Palaeoproterozoic banded iron formation-hosted high-grade hematite iron ore deposits of the Transvaal Supergroup, South Africa

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Banded iron formation-hosted high-grade (>60 weight percent (wt%) iron (Fe)) hematite ore deposits make up the bulk of the world's iron ore production and reserves. They developed mainly through supergene and/or hydrothermal leaching of silica from the iron formation host rock under oxidizing conditions. Early Palaeoproterozoic iron formations of the Transvaal Supergroup host several such high-grade hematite ore deposits. The largest ones are developed in the Asbesheuwels Subgroup iron formation on the Maremane Dome, between Sishen and Postmasburg in the Northern Cape Province of South Africa. These deposits currently produce virtually all of South Africa's annual supply of about 78 million tonnes (Mt) of high-grade hematite ore, to the local and export market from the Sishen, Khumani, Beeshoek and Kolomela Mines. These represent ancient supergene deposits that formed along the approximately 2.2 to 2.0 Ga unconformity at the base of the Gamagara/Mapedi red bed succession of the Keis (formerly Kheis) Supergroup. Smaller ancient supergene deposits are also developed along the same unconformity such as where it intersects the Rooinekke Iron Formation of the Koegas Subgroup at the Rooinekke Iron Ore Mine to the south of the Maremane Dome and the intersection of the Hotazel Iron Formation of the Voëlwater Subgroup of the Transvaal Supergroup, in the Kalahari Manganese Field to the north of the dome. The supergene ores occur in four types, namely laminated, massive, brecciated and conglomeratic ores, the latter forming part of the Gamagara/Mapedi red bed succession. With the exception of the ore at Rooinekke, which is manganiferous, the supergene ores are of high grade

(>60 wt%) and they also have low silica and phosphorous contents. Normalized rare earth elements, in contrast to the banded iron formation protolith, show light rare earth element depletion and the oxygen isotopes are slightly depleted to slightly enriched in ¹⁸O.

Hydrothermally enriched deposits include: Thabazimbi, situated in the Penge Iron Formation of the Transvaal outcrop area of the Transvaal Supergroup in the metamorphic aureole of the Bushveld Complex; and the Bovenzeekoebaart and magmatic hydrothermal Nauga East deposit, both located in the Kuruman Iron Formation of the Asbesheuwels Subgroup, along the southern extremity of the Griqualand West outcrop area of the Transvaal Supergroup. These hydrothermal iron ores are all developed at the bottom contact between the host iron formation and underlying carbonaceous shale that marks the transition into the Malmani-Campbellrand carbonate platform succession below. In some instances this contact is faulted. The ore grades upwards into oxidized iron formation, with isolated lenses sometimes developed at higher stratigraphic levels. Fault systems intersect the iron formations and the mineralisation is concentrated between mafic sills, higher up in the iron formations and the bottom shale contact. At Nauga East, mineralisation is developed in contact with a steeply dipping zoned syenite-carbonatite dyke. The hydrothermal ores are of high grade (>60 wt%), but can have higher phosphorous contents of up to 0.25 wt%. Normalized rare earth elements are enriched but similar to that of the host iron formations and the oxygen isotopes are generally depleted in ¹⁸O.

The mining of iron ore in South Africa dates from

between 800 and 1200 AD, with modern exploration and mining starting from 1916. The first production of high-grade banded iron formation-hosted ore commenced in 1931 from the Maremane Dome and Thabazimbi. The first truly world class iron ore mine in South Africa, Sishen, was opened in 1953 and still operates today. The deposits at Khumani and Welgevonden have gone into production as recently as 2008 and 2011 respectively. Current estimates place the life of mine of the larger deposits at between 15 and 40 years.

Introduction

Banded iron formation-hosted high-grade hematite ore deposits have, for many decades, provided by far the bulk of all iron ore mined annually (~3.1 Bt total global iron ore mined in 2014; USGS, 2015) in the world and continue to do so. Banded iron formations (BIFs) are chemical sedimentary rocks that contain an anomalous amount of iron as iron-rich oxides, -carbonates and -silicates, along with mostly chert and they are commonly laminated or banded (James, 1954; Trendall, 1983; Klein, 2005). BIFs themselves are not of great economic significance due to their relatively low iron and high silica contents (~43 wt% iron-oxide [Fe_2O_3] and ~47 wt% silicon-dioxide [SiO_2] on average; Gutzmer *et al.*, 2008) when compared to the

economically exploitable BIF-hosted high-grade iron ores (typically more than 60 wt% Fe and only minor silica contents; Hagemann *et al.*, 2008). An epigenetic process is therefore required to enrich the iron content through the removal of silica. The most common modes of enrichment through epigenetic fluid-rock interactions in BIFs are considered to be supergene, hydrothermal, or supergene-modified hydrothermal in nature (i.e. genetic types; Beukes *et al.*, 2003). Well-known examples of hydrothermally enriched BIF-hosted iron ores include Mount Tom Price in Western Australia and Thabazimbi in South Africa. Supergene enriched examples include the ores of the Maremane Dome in South Africa and the Urucum district in Brazil. Supergene modified hydrothermal ores include the Sandur schist belt in India and the Carajas district in Brazil (Beukes, *et al.*, 2003; Gutzmer *et al.*, 2008).

South Africa has several high grade BIF-hosted iron ore deposits that all occur within the Griqualand West and Transvaal areas of the Neoarchaeon to Palaeoproterozoic (~2.6-2.2 Ga; Eriksson *et al.*, 2006) Transvaal Supergroup (Fig. 1). The largest and best known examples are hosted by the BIFs of the Asbesheuwels Subgroup of the Ghaap Group (Griqualand West area) and Penge Iron Formation of the Chuniespoort Group (Transvaal area; Fig.1). However, high-grade iron ore also occurs in the BIF of the Koegas Subgroup and the Hotazel Formation of the Postmasburg Group in Griqualand West (Cairncross and Beukes, 2013). Supergene examples include the Asbesheuwels Subgroup-hosted ores of the Maremane Dome (Fig. 2) such as Sishen, Khumani, Beeshoek and Welgevonden (the latter also known as Sishen

Figure 1: A general locality map indicating the position of the Transvaal and Griqualand West sectors of the Transvaal Supergroup in South Africa. Also illustrated are generalized stratigraphic columns for the Transvaal Supergroup in the Transvaal and Griqualand West areas respectively (Adapted from Eriksson *et al.*, 2006; Van Deventer, 2009).

South and mined in Kolomela Mine); the Koegas Subgroup-hosted Rooinekke deposit; and the Hotazel Formation-hosted ores in the Kalahari Manganese Field (KMF) (Fig. 1). Hydrothermal deposits include the Penge Iron Formation-hosted deposit at Thabazimbi and the Kuruman Iron Formation-hosted deposits at Bovenzeekoebaart and Nauga East (Fig. 1). The latter deposit is also considered to be a magmatically induced hydrothermal end member deposit (Gutzmer *et al.*, 2008). This contribution aims to summarize and compare the geological setting, petrography, geochemistry and genesis of the BIF-hosted iron ores of the Transvaal Supergroup based upon previously published material as well as recent field work by the authors.

