RHODES UNIVERSITY
Grahamstown • 6140 • South Africa

Exploration Status for Oxide and Sulphide Zinc Ores at Skorpion Zinc Mine, Namibia

By

Stefanus Sitoka

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Geology Department

Rhodes University

P.O. Box 94

Grahamstown 6140

South Africa

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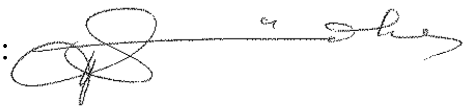
My last note and final words in my acknowledgments are in honor of my late father Joseph Himarwa Sitoka, who always encouraged me to go one step further. He accompanied me during the most important times of my life, I am forever grateful.

Declaration

I, **Stefanus Sitoka** declare this thesis to be my own work except where due acknowledgement has been made. It is submitted in partial fulfillment of the Degree of Master of Science at Rhodes University. It has not been submitted before for any degree or examination in any other University or tertiary institution.

Signature of the candidate: 

Date: **2015.03.05**

Dedicated to my parents

My late father Joseph Sitoka and my mother Pauline Sitoka

Abstract

The thesis is inspired by recent interests in oxide zinc ores caused by new developments in the technology of hydrometallurgy. The improved techniques turned the non-sulphide zinc ores in to attractive exploration targets due to a number of advantages such as low metal recovery costs and favorable environmental aspects such as the obvious absence of sulfur (Large, 2001). Historically extraction of zinc metal from oxide ores was not possible until recently. The metallurgical complexity resulted in a lack of interest and hence some economic oxide zinc ores might have been missed by conventional exploration techniques.

The study presents a review of exploration status at Skorpion mine based on different exploration techniques and their application to sulphide and oxide zinc ore exploration. The challenge facing the mineral exploration industry today is the inability to detect mineral deposits under cover. Therefore a key to successful exploration program lies in the selection of the right exploration technique. Important parameters that should be highlighted in the exploration methodology are the geological situation of an area, equipment applicability and effectiveness, survey limitation, equipment mobilization and the safety aspects involved. The aim of this thesis is to provide a general guideline for sulphide and non-sulphide zinc ore exploration on the Skorpion area and other similar geological environments.

Geochemical surveys appears to be more complimentary in exploration of non-sulphide zinc exploration. Although geochemical techniques are preferred, it is equally important to choose the right soil horizon. Furthermore, sample media may mean the difference between success and failure in geochemical exploration of non-sulphide zinc mineralization, due to high mobility of zinc in the surficial environment. On cost comparison, surface geochemical surveys programs are more cost effective except for litho-geochemical sampling which are commonly carried out through subsurface drilling.

Geophysical techniques have limited application in exploration of non-sulphide zinc mineralization due to a lack of major physical properties (e.g., magnetic and electrical properties) in non-sulphides unlike their sulphide counterparts. However geophysical methods are commendable in delineating massive and disseminated sulphides mainly if they are associated with major Fe minerals (pyrrhotite or magnetite). In addition, geophysical techniques may be effective in mapping of subsurface primary and secondary structures such as basin faults which might have acted as pathways for metal-rich fluids.

Terms non-sulphide and oxide zinc mineralization are used interchangeably throughout the thesis. Recommendations on regional and local target generation are presented in the thesis to give some basic guide lines on target generation strategies. The most important conclusion reached in this study is that, success in exploration for non-sulphide or sulphide zinc mineralization might be enhanced through the integrated exploration methodology.

Key words: Namibia, Skorpion Mine, Zinc, Gariep Belt, Port Nolloth, Rosh Pinah Formation, Oxide, Sulphide, Non- Sulphide, Mineralization, Exploration

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1 Introduction

1.1 Background

Early exploration drilling at the Skorpion project area targeted sulphide mineralisation until it was realised that zinc oxide mineralization with excellent grades was situated closer to surface. Soon after the discovery, the Skorpion project was mothballed due to the complexity of extraction of zinc metal from the oxide ores. Besides, up to February 2002, the exploration model for oxide zinc mineralization was poorly constrained (Schaefer, 2003, Unpubl.) hence, some economic sulphide and oxide zinc ores might have been missed. Based on this motive the conventional exploration methods are reviewed (Chapter 4) based on their application in exploration for sulphides and oxide zinc ores.

The commercial exploitation of "zinc oxides" deposits has rapidly become an important source of metallic zinc (Kärner, 2006, Unpubl.). Economically, oxide zinc ores can provide a quick return for investment due to their high grade commonly associated with significant tonnages. The rising demand for zinc in the automobile and construction industry has positioned zinc well in the ranks of major global economic mineral commodities like iron, copper and lead. As the developing countries (China and India) continues to industrialize, the consumption of zinc is increasing:- 47% is used for galvanized steel, 19% for brass, and 16% for zinc alloys (ECIC, 2007).Therefore it's obvious to assume that the domestic demand for base metals in developing countries will remain strong.

The zinc prices have been stable for the past 3 years ranging between U$1600 and U$2400 per tonne which is incentive for investing the commodity. Although the global zinc prices dropped in 2012 compared to the previous years, the long term forecast looks stable (Namibia Chamber of Mines, 2013). In addition to metal zinc price incentive, Namibia is a favourable country in terms of mining and exploration investments. It has a stable, democratic, and low political risk with a well-developed mining industry. The country has an effective mining and taxation legislation with transparent mining and exploration tenure system.

1.2 Location of study area

The Skorpion Zinc Mine is situated about 20 km north of the town of Rosh Pinah in in the restricted Diamond Area 1 (Spergebiet) in south-western Namibia (Fig.1). The Mine area is located within Exclusive Prospecting Licence (EPL) 2229 with a borderline area of 9 km^2. The Skorpion Zinc Mine owned by Vedanta Resources Plc. is an integrated world-class mining and refinery operation located near the southern town of Rosh Pinah (VZI, 2014). Open-cast mining and hydrometallurgical systems are used to mine and refine zinc oxide to produce Special High Grade (SHG) Zinc (VZI, 2014). The initial mine resources prior to the start of mining in 2001 was estimated at 24.6 million metric tons of zinc ore with an average grade of 10.6 weight percent zinc. Currently, the operation is nearing the end of the life of mine, predicted to be in 2016, and efforts are underway to extend the mine life through investigations into the copper, zinc sulphide and deep oxide zinc potential of the deposit.

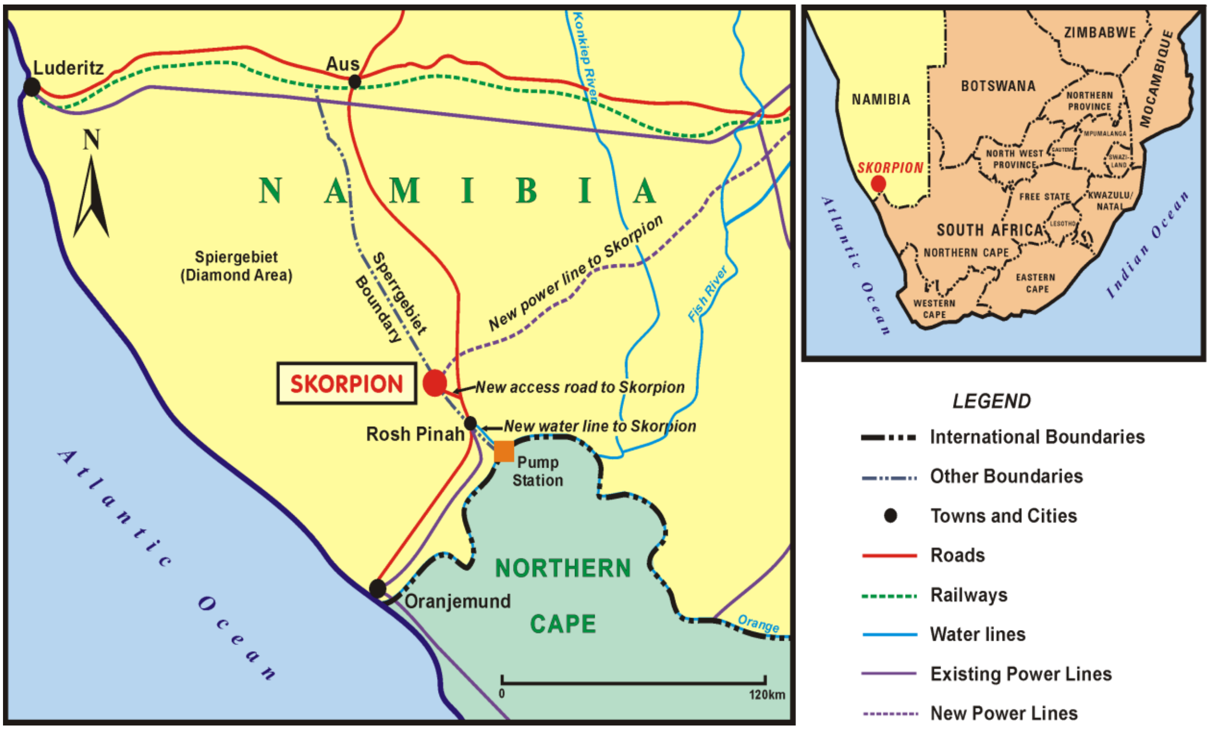


Figure 1: Location of the Skorpion Mine in southern Namibia (Schaefer, 2005, Unpubl.).

1.3 Objectives of study

Historically, conventional exploration techniques applied on the Skorpion area were tailor made for massive sulphide mineralization and, that the discovery of the Skorpion non-sulphide zinc deposit was coincidence as initial holes targeted a massive sulphide model. Until February 2002, the exploration model for non-sulphide zinc mineralization was poorly constrained (Schaefer, 2003, Unpubl.). The Skorpion deposit formed through a sequential coincidence of several mechanisms which require a pre-existing sulphide resource (Schaefer, 2003, Unpubl.).

The improved knowledge about the geochemical characteristics of non-sulphide zinc deposits offer the chance for a more specific and successful exploration of non-sulphide zinc deposits (Reichert, 2007, Unpubl.). However, success favours a more integrated exploration approach, as multiple data integration gives better anomaly definition and reduces the odds of drilling a false anomaly.

Although there is no formula in exploration of any particular commodity or deposit-type, it is anticipated that this study review on the exploration status might add to the existing knowledge of exploration of sulphide and non-sulphide zinc ores in the Skorpion area and similar geological environments.

The main objectives of the study are to:

1. Review status and application of exploration techniques at the Skorpion Mine;
2. Provide guidelines for exploration of sulphide and oxide zinc mineralization;
3. Recommend target generation strategies for regional and local exploration approach and;
4. Train the author in data collection and compilation.

2 Regional Geology

2.1 The Gariep Belt

The Gariep Belt is a southern coastal correlative of the Damara Mobile Belt system, comprising a northern coastal branch, the Kaoko Fold Belt, and an inland branch, the Damara Belt sensu-stricto, within coastal and central Namibia (Fig. 2, Borg et al. 2003). The belt forms an integral part of the Neoproterozoic to Early Palaeozoic Orogenic Belts in southern Africa (Rozendaal et al. 1999). The geology of the belt reflects a plate tectonic framework in which a Neoproterozoic supercontinent (Rodinia) started to break-up along triple-point craton junctions at ~741 Ma during continental uplift (Fig.2) and separation (Frimmel et al. 1996). Rifting occurred within basement granites and gneisses of the Mesoproterozoic Namaqua Province containing local remnants of the 2000 to 1900 Ma volcanic and intrusive rocks of the Richtersveld Subprovince (Reid, 1997; Borg and Armstrong, 2002).

These rocks are bound to the east and west by the ~1100 to ~1000 Ma, granulite facies granitic gneisses and remnant belts of supracrustal of the Gordonia and Bushmanland Subprovince (Alchin et al. 2005). Pre-rift syenitic-to granitic alkaline intrusives of the Richtersveld Igneous Complex mark the onset of rifting (Alchin et al. 2005). The belt is subdivided into a western allochthonous (Fig.2b), oceanic Marmora Terrane, which has been thrust over the eastern, para-autochthonous, predominantly sedimentary Port Nolloth Zone along the Schakalsberg thrust during continental collision and subduction (Von Veh, 1993). The Port Nolloth Zone comprise siliciclastic units with associated carbonates and bi-modal volcaniclastics, the Marmora terrane comprise primarily of oceanic basalts.

The intracratonic Rosh Pinah Graben, which formed during early rifting along the continental margin prior to continental break-up, hosts massive sulphide mineralization and forms part of the sedimentary Port Nolloth Zone (Alchin et al. 2005).The Gariep Belt’s history begins with continental rifting-(Fig.3, Frimmel and Frank, 1998), and its maximum age is constrained at 771 ± 6 Ma by the youngest intrusive body in the pre-Gariep basement (Frimmel et al. 2001). The coarse-grained siliciclastic rift sediment deposition was followed by the intrusion of mafic dykes and later by bimodal, but predominantly felsic, volcanism (Rosh Pinah Formation, Frimmel, 2000).

The exposed lithotypes are characteristic indicators of the depositional and tectonic environment, although the limited and discontinuous nature of the outcrops and the complex deformational patterns severely inhibit stratigraphic correlations (Reid et al. 1991; Stanistreet et al. 1991; Frimmel et al. 1996a; Frimmel and Frank, 1998; Jasper et al. 2000).

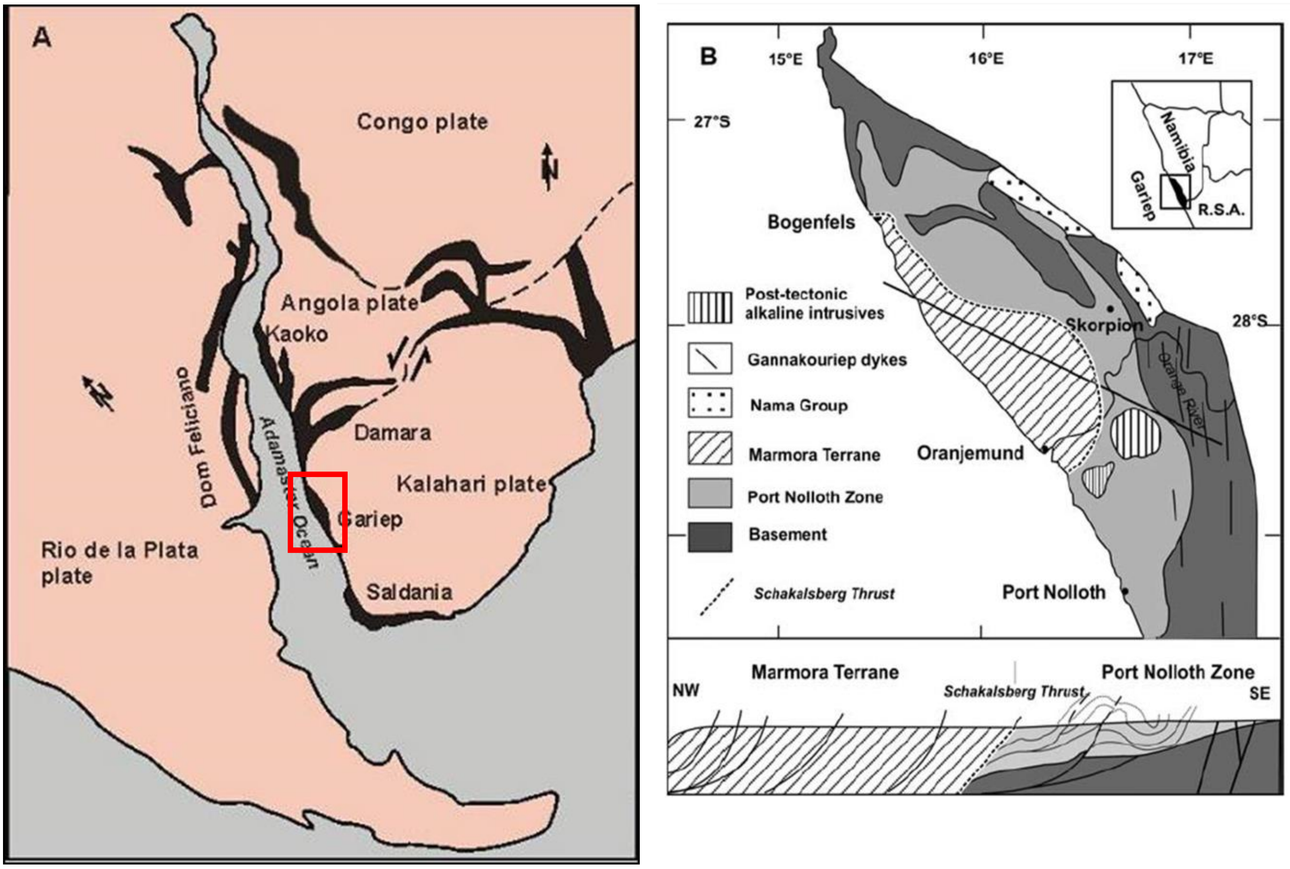


Figure 2: Geological setting of the Gariep Belt (red square). (a) Simplified distribution of Neoproterozoic Orogenic in South West Africa (b) Distribution of tectonic-stratigraphic units of the Gariep Belt with a NW-SE cross-section (After Frimmel and Frank, 1998).The insert shows the position of the Gariep Belt in Namibia relative to South Africa (Frimmel and Frank, 1998)

The tectonic evolution (Fig.3, Frimmel and Frank, 1998) of the Gariep Belt is subdivided into an earlier sinistral transpressive phase (Davies & Coward 1982; Gresse, 1994) with south-south eastwards directed thrusting and a later easterly to north easterly verging deformation that affected the western part of the Gariep Belt (Gresse, 1994). This deformation overprint is marked by NW-SE trending transform faults in the Rosh Pinah/Skorpion basin.

