Otavi Minen und Eisenbahn Gesellschaft (OMEG). Production was suspended in 1925 when an avalanche of underground water flooded the mine. Goldfields of South Africa, operating as Tsumeb Corporation Limited (TCL), resuscitated the operations with initial exploration in 1954 and ore milling in April 1962. During the period 1962 – 1981, the production in mill heads amounted to 5.53 Mt of ore with a grade of 2.32% Cu, 1.94% Pb and 18.0g/t Ag. Production under TCL continued until 1999 when the company was placed under liquidation by the Holding Company, Gold Fields of South Africa due to viability problems of the group as a whole. *“With no advance notice to employees, Mine Workers Union of Namibia, or the Government; Goldfields of Namibia closed down all mining and smelting operations in Namibia and laid off 2000 workers.*

Goldfields reported strike related losses of US\$7 million in 1996 and operating loss of US\$12 million in 1997” (Coakley, 1997).

Through the combined efforts of labour unions, management and government regulatory institutions of Namibia, Ongopolo Mining and Processing Ltd successfully brought the TCL mines and the Tsumeb Smelter back into production on the thirteenth day of March 2000. However, due to serious cash flow problems faced by the Ongopolo operations in Namibia that almost culminated in liquidation again, the whole company was “saved” by Weatherly Mining Namibia in June 2006. Since then, production has been ongoing at Kombat mines until Tuesday the fifteenth of January, 2008.

A major recent development at Kombat mines was the sinking and commissioning of the appraisal Asis Far West Shaft (Fig. 1.3) towards the end of 2005 by Murray and Roberts (Cementation Mining) of South Africa for Ongopolo Mining and Processing Limited. The ~800m shaft was motivated mainly to carry out underground exploration (Underground mineralization at Asis Far West Orebody was projected to be ~800m vertically down from surface rendering surface exploration drilling for vertically oriented orebodies ineffective (geometry, complex deflections in phyllite and timing) and very expensive) to identify new mineralization to replenish diminishing Kombat ore. However, thirty four diamond drill holes were drilled from surface and generated a combined Inferred Ore Resource of 2.2Mt @ 2.29% Cu, 18.74g/t Ag (Louw, 1998). 38 Underground drill holes were subsequently drilled at Asis Far West. Initial development was started at Asis Far West but was suspended in January 2007 following take over by Weatherly Mining Namibia when it was decided that a new exploration strategy was required for Asis Far West.

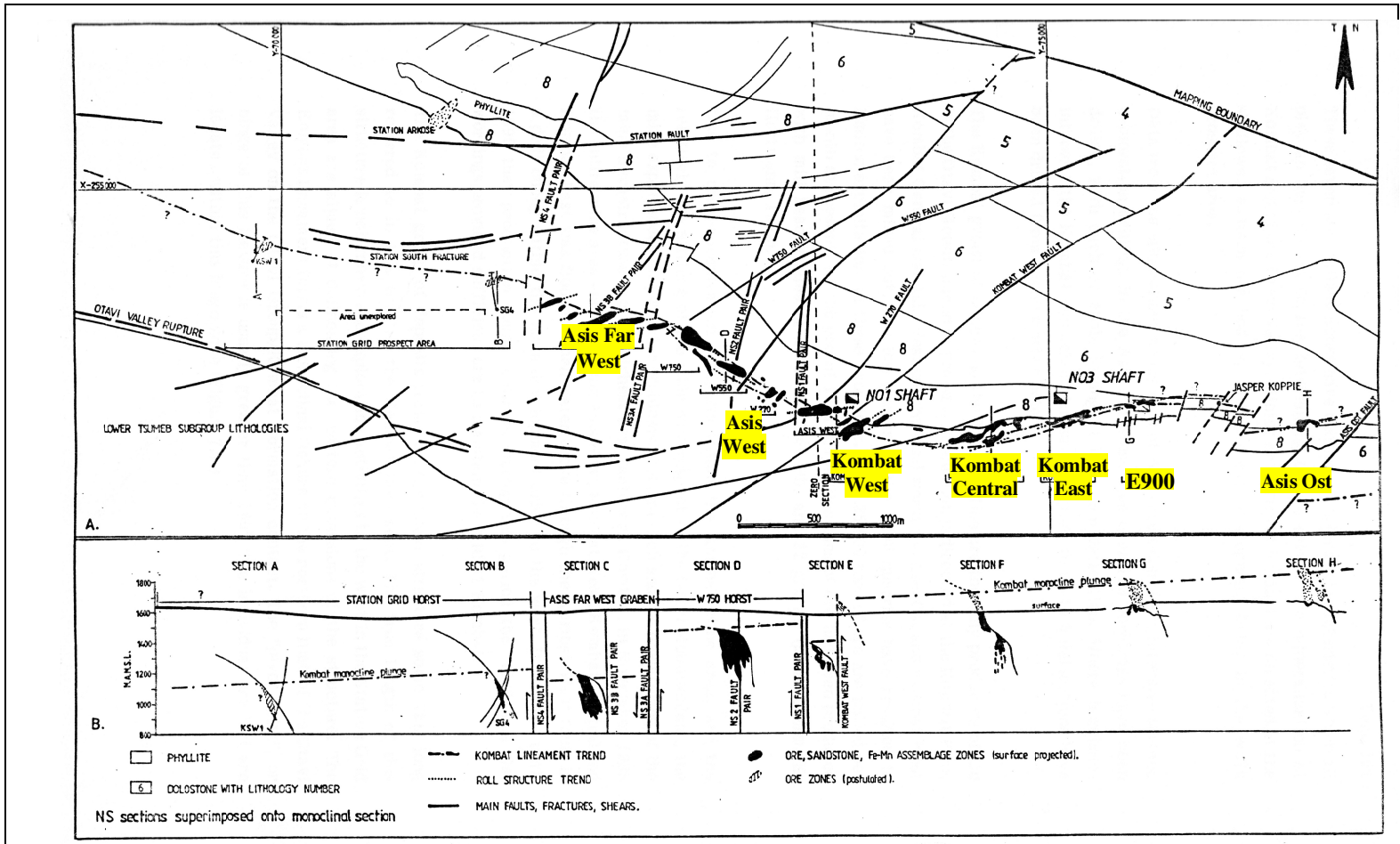


Figure 1.2: Surface Geological Map of the Kombat Mining Complex modified after Galloway (1988) and Tsumeb Corporation Ltd, showing locality of the Kombat orebodies, Local Stratigraphy, Otavi Valley rupture.



Figure 1.3: Aerial View of the new appraisal “Asis Far West Shaft”, showing the now redundant but brand new Shaft system, waste dumpsite and mine surface buildings and the Kombat Valley type vegetation.

The biggest challenge for mining at Kombat mines has always been and is still high pressure underground water, which has forced the mine to close on a number of different occasions, with the first one dating as far back as 1925. Loss of life also occurred in 1988 following a sudden inrush of water (SRK, 1992). In 2001, flooding occurred after development blasting opened up the “infamous” W270 fault resulting in total mine flooding within 48 hours. The latest flooding occurred on the second day of December 2007, following two one-hour power outages. Because of the outages, control on underground water was lost. It was at this stage that the executive made a decision to stop pumping water at Kombat and remove all the equipment from Number 1 Shaft. The natural water table around the Kombat Mining district is around 80m below surface (around 3 level of the underground mine).

For the purposes of this study it is important to note that Kombat Mine Geologists have over time carried out geological work with the prime objective of mining related production activities with little or no effort at all to publish the data or carry out detailed geological analyses from the data. In this regard, there are a number of geological plans and sections that have been produced by mine geologists over time that will be modified in this study to make them suitable for detailed geological analyses. The modification will be acknowledged throughout the study.

1.2 Statement of problem

Kombat (Copper – Lead – Silver) mines are very important to the Namibian national economy in general and to the direct stakeholders (shareholders, employees and the Kombat community) in particular. The viability of the Kombat mines is on the spotlight at the moment and if no viable and lasting practical solutions are identified in a timely manner, operations will be forced to cease. This will have a serious negative impact to the groups identified above at variable scales. Even though mining has taken place in this mining district over a lengthy period of time, there are a number of geological parameters that are not well understood. During the foregoing period, mineralisation was still abundant and strict geological understanding of the mineralisation patterns and controls did not dictate the viability of the mining operations. Since mining by its nature is exhaustive, the “easy” ore bodies are now mined out, clear cut geological understanding of the mineralisation patterns and controls is now central to the continued existence and viability of the operations.

The current geological mining models (as explained under previous work) for the Kombat mines are not adequate to handle the aspects described above, new geological models might yield new exploration philosophies and strategies for the Kombat mines. All current mining

focus, philosophy and trends have not had the necessary paradigm shift as the requisite “new” geological controls on mineralisation are not formalised or not available at all. Without a proper understanding of the apparent change, mining operations at Kombat will continue experiencing production related problems among other challenges faced by the mines including the perennial underground water problems.

1.3 Objectives of the study

- To investigate the controls on mineralisation at the Kombat mines. Mineralization is known to exist at Kombat mines but the mines are currently experiencing serious geological problems like the Asis Far West mine which was recently commissioned but has been made redundant because no ore could be found underground though some surface diamond drilling had indicated mineralization of economic grading. The structural and lithological patterns need to be looked at again and reinterpreted taking into account the fact that most of the previous research has focussed on the upper levels of the mine and now mining activities are focussed on the lower levels. The models that were applied previously seemed to handle the geological requirements then but these new areas require a review to this. Integrating current geological mapping and petrographic studies with available 3D modelling geological software might solve these problems.
- Define petrological and structural controls to the mineralisation patterns at the Kombat mines which will be applied to current and future geological exploration and mining economics around the study area.

1.4 Research methodology and analytical techniques

Use was made of all available previous literature and/or reports on the Kombat mines especially on such aspects as lithological identification which has been covered through previous research work but this thesis will still analyse the geological variations of lower underground levels of mining that have been opened up with recent mining (2000 – 2007). Underground and surface geological and structural mapping and core logging were the most important source of data. Laboratory analysis was undertaken at both the Ongopolo Mining and Processing Kombat and Tsumeb facilities and the University of Namibia (UNAM). The mine laboratories mainly provided assay data for mineralized core and both underground and surface grab samples whilst the UNAM laboratory provided the microscopic study framework. Dr B. S. Mapani and Dr A. F. Kamona of UNAM provided professional guidance from inception to the finalisation of the project research. Micromine 3D geological software was used to integrate the data over the whole deposit and help in the interpretation of occurrence of the mineralization patterns.

This thesis will present the findings in chronological chapters in an effort to characterise the various geological processes that have been identified during the study. The findings of previous researchers and findings of this study are presented, compared and contrasted whilst the discussion of the major findings are allocated a chapter on its own.

1.5 Previous work

Whilst studies have been undertaken within the Otavi Mountainland (OML) and at Kombat mines, new information has been generated and added to the existing geological database around the Kombat Mines especially during the period 2000 – 2008. This incorporates the

new Appraisal Asis Far West Shaft, Asis West underground mining up to W845 (mine geological section) on 12 level, the 2006/2007 surface reappraisal exploration and the acquisition of Micromine geological modelling Software. Recent investigations have shown the complexity of the Kombat mineralization from Asis Ost to Asis Far West orebodies highlighting clearly the vast differences in mineralization morphology, geometry, patterns from one locality to the other to the extent that findings from one locus of mineralization at Kombat does not necessarily extend to the next mining locality. Table 1.1 shows the stratigraphy of the Damara Orogen modified recently by Hoffmann and Prave (2008).










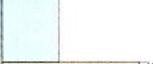



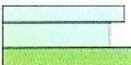
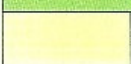

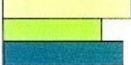






On a regional scale, Hoffman et al (2004), carried out U-Pb Zircon dating of the Neoproterozoic Ghaub Formation, yielding dropstone – bearing glaciomarine sedimentary rocks of the Ghaub Formation within metamorphosed massive carbonate –clast dominated diamictite.

Neoproterozoic basinal strata (Swakop Group) in central Namibia contain interbedded mafic lava flows and thin felsic ash beds. The U-Pb zircon geochronology of an ash layer constraints the deposition of the glaciomarine sediments to 635.5 +/- 1.2Ma, providing an age of what has been described as a “Marinoan-type” glaciations (Hoffman et al, 2004).

Over 600 occurrences of base metals sulphide mineralization are known from the OML and these are hosted by platform carbonates of the Otavi Group in a foreland fold and thrust belt setting (Chetty & Frimmel, 1999). A number of different views have been expressed about their genesis ranging from a genetic relationship to igneous activity to karstification, basin dewatering and expulsion of orogenic brines (Chetty & Frimmel, 1999).

Table 1.1: Lithostratigraphy of the Otavi Mountainland

Revised after Tsumeb Corporation (Pty) Ltd, SACS (1980),
Hoffmann and Prave (2008 - unpublished data)

MULDEN GROUP					
	Tschudi			Arkose, feldspathic quartzite, grit, conglomerate; minor shale.	
	Kombat			Dark grey shale with interbedded lenticular dolostone.	
OTAVI GROUP	TSUMEB SUBGROUP	Hüttenberg	T ₈		Grey dolostone and light grey bedded dolostone with algal markers and chert beds; prominent pisolite-oolite chert beds at top.
			T ₇		Alternating dark and light grey dolostone with minor grey to very dark laminated limestone and shale; black oolitic chert; anhydrite horizons; local thick silified reef/bioherm (Tschudi area).
			T ₆		Light grey bedded dolostone with algal mats, thin white chert, silicified stromatolites ('Tuten' marker beds in Tsumeb area)
		Elandshoek	T ₅		Massive light grey and bedded dolostone with characteristic shaly and siliceous seams; algal mats and jasperoid zones at base.
			T ₄		Massive light grey dolostone with widespread silicified and jasperoid zones in upper part; local associated brecciation and fracturing.
		Maieberg	T ₃		Thin-bedded and laminated grey dolostone.
			T ₂		Thin-bedded and laminated grey, brownish grey and pink limestone-marl and dark greenish-grey shale; local thick shale unit at base; local thick intraformational breccia in upper part.
	Keilberg			Very fine-grained laminated to massive pale pink and pinkish grey dolostone, quartz/sparry dolomite-calcite filled 'tube' structures	
	Ghaub	T ₁		Massive carbonate-clast dominated diamictite, medium to thin bedded diamictite with dropstones at top.	
	ABENAB SUBGROUP	Auros	Upper		Medium grey dolostone and stromatolite (upper part), thin-bedded grey limestone (base).
			Shale Band		Laminated shale and thin interbedded tan dolostone (base) and buff limestone-marl (top).
			Middle		Medium to dark grey dolostone and stromatolite; fine-grained dolostone and marly dolostone in lower part.
			Lower		Massive medium to dark grey cherty/silicified ('jasperoid') oolitic dolostone, oolitic/intraclastic limestone and thinly bedded and laminated limestone and marl.
		Gruis			Laminated shale, interbedded laminated tan dolostone and medium grey laminated limestone.
		Gauss	Upper		Pink and light pinkish grey fine-grained to micritic dolostone and chert (lower part) and light to medium grey dolostone (upper part), oolite and stromatolite at top, local interbedded shale.
Middle				Very light grey, pinkish grey and buff enterolithic dolomite; tepee/dessication structures; and local microbialaminite/stromatolite	
Lower				Very light to medium grey and buff massive dolostone with characteristic vuggy/colloform texture; local thick dolostone breccia in lower part, and local stromatolite and oolite in upper part.	
Berg Aukas		Upper		Grey to light grey, buff and pink medium and thin-bedded and laminated dolostone; local interbedded shale in basal part.	
		Lower		Dark grey microbialaminated / stromatolitic dolostone; local chert.	
Varianto (Chuos)			Light grey thin-bedded and laminated dolostone (rhythmite)		
				Diamictite, pebbly grit, ironformation	
NOSIB GROUP	Nabis			Feldspathic quartzite, arkose, conglomerate	

During a hunting trip, Mckiernan and Thomas (in Cairncross, 1997) discovered the site of Cu mining at Gross Otavi another satellite mine, 14km west of the main Kombat Mining Complex (Cairncross, 1997).

Petzel (1992) said, “the Kombat mine has a maximum life of ten years and therefore the main aim of the exploration conducted in the area is to delineate new ore bodies to the west of Kombat mine a.s.a.p. and to sink an exploration/mining shaft for which the exploration drives can be developed, in order to investigate ore bodies delineated by surface drilling in more detail”.

Innes and Chaplin (1986) described the Kombat copper-lead-silver orebodies as comprising epigenetic hydrothermal replacement and fracture fill deposits hosted within relatively unmetamorphosed dolostones of the Hüttenberg Formation of the Upper Proterozoic Otavi Group of the Damara Supergroup in northern Namibia. Mineralization is spatially associated with a regional unconformity between the dolostone and younger slate (phyllite), with discrete zones of penetrative deformation and with intruded bodies of feldspathic sandstone on the northern flank of the regionally extensive Otavi Valley synclinorium.

Mineralization at Kombat can be divided into two; the Kombat Type (Cu + Pb + Ag +/- Zn) and possibly the Mississippi Valley/Karst Type (V + Pb + Zn + Cu). Moore (1989) also stressed that the low sulphur isotopic values (13.1‰) might indicate that the mineralizing brines will be related to fluids which were derived from deep basinal areas while the high sulphur isotope values (26.1‰) encountered in the sulphides of the Tsumeb mine might indicate a shallow source (Congo Craton) for the mineralizing fluids. The main phase of the Kombat Cu – Pb (Ag) mineralization is interpreted as being stratabound and syntectonic. The mineralization occurs on the contact with the overlying Kombat Formation Phyllite.

Characteristic features are the abundance of sandstone in Damara age karsts, Fe/Mn oxide silicate assemblages, intense faulting, fracturing, shearing and brecciation (Petzel, 1992).

Geological mapping done by Söhnge (1957) provided a baseline for the identification of the main lithologies within the area of research, has been modified over time, and is still being reviewed. The mapping shows the broad geological units within the study area.

Kamona and Günzel (2007) produced a publication on Stratigraphy and Base Metal Mineralization for the generalized Otavi Mountainland (Table. 2.1). This modified the existing stratigraphy.

Smit (1959) carried out the regionalized structural setting of the area. Dean (1993) refers to 6 phases, which are responsible for deformation within the Otavi valley (D1 –D6). The last direction of movement of faults is oblique as observed from slicken sides and lineations on the fault surfaces, sigmoidal structures and second order fractures where exposed (Greenway, 1994). The W270 – 2 fault in the W270 – 12 Central Stope at 1219.5m elevation has internal structures indicative of left lateral movement, but the second order shears emanating from the fault indicate right lateral movement in an oblique sense. The second order shears are a subsidiary set of faults which branch off the main fault at an angle of 30° . The displacement along these shears is not in the same sense as that of the main fault. The acute angle between the main and subsidiary faults points in the direction in which the block containing the subsidiary fault was moving (Billings, 1972). Faulting is intimately associated with the supergene mineralization and some remobilization of the primary sulphides has occurred within some of the fault zones (Greenway, 1994). Displacement of the faults, except the KWF has been minimal implying minor displacement of the ore bodies (Greenway, 1994). Galloway (1988) described the KWF as a broad zone of faulting which has acted as an

aquifer and channel way for hydrothermal fluids influencing the E15 and E140 stopes. However, most geologists see faults as post mineralization influencing supergene mineralization. Between KWF and Kombat West Fault 2 (KWF2), ore assemblages consist of chalcocite, malachite and cerussite mineralization. Between KWF2 and Kombat West Fault3 (KWF3), a chalcocite, bornite, galena ore mineral assemblage occurs. West of KWF3, primary sulphide ore (chalcopyrite, bornite) mineralogy predominates (Greenway, 1994). The KWF separates the Kombat Ore body from the Asis West ore body and when intersected in development, the fault is up to 3m width containing crustiform calcite (Coxon, 1984). Monoclinial flexures, referred to as roll structures, create localized zones of flat bedding on the northern synclinal limb where fault structures dissect these rolls, ore lenses/bodies are found to hang like pendants below the shallowly dipping/flat limbs. The flexures are thought to be the product of buckling during deformation along shear zones defined by sandstone and Fe/Mn filled depositories (Galloway, 1988). Deformation of the contact in the form of sharp infolds of slate into dolostone has a definite influence on the distribution of ore lenses (Galloway, 1988). Infolds act as traps along the contact resulting in the concentration of ore at these localities (Galloway, 1988). The Otavi Valley structure is an overturned, doubly plunging syncline that resulted from the Damara Orogenic event during which a series of recumbent folds, overturned to the north, were formed as geosynclinal sediments were pushed up against the northern platform (Galloway, 1988). The degree of dolomitization is a significant influence on fracture development and distribution with carbonate strata (Altobi, 1993). A fault may consist of 0.5m of layered sparry calcite in places usually with a thin fracture in the centre surrounded by a broad fracture zone either side of the main fault, elsewhere this fault maybe barely recognizable as it is composed of several thin slightly MnO₂ stained fractures with minor secondary mineralization (Greenway, 1994). Innes and Chaplin (1986) briefly refer to several northeast trending faults which cause only minor displacement of the ore lenses, an exception being the Kombat West Fault (KWF).

Tectonically, the Kombat area is situated on the boundary of the stable platform, the southern edge of the Congo Craton and the northern graben of the Intracontinental branch of the Damara Orogen (Petzel, 1992). The Kombat mine is closely related to its tectonic setting. The Kombat Strike Slip Fault (Otavi Valley Rupture) which represents the rejuvenated northern graben fault of the Nosib Graben, acted as a conduit for ascending mineralizing fluids, is a proposed ore genesis model for the Kombat mineralization.

Gleeson (1983), wrote; “recent observations by myself and work done by the staff at Kombat however, throws some doubt to the hypothesis that, in my previous communication, a set of two faults (pre-ore), forming a couple, between the tensional field of stress was built in up in the block outlined by these faults. This leading to fracturing and shearing of the block and so allowing the ingress of the ore bearing hydrothermal fluids into this area was discussed. It now seems more likely that the faults are in fact post ore”.

The intensity of deformation and metamorphism decreases from the Central Damara belt northwards and the effects on the northern platform were thus relatively small, with a series of east – west trending folds, synclines and anticlines dominating the structure of the OML (Chetty & Frimmel, 1999). Subsequent exhumation of the thickened crust and erosion resulted in the sedimentation of the predominantly siliciclastic Mulden Group. The relation between mineralization and the main deformational structures in the Upper Tsumeb subgroup indicates syn-deformational origin of the mineralization (Frimmel, 1999). A regional metamorphic grade in the Otavi Valley, based on the mineral assemblage calcite – dolomite – quartz, the absence of talc and tremolite and the development of phengitic muscovite and minor chlorite, is regarded as being of lower greenschist facies (Deane, 1995). Three Damara deformational events have affected the OML (Deane, 1995). The Otavi Valley sub basin is classified as a subsidiary Intracontinental rift basin to the northern rift, situated on the Congo

Craton. The environment during the formation of the Kombat ore deposits was tectonically active, being the final stages of rift tectonism, and the main phase of the Damara Orogen (Deane, 1995).

Hughes (1987) conducted a detailed analytical study on mineralization of the Tsumeb deposit and his main conclusions were that the Tsumeb pipe and associated stratabound cavities formed by karsting and solution collapse during sub aerial exposure of the top of the Tsumeb Subgroup, that mineralization at Tsumeb and other Otavi valley deposits occurred before the major deformation of the Mulden Group and that the unique mineralogical and chemical composition of the Tsumeb-type ore both in the Otavi Mountainland and throughout Central Africa, resulted from unique compositions of fluids which these ore bodies.

Ypma (1978) carried out fluid inclusion studies on ore deposits in the Otavi Mountainland, and concluded that the Kombat Deposits, like the Tsumeb ore body, are hydrothermal, epigenetic deposits emplaced in arkose – filled karst holes.

Carbonate alteration around and within the individual deposits is recognized as any textural or mineralogical change from the original dolomite/limestone host to that carbonate rock deemed least altered (Frimmel, 1999). A strong calcite alteration halo encompasses the ore deposits. The calcite alteration is of various ages and therefore not always related to the mineralizing event (Deane, 1995). The Kombat ores show an overall enrichment in most trace elements in particular, Mn, Pb, Zn, Cu and in Rare Earth Elements (REE), evident in the secondary hydrothermal and mineralized carbonate generations relative to the least altered host rocks (Frimmel, 1999). Recalculating the formation temperature for the Kombat using the 20Wt% NaCl equivalent value, and average Th of 250⁰C obtained by Ypma (1984), yields 405⁰C (Frimmel, 1999). In contrast to previous studies, the results of Frimmel (1999)

clearly indicate that the mineralizing and sulphide remobilizing fluids in Tsumeb Type deposits were highly saline (Frimmel, 1999). Geochemical data on the carbonate wall rock alteration associated with base metal sulphide mineralization in the OML provide further evidence for the existence of two distinct types of such mineralization and this important ore province (Berg Aukas and Kombat). Furthermore, our data support an orogenic brine model for the Tsumeb type mineralization. The results of Frimmel (1999) also indicate mineralizing fluids of high salinity, emphasizing the importance of salinity for a fluid's potential of carrying large amounts of base metals and the high salinity comes from the interaction with evaporates. The Berg Aukas type has been interpreted to represent an earlier MVT whereas the Tsumeb Type has been ascribed to hotter, orogenic brines that were expelled from the Damara orogen (Pirajno & Joubert, 1997). It maybe speculated that some of the base metals found in the deposits of the OML were derived from Rosh Pinah type sulphide deposits in the Nosib Group which is comparable both lithologically and stratigraphically to the Stinkfontein Subgroup of the Gariiep Belt (Frimmel et al, 2004). The structural evolution of the Damara Orogen is still unclear although economically important base metal deposits in this area are structurally related (Laukamp, 2007).

A major geochemical problem in the MVT deposits is whether metals and reduced sulphur (H_2S) and perhaps H_2S were transported together to the site of deposition or whether the metals were carried in an essentially H_2S free solution and were precipitated by addition of H_2S as the solution passed through the carbonate host rocks (Anderson & Macqueen, 1998), as he approximated the Kombat deposit to the MVT. Woodall (1993), in the opening sentence of his paper wrote, "modern mineral exploration is scientific inquiry and research"; first there must be the idea, the vision or the initiative thought, then the experiment follows; in another line Woodall (1993) stated; "mineral exploration is going and looking, but today we must look with more than our eyes and think before we go" (Woodall, 1993 in Pirajno, 1999). Past

achievements and future challenges in the use of mineral deposit models, regional tectonics, and metallogeny in mineral exploration is the way forward.

No satisfactory genetic model for the Kombat mineralization exists to date, but theoretically either a syngenetic or epigenetic model maybe applicable. Non circumstantial evidence suggests that the Fe/Mn oxide silicate assemblages represent syngenetic exhalative deposits that accumulated on the unconformity surface from a fumarolic source. Field observations and isotope results support an exclusively epigenetic, hydrothermal and metamorphic model for the Cu mineralization that selectively utilized the phyllite/dolostone contact and various cross cutting structures for emplacement, which could subsequently have been remobilized. A variation of this possibility is an orogenic brine model (Oliver, 1986), with mineralization related to the Damara Orogen (Deane, 1995). Hughes (1987) carried out regional scale research in the Otavi Mountainland giving generalized comparison of the Kombat deposit to the Tsumeb pipe mostly from the karsting geometry/system. It is generally accepted that the Kombat ore bodies hang like pendants on the dolostone/phyllite contact Galloway (1988), but all the bodies currently being mined at Kombat and Asis Far West mines do not exhibit this geometry. Surface drilling, however, only gives an indication of the presence of mineralization and the exact morphology, tonnage and grade of such an ore source can only be calculated from massive underground drilling. An aeromagnetic interpretation (Lubbe, 1990), indicates the possibility of Kombat Type mineralization as far as 4km to the west of Asis Far West (AFW) ore lenses and possible ore reserve predictions of 1.7 Million tones can be calculated for the Gross Otavi area (Petzel, 1992).

Chapter 2

Regional Geological Setting

2.1 Introduction

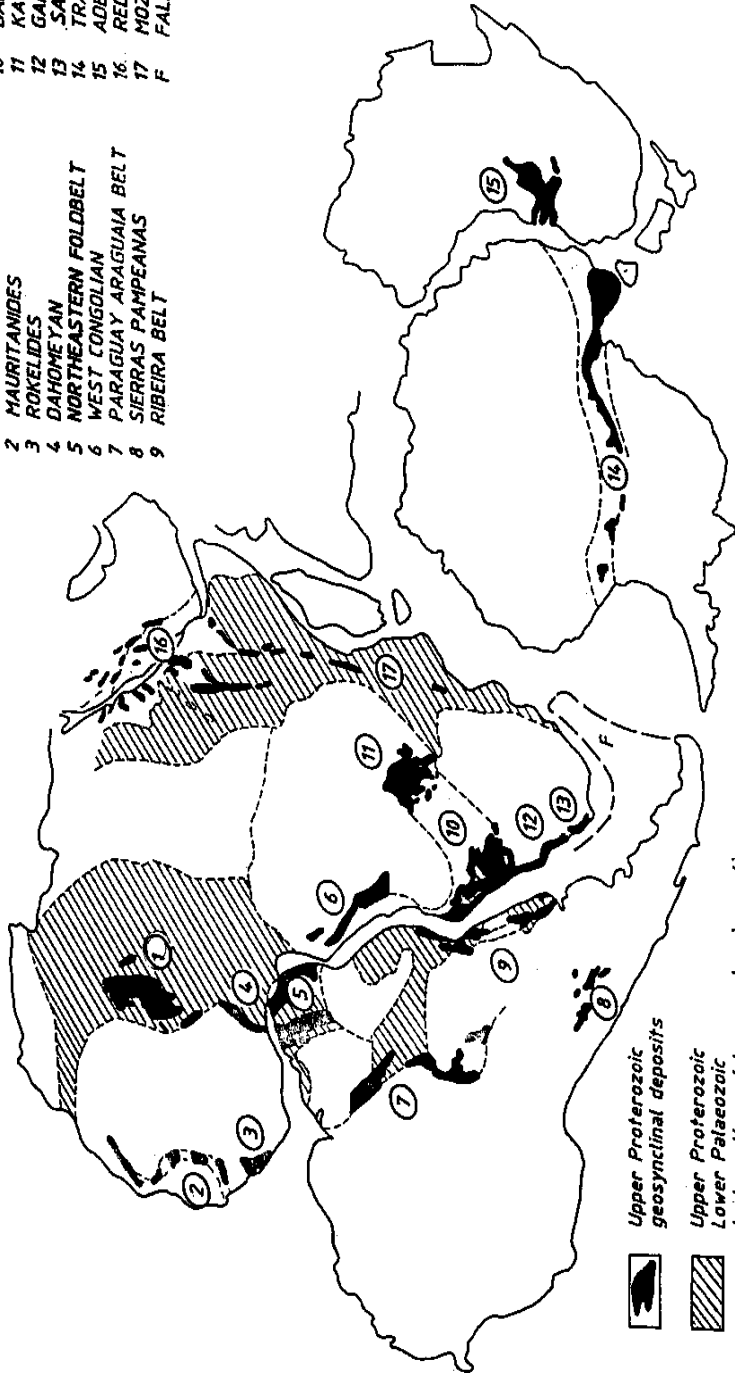
The period 900-950Ma was marked by extensive continental fragmentation with geosynclinal deposition in a major Late Proterozoic – Early Paleozoic tectono - thermal event referred to as Pan-African event (Master, 1991). Downward flexuring of the craton margins produced extensive intracratonic foreland basins (Thomas et al, 1993). Figure 2.1 shows the Pre-drift assembly of the Gondwana continent showing the distribution of the upper Proterozoic (Pan African) geosynclinal deposits modified after Porada (1985). Of significance to note is the relative location of the Damara orogenic belt to the global Gondwanaland.

2.2 Damara Orogen

The late Proterozoic to Early Paleozoic Damara belt forms part of the Pan-African mobile belt system, which surrounds and bisects the African continent; (Martin. 1983., Miller. 1983a), (Fig. 2.2). The Pan African belts form a network of sedimentary and volcanic sequences and are characterized by regional metamorphism and related granitic intrusions. Martin (1983) distinguished between two types of Pan African belts based on structural analysis;

- Belts such as Mozambique and Zambezi with thermally and tectonically rejuvenated, older Precambrian basements.

- 1 PHARUSIAN
- 2 MAURITANIDES
- 3 ROKELIDES
- 4 DAHOMEYAN
- 5 NORTHEASTERN FOLDBELT
- 6 WEST CONGOLIAN
- 7 PARAGUAY APAGUAIYA BELT
- 8 SIERRAS PAMPEANAS
- 9 RIBEIRA BELT
- 10 DAMARA BELT
- 11 KATANGA BELT
- 12 GARIEP BELT
- 13 SALDANIA BELT
- 14 TRANSANTARCTIC BELT
- 15 ADELAIDEAN
- 16 RED SEA FOLD BELT
- 17 MOZAMBIQUE BELT
- F FALKLAND PLATEAU



Upper Proterozoic
geosynclinal deposits

Upper Proterozoic
Lower Palaeozoic
tectono thermal basement rejuvenation

FIGURE 2.1.: Pre-drift assembly of the Gondwana continent showing distribution of the upper Proterozoic (Pan-African) geosynclinal deposits. Modified after Porada (1985).

- Late Proterozoic ‘geosynclines’ which experienced or passed through a stage of subsidence and sedimentation. The Damara orogen belongs to this group. Thomas et al (1993) described the Damara orogen as having divergent branches that extends northeastwards from Damara belt to Lufilian Arc and Zambezi belt of Zambia and into Zimbabwe. Reeves (1978) interpreted the geophysical features to represent an inland branch that extends further to the east into the Katanga and Zambezi belts forming a triple junction with the Mozambique belt in East Africa. Northwards, the Damara orogen extends to the Kaoko and west Congolian belts and southwards to Gariep and Saldania belts (Martin et al., 1997). Porada (1979) suggested the Rebeira orogen of Brazil to represent the west limit of the Damara orogen. Figure 2.3 depicts the Neoproterozoic Pan African belt systems in Southern and Central Africa.

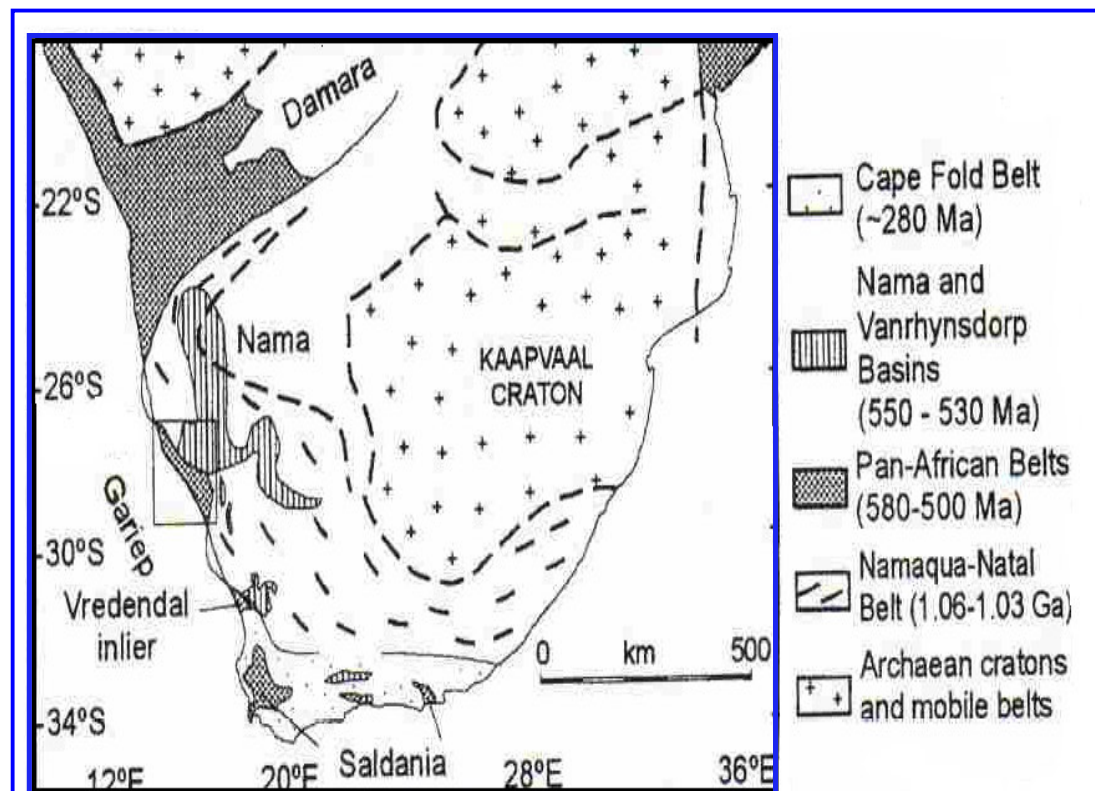


Figure 2.2: Location of the Pan African Belts, Archaean Cratons, the Namaqua – Natal Metamorphic Province and the Cape Fold Belt modified after Miller (1983a).

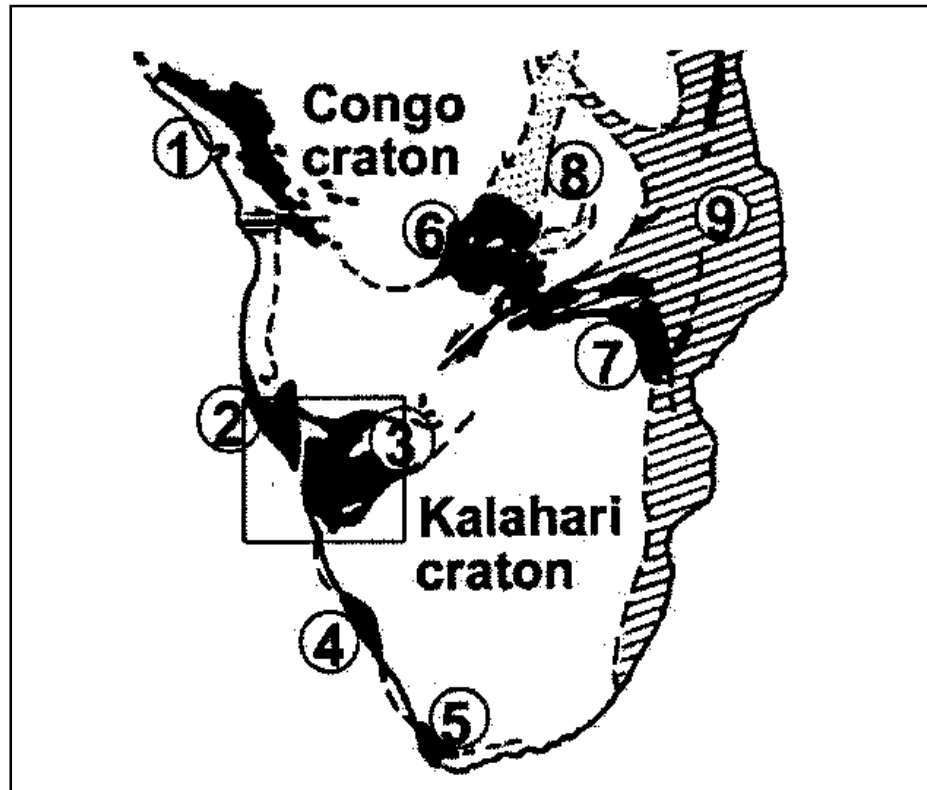


Figure 2.3: Neoproterozoic Pan African belt systems in Southern and Central Africa (modified after Porada, 1989). 1 = West Congolian Belt, 2 = Kaoko Belt, 3 = Damara Belt, 4 = Gariiep Belt, 5 = Saldania Belt, 6 = Lufilian Arc, 7 = Zambezi Belt, 8 = Shaba aulacogen, 9 = Mozambique Belt. (Box insert referenced to Figure 2.4 below).

The NE-trending Pan-African Damara Belt is 400 km wide and extends to the Lufilian arc located between the Congo and Kalahari Cratons in the southwest region of Southern Africa (Figs. 2.2 & 2.3); (Miller, 1983a & Porada, 1989).

The Damara sequence consists of a northeast trending intracontinental arm and a north south trending coastal arm with a present outcrop width in Namibia of 150km (Fig. 2.4). The triple junction between these two arms is located off the coast near Swakopmund (Miller, 1983c). Evolution of the belt involves a complex history involving intracratonic rifting, spreading, convergence and collision of Kalahari and Congo Cratons (Kukla, 1992). Deformation, metamorphism and magmatism accompanied the collision. The belt underwent episodes of

continental rifting, ocean floor spreading, glaciation, subduction, collision and metamorphism over a time span of about 250Ma. Syntectonic base metal deposits including the Kombat Cu – Pb – Ag - Zn mineralisation occurred from ~800Ma onwards.

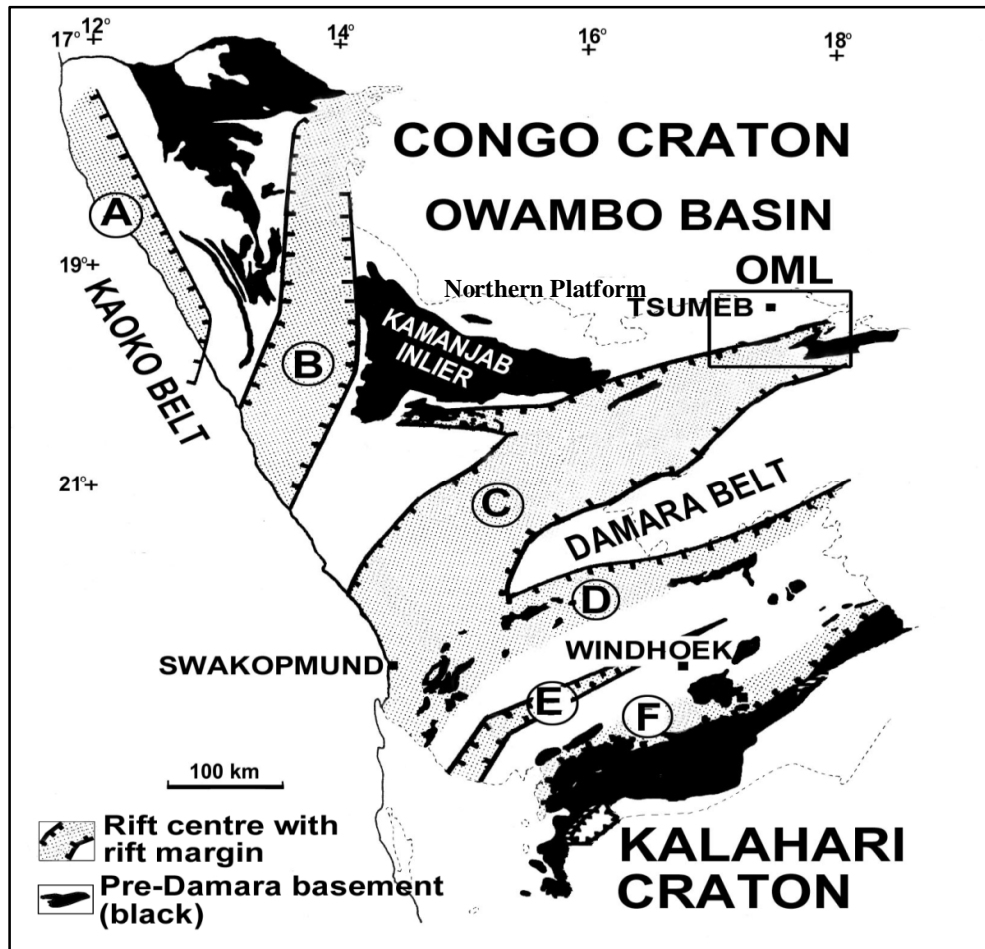


Figure 2.4: Location of the Otavi Mountain Land (OML), the Owambo Basin and the presumed location of the continental rift structures during the rifting stage of the Damara and Kaoko Belts (from Porada 1989). A = Kaoko Rift, B = Sesfontein, C = Northern Rift, D = Central Rift, E = Khomas Rift, F = Southern Rift. Note that the southern and eastern limits of the Owambo Basin are defined by the Northern boundaries of the Kamanjab inlier and the Northern Rift (C) as well as the eastern margin of the Sesfontein Rift (B), modified after Kamona and Günzel (2007).

2.3 Stratigraphy

2.3.1 Introduction

Rocks of the Damara sequence were deposited on an Archaean granite-gneiss basement exposed in the northern zones, southern zones and inliers in the centre of the belt (Jacob & Kroner, 1977). The Kombat deposit is located within the Damara belt and an understanding of the basic Damara stratigraphy is necessary to constrain this deposit from a regional perspective. Table 2.1 shows the stratigraphic column for the Otavi Mountainland (OML) modified after Hoffmann and Prave (2008). The stratigraphy of the study area has been studied in detail previously and the findings of the previous researchers will be incorporated herein as it will aid in explaining the processes occurring within the Kombat deposit.

2.3.2 Basement complex

The Pre-Damaran basement is largely granitic, of variable radiometric ages with the oldest age in the order of 2000Ma in the Central Zone and the youngest in the order of 1000Ma located in the southern part of the Orogen, in the Eastern Khomas trough (Pfurr et al., 1991). The basement complex crops out in several major inliers along the northern and southern margins of the Damara province, as well as numerous small inliers in the central parts. It consists predominantly of granitoids, with infolded remnants of medium to high grade metavolcanic and metasedimentary country rocks.

The northern platform margin is marked by an arcuate chain of major basement ridges and domes which extends over 1000km from Grootfontein in the north east, through the inlier into the Kaokoveld inlier in the northwest. The northern inliers were positive morphological

features during deposition of the Damara sequence and influenced facies changes in the area. They may have provided the source material for the Mulden Group siliciclastics in the Owambo basin (Basement complex, 1993).

2.3.3 The Nosib Group

The Nosib Group unconformably overlies the basement complex. It consists of the Nabis, Ghaub and Askeveld formations (Table. 2.1) and they are principally exposed mainly in the central and southern parts of the OML. The lower Nabis Formation consists predominantly of a basal conglomerate and feldspathic quartzites (Söhnge, 1957, Botha, 1960 & Grobler, 1961) forming the flanks and flat lying areas of anticlines in the central OML. The Upper Nabis Formation consists of shale and phyllite (Table. 2.1).

Overlying the Nabis Formation is the Ghaub Formation consisting predominantly of tillite, pyroclastics and ironstone. The Askeveld Formation is limited to the southern part of the OML where it occurs as a metavolcanic unit consisting of epidosite, agglomerate, and chlorite schist (Söhnge, 1957, Smit, 1962 & Petzel, 1991). The Nosib Group developed as a result of intracontinental rifting of the Congo Craton prior to 756 Ma (the age of the intrusive Oas syenite). Rifting and clastic sedimentation continued up to at least 746Ma when rift related volcanism produced bimodal volcanic rocks in the northern rift of the Damara Orogen. The environment of deposition progressively developed from predominantly fluvial, during deposition of the poorly sorted and locally derived conglomerates, to shallow marine when finer grained shales were deposited (Kamona & Günzel, 2007).

Table 2.1: Stratigraphic column for the Otavi Mountainland, revised after Hoffmann and Prave (2008).

SEQUENCE	GROUP	SUB GROUP	Age, Ma	FORMATION	LITHOLOGY	ZONE
Deposits	MULDEN		550	Tschudi Kombat	Arkose, feldspathic sandstone, grit conglomerate Phyllite, interbedded with lenticular dolostone	
		Disconformity	570			
Kombat (Cu – Pb – Ag)	OTAVI	Kombat Ore Bodies	760?	Hüttenberg	Thin Bedded Light dolostone with algal markers and chert beds, prominent pisolite-oolite chert beds at the top	T8
					Thin Bedded Dark Dolomites with Phyllite, black oolitic chert, anhydrite horizons silicified reef/bioherm (Tschudi area)	T7
	Thin Bedded Limestone and Shale					
	Bedded Light Dolomite and Chert (Algal), stromatolites ("Tuten" marker beds in Tsumeb)	T6				
Tsumeb (Cu – Pb – Zn – Ag)	OTAVI	Tsumeb		Elandshoek	Massive and Bedded Light Dolomite	T5
					Massive Light Dolomite, with bedded dolostone	T4
Abenab (Pb – Zn – V)	OTAVI	Abenab		Maieberg	Thin Bedded Dolomite	T3
					Thin Bedded Limestone, Quartzite	T2
					Bedded Dolomite, Thin-bedded Limestone, greenish-grey shale	
					Thin-bedded Limestone and Shale	
	Localized Tillite and Limestone					
DAMARA	OTAVI	Abenab	Disconformity	Keilberg	Fine grained laminated to massive pale pink dolostone	
				Ghaub	Massive carbonate clast dominated diamictite	T1
	Medium to thin bedded diamictite with dropsotnes					
Berg Aukas (Pb – Zn – V)	NOSIB	Abenab		Auros	Bedded Dolomite (Quartz Clusters)	
					Massive Dolomite (Algal – Columnar)	
					Bedded Limestone and Shale	
					Massive Dolomite (Algal – Columnar)	
	Bedded Limestone and Shale					
	Massive Dolomite (Algal – Cryptozoon)					
	Bedded Limestone and Shale					
	Massive Dolomite (Jasperoid)					
	Bedded Limestone and Shale					
	Disconformity		830	Gruis	Pink and light pinkish grey fine grained, micritic dolostone and chert, oolite and stromatolite at top, interbedded with shale locally.	
	NOSIB	Abenab		Gauss	Very Light grey, pinkish grey and buff enterolithic dolomicrite desiccation structures and microbial, stromatolite, micrite	
			Very light to medium grey and buff massive dolostone with vuggy/colloform texture local stromatolite and oolite			
			Grey to light grey, buff and pink medium and thin bedded and laminated dolostone			
			840	Berg Aukas	Dark grey microbial laminated/stromatolitic dolostone, local chert laminated rhythmite dolostone	
				Varianto(Chuoes)	Diamictite, pebbly grit, iron formation	
				Nabis	Shale, Phyllite	
					Conglomerate, Arkose, Quartzite	
			1000			
			1800			
BASEMENT COMPLEX					Diabase, Granite and Gneiss, Diorite, Gabbro, Serpentinite	

2.3.4 The Otavi Group

The Otavi Group unconformably overlies the Nosib Group and Basement complex (Hedberg, 1979). The Otavi Group is subdivided into the Abenab and Tsumeb Subgroups.

2.3.4.1 Abenab Subgroup

The Abenab Subgroup consists of the Varianto, Berg Aukas, Gauss and Auros Formations (Söhnge, 1957).

The basal Chuos (Varianto) Formation unconformably overlies both the Nosib Group and the Basement complex and may be missing in some areas grading into the Berg Aukas Formation. The Chuos (Varianto) Formation is a diamictite consisting of conglomeritic siltstone, feldspathic sandstone, and banded iron formation with angular and subangular pebbles, including volcanic fragments (Kamona & Günzel, 2007). Its schistose quartz-chlorite-biotite matrix is variably feldspathic and ferruginous (Kamona & Günzel, 2007). The Varianto Formation is limited mainly to the northern flank of the Nosib anticline in the Central part of the Otavi Mountainland where it varies in thickness from 10m at the Nosib prospect to 100m further west (Kamona & Günzel, 2007). The poorly sorted and faceted pebbles and occasional dropstones observed in the Varianto Formation indicate an unstratified diamictite formed through glacial abrasion and direct deposition of glacial marine sediments from ice. The glaciation was accompanied by volcanism dated at 746 +/- 2 Ma (Hoffman et al., 1996) as shown by the presence of andesitic and basaltic fragments in the diamictite (Kamona & Günzel, 2007).

The Berg Aukas Formation overlies the Varianto Formation but in places overlies the Nosib Group and the Basement complex where the Varianto Formation is missing. It consists of 206m of light to dark grey, laminated dolostones with minor stromatolites in the type section on Elandshoek farm (Hughes, 1987). In places, reworked detritus from the Nosib Group or the Basement complex form a clastic unit interbedded with the limestone and dolostone up to 350m thick at the base of the formation (Kamona & Günzel, 2007). Sedimentary slump breccias occur in the upper laminated and banded dolostone, whereas oolitic chert, oolitic and stromatolitic dolostone appear towards the stratigraphic top of the unit, especially in the Rietfontein and Berg Aukas areas (Kamona & Günzel, 2007).

The Gauss Formation conformably overlies the Berg Aukas Formation. Its base is marked by the significant transition from the laminated Berg Aukas dolostone to massive beds typical of light to medium grey dolostone of the Gauss Formation (Hughes, 1987). Kamona and Günzel (2006) described the Gauss Formation as a varied massive dolostone sequence of grainstone, mudstone and boundstone with megadomal stromatolites at the top of the package. The massive dolostone (up to 1000m thick at Gauss) displays a primary porosity now partly filled with sparry dolomite, sphalerite and galena and ovoid to irregular masses of chert and secondary quartz (Söhnge, 1957).

Overlying the Gauss Formation conformably is the Auros Formation and its type section is the Elandshoek farm (Hughes, 1987), where it consists of 220m of variably bedded dolostone, limestone and shale, where its base is defined as the lowermost limestone bed (Hedberg, 1979). Three major cycles of carbonate sedimentation, each beginning with a marl gradationally overlain by massive dolostone and ending with a prominent stromatolitic boundstone, characterize the Auros Formation (Kamona & Günzel, 2007).

The Abenab Subgroup developed in a shallow-marine environment initially characterized by interbedded clastic and carbonate units of the Berg Aukas Formation, which represents the transition from clastic deposition to predominantly chemical precipitation. A high energy, shallow outer shelf with a stromatolitic reef is indicated by the presence of intraformational sedimentary breccias as well as stromatolitic and oolitic grainstones. During the deposition of the Gauss Formation, a low energy, shallow-marine middle shelf environment with high carbonate production is indicated by the accumulation of massive dolostone averaging 750m thickness. The Euros Formation represents a Neoproterozoic stromatolitic reef developed in shallow water with a back-reef zone in which massive and oolitic carbonates and siliciclastic sediments accumulated (Kamona & Günzel, 2007).

2.3.4.2 Tsumeb Subgroup

The Tsumeb Subgroup of the Otavi Group disconformably overlies the Abenab Subgroup and its basal unit is the diamictic Ghaub Formation. The sequence of the Tsumeb Subgroup is the basal Ghaub Formation, overlain by the Maieberg Formation, Elandshoek Formation, capped by the Hüttenberg Formation, which is the uppermost unit of the Tsumeb Subgroup. The Ghaub Formation is a glacio – marine tillite with faceted and striated pebbles derived mainly from the underlying carbonates of the Abenab Subgroup, the Nosib Group quartzite and basement gneiss and granite (Kamona & Günzel, 2007). This glacial event at around 650 Ma was followed by melting of ice and deposition of cap dolostone overlain by thinly bedded limestone to form widespread carbonate platform over the whole Otavi Mountainland, as indicated by the regional distribution of the Maieberg Formation.

Overlying the Ghaub Formation is the widespread Maieberg Formation characterized by thinly bedded, platy limestone overlain by dolostone beds. Slump folds also characterize it.

The Maieberg Formation can be subdivided into lower limestone (with aragonite fans) and subordinate upper dolostone (zones T2 and T3, respectively of Söhnge, (1957)), both in the stratotype and elsewhere throughout the Otavi Mountain Land (Hughes, 1987). The main limestone member consists of argillaceous lower beds with disseminated sulphides (pyrite, pyrrhotite and marcasite) overlain by laminated and banded limestone with shaly intercalations lacking pyrite (Söhnge, 1957).

The Elandshoek Formation (~1000m thick) conformably overlies the Maieberg Formation and consists principally of three dolostone units recognized throughout the Otavi Mountainland: a lower massive grainstone, a middle dolostone unit with oolitic and stromatolitic chert interbeds and an upper unit with repetitive minor cycles of dolomitic mudstone capped by boundstone. Contorted bedding, argillaceous layers as well as intraformational conglomerates and local pisolites are also present. The upper member typically contains silicified dolostone and stromatolitic chert bands (up to 10m thick) which are common in most areas but are absent in the western part of the Otavi Mountainland (Kamona & Günzel, 2007). Hughes (1987) stated that the stratotype begins with the abrupt change from thin – bedded and laminated Maieberg dolostone to the 311m thick massive, lightgrey, basal dolostone member of the Elandshoek Formation (zone T4). This is unbrecciated at the base but becomes moderately brecciated upwards, both at the top of the basal member and in the base of the overlying member, where breccia fragments a centimeter to several meters in diameter occur. The breccias have secondary quartz and dolomite spar cement, which contains disseminated galena and sphalerite (Hughes, 1987). The Hüttenberg Formation caps the Tsumeb Subgroup. It is in the Hüttenberg Formation where the Kombat mining complex is stratigraphically located.

The chert – rich Hüttenberg Formation is well developed in the northern part of the Otavi Mountainland and in the Kombot area, but it is absent in the eastern and central areas due to erosion (Kamona & Günzel, 2006). A prominent 10 – 14m thick silicified and brecciated stromatolitic grainstone–mudstone zone, the North Break Zone (NBZ) (Lombard et al., 1986) occurs near the base of the T6 unit at Tsumeb. The middle lithozone (T7) consists of alternating dark and light dolostone, minor limestone and thin interbeds of shale and chert. A 9m thick evaporite bed of nodular anhydrite and calcite had been intersected in a drill hole in the Tsumeb area within 100m of interbedded limestone containing gypsum and anhydrite (Kamona & Günzel, 2007). Native sulphur is also known to be associated with gypsum and anhydrite in other drill holes at Tsumeb and Kombot (Hughes, 1987). The Hüttenberg Formation is capped by prominent oolitic shoal horizons in the uppermost member (T8). The Kombot Cu – Pb – Ag deposit is placed in the Hüttenberg Formation of the Tsumeb Subgroup of the Otavi Group. Phosphate minerals such as apatite crystals and cellophane are associated with pyrolusite and disseminated copper sulphides in these silicified oolite beds at Tsumeb and Kombot (Hughes, 1987). Figure 2.5a and 2.5b show the typical T6 Unit as observed at Asis Ost mine and Figure 2.5c shows the brecciated dolostone of the T8 Unit at E900 (Fig. 1.2), Kombot mine.



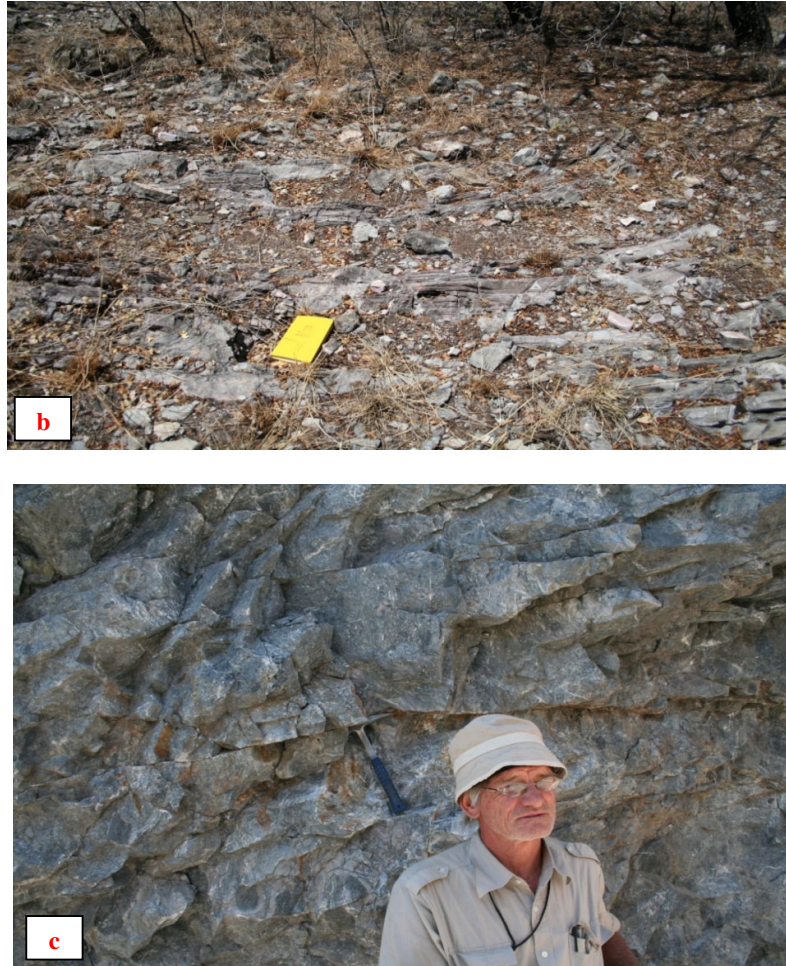


Figure 2.5: Hüttenberg Formation lithological successions; **a.** Stromatolitic dolostone typical T6 unit, basal Hüttenberg Formation from the E900 area at Kombat. **b.** Bedded dolostone with rhythmic layering, the T6 unit around the Asis Ost area, Kombat. **c.** Brecciated dolostone, T8 Unit, E900 open pit area, Kombat.