History of BIF-hosted iron ore mining in South Africa

Currently, the bulk of South Africa's high-grade BIF-hosted iron ore production comes from four mines on the Maremane Dome in Griqualand West, namely the Sishen and Khumani Mines along the northern margin of the dome, and the Beeshoek and Kolomela Mines in the south (Fig. 2). In 2014 these produced 76.9 million tonnes [Mt] of high-grade hematite ore with the remaining 1.1 Mt coming from the Thabazimbi mine (USGS, 2015; Kumba annual results, 2014). The Rooinekke Mine produced small tonnages of manganiferous high-grade hematite for a few decades up to about

Figure 2: Regional geological map of the Maremane Dome region in the Northern Cape Province indicating the location of the Sishen, Khumani, Beeshoek and Sishen South iron ore deposits (modified after Van Schalkwyk and Beukes, 1986).

1990 but is currently closed. The Nauga East deposit has been investigated by small scale inclined tunneling, the Bovenzeekoebaart deposit by field mapping and exploration drilling and the ores of the Hotazel iron formation are only known from intersections in exploration drill cores for manganese and a few exposures in mines of the Kalahari Manganese Field (KMF).

The extraction and use of BIF-hosted iron ore in South Africa can be dated back to between 800 and 1200 AD when Khoisan miners extracted specularite from Doornfontein in the Northern Cape Province (Cairncross *et al.*, 1997). Other pre-colonial mining activities include: the extraction of specularite used for cosmetic purposes at Blinkklipkop close to Postmasburg in the Northern Cape Province, by local Tswana inhabitants (Cairncross *et al.*, 1997); and mining shafts and furnaces dating from 1500 AD in the Thabazimbi area (Netshiozwi, 2002). However, industrial production of BIF-hosted iron ore only commenced in 1931 when a company with the name South African Manganese, from which SAMANCOR later developed, supplied 1,400 tonnes of hematite iron ore from the Maremane dome to a blast furnace at Newcastle in KwaZulu-Natal, for the production of pig iron. Prior to that, all production of iron ore for pig iron in South Africa came from oolitic iron ore deposits of the Timeball Hill Formation of the Pretoria Group of the Transvaal Supergroup at Pretoria (Cairncross *et al.*, 1997). This operation was initiated by an engineer named Cornelius Delfos in 1916. It was also from these oolitic iron ores that the first steel was produced in South Africa by the Steel Corporation of South Africa (ISCOR) in the early 1930s. However, very soon these deposits could not keep up with demand for ore from the Steel Works and in 1931 the Thabazimbi Iron Ore Mine was opened (Netshiozwi, 2002), to supply high-grade BIF-hosted hematite ore to the steel works, a function it still performs after eight decades, though now on a small scale.

Large scale production of high-grade BIF-hosted hematite ore from the Maremane Dome in Griqualand West commenced in 1953 with the opening of the Sishen Iron Ore Mine by ISCOR, mainly to fulfill demand for high-grade iron ore from their new steelworks at Vanderbijlpark. Export of the high-grade hematite ores from the Maremane dome first took place in 1964 via Port Elizabeth harbour (1,106 km distance) from ASSMANG's newly opened Beeshoek Mine near Postmasburg. Export of the ores in amounts of several tens of millions of tonnes per annum from the area, however, only started in 1976 from Sishen Mine after completion of the Sishen-Saldanha railway line over a distance of 851 km (Cairncross *et al.*, 1997). In recent years two major new mines have come into production on the Maremane Dome: Khumani, owned by ASSMANG, immediately south of Sishen, in 2008; and Kolomela, owned by Kumba, south of Beeshoek, in 2011 (Fig. 2).

Geological setting

Supergene ores

The most well-known supergene iron ores of the Transvaal Supergroup occur in the Northern Cape Province within the Maremane Dome, along an approximately 90 km long north-south trending line perpendicular to the fold axis of a double plunging anticline, between the towns of Sishen in the north and Postmasburg in the south (Fig. 2). The Maremane Dome dips gently to the east and is mostly composed of the dolostones of the Campbellrand Subgroup and iron formations of the Asbesheuwels Subgroup. An erosional unconformity,

called the pre-Gamagara unconformity (also known as the Mapedi unconformity), cuts through this anticline and is succeeded by the Gamagara/Mapedi red bed succession (Fig. 3B). The unconformity, which is regionally developed over the entire Griqualand West area, is consistently marked by the presence of a ferruginous lateritic weathering profile in the rocks immediately below (Fig. 3A). Formation of the unconformity and weathering took place around 2.2 to 2.0 Ga, at the time of lower Elim Group deposition (Dalstra and Rosière, 2008), following a period of folding and uplift of Transvaal Supergroup strata. Because of the folded nature of the strata below, the unconformity transects a wide variety of rocks, the compositions of which determine lateral variations along the lateritised surface (Fig. 3A and B). Towards the west of the Maremane Dome, older rocks of the Transvaal Supergroup, including the Koegas Subgroup, Makganyene diamictite and Ongeluk lava, have been thrust over the post-Mapedi/Gamagara units along the Black Ridge thrust (Fig. 2) (Beukes and Smit, 1987).

High-grade hematite iron ores are only developed in areas where the unconformity transects BIF. Well-known high grade iron ore deposits developed below the pre-Gamagara/Mapedi unconformity include the Sishen, Khumani, Beeshoek, Welgevonden (Sishen South) and Rooinekke deposits (Fig. 3A and B). The ores are apparently derived from the leaching of chert from the BIF during supergene alteration. Three iron formation successions are involved, namely: (i) the Asbesheuwels Subgroup, comprising the Kuruman and Griquatown Iron Formations overlying Campbellrand Subgroup carbonates; (ii) the Rooinekke Iron Formation of the Koegas Subgroup; and (iii) the Hotazel Iron Formation overlying basaltic andesites of the Voëlwater Subgroup (Fig. 3A).

However, large to superlarge deposits of high-grade iron ore are only developed in karstic laterite settings, where Asbesheuwels BIF has slumped into carbonates of the underlying Campbellrand Subgroup along the Maremane dome (Fig. 3B). In this region the enriched sections of the Asbesheuwels Subgroup in these karstic slump structures are also known as the Manganore Formation (Beukes, 1978; Van Schalkwyk and Beukes, 1986). The iron ores are typically overlain by reworked conglomeratic iron ores of the Doornfontein Member of the Elim Group, Keis Supergroup, as well as highly aluminous diaspore-rich shales and closely associated pisolitic lateritic palaeosol profiles (Van Schalkwyk and Beukes, 1986; Gutzmer and Beukes, 1998; Gutzmer *et al.*, 2008). From the unconformity contact downwards, the ore grades into oxidized BIF mostly of the Kuruman Iron Formation. Iron ore can also occur below the main ore body within the BIF as ore lenses. Brecciation and associated specularite veinlets are common throughout the ore and BIF. Multiple dolerite sills also intersect the BIFs and ore at various stratigraphic levels. Although these sills are highly ferruginized themselves, there is no clear iron upgrade of the ore or BIF associated with the sills. A siliceous chert breccia, known as the Wolhaarkop breccia, marks the dissolution surface between the dolomite and overlying ore-bearing iron formation (Fig. 3B). In areas outside of karst slump structures only thin (1-2 m thick) high-grade hematite ore beds are locally preserved below the unconformity. This is, for example, the case where the unconformity transects the Hotazel Formation in the KMF (Fig. 3A). However, this upper lateritic iron ore capping has often been removed by erosion prior to deposition of the overlying Gamagara red beds. In such cases, only a thick oxidized palaeo-weathering profile, without removal of chert, is preserved in the underlying iron-formation.