The earlier Gariepian deformation phase (G1) is dated at between 542±4 Ma and 546±10 Ma by Reid et al. (1991); using a metamorphic overprint age on earlier Gannakouriep dykes that predates the deposition of the Gariep Sequence. The later (G2) event is correlated to the late Pan African/Brasiliano event (at approx. 500 Ma) that affected the Nama foreland deposits up to 50 km farther towards the east at the Neint Nababeep Plateau (Gresse, 1994).

The structural style of the G1 event is dominated by thrust structures that strike north north-east to south-southwest in the central and northern part of the belt and northeast southwest in the southern part of the belt (Alchin et al. 2005). The most prominent structure is the Schakalsberg thrust that represents a major terrane boundary juxtaposing the oceanic allochthonous Marmora Terrane (towards the west) with the continental para-autochthonous Port Nolloth Zone towards the east (1990; Frimmel 2000b; Jasper et al. 2000).

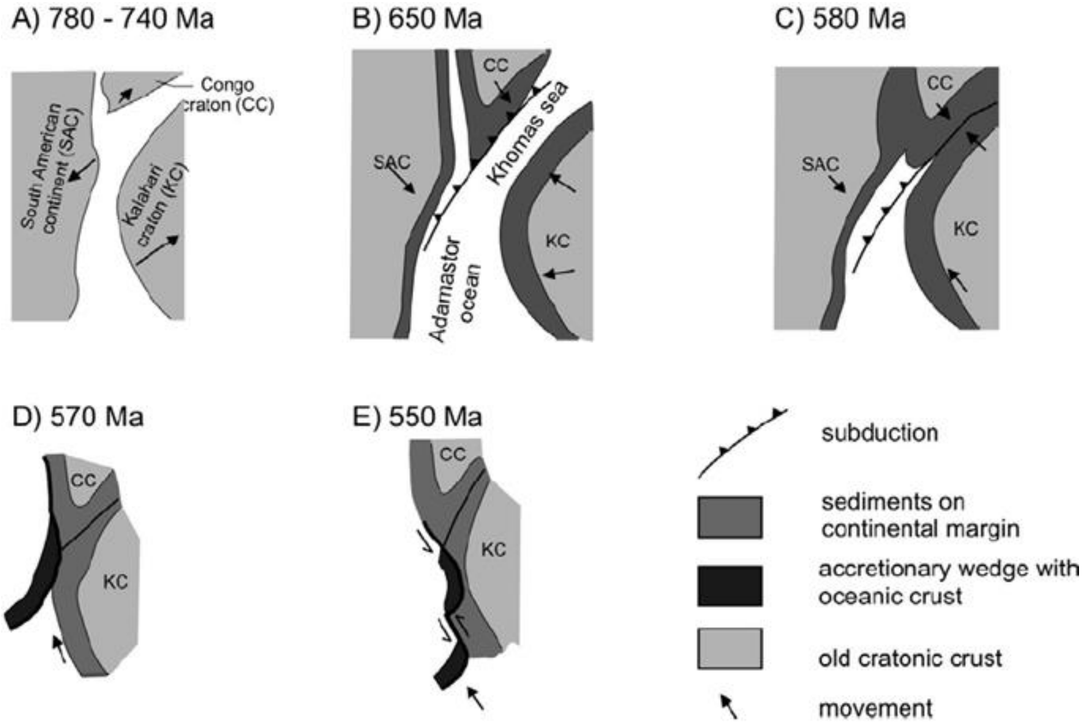


Figure 3: Schematic diagram showing successive stages of the tectonic evolution that led to the development of the Gariep Belt: (A) rifting, followed by the opening of the Adamastor ocean and the Khomas sea; (B) closure of the Khomas sea and north-westward subduction; (C) continent-continent collision in the Damara Belt and formation of an accretionary wedge further southwest (Chameis Complex); (D) Obduction of accretionary wedge; and (E) oblique collision in the Gariep Belt (Frimmel and Frank, 1998).

2.2 Stratigraphy

Regional stratigraphic correlations of the Late Proterozoic rock sequence within the Gariep Belt have been subject of considerable debate and several stratigraphic schemes have been proposed by different authors, e.g. SACS (1980), von Veh (1993), Frimmel (2000), and Alchin et al. (2005). The proposed stratigraphy by several workers is illustrated on Figure 4. The Late Proterozoic Gariep cover rocks, which lie in most places tectonically on the Palaeoproterozoic basement rocks, approximately correspond to sequences assigned regionally to Stinkfontein and Hilda Subgroups, including Gumchavib, Pickelhaube, and Rosh Pinah Formations.

The Rosh Pinah Formation which is located at the base of the Hilda Group is the thickest with approximate thickness of 900m. However, no reliable correlation is presently possible because these formations are characterised by rapid lateral facies changes and multiple deformation (Kärner, 2006). The basement, on which the rocks of the Port Nolloth Zone rest, is part of the some 1.0 Ga old Namaqua-Natal Metamorphic Belt and includes 1730 - 1900 Ma Vioolsdrift Suite granites and 2000 Ma volcanics of the Haib Subgroup (von Veh 1993, Alchin 1993). Major stratigraphic units of the Port Nolloth are discussed in detail by Alchin et al., (2005).

Stinkfontein Subgroup consists of thickly bedded, partly through cross-bedded sandstone with intercalated conglomerate beds (Lekkersing Formation) and trough cross-bedded, upwards fining cycles of sandstone, arkose and greywacke, grading into ripple-marked siltstone, that become progressively more calcareous towards the top (Vredefontein Formation, Alchin et al. 2005). The succession is followed by a massive diamictite (Kaigas Formation) with an, in places, conformable contact (Alchin et al. 2005).The Hilda subgroup formed from a chaotic environment resulting from the erosion of the underlying Kaigas Formation (Alchin et al. 2005).

Alchin et al. (2005) describes the Hilda subgroup as more distal positions, as the next phase of sedimentation, in the form of post-glacial, largely dolomitised carbonates of the Pickelhaube Formation. Subsequent uplift or eustatic sea level fall exposed the Pickelhaube carbonates to weathering and mechanical erosion, which resulted in the re-sedimentation as clastic carbonate beds alternated by sporadic influx of sandy material to form interstratified calcareous sandstone (calcarenite) units, and finally as pure clastic allodapic limestone beds (Alchin et al. 2005).

The Stinkfontein Subgroup is exposed mainly in South Africa along the southern and southeastern front of the Gariep Belt (Frimmel, 2000b). Northward thinning of the subgroup is believed to be due to stratigraphic onlap (Kärner, 2006). The Stinkfontein Subgroup contains siliciclastic sediments in its lower part, containing mainly quartzarenites, feldspathic arenites and conglomerates of the so-called Lekkersing Formation (Kärner, 2006).

The Lekkersing Formation is conformable overlain by the Vredefontein Formation, which includes feldspathic arenites and minor metamorphosed felsic volcanic rocks (Frimmel, 2000b; Alchin et al. 2005).

The Rosh Pinah Formation siliciclastic unit are part of the deep water turbidite that formed during the formation of a divergent margin. The siliciclastic facies are usually displayed by a series graded bedding or bouma cycles which are bands of fine and coarse grained dirty sandstones. The turbidite sequences (Rosh Pinah, Wallekraal, Pickelhaube and Dabie River Formation) in the basin have been interpreted by several workers to be stratigraphic equivalent. Moving from the east to the west is the Pickelhaube carbonates which can be further classified in shallow and deep water facies. The deep water facies rock outcrops are observed near the contact with the Rosh Pinah Formation while shallow facies are observed to the west near the contact with Wallekraal arenites. To the west an arenitic unit (Wallekraal Formation) appears to overlie the Pickelhaube Formation. Part of the western Rosh Pinah Formation (bi-modal) sequence hosts the Skorpion deposit. To the west the Rosh Pinah Formation is overlain by the Wallekraal Formation which comprises mainly arenites and conglomerates.

The Numees Formation which overlies the turbidite sequences is a glacio-marine turbidite flow (diamictite) with a maximum thickness of 500m. The lower part of Rosh Pinah Formation consists mainly of metarhyolite, rhyolitic agglomerates and ignimbrites (Kärner, 2006, Unpubl). The upper part of the Rosh Pinah Formation consists predominantly of meta-tuffites, impure, mainly metacalcarenite and largely dolomitic marble beds (Kärner, 2006, Unpubl). Additionally two black shale horizons occur in the middle and upperparts of the sequence, respectively, with the lower one being rich in sulphides (Kärner, 2006, Unpubl). In its lower part, the Rosh Pinah Formation hosts the stratiform Pb-Zn-Cu sulphide bodies of the Rosh Pinah mine (Alchin et al. 2005). The sulphide precursor of the non-sulphide Skorpion deposit and remnants thereof are most likely also hosted by rocks of the Rosh Pinah Formation as they consist mainly of felsic metavolcanic rocks, e.g. metarhyolites and meta-tuffites, which make up a significant part of the Rosh Pinah Formation (Kärner, 2006, Unpubl).

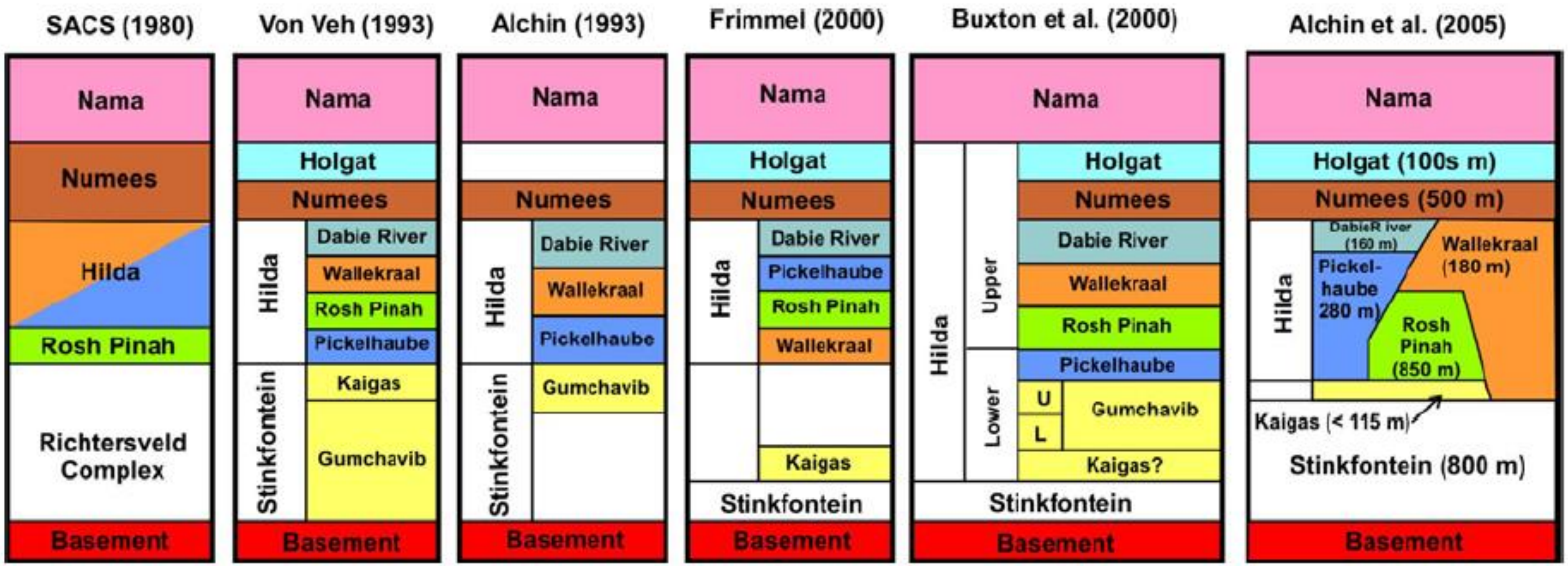


Figure 4: Schematic stratigraphic schemes for the Late Proterozoic Gariep sequence (Kärner, 2006 originally from SACS, 1980; Von Veh, 1993; Alchin, 1993; Frimmel, 2000; Buxton et al., 2000, Alchin et al. 2005).

3 The Skorpion Mine

3.1 History

The Skorpion deposit was discovered by Anglo American Prospecting Services (AAPS) when they entered into an agreement with Consolidated Diamond Mines (CDM) which was solely owned by De Beers at that time. The agreement was to explore for base metals in the Spergebiet (Diamond Area 1) in the early 1970’s. Prior to 1970s, the Spergebiet was a forbidden area (until today) as the name suggest in the native German language. The forbidden status of the Spergebiet was introduced by the German colonial government owing to the discovery of a diamond by a local labourer Zacharias Lewala during a railway construction at Grasplatz near Lüdertz in 1908. Within a year of the discovery the area was swarming with small mining syndicates, mostly holding a 50-year concession granted by the Deutsche Koloniale Gesselschaft (DKG) (Badenhorst, 2003). The German government, in agreement with DKG, decreed a desolate, under-populated coastal strip of land extending some 350 km north of the Orange River as a restricted area, thus, the Spergebiet or Forbidden Territory was formed (Badenhorst, 2003).

Going forward between 1976 and 1977, AAPS initiated an exploration program focussing on geochemical drainage and gossan sampling. The Skorpion area drew attention because of small outcrop of barite/Fe-oxide gossan and geochemically anomalous drainage samples where a subsequent preliminary percussion and diamond drilling program proved a reserve of 8 Mt @ 11% Zn. Further work in 1979 and the first bulk sampling program showed a very high-grade ore (approximately 20% Zn). However the deposit was subsequently mothballed due to metallurgical problems with the unusual character of the non-sulphide ore.

In 1996 Anglo formed a joint venture in which the company carried out another diamond and RC drilling campaign in 1997/8. This program increased the proven resource to 18 Mt @ 11% Zn. Between 1996 and 1998 Reunion Mining commissioned a tailor-made solvent-extraction and electro-winning process (Technicas Reunidas, Spain) which turned the deposit into a minable reserve. Reunion Mining was bought out by Anglo American in 1999 and as a result Anglo American again became the sole owner of the Skorpion deposit. Mining commenced in October 2001 with the stripping of the overburden and exposure of the ore body, which had a resource of 24.6 Mt at 10.6 % Zn by then (Mining Journal, 2000).

3.2 Geological framework

The Skorpion deposit is hosted by metamorphosed volcano- sedimentary rocks of the Port Nolloth zone within the Neoproterozoic Gariep belt (Fig.6, Borg et al. 2003). It is hosted by a volcano-sedimentary succession of Neoproterozoic age, the so-called Hilda Sequence (Von Veh, 1993; Frimmel, 2000b). The depositional, geological, and tectonic setting of the Skorpion area is generally dominated by strong, episodic extensional tectonics, bimodal volcanism, and rapid lateral and vertical facies variations in a subaqueous, mixed siliciclastic carbonate depositional environment (Borg et al. 2003).