2.3.5 Mulden Group

The uppermost group of the Damara sequence, the Mulden Group consists of a lower Tschudi Formation and upper Kombat Formation. Total thickness of the Mulden Group is in excess of 2000m (Hedberg, 1979). The Mulden Group occurs in the cores of synclines, particularly in the northern and southern parts of the Otavi Mountainland and is eroded from the anticlinal areas of the central Otavi Mountainland (Kamona & Günzel, 2007). The Tschudi Formation

consists of a basal conglomerate and a fining upward feldspathic arenite with minor greywacke and intraformational breccias (Kamona & Günzel, 2007). The middle Kombat Formation is a slate with disseminated pyrite showing pyrrhotite overgrowths of metamorphic origin in the Kombat mine area (Innes & Chaplin, 1986). In places it has intercalations with greywacke. It is more than 500m thick (Miller; 1992) and occurs mainly on the northern side of the Otavi Valley in the Kombat area where it directly overlies the Hüttenberg Formation dolostone. Some workers like Basement complex (1995) and Frimmel et al (1996a) regard the Kombat Formation as the stratigraphic top of the Otavi Group in the Kombat area. This is due to the occurrence of the phyllites south of Kombat which have been interpreted by Frimmel et al (1996a) as a facies change of Tsumeb Subgroup carbonates (Kamona & Günzel, 2007). The karsted upper surface of the Hüttenberg Formation indicates that a hiatus in sedimentation occurred prior to deposition of the Mulden Group, which has been interpreted as a molasse deposited during the early stages of the Damara Orogen (Hedberg, 1979). The Mulden Group probably represents terrigenous clastic sedimentation within intermontane basins in a predominantly continental environment as indicated by the lack of carbonates and presence of chert pebbles derived from the underlying Otavi Group (Kamona & Günzel, 2007).

2.4. Intracontinental Arm

The northern Congo Craton is separated from the southern Kalahari Craton by the intracontinental arm of the Damara Sequence and Miller (1983a) has divided this arm into several zones based on stratigraphy, structure, metamorphic grade, magmatic rocks, age, geochronology and aeromagnetic expressions. Miller (1983c) categorized the zones as follows; (from north to south) Northern Platform Zone (NPZ), Northern Zone (NZ), Central

Zone (CZ), Okahandja Lineament Zone (OLZ), Southern Zone (SZ), Southern Marginal Zone (SMZ) and Foreland Zone (FZ) (Fig. 2.6).

The OLZ and SZ occur in a NE-trending Khomas Trough bounded by CZ in the north and SMZ to the south and considered to have been a sea (Khomas Sea) (Martin, 1965). The SZ that hosts cupriferous deposits (Matchless Belt) is bound to the north by the OLZ. North of the OLZ is a dome and basin structural style while steep isoclinal folding and thrusting occur in the southern side of the lineament (Kasch, 1986). Porada (1985) simplified the zones as depicted in Figure 2.6b into a Northern Platform Zone, a Transitional Zone (Miller's Northern Zone), a Central Zone and a Southern Marginal Zone (this includes Miller's Okahandja Lineament Zone Southern Zone, and Southern Marginal Zone). Aeromagnetic surveys show that the Damara structural trends of the Intracontinental arm extend north eastwards through northern Botswana into the Katanga succession of Democratic Republic of Congo and South Western Zambia (Reeves, 1978).

2.4.1 Structural Evolution of the Intracontinental Arm

The Intracontinental arm of the Damara Orogen, or the Damara Belt "*sensu stricto*", is dominated by northeast trending, taphrogenic faults, while the coastal arm is controlled by north – northwesterly taphrogenic faults which also guided the separation of the Africa and South America plates.

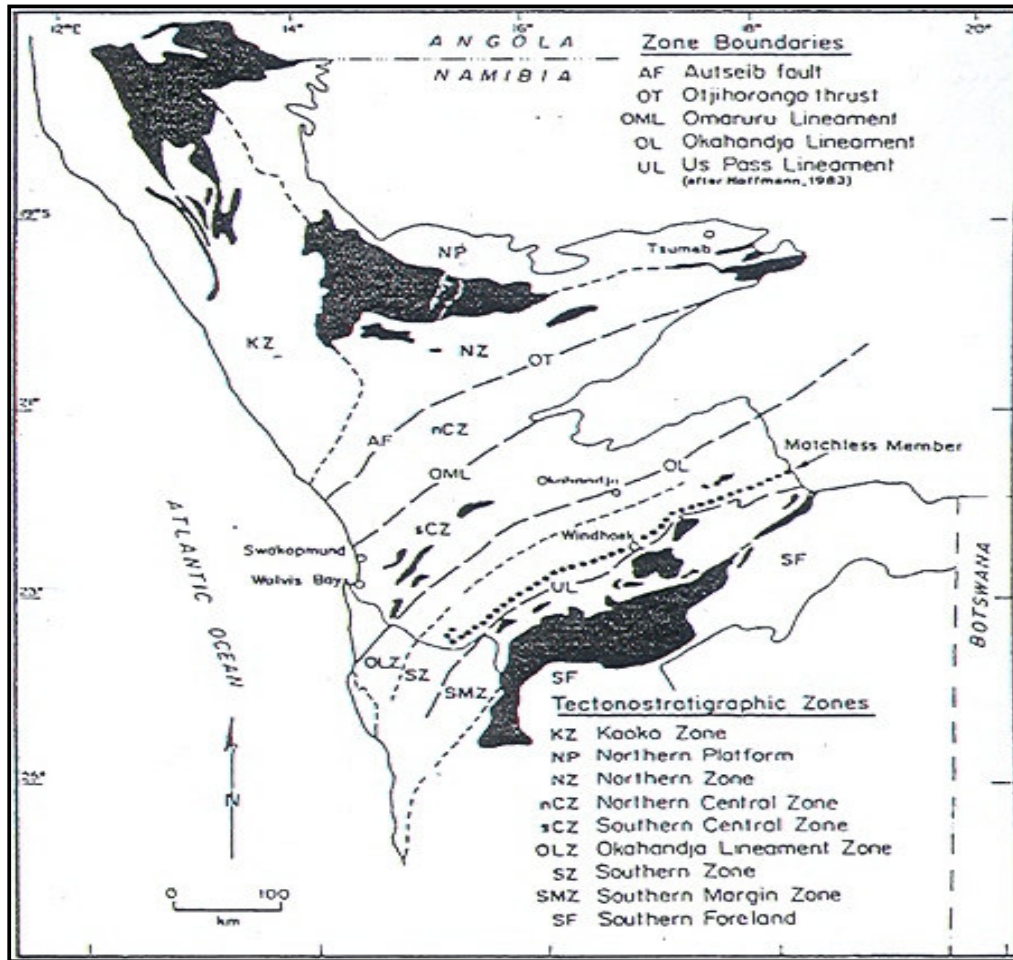


Figure 2.6a: Tectonostratigraphic Zones around the Damara Mobile Belt – Intracontinental Arm, after Miller (1983a).

2.4.2.1 Phases of Deformation

Three deformation episodes have been identified as D1, D2 and D3, (Porada, 1979; Basement complex, 1993).

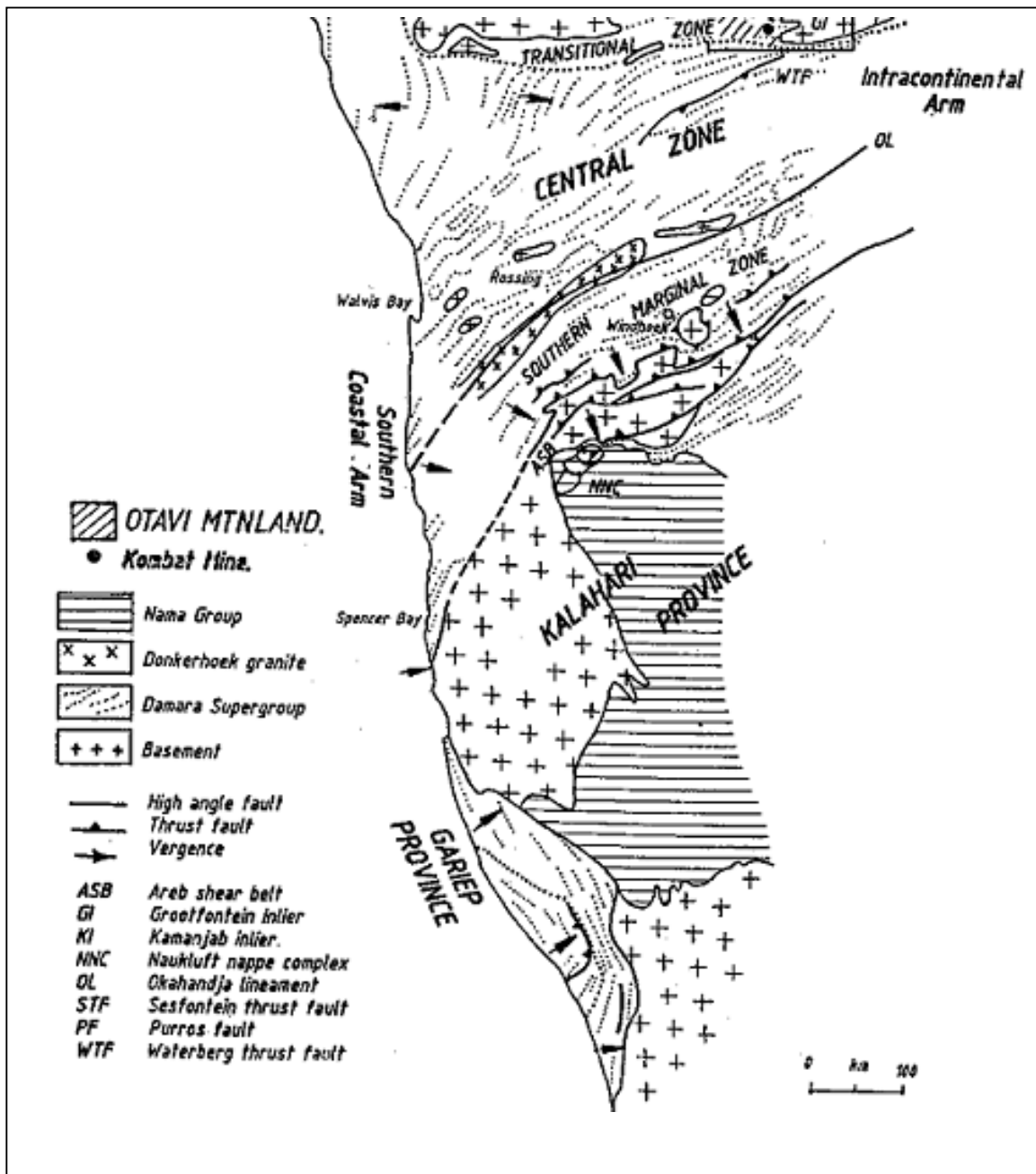


Figure 2.6b: Tectonic map of the Damara and Gariep Provinces showing the tectonic zones, pre-Damara basement inliers, and southern margin thrust zone modified after Porada (1985).

D1, this is characterized by large recumbent folds which verge to the south and south east and carry intensely deformed high grade rocks over the platform carbonates of the southern Congo Craton (Deane, 1993). Porada (1979) suggested that the D1 deformation phase is related to the closure of the Pan African Ocean, although the position of the suture is unknown (Deane, 1993). The syn-tectonic deposition of the Mulden Group sediments took

place in large north – south trending intermontane basins, which formed as a result of the intense folding. Miller (1983c) proposed an age of 630 – 650Ma for the D1 deformational phase.

D2, generally this phase involved recumbent shearing with over thrust sense to the southwest. The D2 phase involved oblique closure with the main part of the intracontinental arm overthrusting to the southeast on a low angle shear zone (Deane, 1993) in the OML.

D3 phase involved a change in relative plate movement which led to intense south east directed folding and thrusting of the Khomas Trough fill into the Kalahari Craton (Deane, 1993). An important aspect is that the deformational events in the Damara Orogen occurred at the same time within the different tectonic boundaries, as such deformation events may be overlapping between the southern zone and the OML.

Structural data from the Damara Orogen suggests a reversal of spreading and north westward subduction as a result of the African and South American Cratons collision (the Sao Francisco Craton); and of the Kalahari Craton with the Congo, during Mulden deposition. D1 recumbent folding was followed by the intrusion of the granites with subsequent uplift and erosion of the northern Coastal arm and deposition of the Northern molasse, the Mulden Group (Deane, 1993)

2.4.3 Metamorphism of the Damara Orogen

In the Otavi Mountainland of the Damara Orogen, a metamorphic grade in the lower greenschist facies is inferred from the existence of the assemblages calcite + dolomite + quartz and magnesian siderite + quartz + calcite, absence of talc and tremolite and by

development of phengitic muscovite and minor chlorite in rocks of appropriate bulk composition (Innes & Chaplin, 1986). The evolution of the Damara province was polycyclic and 2 distinct metamorphic events of 550Ma and 460Ma have been identified with a 650Ma postulated (Deane, 1993). Ahrendt et al. (1983) dated the Kombat phyllites using the K-Ar and got an age of 460Ma. Claire and Kroner (1979) dated the Mulden Group metasediments in the Etosha Pan area and concluded that there were two metamorphic events at 535Ma and 455Ma.

The northern margin of the intracontinental branch of the African Damara orogen shows dramatic along strike variation in metamorphic character during convergence between the Congo and Kalahari Cratons (M3 Metamorphic cycle) (Goscombe et al, 2004).

2.4.4 Kombat deposit metamorphism

2.4.4.1 Introduction

Figure 2.6c is a paragenetic chart – Kombat mineralization showing the different alteration types, mineralization types and deformation events at Kombat mine over time after Innes and Chaplin (1986).

2.4.4.2 Metamorphism and mineral assemblages

Metamorphism around the Kombat Mining Complex revolves around the metamorphic mineral assemblages; calcite + dolomite + quartz, magnesian siderite + quartz + calcite, the absence of talc and tremolite, and by the development of phengitic muscovite and minor chlorite in rocks of appropriate bulk composition. The conversion of authigenic pyrite to

pyrrhotite in the Kombat Formation is consistent with a lower greenschist facies grade of metamorphism. The Kombat phyllite consists of the assemblage; quartz –talc- muscovite. It has been proposed that the molasse – like sediments of the Mulden Group in the Etosha Basin comprises zeolite facies to prehnite – pumpellyite facies assemblages (250 – 300⁰C, up to 2Kb) developed in consequence to two, regional tectono thermal events dated at 537 +/- 7 and 457 +/- 12 Ma. The similarity of these assemblages to those present in the Kombat Formation pelites indicates a very low metamorphic gradient northwards from the southern flank of the Otavi Valley synclinorium, concomitant with decreasing intensity of deformation (Innes & Chaplin, 1986).

Within the Kombat mine environment mineral assemblages are however indicative of higher temperatures. Metamorphic minerals related to the Fe-Mn oxide/silicate assemblages are vesuvianite, actinolite, and magnesio – richterite. Quartz veins within the Kombat Formation phyllite have associated talc and ankerite. The quartz veins are regarded as being the same age as the mineralisation. The presence of talc suggests a minimum temperature of 350⁰C. The presence of vesuvianite suggests low X_(CO₂) values of 0.01, and the absence of anorthite indicates temperatures below 480⁰C (Spear, 1993). The Kombat bodies therefore formed in a temperature range between 350⁰C and 480⁰C (Basement complex, 1995). It appears that the regional lower greenschist metamorphic conditions were too low to produce the higher temperature assemblages of the quartz veins (minimum temperature, 350⁰C) and the Kombat ore bodies (approx, 440⁰C). This suggests that the ore carrying fluids at Kombat, and possibly the quartz veins must have been derived from a higher temperature terrain. This higher temperature terrain is more likely to be a higher metamorphic province, as no magmatic activity is evident in the near vicinity of the Otavi Mountainland. The quartz veins associated with the Kombat Formation phyllite are commonly located near zones of deformation such as fold hinges and fault planes.

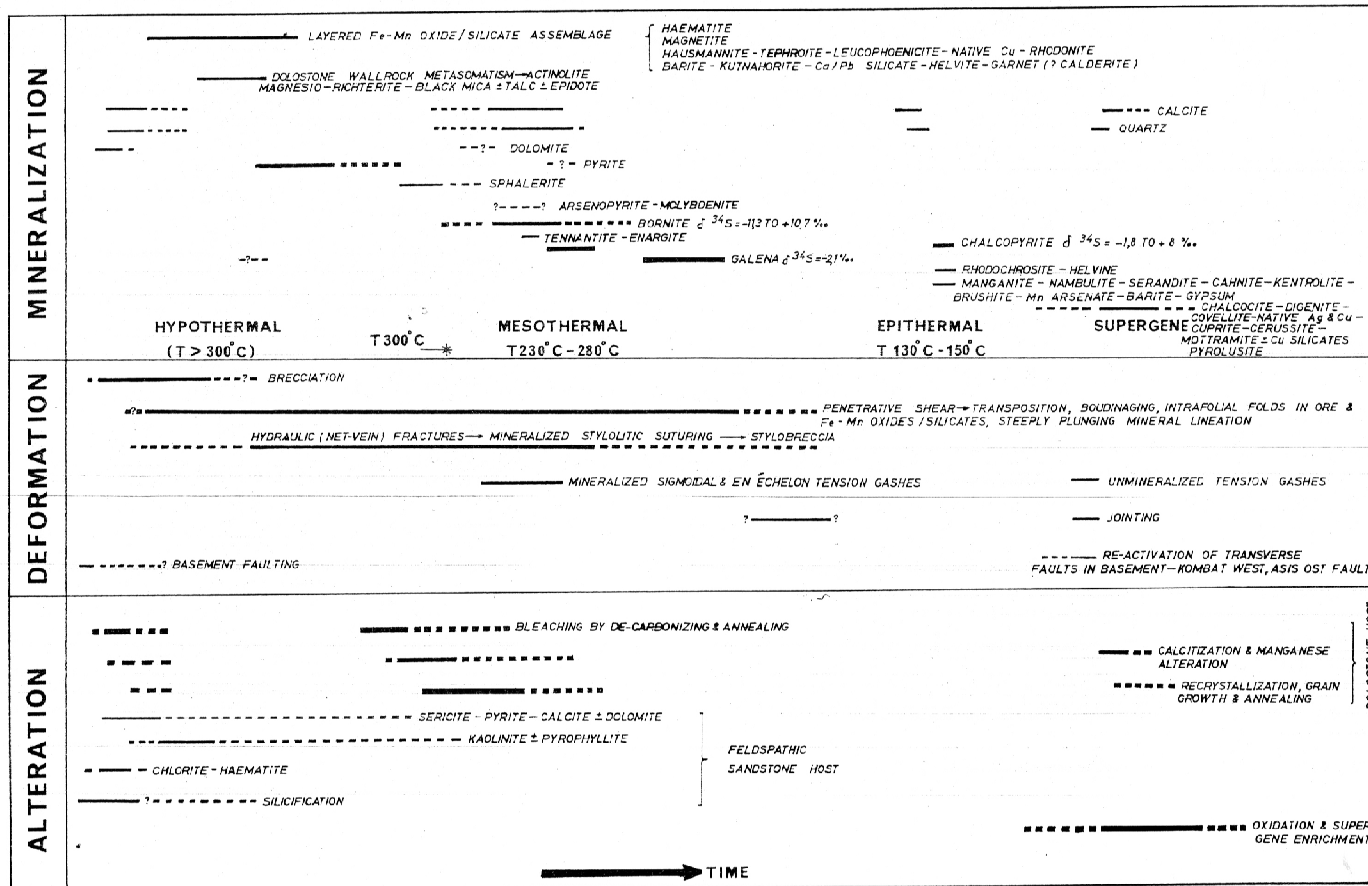


Figure 2.6c: Paragenetic chart – Kombat mineralization showing the different alteration types, mineralization types and deformation events at Kombat mine over time, after Inness and Chaplin (1986).

Abundant quartz veining is commonly associated with the Otavi Valley rapture (section 4.1). These may well represent fluid pathways during major dewatering events from the Damara basin bringing fluids with elevated temperatures from the higher temperature Central Zone.

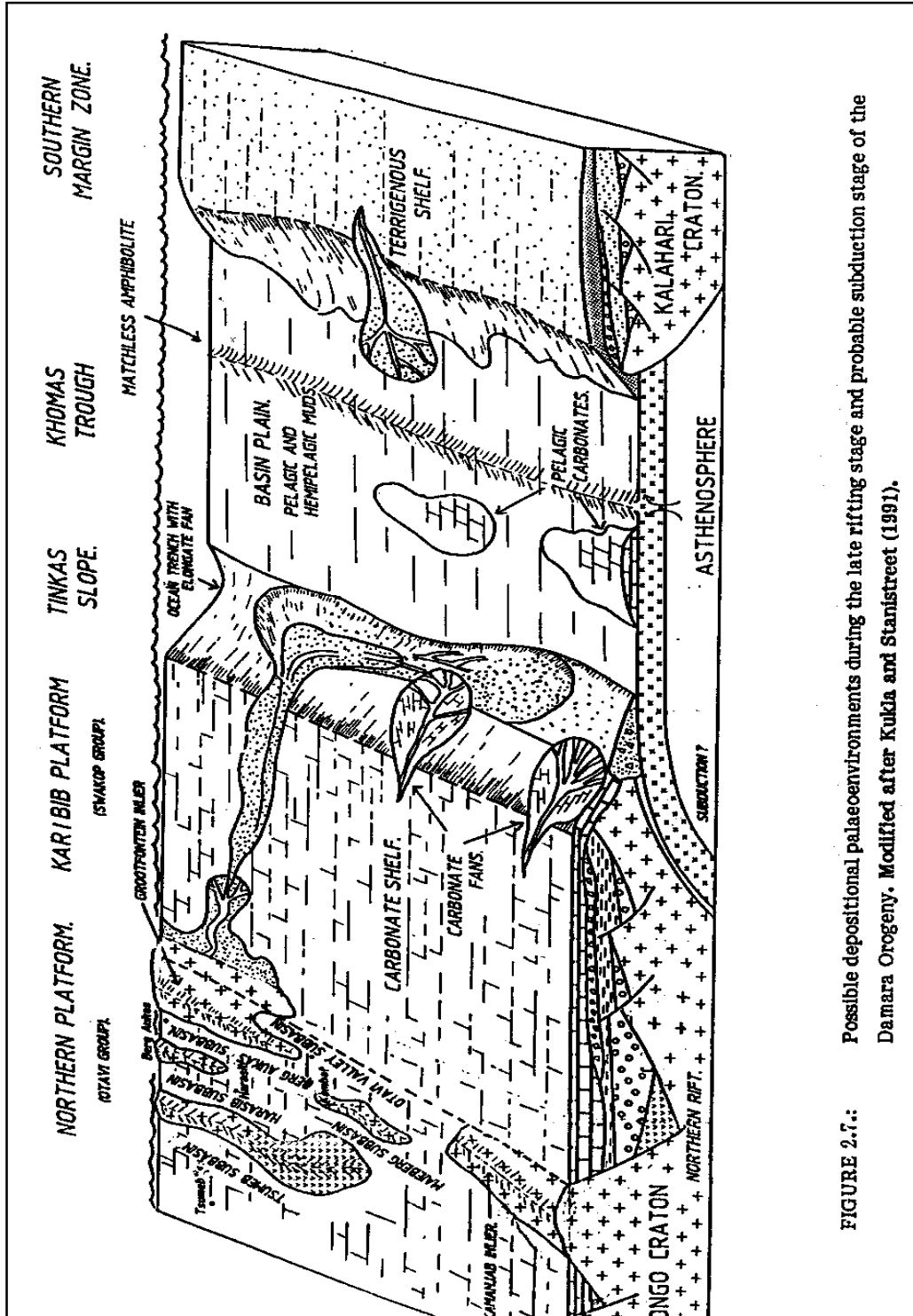


FIGURE 2.7.: Possible depositional palaeoenvironments during the late rifting stage and probable subduction stage of the Damara Orogeny. Modified after Kukia and Stanistreet (1991).

2.5 The Otavi Valley Basin

Hedberg (1979) has classified the Northern Platform (the locality of the Otavi Valley Deposits) as a miogeosyncline (*'old term which is no longer in common use though*). The model for the evolution of the Damara basin is based on the passive mantle hypothesis. Passive mantle rifting proceeds rapidly and may lead to ocean opening after only 15 – 20Ma (Porada, 1985).

The Damara episode was initiated around 900Ma ago during widespread fluvial deposition of the Nosib Group onto basement from local sources within and marginal to intercontinental rifts trending north – northwest, northeast and south away from the triple junction near Swakopmund (Deane, 1993). At the end of the Nosib Group sedimentation, two important trends controlled further deposition in the intercontinental arm.

Firstly, the area of deposition widened so that the original four rifts coalesced and sediments overstepped the basement highs. Secondly, the Owambo basin developed on the Congo Craton so that a platform succession, Otavi Group accumulated on a gently subsidizing but stable platform (Deane, 1993).

2.6 The Otavi Mountainland of the Intercontinental Arm of the Damara Orogen

The focus of this study is the occurrence of base metal mineralisation at Kombat mines, located in the Otavi Mountainland (OML) of the Intercontinental Arm of the Damara Orogen. The OML is located in the north-eastern part of the Damara Belt, where various Neoproterozoic formations of the Damara Supergroup have folded into generally east – west trending synclines and anticlines (Figs. 2.8 & 2.9 respectively).

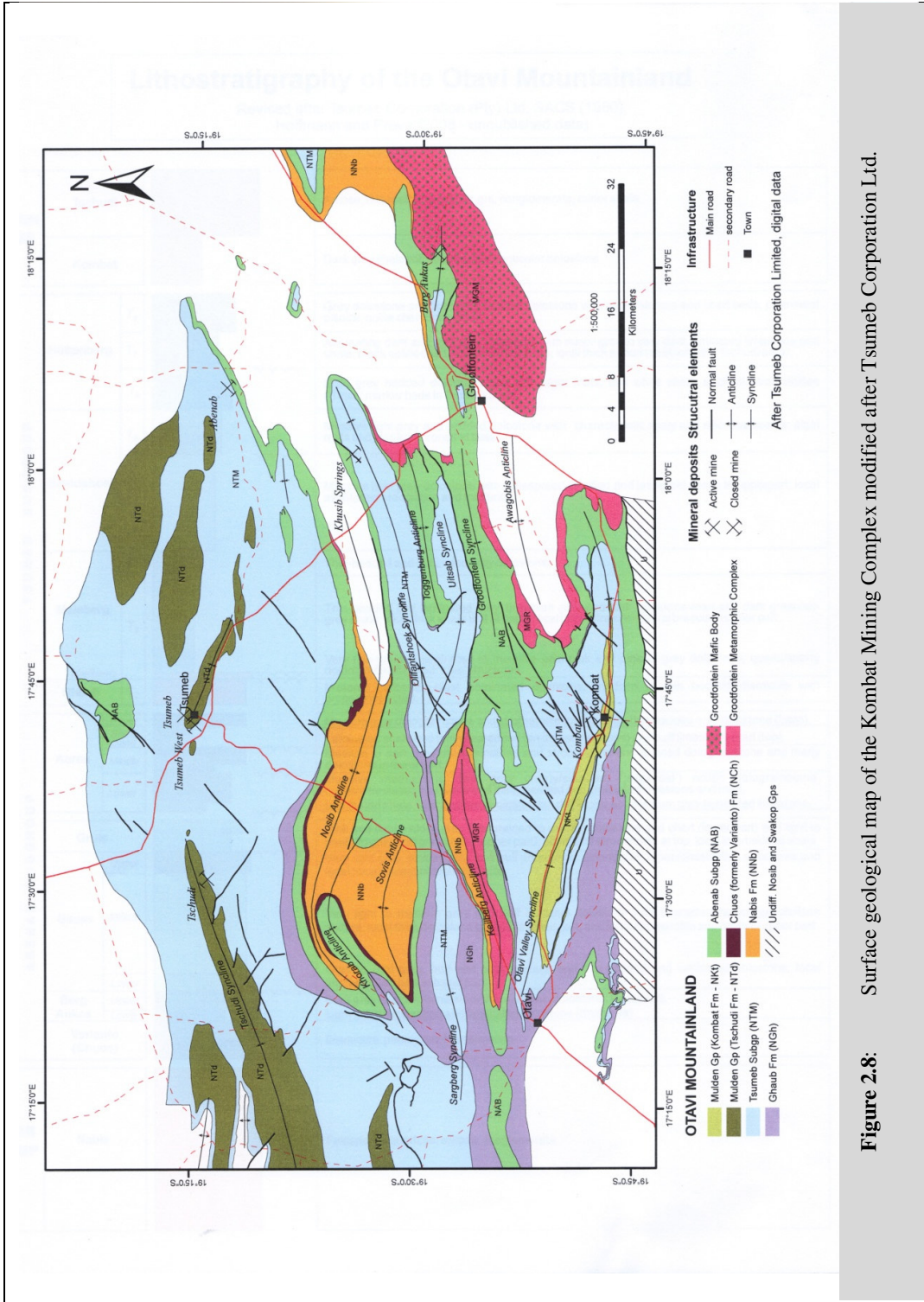


Figure 2.8: Surface geological map of the Kombat Mining Complex modified after Tsumeb Corporation Ltd.

The generalized geometry and structure of the OML is illustrated in Figure 2.9 showing a north – south cross section indicating contrasting styles of folding, major faults and positions of some deposits in the various units of the Damara Supergroup from the northern platform to

the central zone. The northern platform in the Owambo Basin is characterized by thick, relatively unmetamorphosed platform carbonates of the Otavi Group overlain by sedimentary rocks of the Mulden Group and the Karoo Supergroup.

The gentle and open flexural slip folds of the northern platform decrease in amplitude and increase in wavelength northwards and eastwards, towards the Congo Craton. Most of the base metal deposits including the Kombat Mining Complex Deposits are concentrated within the shallow – to moderate depth marine carbonates of the northern platform (Fig. 2.9), (Kamona & Günzel, 2007). Recent data suggests that there occurs a large sub-basin between the Tsumeb basi and the Kombat basin. The sub basin lies in the environs of the Ghaub Farm, where the Nosib group is well on both the northern and southern shoulders of the Ghaub sub-basin.

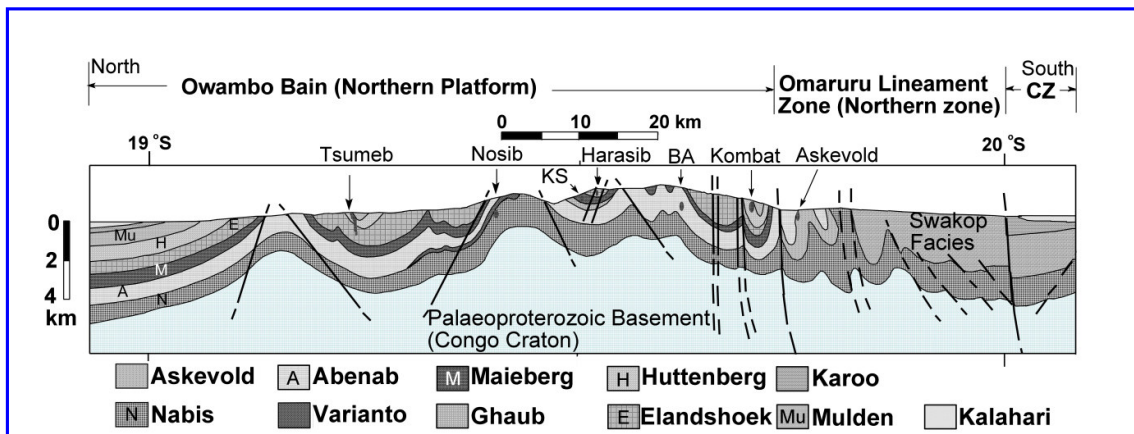


Figure 2.9: Generalized north – south section across the Otavi Mountainland (OML), showing the major structures in the Owambo Basin, the Omaruru Lineament and the Central Zone (CZ) with the location of some deposits and prospects, including Khusib Springs (KS) and Berg Aukas (BA). The undifferentiated Swakop facies is the equivalent of the Otavi Group in the Omaruru lineament and central zones of the Damara orogen. The section is modified after Kamona and Günzel (2007).

The contact between the Northern Platform and the Northern Rift is marked by an arcuate chain of major basement ridges and domes which extend over 100km. With initial rift evolution, the basal formations of the Damara Sequence, the Nosib Group, were deposited. In the Northern Rift, bimodal volcanic and coarse clastic sediments dominate these formations. On the Northern Platform, the OML area, the Nosib Group is only locally developed. In the OML, basement highs separated four subsidiary intercontinental rift basins in which the carbonate rocks of the Otavi Group, which overlie the Nosib Group, are preserved in synclinoria. The southern most of these sub basins is the Otavi Valley sub basin in which the Kombat deposits are located. The Otavi Group is divided into 2 Subgroups, namely a lower Abenab Subgroup and an Upper Abenab Subgroup. Generally, the Pb – Zn Mississippi Valley Type (MVT) deposits are located in the Abenab Subgroup and the more economical Cu deposits are located in the Tsumeb Subgroup. A final phase of the rift subsidence in the Northern Rift resulted in the drowning of the southern parts of the Otavi Valley sub basin and the cessation of carbonate deposition. The phyllite of the Kombat Formation was deposited over the Tsumeb Subgroup as an onlap unconformity. With the onset of the Damara Orogen the molasse – type Mulden Group was deposited syntectonically. In the Otavi Valley sub – basin the Mulden Group is only found as large sandstone lenses within karst structures developed in the subsurface environment directly under the phyllite/carbonate contact zone. This sandstone is referred to as the Otavi valley sandstone (Basement complex, 1995) whereas the phyllite is referred to as the Kombat Phyllite.

Chapter 3

Geology of Kombat Mining Complex

3.1 Introduction

The Kombat Mining Complex straddles the Hüttenberg Formation, the upper unit of the Tsumeb Subgroup and the younger Kombat Formation of the Mulden Group of the Damara Sequence (Table. 2.1). Mineralization at Kombat Mines is situated on the northern limb of the Otavi Valley Synclinorium (Figs. 2.8 & 2.9). The synclinorium is a doubly plunging, canoe shaped structure which strikes west – north – west for approximately 50km (Innes & Chaplin, 1986). Figure 1.2 shows the geological map of the Kombat Mining Complex modified after Galloway (1986) and Tsumeb Corporation Ltd, incorporating the local stratigraphy (with the T lithological zones classification of Söhnge (1957), faulting and the main centres of mineralization. Figure 3.1 shows the detailed surface geological map for the Kombat Mining Complex modified in this study after Galloway (1986) and Tsumeb Corporation Limited. An overview of the Kombat stratigraphy based on previous work will be described in brief to allow placement of the Kombat geology in its correct stratigraphic context.

3.2 Kombat deposit Stratigraphy based on work done by various previous researchers

3.2.1 Hüttenberg Formation

The Hüttenberg Formation consists of Söhnge's (1957) T6, T7 and T8 lithological zones, (Table. 2.1 and Fig. 1.2).

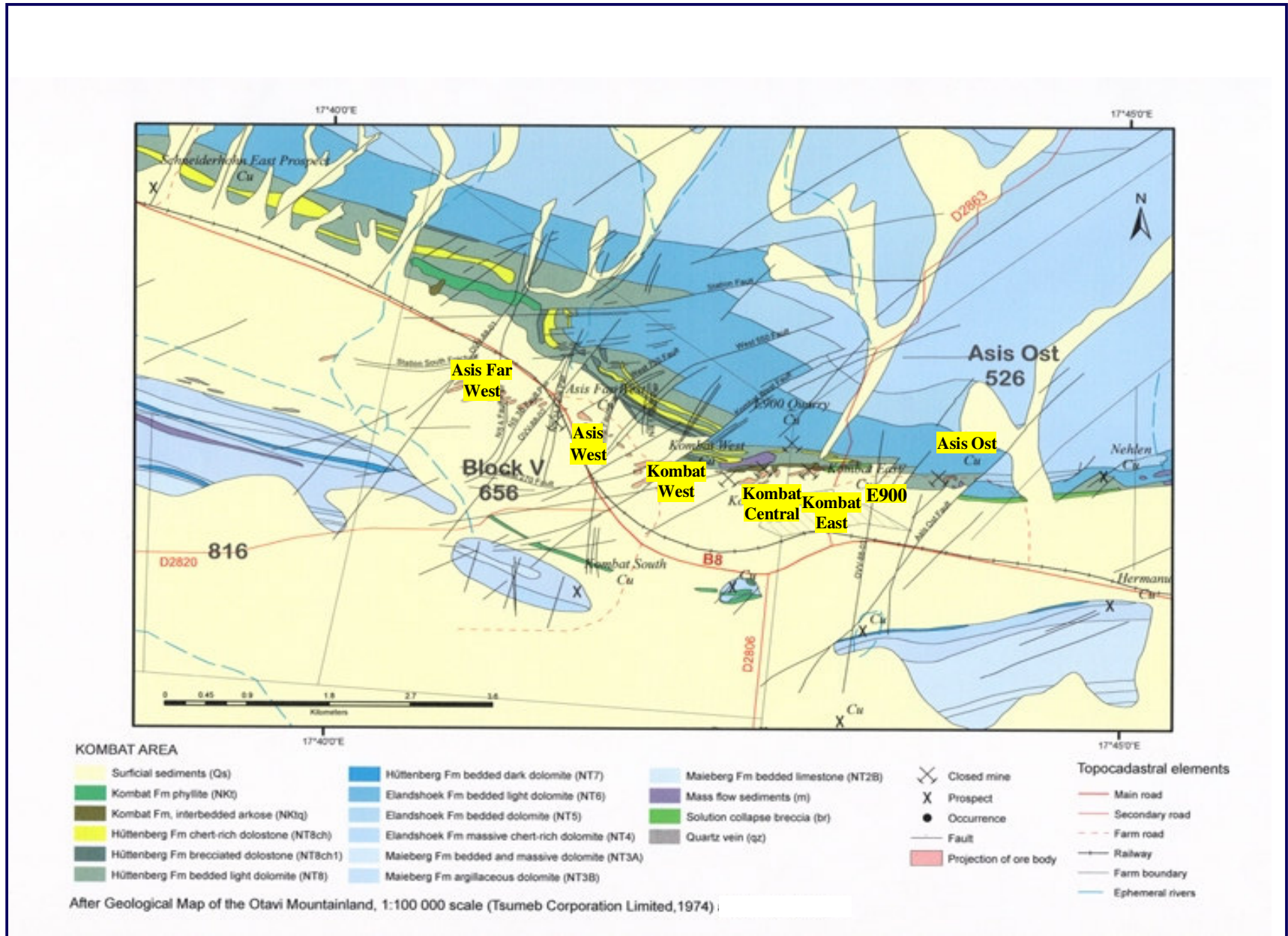


Figure 3.1: Surface geological map of the Kombat Mining Complex modified by Changara (2007) Galloway (1988) and Tsumeb Corporation Ltd.

3.2.1.1 T6 Zone

The T6 Zone comprises bedded, light grey, silicified, cherty algal dolostone. Stromatolites are common and occur as laminar mats and Conophyton.

Various Kombat Mine Geologists have described the T6 type dolostones over time including Visser (1970), core logging of surface diamond drill hole AO93; as silicified, shattered, and brecciated with chalcocite and bornite mineralization. Its known occurrence at Kombat Mining area is the area around the Asis Ost mine (Figs. 1.2 & 3.1). Part of the Asis Ost mineralization occurs in the T6 Zone (Galloway, 1988). The beds are commonly highlighted by chert, which selectively replaced individual algal/stromatolite layers (Deane, 1993). Figure 3.2 shows the appearance of the typical T6 type dolostone as seen in diamond drill core at Asis Ost Mine which shows lamination of chert associated with algal and stromatolite layers.



Figure 3.2: Typical T6 Zone dolostone (AO93, Asis Ost diamond drill hole), showing lamination of chert associated with algal stromatolite layers.

3.2.1.2 T7 Zone

Söhnge's (1957) T7 Zone has not been recognized in the Kombat Environments (Galloway, 1988). Current mine drill core and surface mapping suggests a sedimentological pinching out.

3.2.1.3 T8 Zone

For the purposes of this study, the T8 Zone of Söhnge (1957) is regarded as the most important lithological unit (stratigraphic horizon) for the mineralization at the Kombat mines, particularly the Upper T8 Zone. Figure 3.3 is an underground geological map generated in this study showing the interrelationships of lithology, structure and mineralization in the Asis West 12Level W750 area. Most underground geological mapping detail will be discussed alongside mineralization and structure in later chapters. Lithologically, the T8 Zone consists of thin bedded, brecciated, stromatolitic, oolitic dolostone (Figs. 3.4a, 3.4b, 3.4c, 3.4d & 3.4e). Colouration is variable from light grey to dark grey, normally because of alteration. Normal oolitic dolostone occurrence is within the actual ore zones, or around the margins of mineralization sometimes as replacement by sulphides especially pyrite and chalcopyrite (Figs. 3.3 & 3.4b). Brecciation is common throughout the Kombat Mining Complex. Figures 3.4c, 3.4d and 3.4e show the different forms of brecciated dolostones that characterize the T8 Zone. Extensive slump breccias within the T8 Unit are intimately associated with the massive disturbance of the carbonate platform due to tectonic triggers along the East – West platform margin and along deep-seated zones of crustal weaknesses. The disturbed nature of the intertidal lagoon deposit is ascribed to localized horst and graben features resulting from this crustal movement, which simultaneously initiated break-up of the algal reef zone and the formation of polymict slump breccias. Silicification of oolitic material is ubiquitous (Galloway, 1988). Two marker horizons (the Stromatolitic marker (Fig. 3.4a) and the Oolitic

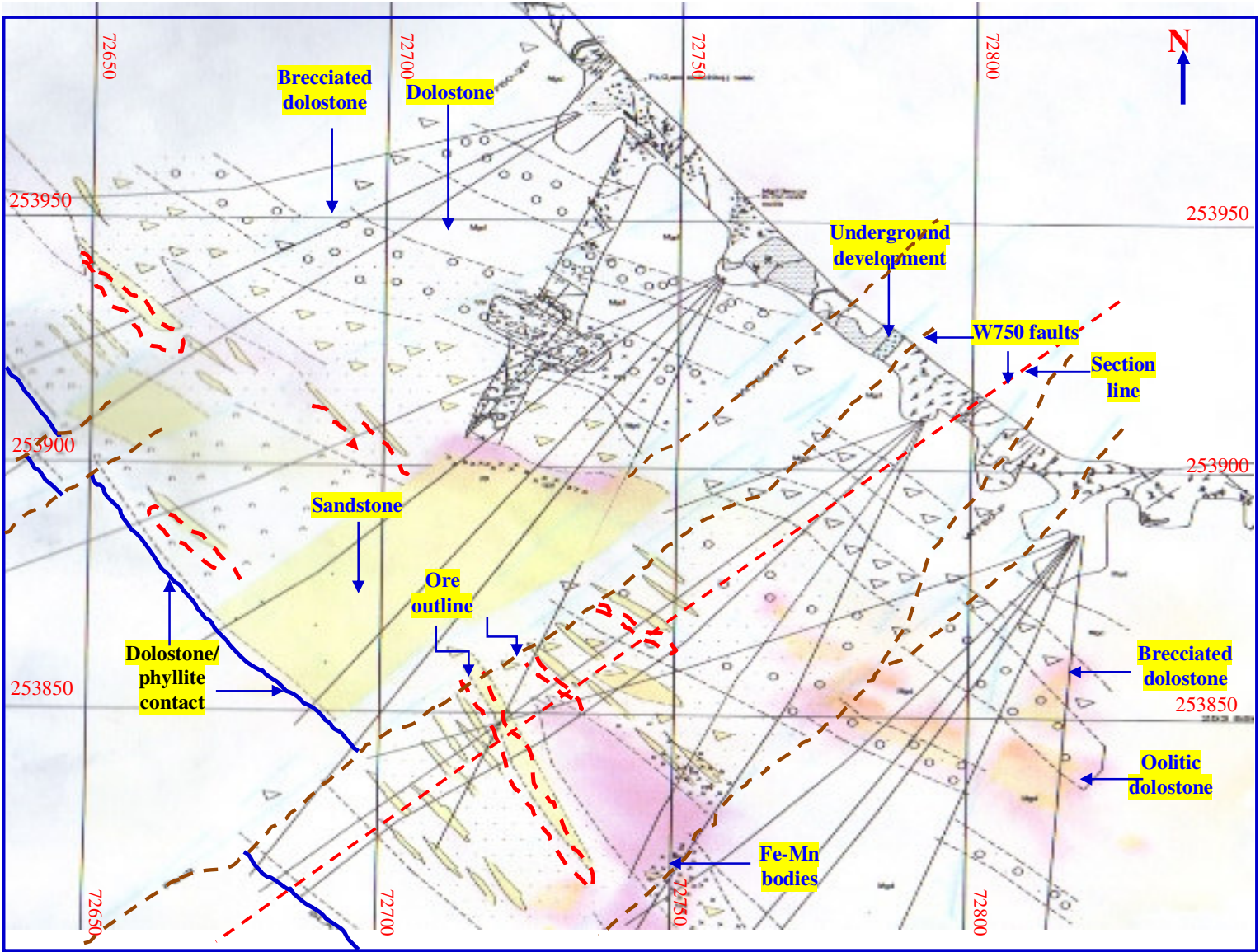


Figure 3.3: Asis West, 12level W750; geological plan showing structure, mineralization, and lithological patterns at ~1200m elevation.

Marker (Fig 3.4b)) have been suggested by Dean (1993) as typifying the T8 Upper Lithozone. The stromatolite marker represents a zone of high energy where abundant broken up chertified stromatolite fragments occur within grainstone matrix. The oolite marker is

essentially a well-bedded silicified zone of well sorted oolites. No grading is evident suggesting reworking of original oolitic shoals (Fig. 3.4b).

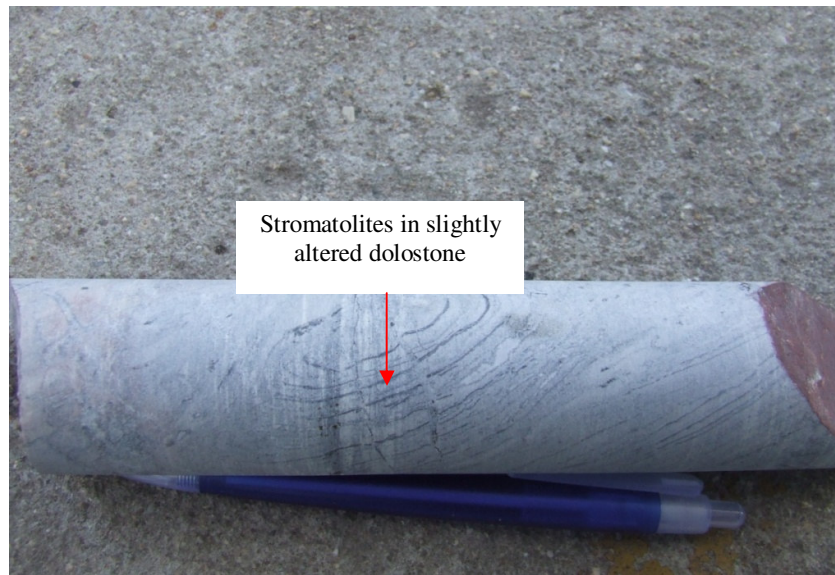


Figure 3.4a: Stromatolitic dolostone – T8 lithozone (Au12/265, Kombat 12level underground diamond drill core).

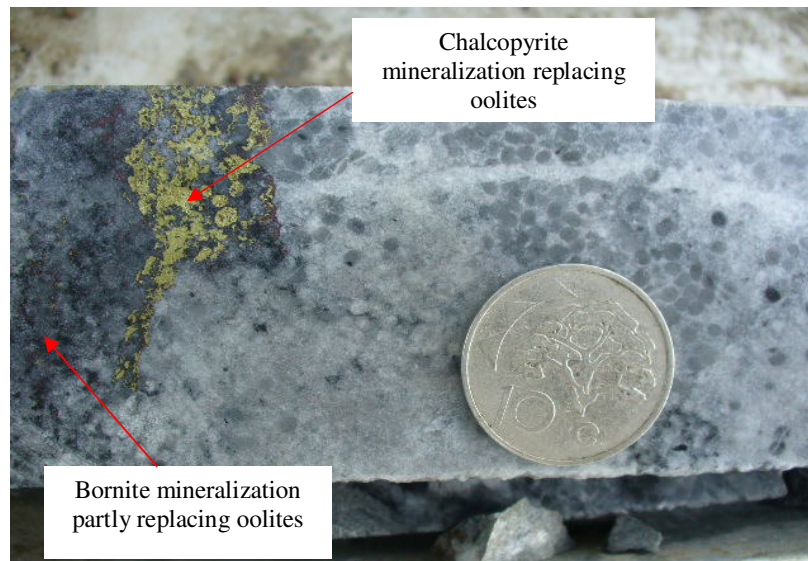


Figure 3.4b: Bedded oolitic dolostone, T8 lithozone (Au12/284, Kombat Mine underground diamond drill core, also showing the replacement of oolites with chalcopyrite and bornite mineralization).



Figure 3.4c: Fe/Mn sedimentary breccia, Kombat East surface, the clasts are generally dolomitic and the Fe/Mn coloration could signify a hydrothermal origin to these bodies.



Figure 3.4d: Chemical breccia, T8, mineralized (Au12/284, Kombat underground diamond drill core), the sample also shows some microfaults and the breccia zone is partly tectonized with anastomosing microfaults and chalcopyrite mineralization.



Figure 3.4e: Brecciation of the T8 Unit, Hüttenberg Formation, E900 area, surface, Kombat mine, showing the breccia clasts and the carbonate matrix.

3.3 The Kombat Formation

3.3.1 Introduction

The stratigraphic correlation of the Kombat Formation and the nature of its contact with the Hüttenberg Formation has been unclear until recently where it has been demonstrated to be thrust on top of the Hüttenberg Formation. Some workers (Basement complex, 1995; Frimmel et al., 1996a) regard the Kombat Formation as the stratigraphic top of the Otavi Valley Group in the Kombat area. This is due to the occurrence of phyllites south of Kombat which have been correctly interpreted by Frimmel et al (1996a) as a facies change of Tsumeb Subgroup carbonates (Kamona & Günzel, 2007). This Phyllite unit of the Kombat Formation crops out extensively around the Kombat mine and it is important for mine exploration development as it is barren of any Cu – Pb – Ag mineralisation. Botha (1960) reported that in 1939 the Geological Survey believed the phyllite to be an isoclinally folded intercalation within the Otavi Group (Deane, 1993). Berning (1952) suggested that the phyllite might

represent a wedge of pre Otavi Group Basement. Mapping around the Kombat mine has shown that the larger intercalations (the two phyllite bands) are a consequence of repetitive isoclinal infolding of the Kombat Formation (Deane, 1993). Figure 3.5 is an underground geological section within the Asis West orebody showing the interpreted infolding of the Phyllite. The interfingering nature of the various rock types of the lower and middle Tsumeb Subgroup with the Phyllite in the southern limb (not the phyllite bands), as well as the regional mapping, support the idea of depositional onlap by the Kombat Formation (Deane, 1993). For the purposes of this study, the phyllites occurring at the core of the synclinorium previously called the Otavitalschiefer of Schneiderhohn (1921), in Inness and Chaplin (1986) and Otavi Valley Phyllite, Hedberg (1979) will be regarded as a unit of the Kombat Formation.

3.3.2 The Kombat Formation Phyllite

The phyllites identified in logged diamond drill holes generally exhibit a shear foliation at 60 – 90 degrees to the core axis (Fig. 3.6). Also closely associated with the phyllite unit is pyrite and pyrrhotite mineralization. Assaying of the mineralized phyllite shows no mineralization in Cu, Pb, Ag or Au. Pyrrhotite and pyrite occur in varying amounts throughout the phyllite, the pyrite is commonly remobilized into the S1 planes where it usually inverts into pyrrhotite. The highest concentrations of pyrite occur within the dark grey variety of the phyllite (Deane, 1993). The contact between the underlying Hüttenberg Formation to the phyllite is sharp and Dean (1993) suggests that it is a tectonic contact and not a sedimentary unconformity. The graphite and pyrite concentrations within the phyllite are probably primary sedimentary features suggesting deposition under anoxic conditions (Deane, 1993).

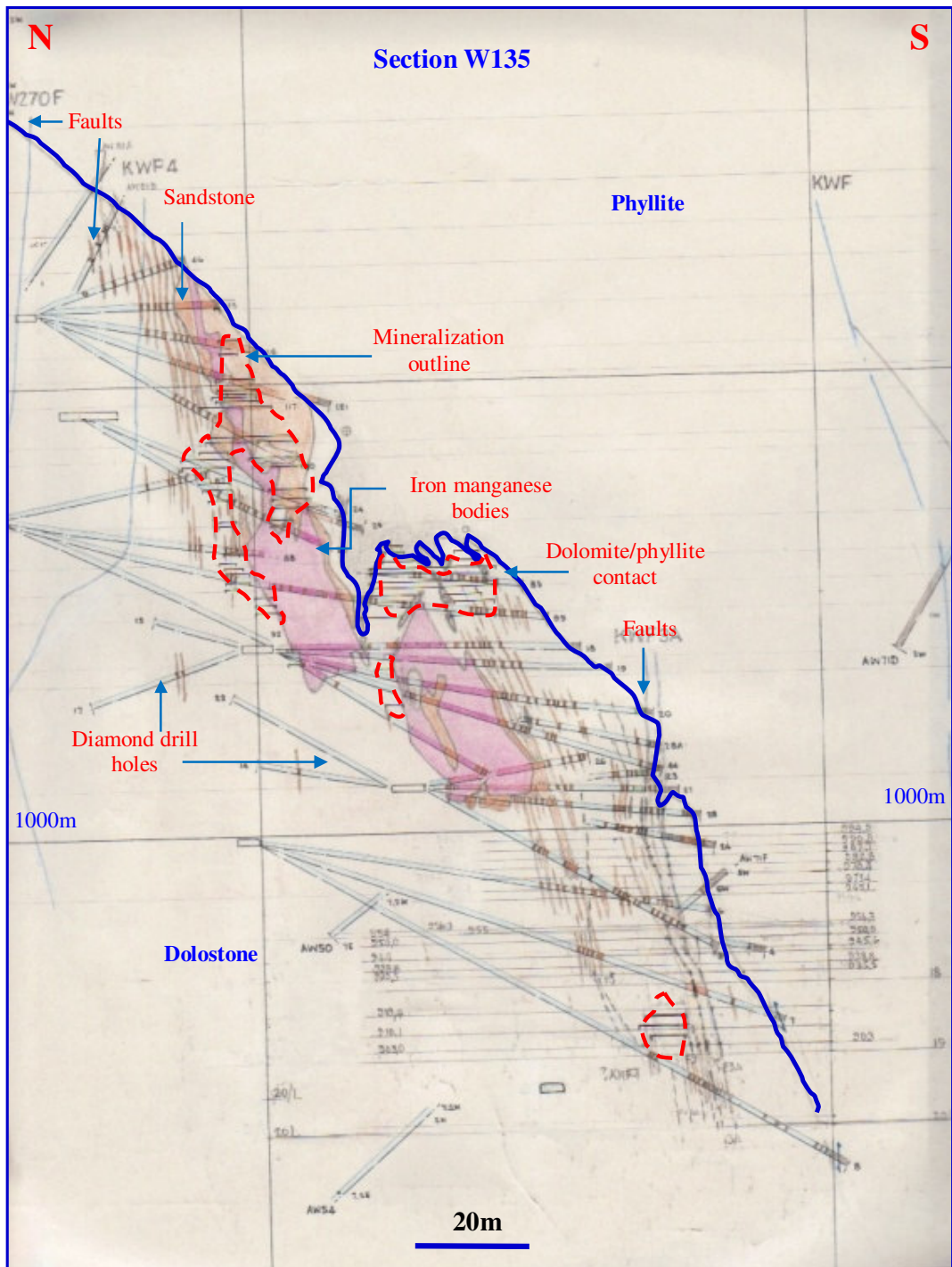


Figure 3.5: Asis West, geological cross section north – south looking east, showing the dolostone/phyllite folded contact and the relationship of the Fe/Mn bodies and sandstone to mineralization and contact, mineralization, sandstone and Fe-Mn relationships, modified by Changara (2007).

Otavi Group to a continental regime (Hedberg, 1979). This is evidenced by the presence of basal conglomerates and sedimentary breccias. It is generally concluded that the contact between the Otavi and Mulden groups marks a hiatus.



Figure 3.6: Kombat typical phyllite, showing lamination and fracturing, Asis Far West underground diamond drilling 19 level.

The Karsting which formed the Tsumeb pipe and which formed the numerous karst features in the Kombat area is circumstantial evidence for this hiatus. This hiatus may have been a period of relative non-deposition and local erosion conducive to the formation of karst structures. The Mulden deposits are believed to be the product of uplift and erosion associated with the Damara Orogen, representing molasse deposits. However, the source of the great thickness of the Mulden sediments poses a problem. Hedberg (1979) suggested that a greater portion of the sediments might have come from areas to the south and west of the Otavi Mountainland, as well as from the present basement outcrop belt within the Otavi mountainland (Deane, 1993). The sharp and complexly folded (Fig. 3.5) contact between the Hüttenberg Formation dolostones and the Kombat Formation is very important, as it is closely associated with mineralization at Kombat mines. Innes and Chaplin (1986) described the phyllite as light grey to black slate of the Kombat Formation (previously the Otavitalschiefer” of Schneiderhohn (1921) in Innes & Chaplin, (1986), Otavi Phyllite of Hedberg (1979), a laminated feldspar – quartz – muscovite rock with a regionally developed fissility imparted by a first generation S1 cleavage. This will be described and explained in detail in subsequent chapters.

3.4 Kombat petrology done in this study

3.4.1 Introduction

Changara (2007) has generated a litho classification scheme recently for the Kombat Mining Complex. The main objective of the classification scheme was to standardize geological data that has been collected over time and use it to generate a computer aided geological model for the Kombat Mining Complex. All lithologies at Kombat mine will fall into one of the following litho units; dolostone, breccia, sandstone, iron manganese, calcite vein, quartz vein, phyllite, oolitic dolostone. The classification (appendix 5), will cover lithology, alteration (type, style, intensity), structure, mineralization (type, style, intensity), weathering (intensity) and grain size.

