



Dolerite control on the distribution of high-grade iron orebodies at Assen Iron Ore mine, South Africa

Elekanyani Shadrack Negwangwatini

1986493

A thesis submitted to the Faculty of Science, University of the Witwatersrand, in fulfilment of the requirements for the degree of

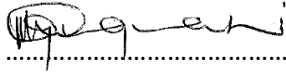
Master of Science in Economic Geology

University of the Witwatersrand, School of Geoscience, 2020

01 November 2021

Declaration

I declare that this research report is my own original work, conducted under the supervision of Prof. Glen Nwaila. It is submitted in fulfilment of the requirements for the Master of Science in Economic Geology at the University of Witwatersrand, School for Geoscience.


.....

Elekanyani Negwangwatini 01-11-2021

Abstract

The Assen Iron Ore deposit is located in the Crocodile River Inlier which lies within alkali rocks of the 2.05 Ga Bushveld Igneous Complex (BIC). The host rocks to the Assen Iron Ore deposit are contained in the lower portion of the Penge Formation of the Transvaal Supergroup, close to the contact with the underlying dolomite of the Malmani Subgroup. This study presents a detailed geological mapping of the Assen Iron Ore deposit. Petrographic and mineral characteristics of different iron ore facies and the dolerite intrusions from three iron ore mineralised portions named west, middle, and east orebody were conducted. The study investigated whether the intrusions control the mineralisation of high-grade iron orebodies. The different types of hematite and dolerite intrusions were sampled from the Assen Iron Ore mine's current operating pits and analysed using X-ray powder diffraction (XRD) and optical microscopy. Existing X-ray fluorescence (XRF) from the previously drilled diamond cores were used to compare and correlate different oxides with different iron ore facies.

The banded iron formations (BIFs) that constitute the Penge Formation in the Assen area comprise several stratigraphically conformable rocks, namely shale, limestone, and mineralised units represented by calcitic hematite, high-grade hematite ore (i.e., laminated, and massive hematite ore), and goethite-rich hematite ore. The shale forms a basal layer consisting mainly of chert-rich BIF lenses with pyroclastic and tuffaceous sections. The intermediate layer with micro- and meso-layering consists of hematite and calcite, typical of carbonate facies. A high-grade hematite-rich ore directly overlies the calcitic ore. Lying above the high-grade hematite is atypical goethite-rich ore with grades between 50 to 55 % Fe. Detrital iron ore is located at the base of the southern slope of the Assen ridge. This ore is unconsolidated and occurs as small, rounded cobbles and pebbles of iron-rich sandy sediment from 1 m to 2 m thick.

The geological mapping and exploration drilling indicate that the orebodies are structurally controlled along the dolerite sills that intruded the BIF sequence of that Transvaal supergroup. At places, goethite-rich and laminated hematite are found above or on the hanging wall of the dolerite sills. Massive hematite tends to be underlain by the dolerite. Calcitic hematite is always located in the stratigraphy below massive and laminated hematite and is underlain by either the dolerite on the edge of iron formation or shale. At Assen Iron Ore mine, dolerite sills intruded the BIF of the Penge Formation. Post-deposition and intrusion, both the dolerite intrusions and BIF were affected by the three stages of folding (F1, F2, F3-folds) and faulting which caused deformation and partial metamorphism. Thermal metamorphism is associated with the BIC which surrounds the Inlier and resulted in alteration of primary minerals, change in bulk rock chemistry, and visual appearance of the rocks.

The XRF analysis showed the downward increases in % iron (Fe), downward decrease in silica (SiO_2) in both BIF, goethite, laminated and massive hematite. The calcitic hematite showed a downward decrease in iron (Fe) and a downward increase in calcium (Ca). The laminated hematite (55-59 % Fe) and high-grade Fe in BIF (50-55 % Fe) ore types showed some clear removal of almost all silica in between hematite bands to partial removal of silica in the high Fe BIF. Both high-grade BIF and laminated hematite remained with the preserved primary layers of hematite bands that compacted through time due to pressure and folding to form a high-grade bedded iron ore. The space that was occupied by silica is at places filled with thin and scattered recrystallised quartz or goethite matrix. The goethite-rich, friable soft hematite, sometimes in a dark grey powder was formed by the weathering and dissolution of Fe from the BIF by the descending surface or meteoric water. The spatial relationships between the dolerite intrusions and the high-grade hematite ore suggest that the dolerite intrusions caused changes in mineral texture and ore grade. The XRF analysis from the drilled cores showed clear evidence that at closer contacts, hematite orebodies in contact with sills

underwent enrichment in Fe and reduction in SiO_2 . This result shows that aside from secondary supergene enrichment, tertiary Fe enrichment can occur due to igneous activity such as dolerite intrusion.

Acknowledgements

Firstly, I would like to acknowledge the University of Witwatersrand for accepting my application as an MSc candidate and granting me the opportunity to study with them to obtain my MSc in Economic Geology. The university has also granted me access to use their laboratories and their facilities and assisted in preparing thin sections and analysing the thin sections using a petrographic microscope for the project.

I would like to thank my Professors for all the knowledge impartation, academic support, and advice throughout my studies, without them this research report wouldn't be possible. My deepest gratitude goes to my internal project supervisor Prof. Glen Nwaila for the sterling guidance, assistance, and supervision throughout the project. The constant steering and tireless effort to my research report were endearing and I was honored to have his supervision throughout the project. Prof. Glen Nwaila also assisted in suggesting important publications to read and get us some research specialists to impart knowledge to us during our biweekly meetings. My sincere gratitude goes to Prof. Judith Kinnard for the much-needed suggestions and valuable ideas for my research proposal. I would also like to thank Prof. Paul Nex who gave guidance in mineral correlation and all the support throughout my research.

My heartfelt gratitude to Mr. Matodzi Nesongozwi, the CEO of Manngwe Mining Company who approved the financial support for the project and providing necessary permissions and facilities to access the Assen Iron Ore mine exploration boreholes data necessary for the project. Mr. Matodzi Nesongozwi also granted me the time to focus on my studies while working for him. His leniency allowed me to be flexible in my schedule to complete my masters and continue working concurrently. Manngwe Mining Company also helped me in using their geological modelling software for me to produce the 3D geological model and ArcGIS software to produce some 2D geological maps. I would like to acknowledge MQA for their financial support in funding my studies by granting me a bursary. Assen Iron Ore mine provided access to the pits for sampling and geological mapping and provide the required drill cores.

I would like to thank Mr. Ernst Makupula and Mr. Vhusafheli Ramanugu for their help in the geological modelling of the orebody using Leapfrog and Datamine. I would also like to thank Mr. Katekani Musisinyani, who is not just a colleague but is also my friend who assisted me with collecting the samples, sample preparation, and his input to my research report. I am grateful to Thapelo Sialo from the South African Bureau of Standards (SABS) laboratory for doing XRF analysis for some of the Iron Ore samples and his team for their abundant and helpful support.

Thank you to my Fiancé, Nompumelelo Mokgethoa for the love, support, prayers, and encouragement throughout my research. Nompumelelo is a qualified geologist who assisted me in my research work, the editing of my research report, and the input required to complete my research report. Finally, to my parents, thank you for the constant prayers, support, love, and most importantly patience, and understanding. I have spent most of my time away from home due to my studies that even during festive seasons and holidays I would not visit while I would be chasing the deadline for my research report.

TABLE OF CONTENTS

Declaration	i
Abstract	ii
Acknowledgements	iv
List of Figures	vii
List of Tables	ix
List of figures of the appendices:	Error! Bookmark not defined.
List of tables of the appendices:	ix
List of abbreviations and acronyms	x
List of abbreviations of rock types, minerals and elements	x
CHAPTER 1	1
1. Introduction	1
1.1 Background	1
1.2 Aims and the objectives of the research.	2
1.3 Scope of the study	2
1.4 Previous Work	3
1.4.1 The depositional model of the BIF	3
1.4.2 High-grade iron ore genetic models	4
1.5 Statement of the Problem	7
1.6 Project Methodology	7
1.6.1 Detailed geological mapping	7
1.6.2 Chemical analysis using X-ray fluorescence	8
1.6.3 Quantitative X-ray powder diffraction analysis	8
1.6.4 Reflected light microscopic study.	8
1.7 Research structure	8
CHAPTER 2	9
2. Literature review	9
2.1. Iron ore deposits and their classification schemes	9
2.1.1. Iron ore deposits	9
2.1.2. Classification of iron ore deposits	10
2.2. Regional Geology	13
2.2.1. Kaapvaal Craton	13
2.2.2. Transvaal Supergroup	14
2.3. Deposit Geology	18
2.3.1. Lithostratigraphy	18
2.3.2. Mineralisation Style	20
2.3.3. Geological structures	21
2.4. Iron ore and gangue mineralogy	23

CHAPTER 3	25
3. Samples and methodology.....	25
3.1. Sample descriptions	25
3.2. Methods.....	26
3.2.1. Geological mapping.....	26
3.2.2. Chemical analysis using X-ray fluorescence	27
3.2.3. Petrography and Mineralogy	27
CHAPTER 4	30
4. Detailed geological mapping.....	30
4.1. Regional-scale observations	30
4.2. Deposit-scale observations	33
4.3. The lithostratigraphy of the Assen deposit	37
4.4. 3D implicit modelling of the Assen iron deposit	38
CHAPTER 5	51
5. Mineralogy and Petrography	51
5.1. Calcitic hematite	51
5.2. Massive hematite	53
5.3. Laminated hematite	53
5.5. Dolerite intrusions.....	55
5.6. The XRF geochemistry of iron ore.....	56
CHAPTER 6	60
6. Discussion	60
6.1. Paragenesis of different iron ore types	60
6.2. The relationship between the dolerite and hematite ores	61
6.3. The relationship between the Faults and folds with hematite ores	63
6.4. Fe grade distribution in the Assen Iron Ore deposit	63
CHAPTER 7	64
7. Conclusions	64
References	66
Appendices	71
Appendix A. 1. Quality assurance and quality control analysis.....	71
Appendix A. 2. Certified reference materials in different samples	72
Appendix A. 3. Accuracy of CRM's	73
Appendix B. 1. Block's validation statistics	74
Appendix C. 1. Semi-Variograms for east, middle, and west orebody.....	76
Appendix D. 1. Histograms of elements distribution in both east, west, and middle orebody.	84

List of Figures

Figure 1: Classification of major types of high-grade hematite ore deposits and their model of enrichment (Beukes et al., 2002).	5
Figure 2: Distribution of the abundance of Iron Formations through time (After Klein, 2005).	10
Figure 3: The genetic model for the major BIF-hosted iron ores of the world showing the transformation from BIF to different iron ore types (modified from Morris, 1998).	12
Figure 4: The geological map of the Kaapvaal Craton showing the terrain boundaries and the location of different greenstone belts (From Poujol et al., 2003).	14
Figure 5: Generalized stratigraphy of the Transvaal Supergroup in the Northwest Province and Crocodile River Inlier Stratigraphy (after Hartzer, 1995).	15
Figure 6: Regional Geological map of the Transvaal basin of the Transvaal Supergroup illustrating the Assen Iron Ore deposit in the Crocodile River Inlier (Modified after Eriksson et al., 2006; Netshiozwi, 2002).	16
Figure 7: Schematic N-S cross-section through the Assen ridge showing different lithologies (From Kevin, 2015).	19
Figure 8: The stratigraphy of Assen Iron Ore deposit showing different lithologies (Mineral Corporation, 2012).	20
Figure 9: Geology of the Crocodile River Inlier showing the east-northeast trending syncline through the western portion of the Assen Iron Ore mining license - marked in red. (from Hartzer, 1989).	21
Figure 10: Tectonic development of the Crocodile River Inlier. In (A) shows deposition of the Pretoria Group and folding along pre-existing structural lineaments. In (B) Bushveld Complex intrusion deformed the Inlier. In (C) two major faults caused the Inlier doming against the surrounding rocks (after Hartzer, 1995).	22
Figure 11: The methods and procedures followed in conducting the studies.	25
Figure 12: Regional geological map of Crocodile River fragment showing the location of Assen area and the geological structures within the area (Modified after Hartzer, 1995).	30
Figure 13: Three synform where a large volume of hematite ore is concentrated at Assen Iron Ore deposit.	33
Figure 14: The geological map of the Assen iron ore deposit showing three mineralised portions at Assen.	36
Figure 15: The lithostratigraphy of the Assen Iron Ore deposit the Penge Iron formation rocks intruded by the dolerite sills.	37
Figure 16: Boreholes showing the alternating lithologies of the drill holes that created an alternating succession.	40
Figure 17: The 3D implicit lithological model showing distinctive hematite mineralisation trends at Assen Iron Ore deposit. The hematite ores are parallel to bedding and located close to the contact of dolerite and shale in both west, middle, and east orebody.	40
Figure 18: Univariate statistics and histograms of major, minor elements, and specific gravity of high-grade hematite at the west orebody	43
Figure 19: East-west view of Fe (%) distribution on east and middle block model all Domains	45
Figure 20: Isometric view of geological domains in east and middle orebody.	45
Figure 21: East to west view of Fe (%) distribution - West orebody block model of all domains	46
Figure 22: Omni-directional Variogram - Fe- high-grade hematite domain at the west orebody	47
Figure 23: Field observations from the Pit1 and Pit 2 at the middle orebody of the Assen Iron Ore deposit. A) Approximately 2.5 m of shallow dipping hematite layer underlain by the dolerite. B)	

North-South cross-section of the outcropping shale, hematite, and dolerite dipping to the north at an angle of approximately 60° at pit 2 in the middle orebody. C) Pit 1 benches affected by the Northeast-southwest fault and the wavy hematite located above the dolerite.	50
Figure 24: Photographs of representative rock samples from the west, middle, and east orebody at the Assen Iron Ore deposit representing the available iron ore facies. The ore types gradually grade from one ore type to another. The Carbonaceous facies is represented by A, B, and C. The sample A and B shows the alternating bands of hematite and calcite. Sample C is very rich in calcite having large crystals of calcite and some patches of hematite in between the crystals. BIF is represented by samples D and E, where BIF D upgrades to BIF E, with increasing Fe and decreasing SiO ₂ . Sample F is a Friable goethite-rich hematite. Samples G and H are laminated hematite, micro-banding in H while G has thick bands of 0.5 mm hematite with goethite and Chert matrix between the hematite bands. Massive hematite is I, which is a bluish-grey, shiny, and flinty fine-grained hematite.	52
Figure 25: Semi-quantitative mineralogy in Vol.% of selected iron ore and dolerite samples from the diamond drilled hole.	53
Figure 26: The reflected light image of different iron ore types (A-G): BIF (A, B, and C), calcitic hematite (D), goethite (E), laminated hematite (F), massive hematite (G) and dolerite (H).	54
Figure 27: Element's correlation graphs in different iron ore lithologies representing: A. Goethite-rich hematite, B. Laminated hematite, C. Massive hematite, and D. Calcitic hematite.	58
Figure 28: Dolerite Vs hematite graph showing the high Fe concentration towards the dolerite contacts. Red dots indicate the dolerite, green dots indicate the dolerite/hematite transaction, blue dots indicate hematite. Hematite (% Fe) shows an increase when it is near the dolerite and decreases as it moves further away from the dolerite.	59
Figure 29: The stratigraphy of different boreholes located at Assen Iron Ore showing the location of hematite (red) in relation to the dolerite (green). ASNRC 001, the hematite is located on the dolerite footwall, PB 006- high-grade hematite is in the hangwall of the dolerite, In SH 015 and AMI 001- The hematite is located both at the hangingwall and footwall of the dolerite sill branches, in A 061 thin hematite is associated with shale and in A61, no hematite intersected.	62

List of Tables

Table 1: The Assen logged drill hole rock units and their relative time scale in relation to corresponding regional geological units. The logged lithologic units belong to the Chuniesport Group of the Transvaal Supergroup and the dolerite sills of the post karoo age. Table compiled from different sources such as Button (1981); Eriksson et al. (2005; 2006; 2011); Fockema (1945); Hammerbeck et al. (1976); Hartzer (1987;1989;1995).....	32
Table 2: Table providing a summary on geo domains modelled in this project.....	41
Table 3: Block model variables used for both west, east, and middle orebody.....	42
Table 4: The variogram modelling parameters.....	44
Table 5: Block validation statistics: Block estimates vs Composite's statistics in west orebody high-grade hematite domain	48
Table 6: Block validation statistics: Block estimates vs Composite's statistics in west orebody low-grade hematite domain	49
Table 7: Block validation statistics: Block estimates vs Composite's statistics in west orebody calcitic hematite.....	49
Table 8: The exploration borehole SH 015 XRF analysis for different types of hematite with depth. .	57

List of tables of the appendices:

Table A. 1. Assen Iron Ore compliance to the QAQC basic principles	71
Table B. 1: Block validation statistics: Block estimates vs Composite's statistics in west orebody high-grade BIF domain	74
Table B. 2: Block validation statistics: Block estimates vs Composite's statistics in east orebody high-grade hematite domain	74
Table B. 3: Block validation statistics: Block estimates vs Composite's statistics in middle orebody high-grade hematite domain	74
Table B. 4: Block validation statistics: Block estimates vs Composite's statistics in middle/east orebody calcitic domain.....	75
Table B. 5: Table: Block validation statistics: Block estimates vs Composite's statistics in middle orebody high-grade BIF domain	75

List of abbreviations and acronyms

Avg. dist	Average anisotropic distance to samples
BIC	Bushveld Igneous Complex
BIF	Banded Iron Formation
Block var	Block variance
CRM	Certified Reference Material
CSIR	Council for Scientific and Industrial Research
EDS	Energy-Dispersive Spectroscopy
EDX	Energy-Dispersive X-rays
EMPA	Electron Microprobe Analysis
Fm	Formation
g/t	grams per metric ton
GIF	Granular Iron Formation
GPS	Global Positioning System
HG	High-grade
krig eff	Kriging efficiency
krig var	Kriging variance
Lg	Lagrange multiplier
LG	Low-grade
Neg weight	Number of negative weights
Num dh	Number of drill holes
Num samp	Number of samples
QAQC	Quality Assurance and Quality Control
RIF	Rapitan Iron Formation
SABS	South African Bureau of Standard
SANAS	South African National Accreditation System
SG	Specific Gravity
USGS	United States Geological System
wt. %	Weight Percentage
XRD	X-ray Diffraction
XRF	X-ray Fluoresces

List of abbreviations of rock types, minerals and elements

Am	Amphibole
BIF	Banded Iron Formation
Al ₂ O ₃	Aluminium Oxide
Ca	Calcium
CaCl ₂	Calcium Chloride
Cal	Calcitic hematite
CaO	Calcium Oxide
Chl	Chlorite
Db	Dolerite

Dol	Dolomite
Fe	Iron
Fe ₂ O ₃	Hematite
Fe ₃ O ₄	Magnetite
FeOOH	Goethite
Fsp	Feldspars
H ₂	Hydrogen
H ₂ S	Hydrogen Sulfide
K ₂ O	Potassium Oxide
Ls	Limestone
Mg	Magnesium
MgO	Magnesium Oxide
Mn	Manganese
MnO	Manganese Oxide
NaCl	Sodium Chloride
P	Phosphorus
Qtz	Quartz
Sh	Shale

CHAPTER 1

1. Introduction

1.1 Background

Banded Iron Formation (BIF) hosts the major world high-grade iron ore deposits, primarily in the form of hematite (Smith and Beukes, 2016). To date, hematite remains the main source of iron ore for the world's steel industries, contributing approximately 98 % in steelmaking (Shaltami et al., 2020). The world steel demand increased by 3.9 % in 2019 and was expected to increase by 1.7 % in 2020 mainly due to growth and high demand in developed and developing economies (USGS, 2019). The grade of iron ore deposits ranges from 20 to 30 % for low-grade deposits and 60 to 70 % for high-grade deposits (Slack and Comtois, 2016). The acceptable iron ore grade recommended globally in steel industries for making pig iron ranges from 58 % to 65 % iron for countries having high-grade iron ore reserves of 50 % Fe and above. The depletion of high-grade hematite iron ore reserves and declining ore grade in the United States of America and high demand for iron ore in China have led to low-grade iron ore processed. In 2019, Australia was the largest iron ore producer contributing 37 % of world supply, followed by Brazil at 16 % and China at 12 %. South Africa is ranked the 7th in the world, contributing an average of 3 % per annum to the global output (USGS, 2020).

Known iron ore mining activities in South Africa started between 1 200 AD and 15 000 AD and was led by the Khoisan people in Northern Cape and Thabazimbi area (Cairncross et al., 1997). South Africa host and produce iron ore from Palaeoproterozoic iron formations (approximately 2.2 to 2.0 Ga) of the Transvaal Supergroup in the Griqualand West and the Transvaal basins. The major deposits occur in Asbesheuwels Subgroup iron formation, Rooinekke Iron Formation of the Koegas Subgroup, the Hotazel Iron Formation of the Voëlwater Subgroup, the Penge Iron Formation of Chuniespoort group, and Kuruman Iron Formation of the Asbesheuwels Subgroup (Beukes et al., 2003). In 2018, South Africa had approximately 770 million tons of known iron ore reserves which were approximately 0.9 % of global reserves. In the same year, South Africa produced approximately 81 000 million metric tons of iron ore. The current study focuses on the Assen Iron Ore which has a total of 30 million tons of iron ore, and it is currently the 3rd Iron ore producer in South Africa. The deposit falls under a class of Superior-type Iron Formation, and it is part of the Transvaal Basin, located in the Northwest Province ± 60 km south of Thabazimbi mining district.

It is now well known that the Superior-type represents one of the best-preserved, chemically precipitated iron formations formed in marine continental shelves and in shallow basins (Smith and Beukes, 2016). This class of iron formations is commonly interlayered with other sedimentary or volcanic rocks such as shale and tuff. Most Superior-type BIFs formed during the Paleoproterozoic age, between 2.5 and 1.8 Ga years ago. In South Africa, the Penge Formation is widely distributed within the Transvaal Basin. This basin is developed on the Kaapvaal Craton which has been tectonically stable for at least 2.5 Ga. The Transvaal Supergroup has an age between 2.1 and 2.3 Ga of years which is comparable to the formation age of Lake Superior iron ore deposits. The economic iron ore occurs in the basal Penge Formation, immediately above the lowest shale unit, a 10 m thick

chert-rich band that immediately overlies the thick dolomite and chert succession of the Malmani dolomite.

All high-grade hematite iron orebodies in the world have similar characteristics in terms of origin and mode of formation. The differences in qualities and quantities of hematite are due to the intensities of supergene modification and hydrothermal fluid interaction with the host rock BIF (Smith and Beukes, 2016). The BIF that constitutes the Penge Formation in the Assen Iron Ore Deposit comprises several stratigraphically conformable lithological subdivisions.

In this study, detailed geological and structural mapping over the Assen Iron Ore deposit with the aid of drill hole data to produce an integrated 3D geological model encompassing the orientation and geometry of the iron ore deposit was undertaken. The mineralogical and geochemical characteristics of different iron ore facies were determined using Thermo Fisher's ARL Advant'X family of X-ray fluorescence (XRF) sequential spectrometers, Quantitative X-ray powder diffraction (XRD), and reflected light microscopy. Lastly, lithostratigraphic and litho-geochemical correlations between iron ore grade and dolerite intrusions are done on the premise of localised secondary Fe enrichment.

1.2 Aims and the objectives of the research.

The Primary aim of this study is to investigate the relationship between dolerite intrusions and iron ore grade. Although much of the Fe enrichment was brought by supergene enrichment, it is hypothesised that the intrusion of dolerite dykes and sills led to localised post-depositional alteration which upgraded the Fe grade.

In order to fulfil the aim of this study, the following objectives were addressed:

- Detailed field mapping in order to acquire field relation data between dolerite intrusions and hematite ore.
- Determination of Fe and associated major elements distribution on pristine ore and proximal to the dolerite intrusions; and
- Petrographic and mineralogical studies of both dolerite and Fe ores in order to understand their composition, association, and paragenesis.

1.3 Scope of the study

The Assen Iron Ore deposit occurs in the Crocodile River Fragment, an inlier of Transvaal Sequence rocks surrounded by younger alkali rocks of the felsic Lebowa Granite Suites (2.052 Ga) of the 2.060 and 2.050 Ga Bushveld Igneous Complex. The mafic phase of the Bushveld Complex is not in direct contact with the inner inliers, and this is confirmed by geophysical data indicating that the Crocodile River Inlier is not underlain by the Bushveld Complex (Hartzer, 1989). The Assen Iron Ore deposit has three adjacent and disconnected hematite-bearing lenses which are developed along the crest on the farms Assen 140 JQ, Assen 161 JQ, Buffelspoort 149 JQ, Doornkloof 141 JQ, and Swarthoek 10 JQ halfway between Brits in the Northwest Province and Thabazimbi in the Limpopo Province of South

Africa. The deposit is along the east-west trending ridge of hills southeast of the confluence of the Pienaars and Crocodile River.

Commonly, oxygen isotopes are used to differentiate between the supergene and hypogene iron ores because the $\delta^{18}\text{O}$ composition of hydrothermal iron ore deposits range between +0.9‰ to -7.3‰ while in supergene iron ore deposits the $\delta^{18}\text{O}$ composition range between +2.0‰ and -3.9‰ (Gutzmer et al., 2006). In this study, stable isotopes are excluded and fall outside the scope of the study. The microthermometric studies of fluid inclusions to distinguish the type of fluids involved in the iron formation were also beyond the scope of this work. The research covers the mineralogy, geochemistry, and textural characteristics of both the iron formations and the dolerite intrusions. Conventional XRF geochemistry, scanning electron microscopy studies, X-ray diffraction (XRD) were used to analyse the chemistry, mineralogy, and texture. The geochemical studies focused on analysing major elements in both Iron Formations facies and the dolerite intrusions. The trace elements and Rare Earth Elements (REE) were not covered in this study.

1.4 Previous Work

The host rocks of the Assen Iron Ore deposit are contained in the lower portion of the Penge Formation of the Transvaal Supergroup, close to the contact with the underlying dolomite of the Malmani Subgroup. The iron ore deposit is found in the northern margin of Transvaal Basin, ± 60 km south of Thabazimbi mining district and the geological sequence lies within the Crocodile River Inlier. Several genetic models have been proposed by different authors as having been responsible for the formation of high-grade iron ore deposits from the chemical sedimentary rocks, namely, supergene (Wagener, 1921), hydrothermal (Netshiozwi, 2002; Gutzmer et al., 2015; Beukes et al., 2003) and supergene-modified hydrothermal (Van Deventer et al, 1986; Strauss, 1964; Du Preez, 1944) and magmatic model (De Villiers, 1944). This research will attempt to evaluate the possible link between the high-grade hematite and dolerite intrusions, the geochemistry of both the iron ore facies and dolerite intrusions, and the process that lead to the transformation and enrichment of low-grade BIF to high-grade hematite.

1.4.1 The depositional model of the BIF

The genesis of BIF in the Transvaal Supergroup in South Africa and the Dales Gorges Member of the Brockman Iron Formation at Hamersley Group in Australia was studied recently using the Fe and Si isotope composition of coexisting mineral phases by Steinhoefel et al. (2010). Their finding from the samples taken suggests that there was a high concentration of Fe and Si in seawater, ± 6 to 10 ppm ferrous iron (Fe^{+2}) (Klemm, 2000) and these elements precipitated in a steady-state large ocean basin. They also suggested that chert may also be coming from Precambrian marine basins as depicted by heavy Si isotopes and Fe sink containing heavy Fe isotopes might have been pelagic sediments.

Lascelles (2007) came with the model for the origin of BIFs and suggested that hydrothermal fluids enriched with iron and silica inflow into the oceans as black smokers to mid-ocean ridges and continental margins were after cooling and spreading ferrous iron (Fe^{2+}) in solution and hydroxide

(OH⁻) particles, reacts with dissolved silica to form hydrous Al-poor iron-rich silicates ((Fe,Mg)SiO₃), and together with excess iron precipitated as hydrous oxides form mounds around vent chimneys. Bekker et al. (2010) proposed that submarine volcanism was responsible for generating a large amount of ocean and basin-scale anoxia by venting more fluxes of reductants hydrogen (H₂), hydrogen sulfide (H₂S), iron II (Fe⁺²), and manganese III (Mn⁺³) in BIFs formed during Precambrian and Phanerozoic times.

1.4.2 High-grade iron ore genetic models

According to Hagemann et al. (2016), the BIF of 30 to 35 % Fe is enough to result in high-grade hematite and goethite-rich deposits that can contain 55 % Fe and above. In their report, they stated that BIFs may be transformed in the process of interaction with hot fluids circulating and channelled along geological structures such as faults and more permeable, interbedded horizons such as dolomite during deformation. This may remove large volumes of silica, resulting in a concentration of iron. Iron, in the form of microplaty hematite, can also crystallise in structurally controlled sites such as fold hinges and along detachment faults. In the Crocodile Inlier, the intrusion of the Bushveld Complex may have been a driver in providing heat to circulating fluids within the Transvaal Supergroup.

1.4.2.1 Supergene enrichment

Fluids responsible for the formation of high-grade BIF-hosted iron ore are classified into 1. Silica undersaturated alkaline fluids for dissolving chert from BIF and to form metasomatic carbonate and 2. oxidized fluids that result in the oxidation of magnetite to hematite (Hagemann et al., 2016). The two processes that lead to the formation of supergene mimetic and supergene lateritic iron ore deposits were defined by (Ramanaidou and Morris, 2015). To differentiate the two, Ramanaidou and Morris (2015) stated that the supergene mimetic process happens where goethite pseudomorphs, the primary gangue minerals conserving all the original BIF textures and supergene lateritic process disbands the BIF constituents in a destructive and subtractive process that removes the gangue and reprecipitates the iron mostly as aluminous goethite and hematite with original BIF textures lost.

According to Smith et al. (2016), supergene iron ore deposit occurs because of chert leaching from the BIF during supergene alteration. A classic example is found in the Transvaal Supergroup in the Northern Cape Province within the Maremane Dome, South Africa. Strauss (1964) suggested that metasomatic alteration of BIF was followed by supergene processes which resulted in the formation of the iron-rich deposits (Fig. 1). An earlier study by Van Deventer (1985) suggested that the ores reflect initial chemical sedimentation, followed by metamorphism and supergene enrichment of the iron content of the ores. If there is an association of the alteration of the Penge Formation with the placement of the underlying Bushveld Igneous Complex, this has not been established. The orebodies are intruded by dolerite sills like those identified at Assen.

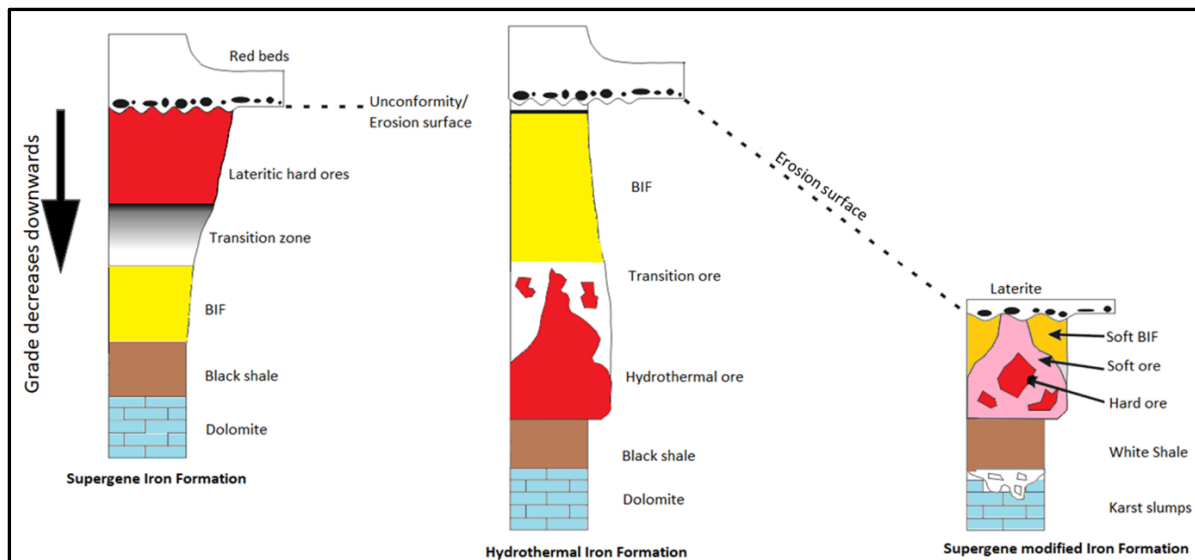


Figure 1: Classification of major types of high-grade hematite ore deposits and their model of enrichment (Beukes et al., 2002).

1.4.2.2 Hydrothermal processes

The Thabazimbi Iron ore deposit at the Penge Iron Formation in South Africa is known to be a hydrothermally enriched BIF-hosted iron ore. The orebody originated from the interaction between BIF with a hydrothermal fluid of meteoric origin at temperatures of not more than 160°C to 200°C (Netshiozwi, 2002). Cooling of hydrothermal fluid is thought to have resulted in the formation of hematite, as the process does not require higher oxygen fugacity compared to magnetite formation. Ore formed from silica leaching from chert, dissolution, and recrystallisation of ferrous iron minerals like siderite, ankerite, and iron silicates into microplaty hematite, magnetite, and martite (Beukes et al., 2003). Netshiozwi (2002) concluded that the high-grade hematite mineralisation is due to hydrothermal processes as verified by ore petrography, fluid alteration, fluid composition, and stable isotope geochemistry. The hydrothermal alteration zonation, high and low temperature, and salinity of fluid inclusions in hematite analysed samples in some major iron ore deposits around the world implies that fluid channelled through geological structures such as Faults and hydrothermal processes resulted in the alteration and conversion of BIF to high-grade hematite (Hagemann et al., 2007).

Recent studies done by Basson and Koegelenberg (2016) showed that structural control on hydrothermal or hypogene hematite mineralisation at the Penge Iron Formations within the Thabazimbi Iron Ore deposit resulted in the high-grade hematite at 60 % Fe. The study showed that the high-grade hematite mineralisation is mostly limited to sheared detachment zones at the contacts between Malmani dolomite, shale, and BIF (Fig. 1). These detachments acted as a structural control on fluid flow where mineralisation occurs, especially in fold limbs and along the main east-west to east-northeast trending fold and thrust Belt, conjugate shear joints, normal and reverse faults, and thrusts. Dolerite sills and dykes also intrude and crosscut the iron formations at Assen Iron Ore mine. Stratigraphically controlled hematite occurs along dolerite dykes and sills and along black shale in Penge Iron Formation where the Assen Iron Ore deposit is located and in the Hamersley Province (Taylor et al., 2001). Iron, in the form of microplaty hematite, can also crystallize

in structurally controlled sites such as fold hinges and along detachment faults. In the Crocodile Inlier where the Assen Iron Ore is located, the intrusion of the Bushveld Complex may have been a driver in providing heat to circulating fluids within the Transvaal Supergroup (Netshiozwi, 2002).

1.4.2.3 Supergene-modified hydrothermal

Supergene modifications make the size and quality of the iron orebodies to be large, but not important as compared to the hydrothermal ore-forming process (Gutzmer et al., 2015). According to Beukes et al. (2003), magnetite and carbonate mineralisation resulted at the initial stage of iron ore deposits where the alkaline hydrothermal fluid carried Ca^{++} and Mg^{++} . This environment resulted in the leaching of silica. High-grade hematite of Penge Formation owes their origin to a Late Paleoproterozoic event of extensive oxidative carbonate metasomatism and Gutzmer et al. (2015) described its genetic as the process of calcification where ferrous iron in BIF oxidised and residually enriched. Hydrothermal fluids are transported along steep, parallel bedding, and fault structures. Alteration effective where basal shale was in direct contact with microbanded carbonate-magnetite iron formation. This chert-poor but carbonate-rich iron formation facies was very conducive to chemical corrosion and enrichment hard, high-grade martite and martite-microplaty hematite ore formed in close association with low-grade carbonate-rich ore in this process.

1.4.2.4 Magmatic model

Although outdated, a study by De Villiers (1944) regarding the Thabazimbi iron ore deposit genetic model did not agree with the theory that the iron was leached out of the BIFs or in any association with the underlying dolomite. He concluded that the Iron ore deposit is of magmatic origin and connected genetically with the Bushveld Igneous Complex granite intrusion and the deposition of high-grade hematite took place when ascending Fe-rich magmatic waters mixed with oxygenated meteoric water. The evidence brought forward was the presence of high-temperature manganese minerals and the chemical properties of the mineralizing solutions. Studies on the hydrothermal controls on iron and lead mineralisation on the northern side of Thabazimbi Iron ore district by Möller et al. (2014) showed that high salinity NaCl-CaCl_2 -rich brines occurrence showed that the fluids originated from deep-buried sedimentary sequence where fluids interacted with host rocks and further reacted with the carbonate wall rocks during iron and lead deposition. This ruled out the magmatic fluid influx model due to low temperatures, the absence of boiling assemblages, the absence of crystals, and the stable isotope signatures of the fluids.

The high-grade deposit model of ore formation remained not well understood and unclear due to the overprinting that happened as a supergene modification and alteration. The influence of dolerite dykes and sills on iron ore mineralisation and their local relationships to the distribution of iron ores needs further investigation. It looks like where some dykes and sills are in contact with the ore, the iron ore grades increase.

1.4.2.5 Importance and benefits of the study

Evaluating the geologic, geochemical, and spatial relationship between the dolerite intrusions and the high-grade iron ore and the effects of dolerite intrusions on iron ore grade will give guidance in the exploration of new iron ore deposits. According to Netshiozwi (2002), the dolerite dykes and sills crisscross the Penge iron formation BIF. The phenomenon where dolerites crisscross the BIF occurred also at Crocodile River Inlier where the Assen Iron Ore deposit is located.

The genetic relationship between the dolerite intrusions and the high-grade iron ore will help in reviewing the epigenetic ore-forming processes and some genetic models of the high-grade BIF-hosted ores of the Transvaal Supergroup. The relationship between the two will require a different exploration strategy to get the new and undiscovered iron ore reserves. Detailed mineralogical and ore genesis studies of different iron ores coupled by X-ray diffraction, scanning electron microscopy energy dispersive spectroscopy are critical in developing, processing, and beneficiation mechanisms to get the desired iron ore product qualities.

1.5 Statement of the Problem

The research done by Netshiozwi (2002) and Chisonga (2012) on Penge Iron Formation from Thabazimbi district and Taylor et al. (2001) at Hammersley iron ore province in Australia detailed well the dolerite intrusions association with the hematite, the origin of based on the petrographic analysis, fluid inclusion and stable isotope geochemistry studies. Further studies characterised the high-grade hematite are associated with shale, normal faults, and folds (Mukhopadhyay et al., 2008; Gutzmer et al. 2008). While Hartzer (1987), Hartzer (1989), and Hartzer (1995) documented well the geology and tectonic deformation of Crocodile River Inlier where Assen Iron Ore deposit occurs. Although the literature on petrogenesis and geochemistry of the major iron ore deposits in South Africa are well known, there is no published information on the genetic relationship and geochemistry of iron ore facies and dolerite intrusions found in Crocodile River Fragment.

Despite genetic models proposed to have resulted in the formation of high-grade iron ore deposits around the world, the processes of high-grade mineralisation vary from deposit to deposit and at the Assen Iron Ore mine, the processes of enrichment are not clearly understood.

1.6 Project Methodology

1.6.1 Detailed geological mapping

Geological mapping of the Assen Iron Ore deposit covering the farms Assen 140 JQ, Assen 161 JQ, Buffelspoort 149 JQ, Doornkloof 141 JQ, and Swarthoek 10 JQ was undertaken as part of this study. All lithological contacts, strikes, and dips of different rock types and all geological structures within the area were mapped. Diamond drilling was done within the farms to correlate different lithological units and geological structures within the study area. Parallel traverse lines that pass through the west, middle and east orebody were done, and geological observations were plotted and extrapolated within the mining pit. Detailed 3D geological and structural models of the study area were produced to establish any relationship between dolerite intrusions and hematite ore.

1.6.2 Chemical analysis using X-ray fluorescence

The existing geological database from diamond drilling core data and some selected reverse circulation (RC) was accessed to retrieve chemical assets. A total of 206 holes have already been drilled within the middle, east, and west orebody. A total of 196 holes are diamond holes with cores that have already been logged. A total of 12 holes are RC drilled holes analysed from the Anglo research laboratory and South African Bureau of Standards (SABS) lab. XRF analyses have been done for the following major elements: SiO_2 , Al_2O_3 , Fe, Fe_2O_3 , TiO_2 , CaO, MgO, K_2O , MnO, P, S. These analyses were used to create the Fe assay model at the Assen Iron Ore deposit and to determine spatial iron and associated major elements distribution on pristine ore and proximal to the dolerite intrusions.