The depositional, geological, and tectonic setting of the Skorpion area is generally dominated by strong, episodic extensional tectonics, bimodal volcanism, and rapid lateral and vertical facies variations in a subaqueous, mixed siliciclastic carbonate depositional environment (Borg et al. 2003).The Skorpion deposit occurs in the Rosh Pinah Formation which is part of the Port Nolloth Group. Coarse-grained siliciclastic rift sediment deposition was followed by the intrusion of mafic dykes and later by bimodal, but predominantly felsic, volcanism (Rosh Pinah Formation, Frimmel, 2000).The Rosh Pinah Formation is laterally very variable sequence of rocks, which indicated lateral variations in depositional environment (Hart, 1998, Unpubl.).

The deposit does not outcrop on surface and is covered under extensive tertiary sediments of various thicknesses. The only surface mineralization indicator was a Fe gossan (currently engulfed by the pit) which prompted early workers to investigate for sulphide mineralization rather than non-sulphides. The orebody was exposed to several deformation and thrusting events which resulted in a complex faulting and folding structures. Therefore without drilling exploration the Skorpion oxide resource might have not been discovered given its low geophysical signature. Figure 5(Borg, 2003), below shows the outcrop geology of the Skorpion area were most of the area is covered by young cover. Limestone (marble) units dominate (as shown on Figure 6 cross section) the eastern part of the mine with a friable porous siliciclastic unit (arkose) appears to the west. The bimodal volcanic unit intruded the contact between arkose and limestone. The Gariep succession in the Skorpion-Rosh Pinah represents a para-autochnous initial rift sequence (Port Nolloth Zone, Kärner, 2003, Unpubl.). The rifting and successive uplift during Late Mesozoic and Cenozoic times had major implications for the subsequent landscape evolution through its interaction with, and modification of, antecedent drainage patterns (Kärner, 2006, Unpubl.).

The Gariepian rocks at the Skorpion deposit have been metamorphosed to uppermost greenschist to lower amphibolite facies, as indicated by metamorphic green hornblende in metabasalts and newly grown grossularite in carbonate hosted accretionary lapilli preserved a few kilometers north of the Skorpion deposit (Borg et al. 2003). Chlorite and sericite assemblages are common and are the result of retrograde metamorphism (Borg et al. 2003). These local metamorphic indications are in general agreement with the results of Frimmel and Frank (1998), who constrained the timing of the peak of metamorphism to approximately 540 Ma (Borg et al. 2003).

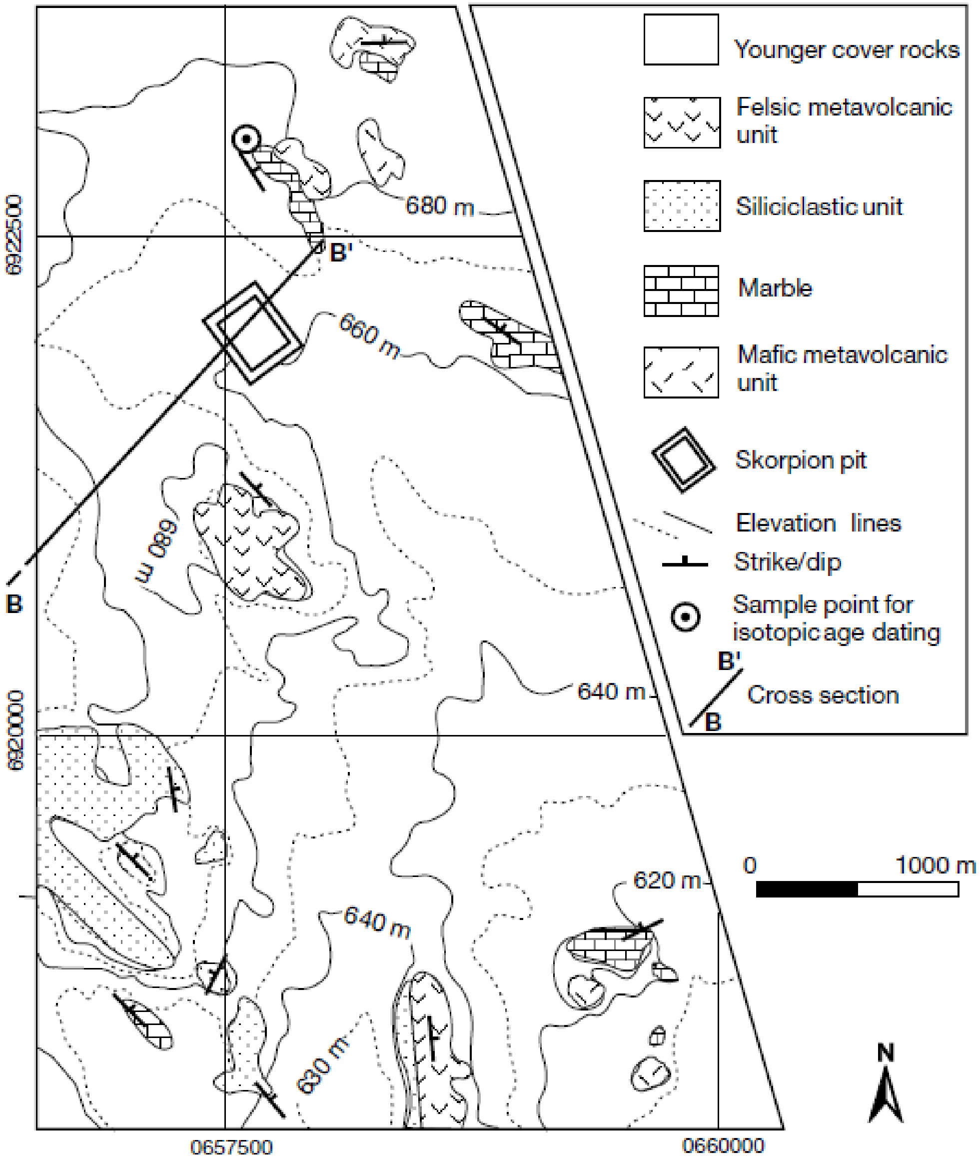


Figure 5: Geologic outcrop map of the Skorpion mine area. The regional correlation of the local stratigraphy at Skorpion sensu-stricto is uncertain owing to the limited outcrop and the complexly faulted, folded, and thrusted geology, which is known largely from borehole information. The approximate position of a portion of the geologic cross section of Figure 5 is indicated by the line B – B' (Borg, 2003).

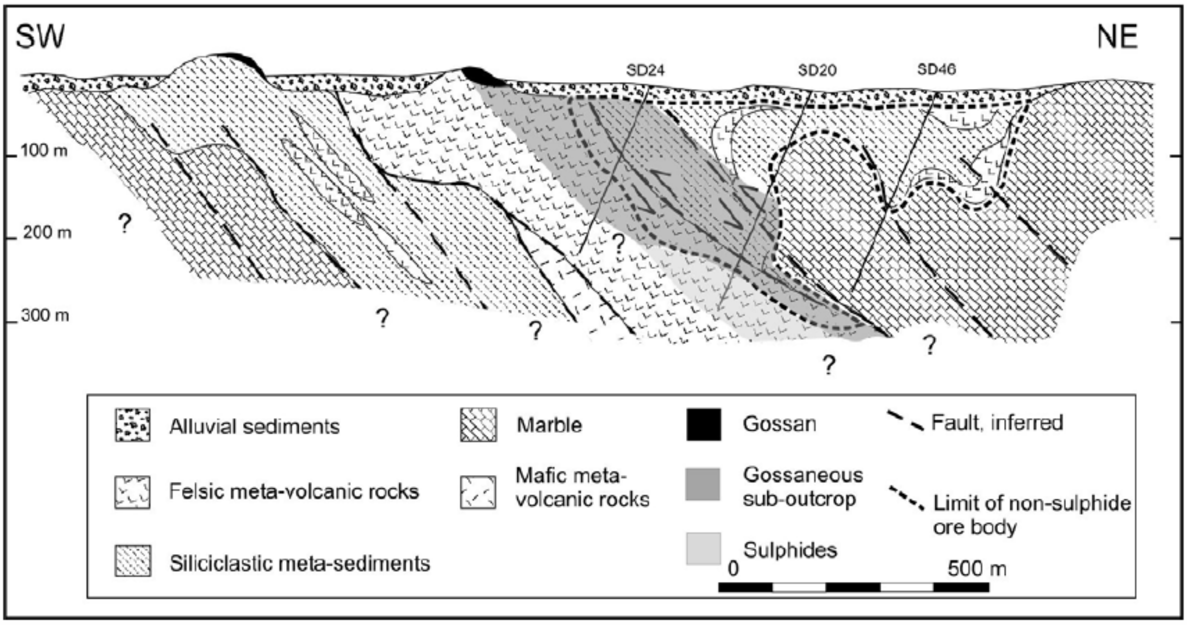


Figure 6: A Cross section through the Skorpion non-sulphide deposit as interpreted by Kärner (2006) from borehole information shows ore-grade mineralization occurring mainly in the meta-siliciclastic rocks and subordinately in felsic metavolcanic rocks. Supergene mineralization crosscuts sedimentary bedding within this package of rocks and the marble unit is generally devoid of mineralization where a dashed line on the figure below indicates the approximate limit of the non-sulphide orebody (Borg, 2003).

3.3Host rock lithology

The host rock lithology of the Skorpion Mine comprises four major units (Table 1), felsic metavolcanic, siliciclastic rocks, limestone and mafic metavolcanic rocks. Oxide mineralization is usually associated with the siliciclastic rocks while the sulphide mineralization has been observed to be associated with felsic and mafic metavolcanic rocks.

The Skorpion non-sulphide zinc ore mineralization is mainly hosted in the siliciclastic facies (arkose - mining term) and between the arkose-limestone interface. The limestone which is located to the east of the pit acted as a redox barrier to the down percolating acidic fluids during a supergene process. The limestone is barren of mineralization while some disseminated and stringer sulphide minerals have been observed within the felsic and mafic volcanic rocks.

No oxide zinc mineralization has been observed in the mafic volcanic units. The interface between arkose and calcareous siliciclastic rocks can be regarded as a karstic weathering front in most places. The ultimate morphology of the arkose-“limestone” interface was controlled by permeability along pre-existing tectonic structures such as thrusts and brittle faults, the limestone quality (weathering resistance), and possibly by the local abundance of acid-generating sulphide (Schaefer, 2003, Unpubl.).

This study uses sedimentary rock classification in line with the mine rock naming nomenclature rather than metamorphic nomenclature. It is also to keep consistence with other rock nomenclature used on other satellite areas within the Rosh Pinah basin. The table below gives a summary of the generalized lithologies at Skorpion mine and their association to sulphide and oxide zinc ore mineralization.

Table 1: Generalized lithologies, sulphide and non-sulphide mineralization at the Skorpion Mine (Modified after Borg et al. 2003).

Lithology	Present Mineralization	Primary Sulfide and Pseudomorphs after sulfides	Primary Ore Textures	Secondary Sulfides and Non-sulfides	Secondary Ore Textures
Metavolcanic Rocks Felsic	Sulfide	Pyrite -FeS2, Chalcopyrite - CuFeS2, Titan magnetite Fe(Fe+2,Fe+3,Ti)2O4	Disseminated, stringers	Brunckite - colloidal ZnS, Galena - PbS, Chalcocite - Cu_2S, Greenockite - CdS, Pseudomorphs of Barite - $BaSO_4$ after Pyrite	Replacement and open space filling
Siliciclastic Rocks	Non-sulfide (Zinc orebody)	Pseudomorphs of iron hydroxides after sulfides	Disseminated, stringers, rare layers	Smithsonite - $ZnCO_3$, Sauconite - Na_3 $\cdot 3Zn_3(Si,Al)4O_{10}(OH)_2$ x $4H_2O$,Hermimophite - $Zn_4Si_2O_7$ $(OH)_2$ (H_2O),Hydrozincite - $Zn_5(CO_3)2(OH)8$,Hydrohetaerolite - Zn_2Mn4O_8 (H_2O), Chalcophanite - (Zn,Mn, Fe)$Mn3^{+4}O7$ $(3H_2O)$),Scholzite - $CaZn_2$ $(PO_4)2$ (H2O), Malachite,$Cu_2Cl(OH)3$,Goethite -FeO(OH), Hematite - Fe_2O_3	Replacement and open space - fracture filling, breccias
Marble (Limestone)	Barren	Barren	Not Applicable	Barren	Not Applicable
Metavolcanic Rocks Mafic	Sulfide	Pyrrhotite - Fe1 - XS, Magnetite - Fe, Mg (Fe2O4)	Disseminated and Stringers	None	Not Applicable

Siliciclastics

Siliciclastic comprises a wide range of rocks (sandstones) that formed in a deep marine setting as a result of turbidite settling. At the Skorpion Mine this include limestone (although discussed below as a separate unit), calcareous arkoses (Fig.7), sandstones, wackes and phyllites. The most significant of all the siliciclastic rocks is the calcareous siliciclastic rocks or arkose which hosts the oxide zinc ore minerals. The arkose is a term used at the mine to describe a variety of sandstones with a variable colour depending on the impurities. Impurities comprise iron (Fe), ferruginous arkose which gives the arkose a rusty brown colour. Other impurities include manganese (Mn) and copper (Cu).

Figure 7: Core photo of the Skorpion arkose in a 1m HQ core box displaying intense fracturing usually filled with iron oxides (this study, 2014).

Marble (Limestone)

The marble unit (Limestone) occurs to the east of the mine and it’s barren of mineralization. Limestone is a chemical sedimentary rock made of calcium carbonate and reacts with 10% concentration of HCl to produce a fizzing reaction. At Skorpion the limestone (Fig.8) is highly variable and ranges in colour from blue to grey blocky fresh limestone. The grey colour normally indicates high concentration of $CaCO_3$.

Figure 8: Core photo of the Skorpion limestone in a 1m HQ core box, the colour varies from light grey to dark grey limestone with varying content of $CaCO_3$ (this study, 2014).

Felsic metavolcanics (rhyolite)

The metavolcanic rhyolite at Skorpion is usually sheared and it appears in secondary form. Rhyolite itself is an extrusive rock which is hard due to the higher concentration of SiO_2. Shearing of the rhyolite resulted in the formation of secondary rock types, the quartz sericite schist here referred as QSS (Fig.9) and the sheared sericite schist here referred to as SSS both rock types consist of quartz which is light in colour and sericite. The SSS unit is found at the centre of the orebody cutting it in half sections of ore west and ore east. Along strike the SSS appears to pinch out on both ends suggesting that the shearing is associated to the formation of secondary zinc mineralization.

Figure 9: Core photo of the sheared quartz sericite schist (QSS) in a 1m HQ core box displaying intense foliation (this study, 2014).

Mafic metavolcanics

The metavolcanic rocks (Fig.10) essentially comprises of the chlorite amphibole biotite schists and the quartz muscovite biotite schist. Typically this rock types are barren of oxide zinc mineralization, however stringers of sulphide mineralization has been observed on drill core. At some places coarse random orientation of amphibole needles can be observed especially from core drilled below the current pit shell.

Figure 10: Core photo of the chlorite biotite schist in a 1m HQ core box, the dominant mineral in the mafic rocks units are mainly amphibole and biotite (this study, 2014).

3.4 Structure and tectonics

The Pan-African orogeny deformed rock sequence has been affected by a later brittle-ductile deformation event in a transpressive shallow crustal regime (Borg et al. 2004), which might be correlated to the opening of the South Atlantic Ocean in the Jurassic (Dirks, 2004, Unpubl.). The Skorpion host rocks have been dissected by steeply dipping brittle-ductile shear zones, which show movement indicators for dip slip, oblique slip, and reverse slip (Kärner, 2006, Unpubl.). The current mining activities exposed the rock sequence of the uppermost part of the supergene Skorpion ore body and thus tectonic structures within the Late Proterozoic sequence (Kärner, 2006, Unpubl.). The structures display a high intensity of deformation including folding, faulting, and thrusting in the mining area as a result of a multi-stage deformation process in different periods since the Late Proterozoic (Kärner, 2006, Unpubl.).