3.4.2 Dolostone

The Dolostone unit is ubiquitous in the study area. It occurs in various forms from light grey - medium grey to dark grey dolostone (Figs. 2.5a, 2.5b, 2.5c & 3.7). All show different dolostones observed at Kombat and studied in detail. The light – medium dolostone varieties dominate. The coloration in the dolostones does not have much significance to association with mineralization but rather mostly a consequence of alteration and dolomitic mineralogical compositional variation that will be described in subsequent chapters. Some dolostone specimens are thin bedded, or laminated, others are massive. Bedding and laminae are mainly defined by grain size variation and not compositional variation.

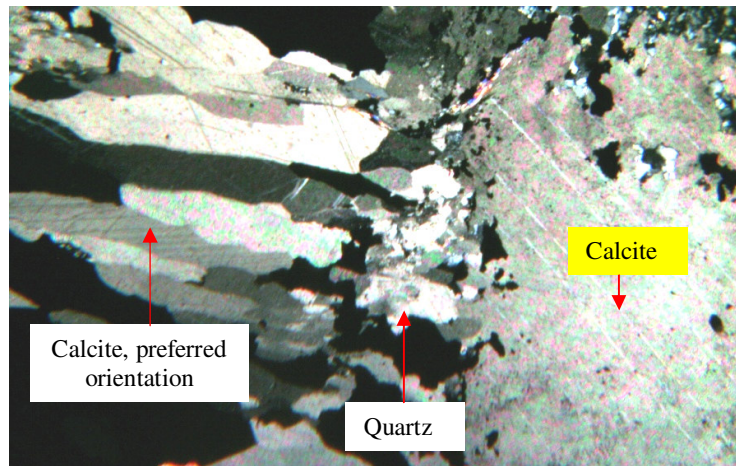


Figure 3.7: Thin section, slightly sheared and altered dolostone with a slight preferred orientation (x10 Magnification)

Dark laminae consist of fine grained microspar (0.1 – 2.0mm). The spar occurs as radial crystal aggregates in many specimens, and they project inwards from opposing walls of some layers. The centers of such layers are filled by quartz, micro quartz and chlorite, or by single carbonate crystals elongated parallel to layers. Silica and chlorite are restricted to these sites in most specimens. These cavity – filling textures indicate former solution activity along bedding planes, possibly during dolomitization or late diagenesis.

3.4.3 Sandstone

Stratigraphically the sandstone is tentatively placed in the Tschudi Formation of the Mulden Group (Table. 2.1). The sandstone has historically been regarded as a pseudo aplite because it occurs in a pipe like body, which is strongly discordant to the enclosing sedimentary rocks. It is normally fine grained, very well sorted, greenish to grey. Colouration is thought to be a result of the effects of kaolinization. Sulphidization, normally of chalcopyrite and pyrite is normally finely disseminated throughout the rock unit. Sandstones are thought to originate from old streams.

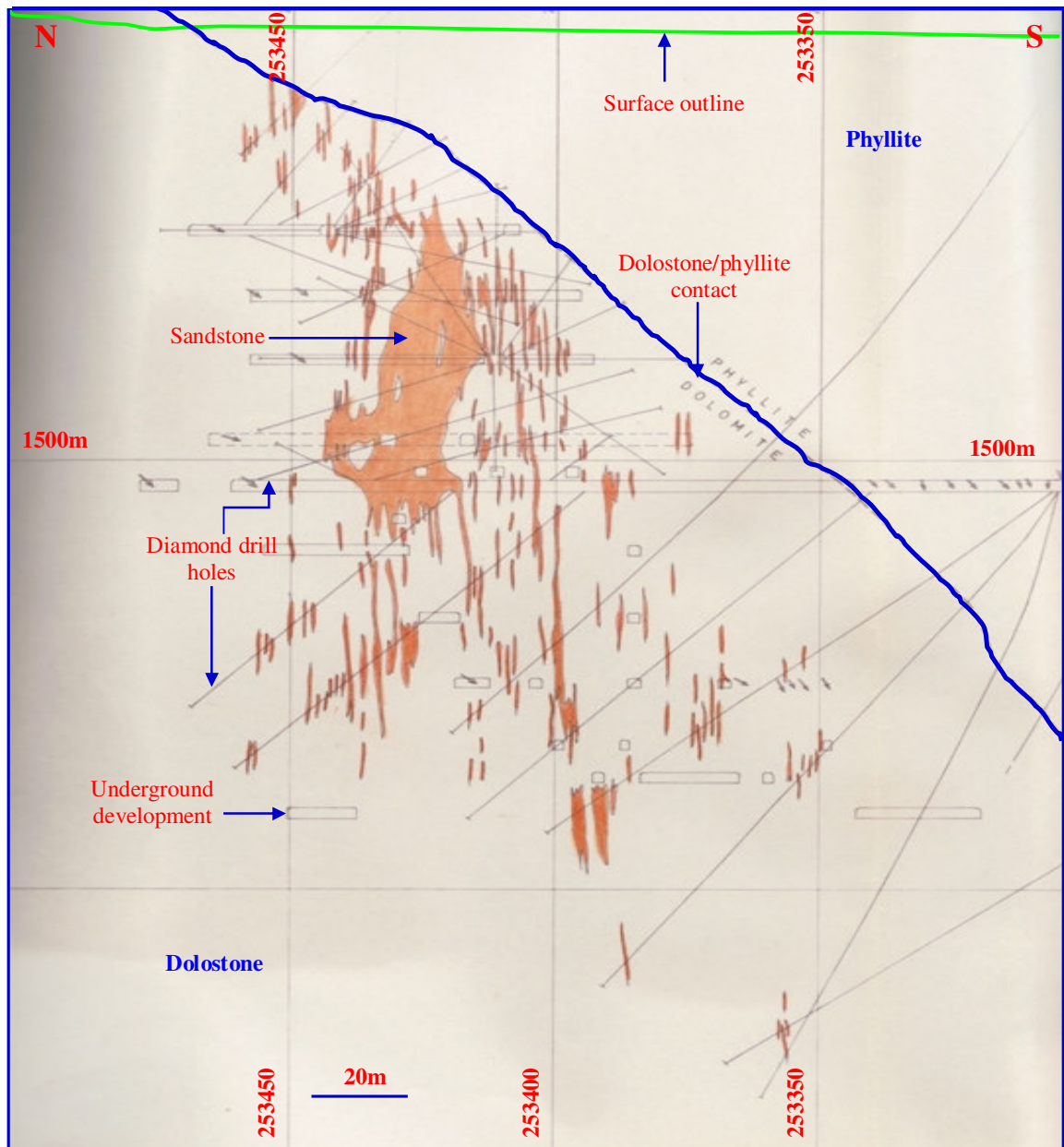


Figure 3.8: Kombat West; north – south cross section zero, looking east showing the sandstone profile and the association with the dolostone/phyllite contact (Changara, 2007).

There is a close association between sandstones and mineralization as well as iron manganese bodies. Emplacement of the sandstone is controlled partly by bedding, but mainly by brecciation, joints, fracture cleavages and net vein fractures in the dolostones. Texturally, the sandstone is comprised of an aggregate of equigranular, generally well-sorted, subangular,

clastic quartz, oligoclase, andesine, and potash feldspar grains in a calcite – kaolinite matrix. Figure 3.8 shows the occurrence of sandstone in some parts of the mine though this is not the only pattern and detail will be described in the mineralization chapter. Figure 3.9 shows the appearance of the sandstone from Kombat underground samples showing a sugary appearance texture.



Figure 3.9: Sandstone, (Asis Far West underground diamond drill core, AFW19/46), showing the sugary quartz-feldspathic grains.

3.4.4 Phyllite

The phyllite of the Kombat Formation is very common throughout the study area. Structurally, the phyllite overlies the dolostones of the Hüttenberg Formation. The phyllite is typically a greenish – grey to black finely foliated normally associated with pyrite-pyrrhotite mineralization though with no known Cu, Pb, Ag, Zn, Au mineralization within the Kombat Mining district. Figure 3.6 shows a typical Phyllite. Figure 3.10 shows the model appearance of part of the phyllite around the Kombat Mining Complex. It has been used historically as a marker horizon especially for exploration as there is no Cu mineralization in the phyllite and

beyond; such that during drilling once phyllite is intersected then the hole is stopped. The contact between the phyllite and the dolostones is sharp.

3.4.5 Oolitic dolostone

The oolitic dolostone is a very common lithology within the Kombat mining complex occurring normally around and within ore bodies. Generally, the oolitic dolostone is well sorted with clasts about 3mm in diameter. Figure 3.11 shows the oolitic dolostone from underground core samples with a subtle preferred orientation indicating deformation.

3.4.6 Iron Manganese (Fe/Mn)

Iron manganese bodies have been seen to show a close association to mineralization. In general terms the iron manganese bodies rims the margins of Cu ore bodies like the Asis West stope shown in Figure 3.10 and on surface at Kombat East. The mineral specularite has been identified within the Kombat East mining locality and exploration activities and economic potential of the mineral is being looked at. The iron manganese oxide-silicate association is a compositionally and texturally layered assemblage of iron and manganese minerals that forms the integral part of the orebodies at Asis West, Kombat Central and Kombat East and is also disclosed by exploration diamond drill holes, west of the orebodies.

The larger, composite bodies consist of hematite (specularite) and magnetite ores in juxtaposition to layered manganese oxide and silicate assemblages, within the zone of transposition.

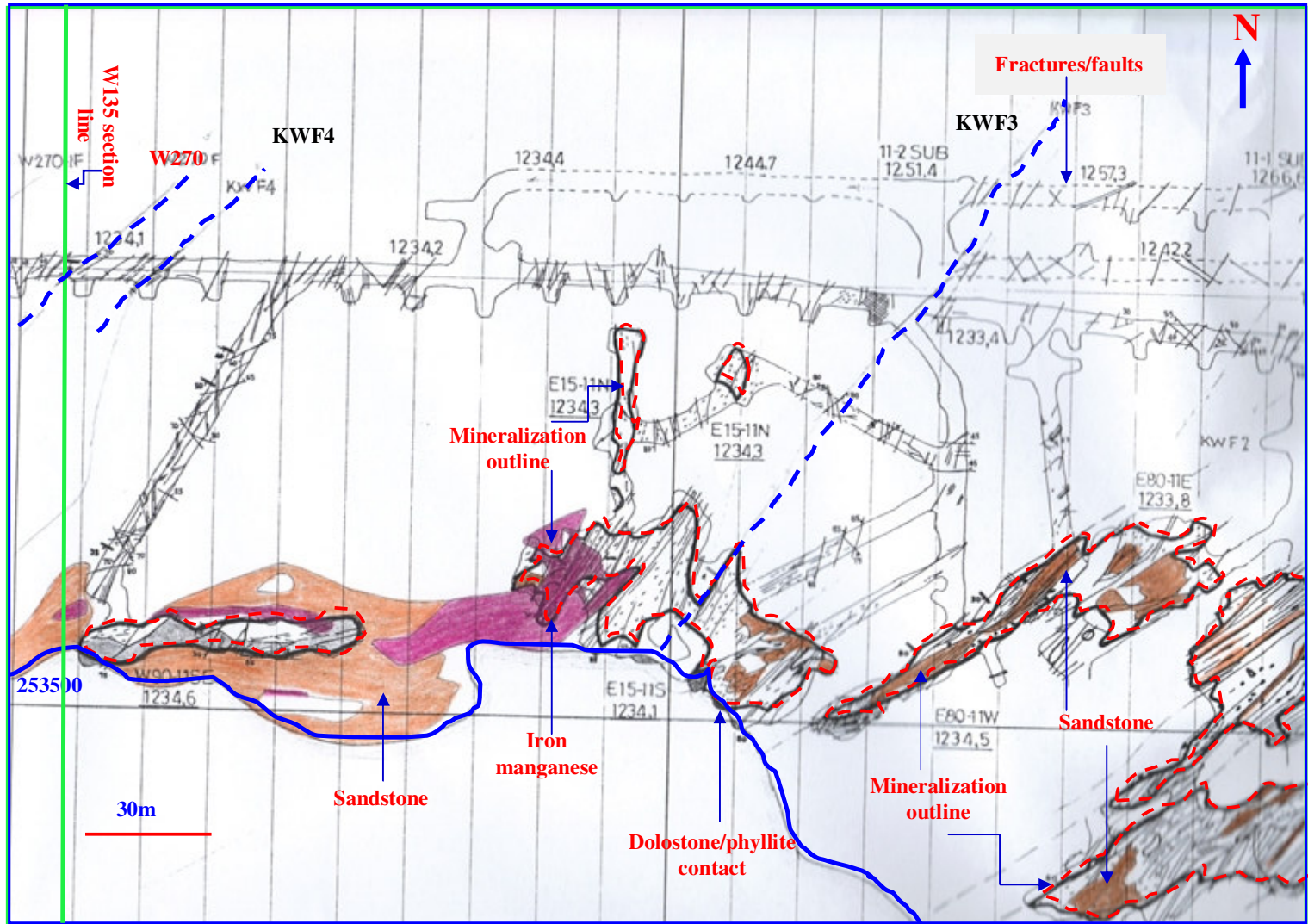


Figure 3.10: Asis West geological plan; showing different stopes and relationships of the dolostone/phyllite contact to the orebodies, Fe-Mn and sandstone bodies, modified by Changara, 2007.

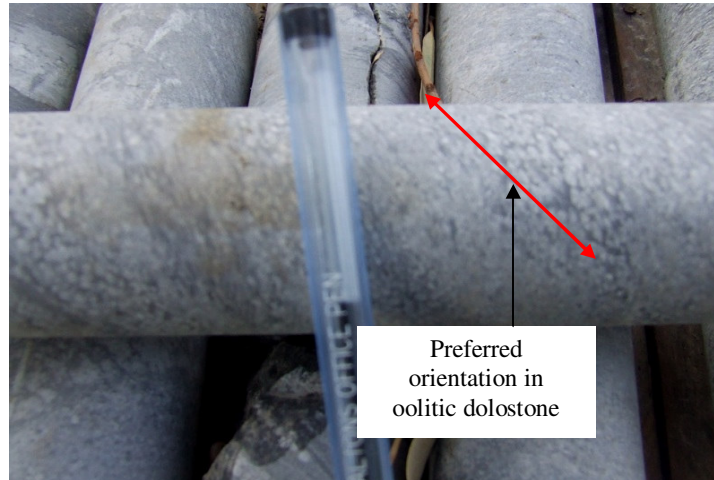


Figure 3.11: Oolitic dolostone (Au12/284, underground diamond drill core sample), with a subtle preferred orientation.

Mineralogically, the banded ores are characterized by the presence of magnetite, hausmannite, hematite, barite, calcite, tephroite, alleghanyite and pyrochroite, with small amounts of a pinkish jasperoidal rock believed to be a siliceous sinter. However, current views suggest a possible hydrothermal origin to the iron manganese bodies, especially from their association with orebodies. This will be discussed in detail along with mineralization. Figures 3.12a and 3.12b show varieties of the Fe/Mn around the Kombat Mining Complex. In Figure 3.12a, the iron manganese is associated with the dolostone with banding. The iron manganese bodies in Figure 3.12b show that they have been tectonized, whilst in Figure 3.4c the sedimentary breccia displays hydrothermal alteration.

3.4.7 Quartz and Carbonate Veins

Late stage fracture fill quartz and carbonate veins are also found around the Kombat mining complex exhibiting various geometries. They are estimated to post date mineralization so not much value is ascribed to them. Figure 3.12c shows en echelon quartz vein lets (Kombat East Orebody).



Figure 3.12: a. Iron Manganese – specularite bands, Kombat East, surface occurrence associated with dolostone; b. Sedimentary breccia with Iron Manganese matrix/alteration, tectonized also indicating the hydrothermal nature of the Fe/Mn bodies.

They are located on the margins of the stope and also within the waste patches/middling of the stope. These structures testify the fact that tectonism (shearing, brittle shearing) continued post mineralization and also as an indication of regional stress within the Kombat area.



Figure 3.12c: En echelon quartz - carbonate vein lets (3L E750, Kombat East, underground mine), the matrix is generally quartz and carbonate in a dolomitic host.

3.4.8 Breccias at Kombat Mining Complex

Different types of breccias have been identified around the Kombat mine area and distinguished below. The importance of the different breccias at Kombat is that some of them are closely associated with mineralization and others have no association with mineralization at all. In a broad sense, the breccias can be categorized as follows; sedimentary, tectonic, hydraulic and chemical breccias (Changara, 2007).

3.4.8.1 Sedimentary breccias

Sedimentary breccias are distinguished on the following basis. They are well sorted, generally lack any veining, and restricted to certain lithological units and bedding parallel in nature, clasts are normally angular and normally matrix supported. Figures 3.4c, 3.13a and 3.13b, show the appearance of sedimentary breccias at Kombat mines. Clasts are normally small (<20cm), with a carbonate mudstone matrix.



Figure 3.13a: Sedimentary breccia, Kombat environs, surface outcrop showing an undisturbed, poorly sorted breccias.

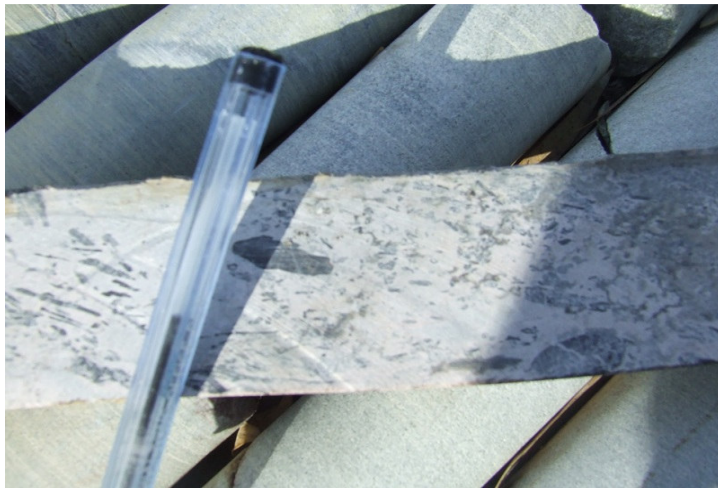


Figure 3.13b: Sedimentary breccia, (Au12/284, Asis West, underground diamond drill core), with a preferred orientation to the elongate clasts.

The absence of slump structures such as soft sediment folding suggests semi lithification before brecciation. Stromatolitic development is another common feature of sedimentary breccias. Very little association between mineralization and sedimentary breccias has been noted in the area of study. However, the sedimentary breccias are found at invariable

distances from the ore bodies. Sometimes, as observed on 12Level around the 12LW800 Stopes they are close to mineralization as shown in Figure 3.3. The fragments of the sedimentary breccias are variable, from carbonate clasts, stromatolites and not limited to algal fragments with oriented fragments (Figs. 3.4c, 3.13a & 3.13b).

3.4.8.2 Tectonic breccias

For the purposes of this study, tectonic breccias at Kombat Mining Complex have been divided into the following categories; Karst Breccias and Fault Breccias. In general, karst breccias are not tectonic breccias per se but have developed as a result of previous tectonic event mostly faulting.

3.4.8.2.1 Karst breccias

Early karst structures are associated with Kombat deposits and are predominantly filled in by the Otavi Valley Sandstone. Au12/200 (underground diamond drill hole) has an intersection of 16m @ 10.35% Cu in a typical karst breccias structure. The Cu mineralization occurs in the form of native copper, malachite, chalcocite, and moderate to minor bornite with minor inherent sandstone and oxidation. A model proposed for the formation of Karst breccias is where sediments are washed into cavities via solution pipes (e.g. sink holes) or underground streams. Solution collapse breccias form in the same cavities, and clasts from these cavities and clasts from there are incorporated in the introduced sediment. Karst breccias are commonly discordant to bedding, and contain some components that are foreign to the enclosing rock.

3.4.8.2 Fault breccias

Fault breccias are associated with brittle deformation resulting from late stage faulting. They normally show small clasts (<3mm) and where faults widen, they have coarse calcite infill associated with them. Fault breccias are generally developed where a zone of faulting bound by two faults occur. As such they represent zones of high porosity if the fault jig is extensional and less porous if the fault jig is compressional.

3.4.8.3 Hydraulic breccias

Two types of hydraulic breccias are distinguished at the Kombat Mining Complex, hydraulic ore forming and crackle breccias. The hydrothermal breccias are thought to form from ascending pore fluid pressure.

Hydraulic ore forming breccias form as a result of percolating hydrothermal fluids, hydraulically fracturing the country rock. The hydrothermal fluids are characteristically ore forming. These breccias are closely associated with mineralization. Figures 3.14a and 3.14b (Au12/265 and Au12/259 respectively) are from recent underground diamond holes that show the typical ore forming hydraulic breccias. Mineralization is of bornite and minor chalcopyrite sulphidization which will be described in detail in later chapters. In the photographs, chalcopyrite and bornite form the matrix around dolostone clasts.

Deeper below the massive ore, the breccias continue and are commonly referred to as net vein calcite fracture systems. The control on these breccias is clearly north – northeast faulting and shearing related to the D_{3b} deformation (Deane, 1993). Figure 3.14c also show the hydraulic ore forming breccia from Kombat E900 open pit and 3level E750 underground

stope respectively. Figure 3.14d is a thin section of a hydraulic ore forming breccia from the 13level, W270 stope.

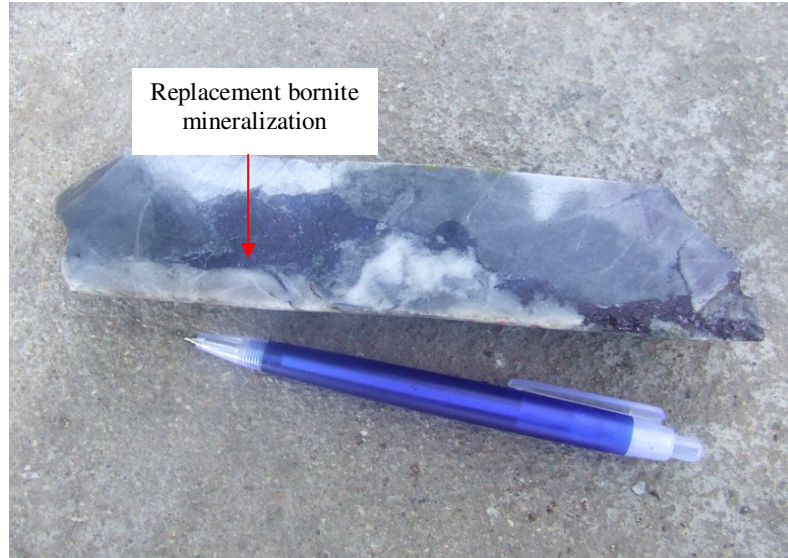


Figure 3.14a: Hydraulic ore forming breccia (Au12/265, underground diamond core), replacement with bornite mineralization.



Figure 3.14b: Hydraulic ore forming breccia (Au12/259, underground diamond core), mineralized in bornite as replacement and fracture fill.

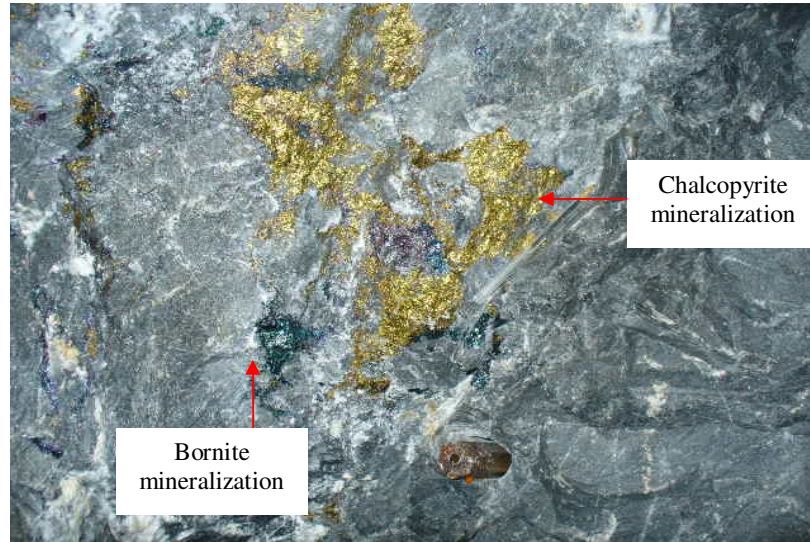


Figure 3.14c: Hydraulic ore forming breccia, E900 open pit, Kombat, mineralized in chalcopyrite and bornite.

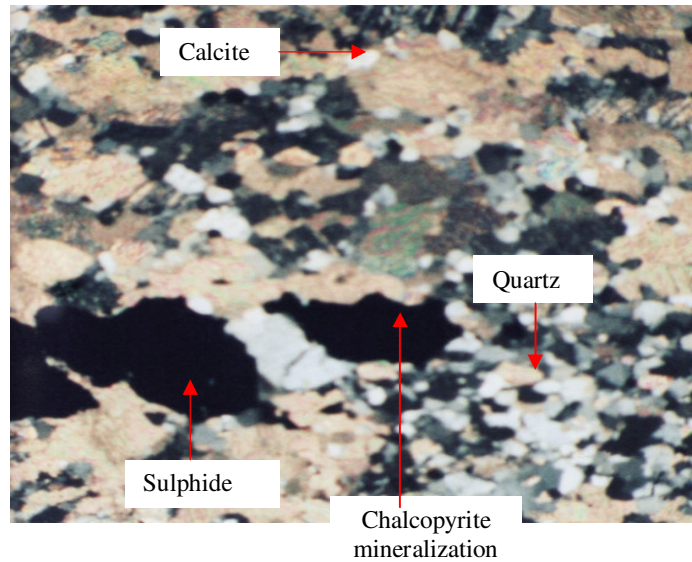


Figure 3.14d: Thin section of hydraulic ore forming breccia (x10), 13level, W270 stope, Asis West orebody.

These breccias are characterized by rotated clasts and the bimodal distribution of large and smaller clasts. In certain instances where brecciation did not recur, the bimodal feature is

absent. These breccias also tell us that the mineralizing fluid was not a single pass event. This is borne by the paragenetic sequence of sulphides that show two or three sequences.

Crackle breccia is a term usually designated to brecciation of a hydrothermal origin where the fluids are barren of any mineralization. Here the term used to describe crackle brecciation is anastomosing silica vein networks found generally in the more massive carbonate rock types. No mineralization is associated with this breccia type. This type of breccia has been logged on several holes at Asis Far West and Asis West underground diamond drill holes. It is normally situated at least 30m from mineralization which will thus be regarded as related to mineralization once other conditions are favourable.

3.4.8.4 Chemical breccias

Two subdivisions of chemical breccias occur within the Kombat mine complex, viz; Solution Collapse and Replacement breccias

These oligomictic breccias involve the replacement of the country rock by calcite or the original clasts by an alteration product. There is a close association between the replacement breccia and the solution collapse breccia. Typical characteristics of the replacement breccias are absence of rotation between clasts and the progressive “digestion” of the dolostone which leads to well rounded remnant dolostone clasts. Figure 3.15 shows typical replacement breccia in underground core at Kombat mine.



Figure 3.15: Replacement breccia, (Au12/279, underground diamond drill core), dolostone has been replaced by silica and late calcite alteration (white).

The dissolution of carbonate with subsequent collapse of rock into the resulting cavities is a common feature of karst topographies. Most Mississippi valley type deposits are formed in solution collapse breccias and are commonly related to unconformities. At Kombat there is a close association between mineralization and solution collapse brecciation. In general terms the matrix of the solution collapse breccia is calcite.

3.5 Comparative Kombat petrographic analyses between upper and lower levels

Most of the previous researches conducted for the Kombat deposit were done on the upper levels but mining activities have opened up lower levels of the mine and extended to the new Asis Far West mine.

This study shows similarities, differences and new findings to what has been known about the Kombat petrography. The similarities are mainly on litho-identification and the interrelationships of the lithologies. The Kombat mining complex is composed mainly of

dolostone, sandstone, iron manganese, phyllite and quartz-carbonate veining. However, detailed mapping and thin section analyses indicate complex variabilities within these litho – units. The breccias in particular, show great variability which forms an integral part to the controls on mineralization. This study has demonstrated the close association of mineralization to brecciated dolostones as well as the sandstone. This will be discussed in detail in subsequent chapters.

3.6 Basic Hydrogeology

3.6.1 Introduction

Whilst the main objective of this study is to explore the controls on mineralization at Kombat mines, it is prudent to have a basic understanding and appreciation of the Kombat hydrogeology as it is a major risk to any mining activity at the mines. Mining operations at Kombat have been suspended on several occasions dating as far back as 1925 due to sudden flooding sometimes with loss of life. The most serious flooding to date occurred in 1988 where the mine was lost within 48 hours with the unfortunate loss of life to some mine workers. In December 2007, the mine was flooded following two successive one hour power outages culminating in the suspension of mining operations until a reviewed water management strategy is worked out.

The Otavi Mountainland area is also known as the Karst area due to the abundance of carbonate rocks associated with characteristic karst features. The carbonate rocks host a ground water resource of good quality and national interest. The large potential of the Karst aquifers can be explained by the comparatively high rainfall (+/-600mm), lack of a thick soil

cover facilitating rapid infiltration of rainfall and high permeability of the dolomite and limestone which is a result of intense fracturing and chemical weathering.

3.6.2 Hydrogeological Factors

The dolostones at Kombat mine lack primary permeability or porosity but the ground water flows along joints, fractures, faults and contact zones (SRK, 1992). With no inflow from regions outside the Otavi Mountainland, all groundwater is autochthonous, i.e. directly recharged from rainfall in the area. The transmissivity of the heterogeneous rocks may vary between 10 to several 100 m²/day and reach more than 1000 m²/day locally (Labuschagne & Johnstone, 2007). The low permeable phyllites and sandstones of the Kombat Formation constitute the fractured Mulden Group Aquitard (MGA) with transmissivity values of 3m²/day (Labuschagne & Johnstone, 2007). From the top down, the Otavi Dolomite Aquifer (ODA) is composed of the fractured to karstified dolomite aquifer of Hüttenberg Formation, while the thin bedded limestone and shale of the lower Maieberg Formations act as an Aquitard.

The rainfall figures show that Kombat mine receives ~600mm per year, with a catchment area of ~600km² and a recharge rate of 17%, there is an average of 62 x 10⁶m³/year. The department of water affairs estimates that the sphere of influence of groundwater is 120km² (Labuschagne & Johnstone, 2007). The majority of the ground water and storage in the area appears to be confined to the NE-SW trending faults (discussed in detail in Chapter 4) with small amounts of storage associated with fractures and contact with the Phyllite. The following faults; Kombat West, W270, W270-1, and W550 (Fig. 4.3b) have resulted in hydrogeological problems and delays in development, grouting cost, high pressure water in faults and high water storage in faults. Phyllites of the Kombat Formation are considered to

be relatively impervious and may behave as a barrier to southward flow of the ground water from the dolomite hills to the north of Kombat. Large faults like the Kombat West faults may also behave as barriers to the flow in a southeast direction and pathways for flow in a southwest direction. Generally, the water flows from north towards the south.

Analysis of the available data and information at Kombat suggests that;

- Limited water ingress occurs on the higher mining levels closer to surface (from surface up to 4 level which is approximately 100m below surface). This is also the elevation of the regional piezometric heads extends to. The main sources of water towards these shallow levels seem to be from surface infrastructure like overflows from dams, seepages from the earth trenches.
- The more significant water strikes along the fault systems occurred from 8 level and below and seem to increase in severity with depth.
- Before commencing production/development in a new area extensive exploratory drilling is undertaken from surface and from underground by vertically and horizontally drilled pilot holes respectively in front of an advancing face. The purpose of these holes is dual, firstly the holes are drilled to assist in planning the development and secondly the boreholes identify faults, fractures and major water intersections for grouting.

- Water intercepted by the major fault zones seems to have a reddish/brown colour with sediment fines. This suggests that flow along the major fault zones is associated with weathering.
- Figure 6.1 shows some water strikes, experienced during diamond drilling underground. It can be seen that all occurred during intersection with the W270-3F fault zone. Whilst it is an intersection on one level, it gives a good understanding of the order and scale of water strikes. Such quantities of water have been recorded elsewhere on different faults.
- The main ingress (1988 Kombat Mine Flood Disaster) occurred on the 14 to 15/1 level during the intersection of mine development with the W270 fault system during blasting.
- According to historical data, after the last blast on 6 January 1997 water was intersected in the 10/1 to 9 Level Ramp when the W550 Fault zone was intersected. The initial flow was estimated at 200m³/h and increased to approximately 900m³/h after 30 hours. According to historical data (Kombat Mine Water Action Plan, 1998) pumping on 11 level was 900m³/h, 14 level 700m³/h and 18 level 500m³/h, (totalling approximately 2100m³/h).

Table 3.1: Underground diamond drilling water intersections, Kombat Mine.

BHID	Water (Gallons per Hour)	Depth (m)	Section	Fault	m³/hour
Au 12/81	10000.00	84.70	W315	W270-3F	45.4

Au 12/81	20000.00	142.60	W315	W270-3F	90.8
Au 12/122	10000.00	69.40	W315	W270-3F	45.4
Au 12/123	10000.00	73.10	W315	W270-3F	45.4
Au 12/123	15000.00	94.00	W315	W270-3F	68.1
Au 12/123	40000.00	150.60	W315	W270-3F	181.6
Au 12/117	10000.00	100.00	W345	W270-3F	45.4
Au 12/82	5000.00	107.80	W360	W270-3F	22.7
Au 12/83	10000.00	109.80	W360	W270-3F	45.4
Au12/106	50000.00	112.50	W405	W270-3F	227
Au 12/103	30000.00	70.70	W405	W270-3F	136.2
Au 12/95	5000.00	70.30	W375	W270-3F	22.4
Au 12/95	30000.00	81.20	W375	W270-3F	136.2
Total					1112.3

The recharge area of the local dolomitic aquifer zone is in the northern mountain areas. Water levels are monitored by the department of water affairs with a number of boreholes located at various points around the Kombat mining area (Labuschagne & Johnstone, 2007). The details of the measurements are beyond the scope of this study but the data is available from the Department of Water Affairs (DWA).

3.6.3 Underground water pumping

Underground water pumping at Kombat is very complicated and expensive. The power consumption at Kombat was costing around N\$1.5m per month at the time when pumping was stopped at a reported rate of 2000 cubic meters per hour. At the same time an average of 32 pumps were pumping concurrently at different levels of the mine. The pumps come in

different sizes and types. Stage pumping is employed with Pump Stations at 17/1level, 14/1level, 11/1level. Down ramps are also utilized to install pumps especially during sudden inrushes of water.

From the water pumping results over the last 24 months before the final closure of the mine pumping progress was definitely low and below expectations. A reviewed approach is required as the current Engineering Pumping design was not yielding the desired results.

3.6.4 Recommendations for dewatering

Mining under complex hydrogeological conditions may be extremely costly, influencing the overall viability of the project, and from past experience an accurate prediction of mine water inflow is necessary during the feasibility stages. The following recommendations are based on the current knowledge and understanding of the Kombat mine and also available hydrogeological data.

It can be concluded that several geohydrological/geological and mining aspects forms an important interrelationship in terms of the understanding of water flow and associated mine dewatering. The following represents the interrelationship aspects that need to be understood before a supplementary dewatering system can be developed.

- Explore zone of highest permeability and associated groundwater flow.
- Determine depth of groundwater circulation or flow cycle – if any.
- Determine fracture system, and
- Hydraulic head and gradient towards localized pumping zones

3.6.4.1 Proposed dewatering concept

It is recommended that the existing cover cementation and pump out (dewatering) system continue as is. However, a supplementary system is recommended. The main objective of the supplementary system is to relieve the recharge zone towards the mine and to break steep groundwater flow gradients towards the mine through a proactive dewatering system. The objective will be to start at the source of the groundwater flow path and to take some pressure off the receiver or the existing in mine dewatering and grouting system. Since the major inflow starts at 8 Level (1300m a.m.s.l) and increases with depth, dewatering should therefore ensure that a cone of depression is created to at least 1300mamsl (250 – 300m below ground level).

To determine the number and types of pumps for dewatering, the volume of the groundwater storage needs to be determined. When a well is pumped in a confined to semi confined aquifer, the water is obtained from the elastic or specific storage of the aquifer. The product of the specific storage and the aquifer thickness is an aquifer parameter called storativity. For a confined aquifer, it is generally small (0.005 or less) and pumpage affects a relatively large area of the aquifer. No data is currently available regarding the storage coefficient of the local aquifer system. An estimated initial pumping capacity of approximately 1000m³/hour is required; this will increase initially and continue for 1 to 5 years or until equilibrium conditions are obtained. Thereafter, the pumping capacity can be reduced to approximately 500m³/hour for the remainder of the mine life to handle aquifer recharge and to sustain the draw down.

It is also very important that water usage is included as a factor during the planning of a supplementary pumping system. The current discharge system (earth trench from the shaft

area towards the southern hills) is not ideal and needs to be upgraded to ensure the maximum re use of mining water by the local farmers or public.

Apart from the monitoring of boreholes done by the DWA, it is necessary that groundwater level monitoring is done at available exploration boreholes. The sealing of old exploration boreholes should be confirmed as they can serve as recharge zones to both the top weathered dolomite and lower environments. The recycling of water between 8 and 14 levels (under current conditions) was evident from broken pipes, dams, and overflows. Water is for instance pumped from the ramp canal on 13level to a higher level but the pipe is broken and the water flows back to its origin. Most of the pipe flows are reduced through the precipitation of Ca/Mg within the columns; this also puts unnecessary strain on the dewatering capacity.

The main Kombat Mine (Number 1 Shaft) is flooded from 3L downwards.

3.6.5 Other recommendations

- A hydrogeological model for Kombat mining area is required.
- Investigate fully the effect of inflow on pumping and how to mitigate it.
- Standby Power source (Generator).
- Increase the knowledge of grouting effectiveness, time delays due to grouting and costs.
- Assess the feasibility and contribution to the cost effectiveness of water management by shallow well dewatering.
- Assess the need for reduction of water pressure outside the grouted zones.

- Assess the hydraulic characteristics of the water bearing faults and their association with the near surface weathered aquifer.

Chapter 4

Structure

4.1 Introduction – regional perspective and historical findings

Whilst the first part of this section will look at the historical structural geological findings, most of the data requires modification for publication purposes and suitable diagrams and photos have been generated to explain these previous findings and used in this study. Hence the first part is mixed old and current data whilst the second section will be exclusively findings of this study. The main reason being that most the historical information is not of an academic nature (mostly unpublished geological plans and sections for mine production purposes) and does not satisfy the needs of this research.

The Kombat Mining Complex (KMC) in the Otavi Mountainland (OML) is located on the boundary of the stable platform, the southern edge of the Congo Craton (Northern Platform) and the northern rift of the intercontinental branch of the Damara Orogen (Fig. 2.4). The Northern Rift underwent multiple phases of subsidence and a final phase of rift subsidence in the Northern Rift resulted in the drowning of the southern parts of the Otavi Valley sub-basin and the cessation of carbonate deposition. The phyllite of the Kombat Formation was deposited over the Tsumeb Subgroup as an onlap unconformity. With the onset of the Damara Orogen, the molasse type Mulden Group was deposited syntectonically.

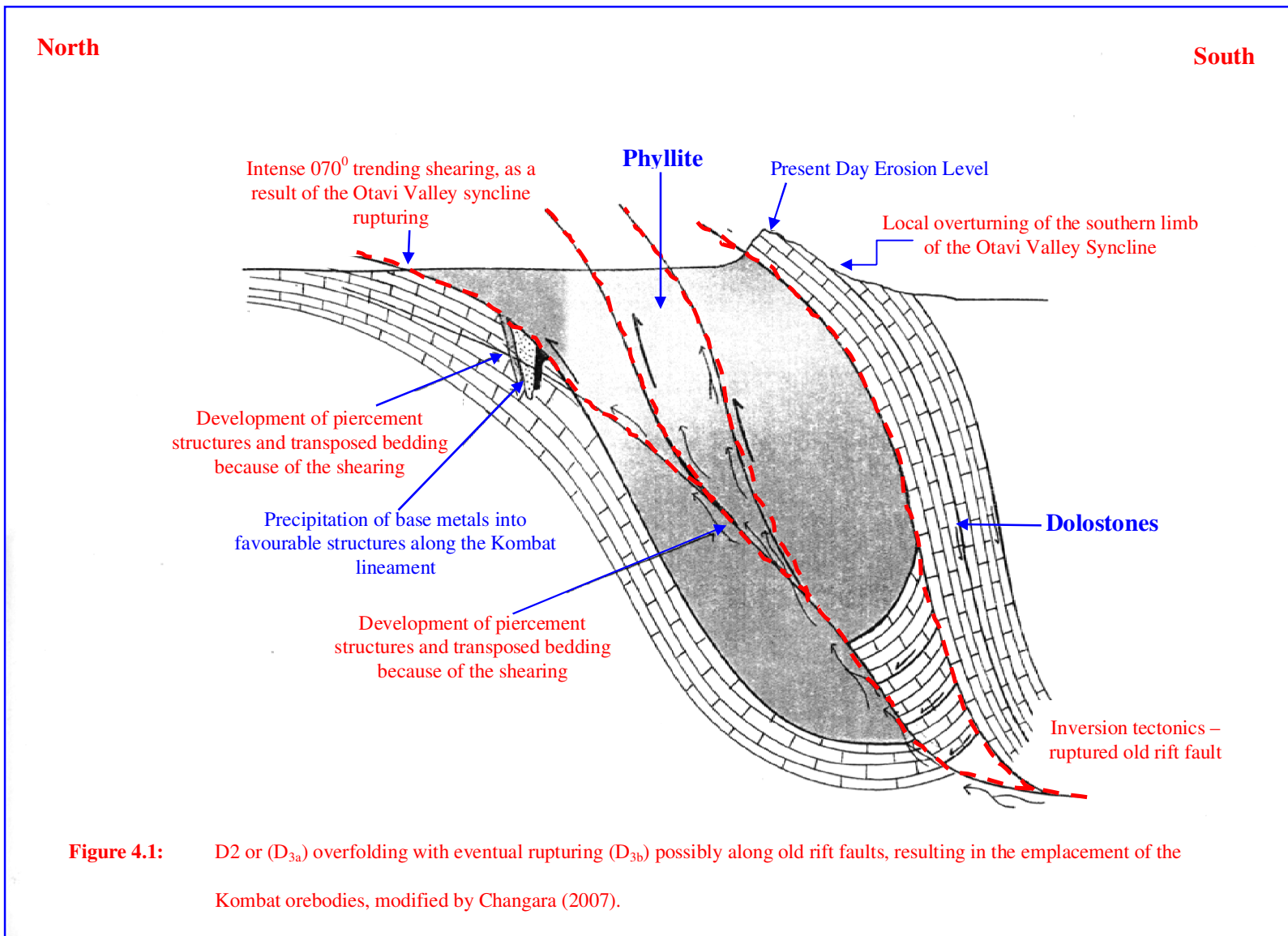
It is important to note that studies by Deane in 1993 and 1995 were more on a regional scale whilst this study focused on the mine lower levels which have been exposed through recent underground mining.

4.2 Phases of Deformation

The OML has been affected by three Damara deformational events referred in the Damara geology as D1, D2, and D3.

The effects of the D1 event (with an approximate age of 650Ma) in the OML are minimal, with only gentle north – south trending open warps evident on a large scale. It is envisaged that during the D1 event, most parts of the OML underwent a period of non deposition lasting up to 20Ma and numerous karst structures developed. The earliest Damaran – age ductile deformational structures at Kombat occur to the south of the Kombat mine where stratigraphic replication of the Tsumeb Subgroup has taken place. These are interpreted as representing the D1 event. The Asis Ost fault is also correlated to the D1 deformational phase.

The D2 event was the main phase of deformation in the Intracontinental arm during Damara Orogen. In the OML, the D2 event resulted in the development of northwestward-vergent folds and thrusts to form the Otavi Valley Syncline (Fig. 2.8). These large scale folds are east – west (120°) trending and isoclinal. The age of the D2 is approximated at 537Ma – 550Ma (Deane, 1993). The main phase of the Mulden Group sedimentation occurred during the D2 deformation when basement structures in the OML were exposed. The D2 is divided into D_{2a} and D_{2b} with D_{2a} producing the northward vergent, locally recumbent F₂ folds and the D_{2b} resulting in the rupturing of the Otavi Valley syncline along its synclinal axis. Most small scale folds at Kombat are disharmonic – style F₂ with a near vertical east – west trending axial planar cleavage (S_{2a}). Also falling under the D2 event are the D_{3a} and D_{3b} subdivisions.



The D_{3a} is recorded as an overfolding event whilst the D_{3b} involved reverse tectonics and rupturing of the Otavi Valley Syncline (Fig. 4.1) modified by Changara (2007) showing the geometrical relationships during the rupturing phase and possible mineralization.

The Otavi Valley Rupture (Fig. 3.1a) possibly explains the structural setup that could have produced the pathways for Kombat type mineralization. Pressure fringes of quartz associated with deformed pyrite define lineation (L_{2b}) on both S_1 and S_{2a} surfaces.

In areas of intense F_2 folding, chert nodules and oolites have become extremely elongated (L_{2c}) parallel to the foldaxes. The large east – west trending D_{3b} Otavi Valley Rupture probably represents inversion tectonics where an older, normal fault (such as a rift) has been reactivated to form a ramp.

The D_3 event resulted in the formation of the northwest-trending open, upright warps and an age of 450 Ma - 457Ma is suggested (Deane, 1995). The Otavi Valley syncline is a doubly plunging and canoe shaped.

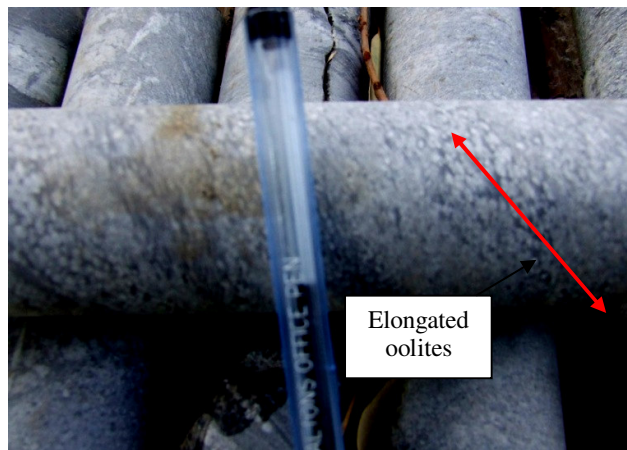


Figure 4.2a: Elongated Oolites in areas of extreme folding (F_2), the oolitic dolostone zones normally occur close to or within zones of mineralization.

4.2.1 Folding

Folding within the Otavi Valley synclinorium occurs at both regional and local scales. Figure 4.2b shows a specimen of folded altered dolostone with carbonate material markers. Geological mapping of the Otavi valley indicates that folding of the Otavi Group preceded deposition of the Mulden Group in which the Kombat Formation is tentatively placed. The earliest macroscopically recognizable folding is an isoclinal phase (F_1) with an east trending axial plane cleavage (S_1) developed in the phyllite of the Kombat Formation. In outcrop, S_1 is seen to be folded in a near coaxial, concentric style by a second phase (F_2) which locally produced north verging recumbent folds on the southern flank of the synclinorium and was responsible for several inliers of the Otavi Group dolostone within the outcrop area of the Kombat Formation. Mesoscopically, the S_1 surface into which the original sulphide and colour lamination (S_0) has been transposed is superposed by the surface S_2 , a crenulation cleavage, into which the sulphides are mobilized. Pyrite metacrysts occur in S_2 and pressure fringes of quartz associated with sulphides define lineations in the S_1 and S_2 surfaces. A late fracture cleavage S_3 , which is non-penetrative in phyllite on the mesoscopic scale, is axial planar to minor chevron style folds (F_3) and kink bands.

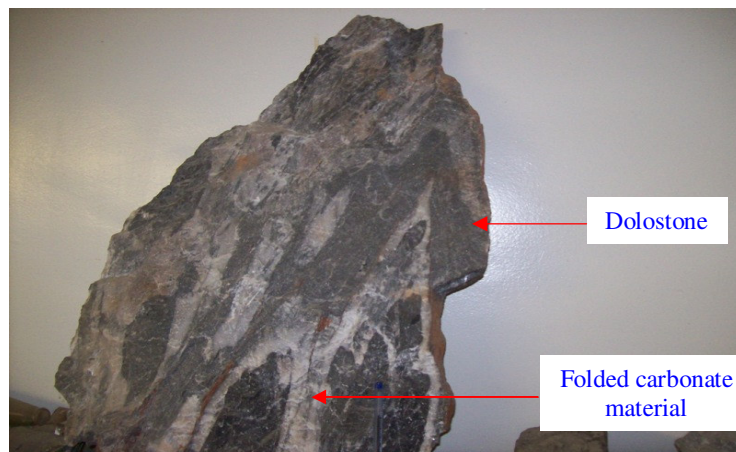


Figure 4.2b: Folding at Kombat Mine, unidentified locality but it demonstrates the folding at Kombat. Folds are rarely seen in outcrop at Kombat but rather from interpretation of structural data.

The F_3 structures could be related to the north – east trending dip and strike slip faults. Within the dolostone of the Hüttenberg Formation, mesoscopic folds are seldom observed and their temporal relationships are unclear due to lack of exposure. The most frequent of these are disharmonic – style F_1 and F_2 folds with a near vertical axial plane foliation, which trends sub parallel to the strike of the contact between the dolostone and the phyllite. Underground mine workings at Kombat mine have exposed a number of small, parasitic folds associated with a large F_3 infold on the contact between the phyllite and the dolostone. The fold axes are vertical and associated with a weak crenulation lineation S_{3L} and a steep, north – east trending fracture cleavage S_3 which is developed in both the dolostone and in the marl at the contact with the phyllite. The folded foliation (S_2) of the marl contains veinlets of chalcopyrite, pyrite and pyrrhotite, which mimic transposition fabrics although the chalcopyrite occurs locally along the S_3 fracture cleaving in dolostone. Intensely foliated, steep, north east to east trending zones of deformation occur at many of the centres of mineralization in the dolostone over a strike distance of 5km along the contact with the Kombat Formation. These zones represent shear extensions of attenuated fold hinges and contain abundant veins of quartz, chert, sandstone, and dolostone and display transposition of sedimentary and mineral layering and of sulphide veinlets. In general terms folding is pronounced around the contact zone – phyllite and dolostone, which could be explained in terms of the vast competence contrast and differential stress – strain of the dolostone phyllite.

4.2.2 Major faults occurring at Kombat mines

Faulting at Kombat mines has been studied previously and the following section is an overview of these faults as they have a bearing to the discussion on controls to mineralization. Some of the findings of the previous researchers have been refined in this study incorporating new data or reinterpretation of the existing data as noted in text.

The major faults occurring within the KMC have been given various names over time but the following system is now generally accepted formalized.

4.2.2.1 Asis Ost Fault

The Asis Ost fault is the eastern most fault around the KMC located around the Asis Ost centre of mineralization (Fig. 3.1). The north-northeast trending, subvertical Asis Ost Fault has been interpreted as representing a syn-sedimentary fault as there are sedimentary/lithological changes against this fault. These changes are possibly facies changes in carbonates, that denote deepening/shallowing and represents a large basement structure that has been re activated during post Damara orogenic times, and therefore appears undeformed on plan.

4.2.2.2 Kombat West Fault (KWF)

The KWF is major structural break around the KMC (Figs. 3.1 & 4.3). Its major displacement is also accompanied and marked by major different mineralization types and styles that will be discussed in detail in Chapters 7 and 8.

Recorded displacements are oblique with ~400m in a horizontal sense and 200m vertically with the western side downthrown. Movement along the fault is constrained as right lateral and diamond drilling indicates a thin phyllite sliver adjacent to the fault on some sections due to drag of the phyllite during faulting. The KWF separates the Asis West bodies from the Kombat ore bodies (Kombat East, Kombat Central and Kombat West) and where intersected

in development the fault is up to 3m wide containing crustiform calcite. It is an extremely dangerous fault in terms of high water pressure.

4.2.2.3 Kombat West – 1 Fault (KWF1)

The KWF1 fault displaces the Orebody in E140-13 stope in a left lateral sense by 16m at an elevation of 1272.4m above mean sea level, (a.m.s.l) and 25m at elevation 1274.0m a.m.s.l; (Fig. 4.3). In section, the phyllite/dolomite contact indicates that the eastern side has been down thrown. The fault is also exposed in E80-15 South stope where it changes in character quite rapidly from large calcite crystals lined cavity to a thin 2cm calcite fault at elevation 1091.3m a.m.s.l. Whilst this fault has huge quantities of water the water is not under any significant pressure and does not cause mining related problems.

4.2.2.4 Kombat West – 1A Fault (KW1A)

KWF1A is a fault zone of all the faults between KW1 – KW faults, in places it splays off KWF1 with a right lateral movement as determined from the second order fractures emanating from the fault (Fig. 4.3). The type section is exposed within the E140-15 Stope where it occurs as a broad highly faulted oxidized zone carrying huge volumes of pressurized water and is extremely difficult to seal.

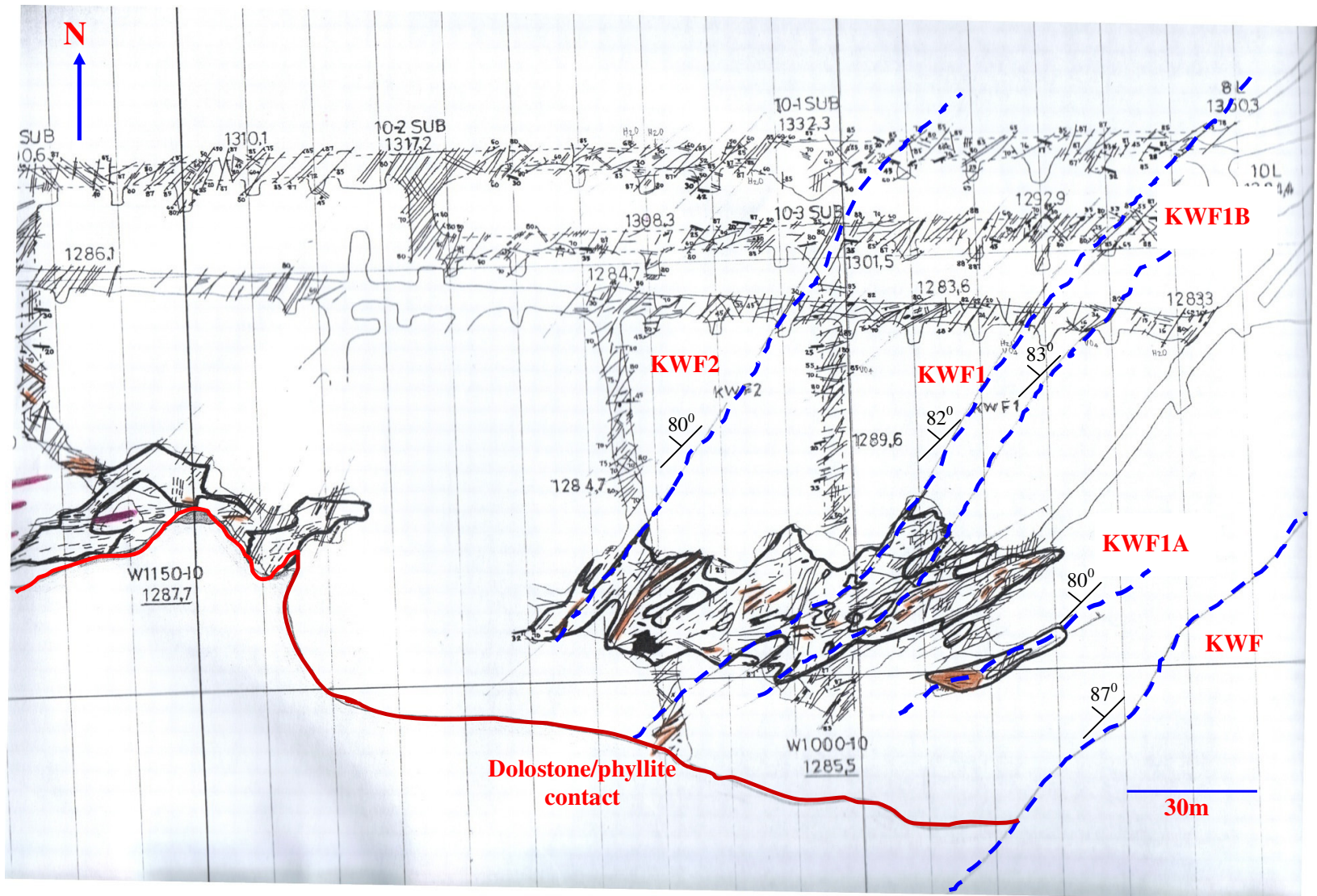
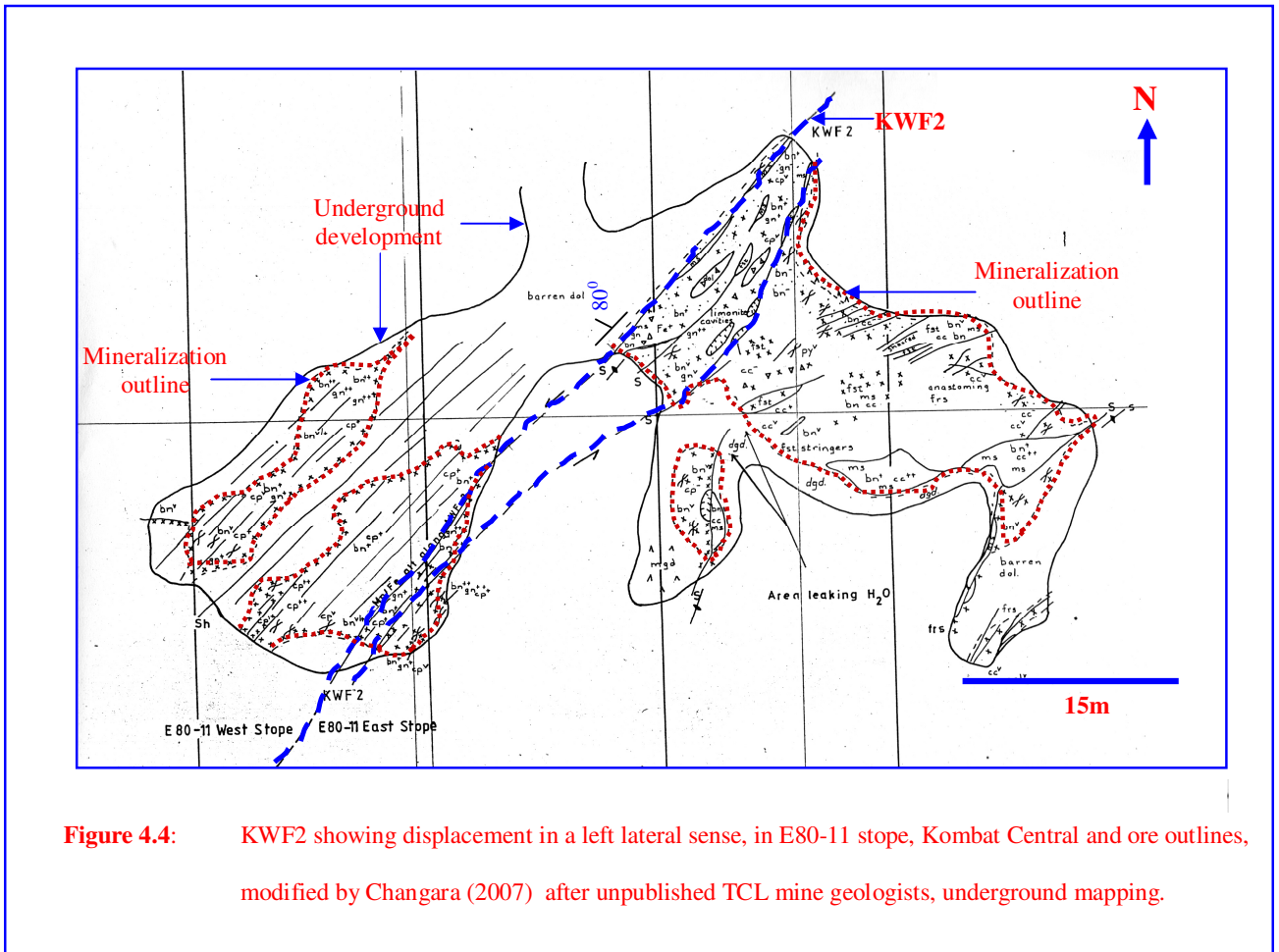


Figure 4.3: Kombat West faults showing the KWF, KWF1A, KWF1, KWA2 faults and their relationship to fracturing, mineralization and the dolostone/phyllite contact, modified by Changara (2007).