1.6.3 Quantitative X-ray powder diffraction analysis

A total of Twenty-four representative samples were sampled from both west, middle, and east orebodies from the mine pits and trenches for both XRF and XRD analysis. The samples were four BIF, six dolerite samples, four laminated hematite, six massive hematite, and four calcitic hematite samples. Samples of hard massive and laminated hematite, BIF, calcitic hematite, and dolerite intrusions were collected from different freshly exposed pits, trenches, and outcrops to understand their mineral composition and association.

1.6.4 Reflected light microscopic study.

A different type of BIF and high-grade hematite (hard bluish-grey massive hematite, laminated hematite, friable goethite rich hematite, calcitic hematite) and dolerite intrusion were sampled from the pits, trenches, and exposed outcrops and sent for petrographic thin sections. They were studied under the reflected light in the optical microscope to identify the different types of minerals and paragenesis of different iron ore facies, their crystal shapes, and mineral associations.

1.7 Research structure

The research report has six chapters. Chapter 1 is the introductory chapter and gives the context that gives rise to the study, the main aim, and objectives of the research. Chapter 2 describes the different types of iron ores and their classification, regional geology of Kaapvaal Craton and Transvaal Supergroup, and local geology of Penge Iron Formation. Chapter 3 detailed geological and structural mapping of the Assen Iron Ore deposit. Chapter 4 covers methods, steps, and analytical techniques applied in the petrographic study of different iron ore facies and dolerite intrusions and their mineralogy. It also presents the geochemical results. Chapter 5 contains the findings and analysis of the results from the techniques applied. Chapter 6 discusses the effects of dolerite intrusions on ore mineralisation, the geologic and geochemical character of the iron ore, and the concluding remarks of this study.

CHAPTER 2

2. Literature review

2.1. Iron ore deposits and their classification schemes

2.1.1. Iron ore deposits

Iron ore has been mined for many years from igneous, metamorphic, and sedimentary rocks. The most important sedimentary hosted iron ore deposits include the Precambrian BIFs. The Precambrian BIFs occur as an alternating layering of iron and chert or quartz, black bands and clay band ore, bog iron ores, and laterites (Mohanta, 2007). Sedimentary-hosted deposits dominated by hematite or magnetite bedded in metamorphosed sedimentary BIF account for most of the current world production and resources of high-grade iron ore (Clout and Simonson, 2005). Other iron ore deposits that contribute 10 % of the current iron ore produced worldwide include magmatic magnetitic ore type, volcanic-hosted type, skarns type, hydrothermal type whereas in some other deposits, iron is produced as a bi-product (Yiming et al., 2014).

Currently, the Precambrian metamorphosed sedimentary hosted iron deposits (BIF) are the world's major source of hematite and main contributors in terms of production at approximately 90 %. The BIF on its own is not economically viable due to low % Fe (20–35 %) and high SiO₂ (40–50 %) (Trendall and Blockley, 1970) as compared to the hematite that they host (52–67 % Fe). The BIF-hosted hematite reserves are at approximately 60 % and constitute 70 % of high-grade ore ranging from 52–67 %. This type of sedimentary hosted deposit is hosted by chemical sedimentary iron-rich rocks. They have deposited in Precambrian time at 3.8 to 2.5 Ga where it reaches a peak and ceased at 1.8 Ga (Fig. 2). The process continued again from 0.8 to 0.6 Ga (Klein, 2005). Examples of these types of deposits include the Thabazimbi and Sishen iron ore districts in South Africa, the Quadrilatero Ferrifero district and Carajas in Brazil, Hamersley iron ore province in Australia, Kursk deposit in Russia, Central Province of India, and Anshan-Benxi in China (Yiming et al., 2014).

Iron ore products are classified into four types; namely: 1. High-grade direct shipping ores that requires only crushing and grinding and then feed to blast furnace with grades ranging in % Fe from 55–65 %. 2. Concentrates magnetite ores with 30 % Fe that have undergone a process of crushing, grinding, and magnetic separation which upgrades the ore to > 60 % Fe. 3. Pellets where the fines resulting from the concentration process or ground ore are agglomerated, mixed with a bentonite binder, and burnt in a grate-kiln 4. Sinter, an agglomerated product formed by firing iron ore fines and coke plus limestone to produce as a furnace feed. Three sizes of the iron ore products are Lump ranging in size from 6.3–31.7 mm and is directly fed to blast furnace, the fine product sinter ranging from 0.15–6.3 mm and agglomeration by sintering to be fed in blast furnaces and the third one is the Pellets which are < 0.15 mm in size formed by agglomeration and pelletising to be fed to blast furnace.

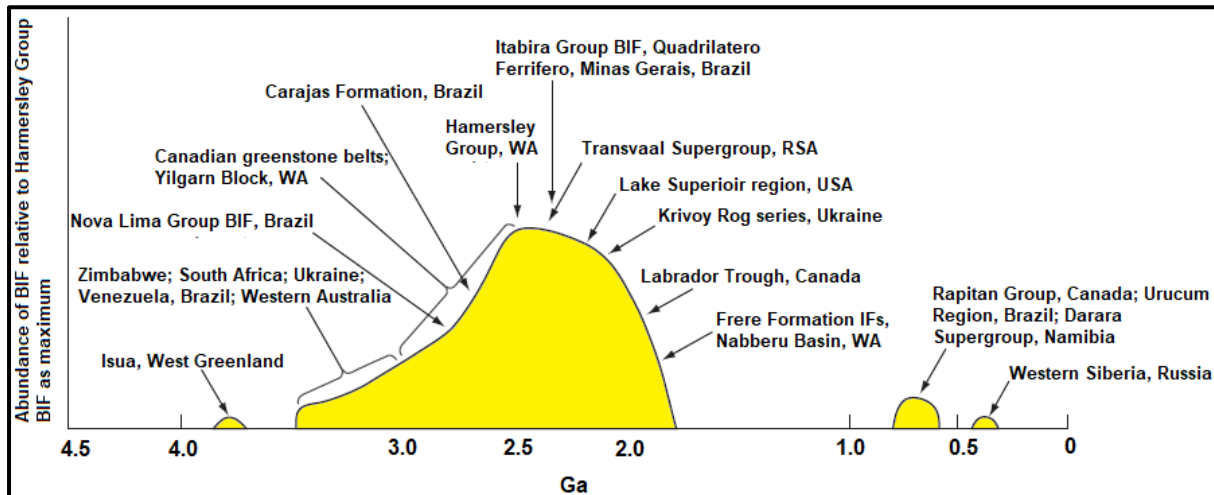


Figure 2: Distribution of the abundance of Iron Formations through time (After Klein, 2005).

2.1.2. Classification of iron ore deposits

This study is focused on Iron Formation-hosted iron ore deposits. The classification of iron ore deposits evolved over time as more and more studies were done. One of the earliest classifications was done for North American iron ore deposits by Gross (1980) and Gross et al. (1983) where they classified them into the Lake Superior type, the Algoma Iron Formation, and Rapitan Iron Formation. Hagemann et al. (2016) simplified this classification of Iron Formations and noted that the classification is dependent on their textural characteristics and depositional time and geotectonic settings of the host Iron formation; namely, BIFs, Granular Iron Formation (GIF), and Rapitan Iron Formation (RIF) (Gutzmer and Beukes, 2009). High-grade iron ore deposits are also classified according to the genetic model, depositional settings, their textural characteristic, geochemistry, and mineralogy with varying grades and physical characteristics (James, 1992; Netshiozwi, 2002; Smith and Beukes, 2016; Beukes et al., 2003).

Iron formations are divided into two groups of textures which are BIFs which occurred mostly between Archean and earliest Paleoproterozoic time and Granular Iron Formation (GIF) that occurred later in Paleoproterozoic successions (Trendall, 2002). Based on the depositional environments and associated rock types, BIF is further subdivided into two types: Lake Superior and the Algoma Iron Formations (Hagemann et al., 2016). The Lake Superior type is unmetamorphosed and undeformed (Lascelles, 2007) and is stratigraphically associated and interlayered with quartzite, dolomite, and black shales in near shore continental shelf environments (Hagemann et al., 2016). The Hamersley-type BIF host the world's largest known iron ore deposit. An example of this type of Iron Formation in South Africa is found in the Neoarchean to Paleoproterozoic Transvaal Supergroup which hosts approximately 2.5 Ga Asbesheuwels and Penge Iron Formations (Smith, 2018). The Algoma Iron Formations are highly deformed and metamorphosed (Lascelles, 2007) and in South Africa are hosted by Meso- to Neoarchean granite-greenstone belts (Smith, 2018). Their deposition is associated with greywacke and volcanic rocks in deep-seated faults and fractures, rift zones, and volcanic arcs and may also be formed by exhalative hydrothermal processes (Gross, 1980).

The Granular Iron Formations which were deposited between 1.8 and 2.1 Ga are characterised by coarse layering and granules of chert and iron oxides. Clout and Simonson (2005) noted three primary textural components in Granular Iron Formations which are a framework of clasts, fine-grained matrix, and cement of minerals filling interstitial voids. Rapitan Iron Formations are limited to Neoproterozoic geologic time between 0.715 to 0.58 Ga. In Southern Africa, this type of Iron Formation is found in the Gariep Belt of the Northern Cape Province in South Africa, southern Namibia, and Damara and Otavi Belts of northern Namibia (Smith, 2018). These deposits are believed to have been deposited during the global Sturtian glaciation and are associated with glaciogenic sedimentary successions (Hagemann et al., 2016). The iron enrichment was due to either supergene or hydrothermal processes that leached SiO_2 and oxidised all Fe-bearing minerals.

Beukes et al. (2003) studied different BIF-hosted deposits around the world which include Sishen-Beeshoek and Thabazimbi iron ore deposits in South Africa, Quadrilatero Ferrifero and Carajas deposits in Brazil, Noamundi and Dalli-Rajhara Iron ore in India, and Hamersley iron ore deposits in Australia. From their studies, they classified the deposits into three genetic models which are supergene, hydrothermal, and supergene-modified hydrothermal deposits. They stated that in supergene iron ore deposits, mineralisation decreases from top to bottom into unmineralised BIF and this is represented by the Asbesheuwels Subgroup-hosted deposits at Sishen, Khumani, Beeshoek, and Kolomela in the Northern Cape Province of South Africa (Smith, 2018). Hydrothermal deposits increase the grade from bottom to top into low-grade BIF and an example is the Penge Iron Formations-hosted deposit at Thabazimbi in the Limpopo Province of South Africa. The Quadrilatero Ferrifero and Carajas deposits in Brazil have bulk friable saprolitic ores that originated from supergene enrichment of earlier hydrothermally and altered hematite and they are a representation of supergene-modified hydrothermal deposit (Beukes et al., 2003).

According to Clout and Simonson (2005), for high-grade hematite deposits to form, there must be an iron-rich BIF with sufficient composition, right textures, and structural architecture such as faults. The major and minor faults must be coupled with regional deformation to permit the fluid flow. The enrichment to high-grade hematite from BIF is controlled by the geological structures that channel the upward and downward fluid flow through the structures and hypogene alteration leading to the deposition and precipitation of various iron ore types. The enrichment process starts with the leaching of silica to form magnetite and carbonate, then followed by the oxidation of magnetite to form hematite (Fig. 3) and further dissolving gangue chert, quartz, and iron silicates to form martite, microplaty hematite, specular hematite, and carbonate (Hagemann et al., 2016). Although the physical characteristics of iron ore vary considerably from deposit to deposit, Netshiozwi (2002) studied the mineralogical and physical characteristics of Thabazimbi Iron ore deposit and classified iron ores into three types which are hard hematite ore, carbonate ore, and supergene modified ores. Like Assen Iron Ore deposit, carbonate hematite occurs at the bottom of the Iron Formations and increases the grade to the overlying massive hematite and supergene ore formed closer to the surface.

Ramanaidou and Wells (2014) classified the BIF-hosted iron ores into two main types which are the bedded iron deposits and detrital iron ore deposits. They noted that bedded iron deposits are strata-bound iron ore deposits. The detrital iron deposits formed due to weathering, erosion, and deposition on the valley or foot of the mountain. Bedded iron ore deposits are further subdivided

into three classes: unenriched primary Iron Formation (30 to 45 % Fe), residual iron ore (56-63 % Fe), martite-goethite ores (56-63 % Fe), and hard hematite ores (60-68 % Fe) which include martite and microplaty (Beukes et al., 2002; Clout and Simonson, 2005). The low-grade iron ore mining in China is an example of unenriched primary iron formation and includes both magnetite and hematite-rich Iron Formation. Iron minerals in unenriched primary iron formations vary in composition and mineralogy representing sedimentary variations through geologic time.

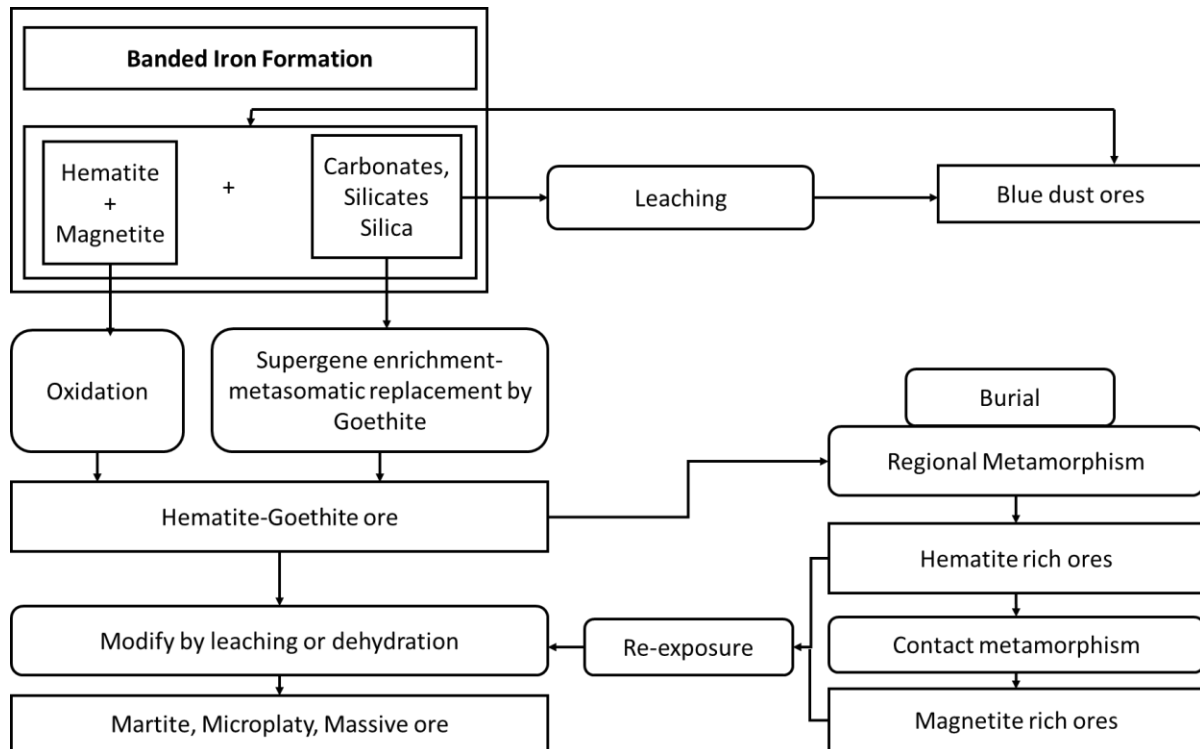


Figure 3: The genetic model for the major BIF-hosted iron ores of the world showing the transformation from BIF to different iron ore types (modified from Morris, 1998).

The residual iron ore form because of supergene weathering of BIF (Smith, 2018) that result in iron upgrading and generating high quality by dissolving the unstable minerals or gangue by lateritic alteration mostly by groundwater to give residual concentrates of Fe oxides also known as blue dust ores (Fig. 3) (Morris, 1998) and reprecipitation of secondary iron minerals in the upper part of a formation with the original textures changed. The ore quality ranges from a silica-rich (40 %) friable BIF to a high-grade above 60 % residues of martite (Morris, 1980). Unlike the residual iron ore, the martite-goethite ore is formed by supergene processes, where hydrous iron oxides are upgraded to above 60 % Fe (Clout, 2013) with the ore preserve the original texture of the BIF such as banding and goethite pseudomorphed microtextures (Morris, 1998) remain unchanged and conserved during the process of weathering or metamorphism. The mineral hematite remains unchanged, and the magnetite is oxidised (Fig. 3) to martite, and impurities like chert, silicates, and iron-rich carbonates are replaced or leached out. Al-rich silicate is also leached out and replaced by clay to form shale bands, and phosphorus levels range from around a moderate 0.07 % to an extremely high 0.17 % P.

The hard high-grade hematite which includes martite-hematite and microplaty hematite has greater than 60 % Fe with less than 15 % goethite and originated from hypogene or metamorphic process overprinted by supergene enrichment (Clout, 2013). Hagemann et al. (2016) classified the hematite

and magnetite-based iron ores into microplaty hematite with little or no goethite, martite hematite, martite-goethite, granoblastic hematite, specular hematite, and magnetite into magnetite-martite, magnetite-specular hematite, and magnetite-amphibole. The microplaty hematite is composed of microplates of hematite with variable porosity and hardness (Clout and Simonson, 2005). Primary BIF relationships and enrichment to different high-grade hematite were summarised by Clout and Simonson (2005) as follows chert or carbonate layers are replaced by microplaty hematite to form microplaty hematite ores, magnetite layers by martite hematite, and Al silicate bands by shale or clays. Martite-goethite ore occurs when BIF chert or carbonate layers are replaced by goethite disseminated martite, magnetite layers by martite, and Al silicate by shale. Other types of hematite ores such as itabirite and friable hematite are formed by the leaching of chert or carbonate layers from BIF due to residual accumulation of friable hematite-residual quartz, magnetite, hematite, and Al silicate layers.

Iron ore is also classified in terms of the ore texture of which the main textural types are massive, laminated, brecciated and conglomeratic, and carbonate hematite (Smith and Beukes, 2016). All these petrographic characteristics can be found or associated with all the genetic models discussed above. The laminated ore forms from both supergene and hydrothermal enrichment from microbanded BIF while massive ores are enriched from clastic textured muddy BIF called lutite (Beukes and Gutzmer, 2008b) and the three main textural occurrences are microplaty hematite, patchy hematite, and hematite pseudomorphs of magnetite (Smith and Beukes, 2016).

The detrital iron ore is formed by physical weathering, erosion, and the deposition of colluvial iron ore at the valley or foot of the mountain slopes. It can also be the deposition of scree material in an escarpment or syncline sourced from the iron formation. The top part of detrital iron ore is mostly unsorted detritals which comprise BIF clasts underlain by well sorted and rounded to subrounded detritals which consists of hematite. Detrital iron ore also occurs as unconsolidated or is cemented as a hematite conglomerate with pebbles ranging from coarse to boulder-sized material (Ramanaidou and Wells, 2014).

2.2. Regional Geology

2.2.1. Kaapvaal Craton

The Kaapvaal Craton is the most stable, oldest, and well-preserved Archaean continental crust and covers a larger portion of the northern part of South Africa, Swaziland, and a portion of eastern Botswana (Bumby et al., 2011). The Craton covers an area of 10^6 Km² (Fig. 4) and is surrounded by The Proterozoic Namaqua-Natal Mobile Belt and the Lebombo monocline which form the eastern and southern border, the Kheis overthrust belt form the western boundary while the Mozambique Belt boards the northern side and is also separated from the Zimbabwean Craton by the Limpopo Belt (De Wit et al., 1992). The Kaapvaal Craton is made up of a 3.6–2.6 Ga granite-greenstone basement overlain by 3.1–2.6 Ga Neoarchaean to Palaeoproterozoic volcano-sedimentary cover sequences covering a larger portion of the craton. The Craton evolved between 3.0 and 1.8 Ga resulting in the development of five orderly stratigraphic successions of sedimentary basins which are the Dominion Group, the 3.1–2.8 Ga placer gold-bearing, and the oldest known depository

Witwatersrand (Eriksson et al., 2009), Ventersdorp, Transvaal and Waterberg Supergroup respectively.

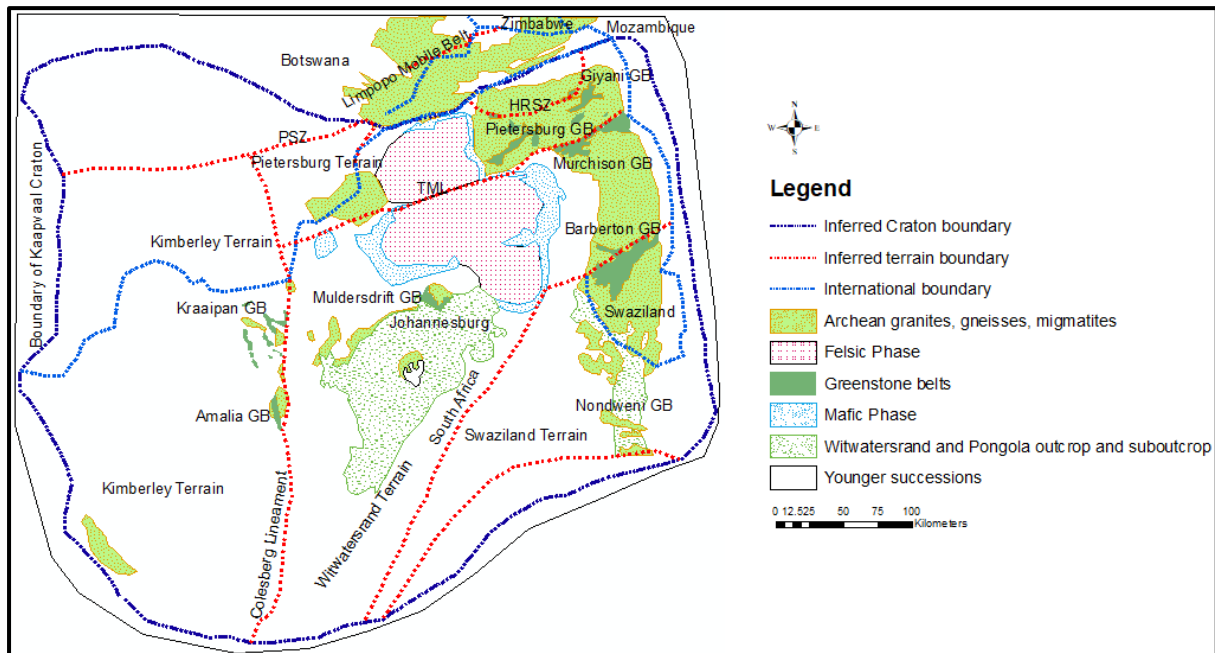


Figure 4: The geological map of the Kaapvaal Craton showing the terrain boundaries and the location of different greenstone belts (From Poujol et al., 2003).

Eglington and Armstrong (2004) showed that the development of new crust occurred in the south-eastern, eastern, northern and the central zone of the Limpopo Mobile belt of the Kaapvaal Craton are connected by granitoid intrusions between 3.25 Ga and 3.1 Ga. The numerous igneous activities along Colesberg lineament and Thabazimbi-Murchison lineament at approximately 3.1 Ga to 2.8 Ga acted as suture zones (Anhaeusser, 2006) where younger domains were accumulated and amalgamated during the formation of the Kaapvaal Craton. By approximately 3 Ga, the lithosphere was stable, allowing the deposition of Dominion, Witwatersrand, and Pongola sedimentary basins. The massive volcanism and granitoid throughout the Craton followed together with the deposition of Ventersdorp. At approximately 2.6 Ga the sedimentation of the overlain Transvaal Supergroup occurred, and the volcano-sedimentary rocks of this basin acted as floor rocks for the Rooiberg felsites which resulted from the massive magnetic event of the Bushveld Igneous Complex (2.06 Ga). the latter was followed by the deposition of sediments comprising the Waterberg and Soutpansberg Groups (Poujol et al., 2002; 2003).

2.2.2. Transvaal Supergroup

The 2.7 Ga to 2.05 Ga Transvaal Supergroup rocks (Eriksson et al., 2005) cover approximately 250 000 km² (Button, 1981) which is exposed and preserved in three separate basins which are the Transvaal basin in the northern side of Kaapvaal Craton, the Griqualand West basin found in the south-western part of the Kaapvaal Craton and Kanye basin in the western part of the Transvaal Supergroup in Botswana (Eriksson et al., 2006). The Transvaal basin and the Griqualand West basin are separated by major basement high, north-northwest trending Vryburg arch (Moore, 2001). The Transvaal succession's thickness is up to 15 km (Button, 1981) of unmetamorphosed volcanic, clastic, and chemical sedimentary rocks (Eriksson and Clendenn, 1990). This Supergroup is underlain by

Witwatersrand and Ventersdorp Supergroup. The Griqualand West basin is further subdivided into Ghaap Plateau and Prieska sub-basins.

Eriksson et al. (2001, 2006) detailed the stratigraphy of the Supergroup and classified it into four stratigraphic units (Fig. 5), from bottom to top: 1. Protobasinal rocks comprise volcanic and immature siliciclastic sedimentary rocks 2. Black Reef Formation of approximately 30-60 m (Eriksson et al., 2011) made of thin and sheet sandstones formation (Eriksson and Reczko, 1995) 3. Chuniespoort Group is less than 2 km thick and composed of a chemical sedimentary succession of dolomites with chert in some areas and limestone of Malmani Subgroup carbonates, Penge Formation BIFs, and shaley Duitschland Formation. 4. Pretoria Group is composed of interbedded mudrocks, quartzite, and sandstones with some basaltic-andesitic lavas (Eriksson et al., 2005).

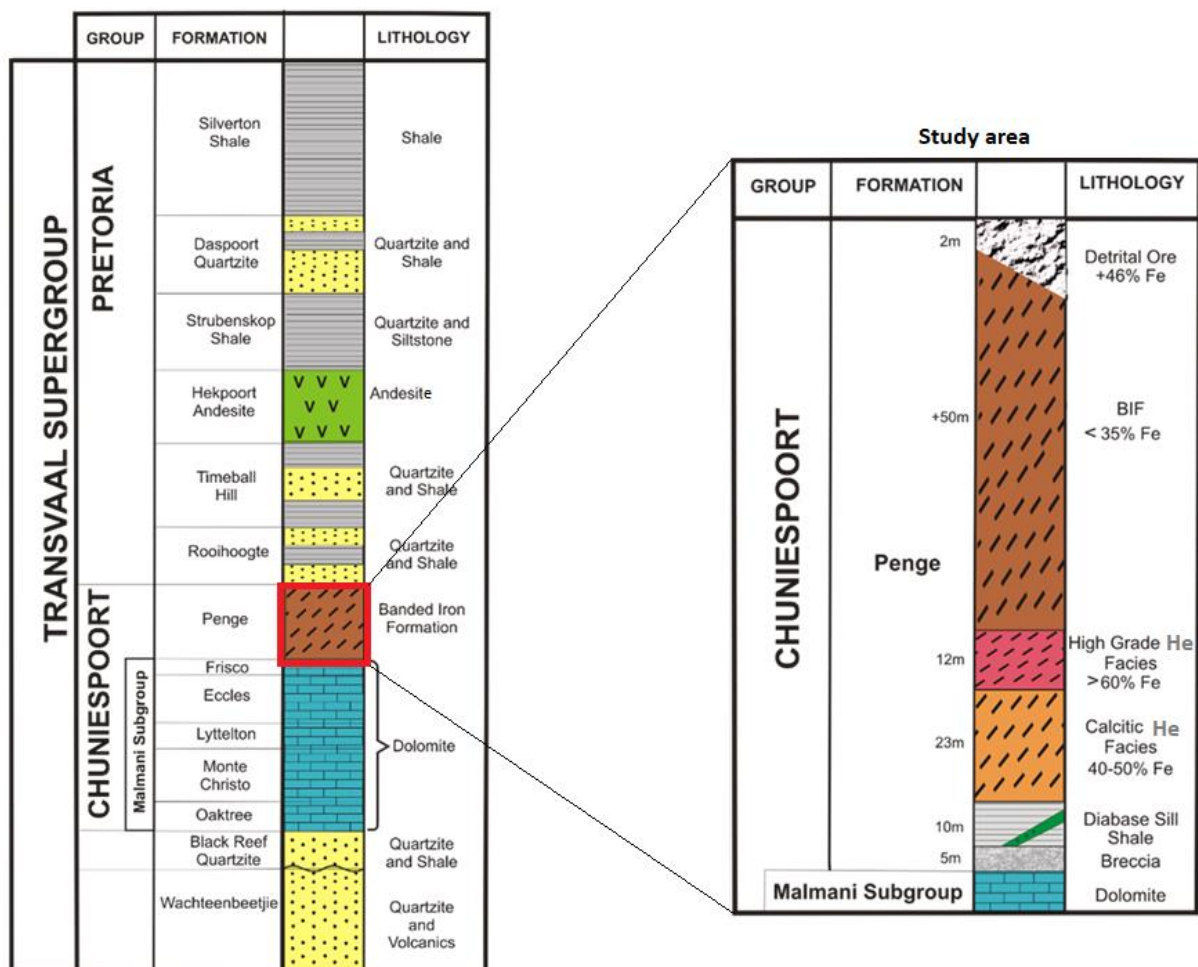


Figure 5: Generalized stratigraphy of the Transvaal Supergroup in the Northwest Province and Crocodile River Inlier Stratigraphy (after Hartzer, 1995).

The number of structural domains has been observed and studied (Button, 1981). In the Transvaal basin five rocks are surrounded by approximately 2.06 Ga intrusive Bushveld Complex and their occurrences are known as the Rooiberg, Crocodile River, Stavoren, Marble Hall, and Dennilton Inliers (Hartzer, 1995). The floor-attached domes and roof pendants-the Crocodile River and Marble Hall-Dennilton inliers are the attached structures that have remained attached to the floor of the Transvaal Basin (Hartzer, 1995). Their deformation pattern reflects regional deformation patterns observed outside of the Bushveld Complex, which were distorted by the emplacement of the

Bushveld Complex, and the Stavoren and Rooiberg fragments which were detached and are underlain by Bushveld Complex granites (Eriksson et al., 2006). Only the Carbonate-BIF succession of the Chuniespoort Group, the Crocodile River Inlier, and the Penge Iron Formation which host the Assen Iron Ore deposit will be discussed in this section:

2.2.2.1. The Crocodile River inlier

The Crocodile River inlier is located at the western part of the preserved Transvaal basin (Hartzer, 1995). The Assen Iron Ore deposit occurs in the Crocodile River Fragment, an inlier of Transvaal Sequence rocks surrounded by younger alkali rocks of the felsic Lebowa Granite Suites of the Bushveld Igneous Complex (Fig. 6). The Bushveld Complex intrudes into the Transvaal Supergroup as bimodal intrusive magmas of mafic and felsic characteristics, with the Magaliesberg Formation of the Pretoria Group forming the floor of the Complex in most areas. The mafic phase of the Bushveld Complex is not in direct contact with the inner inliers, and this is confirmed by geophysical data indicating that the Crocodile River Inlier is not underlain by the Bushveld Complex (Hartzer, 1989). The Crocodile River, Marble Hall, and Dennilton Inliers consist of highly deformed, lower Transvaal strata that were subjected to low-grade metamorphism. The domes were formed by interference folding that was accentuated by the intrusion of the Bushveld Complex. They acted as physical barriers to the emplacement of the mafic rocks of the Bushveld Complex in the centre of the Transvaal Basin. The Crocodile River dome is located at the intersection of two major anticlines with an east-northeast and a northwest striking fold axis, respectively.

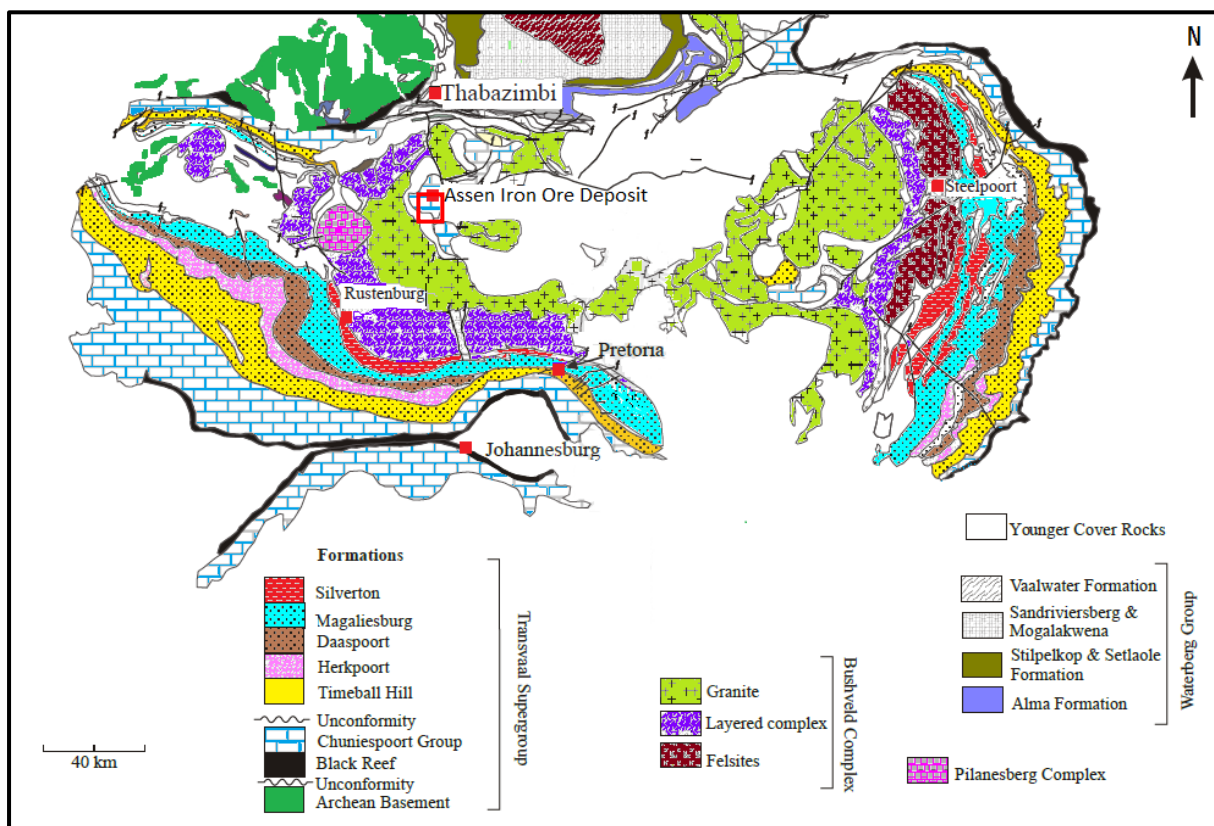


Figure 6: Regional Geological map of the Transvaal basin of the Transvaal Supergroup illustrating the Assen Iron Ore deposit in the Crocodile River Inlier (Modified after Eriksson et al., 2006; Netshiozwi, 2002).

2.2.2.2. Chuniespoort Group

Stratigraphically the Chuniespoort Group consists of the lower Campbellrand-Malmani carbonate succession and the Penge Iron Formation and the upper Deutschland Formation (Eroglu et al., 2015). The Chuniespoort group comprises the chemical sedimentary rocks, are exposed throughout the Transvaal basin, and varies in thickness up to 3500 m (Button, 1981). A similar stratigraphy is found in the Griqualand West basin where these types of rocks occur in Campbell and Griquatown groups.

2.2.2.3. The Malmani Subgroup

The dolomite succession which forms the bottom of the Chuniespoort Group known as Malmani dolomite also occurs in Campbell Group in the Northern Cape. The Malmani dolomite is subdivided into several units depending on physical and chemical properties such as colour, texture, and chemistry of the dolomite and the concentration of chert, shale, and limestone while Grunerite is restricted to the Transvaal basin due to metamorphism caused by intrusive Bushveld Complex (Button, 1981). A basal Malmani Subgroup has five formations (Fig. 5), namely: Oaktree (10–200 m), Monte Cristo (300–500 m), Lyttelton (100–200 m), Eccles (400–600 m), and Frisco (300–400 m) (Catuneanu and Eriksson, 1999). The Malmani dolomites had a gradual transition to the overlying iron-rich facies of the Penge Formation. The thickness of Penge varies from area to area and has a maximum thickness of 2100 m in the Crocodile River Inlier (Eriksson and Reczko, 1995). The Oaktree Formation, which is at the bottom, is a transition zone between the Black Reef Formation clastic sedimentary rocks and the overlying carbonate rocks.

2.2.2.4. Penge Iron Formation

The rocks of the Penge Iron Formation host economic deposits of both hematite, crocidolite, and amosite and are exposed at the contact metamorphic aureole of the Bushveld Complex in the eastern Transvaal basin of the Transvaal Supergroup (Miyano and Beukes, 1997) and its thickness is approximately 640 m in the Transvaal basin and approximately 2000 m in Northern Cape. The same stratigraphic section and correlation occur in the Griquatown Group of the Asbesheuwels and Koegas formations in the Northern Cape (Dulski, 1996).

Penge Iron Formation is highly affected by regional contact metamorphism due to the Bushveld Complex intrusion resulting in magnetite-quartz concentrations in BIF (Dulski, 1996). Hartzler (1989) subdivided the lithofacies of the Penge Formation into four zones and the lithofacies cycle grunerite-microbanded chert→grunerite-magnetite rhythmite→magnetite-grunerite rhythmite with the bottom part of Penge being chert-rich and increases in oxides facies upwards. The BIF depict macro, meso, and micro-BIFs (Button, 1981) interbedded with carbonaceous mudstones. The major minerals are quartz, magnetite, hematite, stilpnomelane, riebeckite, minnesotaite, grunerite, and carbonates minerals of siderite, ankerite, dolomite, and calcite (Beukes, 1973).

Thabazimbi Iron Ore mine is located 60 km to the north-northwest of Assen and has been mining iron ore from the same stratigraphy as that of Assen Iron Ore mine. The base of the Penge Formation comprises sporadic chert-rich shale, $\pm$ 1–2 m thick, which is frequently brecciated due to the karstification of the underlying dolomites. This is succeeded by approximately 350 m of overlying

iron-rich rocks. The iron orebodies occur in the basal 80 m thick iron oxide BIF of the Penge Formation. The ore is defined as having over 60 % Fe and less than 15 % SiO₂. The ore occurs as irregular, tabular bodies over a strike length of 12 km. This directly correlates to the stratigraphy of the Assen Iron Ore deposit. With depth, the orebodies pass laterally into a carbonate-hematite rock which also directly correlates with the calcitic facies found at the Assen Iron Ore mine. This facies is often underlain by a basal shale unit of the Penge Formation which has also been recorded at Assen (Van Deventer et al., 1986).

The calcitic iron ore, in all aspects like that, found at Thabazimbi, is also found on Pylkop 26 JQ ± 20 km from the Assen Iron Ore mine. The ore is situated at the base of the iron formation and is underlain by dolomites. It forms a high hill with a steep dip-slope on its southern margin: strike length is 240 m; the average width is 45 m, and the reserves are estimated at ± 1.5 Mt per 30 m down dip. The ore is finely banded and is composed of alternating layers of hematite and white calcite, with practically no chert (Hammerbeck et al., 1976). No high-grade hematite ore and calcitic ore are present in a prominent ridge of BIF extending eastwards from Doornkloof 141 JQ to Buffelspoort 149 JQ along the common boundary with Assen 140 JQ. A composite sample assayed by Mineral Corporation (2012) contained 42.3 % Fe, 35.2 % CaCO₃, and 3.1 % SiO₂. According to Hartzer (1987), the carbonate rocks in the Crocodile River Inlier contain mineral assemblages of low to medium grade metamorphism with abundant tremolite, occurring in association with talc, calcite, quartz, and dolomite.

2.3. Deposit Geology

2.3.1. Lithostratigraphy

The host rocks to the Assen Iron Ore deposit are contained in the lower portion of the Penge Formation of the Transvaal Supergroup, close to the contact with the underlying Malmani Subgroup dolomite. The geological sequence lies within the Crocodile River Inlier.

