

Chapter 7

Discussions and Conclusion

During the course of this research, different applied geochemical techniques were employed to investigate and confirm the location of the Areachap and Kantienpan concealed ore deposits by analyzing rock and regolith samples. In the following sections these aspects would be addressed under:

- 1) The recognition of evidence for hydrothermal alteration in the footwall and hangingwall rocks related to VHMS ore deposits, and the use of this in regional lithogeochemical exploration.
- 2) The recognition of secondary geochemical dispersion within a non-residual, wind blown sand cover above a massive sulphide ore body.
- 3) The suitability of the geochemistry of the near surface calcrete layer in detecting the signature of mineralization.

Lastly, an integrated geochemical approach would be recommended for the identification of undiscovered concealed mineralization in this and similar environments.

7.1. Lithogeochemical characteristics of the hydrothermal alteration zones in VHMS deposits and vectors for further exploration

Various lithogeochemical and mineralogical methods were used to identify, characterise and investigate the lithogeochemical characteristics of the footwall alteration zones of VHMS deposits in upper amphibolite to granulite-grade

metamorphic rocks. Whereas a hydrothermal alteration zone has been identified in the past at the Prieska Cu-Zn deposit at Copperton (Theart, 1985), this study has now confirmed the presence of similar zones at Kantienpan and Areachap. The metamorphic minerals that characterize the alteration zones at these latter two VHMS deposits include plagioclase, almandine, pyrope, enstatite, clinoenstatite, cummingtonite, gedrite, cordierite, sillimanite, and retrograde chlorite, chamosite and pinite. Some of these minerals display characteristic mineral chemical variations relative to their respective positions in the alteration system, such as;

- a) Plagioclase is more Ca-rich (anorthite rich) close to the ore zone and more Na-rich (albite rich) further away from the ore zone.
- b) Pyroxene adjacent to the ore zone in KN11 has the highest relative Mg contents ($Mg^* \text{ ratio} = Mg/(Mg+Fe+Ca)$) and this value decreases in the stringer footwall zone and also in the hangingwall zone. The Mn and Fe content of pyroxene near the ore zone and alteration zones are lower than those in pyroxene further away from these zones.
- c) The Mg number ($Mg \text{ number} = 100 * Mg/(Mg+Fe)$) in cordierite is the highest in the ore zone and this decreases away from the ore zone into the host rocks. The Mn content of cordierite in the ore zone is higher than that in the footwall alteration zone.
- d) The almandine and pyrope components calculated for garnet are high in the alteration zones, whereas the spessartine and grossular components are low. Garnet in the ore zone has high Ca contents, but low Mg contents when compared to garnets in footwall and hangingwall.
- e) Based on the Mg and Fe values in mica, the Mg-rich variety, phlogopite is more common adjacent to the ore zone.
- f) The peraluminous nature of the footwall alteration zone is reflected by the presence of spinel (gahnite type close to the ore zone).

g) Retrograde chlorites of the ore zone are characterised by the highest Mg# ($Mg\# = Mg / (Mg + Fe)$) when compared to those in the footwall and hangingwall succession. This suggests that the system behaved relatively closed during the retrograde stages of its evolution as the chlorite reflects the precursor bulk rock composition.

The abovementioned mineralogical characteristics together with the PER analyses of the compositions of cordierite, pyroxene and garnet may be used to constrain the proximity to sulphide mineralization when conducted on drill core during exploration.

Geochemically, the peraluminous ratio ($Al_2O_3 / (Na_2O + K_2O + CaO)$) is high for samples adjacent to the ore zone in Areachap and Kantienpan VHMS ore deposits. Mineralogically and lithologically these samples represent to the garnet-sillimanite-cordierite-gneiss, identified as the rock type representing metamorphic equivalent of the originally formed in the hydrothermal footwall alteration zone. However, in borehole AP5, the high peraluminous ratios occur structurally above the ore zone suggesting that the original sequence have been inverted.

Based on the variation of the major oxides variation, the borehole sampling intervals with low CaO and Na₂O and high MgO and K₂O represent the alteration zone in the original footwall rocks of the deposit. This interpretation requires that the ore body in borehole AP5 were structurally overturned in acquiring its present habit confirming the conclusion based on the interpretation of the peraluminous ratio.

Isocon studies have shown that the alteration zones at the Areachap and Kantienpan deposits are enriched in Mg, Fe (total), S, Zn, Si, Co and F and depleted in Na, Ca, Sr, Ni, V and La. Ba is enriched in the footwall alteration zone at the Areachap, but depleted at the Kantienpan deposit. Elements that behaved relatively immobile include Zr, Ti, P, Mn, Al, Y, and U. Theart (1989) reported that the alteration zone at the Prieska Cu-Zn Mine is similarly enriched in Mg, K, V, Sc, Ni, Ba, Cu and Zn, and depleted in Ca, Na, Sr and Si.