4.2.2.5 Kombat West – 2 Fault (KWF2)

It shows a left lateral displacement like in E80-13 Stope with minor displacement to the ore body. The fault occurs as a fairly broad zone, up to six meters wide in places (Figs. 4.3 & 4.4).



4.2.2.6 Kombat West 3 Fault (KWF3)

Between the KWF3 and KW is a large water bearing faulted zone; the faults in this area are defined as narrow calcite/gouge faults surrounded by intense fractured rock. It indicates a left lateral displacement with a down throw to the south.

At elevation 1261.6m a.m.s.l there is a right lateral throw of the phyllite, elsewhere the phyllite only shows a dimpling. This fault is shown in Figure 4.5 on the W210-20 stope.

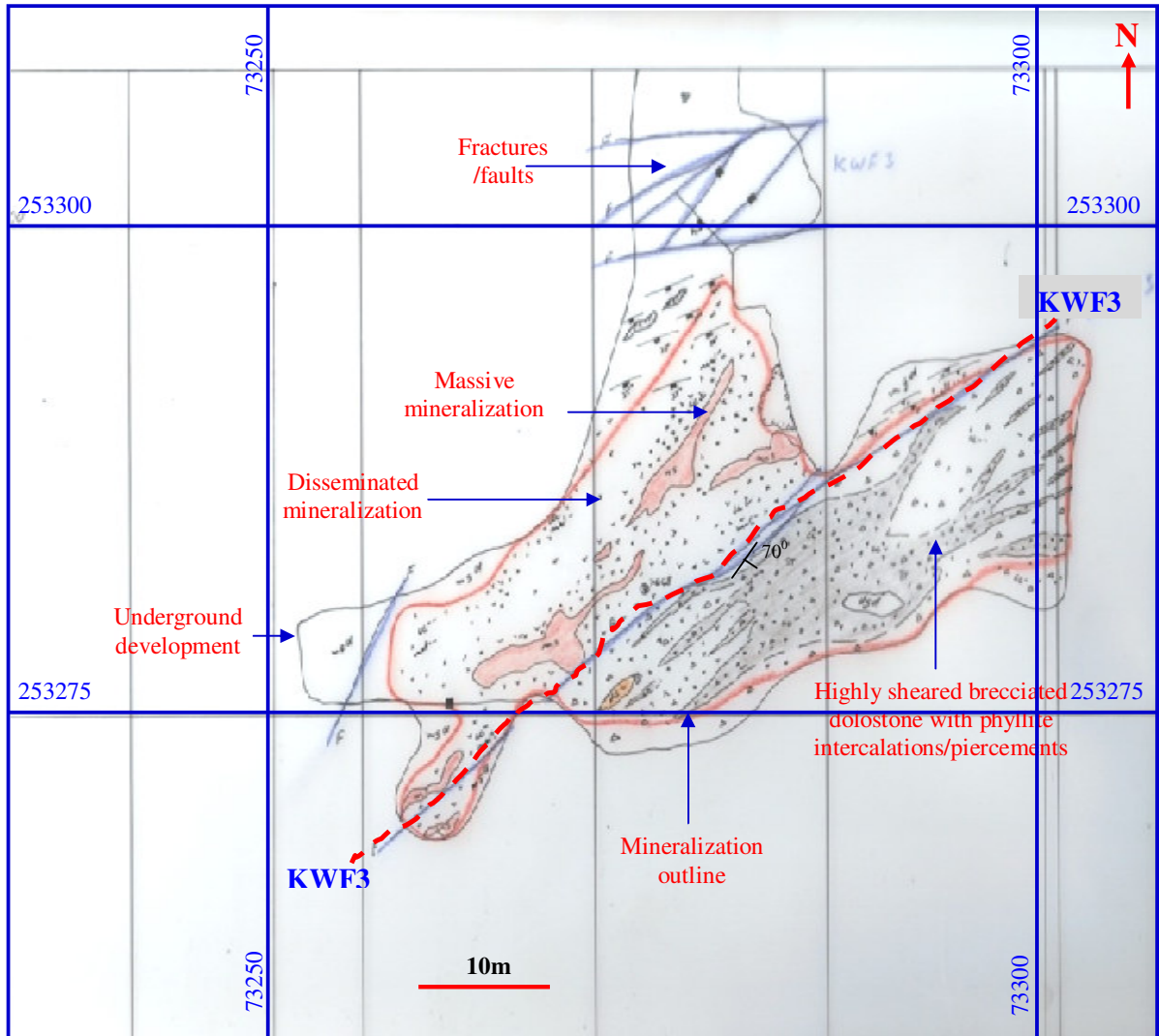


Figure 4.5: Asis West; W210-20 Stope, plan view showing mineralization relationships to lithology and faulting (~900m elevation), modified by Changara (2007).

4.2.2.7 Kombat West 3A Fault (KWF3A)

The KWF3A splays off from the KWF2 near the 15/1 Sub level but with depth becomes a separate fault. In W90-14, the fault shows right lateral movements with a down throw to the east. However the phyllite/dolomite contact shows a left lateral throw.

4.2.2.8 Kombat West – 4 Fault (KWF4)

Mapping of the W90 – 12 SW Stope at elevation 1197.7m a.m.s.l indicates a right lateral movement with no displacement of the ore bodies. On 15 level there are three dimensional sigmoidal structures indicating an oblique sense of movement. It is also a known high water pressure bearing fault which causes problems to mining and cementation. This fault is shown in Figure 3.10.

4.2.2.9 W270 Fault

The W270 Fault is extremely dangerous in terms of water causing several mining delays in sealing it in development. On surface it has a right lateral movement. Within the W210-12 Number 9 stope, at 1205.5m a.m.s.l. elevation the W270 fault has second order fractures which indicate a left lateral movement with the southern side being downthrown. The exposure on 15 level has microstructures which indicate that the southern side is up thrown accompanied by a right lateral movement. This fault is shown in Figures 3.10 and 4.6.

4.2.2.10 W270 – 1 Fault

Within the 11 Level access to W270-12 Central Stope, (Fig 4.6) the fault displays a right lateral movement with the western side up thrown. The fault generally occurs as a zone of up to 5m wide containing numerous thin calcite faults but is exposed in places as a 30cm calcite fault. It is also water bearing and splays between the W270 – 1 and the W270 faults enhances the water hazard of this fault.

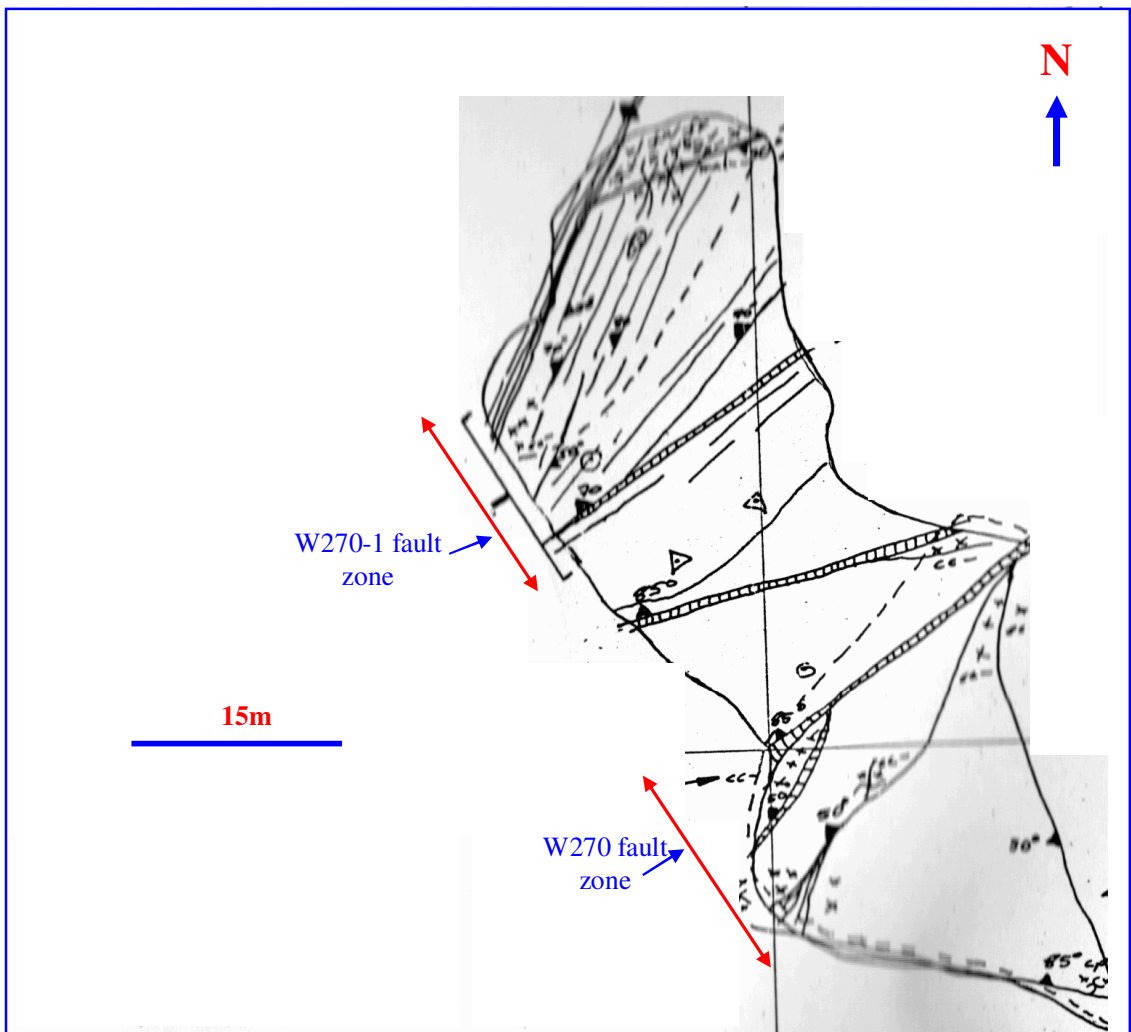


Figure 4.6 W270 and W270-1 fault zones showing the occurrence of the faults and that they normally occur as a zone with sympathetic fractures and these particular faults are associated with brecciation, modified by Changara (2007b).

4.2.2.11 W270 – 2 Fault

The W270 – 2 Fault is intimately associated with the W270-12 central stope where it cuts off mineralization at 1213.0m a.m.s.l. It has a right lateral movement as is evident from the second order fractures that are seen in the numerous maps of the W270 – 12 Central stope. The fault generally dips to the east at about 70 degrees and is a generally dry fault.

4.2.2.12 W270 – 3 Fault

The sense of movement on this fault is unclear but has a right lateral throw at the phyllite/dolostone contact on 10Level. The upper sections indicate a left lateral movement with a throw of about 20m implying a slight dimpling of the phyllite. It is a vertically oriented fault.

4.2.2.13 W270 – 4 Fault

It is a fairly tight fault and cuts off mineralization in the W270 – 10 Stope on 13 Level. It has very minor displacement to the phyllite/dolostone contact. Exploration investigative work west of this fault is worthwhile as it terminates a highly mineralized stope.

4.2.2.14 W550 Faults

Mapping by Gleeson (2000) indicates a left lateral throw at the dolostone/phyllite contact but Hartmann (1992) shows it as not displacing the dolostone/phyllite contact but displacing the T₈/T₆ and the T₆/T₅ contact by 200m in a right lateral horizontal sense. The T₅/T₄ throw appears to be about 300m.

The W550 fault zone is characterized by high water pressure water and major mining problems have been associated with this faulting. Stopes occurring around this fault zone are normally characterized by native copper, secondary mineralization and a marked increase in

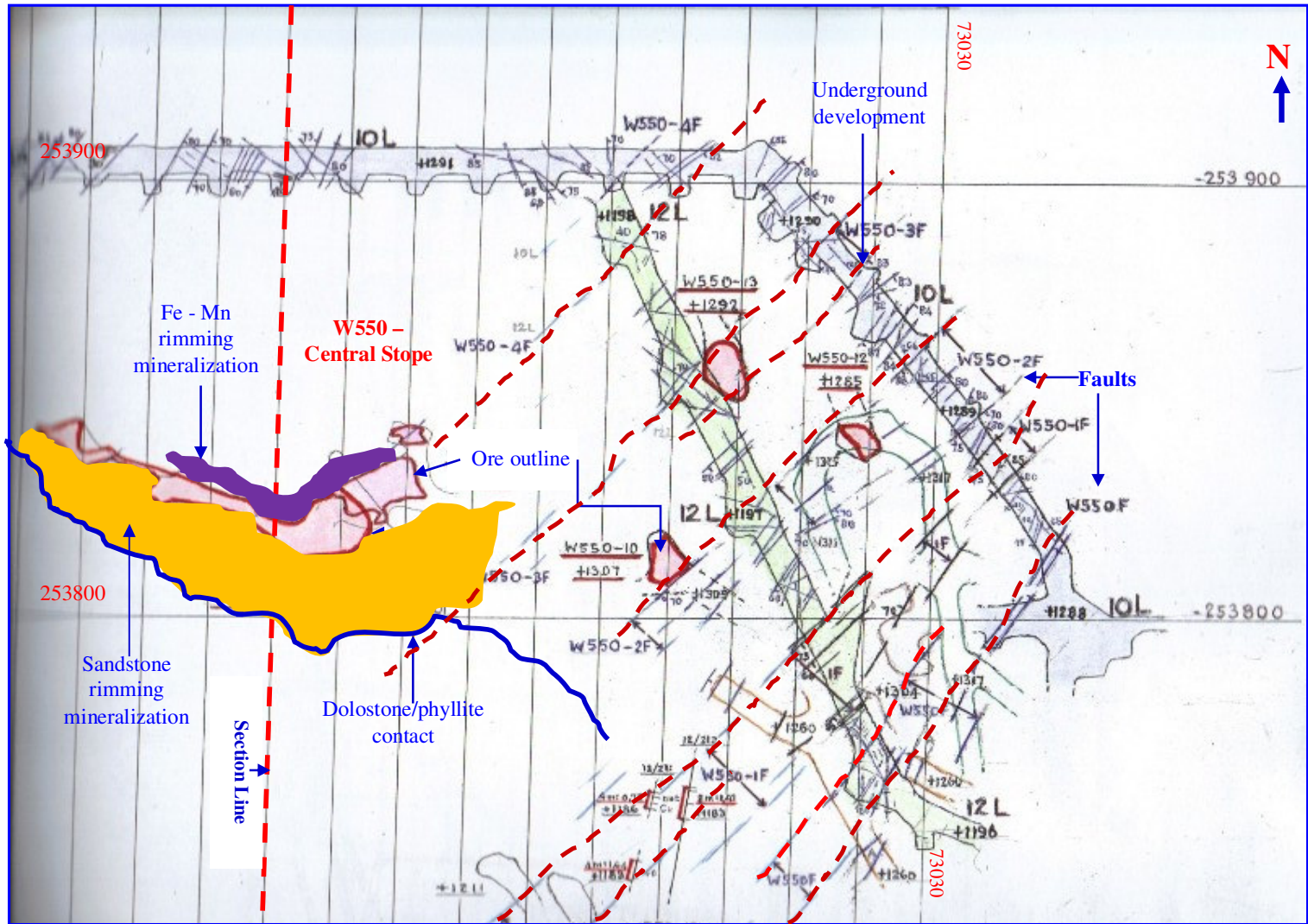


Figure 4.7: Asis West; W550 Area geological plan showing mineralization, structural and lithological patterns, and the orientation of the W550 faults series modified after Lombaard (2008) by Changara (2007).

oxidation. The W550 faulting is shown in Figure 4.7 modified after investigation carried out by Lombaard (2008).

With development only on one main level underground and limited diamond drilling not much detail has been gathered as far as displacement for the Asis Far West faults is concerned.

4.2.3 19-20 levels structural investigation by Mapani and Kamona (2002)

Mapani and Kamona (2002) conducted a structural analysis on 19/1 sublevel, 19/1 to 20/1 ramp and the 20/1 sublevel of the Asis West orebody underground. Their findings are summarized below;

4.2.3.1 The 19/1 Sublevel

Three fault populations are identified on this level;

- Low angle thrusts which are essentially thrusts are dipping at 12° to 15° to between 200° and 240° .
- Moderately dipping faults at 35° – 45° , towards 225° and 180° .
- Steeply dipping faults at 70° – 80° towards 220° and 180° .

The geometrical arrangements of the faults have led to the development of wedges in different configurations. The results of the analyses are shown in Figures 4.8a and 4.8b stereographic projection perspectives (as poles and great circles).

4.2.3.2 The 20/1 Level

This level is characterized by thrust migration as the dolomitic rock becomes brecciated in certain zones. The orientation of the faults is shown in figures 4.9a and 4.9b as poles and great circles respectively.

From this analysis, the paleo-stress orientation for the three zones that are mapped is σ_1 dips towards 11° towards 225° , σ_2 dips at 12° towards 135° and σ_3 dips at 79° towards 045° . It was also observed that the faults have had multiple movements, and both reverse and normal faults were observed. Banding in the dolostones which is defined by alternating dark and light grey, brecciated with new white calcite and recrystallized bands is also observed in all the area and its orientation is shown as great circles, Figure 4.10.

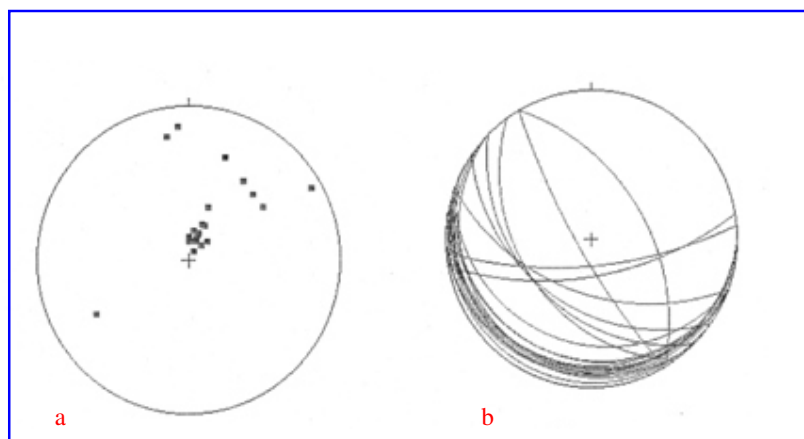
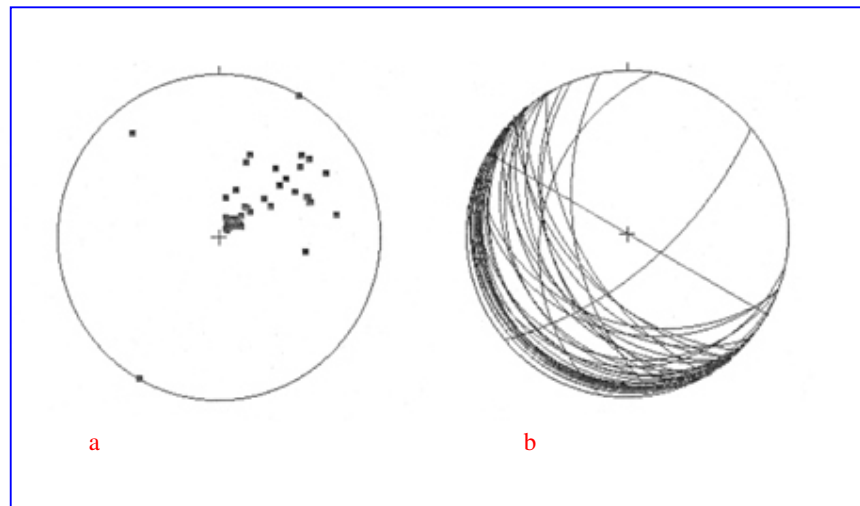


Figure 4.8: Plot of faults as poles (a) and great circles (b) on the 19/1 sublevel, Kombat mine (Mapani & Kamona, 2002).



Figures 4.9a and b: Kombat 20/1 sublevel plot of faults as poles and great circles. Notice the small wedges that pose a serious threat to rock falls, Kombat mine (Mapani & Kamona, 2002).

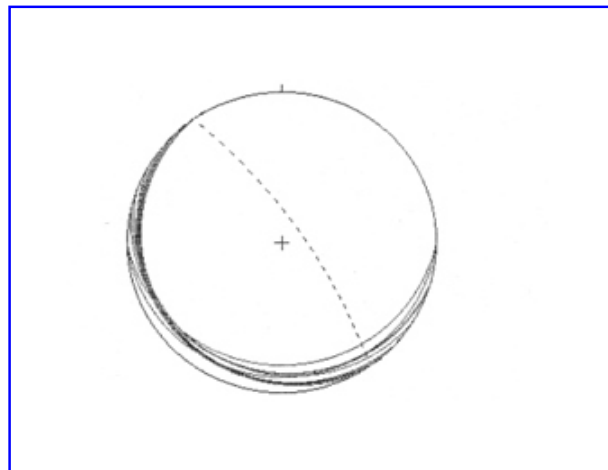


Figure 4.10: Plot of banding in the dolomite succession at Kombat. This is observed to be in more or less the same direction as the fault systems, Kombat mine (Mapani & Kamona, 2002).

4.3 Kombat Mining Complex Structural analyses – findings of this study

4.3.1 Introduction

Structural elements are observed at various scales and geometries around the KMC and an overview of these structural elements is presented below. The relationships and interrelationships of the structural trends at KMC will be reviewed in Chapter 7 and 8 (Mineralization and Discussion respectively). Both brittle and ductile response to deformation has occurred within the KMC.

4.3.2 Faulting

Figures 4.11a, 4.11b and 4.11c show the location of the main faults studied at the Kombat mines from Asis Ost to Asis Far West orebodies. Except for the Asis Far West faults, the Asis Ost and Asis West orebodies faults generally trend northeast – southwest and are generally steeply dipping. The structural data of these and other associated faults is shown in Table 4.1. Individual faults tend to differ in character from place to place. A fault may consist of 0.5m of layered sparry calcite in places, usually with a thin fracture at the centre, surrounded by a broad fractured zone either side of the main fault. Elsewhere this same fault may be barely recognizable as it is composed of several thin slightly MnO₂ stained fractures with minor secondary mineralization. It is apparent that the structure observed within a fault records the final movement event albeit other earlier movements that could have occurred. The major concern is whether and to what extent these structures influence and control the orebodies. If the orebodies are substantially displaced, then the complexity of interpretation increases, forecasting made nearly impossible and extraction becomes more costly.

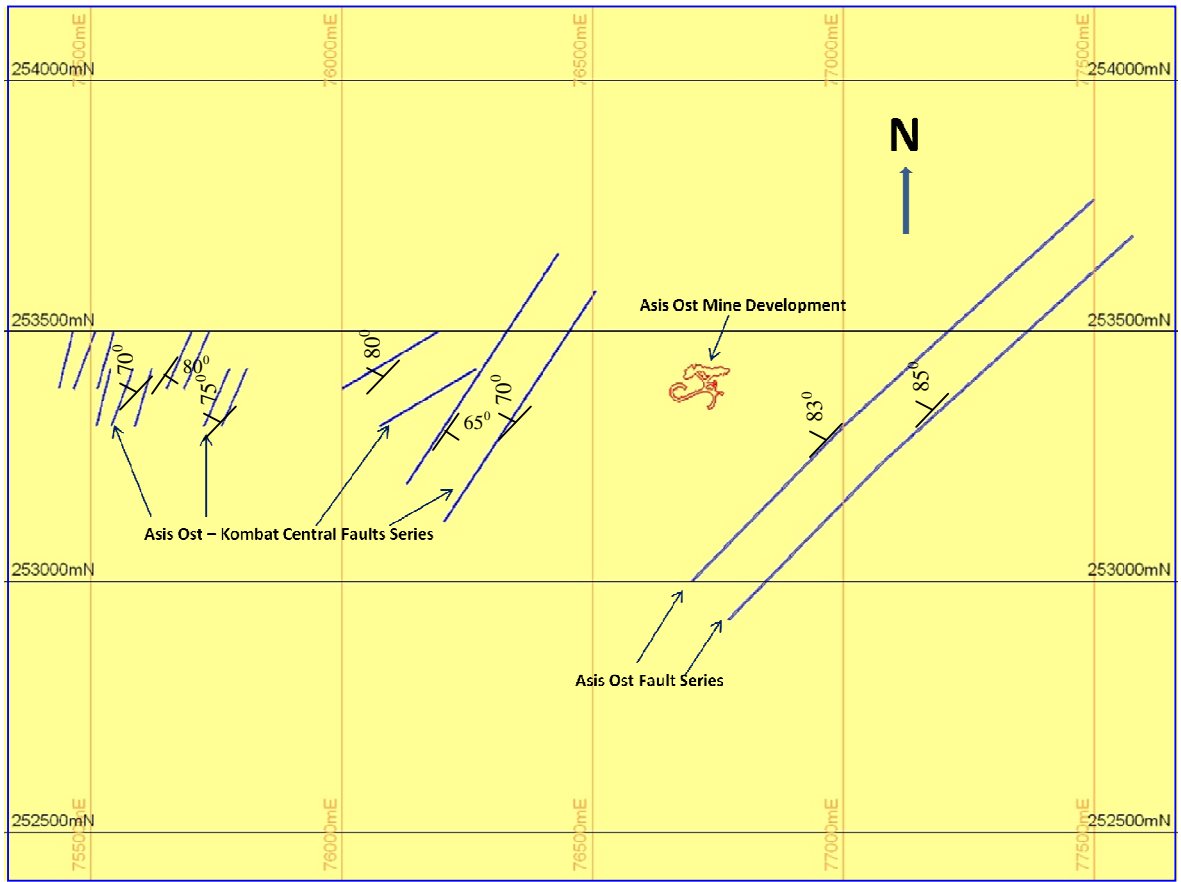


Figure 4.11a: Asis Ost – Kombat Central Faults, surface projections, underground geological and structural plans show the detailed faulting and associated joints (Changara, 2007b).

The W750 fault zone is exposed on 12level and is generally composed of narrow faults with a right lateral sense of movement but the throw is very slight. The faults are generally dry and no problems have been encountered on mining across it. Splays also occur from the main fault. The W750 faulting is shown in Figures 3.3.

Faulting propagates all the way to Asis Far West (Figs 3.1 and 4.11c). At Asis Far West, faulting data has been generated from diamond drilling (surface and underground), underground cementation cover drilling and underground mapping on 19 level (900m a.m.s.l). Two dominant fault strike directions are preserved viz; 055° and 070° .

Another fault set trends 120° but its development is minor. En echelon quartz – carbonate veins are also preserved. Very minor displacement is apparent throughout the faults sets at Asis Far West mine. The Asis Far West faults are generally steeply dipping (with dips generally more than 70° in various orientations as shown in Figure 4.11c).

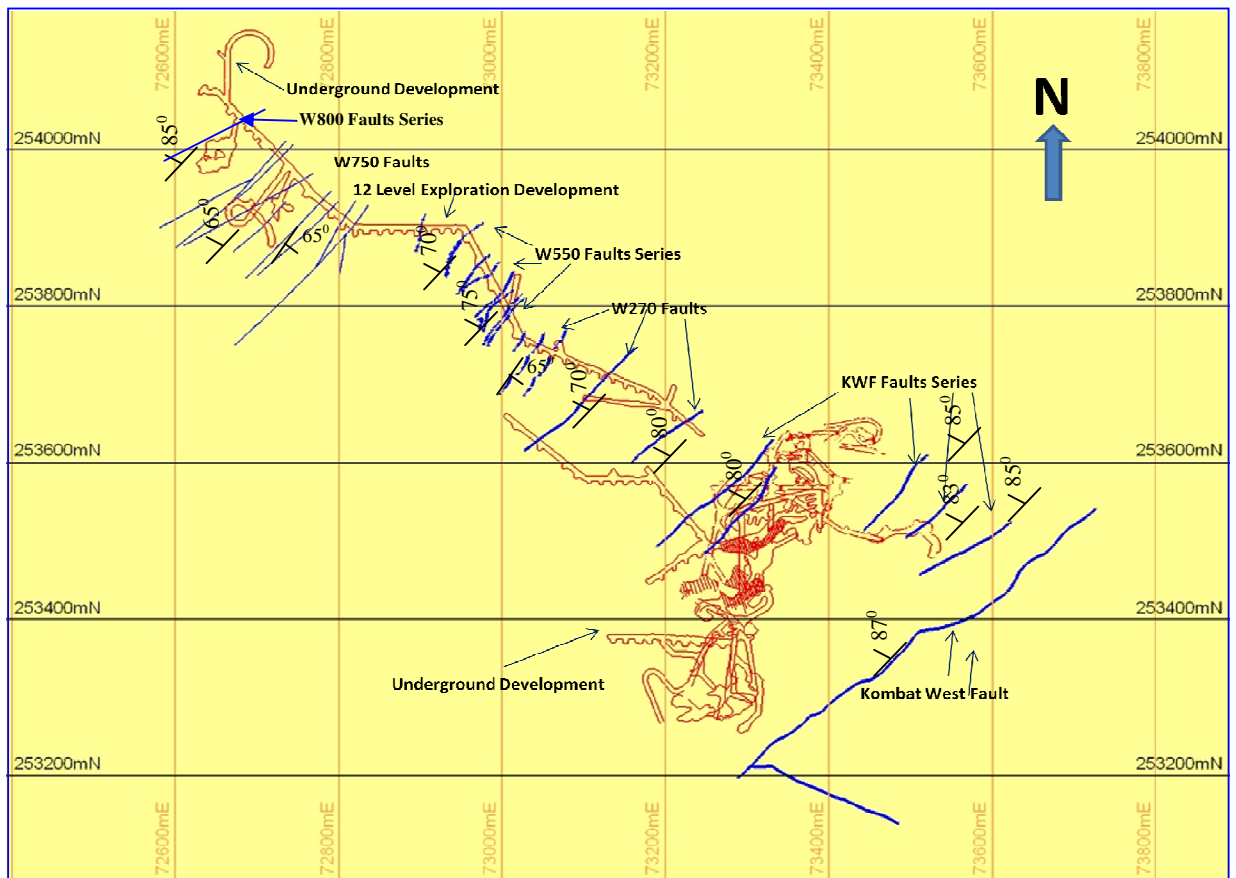


Figure 4.11b: Asis West Faults, projected to 12Level Underground Development, these are the **major** faults in the area but mapping as discussed in chapter 8 shows detailed fracturing and as source data for Table 4.1, after Changara, (2007b).

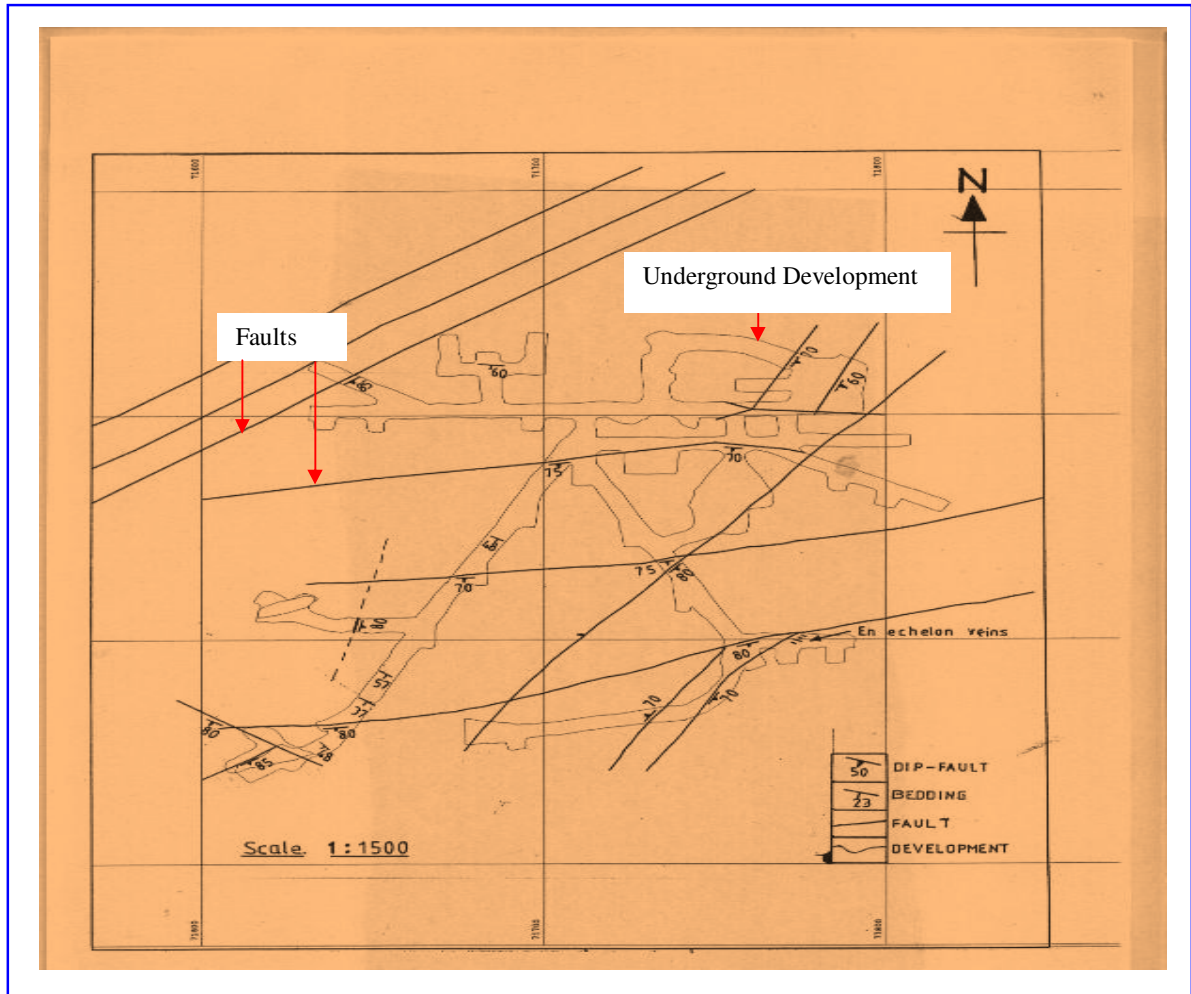


Figure 4.11c: Faulting at Asis Far West Mine, Underground perspective, projected to 19 Level (~900m a.m.s.l.), showing three main directions of faulting/fracturing (Changara, 2007b).

Table 4.1: Kombat Mining Complex, Faulting Structural Data, used to generate stereoplots.

Fault ID	Strike ($^{\circ}$)	Dip ($^{\circ}$)	Dip Direction	Comments
AOF	048	85	NW	Surface
AO1	039	80	NW	Surface
AO2	038	85	NW	Surface
AO3	033	82	NW	Surface
KWF	048	87	NW	Underground
KWF1	051	82	NW	Underground
KWF1A	053	80	NW	Underground
KWF1B	060	83	NW	Underground

KWF2	055	80	NW	Underground
KWF3	030	82	NW	Underground
KWF3A	045	70	SE	Underground
KWF4	030	70	NW	Underground
W270	050	85	NW	13Level, AW
W270-1	035	70	NW	13Level, AW
W270-2	055	70	SE	13Level AW
W270-3	044	70	E	13Level, AW
W270-4	030	70	E	13Level, AW
W270-5	130	20	SW	13Level, AW
W550	050	70	NW	10 Level, AW
W550-1	040	75	NW	10 Level, AW
W550-2	053	70	NW	10 Level, AW
W550-3	045	70	NW	10 Level, AW
W550-4	044	73	NW	12 Level, AW
W750A	033	72	NW	12 Level, AW
W750B	034	65	SE	12 Level, AW
W750C	035	75	NW	12 Level, AW
W750-1	045	70	SE	12 Level, AW
W750-1B	043	70	SE	12 Level, AW
W750-2	060	65	SE	12 Level, AW
W750-3	059	70	SE	12 Level, AW
W750-4	030	70	SE	12 Level, AW
W750-5	355	70	W	12 Level, AW
W800-1	042	85	NW	12 Level, AW
W800-2	337	70	NE	12 Level, AW
AFW1	055	80	SE	19 Level, AFW
AFW3	055	70	SE	19 Level, AFW
AFW4	055	80	SE	19 Level, AFW
AFW5	070	80	SE	19 Level, AFW

AFW6	070	70	SE	19 Level, AFW
AFW7	070	85	SE	19 Level, AFW
AFW8	070	80	SE	19 Level, AFW
AFW9	055	85	SE	19 Level, AFW
AFW10	120	70	SE	19 Level, AFW
AFW11	120	80	SE	19 Level, AFW
AFW12	030	65	SE	19 Level, AFW
AFW13	090	80	S	19 Level, AFW
MF1	120	70	NE	19 Level, AFW
MF2	060	85	SE	19 Level, AFW
MF3	055	70	SE	8L, AW
MF4	077	65	S	8L, AW
MF5	078	70	NW	W800, AW
MF6	074	65	NW	W800, AW
MF7	082	35	NW	W800, AW
MF8	085	70	S	W800, AW
MF9	018	80	E	W800, AW
MF10	025	80	W	W800, AW
MF11	045	80	SE	13L, AW
MF12	050	75	NW	3L, KE
MF13	077	15	SSE	3L, KE
MF14	078	15	SSE	3L, KE
MF15	038	80	NW	3L, KE
MF16	048	70	SE	3L, KE
MF17	015	70	W	8L, AW
MF18	049	80	NW	8L, AW
MF19	070	85	SE	8L, AW
MF20	040	70	SE	8L, AW
MF21	040	70	SE	8L, AW
E900-1	005	85	W	Surface

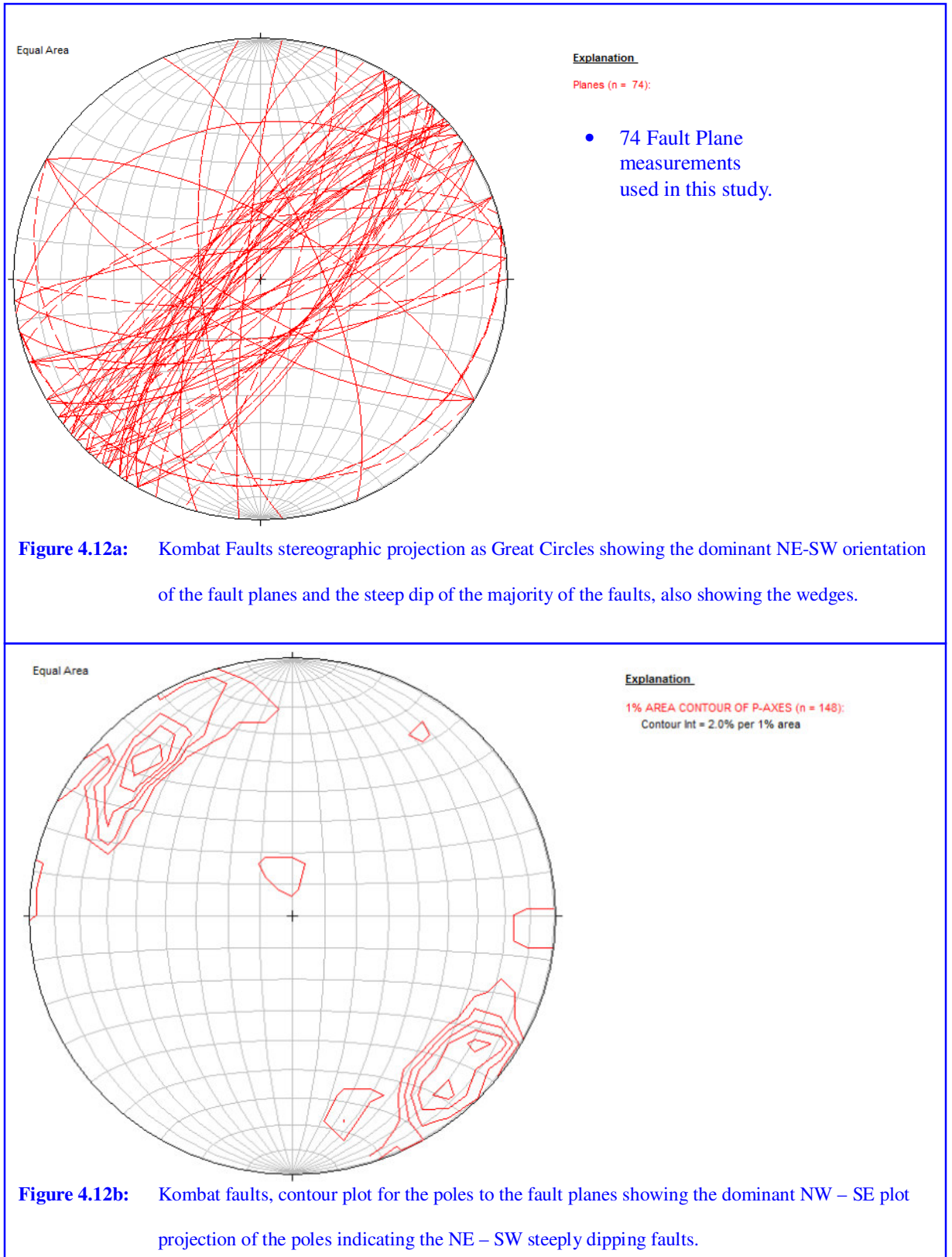
E900-2	005	85	W	Surface
STATION F	085	80	W	Surface
NS3BF	035	90	NE	Surface

The Kombat faulting data in Table 4.1 has been reduced to plots of great circles, poles contours, poles and cylindrical best fit and conical best fit with northern and southern hemisphere projections as shown in Figures 4.12a, 4.12b, 4.12c and 4.12d respectively. Figure 4.12a shows the dominant NE-SW orientation of the fault planes associated with a steep dip. A subtle NW-SE orientation of steeply dipping fracture planes is also shown in the diagram and this geometry is also displayed in Figure 4.12b as poles to the fault planes.

4.3.2.1 Bedding parallel and low angle faults

Apart from the generally occurring northeast – southwest trending faults; numerous low angle thrust faults normally parallel to sub parallel to bedding are found in numerous places around the mine. The faults generally occur as a zone of about 0.5m wide with few individual faults 10cm thick with a talcose gouge with calcite tension gash veins within the fault and the entire fault zone. The gouge is foliated and indicates a normal sense of movement but the foliation has been produced by dragging. They have been found outcropping at 18/1 sublevel, 17/1 sub level. On 17/1 sublevel horst and graben structures occur perpendicular to the thrusts and have had a scissor movement (rotational) evidenced by the differential displacement of the thrust on either side of the development. Due to the compressional tectonics forming the thrusts, they are tight and contain no water and are not a hazard to mining activities as far as water is concerned. The relationship between the thrusts and mineralization is not clear but is probably related to the deformation event that produced the Otavi valley rupture. Accesses, drives and developments on 19/1 Sublevel, 19 Level, 20/1 Sublevel and 20 Level shows a

previously unknown structural environment which is characterised by essentially two sets of prominent faults.



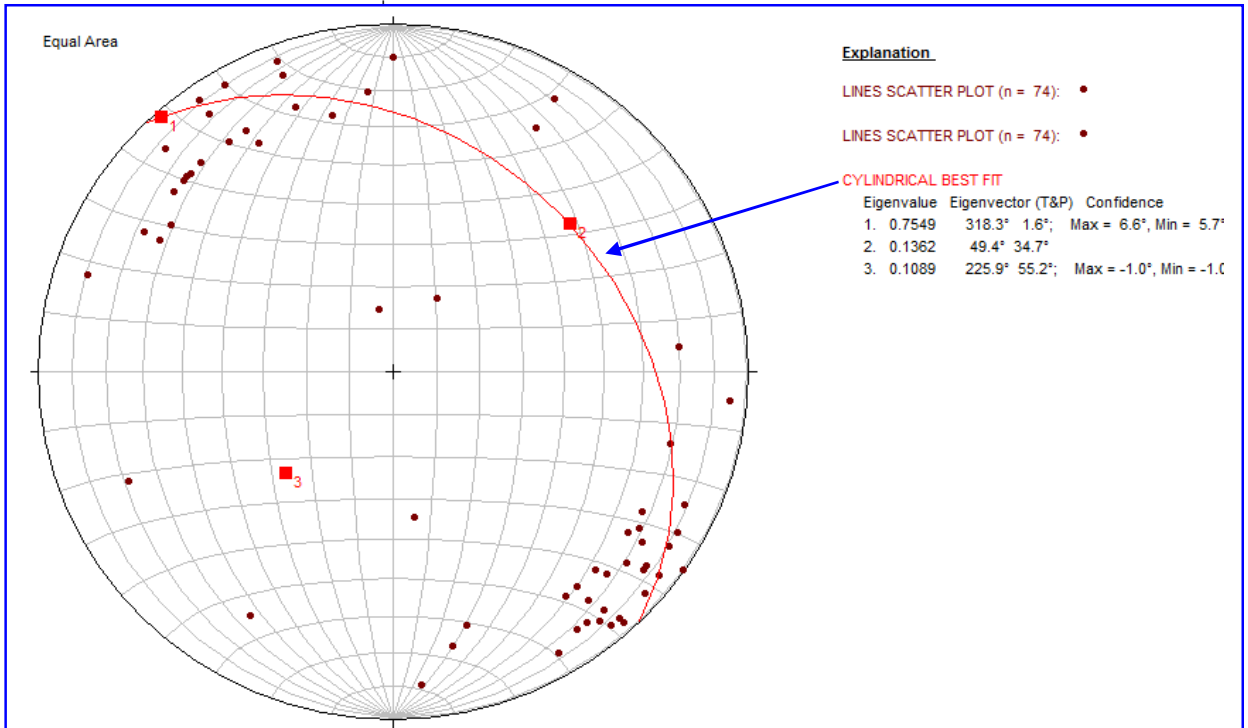


Figure 4.12c: Kombat faults poles to the fault planes with a cylindrical best fit projection as a great circle and the associated Eigenvalues and Eigenvectors.

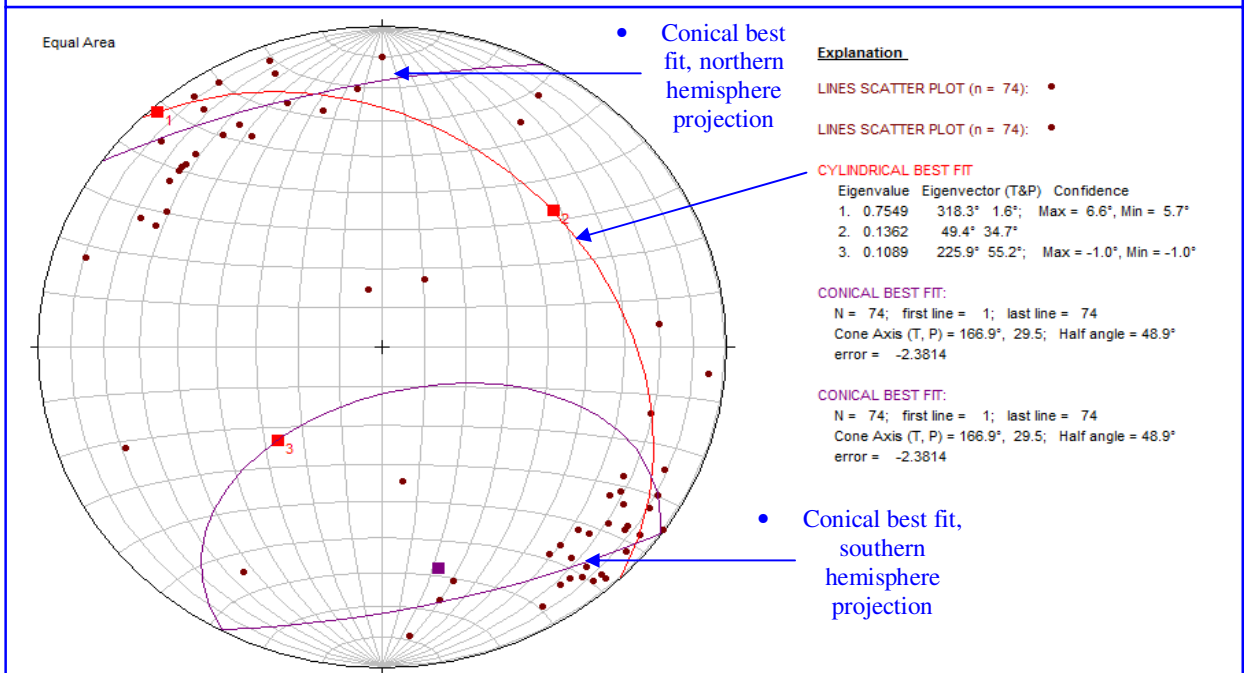


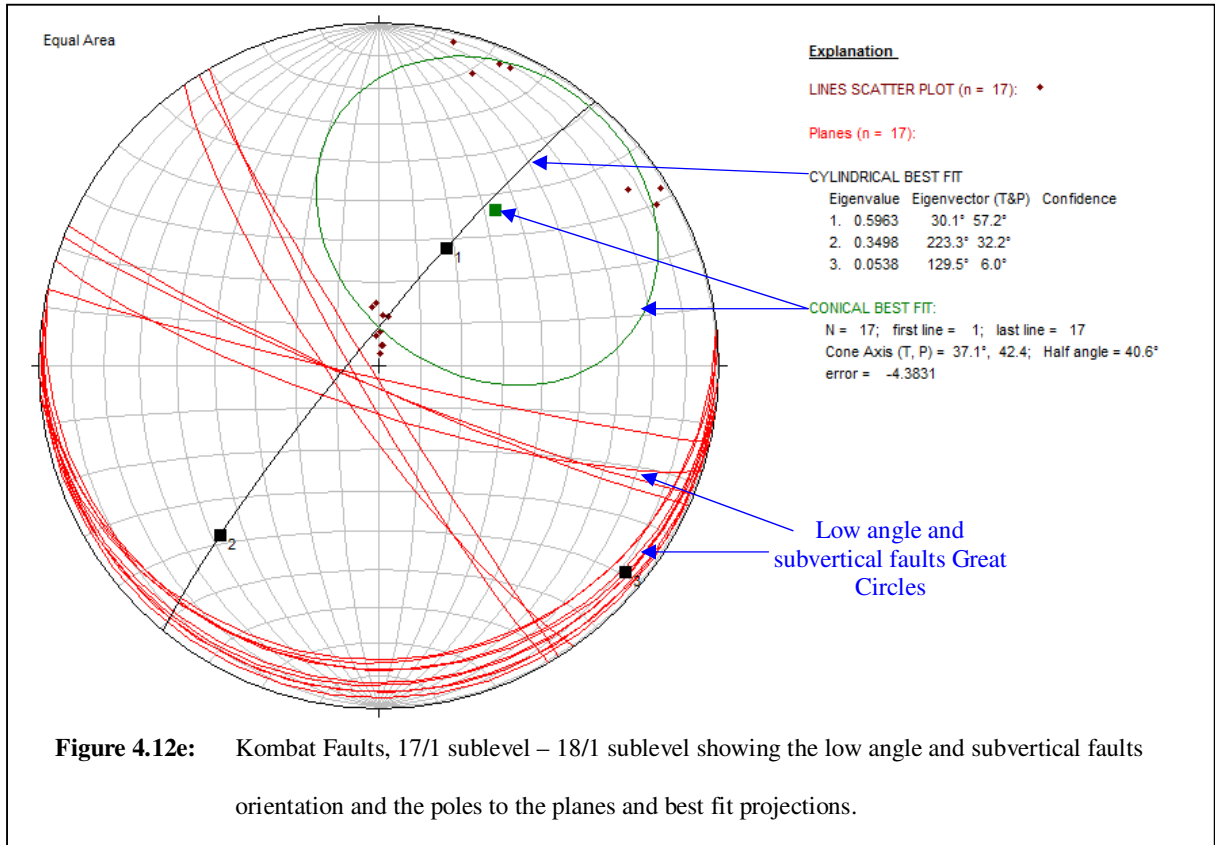
Figure 4.12d: Kombat faults, poles to the fault planes, associated cylindrical best fit, with the conical best fit as northern hemisphere and southern hemisphere projections.

These are low-angle faults dipping at 5°-15° southwards, and sub-vertical faults showing a dip of 15° off the vertical. Both fault sets shows varying amounts of relative displacement.

Figure 4.12e displays the stereographic projection of this structural data.

Table 4.2: 17/1 and 18/1 structural data, only low angle faults and the subvertical faults excluding the dominant NE trending faults.

Fault ID	Strike (°)	Dip (°)	Dip Direction	Comments
MF1a	283	05	S	17/1-18/1 underground
MF2a	98	03	S	17/1-18/1 underground
MF3a	268	15	S	17/1-18/1 underground
MF4a	274	12	S	17/1-18/1 underground
MF5a	273	8	S	17/1-18/1 underground
MF6a	101	12	S	17/1-18/1 underground
MF7a	277	5	S	17/1-18/1 underground
MF8a	265	7	S	17/1-18/1 underground
MF9a	264	14	S	17/1-18/1 underground
MF10a	148	88	SW	17/1-18/1 underground
MF11a	294	85	SW	17/1-18/1 underground
MF12a	288	79	SW	17/1-18/1 underground
MF13a	283	87	SW	17/1-18/1 underground
MF14a	150	84	SW	17/1-18/1 underground
MF15a	145	79	SW	17/1-18/1 underground



The low-angle faults in general have a dip of 5° - 15° southwards striking more or less east – west, figure 4.16. These are the most prominent fault zones with well developed mylonitic shear zones. There seems to be two generations of these faults, which can be differentiated on the basis of :

- 1 varying concentrations of sulphides (chalcopyrite, pyrite), ranging from high to zero;
- 2 varying amounts (and direction?) of relative movement;
- 3 varying fault plane geometries in that some have smooth mylonite/host-rock contacts, while others display an irregular mylonite/host rock contacts quite similar to compaction (sole) structures.

The extent of relative displacement on these faults is very difficult to establish, owing to the lack of internal structure (bedding, etc) of the host dolomite.

4.3.2.2 Sub-Vertical Faults

The sub-vertical faults (Fig. 4.13) in general cut and displace the low-angle faults indicating a more recent event. The relative movements are more easily observed because of the displacement of the low-angle faults. Observed relative movements range from a few millimetres to more than two metres. These sub-vertical faults seems to belong again to at least two generations, again of different ages, distinguished at least on the basis of ;

- varying amounts of displacement, but in opposite directions.

One of these fault sets can be explained in terms of the formation and internal structure of the Otavi Synclinorium, while the other does not seem to fit a rational explanation.

4.3.3 Folding identified in this study

Folding at Kombat mines is not easily identifiable on outcrops but rather through interpretation. Folding had been identified to be associated with the dolostone/phyllite contact but this would supposedly be ascribed to competence contrasts of the lithologies. Figure 4.14 shows folded dolostone/phyllite contact for the Asis West orebody whilst 4.15 shows bedded sedimentary breccias close to the 4L E600 Stope (Kombat East mine).

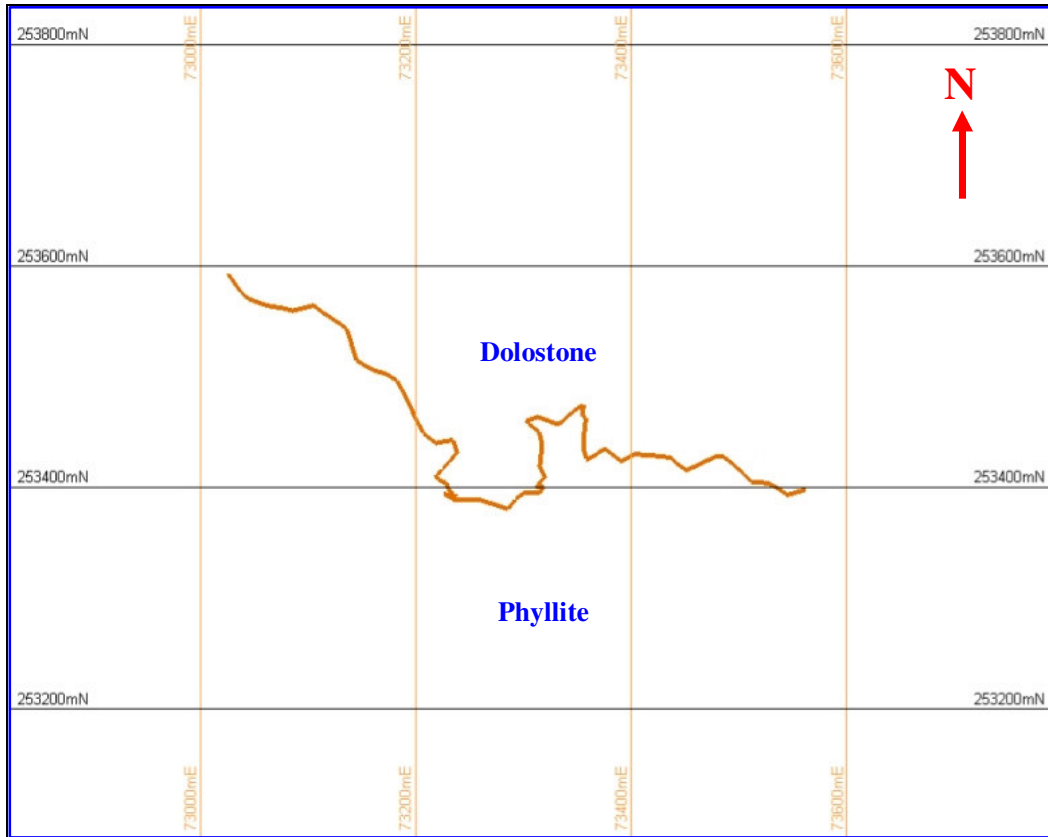


Figure 4.13: Complex folding of the dolostone/phyllite contact, 1120m, Asis West Mine, plan perspective.



Figure 4.14: Slightly folded, bedded sedimentary breccia – Kombat East, 4 level E600 stope.

Figure 4.15 below shows an interpreted type north - south section looking east of the Asis West Ore bodies looking east. If the dolomite phyllite contact is rotated to the horizontal, it appears as though the orebodies close to the contact were in karst type sink holes and could imply a perfect hiatus similar to the Tsumeb deposit.