The Penge Formation in the Assen area comprises several subdivisions: An upper layer, comprising a more typical siliceous BIF (Fig. 7) with a layering of chert and goethite-hematite, partially metasomatised and containing primary magnetite in unaltered sections. The upper layer appeared visually like amphibolite and contains crocidolite, asbestos, and nontronite mineralisation (Mineral Corporation, 2012). These mineralogical observations render the mineralisation like the talc ore reported at Khumba Iron Ore in Thabazimbi. The calcitic hematite rock is mostly brecciated in appearance and forms prominent outcrops at Assen. This rock type may be a metasomatised product of the magnetite-carbonate BIF. Its mineralogical composition appears to be quite consistent between boreholes. The low-grade hematite facies is typical of a distal facies iron-rich chemical sediment with layers of chert or silica 5–30 mm thick and laminated at millimetre or sub-millimetre scale. This occurrence has been described by Hartzer (1995) as being analogous to Superior-type mineralisation.

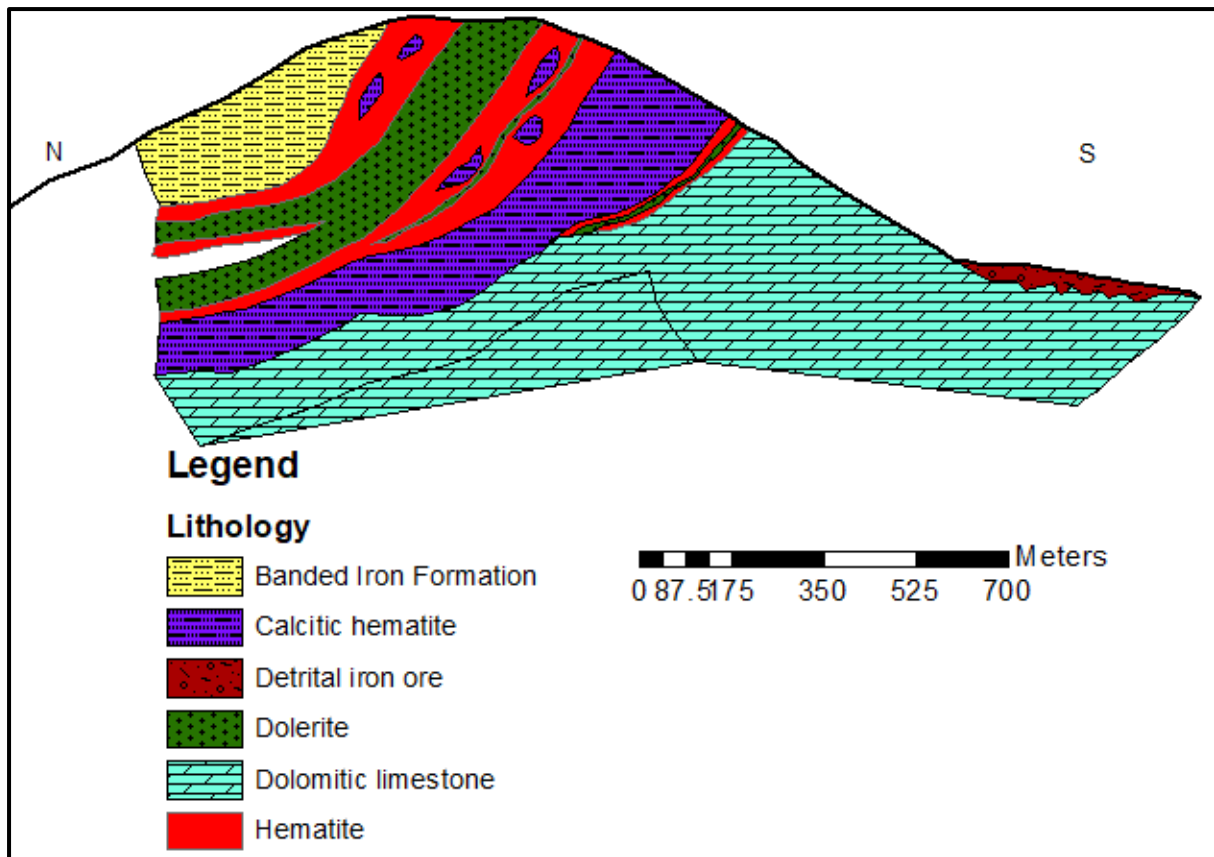


Figure 7: Schematic N-S cross-section through the Assen ridge showing different lithologies (From Kevin, 2015).

Shales from the Penge Iron Formation are ferruginous indicating that shale deposition occurred in iron-rich waters (Dulski, 1996). A poorly exposed basal shale layer consists mainly of chert-rich and BIF lenses with pyroclastic and tuffaceous sections. Fockema (1945) stated that shale overlies dolomitic limestones and mostly thin layers of fine-grained black shale. At the Assen Iron Ore mine, the shale layer becomes amphibole-rich near the basal contact with the Malmani dolomite. Concordant to transgressive intrusives of dolerite composition with altered upper zones have been observed throughout the area in borehole cores and reverse circulation drilling chips.

The dolomite presents itself as an irregularly eroded karst sub-surface floor (Fig. 7) upon which a well-sorted and winnowed detrital hematite bed has been deposited (Kevin, 2013). The Malmani dolomite extends in an undulatory manner two-thirds of the way to the crest of the ridge becoming progressively grainier upwards to sandy marl at the contact with the overlying ironstone formations belonging to the lower portion of the Penge formation of the Transvaal Supergroup. The dolerite dykes and sills crosscut the Iron Formations (Kevin, 2015). Observation in the extraction pits shows intense shear lamination parallel to the dolerite intrusion margins with epidote-amphibolite veining, as well as blister pitting of the hematite in places giving the material a pig iron appearance. Green serpentinite dykes were also encountered within the high-grade hematite zone which contain traces of copper, nickel, lead, zinc mineralisation (Kevin, 2013). According to Fockema (1945), Banded ironstones and shales in the Crocodile River Inlier are intruded by dolerite sills of thickness less than 50 m. The sills are altered to hornblende-plagioclase because of metamorphism.

2.3.2. Mineralisation Style

Three types of iron mineralisation have been observed at the Assen Iron Ore deposit. The high-grade ore of greater than 60 % Fe, the medium grade ore of 50–60 % Fe is hematite rich with varying degrees of goethite oxidation. Massive mineralisation is either laminated (soft and crumbly) or blue-grey (hard and flinty). These mineralisation types of outcrops close to the crust of the hill. The calcitic hematite rock entirely composed of hematite and calcite contains up to 50 % Fe and forms prominent outcrops along the steep southern slope of the crest. A magnetite carbonate rock is observed at depth only and is considered the protore at Assen. There is a notable absence of magnesium content in the deposit.

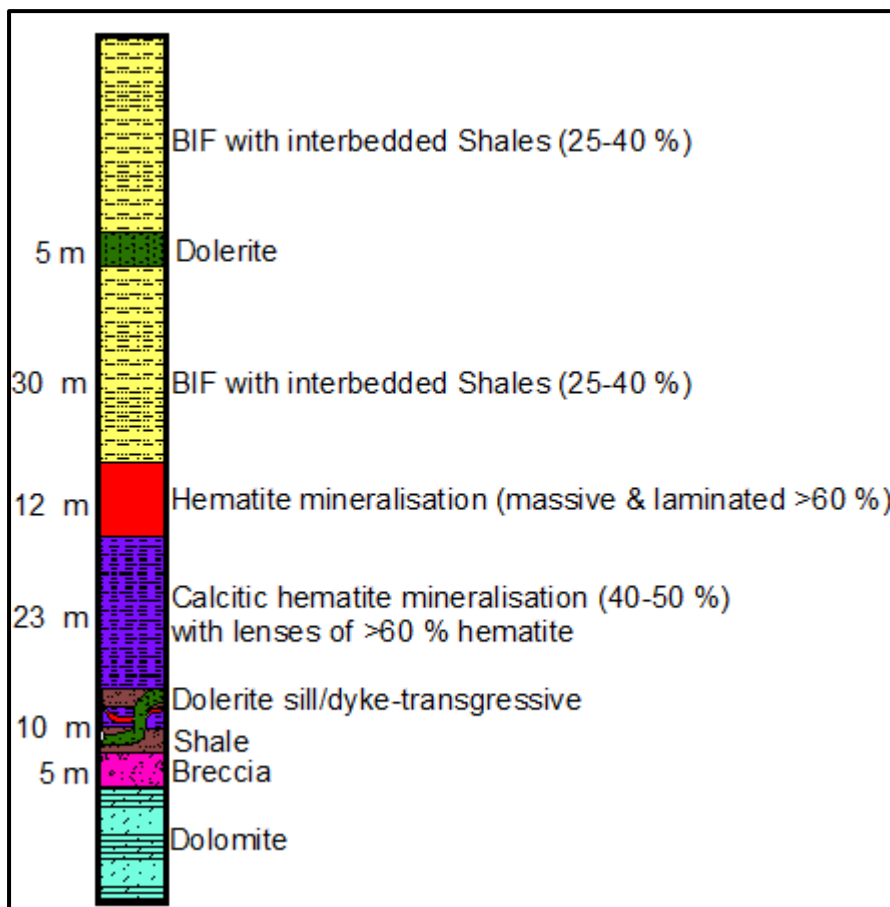


Figure 8: The stratigraphy of Assen Iron Ore deposit showing different lithologies (Mineral Corporation, 2012).

Three distinct mineralisation types occur in the Assen Iron Ore deposit which is strata-bound to the specific host rock types, namely:

1. Magnetite carbonate,
2. High and medium grade hematite ore which is goethite/ hematite rich,
3. The calcitic hematite

In the Mineral Corporation Report (2012), the geological mapping and field observations (Fig. 8) are as follows:

Lying above the high-grade hematite is sedimentary BIF which is goethite or hematite rich and typically grades between 35 to 50 % Fe. This facies is termed by the mine as the low-grade BIF. A

high-grade hematite ore directly overlies the calcitic hematite ore. The mineralisation is either laminated or blue-grey in colour which is very hard and flinty. This facies is referred to as high-grade hematite ore and typically assays of this ore are greater than 60 % Fe. The lower unit of the ironstone formation comprises heavily calcite-banded hematite which is very hard and resistant to weathering (Petzer, 2015). This carbonate rock is the protore at Assen and consists of magnetite, hematite, talc, quartz, calcite, and amphibole and is referred to by the mine as calcitic facies. This zone is generally intruded by dolerite with parallel shearing. According to Hammerbeck et al. (1976), the Crocodile River Fragment which lies south of Thabazimbi has BIF enriched to high-grade hematite ore. On Boschkop 138 JQ three unconnected lenses, 60 to 230 m long and 2.5 to 9 m thick contain ore with 65–68 % Fe. The reserves are between 2 and 4 Mt. The presence of high-grade hematite orebodies on the ridge is more than 30 m thick.

2.3.3. Geological structures

Folding resulted in the stratigraphic sequence to dip at an angle between 40° to 60° northwards and formations strike east-west at the Assen lease area. This forms the southern limb of an east-northeast plunging syncline. The more resistant BIF contained iron mineralisation and form the prominent ridge along the top of the hills. The Transvaal Supergroup on the Assen Lease area is dominated by a large southwest-northeast trending synform (Fig. 9). The entire ironstone unit is folded, flexed along the crest of the ridge (Mineral Corporation, 2012).

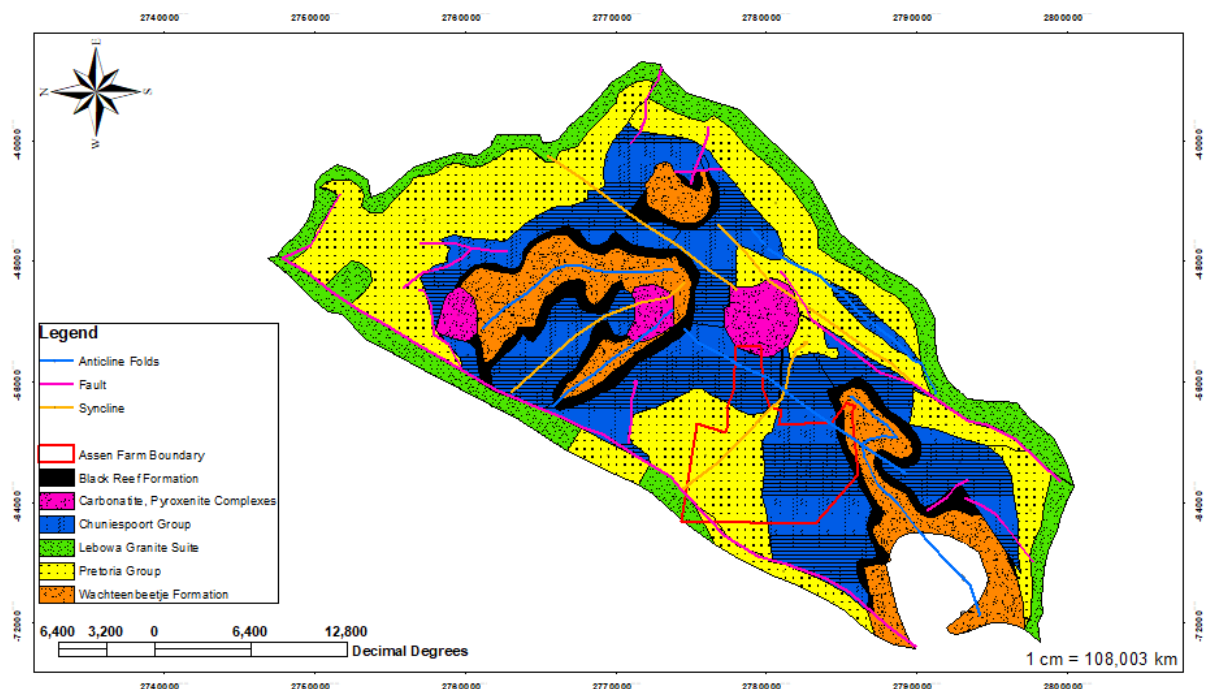


Figure 9: Geology of the Crocodile River Inlier showing the east-northeast trending syncline through the western portion of the Assen Iron Ore mining license - marked in red. (from Hartzer, 1989).

The general geological structures of the Crocodile River Inlier are well documented by Hartzer (1989), Hartzer (1987), and Hartzer (1995) as follows:

The Crocodile River Inlier consists of highly deformed, lower Transvaal strata that were subjected to low-grade metamorphism (Fig 9). The domes were formed by interference folding that was

accentuated by the intrusion of the Bushveld Complex. They acted as physical barriers to the emplacement of the mafic rocks of the Bushveld Complex in the centre of the Transvaal Basin. The Crocodile River dome is located on the intersection of two major anticlines with an east-northeast and a northwest striking fold axis respectively.

A major east-northeast striking syncline dominates the central part of the Crocodile Inlier. This is manifested as an east-northeast striking ridge comprised of the Penge Formation on the Assen Lease area. The metamorphic temperature in the Crocodile Inlier has been estimated by Hartzer (1987) to be in the range 410-510° C (Fig. 9). The carbonate rocks in the Inlier contain mineral assemblages of low- to medium-grade metamorphism with abundant tremolite, occurring in association with talc, calcite, quartz, and dolomite. Hartzer (1989) mapped the two well-known faults (F1 and F2) that are striking south-east and north-west and are marked by breccia, Iron Formation, and dolomite. The faults displaced the Bushveld Complex and Transvaal Supergroup rocks and can be traced to the south as far as Brits Graben. The stratigraphic displacement of the F2 fault is up to 4000 m in the south and the amount of throw on both faults decrease northwards. There are also minor faults associated with the folding and the strike-slip faults in the southern side of the Fragment. The western side of the Fragment is dominated by numerous folds striking to the north-west and the basin-shaped structures caused by refolding. The intrusion of the Nooitgedacht Complex into the Crocodile River Inlier caused thrusting and faulting resulting in the duplication of the Penge Formation.

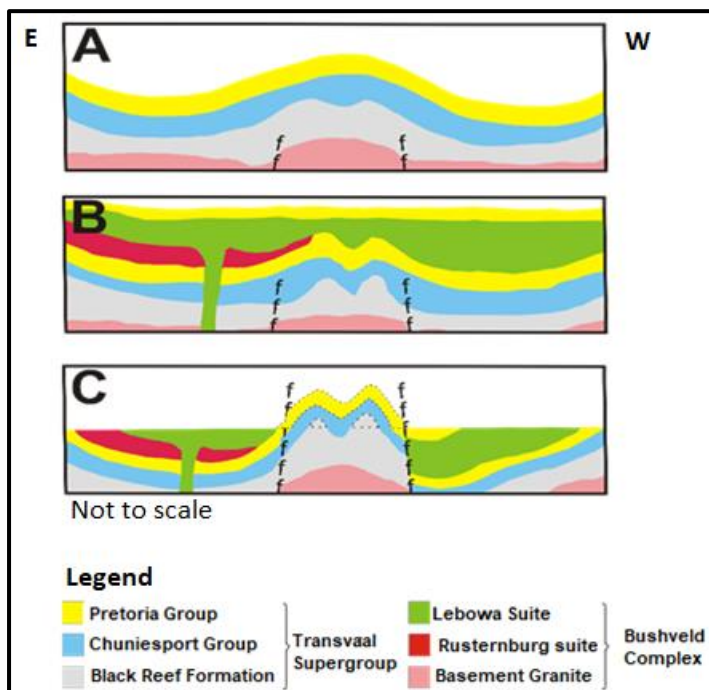


Figure 10: Tectonic development of the Crocodile River Inlier. In (A) shows deposition of the Pretoria Group and folding along pre-existing structural lineaments. In (B) Bushveld Complex intrusion deformed the Inlier. In (C) two major faults caused the Inlier doming against the surrounding rocks (after Hartzer, 1995).

Several models for the tectonic development (Fig. 10) of the inliers have been proposed by various authors ranging from thrusting (De Waal, 1970), xenolithic emplacement, roof pendants (Verwoerd, 1963) by the process of cone-fracturing, and even as points of impact from extraterrestrial bodies. The rocks of the Penge Iron Formation have been plastically deformed, partially metamorphosed,

metasomatised, and recrystallised due to the proximity to the Bushveld Complex which surrounds the Inlier. This has altered the original mineralogy, geochemistry, and visual appearance of the rocks. Hartzler (1989) stated that the three stages of folding and major faulting trending north-west to south-east caused the complexity in Penge Formations. He recorded that the first stage of folds (F1-folds) has an axial trend and varies from the northeast in the northern side of the inlier to the northwest in the southern portion of the inlier. The refolding of F1 folds occurred along the axis (F2-folds) and striking east-northeast and resulted in the major syncline in the eastern-central part of the fragment. Stage three of folding (F3-folds) is represented by north-west to south-east folds in the western part of the inlier and is depicted by major anticline in the south.

2.4. Iron ore and gangue mineralogy

The three most common iron ore minerals are magnetite (Fe_3O_4), hematite (Fe_2O_3), and goethite (FeOOH). Magnetite which occurs as fine to coarse-grained euhedral crystals is from the sedimentary and magmatic origin, hematite resulting from oxidation of magnetite in the near-surface environment. The brown and yellow goethite is iron oxyhydroxide and the most common iron ore mineral in altered metasedimentary near-surface iron ore deposits. Other Iron ore minerals include Maghemite, Kenomagnetite, Martite, Hydrohematite (Bekker et al., 2014).

The most common gangue mineral in an unweathered iron ore deposit is chert and crystalline quartz in metamorphosed deposits (Bekker et al., 2014). The silicate minerals are minnesotaite and stilpnomelane while kaolinite and gibbsite dominate altered supergene and surficial iron ore deposits. Other silicate impurities include amphiboles and chlorites. Carbonates facies are dominated by siderite, ankerite, calcite, and dolomite dominates, sulphides facies gangue minerals include pyrite, and in oxides facies is pyrolusite.

According to Ramanaidou and Wells (2014), the high-grade iron ores required by steel industries should have above 55 % Fe, 5 % or less of SiO_2 and Al_2O_3 , and less than 0.075 % P with no chlorine and sulphur. Phosphorus is one of the most ruinous impurities in iron ore as it forms iron phosphides in blast furnaces that cause steel to be brittle. A high concentration of phosphorus has a negative impact on the price of iron in the steel industry (Smith, 2018) and the acceptable % is less than 0.08 wt % P on the iron feed. Ore that forms because of supergene metasomatic enrichment of BIF like goethite ore mostly has high levels of phosphorus, Silica, and aluminium and it is difficult to separate it during ore processing discarding valuable ore (Pownceby et al., 2019).

The mineralogy of the Precambrian Iron Formations varies depending on three metamorphic grades which are diagenetic to very low, medium-grade, and high-grade metamorphism. Regional metamorphic grade plays a major role and an increase in metamorphic grade causes the mineralogical changes because of high temperature and burial pressure. High temperature is associated with minerals such as amphiboles, almandine, pyroxene, and olivine (Ramanaidou and Wells, 2014). The mineralogy of Iron Formations is mostly dominated by silica (SiO_2) and various Fe-rich and Al-poor minerals. The magnetite or hematite forms an alternating band of several millimetres with silica microcrystalline bands (Bekker et al., 2014).

There are four lithological Iron facies based on the dominant iron mineral present (James, 1992): silicate, carbonate, oxide, and sulphide. Oxide facies is the most dominant, largest, most economic BIF facies (Lascelles, 2007) and comprises magnetite subfacies or hematite subfacies. The carbonate facies consist of siderite or ankerite with minor silicate mesobands and minor oxide laminae. The silicate facies Iron Formation is mostly dependent on the degree of metamorphism where low-grade metamorphism is associated with minerals like biotite, greenalite, minnesotaite, stilpnomelane, chamosite, ripidolite, riebeckite, and ferri-annite and high-grade metamorphism minerals are cummingtonite, grunerite, pyroxene, garnet, and fayalite. Sulphide facies are pyritic carbonaceous shales or slates resulting from seafloor hydrothermal, iron-rich exhalites, and sulfidic cherts (Bekker et al., 2014).

CHAPTER 3

3. Samples and methodology

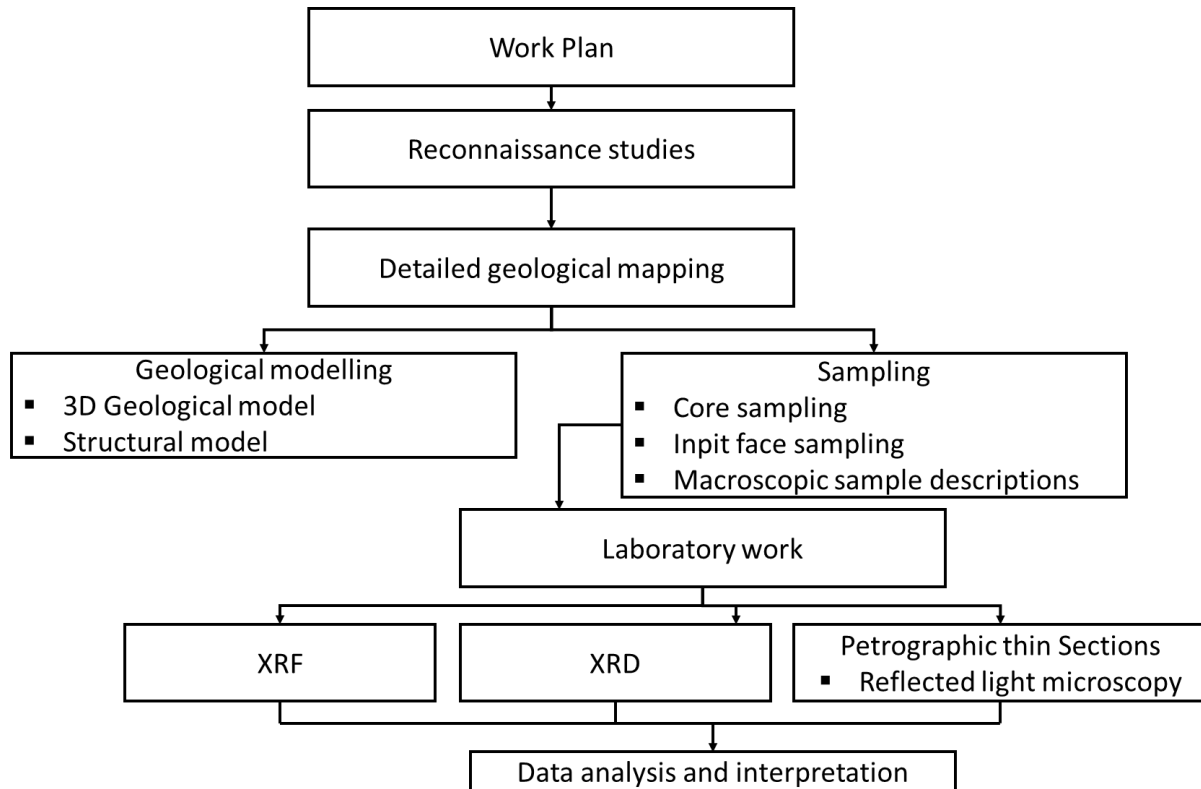


Figure 11: The methods and procedures followed in conducting the studies.

Figure 11 above summarises the work done which involved the geological mapping fieldwork and sampling, the petrographic analysis and geochemical techniques used in the study. The final product was to produce a 3D geological, 3D structural model from drilled boreholes. The geochemical and petrographic studies were done to give field relationship between dolerite intrusions and hematite ore and to determine the Fe and associated major elements distribution on pristine ore and proximal to the dolerite intrusions; and to understand their composition, association, and paragenesis.

3.1. Sample descriptions

Five sampling positions were selected in three different pits comprising 24 samples which were sampled in the current operating and old pit for different iron ore facies and dolerite intrusions perpendicular to the stratigraphic section. The samples were collected in a profile where the full stratigraphy from bottom to top is exposed and includes shale, dolerite, calcitic hematite, high-grade hematite, and BIF. The samples were packaged and sent to XRD – Analytical & Consulting for the identification of different minerals and their volume percentages. The analysis and quantification were done by Dr. Sabine Verryn of XRD – Analytical & Consulting. Major and minor elements were analysed using XRF. The high-grade iron ore samples collected include BIF, massive, laminated, and

calcitic ores. These rock types occur at the bottom portion of Penge formation in the Chuniespoort of the Transvaal Supergroup.

The database available for the Assen Iron Ore mine comprises the diamond, reverse circulation, and percussion drilling data. Overall, the database includes 200 holes and 8 474 drill core and chip samples. Boreholes used in this study have been checked and cross-referenced for validity in terms of x, y, and z coordinates, lithological logging, assays, 'to's and from's, and QAQC. This data has been entered into a CSV file and imported from Assen 2019 access database which was then imported to Leapfrog 6.0 software in which the geological model was created using wire-framing.

The following field sampling procedure was followed: Ca. 40 kg sample was taken at 1 m interval at the face or drilling chips. A riffler 25/75 was used to split the sample, 25 % was taken while 75 % of the sample was reserved as a backup. After each completion of a meter, a splinter was cleaned by a steel brush. A 25 % sample obtained from 25/75 riffler was further split by 50/50 riffler to obtain two samples for field and laboratory analysis while the rest was stored. The Sample bag was identified according to borehole number and meter number. After splitting each meter, the sample bag was closed (stapled) to avoid external contamination. Another sample for geological logging was taken from the reject portion by screening out the coarser fraction. The chips were cleaned properly on-site and put in plastic chip trays. After drying, the sample was characterised macroscopically to obtain a rough idea of the petrography and minerals present. For the diamond drilling, every meter was sampled and taken to the laboratory.

3.2. Methods

3.2.1. Geological mapping

Geological and structural mapping was carried out at Assen located on the farms Assen 140 JQ, Assen 161 JQ, Buffelspoort 149 JQ, Doornkloof 141 JQ, Swarthoek 10 JQ in Brits district of the Northwest Province in South Africa. The geology of the mapped areas occur in the Transvaal basin, the northern portion of the Transvaal Supergroup of South Africa. The host rocks to the Assen deposit are contained in the lower portion of the Penge Formation of the Transvaal Supergroup, close to the contact with the underlying Malmani Subgroup dolomite. The three high-grade mineralised areas were believed to be separated by low-grade BIF and were of sufficient size to be considered as separate entities for mapping. The terms west, middle, and east bodies were used in this study based on their geographical positions along the ridge. The nature of the boundary between the west, middle and east bodies has not been determined and this mapping confirmed that the three are connected. The complete stratigraphic column from basal Malmani dolomite to Penge BIF is represented in the Assen mapped area. A sporadically developed talus deposit of hematite fragments and boulders is developed on the southern slopes of the hill and serves to mask the underlying outcrop and is currently mined as detrital iron ore.

The geological mapping started in January and February 2020 by confirming and assessing the locations of historical drilled boreholes collars in the field in relation to the available regional geological map, viewing the outcrops of different geology and mineralisation of different rock types

outside the current operating pit. Most of the drilled holes are high-quality diamond core drilled with 12 reverse circulations drill holes. Regional geological descriptions, historical Yskor borehole data and the regional geological map provided by Kumba Iron Ore used and portrayed the surface geological expression of the Assen Iron Ore. Geological field mapping was carried out in both west, middle and east orebody at an extent of 5 km by locating the contacts of different rock types, taking photographs, petrographic descriptions such as textures, recording the geometry of different rock types such as strike and dip measurements using Bruton compass, and the collection of physical samples. Major geological structures such as faults, dykes, and sills were mapped. The location of the mapping points was marked using Garmin GPS Map64s and Trimble GPS. All mapping points were collected, validated, and imported into the ArcGis 10.0 and Leapfrog 6.0 geological software. The mapping information was used to produce the 3D geological model of the Assen deposit and to construct cross-sections through the ridge.

3.2.2. Chemical analysis using X-ray fluorescence

Several laboratories have been used for various historical drilling and sampling campaigns. However, the South African Bureau of Standards lab (SABS) analysed most of the samples used in this study and its analytical procedures are well documented. The SABS laboratory located at the Council for Scientific and Industrial Research Complex in Pretoria is a South African National Accreditation System (SANAS) accredited laboratory. All elements were analysed by XRF with levels of detection of 0.01 % except for MgO which was 0.03 %. The laboratory receiving protocol was as follows: The samples were dried for 4 hours first and once the samples were dry, they were crushed to 10 mm. The sample was split into three parts using a rotary splitter, one for analyses and the other for storage. Then bagged and labelled with the laboratory numbers. The laboratory used Advant XP Sequential XRF (Thermo Fisher) to analyse the bulk chemical composition of the samples. The samples analysed for the following major oxides and element: SiO₂ %, Al₂O₃ %, Fe %, Fe₂O₃ %, TiO₂ %, CaO %, MgO %, K₂O %, MnO %, P % and total oxides %.

3.2.3. Petrography and Mineralogy

West orebody

Six samples were taken from the west orebody from the exposed stratigraphic profile and sampled perpendicular to the dipping strata. The west orebody has been mapped along 350 m along the strike. The medium-grade hematite, approximately 50-60 % Fe, 15 % SiO₂, and 1.6 % Al₂O₃ is yellow-brown in colour and occurs stratigraphically above the reddish-grey high-grade hematite zone. The high-grade hematite, >60 % Fe mineralisation was a soft and friable laminated type hematite. The highest-grade mineralisation grading >60 % Fe appears to have formed through supergene enrichment of the upper levels. Contacts between the goethite and hematite mineralisation and the hematite and calcite hematite mineralisation were sharp and distinct. Thin layers of grey massive and hard mineralisation are very limited in extent but carry 66 % Fe with 3 % SiO₂, 0.6 % Al₂O₃, and 0.3 % Mn as observed from the already drill holes sampling. The calcitic hematite mostly outcrops on the steep southern slopes of the ridge below the massive or laminated high-grade outcrop zone and

is developed over an average 15–20 m width. Average grades across the drilling programme are reported to average at 47 % Fe, 2 % SiO₂, 0.6 % Al₂O₃, and 17 % CaO.

Middle orebody

The middle orebody consists of the middle, east, and west zone. The middle zone is situated in a saddle area of the ridge where currently Pit 2 is operating and proceeds continuously eastwards as a narrow extension. The structure of the middle zone is complex. A narrow high-grade hematite zone was revealed to the south of the middle zone high-grade hematite body and is named the south footwall zone. The ironstone sequence of the middle zone is discussed upwards from contact with the basal Malmani dolomite unit.

The middle south footwall zone comprises a narrow high-grade hematite body immediately above the Malmani dolomite contact and has been traced over 320 m along the steep southern flank of the ridge. Steep slope scree obscures the western extension, and the horizon is truncated to the east upon the sandy dolomitic marl of the Malmani dolomite. The middle south zone is overlain by a ± 20 m thick calcitic hematite horizon which is hard and resistant to weathering. Three samples of dolerite, hematite and calcitic hematite were collected in this area from the exposed mining face.

The middle high-grade zone followed in a complex fashion with frequent thick calcite ironstone pods and lenses and a thickness of up to 30 m. The middle high-grade zone dips at 45° to 50° north appearing to flatten and pinch down-dip below a ± 20 m thick dolerite sill. On flattening the diabase intrusion splits and high-grade hematite pinches and becomes erratic. A thick flatter lying high-grade hematite body overlies the dolerite intrusion on the north also with randomly dispersed calcitic hematite lenses and pods and pinching down-dip. The unit is then overlain by very thick silica layered BIF. A stratigraphic profile was selected in an operating pit 1 where samples were taken from the bench profile exposing from the bottom, dolerite sill, calcitic hematite, hematite, and BIF.

East orebody

The east high-grade hematite horizons consist of soft friable free dig material to a shallow depth of between 3 m and 6 m while becoming a hard-bluish grey lumpy material at a depth beyond 6 m. The east zone is an extension of the middle zone with a strike length of ± 600 m. Diamond core boreholes placed north of the horizon and drilled at angles of 50° to 70° toward the dip of the high-grade hematite unit intersected only BIF underlain by calcitic hematite above the Malmani dolomite basement. Visually the hematite content appears to be high with a low magnetite concentration in the calcitic hematite. Two hematite samples were taken which are the friable hematite sample and hard bluish-grey hematite from the trench. The BIF sample comprising the alternating layers of chert and hematite and the calcitic hematite sample composed of white calcite and reddish-brown hematite were sampled where they are outcropping down a slope.

3.2.3.1. Reflected light microscopy study

Ten representative samples of different types of BIF, high-grade hematite (hard bluish-grey hematite, laminated hematite, Friable hematite, calcitic hematite), and dolerite intrusions were sampled. The samples were taken from the pits, trenches, and exposed outcrops and sent for petrographic thin sections. Thin sections were studied under a reflected light optical microscope at the University of Witwatersrand laboratory. The samples were cut from the pit using a diamond saw along with the 50 mm spacing and marked lines in a bench face along the stratigraphic section and from the outcropping rocks and trenches. Thin sections were prepared to characterise the various minerals present in a sample, microstructure, and textural framework. This will include describing textural changes from one iron ore facies to another, the protore BIF to the micro-banded martite and microplaty hematite ores, as well identifying the alteration phases within the narrow shear zones in and around the massive ore lenses.

The laboratory procedure followed to cut each sample into rectangular blocks of 50 x 80 mm in size using a diamond saw. The rectangular blocks were trimmed to 30 x 40 mm sizes using a petro-trim machine and samples were then polished using silicon carbide grit in a sequence of 120, 220, 400, and 800 grit sizes until samples were smooth for the bonding process. The polished samples were then cleaned by washing in an ultrasonic bath before they were dried at 80 °C for 15 minutes in the drying oven. After drying, samples were cooled to room temperature before they were bonded. The bonding agent (epoxy) was prepared by mixing hardener and resin using a ratio of 2:15 (2 parts hardener and 15 parts of resin) and samples were bonded on frosted glass slides using the epoxy.

The samples were then placed on a bonding jig overnight for effective bonding. The bonded samples were placed on Accutom-50 cutting machine and were reduced to a thickness of 10 mm in a cutting process that lasted for 13 minutes per sample. The Accutom-50 cutting machine was further used for the grinding of samples to a thickness of 50 micrometres in a process lasting 30 minutes. During the process of cutting, the instrument was programmed to cut and stop automatically. The ground samples were then placed onto a RotoPol-35 polishing machine and polished using a polishing disk for 2 hours. Once polished, the thickness of the sample was checked using a micrometer gauge to confirm the required less than 30 micrometers thickness for petrographic studies.

3.2.3.2. Quantitative X-ray powder diffraction analysis

The XRD studies of the samples were carried out by using a Malvern Panalytical AERIS X-ray diffractometer equipped with a flat spinning stage and PIXcel detector and fixed slits with Fe-filtered Co-K α radiation, 6-position sample changer for analyses. The analytical procedure involves backloading sample preparation method where Minerals in the scans will be identified using Malvern Panalytical High score plus software and PAN-ICSD 2016 database after which quantification (weight percent) is performed using the Rietveld method. XRD detection limit was 0.5–2 Wt % depending on the matrix resulting in minerals present in trace amounts not being detected. The analysis revealed the presence of various iron mineral phases, the nature of iron-bearing minerals, gangue minerals, and textural characteristics of samples. Sample preparation included sample drying, crushed to 10 mm, then riffle split, and milled in a tungsten carbide milling pot to ca. 80 % below 75 μ m.

CHAPTER 4

4. Detailed geological mapping

4.1. Regional-scale observations

The regional geological map of the area around the Assen (Fig. 12) and the surrounding area was compiled from geological and structural mapping studies done by Fockema (1947) and Hartzer (1989, 1995). The regional geological relationships between the Assen Iron Ore deposit and to the Crocodile River Inlier are: The Assen iron deposit is within the Crocodile River Inlier and the inlier formed as a large domal structure with the beds of the Chuniespoort Group and Pretoria Group dipping at very high angles into the surrounding Bushveld granites (Fig. 12). The Geological structures available in both are folds and faults that occurred during the emplacement of the Bushveld Igneous Complex and the dolerite sills of post-Karoo times. The Crocodile River Fragment lifted above the molten gabbro or basic magma and floated due to a higher density of magma than that of the inlier sediments.

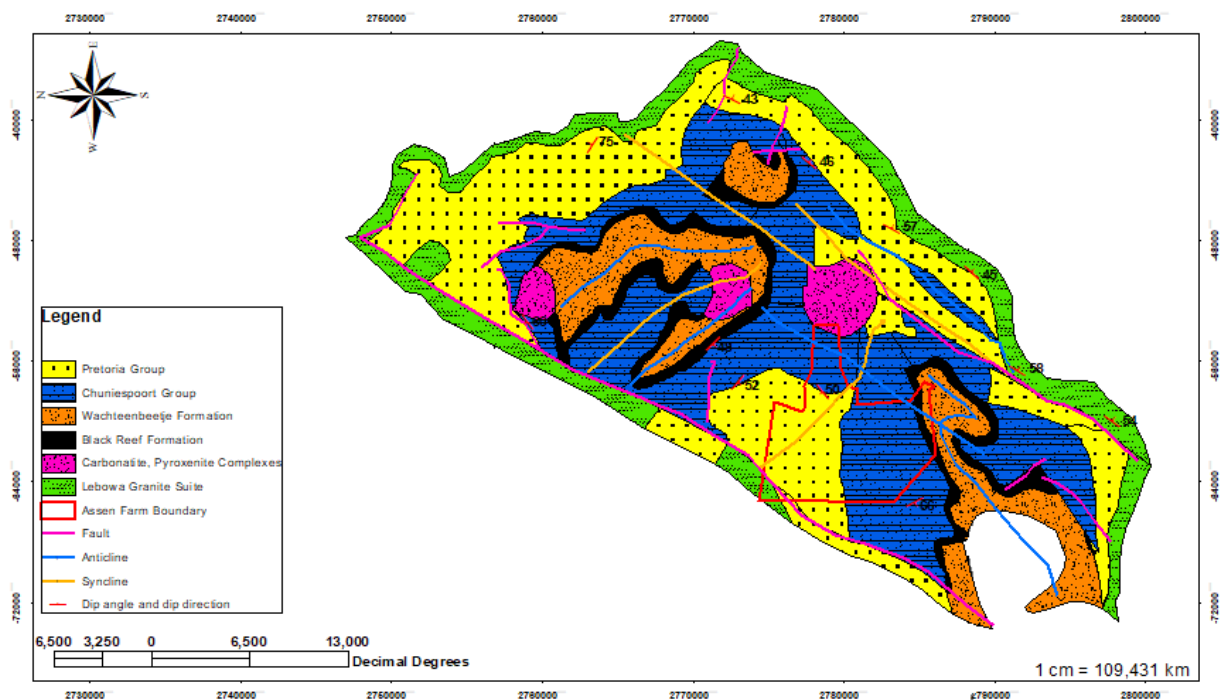


Figure 12: Regional geological map of Crocodile River fragment showing the location of Assen area and the geological structures within the area (Modified after Hartzer, 1995).