Figure 3. A schematic north-south cross section through (A) the western margin of the Griqualand West area and (B) the Maremane Dome (modified after Cairncross *et al.*, 1997; Van Deventer, 2009). Sub-surface dips of lithologies are exaggerated for illustrative purposes.

The Rooinekke deposit is situated approximately 60 km west of Griquatown in the Northern Cape Province (Fig. 1) and is hosted in the Rooinekke Iron Formation of the Koegas Subgroup (Fig. 3A). The Koegas Subgroup overlies the Asbesheuwels Subgroup and is composed of mudstone, siltstone, quartzite and iron formations (Grobbelaar *et al.*, 1995; Nel, 2013). Just as with the Maremane Dome, the area around Rooinekke is characterized by deformation in the form of regional open folding. In the Rooinekke deposit area, the top of the Campbellrand, Kuruman and Koegas Subgroups have been thrust onto the Keis Supergroup (Grobbelaar *et al.*, 1995) by the previously mentioned Black Ridge Thrust (Beukes and Smit, 1987). The Rooinekke iron ore is developed at the contact between the Rooinekke Iron Formation and the pre-Gamagara/Mapedi unconformity (Holland and Beukes, 1990) which is, in turn, overlain by the Mapedi Shale of the Keis Supergroup. The base of the Mapedi Shale at Rooinekke is also marked by a basal lag and the overlying conglomerate, which correlates to the Doornfontein Member in the Maremane Dome, contains hematite pebbles (Grobbelaar *et al.*, 1995).

The Hotazel Formation of the Voëlwater Subgroup, which conformably overlies the Ongeluk Lavas towards the top of the Transvaal Supergroup, also contains BIF-hosted iron ores in some areas that occur in close association with the manganese ores of the KMF. These medium to high grade iron ore units are at most a few metres thick and are developed where the pre-Gamagara/Mapedi unconformity intersects the Hotazel Formation within the KMF (Fig. 3A; Gutzmer, 1996; Chisonga, 2012). The BIFs of the Hotazel Formation occur as four units and form part of three broad sedimentary

cycles marked by manganese beds at their centres (M1, M2 and M3 manganese beds), grading into hematite lutite and BIF above and below. Depending on the stratigraphic position of the pre-Gamagara unconformity in an area, iron ore can be developed in any of the four BIF units. Ores developed towards the base of the Hotazel Formation are not as thick and laterally continuous as those developed towards the top (Chisonga, 2012).

Hydrothermal ores

The best known hydrothermal BIF-hosted iron ore deposit in South Africa occurs close to the town of Thabazimbi in Limpopo Province (Fig. 1). It is situated along the east-west trending Mohlapitsi fold belt (Netshiozwi, 2002) and is hosted within the Penge Iron Formation in the Transvaal Basin of the Transvaal Supergroup. Two major east-west striking mountain ranges and one major north-south striking mountain range occur in the area, with major ore occurrences in the east-west striking mountain ranges (Netshiozwi, 2002). The Penge Iron Formation at Thabazimbi is underlain by the Malmani Dolostone and overlain by shales of the Timeball Hill Formation. Due to its location within the Mohlapitsi fold belt as well as the occurrence of two major east-west trending thrust fault systems, the Penge Iron Formation in the region is intensely folded and faulted (Du Plessis, 1990; Netshiozwi, 2002). The ore occurs as strata-bound lenses near the base of the deformed BIF in contact with underlying black shale (Beukes *et al.*, 2003; Gutzmer *et al.*, 2008). Dolerite sills and dykes also intrude and crosscut the BIF. Just as observed with

the ores of the Maremane Dome (previous section), the associated BIF at Thabazimbi has been oxidized (i.e. hematitized; Netshiozwi, 2002).

Less well-known hydrothermal BIF-hosted iron ore deposits in South Africa include the Kuruman Iron Formation-hosted Bovenzeekoebaart and Nauga East Deposits in the Northern Cape Province of South Africa. The Bovenzeekoebaart deposit is situated approximately 65 km northwest of the town of Prieska. It consists of two major strata-bound lenses of steeply dipping and overturned iron ore at the base of the Kuruman Iron Formation and has a conformable contact with the underlying Klein Naute shale and dolostones of the Nauga Formation of the Campbellrand Subgroup. The associated BIF is hematitized and intensely deformed and folded. The southwest to northeast trending Doringberg fault system cuts the Kuruman Iron Formation in this area and is associated with major vertical displacements (Harding, 2004). The Kuruman Iron Formation east of the deposit is intruded by the Leelykstraat diabase sill that predates deformation, and all mineralisation is concentrated between the sill and the Klein Naute shale (Harding, 2004). Complex boxworks of deformed quartz veins transect the Kuruman Iron Formation above and the Klein Naute shale below the ore lenses. The shale and BIF within which the quartz veins occur, are highly ferruginized and magnetic. The contacts between ore lenses and the surrounding strata are difficult to delineate in the field and appear to be gradual.

Magmatically induced hydrothermal ores

The Nauga East BIF-hosted iron ore deposit is situated 15 km from the town of Koegas in the Northern Cape Province. The deposit is marked by up to 40 m thick tabular high grade ore bodies (two major and one minor), developed where a steeply dipping zoned syenite-carbonatite dyke crosscuts the Kuruman Iron Formation (Harding, 2004; Gutzmer *et al.*, 2008). Just as at Bovenzeekoebaart, highly oxidized Kuruman BIF overlies the Klein Naute shale and dolostones of the Nauga Formation of the Campbellrand Subgroup. The zoned syenite-carbonatite dyke appears to have intruded along a set of north-south trending joints. The dyke follows the contact between the Kuruman BIF and Klein Naute shale in the south, but towards the north it crosscuts the BIF (Harding, 2004). The dyke is generally considered to be the footwall to the ore, and the ore grades upwards into oxidized BIF (Harding, 2004).

Description of currently mined deposits

Supergene high grade BIF-hosted iron ore deposits from which significant quantities of iron ore are currently produced include, from north to south, the Sishen, Khumani, Beeshoek and Kolomela deposits (Fig. 1), which are all situated in the Maremane Dome (Figs. 2 and 3B). The only BIF-hosted hydrothermal high grade iron ore deposit of the Transvaal Supergroup from which significant iron ore production occurs is the Thabazimbi deposit in the Transvaal Basin (Fig. 1). The Rooinekke, Hotazel, Bovenzeekoebaart and Nauga East deposits are not discussed in this section as they are either not currently producing high grade iron ore, or have not been developed for mining.