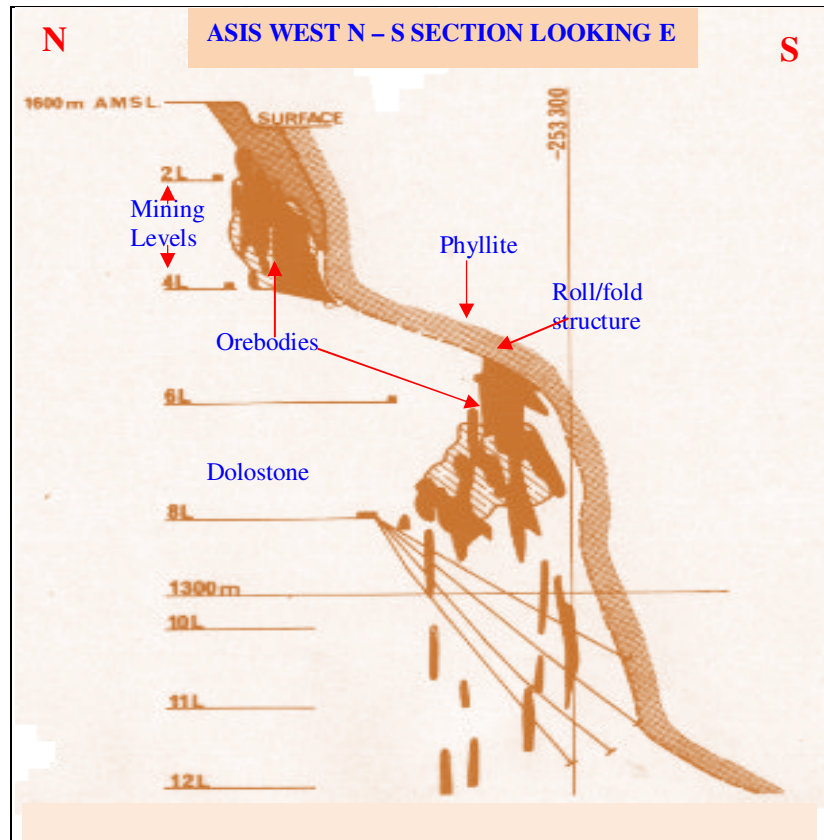


Figure 4.15: North – South Geological Section Looking East, Asis West orebodies displaying the “roll”/fold geometry of the dolomite/phyllite contact, modified by Changara (2007) after TCL, mine geologists unpublished reports.

4.3.4 Supporting structures

There are a number of different structures that may not necessarily affect the mining economics like the minor faults and minor faults zones, en echelon vein fractures,

fractures/joints, but must be considered in order to support a rational explanation of the observed structures.

4.3.4.1 En echelon vein fractures

A common feature at the KMC is the occurrence of en echelon quartz – carbonate veins and veinlets at variable scales and geometries. En echelon veins and veinlets have been mapped at Kombat East (3level, E750 Stope), Kombat East, E650, 4 level stope, Asis West (12level, 13level and 8level) and at Asis Far West (around the W1680). Figures 4.16a and 4.16b indicate the en echelon veins and veinlets from the Kombat East area. The en echelon veins and veinlets generally occur close to and within the mineralized zones as well as within the main fault zones.

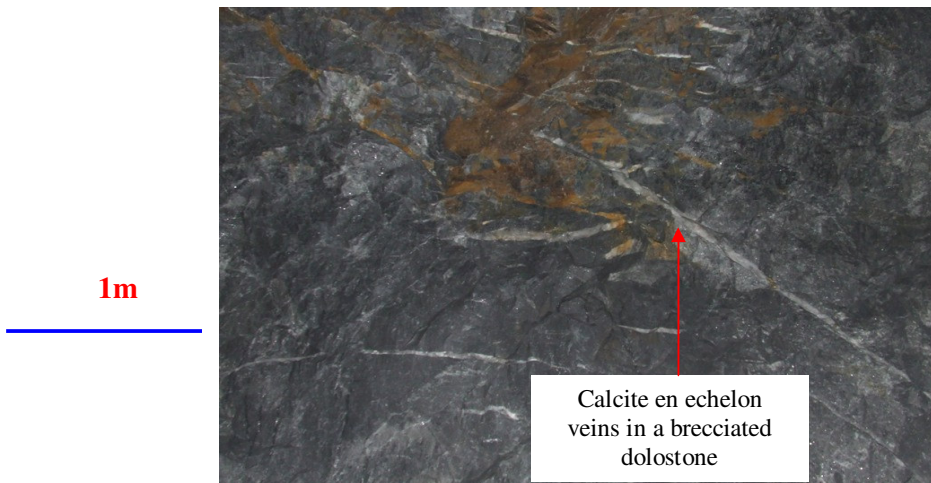


Figure 4.16a: 3level, E750 Stope, Kombat East orebody en echelon veinlets occurring within a main strain zone, around the margins of mineralization.

4.3.4.2 Slicken side lineations

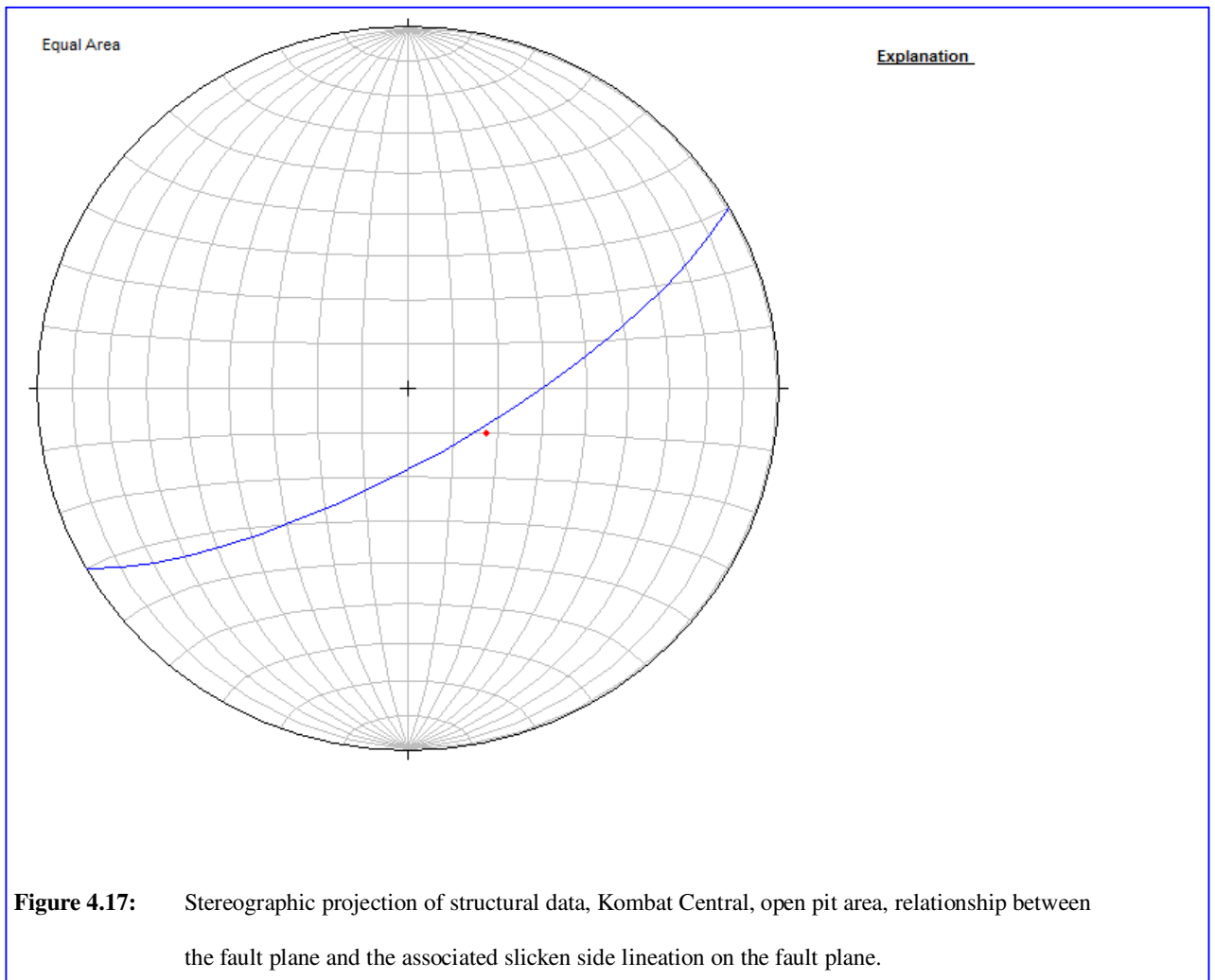
Slicken side lineations are rarely observed on fault planes around the KMC. A few were observed at Kombat Central North pit with the following structural data;



Figure 4.16b: Calcite filled en echelon veins, in a brecciated dolostone, very slightly mineralized, Kombat East E650, 4level underground.

- Slicken Sides Lineations Plunge 70° ,
- Plunge Direction 120° ,
- Fault Plane Dip 74° ,
- Dip Direction of Fault Plane 150° .

This structural data is shown in Figure 4.17 as a stereographic projection.



4.3.4.3 Shear zones

Shearing is not a straight forward process within the Kombat mining environment. Zones of shearing and penetrative deformation with a 070° strike occur between the north – east trending faults. Transposed sandstone and Fe-Mn bodies are located within the dolostones, sheared along the 070° direction at Asis West mine. Late shearing with variable attitudes is found along contacts between lithotypes on a localized scale.

4.3.4.4 Joints and veins

Whilst jointing and veining at Kombat mines has not caused any significant geomechanical problems to mining operations they are a common feature. In general terms jointing and veining occur in a single orientation generally steeply dipping with marked separation rendering them not so problematic to mining operations. However they have significance in as far as they indicate brittle response to stress/strain relationships and possible rotation effects. Figure 4.18 indicates undergrounding localities showing the occurrence of jointing and veining. Jointing occurs throughout the mine irrespective of mineralization localities. For veining the infill material is generally calcite and sometimes quartz.

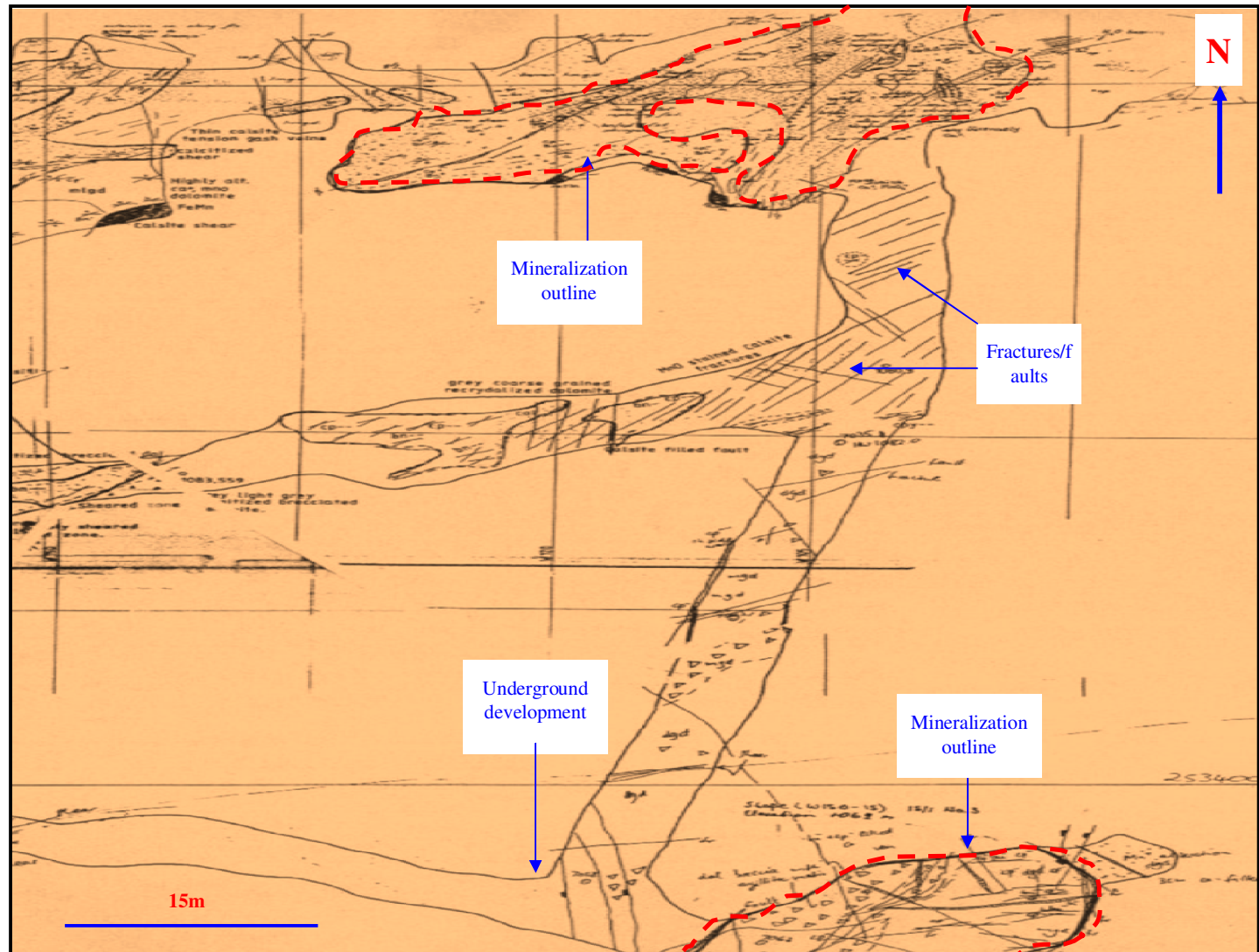


Figure 4.18: Jointing/Fracturing, Asis West underground, 15 Level, showing three dominant faulting/fracturing directions (NE – SW, E – W) and NW – SE), modified in this study from TCL, mine geologists underground mapping.

4.4 Comparative analyses of the structural findings of this study to the existing Kombat structural data

This study has added and reviewed the existing Kombat mine structural data. Some similarities between the existing dataset and the current studies (like faulting) have been identified whilst new features (mostly interpretive structural controls to mineralization) have been identified. The most important aspect of this study compared to previous researches done at Kombat mines is that most of the data used has been collected from the lower levels and the new mine (Asis Far West) which have just been opened up with recent mining. Previous researches focused on upper levels of the mine and surface areas which were accessible at the time. The specific details will be discussed in detail in Chapters 7 and 8 (Mineralization and Discussion respectively).

Chapter 5

Alteration Types

5.1 Introduction

Previous studies on alteration were done on upper levels whilst this study focuses on levels below 10 level and other satellite ore bodies that have recently been opened up through recent mining.

Alteration of the host rocks around the Kombat Mines is ubiquitous, variable and complex. Whilst it is generally accepted that dolomite is not precipitated as a primary carbonate but rather a product of dolomitization, this thesis will look at alteration after the formation of the host rocks (dolostones) and the process of dolomitization will not be described. The following alteration types have been identified; calcitization, iron manganese, silicification and minor sericitization, and chloritization.

5.2 Calcitization

Calcitization occurs in various forms from decolourizing of the light to dark grey dolostones along fractures and along the margins of breccia clasts, followed by broadening of the bleached zone and calcitization of the dolostone.

Decolourizing results from an outward migration of argillaceous and carbonaceous inclusions from intragranular sites to the dolomite grain boundaries, concomitant with a slight coarsening in grain size. Calcitization may be followed by annealing into a coarser grained,

saccharoidal textured rock. Calcitization has been observed to have occurred at variable timings within the Kombat dolostones. The earliest phase of calcitization seems to be syndepositional, from the presence of calcitized fragments of dolostone in syndepositional slump breccias and debris flows. Calcitization displays variability in intensity which is a function of the permeability rock through which the hydrothermal fluids pass and host rock porosity.

Figure 5.1 shows a moderately calcitized dolostone (with two zones one slightly altered (whitish) and the other zone moderately altered (grayish) in the center of the split core. This is a very common phenomenon highlighting the importance of the porosity of the host rock to the percolating hydrothermal fluids.



Figure 5.1: Slight – moderately calcitized dolostone (underground diamond drill Core, 12 level), the calcitization is recognized as white colouration as opposed to the grey in this photograph which is very slightly altered.

Figure 5.2 shows pervasive calcitization of dolostone. All mineralization observed around the Kombat mining complex exhibit a certain degree of calcitization. However, there are a lot of

areas where strong calcitization is not associated with any mineralization like the access development at Asis Far West orebody.

Calcitization sometimes shows rudimentary bleaching and this kind of alteration is seldom associated with any mineralization.



Figure 5.2: Strongly calcitized dolostone (underground diamond drill core, 20level), where the original dolostone is replaced by calcite. Stylolites retain dark organic or phyllosilicates imparting a dark colour to the contacts of the stylolites and the calcitized dolostone.



Figure 5.3: Bleached brecciated dolostone (underground diamond drill core, 12 level), pink to intense rouge-coloured manganoan calcite with nodules and dendritic growths of black manganese oxides, mostly pyrolusite, are often associated with intense calcitization in areas proximal to ore.

Where mineralization is associated with the bleached zones, it is normally of a secondary

origin. Figure 5.3 shows bleached dolostone located about 30m outside the limits of copper mineralization. The bleached brecciated dolostone is pink to intense roge-coloured manganian calcite with nodules and dendritic growths of black manganese oxides, mostly pyrolusite, are often associated with intense calcitization in areas proximal to ore.

Calcitization sometimes occurs in a pervasive form in breccias (where both the matrix and the clasts are strongly calcified) (Fig. 5.4), forming a replacement type breccia.

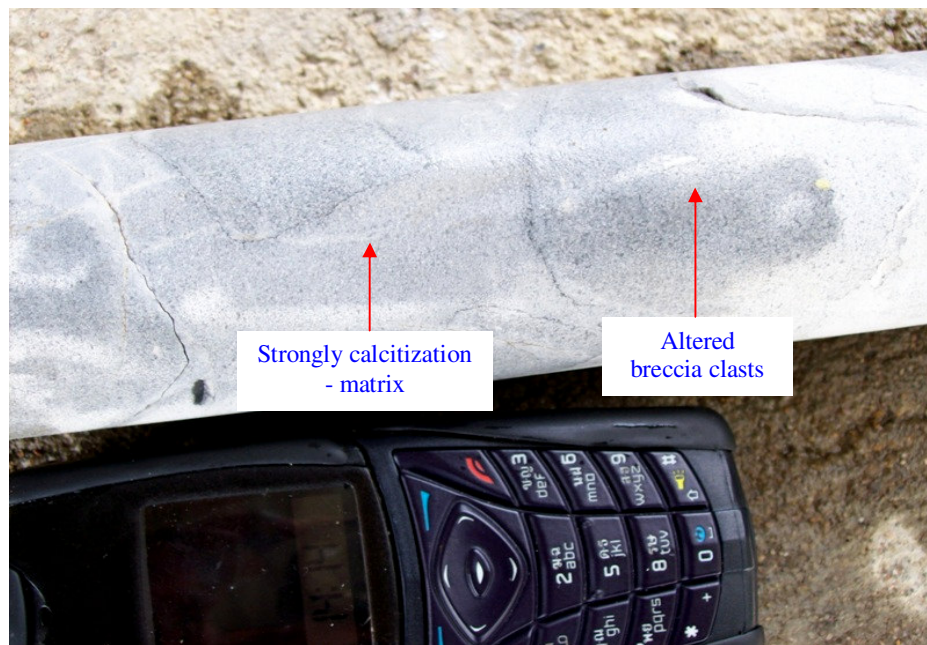


Figure 5.4: Pervasively calcified replacement breccia (underground diamond drill core, Asis Far West.), the matrix of the breccia is strongly calcitized and the clasts are entirely calcitized.

There is also a close association of mineralization and calcitization (Fig. 5.5). In this specimen, bornite replaces the strongly calcitized zones.

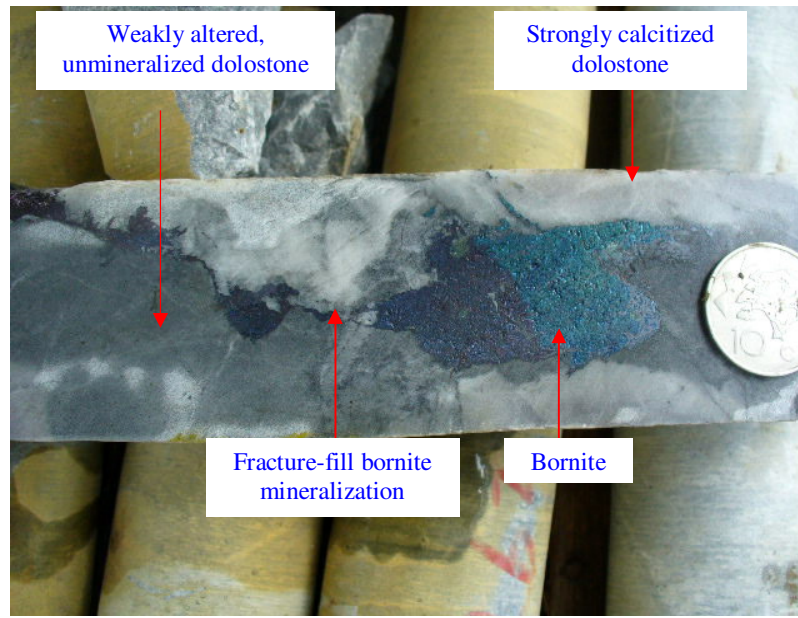


Figure 5.5: Altered – mineralized dolostone (underground diamond drill core, 12 level), showing bornite occurring in replacement form, replacing the strongly altered dolostone and poor mineralization in zones that are weakly altered.

A late phase of calcitization is a replacement and fracture fill type of alteration. Normally the calcite fills karsts, faults, net vein fractures, and where associated with mineralization its normally late vein fracture fill type of mineralization. Figure 5.6 shows calcite filled en echelon veins. Table 5.1 shows calcitization phases which have been simplified into three phases, an early, middle and a late phase. This classification is apparent in mineralization within the E900 area and could thus be applied to other centres of mineralization. The middle phase of calcitization is the one associated with the bulk of Kombat mineralization and associated with the 2nd Damara tectono-thermal event. Figures 5.7 and 5.8 show varieties of calcitization in dolostones within selected orebodies. They are the last recognizable phase of alteration within the Kombat mining area.

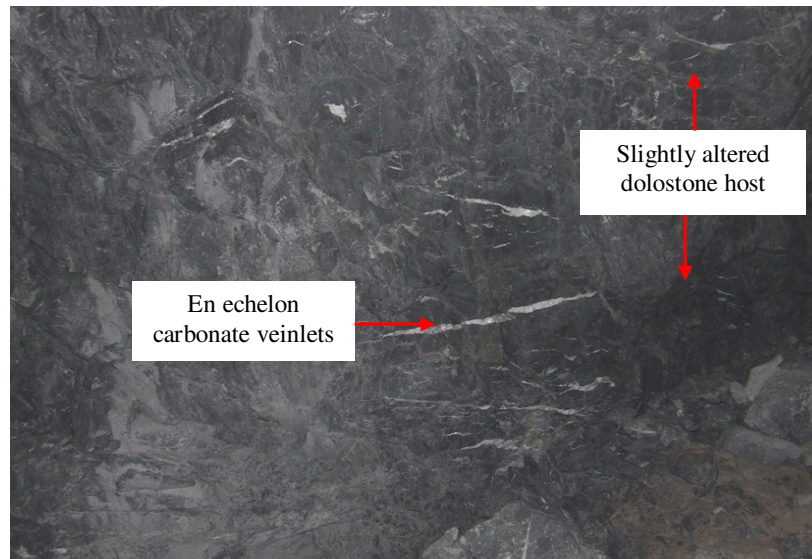


Figure 5.6: En Echelon calcite filled veins (3 level, E750 stope margins), these veins are post ore and are sympathetic to shearing that has occurred in the area.

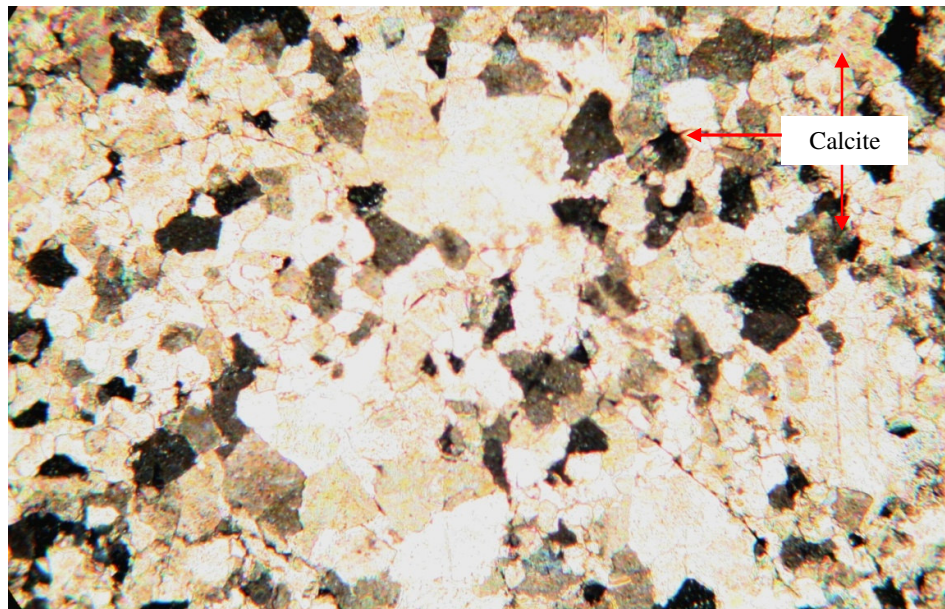


Figure 5.7: Calcitized dolostone, (3 level, E750 stope margins, Kombat East orebody, thin section x5 magnification).

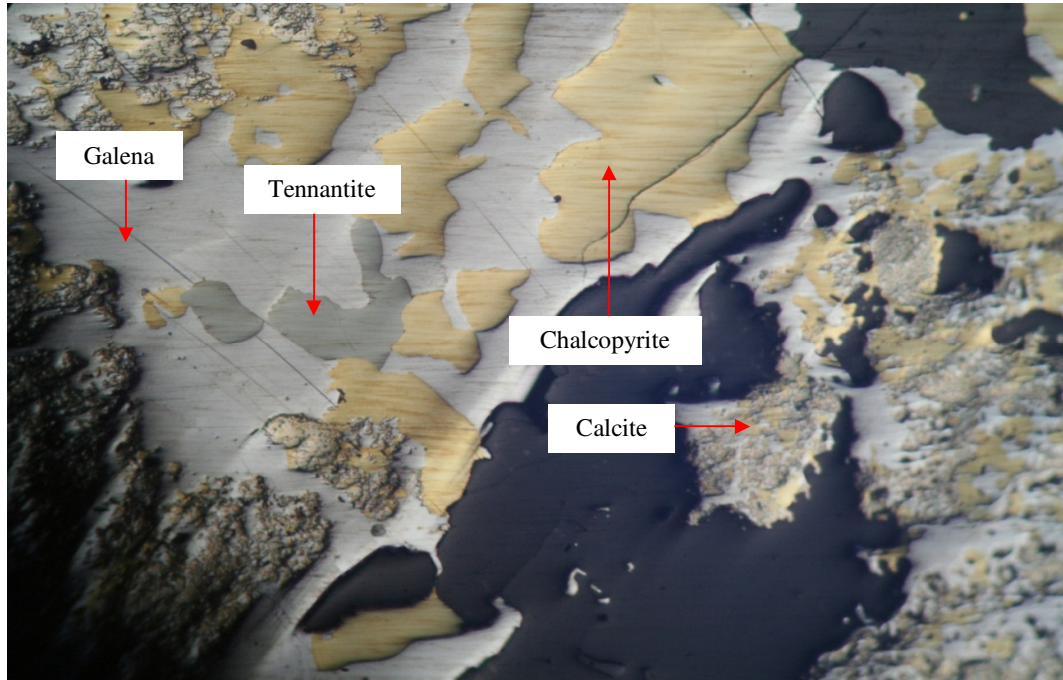


Figure 5.8: Replacement chalcopyrite mineralization is altered dolostone, also showing galena and chalcopyrite mineralization, 3level, E750, Kombat East orebody, polished section x10 magnification.

Table 5.1: Calcitization phases have been simplified in this study into three phases, an early, middle and a late phase. This classification is apparent in mineralization within the E900 area and could thus be applied to other centres of mineralization.

	Early	Middle	Late
Characteristics	Associated with post sedimentation of carbonates, probably involved sea water dynamics or CO ₂ /Oxygen dynamics, sometimes with diagenetic Py.	Associated with first phase of mineralization, commonly rims mineralization and generally associated with replacement and brecciation, normal mineralization associated with it is CC + Cpy + Pb + Bn +/- Zn	Associated with late phase mineralization possibly Zn + Cu

5.3 Manganese alteration

The iron manganese zones have over time been regarded as zones of mineralization, however, in this study they will be described and explained spanning across mineralization and alteration. Manganese alteration is a very important hydrothermal process which predates Cu – Pb – Ag mineralization at the Kombat Mining Complex. It shows a very close association with Cu – Pb – Ag mineralization but it mostly occurs around margins of mineralization. The Manganese alteration occurs in loci with favorable porosity and permeability, also with an intimate association with the sandstone. Figure 3.10 is a geological map of underground mapping at Kombat showing the zonation and patterns that are commonly formed by the iron-manganese bodies in relation to mineralization, alteration, structure and the dolostone/phyllite contact. The iron manganese bodies rim the zones of copper mineralization and are intercalated with the sandstone. Figures 3.4c and 3.12 show the iron manganese alteration at two distinct localities of the Kombat Mining area; namely the Kombat East (Glory hole open pit) and the 12 level, W800 underground area – diamond drilling respectively. In the two localities (Figs 3.4c & 3.12) the iron – manganese alteration occurs in breccia zones of sedimentary origin suggesting that alteration occurred prior to orogenic deformation.

5.4 Silicification

Silicification is observed in the dolostones and it is defined essentially where silica has replaced the original rock. In these dolostones, silicification in the form of chert normally replaces original oolites, stromatolites and algal mats. Elongated quartz blades of hydrothermal origin are abundant, and are mostly confined to the matrix of silicified breccia.

Very late quartz veins are also found in tension gashes especially at Asis Far West and 12 level, Kombat Mine (Asis West).

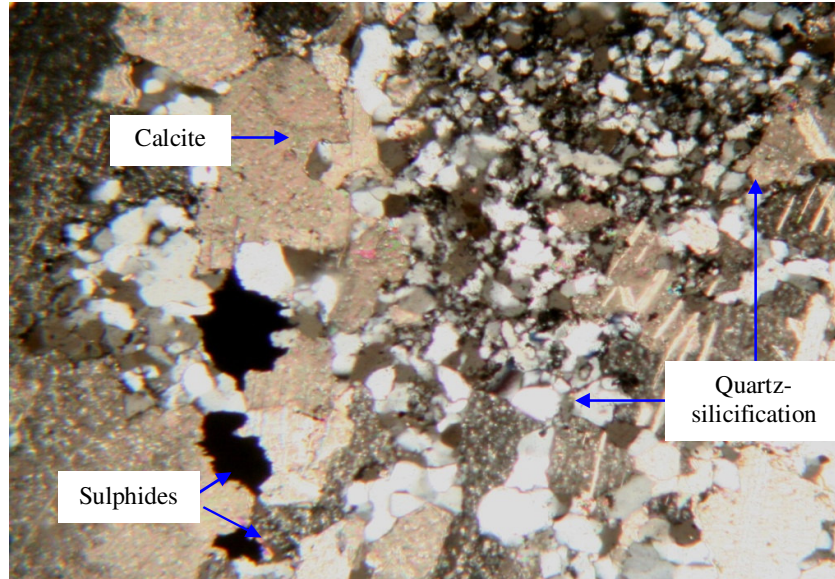


Figure 5.9: Silicification in a slightly calcified dolomitic host, thin section (x5 magnification), Asis West, 13level at the margins of 13L W270-10 stope, 1160m a.m.s.l.

Silicification is an important alteration process in the sandstones in a pervasive form. With the variability in bulk composition of the sandstone unit, feldspar grains are extensively altered to kaolinite or to sericite, with alteration facies comprising the associations; quartz + sericite + pyrite +/- chalcopryrite, chlorite + hematite, and kaolinite + pyrophyllite in the feldspathic sandstones. The chemistry of the silicification process is simple, being replacement of dolostone by SiO_2 . The high $\text{MgO}/(\text{MgO} + \text{CaO})$ ratios of the rocks result from the presence of dolomite rather than calcite, in the intensely silicified rocks. Figure 5.9 shows silicification alteration in an altered dolomitic host.

5.5 Other alteration types

Sericitization is a less common form of alteration and is confined to sandstones where sericite has formed after feldspar and after rare grains of biotite. The normal mineral paragenetic assemblage becomes; sericite-pyrite-calcite+/- dolomite.

Chloritization of feldspars is present in a few areas and absent in most areas. It also forms from the replacement of mainly feldspars and has an association with the iron manganese bodies. The normal mineral assemblage becomes chlorite-hematite. These minor alteration styles do not show any close association to mineralization.

5.6 Discussion of the alteration patterns identified in this study to the previous findings

The alteration patterns identified in this study compare very well with those of the previous researchers and will be used to discuss the controls to mineralization in subsequent chapters. The most important aspect identified in this study is that all the orebodies studied are associated with alteration in one form or the other and sometimes combinations but there are still some areas that are extensively altered but are not host to any mineralization.

Chapter 6

Geochemistry

6.1 Introduction

Geochemical signatures can be very important in characterizing mineralizing fluids sources, pathways and ore characteristics. Geochemical analysis was done with samples from the Kombat Mining Complex during the course of this study and this was integrated with existing geochemical data.

6.2 Mineralogical analysis conducted in this study

6.2.1 Introduction

Three coarse samples were collected from Kombat East and Kombat Central near surface ore bodies (Fig. 3.1) and sent to the Minerals Processing Division at Mintek in the Republic of South Africa for the determination of the mineral proportions, Cu-department and liberation sizes of Cu-bearing minerals. The objective of the analysis was for mineralogical and metallurgical investigations for the feasibility of open pit mining. For the purposes of this research only the mineralogical analysis will be discussed. The three samples were collected at various depths as follows;

- Kombat East (0-15m)
- Kombat Central (0-4m)
- Kombat Central (4-9m)

6.2.2 Experimental procedures

The three samples were split using a spinning riffler to obtain subsamples for 6 unsized bottle mount polished sections and an X-ray diffraction (XRD) sample each. The XRD sample was pulverized in a Sieb technik mill for ~2 minutes and scanned on a Siemens D-500 diffractometer, using $\text{CuK}\alpha$ radiation, over the range of 5 to 80° , 2θ , with a step size of 0.02° 2θ . This configuration gives a lower detection limit of approximately 3 to 5 mass percent of the crystalline phases present. Amorphous phases will not be detected and poorly crystalline phases will be underestimated by XRD. The QEMSCAN (quantitative analysis using scanning electron microscopy) was employed to map the particles and to obtain modal analyses, liberation and size data.

6.2.3 Results

6.2.3.1 Modal proportions

Carbonates are the predominant gangue minerals in all three samples, comprising more than 60% by mass, the most prominent (~70%) in the deep samples (the Kombat East (0-15m) and Kombat Central (4-9m)). The dolomite: calcite ratios change from 7.4 to 5.5 to 0.4 from Kombat Central (0-4m) to Kombat Central (4-9m) to Kombat East (0-15m). The second most common gangue mineral is quartz, ranging from ~25 mass% in the shallow sample (Kombat Central (0-4m)), ~20 mass% in the deep sample (Kombat Central (0-9m)) to ~10 mass% in the Kombat East (0-15m) (Table. 6.1). Quartz and dolomite have average diameters in the region of 30 μm . There is a decrease in malachite content with depth with an associated increase in wad with depth. There are more Fe/Mn bearing minerals in the Kombat East sample compared to the Kombat Central samples. The remaining gangue minerals are predominantly

micas, chlorite and apatite, their combined contribution slightly less than 5 mass%, the former two with an average diameter of ~10 µm. Pyrite (Cu-barren) occurs in levels of less than 1%, the most common in the Kombat Central (4-9m) sample (0.1 mass %).

Most of the remaining minerals are Cu-containing and can be grouped as:

- Sulfides: chalcocite, chalcopyrite, bornite
- Oxides: cuprite, wad→lampadite
- Carbonates: malachite, Mn-carbonate
- Phosphates: Pseudomalachite
- Hydroxides: Goethite

Table 6.1: Mineralogical analysis results of samples from Kombat nine (3 samples from Kombat East and Kombat Central orebodies).

Element (%)	Kombat Central (0-4m)	Kombat Central (4-9m)	Kombat East (0-15m)
Mg (calculated)	7.7	8.1	2.3
Mg (chemical)	7.8	8.4	3.4
Al (calculated)	0.2	0.2	0.3
Al (chemical)	0.6	0.4	0.6
Si (calculated)	11.6	9.1	6.4
Si (chemical)	9.6	6.9	6.9
S (calculated)	0.1	0.1	0.1
S (chemical)	0.1	0.1	0.1
Ca (calculated)	16.3	18.8	22.5
Ca (chemical)	18.5	19.6	23.0
Mn (calculated)	0.2	0.3	1.1
Mn (chemical)	0.3	0.2	1.4
Fe (calculated)	1.4	0.9	8.7
Fe (chemical)	0.8	0.6	6.3
Cu (calculated)	2.0	1.2	1.5
Cu (chemical)	2.0	1.5	1.5
Mineral	Kombat Central (0-4m)	Kombat Central (4-9m)	Kombat East (0-15m)
Chalcocite	0.2	0.3	0.1
Chalcopyrite	<0.1	<0.1	<0.1
Bornite	<0.1	0.1	<0.1
Pseudomalachite	<0.1	<0.1	<0.1

Malachite	2.2	1.0	0.5
Wad	1.2	1.3	4.8
Goethite/Magnetite	1.8	0.6	12.2
Pyrite	<0.1	0.1	<0.1
Quartz	24.0	18.7	12.4
Mica	1.1	0.7	0.8
Chlorite	0.3	0.4	0.9
Dolomite	58.4	61.2	16.1
All Others	0.1	0.1	0.1
FeTi_oxides	0.1	<0.1	<0.1
Wad-noCu	1.0	1.2	3.7
Iron-oxide(Cu)	0.4	0.6	0.4
Calcite	7.7	11.0	44.8
Apatite	1.3	2.8	2.2
MnFe-carbonate	<0.1	<0.1	0.3
Mn-carbonate	<0.1	<0.1	0.5
Cuprite	0.4	<0.1	<0.1

Cu-bearing sulphides constitute less than 0.5 mass% in the samples, more prominent in the Kombat Central (4-9m) sample due to slight increase in the bornite content (Fig. 3.1). These sulphides have average diameters in the region of 10 μm to 15 μm .

Cu-containing oxides consist of cuprite, lampadite (Cu-content of 20%) and wad which has a variable Cu-content, Figure 6.1, ranging between 2% and 15%. Lampadite is included in wad in the groupings. The Cu-oxides constitute ~3 mass% (Kombat Central samples) and ~10 mass% in the Kombat East, the latter boosted by an increase in the wad content of the sample (Fig. 6.1). Cuprite is most abundant in the shallow sample, but this is most probably insignificant as one relatively large grain was detected.

Cu-carbonates comprise malachite and Mn(Cu)-carbonate, the latter containing Cu up to 10% (estimated from the Cu-peak height on the EDS spectrum), but can also be Cu-barren. Malachite constitutes ~2 mass%, ~1 mass% and ~0.5 mass% in the Kombat Central (0-4m), Kombat Central (4-9m) and Kombat East (0-15m) samples respectively, with Cu-containing Mn-carbonate above 0.1 mass% only in the Kombat East (0-15m) sample.

Pseudomalachite is the only Cu-phosphate, more prominent in the deep sample (Fig. 6.1). Cu in hydroxide form is present in goethite which can either be Cu-barren or can contain up to ~10% Cu, the most common in the Glory pit sample.

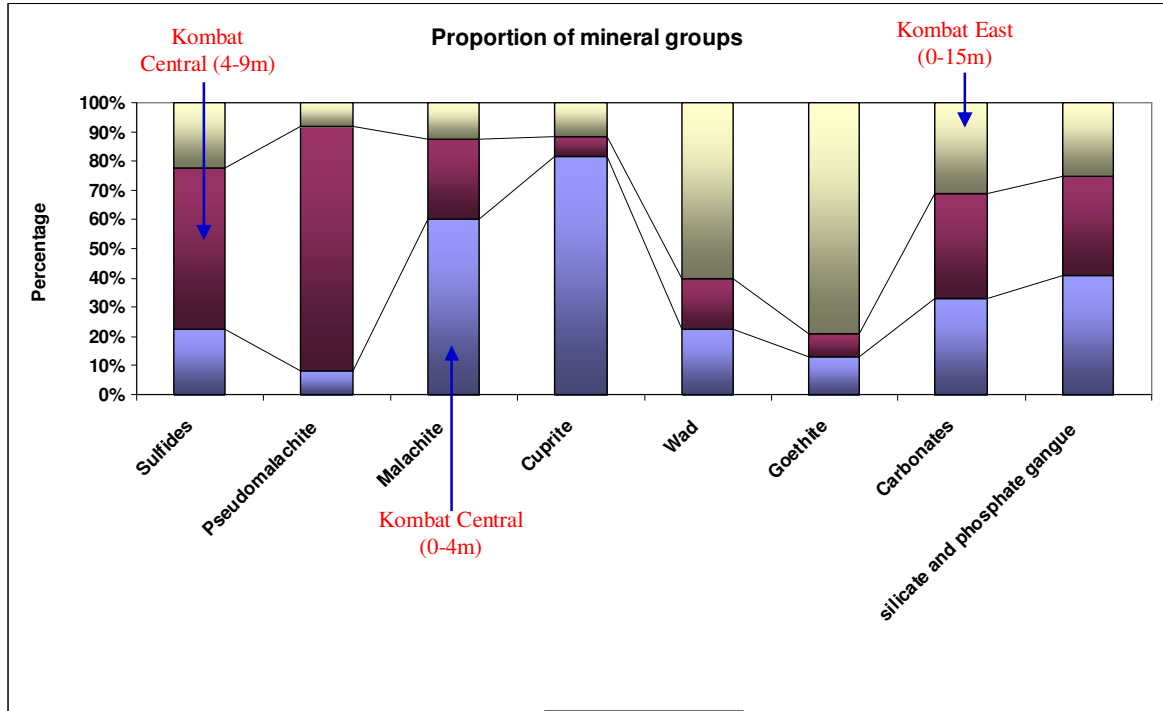


Figure 6.1: Mineralogical analyses; proportion of mineral groups from Kombat East and Kombat Central orebodies.

Figure 6.2 shows chalcocite inclusions in malachite in the Kombat Central (0-4m) sample whilst Figure 6.3 shows Cuprite (C) surrounded by malachite (Mal) in a calcite host (carbonate) and Mottramite (mot) in a wad host in the Kombat East (0-15m) is shown in Figure 6.4.

6.3 Cu-deportment

Malachite is the major Cu-bearing mineral in the Kombat Central samples, hosting ~65% and ~50% of the Cu respectively (Table. 6.1). The Cu-contribution of Mn(Cu)-carbonate is negligible and comprises less than 1%.

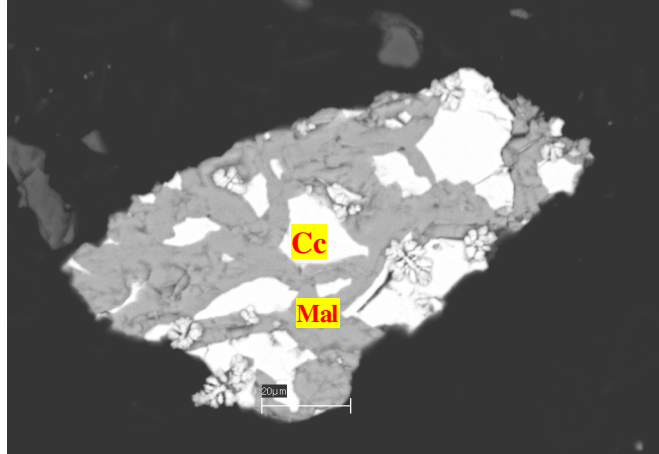


Figure 6.2: Chalcocite (Cc) inclusions in malachite (Mal), Kombat Central (0-4m), suggesting that the original sulphides have been oxidised, leaving “islands” of chalcocite. Scale bar 20 μm .

Cu hosted in oxides comprise ~25% in both samples, in wad and cuprite, the former containing ~10% and 20% of the Cu respectively.

Cu in sulfides are more prominent (~20% of the Cu) in the Kombat central (4-9m) sample compared to the Kombat Central (0-4m) sample (~10% of the Cu), mostly in chalcocite, with trace amounts in bornite and chalcopyrite. Pseudomalachite hosts less than 5% of the Cu in both samples.

Goethite can either be Cu-barren or contain Cu up to 10%, its Cu-contribution minor (5%) in the deep and shallow samples.

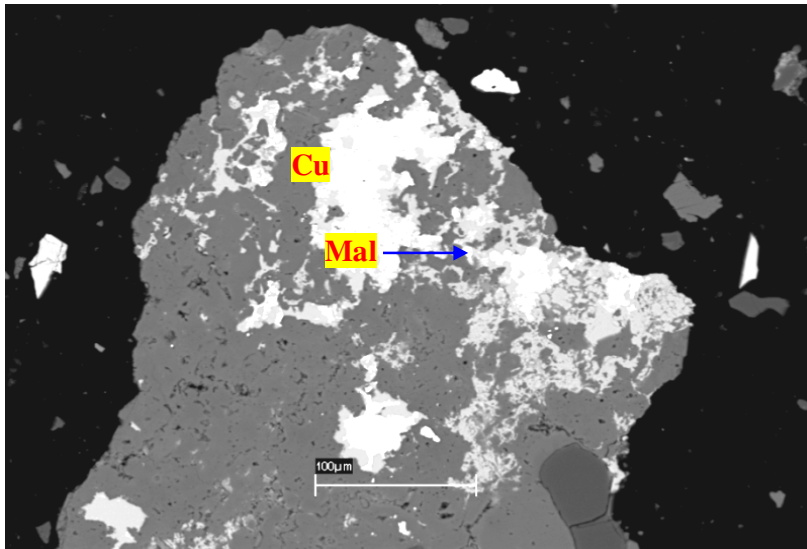


Figure 6.3: Cuprite (C) surrounded by malachite (Mal) in a calcite host, Kombat Central (4-9m), scale bar 100 μm .

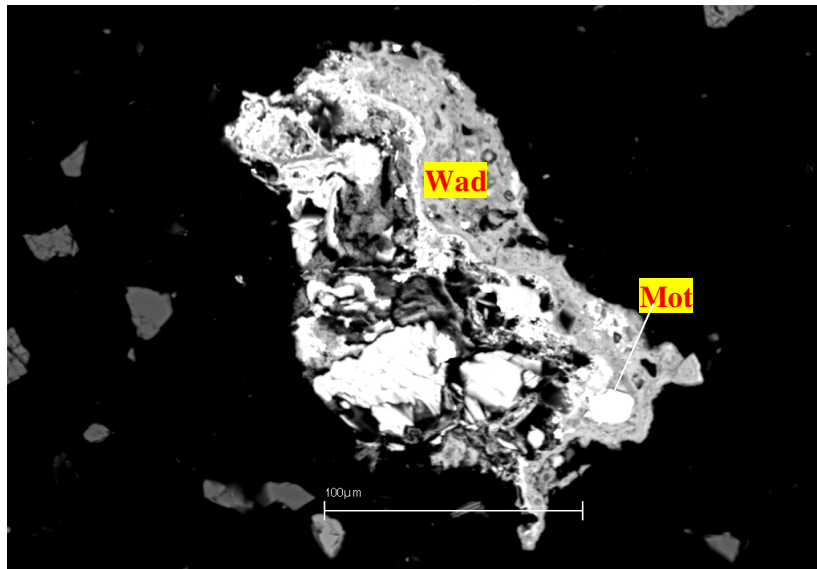


Figure 6.4: Mottramite (mot) in a wad host in the Kombat East (0-15m), scale bar is 100 μm .

In the Kombat East Sample (0-15m), Cu is mostly contained in wad (~65%), with malachite and chalcocite are the other most prominent Cu-hosts, the former containing less than 20% and the latter ~10% of the Cu.

Cu in sulfides in the Kombat East sample comprises ~5%, mostly contained in chalcocite.

The calculated Cu-grades compare favourably with the assays, as well as the oxide Cu, calculated using the total Cu minus sulphide Cu (Table. 6.1) and total Cu minus (sulphide Cu plus hydroxide Cu).

6.4 Liberation and associations of Cu-containing minerals

The following liberation groupings are used:

- Liberated: constitute more than 80% of the mass of the particle
- Middlings: between 30% and 80% of the mass of the particle
- Locked: less than 30% of the mass of the particle

6.4.1 Liberation and associations of the major Cu-bearing minerals in the Kombat Central (0-4m) Sample

Chalcocite

- The majority (90%) of chalcocite is smaller than 10 μm in diameter, the remainder smaller than 30 μm in diameter (Table. 6.2).
- Chalcocite is predominantly (~80%) locked, with an average of 5 μm , mostly (70%) in malachite but also in carbonates (10%).
- Liberated chalcocite is mostly smaller than 10 μm in diameter.

Malachite

- Approximately 85% of the malachite has diameters between 20 and 40 μm of which 40% is liberated and most of the remainder occurring as middlings. Malachite smaller

than 20 μm are also relatively well liberated, primarily occurring as middlings or liberated grains.

-
- Malachite middlings are mostly associated with chalcocite (50% of total malachite), the latter as inclusions (Fig. 6.2).

Cuprite

- Cuprite is predominantly liberated, as 70% of the cuprite comprises one relatively large (~25 μm in diameter) liberated grain.
- Most of the locked cuprite is associated with malachite (Fig. 6.3).

Wad

- Wad is associated with a variety of minerals, and can occur interstitial to or intergrown with carbonates, encrustations on quartz, as fine intergrowths with other silicates. The wad can be of variable composition containing minute Cu-sulphide inclusions (Fig. 6.5).

Table 6.2: Liberation of malachite, chalcocite, cuprite and wad in the Kombat Central (0-4m) Sample (mass%).

Liberation	<10 μm				10-20 μm				20-30 μm				30-40 μm				Total			
	<i>Ch</i>	<i>M</i>	<i>Cu</i>	<i>W</i>	<i>Ch</i>	<i>M</i>	<i>Cu</i>	<i>W</i>	<i>Ch</i>	<i>M</i>	<i>Cu</i>	<i>W</i>	<i>Ch</i>	<i>M</i>	<i>Cu</i>	<i>W</i>	<i>Ch</i>	<i>M</i>	<i>Cu</i>	<i>W</i>
Liberated	5	3	4	6	<1	2	<1	1	<1	17	71	-	-	16	-	-	5	38	75	7
Middlings	2	2	7	25	<1	7	<1	15	12	16	<1	-	-	34	-	-	14	59	7	40
Locked	81	2	19	53	<1	1	<1	<1	<1	<1	<1	-	-	<1	-	-	81	3	19	53
Total	88	7	30	84	<1	10	<1	16	12	34	71	-	-	50	-	-	100	100	100	100

(Ch-chalcocite, M-malachite, Cu-cuprite, W-wad)

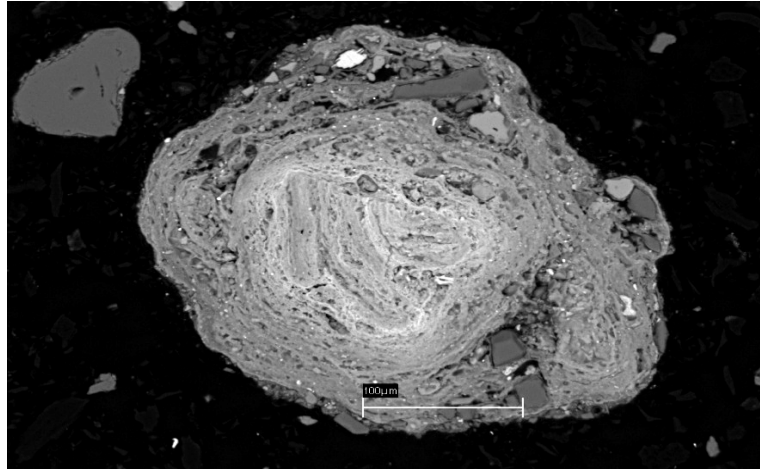


Figure 6.5: Wad of variable composition, Fe,Mn,Cu-rich in the centre and Al and Si-rich towards the edge. Very small Cu-sulphide inclusions are present (white dots), Scale bar 10 μ m.

6.4.2 Liberation and associations of the major Cu-bearing minerals in the Kombat Central (4-9m) sample

Chalcocite

- Chalcocite predominantly occurs as middlings (Table 6.3), mainly due to one relatively large grain (25 μ m in diameter).
- Locked chalcocite is associated with Fe-oxide/hydroxide (as veins or rims), carbonates and/or malachite. These chalcocite grains are predominantly smaller than 10 μ m in diameter.

Malachite

- Approximately 80% of the malachite occurs as middlings, of which 75% is represented by one relatively large grain of 35 μ m in diameter. This grain also constitutes ~85% of the malachite/Fe-oxide or hydroxide association which comprises 70% of the total malachite.

- Locked malachite is primarily associated with chalcocite or carbonates and to a lesser extent, also wad and/or quartz.
- The locked malachite is mostly smaller than 20 µm in diameter.

Cuprite

- Cuprite is predominantly (~90%) smaller than 10 µm in diameter
- The mode of occurrence indicates an almost even distribution as liberated grains (of which almost 100% is smaller than 10 µm in diameter), middlings and locked (both predominantly with malachite).

Wad

- Most of the wad (90%) occurs as small grains (<20 µm in diameter), but can be up to 40 µm in diameter.
- Wad is mostly present as locked grains (60%), mostly associated with carbonates, quartz, malachite and apatite (Fig. 6.6).
- Wad middlings form composite and intergrowths with a variety of minerals.

Table 6.3: Liberation of malachite, chalcocite, cuprite and wad in the deep sample (Mass%)

Liberation	<10µm				10-20 µm				20-30 µm				30-40 µm			
	Ch	M	Cu	W	Ch	M	Cu	W	Ch	M	Cu	W	Ch	M	Cu	W
Liberated	5	3	17	4	2	2	5	2	5	1	-	1	3	1	-	1
Middlings	2	2	30	11	5	10	2	10	57	4	-	5	<1	61	-	4
Locked	14	4	44	29	4	6	1	31	<1	<1	-	<1	<1	<1	-	<1
Total	21	9	91	44	11	18	8	43	63	5	-	7	4	62	-	6
Liberation	40-50 µm				50-60 µm				60-70 µm				Total			
	Ch	M	Cu	W	Ch	M	Cu	W	Ch	M	Cu	W	Ch	M	Cu	W
Liberated	-	1	-	-	-	<1	-	-	-	4	-	-	18	12	22	9
Middlings	-	1	-	-	-	<1	-	-	-	<1	-	-	64	77	33	31
Locked	-	<1	-	-	-	<1	-	-	-	<1	-	-	18	11	45	60
Total	-	2	-	-	-	<1	-	-	-	4	-	-	100	100	100	100

- (Ch-chalcocite, M-malachite, Cu-cuprite, W-wad)

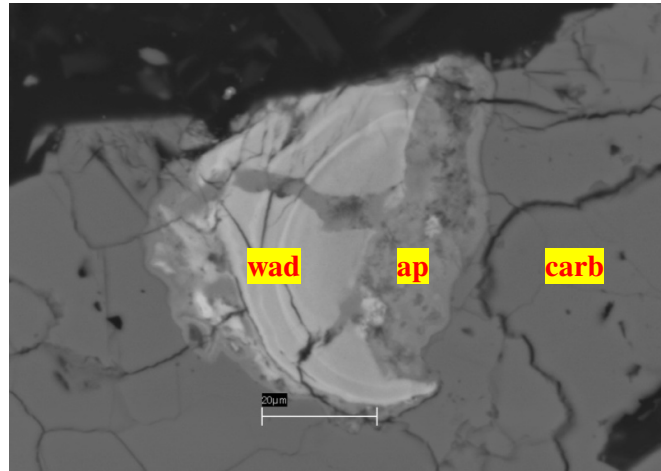


Figure 6.6: Banded wad surrounded by apatite (ap) in a calcite (carb) host. The lighter-grey bands in the wad are Mn-rich.

6.4.3 Liberation and associations of the major Cu-bearing minerals in the Kombat East (0-15m) sample

Chalcocite

- All the chalcocite detected is smaller than 20 µm in diameter.
- Half of the chalcocite is present as locked grains, mostly in malachite and to a lesser extent, also quartz and/or Fe-oxide/hydroxide (Fig. 6.4).

Malachite

- The liberation data for malachite might be slightly skewed to a relatively large (25 µm) predominantly liberated grain comprising 85% of the liberated component. However, approximately 65% of the malachite (number %) is liberated.
- Malachite middlings are mostly composite grains with Cu-containing Fe-oxide/hydroxide.

Goethite (major Cu)

- Goethite can contain Cu in variable amounts and major Cu-containing goethite has been grouped separately from other goethite containing equal to or less than 1% Cu (including barren goethite).

- A large portion of the Cu-goethite (~55%) is smaller than 10 µm in diameter and ~25% between 10 µm and 20 µm in diameter.
- Cu-goethite middlings constitute 40% and are predominantly composites with other goethite (either barren or containing trace Cu).
- Locked Cu-goethite has a variety of hosts and is almost evenly distributed with carbonates, other goethite and/or wad.

Wad

- Most of the wad (~80%) is smaller than 20 µm in diameter and can be up to 50 µm in diameter.
- Wad forms composites with a variety of minerals, mostly comprising at least 30% of the particles. The other components of these particles are predominantly carbonates, quartz and Fe-oxide/hydroxides. This mode of occurrence is also valid for locked wad.

Goethite (minor to barren)

- Goethite has a large size range and can be up to 150 µm in diameter (Table. 6.5).
- Most of the goethite (~75%) comprises more than 80% of the hosts with unliberated goethite mostly associate with quartz, carbonates and/or wad.

Table 6.4: Liberation of malachite, chalcocite, Cu-goethite and wad in the Kombat East (0-15m) Sample (mass%)

Liberation	<10 µm				10-20 µm				20-30 µm				30-40 µm				40-50 µm				Total			
	Ch	M	G	W	Ch	M	G	W	Ch	M	G	W	Ch	M	G	W	Ch	M	G	W	Ch	M	G	W
Liberated	16	10	3	3	8	1	<1	2	-	67	-	1	-	-	<1	-	-	-	1	24	78	3	7	
Middlings	14	8	12	10	11	4	27	33	-	<1	-	8	-	-	<1	-	-	-	11	24	13	39	61	
Locked	51	8	57	32	<1	1	<1	<1	-	<1	-	<1	-	-	<1	-	-	-	<1	51	10	57	32	
Total	81	26	73	45	19	6	27	35	-	68	-	9	-	-	<1	-	-	-	12	100	100	100	100	

(Ch-chalcocite, M-malachite, G-Cu-goethite, W-wad)

Table 6.5: Liberation of malachite, chalcocite, Cu-goethite and wad in the Kombat East (0-15m) Sample (mass%)

Liberation	<10 µm				10-20 µm				20-30 µm				30-40 µm				40-50 µm				Total			
	Ch	M	G	W	Ch	M	G	W	Ch	M	G	W	Ch	M	G	W	Ch	M	G	W	Ch	M	G	W
Liberated	16	1	3	3	8	1	<	2	-	67	-	1	-	-	-	<	-	-	-	1	24	78	3	7
Middlings	14	8	1	1	11	4	27	33	-	<	-	8	-	-	-	<	-	-	-	11	24	13	39	61
Locked	51	8	5	3	<	1	<	<	-	<	-	<	-	-	-	<	-	-	-	<	51	10	57	32
Total	81	2	7	4	19	6	27	35	-	68	-	9	-	-	-	<	-	-	-	12	10	10	10	10

(Ch-chalcocite, M-malachite, G-Cu-goethite, W-wad)

6.5 Summary and discussion

6.5.1 Modal proportions

Carbonates are the predominant gangue minerals in all three samples, comprising more than 60% by mass, the most prominent (~70%) in the deep sample. The dolomite to calcite ratios change from 7.4 to 5.5 to 0.4 from shallow to deep to Kombat East sample. These ratios must be read in comparison to the host dolomite, which amasses the orebody. The calcite is mainly a hydrothermal mineral together with quartz. The second most common gangue mineral is quartz, ranging from ~25 mass% in the Kombat Central (0-4m) sample, ~20 mass% in the Kombat Central (4-9m) sample to ~10 mass% in the Kombat East (0-15m) sample.