The granite intruded in Bushveld Igneous Complex above the gabbro and sank until it reached a more basic horizon with a high enough density to support it causing some synclinal basins and anticlinal dome. The fragment sinks again after a new injection of magma or a further stage of differentiation. The Formation of the domal structures was caused by the granite magma which surrounded the sedimentary rocks of the Crocodile River Inlier. As they solidify, they sank down, exerting strong horizontal pressure that caused the shearing and fracture cleavage in of Chuniespoort group and Dolomite into synclines and anticlines as observed at Assen and the surrounding farms. Both the BIF, hematite, shale, and dolomite at Assen are folded into smaller

synclines and anticlines with an amplitude of ± 91 m. The BIF layers slide across each other resulting in slickensides, joints, and fractures in the synclines.

The dolerite sills at Assen run parallel to the Iron Formations and have been folded and faulted together with the BIF, this is visible at the middle orebody pit. These sills are well preserved and visible in drilled cores and outcrops. The dolerite intrusions showed signs of shearing and alteration along the contact zones. At the west orebodies, concordant to transgressive intrusives of dolerite intrusion composition with altered upper zones have been observed throughout the area in the borehole core. A single occurrence of quartz-porphyry has been noted in one of the boreholes drilled into the west orebody. Numerous folds complicated the regional geology and its structural setting while the two prominent southeast to northwest striking faults (F1 and F2) cut the stratigraphy. The occurrence of two major faults (F1 and F2) is marked by the occurrence of approximately 100 m breccia, Iron Formation, and dolomite. The faults happened after the emplacement of the Bushveld Complex with major lineaments that can be traced southwards up to Brits Graben. The amount of vertical stratigraphic displacement along the eastern fault (F2) is between 3000-4000 m in the southern part of the Crocodile River Inlier.

In the southern portion of the inlier, a large anticline is visible in the outcrops of the Black Reef Formation while at the base of the anticline is delineated by the Wachteenbeetje Formation. There are minor faults associated with folding. Strike-slip faults result in the Penge Formation being in contact with the Black Reef and Wachteenbeetje Formations. In the central portion of the inlier, a major syncline occurs in the east and is well depicted in the Penge Formation. Further overfolding and thrusting in the centre of the fragment is caused by the emplacement of the Kruidfontein and Nooitgedacht Complexes shown by the disturbance of the Penge Formation stratigraphy. The western part has numerous northwest-striking folds that occurred and the domal structure is caused by refolding. The northern part of the inlier marked by the Black Reef Formation having a series of northeast-striking folds with curved axial planes.

Table 1: The Assen logged drill hole rock units and their relative time scale in relation to corresponding regional geological units. The logged lithologic units belong to the Chuniesport Group of the Transvaal Supergroup and the dolerite sills of the post karoo age. Table compiled from different sources such as Button (1981); Eriksson et al. (2005; 2006; 2011); Fockema (1945); Hammerbeck et al. (1976); Hartzer (1987;1989;1995).

Time Scale (Ga)	Regional			Local		Volcanism/deposition	Deformation	Iron Mineralisation
	Supergroup	Groups	Subgroup	Formation	Logged Geological Units			
2.046	Transvaal Supergroup	Pretoria						
2.047								
2.048								
2.049								
2.050								
2.425								
2.430				Silverton Formation				
2.431				Daspoort Formation				
2.432				Strubenkop Formation				
2.435				Dwaalheuwel Formation				
2.440				Hekpoort Formation				
2.445								
2.450								
2.455								
2.460		Chuniesport						
2.461								
2.462				Penge Formation	Banded Iron Formation	The iron formation of the Penge Formation was deposited in a deep marine basin through a volcanic biological sedimentation process.	F1-folds	
2.463					Dolerite		F2-folds	
2.464					Hematite		F3-folds	high-grade massive, micro-platy hematite, Goethite
2.465					Calcitic hematite			lower-grade, carbonate-rich, micro-platy hematite
2.470					Breccia			
2.475					Shale		Intensely sheared, Folded	
2.480				Frisco Formation	Dolomite		F1-folds	
2.485				Eccles Formation			F2-folds	
2.490				Lytlelton Formation			F3-folds	
2.495				Monte Christo Formation		Shallow marine carbonate platform, upon which the carbonate rocks of the Malmani Subgroup was deposited.		
2.500				Oaktree Formation				
2.505								
2.510								
2.515								
2.520								
2.525								
2.530								
2.535								
2.540								
2.545								
2.550								
2.555								
2.560								

The Black Reef and Penge Formations depict the deformational pattern and the distribution in the inlier. The deformation involved the three phases of folding accompanied by major faulting trending the northwest and southeast. In the first phase, the F1-folds have been refolded along axes with an east-northeast strike (F2-folds) and this is shown by the major syncline in the eastern-central part of the inlier. Folding with an axial trend that varies from north-east in the northern part of the fragment to the northwest in the southern part. The initial strike direction of the F1-axial planes was probably northwest to the southeast. The third folding phase (F3-folds) is represented by north-west to south-east striking folds in the western part of the fragment. F3-folding is depicted by the major anticline in the south, which has been refolded along a northwest-striking axial plane running nearly parallel to the original F1-axial plane.

4.2. Deposit-scale observations

The Assen Iron Ore deposit is generally striking in the east-west direction with an average dip of 55°, varying from 35° to 60°, dipping towards the north direction. The three zones where a higher concentration of hematite ore occurs are in three synforms separated by antiform and the mineralised synform named east, middle, and west orebody respectively (Fig. 13). The Assen area forms the southern limb of the east-northeast plunging syncline in the Crocodile River Fragment. Where the two-fold limbs intersect each other, the three orebodies (east, middle, and west) are known to be connected.

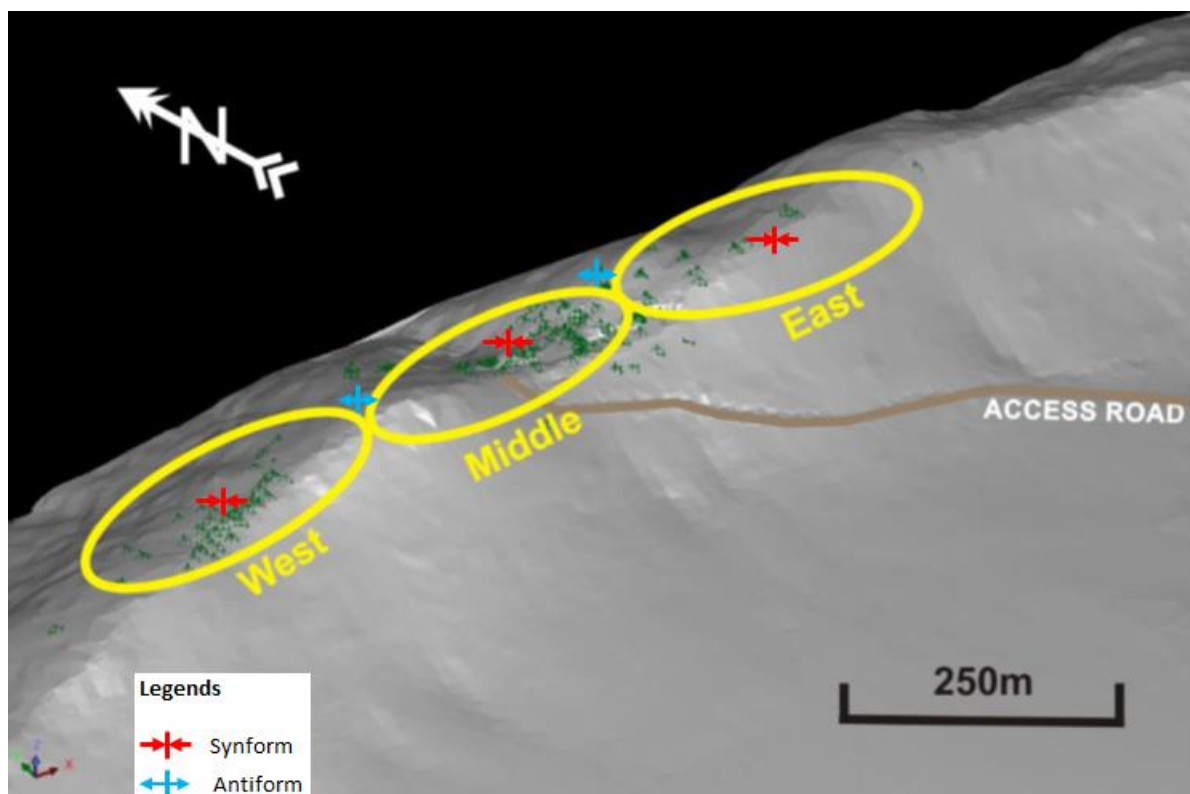


Figure 13: Three synform where a large volume of hematite ore is concentrated at Assen Iron Ore deposit.

High-grade hematite occurs in three distinct structural and stratigraphic positions. The high-grade hematite mineralisation in east, west, and middle orebody is associated with; 1. the southwest-northeast trending faults and the strike-slip faults. The hematite is enriched along the fault plane. 2. A very thick laminated hematite of the grade ranging from 59–67 % was observed at the middle and west orebody along the faults. This laminated ore seems to constitute the bulk of the ore resource and is particularly well developed in the west orebody and range in thickness between 7 m and 25 m and occur just above the faulted contact between the Penge Iron Formation and the dolerite which is underlain by black shale.

At the Assen Iron Ore deposit, dolerite sills form the east-west trending layers (Fig. 14) through and parallel to both BIF and hematite. 3. High-grade mineralisation is also associated with dolerite intrusions. High-grade (> 60 %) hematite is developed parallel to dolerite either above or below the dolerite sill. An example is the small, lenticular orebodies at the middle orebody and massive hematite at both middle and west orebody. Distal to these dolerite sills, the hematite tends to be reduced the % Fe and increase in the concentration of silica. The massive hematite associated with the dolerite up to the thickness of 12 m. In the middle orebody at pit one, the sill on the Synclines commonly follows the BIF-hematite contacts, separating hematite ore from BIF. A small, lenticular hematite body of ± 2 m occurs consistently distributed throughout the lower portion of the Assen Iron Ore deposit below the carbonate facies. This hematite is in some areas underlain by shale and in other areas developed above the shale. The open pit mapping data combined with extensive field studies and exploration data showed that the concentration of most of the high-grade iron orebodies are located along the hinge portion of the folds with a fold axis trending east-northeast. High-grade hematite ore is concentrated in syncline in a folded area. Either the hematite is enriched on the toe of the syncline or on the hinge of the fold.

West orebody

The orebody is situated in the farms Swarthoek 10 JQ and Assen 161 JQ. The Iron Formations comprise calcitic hematite at the bottom developed over an average 21 m width and grading upwards to hematite-rich calcitic hematite and the overlying high-grade hematite (>60 %). The high-grade hematite body is a lenticular horizon ± 350 m in strike length reaching a maximum thickness of around 20 m and pinching at both ends. Narrow 1 m to 2 m BIF and calcitic lenses are commonly intercalated. Two dolerite sills occur at the west orebody, one close to the bottom of the stratigraphy and the other one separating the BIF from the high-grade hematite towards the top of the stratigraphy. The past and present drilling has also intersected several narrow dolerite sill intrusions within the high-grade hematite body. Bedding strikes east-west and dips 39°–58° to the north but steepens towards far east at 55°–60°.

Middle orebody

The structure of the middle zone is complex with frequent thick calcite ironstone pods and lenses and a thickness of up to 30 m. The zone dips at 45° to 50° north appearing to flatten and pinch down-dip below a thick ± 20 m dolerite sill. On flattening the dolerite intrusion splits and high-grade hematite pinches and becomes erratic. A thick flatter lying high-grade hematite body overlies the dolerite intrusion on the north also with randomly dispersed calcitic hematite lenses and pods and

pinching down-dip. The unit is then overlain by a very thick silica-rich layered BIF. A short diamond drilling indicated its downward extension to 15 m below the surface. A trench opened along the strike exposed numerous narrow dolerite sill intrusions within the hematite body. The central/west/east body in the middle orebody is associated with a thick dolerite sill intrusion dipping $\pm 50^\circ$ northwards and flattening northwards at shallow depth. The broad high-grade hematite body is complicated by frequent calcitic hematite lenses.

East orebody

The east zone comprises a continuous narrower extension of the middle zone with a strike length of ± 600 m and a thickness of around 6 m to 12 m. Drilling placed north of the horizon and drilled at angles of 50° to 70° toward the dip of the high-grade hematite unit intersected only Banded Iron and calcitic hematite above the Malmani dolomite basement. The unit, therefore, does not continue to depth. bedding strikes east-west and dips 38° – 58° to the north but decreases in steepens to around 38° towards the middle orebody (Fig. 14).

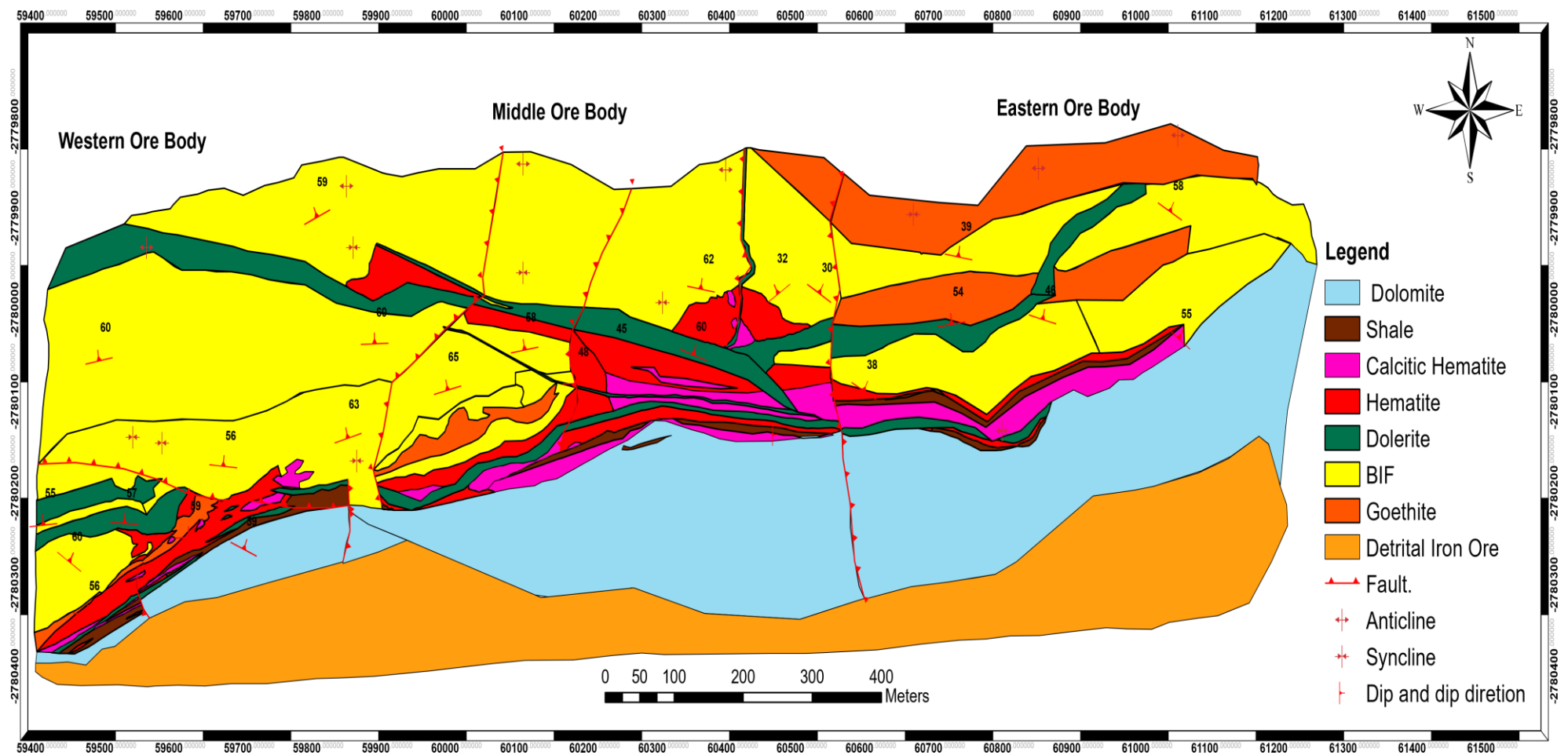


Figure 14: The geological map of the Assen iron ore deposit showing three mineralised portions at Assen.

4.3. The lithostratigraphy of the Assen deposit

The complete stratigraphic column from basal Malmani dolomite to the BIF of the Chuniespoort Group occurs in the area at the Assen Iron Ore deposit intruded by the Karoo dolerite sills (Fig. 15). These rocks are dipping at an angle of between 35° and 60° north and the general trend is east-west. At the foot of the east-west trending mountain is a detrital iron ore of approximately 2 million tons composed of well-sorted, rounded to sub-angular hematite, chert, and magnetite-bearing fragments and pebbles ranging in thickness from 45 cm to 150 cm and an average of 100 cm. The size of this detrital iron ore ranges from a few mm up to 10 cm. The detrital deposit occurred because of weathering, transportation by rainwater and gravity, and deposition into an open undulating and Karst dolomite. The movement of the weathered detrital material was from north to south and developed on the southern slopes of the hill and serves to mask the underlying dolomite outcrop. Along the slope to the mountain is ± 50 cm in thickness scree, which is a combination of hematite, calcitic hematite, or the BIF coming from different stratigraphic rocks.

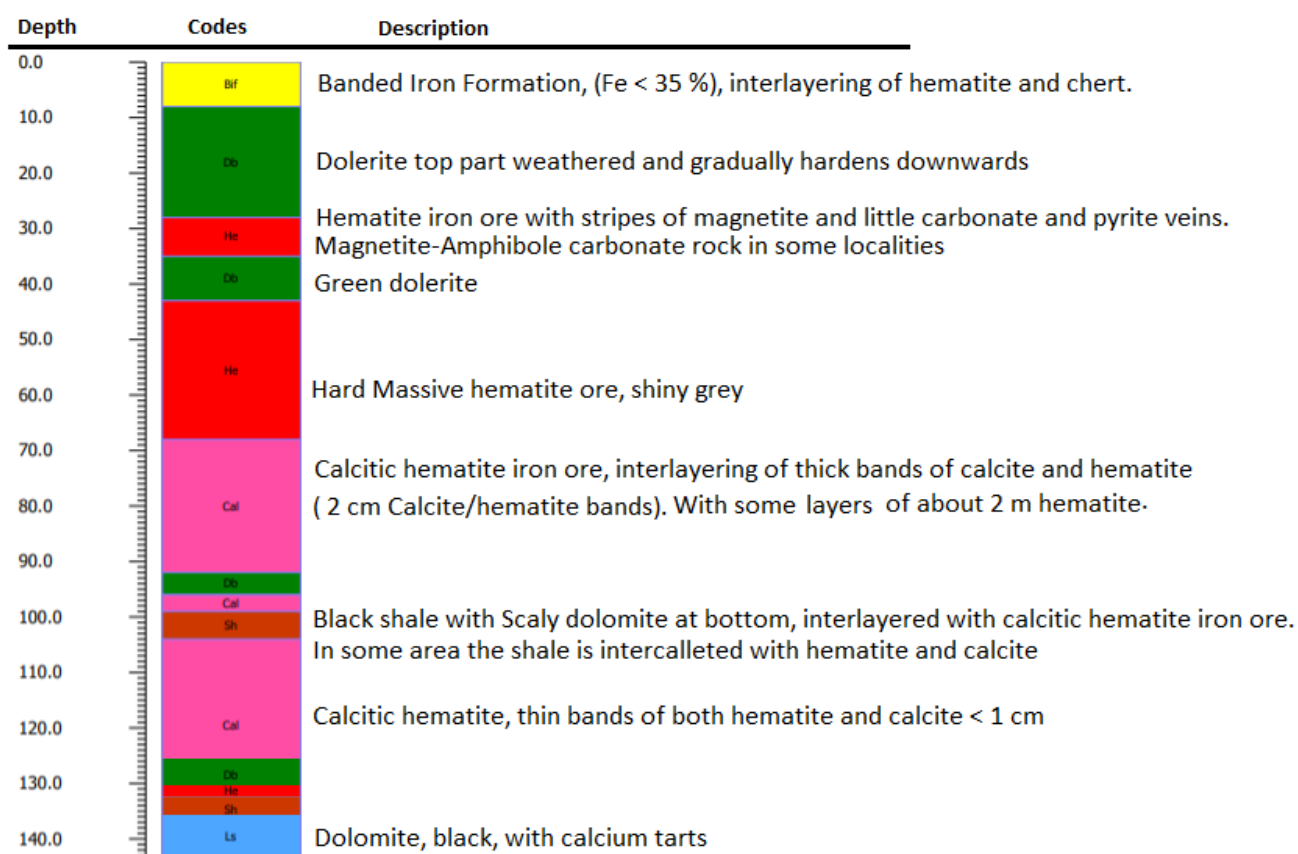


Figure 15: The lithostratigraphy of the Assen Iron Ore deposit the Penge Iron formation rocks intruded by the dolerite sills.

Different iron formation outcrops exposed at the mountain and underlain by Malmani Subgroup dolomites: An upper layer, comprising a more typical siliceous chert of approximately 2.5 cm with the layering of very thin or micro bands of hematite, goethite. In certain areas like the northern part of the west orebody, amphibolite and crocidolite asbestos layers occurred and are visible in the drilled cores. These siliceous chert-rich layers grade into 1.5 cm alternating bands of both hematite and chert. This BIF in the middle orebody is separated by a dark brown shale layer. This BIF grades again into thick bands of approximately 1.8 cm bands of hematite alternating with thin chert bands. The intrusive dolerite which is concordant to transgressive has been observed

throughout the area in borehole core and outcrops. The dolerite sills run parallel to the Iron Formations. Pit 1 in the middle orebody showed the parallel dolerite intrusion with high-grade hematite above and below the dolerite. The dolerite in weathered zones is yellow in colour and in fresh unweathered portions. Green serpentinite sills were also encountered within the high-grade hematite zone. Hornblende-plagioclase occurred and was caused by metamorphism. A single occurrence of quartz-porphyry has been noted in one of the boreholes drilled into the west orebody.

The carbonaceous hematite rock is calcitic hematite that forms a sharp contact with the massive or laminated hematite. It also occurs as a thin lens of 1–2 m within the massive hematite. It forms the largest outcrop on the southern side of the east-west trending mountain. This iron ore facies occur as interlayer bands of either white calcite or brown calcite and hematite, calcite intercalated with hematite, or the brecciated calcite at the bottom where calcite crystals are cemented by hematite matrix. It is believed that this type of rock might have formed from as a metasomatised product of the magnetite-carbonate BIF (Steinhöfel, 2010). Shales from Assen Iron Ore occur in two portions in the stratigraphy; 1. In between the Banded Iron Formation and 2. Immediately above the Malmani dolomite. The shale in between the BIF is ferruginous reddish-brown in colour, indicating that it is iron-rich. The basal shale layer separating the dolomite and the iron formations is black in colour and it alternate with thin lenses of hematite and in other locations with brecciated calcitic hematite.

The Full stratigraphy of Malmani dolomite is visible at Assen Iron Ore which has an estimated thickness of up to 850 m in the Crocodile River Fragment region. The dolomite immediately below the shale layer is of the transition zone and is shiny reddish-grey and dark-grey in colour. The reddish colour is due to its high concentration of iron. The north-south quartz veins were observed at the west and middle orebody cutting across the dolomite. The dolomite is irregular and formed karst sub-surface floor. The Karst sub-surface floor is filled with detrital iron ore and reddish-brown ferruginous soil. The logged and analysed cores showed that 25 m from the contact with shale, the dolomite formation is dark-grey and chert-free dolomite.

4.4. 3D implicit modelling of the Assen iron deposit

The database available comprised diamond and percussion drilling data. Overall, the database includes 200 holes and 8474 samples. The analytical database from boreholes used in this research has been checked and cross-referenced for validity in terms of X, Y, and Z coordinates, lithological logging, assay to's and from's, and QAQC. The structural interpretation by a 3D geological modelling using the available drill hole data and structural data mapped in the field by tracing the contacts for both the east, west and middle orebody. Three 3D models are lithological boundary wireframes, assay results, and structural trends from the models created (Fig. 17). The drill hole data helped (Fig. 16) to identify and analyse trends in large drill hole datasets and relate them to known and mapped structures observed in the field. The geometric models were combined with field observations to develop a conceptual model, which aims to explain the structural setting and control of mineralisation within the Assen Iron Ore deposit.

4.4.1. 3D implicit lithological model

The three iron formations together with dolerite and shale that make up the Assen Iron Ore deposit were used to generate the 3D lithological model (Fig. 17). Drillhole intercepts were used to investigate and visualise the spatial relationship between dolerite intrusion and hematite mineralisation. The Assen orebody was sub-divided into three orebodies; namely, East, Middle, and West orebody, and each was interpreted and estimated individually as the stratigraphy/lithology and grade distribution used in geological interpretations. The geological domains were interpreted based on the mineralised zones and were treated as hard boundaries (Hematite, Calcitic hematite, and BIF).

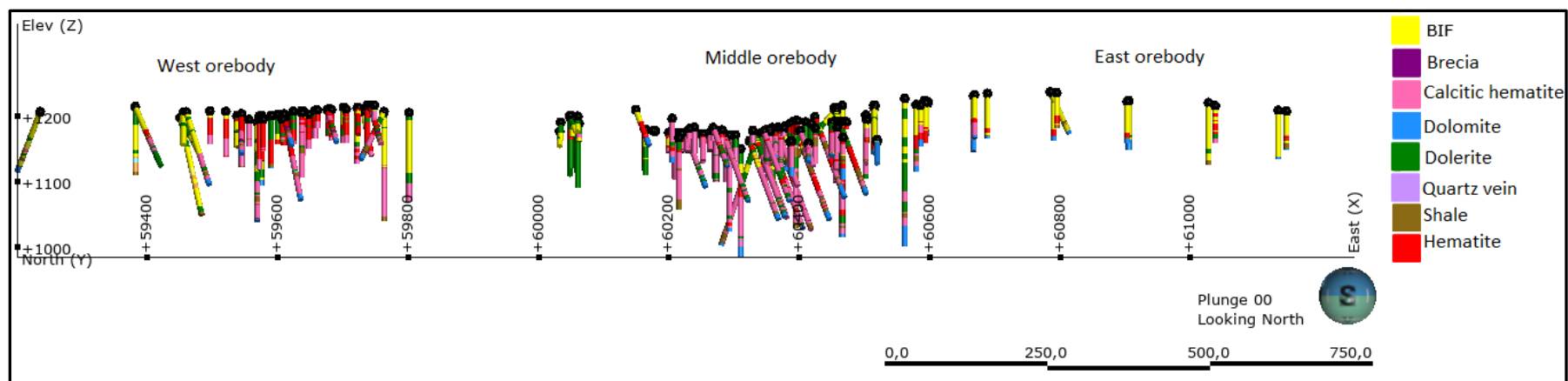


Figure 16: Boreholes showing the alternating lithologies of the drill holes that created an alternating succession.

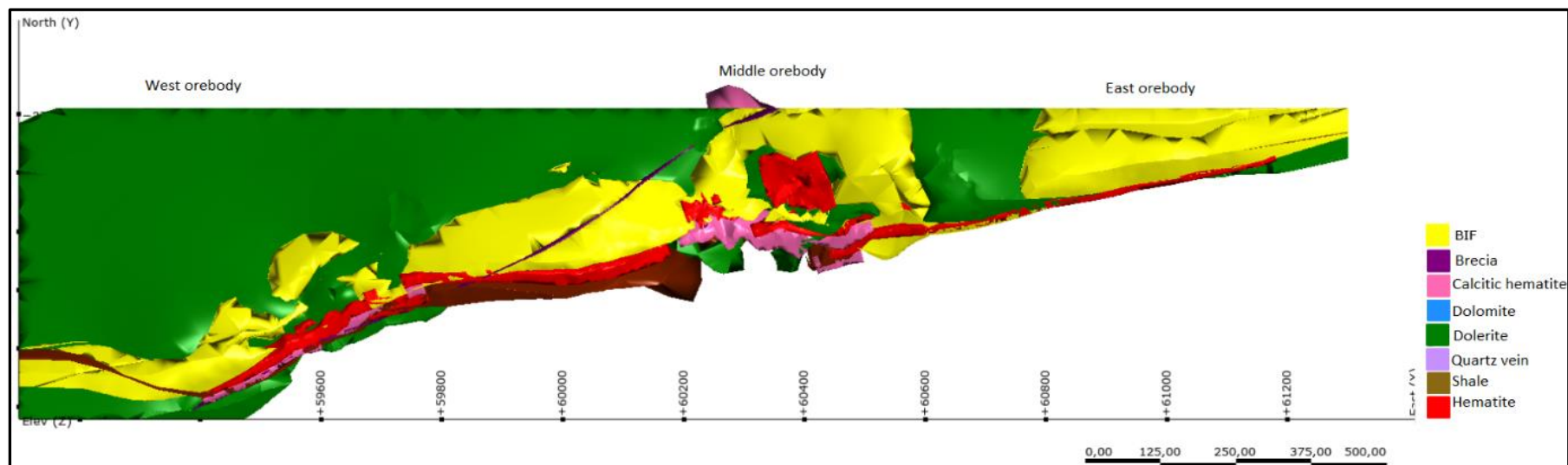


Figure 17: The 3D implicit lithological model showing distinctive hematite mineralisation trends at Assen Iron Ore deposit. The hematite ores are parallel to bedding and located close to the contact of dolerite and shale in both west, middle, and east orebody.

4.4.2. 3D implicit assay model

A total of 8474 samples of iron ore coming from the diamond core drilling and a few from reverse circulation drilling were sampled at 1 m intervals core segments. Exploratory data analysis was carried out on the 1 m composite file from each domain and statistics of each variable were assessed. The drill hole sample database was composited in Leapfrog based on a 1 m length and compositing done per domain. The composite files comprised nine major assay variables which are 1. Iron (Fe), 2. Phosphorus (P) and oxides 3. Silica oxide (SiO₂), 4. Aluminium oxide (Al₂O₃), 5. Calcium oxide (CaO), 6. Potassium oxide (K₂O), 7. Magnesium oxide (MgO), 8. Manganese oxide (MnO) and 9. specific gravity (SG). The 1 m downhole composite lengths were split by Domain code. North-south sections were created, in leapfrog, on each orebody where the spacing between the sections was based on the drill hole spacing within each orebody. The colour-coded closed strings were digitised on sections by snapping the points to the lithological contacts to delineate mineralised boundaries/domain on each geo-domain. The strings of the same geo-domain are linked together to generate a closed solid.

Table 2: Table providing a summary on geo domains modelled in this project.

Geo Domain	Rock	Grade range (Fe%)
HG Hematite	Hematite	60+
LG Hematite	Hematite	55-59.99
HG Calcitic hematite	Calcitic hematite	40-60
HG BIF	BIF	40-55

Variography was based on 1 m composited data for all nine variables which are 1. Fe, 2. SiO₂, 3. Al₂O₃, 4. CaO, 5. K₂O, 6. MgO, 7. MnO, 8. P and 9. SG. An overview of the variography procedure is as follows: The data was separated into a high- and low-grade hematite, calcitic hematite, and high-grade BIF domain. Only the Fe variogram was modelled in the BIF domain. Omnidirectional variograms were calculated. The nugget variances were modelled from average downhole variograms based on 1 m lag, reflecting the downhole composite spacing. The downhole variogram model provided the nugget and approximated the minor axis for the 3D variogram model. The objectives of variography were to: Establish a major direction of continuity for the 9 variables in the domain and to quantify spatial continuity (variability, anisotropy, and overall continuity), and provide variogram model parameters for use in geostatistical grade interpolation (Ordinary Kriging).

The Assen Iron orebody was drilled on an irregular grid pattern which ranged from more than 100 m by 100 m drill spacing at the east orebody down to 10 m x 10 m in parts of the middle orebody. The modelling parent block size of 10 m by 10 m by 5 m (X, Y, and Z) was used. The block model origin and extensions are listed in table 3. Variables were assigned to each block and set to default values. Each block variable was then flagged by the closed solids and assigned a value. The variables created for the geological model prior to estimation are summarised in table 3. The drill hole sample database was composited in Leapfrog 10.0 based on a 1 m length and compositing done per domain. The composite files comprised nine major assay variables which are 1. Fe, 2. SiO₂, 3. Al₂O₃, 4. CaO, 5. K₂O, 6. MgO, 7. MnO, 8. P and 9. SG. Due to the lack of assay data in some boreholes, Sulphur (S) was not included. The 1m downhole composite lengths were split by domain code. Assay intervals that were not sampled for Fe were flagged as -99.0 (Table 3).

Table 3: Block model variables used for both west, east, and middle orebody

Attribute Name	Type	Decimals	Background	Description
Al ₂ O ₃ %	Real	3	-99	Aluminium Oxide
Avg_dist	Real	3	-99	Average anisotropic distance to samples
Block_var	Real	3	-99	Block variance
CaO %	Real	3	-99	Calcium oxides
Category	Character	-	null	Measured, Indicated, and Inferred
Fe %	Real	3	-99	Iron
K ₂ O %	Real	3	-99	Potassium Oxides
krig_eff	Real	3	-99	Kriging efficiency
krig_var	Real	3	-99	Kriging variance
Lg	Real	3	-99	Lagrange multiplier
MgO %	Real	3	-99	Magnesium oxide
MnO %	Real	3	-99	Manganese Oxide
Neg_weight	Integer	2	-99	Number of negative weights
Num_dh	Integer	2	-99	Number of drill holes
Num_samp	Integer	2	-99	Number of samples
Ore_types	Character	-	null	Hematite, Calcitic Hematite BIF
P %	Real	3	-99	Phosphorus
Reg_slop	Real	2	-99	Conditional bias slope
Rock_types	Character	-	null	Hematite, Calcitic Hematite BIF
Samp_dist	Real	3	-99	Average true distance to samples
SG	Real	2	-99	density
SiO ₂ %	Real	3	-99	silica
Tdist_samp	Real	3	-99	Average true distance to sample

Exploratory data analysis (EDA) was carried out on the 1 m composite file from each domain and statistics of each variable were assessed. This involved the following analysis: Univariate Statistics and histograms for a full suite of histograms (Fig. 18). More of these Univariate statistics and histograms of major, minor elements, and specific gravity of different iron ores were presented in appendix D.1. Variography was based on 1 m composited data for all nine variables which are 1. Fe, 2. SiO₂, 3. Al₂O₃, 4. CaO, 5. K₂O, 6. MgO, 7. MnO, 8. P and 9. SG. An overview of the variography procedure is as follows: The data was separated into a high- and low-grade hematite, calcitic hematite, and high-grade BIF Domain (Table 2). Only the Fe variogram was modelled in the BIF Domain. Omnidirectional variograms were calculated (Fig. 22). The nugget variances were modelled from average downhole variograms based on 1 m lag, reflecting the downhole composite spacing. The downhole variogram model provided the nugget and approximated the minor axis for the 3D variogram model. Variograms were modelled using an absolute variogram. The objectives of variography were to establish a major direction of continuity for the 9 variables in the domain and quantify spatial continuity (variability, anisotropy, and overall continuity), and provide variogram model parameters for use in geostatistical grade interpolation (Ordinary Kriging). The spherical scheme model was used to derive all variogram parameters from the experimental variograms.

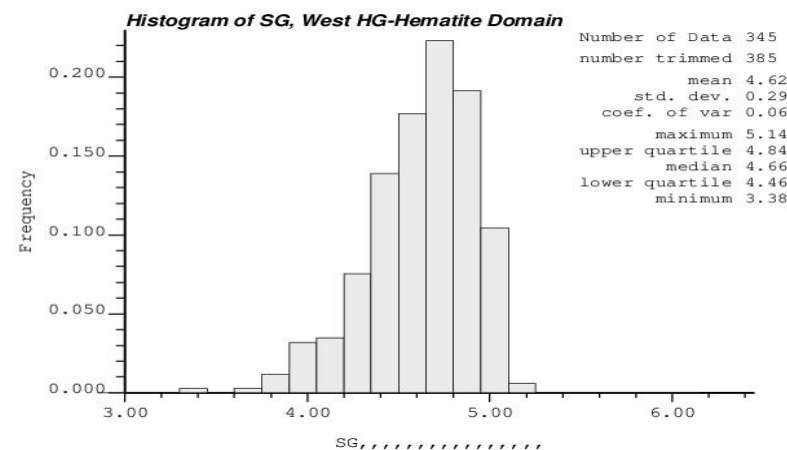
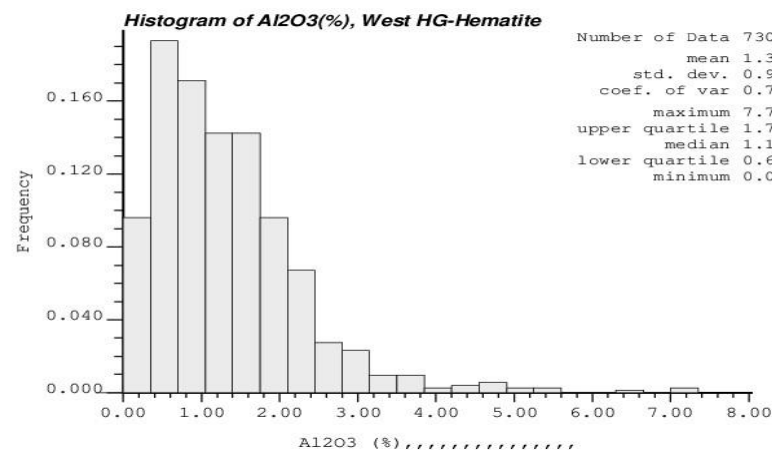
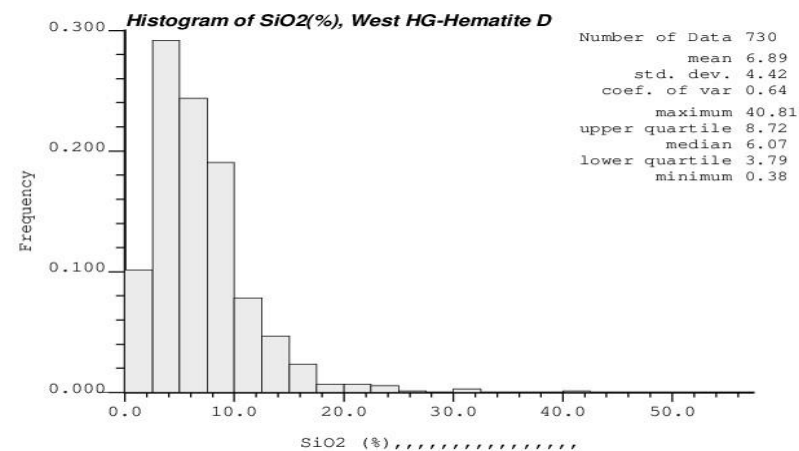
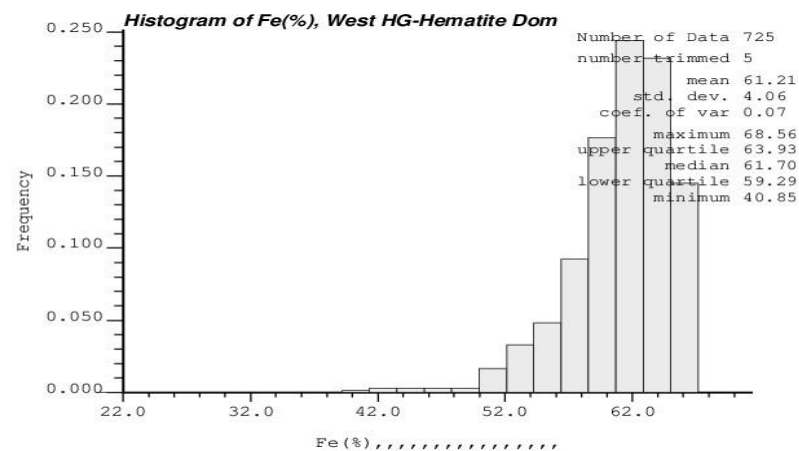


Figure 18: Univariate statistics and histograms of major, minor elements, and specific gravity of high-grade hematite at the west orebody

Table 4: The variogram modelling parameters.