Sishen deposit

Sishen Mine is one of the world's major, high-grade, lump ore producers and is owned by Kumba Iron Ore. From December 2013

to December 2014 the mine produced 35.5 Mt of ore (Kumba annual results, 2014) from one continuous pit (Carney and Mienie, 2003). At the end of 2014, Sishen's life of mine was estimated at 16 years (Kumba annual results, 2014). The mine is situated at the northern extremity of the Maremane Dome directly to the west of the town of Kathu (Fig. 2). Four ore types occur, namely: laminated; massive; brecciated and conglomeratic ore (Van Schalkwyk and Beukes, 1986; Carney and Mienie, 2003). The laminated and massive ores form part of what were originally the Kuruman and Griquatown Iron Formations of the Asbesheuwels Subgroup. Brecciated ore also occurs within the latter stratigraphy, but is better developed within deep palaeosinkholes on the southern portion of the deposit (Beukes and Gutzmer, 2008a). A sill is commonly found between the ore and the underlying BIF and is generally less than 2 m in thickness (Carney and Mienie, 2003). The conglomeratic ore occurs above the pre-Gamagara/Mapedi unconformity within the Doornfontein Member conglomerate of the Gamagara Formation and comprises detritally reworked laminated and massive ore. The previously mentioned Black Ridge thrust has emplaced the Makganyene diamictite and Ongeluk lavas of the Transvaal Supergroup on top of the Gamagara Formation lithologies towards the west of the deposit (Beukes and Gutzmer, 2008a).

Although the Sishen ore deposit is fairly continuous when compared to other deposits in the region, different ore bodies are recognized, namely the North, Middle, and South Mines (Beukes and Gutzmer, 2008a). Interference folds, leading to basin and dome structures throughout Sishen (Fig. 4 A), have been modified by normal faulting and low angle thrusts (Carney and Mienie, 2003). The ore is best preserved within the basin structures with only barren footwall occurring in the domal structures (Fig. 4 A) (Carney and Mienie, 2003). The floor and thickness of the ore bodies are irregular due to their karstic setting. Early joint systems in the underlying dolostones are believed to have had a strong influence on the development of early karst structures and therefore the structure of the ore deposit (Van Schalkwyk and Beukes, 1986; Beukes and Gutzmer, 2008a).

Khumani deposit

The Khumani deposit is mined from the Khumani Iron Ore Mine and is owned by Assmang. The mine produces approximately 10 Mt of high grade iron ore per annum, with recent expansion projects increasing annual production to approximately 14 Mt (www.assmang.co.za). At the end of 2014 Khumani was estimated to have a remaining mineable reserve of 550 Mt (Assmang integrated annual report, 2014), translating to an approximate life of mine of 39 years under current annual production and iron ore prices. The deposit is situated north of the fold axis of the Maremane Dome, approximately 30 km south of the town of Kathu (Fig. 2) on the farm Bruce, and represents a southern extension of the Sishen deposit, as well as on the farms King and Mekaneng to the south (Beukes and Gutzmer, 2008a). The general stratigraphy and ore types in the northern parts of Khumani are therefore very similar to those encountered at Sishen, which include Transvaal Supergroup lithologies thrust over the Gamagara Formation to the west. However, the ores at Khumani occurred in outcrop and suboutcrop before mining production began, whereas those at Sishen originally dipped below the Gamagara and Kalahari lithologies (Beukes and Gutzmer, 2008a). Whereas in the north of the deposit (Bruce farm) Asbesheuwel Subgroup-hosted laminated, massive and brecciated ore makes up 80% of the mineable

Figure 4: East-west cross sections illustrating the (A) Sishen iron ore deposit (adapted from Carney and Mienie, 2003; Van Deventer, 2009); (B) Beeshoek iron ore deposit (adapted from Van Deventer, 2009); and (C) Leeuwfontein ore body of the Welgevonden iron ore deposit (adapted from Alchin and Botha, 2006).

reserve and Doornfontein Member-hosted conglomeratic ore only 20% (similar to Sishen), this trend is reversed towards the south of the deposit on the King and Mokaeng farms, with conglomeratic ore making up 80% of the mineable reserve (Beukes and Gutzmer, 2008a). In addition, hematitized BIF and laminated hematite ore are absent in the south of the deposit, although brecciated Asbesheuwels Subgroup-hosted ore is still present (Van Deventer, 2009).

At the Khumani mine the ore is situated in karstic depressions as illustrated by the irregular floor and thickness of the ore bodies. Two main groupings of ore bodies occur on the farms of Bruce in the north and King in the south respectively (Beukes and Gutzmer, 2008a). When compared to the Beeshoek deposit further to the south, Khumani is characterized by larger stratiform ore bodies (Van Deventer, 2009) and more prominent hanging wall outcrops, due to less erosion having taken place at Khumani.

Beeshoek deposit

The Beeshoek deposit, also known as the Beeshoek-Olynfontein deposit (Van Deventer, 2009), is mined from the Beeshoek Iron Ore Mine and is owned by Assmang. Between 1994 and 2006 an average

of 4.6 Mt of ore produced from the mine was sold annually. At the end of 2014, Beeshoek had a remaining mineable reserve of approximately 46 Mt (Assore integrated annual report, 2014). The deposit is situated south of the fold axis of the Maremane Dome, approximately 7 km west of the town of Postmasburg (Fig. 2). The general stratigraphy and ore types are similar to those encountered at Sishen and Khumani, which includes Transvaal Supergroup lithologies thrust over rocks of the Gamagara Formation to the west (Grobelaar *et al.*, 1995). Conglomeratic ore is generally more common at Beeshoek (Fig. 4B), especially towards the north of the deposit, than at the Sishen and Welgevonden deposits.

The Beeshoek ore bodies are preserved in localized, smaller depressions in the form of sinkholes (Fig. 4B) (Grobelaar *et al.*, 1995). A very prominent structural feature at the Beeshoek deposit is pre-Kalahari to present day erosional karstic slumping.

Welgevonden (Sishen South) deposit

The Welgevonden deposit, also known as the Sishen South deposit, is located on the southern extremity of the Maremane Dome, 9 km southwest of the town of Postmasburg and 65 km south of

Sishen Mine (Fig. 2) (Carney and Mienie, 2003). The deposit is made up of several smaller ore bodies and is currently mined at Kolomela Mine under the ownership of Kumba Iron Ore. From December 2013 to December 2014 the mine produced 11.6 Mt of ore from three pits and Kolomela's life of mine was estimated at 21 years (Kumba annual results, 2014). The general stratigraphy of the Asbesheuwels Subgroup and the overlying Gamagara Formation and the ore types at Welgevonden (Alchin *et al.*, 2008), are similar to those encountered at the Sishen deposit. The only BIF present at Welgevonden appears to be that of the Kuruman Iron Formation, with the Griquatown Iron Formation having been removed by erosion (Alchin *et al.*, 2008). The Gamagara Formation lithologies are truncated by the Dwyka diamictite (Carney and Mienie, 2003; Alchin *et al.*, 2008), and have not had the Transvaal Supergroup lithologies thrust over them as occurs in other parts of the Maremane Dome (Fig. 4C). A gabbroic sill that attains a thickness of up to 30 m occurs between the ore and the underlying BIF (Carney and Mienie, 2003) (Fig. 4C).

