CHAPTER SIX

DISCUSSION AND MODEL

6.1 INTRODUCTION

In this chapter, the petrography, mineralogy, whole-rock geochemistry and stable isotope geochemistry are combined and discussed to develop comprehensive metallogenetic models for the occurrence of high-grade hematite iron ore deposits at both Zeekoebaart and Nauga East. Once a sound genetic model has been given, the deposits will be compared to other well-known iron ore deposits in both South Africa and abroad. The exploration potential for similar, and perhaps larger deposits will also be evaluated, according to the proposed metallogenetic models.

6.2 CURRENT THEORIES ON THE ORIGIN OF HIGH-GRADE HEMATITE ORE DEPOSITS

Beukes *et al.*, (2002) recognise three general genetic types of high-grade BIF-hosted hematite ore deposits, compiled from both field investigations and literature surveys of deposits in South Africa, Brazil, India and Australia. These are; (1) ancient supergene, (2) hydrothermal, and (3) supergene-modified hydrothermal deposits.

Ancient supergene high-grade hematite ore deposits, which include Sishen-type deposits in South Africa, develop in areas where long-lived erosional unconformities transect carbonate-rich iron formations (Fig. 6.1). The high-grade hematite ore is derived from the leaching of carbonate and chert during weathering and grades downward into oxidized and the unaltered iron formation. Microcrystalline hematite ore develops in the iron formation, with detrital conglomeratic ores, generated from the erosion of the underlying ore, overlaying. The ancient supergene ore deposits display positive Ce_{PAAS} anomalies, indicating leaching of REE under oxidizing conditions during supergene alteration.

The Thabazimbi deposit in South Africa, and Mount Tom Price in Australia represent hydrothermal high-grade hematite ore deposits (Beukes *et al*., 2002). These deposits are usually associated with extensional faults that transect carbonaceous shale units that constitute the base of the iron formation host (Fig. 6.1). Mineralization is ascribed to the leaching of silica and carbonates and oxidation of all iron to hematite. A halo of oxidized iron formation commonly surrounds the ore bodies. Hydrothermal deposits develop slight to no $\mathrm{Ce}_{\mathrm{PAAS}}$ anomalies, similar to the protore iron formation.

Supergene-modified hydrothermal ores are characterized by an abundance of friable (soft) hematite ore in very deep lateritic weathering profiles (Beukes *et al*., 2002). These ores, which develop at depths >100m and up to 500m, are commonly composed of hematite, specularite and martite. Hard hematite ore, which occurs as tabular bodies, are also associated with and typically surrounded by friable ore and occur in the lower part of the iron formation succession (Fig. 6.1). Smaller, lenticular ore bodies generally occur higher up in the succession. Leaching of silica and carbonate from banded iron formations under the deep lateritic weathering conditions is generally considered as the mode of occurrence for the highly porous ore deposits (Beukes et al., 2002). Carajas, in Brazil, is the most prominent example of this type of high-grade hematite ore deposit.

