4 REGIONAL GEOLOGY

Outcrop is good in the bulk of the project area, except for areas in and around alluvium-filled washouts or streambeds. In the north, outcrop diminishes beneath the sand of the Kalahari Group and, towards the south, near Copperton; the sediments of the Karoo Supergroup cover the Areachap Group.

4.1 STRATIGRAPHY

4.1.1 Introduction

The mid-Proterozoic Areachap Group consists of varying proportions of amphibolite, hornblende gneiss, quartzo-feldspathic gneiss, calc-silicate and pelitic schist's (Geraghty *et al.,* 1996). It forms a prominent sequence of supracrustal rock types between the eastern margin of the Namaqua Province and the older Kheis Subprovince (Figure 4). The Areachap Group's importance lies in the base metal sulphide deposits within the 250 km outcrop length, and Its fossil meta-island arc character (Geringer *et al.,* 1994).

The stratigraphy of the Areachap Group is given in Table 3 (Geringer *et al.,* 1994). Finality has not been reached with regards to the stratigraphic status of the Areachap Group, but the suggested succession presented in the table below is used for the purpose of this treatise.

Table 3. Lithostratigraphy of the Areachap Group and Relative Equivalence of the Upington, Klein Begin, Boksputs and Copperton Subprojects adapted on Geringer (1994).

<table>
<tr><th colspan="2">Upington and Klein Begin Subproject</th><th>Boksputs Subproject</th><th>Copperton Subproject</th></tr>
<tr><td colspan="4">Namaqua Province (Keimoes Suite Granite)</td></tr>
<tr><td colspan="4">>>>>>>>>>>>>>>>>>>>> Discordant Contact >>>>>>>>>>>>>>>>>>>></td></tr>
<tr><td rowspan="4">AREACHAP GROUP</td><td>Bethesda Formation</td><td>Jacomynspan Formation
Van Wyks Pan Formation
Kantienpan Formation</td><td></td></tr>
<tr><td>Jannelsepan Formation:
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6</td><td>Boksputs Formation:
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6</td><td>Copperton Formation:
Vogelstuisbult Member
Prieska Copper Mines Member
Smouspan Gneiss Member</td></tr>
<tr><td colspan="3">>>>>>>>>>>>>>>>>>>>>> Faulted >>>>>>>>>>>>>>>>>>>>></td></tr>
<tr><td colspan="2">Sprigg Formation</td><td>Eyerdop Pan Formation</td></tr>
<tr><td colspan="4">>>>>>>>>>>>>>>>>>>>>>>> Faulted >>>>>>>>>>>>>>>>>>>>>>></td></tr>
<tr><td colspan="4">Kheis Subprovince</td></tr>
</table>

4.1.2 The Upington and Klein Begin Subprojects

The exploration activities in the Upington and Klein Begin subprojects are concentrated on the Jannelsepan, Sprigg and Bethesda Formations. These formations are grouped together as the Areachap Group on the grounds of:

their geographical position relative to the boundary with the older (2 000 Ma) Kheis Subprovince, their conformable character, their relationship with the late tectonic granites (Keimoes Granite Suite), and the shearing in the area (Geringer *et al.*, 1994).

4.1.2.1 Sprigg Formation

The Sprigg Formation was originally defined by Stowe (1979) as a thin sliver of schist between the Dagbreek Formation (Kheis Subprovince) and Jannelsepan Formation, which comprises a series of outcrops limited to the eastern part of the Areachap Group (Figure 3). The Sprigg Formation contains a predominantly micaceous schist (locally pelitic), including quartzo-feldspathic gneisses, quartzites, amphibolite and a quartzitic conglomerate in the south (Geringer *et al.,* 1994).

The Sprigg Formation's contact with the older immature quartzites of the Dagbreek Formation (Kheis Subprovince) to the east is fault-bounded. An autochthonous origin for the Sprigg Formation is derived from the easterly provenance for the conglomerate clasts.

Faulted contacts between the Sprigg Formation and Jannelsepan Formation are suggested by Vajner *et al.*, (1980), Humphreys (1985), and Pretorius (1986), while Geological Survey maps (Moen, 1988) show intercalation between the Sprigg and Jannelsepan Formation. Poor exposure and lack of contact definition preclude a definite solution to this contradiction.