The main structural characteristic in the west of the Welgevonden area is the Wolhaarkop Dome, an overturned anticline replicating the larger Maremane Dome, which occurs in the east of the deposit (Alchin *et al.*, 2008). The Campbellrand Subgroup dolostones, which form the basement of the ore bodies, are exposed at surface in the Wolhaarkop Dome, with ore bodies occurring along the flanks of the dome (Alchin and Botha, 2006). The Welgevonden ore bodies are subdivided into five groups: the Welgevonden, Kapsteveld, Klipbankfontein, Ploegfontein and the Leeuwfontein ore bodies (Fig. 4C) (Alchin and Botha, 2006). The ore bodies are intensely folded and faulted, and are preserved within erosional remnants that are not as continuous, but are of similar structural types to those encountered at Sishen (Fig. 4A) (Carney and Mienie, 2003). Two tectono-stratigraphic settings for the ore bodies have been defined by Alchin and Botha (2006): a palaeosinkhole-hosted setting applicable to the Ploegfontein, Leeuwfontein (Fig. 4C) and Klipbankfontein ore bodies; and a synclinal basin setting applicable to the Welgevonden and Kapsteveld ore bodies. Marginal deformational effects, thought to be related to the ~2.2 Ga Kheis event, occur towards the west of the deposit and decrease rapidly to the east (Alchin and Botha, 2006). The scattered nature of the ore bodies at Welgevonden could be due to the removal of upper lithologies by erosion (Carney and Mienie, 2003) and/or due to smaller, less connected underlying palaeosinkhole, pseudo-graben and synclinal structures. The Sishen South deposit is also much smaller than the main ore body at Sishen and early exploration estimates put its mineable ore reserves at approximately 25% of those at Sishen (Carney and Mienie, 2003).

Thabazimbi

The Thabazimbi deposit occurs next to the town of Thabazimbi which is located approximately 200 km northwest of Pretoria. The deposit is currently mined at Thabazimbi Mine under the ownership of Kumba Iron Ore and from December 2013 to December 2014 the mine produced 1.1 Mt of ore (Kumba annual results, 2014). Due to the low iron ore price at the end of 2014, the future of the mine was under review, with closure procedures started in mid-2015. At peak production, mining took place within two major east-west striking mountain ranges called the Northern and Southern ranges. Five ore bodies are located within the Northern range, two in the Southern Range with another minor ore body occurring in a smaller east-west striking mountain range called the Middle range (Netshiozwi, 2002).

Due to normal low-angle lystric faults in the area of the deposit, strata of the Malmani Dolostone and Penge Iron Formation are absent. Mineralisation occurs along these normal low-angle lystric faults (Fig. 5A and B) (Beukes *et al.*, 2003; Gutzmer *et al.*, 2008).

The hematite ore occurs in large tabular, stratabound ore bodies in the basal and lower parts of the Penge Iron Formation (Fig. 5A), with some duplication of the ore bodies having been caused by east-west trending thrust faults. Three stratigraphic types of ore bodies, namely the basal, upper and lenticular types are distinguished, of which the basal type is the most common (Netshiozwi, 2002). The basal type ores occur as tabular ore bodies developed along the BIF and shale contact and pinch out laterally (Fig. 5A). The upper type ores only occur above a diabase sill that cuts the succession (Fig. 5B) and are tabular and stratabound. The lenticular type ores occur as small irregular lenses at different stratigraphic levels in the middle to lower parts of the BIF (Netshiozwi, 2002). Although there are some differences between the ore bodies of the Thabazimbi deposit, numerous commonalities occur. The basal, tabular ore type is most common throughout and generally dips steeply (~35–55°) along the basal BIF-shale contact. In numerous cases hematite ore grades into carbonate ore at depth (Fig. 5A). As previously mentioned, a diabase sill occurs within the Penge Iron Formation at different stratigraphic levels above the basal ore bodies. The entire stratigraphy of some of the ore bodies is cut by northwest to southeast trending diabase dykes (Fig. 5A) (Netshiozwi, 2002). Some of the deposits show slumping into karstic structures up dip at shallower depths, with some friable

Figure 5. North-south cross section through the (A) Kwaggashoek East and (B) Donkerpoort West ore bodies that occur within the Northern range of the Thabazimbi iron ore deposit (adapted from Netshiozwi, 2002).

supergene ore developed on outcrops (Fig. 5B). The karstification and supergene enrichment is likely related to the weathering of the Cretaceous-Tertiary African land surface to form post-African land surfaces (Partridge *et al.*, 2006).

Petrography of iron ores

The following is a short summary of the main textural types of ore and hematite encountered within the Transvaal Supergroup-hosted iron ores of South Africa. More detailed petrographic characteristics and mineralogy can be found in Van Schalkwyk and Beukes (1986), Netshiozwi (2002), Carney and Mienie (2003) and Harding (2004).

Four ore types are present in the major supergene BIF-hosted iron ore occurrences within the Griqualand West area, namely: laminated (Fig. 6a); massive (Fig. 6b); brecciated (Fig. 6c); and conglomeratic ore (Fig. 6d) (e.g. Van Schalkwyk and Beukes, 1986; Carney and Mienie, 2003; Alchin *et al.*, 2008). The exception is in the Hotazel Formation-hosted ores, where brecciated and conglomeratic ores are generally less abundant or absent (Chisonga, 2012). Laminated, massive and brecciated ores occur within the BIF sequences, whereas conglomeratic ore occurs above the pre-Gamagara unconformity in the Doornfontein Member conglomerate.

Hydrothermal ores are all BIF-hosted and show the same three main textural types as the supergene ores, namely laminated, massive (Harding, 2004) and brecciated ore (Netshiozwi, 2002). In addition to the main three ore types, carbonate-hematite brecciated ores as well as supergene modified ores, are also encountered at Thabazimbi (Netshiozwi, 2002). The carbonate-hematite brecciated ores contain more than ten volume percent secondary sparitic carbonates, whereas the supergene modified ores have been modified in modern times and can be friable, porous or goethite-rich. The magmatically induced hydrothermal ores at the Nauga East deposit, mostly show a massive texture (Harding, 2004).

In both the supergene and hydrothermal ores, the laminated ores appear to have been derived from enrichment of microbanded BIF (termed ferhythmite) (Fig. 6e), whereas massive ores appear to represent enriched clastic-textured muddy BIF (termed lutite) (Fig. 6f) (see Beukes and Gutzmer, 2008b, for BIF classification) respectively. The ores are mostly composed of fine-grained compact hematite aggregates in three main textural occurrences: microplaty (lath-like and tabular) hematite, patchy hematite (Fig. 6g) and hematite pseudomorphs of magnetite (also termed martite) (Fig. 6i) and iron-rich carbonates. Massive ores are mostly composed of one or the other textural hematite type, whereas the bedding observed in laminated ores is due to alternating bands of microplaty hematite and martite. Bands with abundant microplaty hematite are also sometimes marked by voids. The hematite plates can be bedding parallel but are mostly randomly orientated. Other minerals present include

minor quartz and trace amounts of micas, clays and apatite. Brecciated ore is composed of angular blocks of laminated and massive ore in a fine grained hematite and quartz matrix. Conglomeratic ore is composed of subrounded to angular clasts of laminated and massive ore in a muddy, hematite-rich matrix.

Specularite veinlets crosscut underlying oxidized BIF as well as the ore and are especially abundant in brecciated ore (Fig. 6h). They are composed of coarser grained microplaty hematite (i.e. specularite) in random orientations, along with major quartz and in some cases can contain calcite.

Figure 6: Core scans (A-D and H), thin section scans (E and F) and reflected light photomicrographs (G and I) of the main ore types encountered in the Transvaal Supergroup-hosted high grade iron ores of South Africa. The main ore types are: A) laminated; B) massive; C) brecciated; and D) conglomeratic ore. Thin section scans illustrate the likely protoliths of laminated and massive ore, namely Kuruman Iron Formation-hosted E) ferhythmite and F) stilpnomelane lutite respectively. The photomicrographs illustrate the main textural types of hematite present: G) microplaty; patchy; and I) martite hematite. A specularite vein with associated quartz that occurs commonly throughout the ore and its surrounding stratigraphy is illustrated in H. All samples are from exploration drill core from Sishen mine except for E and F, which are from deep level drill core that intersected unaltered Kuruman Iron Formation.