Horizontal Angle Tolerance	180°
Vertical Angle Tolerance	90°
Horizontal Distance Bandwidth	150 m
Vertical Distance Bandwidth	10 m
Lag Distance	10m
Lag Tolerance	10 m

The variogram interpretation and identified spatial mineralisation characteristics:

The West orebody hematite variogram has nugget effects ranging from 15 to 40 % and near isotropic with short-range 2-40 m across all domains. A sensitivity study was done on the variogram by capping lower values below 55 % Fe the extreme values above 64 % Fe in hematite. The results show similar trends of variograms. This concluded that the lower and extreme values have less influence on the data other than on the histograms where they have an impact on the long tails on the skewing of the data.

Grade estimation of the Assen orebody was carried out using linear estimation methods. The geostatistical (Ordinary Kriging or OK) which uses model parameters from the variography was used for the estimation of the nine variables 1. Fe, 2. SiO₂, 3. Al₂O₃, 4. CaO, 5. K₂O, 6. MgO, 7. MnO, 8. P and 9. SG. The BIF domain was estimated using Inverse Distance Squared ($1/d^2$), as there were not enough data to model variograms in this domain. Estimation panel sizes were governed by the parent block size which was 10 m by 10 m by 5 m (Table 4). Given the nominal average infill drilling density of 20 m by 20 m. The parent block size for the Assen orebody is adequate to ensure local estimation quality and to reduce the risk of conditional bias.

Ordinary Kriging model

- A One-pass Kriging model was used with a single sector (no octant search) for the ore domain.
- Block discretisation was set to 3 (X) by 3 (Y) by 3 (Z) to estimate grades in panels of 10 m by 10 m by 5 m.
- A minimum of 8 samples (first pass) and a maximum of 36 samples were used. A limit of three samples per drill hole was applied. A visual validation was done.
- Search ellipsoid orientations were based on the orientation of the semi-variogram.
- The same search neighbourhood orientations and dimensions were used across the nine variables in the domain.
- No sample restraining was applied on the samples
- Horizontal search orientation ellipse was applied.

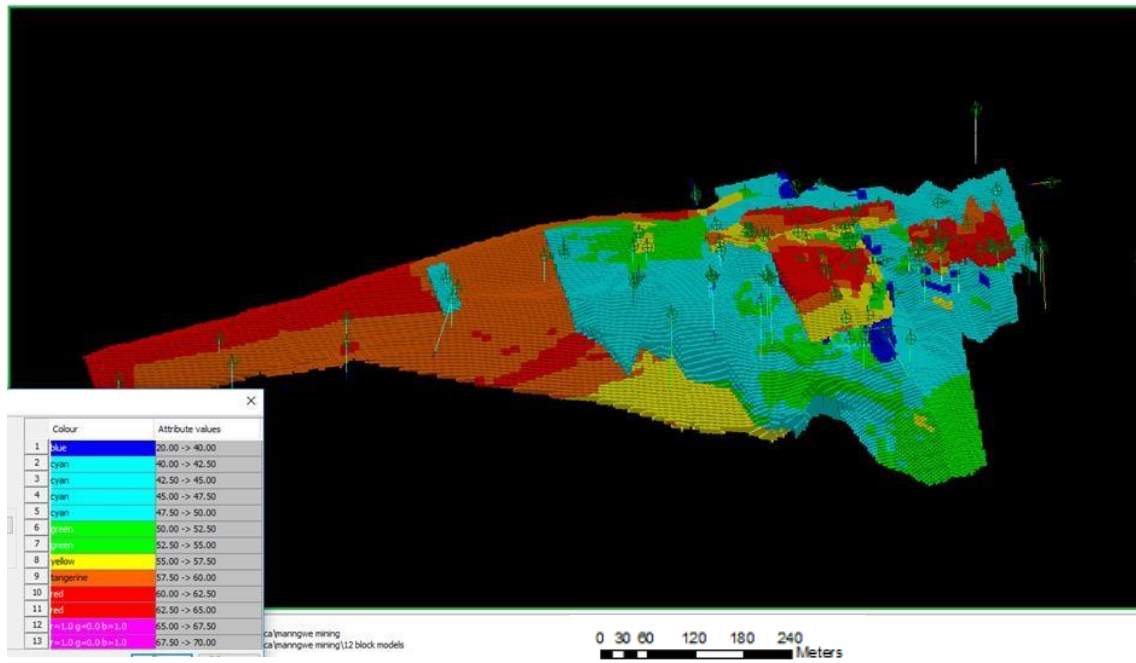


Figure 19: East-west view of Fe (%) distribution on east and middle block model all Domains

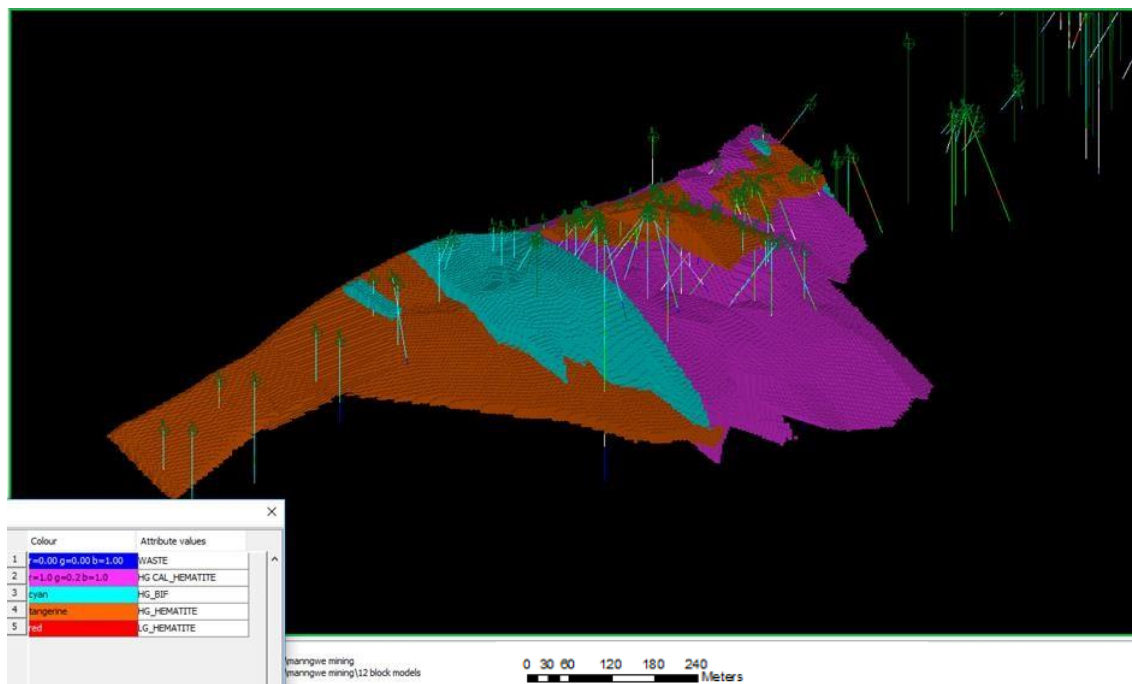


Figure 20: Isometric view of geological domains in east and middle orebody

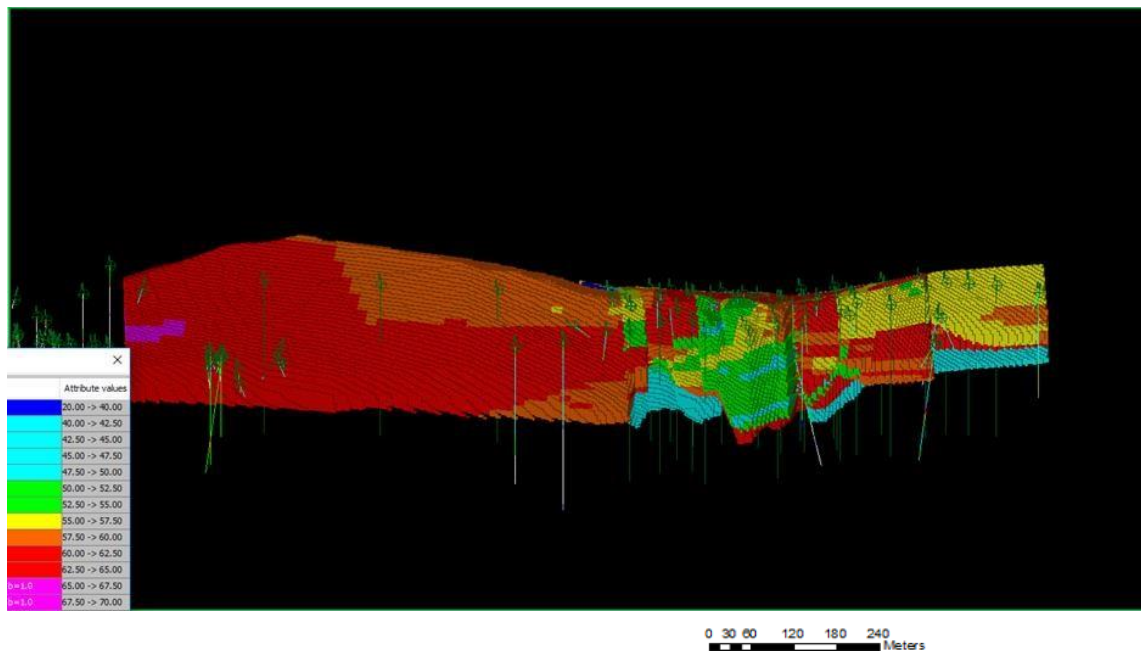


Figure 21: East to west view of Fe (%) distribution - West orebody block model of all domains

An example of a generated variogram is shown in Figure 22 below. All generated variograms are contained in the Appendix C.1. of this study.

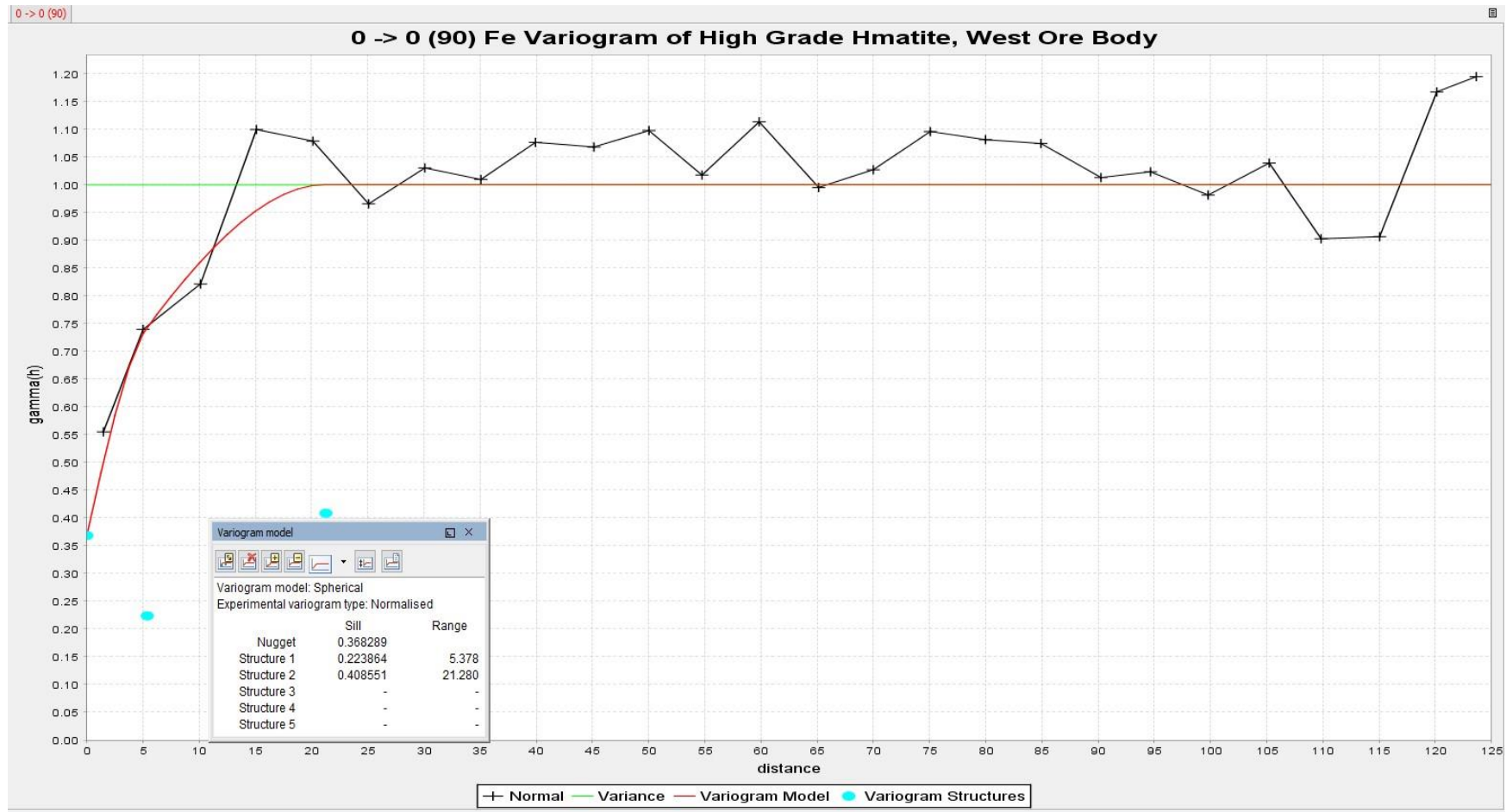


Figure 22: Omni-directional Variogram - Fe- high-grade hematite domain at the west orebody

4.4.2.1. Visual validation of grade estimates

Statistical and visual assessment of the block model was undertaken to assess the successful application of the various estimation passes. This validation is performed to ensure that all blocks in the domain were estimated, and the model estimates performed as expected. As a general comment, the validations generally only determine whether the Kriging has performed optimally. Acceptable validation results do not necessarily mean the model is correct or derived from the right estimation approach. It only means the model is a reasonable representation of the data used and the estimation method applied. Visual assessment of grade estimates was also done. An on-screen validation between samples and block was performed on the model. The on-screen validation process involved comparing block estimates and composites grades in section and plan views. Where the kriged block model was superimposed on the drill holes data, both data were colour coded with the Fe grade (Fig. 18, 19, and 20), and the model was sliced onto various sections perpendicular to the strike of the orebody.

The global mean grade of block model estimates was checked to assess the reproduction of the mean grade of the data (1 m composites) and to validate for obvious interpolation errors such as incorrect sample selection for estimation in the domain. Global statistics were compared between the block model and drill hole database. Statistics were performed for each kriged. The statistical analysis provides the following information (Table 5, 6 and 7):

- A check on the reproduction of the mean grade of the composite data in the OK model over the global domain. This is shown by OK/DH (%) and should be close to 100 % and provides an indication that the Kriging estimates are not globally biased.
- The smoothing effect of the estimation is indicated by the actual variance adjustment ratio, which is the OK block variance divided by the 1 m composite variance. The blocks validation statistics for the middle and east orebody domains are in the appendix B. 1.

Table 5: Block validation statistics: Block estimates vs Composite's statistics in west orebody high-grade hematite domain

	Assen West Domain HG hematite.mdl									west_hg_hem_compo.str								
Variable	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG
Number of samples	5869	5869	5869	5869	5869	5869	5869	5869	5869	730	730	730	730	726	607	726	726	345
Minimum value	42.083	2.526	0.2553	0.05	0.011	0.114	0.251	0.01	3.69	24.7	0.38	0.01	0.01	0	0.01	0.08	0	3.38
Maximum value	67.221	27.45	50.683	17.4	0.116	0.987	1.014	0.22	4.82	68.56	40.81	7.699	25.04	0.31	2.09	3.12	0.94	5.14
Mean	61.746	6.554	0.9255	0.65	0.03	0.261	0.452	0.06	4.62	61.04	6.891	1.321	0.811	0.04	0.3	0.55	0.07	4.62
Median	61.913	5.964	0.9849	0.33	0.027	0.259	0.411	0.05	4.61	61.64	6.075	1.175	0.243	0.03	0.21	0.46	0.05	4.66
Variance	6.0622	3.115	0.7215	0.96	0.00	0.014	0.017	0	0.01	20.79	19.56	0.922	5.79	0	0.07	0.11	0.01	0.08
Standard deviation	2.4622	1.765	0.8494	0.98	0.017	0.117	0.129	0.04	0.1	4.56	4.423	0.96	2.406	0.04	0.27	0.33	0.08	0.29
Coefficient of variation	0.0399	0.269	0.9178	1.51	0.573	0.449	0.286	0.71	0.02	0.075	0.642	0.727	2.968	0.99	0.91	0.61	1.2	0.06
Skewness	-0.762	1.58	35.747	5.53	0.733	0.862	1.367	0.69	-0.31	-2.04	2.007	1.902	6.419	2.46	2.28	2.03	4.79	-0.8
Kurtosis	4.7764	8.664	2033.5	65.7	3.102	4.545	4.868	2.53	4.34	11.85	11.06	9.618	51.97	10.5	10.8	11.3	39.4	3.91

Table 6: Block validation statistics: Block estimates vs Composite's statistics in west orebody low-grade hematite domain

			Assen Western Domain LG Hematite.mdl										west_Lg_hem_comp0.str							
Variable	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG		
Number of samples	1082	1082	1082	1082	1082	1082	1082	1082	1082	207	207	207	207	195	176	195	195	53		
Minimum value	45.90	9.95	4.08	0.05	0.05	0.32	0.28	0.01	4.25	16.40	1.70	0.31	0.00	0.00	0.08	0.03	0.01	3.49		
Maximum value	59.58	25.12	56.68	2.41	0.16	1.23	0.78	0.18	4.25	63.50	39.41	10.92	24.83	0.93	3.06	1.66	0.48	4.79		
Mean	54.57	15.98	9.03	0.37	0.08	0.66	0.55	0.06	4.25	55.03	15.70	2.15	0.45	0.09	0.59	0.59	0.07	4.23		
Median	55.80	15.68	4.26	0.34	0.08	0.61	0.56	0.06	4.25	56.90	13.53	1.85	0.24	0.07	0.46	0.52	0.04	4.25		
Variance	7.82	6.19	209.04	0.09	0.00	0.03	0.01	0.00	0.00	41.67	56.11	2.46	2.96	0.01	0.22	0.11	0.01	0.06		
Standard Deviation	2.80	2.49	14.46	0.30	0.02	0.17	0.10	0.04	0.00	6.46	7.49	1.57	1.72	0.09	0.47	0.33	0.07	0.25		
Coefficient of variation	0.05	0.16	1.60	0.81	0.27	0.26	0.18	0.63	0.00	0.12	0.48	0.73	3.80	1.06	0.80	0.56	1.10	0.06		
Skewness	-0.67	0.26	2.69	2.08	1.26	0.64	0.01	0.25	0.00	-2.83	1.15	2.53	13.73	5.52	2.78	0.50	2.76	-0.30		
Kurtosis	2.31	3.40	8.27	9.40	4.96	3.14	2.65	1.60	0.00	13.11	4.16	11.71	194.34	45.32	12.21	2.76	13.45	3.59		

Table 7: Block validation statistics: Block estimates vs Composite's statistics in west orebody calcitic hematite

		Assen Western Domain CAL_ Hematite.mdl										west_hg_calhem_comp0.str									
Variable	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG			
Number of samples	1884	1884	1884	1884	1884	1884	1884	1884	1884	393	393	393	393	380	285	380	380	159			
Minimum value	37.63	1.10	0.26	2.35	0.01	0.36	0.00	0.00	3.87	21.50	0.09	0.01	0.20	0.00	0.03	0.05	0.01	3.34			
Maximum value	55.92	23.29	1.43	20.56	0.22	1.54	0.77	0.11	4.29	64.60	21.40	7.94	42.26	0.44	7.25	1.46	0.59	4.90			
Mean	46.98	2.96	0.58	15.28	0.09	0.75	0.31	0.01	4.10	46.74	3.10	0.63	15.42	0.02	0.52	0.40	0.07	4.12			
Median	47.12	2.58	0.52	15.64	0.09	0.79	0.36	0.07	4.10	46.52	2.05	0.37	16.05	0.02	0.33	0.37	0.06	4.08			
Variance	8.67	1.70	0.04	5.00	0.00	0.04	5.26	5.21	0.01	53.72	9.49	0.78	42.45	0.00	0.44	0.04	0.00	0.10			
Standard Deviation	2.94	1.30	0.21	2.24	0.03	0.19	2.29	2.28	0.07	7.33	3.08	0.88	6.52	0.04	0.67	0.19	0.04	0.32			
Coefficient of variation	0.06	0.44	0.36	0.15	0.30	0.25	7.41	157.62	0.02	0.16	1.00	1.40	0.42	1.84	1.28	0.47	0.63	0.08			
Skewness	0.10	2.67	1.25	-0.30	0.71	0.38	-43.14	-43.37	0.11	-0.17	2.36	4.04	-0.07	5.43	4.94	1.57	6.44	0.26			
Kurtosis	3.14	33.60	4.91	2.86	4.37	3.16	1868.45	1881.93	2.90	3.36	10.48	24.75	3.22	40.78	40.89	8.09	70.39	2.89			

Both the 3D implicit lithological and assay models revealed that most iron ore mineralisation is in the west orebody. The highest-grade hematite and most extensive high-grade hematite zones occur close to lithological contacts, especially with the dolerite. Three geometrically and spatially distinct high-grade hematite mineralisation trends can be defined. One prominent high-grade mineralisation trend is associated and occurs both in the hanging and footwall of the dolerite. The second high-grade hematite mineralisation trend occurs above and parallel to the shale layer and is most visible in the east orebody and can be traced for approximately 400 m. This type is less voluminous and has high silica compared to the hematite mineralisation along the dolerite. The third high-grade hematite is controlled by normal faults trending southwest-northeast and occurs mostly along the fault planes.

4.4.3. 3D implicit structural trend model

The linear and planar structural data of bedding, folds, and faults within an area of approximately 4 km × 3 km within the lease area of Assen deposit, covering the farms Assen 140 JQ, Assen 161 JQ, Buffelspoort 149 JQ, Doornkloof 141 JQ, Swarthoek 10 JQ in Brits district of the Northwest Province in South Africa. The computed structural trend surfaces were based on deposit scale measurements to visualise the 3D structure at Assen. The minor southeast-northwest trending faults (Fig. 23) in the study area were not all represented and mapped on the local geological map however, major reverse faults have been identified and represented that is northeast-southwest at both west and middle orebody. Two anticlines and three synclines are represented in the 3D structural trend

model, the small-scale geological structures such as minor thrust faults along with the dolerite intrusions and parasitic folds are not visible in the trend. The Assen Iron Ore general 3D structural model is well reproduced and displayed by the leapfrog computed surfaces. The 3D implicit structural trend model managed to delineate the shape and dimensions of the deposit and was able to depict well the location of the Assen deposit within the regional structural framework. The 3D implicit structural trend model outlines the shape and dimensions of the west, middle, and east syncline. In the east-west cross-section, the west orebody has an amplitude of approximately 85 m and a wavelength of approximately 400 m. The east-west cross-section of the Assen Iron Ore showed a measured amplitude of ± 30 m for east orebody, 100 m for middle with a wavelength of approximately 245 m east, 350 middle orebodies. The general structural trend surfaces dip between 35° and 60° to the north.

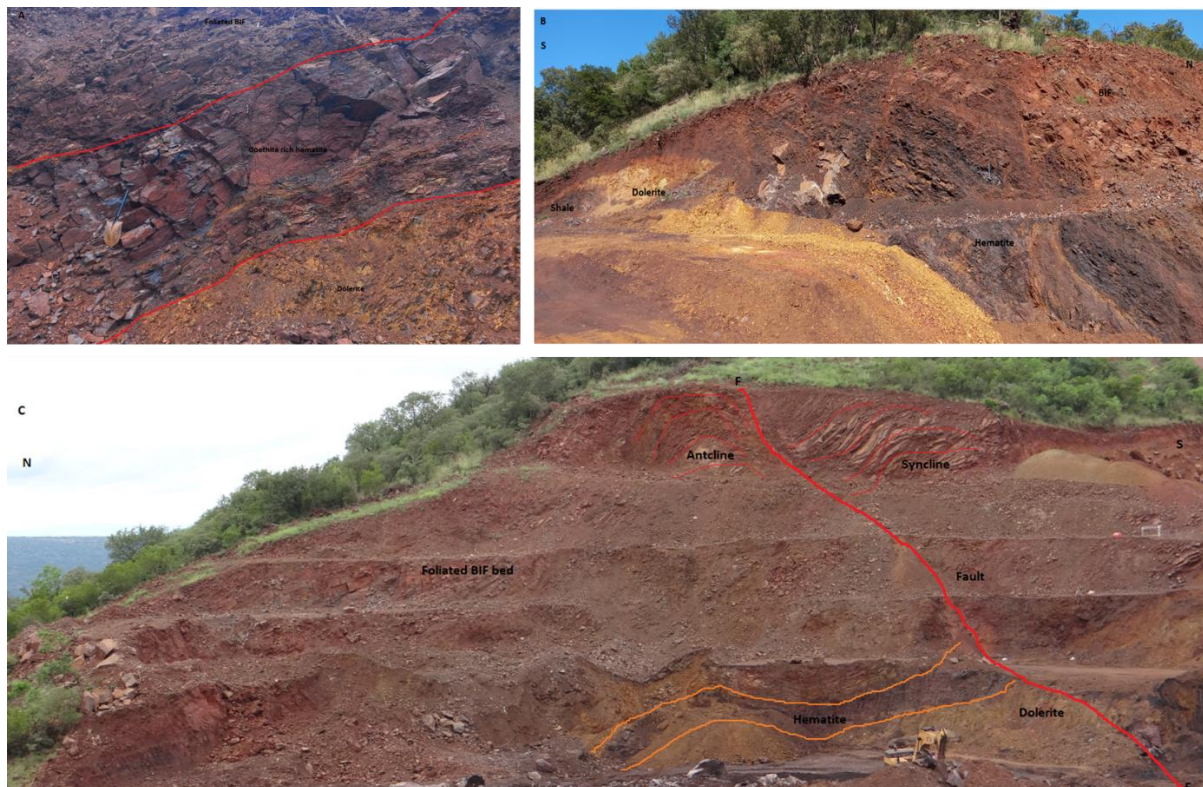


Figure 23: Field observations from the Pit1 and Pit 2 at the middle orebody of the Assen Iron Ore deposit. A) Approximately 2.5 m of shallow dipping hematite layer underlain by the dolerite. B) North-South cross-section of the outcropping shale, hematite, and dolerite dipping to the north at an angle of approximately 60° at pit 2 in the middle orebody. C) Pit 1 benches affected by the Northeast-southwest fault and the wavy hematite located above the dolerite.

CHAPTER 5

5. Mineralogy and Petrography

The mineralogic and the petrographic features of the BIF, massive, laminated, goethite-rich, and calcitic hematite facies and dolerite determined using XRD for qualitative and semi-quantitative analysis. The relationship between iron ore minerals and dolerite intrusion was assessed using an optical microscope using polished thin sections under transmitted and reflected light. The mineralogical description is done on Iron ore facies and dolerite of the Penge Iron formation at the Assen Iron Ore deposit. This section further determines different iron ores to understand their composition, association, and paragenesis. Based on the main iron minerals, Assen Iron Ores are hosted by BIF and comprise hematite ores (Massive and laminated ore), goethite-microplaty ore, calcitic hematite. From the selected representative holes, there are several iron ore horizons available at different stratigraphic depths.

5.1. Calcitic hematite

The hematite at the base of iron formations is calcite-rich and grades up to the high-grade massive/laminated hematite. The calcitic hematite is divided into three subtypes depending on the mineralogical orientation, physical properties, and textural appearance (Fig. 24): 1. Closer to the massive hematite, the calcitic hematite is composed of an alternating layer of hematite and calcite, with both hematite and calcite bands of ± 1.5 cm. 2. Approximately 4 m away from the contact with the massive hematite or laminated hematite, both hematite and calcite band become thinner, gaining more calcite until all the alternating bands disappear. 3. The third one comprises thick calcite crystals with some patches of hematite. In some areas, the calcite is intercalated to hematite.

Two synclines at Assen forming the middle and west orebody comprise at the bottom of ironstones hematite layers which alternate with calcite layers. In some localities, it looks like calcite replaced the chert layers with practically no silica. The dolerite that intruded the BIF seems to have driven the chert appears to the anticlines as these anticlines are dominated by chert. The width of the calcite layers increases from ± 1 cm closer to the contact with overlying massive or laminated hematite to 5 cm closer to the contact with dolomite in the footwall. The calcite in calcitic hematite occurs as coarse, pure white or black bands which contain fine-grained iron ore inclusions. The inclusions increase gradually and finally form a solid ironstone layer against the calcite layer. The calcite layer is often separated from dolomite by a thin shale layer. The calcitic hematite contains hematite ranging from 29.6–60.3 vol.% depending on its stratigraphic location, calcite ranging from 28.9 to 67.6 vol.%, quartz ranging from 0.7 to 3.9 vol. % and magnetite between 0 to 1.2 vol.%.

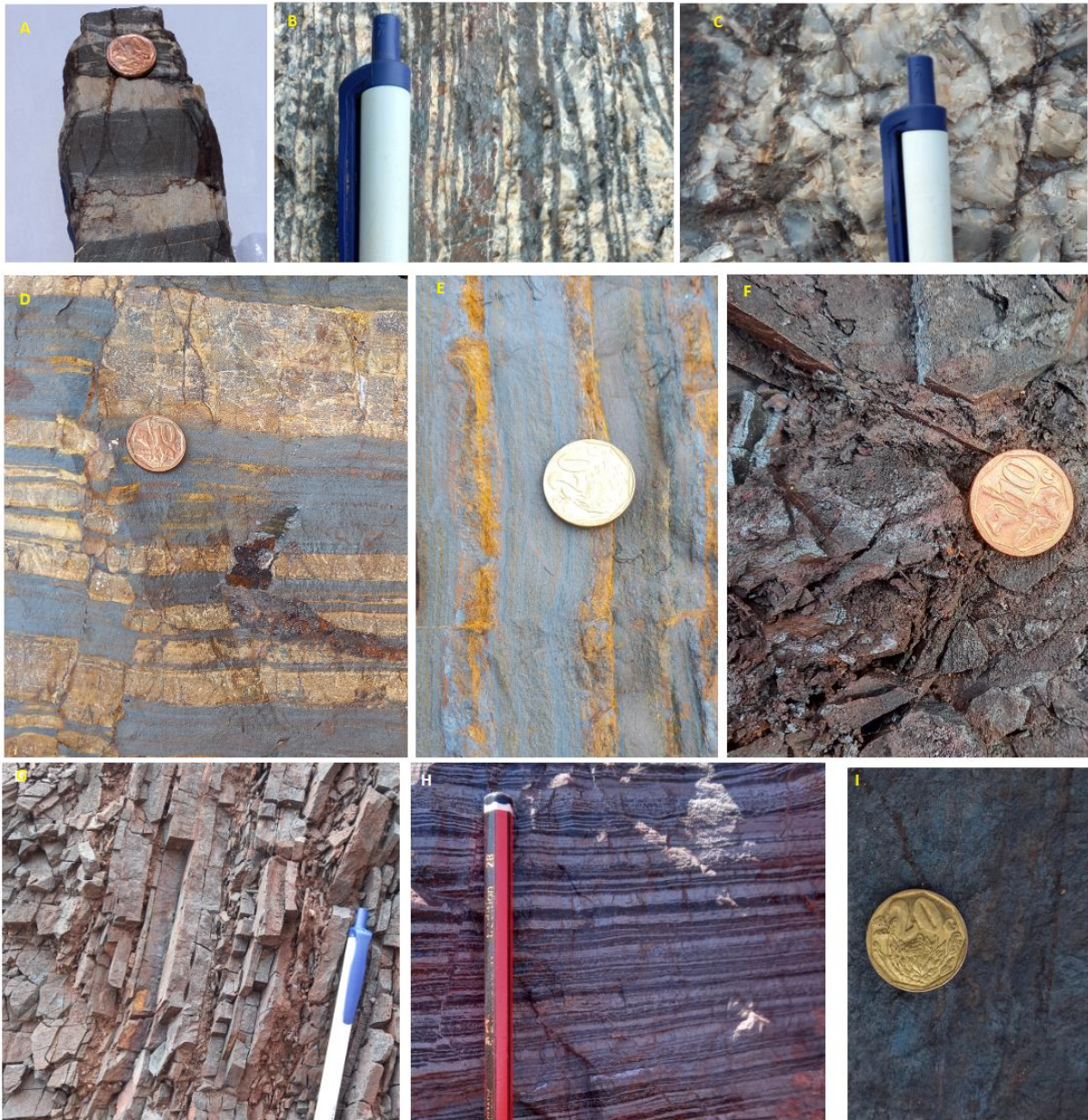


Figure 24: Photographs of representative rock samples from the west, middle, and east orebody at the Assen Iron Ore deposit representing the available iron ore facies. The ore types gradually grade from one ore type to another. The Carbonaceous facies is represented by A, B, and C. The sample A and B shows the alternating bands of hematite and calcite. Sample C is very rich in calcite having large crystals of calcite and some patches of hematite in between the crystals. BIF is represented by samples D and E, where BIF D upgrades to BIF E, with increasing Fe and decreasing SiO_2 . Sample F is a Friable goethite-rich hematite. Samples G and H are laminated hematite, micro-banding in H while G has thick bands of 0.5 mm hematite with goethite and Chert matrix between the hematite bands. Massive hematite is I, which is a bluish-grey, shiny, and flinty fine-grained hematite.

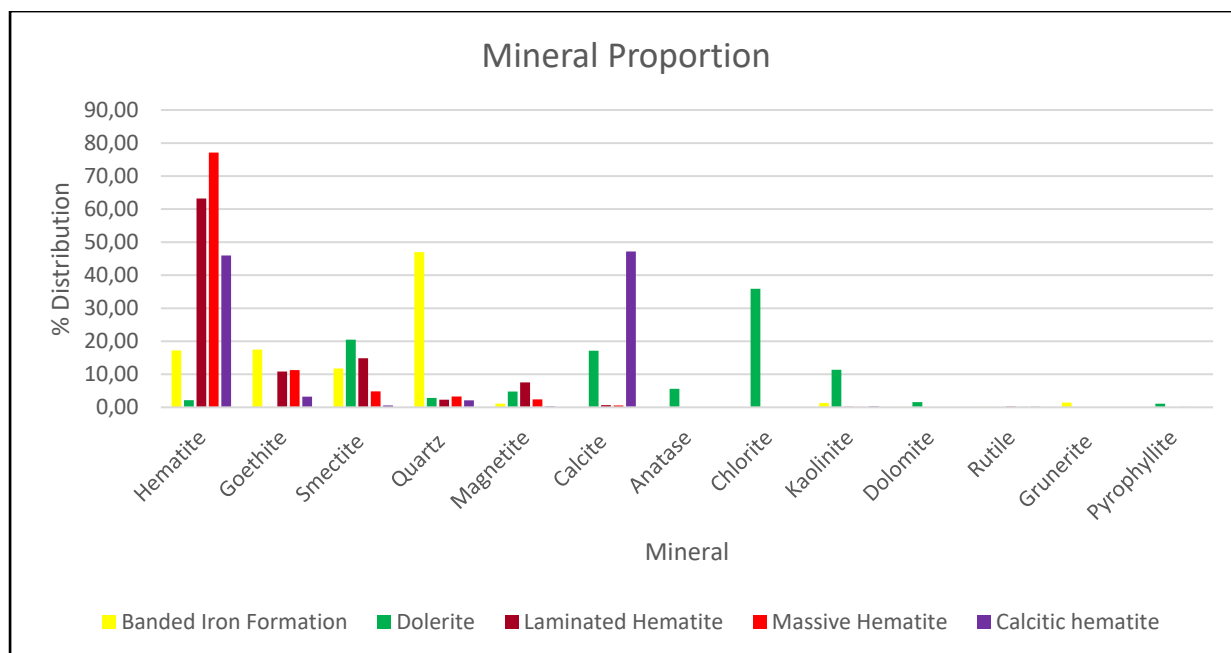


Figure 25: Semi-quantitative mineralogy in Vol.% of selected iron ore and dolerite samples from the diamond drilled hole.

5.2. Massive hematite

The massive hematite is mainly monomineralic hard, slightly, or not weathered, and composed mostly of hematite (Fe_2O_3) with minor goethite and scattered micro-quartz. Unlike microplaty and friable ore, it is not porous. The ore is shiny grey with a metallic luster (Fig. 18). Massive hematite ore is fine-grained and tightly packed forming a compact mass in this type of ore. The minor ore minerals are fine-grained quartz (SiO_2) and magnetite (Fe_3O_4). Some visible traces of Smectite mineral can be seen also. The massive hematite constitutes between 72.9–80.6 vol.% hematite, with goethite ranging from 4.5 to 16.7 vol. %, smectite is 1.3 to 8.1 vol.%, Quartz is at 1.9 to 4.7 %. magnetite and calcite are less than 2 vol.% (Fig. 25). The monomineralic massive hematite is represented by photomicrograph G in figure 26.

5.3. Laminated hematite

Hard laminated hematite ore is fine to medium-grained, reddish grey in colour, and relatively high-grade (mostly above 58 %). The ore comprises bands of hematite and exhibits similar patterns in both the west, middle and east orebody. There is a microfracture in these bands that confirms the dissolution of chert bands during the formation of hard laminated ore leaving very minor silica in the interstitial spaces that strongly indicates their mode of formation (Fig. 26). The laminated hematite modal mineral abundances are 58.8–76.7 vol.% hematite, smectite is 11 to 20.5 vol.%, goethite ranging 8.4 to 13. vol. %, magnetite at 4.9 to 9.1 vol.%, quartz at 2.4 to 2.7 vol.% calcite is less than 1.5 vol.%. The Photomicrographs in figure 26 below represent: The photo A-C are BIF depicting their textural relationship and the micro-faulting. The mesobands at sample A and B, while microbands are found in BIF C. Thick bands of alternating calcite and hematite up to 1.5 cm in Photo D., Friable goethite-rich hematite represented by E, having some stripes of very thin and wavy quartz bands. Laminated hematite F with some Scattered quartz. Monomineralic massive hematite G. Chloritised dolerite H, with some calcite spots.

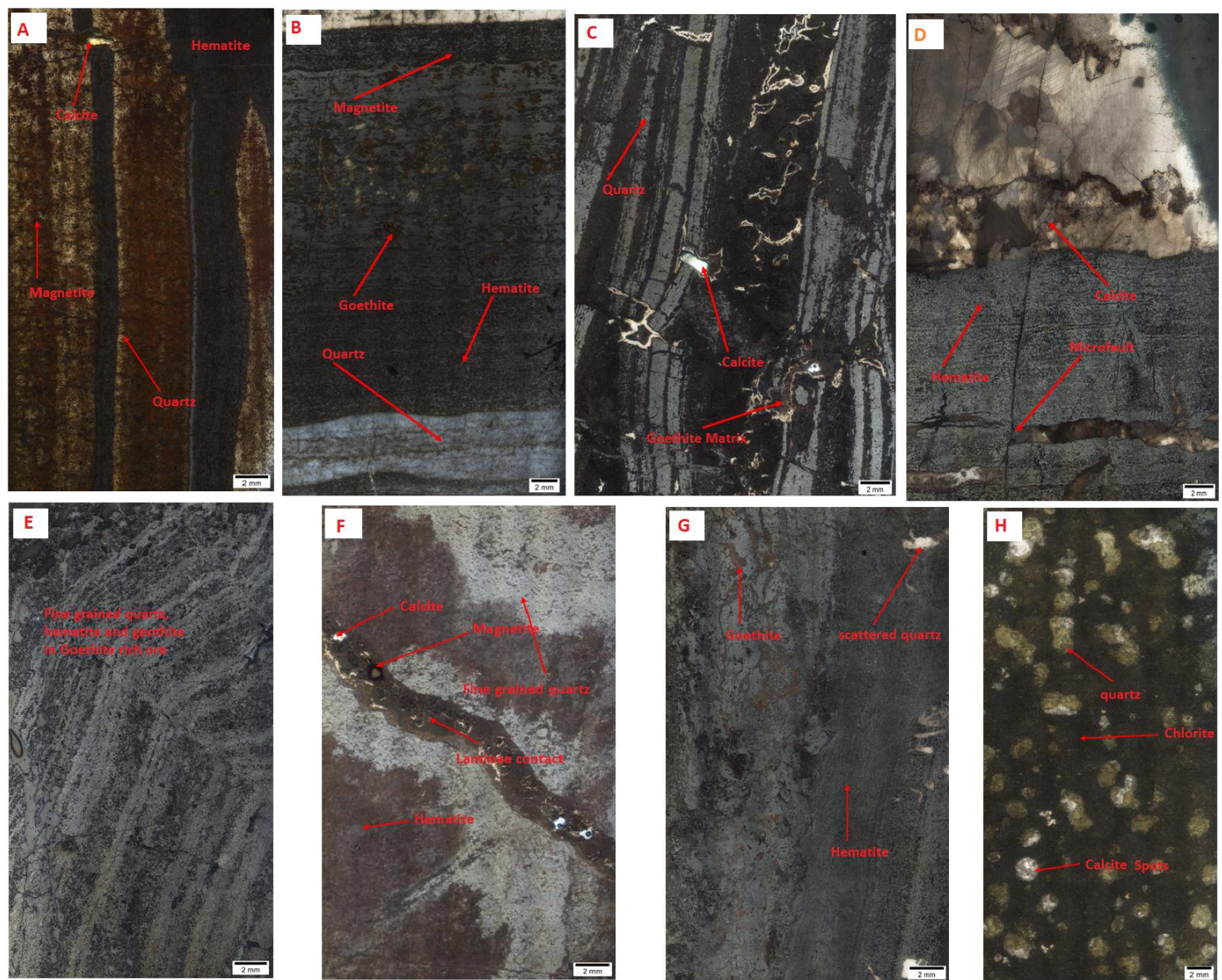


Figure 26: The reflected light image of different iron ore types (A-G): BIF (A, B, and C), calcitic hematite (D), goethite (E), laminated hematite (F), massive hematite (G) and dolerite (H).