For the purpose of this text, the Sprigg Formation is regarded as a separate lithological unit from the Jannelsepan Formation on the grounds that the Sprigg Formation could have been derived from the quartzitic rocks east of the Brakbosch-Copperton fault (Figure 4) (Geringer *et al.*, 1994).

4.1.2.2 Jannelsepan Formation

The predominantly meta-volcanic Jannelsepan Formation is the most important unit of the Areachap Group in terms of VHMS exploration and is bounded by shear zones and numerous intrusions of the Keimoes Suite granite of the Namaqua Province (including Straussburg and Louisvale granite).

The Jannelsepan Formation is essentially a succession of metavolcanic and reworked volcanic rocks subdivided into six members (Table 3).

Unit 1 is a quartz-feldspar gneiss comprising intercalated layers and lenses of quartz-feldspar-muscovite gneiss/schist, biotite-muscovite schist and coarse-grained quartz-feldspar-muscovite gneiss with hornblende. Epidote and almandine garnets are occasional accessory minerals. Unit 1 is plausibly derived from felsic volcanics of rhyodacitic composition (Geringer *et al.*, 1987).

Unit 2 consists of massive amphibolites (hornblende) intercalated with quartz-feldspar gneiss (Humphreys, 1985).

Unit 3 comprises feldspathic amphibole gneiss and chloritized feldspathic gneiss.

Unit 4 occurs as lenses of ferruginous amphibole schist and ferruginous chert. Malachite staining is present in the amphibole gneiss.

Unit 5 is described by Cilliers (1987) as a sequence of alternating layers and lenses of homogenous, fine-grained amphibolite, dark-grey medium-grained amphibolite, schistose black amphibolite, calc-silicate-bearing amphibolite and thinly layered calc-silicate and amphibolite.

Unit 6 comprises lenses of black-banded chert and black chert (BIF), which occur on the western flank of the Kraalkop antiform intercalated with ferruginous muscovite schist.

Unit 1 is alternatively known as the Skietbaan Member, while Unit 2 is often referred to as the Donkerspruit Member. Unit 3 and 4 are often grouped together as the Quarry Member, while unit 5 and 6 combined are known as the Swartkop Member (Swartz, 1987).

4.1.2.3 Bethesda Formation

The rocks of the Jannelsepan Formation are, on the west, juxtaposed against the Bethesda Formation. The Bethesda Formation consists of biotite-muscovite schist and metapelitic gneisses. These gneisses were regarded earlier by Vajner (1978) as part of the Jannelsepan Formation. The contact between the Jannelsepan Formation and the Bethesda Formation is obscured by the intrusion of the Keimoes Suite (Louisvale) granite of the Namaqua Province.

Towards the west, the relationship between the Bethesda Formation and the gneisses of the Korannaland Sequence (Namaqua Province) is also obliterated by the intrusion of the late-tectonic Keimoes Suite granites.

4.1.3 Boksputs Subproject

The lithological sequences in the Boksputs subproject are broadly equivalent to those found in the Upington subproject (Table 1), but the sequences represent a separate volcanic centre (Geringer, 1994).

4.1.3.1 Sprigg Formation

See paragraph 4.1.2.1.

4.1.3.2 Boksputs Formation (Jannelsepan Formation)

The Boksputs Formation (Hartebeestpan Formation of Humphreys, 1985) is a lateral equivalent of the Jannelsepan Formation in the Upington area, but represents a separate volcanic centre (Geringer, 1994).

4.1.3.3 Kantienpan Formation

The Kantienpan Formation (Geringer *et al.*, 1987) is equivalent to the Upper Hartebeestpan Formation of Humphreys (1985).

Rocks of the Kantienpan Formation, bounded to the east by the Rooiputs shear, occur mainly in the western portion on the farm Kantienpan and in the northern portion on the farm Van Wyks Pan. These dark, often glassy rocks, with or without garnet, consist mainly of aluminous pelitic gneisses and are intercalated with amphibole gneisses, garnet amphibole gneisses and amphibolites (Geringer, 1994).

4.1.3.4 Van Wyks Pan Formation

This formation consists mainly of granitic-biotite gneisses and quartz-feldspar gneisses intercalated by thin layers of amphibole gneisses (containing garnet and biotite) and amphibolites (Humphreys, 1985).