6.5.2 Copper containing minerals

Most of the Cu-containing minerals can be grouped as:

- ❖ Sulfides: **chalcocite**, chalcopyrite, bornite
- ❖ Oxides: cuprite, **wad**→lampadite (variable Cu-content)
- ❖ Carbonates: **malachite**, Mn-carbonate

- ❖ Phosphates: Pseudomalachite
- ❖ Hydroxides: Goethite (variable Cu-content)

6.5.3 Copper department

- Malachite is the major Cu-bearing minerals in the Kombat central (0-4m) and Kombat central (4-9m) samples respectively hosting ~65% and 50% of the Cu with ~65% of the Cu contained in wad in the Kombat East (0-15m) samples.
- Oxide Cu comprises ~25% in the Kombat Central each.
- Malachite and goethite contain ~20% and ~10% of the Cu in the Kombat East sample.
- Minerals containing minor to trace amounts of Cu are pseudomalachite, Mn-Cu-carbonate, bornite, chalcopyrite, Cu-arsenide, Cu-Fe-sulphur - arsenide and mottramite.

6.5.4 Associations

- Malachite has a close association with chalcocite with the latter often present as small inclusions and recovery of the malachite will recover ~50% of the chalcocite in the shallow and deep samples. Liberation of the chalcocite should be avoided as ~90% is smaller than 10 μm in the Kombat central (0-4m) sample.
- Cuprite in the Kombat central (0-4m) sample is also closely associated with malachite and can contribute to recovery by flotation.
- In the Kombat Central (4-9m) sample and Kombat East (0-15m) sample malachite is often associated with Fe-oxide/hydroxides which might be detrimental to flotation.
- Malachite in the Kombat Central (4-9) sample and Kombat East (0-15m) sample are occasionally locked and/or intergrown with carbonates, wad and/or quartz.

- Wad can be associated with almost every other mineral and in almost every form possible, as encrustations, intergrowths, or attachments and can often contain inclusions of other Cu-bearing minerals.

6.6 Host rock geochemical analyses – Historical data

6.6.1 Introduction

Other Geochemical investigations have been carried out over time and their findings will be presented here. The findings will be integrated with analyses results of this study highlighted above to constrain the lithological and structural controls to mineralization within the Kombat Mining Complex.

6.6.2 Material analyses and analytical techniques

Borehole core and whole rock samples from 4 mines (Kombat, Tsumeb, Berg Aukas and Abenab) were analyzed by separating each into various carbonate generations by Chetty and Frimmel (1999). Optical cathodoluminescence imaging was used to verify the presence of more than one carbonate generation in polished thin sections of selected samples. This was done using a Technosyn cold cathodoluminescence model 8200 MkII. In total, 33 samples representing various carbonate generations were analyzed by X Ray fluorescence spectrometry (XRF) on a Philips X'Unique II PW1480 spectrometer, as outlined by Duncan et al (1984). Solutions of 33 powdered carbonate generations were analyzed for rare earth elements (REE) using gradient high performance ion chromatography (HPIC) on a Dionex 4000i ion chromatography, following the method of Le Roex and Watkins (1990). Stable Isotope measurements were made on 22 samples after conventional extraction of CO₂ on a

carbonate line (McCrea, 1950) and extraction via the Bremen technique. In the latter, carbonates were reacted automatically with 100% H₃PO₄ at 71⁰C, with liberated CO₂ analyzed in an accompanying Finnigan Matt gas mass spectrometer. Carbon Isotope data are reported relative to the Peedee Formation Bellemnite (PDB) standard, whereas O isotope data are reported relative to the Vienna Standard Mean Ocean Water (V-SMOW) standard. For the C and O isotope analyses, reproducibility was better than $\pm 0.1\%$ for $\delta^{13}\text{C}$ and $\pm 0.2\%$ for $\delta^{18}\text{O}$. Microthermometry was carried out on 14 selected samples, which contained fluid inclusions of measurable size, using USGS heating freezing stage. Crush-leach analyses of 20 samples were effected using HPIC on a Dionex DX300 ion chromatograph for the ionic composition of the resultant fluid inclusion leachates.

6.6.3 Geochemical results by Chetty and Frimmel (1999)

Table 6.6 shows the Geochemical results of the analysis of the Dolomite generation I and Calcite generation II. These samples are selected from the range done by Chetty and Frimmel as they have relevance to the Kombat deposit.

Table 6.6: Geochemical Analysis Results for the Kombat Dolomite generation I and Calcite generation II, Kombat mine, after Chetty and Frimmel (1999)

Traces (ppm)	Dolomite 1	Calcite II
Mo	n.d.	n.d.
Zr	5.70	2.40
Y	2.40	5.20
Sr	63.00	118.00
Rb	6.80	n.d.
Ba	39.00	12.00
Sc	n.d.	n.d.
Cr	7.20	n.d.
V	8.20	3.30
Mn	1206.00	1799.00
Pb	n.d.	4.90
Zn	9.20	52.00
Cu	4.20	150.00
U	n.d.	n.d.
Nb	n.d.	n.d.
Co	n.d.	n.d.

Th	n.d.	n.d.
Ni	n.d.	n.d.
S	58.00	318.00

REE (ppm)

La	0.72	3.56
Ce	2.09	7.46
Pr	n.d.	n.d.
Nd	1.17	2.64
Sm	0.29	0.59
Eu	0.07	0.14
Gd	0.32	0.62
Tb	0.05	0.11
Dy	0.28	0.70
Er	0.17	0.40
Yb	0.10	0.31

n.d. Not detected

At Kombat there is an enrichment of most trace elements, in particular Mn, Pb, Zn, and Cu and in REE is evident in the secondary hydrothermal and mineralized carbonate generations relative to the least altered host rocks and significant differences exist in the REE distribution (Fig. 6.6). At Kombat, the mineralized carbonate generations are particularly enriched in Mn, which is also indicated by a bright red cathodoluminescence of these carbonates compared to a dull orange – yellow displayed by the host rocks. An increase in Sr and Y is also noted with progressively younger age of the carbonate generation (except supergene phases) at Kombat mine. The mineralized generations are also typically more enriched in light REE than heavy REE (La/Yb = 10-30) and most of them display a negative Eu anomaly. Figures 6.7, 6.8, and 6.9 show the host rock normalized trace element profiles for selected carbonate generations at Kombat, Chondrite normalized REE plots for selected carbonate generations from Kombat and the $\delta^{18}\text{O}$ vs $\delta^{13}\text{C}$ plots of carbonate generations from Kombat respectively (Chetty & Frimmel, 1999).

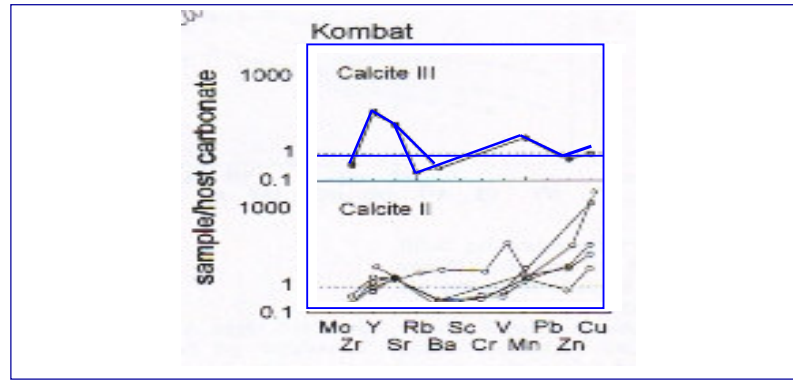


Figure 6.7: Host rock normalized trace element profiles for selected carbonate generations at Kombat (Chetty & Frimmel, 1999).

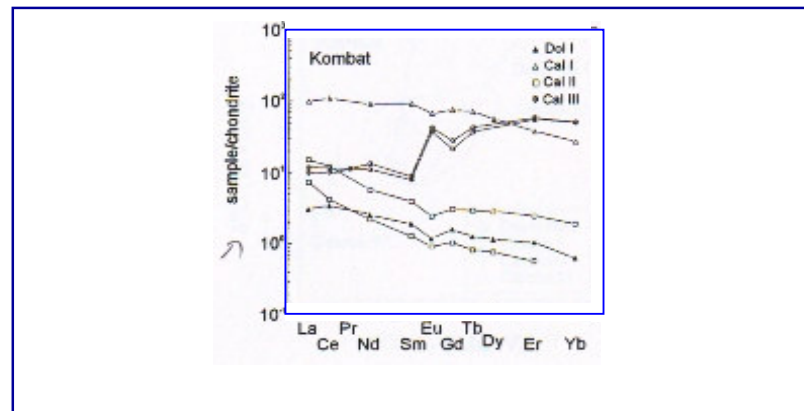


Figure 6.8: Chondrite normalized REE plots for selected carbonate generations from Kombat, Dol (Dolomite), Cal (Calcite), Chondrite composition after Sun and McDonough (1989) (Chetty & Frimmel, 1999).

6.7 Carbon and Oxygen Isotope data

The unaltered host rocks all have $\delta^{18}\text{O}$ values typical of marine carbonates, i.e. between 19.3 and 29.8‰. Younger carbonate generations are generally depleted in both ^{13}C and ^{18}O , with the ^{13}C depletion being much pronounced at Kombat. As alteration becomes more intense and sites of mineralization are approached in particular $\delta^{18}\text{O}$ values tend to decrease.

6.8 Fluid inclusion analyses and evolution of mineralizing fluids

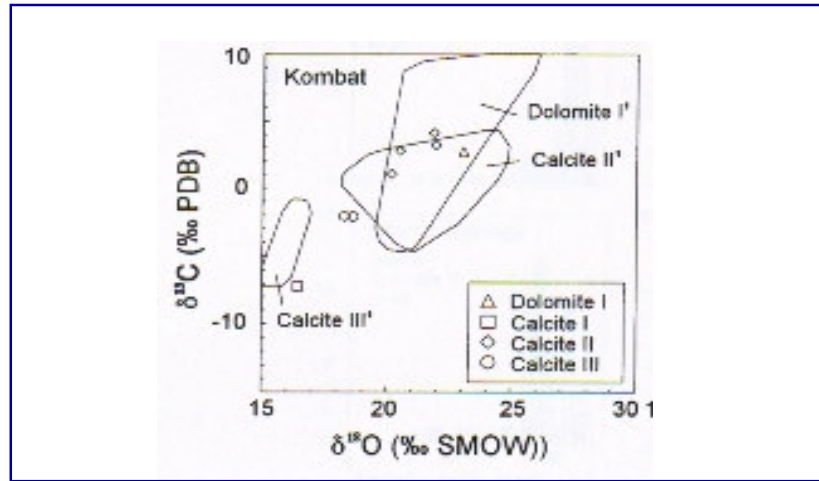


Figure 6.9: $\delta^{18}\text{O}$ vs $\delta^{13}\text{C}$ plots for carbonate generations from Kombat (after Chetty and Frimmel, 1999).

Recalculating the formation temperature for the Kombat ores, using the 20wt% NaCl equivalent value and average Th of 250⁰C obtained by Ypma (1984), yields 405⁰C as the temperature for the main mineralization event (Chetty & Frimmel, 1999).

In contrast to previous studies, the results here indicate clearly that the mineralizing and sulphide remobilizing fluids in the Kombat deposits (Tsumeb type) were highly saline. All Cl/Br and Na/Br ratios obtained in this study, irrespective of sample locality and including examples from Tsumeb type deposits, plot close to the seawater evaporation curve and are far removed from the ratios of normal seawater. This result indicates a large component of evaporitic residual brines in the overall chemistry of the mineralizing fluids in all of the deposits.

Results of the geochemical investigation show the possibility of an orogenic brine model for the Tsumeb type mineralization at Kombat and that the mineralizing fluids are high in salinity

thus emphasizing the importance of salinity for a fluid's potential to carry large amounts of base metals. First fluid inclusion leachate data from this region clearly demonstrate that the high salinity was derived from the interaction with evaporites. Such evaporites were present not only in the internal parts of the Damara Belt further to the south but also in the immediate vicinity of the deposits. Thus the metal source for these deposits does not have to be located necessarily in the distant, more central region of the Damara belt but could have been nearby in the strata underlying the Otavi Group in the southern OML. Dean (1993) concluded that the Kombat Fe-Mn oxide/silicate assemblages differ from other iron formation types in their relatively high CaO, Ba, Sr, Y and Cu, and depleted MgO, Al₂O₃, Cr, Ni, Zr and Co contents. However, the Kombat iron formations can be compared more favorably to the sediment-hosted Lake Superior-type rather than the volcanic-associated Algoma -type deposits.

6.9 Stable Isotope studies

Stable isotopic studies by Chetty and Frimmel (1999) on samples of calcite associated with the Kombat deposits reveal that the primary mineralized calcite veins (those that host bornite and chalcopyrite), show similar isotopic ratios to the pervasive calcite associated with the altered and mineralized dolostone at Kombat. The $\delta^{18}\text{O}$ ratios of the mineralized calcite veins are elevated and range between 18.4‰ and 21.5‰ whereas the $\delta^{13}\text{C}$ ratios range between -1.9‰ and +2.5‰ (Chetty & Frimmel, 1999).

6.10 Constraints on mineralization based on C and O Isotope results

Geochemistry cannot be used alone to provide information on the temperature of formation and origin of waters and the source of the carbonate from the $\delta^{18}\text{O}$ and the $\delta^{13}\text{C}$ values as

there is more than one geochemical process that may produce the same isotopic result and the same geochemical process can yield entirely different isotopic characteristics under different conditions. From the above studies the following can be constrained;

- The observed calcitization commonly has associated primary mineralization (bornite and chalcopyrite) so it is assumed that the fluids which precipitated the calcite are of the same source.
- It can be assumed that metamorphism must have played some role in the genesis of the Kombat deposits.
- The age of the first mineralizing event can be established with some certainty to be pre D3. Chalcopyrite stringers within the Kombat Formation Phyllite are deformed and folded by the D3 deformation.
- The main mineralizing event at Kombat took place syn – to post D3 deformation.
- The ore fluids were introduced syn- to early post deposition of the Otavi Valley Sandstones. These sandstones appear to have been unconsolidated at the time of the D3b deformation.
- It is unlikely that the ore fluids were directly related to any magmatic process as the nearest magmatic intrusion of this age is approximately 100km to the south of Kombat.

Chapter 7

Mineralization

7.1 Introduction

The Kombat Mining Complex (KMC) hosts 7 known ore loci; from east to west identified as Asis Ost, E900, Kombat East, Kombat Central, Kombat West, Asis West and Asis Far West (Fig. 7.1). The mineralized localities host Cu, Pb, Ag and minor Zn occurring in variable quantities, geometries and distribution. Cu, Pb and Ag have been exploited economically at Kombat over a very long period of time dating back as early as 1911 until December 2007 when operations were suspended as a result of flooding.

Mineralization within the KMC is hosted in the T8 lithological unit of the Hüttenberg Formation except for the Asis Ost which extends into the T6 unit of the Hüttenberg Formation from the T8 Unit. In the Kombat area, the T8 comprises a lower massive detrital dolomite with occasional stromatolitic chert lenses; a middle unit of oolitic dolomite and an upper unit of slump breccias. Extensive slump breccias within the T8 lithozone are intimately associated with the massive oolites and are a result of periodic disturbance of the carbonate platform.

Sandstone occurs associated with the ore bodies and seems to increase progressively westwards. In the eastern orebodies, sandstone occurrences are limited to a few small lenses within the ore bodies but become more prominent westwards. In the W550, W750 (Asis West) and Asis Far West areas, sandstone forms the matrix in talus breccias and also occurs, as multiple lenses within recrystallized dolomite as well as megabodies, tens of meters wide, oblique to the dolomite beds.

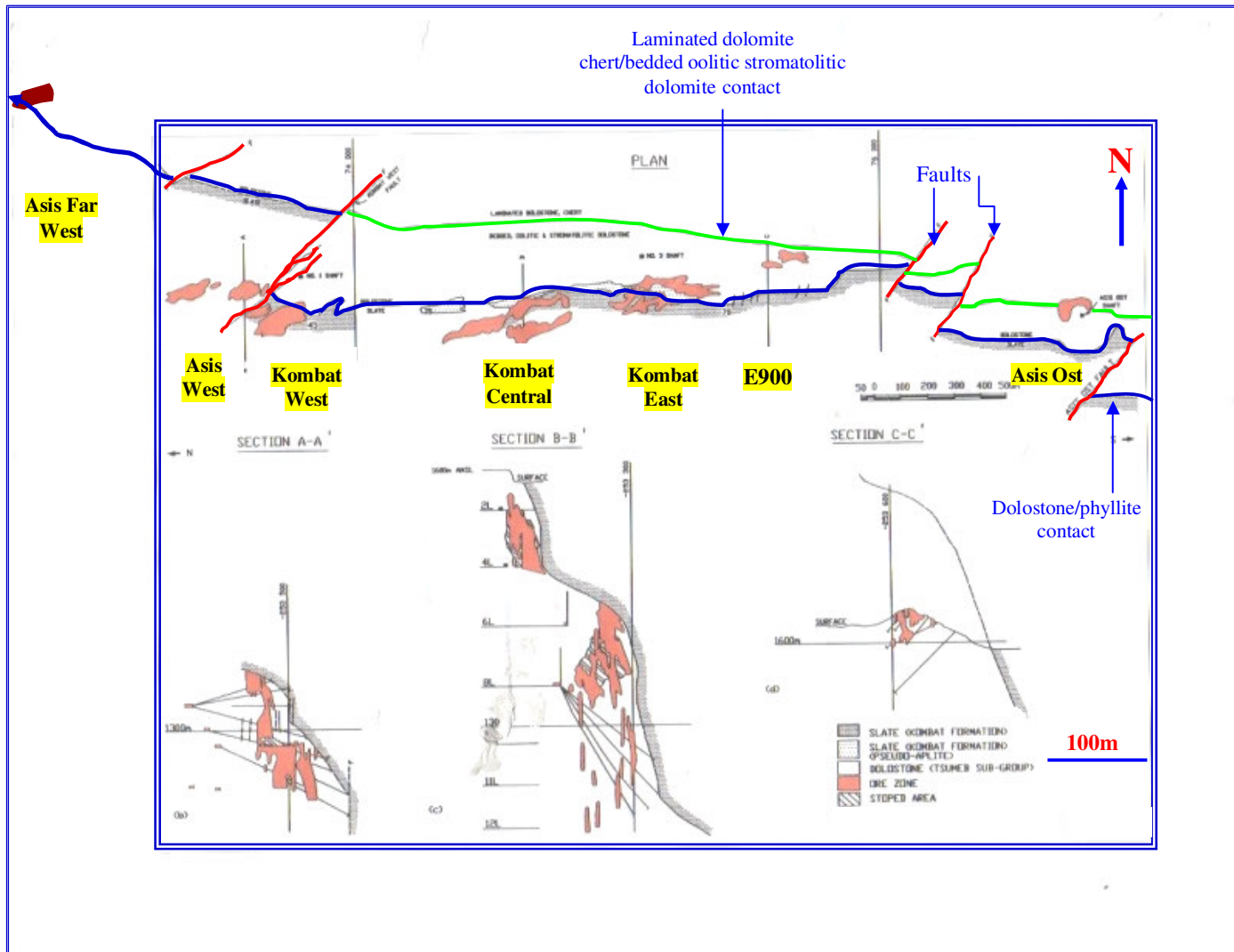


Figure 7.1: Kombat Mining Complex (KMC), Locality plan of the defined centres of mineralization, modified by Changara (2007) also showing a few selected geological cross sections.

Iron manganese bodies are known to exist at various localities within the KMC.

7.2.1 Introduction

Mine geologists at Kombat mine have collected geological information on the deposit from as early as 1911, but this data has been used almost entirely for mining production purposes, with little or no views at all to publish this data. This data has been re examined, reviewed and modified (and acknowledged) in this study and integrated with original data collected and analyzed in this research in an attempt to model the geological controls to Kombat mineralization. On this basis, a section has been created to examine the strict geological implications of the data (unpublished normal production related geological information) collected over time to the controls on mineralization and synthesized with the real time geological data collected and examined during this study.

7.2.2 Dolostone/phyllite controls to mineralization

The orebodies at Kombat have been described as hanging like pendants from the dolostone/phyllite contact (Petzel, 1992). The dolostone/phyllite contact at the KMC has been regarded as the most important control to mineralization and several authors including Deane, 1993 went to the extent of describing the mineralization at Kombat as “contact type mineralization. Some stopes in the Kombat West orebody (Fig. 7.1) shows the ore – contact (dolostone/phyllite) relationship which culminated in coining of this term.

Figure 7.2 shows plan view of mineralization at 1540m elevation of the Kombat West orebody. Mineralization exhibits the general 070⁰ orientation with a core of massive mineralization. The Kombat West Fault marks the western limit of the Kombat West orebody

mineralization. It is the western most orebody that outcrops on surface beyond which mineralization has been displaced downwards and laterally by the Kombat West Fault.

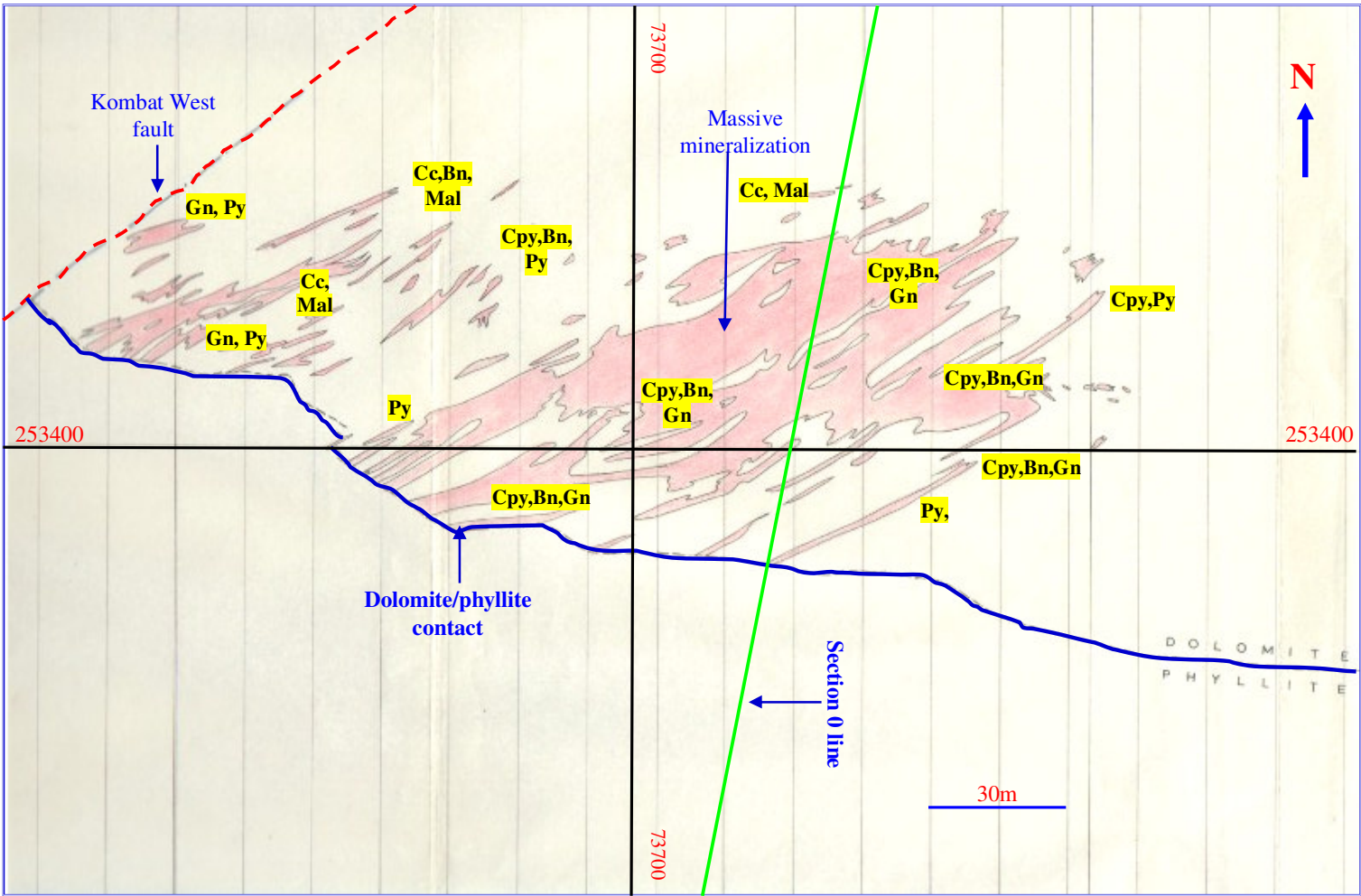


Figure 7.2: Kombat West Stope, mineralization patterns and the relationship to the dolostone/phyllite contact, 1540m, modified by Changara (2007) after TCL unpublished company reports.

The mapping depicts pyrite – chalcoite – malachite generally rimming the centres of stringer
 to massive malachite – chalcocite – bornite. Mineralization in this zone is defined as Cu of

>1.0% or Pb >3.0%. Mineralization typically terminates at the dolostone/phyllite contact. Figure 7.3 is a structural map of the same stope shown in Figure 7.2. Two prominent structural directions are apparent, the NE trending fractures sympathetic to the Kombat West Fault and the less developed WNW fractures, which are not continuous. A cross section, thorough the stopes is shown in Figure 7.4. It clearly depicts the termination of mineralization on the dolostone/phyllite contact. However, on close inspection of the associated geological parameters (structure, lithology), it is clear that the contact is not the only mineralization controlling parameter.

The W550 area is defined laterally between Lo, E72790.8 – E73030.8 (Lombaard, 2008) and shows close association of mineralization to the dolostone/phyllite contact. A number of small stopes have been exposed and mined within this area. The stope of significance is the W550 – Central (Figs. 4.12 & 7.5) (geological plan and geological section respectively). The stope consists of hanging wall sandstone that is fairly uniform with light grey to medium grey as the dominant colours. In the eastern part of the sandstone body, gritty and pebbly layers become more plentiful within the dominantly medium grained sandstone, evidence of layering from bedding is apparent. Some minor conglomerate layers have been identified. The wallrocks of the sandstone comprise phyllite, dolomite and the Fe-Mn assemblage. Evidence indicates that phyllite wraps around the lowest part of the sandstone body and in places continues for some distance upwards along or close to the northern (footwall) contact of the sandstone (Fig. 7.5). The main ore in the W550 – Central Stope is sandwiched between the footwall Fe – Mn bodies and the hanging wall sandstone. The ore is composed of chalcopyrite, and subsidiary bornite.

These minerals are finely disseminated together with pyrite, in the main ore body and occur as veins and patches in the adjacent altered dolomite accompanying sandstone and Fe-Mn lenses.

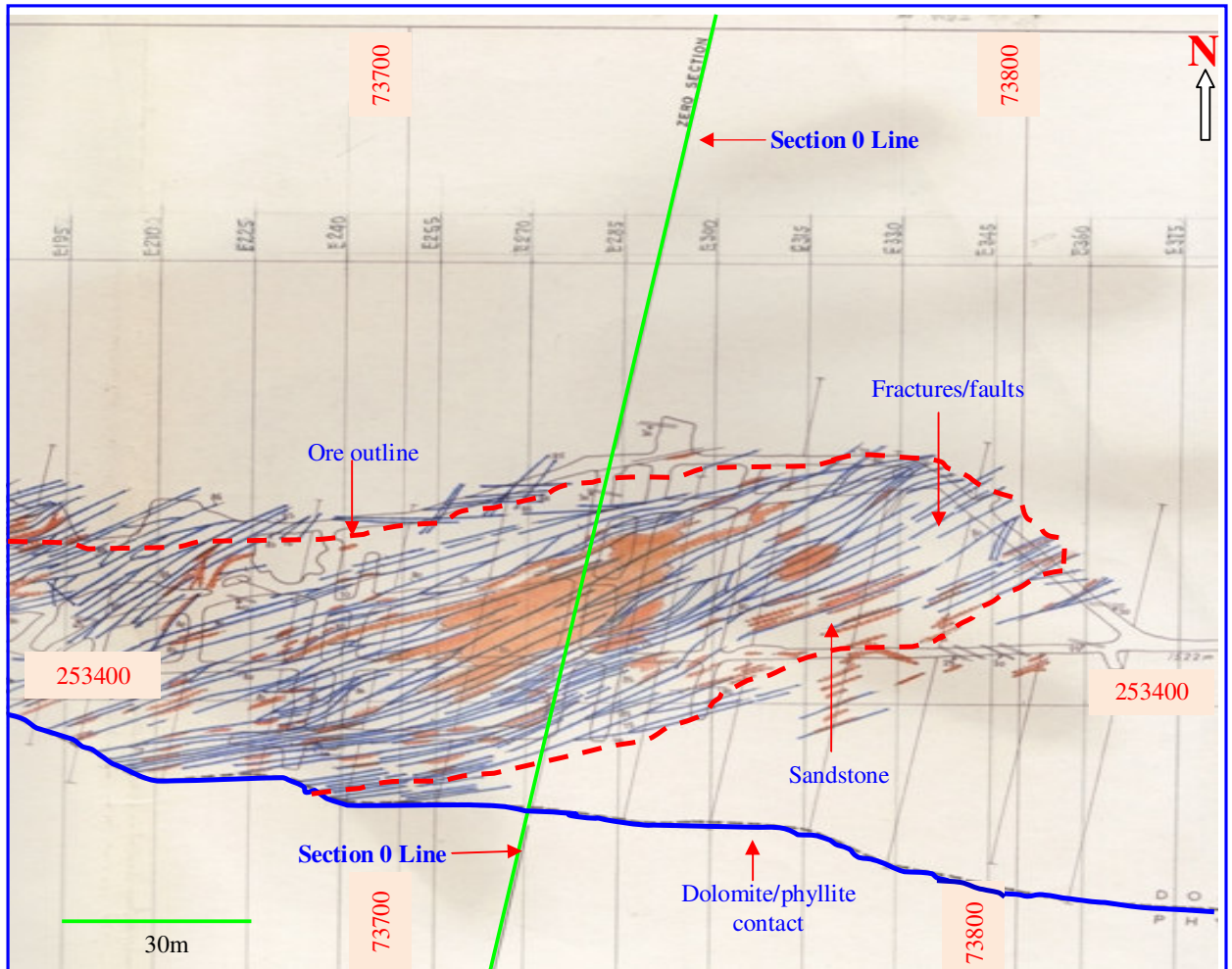


Figure 7.3: Kombat West Stope, plan view showing the structural orientation of mineralization and its relationship to the dolostone/phyllite contact sandstone body, 1560m elevation, TCL unpublished company geological reports, modified by Changara (2007b).

7.2.3 Sandstone and iron manganese controls to mineralization

The Kombat mine sandstone and iron manganese bodies have been described as controlling mineralization or described as centres of mineralization by several previous workers on the Kombat mine including, Innes and Chaplin (1986) and Dean (1993).

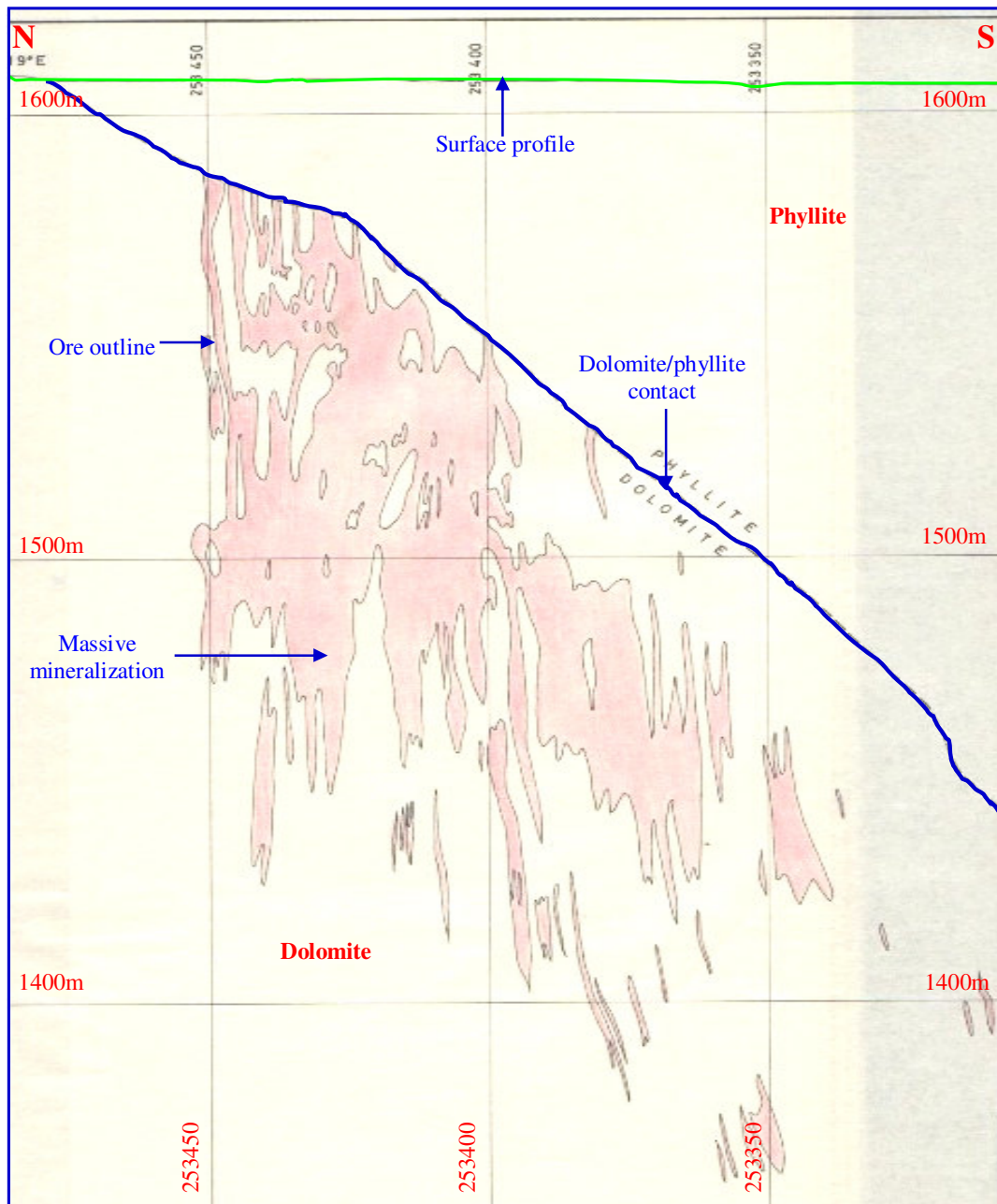


Figure 7.4: Kombat West; geological cross section 0, looking east showing the ore mineralization profile with the dolostone/phyllite contact –ore relationship, modified by Changara (2007b).

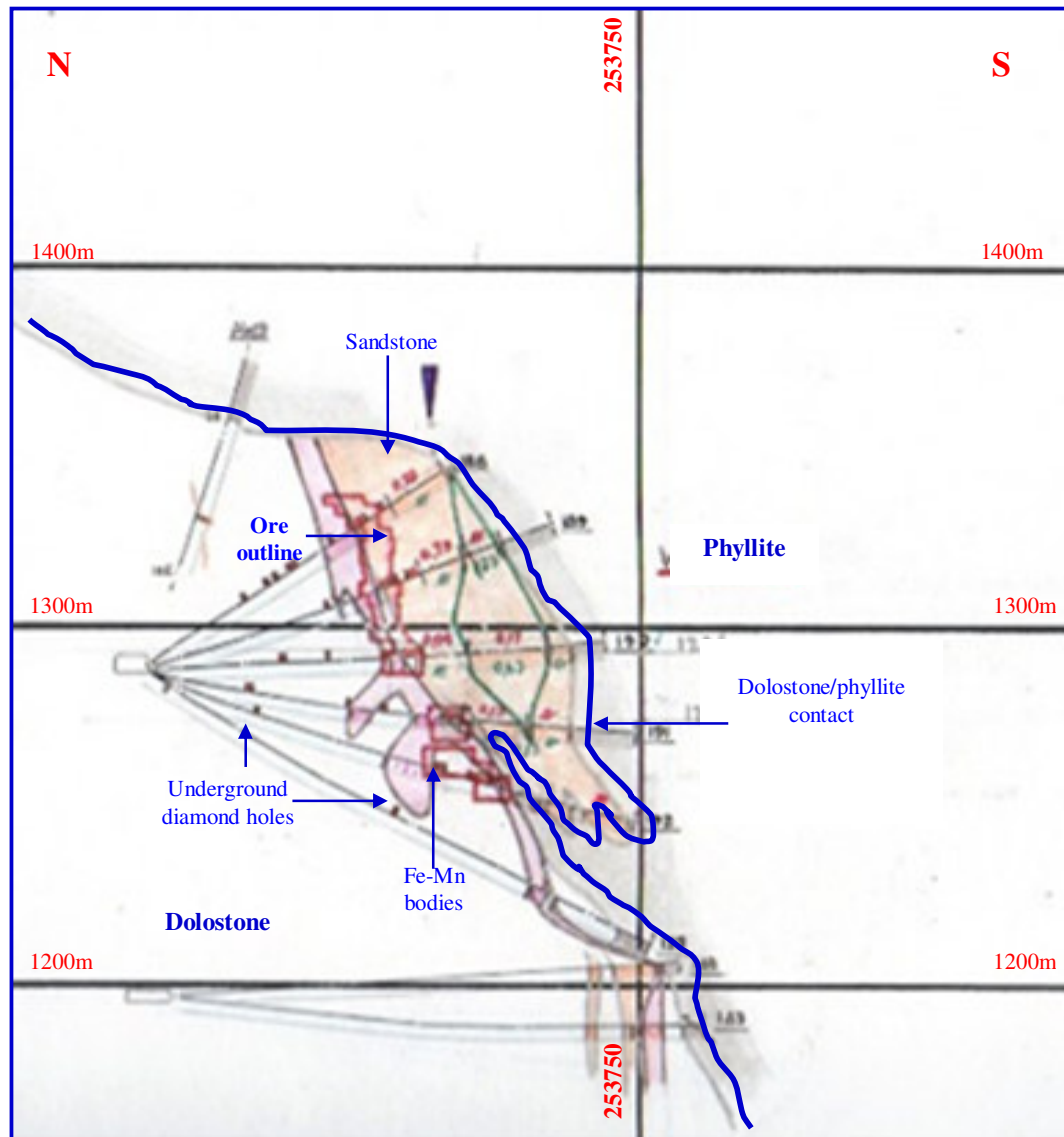


Figure 7.5: Asis West; W550 –Central stope cross section showing the dolostone/phyllite, sandstone and Fe-Mn and mineralization relationships modified after TCL, geological mapping.

Figure 7.3 is a geological plan of a Kombat West stope (ore outline of the same stope displayed in Figure 7.2) showing the sandstone outline and its relationship to mineralization. The sandstone profile of the mineralization displayed in Figure 7.4 is shown in Figure 3.8

It shows a definite positive correlation with the zones of massive mineralization. In the zones where mineralization is weak or disseminated or of stringer form, the sandstone bodies also show similar geometrical patterns. The sandstone dips vertically and has a central massive

zone with stringer rims. Mineralization also terminates (hangs) on the dolomite/phyllite contact.

Figures 3.5 and 3.10 show the iron manganese – mineralization relationships of selected Asis West orebodies as plan view and cross section respectively.

There is a very close association between mineralization and the iron manganese orebodies and the sandstone. Figure 3.10 is a plan view around 1230m elevation of the eastern most Asis West orebodies. The dolomite/phyllite contact is folded with some ore bodies just touching the contact whilst others terminate some distance from the contact at this elevation. The eastern orebodies are characterized by sandstone lenses and stringers aligned in a NE - SW direction. Brecciation of the dolomites is important. No iron manganese bodies are preserved on the eastern ore bodies but rather on the western W90. The central bodies show inclusions of sandstone and iron manganese bodies within the ore mineralization. Westwards, the iron manganese and sandstone bodies surround the main ore body of mineralization. Whilst the dominant structural fabric in this area is the NE – SW direction, there is also an E – W trend and a subtle NW – SE trend. The fractures vary from joints to faults with no displacement. The faulting is sympathetic to the main Kombat West Fault but with no apparent displacement. Figure 3.5 is a cross section across the orebodies and depicts intricate relationships between mineralization and the iron manganese and sandstone bodies. The dolomite/phyllite contact displays complex folding/rolling/slumping.

Another striking structural feature occurring in the W90 stopes is defined by a series of phyllite and sandstone wedges or piercement structures which penetrated the carbonate rocks. These piercement structures of clastic sedimentary rocks are strongly foliated and have a close relationship to massive sulphides. Indeed, the largest bodies of massive chalcopyrite or bornite lay either adjacent to or at the apices of these clastic rock wedges. The sandstone

wedges are generally not internally mineralized; however the phyllite piercements contained elongate nodules of pyrrhotite up to 40cm long and 10cm wide. Two sulphide textures occurred in this area, a fine grained sulphide with clasts or fragments of carbonate rock, and a very coarse grained sulphide with no wall rock inclusions. The coarse grained end lens always pinched out whereas the finer grained end led into a larger mass of fine grained.

7.2.4 Faulting controls to mineralization

The Kombat West fault (Fig. 7.6) displaces mineralization of the Kombat West and Asis West orebodies in both horizontal (~300m) and vertical (~200m) senses.

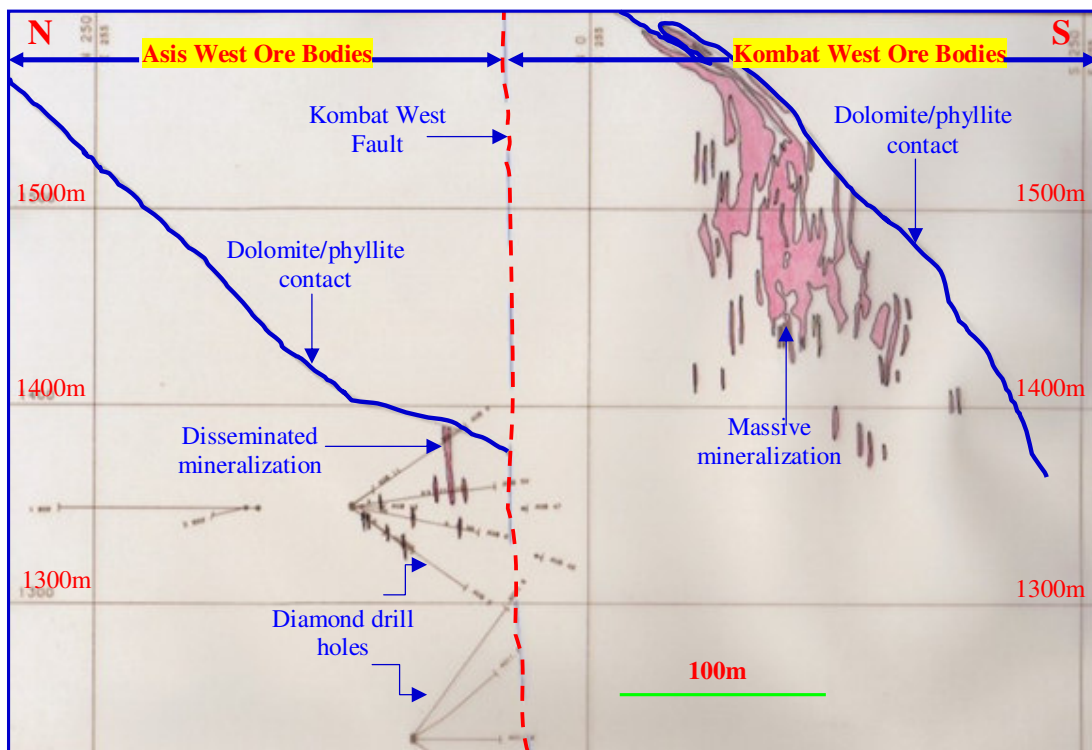


Figure 7.6: Asis West; cross section showing displacement of the orebodies by the Kombat West Fault and the relationship of the orebodies to the dolostone/phyllite contact and underground diamond drill holes modified by Changara (2007)

The most important structural control element to mineralization hitherto has been ascribed to the NE structural fabric imparted on “all” orebodies. The NE strike orientation is shown in Figures 3.10, 7.2 and 7.3.

7.3 Mineralization patterns identified and analyzed in this study

A number of stopes have been studied in detail (geological and structural mapping and analyses, thin and polished sections analyses, geochemical investigations, petrography and 3D modeling) during this research and the findings are presented herein.

7.3.1 Dolostone/phyllite contact - mineralization relationships

This study has shown that the dolostone/phyllite contact is very important to mineralization but its relationship to mineralization is much more complicated than previously described. The following Figures; 7.7, 7.8, 7.9, 7.10a and 7.10b show the variable nature of the dolostone/phyllite – mineralization relationships. In Figure 7.7, the mineralization terminates on the dolostone/phyllite contact. In Figure 7.8, the mineralization just stops short of the dolostone phyllite contact in the Kombat West orebody.

The mineralization in the Kombat East orebody (E75250 stope) (Fig. 7.9) and Asis West, W800 orebody (Figs. 7.10a & 7.10b), geological plan and section respectively and the Asis Far West, W1830 stope (Fig. 7.11) is now located some considerable distance from the dolostone/phyllite contact.

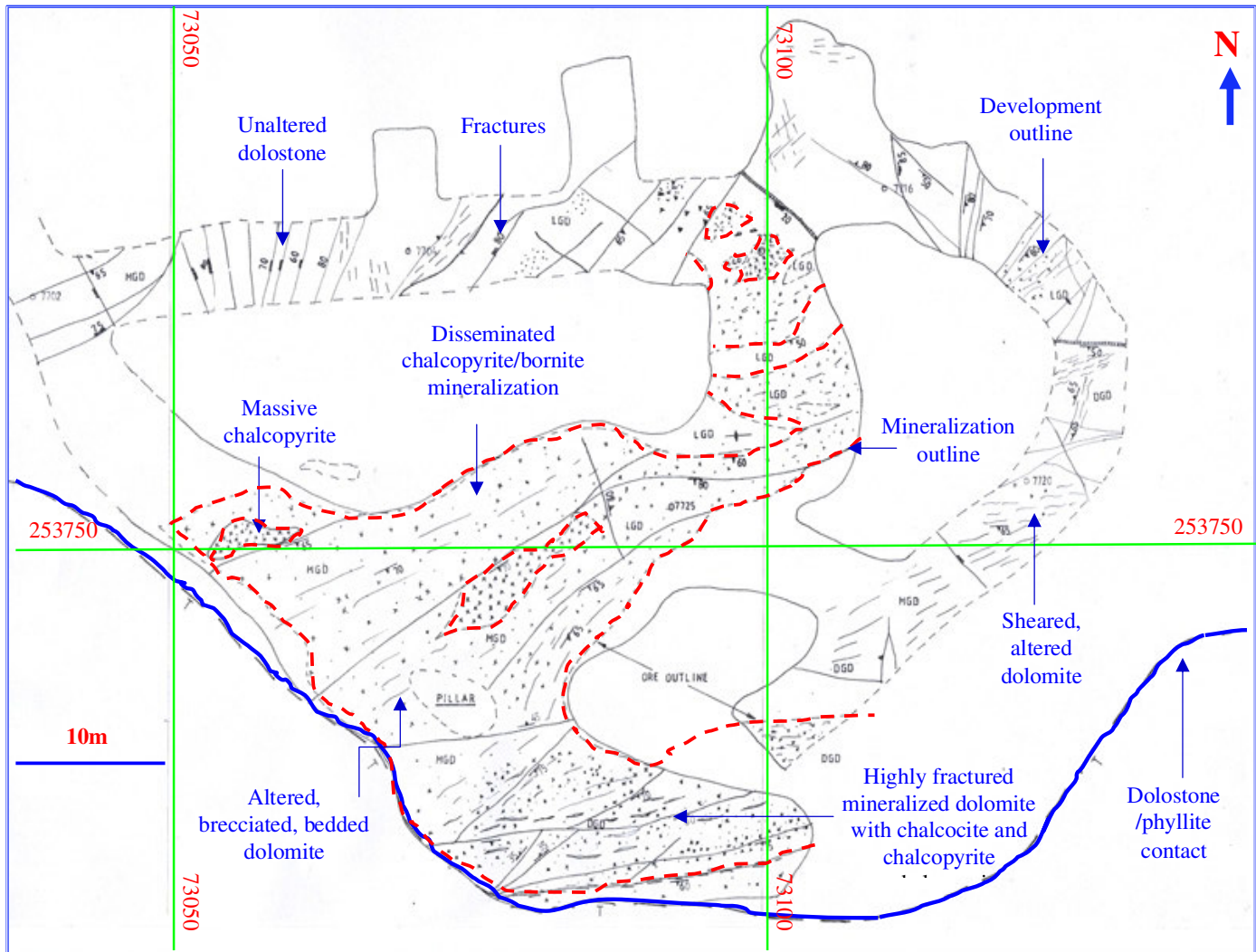


Figure 7.7: Asis West; 8 level W270 orebody, 1350m elevation mineralization, structural – lithological and the dolostone/phyllite relationships.

7.3.2 Karsting – mineralization relationships

Asis Ost mineralization is characterized by karst cavities both on surface and underground.

Figure 7.12 shows the occurrence of the karst features and the association of mineralization

to alteration, karst cavities and some minor brecciation. Mineralization is vertical to sub vertical.

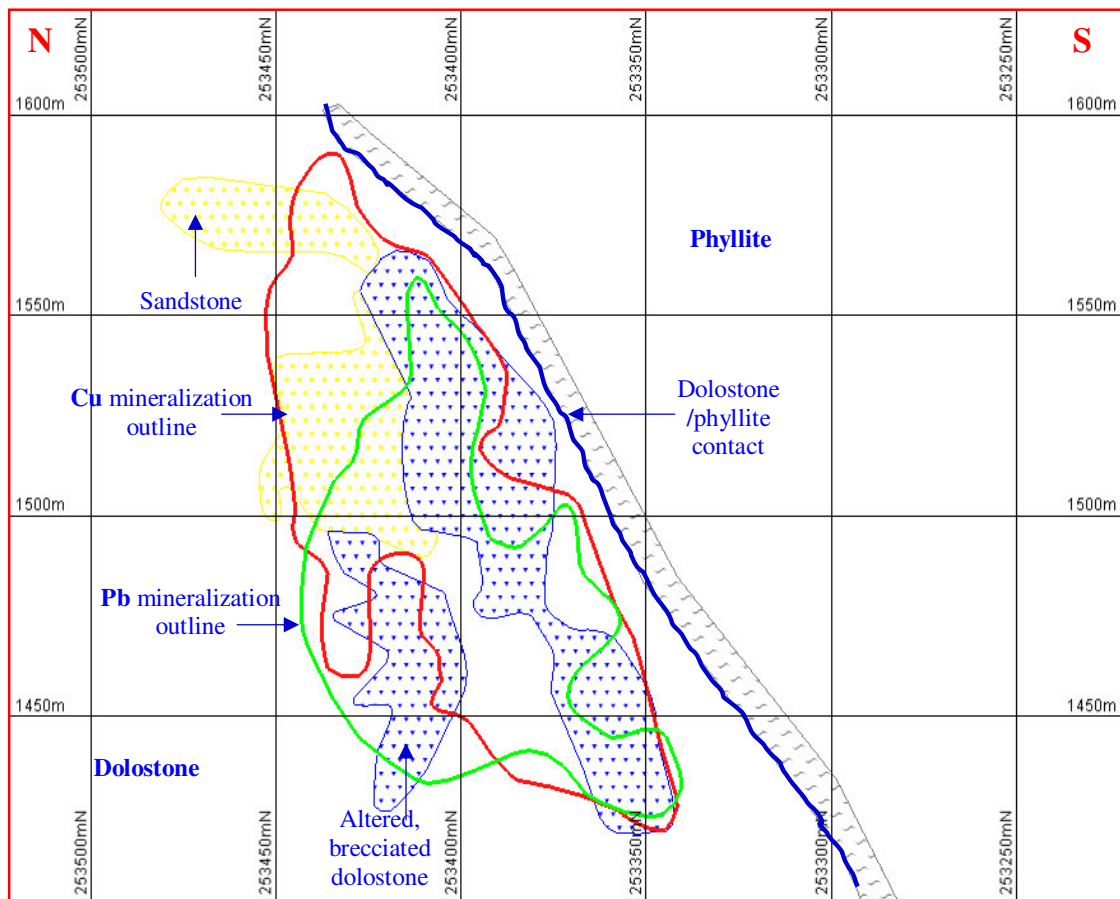


Figure 7.8: Kombat West Orebody, E73720 cross section showing the dolostone/phyllite contact relationship to Cu, Pb mineralization and associated lithologies.

One striking feature that is not common to the other centres of mineralization within the Asis Ost ore body is that the ore bodies are so distal to the dolomite/phyllite contact. Surface mapping indicates that intense calcitization has resulted in replacement brecciation and possible solution collapse. Supergene mineralization outcrops at Asis Ost indicating that the present geographic surface is relatively young.

The original oxidation zone which supplied the copper-rich solutions for enrichment in depth may have been eroded away at a faster rate than that at which oxidation could take place, thus

preventing the formation of a normal oxidation zone. The original supergene zone is now exposed to the ‘elements’ and a second period of oxidation has set in.

The formation of cuprite and native copper from chalcocite at the Asis Ost deposit is evidence of this second period of oxidation. The decrease in the amount of oxidation with an increase in depth is well illustrated in samples from drill holes at Asis Ost prospect.

7.3.3 Lithology – alteration – mineralization relationships

Geological mapping and petrographic studies have shown complex relationships between lithology, alteration and mineralization. Figures 7.7, 7.8, 7.10a and 7.10b show the close association of mineralization to brecciation. The E73720 stope (Fig. 7.8), Kombat West and E75250 stope (Fig. 7.9), Kombat East are stopes that have mined specifically for lead with copper as a byproduct whilst others have been abandoned and to date they have available ~500 000 tonnes of lead. These galena rich ores are associated with steep breccia bodies with pipe like configurations as shown in Figures 7.8 and 7.9.

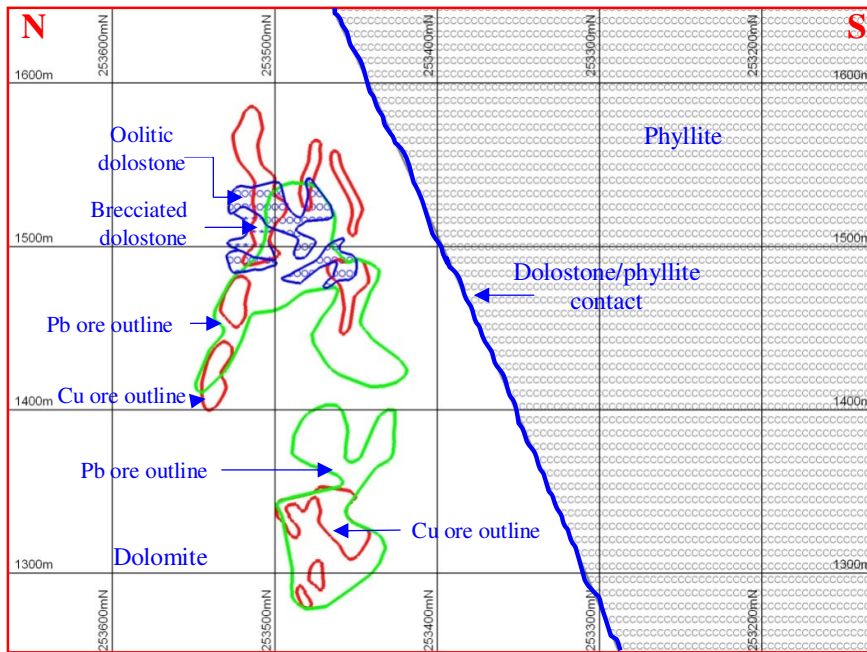


Figure 7.9: Kombat East, North – South cross section E75250 stope, looking east, showing the ore outlines, lithology and dolostone/phyllite associations and relationships.

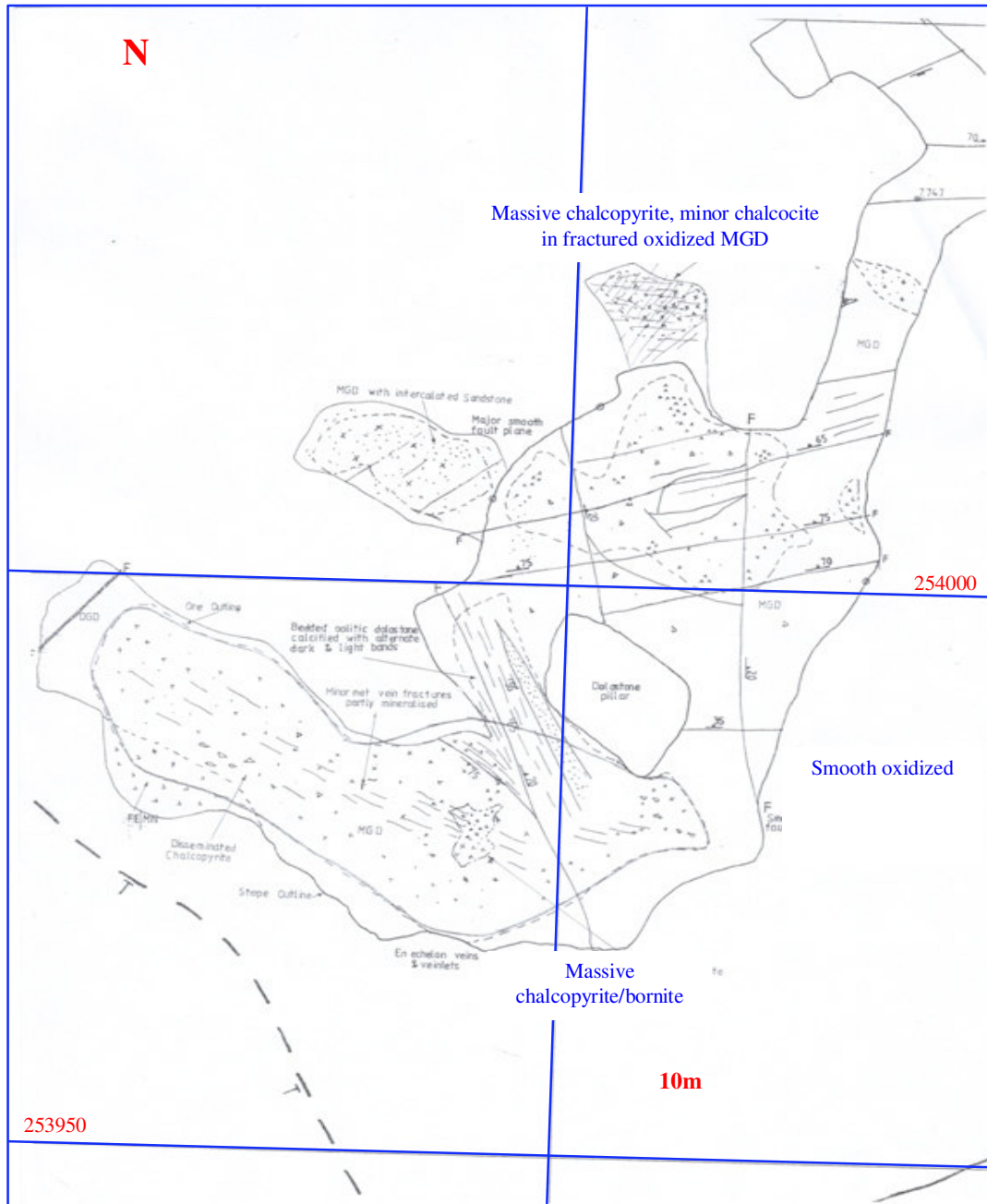


Figure 7.10a: Asis West; 12 level W800 Stope, geological map with mineralization, lithological, structural dolostone/phyllite contact relationships.