5.4. Banded Iron Formation

The mineralogy of the BIF at the Assen deposit varies both in composition and distribution with depth. In the middle orebody, the BIF is underlain by the dolerite while in the east orebody it is mostly underlain by calcitic hematite. It is consisting of brownish-white chert bands alternating with greyish iron oxide (hematite) bands. The bands are continuous with some pinching and swelling observed from the drilled cores. Bands thickness are irregular, with the thickness of silica bands decreases with depth while the hematite thickness increases with depth. In the northern portion of the west orebody, the BIF consists of magnetite, with occasional weathered goethite, but in the middle orebody area, hematite forms the bulk of the layering in BIF. The BIF underwent metamorphism, deformation, and hydrothermal processes resulting in the changes in mineral assemblages and textures that lead to the formation of high-grade hematite and calcitic hematite deposits (Fig. 26). The three types of BIF change with stratigraphy. The type 1 BIF is completely silicified and consists of thin iron bands which alternate with thick bands of chert of up to 2.5 cm thick. The contacts between the individual layers are distinct and sharp. This BIF mostly forms the top portion in the stratigraphy. Type 2 comprises the microbanding, 0.5-6 mm thick of reddish-grey hematite and chert bands. The alternating thin layers are cut by recrystallised quartz veins and sometimes calcite veinlets. The veinlets are $\pm$ 0.5–1.5 mm thick. The greenish to yellowish amphibole is disseminated in the interband. The type 2 BIF mostly grades to type 3 BIF and still shows the well-preserved primary banding, foliated and shows locally weak layers contacts. The primary texture consists of alternating 10-50 mm thick mesobands composed of hematite and chert with minor amphiboles.

The total thickness of BIF varies from 46 m in the middle orebody to 152 m in the east orebody. It is believed that beds thickened by the process of constant shearing along the strike (Fockema, 1945). The BIF also showed the micro-faulting and micro-folding (Fig. 25 and 26) as the main orebody is also folded and faulted. These micro-structural has been observed on a local scale from the drill cores and some outcrops. Crosscutting micro-folds and micro-faults are shown to have acted also as a conduit for the fluid flow. The dominant mineral assemblage of the Assen BIF is quartz-goethite-hematite-smectite. The iron-rich bands are composed of hematite and chert, which is fine-grained quartz. The fine-grained quartz is euhedral to subhedral with grains ranging from 2 μ to 8 μ . The BIF contains 44.1–60.7 vol.% quartz, goethite ranging from 13.5 to 21.4 vol. %, smectite is 6.5 to 25.2 vol.%, hematite ranging from 5.2 to 28.4 vol.%, magnetite at 0 to 2.4 vol.% and with no calcite, ankerite, siderite, and chlorite are very minimal.

5.5. Dolerite intrusions

The dolerite exposed throughout Assen deposit at both east, middle, and west orebody and emplaced mostly parallel to the primary bedding of the iron formation. In some areas, it forms the footwall and the hanging wall of the high-grade hematite as direct contact with the orebody. The dolerite has a phaneritic texture and is greenish in appearance with visible calcite veins and amphibole to the naked eyes. The crystalline and interlocking grains are well-preserved. Microscopically, the dolerite is chloritised and hematised where it is in contact with hematite or calcitic hematite due to the hydrothermal alteration associated with the formation of this high-grade hematite ore (Fig. 20). The following mineral assemblage was observed on the dolerite: Chlorite-

smectite-calcite-Kaolinite-anatase±magnetite/hematite with olivine being absent. The Volume percentage of minerals in dolerite are chlorite at 25.5-45.1 %, smectite at 16.2–24.2 %, calcite 7.8-31.5 %, Kaolinite 8.2-14.5 %, anatase 4.4-6.5 %, magnetite 1.9-6.7 % and hematite 0.6-6.2 %.

5.6. The XRF geochemistry of iron ore

This section of chapter 5 presents and explains the chemical analyses of the BIF, its associated high-grade hematite ores, and dolerite intrusions encountered at the Assen Iron Ore deposit. The major and minor elements XRF analyses were conducted and the geochemical data were acquired from selected samples on borehole SH 015. The geochemical data from SH 015 borehole presented in table 6 are obtained by X-ray fluorescence spectrometry (XRF) using an Advant XP Sequential XRF (Thermo Fisher) to analyse the bulk chemical composition of the samples at the South African Bureau of Standards laboratory located at the Council for Scientific Industrial Research complex in Pretoria in South Africa. All elements were analysed by XRF with levels of detection of 0.01 % except for Mg which was 0.03 %. The major element compositions of samples from the borehole representing high-grade BIF/goethite, high-grade hematite ore (Massive and laminated), and calcitic hematite ore are summarised in Table 8.

The SH 015 borehole was drilled at the west orebody and the location coordinates are Y=-2780272,209 X=59543,661 and Z =1202,752. The borehole statistical parameters (mean and data correlation) of the geochemical data were done to present different elements' variations with depth and to depict how the elements compare with each other. The statistical parameters of the geochemical data are calculated in the table below. The major elements Si and Fe are dominant in both BIF, hematite ore (massive and laminated) while in calcitic hematite samples, Si is low below 6 % and Ca is high above 10 % and can be as high as 50 %. The Si, Fe, and FeO constitute > 90 wt. % in BIF and hematite ores while Ca, Fe, and FeO constitute >90 wt. % in calcitic hematite. Other constituents have low concentrations, with Mn and Al contents of <2 wt. % and other elements generally > 0.10 wt. %. The enrichment from BIF to high-grade hematite ores which are laminated, and massive hematite shows enrichment of Fe with a corresponding depletion of Si and Ca. The massive and laminated hematite (>60 %) showed strongly depleted in Mg and Ca (mobile elements) and weakly depleted to unchanged in Al and Ti immobile elements). The correlation between Fe and Si is done using the Scatter plots as they are the most dominant elements in most of the iron ore facies sampled. The samples from different iron ore facies were plotted to be able to get the relationship between these elements. The relationship between Si versus Fe is inversely proportional and depicts a clear negative correlation and this type of trend is observed in all types of iron ores.

Table 8: The exploration borehole SH 015 XRF analysis for different types of hematite with depth.

Goethite rich hematite													
Samp_ID	From	To	Si	Al	Fe	Ti	Ca	Mg	Mn	P	S	SG	FeO
H 4001	0	1	3,65	0,58	60,19	0,04	0,21	0,10	0,55	0,01	0,01	4,39	86,07
H 4002	1	2	5,59	0,50	57,16	0,04	0,40	0,17	0,53	0,02	0,01	4,10	81,75
H 4003	2	3	5,57	0,49	54,97	0,03	0,34	0,11	0,56	0,01	0,01	4,19	78,60
H 4004	3	4	3,66	0,87	58,36	0,04	0,25	0,15	0,86	0,02	0,01	4,22	83,45
H 4005	4	5	5,07	1,27	54,62	0,08	0,62	0,36	0,63	0,02	0,01	3,88	78,10
H 4006	5	6	4,94	0,88	56,27	0,05	0,10	0,20	0,50	0,01	0,01	3,95	80,45
H 4007	6	7	6,76	1,38	51,06	0,08	0,13	0,34	0,76	0,02	0,01	3,66	73,01
H 4008	7	8	5,86	1,34	51,34	0,06	0,40	0,31	0,63	0,02	0,01	3,72	73,41
H 4009	8	9	5,04	1,26	54,37	0,05	0,16	0,25	0,85	0,01	0,01	3,88	77,75
Minimum			3,65	0,49	51,06	0,03	0,10	0,10	0,50	0,01	0,01	3,66	73,01
Maximum			6,76	1,38	60,19	0,08	0,62	0,36	0,86	0,02	0,01	4,39	86,07
Arithmetic Mean			5,13	0,95	55,37	0,05	0,29	0,22	0,65	0,02	0,01	4,00	79,18
Number of Samples			9	9	9	9	9	9	9	9	9	9	9
Laminated hematite													
Samp_ID	From	To	Si	Al	Fe	Ti	Ca	Mg	Mn	P	S	SG	FeO
H 4010	9	10	4,37	1,02	56,85	0,04	0,12	0,25	1,29	0,02	0,01	4,21	81,29
H 4011	10	11	6,40	1,32	57,12	0,07	0,20	0,54	0,38	0,01	0,01	3,96	81,66
H 4012	11	12	6,21	0,42	57,99	0,03	0,08	0,15	0,23	0,01	0,01	4,19	82,93
H 4013	12	13	5,11	0,83	58,08	0,05	0,11	0,34	0,31	0,01	0,01	4,11	83,04
H 4014	13	14	3,77	0,82	60,40	0,06	0,08	0,25	0,36	0,01	0,01	4,40	86,37
H 4015	14	15	3,13	0,67	61,99	0,04	0,05	0,14	0,43	0,01	0,01	4,50	88,63
H 4016	15	16	4,16	0,68	59,61	0,05	0,09	0,23	0,33	0,01	0,01	4,29	85,23
H 4017	16	17	2,44	0,61	62,98	0,05	0,13	0,11	0,42	0,01	0,01	4,58	90,07
H 4018	17	18	2,71	0,78	60,21	0,03	0,09	0,11	0,67	0,01	0,01	4,40	86,10
H 4019	18	19	2,79	0,83	63,29	0,03	0,13	0,14	0,68	0,01	0,01	4,70	90,51
H 4020	19	20	2,09	0,41	63,13	0,02	0,05	0,13	0,21	0,01	0,02	4,56	90,27
H 4022	20	21	2,85	1,02	61,99	0,05	0,13	0,17	0,58	0,01	0,01	4,54	88,64
H 4023	21	22	2,08	0,79	61,45	0,03	0,03	0,07	0,75	0,01	0,01	4,65	87,87
H 4024	22	23	2,54	0,84	59,96	0,04	0,10	0,15	0,84	0,01	0,01	4,54	85,74
H 4025	23	24	2,23	0,87	62,78	0,05	0,11	0,17	0,49	0,02	0,01	4,61	89,78
Minimum			2,08	0,41	56,85	0,02	0,03	0,07	0,21	0,01	0,01	3,96	81,29
Maximum			6,40	1,32	63,29	0,07	0,20	0,54	1,29	0,02	0,02	4,70	90,51
Arithmetic Mean			3,52	0,79	60,52	0,04	0,10	0,20	0,53	0,01	0,01	4,42	86,54
Number of Samples			15	15	15	15	15	15	15	15	15	15	15
Massive hematite													
Samp_ID	From	To	Si	Al	Fe	Ti	Ca	Mg	Mn	P	S	SG	FeO
H 4026	24	25	1,04	0,92	66,37	0,02	0,01	0,05	0,31	0,01	0,01	4,94	94,89
H 4027	25	26	1,37	1,17	63,58	0,02	0,03	0,04	0,39	0,03	0,01	4,84	90,91
H 4028	26	27	1,31	0,83	65,39	0,04	0,02	0,07	0,47	0,01	0,01	4,90	93,49
H 4029	27	28	0,79	0,58	67,16	0,02	0,01	0,03	0,39	0,02	0,01	5,00	96,04
H 4030	28	29	0,87	0,55	64,71	0,02	0,02	0,05	0,43	0,01	0,01	4,98	92,53
H 4031	29	30	3,41	0,21	63,49	0,01	0,01	0,02	0,38	0,01	0,01	4,72	90,78
H 4032	30	31	1,29	0,67	65,20	0,02	0,03	0,07	0,46	0,02	0,01	4,92	93,24
H 4033	31	32	1,33	0,36	62,13	0,02	0,03	0,02	0,52	0,03	0,03	4,96	88,84
H 4034	32	33	0,88	0,38	66,81	0,02	0,02	0,05	0,38	0,02	0,01	5,02	95,52
H 4035	33	34	0,76	0,21	66,48	0,01	0,02	0,02	0,59	0,03	0,01	5,05	95,06
H 4036	34	35	0,78	0,43	65,50	0,01	0,13	0,06	0,40	0,06	0,02	5,09	93,66
H 4037	35	36	0,52	0,11	67,10	0,01	0,02	0,02	0,55	0,03	0,01	5,08	95,95
Minimum			0,52	0,11	62,13	0,01	0,01	0,02	0,31	0,01	0,01	4,72	88,84
Maximum			3,41	1,17	67,16	0,04	0,13	0,07	0,59	0,06	0,03	5,09	96,04
Arithmetic Mean			1,20	0,53	65,33	0,02	0,03	0,04	0,44	0,02	0,01	4,96	93,41
Number of Samples			12	12	12	12	12	12	12	12	12	12	12
Calcitic hematite													
Samp_ID	From	To	Si	Al	Fe	Ti	Ca	Mg	Mn	P	S	SG	FeO
H 4038	36	37	1,12	0,38	52,76	0,03	6,76	0,38	0,23	0,04	0,01	4,30	75,44
H 4039	37	38	0,41	0,05	42,81	0,01	11,24	0,14	0,23	0,04	0,01	4,04	61,22
H 4040	38	39	0,41	0,04	42,80	0,01	12,87	0,11	0,23	0,11	0,01	4,03	61,20
H 4041	39	40	0,46	0,04	41,52	0,01	13,30	0,22	0,22	0,06	0,01	3,95	59,36
H 4043	40	41	0,38	0,01	33,80	0,01	16,49	0,81	0,34	0,06	0,01	3,71	48,33
H 4044	41	42	0,37	0,08	31,39	0,01	18,81	0,13	0,26	0,06	0,01	3,65	44,89
H 4045	42	43	0,24	0,01	28,51	0,01	18,70	0,71	0,33	0,05	0,01	3,56	40,75
H 4046	43	44	0,36	0,02	25,31	0,01	15,57	4,58	0,69	0,06	0,01	3,46	36,18
H 4047	44	45	1,02	0,02	33,86	0,01	14,62	1,52	0,50	0,04	0,01	3,68	48,42
H 4048	45	46	0,57	0,04	34,01	0,01	15,99	0,50	0,30	0,04	0,01	3,74	48,64
H 4049	46	47	2,03	0,83	31,86	0,04	19,45	0,92	0,33	0,29	0,02	3,48	45,55
H 4050	47	48	0,27	0,03	39,23	0,01	14,57	0,08	0,19	0,06	0,01	3,91	56,10
H 4051	48	49	0,49	0,04	35,95	0,01	16,16	0,13	0,26	0,03	0,02	3,78	51,40
H 4052	49	50	0,18	0,03	30,05	0,01	18,32	0,09	0,29	0,04	0,01	3,63	42,96
H 4053	50	51	4,95	2,39	28,25	0,11	11,99	2,86	0,27	0,06	0,01	3,24	40,39
H 4054	51	52	0,17	0,03	37,42	0,01	15,89	0,07	0,21	0,05	0,01	3,93	53,50
H 4055	52	53	0,29	0,10	34,55	0,01	15,84	0,10	0,29	0,07	0,01	3,79	49,40
Minimum			0,17	0,01	25,31	0,01	6,76	0,07	0,19	0,03	0,01	3,24	36,18
Maximum			4,95	2,39	52,76	0,11	19,45	4,58	0,69	0,29	0,02	4,30	75,44
Arithmetic Mean			0,81	0,24	35,53	0,02	15,09	0,78	0,30	0,07	0,01	3,76	50,81
Number of Samples			17	17	17	17	17	17	17	17	17	17	17

In goethite-rich hematite, there is a decrease in % Fe as the drilling depth increases while the % Si showed the inverse relation. The % Si decreases as the drilling depth increases (Table 8). Laminated hematite is showing the inverse relationship of % Fe and % Si when compared to the goethite-rich hematite. The % Fe increases with the increase in drilling depth, while the % Si decreases. It is expected in most iron ore minerals that the relationship between Fe and Si is always inverse unless other elements are increasing like in the calcitic hematite where calcium will have an impact. Massive hematite is showing good homogeneity of all the elements results. Even if the drilling depth increases the results fairly remain consistent with little variation among the samples during 12 m of the drilling depth. Calcitic hematite shows a decrease in % Fe as the drilling depth increases, while the % Si is indicating consistent analysis with 2 samples results that can regard as outliers (Fig. 27). This relationship is due to the increase in the % Ca with an increase in the drilling depth. As the drilling is increasing towards the base, which is the dolomitic limestone, it is expected that the % Ca increase as the depth is approaching the dolomitic limestone as it is high in calcium.

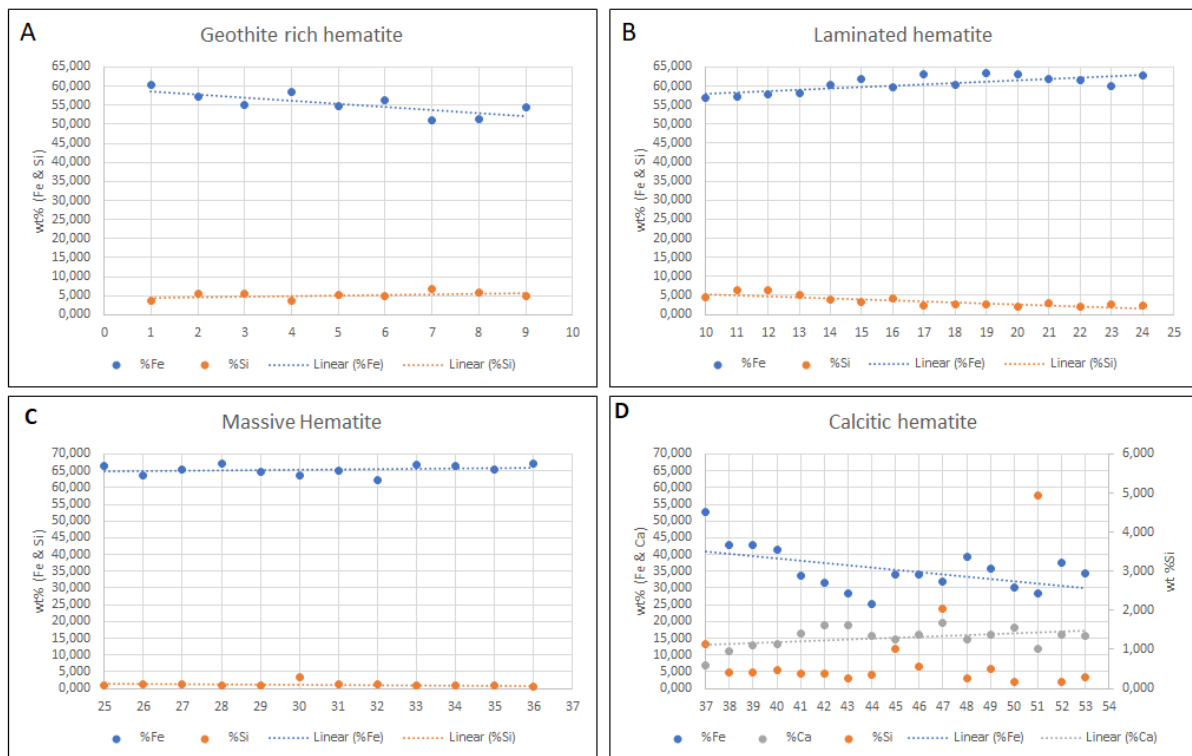


Figure 27: Element's correlation graphs in different iron ore lithologies representing: A. Goethite-rich hematite, B. Laminated hematite, C. Massive hematite, and D. Calcitic hematite.

Another selected borehole is ASNRC 001 representing the full stratigraphy of the Assen Iron Ore deposit and covers all the iron ore facies, dolerite, shale, and dolomite but only the portion of hematite overlain and underlain by dolerite was selected and the XRF results analysed for this study. The major oxides and elements analysed are SiO_2 , Al_2O_3 , Fe, TiO_2 , CaO, MgO, KO, MnO, P, S, and FeO. The borehole results were taken from 70 to 120 m depth. The Forty (40 m) meters of hematite ore is overlain by and underlain by dolerite. The six (6 m) meters of dolerite were taken on the hanging wall and 4 m on the footwall.

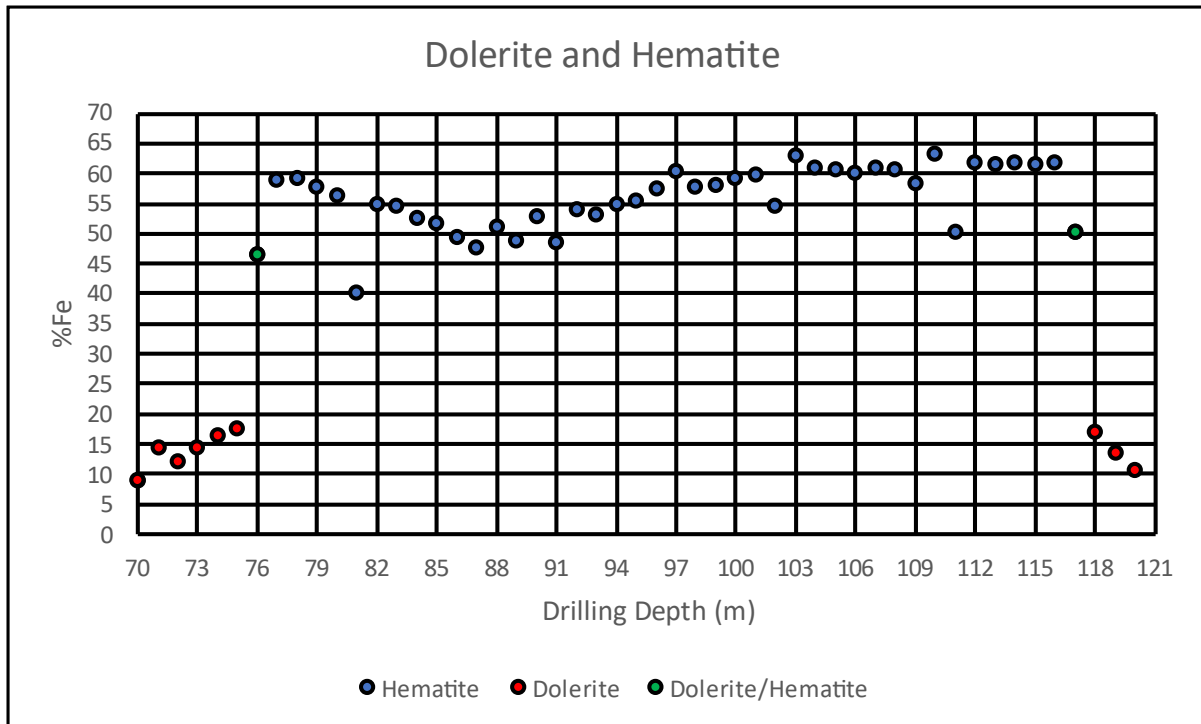


Figure 28: Dolerite Vs hematite graph showing the high Fe concentration towards the dolerite contacts. Red dots indicate the dolerite, green dots indicate the dolerite/hematite transaction, blue dots indicate hematite. Hematite (% Fe) shows an increase when it is near the dolerite and decreases as it moves further away from the dolerite.

The results confirmed that high-grade hematite (59 % and above) enrichment is closer to the contact. High Fe content is proximal to the dolerite. The Figure above is showed the relationship between the dolerite and the Fe content (Fig. 28). As the % Fe is enriched, the depletion of SiO_2 , CaO , MgO , K_2O and MnO was observed.

CHAPTER 6

6. Discussion

The high-grade iron ores at the Assen deposit can be broadly divided into the following categories: Massive, laminated, goethite-rich friable, and calcitic hematite. The iron enrichment is from the hangingwall BIF. These types of iron ores occur in close association with dolerite sills. Another thin layer of hematite is also associated with shale especially at the east orebody and along the shale that occurs immediately above the dolomitic limestone. For these different types of iron ores, different processes lead to different textures and mineral orientations, mineral assemblage due to fluids involved. The time and sequence of the removal of the silica and other deleterious elements from BIF also played a major role even though they occurred at different stratigraphic positions.

6.1. Paragenesis of different iron ore types

The different types of iron ores with varying percentages of Fe; formed because of BIF alteration processes and the geological structures that either acted as conduits, barrier or traps which resulted in the iron solutions forming a hematite deposit. The Supergene iron ore that occurred along the dolerite hanging wall in both the middle and west orebody showed that the hydrothermal fluids or low-temperature supergene fluid from the surface carrying iron oxides failed to penetrate the dolerite and precipitated along the dolerite to form a friable and goethite rich hematite ore. After this supergene process, the remaining material in the process was a thick chert band up to 2.5 cm separated by micro bands of hematite, showing that the silica (Si) was immobile while the ferric oxide was leached out with no calcite and dolomite from the BIF. The ore is not competent, it is porous, and can easily be mined without any blast. It is locally deposited above the dolerite sills or the shale layer. The primary texture of the parent rock is destroyed in the settled residue.

The Assen Iron Ore deposit postulates the downward increases in iron percentage, downward reduction in silica, and downward increase in calcium oxide during the transformation of unmineralised low iron BIF to high-grade hematite ore. This offered proof for the interaction and alteration of BIF by the hydrothermal fluids in both east, middle, and west orebody. The different alterations of BIF led to the transformation of one iron ore type to another by hydrothermal fluids supported by the existing geological structures. The laminated hematite (55-59 % Fe) and high-grade BIF (50-55 % Fe) ore types showed some clear removal of almost all silica in between hematite bands to partial removal of silica in the high-grade BIF (Fig. 24). Both high-grade BIF and laminated hematite remained with the preserved primary layers of hematite bands that compacted through time due to pressure and folding to form a laminated bedded iron ore. The space that was occupied by silica is filled with thin and scattered recrystallised quartz or occupied by the goethite matrix. The high iron BIF (50-55 %) upgraded to laminated hematite and the two are the second most abundant type of ore after calcitic hematite. According to Taylor et al. (2001), the low temperature reduced and alkaline basinal brine hydrothermal fluids of temperature between 150° to 250°C containing a high concentration of sodium and magnesium salts most likely dissolved silica in BIF to leave the primary iron and carbonate. The very same process is believed to have resulted in the formation of the type of hematite found at Assen Iron Ore. The silica (SiO₂) reduction and depletion increase with

depth until the silica bands are completely replaced by calcite. The calcite that replaced chert at the bottom of the stratigraphy is coming from the underlying dolomitic limestone. The calcite veins are visible where the dolomite is blasted to create the access roads towards calcitic hematite, cutting across the dolomite to intersect the calcitic hematite at the footwall of Iron Formation. The calcium oxide is very low in the laminated, massive and hangingwall BIF which is less than 3 % CaO, showing that the calcite rich fluids didn't pass through to the hangingwall rocks.

6.2. The relationship between the dolerite and hematite ores

The spatial relationships between the dolerite and the high-grade hematite ores is that the dolerite intrusions influenced the deposition of the hematite as reflected by the mineral assemblage proximal and distal to the dolerite. To assess and comment on these relationships, different boreholes samples were taken to analyse the minerals closer and at distance from the contacts reviewing the occurrence of iron ore mineralisation. The current study postulates that the dolerite sills have a direct relationship with the iron ores enrichment. The XRF analysis from the drilled cores showed clear evidence that at closer contacts, hematite bodies in contact with sills, underwent the enrichment in iron content and reduction in silica because of its proximity to the dolerite. The hematite ore of Fe greater than 60 % is mostly overlain by dolerite.

In most areas, the hematite mineralisation follows the strike and dip direction of the dolerite intrusions and their lateral extent. Where the intrusion terminates, the mineralisation thins. In the absence of dolerite, the sudden decrease in the grade of hematite occurs and the Fe significantly drops with an increase in silica, making it to be the BIF. The dolerite intruded the BIF and the dolomite, but it is younger than the high-grade hematite mineralisation. The east orebody is least affected by the dolerite and the hematite ore is very thin as compared to the middle and west orebody. The thin layer of hematite which is approximately 4 m or less in thickness is located above the iron-rich black shale. The hematite in this area is also high in silica >10 % and to the far eastern portion of the orebody, no hematite intersected from the boreholes, only the BIF underlain by dolomitic limestone is present.

In some locations like at the northern side of the middle ore body, hematite occur as a xenoliths within the dolerite sill where the fine-grained hematite is enclosed within the dolerite. At the edge or contact, the hematite reacts with dolerite to be one rock type. In areas like east orebody, which is least affected by the dolerite, the thick BIF is up to 60 m and is underlain by the dolomite or shale layer. Borehole A60 and A61 above are examples of areas in the east orebody with no dolerite and no hematite exists or thin dolerite with less than 6 m hematite exists above it. In some places like in the middle orebody, the dolerite branches up, creating a y-shape where the iron ore mineralisation is along all the dolerite branches. This confirms that mineralisation happened after the intrusion of the east-west trending dolerite sills, and it may have happened between 2.435 and 2.460 Ga.

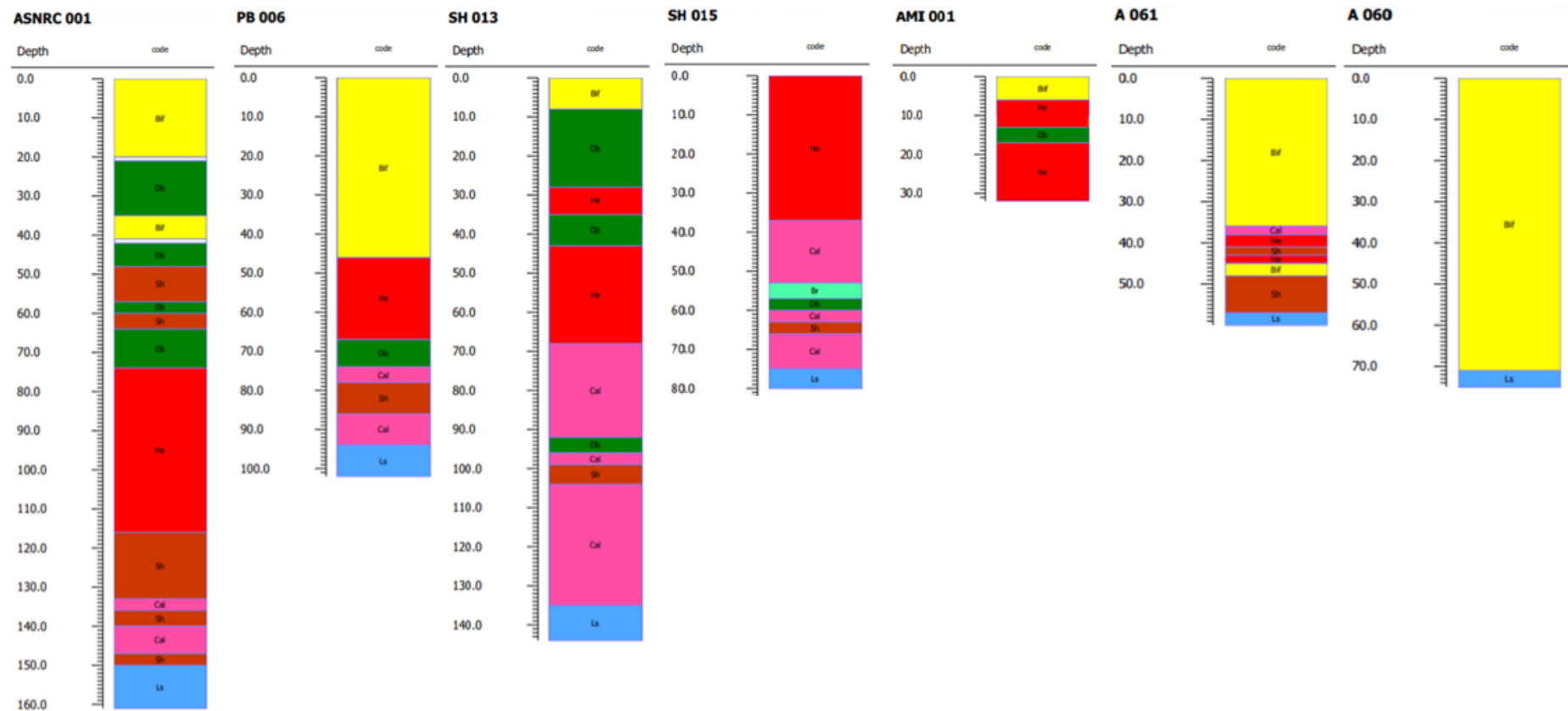


Figure 29: The stratigraphy of different boreholes located at Assen Iron Ore showing the location of hematite (red) in relation to the dolerite (green). ASNRC 001, the hematite is located on the dolerite footwall, PB 006- high-grade hematite is in the hangwall of the dolerite, In SH 015 and AMI 001- The hematite is located both at the hangingwall and footwall of the dolerite sill branches, in A 061 thin hematite is associated with shale and in A61, no hematite intersected.

6.3. The relationship between the Faults and folds with hematite ores

The dolerite sills at Assen intruded Transvaal supergroup BIF first, thus confirming the studies done by Chisonga (2012) in Thabazimbi iron ore that occurs in the same stratigraphy of Penge Formation, that the sills are younger than the BIF but older than the hematite mineralisation. Both the dolerite intrusions and BIF were later affected by the three stages of folding (F1, F2, F3-Folds) and reverse faulting (Hartzer, 1989), causing deformation and partial metamorphism due to the proximity to the Bushveld Complex granites which surrounds the Crocodile River Inlier resulting in the alteration of the original mineralogy, geochemistry, and visual appearance of the rocks. In the geological map produced at Assen for this study, it showed the northeast-southwest trending faults and the strike-slip faults. The hematite is enriched along the fault planes. The 59-67 % Fe laminated hematite in pit 2 of the middle orebody is also located at northeast-southwest trending reverse fault.

6.4. Fe grade distribution in the Assen Iron Ore deposit

The Fe in the hematite domain showed negative skew distribution across all three orebodies (east, middle, and west). The west orebody hematite data sets indicate the highest mean composite grade Fe 61.21 %, middle at 59.35 % Fe and the east orebody hematite has the lowest mean values of 57.29 % Fe. The negatively skew distribution in the hematite domain might be due to the result of smearing of low-grade values from the dolerite contacts as they predominate in the area as sills. In both the middle and west orebody, Fe has a normal distribution in the calcitic hematite. In the BIF, Fe displays a bimodal distribution which is due to the smearing of the high-grade values from the contacts between the hematite and BIF and scattered hematite lenses found in BIFs. Other elements are characterised by a positively skewed distribution across all the domains. Due to lower Fe grade in the upper portions of the high-grade hematite orebody, the east orebody hematite was statistically further subdivided into two grade domains, low-grade domain (55–60 % Fe) and high-grade (>60 % Fe).

CHAPTER 7

7. Conclusions

The conclusion for the relationship between dolerite intrusion and iron ore grade is based on the 3D implicit models, Detailed field maps, extensive petrographic and geochemical analysis with special attention to the SiO_2 , CaO , and MgO . From the study, it was deduced that the spatial relationships between the dolerite and the high-grade hematite ores suggest that the dolerite intrusions influenced the deposition of the hematite as reflected by the mineral assemblage proximal and distal to the dolerite. The study demonstrated that the hematite mineralisation is linked to local dolerite intrusion as also depicted by the 3D implicit models which enhances the identification and assessment of structural controls on hematite mineralisation. It also demonstrated the importance and the role of dolerite sills in locally controlling and remobilising iron ore mineralisation on precipitation and deposition of orebodies. The deformed BIF provided the channel ways for iron-rich fluids to flow down the stratigraphy during the process of ore enrichment.

The prominent contributors for the formation of types of hematite ore with different grades are the dolerite intrusions and reddish and black shale which often occurs immediately above Malmani dolomite. The pale grey massive hematite often occurs below the dolerite, and it overlies banded calcitic hematite. This type of hematite also occurs above the shale layer. A goethite rich hematite and occurs above the dolerite and in the hinge where the dolerite is folded. The laminated hematite is also found along the fault planes. The hematite always formed a sharp contact with the dolerite. Proximal to the dolerite intrusion, especially within 2 m either on the hangwall or footwall of dolerite, the hematite showed a sudden increase in Fe while the major oxides SiO_2 , CaO , and MgO decreases while in the distal portions, the Fe decrease while the major oxides SiO_2 , CaO , and MgO increases. In most areas, the hematite mineralisation follows the strike and dip direction of the dolerite intrusions and their lateral extent. Where the intrusion terminates, the mineralisation thins or sudden change in the grade of hematite occurs and the Fe significantly drops with an increase in silica, making it to be the BIF. The cores analysed showed the downward increases in % iron (Fe), downward decrease in silica (SiO_2) in both BIF, goethite, laminated and massive hematite. The calcitic hematite showed a downward decrease in iron (Fe) and a downward increase in calcium (Ca).

The sequence of high-grade iron ore facies at the Assen Iron Ore mine occurs as strata bound and is closely associated with dolerite intrusions, shale, and dolomitic limestone. These facies are located at the southern major anticline of the Crocodile River Inlier of the Transvaal Supergroup, acting as Xenolith within the Bushveld Igneous Complex. The BIF experienced three phases of successive deformations (F1, F2, and F3) resulting in bedding to be folded and refolding, foliation, and major and minor faults. The studies integrated diamond and reverse circulation borehole data interpretation and petrographic studies of the high-grade hematite host BIF and the associated iron ores, lithological, structural control on the localisation and genesis of the high-grade hematite iron ores. The hematite ores are mainly controlled by the structural features such as folds and faults which have channelled the migration of ore fluids either by hypogene or supergene processes and deposited on the hanging wall or footwall of the dolerite intrusion, on the fault plan and hinge of the synclines.

The steepness of the bedding BIF might have also contributed to or facilitated the leaching of hematite, especially the goethite-rich hematite that formed through the supergene process. The laminated hematite (55-59 % Fe) and high-grade Fe in BIF (50-55 % Fe) ore types showed some clear removal of almost all silica in between hematite bands to partial removal of silica in the high Fe BIF. Both high-grade BIF and laminated hematite remained with the preserved primary layers of hematite bands that compacted through time due to pressure and folding to form a high-grade bedded iron ore. The space that was occupied by silica is at places filled with thin and scattered recrystallised quartz or goethite matrix. The goethite-rich, friable soft hematite, sometimes in a dark grey powder was formed by the weathering and dissolution of Fe from the BIF by the descending surface or meteoric water.