Regionally, the rocks have been folded into verging, tight to isoclinal F1-folds, which have been re-folded by W-verging, open F2-folds with a dominant, penetrative E-dipping cleavage. Fold axes of both F1- and F2-folds and prolate tectonic features (rodding) have a shallow to moderate plunge towards NNW (Borg et al. 2004).

Pilote (2012, Unpubl.) distinguished two domains of folding related to the deformation of the initial thrusts and the two domains are thought to represent differences in folding intensity and heterogeneous distribution of strain within the Gariep fold belt (Pilote, 2012, Unpubl.). The schematic SW-NW cross-section illustrates the general altitude of F2 folds and defines two structural domains according to degree and style of deformation (Pilote, 2012, Unpubl.). The southwest domain is a zone of intense deformation characterized by well-defined structures and tight folds with a 25˚ plunge to the NNW (Pilote, 2012, Unpubl.).

In plain view of the pit area, this NW- to N-trending brittle ductile shear zone is the most prominent feature forming an anastomosing array (Kärner, 2006, Unpubl.). Commonly, extensional quartz veins mark the center of some of these shears zones (Kärner, 2006, Unpubl.). They are variable folded, boudinaged, and recrystallized (Borg et al. 2004; Dirks, 2004). These zones have been interpreted by Borg et al. (2004) as the upper, marginal part of a dextral wrench fault system, which might be part of a positive flower structure (Fig. 11).

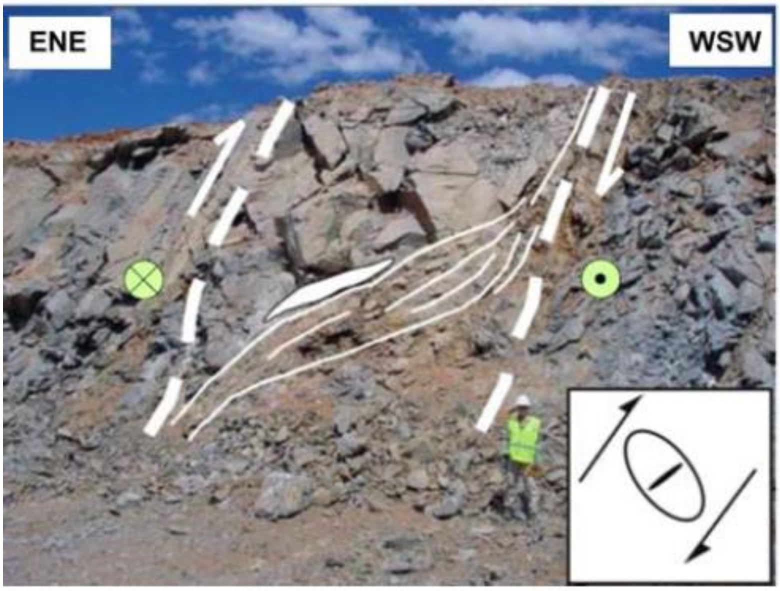


Figure 11: View of the southern pit wall showing a dextral reverse fault set with a sigmoidal shear body and an extensional quartz vein as an example for the reverse oblique-slip fault zones as part of a positive flower structure (After Kärner 2006, Unpubl photo from Borg et al., 2004).

Dirks (2004, Unpubl.) subdivided the Late Proterozoic rock sequence, which is exposed in the open pit area, into five structural domains (Fig. 12) based on the distribution pattern of the Mesozoic brittle-ductile shear zones, which correspond to the dextral wrench fault system defined by Borg et al. (2004). The westernmost domain (Domain I) consists mainly of felsic metavolcanic rocks and metasiliciclastic rocks (e.g. argillaceous and arenitic meta-arkoses, metasubarkoses, metasand and siltstones) (Kärner, 2006, Unpubl.). Argillite meta-arkoses as well as mylonites metavolcaniclastic rocks (mining term: sheared-sericite–schist) and very minor marble occur within Domain II, which follows to the east (Dirks, 2004, Unpubl.). Within the northernmost part of the Skorpion open pit, metasiliciclastic rocks form a separate domain (Domain III). Felsic metavolcaniclastic and metavolcanic rocks (mining term: quartz-sericite-schist) are the main rock types within Domain IV, whereas Domain V consists exclusively of marble (mining term: limestone, Dirks, 2004, Unpubl.).

Near the center of the pit shear zone can be clearly observed essentially displaying a dextral shear movement which might be attributed to the tertiary to recent tectonic activity (development of Namibia plate boundaries?). This shear zones which are essentially marked by the sheared sericite schist (sheared rhyolites) can be traced for about 7km along strike on the Skorpion area.

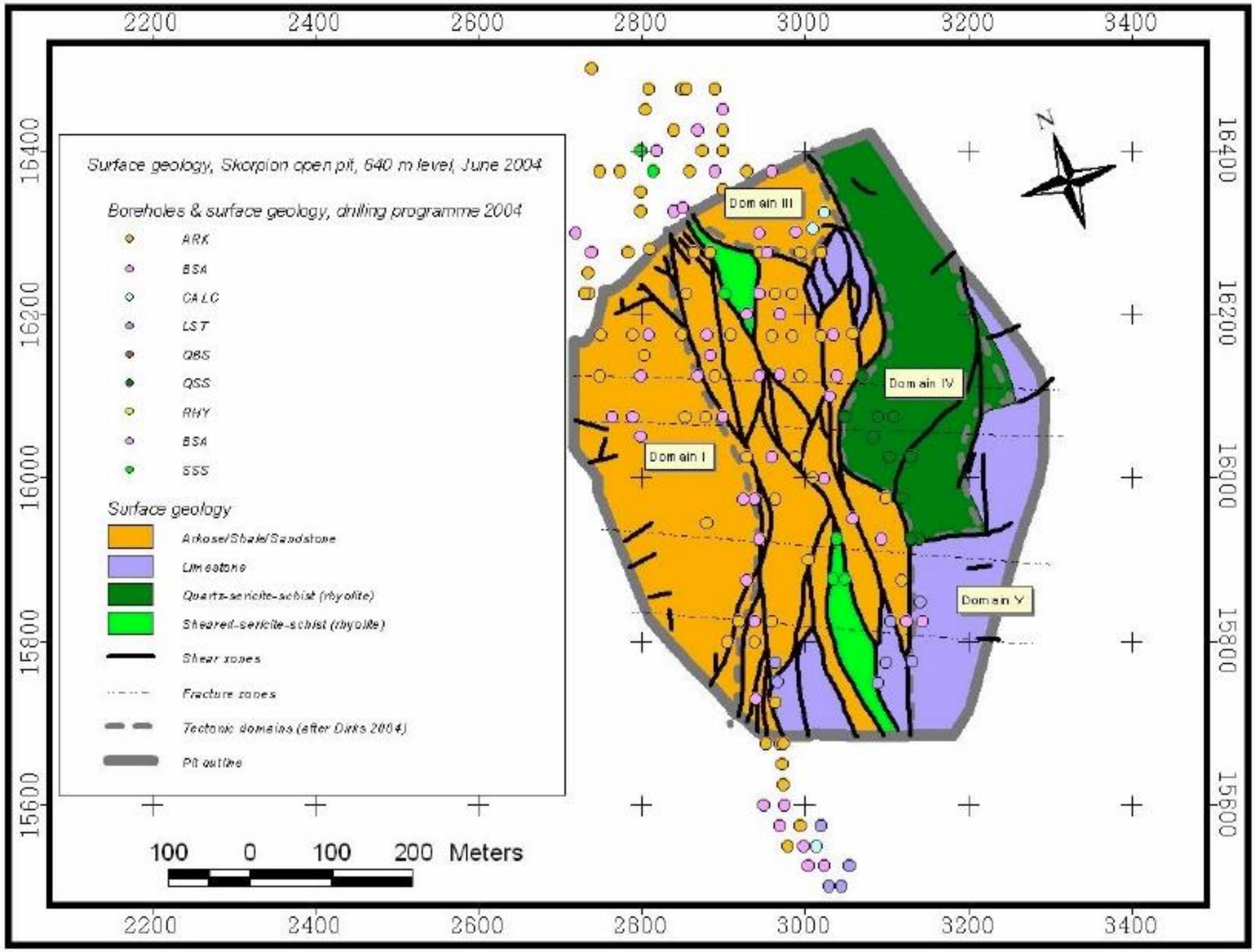


Figure 12: Structural domains in the Skorpion open pit after Dirks (2004). Domain boundaries are defined by Mesozoic brittle-ductile shear zones. Later Cenozoic fracture zones (dashed lines appear to transect the domains (Dirks, 2004, Unpubl.)

3.5 Mineralization

Process model

The non-sulphide (oxide) zinc mineralization is believed to have originated from the primary weathering of sulphide mineralization (e.g., Hitzman et al. 2003; Borg et al. 2003, Boni et al., 2003), therefore exploration models should focus on constraining areas favourable for base metal formation. Additionally Hitzman et al. (2003) suggested that formation of economically significant supergene non-sulphide zinc deposits depends on (1) a pre-existing zinc deposit, (2) efficient oxidation promoted by tectonic uplift and/or prolonged, seasonal deep weathering, (3) permeable wall rock to allow for ground-water movement, (4) an effective trap site, and (5) a hydrogeological environment that does not promote dispersion and loss of supergene Zn-bearing fluids. The modest iron sulphide content in the original zinc deposit is conducive, though not essential; to the formation of supergene non-sulphide zinc deposits, because greater acid-generating capacity aids the dissolution of sphalerite and consequent zinc transport (Hitzman et al. 2003).

Some minerals associated with base metal mineralization, when exposed to oxidising environments they become unstable and disintegrate. For sulphide bodies with a higher concentration of Fe and Mn the reactions with O_2 produce gossans and forms secondary dispersions haloes. Sulphide minerals are particularly vulnerable to oxidation and solution (Rose et al. 1979). Pyrite and marcasite oxidation produces iron hydroxides and sulphuric acid , similarly sphalerite oxidation produces zinc in solution and sulphuric acid, the reaction is best written in steps (Levinson 1974):

$$\mathbf{2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4} \qquad \mathbf{(4.5.1.1)}$$

The ferrous sulphate is then oxidized,

$$\mathbf{4FeSO_4 + O_2 + H_2O \rightarrow 4Fe\,(OH)_3 + 4H_2SO_4} \qquad \mathbf{(4.5.1.2)}$$

The ferric hydroxide is finally transformed to goethite or lepidochrocite,

$$\mathbf{4Fe\,(OH)_3 \rightarrow 4FeO(OH) + 4H_2O} \qquad \mathbf{(4.5.1.3)}$$

By combining equation **(4.4.1.1)**, **(4.4.1.2)** and **(4.4.1.3)** it is seen that weathering of iron sulphide involve the oxidation of both iron and sulphur:

$$\mathbf{4FeS_2 + 15O_2 + 10H_2O \rightarrow 4FeO\,(OH) + 8H_2SO_4} \qquad \mathbf{(4.5.1.4)}$$

Once sulphuric acid has been formed it may react with more pyrite and marcasite:

$$FeS_2 + H_2SO_4 \rightarrow FeSO_4 + H_2S + S \quad (4.5.1.5)$$

The breakdown of Iron sulphide (pyrite) leads to the formation of acids (pH ~ 2.5). The formation of acid then leads to the breakdown of other sulphides in the host rock.

Multi-cyclic oxidation and leaching, similar to that observed in some copper porphyry environments may occur in wall rock replacement bodies. Secondary leaching of massive Smithsonite bodies results in the formation of porous brown to reddish Smithsonite with intergrown Hemimorphite (Hitzman et al. 2003). Beside the geochemical parameters of the host rock such as limestone and dolomite, climatic and morphologic effects are other important factors for an effective oxidation process and the formation of supergene non-sulphide zinc deposits (Reichert, 2007, Unpubl.).

A lateral zonation in mineralogy has been observed at the Skorpion Mine; therefore the exploration model should be defined based on lateral variation of mineralogical facies. For example, Schaefer (2007, Unpubl.) suggested that the present situation at Skorpion ore body is a metal zonation (Fig.13) with Fe/Pb shows near proximal which can be an essential exploration tool, Cu intermediate zone and Zn at distal areas. Metal zonation resulted accumulations of very clean zinc ores (Zn/Pb >100) super high grade zinc (Schaefer, 2003, Unpubl.).

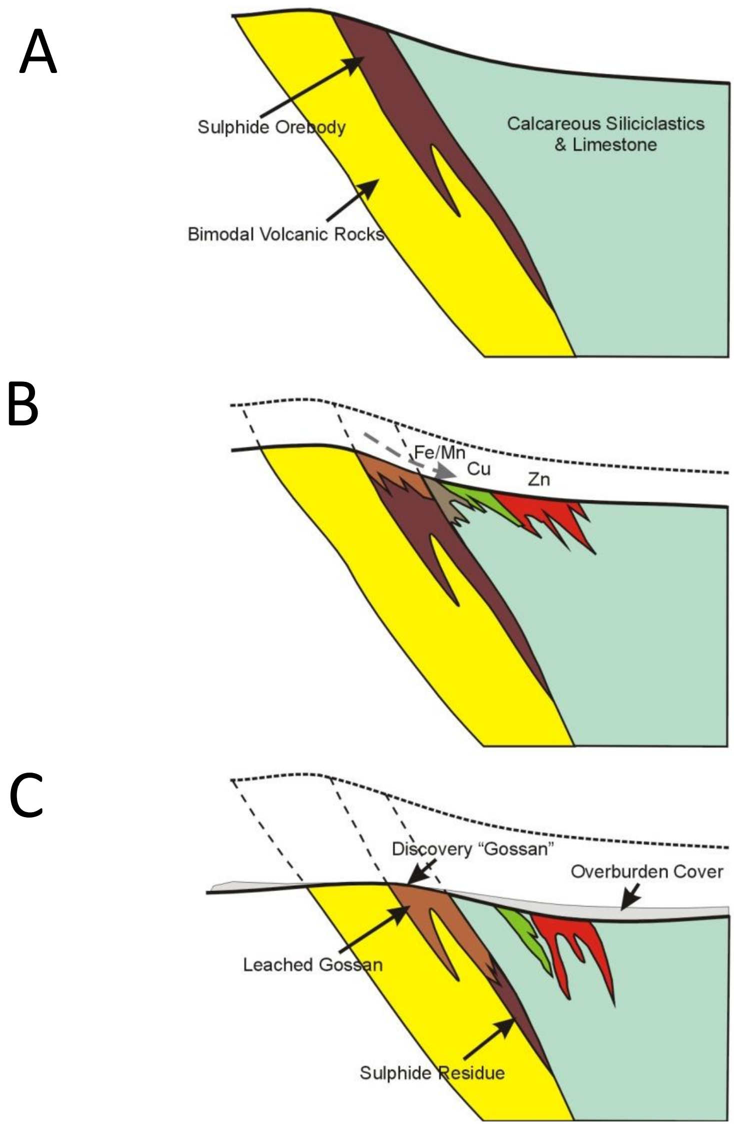


Figure 13: Schematic progression of the development of the Skorpion ore body. The model suggests a steeply dipping massive sulphide orebody lying east of the current pit. Surface exposure of the sulphide orebody is associated by uplift tectonics recorded during the break up of Gondwana at about 140 Ma. A: sulphide mineralization before weathering. VMS sulphide precursor hosted by bimodal volcanics (syn-rifting = 750 Ma); B. Weathering and leaching of primary sulphides during Tertiary (48-37 Ma + later events) Gradual migration, separation and re-precipitation of metals. Alkaline faulted carbonate environment forms chemical barrier; and C. Present situation. Strong Zonation of Pb (Fe/Mn) -> Cu -> Zn, Zn most distal to original sulphide source. Very clean Zn ore (Zn/Pb > 100), after Schaefer (2007, Unpubl.).

Oxide orebody

The ore body (Fig.14) is hosted by Late Proterozoic siliciclastic-volcaniclastic meta-sediments, resting on predominantly bi-modal metavolcanic, hyaloclastic and minor volcaniclastic/siliciclastic footwall rocks (Borg et al. 2003). The footwall contains substantial remnants of hypogene VHMS mineralization, consisting of pyrite, sphalerite, and minor galena and chalcopyrite (Borg et al. 2005). The protore is hosted by partly silicified and K, Ba and locally Mg-chlorite altered metarhyolitic hyaloclastites and breccias (Borg et al. 2003).