4.1.3.5 Jacomynspan Formation (Bethesda Formation)

South of the Boven Rugzeer shear zone (Figure 4) the country rock consists of a monotonous sequence of porphyroblastic quartz-feldspar-biotite-garnet gneiss containing minor meta-diorite and amphibolite lenses. Further to the south on the farm Rokoptel, pink gneisses, ranging from fine-grained to coarse pegmatitic or porphyritic muscovite or biotite-muscovite gneiss, often rich in garnets, occur. Differentiated mafic intrusive rocks, such as norite, harzburgite and pyroxenite, grading into anorthositic gabbro, occur as sheet-like structures or dykes. These mafic intrusions form the host rock for low-grade nickel-copper mineralisation on the farms Jacomynspan and Rokoptel (Attridge, 1986).

4.1.4 Copperton Subproject

The meta-volcano-sedimentary rocks in the Copperton Volcanic Centre are broad equivalents of those in the Upington Volcanic Centre.

4.1.4.1 Eyerdop Pan Formation

The Eyerdop Pan Formation is tectonically in the same position as the Sprigg Formation (see paragraph 4.1.2.1) of the Upington Subproject Area and consists of 150 m thick conglomerate within a schistose matrix (Humphreys, 1985).

4.1.4.2 Copperton Formation

The meta-volcano-sedimentary sequences in the Copperton and Kielder region are recognised as lateral equivalents of the Jannelsepan Formation (Upington Subproject) and the Boksputs Formation (Boksputs Subproject), owing to its geochemical composition and tectonic history (Humphreys, 1985).

The Copperton Formation consists of essentially of three main members, which can be correlated with the six units in the Jannelsepan and Boksputs Formations (Theart, 1985 and Theart *et al.*, 1989). The three members are summarized by Theart *et al.* (1989) and are as following:

- The Smouspan Gneiss Member is a metaluminous, homogeneous gneiss, which consists mainly as a biotite-hornblende-quartz-plagioclase gneiss. This Member is considered to form the base of the Copperton Formation and is believed to have originated as a dacitic lava.
- The Prieska Copper Mines Member consists of peraluminous silicate rocks and hosts the massive sulphide ore of the Prieska Zn-Cu mine. The contact with the Smouspan Gneiss Member and this Member is gradational, so also is the contacts between the different rock types within this Member. The Prieska Copper Mines Member mainly consist of a gedrite fels, the hydrothermally altered dacite protolith of the Smouspan Gneiss Member, and a quartz-perthite-sillimanite gneiss, originating from precipitation of

silica, sericite and trace minerals in basin-floor sediments close to the fumarolic vent.

- The Vogelstruisbult Member consists of a tholeiitic banded hornblende gneiss of intermediate composition, a laminated amphibolite, originating from a basaltic lava or subaqueous tuff, and metapelites originating from immature sediments derived from basaltic to intermediate volcanic rocks. The Vogelstruisbult Member is thought not to reflect the ore-forming hydrothermal alteration and is considered to lie stratigraphically above the Prieska Copper Mines Member.

Massive amphibolite layers, believed to have a tholeiitic lava as precursors, randomly occurs throughout the Copperton Formation and are not considered to be part of the original layered sequence (Gorton, 1981). Theart (1985) concluded that the massive amphibolite layers probably intruded the sequence as dykes or sills after the ore formation, but prior to the regional deformation and metamorphism.

4.2 STRUCTURE

4.2.1 Introduction

The Areachap Group extends across two tectonic provinces, the Kheis Subprovince and the Namaqua Metamorphic Province. The Kheis Subprovince is also known as the Eastern Marginal Zone of the Namaqua Province (Humphreys, 1985 and Stowe, 1983). Joubert (1986) suggested that the Namaqua Province should be divided in a Gordonia Subproince in the east and the Bushmaland Subprovince in the west, separated by the Hartebeest River thrust, which have a northwest-southeast (Figure 4). Stowe (1986) describes the Gordonia Subprovince as a microcontinent-arc complex that was accreted during the early stages (1300 Ma) of the Namaqua orogeny.

The Brakbosch fault, in the east, and the Bovenrugseer shear zone, in the west, defines the Areachap terrane. The Trooilapspan or Koegrabe shear zone distinguishes between the Jannelsepan Formation to the west and ultramafic rock to the east, which are not part of the Areachap Group. The Areachap Group thins towards the south-east where the Bovenrugseer shear and Brakbosch fault merge (Prinsloo, 1998).