Figures 3.14a and 3.14b show typical bornite dominated hydraulic breccia samples from underground diamond drill core, Au12/265 and Au12/259 respectively of the Asis West orebody, W270 orebody, 13level.

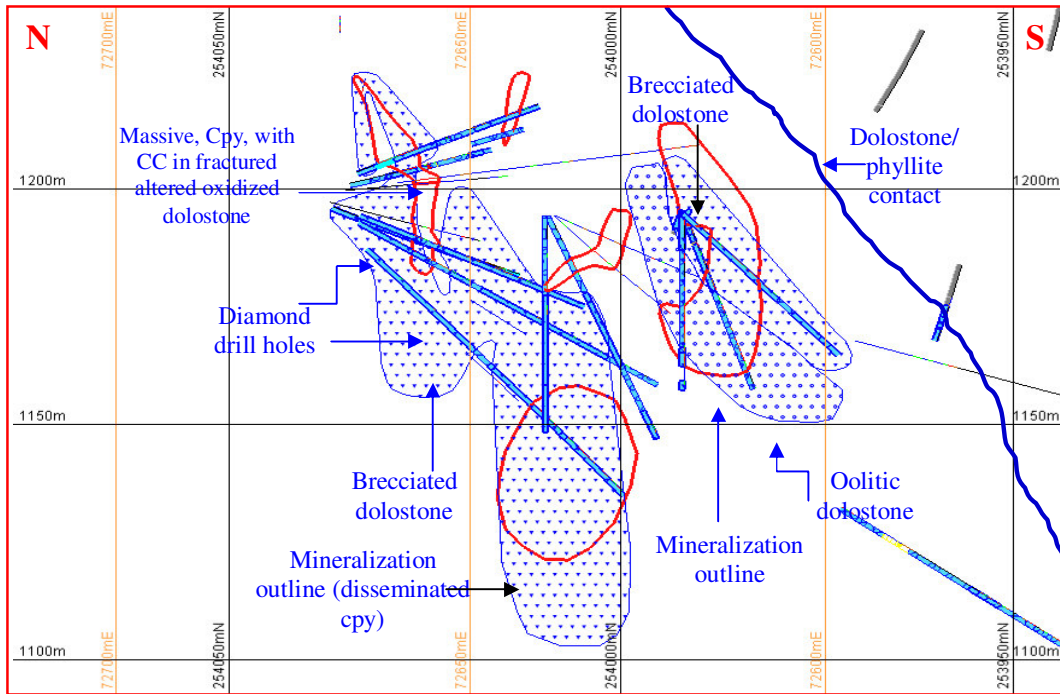


Figure 7.10b: Asis West, cross section through the 12level W800 orebodies, showing the lithology, mineralization and dolostone/phyllite relationships.

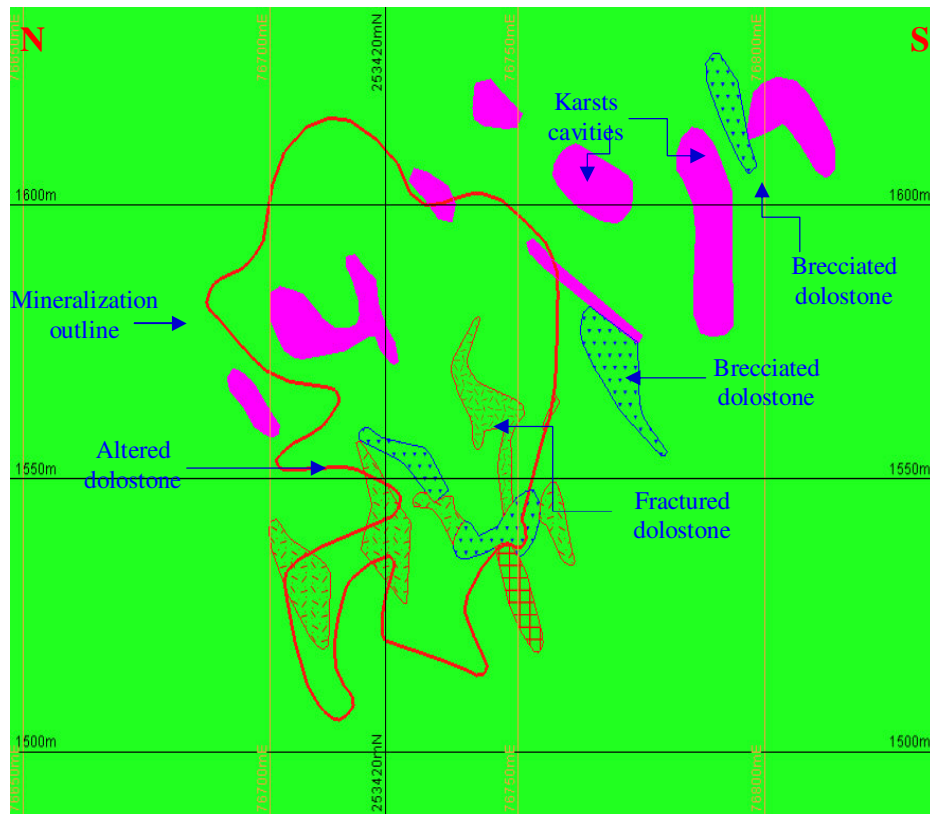


Figure 7.11: North - South geological cross section looking east across the Asis Ost Orebody, showing karsting and its relationship to mineralization and lithology.

In Figures 3.3 and 7.12, the Asis West, W750, 12level stope, mineralization was identified through diamond drilling and structural interpretation and projection. Drilling was done from the exploration drive situated approximately 100 – 150m north of the dolomite phyllite contact (Fig 3.3). The typical sequence of the lithologies is as follows, from the exploration drive to towards the dolomite/phyllite contact; a massive fine grained dolomite with occasional stromatolites, slump structures, detritus and sedimentary karst breccias. The dolomite is relatively unaltered and barren of mineralization except for some odd malachite and chalcocite blebs which occur occasional within the calcite matrix of the hydraulic breccias.

The massive dolomite is followed by a sequence of oolitic, detrital dolomite layers and massive dolomite layers. The contact with the massive dolomite is gradational with the detritus consisting mainly of angular clasts of black algal remnants oriented mostly randomly, but laminations do occur occasionally. The fine grained massive dolomite layers are unaltered and barren of any mineralization. The mineralization consists mainly of disseminated pyrite and chalcopyrite within the oolitic matrix with some chalcopyrite replacing the oolites but the grade is normally sub economic.

Above this unit is an extremely calcitized dolomite with occasional sandstone and this unit grades into a matrix supported breccia with angular clasts of extremely calcitized recrystallized dolomite and white chert in a sandstone matrix. Mineralization is normally disseminated pyrite, chalcopyrite and galena within the sandstone matrix. Beyond this, iron manganese oxide and silicate minerals start to replace the sandstone in the matrix of the breccias with abundant hematite and magnetite which increase towards the massive layered iron manganese oxide and silicate body in the centre of the zone. An attempt has been made to link the lithological logging from the different diamond bore holes as shown in Figure 3.3.

The area has been affected by faulting with variable displacements. Figure 7.12 shows a north – south cross section looking east across the W750 orebody and it displays the general relationship of the litho units to mineralization and the dolostone/phyllite contact.

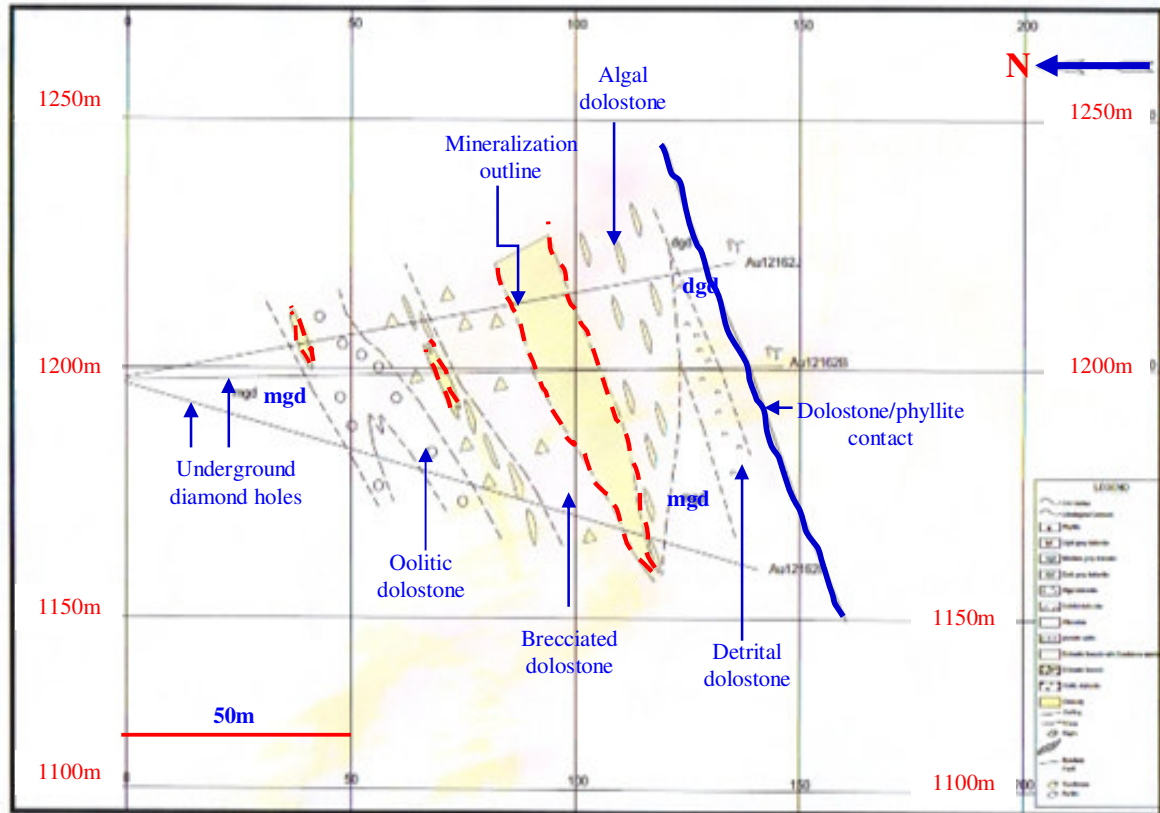


Figure 7.12: Asis West; cross section through the 12 level W750 orebody displaying the lithology, mineralization outline and the dolostone/phyllite contact relationships.

Bornite – galena and tennantite overgrowths are shown in Figure 7.13 whilst Figure 7.14 shows altered dolostone with silicification and a lattice preferred orientation from the W750 area on 12level, Asis West orebody.

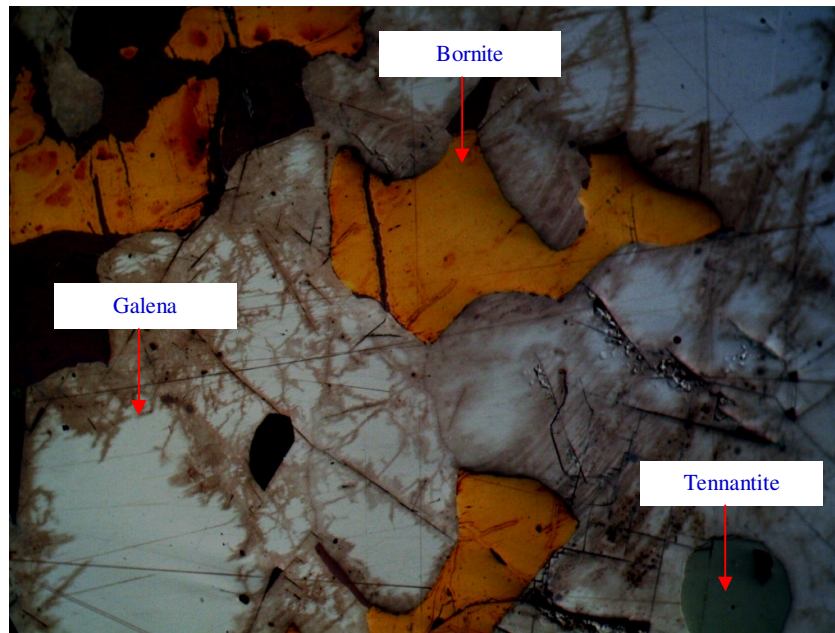


Figure 7.13: Galena, bornite, tennantite overgrowths and reactions rims, in a brecciated dolostone, 12level, W800 stope, Asis West orebody, polished section x10 magnification.

In Figure 7.15, chalcopyrite, galena, tennantite mineralization in an altered brecciated dolostone of the 3level, E750, Kombat East orebody (Fig. 7.16) is shown. Figure 7.17 shows the alteration – mineralization relationships in the 12level, W800 stope (Asis West orebody) of Figure 7.10a. Oolitic dolostones association with mineralization is shown in Figure 3.4b.

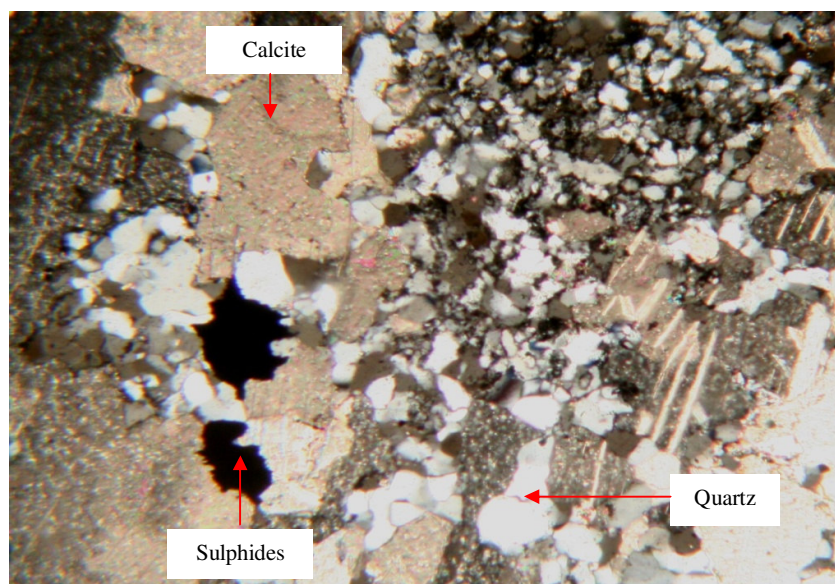


Figure 7.14: Altered dolostone with sulphidization, Asis West, 12level W750 stope 12 level, showing a subtle lattice preferred orientation, thin section, x10 magnification.

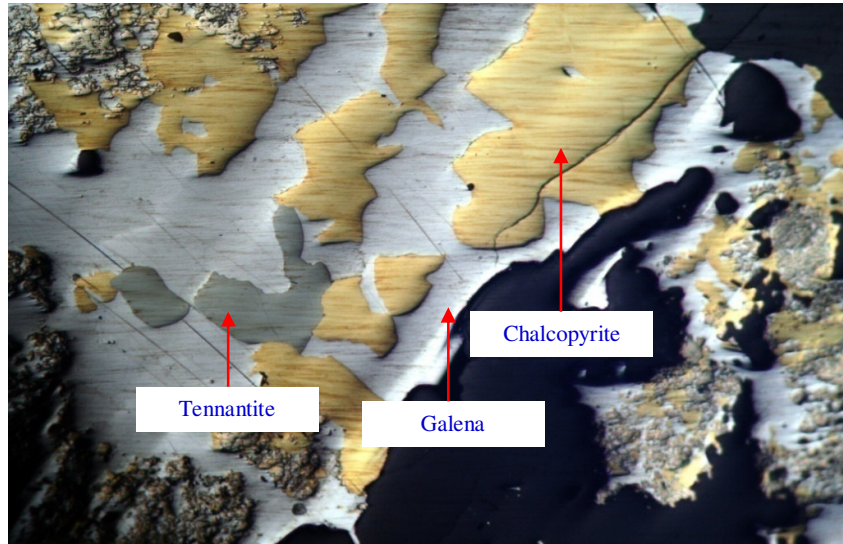


Figure 7.15: Chalcopyrite, galena and tennantite mineralization in altered brecciated dolostone of the 3level E750 stope, Kombat East orebody.

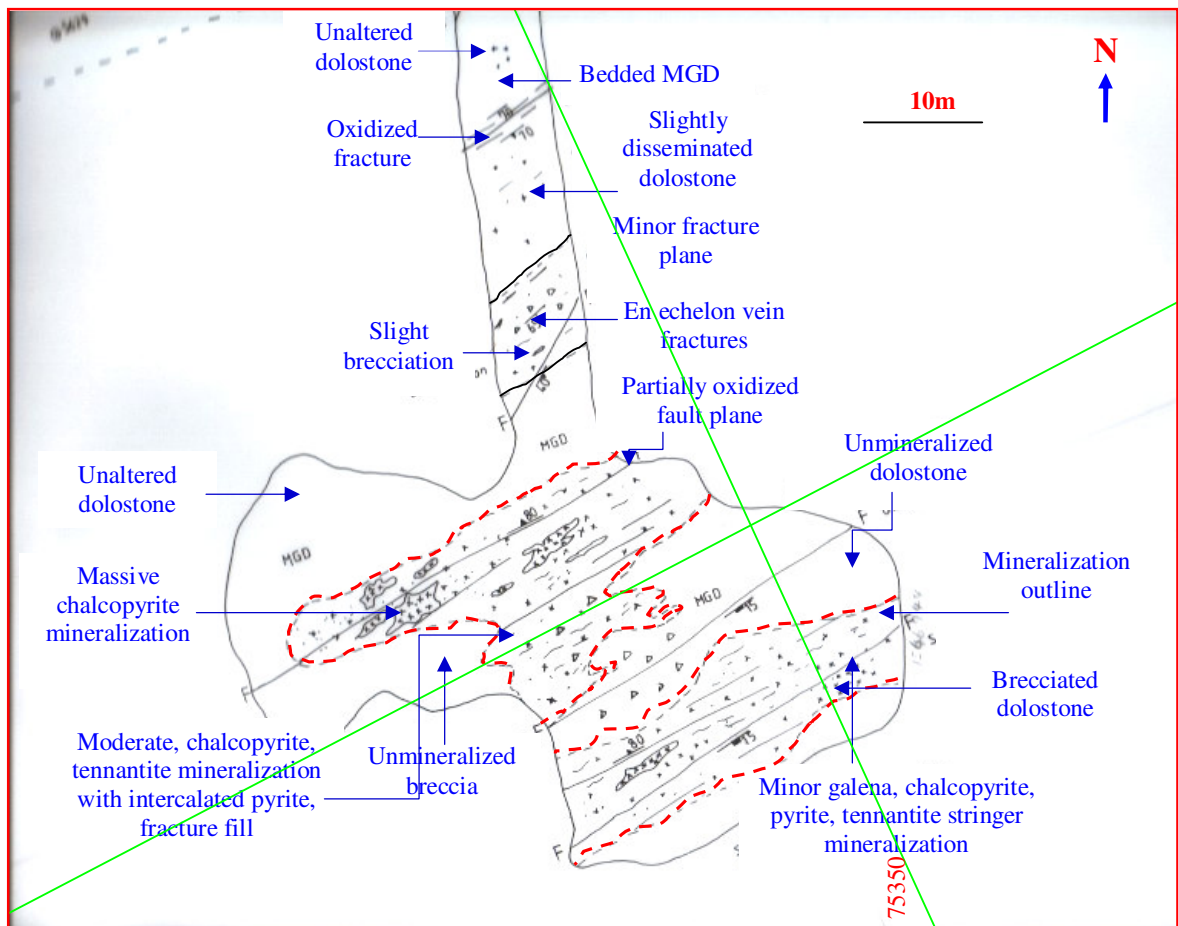


Figure 7.16: Kombat East, 3L E750 Stope, 1560m elevation, plan view, showing alteration – structure – lithology – mineralization relationships.

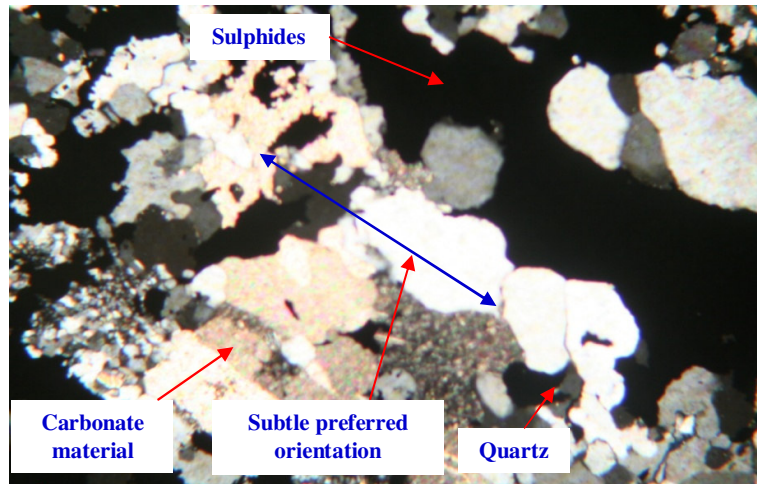


Figure 7.17: Alteration – lithology – mineralization relationships, 12level W800 stope (Asis West orebody).

7.3.4 Structure – mineralization relationships

Structural controls to mineralization at Kombat mines are variable and complicated. These will be described with the aid of figures below.

Replacement and fracture fill is a very common form of occurrence of mineralization within the Kombat orebodies. Almost all the ore bodies at Kombat show some form of replacement. The replacement takes various forms as described below;

Fracture fill is by far the most common form of occurrence of mineralization within the Kombat orebodies. Figures 7.18, 7.19, 7.20 and 7.21 show the various geometries of fracture fill mineralization for the different orebodies at Kombat.

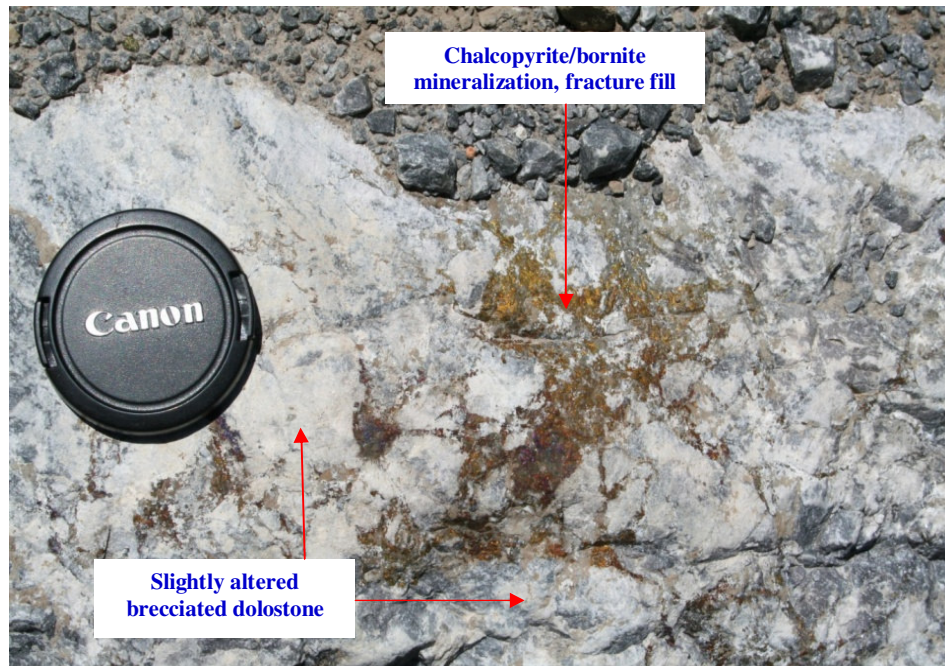


Figure 7.18: Fracture fill type of mineralization at the E900 open pit, the bornite, chalcopyrite and galena filling the second order to third order fractures.

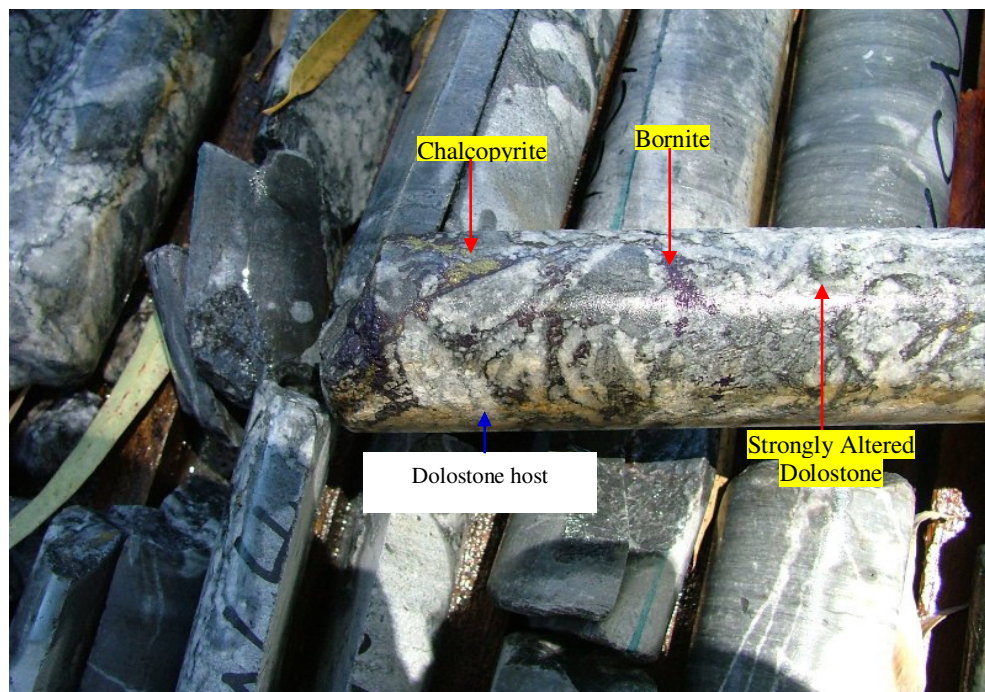


Figure 7.19: Kombat Central; stringer, fracture fill bornite – chalcopyrite mineralization in strongly altered slightly brecciated dolostone, KCN4 surface diamond drill hole.

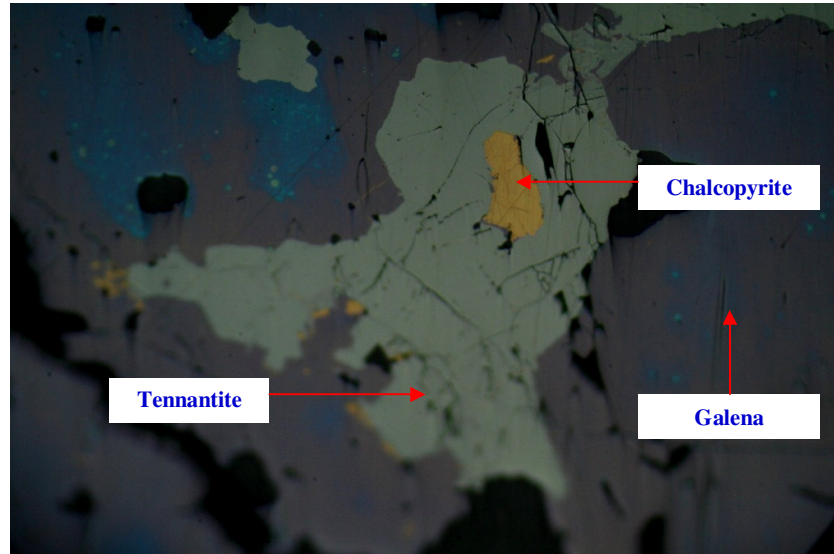


Figure 7.20: Polished section showing replacement mineralization chalcopyrite – tennantite – galena in a brecciated dolostone, 3level, E750 stope, Kombat East orebody, x10 magnification.

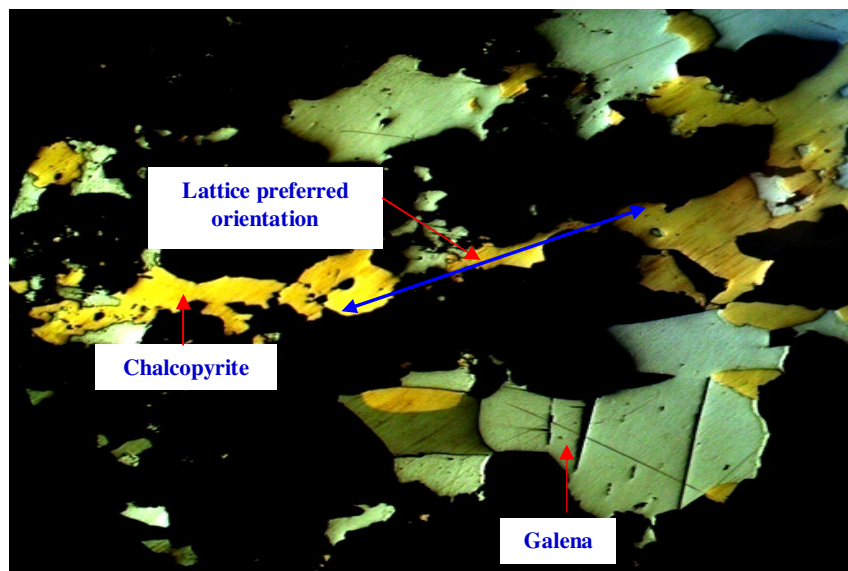


Figure 7.21: Chalcopyrite, galena replacement mineralization in slightly altered dolostone, 4level E600 stope, Kombat East orebody, polished section x5 magnification.

The second and third order generations at Kombat show an association with mineralization in some orebodies. The W210 – 20 stope (Fig. 4.10) is an example of a fault zone stope where supergene mineralization predominate the hypogene sulphides. The entire ore zone consists of dolomite (massive and brecciated), intercalations of phyllite piercements with varying

degrees of alteration. The ore is supergene enriched and consists mainly of chalcocite and Malachite. Other secondary minerals such as cerrusite, brochantite, cuprite and native copper also occur within the mineralized zone. Primary sulphides such as bornite and chalcopyrite do occur sporadically as remnants rimmed by secondary chalcocite. The orebody is bounded by the KWF3 and KWF3A which are characterized by approximately 2m thick zones of intense fracturing and brecciation associated with large open cavities and vughs with calcite infill. Mineralization is situated within the calcite matrix of the hydraulically brecciated dolomite. The lower unit of the ore body mainly consists of massive dolomite with unaltered zones of small blebs of dolomite that have been calcitized giving the dolomite a spotty appearance. The zone of weak alteration is overlain by massive dolomite with numerous tension gashes filled by completely calcitized and recrystallized white dolomite. Alteration in this zone continuously increases to produce a white marble with only small fragments of grey unaltered dolomite. This zone is followed by massive hydraulic breccias with clasts consisting of grey unaltered dolomite as well as totally calcitized and recrystallized dolomite (marble) within a calcite matrix. Malachite, chalcocite and cerrusite, with minor chalcopyrite, bornite and galena occur within the calcite matrix. The breccia is overlain by relatively unaltered massive dolomite which forms a sharp contact with the phyllite. The fractures are oriented generally in a NE – SW strike direction.

In the 13level, W270 stope, Asis West orebody, whilst the dominant faulting occurs in a NE WS direction, the mineralization shows a NW – SE strike orientation (Fig. 7.22). The structural – lithological – alteration – mineralization relationships of the 19 level, W1830 stope, Asis Far west are shown in Figure 7.23. Two dominant trends to mineralization are apparent; NE – SW and NW – SE trends. The 8level W270, 12level W800 (Asis West orebodies), 3level E750 (Kombat east orebody), 13level W270 (Asis West orebody) and Asis Far West orebody; structural – lithological – mineralization geometries are shown in Figures,

7.7, 7.10a, 7.16, 7.22 and 7.27 respectively. Figures 7.24 and 7.25 show the 070° structural trend to mineralization on plan and section respectively and also the horizontal displacement of the mineralization due to faulting.

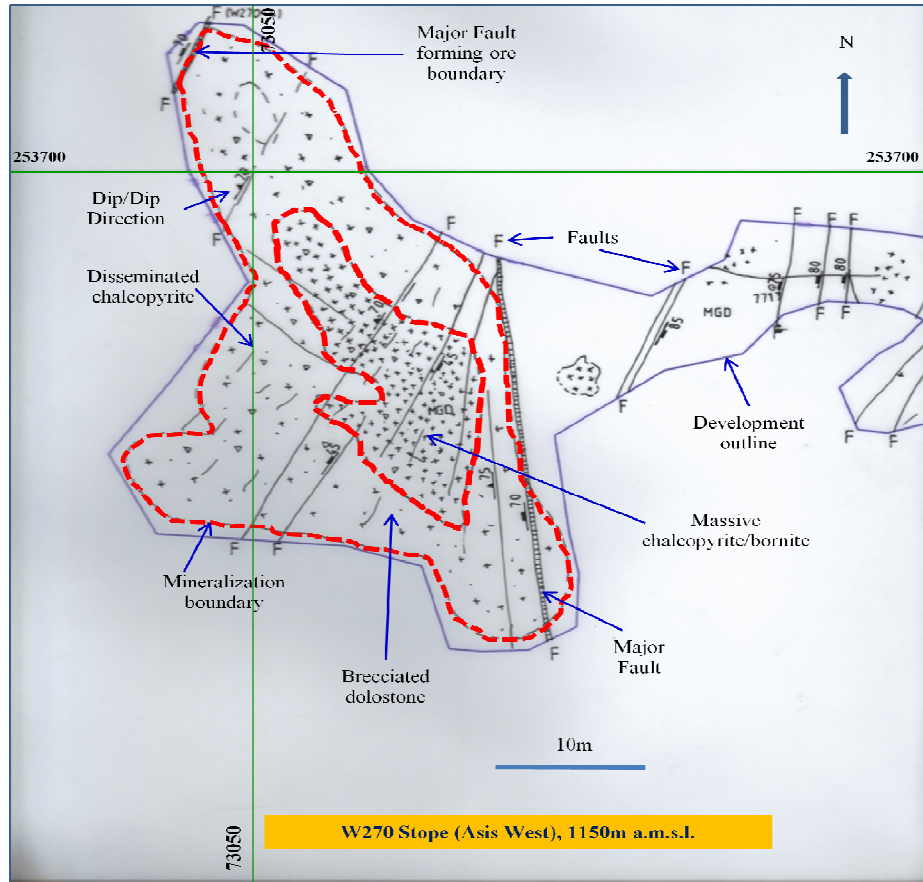


Figure 7.22: 13level, W270 stope, Asis West orebody, 1150m elevation geological plan showing faulting, lithology and structural orientation of mineralization.

7.3.5 Mineralization sandstone – Fe/Mn associations

Figure 7.24 shows the distribution of the sandstone within the Zero 4 and Zero 8 stopes of the Kombat Central orebody. These stopes have been offset by faulting, Figures 7.25 and 7.26. Whilst the cores of mineralization in the displaced ore body are massive, the sandstone core is only massive in the hanging wall part of the ore body whilst the footwall sandstone occurs in stringers. The displacement has also affected the sandstone highlighting a late stage faulting event. The faulting has a right lateral sense of displacement. An early subtle East –

West structural fabric is preserved but now the dominant one is the north east – southwest structural orientation. These ore bodies still exhibit a generally 070° orientation to the ore bodies with hydraulic fracturing and sandstone infill, figure 7.24. Sandstone occurrence has been also observed around the E73720 stope (Fig. 7.8), 12level W750 stope (Fig 3.3), 12level W800 stope (Fig. 7.10a) and Asis Far West Orebody (Fig. 7.24).

Iron manganese bodies have been observed in 12level W800 stope (Fig. 7.10a), 12level W750 stope (Fig. 3.3) and samples shown in Figures 3.4c, 3.12a and 3.12b were taken from the Kombat East, surface open pit. The samples show the tectonic nature of the iron manganese bodies, alteration around a sedimentary breccia and bedding parallel nature with development of Specularite respectively.

7.3.6 Mineral zonation

Mineral zonation has been observed in the Kombat East orebodies. Figures 7.8, 7.9, 7.16 and 7.28 show different patterns of mineral zonation as observed during this study. In the E73720 stope (Fig. 7.8) and the cone 4 level (Fig. 7.28) of the Kombat East orebody, well developed mineral zonation is developed both vertically and horizontally.

Generally, bornite is preserved at the cores of the ore bodies and is successively surrounded outward by a bornite – chalcopyrite assemblage, a chalcopyrite zone with or without tennantite and sphalerite, a chalcopyrite-galena-pyrite zone and pyrite+/-galena zone (Fig. 7.28).

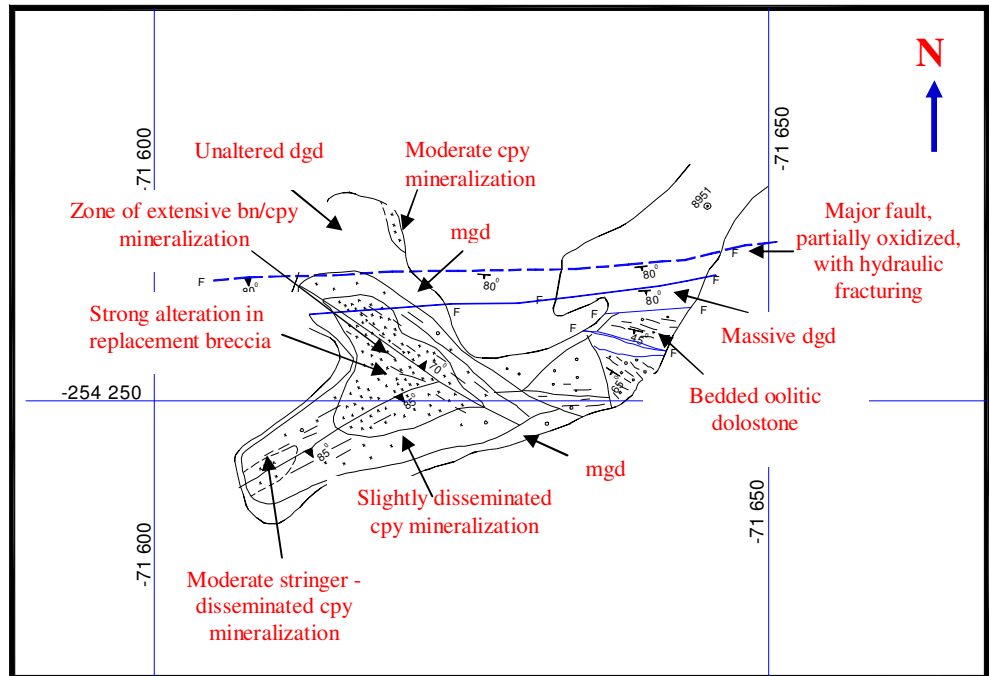


Figure 7.23: W1830 stope, Asis Far West orebody geological map showing faulting, structural orientation, lithology and alteration relationships to mineralization at 900m elevation.

The mineral zonation is distinct though it may not occur at the same level. In general, the mineral assemblage varied from low sulphur-high copper at the centre of the mineralized body to high sulphur-low copper at the periphery; i.e. bornite, chalcopyrite, tennantite, sphalerite, galena, pyrite respectively whilst proportionality varied from stope to stope.

Figure 7.10a shows 4 centres of economic mineralization occurring in close proximity within the 12level, W800 stope (Asis West. All the 4 stopes, despite their close proximity have varied differences.

Whereas stope 1 is essentially disseminated chalcopyrite – bornite with a northwest – southeast structural trend, the number 4 stope is highly mineralized in chalcocite, malachite with extensive fracturing and oxidation.

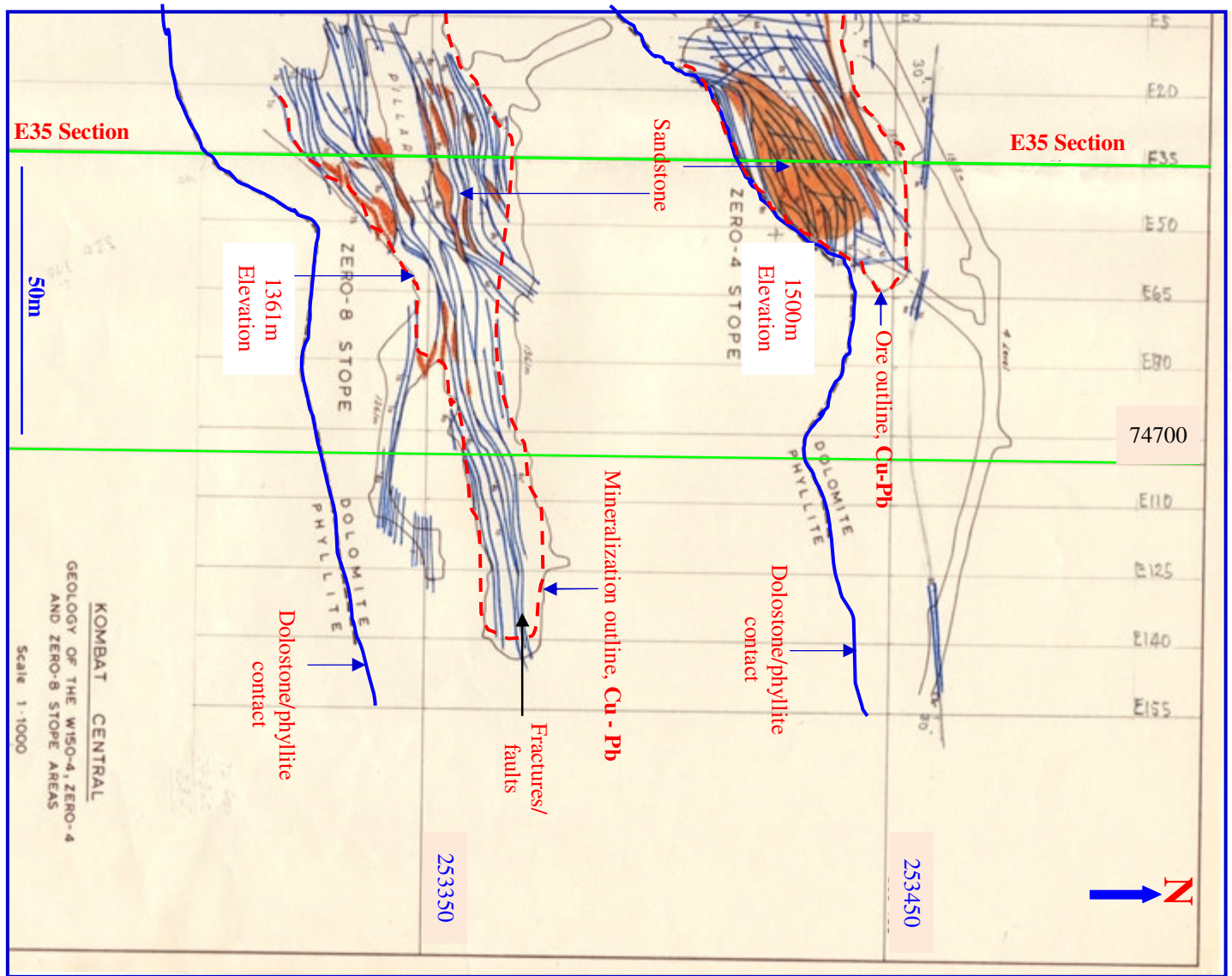


Figure 7.24: Kombat Central Orebody, Zero 4 and Zero 8 Stopes showing structural trends, ore outlines and sandstone, plan view, modified after Changara (2007b).

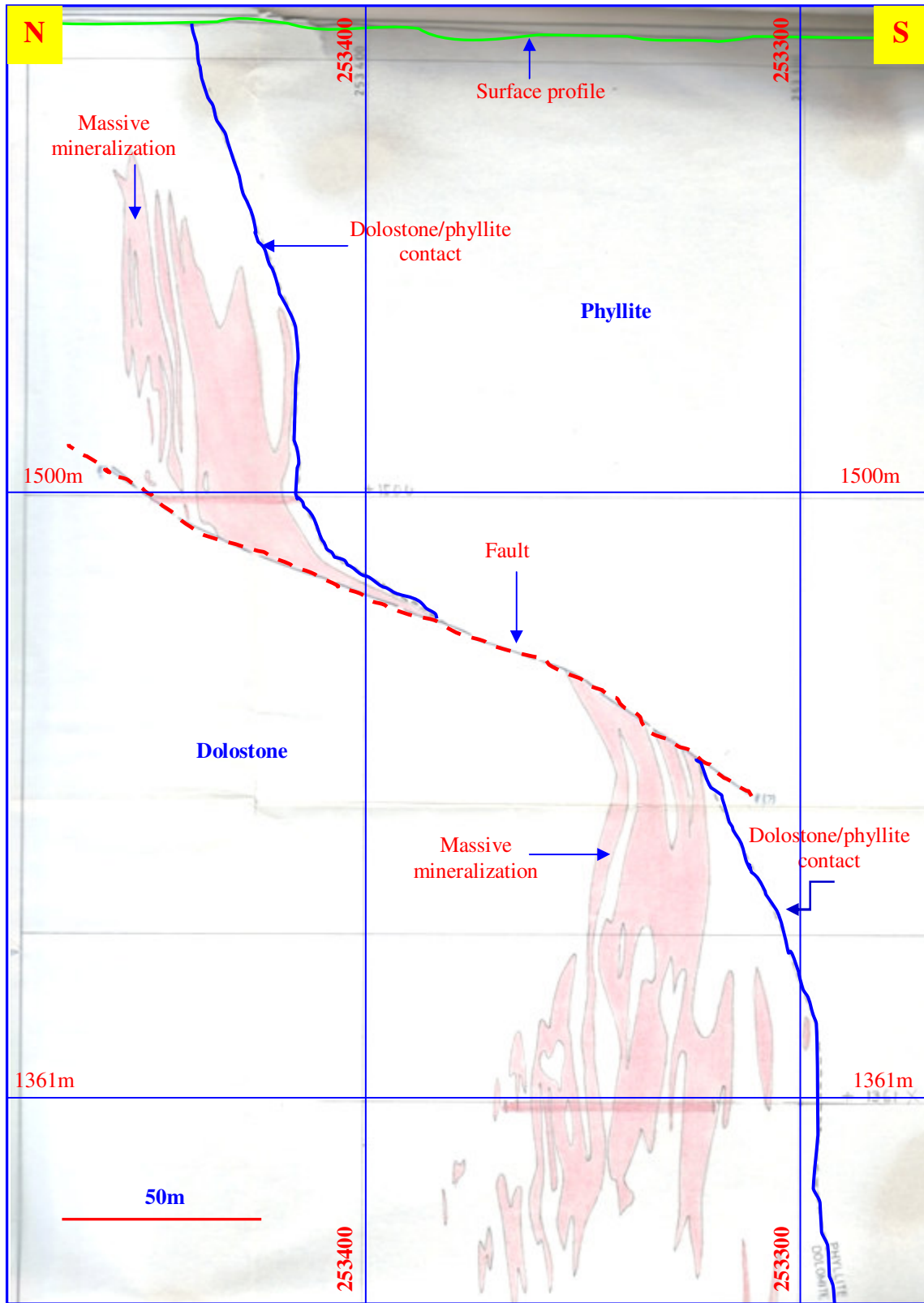


Figure 7.25: Kombat Central, E35 cross section across the Zero 4 and Zero 8 stopes, looking east, showing the mineralization profile geometry, modified after Changara (2007b).

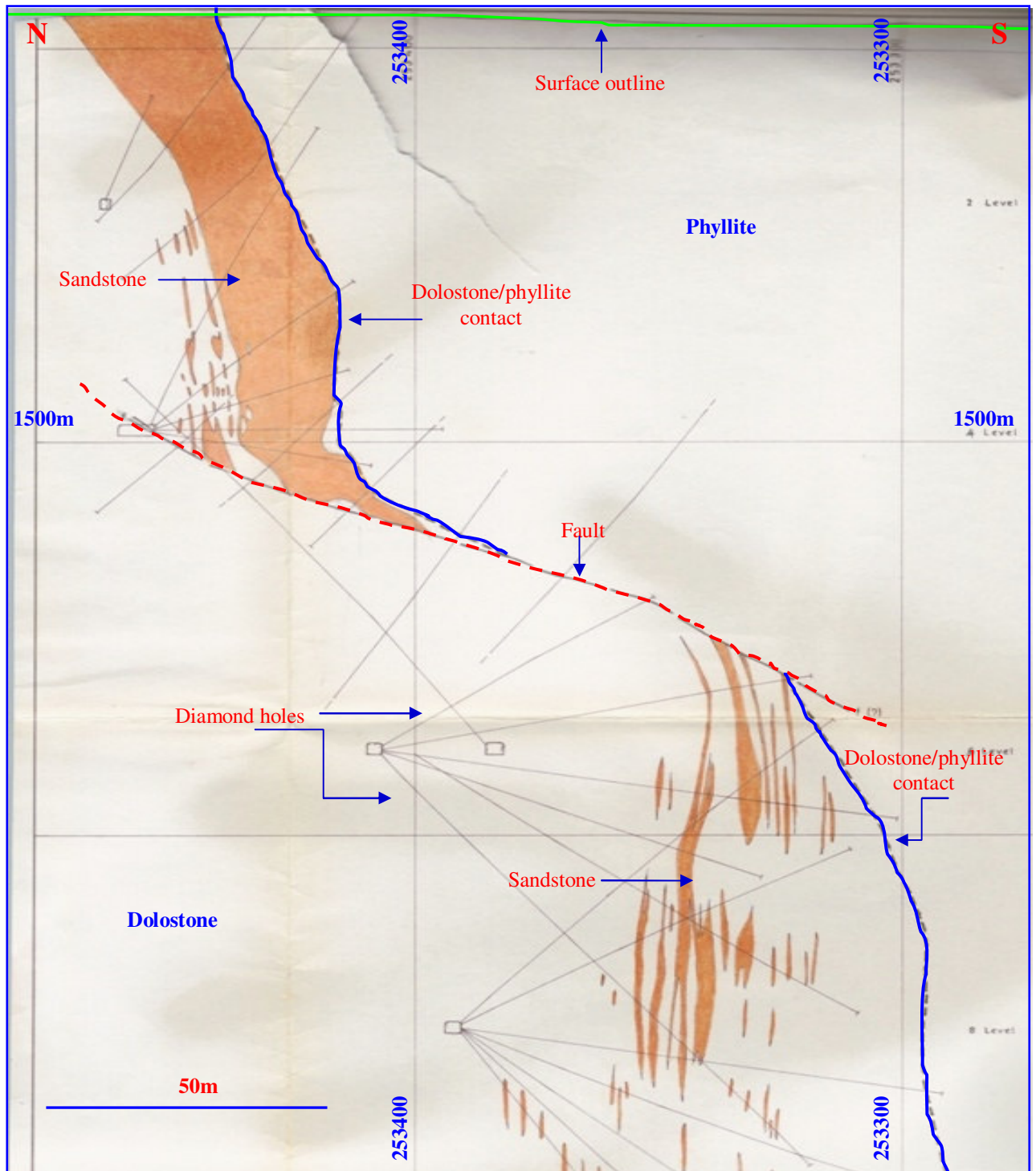


Figure 7.26: Kombat Central, E35 Cross Section across the Zero 4 and Zero 8 stopes, looking east showing the sandstone profile geometry, modified after Changara (2007b).

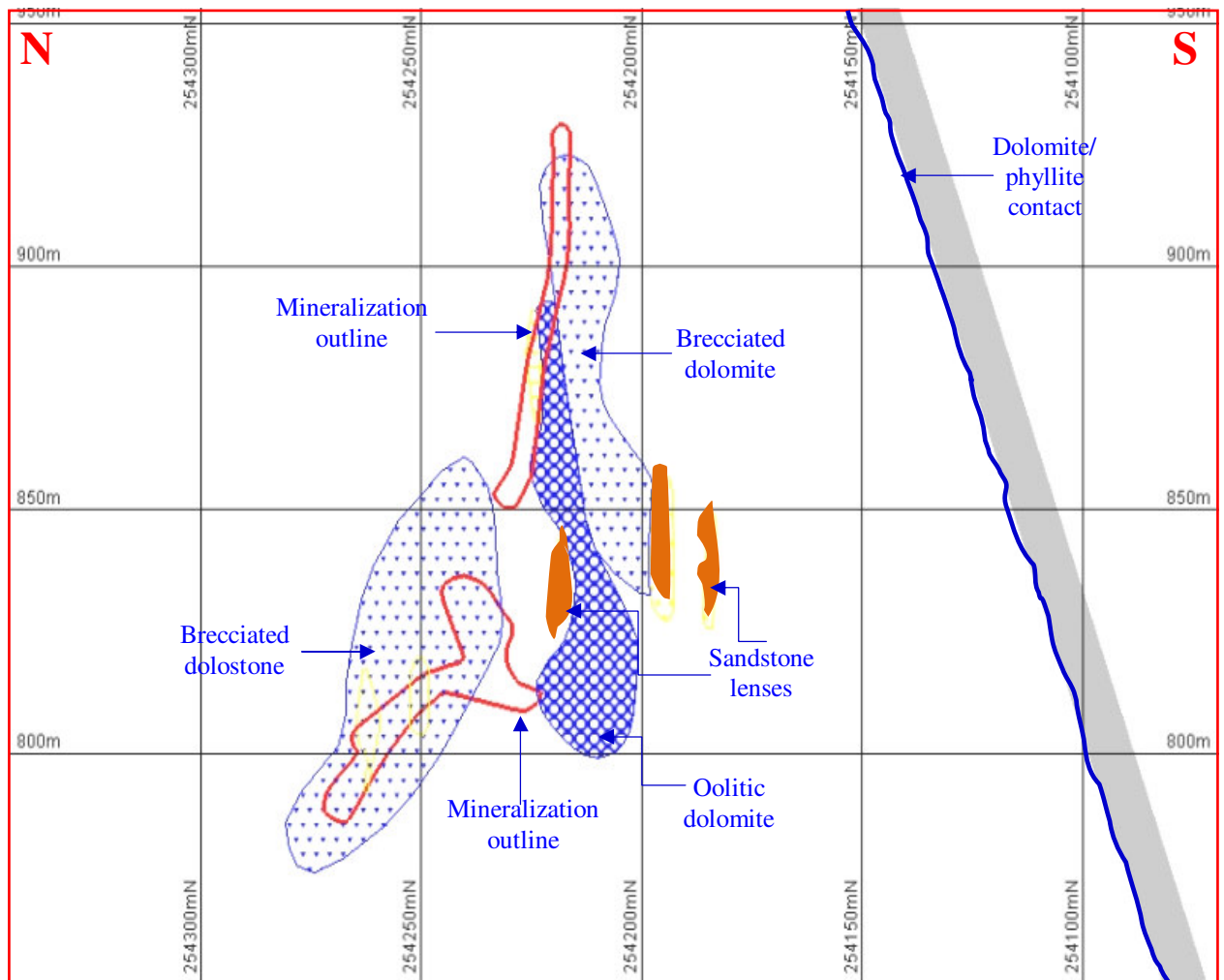


Figure 7.27: 19 level, W1830 Stope, Asis Far West (900m, E71650, N254250m), geological section showing the occurrence of brecciated dolostone, oolitic dolostone, sandstone, dolostone/phyllite contact and mineralization relationships.

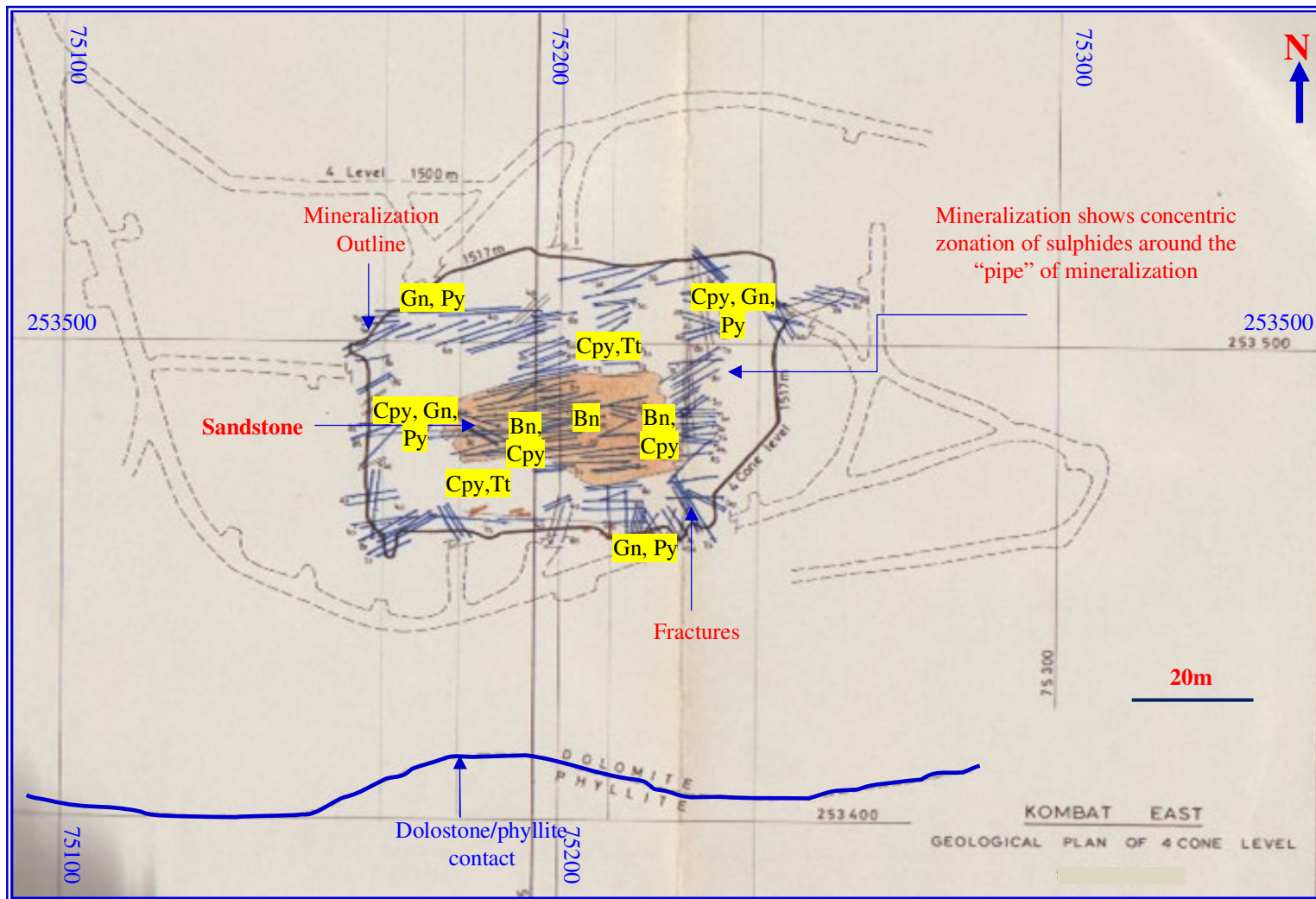


Figure 7.28: Kombat East, 4 Cone level Stope, showing sandstone occurrence, structure and mineral zonation, modified after Changara (2007b).