References

- Anhaeusser, C.R. 2006. A re-evaluation of Archean intracratonic terrane boundaries on the Kaapvaal Craton, South Africa: Collisional suture zones? In: W.U. Reimold and R.L. Gibson (Editors) Processes on the Early Earth, Geological Society of America special publication, Boulder Company, 405, 315-332.
- Bekker, A., Planavsky, N., Rasmussen, B., Krapez, B., Hofmann, A., Slack, J., Rouxel, O. and Konhauser, K. 2014. Iron formations: Their origins and implications for ancient seawater chemistry. In: H.D. Holland and K.K. Turekian (Editors) Treatise on geochemistry. Oxford, United Kingdom, Elsevier, 561-628.
- Beukes, N.J., Gutzmer, J. and Mukhopadhyay, J. 2003. The geology and genesis of high-grade hematite iron ore deposits. Applied Earth Science, 112, 18-25.
- Beukes, N.J., Gutzmer, J. and Mukhopadhyay, J. 2002. The geology and genesis of high-grade hematite iron ore deposits. Australasian Institute of Mining and Metallurgy, 7, 23-29.
- Button, A. 1981. The Cratonic environment, The Pongola Supergroup. In: D. R. Hunter (Editor) Precambrian of the Southern Hemisphere. Elsevier, 501-510.
- Cairncross, B., Beukes, N.J. and Gutzmer, J. 1997. The Manganese Adventure, Associated Ore and Metal Corporation Limited, Johannesburg, 236 pp.
- Cheney, E.S. 1996. Sequence stratigraphy and plate tectonic significance of the Transvaal succession of Southern Africa and its equivalent in Western Australia. Precambrian Research, 79, 3-24.
- Chisonga, B.C. 2012. Proterozoic mafic dykes and sills associated with BIF-hosted iron ore, South Africa-Implications for the distribution of the Bushveld and Umkondo large igneous provinces. Doctoral dissertation Thesis (unpubl.). University of Johannesburg, Johannesburg, South Africa.
- Clout, J.M.F. and Simonson, B.M. 2005. Precambrian iron formations and iron-formation hosted iron ore deposits. Economic Geology, 100th anniversary, 643-679.
- De Villiers, J.E. 1944. The origin of the iron and manganese deposits in the Postmasburg and Thabazimbi area. Transvaal Geological Society of South Africa, 47, 123-135.
- De Waal, S. A. 1963. Die plooikompleks van die Sisteem Transvaal noord van Marble Hall en die meegaande metamorfe en intrusiegesteentes. Master thesis, University Pretoria, Pretoria, South Africa.
- De Wit, M.J., Roering, C., Hart, R.J., Armstrong, R.A., De Ronde, C.E.J., Green, R.W.E., Tredoux, M., Peberdy, E. and Hart, R.A. 1992. Formation of an Archaean continent, Nature, 357, 6379, 553-562.

Dulski, M. B. P. 1996. Distribution of yttrium and rare-earth elements in the Penge and Kuruman iron-formations, Transvaal Supergroup, South Africa. *Precambrian Research*, 79, 37-55.

Eglington, B. M. and Armstrong, R. A. 2004. The Kaapvaal Craton and adjacent orogens, southern Africa: a geochronological database and overview of the geological development of the craton. *South African Journal of Geology*, 107, 13-32.

Eriksson, P.G., Altermann, W. and Hartzler, F.J. 2006. The Transvaal Supergroup and its precursors. In: M.R. Johnson, C.R. Anhaeusser and R.J. Thomas (Editors) *The Geology of South Africa*, Geological Society of South Africa and Council for Geoscience, Johannesburg, 237-260.

Eriksson, P.G., Catuneanu, T. O., Els, B.G., Bumby, A.J., Van Rooy, J.L. and Popa, M. 2005. Kaapvaal craton: Changing first- and second-order controls on sea level from c. 3.0 Ga to 2.0 Ga. *Sedimentary geology*, 176, 121-148.

Eriksson, P.G. and Clendenn, C. W. 1990. A review of the Transvaal Sequence, South Africa. *Journal of African Earth Sciences*, 10, 1/2, 101-116.

Eriksson, P. G., Rigby, M. J., Bandopadhyay, P. C. and Steenkamp, N. C. 2011. The Kaapvaal Craton, South Africa: no evidence for a supercontinental affinity prior to 2.0 Ga?'. *International Geology Review*, 53, 1312-1330.

Eroglua, S., Schoenberg, R., Wille, M., Beukes, N. and Taubald, H. 2015. Geochemical stratigraphy, sedimentology, and Mo isotope systematics of the ca. 2.58-2.50 Ga-old Transvaal Supergroup carbonate platform, South Africa. *Precambrian Research*, 266, 27-46.

Fockema, R. A. P. 1945. The geology South of The Confluence of The Pienaars and Crocodile Rivers. *Transvaal geological Society of South Africa*, 51, 63-75.

Government of Western Australia Department of Jobs, Tourism, Science and Innovation. 2020. *Western Australia Iron Ore Profile*.

Gross, G.A. 1980. A classification of iron-formation based on depositional environments. *Canadian Mineralogist*, 18, 215-222.

Gutzmer, J., Mukhopadhyay, J., Beukes, N. J., Pack, A., Hayashi, K. and Sharp, Z. D. 2006. Oxygen isotope composition of hematite and genesis of high-grade BIF-hosted iron ores. *Geological Society of America Memoir*, 198, 257-268.

Hagemann, S.G., Angerer, T., Duuring, P., Rosière, C.A., Figueiredo e Silva, R.C., Lobato, L., Hensler, A.S. and Walde, D.H.G. 2016. BIF-hosted iron mineral system. A review: *Ore Geology Reviews* 2016, 76, 317-359.

Hammerbeck, E.C.I., Fourie, G.P., Snyman, A.A. and Schoeman, J.J. (eds.) 1976. *Iron, Mineral Resources of the Republic of South Africa. Handbook 7*, 147-158.

Hartzer, F.J. 1995. Transvaal Supergroup inliers: geology, tectonic development and relationship with the Bushveld Complex, South Africa. *Journal of African Earth Sciences*, 21, 4, 521-547.

Hartzer, F. J. 1989. Stratigraphy, structure, and tectonic evolution of the Crocodile River Fragment. *South African Journal of Geology*, 92, 2, 110-124.

Hartzer, F.J. 1987. Die Geologie van die Krokodil rivier fragment, Transvaal. Master of Science dissertation Thesis, Rand Afrikaans University, Johannesburg, South Africa.

Jahn, B. M. and Condie, K.C. 1995. Evolution of the Kaapvaal craton as viewed from geochemical and Sm-Nd isotopic analyses of intracratonic pelites. *Geochimica et Cosmochimica Acta*, 59, 2239-2258.

James, H. L. 1992. Precambrian Iron-Formations: nature, origin, and mineralogic evolution from sedimentation to metamorphism. In: K.H. Wolf and G.V. Chilingarian (Editors) Reprinted from: *Diagenesis, III. Developments in Sedimentology*, 47.

Klein, C. 2005. Some Precambrian banded iron-formations (BIFs) from around the world: Their age, geologic setting, mineralogy, metamorphism, geochemistry, and origins. *American Mineralogist*, 90, 10, 1473-1499.

Klemm, D. D. 2000. The formation of Palaeoproterozoic BIFs and their associated Fe and Mn deposits, with reference to the Griqualand West deposits, South Africa. *Journal of African Earth Sciences*, 30, 1, 1-24.

Lascelles, D. F. 2007. Black smokers and density currents: A uniformitarian model for the genesis of banded iron-formations. *Ore Geology Reviews*, 32, 381-411.

Lenhardt, N. and Eriksson, P. G. 2012. Volcanism of the Palaeoproterozoic Bushveld Large Igneous Province: The Rooiberg Group, Kaapvaal Craton, South Africa. *Precambrian Research*, 214-215.

Mineral Corporation. 2012. Preliminary Technical Due Diligence and Prospectivity Report on the Assen Deposit, Northwest Province, South Africa, Internal report No. C-MNG-AIO-1248-781.

Miyano, T. and Beukes, N. J. 1997. Mineralogy and Petrology of the Contact Metamorphosed Amphibole Asbestos-bearing Penge Iron Formation, Eastern Transvaal, South Africa. *Journal of petrology*, 38, 5, 651-676.

Moeller, V., Klemm, R., Joachimski, M., and Barton Jr., J.M. 2014. Hydrothermal controls on iron and lead mineralisation on the farms Leeuwbosch and Cornwall, Thabazimbi District, South Africa. *Ore Geology Reviews*. 63, 40-63.

Mohanta, M.K. 2007. Geochemistry of iron ores. In: *Proceeding of iron ore*. Jamshedpur, 44-57.

Moore, J.M., Tsikos, H.A.N.D. and Polteau, S. 2001. Deconstructing the Transvaal Supergroup, South Africa: implications for Palaeoproterozoic palaeoclimate models. *Journal of African Earth Sciences*, 33, 437-444.

Morris, R. C. 1998. BIF-hosted iron ore deposits-Hamersley style. *AGSO Journal of Australian Geology & Geophysics*, 17, 4, 207-211.

Morris, R. C. 1980. A textural and mineralogical study of the relationship of iron ore to Banded Iron Formation in the Hamersley Iron Province of Western Australia. *Economic geology*, 75, 184-209.

Netshiozwi, S.T. 2002. Origin of high-grade hematite ores at Thabazimbi Mine, Limpopo Province, South Africa. Master of Science dissertation Thesis (unpubl.), Rand Afrikaans University, Johannesburg.

Petzer, K. 2015. Final Resource Statement. K&J Technical Services, Assen Iron Ore, Internal Report No. 06/15, South Africa.

Petzer, K. 2013. Geological Report Assen Iron Ore Deposit. K&J Technical Services, Internal Report No. 07/13, South Africa.

Poujol, M., Robb, L.J., Anhaeusser, C.R. and Gericke, B. 2017. A review of the geochronological constraints on the evolution of the Kaapvaal Craton, South Africa. *Precambrian Research*, 127, 181-213.

Poujol, M., Robb, L.J., Anhaeusser, C.R. and Gericke, B. 2002. Geochronological constraints on the evolution of the Kaapvaal Craton. *Economic geology research institute information circular*, University of the Witwatersrand, Johannesburg, South Africa, 360, 1-37.

Pownceby, M. I., Hapugoda, S., Manuel, J., Webster, N.A.S. and MacRae, C. M. 2019. Characterisation of phosphorus and other impurities in goethite-rich iron ores -Possible P incorporation mechanisms. *Minerals Engineering*, 143, 106022.

Ramanaidou, E.R. and Wells, M.A. 2014. Sedimentary hosted iron ores. In: H.D. Holland and K.K. Turekian (Editors) *Treatise on Geochemistry* (Second Edition), Elsevier, Oxford, 13, 313-355.

Ramotoroko, C. D., Ranganai, R. T. and Nyabeze, P. 2016. Extension of the Archaean Madibe-Kraaipan granite-greenstone terrane in southeast Botswana: Constraints from gravity and magnetic data. *Journal of African Earth Sciences*, 123, 39-56.

Shaltami, O. R., De Morais, D., Fares, F. F., EL Oshebi, F.M., Errishi, H. and Bustany, I. 2020. Iron ores: A review. The 22nd International Conference on Ore Deposits (ICOD2020) at: University of Dar es Salaam, Tanzania. (Accessed September 2020: <https://www.researchgate.net/publication/344150935>).

Smith, A. J. B. 2018. The Iron Formations of Southern Africa. In: S. Siegesmund, M.A.S. Basei, P. Oyhantçabal and S. Oriolo (Editors.) *Geology of Southwest Gondwana, Regional Geology Reviews*, Springer International Publishing, 469-491.

Smith, A. J. B. and Beukes, N.J. 2016. Palaeoproterozoic BIF hosted High-Grade Hematite Iron Ore Deposits of the Transvaal Supergroup. *Journal of international geoscience*, 39, 2, 270-282.

Steinhöfel, G., Von Blanckenburg, F., Horn, I., Konhauser, K. O., Beukes, N. J. and Gutzmer, J. 2010. Deciphering formation processes of banded iron formations from the Transvaal and the Hamersley successions by combined Si and Fe isotope analysis using UV femtosecond laser ablation. *Geochimica et Cosmochimica Acta*, 74, 2677-2696.

Strauss, C.A. 1964. The iron ore deposits in the Thabazimbi area, Transvaal. In: S.H. Haughton (Editor) *The geology of some Ore Deposits in Southern Africa*, II. Geological Society of South Africa. Johannesburg, 383-392.

Trendall, A. F. and Blockley, J. G. 1970. The iron formations of the Precambrian Hamersley Group, Western Australia, with special reference to the associated crocidolite. *Geological Survey of Western Australia Bull*, 119, 366.

Taylor, D., Dalstra, H.J., Harding, A.E, Broadbent, G.C. and Barley, M.E. 2001. Genesis of high-grade hematite orebodies of the Hamersley Province, Western Australia. *Economic Geology*, 96, 837-869.

U.S. Geological Survey. 2020. Mineral commodity summaries 2019. U.S. Geological Survey. (Accessed July 2020: <https://doi.org/10.3133/mcs2019>).

U.S. Geological Survey. 2020. Mineral commodity summaries 2020. U.S. Geological Survey. (Accessed July 2020:<https://doi.org/10.3133/mcs2020>).

Van Deventer, J.L., Eriksson, P.G., Snyman, C.P. 1986. In: C.R. Anhaeusser and S. Maske (Editors) *Mineral Deposits of Southern Africa*. Geological Society of South Africa, Johannesburg, 923-929.

Van Deventer, J.L. 1985. Die Ontwikkeling van 'n Eksplorasiemodel vir Ystererts in die Pengeformasie by Thabazimbi. Master of Science dissertation Thesis (unpubl.), Pretoria, University of Pretoria.

Verwoerd, W. J. 1963. Die geologiese struktuur van die Krokodilrivier fragment. *Transactions Geological Society of South Africa*, 66, 49-74.

Walraven, F., Armstrong, R.A. and Kruger, F.J. 1990. A chronostratigraphic framework for the north central Kaapvaal craton, the Bushveld Complex and the Vredefort structure. In: L.O. Nicolaysen and W.U. Reimold (Editors) *Cryptoexplosions and Catastrophes in the Geological Record, with a Special Focus on the Vredefort Structure*. *Tectonophysics*, 171, 23-48.

Yiming, Z., Chengyou, F. and Daxin, L. 2014. The major ore clusters of super-large iron deposits in the world, present situation of iron resources in China, and prospect. *Acta Geologica Sinica*, 88, 6, 1895 - 1915.

Zeh, A., Gerdes, A. and Barton Jr, J.M. 2009. Archean accretion and crustal evolution of the Kalahari Craton-the zircon age and Hf isotope record of granitic rocks from Barberton/Swaziland to the Francistown Arc. *Journal of Petrology*, 50, 933-966.

Appendices

Appendix A. 1. Quality assurance and quality control analysis

Quality assurance involved those steps taken to ensure that the sample collection, preparation, and analytical protocols are producing reliable, repeatable values. Quality control involved those steps taken to ensure that the established sample collection, preparation, and analytical protocols continue to provide reliable and repeatable results for as long as sampling continues. QA and QC were linked together because the procedures used for one, say initial quality assurance, continue to be valid throughout the quality control portion of the sampling program. Lists the elements of QAQC which used to prevent the entry of large errors into the sample database used for modelling purpose, demonstrate that sampling and analytical variances are small relative to the geological variance and provide assurance (confidence) that the accuracy of data underlying the resource model can be confirmed within reasonable limits.

Table A. 1. Assen Iron Ore compliance to the QAQC basic principles

Practice	Manngwe Compliance	
	✓	x
Routine insertion of unprepared, barren (blank) samples	✓	
Routine submission of duplicate field samples	✓	
Resubmission of 5 to 10% of the sample preparation duplicates (sample pulps)		x
Insertion of control samples		x
Insertion of reference (standard) samples;	✓	
Randomization of sample numbers before submission to the laboratory	✓	
Analysis of 5 to 10% of the sample pulps at an umpire assay or analytical lab	✓	

Assen Iron Ore QAQC protocols have varied markedly between the different drilling campaigns over the years. The Assen drilling Quality Control (QC) programme comprised the following:

- Certified reference materials (CRM's or standards/blanks) of which one was inserted as the last sample of each borehole or every 10th sample.
- Duplicates (pulp splits from original samples) which were both randomly inserted into the sampling stream or inserted every 21st field sample.
- Laboratory inserted CRM's inserted as part of the assay batches.

Several different Certified Reference Materials as part of the samples submission to the laboratories were sourced from AMIS and Mintek Companies.

The CRM's used were:

- AMIS 0435 (superseded by AMIS 0597) – value range 2 x SD
- AMIS 0436 (superseded by AMIS 0598) – value range 2 x SD
- AMIS 0437 (superseded by AMIS 0599) – value range 2 x SD
- SARM 132 (Mintek) – value range 2.3 x SD

Laboratory certified reference materials

A SABS internal CRM, JK28, was inserted into assay batches which was determined by 11 participating independent laboratories. UIS Lab inserted the GIOP CRM's as blind QA/QC samples they use (these CRMs) for our internal controls.

Appendix A. 2. Certified reference materials in different samples

The Eight holes named AMI 001-AMI 008 had 387 samples assayed and analysed at the Anglo-American Laboratories. The assay certificates are available from the assay laboratory and the results of 83 field duplicates for all 8 holes (Appendix A.1). Eight SH boreholes named SH011-SH018 analysed at SABS laboratory had the following QAQC: CRM AMIS 0435 applied to holes 12, 13, 14, 15, 16, CRM AMIS 0436 applied to holes 17, 18, CRM AMIS 0437 applied to holes 17, 18, CRM SARM 132 applied to holes 12,13,14,15, 16, SABS Internal CRM's applied on a sample batch basis and included holes 12, 13, 15, 17, 18. Field duplicates are 23-5 from borehole SH 011, 5 from SH 012, 4 from SH 013, 3 from SH 014, 2 from SH 015, 2 from SH 016, and 2 from SH 018. Intervals of insertion varied from 20 to 40 samples (Appendix A.1). Four ARC boreholes were drilled and the following QAQC was recorded: Fourteen field duplicates numbered-3 from borehole ARC 001, 3 from ARC 002, 4 from ARC 003, and 4 from ARC 004. The objective was to place a field duplicate every 11 samples but occasionally this slipped to 16 samples. Internal CRM's were inserted into boreholes ARC 010 and 036 which were assayed at SABS laboratories. Internal CRM's were inserted into the ARC 001-004 assay batches for the samples assayed at the UIS Laboratories (Appendix A.1). The following QAQC for 4 ARC exploration holes were recorded: Field duplicates numbered 14-3 from Borehole ARC 001, 3 from ARC 002, 4 from ARC 003, and 4 from ARC 004. The objective was to place a field duplicate every 11 samples but occasionally this slipped to 16 samples. Internal CRM's were inserted into boreholes ARC 010 and 036 which were assayed at SABS laboratories. Specific Densities were measured for all assayed samples at the UIS laboratory.

Table A. 2. Summary of QAQC available for this research project

Drill Campaign	Holes with QAQC	No. Assay Samples	No of CRM's	% of CRM's	No of Duplicate	% of Duplicates
A	0	0	0	0	0	0
AMI	8	387	18	5	78	20
ARC	39	997	48	4.8	50	5
SH	7	705	19	3	23	3
ARC	2	122	6	5	14	11
ERC	3	152	3	2	8	5
SRC	6	143	15	10	7	5
WRC	12	208	21	10	11	5
ASNRC	14	1473	23	2	65	4
PB	5	578	7	1	16	3

A total of 16 ASNRC holes were used for this research project. SABS laboratory certificates were included for all holes except for ASNRC 014. A total of 23 CRM's was assayed for the ASNRC drill holes. The CRM used by SABS was JK28 which was determined by 11 participating independent laboratories. Five PB exploration holes used for this research project are PB 001, 003, 004, 005, 006, and 010. Of these holes all, except for PB 003, had QAQC duplicates. PB 005, and 006 had three. Inserted field CRM's assayed are AMIS 0435, AMIS 0436, and SARM. PB 005 also had a SABS laboratory inserted CRM. The CRM used by SABS was JK28 which was determined by 11 participating independent laboratories (Appendix A.1).

Appendix A. 3. Accuracy of CRM's

There is wide range of CRM's which allow the analysis of the deposit. The AMIS CRM's generally return low values in terms of the value ranges. In particular, SiO₂, K₂O, and Al₂O₃. CaO returns erratic values. Fe consistently lies within the ranges with no major outliers. SARM CRM's tend to return low values for SiO₂, K₂O, Al₂O₃, and also erratic values for CaO. SABS internal CRM's all fall within the certified ranges. UIS Labs' internal CRM's all fall within or very close to the certified ranges. All duplicate sampling was carried out by SABS. In most cases, the Correlation Coefficient is more than R² = 9.8. In two instances, AMI and SH holes, the Sulphur R² is low but this is probably due to the very low % S approximating the XRF level of detection. The main area of concern is the quantum and frequency of CRM and duplicate insertion into the sampling programmes. However, the results from the CRM's that were inserted consistently return values within the ranges with very few outliers. The duplicates also return very high correlation coefficients. It is the authors' opinion that the data used in this report is accurate enough to represent the true grade of the orebody. Where drilling programmes have not been exposed to QAQC then those sampling results are compared on a block-by-block basis to results of drilling where QAQC has been performed.

Appendix B. 1. Block's validation statistics

Table B. 1: Block validation statistics: Block estimates vs Composite's statistics in west orebody high-grade BIF domain

		Assen Western Domain HG BIF.mdl										west_hg_bif_comp0.str									
Variable	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG			
Number of samples	541	541	541	541	541	541	541	541	541	151	151	151	151	151	138	151	151	48			
Minimum value	49.83	12.58	0.55	0.09	0.01	0.27	0.08	0.02	3.58	24.61	5.17	0.01	0.04	0.01	0.14	0.02	0.01	3.01			
Maximum value	62.85	37.41	5.44	2.42	0.26	1.39	1.68	0.16	4.18	63.11	53.74	8.55	10.21	0.69	3.22	3.40	0.80	4.61			
Mean	58.18	25.50	2.04	0.60	0.08	0.70	0.53	0.04	3.78	49.15	24.08	1.92	0.65	0.07	0.64	0.53	0.05	3.81			
Median	59.10	26.22	1.78	0.47	0.06	0.72	0.39	0.04	3.77	51.42	23.13	1.58	0.26	0.05	0.41	0.37	0.04	3.84			
Variance	8.07	21.01	0.87	0.23	0.00	0.05	0.10	0.00	0.01	54.83	73.91	2.58	2.34	0.01	0.42	0.28	0.00	0.12			
Standard Deviation	2.84	4.58	0.93	0.48	0.05	0.21	0.32	0.02	0.10	7.40	8.60	1.61	1.53	0.09	0.65	0.53	0.07	0.35			
Coefficient of variation	0.05	0.18	0.46	0.80	0.59	0.30	0.60	0.56	0.03	0.15	0.36	0.84	2.34	1.19	1.01	1.00	1.44	0.09			
Skewness	-0.34	-0.14	1.25	1.81	1.17	0.04	1.15	2.57	0.70	-1.28	0.38	2.24	4.55	3.44	2.30	1.90	8.52	-0.11			
Kurtosis	2.04	2.81	4.31	6.13	3.81	2.41	3.66	10.46	3.39	4.69	2.94	8.91	23.64	20.03	7.97	8.78	88.03	2.63			

Table B. 2: Block validation statistics: Block estimates vs Composite's statistics in east orebody high-grade hematite domain

	East Model.mdl										east Hg Hem Comp0.str								
Variable	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG	
Number of samples	4577	4577	4577	4577	4577	4577	4577	4577	4577	250	250	250	250	240	209	240	240	99	
Minimum value	28.49	0.96	0.19	0.56	0.01	0.37	0.20	0.06	4.00	25.50	0.01	0.01	0.05	0.00	0.09	0.04	0.02	3.92	
Maximum value	61.92	23.56	2.33	28.76	0.09	2.50	0.89	0.19	4.65	65.52	49.00	3.58	33.10	0.10	4.73	2.17	0.40	4.99	
Mean	58.26	5.93	0.72	4.02	0.02	0.72	0.43	0.08	4.58	57.29	5.10	0.68	5.16	0.02	0.79	0.39	0.09	4.57	
Median	59.42	5.89	0.71	3.37	0.02	0.64	0.41	0.08	4.61	58.81	3.24	0.57	4.28	0.01	0.58	0.30	0.08	4.61	
Variance	6.73	8.34	0.06	7.63	0.00	0.08	0.02	0.00	0.00	46.66	38.00	0.32	31.87	0.00	0.40	0.09	0.00	0.04	
Standard Deviation	2.59	2.89	0.25	2.76	0.01	0.29	0.16	0.02	0.07	6.83	6.16	0.56	5.65	0.02	0.63	0.30	0.05	0.20	
Coefficient of variation	0.04	0.49	0.35	0.69	0.40	0.40	0.36	0.28	0.01	0.12	1.21	0.82	1.09	0.90	0.79	0.76	0.61	0.04	
Skewness	-2.62	0.30	0.05	1.30	0.78	0.98	0.36	1.40	-3.12	-2.45	4.30	1.85	2.58	2.44	2.71	2.79	2.50	-1.07	
Kurtosis	14.37	2.75	2.89	6.62	4.90	3.43	1.74	4.60	18.27	9.62	27.89	8.60	10.86	10.59	14.20	13.85	11.54	4.47	

Table B. 3: Block validation statistics: Block estimates vs Composite's statistics in middle orebody high-grade hematite domain

		Middle Hematite.mdl											middle Hg Hem Comp0.str								
Variable	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG			
Number of samples	945	945	945	945	945	945	945	945	945	372	372	372	372	352	252	352	352	50			
Minimum value	50.98	1.00	0.36	0.07	0.01	0.16	0.28	0.02	3.36	15.34	0.90	0.07	0.00	0.01	0.03	0.18	0.01	3.20			
Maximum value	64.95	30.19	3.57	29.73	0.26	1.47	1.14	0.21	4.64	67.86	42.42	8.63	63.50	0.84	5.24	2.84	1.85	4.91			
Mean	58.98	7.92	1.36	2.41	0.06	0.48	0.69	0.06	4.28	59.24	7.40	1.32	2.49	0.06	0.48	0.63	0.07	4.28			
Median	59.27	7.98	1.21	0.90	0.05	0.44	0.74	0.06	4.30	61.14	5.71	0.98	0.30	0.03	0.23	0.55	0.04	4.38			
Variance	6.94	9.53	0.26	15.38	0.00	0.05	0.03	0.00	0.04	50.57	28.71	1.28	61.34	0.01	0.45	0.11	0.01	0.17			
Standard Deviation	2.63	3.09	0.51	3.92	0.04	0.23	0.17	0.04	0.19	7.11	5.36	1.13	7.83	0.09	0.67	0.33	0.12	0.42			
Coefficient of variation	0.04	0.39	0.37	1.63	0.63	0.48	0.25	0.57	0.04	0.12	0.72	0.85	3.14	1.50	1.41	0.53	1.80	0.10			
Skewness	-0.32	1.13	1.02	2.86	1.63	1.18	-0.50	1.06	-2.21	-2.29	1.83	2.32	5.77	4.48	3.49	1.96	10.90	-0.86			
Kurtosis	2.78	7.91	3.76	12.47	7.12	4.20	2.33	4.01	9.79	10.94	8.44	10.91	40.42	31.29	18.54	10.29	157.42	3.25			

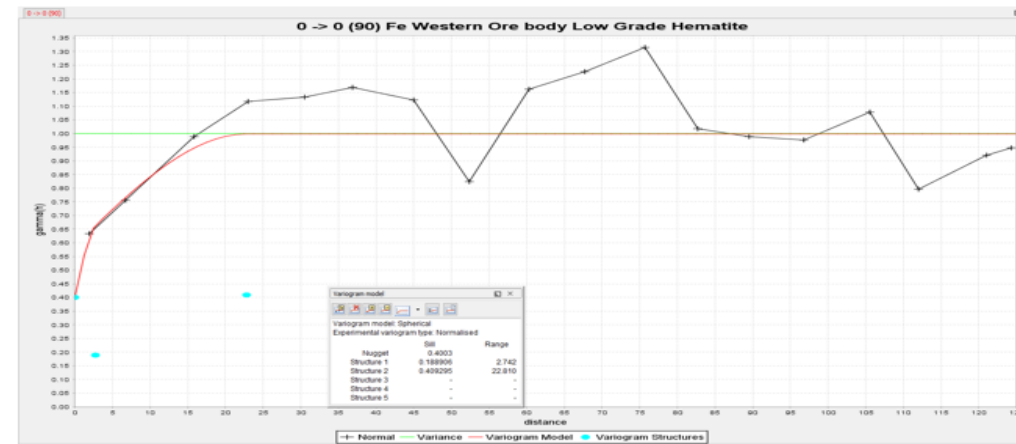
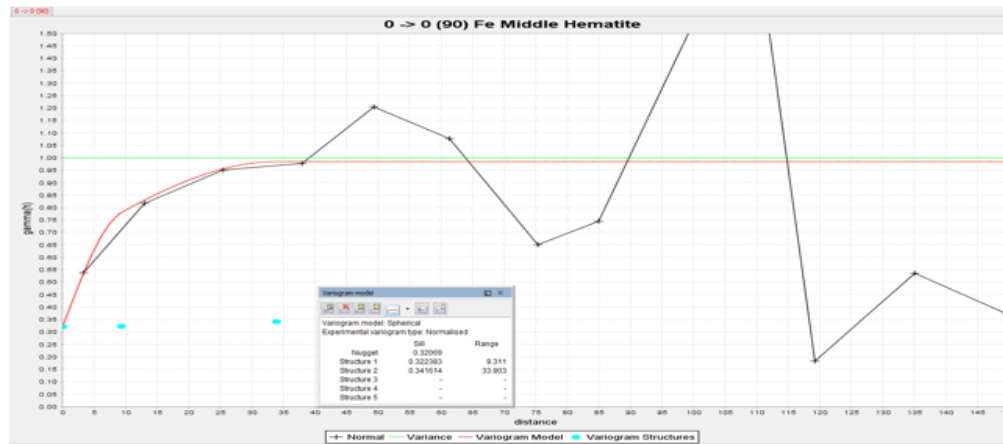
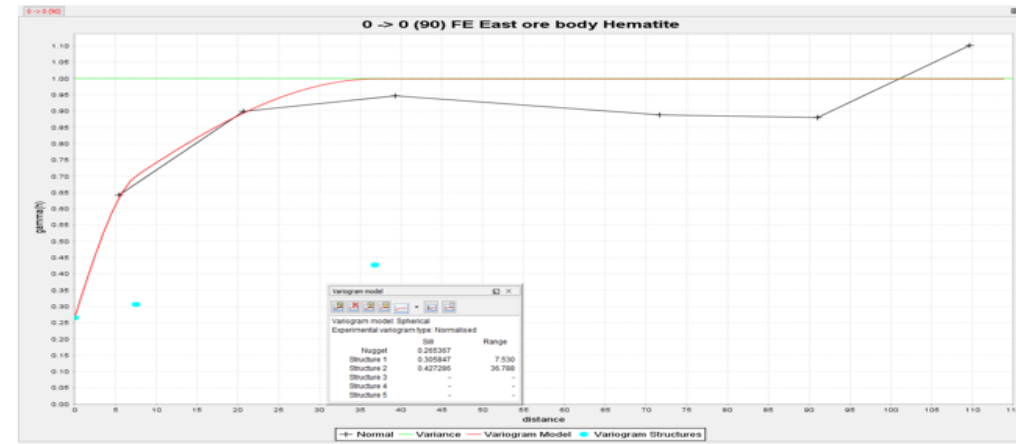
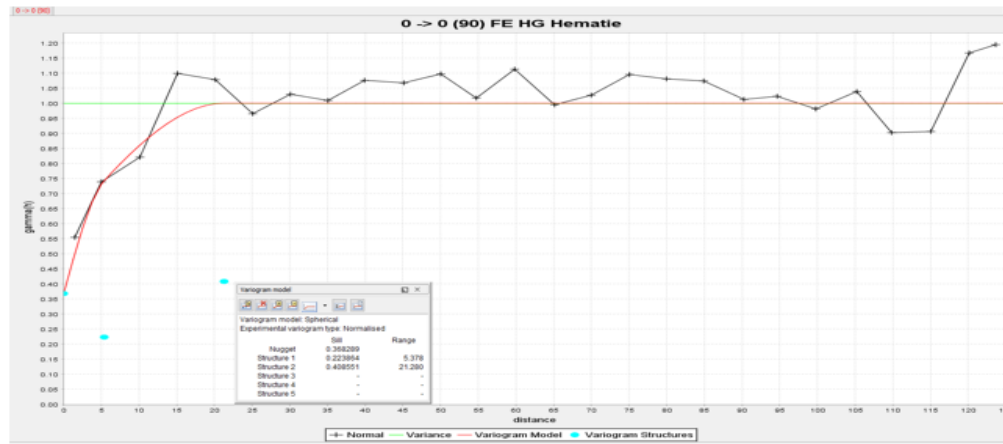
Table B. 4: Block validation statistics: Block estimates vs Composite's statistics in middle/east orebody calcitic domain

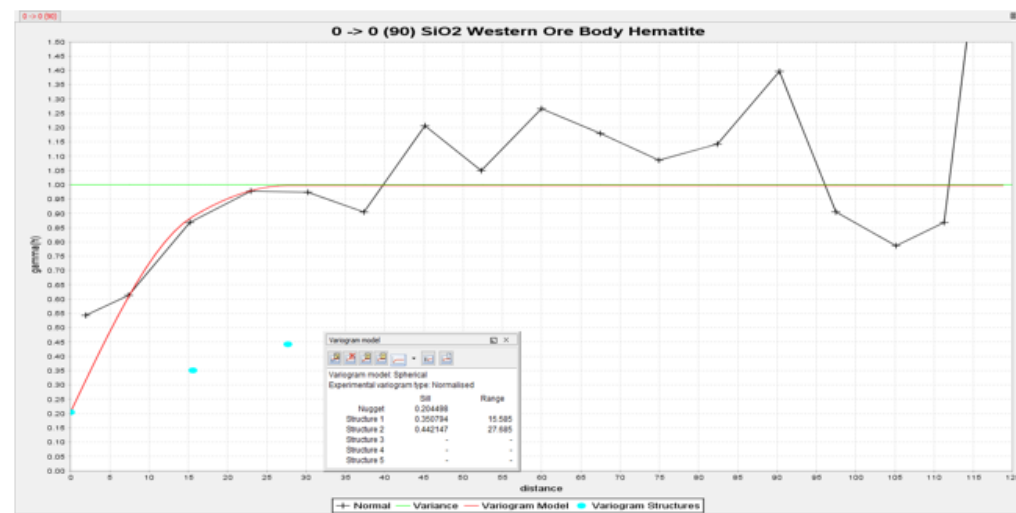
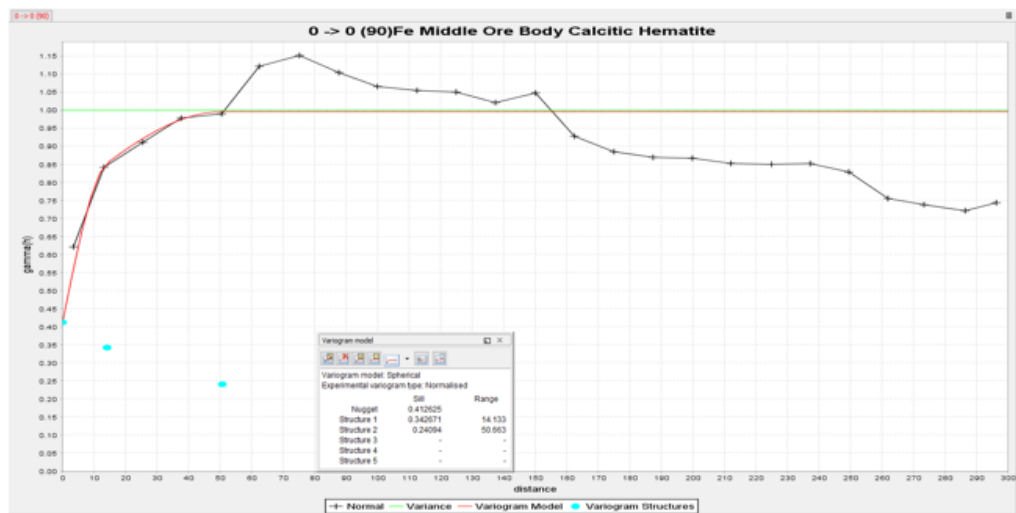
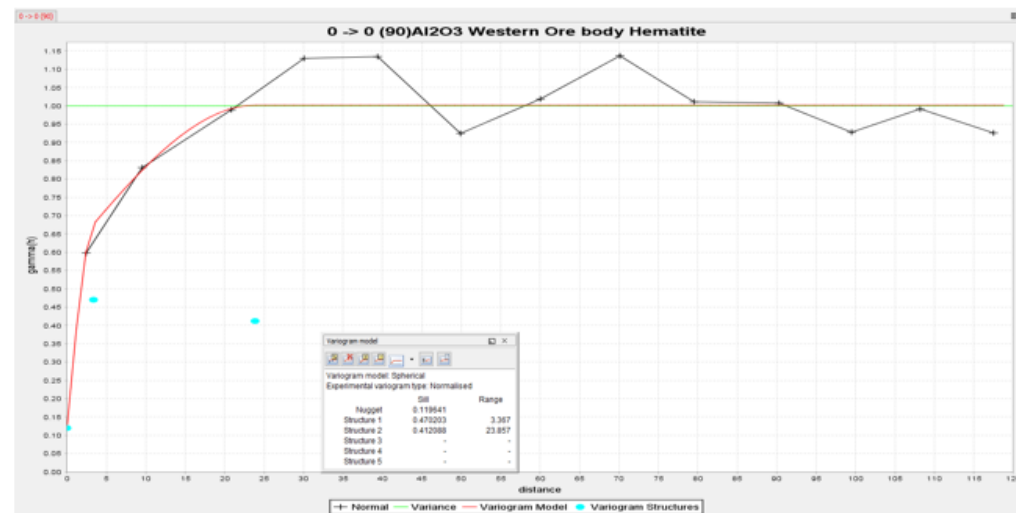
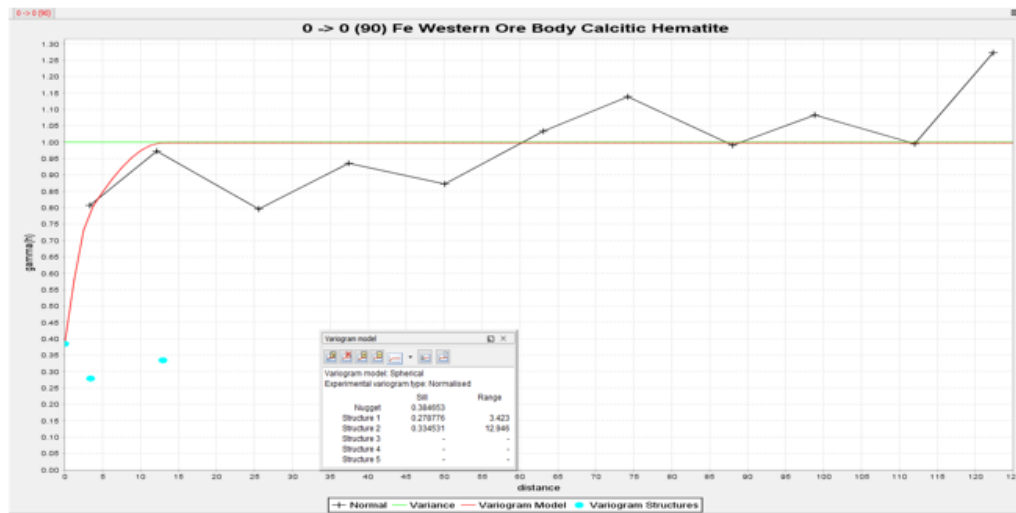
			Assen East Middle Domain.mdl											east Hg Cal Hem Comp0.str						
Variable	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG		
Number of samples	7289.0	7289.0	7289.0	7289.0	7289.0	7289.0	7289.0	7289.0	7289.0	1541.0	1531.0	1541.0	1541.0	1399.0	1311.0	1399.0	1399.0	576.0		
Minimum value	20.53	0.06	0.18	2.14	0.00	0.27	0.25	0.04	3.29	2.42	0.01	0.01	0.16	0.00	0.03	0.00	0.01	2.66		
Maximum value	58.56	46.75	8.92	30.59	0.50	9.03	1.07	0.26	4.36	67.06	59.75	18.11	52.78	1.48	20.93	2.74	0.93	4.88		
Mean	47.01	3.75	0.85	13.27	0.02	1.29	0.55	0.08	4.03	45.14	4.54	1.03	14.51	0.03	1.44	0.53	0.09	4.02		
Median	47.69	2.60	0.63	13.15	0.01	1.03	0.55	0.08	4.04	46.30	2.27	0.53	13.95	0.01	0.83	0.47	0.08	4.04		
Geometric Mean	46.71	2.70	0.65	12.57	0.02	1.08	0.54	0.08	4.03	43.46	2.25	0.48	11.25	Not Calculated	0.82	Not Calculated	0.07	4.00		
Variance	24.89	13.70	0.68	17.48	0.00	1.07	0.01	0.00	0.02	97.28	59.95	3.67	66.69	0.01	6.00	0.06	0.01	0.14		
Standard Deviation	4.99	3.70	0.83	4.18	0.03	1.03	0.12	0.03	0.14	9.86	7.74	1.92	8.17	0.10	2.45	0.25	0.09	0.37		
Coefficient of variation	0.11	0.99	0.97	0.32	1.41	0.80	0.21	0.36	0.03	0.22	1.71	1.86	0.56	3.19	1.71	0.47	0.93	0.09		
Skewness	-1.43	3.40	3.54	0.30	6.99	3.73	0.45	1.50	-0.54	-1.23	4.05	5.21	0.53	9.03	5.14	2.03	5.52	-1.06		
Kurtosis	6.17	22.78	20.77	2.91	70.60	20.85	2.67	5.90	4.47	5.54	20.88	34.22	3.37	101.37	32.66	12.69	44.83	4.97		