Stratigraphic contacts between the different formations are not easily defined accurately, owing to complex structural textures. Ludick (1987) found that the contact between the Jannelsepan and Bethesda Formations are obscured by shearing, implying that the Bethesda Formation does not necessarily post date the Jannelsepan Formation. However, Geringer (1983) observed from borehole data that the Bethesda metapelites might overlie the Jannelsepan Formation stratigraphically.

4.2.2 Faulting and Folding

The Areachap Group has been greatly affected by tectonic events (Table 4) since it represents an island arc deposit sandwiched on the east by the Kheis Subprovince (the eastern margin of the Kaapvaal Craton) and on the west by the Namaqua Province. A number of smaller and larger splay faults form a network of mainly NW-SE-trending faults and shears across the Areachap Group. This network of faults divides the area up into sub-parallel shear domains (Stowe, 1983 and Humphreys, 1985).

Very prominent faulting occurs throughout the Areachap Group. The Brakbosch Fault, which can be traced from satellite images for 220 km from north of Upington to south of Copperton, forms the boundary of the Areachap Group with the Kheis Subprovince (Figure 4). Other large faults and shear zones, like the Boven Rugzeer shear zone, play an important role in the structural setting of individual formations in the Areachap Group. Shears and faults of lesser significance are common (Stowe, 1983 and Humphreys, 1985).

Table 4. Characteristics of Deformation Phases in the Kheis Subprovince and Namaqua Provinces

	Kheis Subprovince	Namaqua Province
F1	- F1a Isoclinal, SE vergence NNE trend. - F1b Isoclinal N to NE trend.	Only one phase distinguished; isoclinal to tight, yielding widespread S1 foliation.
F2	NNW-trending tight folds producing strong L2 in quartzites.	NNW-trending closed to tight folds commonly with an L2 lineation and developing rare S2 axial planar foliation.
F3	Frequently box-folds on mesoscopic scale. Not as well-developed as F2; attitude uncertain.	ENE- to NE-trending open folds creating dome-and-basin terrain with F2; frequently undulating.
F4	Rare monoclinal structures.	Macroscopic structures, near co-axial with F2, causing steepening of western limbs of F2 antiforms and loss of intervening synforms.
F5	Faults.	Shears and faults.

The deformation phases to which the Areachap Group are subjected are (Stowe, 1983 and Humphreys, 1985):

- Early deformation (F1) imparts a strong penetrative foliation (S1) in the Namaqua Province. This deformation gradually weakens eastward, so that in the Kheis fold-and-thrust belt the F1 it is only penetrative in schistose lithologies. At the Prieska Zn-Cu deposit the earliest deformation seen as isoclinal folds, originally with subhorizontal coaxial planes may belong to this phase (Theart, 1985).
- F2 deformation, directed initially from the south, is expressed as NNW-trending closed syn- and antiforms. It has an almost upright axial planar attitude with slightly WSW strike. The earlier isoclinal fold at the Prieska Zn-Cu deposit was deformed in tight folds with a vertical axial plane that may be correlated with this event (Theart, 1985).
- The wavy F3 deformation, possibly the result of slip on contemporary conjugate shears, varies in trend from E-W in the north to NE-SW in the south, and forms a dome-and-basin pattern with F2. This is also seem at the

Prieska Zn-Cu mine, as isoclinal folds with subhorizontal coaxial planes that were refolded by subsequent F3 and F4 interference dome structures (Theart, 1985).

- F4 is represented by large-scale folds, which steepen and shear the westerly F2 antiform limbs.
- F5, encompassing a distinctly earlier (F5a) and later (F5b) deformation stage, culminates in strike-slip activity which commences during the F2 stage. The faulting is predominantly right-lateral and trends NNE to NW.Joint analysis of the F5a phase of deformation shows that the maximum principal stress is directed NE-SW. The undulation in the postulated stress field suggests that F5b faulting is responsible for a degree of rotation, though this cannot be directly proved or evaluated.

The VHMS conceptual model relies heavily upon recognising the respective geometry of footwall and hanging wall alteration. An understanding of the folding is vital to the VHMS model, since overturned beds owing to overfolding are a common occurrence in the Areachap Group. This complexity has resulted in directly opposing interpretations by Wagner and Van Schalkwyk (1986) and Theart (1985) and Theart *et al.* (1989).