The lithogeochemical and mineralogical characteristics of these alteration zones may now be used in exploration in this and similar terranes to identify concealed VHMS

mineralization. The box plot suggested by Large et al. (2001) and modified for metamorphic rocks here, is shown to be an effective method in identifying those rocks that were affected by hydrothermal alteration processes at the time of ore formation. In this case, the combination of the highest AI (Alteration Index) and CCPI (Chlorite-Carbonate-Pyrite Index) values ($CCPI > 70$ and $AI > 70$) correspond to the footwall alteration zone. Based on the investigation of the regional data set provided by Kumba Resources Limited, the location of peraluminous samples with extremely high Mg ($MgO \gg K_2O$, $AI > 90\%$ and $CCPI > 98\%$) may be categorized as highly prioritized anomalous areas, those with high Mg ($MgO > K_2O$, $AI > 64\%$ and $CCPI > 93\%$) as moderate to highly prioritized anomalous areas, and the samples with high K ($K_2O > MgO$, $AI > 64\%$ and $55\% < CCPI < 93\%$) as lower priority anomalous areas in an lithogeochemical exploration programme.

A statistical analysis of whole rock analyses has shown that, the rocks in the footwall alteration zone of VHMS metamorphic deposits are peraluminous and that the peraluminous factor has the highest values. This zone may be further recognized by MgO contents that are higher (to extremely high) than K_2O contents, or display the highest alteration factor values.

The statistical analyses of the regional data set shows that the variations in the scores for the altered rock factor (FAR) versus the peraluminous factor (FPer) and the pelitic factor (FPR) may be used to differentiate the originally altered samples from the metapelitic samples. Altered samples are characterised by high scores for the FAR ($FAR > 23$), low scores for the peraluminous factor ($FPer < 15.7$) and pelitic factor ($FPR < 7$). The peraluminous samples may be separated from the amphibolite samples by introducing a lower cut off value of three for the peraluminous factor and a very low scores for the ortho-amphibolite1 factor ($Forth-Amp1 < 8$). In order to distinguish the peraluminous samples from the hornblende-gneiss samples, lower cut off value of three may also be used for the scores of the peraluminous factor; where samples returning a score of greater than three samples belong to the peraluminous variety of hornblende gneisses indicating rocks of intermediate composition that could have been affected by hydrothermal alteration prior to metamorphism. Applying these principals now to a regional lithogeochemical data set (the Kumba data set), it is

possible to identify samples from specific areas where no previously discovered VHMS deposits are known and such areas are prioritized as highly prospective.

7.2. The appropriateness of regolith geochemical survey in this region

The concealed mineralization at Kantienpan and Areachap were effectively defined in samples of the wind blown Kalahari sand cover. Indicating the transfer of anomalous concentrations of the ore related elements to the sand in the relatively short period since its deposition. These anomalies were detectable by both the total analytical method (XRF) and partial extraction methods followed by ICP-MS.

In regolith geochemical surveys, the size of the dispersion haloes is more important than the peak to background ratio, because this will increase the possibility of detecting mineralization where samples are spaced relatively far apart. This study came to different conclusions regarding the size of dispersion halo that can be detected at the two investigated deposits. At Kantienpan where the sand cover is very shallow to absent, dispersion appears to be more related to the secondary redistribution of gossaniferous clasts, than dispersion of mobile metal ions on the surface of sand particles. In this area, the total analytical approach (XRF method) shows up a wider dispersion halo than methods based on partial extraction. Whereas, at Areachap, where relatively thick sand (approximately one metre) covers the calcrete layer, partial extraction (based on a NH_4EDTA solution) results in a larger, recognizable, dispersion halo than that which could be detected by total analysis (XRF). Based on the results of the three methods (NH_4EDTA , MMI and XRF), MMI results shows a larger span for Zn (about two times that of extraction by NH_4EDTA), followed by NH_4EDTA and finally XRF, and for the Cu, the NH_4EDTA method exhibits the largest span (about one and half times that of XRF analyses) followed by XRF and then MMI.

Cu, Zn and Pb show high values when extracted by partial extraction methods whereas Mn and Fe, in some cases, show high values when analysed by the XRF method. This may suggest that Cu, Zn and Pb are derived from the ore minerals related to the mineral deposits or also referred to as an exogenic source, and Mn and

Fe are derived from both primary minerals, which are not directly related to the mineralization (an endogenic source), and from ore related minerals.

7.3. Signature of the mineralization in the calcrete regolith

Even though it could be expected that the calcrete layer forms an effective geochemical barrier to the secondary dispersion of ore related trace elements. The current study confirmed the presence of elevated contents of these elements in samples collected from above the mineralization.

The calcrete from the studied areas consists of a gossan bearing magnetic and calcite rich non-magnetic part. Based on quantitative XRD analyses of these two parts it is concluded that magnetite and hematite are concentrated in the magnetic fractions, calcite, albite, microcline and quartz are more abundant in the non-magnetic fractions. Calcite is present in both the magnetic and non-magnetic fractions of the sample due to poor liberation during grinding. The distribution of trace elements, especially Cu and Zn, are strongly related to the distribution of magnetite (the magnetic part of the sample) although some of the Cu and Zn are also dispersed in the non-magnetic “cleaned “ fractions of the sample. Pb and V are directly associated with the distribution of magnetite.