Based on drillhole information zinc oxide mineralization is hosted in arkoses (clastic siliciclastics) and subordinately by quartz-sericite schists (volcanic siliciclastics). Other rock types associated with the orebody include mafic volcanics predominantly the chlorite amphibole biotite schist (CABS) and sheared felsic volcaniclastics (sheared sericite schist – SSS) which occurs at the center of the orebody dividing it in to the eastern and western orebody. The eastern limb is associated with calcium and the western orebody is associated with secondary copper mineralization and it extends deeper than the eastern limb.

The orebody is wider at the surface and becomes narrower with depth.The main body of supergene zinc ore at Skorpion is dominated by Hemimorphite and Sauconite and contains lesser Smithsonite (Hitzman et al. 2003). Zinc grades are higher at the contact between arkose and limestone. The orebody interfingers with the limestone forming karst and fill structures. Karstification has been observed in some major non-sulphide orebody which might be a result of acidic fluids eating away in to the carbonate rocks. The development of karst features observed at depth in the Skorpion orebody might be attributed to the heterogeneous migration of fluids in the host rocks (Kärner, 2006). Sinkhole collapse can also lead to mechanical concentration of Smithsonite, often in a hydrozincite matrix (Hitzman et al. 2003).

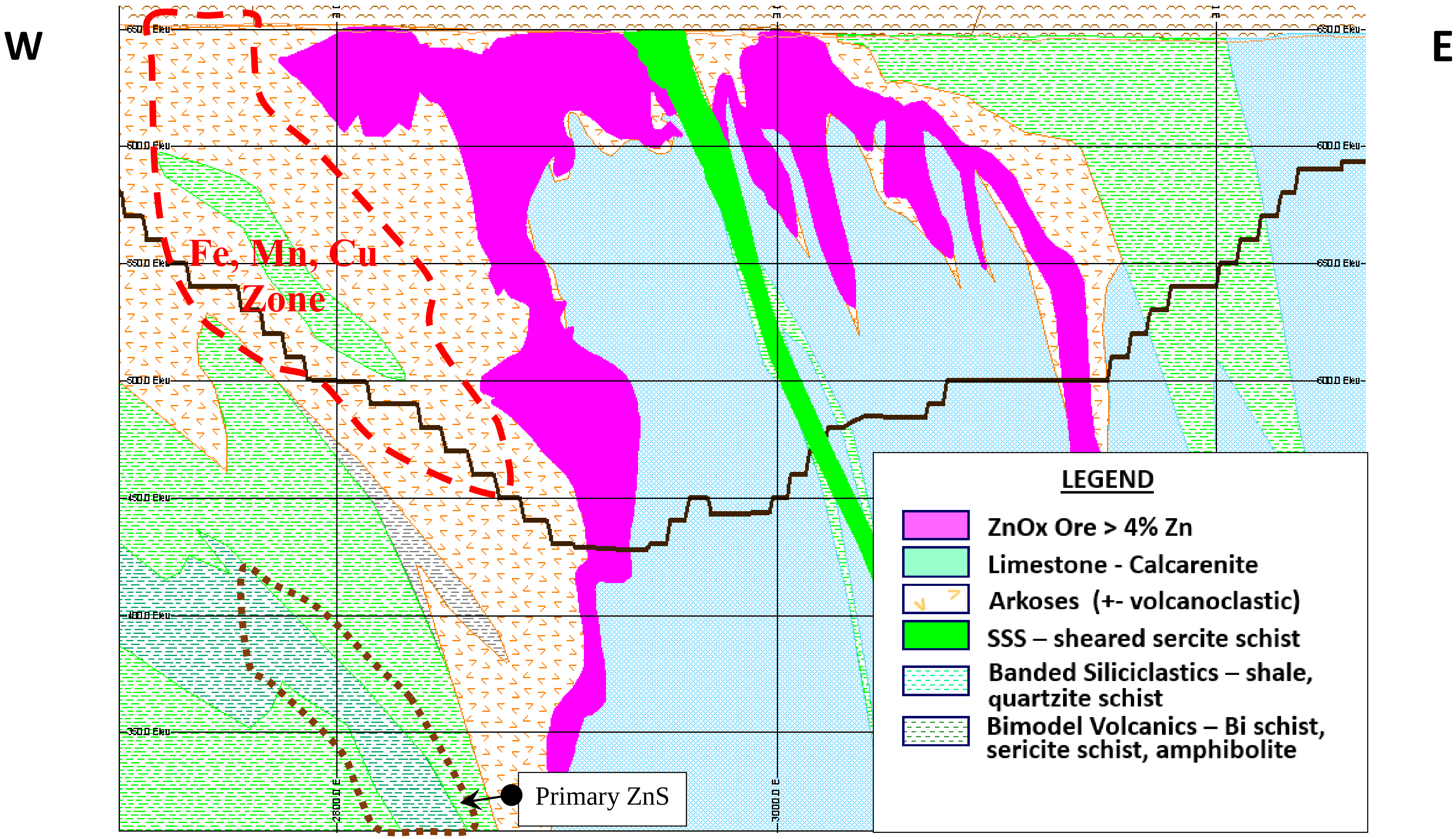


Figure 14: Schematic W-E section through the Skorpion oxide orebody (Schafer, 2006, Unpubl).

4 Review of Exploration Status

4.1 Overview

Area selection in mineral exploration is based on the presence or absence of specific geological features, or alternatively, geophysical and geochemical features which reflect the geology (Hodgson, 1990). The typical exploration cycle follows a process from geological concept formation and reconnaissance exploration, advanced exploration, feasibility studies and possible development (Finisterre, 2003). The result of an exploration project depends primarily on the exploration strategy which involves a series of geochemical or geophysical activities. The best exploration strategy optimizes the balance between cost and effectiveness in the area selection process (Hodgson, 1990). Due to the high risk and uncertainty in exploration, a holistic approach should be taken when selecting a particular exploration technique, taking into account the cost implications.

Mineral exploration and development are investments (Eggert, 2010), and usually mineral exploration is undertaken in the expectation of future profits (Finisterre, 2003). The level and location of investment are determined by expected revenues and costs, adjusted for time and risk (Eggert, 2010). The discovery costs have risen dramatically over the last three decades and there is an urgent need to balance risk versus opportunity (Bosma, 2003).

The risks in exploration may be mitigated through the reduction of cost and cycle times in exploration programmes. However, it should be emphasized that sometimes even if a proficient and cost effective exploration technique is used, it might yield negative results if applied on barren grounds. Several mineral exploration codes (e.g. SAMREC, JORC) recognises that the feasibility of a project is affected by certain elements such as political, socio-economic, and geographical location just to mention a few.

Recently it has been perceived that the major challenge facing the mineral exploration industry is the inability of exploration techniques to detect mineral deposits under cover. For this reason, the principal emphasis should be placed on the exploration methodology, which involves several parameters apart from the cost implications.

Other parameters that should accentuated in the exploration approaches are mainly the geological situation of an area, equipment applicability and effectiveness, survey limitation, equipment mobilization and more recently the safety aspects involved.

Since no one of the exploration methods is all-embracing, there are limitations that need to be taken into account when selecting a particular survey method. A successful exploration project depends on using the right exploration method on the right geological ground. Before commencing with a particular survey program it is recommended to establish an exploration model based on the geological data obtained from the area of interest.

The focus for exploration activities in the future is to find blind orebodies which are stratigraphically, lithologically and structurally complex assuming that all outcropping deposits have been discovered. In areas of active mining activities such as the Skorpion area detailed and careful study of historical data and re-interpretation of geological, geophysical and geochemical data may lead to new discovery in areas previously thought to be barren.

4.2 Geological mapping

A geological map is a human artefact constructed according to the theories of geology and the intellectual abilities of its author (Marjoribanks, 2010). Geological mapping provide fundamental and important geological information of an area based on field observations. However the quality of a geological map may be directly proportional to the mapping experience of a geologist. Furthermore, the quality and scale will vary with the importance of the program and finance available (Moon, 2010).

The traditional technique in reconnaissance mapping in mineral exploration is the field notebook, which may include sketches, compass measurements such as strike, dip, dip direction and plunge of structures. Structures that can be recorded in an area depends on the rock facies, for instance in sedimentary environment (e.g. the Karoo Supergroup sediments) primary structures such as bedding, folds and ripple marks can be measured easily, whereas in metamorphic facies such as granulites primary structures are not well preserved and mapping in this facies has to rely on secondary structures such as foliation and flow banding.

Mapping of structures and lithology may assist in defining the lateral extent of mineralization and alterations. The mapping technique used depends upon the availability of suitable map bases on which to record the field observations (Marjoribanks, 2010). Marjoribanks (2010) noted that the ideal base is an air photograph or high resolution satellite image, as these offer the advantages of precise positioning on landscape/cultural/vegetation features combined with an aerial view of large geological structures that cannot be seen from the ground and for small-scale maps (say 1:5,000 - 1:100,000) remote sensed images are virtually the only really suitable mapping base, although if good topographic maps are available at these scales they can be used as a second-choice substitute.

The drawback in geological mapping is that it depends entirely on observation and measurements of rock outcrops. For this reason vast areas of land covered by exotic cover have experience less exploration activity because exploration stopped where outcrop stopped. Geological mapping in arid and semi-arid environments covered by dune sands and calcretised overburden sands such as the Skorpion area may be challenging due to a minimum surface exposure of rock outcrops. The lack of outcrop particularly in the Skorpion area has caused a lot of uncertainties in terms of the regional and local stratigraphy.

In reconnaissance mapping it is desirable for a geologist to map all small outcrops in more detail as possible. The occurrence of a non-sulphide zinc mineralization in area might be indicated by the occurrence of Pb-Zn-Ag gossans, which during mapping should be recorded in more detail. There is no other way to conduct exploration without establishing the geological situation. Geological investigations to some extent depend on the exploration and genetic models. For example the exploration of syngenetic models (e.g. SEDEX systems) may require a complete basin analysis to establish stratigraphy and ore equivalent horizons.

Mapping status

Oxide zinc mineralization at Skorpion Mine is commonly associated with altered calcarenite rock units with varying degree of silicification. Silicification is a major hydrothermal alteration process that if mapped effectively may act as vectors to mineralization. However, surface geological mapping may not be feasible in the Skorpion area due to a limited number of outcrops, but where possible detailed description and structural measurements of outcrops should be recorded. Landscape analysis may be included at this stage, incorporating all physical structures that may affect or hinder the application of other exploration techniques.

The geology of the Skorpion area presents one of the sophisticated structural deformations which includes folding, faulting and thrusting. The Skorpion deposit geology is discussed more in detail by Corrans et al. (1993) and Borg et al. (2004), and structural concepts are discussed in detail by Dirks (2004, Unpubl.).

The current geological status is the suboutcrop geology map created by Schaefer, (2003, Unpubl).The geological results of the Reverse Air Blast 2002/2003 have been used to draft the suboutcrop geology map (together with airborne EM data – discussed in detail section 6.3) of the Skorpion area as shown in (Fig.15). RAB drilling mostly confirmed the pre-existing sub-outcrop geology in the Skorpion area (Exclusive Prospecting Licence – EPL 2229). Schaefer (2003, Unpubl.) compiled a detailed suboutcrop map on which he identified four main bedrock geology units as follows:

(I) the calcareous siliciclastic rocks (limestone/marble, calcareous arkoses, sandstones, wackes and phyllites), generally just referred to as limestone (mining term);

(II) the Skorpion arkose unit borders limestone to the west. The arkose is mainly composed of highly weathered, soft, friable and very porous siliciclastic rocks (arkose, shale, sandstone, and wacke). This unit is of economic interest as it hosts the oxide zinc ore mineralization;

(III) a succession of bimodal volcanic rocks borders the arkose to the west. The bimodal belt can be traced along strike for about 10 km (detailed discussion of the bi-modal belt under geophysics section). The unit appears thickest close to the Skorpion orebody from where it pinches out in both NW and SE strike directions;

(IV) Felsic volcanic rocks are highly sheared and frequently intercalated with arenitic sedimentary rocks. In several places sheared inhibited the unequivocal distinction between sediments and felsic volcanic rocks. Distinct alteration in form of silicification, Mn-staining and gossan development is present throughout the bimodal felsic unit, but appears particularly concentrated along its north-eastern flank. To the southwest, the bimodal volcanic unit is bordered by siliciclastic sedimentary rocks, namely quartzite, sandstone and (± graphitic) shale (phyllites). The rocks are distinctly different to the weathered and friable arkose E of the bimodal volcanic unit. They appear fresh and unaltered and are somewhat more mature in composition.

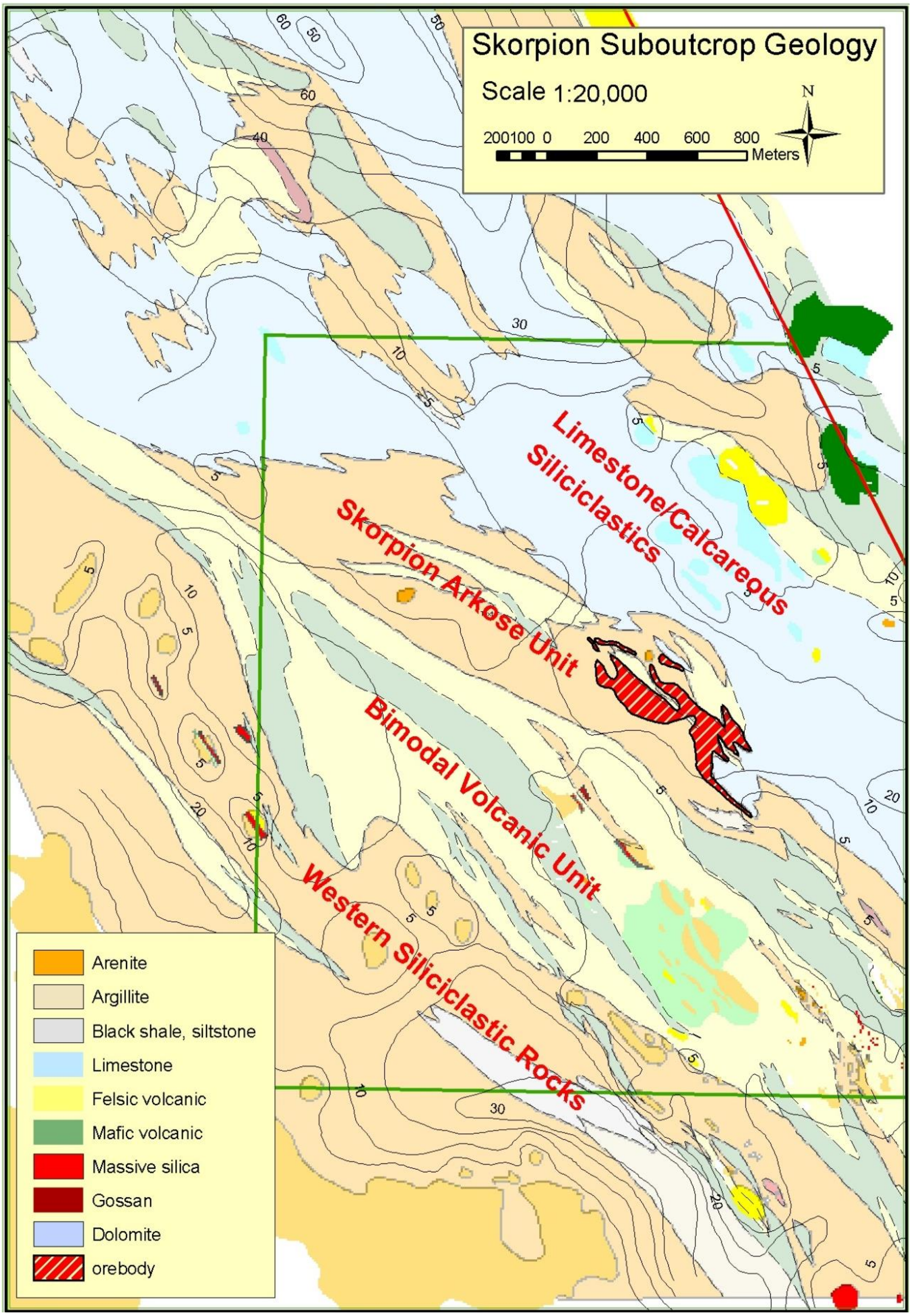


Figure 15: Suboutcrop geology map of the Skorpion area showing major lithological units (Schaefer, 2003, Unpubl)

4.3 Geochemical techniques

Geochemical techniques use chemical composition of the earth's material to determine or infer the location of mineralization. The chemical composition of the earth is driven through the several interaction of matter in the hydrosphere and atmosphere. The techniques of modern geochemical prospecting originated in the Soviet Union and Scandinavia, where extensive research into methodology was conducted during the 1930s (Horsnail, 2001). By 1970 geochemistry had become firmly established as one of the most effective tools of mineral exploration (Horsnail, 2001).