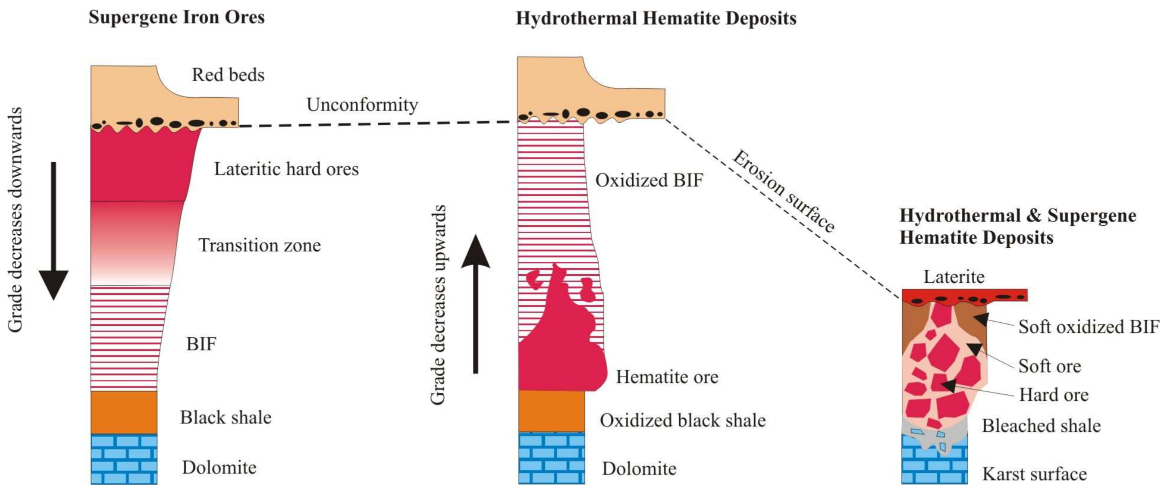

Figure 6.1: The classification of major types of high-grade hematite iron ore deposits (modified after Beukes *et al*., 2002).

6.3 THE KURUMAN IRON FORMATION

The basinal facies of the *Kuruman Iron Formation* is composed of alternating magnetite-siderite (ankerite) micro- to macro-bands (Beukes 1983, 1989). This assemblage is easily affected by alteration and oxidation processes. Carbonates such as siderite and ankerite are easily leached during alteration processes. Magnetite is oxidized, to hematite during the same alteration process. These factors make the basinal portion of the *Kuruman Iron Formation* highly conducive to alteration. This is the case at both the Zeekoebaart and Nauga East high-grade hematite ore deposits.

6.4 METALLOGENETIC MODEL - ZEEKOEBAART

6.4.1 Structure

The Zeekoebaart deposit occurs in an area of major folding and several thrust fault systems (Fig. 3.1A). Asymmetrical folding resulted in an overturned stratigraphy in the study area. The Doringberg fault, which crosscuts the succession, vertically displaces hematitized iron formation that hosts the high-grade hematite ore lenses, whilst the thrust faults juxtapose various lithological units alongside one another. Faulted contacts between the lithological units also occur. Structural geological relationships are thus complex, i.e. the fault has some structural control on the distribution of the lithological units.

The ore body at Zeekoebaart has not been crosscut or intersected by an intrusion. However, a diabase sill does lie to the west of the ore lenses, and acts as a boundary to the deposit. The hematite ore lenses are concentrated near the basal contact between the underlying shales and the oxidized iron formation. These ore lenses decrease eastwards toward the diabase sill, and west of the sill no mineralization occurs (Fig. 3.1A).

6.4.2 Ore Formation

Incipient alteration or oxidation of the basinal *Kuruman Iron Formation* resulted in regional oxidation of the iron formation to an assemblage of alternating hematite-magnetite and chert-quartz micro- to macro-bands. Oxidation of the iron-rich bands in the unaltered iron formation resulted in magnetite being replaced by fine-grained hematite to form kenomagnetite and with further oxidation, martite. Primary hematite grains remained stable during the oxidation process. Small hematite laths also developed in the iron-poor or cherty bands. Oxidation resulted in the leaching of the carbonates, and the resultant decrease in alkali elements, MgO, MnO, CaO and CO_2 with little associated leaching of silica (chert) or aluminium.

Oxidation was accompanied by hematite formation in the iron formation. The hematite ore lenses are concentrated near the basal contact of the hematitized iron formation to the underlying shales. These ore lenses decrease in abundance and size up the stratigraphic sequence and are bounded by a diabase sill to the west. This suggests that circulating hydrothermal fluids were introduced along the basal contact of the iron formation. The hematitized iron formation was transformed into high-grade hematite ore by replacement of euhedral magnetite grains by fine-grained hematite, and efficient leaching and desilicification of the silica (chert) bands. Geochemically, SiO_2 decreases drastically, as total Fe_2O_3 considerably increases. The high-grade hematite ores are characterized by Fe_2O_3 concentrations > 70 wt.%. The former cherty layers were completely replaced by coarse-grained microplaty hematite, or fine-grained hematite. In the iron-rich bands, kenomagnetite is completely replaced by hematite, and along with the martite, is recrystallised into patchy hematite. This stage of alteration causes the oxidized iron formation to develop into a high-grade hematite iron ore dominated by microplaty and patchy hematite. This high-grade hematite ore may be laminated when both iron-poor and iron-rich laminae have been efficiently replaced, or massive, where a macro-band of iron oxide recrystallised.