The variation of the elements of interest in the visually cleaned calcrete shows that the concentrations of Cu, Zn and Pb are much lower at, and near surface than deeper down within the calcrete profiles. The concentrations of these elements that could be expected in calcrete at the surface and the peak to background ratio of anomalies at surface will therefore depend on the thickness of the underlying calcrete layer in the area.

S, as a trace element, does not show the same trend as Cu, Zn and Pb. This may be explained by the presence of different types of sulphur-bearing phases in the sample, i.e., sulphates that form as a result of the ground water compositions and evaporation processes, or sulphates that form as remnants after the oxidized primary sulphide

minerals. The former may result in false S anomalies not related to underlying sulphide mineralization.

The calcrete layer shows the signature of mineralization even though the size of the halo is only restricted to the ore zone. Calcretes directly related to massive sulphide mineralization may be discriminated from those developed in areas away from the mineralization by plotting the Sr-Cu-Zn and V-Cu-Zn contents in triangular diagrams. The original calcrete samples near the ore zone are enriched in CaCO_3 , Cu and Zn. Those samples collected further away from the known mineralization are enriched in V, Sr and MgCO_3 and have higher Na_2O , K_2O and SiO_2 contents.

7.4. An integrated approach to geochemical exploration of arid areas

The VHMS deposit at Areachap, Kantienpan and the defunct Prieska Cu-Zn Mine are hosted by a volcano sedimentary succession known as the Areachap Group, in the eastern part of Namaqua Metamorphic Province, South Africa. A collisional event affected the mineralization and host rocks and the secession was metamorphosed to upper amphibolite-granulite grade (M_1) metamorphic conditions (Theart, 1985; Humphreys et al., 1988). This was followed by widespread intrusion of syntectonic granitic melts in the form of granite intrusion in a large part of the Namaqua Metamorphic Province resulting in high-grade M_2 upper amphibolite grade metamorphic imprint (Theart, 1985; Theart et al., 1989; Cornell et al., 1992). Following uplift and subsequent deformation a metamorphic overprint developed in the form of grain boundary textures (M_3) (Theart, 1985). After the intrusion and deformation, the steady state geotherm was re-established (Cornell et al., 1992) and retrogressive metamorphism (M_4) was caused by ascending hydrothermal fluids (Theart et al., 1989). The rocks were exposed at the surface and were later covered by a thick layer of old sediments of the Karoo Supergroup (Catuneanu et al., 2005). After the erosion of the most of the Karoo sediments the area was again exposed to surface weathering conditions. This was followed by the deposition of the basal Kalahari Group sediments. The semi-arid environment during the onset of Kalahari Group (Netterberg, 1970; Malherbe, 1984) sedimentation led to the calcretization. Sand

covered the whole area during the subsequent arid period (Malherbe, 1984) that still persists.

As demonstrated above the study area suffered various events throughout geological time which complicate the applicability and results of routine exploration methods. Notwithstanding this a number of VHMS style massive sulphide deposits were discovered. As it is believed that there is strong probability for further discoveries, more advanced geochemical techniques were tested and developed to aid future exploration.

It was founded that massive sulphide mineralization concealed by a calcrete layer could be detected by chemical analyses of surface calcrete samples (chapter 6, section 6.7). The detection of anomalous zones could be enhanced by analyzing both calcrete material and magnetic inclusions found within this material. It has been demonstrated that the calcrete layer behaves as a geochemical barrier, which limits the secondary dispersion of the elements of interest above the massive sulphide zone. In profile, the concentration of the ore metal increase with depth (chapter 6, section 6.7.2). The peak to background ratio may therefore be expected to reduce as the thickness of the calcrete increase. Triangular discrimination graphs have been designed to distinguish between calcretes directly related to underlying sulphide mineralization and those from further away (chapter 6, section 6.7.3).

It was also demonstrated in this study that concealed sulphide mineralization can also be detected in non-residual sand (chapter 6, section 6.6), covering the calcrete layer, by the presence and abundance of the ore metals adsorbed onto the sand particles. Different reagents were used to extract these elements. The most successful reagent for anomaly detection was found to be NH₄EDTA solution (Appendix D, section D.1). This method works particularly well where the sand cover is thicker (one to two meters).

In the absence of a calcrete cover, lithogeochemical samples may be collected directly at surface (chapter 2, section 2.4). Utilizing sophisticated lithogeochemical techniques the whole rock analyses could be studied to identify areas affected by primary ore forming alteration processes. The box plot, which gives the variation of AI versus

CCPI, is one of the useful lithogeochemical methods based on whole rock XRF results. This diagram may be used to identify the proximity to the footwall alteration and ore zone, and also to prioritize the anomalous areas for further exploration programmes. In addition, the peraluminous ratio may also be used to distinguish the proximity to the footwall alteration and ore zone. The variation of this ratio, the AI and CCPI versus depth may confirm and clarify the location of the footwall alteration and ore zone.

The exploration methodology developed and tested here is not restricted in its application to this area alone, but would also be applicable to exploration in other similar high grade metamorphic terranes, currently experiencing arid to semi-arid climate conditions.