The surface geochemical signature of each mineral deposit is always unique in some respects, due to differences in geological, geomorphological band environmental settings (Butt, 1995), based on this differences geochemical exploration techniques differs from commodity to commodity. This means that a geochemical technique that works for exploration of PGE (Platinum Group Elements) may not necessarily work for the detection of zinc or copper mineralization. Geochemical anomalies, indicative of commercially important concentrations of elements, can be recognized only by their contrast with un-mineralized areas (Hawkes, 1959). The key benefit of geochemical techniques is that they can quantify direct signature of an element under investigation.

Generally, the exploration geologist should be involved with all aspects of a geochemical or geophysical survey (discussed in the next section), for the reason that the exploration geologist is responsible for all communications and usually acts as a liaison officer with the landowners (farmer, local community or local authorities) in relation to the survey. Depending on the exploration budget, a geochemical exploration programme can be divided into the following phases:

1. **Planning phase**
2. **Sampling phase**
3. **Chemical analysis phase**
4. **Data validation and QAQC phase**
5. **Follow-up phase**

Geochemical exploration can be used in both regional and local scale. At regional scale during reconnaissance surveys on large areas (10-100km^2) can be covered. During reconnaissance, sampling interval can range from 1-100km^2; in this case the sampling interval may be suitable for base metal exploration. During detailed geochemical survey (follow-up sampling) the sample spacing is reduced to 1-10km^2, usually the exploration manager or exploration geologist uses his/her own discretion in survey design as this is frequently are dictated by the budget.

At the Skorpion Mine, a review (Table 1) of the geochemical methods suggests that conventional geochemical methods may not be effective in delineating oxide zinc mineralization due to the mobility of zinc. Overburden geochemistry has proven to be a success at Skorpion Mine. Schaefer (2003, Unpubl) stated that at Skorpion surface geochemical methods proved to be too inconclusive and reverse air blast (RAB) drilling was the geochemical exploration method of choice.

In this review (Table 2) geochemical surveys proves to be more of a feasible technique when it comes to non-sulphide zinc exploration than geophysical methods in the Skorpion area.

Although geochemical methods appear to be more complimentary, there are also drawbacks that may be caused by mineral dispersal in the surficial environment. Mineral (element) distributions may lead to false anomalies, which are a common mechanism when certain elements (e.g. Zn, Ni and Co) are associated with iron and manganese (due to scavenging effects) therefore in this cases orientation surveys are recommended. Orientation survey may give an indication of an ideal sampling medium, sample line spacing and size fraction. The choice of a sampling medium may mean the difference between success and failure in a geochemical survey program.

Table 2: Table of application of geochemical exploration methods in exploration of oxide/sulphide zinc ores (this study, 2014).

Geochemical Methods	Regional or Local	Sulfide Zinc Ores	Oxide Zinc Ores	Limitation	Cost
Stream sediment	**Regional**	Effective	Moderately effective	Large variability in sample sites, Prone to contamination	Cost effective
	Local	Effective	Moderately effective	Large variability in sample sites, Prone to contamination	Cost effective
Calcrete	**Regional**	Moderately effective	Moderately effective	High pH may lead to poor sulfide disintegration	Cost effective
	Local	Moderately effective	Moderately effective	Addition of carbonate downgrades anomalies	Cost effective
Overburden	**Regional**	Effective	Effective	Prone to contamination	Moderate cost
	Local	Effective	Effective	Prone to contamination	Moderate cost
Rock	**Regional**	Effective	Effective	Large variability in sample sites	Moderate cost
	Local (drilling)	Effective	Effective	Budget dependent	High cost

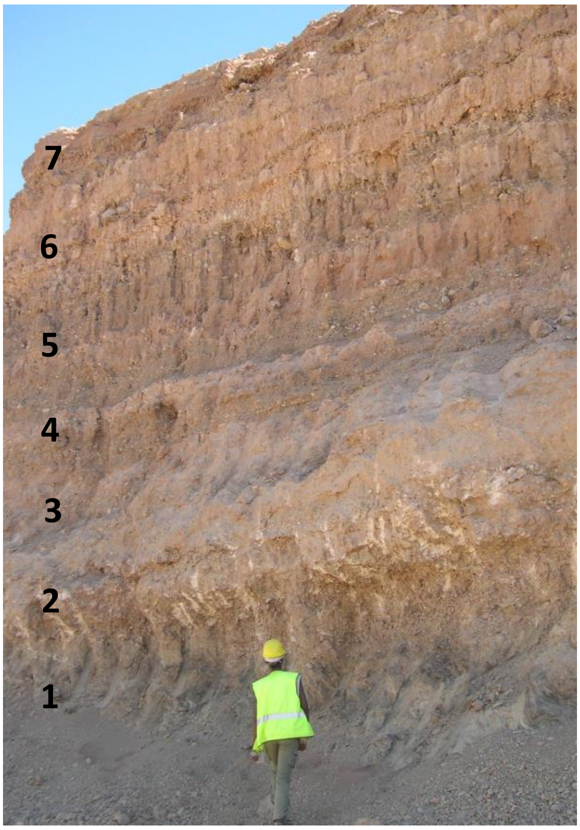
Geochemical exploration status

Bedrock geochemistry proved to be a successful option at Skorpion Mine. Schaefer (2003, Unpubl.) suggested that at Skorpion surface geochemical methods proved to be too inconclusive and RAB drilling was the geochemical exploration method of choice. This is primarily because the transported overburden at Skorpion might not be suitable for surface geochemical surveys as they do not show appropriate lateral dispersion trends.

Generally, when considering conventional surface geochemical techniques such as soil sampling, one is still faced with significant challenges. The principal challenges are the nature of the overburden material itself which covers most of the Skorpion area. The material is ether aeolian or has been transported seasonal flush floods. The overburden material at Skorpion mainly consists of poorly consolidated colluvium that filled valleys and plains on the base of a retreating escarpment (Kärner, 2006, Unpubl.). Commonly the overburden is calcretised with the upper layers forming hard pan calcrete which pose as a challenge for surface soil sampling by masking anomaly contrasts and usually leads to unauthentic anomalies. Therefore calcrete sampling in the search of non-sulphide zinc mineralization should be the last option in any geochemical exploration project; this is because a sample of calcrete will not be a representation of mineralization as calcretization itself leads to the loss of zinc minerals during the process of carbonatization and the high pH of calcrete (mainly carbonates) might as well lead to poor primary sulphide disintegration

At Skorpion, surface geochemical sampling has proven to be too inconclusive and the RAB (Reverse Air Blast) drilling methods (similar to percussion drilling) have shown to be a better exploration tool for non-sulphide zinc mineralization (Schaefer, 2006, Unpubl.).

The RAB drilling which was undertaken in the area targeted the overburden bedrock interface and proved to be a success compared to the other conventional geochemical surveys. Based on the initial orientation survey conducted at Skorpion deposit, order of sampling preference (Fig.16) according to sample media was suggested by Schaefer (2005, Unpubl.). In most cases bedrock sampling is employed at reconnaissance stage with wide spaced sampling lines and sample spacing translating in to a faster and cheaper methods of geochemical investigation, however when used in detailed and follow-up sampling investigations the cost of sampling might increase but generally lower cost compared to other geochemical sampling techniques.



1. **Bedrock**
2. **Fine fraction from gravel at bedrock interface**
3. **Fine fraction from gravels in the lower parts of the profile**
4. **Fine fraction from gravels beneath massive surface calcrete**
5. **Surface sand in contact with massive surface calcrete**
6. **Massive surface calcrete**
7. **Upper parts of sand/soil horizon**

Figure 16: The order of sampling preference (from bottom up) according to sampling media (Schaefer, 2006, Unpubl.). Generally the overburden is calcretised with the upper layers forming hard pan-calcrete which pose as a challenge for surface soil sampling by masking anomaly contrasts and usually leads to unauthentic anomalies.

4.4 Geophysical techniques

Introduction

Geophysics has played an important role in exploration of blind ore bodies since the early 1950's. A geophysical survey system uses the physical properties of the sub-earth to determine or infer the position of mineralization. Geophysical exploration provides preliminary information of the sub-surface environment and is primarily used to define geophysical anomalies related to economic mineralization. The rationale is that in exploration, we should not be looking for geophysical anomalies, but the responses related to mineralization, lithology, and structure that may have economic importance (Da Silva et al. 2003, Unpubl.).

A wide range of geophysical surveying methods exists, for each of which there is an 'operative' physical property to which the method is sensitive (Kearey et al. 2002). The type of physical property to which a method responds clearly determines its range of applications (Kearey et al. 2002). Therefore the challenge in choosing the right geophysical exploration lies in inferring the right physical property on the mineral under investigation. The key physical property used in geophysical surveys are gravity, conductivity (electrical), resistivity (chargeability) and magnetism.

Airborne geophysical techniques such as aeromagnetic and gravity are commonly conducted during reconnaissance stages as they are cheaper and faster to execute over large areas. Airborne geophysics is usually employed at reconnaissance stages, where a faster turnaround of results is desirable. Ground geophysical methods such as resistivity and induced polarization on the other hand are often used in follow-up exploration when an anomaly has been delineated partly because of their price tag and the rate of project execution.

According to Breedt (1995, Unpubl.) in designing a geophysical survey it is desirable to develop a sound geological model because the results of geophysical investigation will ultimately have to be interpreted in terms of subsurface geology. However geophysical methods may be used in mapping structures of an area. At the Skorpion Mine the use of airborne electromagnetic and magnetics enhanced the knowledge of the subsurface geology of the Skorpion area.

Generally, the geophysical exploration programme is conducted by an in-house geophysicist or a geophysical contractor, however it is recommended for an exploration geologist to work hand in hand with the geophysicist or the geophysical contractor. The importance of an exploration geologist in a geophysical exploration programme may not be misjudged. Exploration geologist should work hand in hand with the geophysicist or the geophysical contractor. Moon et al. (2010), suggested that geophysical surveys are often among the most expensive parts of an exploration program and much money can be wasted be few apparently trivial, but wrong decisions.

If the geophysical survey is conducted by a contractor, upon delivery of data an exploration geologist should be able to ask the following questions:

- **What geological constraints applied during the survey?**
- **What geological method/model used?**
- **How much do you know about the sub-surface geology?**

Above questions may assist the exploration geologist to understand the parameters used in the geophysical data interpretation on which he or she can relate the field geology and other field observations. However, it is recommended for geophysical data should be integrated with other data acquired through other techniques such as geochemical, mapping or remote sensing techniques in order to optimise on target generation of a particular project.

Exploration programs have limited and usually predefined budgets, and the geophysical instruments are neither magic wands that reveal everything about an area, nor pieces of useless electronic circuitry inflicted on hard-working geologist specifically to complete their lives (Milsom, 2002).

Reviews of the geophysical techniques (Table.3) suggest that most geophysical methods are inefficient in direct exploration for oxide zinc mineralization. The review further suggest that most conventional methods are moderately applicable in the search for sulphide zinc ores, the primary reason being sphalerite (zinc sulphide) which is not a conductive mineral.

Table 3: Table of application of geophysical methods in exploration of oxide/sulphide zinc ores (this study, 2014)

Geophysical Methods	Air or Ground	Application	Sulfide Zinc ores	Oxide Zinc Ores	Limitation	Cost
Magnetic	**Airborne**	Geological framework	Ineffective	Ineffective	Only responds to magnetic variations i.e. may not detect Zn rich sulphide (with lack of pyrite and pyrrhotite)	Cost-effective
	Ground	Direct targeting	Ineffective	Ineffective	Suffers from cultural noise	Moderate
Gravity	**Airborne**	Geological framework	Effective	Moderately Effective	Ambiguity	Cost effective
	Ground	Direct targeting	Effective	Moderately Effective	Ambiguity	Moderate
Electromagnetic	**Airborne**	Geological framework	Moderately Effective	Ineffective	Cannot differentiate between economic and non economic conductive bodies (e.g. Graphite)	Moderate
	Ground	Direct targeting	Moderately Effective	Ineffective	Cannot differentiate between economic and non economic conductive bodies (e.g. Graphite), suffers from cultural noise	Moderate
Electrical	**Ground**	Direct targeting	Moderately Effective	Moderately Effective	Ambiguous interpretation, Limited depth of penetration (Conventional IP), SP methods cannot operate in waterborne areas	High cost

Geophysical exploration status

In order to test the potential for sulphide zinc mineralization to the north of the Skorpion Mine, two new technology ground geophysical methods (Titan 24 and SQUID TEM) were used in the follow up exploration program. Quantec (a company that acquired Titan 24 data) recommended further infill survey lines in order to reduce the potential artefact between the profiles. Due to the cost implication that comes with IP methods, a decision was made to infill the Titan 24 lines with a fixed loop high temperature SQUID survey (HT SQUID). The advantages of TEM techniques in exploration is that they are versatile and efficient and do not require physical coupling to the ground. For base metal exploration EM systems can be used to map massive sulphide bodies as well as mapping of palaeochannels in the case of oxide zinc exploration (channel ways for supergene processes).

TITAN 24

The Titan 24 system acquires three types of geophysical data: direct current resistivity (DC), induced polarization chargeability (IP), and magnetotelluric resistivity (MT). The MT and DC methods resolve the resistivity distribution of the subsurface by measuring the electric potential (DC) and the variation of natural source electric and magnetic fields (MT). Resistivity can be an indicator of metallic mineralization, but is more often than not controlled by rock porosity and is therefore an indirect indicator of alteration and mineral grain fabric. In the induced polarization method, the electrical capacitance or chargeability of the subsurface is measured. Chargeability is a near-direct indicator of the presence of sulphide mineralization in both massive and disseminated forms. Chargeable mineralization is most commonly various sulphides and graphite, but also includes clay-type minerals potentially making it a useful tool for base-metal exploration. For the Skorpion Mine area survey, only the DCIP data were acquired. The data was acquired by Quantec in quarter 1 (Q1) of 2013. For each line surveyed, the DC-IP utilized a pole-dipole configuration with 100m dipoles with the current injection points spaced every 100m between the potential dipoles along the lines.

SQUID

The superconducting quantum interference device (SQUID) technology was started during pre-Anglo-De Beers split as a collaborative research project with the German research institute in Jena. The aim was initially to develop magnetic SQUID sensors for airborne geophysical survey applications. The project was designed to address Anglo's exploration needs in 2001, i.e. Transient Electromagnetic (TEM) sensors. The technology has since led to number of successful ground TEM surveys in Australia, South Africa and Namibia. Generally ground TEM techniques are used on follow up exploration after airborne techniques have been completed. These techniques use alternating electromagnetic fields at high frequency buy using a combination of electric and magnetic methods, the traditional application of electromagnetic methods in exploration geophysics are commonly used in search of low-resistivity (high conductivity) massive sulphides. The difference between airborne and ground TEM is sensitivity and data resolution, the principal advantage of ground TEM being its ability to have direct contact with the ground. Specifically in the Skorpion area the technology have led to the discovery of the Gergarub deposit which is located about 10km south-east of the Skorpion Mine. Currently there are two types of SQUID, the low and the high temperature magnetometers. The low temperature sensor (LTS) uses niobium metal substrate and attains superconducting properties at -269°C, therefore it operated while submersed in liquid helium. The high temperature sensor (HTS, Fig. 17) is made of ceramic material and functions in liquid nitrogen and usually operates at temperatures of -196°C.

Figure 17: The HT SQUID magnetometer device used in the survey program. Picture taken during survey at Skorpion Mine (this study, 2014).