Geochemistry

A compilation has been made from published and unpublished literature of the average major element (Fig. 7) and rare earth yttrium (REY) geochemistries (Fig. 8) of the different Transvaal Supergroup-hosted iron ore occurrences in South Africa as well as their host, unaltered BIF. In addition, literature values for hematite stable oxygen isotope ($\delta^{18}\text{O}$ ‰) normalized to Standard Mean Ocean Water (SMOW) from the ore occurrences, are also presented (Fig. 9) and discussed.

Major element geochemistry

Average major element geochemistries of supergene, hydrothermal and magmatic hydrothermal BIF-hosted iron ores of the Transvaal Supergroup, when compared to their unaltered precursor BIFs, illustrate that a strong upgrade in Fe_2O_3 contents has taken place (from ~33–46 wt% to ~73–98 wt%) (Fig. 7A). All the ores are high grade ores (~60–69 wt% Fe), with the exception of the Rooinekke ore (~50 wt% Fe). SiO_2 contents have decreased drastically from the unaltered BIF to the ore (from ~46–52 wt% to less than 4 wt%, with the exception of Rooinekke ore) (Fig. 7B), illustrating highly effective leaching of silica by both supergene and hydrothermal fluids during ore formation processes.

MnO contents in the Kuruman-Penge BIFs and ores are generally low (less than 0.3 wt%) (Fig. 7C), with a decrease observed from BIF to ore, suggesting manganese mobilization and removal by ore forming processes. However, the manganese-oxide [MnO] contents in the Rooinekke BIFs and iron ores are drastically higher, with a significant upgrade from the BIF (~2.9 wt%) to the ore (~10.1 wt%). This suggests that at Rooinekke, manganese was immobile and enriched in a similar way to iron during the supergene ore forming event (Gutzmer and Beukes, 2002). The MnO contents in the Hotazel BIFs and iron ores are also significantly higher (~2.1–2.4 wt%), as expected due to its close stratigraphic relationship to the KMF manganese ores. For the Maremane and Hotazel BIF and ores, Al_2O_3 contents show a prominent upgrade in concentration from the unaltered BIF (~0.1–0.3 wt%), to the supergene ores (~1.2–1.5 wt%) (Fig. 7D). The large upgrade in average aluminium-oxide [Al_2O_3] content in the ore relative to the BIF, can be partially explained by the immobility of aluminium during supergene weathering, leading to a residual upgrade. Likely adding to the upgrade is that aluminium-rich ore that formed from an upgrade of aluminium-rich precursors was more representatively sampled than aluminium-rich units are sampled in the BIF. In the hydrothermal ores the Al_2O_3 upgrade is less prominent (~0.3–0.5 wt%), and could be accounted for by all the aluminium remaining behind after silica leaching. The Rooinekke ores show a decrease in Al_2O_3 contents from the BIF to the ore.

Phosphorous is a highly detrimental element to iron ore, with elevated concentration leading to brittle characteristics in the iron and steel produced from such ores. The phosphorous-pentoxide [P_2O_5] contents for the unaltered BIF as well as the ores, are generally below approximately 0.15 wt% (Fig. 7E). It appears that the P_2O_5 is upgraded from the BIF to the ore, which could be accounted for by the relative immobility of phosphorous during ore forming events. However, the Bovenzeekoebaart ores (more than 0.25 wt%) and to a lesser extent the Hotazel ores (~0.18 wt%), show higher P_2O_5 contents that are suggestive of the ore forming fluids introducing additional phosphorous to these ores.

Figure 7: Selected average major element bar graphs from iron ores and their unaltered host BIFs from the Transvaal Supergroup. Data for the Kuruman-Penge BIF ($n=25$), Maremane Dome ores ($n=11$ and $n=16$ for ores A and B respectively), Thabazimbi ores ($n=3$) and Nauga East ores ($n=3$) taken from Gutzmer et al. (2008). Data for the Bovenzeekoebaart ores ($n=3$) taken from Harding (2004). Data for Rooinekke ore ($n=5$) and BIF ($n=14$) taken from Gutzmer and Beukes (2002) and Nel (2013) respectively. Data for Hotazel BIF ($n=5$) and ores ($n=9$) taken from Chisonga (2012).

Rare earth element geochemistry

The Post-Archaean Australian Shale (PAAS) normalized REY patterns of unaltered Palaeoproterozoic BIFs, such as those of the Asbesheuwels Subgroup, Koegas Subgroup, Hotazel Formation and Penge Iron Formation, are well known from literature (e.g. Bau and Dulski, 1996; Pickard, 2003). The BIF patterns typically show heavy REE enrichment with positive europium [Eu] and yttrium [Y] anomalies (Fig. 8A) and no cerium [Ce] anomalies (Fig. 8B), indicative of marine water with a limited hydrothermal component (Dymek and Klein, 1988). Assessing the REY patterns of the iron ores (Fig. 8A) and how they differ from the unaltered BIF, provides insight into the nature of the ore forming fluids.

The supergene ores of the Maremane Dome, in contrast to the Kuruman-Penge BIFs, show light REE enrichment and heavy REE depletion, although the latter occur at similar concentrations to those in the BIF (Fig. 8A). Taking into account that REE immobility during enrichment would lead to an REE concentration upgrade in a residual ore, this could be indicative of the supergene fluids in the Maremane Dome preferentially leaching out heavy REE. The hydrothermal ores show similar REE patterns to the unaltered BIF (Fig. 8A), suggesting immobility of all REE where concentrations are higher than the BIF (e.g. Bovenzeekoebaart and Hotazel ores), or leaching of all REE

Figure 8: (A) Spider diagrams illustrating the average PAAS-normalized REY geochemistries for iron ores and their host BIFs of the Transvaal Supergroup. (B) Binary plot of the PAAS-normalized Ce anomaly versus the PAAS-normalized Pr anomaly after Bau and Dulski (1996). Data for the Kuruman-Penge BIF ($n=25$), Maremane Dome ores ($n=11$ and $n=16$ for ores A and B respectively), Thabazimbi ores ($n=3$) and Nauga East ores ($n=3$) taken from Gutzmer *et al.* (2008). Data for the Bovenzeekoebaart ores ($n=3$) taken from Harding (2004). Data for Hotazel BIF ($n=5$) and ores ($n=9$) taken from Chisonga (2012). PAAS values obtained from Taylor and McLennan (1988).

where concentrations are similar to the BIF (e.g. Nauga East and Thabazimbi ores).

Ce anomalies are important to take into account as they are indicative of oxidizing conditions (Bau and Dulski, 1996). The unaltered BIF show no Ce anomalies but rather positive La anomalies (Fig. 8B). On average this is also the case for the ores at Nauga East, Bovenzeekoebaart and Hotazel. However, the supergene ores of the Maremane Dome, as well as the hydrothermal ore at Thabazimbi, show negative Ce anomalies indicative of the oxidation of Ce, and therefore oxidative conditions during the ore mineralisation processes.