The Areachap Group is situated on the eastern margin of the Namaqualand Mobile Belt which is characterised by the interference of two tectonic environments: the Kaapvaal Craton and, more specifically, the Kheis Subprovince to the east, and the later, more discernible Namaqua Province evolution to the west (Geringer, 1994).

The boundaries of the different provinces are well defined by geological and geophysical constraints and feature as distinct lines on geological maps. The peripheral effects of the main tectonic episodes, however, extend beyond such boundaries. Tectonic effects therefore overlap rather than help to form accentuate natural distinctions between provinces, hence the intense folding found throughout the Areachap Group (Table 4) (Stowe, 1983 and Schalkwyk, 1986).

4.3 GENESIS

4.3.1 Introduction

The major petrographic and geochemical features, as well as the most probable protoliths for the various gneisses of the Areachap Group are given in Appendix F. Rocks of the Areachap Group resemble island-arc related volcanics and volcanic derived sediments (Appendix F) (Geringer, 1994).

4.3.2 The tectonic framework within which the Areachap group formed and its subsequent modification.

Various tectonic models, based on the structural, metamorphic, geochemical, and isotopic character of the Namaqua Province have been proposed. Stowe (1983) and Van Bever Donker (1991) suggest that the structural features of the Namaqua Province can be related to eastwardly directed forces which culminated in subduction and collision of the Namaqua and Kaapvaal Cratons resulting in an island arc environment and the formation of the Areachap Group. Humphreys (1990), however, points out that the long duration of heat flow necessary to cause high temperature/low pressure metamorphism documented in the Areachap Group, is not in favour of a subduction-related model but that hot spots caused the high heat flow in the area.

An alternative possibility for the tectonic evolution of the area is that the entire zone developed in a transtensional structural environment a discussed by Dewey *et al.* (1998) and Krabbendan and Dewey (1998). It is possible that the deformation from at least F3 and onwards, may be related to transtensional deformation.

Current plate tectonic models indicate that calc-alkaline volcanics, as found in the Areachap Group, occur predominantly along destructive plate margins. Calc-alkaline assemblages found in the Areachap Group include low-K arc tholeiite, calc-alkaline basalt, and high-shoshonitic basalt (Geringer, 1994).

Support for the orogenic environment comes from the uranium-lead isotope ratios of the amphibolites (Cilliers, 1987).

Radiometric age determinations on the amphibolites and gneisses indicate that the Areachap volcanic arc formed over a considerable period of time, starting at 1 600 Ma and ending around 1 285 Ma (Cornell *et al.*, 1990). It is difficult to explain the long duration of development in the Areachap volcanic arc by means of a single, continuous process.

Geochemical variations in different areas indicate differences in tectonic environments in which these rocks were deposited.

The low-K tholeiitic, calc-alkaline to high-K, shoshonitic character of the amphibolites from Boksputs to Upington subprojects may either indicate an increase in arc maturity from south to north or it may reflect arc compositional polarity in the same direction (Geringer, 1994).

Chemical variation of the protoliths of the hornblende gneiss and quartz-feldspar gneiss are also reconcilable with arc maturity or polarity, showing an increase in the felsic components from south to north in the area (Geringer, 1994).

Deposition of the Sprigg Formation, with its channel conglomerates, probably took place on a stable shelf back-arc environment but the exact relationship of the Sprigg Formation with the remainder of the Areachap Group is uncertain (Geringer *et al.*, 1994).

The hornblende, biotite, and pelitic gneisses and banded iron formations of the Bethesda, Kantienpan, and Copperton Formations are chemically similar to immature sediments. The biotite gneiss and metapelites may represent products formed from dacitic and rhyodacitic source regions, deposited in fore-arc basins (Geringer *et al.*, 1994).

The large varieties of rocks of the Areachap Group, which are restricted in a defined area, reflect the extremely complex deformational history along the eastern margin of the Namaqua Province. Low pressure/high temperature metamorphism, reconcilable with a subduction related environment reached a peak around 1 200 Ma. Subduction ceased at this point and was transformed into a collision phase. The collision was marked by the emplacement of large volumes of calc-alkaline granite magma of Keimoes Suite (Stowe, 1986 and Geringer *et al.*, 1988). This event was dated at around 1 150 Ma by Barton and Burger (1983).

The tectogenesis ended with large-scale movements along major shear zones (Stowe, 1986) (Table 4) while the last metamorphic effects occurred approximately 943 Ma ago (Cornell *et al.*, 1986).