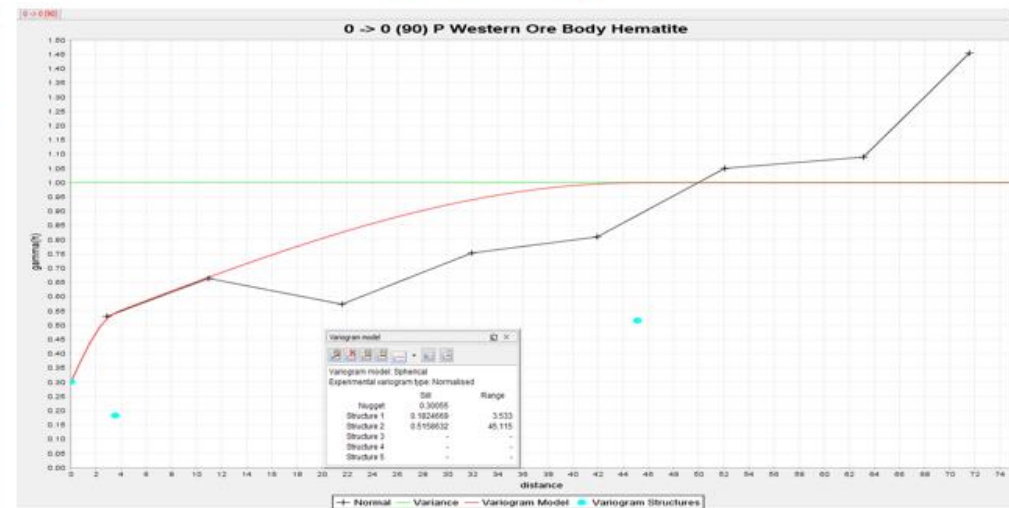
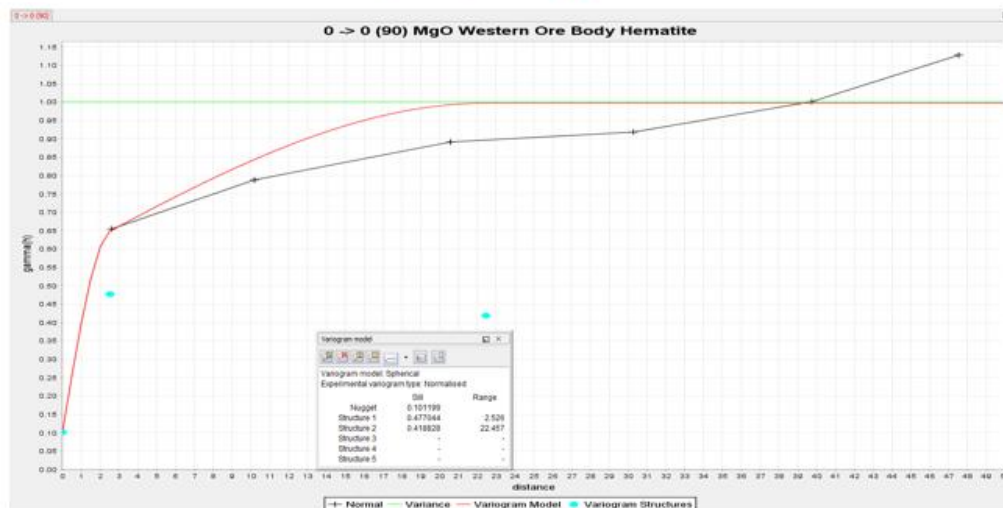
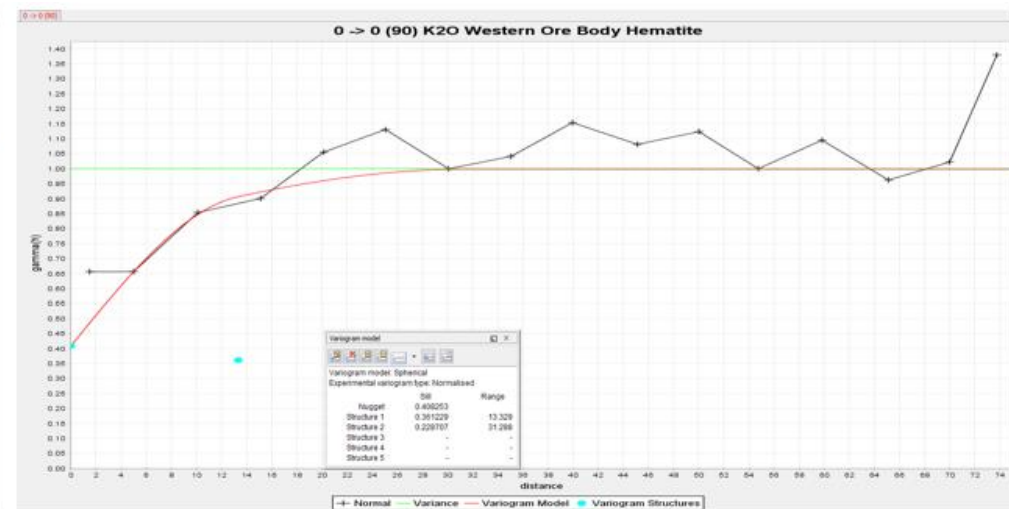
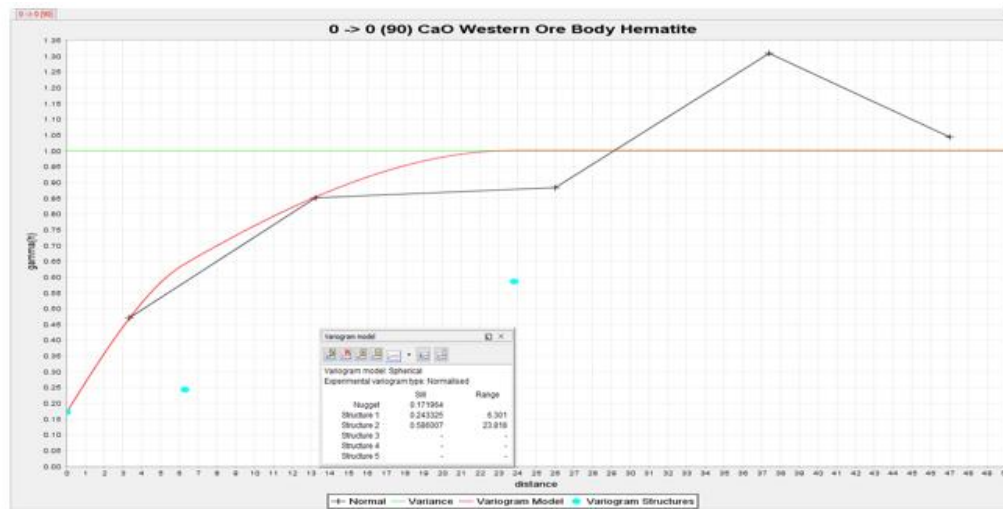
Table B. 5: Table: Block validation statistics: Block estimates vs Composite's statistics in middle orebody high-grade BIF domain

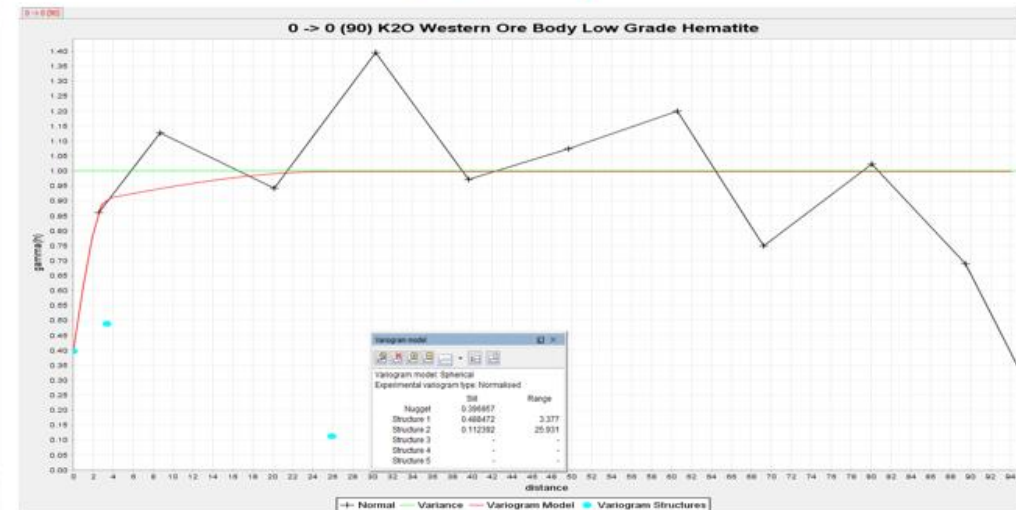
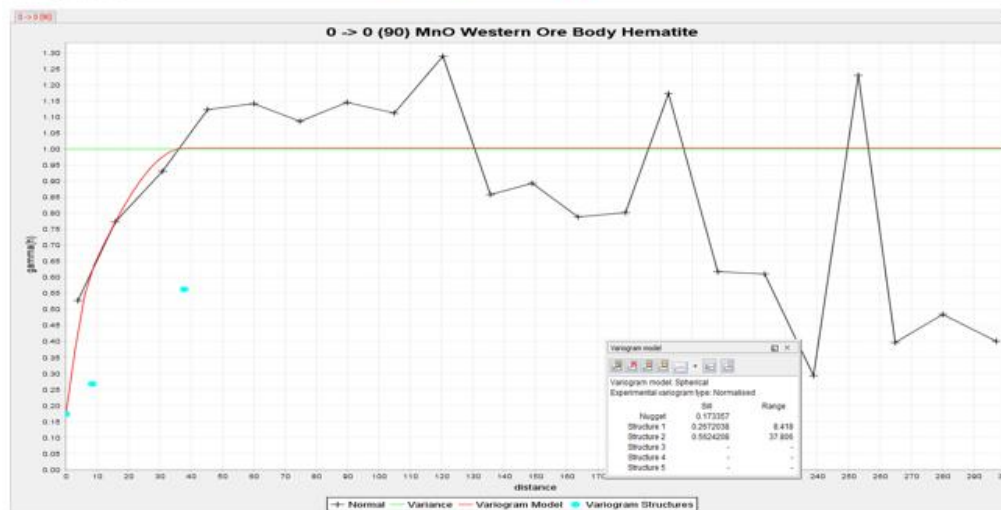
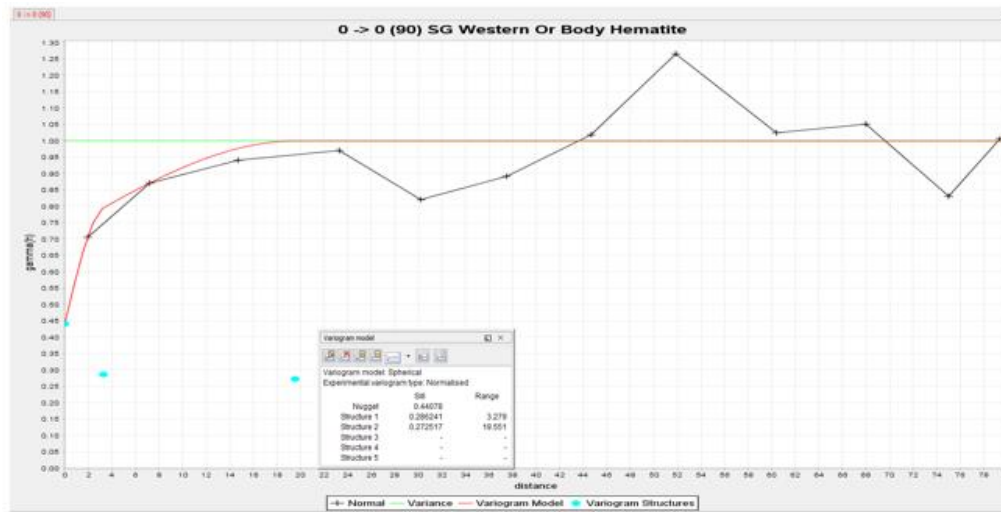
		Assen East Middle Domain.mdl										middle Hg Bif Comp0.str								
Variable	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG	Fe %	SiO ₂ %	Al ₂ O ₃ %	CaO %	K ₂ O %	MgO %	MnO %	P %	SG		
Number of samples	1869	1869	1869	1869	1869	1869	1869	1869	1869	172	172	172	172	172	129	172	172	19		
Minimum value	37.98	6.01	0.62	0.12	0.01	0.13	0.19	0.02	4.01	24.03	0.79	0.01	0.01	0.00	0.03	0.02	0.01	2.99		
Maximum value	57.28	41.43	1.95	5.63	0.08	1.33	1.45	0.11	4.13	64.26	49.16	5.62	39.10	0.36	3.76	3.69	0.48	4.67		
Mean	47.82	24.73	1.16	2.40	0.04	0.50	0.63	0.06	4.08	48.68	22.20	1.10	2.68	0.04	0.52	0.61	0.06	4.08		
Median	47.21	25.81	1.19	2.35	0.04	0.47	0.61	0.06	4.08	49.18	20.40	0.96	0.41	0.02	0.34	0.46	0.05	4.01		
Variance	26.85	81.51	0.06	2.87	0.00	0.04	0.03	0.00	0.00	56.60	208.45	0.56	24.17	0.00	0.32	0.30	0.00	0.15		
Standard Deviation	5.18	9.03	0.25	1.69	0.01	0.19	0.18	0.02	0.01	7.52	14.44	0.75	4.92	0.04	0.56	0.55	0.04	0.39		
Coefficient of variation	0.11	0.37	0.21	0.70	0.32	0.38	0.29	0.28	0.00	0.15	0.65	0.68	1.83	1.03	1.08	0.89	0.78	0.10		
Skewness	-12.07	-0.19	0.04	0.03	-0.16	0.78	1.47	-0.08	-0.36	-0.07	0.17	2.13	3.55	3.45	2.95	2.59	5.58	-0.70		
Kurtosis	345.38	2.12	2.29	1.52	2.41	3.92	7.17	2.25	4.97	2.48	1.47	10.98	21.31	25.10	13.69	11.88	51.96	4.08		

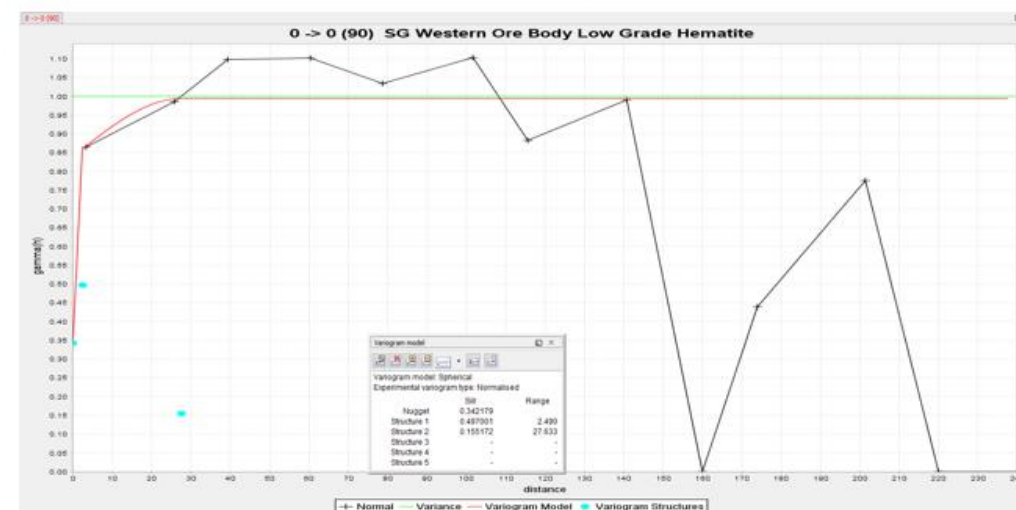
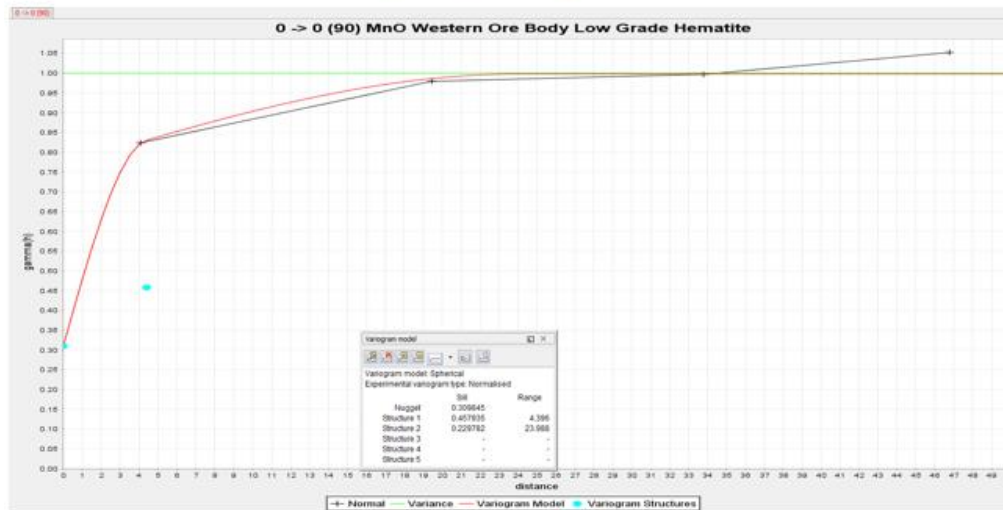
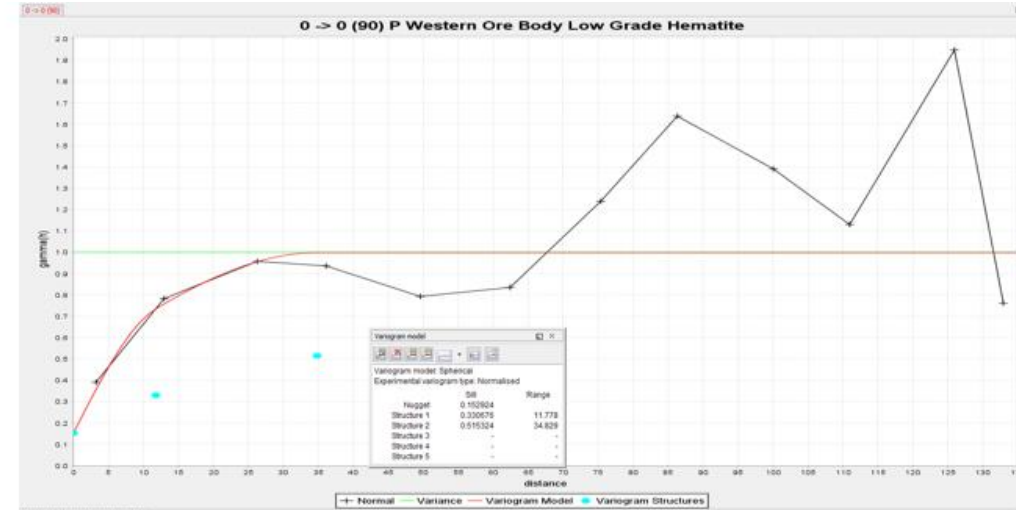
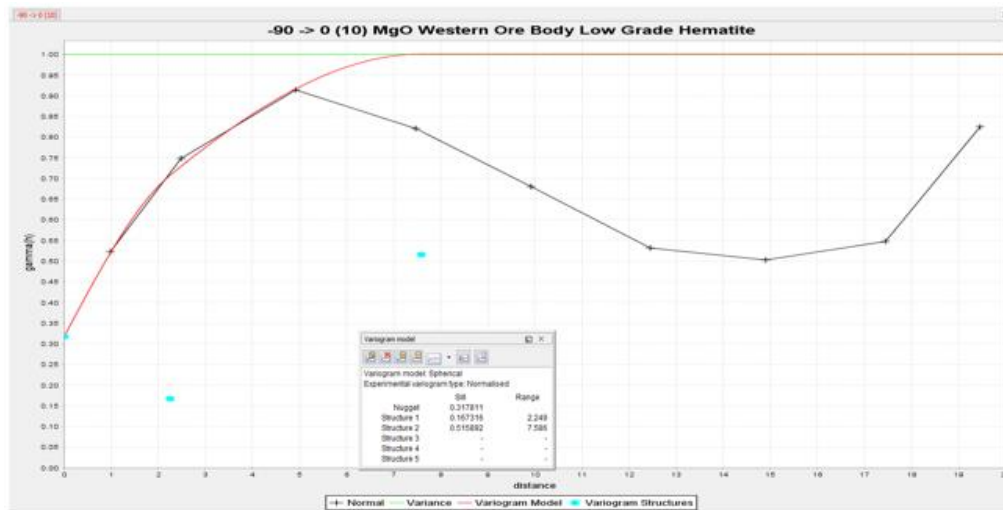
Appendix C. 1. Semi-Variograms for east, middle, and west orebody

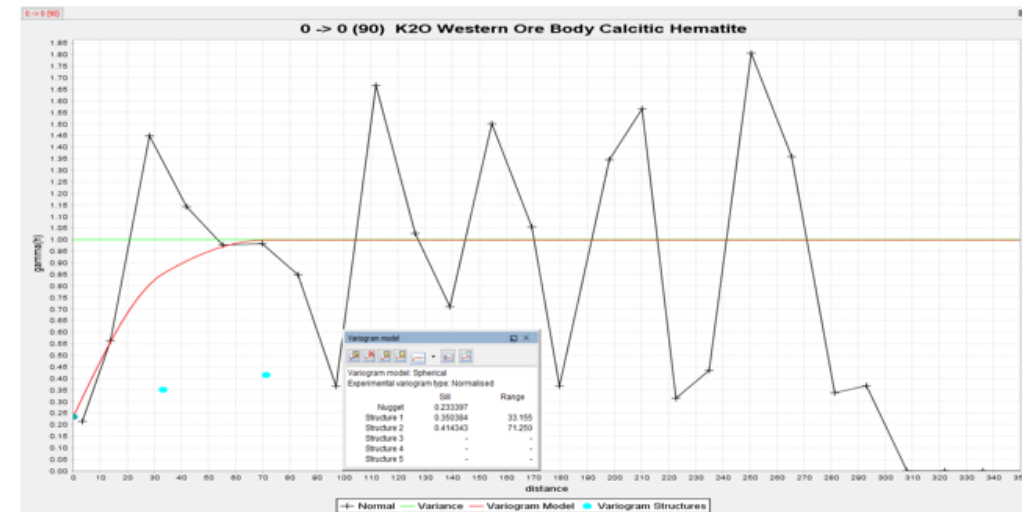
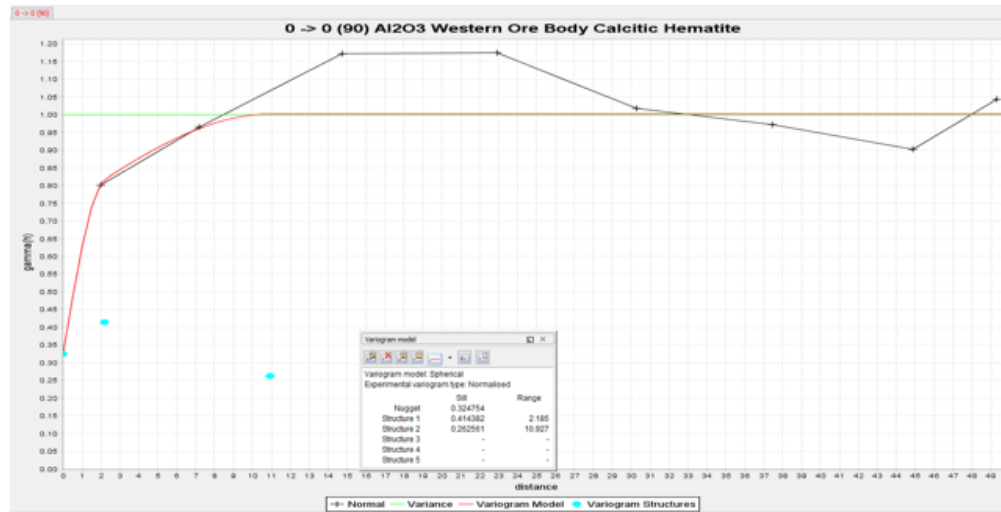
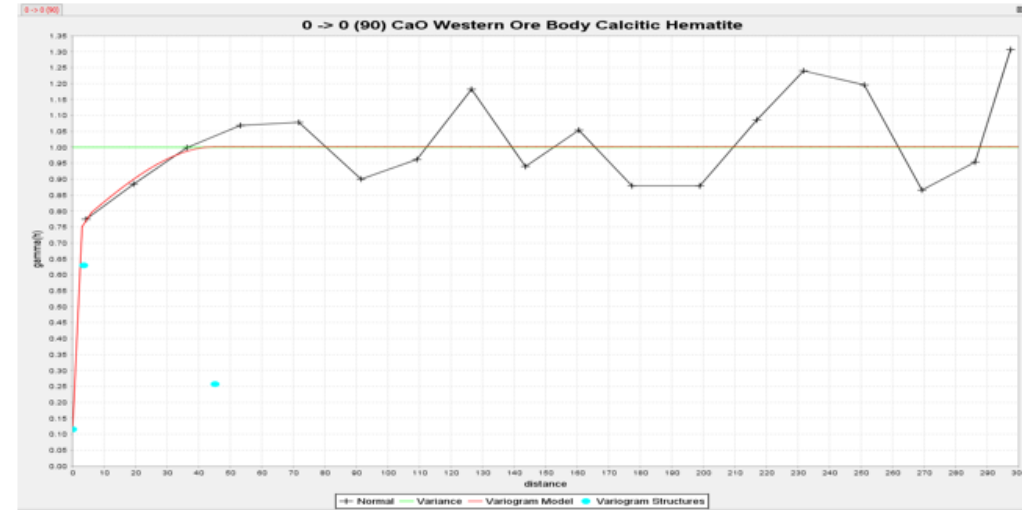
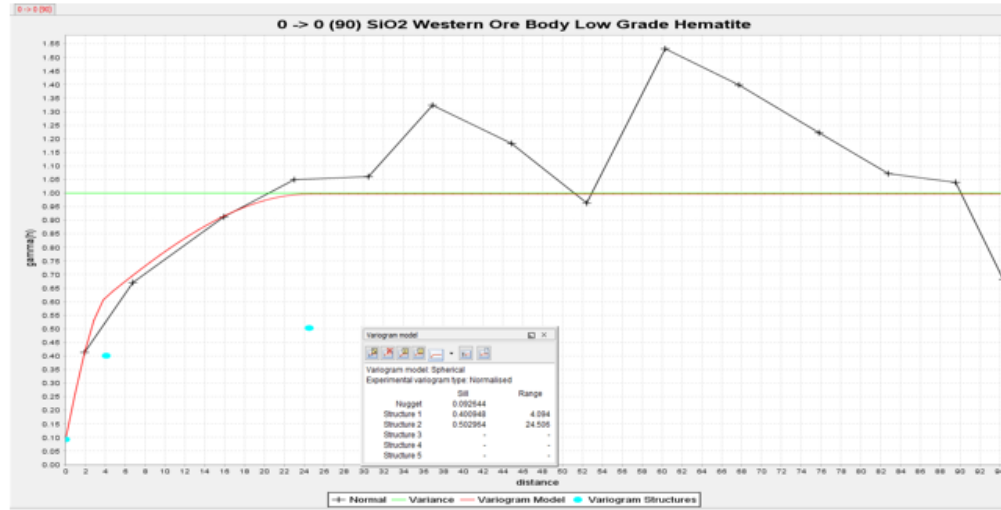


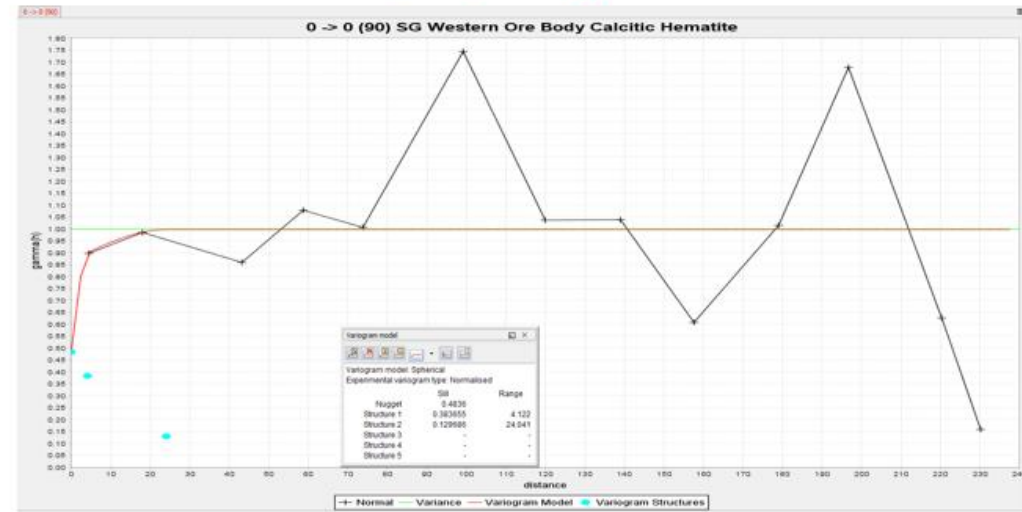
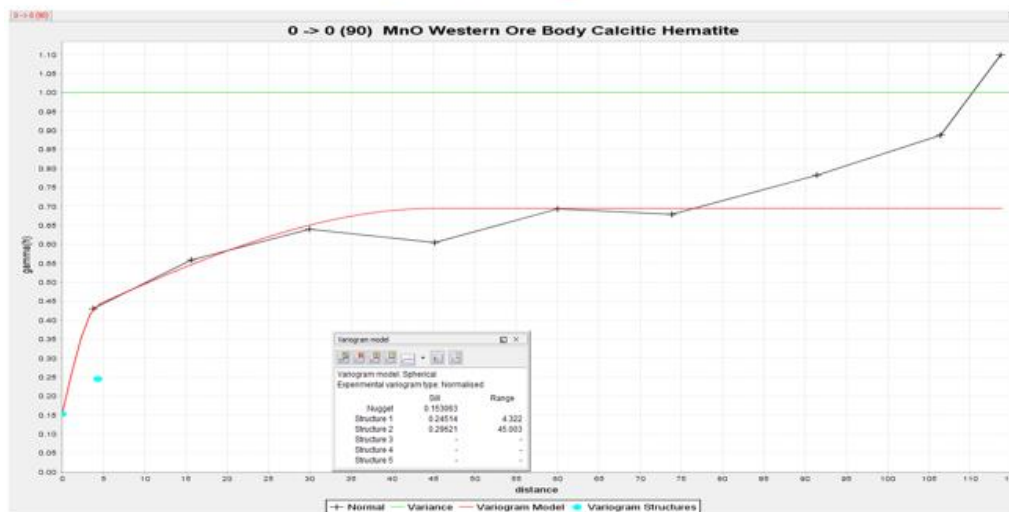
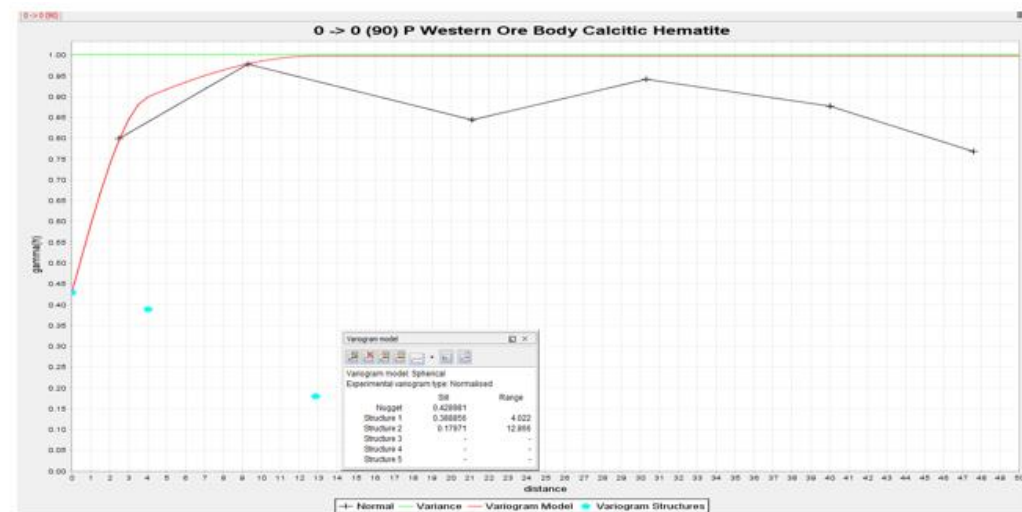
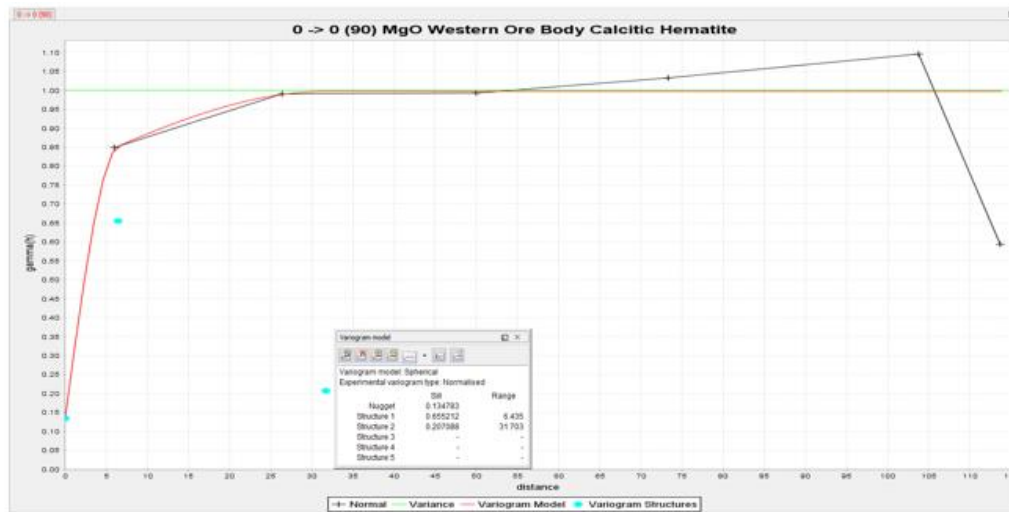


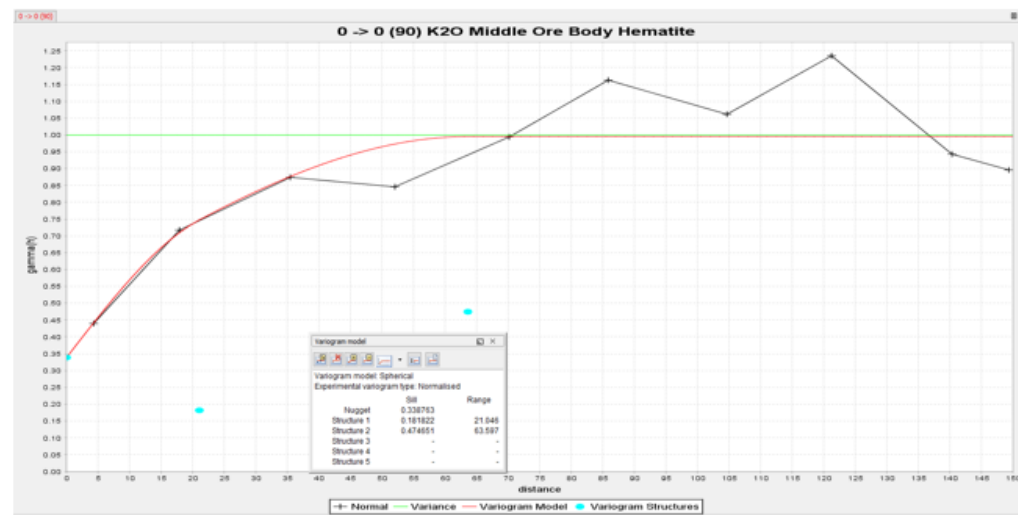
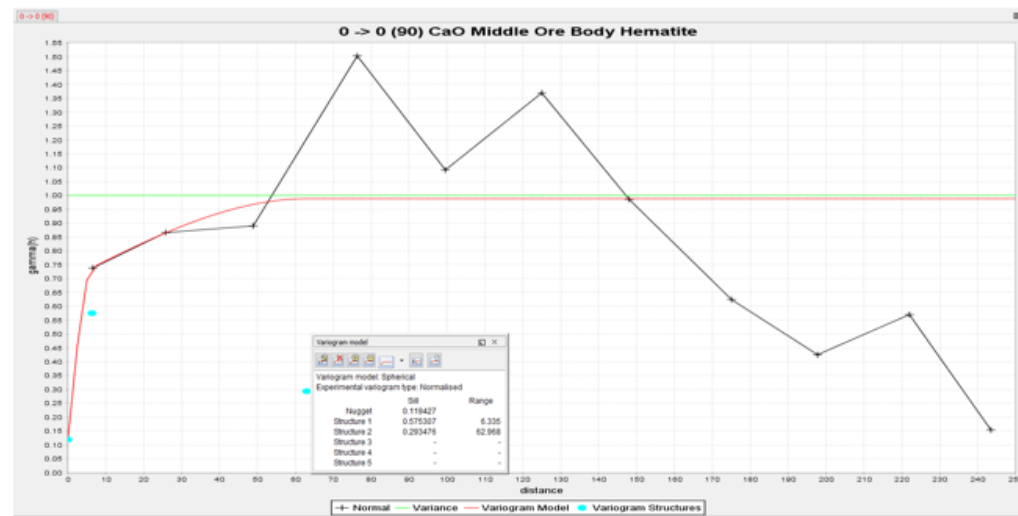
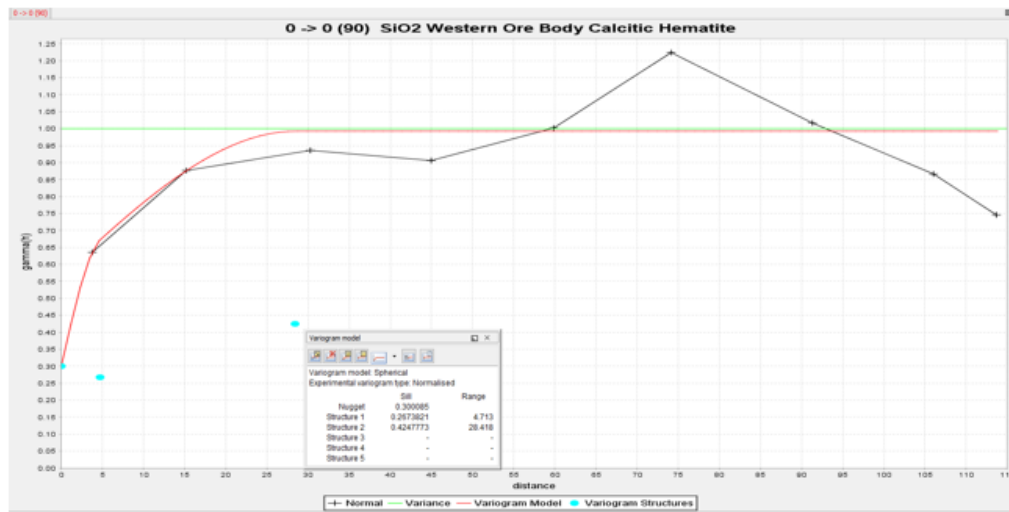












Appendix D. 1. Histograms of elements distribution in both east, west, and middle orebody.