Oxygen isotope composition of hematite

Oxygen isotopes of hematite normalized to SMOW, show a range of approximately -3.9 to $+3.0$ per mil for the supergene BIF-hosted iron ores of the Transvaal Supergroup (Fig. 9). However, the bulk of the values from literature appear to fall between -3 and $+1$ per mil.

The hydrothermal ores show a SMOW-normalized hematite oxygen isotope range of approximately -6.1 to $+3.4$ ‰ with the bulk of the values falling between -6 and -1 per mil (Fig. 9). The hydrothermal ores therefore tend to have more depleted $\delta^{18}\text{O}_{\text{SMOW}}$ values than the supergene ores. Gutzmer *et al.* (2006) suggest that the ^{18}O depletion of hematite in hydrothermal ores indicates that a fluid of shallow crustal origin, such as brines and meteoric water, enriched the BIF to high grade ores in these deposits. In contrast, ore formation in the supergene deposits did not result in a significant ^{18}O shift from what was present in the unaltered BIF (Gutzmer *et al.*, 2006).

Ore genetic models

The focus of this section is to review the epigenetic ore-forming processes of the high grade BIF-hosted ores of the Transvaal Supergroup, and not the depositional model of the host BIF. Reviews of older as well as more recent depositional models of pre-great oxidation event supracratonic (i.e. Superior type) BIF, which are applicable to the Transvaal Supergroup BIF, can be found in Klein (2005), Beukes and Gutzmer (2008b), Bekker *et al.* (2010) and Smith *et al.* (2013).

Supergene ores

As noted earlier, high grade BIF-hosted supergene iron ores in the Transvaal Supergroup only occur where the pre-Gamagara unconformity intersects BIF of the Asbesheuwels Subgroup, Koegas Subgroup and Hotazel Formation (Fig. 3A) (Beukes *et al.*, 2003). From this unconformity downwards there is a general, gradual to sharp decrease in ore grades. These, as well as other characteristics (reviewed for the Maremane Dome ore by Van Deventer, 2009), have led to the generally accepted model that the ores were formed due to the leaching of silica from the host BIF during lateritic weathering from the surface (i.e. pre-Gamagara unconformity) downwards (e.g. Van Schalkwyk and Beukes, 1986; Beukes *et al.*, 2003; Carney and Mienie, 2003).

However, though this model is sufficient to explain supergene ore enrichment in the Koegas Subgroup and Hotazel Formation, it is not sufficient to explain the development of the Asbesheuwels Subgroup-hosted large to superlarge deposits encountered in the Maremane Dome.

Large to superlarge supergene ores of the Maremane Dome

As a result of the numerous stratigraphic, lithological and geochemical similarities between the iron ore deposits of the Maremane Dome, a regional, overarching genetic model will be discussed which is represented in Fig. 10. However, it is important to note that some of the structural history, minor epigenetic processes and post-supergene history, do differ from one deposit to another.

Evidence that supports a supergene ore-forming model for the BIF-hosted iron ore deposits of the Maremane Dome includes the following: the stratigraphic setting of the ores at the top of the Asbesheuwels BIF, below the pre-Gamagara/Mapedi unconformity; palaeomagnetic data from the Beeshoek deposit suggesting that ore-formation took place in a near-equatorial climate supporting a lateritic setting (Evans *et al.*, 2002; De Kock *et al.*, 2008); oxygen isotope ranges in ore-forming hematite suggesting normal meteoric water

Figure 9: Plot of the $\delta^{18}\text{O}_{\text{SMOW}}$ for hematite from selected BIF-hosted iron ores of the Transvaal Supergroup. Data for Sishen, Rooinekke, Thabazimbi and Bovenzeekoebaart taken from Netshiozwi (2002) and Gutzmer *et al.* (2006). Data for Beeshoek taken from Van Deventer (2009).

(Gutzmer *et al.*, 2006; Van Deventer, 2009); and heavy REE depletion is observed in the Maremane Dome ores (Gutzmer *et al.*, 2008; Van Deventer, 2009).

The ore-forming fluids that caused the formation of high grade hematite ores had to have been able to do the following: i) dissolve the underlying Campbellrand dolostones as indicated by the presence of the Wolhaarkop chert breccia below ore sections and the occurrence of the ore bodies in palaeokarstic slump structures; ii) oxidize Fe^{2+} to Fe^{3+} as indicated by the lack of ferrous minerals and a dominance of hematite in the ore when compared to precursor BIF; iii) dissolve and remove silica as indicated by low silica contents in the ore when compared to precursor BIF; and iv) reprecipitate hematite as suggested by a general lack of visible volume loss in laminated and massive ores. These characteristics led Van Deventer (2009) to propose the following genetic model for the formation of BIF-hosted ore on the Maremane Dome: Initially, acidic circulating meteoric fluids dissolved the Campbellrand dolostones, leading to karst formation (Fig. 10B) and slumping of the Asbesheuwels BIF into the karst structures (Fig. 10C). The carbonate dissolution lead to an increase of the fluid's pH, which then enabled the fluid to start leaching silica (Klemm, 2000) from the BIF, as well as oxidize Fe^{2+} to Fe^{3+} leading to the precipitation of hematite and thereby ore formation (Fig. 10D). As a lateritic weathering profile developed above the BIF, descending meteoric fluids would be acidic, leaching iron as Fe^{2+} from overlying layers and transporting it to lower levels (Fig. 10D). Either due to carbonate dissolution or due to mixing with higher pH fluids at depth, the acidic fluids will have increased their pH and allowed the precipitation of hematite which could have replaced the leached silica, limiting the volume loss in the high grade massive and laminated ores. This was followed by erosion, the formation of the pre-Gamagara/Mapedi unconformity and deposition of the Doornfontein conglomerate and its associated conglomeratic ore (Fig. 10E).

The conglomeratic ore overlies the pre-Gamagara/Mapedi unconformity in the Doornfontein conglomerate at all iron ore deposits (Fig. 4) and is the dominant ore in the south of the Khumani and the north of the Beeshoek deposit. A positive conglomerate test on the

hematite pebbles in the conglomeratic ore, which shows random magnetic directions for the different pebbles, indicates that ore enrichment of the pebbles took place before they were deposited in the conglomerate (Evans *et al.*, 2002; De Kock *et al.*, 2008). This suggests that the conglomeratic ores in the Maremane Dome formed as an erosional product of Asbesheuwels Subgroup-hosted massive and laminated ores that were deposited in depressions or basins on the flanks of the Maremane Dome. Some of these depressions or basins occurred above ore and BIF units that had slumped into sinkholes (Fig. 10E). The dome is believed to have had maximum uplift and erosion in its central section, as indicated by surface exposure of the Campbellrand dolostones and a lack of preserved Asbesheuwels Subgroup units in the region. This also explains the dominance of conglomeratic over laminated and massive ores in the southern part of the Khumani deposit, just north of the center of the dome, and the north of the Beeshoek deposit, just south of the center of the dome. It is important to note the role that the formation of karstic structures in the Campbellrand dolostones played, not only in the formation of the BIF-hosted ores but also in the preservation of this ore with regards to pre-Gamagara/Mapedi erosion, as well as in the deposition of conglomeratic ore.

An age range for the main supergene ore-forming event that upgraded the Asbesheuwels Subgroup BIF in the Maremane Dome was obtained through paleomagnetic study and is approximately 2.22 to 2.06 Ga (Evans *et al.*, 2002; De Kock *et al.*, 2008). The results were obtained by measuring the paleomagnetism of hematite pebbles in the Doornfontein conglomerate at Beeshoek and by comparing it to other known Paleoproterozoic poles from the Kaapvaal Craton.