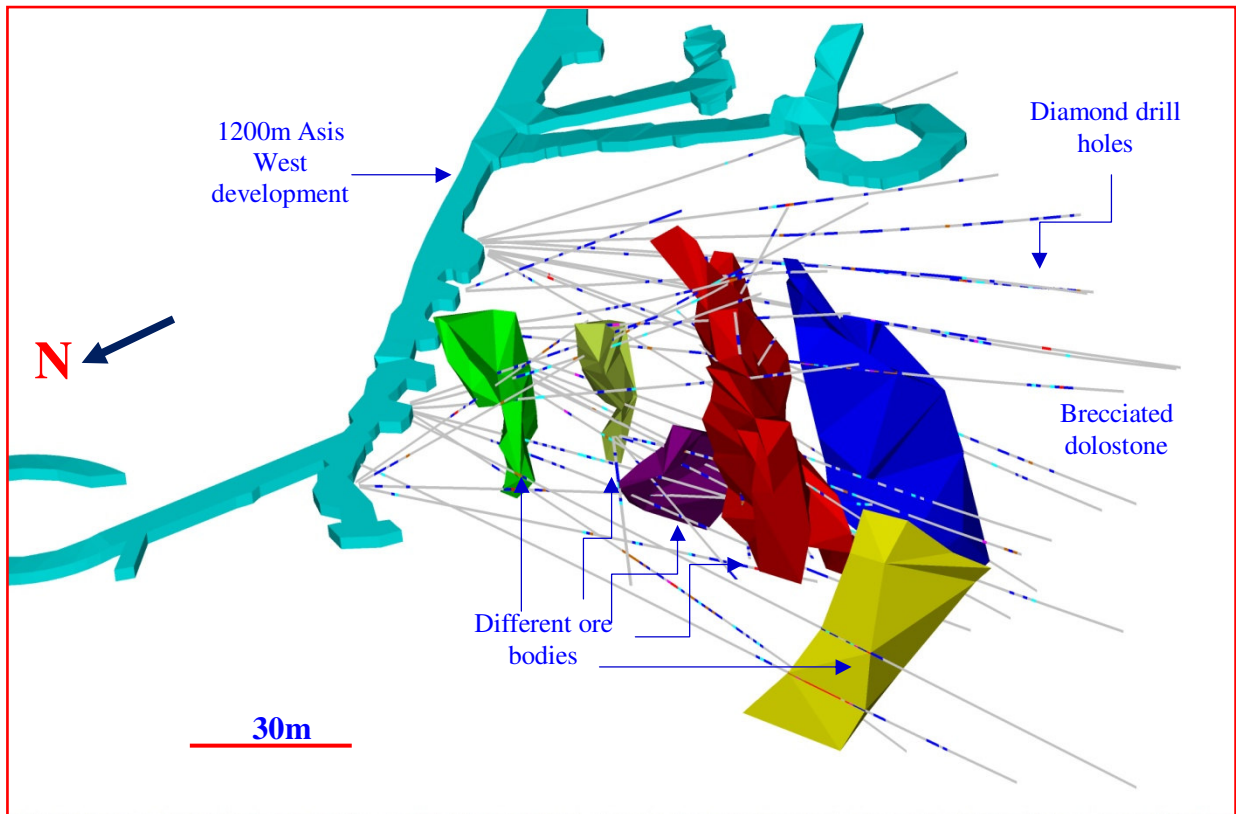


Figure 7.29: Asis West, Cross section through the 12level, W800 ore bodies, showing mine development & DDHs, and rudimentary vertical orientation of the orebodies.

This is an example of fault controlled remobilized mostly secondary mineralization. Minor chalcopyrite is still preserved. Whilst number 4 has some association with sandstone and iron manganese assemblages, this is different for the other 3 orebodies. Figure 7.29 shows a 3D projection, Micromine of the 6 ore bodies showing the rudimentary vertical orientation of the ore bodies. At this elevation the dolomite/phyllite contact is located more than 20m into the hanging wall of mineralization. Figure 7.10b shows a cross section through the 12 level, W800 ore bodies.

The Kombat East ore bodies, display near surface bornite as the dominant mineral phase, whereas at 6 level, 200m below surface, chalcopyrite is the dominant sulphide mineral phase.

One characteristic feature of the Kombat East ore bodies is the presence of lead (galena stopes). This is displayed in Figures 7.8 and 7.9 above where the lead rich stopes are seen to surround the copper mineralization outlines. Figure 7.9 (E75250 stope) displays an interesting feature. The copper and lead mineralization outlines show the footwall orebody, having an upper limit rich in copper and the lower limit is rich in lead whilst for the hanging wall orebody the upper limit is rich in lead and the lower limit is rich in copper.

From the section there is apparent association of mineralization to the brecciated dolomite and the oolitic dolomite both of which are altered. Pre existing fracturing and porosity are apparent in these stopes. All the ore bodies in this area do not terminate on the dolomite/phyllite contact but rather show a stratigraphic control (the T8 Unit).

Chapter 8

Discussion of study findings

8.1 Introduction

The Kombat mineralization has a very complex and long geological history. The discussion of this research will focus mostly on the comparison of different stopes highlighting their differences and their similarities and litho-structural features and attributes around the orebodies in an attempt to unravel and summarize the controls on mineralization to the Kombat orebodies and suggest possible exploration strategies and the future for Kombat mine in the concluding part of the research (Chapter 9). This will be discussed in relation to finding by previous researchers on the Kombat deposit. The regional perspective of the Geology of the Otavi Mountainland as part of the Damara Orogen will be discussed in general terms as it has been covered by previous researchers in detail.

8.2 Dolostone/phyllite contact – mineralization relationships

The dolostone/phyllite contact around the KMC has culminated in the coining of the term “contact type mineralization” (Deane, 1993 & 1995) at Kombat. The contact – mineralization relationships are very complex and their understanding is critical for viable exploration around the KMC.

Previous researchers including Innes and Chaplin (1986) and Galloway (1994) have identified that orebodies at Kombat hang like pendants on this contact on the northern limb of the Otavi Valley synclinorium. This geometry is observed clearly in orebodies like the Kombat West Orebody (Figs. 7.2, 7.3 & 7.4) and Asis West Orebody (Figs. 7.5 & 7.6). However, this contact displays much more complicated relationships to mineralization as in the Asis West (Fig. 3.5), the contact is complexly folded probably as a result of dolostone/phyllite competence contrast relationships. Mineralization terminates very close to the contact; the same geometry is shown in the E73720 stope (Fig 7.8). In the E75250 stope, (Fig. 7.9) the mineralization terminates a considerable distance from the dolostone/phyllite contact, and a similar geometry is displayed by the 12level W800 stope (Figs 7.10a & 7.10b) and the 19 level, W1830 orebody (Fig. 7.27). Apart from the orebodies that terminate on the dolostone/phyllite contact and those occurring close to it, there are some orebodies that are so distal to the contact that explaining them in terms of the dolostone/phyllite contact is not justifiable, e.g. the Asis Ost Orebody (Fig. 7.11), the 3level, E750 stope (Fig. 7.16) and the W270 stope (Fig. 7.22).

8.3 Lithology – alteration – mineralization relationships

Detailed geological mapping of the various orebodies in this study has revealed that all mineralization is associated with alteration. The alteration takes various forms; calcitization, silicification, iron – manganese and sericitization. The dominant alteration is calcitization, and whilst there are various generations of calcitization in different orebodies the association with mineralization is not uniform. Mapping indicates that the orebodies are sandwiched within broad zones of alteration and alteration does not necessarily imply mineralization though the alteration is a pre requisite to mineralization. Mineralization normally occurs as replacement of the

calcitized dolostone zones. These alteration – mineralization relationships are shown in the following Figures; 7.7, 7.8, 7.9, 7.10a, 7.10b and 7.11. The degree of dolomitization has a significant influence on fracture development and distribution within the carbonate strata. The volume of dolomite is less than that of calcite so the replacement of calcite by dolomite in a rock increases the pore space in the rock by 13% and forms an important reservoir rock. Dolomitization can also occur during burial diagenesis (Moore, 1989, Hughes, 1997, Petzel, 1992 & Frimmel, 1999). This process could also have aided fracturing of the rocks in the study area.

This study has identified close associations between lithology and mineralization. The various breccia type have close association to mineralization. Some orebodies like the Asis Ost Orebody (Fig. 7.11), Kombat East Orebody (Fig. 7.9), Kombat West Orebody (Figs. 7.10a & 7.10b show that the mineralization occurs in brecciated dolostone. The most common breccias associated with mineralization are the hydraulic ore forming breccia (Figs. 3.14a, 3.14b & 7.13), chemical breccias (Fig. 3.4d) and sedimentary breccias (Fig. 3.4c). Thin section and polished section analyses show that mineralization normally occurs as replacement of the matrix or becomes part of the matrix (Fig 7.13 & 7.15), a geometry that has also been identified by Innes and Chaplin (1986) and Galloway (1988).

Mineralization is also seen to have a close association with oolitic dolostones. Figure 3.4b shows replacement type chalcopryrite mineralization in an oolitic dolostone, underground diamond drill core through the 12level W800 stope. Replacement type mineralization is also shown in the Asis West Orebody (Figs. 7.10a & 7.10b).

Dolostone without any brecciation is only mineralized when it is either extensively altered (calcitized) or fractured as there will be some secondary porosity generated by the alteration process.

8.3.1 Sandstone bodies

The sandstone occurring at Kombat mines has previously been regarded as pseudo – aplite (Söhnge, 1957, Lombaard et al, 1986 & Innes and Chaplin 1986) owing to uncertainty over its origins (it was thought to be igneous in origin). However, there seem to be general consensus now that its really a sandstone and its origin though not fully understood is thus sedimentary. The sandstone at Kombat is very important for any geological investigations in the area as it shows a close association with mineralization. The mineralization – sandstone geometrical relationships are shown in the following; 12level, W750 stope (Fig. 3.3), 12level W550 stope (Fig. 4.12) and W135 stope (Fig. 3.5) where the sandstone rims around the mineralized brecciated dolostones with very minor intercalations into the mineralization lattices.

In the Kombat Central Orebody (Fig. 3.8), the sandstone profile is a mirror image of the mineralization pattern shown in Figure 7.4. It is in this stope where the mineralization and sandstone appear to have been emplaced by the same primary controlling process in the sense that the mineralizing fluids moved through the same structures used during the deposition on the sandstone, as palaeo subsurface- streams.

However, there are some stopes like the 19level, W1830 (Fig. 7.30) at Asis Far West where the sandstone occurs within and distal from mineralization.

8.3.1.1 Possible origins of the sandstone bodies and their relationship to mineralization

Ore – sandstone and structural relationships indicate that mineralization in the Kombat area postdates the introduction of sandstone into the dolomites. There is a close association displayed between mineralization and the sandstone bodies and the dolostone/phyllite contact. A model is proposed where a large fracture system existed on the Tsumeb Subgroup rock surfaces prior to the introduction of the Mulden group. This fracture system, possibly striking almost east – west was further developed by karstification and a stream – fluvio type system deposited sandstone in the karstic – fracture system. This was thus always a zone of weakness. The absence of an argillaceous equivalent to the sandstone does suggest that the sandstone was introduced into the dolostone prior to the deposition of the more regionally extensive phyllites of the Kombat formation.

It suffices to recognize that the sandstone is a pre ore feature disposed within the plumbing system utilized by later hydrothermal fluids. The ubiquitous association of the sandstone with mineralization indicates that sandstone aquifers provided conduits for metal bearing fluids or at least was deposited under the same setting and structural zones of weakness as with the mineralization. Figure 8.1 shows a possible model depicting rudimentary evolution of the sandstone bodies, mineralization and structural controls to mineralization modified after Gleeson (1983).

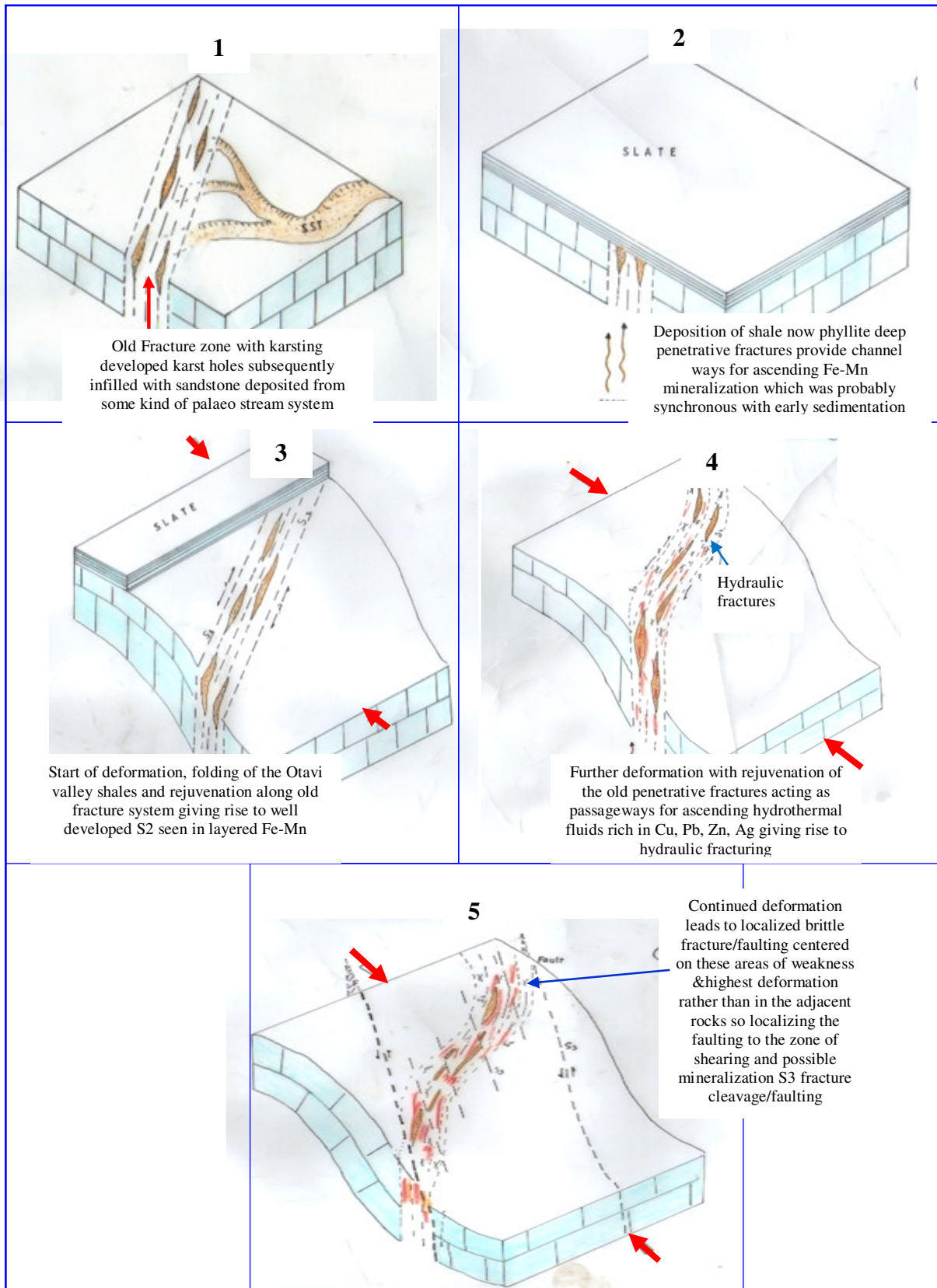


Figure 8.1: Possible model showing rudimentary evolution of the Sandstone bodies, mineralization and structural controls to mineralization, modified in this study after Gleeson (1983).

8.3.2 Iron manganese oxide/silicate – mineralization associations and possible origins

This is a compositionally and texturally layered assemblage of iron and manganese minerals that forms an integral part of the Asis West, Kombat Central and Kombat East orebodies (Fig. 3.1). This assemblage is always associated with feldspathic sandstone and normally occurs in close proximity to the dolostone/phyllite contact (Figs. 3.3, 3.5, 3.10, 7.5 & 7.6). The larger iron manganese bodies consist of hematite (specularite) and magnetite ores in juxtaposition to layered manganese oxide and silicate assemblages, within the zone of transposition (Figs. 3.4c, 3.12a & 3.12b). Mineralogically the banded ores are characterized by the presence of magnetite, hausmannite, hematite, barite, calcite, tephroite, alleghanyite, and pyrochroite, with small amounts of a pinkish Jasperoidal rock believed to be a siliceous sinter. The Mn ores are fine to medium grained, granular, polymineralic aggregates which may contain up to 12 mineral phases in one hand specimen. Sulphides, pyrite, chalcopyrite and galena, are present in small amounts.

Stratabound galena mineralization is locally developed as thin interbeds in carbonate facies manganese ores in the E15-11 stope at Asis West (Fig. 3.10). All composite iron manganese bodies contain interfoliated sandstone slivers and lenticles and large bodies of massive unfoliated sandstone are often adjacent. The layered and banded manganese ores occur only within the zones of tectonic transposition, but there is some dispersion of disseminated magnetite and granules of manganese silicates into the adjacent sandstone and dolostone.

Major and trace element data for the Kombat ores (Fimmel, 1999) suggests that the Kombat Fe – Mn oxide/silicate assemblages represent possible distal equivalents to hydrothermal (chemogenic) Mn rich deposits related to a Lake Superior –type setting. The common model for

the genesis of these deposits involves the leaching of Fe, Mn, Si and base metals from underlying volcanic/sedimentary rocks by hot acidic waters driven by convective processes above a heat source. The hot, metal-rich fluids rise along faults associated with the formation of second order basins. Mixing of these acidic fluids with more saline waters in a sedimentary basin results in rapid precipitation of Fe, Mn, Si in shallow water oxide/silicate environments (Petzel, 1992). The high $\delta^{34}\text{S}$ value of +29‰ for the barite in the Kombat Fe-Mn oxide/silicate assemblages suggests a saline source (Moore, 1989). An alternative origin for the Fe and Mn would be precipitation of the chemical sediments derived from other exhalative sources within the Otavi Valley basin though direct evidence for such an exhalative process is lacking (Basement complex, 1993). The close spatial association of the Fe-Mn oxide/silicate assemblage with the base metal mineralization in most of the orebodies suggests that mineralization and the Fe-Mn oxide/silicate assemblages used the same structural features for their propagation. However, mapping seems to suggest that mineralization postdates the Fe-Mn oxide/silicate assemblages. Litho-structural relationships from underground mapping indicate that the Fe-Mn oxide/silicate assemblages are syn-sedimentary, being deposited prior to the main deformation in the Otavi Valley. The layering of the Fe-Mn bodies seems to represent an original synsedimentary assemblage controlled by the activity of oxygen, which has not been destroyed by the later hydrothermal and deformational history. Dean (1993) suggested the following constraints on the age of the Fe-Mn assemblages;

- The transposed nature of the Fe-Mn assemblages suggests that they formed prior to the D_{3b} deformational event.
- Layers of hausmannite and magnetite are observed outlining mesoscopic folds suggesting that the Fe-Mn assemblages are older than the D_{3a} event.

- The relatively high temperature amphibole-mica minerals are aligned within the S_4 foliation and therefore these high temperature minerals must have formed after the initial Fe-Mn was deposited.

It is possible that the Fe-Mn bodies at Kombat were originally deposited locally in a sub aqueous environment at or near the top of the Hüttenberg Formation. The hydrothermal fluids would have migrated up rift faults in the deeper anoxic parts of the Otavi valley basin depositing the Fe and Mn as oxide, carbonate and silicate facies on reacting with the more oxidized surface waters.

8.4 Structure – mineralization relationships

8.4.1 Introduction

Structural analyses of the Kombat mine orebodies indicate the complex nature of the deformational history of the orebodies. This section will look at the different structural patterns and parameters that have been shown to be associated with mineralization.

8.4.2 Structural orientation of the orebodies

The first apparent structural feature of the KMC orebodies is the near linear E – W orientation of the ore loci over an approximately 6km strike from Asis Ost to Asis Far West from east to west respectively (Figs. 1.2, 3.1 & 7.1). On a regional scale, the orebodies actually display an “en echelon” geometry. Still on the regional scale, displacement of the Asis West bodies from the

eastern orebodies by the Kombat West fault is apparent (Figs. 7.2 & 7.6). The individual orebodies at KMC show individual structural patterns and will be analyzed below.

8.4.3 Faulting

Dean (1993) suggests a general consensus that the genesis of Kombat ore mineralization is related to the D_{3b} age northeast to east-northeast trending shear zones and these fractures were feeders to the Kombat ore. The Kombat faults represent a long and complex tectonic history. The Asis Ost Fault was active during the Otavi Group times, suggesting that it is an early structure predating mineralization. However, the Kombat Faults (Kombat West, W270, W550, and W750) which are parallel to the Asis Ost Fault displace orebodies therefore they have been reactivated through time. Mineralization in some stopes shows a close association to faulting normally also associated with secondary Cu bearing minerals. The secondary minerals like malachite, chalcocite occur in remobilized form within the fault zones. The 20level W210 stope (Fig. 4.10), Asis West orebody is located within a fault zone where supergene mineralization predominate the hypogene sulphides. The entire ore zone consists of dolomite (massive and brecciated), intercalations of phyllite piercements with varying degrees of alteration. The ore is supergene enriched and consists mainly of chalcocite and malachite. Other secondary minerals such as cerussite, brochantite, cuprite and native copper also occur within the mineralized zone. Primary sulphides such as bornite and chalcopyrite do occur sporadically as remnants rimmed by secondary chalcocite. The orebody is bounded by the KWF3 and KWF3A faults which are characterized by approximately 2m thick zones of intense fracturing and brecciation associated with large open cavities and vughs with calcite infill. Mineralization is situated within the calcite matrix of the hydraulically brecciated. Other stopes that occur in zones of faulting and marked by

fault brecciation, secondary sulphidization and minor primary sulphide mineralization are the W800 lense 3 (Fig. 7.10a) and W550 stope (Fig. 4.12).

8.4.4 Mineralized fracture fillings and replacement type ore

Fracture fillings are dilational features developed in predictable geometric relationships to S_3 shears and to transverse faults. Within the KMC, the complex and variable nature of fracture fillings encountered in this study (Figs. 3.4d, 3.12, 3.14a, 3.14b, 3.14c, 7.18, 7.19 & 7.20). Early shear type fractures, containing blebby and disseminated bornite, chalcopyrite, pyrite, chalcocite, and rare galena, are developed adjacent to the steeply dipping, foliated zones of massive replacement sulphides. These fracture fillings are frequently monomineralic (chalcopyrite or bornite) and contain very little hydrothermal gangue. Post ore shears are characterized by peripheral en echelon and sigmoidal gash veins infilled by sparry calcite, quartz and dolomite. A close joint pattern is superimposed on the altered, netvein fractured, and mineralized dolostone, previously described; probably a response to transverse, post ore faults such as the Kombat West and Asis Ost faults. A late generation of solution cavities postdates the major north-east-trending veins containing crustiform fillings, up to 4m in thickness, of comb textured calcite with layered mottramite mineralization.

The hypogene ores, with the exception of the epithermal ores, are syntectonic on the basis of the textures are structural control of mineralization (Innes & Chaplin, 1986). Although the textures indicate that annealing has occurred, the paragenetic sequence illustrated is regarded as a primary one. An early period of widespread pyrite deposition was followed sequentially by the precipitation of sphalerite, bornite, tennantite, chalcopyrite and galena. Sulphides associated with

the iron manganese bodies have suffered synchronous deformation with these bodies, but remnant textures, e.g. pyrite rimming and replacing euhedra of magnetite, shows that sulphide formation has postdated the formation of all layered iron manganese oxides/silicates and associated barite. The amphiboles and some of the manganese silicates possess a nematoblastic habit. The growth of these grains is inferred to have been syntectonic since the decussate rosettes of ritcheite and prisms of leucophoenicite and other manganese silicates outline the geometry of minor folds and lie in a transposed mineral layering which constitutes the fold surface, and also in the axial plane foliation. Layers of hausmannite or magnetite are observed outlining mesoscopic folds and this layering may predate tectonism. Growth of specular hematite appears to have been syntectonic as the basal planes of hematite are aligned in the foliation.

8.4.5 Net vein fracture systems

Net vein fracture systems constitute a very common ore occurrence within the KMC and generally constitute a reticulate or anastomosing mesh of mineralized microfractures that are developed in linear zones adjacent to shears and faults and in the broad zones of pervasive calcitization below the orebodies. In areas of intense deformation, the meshwork develops a preferred orientation and fractures grade into sutured stylolites with amplitudes up to 4cm. The stylolites include magnetite and ore minerals like bornite, galena and chalcopyrite. It is common for mineralization of this type to merge into mineralized alteration breccias and massive replacement copper lead ores. These ores are found throughout all the KMC orebodies (Figs. 3.4d & 7.21).

8.4.6 Roll structures

A phenomenon that has been popularized over time is the development of structures locally termed “roll” structures (Galloway, 1988, Petzel, 1992 & Dean 1993) (Fig. 8.2). The D_{3b} rupturing of the Otavi valley has been cited as the important structural control on the development of the Otavi valley “roll structures”. The “roll structures”, according to studies by Dean (1993) could have been produced by shearing and Figure 8.2 shows the geometry describing the “roll structures”. Detailed interpretation of existing and current mapping however indicates that these geometries develop as a consequence of the competence contrast between dolostone and phyllite during deposition/deformation (Fig. 3.5).

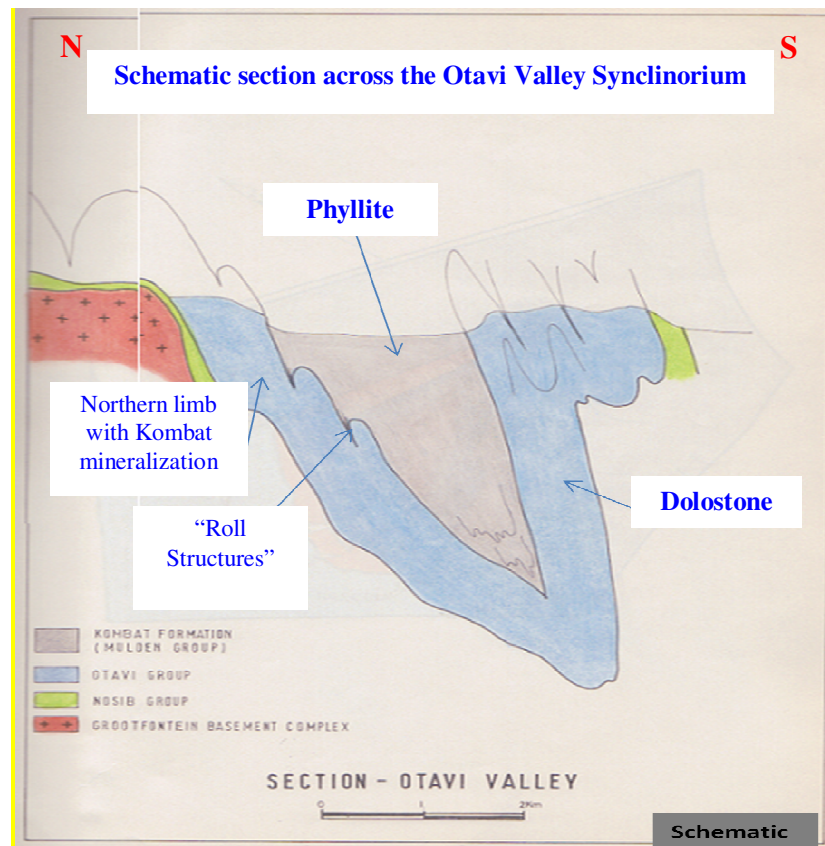


Figure 8.2: Schematic section across the Otavi valley syncline showing the geometry of the “roll structures” and general relationships of the different lithological units modified in this study after Galloway (1988).

The “roll structures” of the northern limb have been interpreted from detailed underground and surface drilling as zones of mineralization. The reason why they have not been identified on the southern limb of the Otavi valley syncline is due to limited drilling data. Tight isoclinal infolding of the phyllite into the dolostone has formed cusp structures along the dolostone phyllite contact. Cusps commonly progress into piercement structures which attain vertical lengths of up to 60m. This study has highlighted several orebodies within the Kombat mining complex which have no close association to the “roll structures” like the W1830 stope (Fig. 7.23), W800 (Fig 7. 10b) and W270 (Fig. 7.22).

Another important feature about the orebodies is that they occupy areas of high strain where deformational effects are more pronounced than in the intervening areas of barren/unmineralized dolostone. It is envisaged that the selective calcitization of the dolostone by ground waters percolating in palaeokarst features or in multiple fold hinges may have created this ductility contrast and that subsequent strain concentrated in the more ductile calcitized dolostone. Shearing movements along the calcitized zones would cause shock loading of the dolostones and propagation of microfractures in accord with the Griffith mechanism. Hydraulic pressure of the pore fluids would increase in rocks adjacent to these zones until net vein fractures were initiated and further propagated. Foliated zones of recrystallized carbonate and lenses of breccia could develop parallel to or sympathetically with these zones to create the loci for later sulphide mineralization (Innes & Chaplin, 1986). Annealed textures in chalcopyrite (Chapter 7), kinking of twin lamellae, piercements of massive sulphide intruding the country rock on the peripheries of orebodies, and the folding of chalcopyrite stringers in the phyllite all suggest that recrystallization and deformation of most of the occur has occurred.

8.6 Ore types

Several ore types are observed within the Kombat Mining Complex and are described on basis of ore – host relationships, structural controls and mineralogy. The following descriptions modified after Innes and Chaplin (1986) will be used in this discussion with examples quoted from the studied stopes;

8.6.1 Massive and semi massive sulphides

Generally, the massive to semi massive sulphides are spatially related to centres of tectonic and sedimentary brecciation in the dolostones. These replacement ores are best developed in breccia matrices, in lenses of feldspathic sandstone and in pervasively calcitized dolostone, particularly in the oolitic, pelletal and detrital units closest to the dolostone/phyllite contact. Massive mineralization also extends away from centres of brecciation along foliated zones of recrystallized dolostone. It has been observed in several areas of this study, e.g. Kombat West orebody, the Zero stope (Figs. 7.2, 7.3 & 7.4), Asis West (Fig. 7.11) and W210-20 stope (Fig 4.10). The massive mineralization in these areas occur in various assemblages of which the following are the most common; bornite + chalcopyrite (+/- galena +/- sphalerite +/- tennantite) – common in the Kombat West and Asis West stopes; galena (common in the Kombat East and Central Stopes); pyrite + galena (common in the Kombat East stopes); chalcopyrite +/- pyrite in carbonaceous hosts (Kombat East, and Central, Asis West); a supergene assemblage consisting of chalcocite + digenite + malachite (+/- covellite +/- cuprite +/- native copper +/- native silver)

– common in Asis Ost, Asis West). The bornite –chalcopyrite type is the most common assemblage and texturally it is characterized by extremely coarse grained exsolution flames, lenses, and trellis like lamellae of chalcopyrite in bornite and vice versa.

8.6.2 Galena rich alteration breccias

These are confined to the Kombat East orebodies with examples like the surface sample (Fig. 3.4c) from the Kombat East 4 level cone stope and Kombat East Orebody (Fig. 7.8) and E75250 stope (Fig. 7.9) are characterized by steep breccia bodies of pipe like configuration which lend themselves to Longhole type of mining. Conversely, the elongate, foliated zones of mineralized dolostone common in the other Kombat ore bodies are only poorly developed here. Mineralization is confined to a breccia locus in which close packed angular dolostone blocks display an unaltered core surrounded by a bleached, calcitized fringe indicating tectonic brecciation induced by hydraulic fracturing which permitted increased fluid flow along the fracture system and alteration by chemical processes. Mineralization is interstitial to the breccias fragments, occurring on pressure solution interfaces in the alteration zone. This structural setting hosts a distinct mineral assemblage, comprising galena, abundant pyrite and very subordinate chalcopyrite.

8.6.3 Pyrite – sericite association

This is an alteration facies of the feldspathic sandstone and is characterized by the association of pyrite, usually fine grained, euhedral and disseminated in a beige or khaki colored sericite – quartz matrix which is generally strongly foliated as at 12level W750 stope (Fig. 3.3) and

Kombat Central orebody at Zero- 4 and Zero 8 stopes (Figs. 7.24, 7.25 & 7.26). The alteration propagates within foliated and massive feldspathic sandstone, often to the extent where the rock becomes fissile and resembles bands of pyritic argillite in a dolostone host which may itself remain unfoliated. Although much of the alteration is affected by penetrative deformation and is therefore believed to have formed early in the mineralization process, some pyrite – sericite shear zones postdate massive sulphide mineralization in the Asis West Orebody as they displace the ore. Ore minerals are seldom present in this assemblage.

8.7 Comparison of the KMC orebodies

Whilst all the other 6 orebodies of the Kombat Mining Complex (KMC) are confined to the T8 stratigraphic unit of the Hüttenberg Formation, the Asis Ost deposit extends into the T6 unit of the Hüttenberg Formation.

Another important characteristic feature of the Asis Ost orebodies is oxidation. Oxidation has been an important process for the mineralization at Asis Ost and could possibly have occurred at least twice. Supergene mineralization outcrops at Asis Ost indicating that the present geographic surface is relatively young. The original oxidation zone which supplied the copper-rich solutions for enrichment in depth may have been eroded away at a faster rate than that at which oxidation could take place, thus preventing the formation of a normal oxidation zone. The original supergene zone is now exposed to the ‘elements’ and a second period of oxidation has set in. The formation of cuprite and native copper from chalcocite at the Asis Ost deposit is evidence of this second period of oxidation. Figure 8.3 is a schematic diagram depicting the supergene enrichment and oxidation in a copper deposit after Guilbert and Park (1986).

The principles of supergene enrichment in copper deposits are depicted in Figure 8.3 and the reactions are summarized below:

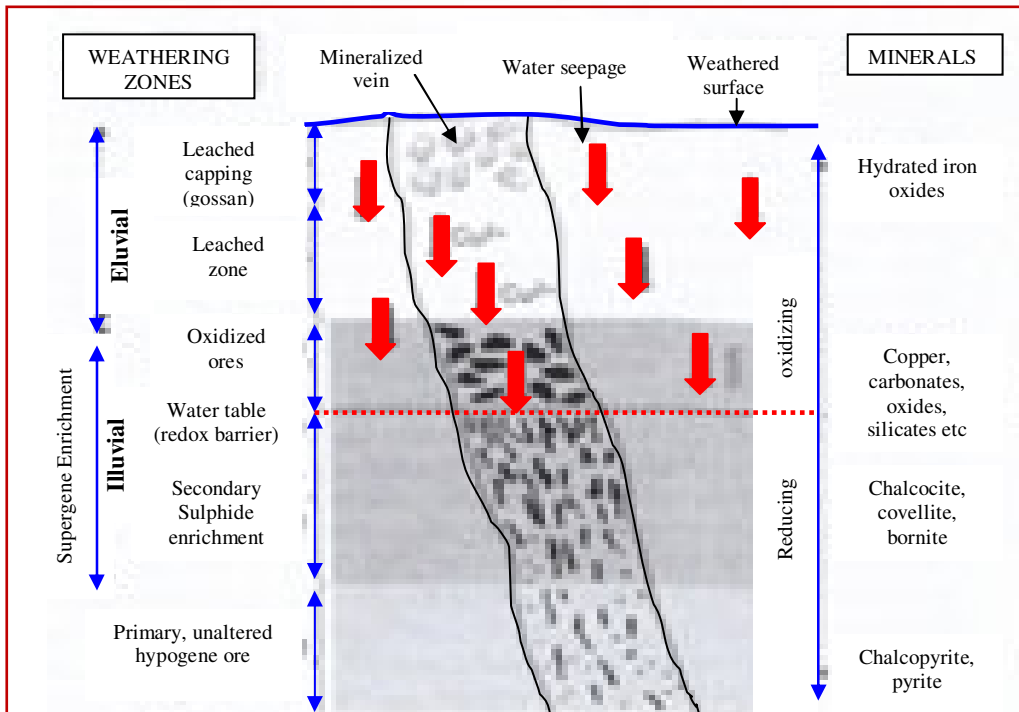
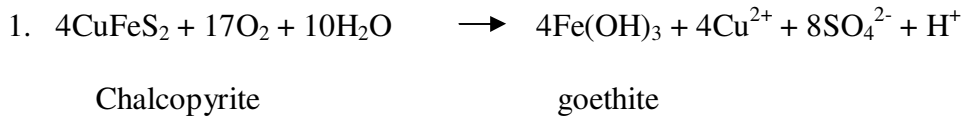
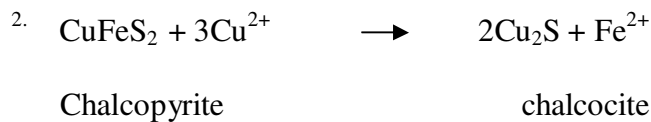


Figure 8.3: Schematic section through a copper deposit showing the typical pattern of an upper, oxidized horizon (the leached or eluvial zone) overlying a more reduced zone of metal accumulation (the supergene blanket or illuvial zone). The uppermost zone of ferruginous material, often containing the skeletal outlines of original sulphide minerals, is known as gossan. The redox barrier may be the water table or simply a rock buffer modified by Changara (2007b) after (Guilbert & Park, 1986).





Supergene enrichment in the proximity of a limestone for example will result in local groundwaters with a high CO_3^{2-} content culminating in the stabilization of minerals such as malachite or azurite under neutral to alkaline conditions. The above process is applicable to the Asis Ost deposit.

Another feature which is unique to the Asis Ost and the E900 bodies is that mineralization is located several meters into the footwall of the dolostone/phyllite contact and shows no close association with the contact.

The E900 orebody is the only ore loci that show repeated histories of calcite alteration yielding replacement type mineralization. At least 3 phases of calcite have been identified; an early white pervasive phase interbedded with the dolostone which has been folded (C1), a brown phase (C2) which is folded together with the host dolostone, (this could be the remnants of a replacement breccias or solution collapse breccias) and a coarse white vein phase (C3) which cross cuts C1 and C2 (Deane, 1993).

Lead mineralization is abundant only in the Kombat West (Fig. 7.12), Kombat East (Fig. 7.13) and Kombat Central (Fig. 7.23) orebodies. Whilst Fe-Mn minerals are present in other orebodies, geochemical investigations indicate that the Kombat East ores have much higher Fe-Mn

concentrations than the other bodies (1.1 Wt% Mn in Kombat East compared to ~0.2%Wt% Mn for the Kombat Central orebodies).

The Kombat West orebodies show classic association of mineralization to the dolostone/phyllite contact. Another very important characteristic feature that is unique to the Kombat West orebodies is the relationship between sandstone and mineralization. The mineralization patterns both on plan and in sectional view are more like a mirror image of the sandstone bodies. These features and characteristics are shown in Figures 7.2, 7.3 and 7.4.

The Asis West and the Asis Far West orebodies have been downthrown by about 200m by the Kombat West Fault. While there is a general NE-SW trend to mineralization in the Kombat area, in the 13Level W270 stope (Fig. 7.22) there is a NNW-SSE trend which has also been identified in the Asis Far West stope 19L W1830 (Fig. 7.23). Another striking structural feature occurring in the W90 stopes (Fig. 3.3) is defined by a series of phyllite and sandstone wedges or piercement structures which penetrated the carbonate rocks. These piercement structures of clastic sedimentary rocks are strongly foliated and have a close relationship to massive sulphides. Indeed, the largest bodies of massive chalcopyrite or bornite lie either adjacent to or at the apices of these clastic rock wedges. The sandstone wedges are generally not internally mineralized; however the phyllite piercements contained elongate nodules of pyrrhotite up to 40cm long and 10cm wide. Two sulphide (chalcopyrite) textures occurred in this area, a fine grained sulphide with clasts or fragments of carbonate rock, and a very coarse grained sulphide with no wall rock inclusions. The two sulphide textures occurred together in lenses along the carbonate foliation zones, typically with one end of the lens containing fine grained sulphide and the other end

containing the coarser grained sulphide. The coarse grained end lens always pinched out whereas the finer grained end led into a larger mass of fine grained inclusion – bearing sulphide.

The Asis Far West orebody is a very important centre of mineralization as it has huge potential for delineation of new mineral resources. Mineralization occurs a considerable distance (up to 250m) into the footwall of the dolostone/phyllite contact. The mineralization also occurs in close proximity to the sandstone bodies and the structural trend changes from northeast – southwest to about northwest to southeast. The Asis Far West is still open ended to the west and the area between the W800 stopes on 12 level and Asis Far has identified mineralization and is available for delineation drilling to pave way for mining.

Below is a comparison of the 12 level W750 and W210- 20 stopes of the Asis West orebody that have been studied in detail in this study.

8.7.1 Comparison of the W750 to the W210 orebodies, Asis West

There is a definite sequence of lithologies striking approximately parallel to the dolostone/phyllite contact in the 12 level W750 (W750) stope (Fig. 3.3) whereas on 20 level in the W210 – 20 stope (W210) (Fig. 4.10) the same lithology is found from the exploration drive south to the dolomite contact. Mineralization at W750 seems to be associated with near vertical foliation zones of calcitized oolitic dolomite as well as with near vertical sandstone lenses and greywacke within the sandstone bodies and are closely related to the iron manganese bodies in contrast to the W210 area there are no signs of sandstone, oolitic dolostone or manganese bodies.

The W210 level mineralization is instead associated with large hydraulically generated breccia bodies which are not present on the 12 level areas at all.

The major structural feature in both areas are the northeast trending fault zones, which on 20 level produced large open cavities and fractures that yield large volumes of ground water. In the W750 area these fault zones do not present such a tremendous ground water problem, but displaces ore bodies and seem to control the orientation of some of the ore bodies, which present a mining and exploration challenge. Previous observations (Greenway, 1994) made that except for the Kombat west faults, faults in the Kombat area do not displace ore is not very accurate as there is clear displacements of ore as well as iron manganese ore bodies associated with the W750 fault series. Displacement by the north east trending fault in the W210 area could not be determined due to lack of drilling data and correlation parameters. There are however indications that a north trending fault displaced the contact by approximately 40m in the east of the drilling area. What is actually important is the presence of low angle thrust faults with an associated joint system which terminates against the breccia body which seems to play an important role in the formation the structures interpreted as monoclonal flexures.

Mineralisation in the W750 area consists mainly of primary sulphides such as chalcopyrite, bornite and galena with minor chalcocite and pyrite. The W210 orebody consists of supergene mineralization, mainly chalcocite and malachite with minor native copper, cuprite and brochantite. Mineralogically, the W210 orebody has grades of 2.85% Cu, 0.23%Pb, and 41.5g/t Ag whilst the W750 ore body has grades of 2.21%Cu, 0.28%Pb and 13.2g/t Ag.

Diamond drilling of the W750 orebody has demonstrated that there is multidirectional displacement of the dolomite/phyllite contact, lithologies and orebodies. Secondary faults serve as stress relief faults trend in various directions, and also have multi directional displacement associated with them. The presence of low angle thrust faults, believed to be the original faults associated with recumbent folding; all over the mining area may have caused the structures to be interpreted as monoclin flexures in the dolomite/phyllite contact. In general, upper level orebodies are associated extremely calcitized oolitic detrital dolomite, sandstone lenses as well as poorly sorted greywacke within the sandstone bodies and is closely related to iron manganese bodies. Orebodies at the bottom levels have no association with oolitic detrital dolomite, sandstone or iron manganese bodies but are instead bounded by fault zones and are associated with large hydraulically brecciated bodies of mineralization.

Ore bodies are randomly oriented and their geometries are a function of the physical trap that caused the ore preposition. This is very well illustrated in the W750 area where the ore bodies associated with the sandstone lenses are oriented parallel to the strike of the lithologies and orebodies confined to the oolitic detrital zones are oriented in the foliation direction associated with the calcitization. The W750 orebody is again confined to a poorly sorted greywacke within a sandstone body which is oblique to the stratigraphy and the ore body is oriented accordingly.

Although the ore bodies are vertically elongated they are not always associated with the monoclin flexures but rather controlled by faulting.

8.8 Origin of the mineralizing brines

The increase in temperature during deformation, most likely the D2 period coupled with the salt content of the expelled fluid would form brine containing metal chlorides, the metal ions being derived from the argillaceous and calcareous rocks of the Swakop Group. The recognition of primary anhydrite in metasediments of the Nosib Group, which underlies the Swakop Group, supports the assumption that concentrated saline solutions may have been trapped in the sediments of certain parts of the basin (Nash & Anderson, 1972). Chlorine and bromine form practically no insoluble minerals and their migration is not affected by alkaline- acid or oxidizing-reducing environments (Nash & Anderson, 1972). This step would represent a considerable increase in the local concentration of the metals now present in the brine as compared to that of the sediments. The distance covered by this brine solution before reaching the area of deposition would not have to be very great as the volume of rock to the immediate south of the Otavi Mountainland is large enough to supply the necessary metal ions to form the different sulphide orebodies (Krauskopf in Barnes et al, 1980). The marbles and schists of the Swakop Group which formed to the south of the Mountainland as a result of the regional metamorphism acted as a large reservoir and ensured a continuous supply of brine to the dolomitic rocks of the Otavi Group which had undergone low-grade regional metamorphism.

8.8.2 The nature of the mineralizing fluids

The nature and source of the mineralizing fluids for the Kombat deposits can be constrained as follows modified after Dean (1993) and Frimmel (1999).

- C, O and Sr isotope data dispute a magmatic source for the Cu mineralizing fluids in the Otavi Valley.
- The apparent high mean of $\delta^{18}\text{O}$ value (+17‰) for the mineralizing fluids supports a metamorphic origin of the fluids.
- $^{87}\text{Sr}/^{86}\text{Sr}$ values suggest late diagenetic to metamorphic signatures for the mineralizing fluids.
- The large spread in both the C and O and Sr isotope values suggests a prolonged mineralization period, which is interpreted as representing at least two fluid infiltration pulses.

8.8.3 Probable source of the metals in the Otavi Mountainland

Two of the larger copper-lead-zinc deposits in the Hakos Subgroup of the Swakop Group are found on the farms Oamites and Hohwarte. These two deposits as well as the numerous traces of copper occurring at other places in this subgroup are probably of syngenetic origin (Martin, 1965). Similar deposits are found in the Khomas Subgroup with the Matchless, Gorob and Hope mines amongst the most important.

Erosion of the provenance area and subsequent deposition of the material in the Swakop basin would represent a concentration of these metals relative to the concentration in the pre-Damara rocks. Transportation of the metals may have taken place in solution and/or as clastic material together with the sediments. The presence of numerous small deposits of copper, lead and zinc

minerals in the Swakop Group is proof that the abovementioned elements were deposited in the area and at least a portion of these was later concentrated to form these small deposits.

8.9 Primary controls on mineralization; a geologic hypothesis for Kombat mineralization

Studies of the Kombat Central Stopes and the Asis West seem to suggest that the primary controls on localizing mineralization were palaeokarst features. The karst features developed at and beneath an originally flat lying contact between the Otavi Group carbonate rocks and the Otavi Valley phyllite at the point where the regional N50⁰E striking fractures transected the contact. The origins with these important, N50⁰E fractures at Kombat also observed at Tsumeb were probably related to the Damara Orogen

As an alternative explanation to the widely accepted origins of most of the karsts, which call on downwardly percolating meteoric waters to dissolve carbonate rock, it is possible that the Kombat karst cavities were produced by degassing of the Damara basin. In West Texas for example, it is postulated that the H₂S and CO₂ bearing fluids by biogenic reduction of sulphates streamed out of the adjoining gas fields in the Pecos evaporate basin which were focused along faults into the fringing carbonate platform (Ford, 1988). Approaching the water table, the H₂S was oxidized by mixing with oxygenated meteoric water to form sulphuric acid, which aggressively corroded the limestone to produce the caverns. At Kombat the H₂S focused by the N50⁰E fractures produced the karsts which breached the surface in early Mulden times. While the karsts filled with clastic sediments, iron, manganese, barium and base metal bearing fluids continued to flow into karsts from the fractures with the iron-manganese oxides and barite precipitating as discordant sulphide veinlets in the carbonate wallrocks. The discordant base

metal mineralization may represent the root or feeder zone to the layered iron manganese oxide-barite bodies. Subsequent physical and tectonic/dynamic remobilization of the base metal sulphides in the phyllite might have taken place during deformation, as ductile sulphides migrated to lower pressure sites along and at the apices of the piercement structures.

The orebodies at Kombat show several variations in styles of mineralization, highlighting the fact that the precursor ore depositional centre was affected by differential geological processes such as fractionation before mineralization and that the mineralization occurred in different styles for each Orebody indicating a long and complex depositional history.

8.9.1 Oxidation of supergene sulphides

From the above discussion it is evident that the regional structural deformation in the Otavi Mountainland was an ongoing process which spanned almost the entire period of sulphide mineralization. It commenced with faulting and brecciation of the country rock which created the loci for the initial pyrite mineralization. This early-formed sulphide together with the country rock was in turn fractured and shattered - thus controlling the localisation of copper mineralization. Further regional structural deformation affected the existing sulphide minerals and country rock, thus creating loci for galena crystallization, which could indicate changes to the geochemical composition of the mineralization fluids or pressure temperature variations. Dissolving of the country rock along the abovementioned fractures and cracks possibly initiated the formation of the present karst topography which is typical of the Otavi Mountainland.

The present concept of the genesis of the sulphide mineralization in the Otavi Mountainland is that it is of low temperature hydrothermal origin (Clark, 1931 & Söhnge, 1964). Leaching of the rocks of the Otavi Mountainland through which the mineralizing fluids moved, could also have provided metals which were later deposited in concentrated form to produce the Kombat orebodies. It must however be remembered that in the evaluation of a sedimentary unit as a source of metals, an analysis of a rock sample cannot give an indication of what the original concentration was as the amount of metal removed cannot be determined (Noble, 1963). The concentration of copper, lead and zinc in the carbonates and shales coupled with the vast area covered by these country rocks could easily supply sufficient material to produce the ore-bodies in the Otavi Mountainland. Krauskopf (in Barnes, 1967) has calculated that only 3 ppm copper, lead and zinc have to be removed from a source area with a volume of 100 km to produce an orebody which contains one million tons of metal.

8.9.2 Summary

The regional structural deformation in the Otavi Mountainland was an on-going process which spanned almost the entire period of sulphide mineralization. It commenced with faulting and brecciation of the country rock which created the loci for the initial pyrite mineralization. This early-formed sulphide together with the country rock was in turn fractured and shattered - thus controlling the localisation of copper and zinc mineralization. Further regional structural deformation affected the existing sulphide minerals and country rock thus creating loci for galena crystallization.

Supergene enrichment has taken place in all the copper deposits in the Otavi Mountainland with the formation of chalcocite and to a lesser extent neodigenite, bornite and covellite. These supergene sulphides are found at the surface outcrops of all the copper deposits.

The presence of algal beds and stromatolitic horizons in the lithostratigraphic units of the Otavi Mountainland indicate that conditions were ideal for bacterial action to take place. The bacterial action resulted in the formation of hydrogen sulphide which remained trapped in the dolomitic rocks. Subsequent folding, faulting and brecciation which took place in these dolomitic rocks at the time when the Swakop Group deposits were structurally deformed, released the trapped hydrogen sulphide. The migrating brines reacted with the hydrogen sulphide to form sulphide deposits in the fault and breccia zones. This implies that the mineralization in the Otavi Mountainland is late syntectonic to early post-tectonic with regard to the deformation of the Damara Super- group which is dated at approximately 550 Ma.

8.10 Grade distribution in the different orebodies

The variability in the mineralization styles (lithological, structural, dolostone/phyllite contact, sandstone bodies, Fe-Mn relationships) described above are also apparent in the grade distribution of the different stopes. This variability shows that the different orebodies show unique characteristics like the Kombat East, Kombat Central and the Asis West orebodies where variation occurs in terms of structure, alteration patterns and types and mineralogy. Appendices 6, 7, 8, 9 shows the collar coordinates, assay values, downhole surveys and geology for selected diamond drill holes for the different orebodies highlighting the variation in distribution of the

mineralization which were partly used in this thesis. The complete diamond drill hole database is so huge that it can't be presented in this thesis, with up to 6000 holes drilled at the KMC.

Appendix 3 highlights the complexity of the Kombat mineral deposit by summarizing the minerals recorded at Kombat and their relative abundance after Innes and Chaplin (1986).

Chapter 9

Recommendations and Conclusions

9.1 Introduction

The Kombat mineralization displays a long and complicated geological history. Whilst several previous researches have attempted to find an all encompassing model for the controls on mineralization at Kombat, this study differs to this approach. Whilst the regional perspective is generally applicable, locally the different orebodies have such unique, obvious and subtle characteristics that factors defining one stope in an orebody are different from another stope in the same orebody and more so for mineralization across the 7 different orebodies. The regional tectonics of the Otavi Mountainland have been discussed in detail by Dean (1993).

In an ore genesis model for the Kombat mineralization, the following factors must be taken into consideration; it is carbonate hosted, (Hüttenberg Formation, T6 & T8 units), the mineralization is closely related to a “monoclinial structure”, the mineralization often occurs in fracture systems which cut the monoclinial structure at an angle, the mineralization is closely related to sandstone lenses which seem to fill palaeo karst structures, it shows a close association to the Fe-Mn layered mineral assemblages and that the mineralization episode is related to the second Damaran tectono thermal event at about 550 – 570 Ma. The distribution of certain lithophile elements, notably Li, Be, B might indicate a possible mixing of reduced seawater sulphate with magmatic sulphur in a hydrothermal system for the Kombat type mineralization (Innes & Chaplin, 1986), though additional data is required to make it a definitive conclusion.

9.2 Recommendations

9.2.1 Future mining

Whilst Kombat mining operations have been suspended due to flooding, the potential for mining still exists. The most economic decision to make would be to exploit the Pb reserve within the Kombat East orebody which is also not affected by flooding after which focus should be directed towards dewatering the Asis West orebodies before turning the attention to the “white elephant” Asis Far West mine which has huge exploration potential.

9.2.2 Exploration

The Kombat Mining Complex still has huge potential for economic Cu-Pb-Ag mineralization and exploitation. Apart from the resources already delineated (BUT flooded) there are a number of targets that require further exploration work. With the MULTI MILLION dollar brand new Asis Far West Shaft rotting and lying idle, it is imperative that stakeholders resuscitate the initial objective of the Appraisal shaft which was to carry out underground exploration as the orebodies are deep below surface (Hans, 1988) (rendering surface exploration diamond drilling very expensive, timeous, ineffective). The exploration philosophy for the area between Asis West and the Asis Far West orebodies would be to project the dolostone/phyllite contact and mine an exploration drill drive at ~250m into the footwall of the contact. The most important exploration drive would be a drive east from the current Asis Far West development to link up with Asis West. Another exploration drive for diamond drilling will be required from the existing

underground development Asis Far West to be mined westwards for at least 500m. There is no geological explanation indicating that there is no mineralization East of Asis Ost deposit. It is an area open to future exploration and with faulting known to cause substantial displacement of the Asis West Orebodies a structural synthesis of the area within the vicinity of the Asis Ost orebody could yield suitable exploration targets.

“With a clear cut exploration strategy incorporating this and existing data, Kombat has huge potential to awaken again”.

9.2.3 Future geological work

The detailed analyses on the association of the KMC mineralization with the Hüttenberg Formation requires Isotopic studies on Carbon, Sulphur, and Oxygen. The best approach would be to find diamond drill core from a hole that was drilled through an orebody and conduct the isotopic studies for both the mineralized zone and the country rock

9.3 Conclusions

This study has demonstrated that lithological variations play an important role to the distribution and occurrence of mineralization. Whilst the ore is hosted within the carbonate rocks of the Hüttenberg Formation, this formation is a thick succession of carbonates which in themselves have extensive variability. Mineralization within the KMC has an affinity to rocks with porosity and/or permeability. Breccias, which occur in various types, are the prime lithologies hosting Kombat mineralization, the only complication is that not all breccias are mineralized.

Mineralization normally occurs as replacement of the matrix or becomes part of the matrix. The following breccia types have been found to be mineralized; karst, solution collapse, replacement, sedimentary and hydraulic. The other very important lithology is the oolitic dolostone which has a close association to mineralization.

Again this rock exhibits porosity/permeability and mineralization normally replaces the oolites. The sandstone and Fe-Mn oxide and manganese bodies are generally associated with mineralization and they are sometimes mineralized. They are a very important exploration tool to use as their presence indicates that one is within areas that could be mineralized. What is important to note is that the sandstone and Fe-Mn bodies have used the same geological features used by mineralization for their deposition. This project proposes that the sandstone and Fe-Mn oxide and silicate assemblages are precursor and were deposited after the carbonates of the Otavi Valley. They, like mineralization have occupied the favorable loci generated possibly by old karsting and some existing old fracture systems.

All mineralization has an association with alteration though there are some altered carbonates within the area that are not mineralized. This implies that alteration occurred in episodes with some alteration occurring concurrently with mineralization. It also shows that the mineralization controlling factors are not confined to one process but rather interrelated geological processes. Carbonate alteration is the most important alteration whilst silicification and Fe-Mn alterations are of a lesser significance.

The earliest interpreted major structure is the so called “monoclinical structure” trending generally east – west. In general terms, all the Kombat orebodies form an “en echelon” geometry to this

structure. This structure is attributed to the Damara Orogen, and whilst it is not the primary structure controlling mineralization, it created the initial surface that was modified by subsequent geological processes for the deposition of mineralization. This structure has not been fully explored east and west of the current mining limits at Kombat.

The location of the Kombat orebodies on the graben fault played an important part in the sedimentological environment, the preparation of the lithologies (fracturing of the lithologies) for mineralization. The Otavi Valley rupture most probably represents the rejuvenation of the graben fault which was reactivated again and again during the Damara times, influencing the sedimentological processes and possibly acting as conduit for ascending mineralizing hydrothermal metamorphic fluids. It is possible that hydrothermal metamorphic fluids moved along fracture systems especially strike slip graben faults through the Askeveld Volcanic pile. Iron and manganese rich fluids with minor copper were the first hydrothermal fluids which ascended along the fracture system in the dolomites and which dammed up against the phyllite of the Kombat Formation. The iron manganese replaced parts of the sandstone lenses and was also deposited in the hydrothermal fracture zones within the dolomites (most of the iron manganese bodies are surrounded by an intense hydrothermal breccia). Later fluids which followed the same conduits were enriched in Cu, Pb, Ag, and Zn and formed disseminated to massive ore around the sandstone lenses and within structurally and hydrothermally brecciated dolostone.

The Kombat orebodies have two general strike orientations; a dominant NE – SW orientation and a less common NNW – SSE trend. Associated to these strike orientations are second and third generation faults. Mineralized net vein fractures are a very common feature and these are really secondary sympathetic structures to the main phases of deformation. The sympathetic

structures occur in various geometries implying that they were not generated in a single deformational event. On examination of individual orebodies, it is clear that there are subtle variations and differences from one orebody to the other. The variability to these processes is also seen in the mineralogy of the orebodies, with some rich in copper whilst others are rich in lead, others are rich in hypogene sulphides whilst others are mixed and sometimes they are characterized by secondary supergene enrichment. The Kombat mineralization geometries provides evidence of a syntectonic nature of the mineralization which combined with the Pb – isotope data and radiometric dating of the polyphase Damara Orogen suggests that the mineralization at Kombat is associated with the second Damaran tectono – thermal event.

Mineralization at Kombat has been popularized as “contact type mineralization” owing to its close association with the dolostone/phyllite contact. This study has demonstrated that mineralization can occur at any distance from 0m up to 250m into the footwall of the dolostone/phyllite contact on the northern limb of the Otavi valley syncline. The importance of this contact is that it is a clear hangingwall marker horizon to mineralization. Whilst “roll structures” have been regarded as critical to mineralization by previous researchers, this study regards the general contact as the most important aspect of it and the rolls or flexures are an occurrence of competence contrast of the dolostone – phyllite but mineralization is controlled by other underlying factors like lithology and structure.

There seems to have been some sequential deposition of sulphides in some orebodies like Kombat East and Central as follows; pyrite through sphalerite, bornite, tennantite, chalcopyrite to galena.

Kombat mineralization is controlled by several interrelated processes with some processes being more pronounced in one ore body than the other and vice versa (deformation, lithology, alteration and metamorphism).

The geometry and distribution of the Kombat orebodies indicate that the Kombat area could be regarded as a large suitable mineralization depositional site and that huge potential still exists for extension and new orebodies to be identified and exploited.

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