Survey results

The key exploration data acquired on the Skorpion area are through the recent geophysical techniques. The SQUID and Titan 24 data correlate very well on a number of units. The Titan 24 survey shows a presence of a number of IP and conductivity targets directly north of the pit. Three main anomalies S1, S2 and S3 are delineated to the north of the pit (Fig.18). The S1 anomaly is associated with a major resistive unit Ra which appears to correlate with the arkose-limestone contact. The S2 anomaly is associated with a major NW-SE major conductive unit C1. The third resistive anomaly S3 is associated with a minor resistive unit (Rc) to the NW area of the pit.

In order to reduce the artifact affect between the Titan 24 profiles it was decided to do one large fixed-loop high temperature SQUID TEM survey to better define the NW-SE striking chargeable conductor (C1) mapped by Titan 24 survey, as well as to detect possible proto-ore sulphide mineralization. Consequently the SQUID survey has delineated three motivating targets. The first conductor is a NW-SE striking steeply dipping conductor north of the Skorpion pit. This conductor mapped by the Titan 24 survey (C1) and appears to be chargeable in places. The second shallow conductor was mapped to the northern most area of the pit which is detected by all geophysical methods (Titan 24, SQUID, and SPECTREM). The third conductor is a large, deep (+/-1km), flat-lying conductor extending underneath the Skorpion pit as modelled by the in-house geophysicist.

All the SQUID data (Fig.19) confirmed the conductive units mapped by the Titan 24 survey. As shown in figure the Titan 24 delineated anomaly S1, S2 and S3. The S1 anomaly appears to correlate with the current oxide orebody as it is modelled along the arkose-limestone contact. The Ra, Rb and Rc are major resistive units in the Skorpion area, and mainly correspond to the non-sulphide orebody and associated calcarenite host rocks.

The S2 anomaly appears to coincide with a mafic unit interpreted on the suboutcrop geology. This has been interpreted to as a major conductive unit C1 which is picked up from a depth of about 250m. The mafic unit has been mapped in some shallow RAB holes drilled on the north-eastern area, the fact that this conductor is only picked up at a depth of 250m suggest that it may not be formational. The S3 anomaly appears to coincide with the elevated zinc values which were picked up at the contact between a felsic unit and the Skorpion arkose. A review of the historical data shows that the area is poorly tested for deep oxide/sulphide mineralization.

Interpretation of geophysical SQUID conductors with downhole geology on section 16800 suggests that the conductors might be attributed to the massive sulphide mineralization which was picked up in drillhole SK29. The lack of pyrrhotite and pyrite in the Skorpion-type mineralization poses a challenge for the TEM technique (SQUID) and instead may pick up anomalous zones as a result of formation contrast (mafic unit vs sedimentary unit). This technique may not be appropriate for oxide zinc exploration as the mineralogy is dominated by hydroxides and oxides which have a poor electrical conductivity.

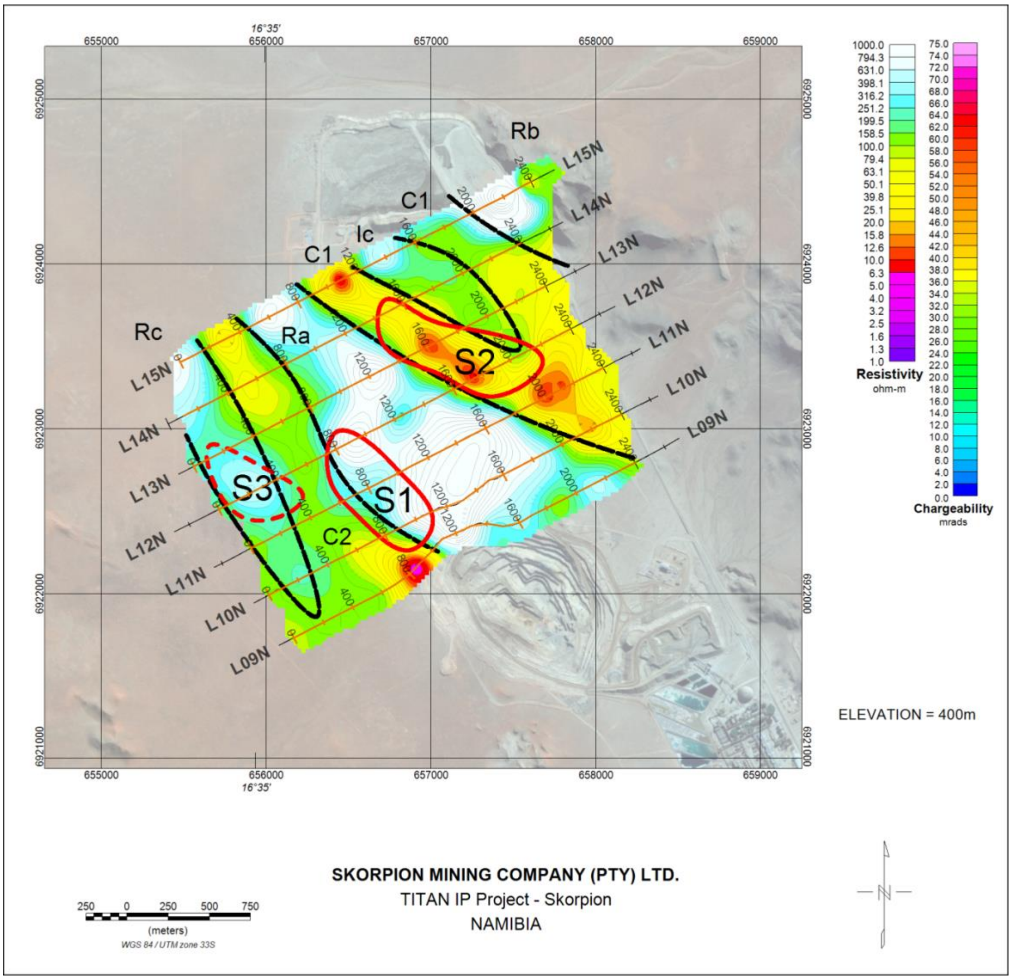


Figure 18: Skorpion plan map at 400m elevation of the DCIP2D results. The DC model map is characterized with a distribution of geo-electric units oriented NW-SE where a limit between the two formations extend from station 400 on L16 to station 1200 on L24 to the east of Ra, a small resistive zone Rb, embedded on an intermediate resistive zone Ia, therefore an overlap of the geophysical interpretation on the simplified geology map indicates a possible correlation of the units Ra and Rb with the carbonates (Quantec, 2013, Unpubl.).

Resistivity IP (Induced Polarization)

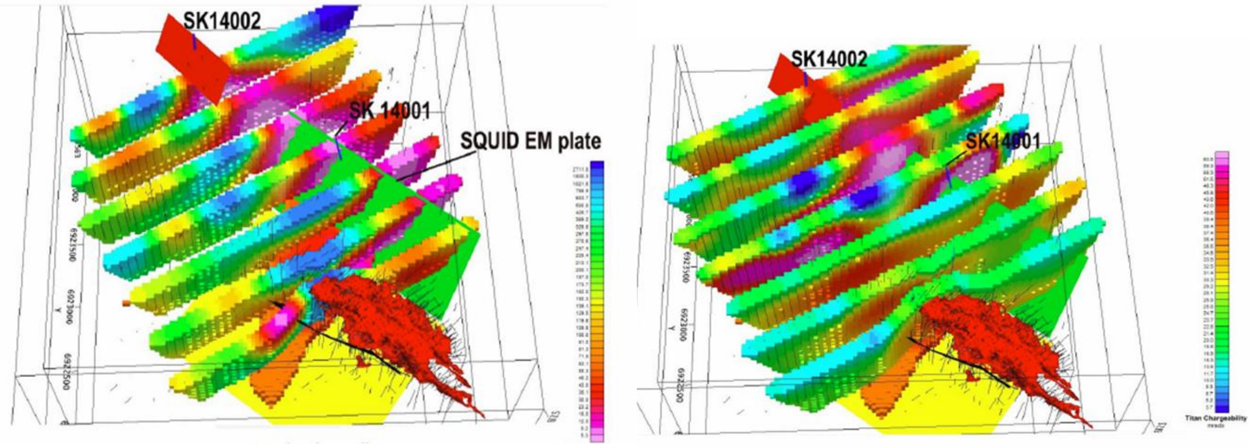


Figure 19: SQUID EM plate models in relation to the DC reference chargeability voxel produced from the Titan data. Position of the Spectrem target (red) shown in relation to the DC reference Titan IP model. The deep lying conductor (yellow) and the steeply dipping conductor (green) (Smit, 2014, Unpubl.). SK14001 and SK14002 are proposed drillholes, where SK14001 was planned to test the steeply NW – SE dipping conductor, whereas SK14002 is planned to test the shallow conductor to the north of the current pit.

4.5 Remote sensing

Remote sensing is the collection and interpretation of information about an object without physical contact with the object. In modern exploration techniques, remote sensing technology has become an integral part of exploration systems globally.

Remote Sensing, in its broadest definition, includes geophysical exploration, instrumental chemical analysis, and all the various techniques that use energy from the electromagnetic spectrum (Breedt, 1995). Remote sensing data collection systems are divided into two primary types such as the passive and active sensors (Whateley, 2010):

- The passive sensors use reflected or transmitted part of the electromagnetic (EM) spectrum as they are dependent on solar energy for illumination of the ground or on thermal radiation for their source of energy; examples are the Landsat Multispectral Scanner (MSS) and the Landsat Thermal Mapper ™.

- Active sensors use their own generated energy which they emit and measure the intensity of the energy reflected by the target, a good example of this is the radar which uses microwave length energy.

In mineral exploration Landsat imagery has been used to provide basic geological maps, to detect hydrothermal alteration associated with mineral deposits and to reduce maps of regional and local fracture patterns, which may have controlled mineralization or hydrocarbon accumulation (Whateley, 2010).

Remote sensing is commonly used as a tool to extract information about the land surface structure, composition or subsurface, but is often combined with other data sources providing complementary measurements. According to Moon et al. (2010), photo geology is the name given to the use of aerial photographs for geological studies.

Moon et al. (2010) further stated that to get out the best of photographs geologist must plan the photo-geological working in the office and in the field as follows:

- Annotation of aerial photographs;
- Compilation of photo geology in topographical maps;
- Field checking;

- Re-annotation and
- Re-compilation for the production of a final photo geological map.

In regolith cover grounds remote sensing is indespensable, as it may provide information on structure and suboutcrop geological mapping. Table 4 lists characteristics of the principal remote sensing systems that are currently available for mineral exploration (Sabin's, 1999). For example Landsat thematic mapper (TM) may be applied in mapping mineral alterations as well as silicification which is an important indicator of hydrothermal alteration in the sulphide and oxide zinc ores. Variations in silica content may be distinguished by high resolution infrared hyperspectral images.

Skorpion Mine Exclusive Prospecting Area (EPL2229) is covered by extensive regolith (overburden material of tertiary to recent in age), hence geological mapping and interpretation has to rely on remote sensing and geophysical techniques. As discussed in the regional structures in chapter 3, major structures can be easily mapped from aerial magnetic data but usually this comes at a high cost.

Remote sensing technologies may enhance knowledge of basin structure (basin analysis) which is important in understanding controls of mineralization especially in the search of syngenetic massive sulphide deposits such as SEDEX systems. However, supergene dispersion of zinc mineralization from the site of mineralization is mainly controlled by the palaeo-hydrology and palaeo-topography of the surrounding area (Schaefer, 2004, Unpubl).

Supergene dispersion of zinc from the site of mineralization is mainly controlled by the palaeo-hydrology and palaeo-topography of the surrounding area and while vertical dispersion of metals within the overburden profile is of lesser importance, lateral dispersion along discrete permeable horizons (palaeo-aquifers) within the overburden is ubiquitous (Hitzman et al. 2003). The most significant palaeo-aquifer leading to dispersion of metals appears to be the overburden-bedrock interface at Skorpion area.

Table 4: Remote sensing systems for mineral exploration (Sabins, 1999).

Characteristic	Landsat 4, 5 thematic mapper (TM)	Landsat 7 enhanced TM	SPOT multispectral scanner (XS)	SPOT panchromatic (Pan)	AVIRIS hyperspectral scanner
Spectral region					
Visible and reflected IR	0.45 to 2.35 µm	0.45 to 2.35 µm	0.50 to 0.89 µm	–	0.40 to 2.50 µm
Panchromatic	–	0.52 to 0.90 µm	–	0.51 to 0.73 µm	
Thermal IR	10.5 to 12.5 µm	–	–	–	
Spectral bands	7	8	3	1	224
Terrain coverage					
East to west	185 km	185 km	60 km	60 km	10.5 km cross-track
North to south	170 km	170 km	60 km	60 km	
Ground resolution cell					
Visible and reflected IR	30 by 30 m	30 by 30 m	20 by 20 m	–	20 m
Panchromatic	–	15 by 15 m	–	10 by 10 m	
Thermal IR	120 by 120 m	60 by 60 m	–	–	

4.6 Drilling techniques

Drilling is one of the most expensive techniques in mineral exploration; hence an understanding of different sub-surface drilling methods is essential as it plays an important role in planning an exploration drilling programme. The choice for particular drilling method depends entirely on the, depth of drilling (all drilling methods have a specific depth limitation), target lithology, sample recovery exploration budget and, more recently the safety issues involved.

The problem with cheaper drilling methods such as augering, percussion or rotary drilling is that the quality of samples is poor (Whateley and Scott, 2010). Commonly the drilling environment (geology situation) and budget dictate what drilling methods should be applied, but it also depends on the commodity under investigation for instance, percussion techniques has proved particularly useful in evaluating deposits which present more of a sampling problem than a geological one e.g. porphyry copper (Whateley and Scott, 2010). A choice for a certain drilling method also depends on the stage of exploration, for instance several companies prefer faster and cheaper methods such as percussion at the reconnaissance exploration stage and use the more detailed and high quality sampling methods such as diamond drilling during resource evaluation stages.

The Skorpion Mine area geology is commonly associated with clay minerals which pose a test for any drilling technique that uses water such specifically diamond drilling. Addition of water expands the clay (e.g. kaolinite) which further leads to poor recovery. It is recommended for diamond drilling to be employed once competent formation (limestone) is intersected (at depths at 200m). In order to achieve maximum recovery in soft formations, it is advisable to use the telescoping drilling method, were drilling starts with a big RC harmer and thereafter changes to a smaller diamond bit as drilling progresses (such as PQ to HQ to AQ for diamond drilling).

Below is a summary (Table. 5) description of different drilling methods with their application to oxide and sulphide zinc ores. Due to the nature of the Skorpion area formation (karst and fill), RC or percussion drilling methods are preferred as it can sample the overburden-bedrock interface cheaply and faster

Table 5: Comparison of different drilling techniques with their application in exploration for oxide/sulphide zinc ores (Modified from Marjoribanks, 2010).

Drill type	Indications	Advantages	Disadvantages	Application	
				Sulfide Zinc Ores	Oxide Zinc Ores
Hand auger	Geochemical sampling in upper few meters of unconsolidated material	Hand portable and operable, Uncontaminated sample, Cheap	Poor penetration	Effective	Moderately effective
Power auger (post-hole digger)	Geochemical sampling in upper few meters of unconsolidated material	Small light weight machine - vehicle mounted or hand operated, Quick, Cheap	Poor penetration	Effective	Effective
Rotary air blast (RAB)	Geochemical sampling to base of regolith, ideal regolith sampling tool	Large sample volume, No site preparation needed, Quick and cheap	Poor penetration of hard rocks, sample contamination, Limited depth, No structural data	Effective	Effective
Aircore	Geochemical sampling where good characterisation of bedrock required	Small rock return, Minimal contamination, Relatively quick and cheap, Can penetrate heavy clay/mud	Small sample size	Effective	Effective
Reverse circulation (RC)	Geochemical sampling hard and soft rocks to 200m + Ore body proving above water table	Uncontaminated Large volume sample. Rock chip geological data, Relatively quick and cheap	Large heavy rig may need access preparation. Limited structural data, Poor orientation control	Effective	Effective
Diamond	Ore targeting and proving to 1,000m + High quality sample, Geological and structural understanding	Maximizes geological information, Uncontaminated undisturbed, high recovery sample, Accurate hole positioning/control	Site preparation required, Water supply required, Small sample size, Slow and expensive	Effective	Moderately effective

5 Recommendations, Discussion and Conclusions

5.1 Recommendation for target generation

5.1.1 Regional exploration

Effective mineral exploration programs maximize the benefit of appropriate technologies in order to increase cost effectiveness by optimizing the use of drilling, reducing risks, and increasing the speed of discovery (Phillips & Chen, 2001). In a similar manner, emphasis is placed on choosing the right exploration technique that may detect mineralization and delineate barren grounds as faster and cheaply as possible. It is recommended for regional exploration of zinc mineralization (base metals) to be conducted in various phases and, usually dictated by the exploration budget.