Hydrothermal ores at Thabazimbi

At the Thabazimbi deposit, the following observations and evidence support a hydrothermal origin for the ore: the occurrence of the tabular ore bodies at the base of the Penge Iron Formation on the contact with the black shales; the presence of hydrothermal sparitic calcite and dolomite within the ore (Netshiozwi, 2002); mineralisation

Figure 10: Diagram illustrating the genetic model for the formation of the superlarge Maremane Dome-hosted high grade iron ore deposits (adapted from Gutzmer and Beukes, 1996; Van Deventer, 2009).

along low angle normal lystric faults (Fig. 5) that removed stratigraphy along the Penge-Malmani contact (Beukes *et al.*, 2003); fluid inclusions in sparitic calcite and dolomite, suggesting two fluids (see next paragraph) of hydrothermal origin (Netshiozwi, 2002); and a depletion in $\delta^{18}\text{O}$ in ore-forming hematite (Gutzmer *et al.*, 2006; 2008).

Through fluid inclusion studies by Netshiozwi (2002), two hydrothermal fluids have been identified: a high salinity brine; and an intermediate salinity brine thought to be of meteoric origin. Hydrothermal fluids most likely used the normal faults as conduits to cause two stages of hydrothermal alteration, with the first stage believed to have caused the oxidation of all ferrous minerals and their replacement by hematite. This stage affected a much larger volume of rock than just that in the ore zones, as can be seen in a wide halo of oxidized BIF and shale surrounding the ore (Netshiozwi, 2002). The second stage of hydrothermal alteration caused the efficient leaching of chert. The leached chert could have been: replaced by porous microplaty hematite to form high grade hematite ore without significant volume loss (Beukes *et al.*, 2003); replaced by sparitic calcite or dolomite to form carbonate-hematite ore seen at depth (Netshiozwi, 2002); not replaced, leading to compaction and increased porosity (Beukes *et al.*, 2003).

The previously mentioned underlying shales, overlying sill and cross-cutting dykes appear to have exerted a control on the localization of the ore bodies at Thabazimbi (Netshiozwi, 2002; Beukes *et al.*, 2003). In some instances ore bodies are only developed next to dolerite dykes and the most commonly occurring basal ore body type exclusively occurs above the basal shale and below the dolerite sill. The shales and pre-ore formation diabase sill therefore appear to have

acted as seals to the hydrothermal fluids due to their low porosity and relative impermeability (Netshiozwi, 2002; Beukes *et al.*, 2003).

Using mineralogical and structural evidence, the timing of ore formation at the Thabazimbi deposit was originally bracketed by Netshiozwi (2002), to be between the intrusion of the Bushveld Complex (~2060 to ~2055 Ma) (Scoates *et al.*, 2012) and triplication of the stratigraphy by thrust faulting. The dolerite sill intruding the Penge Iron Formation above the ore bodies predates ore formation (Netshiozwi, 2002; Beukes *et al.*, 2003) and was determined by Chisonga (2012), using titanite, to have an age of approximately 2047 Ma, thus providing a better constrained maximum age of ore formation at Thabazimbi. A further time constraint can be inferred by the presence of iron ore pebbles within the Waterberg Group, over which Transvaal Supergroup strata have been thrust to the north of Thabazimbi (Netshiozwi, 2002). The minimum age of deposition for the Waterberg Group is approximately 1927 Ma, as indicated by baddeleyite ages for dolerite sills intruding the succession (Hanson *et al.*, 2004). The ore-forming process at Thabazimbi therefore occurred approximately between 2047 and 1927 Ma, although a minimum age of approximately 1930 Ma was proposed by De Kock *et al.* (2008) as based upon regional correlations made in the Waterberg Group by Dorland *et al.* (2006).

Hydrothermal ores at Bovenzeekoebaart

Similarities between the hydrothermal ores at Bovenzeekoebaart and Thabazimbi include the following: the host BIFs are believed to be time equivalents in the Griqualand West and Transvaal regions;

occurrence of laminated and massive ore at both deposits; shales underlying both the ore bodies; oxidized BIF overlying the ore bodies; the occurrence of thrust fault systems; faulted contacts between lithological units; and a diabase sill to the west of the ore bodies (i.e. overlying the ore bodies; Harding, 2004). The Bovenzeekoebaart deposit is different from the deposit at Thabazimbi in the following ways: lack of carbonate ore; major folding and overturning of strata; and lack of any crosscutting intrusions (Harding, 2004).

The strong similarities between the Bovenzeekoebaart and Thabazimbi deposits, led Harding (2004) to propose a similar two stage hydrothermal ore-forming process for the former, comprising oxidation of the host BIF followed by leaching and replacement of chert, with the exception that there is no carbonate replacement at Bovenzeekoebaart. Slight supergene alteration occurred in geologically recent times at Bovenzeekoebaart, as indicated by goethite formation in the ores (Harding, 2004). The exclusive occurrence of the ore bodies above shales and below the diabase sill suggests that these exerted a strong control on the localization of the ore bodies by acting as impermeable seals to the hydrothermal fluids, just as inferred for Thabazimbi. No age constraints are available for ore formation at Bovenzeekoebaart.

Magmatically induced hydrothermal ores at the Nauga East Deposit

At the Nauga East iron ore deposit, the occurrence of the ore bodies, exclusively above the syenite-carbonatite that intruded along the shale-BIF contact, as well as regional oxidation of the Kuruman BIF, led Harding (2004) to conclude that the intrusion of carbonatitic fluid and oxidation, were the main driving forces in the formation of the enriched iron ore. He proposed three stages to ore formation: i) incipient oxidation of the Kuruman BIF and leaching of carbonates with pervasive replacement by hematite; ii) intrusion of the syenite acting as a plug; and iii) intrusion of the carbonatite leading to syenite alteration, dissolution of silica from the BIF and further crystallization of hematite. The hydrothermal ore-forming event at Nauga East was followed by oxidation during supergene weathering, as well as the precipitation of botryoidal hematite. No age constraints are available for ore formation at Nauga East.

Concluding remarks

South Africa was the seventh largest producer of iron ore in the world at the time of writing (USGS, 2015) and the size and variety of its BIF-hosted high-grade iron ore deposits are of global significance and high economic value. Studies of South Africa's deposits have also led to a better understanding of the geological setting and genesis of these ores that can be applied to other iron ore deposits in the world. Much more scientific research can still be carried out on these deposits, especially with regards to better constraining the timing of events, the structural controls on formation and the nature of the mineralising fluids.

With regard to the outlook of iron ore mining in South Africa, at the end of 2014, the total remaining mineable iron ore reserves for the five largest BIF-hosted iron ore deposits were estimated to be approximately 1.51 Bt (Kumba annual results, 2014; Assore integrated annual report, 2014). Based on mining company projections and current production rates, this places the life of mine for the deposits at approximately between 15 and 20 years, with the exception of

Thabazimbi and Beeshoek, which are likely to be mined out sooner. It therefore appears that iron ore production within South Africa will decrease substantially within the next 20 years unless current deposits are expanded to include deeper and/or lower grade ores, unmined deposits are brought into production, Archaean and Bushveld magnetite ores are exploited or new deposits are found.

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