REE patterns of the iron ores at Zeekoebaart display slight negative to slight positive Ce_{PAAS} anomalies, an observation also made at the Thabazimbi (Netshiozwi, 2002) and in the Hamersley Province of Western Australia (Taylor *et al*., 2001).

A final stage of slight supergene alteration is reflected by the formation of goethite in both the hematitized iron formation and high-grade hematite ore lenses as cold oxidizing meteoric fluids in geologically recent times.

6.4.3 Comparison to Other Deposits

The Zeekoebaart high-grade iron ore deposit displays close similarities to high-grade hematite ore bodies mined at Thabazimbi, hosted by the basinal portion of the *Penge Iron Formation* in the Chuniespoort Group of the Transvaal Supergroup, South Africa (i.e. the exact lateral equivalent of the iron formation facies altered at Zeekoebaart). The Thabazimbi deposit constitutes of stratabound lenses of high-grade iron ore, and includes oxidized iron formation, hard hematite ore and carbonate-rich hematite ore (Netshiozwi, 2002). Although other lithologies do occur, just the two types listed above display strong petrographic similarities to the lithologies of the Zeekoebaart deposit. Massive and laminated ore subtypes of Thabazimbi were derived by alteration of banded iron formation protore, by structurally controlled hydrothermal fluid flow. A similar scenario is invoked for the Zeekoebaart high-grade iron ore deposit. The Zeekoebaart deposit, however, lacks the supergene enrichment and carbonate hydrothermal formation that has been described at Thabazimbi (Netshiozwi, 2002).

The Mt. Whaleback mine, situated in the Hamersley Province, Western Australia, where banded iron formation of the *Dales Gorge Member* has been oxidized and converted to a martite and patchy hematite high-grade ore by means of hydrothermal fluid flow, displays characteristics of both the Zeekoebaart and Thabazimbi deposits. (Webb *et al*., 2003, Netshiozwi, 2002). Oxidizing, acidic fluids around Mt. Whaleback dissolved carbonates and silicates form the surrounding iron formation as well as converting magnetite to martite. The altered iron formation was then converted to a porous high-grade ore by means of efficient dissolution of silica (Webb *et al*., 2003). The genesis of hematite ore at Mt. Whaleback displays strong similarities to that of the Zeekoebaart deposit.

The BIF hosted Mt. Tom Price deposit, also in the Hamersley Province, is also similar to the Mt. Whaleback deposit. However, differences do occur, such as carbonate replacement prior to oxidation (Taylor *et al*., 2001). Genesis of the deposit is ascribed to ascending hydrothermal fluids along fault zones resulting in the oxidation of magnetite to hematite, and the desilicification of the chert bands in the BIF wallrocks (Taylor *et al*., 2001). This hydrothermal fluid flow produced high-grade martite-hematite ore. The fundamental steps in the ore genesis described for the Mt. Tom Price deposit are very similar to those described for the Zeekoebaart high-grade iron ore deposit.

6.5 METALLOGENETIC MODEL – NAUGA EAST

6.5.1 Structure

The high-grade hematite ore deposit at Nauga East is developed along the contact of a zoned carbonatite-syenite intrusion. Syenite intruded as a plug along or near the lithological contact between the oxidized iron formation and underlying shale unit. This was followed by an intrusion of a carbonatite that invaded along the same contact as the syentie and replaced parts of the syenite and the surrounding oxidized iron formation by means of desilification and leaching. This resulted in an altered syenite rimmed by carbonatite, with the high-grade hematite ore body developed along the contact between the syenite and the iron formation. Hematite mineralization occurs most significantly where the zoned carbonatite-syenite invades into the oxidized iron formation. The ore body grades into the hanging wall or oxidized iron formation. The carbonatite forms the footwall of the hematite ore body. The intrusion of the carbonatitic fluid and later oxidization were the most probable the driving forces behind the hematite mineralization at Nauga East.

6.5.2 Ore Formation

The basinal unaltered *Kuruman Iron Formation* consists of alternating micro- to macro-bands of carbonate (siderite and ankerite) - magnetite (Beukes, 1978, 1983). The basinal iron formation at Nauga East has been oxidized on a regional scale and is characterized by alternating magnetite (hematite) – chert (quartz) bands, similar to the hematitized iron formation described at the Zeekoebaart deposit. Incipient oxidation of the iron formation involved little leaching of silica and more extensive leaching of the carbonates (siderite and ankerite) and the subsequent decrease in MgO, MnO and CaO. Al_2O_3 and P_2O_5, however, remained essentially immobile or stable during the oxidation process. In the iron oxide bands, oxidation of the magnetite lead to the formation of kenomagnetite and martite, where fine-grained hematite selectively replaces the magnetite. Fine-grained hematite laths also develop in the cherty bands. Any primary hematite grains remained stable during the oxidation process.