Phase 1: Regional target selection

The first phase should involve Identification of early rift structures from regional magnetic data. Regional geology is best highlighted by magnetic surveys. Mapping of major Proterozoic faults which may have acted as channel ways for mineralization can be mapped from magnetic maps. This phase should also involve identification of geological units favorable for hosting zinc mineralization.

Phase 2: Airborne geophysics

Airborne geophysical methods are faster and cheaper, and can cover large areas in a short period of time, usually offsetting the cost of flying. This also depends on the quality and resolution of the airborne data available at a selected area; in some cases it is no need to conduct further airborne surveys. Airborne EM (electromagnetics) techniques are widely used because of their speed and cost-effectiveness, and a large number of systems are available (Kearey et al. 2002). EM methods might be effective in locating sulphide proto-ores in search of non-sulphide mineralization.

An EM map allows the direct estimation of length and conductivity of concealed sulphide bodies. The profile asymmetry may be used to estimate the dips of flat bodies which in turn might optimize initial drillhole planning.

Planning and co-ordination of a geophysical exploration survey is mainly the responsibility of the exploration geologist or project geologist. Generally the exploration geologist should be involved with all aspects of the geophysical survey in both exploration methods, since the exploration geologist is responsible for all communications and usually acts as a liaison officer with the landowners, farmers, stakeholders and local authorities in relation to the geophysical survey.

The exploration geologist should consult the community or the landowner on whose place the survey is taking place to ensure that he/she understands the objectives of the campaign and the possible impacts the survey may cause in the area. One of the long standing issues in exploration is the conflict with land owners particularly farmers and tribal chiefs. These conflicts are commonly driven by personal, traditional or political reasons. Therefore it is best for the exploring company to have a good relationship with the land owners, communities and stake holders.

Phase 3: Reconnaissance mapping

This phase may involve regional reconnaissance mapping aimed at identifying basin stratigraphy favorable of hosting economic zinc mineralization. Both pyritic sedimentary exhalative and volcanogenic massive sulphide deposits appear, in general, to be poor precursors for supergene non-sulphide zinc deposits, but they may be highly favorable if they occur in proximity to good carbonate trap rocks (e.g., Skorpion, Hitzman et al. 2003). This stage may also involve grab sampling from outcrops with detailed mapping of alteration features. In some cases the geologist can map the area while supervising the rock (grab) sampling crew.

It is important to record all alteration patterns as it may indicate occurrence of mineralization. Oxide zinc mineralization in the Skorpion area have been observed to be highly associated with altered felsic volcanics displayed by the occurrence of sericite schist; hence focus should be on the identification of different alteration patters.

However, reconnaissance geological mapping may not be feasible in the Skorpion area due to a limited number of outcrops, but where possible detailed description and structural measurements of outcrops should be recorded. Landscape analysis may be included at this stage, incorporating all physical structures that may affect the next geochemical or a geophysical survey.

Phase 4: Regional geochemistry

Depending on the outcome of desktop studies and reconnaissance mapping, favorable areas may be followed by an extensive geochemical survey. Due to the nature of the exotic cover in the Skorpion area, conventional soil sampling may not be feasible in detecting zinc mineralization; hence RAB drilling a type of percussion drilling aimed at testing the overburden-bedrock contact is recommended in the first pass. Sample line orientation should be planned perpendicular to the main geological structure picked up in stage 1 and 2. A preliminary sample grid of 200m sample line spacing and 400m sample spacing should be sufficient to test the target.

Phase 5: Follow up

This phase is primarily dictated by the exploration budget (high resolution data comes at a price). Infill surveys (either geochemical or geophysical techniques may be employed) as discussed in the next section detailed geochemical or geophysical surveys may be employed depending on the type of anomalies delineated.

5.1.2 Local exploration (Near mine)

In active mining areas such as Skorpion Mine, careful study and re-interpretation of historical data may lead to new discovery in areas previously thought to be barren. Local exploration usually follows geological trends (structure and lithology) from the known environment to the unknown areas. The extrapolation of geological features follows a particular exploration model which has been adopted during regional exploration phases. It is recommended for local target generation for base metal mineralization to be conducted in various phases systematically:

Phase 1: Detailed geochemistry

Experience in the Skorpion area suggests that overburden sampling is not favourable in detecting secondary zinc mineralization. However sampling of overburden/bedrock interface may be employed and, depending on the overburden thickness of the area

Air Core (AC) drilling may be employed or RAB (Reverse Air Blast) drilling (type of percussion) method offering a cheaper alternative. With this type of sampling, it is recommended to sample 10m above the overburden/bedrock interface and 10m below. Bulk samples may be collected at 2m sampling intervals. However for QA/QC purpose it is recommended to have a geologist on site in order to make decisions as when to stop the drilling (mainly due to cost implications). From previous sampling campaigns this method proved successful and, if well planned and executed litho-geochemical trends may be deduced and used as vectors to mineralization during follow up sampling or during an infill sampling program. Below is an AC or RAB survey design that might be used in the geochemical sampling in exploration of oxide or sulphide zinc mineralization:

- Sample line orientation (NW-SE direction) should be planned perpendicular to strike of major local structures and lithological contacts.
- A sample line spacing of 100 m might be suitable at first pass.
- 200 m sample spacing along line.

Phase 2: Detailed geophysics

The exotic regolith cover around the Skorpion area means conventional surface geological mapping may not yield desirable results. However, detailed ground EM methods can be employed to identify local structure and sub-lithological contacts favorable for the generation of secondary zinc mineralization as well as detect disseminated sulphide protore. IP methods are best in delineating chargeability and resistive units (disseminated sulphides). The new technology in TEM techniques, the SQUID may be used in exploration of conductive mineralization (Fe associated massive sulphides) on ground geophysical techniques. Encouraging conductors have been delineated at the Skorpion Mine (pending drill testing). The advantages of TEM techniques in base metal exploration is that they are versatile and efficient, and do not require physical coupling to the ground. For base metal exploration EM systems can be used to map massive sulphide bodies as well as the mapping of palaeochannels in the case of oxide zinc exploration (channel ways for supergene processes).

Phase 3: Data integration

This phase involves integration of data (geological, geophysical, geochemical as well as remote sensing data). It is recommended that the criteria of ranking anomalies should be carried out using multi-variable data analysis such as ArcGIS® or similar software that allows multiple layering of datasets. If geochemical data is used at this phase, the norm-log distributions of geochemical data can be used to identify threshold anomalies. It is further recommended that if geophysical data is to be incorporated in the target generation process, the geologist should have an understanding of the parameters used; otherwise the data may be meaningless. If the budget allows it, in-house or contractor geophysicist may be employed during the target generation process.

Phase 4: Drill testing

If the targets are generated and, based on the quality of the data, such that the geochemical anomaly picked up in phase 2 correlates well with the geological and geophysical datasets as proposed in the exploration model, testing of the target by drilling may be initiated (the most important aspect is that the geology should make sense and fit the exploration model).

Testing of the priority targets generated in phase 3 can be conducted by reverse circulation (RC) methods (usually the exploration budget dictates the type of drilling at this stage. However, this decision is subjective to the geologist (or the exploration manager), as for any particular target selected there should be enough evidence and motivation to warrant exploration drilling, this is because of the high cost implications involved with drilling.

Drilling at the Skorpion area is mainly conducted through two drilling techniques, RC and diamond drilling. Diamond drilling or core rock geochemical surveys are typically applied in oxide/sulphide zinc exploration at a stage when the anomaly or orebody has been delineated by other means of exploration techniques. In some cases litho-geochemistry is applied in the early stages of the exploration project, however due to the high cost and the extent of labour required in running a successful litho-geochemical sampling, it is desirable to apply this technique in detailed exploration investigation (i.e., resource definition). However for Skorpion-type mineralization, RC or percussion drilling methods are preferred as it can sample the overburden-bedrock interface cheaply and faster.

5.2 Discussion

In terms of exploration in the Skorpion area the uncertainty of the zinc being sulphide or oxide remains to be confirmed. Hitzman et al. (2003) suggested that exploration programs for supergene non-sulphide zinc deposits must first establish the presence of geologic situations favourable for the existence, either known or presumed, of primary zinc sulphide deposits, preferably in carbonate host rocks. Historically, oxide zinc ores were not considered as a source for zinc metal due to the complication of metallurgical extraction. Hence, some economic non-sulphide zinc deposits might have been missed by the conventional exploration techniques, and in this case the Skorpion area is not an exception. Since many, if not most, mineral deposits are subsurface or otherwise hidden from direct detection, the challenge has been to use the right techniques for the right mineralization. However, several techniques and instruments have been devised over the years to detect the subtle indications that a mineral deposit may lay hidden (Finisterre, 2003).

In the Rosh Pinah/Skorpion Basin, there is enormous potential for further discovery and development of new economically exploitable base metal deposits due to the areas highly-prospective geological structure. The area hosts three major base metal deposits within a radius of 20km namely, the Rosh Pinah massive sulphide deposit (35MT), Gergarub massive sulphide deposit (17MT) and the Skorpion non-sulphide zinc deposit (27MT). However, several major and junior companies have tested the area with minimal success suggesting that sometimes even when the right exploration techniques are used, if applied to barren grounds they can produce negative results.

The Skorpion area is a mature ground which has been explored by different prospecting companies using different exploration techniques since the 70s. This means that the potential for shallow sulphide/non-sulphide zinc mineralization has been significantly reduced. Additionally a significant contrast exists between different oxide zinc deposits Worldwide which make it difficult to constrain exploration models, suggesting that the potential for another Skorpion in the area may not simulate similar lithogeochemical characteristics and structural orientations.

For any geochemical exploration programme, especially in a near-mine environment, it is of utmost importance that a robust and reliable sampling method and sample media are selected. With the rising costs of field operations, maximum efficient in the application of modern technical aids is demanded in order to reduce the financial risk to reasonable proportions (Rose et al. 1979). Cost/benefit ratios should be considered carefully as it may be that a slightly more expensive method will be the only effective technique (Moon et al. 2010). However, it is equally important for exploration geologist to select a suitable sample media that can allow faster mineralization detection and eliminate barren ground as quickly and cheaply as possible. The degree of success of a geochemical survey in a mineral exploration program is often a reflection of the amount of care taken with initial planning and survey design (Horsnail, 2001).

The author explained in the review of the exploration status that representivity is of paramount importance in geochemical sampling and it is essential that samples taken are representative of the material sampled at any given locality. Therefore consistence should kept during the sampling process such that the same soil horizon is sampled at the same depth to maintain representivity. It is therefore equally significant to ensure that the field technicians and samplers are well trained on basic QAQC protocols to avoid sample contamination and sample labelling errors during the sampling process.

Geophysics, in particular, has become an increasingly important exploration tool as the depth of the average discovery moves from close to surface in the 1950s to hundreds of meters deep (Geosoft, 2013) . It’s obvious that most surface or shallow seated orebodies in the world have been discovered, and this is compelling exploration houses to start looking under cover. However some deep seated orebodies may not be detected by traditional exploration methods, meaning that the only way to delineate blind orebodies is through geophysical techniques. Moreover, using a particular geophysical technique is one thing, but using the right type of geophysical technique for the right exploration model is delicate.

One need to have a basic understanding of the Earth’s physical properties in order to make a meaningful interpretation and key decisions based on geophysical data. For example the TEM techniques detect any conductive feature in the ground such as black shales, graphite and uneconomic minerals such pyrite and pyrrhotite. As a rule of thumb, geophysical data should always be interpreted in relation to other datasets such as geology or geochemical data.

A decade ago there was no culture of looking under cover and that exploration stopped where outcrop stopped either due to a lack of technology to detect deep seated orebodies or due to the availability of shallow prospects around the World. Whatever the reason is the World is still hungry for metals and someone needs to supply it. Therefore the lack of exploration in regolith covered areas may provide opportunities for further investigation particularly in the brownfields environments. Lately, exploration under cover may be possible with the new technological advancements in geophysical methods such as DCIP and SQUID TEM techniques. However the high sensitivity of the TEM magnetometer means they can detect low signals which may arise from the surrounding infrastructures such as power lines or agricultural activities. It is always advisable for the geologist to supply the contractor geophysicist with an infrastructure map so that he can plan his survey accordingly.

A logically designed exploration program progresses through a number of stages, from regional reconnaissance to semi-detailed follow up and hence to detailed evaluation (Milsom, 2002). A geophysical program usually follows the same stages. However not all geophysical programs follows this pattern, sometimes only one or two surveys leads to a successful discovery and in other cases it may take more than two surveys. The first stages of a geophysical program commonly require analysis of historical data which involves analysis of a combination of regional magnetic and gravity data.

Topographic and environmental analysis in conjunction with geological mapping should be conducted to pick out any items or structures that may influence the geophysical survey. Topographical analysis may assist in interpretation of anomalies, particularly in the search of secondary mineralization associated to drainage systems. Failure to conduct a proper topography and environmental analysis may result in the definition of false anomalies.

Milsom, (2002), suggested that presenting different types of data together in a single map is generally useful if they are shown as separate entities that can still be clearly distinguished. Currently computer based programs offered by Geosoft® and ArcGIS® allows multiple layering of data on top of each other and, may assist in a better target generation. However it should be noted that geophysical data interpretation should follow a particular geological parameter which usually requires an experienced and knowledgeable interpreter in order to give meaningful results.

The role of a geologist is significant in both geochemical and geophysical survey exploration, and therefore the geologist should work hand in hand with the geophysicist or the geophysical contractor. Exploration programs have limited and usually predefined budgets, and the geophysical instruments are neither magic wands that reveal everything about an area, nor pieces of useless electronic circuitry inflicted on hard-working geologist specifically to complete their lives (Milsom, 2002).

5.3 Conclusion

In conclusion, Integration of exploration methods may be the way forward as this gives a better definition of anomalies and delineates barren ground faster and cheaply. Experience on the Skorpion area suggest that ggeophysical techniques may not be suitable in the delineating economic non-sulphide zinc mineralization, but may be suitable in delineating disseminated massive sulphides as well as in mapping structures associated with secondary processes such as thrusting and faulting. Geochemical techniques proved (through RAB drilling) to be an appropriate method in the search for non-sulphide zinc mineralization suggesting that secondary dispersion processes of minerals are well detected by geochemical techniques.

However, whatever method is nominated, it is essential to attempt the geological interpretation of the area under investigation on which all observations should be based. Nevertheless Skorpion Mine in particular lacks deep drillhole information which hinders interpretation of subsurface geology at depth, although encouraging conductors are observed (2014 SQUID TEM survey results).

Finally, it should be highlighted in each survey that exploration operation is a major expense, therefore exploration budget optimization may be reached through data integration, where geochemical, geological, geophysical and remote sensing data is intergraded during the target generation stages.

The main conclusions reached in this study are:

- Before commencing with any particular survey program an exploration model on which the interpretation of the geological setting and historical data (geological, geochemical and geophysical data) are based is considered to determine the type of exploration technique to be employed.
- In active mining areas such as the Skorpion careful study and re-interpretation of historical data may lead to new discovery in areas previously thought to be barren.
- At Skorpion Mine potential extension of oxide zinc mineralization to the north and south of the current pit has been significantly reduced by RAB geochemical exploration program.
- There are survey limitations that need to be taken into account when selecting a particular survey method and all efforts should ensure that all technical considerations regarding a survey are addressed holistically.

- The success in exploration for both sulphide and oxide zinc mineralization is enhanced through an integrated exploration approach in which different exploration techniques are incorporated to form an integrated exploration program.

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