A syenite composed predominantly of albite intruded along the lithological contact between the shale and iron formation north striking along a joint, and acted as a plug or dyke. A carbonatitic fluid then followed and invaded along the same contact, bounding as well as highly altering the syenite, creating a zoned syenite-carbonatite intrusion. The carbonatitic fluid aided in the dissolution of carbonates and silica from both the syenite and oxidized iron formation in the immediate contact zone.

An increase in temperature associated with the carbonatitic fluid, transformed microplaty hematite to magnetite (where oxidization initially transformed magnetite to hematite) in the oxidized iron formation. This process resulted in bladed or microplaty kenomagnetite developing. Before the magnetite could completely replace the microplaty hematite, the temperature decreased, causing the microplaty kenomagnetite to once again turn to hematite. The fluid dissolved and reprecipitated some of the iron from the hematitized iron formation, as microplaty hematite. Thus, resultant domination of microplaty hematite with microplaty kenomagnetite remnants spread throughout in the high-grade ores at Nauga East. The ore formation process involves the increase in Fe_2O_3 content and decreases in SiO_2 concentrations. Most other elements are effectively leached, however, dramatic increases in P_2O_5, CaO and CO_2 are encountered. This dramatic increase may be attributed to apatite that was noted in the hematite ores. Carbonate formation may have accompanied the apatite formation in place of silica in the oxidized iron formation.

Oxidation processes during supergene weathering, results in the generation of highly soft porous ore. Specular hematite, commonly found on the fringe zones of the main microplaty hematite, is composed almost entirely of specularite, a textural variety of hematite, and characterized by abundant porous space. Supergene alteration, however, did not completely destroy the remaining minor components, as the specular ore remains strongly enriched in P_2O_5.

The final stage of hematite mineralization is the precipitation of botryoidal hematite, commonly in areas of intense jointing. This colloform hematite develops on both mineralized bodies as well as from some substrate outwards into the supersaturated hydrothermal fluid. This mineralization is characteristic of low temperature, precipitation in open space from a supersaturated fluid. Botryoidal hematite contains very low concentrations of minor elements, (i.e. no P_2O_5 contamination) and is dominated by Fe_2O_3 (> 95 wt.%).

Supergene alteration from cold, oxidizing meteoric fluids that circulated through the hematite ore body and oxidized iron formation resulted in trace amounts of goethite and furthur leaching of carbonates. The supergene process may have processed simultaneously to the development of the botryoidal hematite. Calcite develops on exposed surfaces and vugs, especially in underground exposures, due to more recent ground water flow and resultant precipitation.

6.5.3 Comparison to Other Deposits

The origin of the high-grade hematite ore deposit at Nauga East is different to any other BIF-hosted high-grade hematite ore deposits either in South Africa or elsewhere. The hematite mineralization at Nauga East has a clear structural control but is not controlled by an unconformity. Rather an invading carbonatitic fluid controls it. This mode of occurrence is thus very different to any other described deposits, and represents a completely new mode of occurrence not previously recognized (Beukes, *et al*., 2002).

6.6 EXPLORATION POTENTIAL

Zeekoebaart style deposits, which are similar to those described at Thabazimbi, Mt. Whaleback and Mt. Tom Price, are found to host the majority of economically important high-grade iron ore deposits worldwide. Any such find may thus be of great significance. Some important factors in exploration would include finding areas of structurally disturbed iron formations, along lithological contacts between the iron formation and underlying sediments. Sill or dykes, which affect the fluid flow, should also be taken into account for the delineation of such ore deposits.

The unique geological setting and mode of origin of the Nauga East deposit make an objective assessment of its economic potential difficult. The deposit itself is certainly small and almost certainly restricted to the immediate contact between a syenite-carbonatite dyke and iron formation. The small sizes of the deposit, combined with the greatly elevated phosphorous concentrations make the Nauga East deposit rather unattractive to future mining operations.