GEOLOGICAL CHARACTERISTICS OF IRON OXIDE-COPPER-GOLD (IOCG) TYPE MINERALISATION IN THE WESTERN BUSHVELD COMPLEX.

By

John Paul Hunt

A dissertation in fulfilment of the requirements for the degree of

MSc in Geology

University of the Witwatersrand

2005
ABSTRACT

The occurrence of large, massive iron oxide deposits throughout the Bushveld Complex, South Africa, and its associated roof-rocks is well known. The style of mineralisation and the associated alteration exhibits many characteristics of iron oxide-copper-gold (IOCG) type deposits. The contained mineralisation is dominated by iron oxide and fluorite and is accompanied by a diverse polymetallic association, with anomalous fluorite, copper, gold, barite, uranium and LREE.

The Ruigtepoort orebody, located in the western Bushveld Complex, is such an example and is surrounded by some 20 smaller occurrences in the upper stratigraphic portions of the Bushveld Complex, all displaying strong structural control. These IOCG bodies occur as narrow veins, hydrothermal breccias, subhorizontal sheets, or as pipe-like intrusions usually utilising pre-existing structures. Set in red Nebo granite, the mineralised core consists of severely chloritised rock that is haloed by progressively less-altered granite. The alteration passes from the chlorite core to more hematite-phyllosilicate-dominated alteration, to sericite-illite-dominated alteration; followed by the relatively fresh country granite. These alteration haloes dissipate rapidly away from the body over only a few metres. Sodic-calcic alteration described in other IOCG is not locally observed. Extensive zones of barren feldspar-destructive alteration exist, including K-metasomatism, sericitisation and silicification. Multiple alteration episodes appear to have occurred, resulting in extensive overprinting and a very complex paragenesis.

The primary mineral assemblage consists of Fe-chlorite, fluorite, quartz, hematite, and specularite, with accessory pyrite and chalcopyrite. Multiple generations of hematite, quartz, fluorite and chlorite are also observed. At other localities, the assemblage is dominated by magnetite-actinolite-britholite. Significantly enriched concentrations of Au (2 g/t), Cu (0.45 wt%), Ba, Y and LREE are encountered in the small, mineralised core.
A fluid mixing model is proposed characterised by an initial highly-saline, sulphur-poor magmatic fluid which mixed with a lower temperature oxidised, surficial fluid. Structure was probably a significant factor in determining the initial distribution of hydrothermal centres and the overall morphology of the entire system. Subsequently, continuous brecciation, alteration, mineral precipitation and fault activity helped develop the hydrothermal centres into a complex array of variably mineralised, lenticular, pipe-like and irregularly shaped breccia bodies.
DECLARATION

This dissertation is my own unaided work, conducted under the supervision of Prof. Laurence J. Robb. It is being submitted for the degree of Masters of Science in Geology at the University of the Witwatersrand, and has not been previously submitted for any degree or examination at any other university.

John Paul Hunt
ACKNOWLEDGEMENTS

Sincere thanks to Laurence Robb for guidance and support over the duration of this degree, and criticisms and review of this manuscript.

I am grateful to the following people for assisting in discussions, review and the collection of data:

- Judith Kinnaird and Paul Nex for invaluable discussions on the interpretation of the geochemical and petrographical data;
- Rudi Boer for getting me started on this path by initiating the project;
- Economic Geology Research Institute, Wits, for always keeping the door open and always making a desk available;
- RTX Africa and Ben Joubert for logistical support during the first year of field work and for access to datasets and resources;
- George Sethibelo for tirelessly walking each day whilst mapping;
- Richard Bodkin for reviewing the entire manuscript in spite of not being able to ‘speak’ geology and for pushing me to finish;
- Louis Venter for reviewing the entire manuscript and for questioning everything;
- Martin Klausen for divulging the secrets of fluorine;
- Lynette Greyling for administrative support and coffee breaks;
- ACMS, Jhb, for allowing me to digitally draft my entire map, in spite of my never copying it to disk to use;
- John and Graciela Hunt, and my sisters for never letting me give up and never giving up on me;
- Richard Bodkin, Peter Auret, Chris Pefanis, Kristel Birkholtz, and Chris Volbrecht for standing beside me through it all.
# Table of Contents

1. Introduction and Research Overview

1.1. Introduction to Iron Oxide-Copper-Gold Mineralisation

*Characteristics of IOCG Mineralisation and Proposed Models*  
1

1.2. Iron Oxide-Copper-Gold Examples – Olympic Dam & Carajás

*Olympic Dam Cu-U-Au-Ag-REE Deposit, South Australia*  
Alteration  
Mineralisation  
Fluid Characteristics  
Deposit Model  
10

*Carajás District, Northern Brazil – Salobo Deposit*  
Alteration  
Mineralisation  
Fluid Characteristics & Sulphur Isotopes  
Deposit Model  
22

1.3. Previous Work & Research Objectives

*Research Aims*  
*Significance of the Research*  
*Methodology*  
*Basic Field Mapping*  
*Transmitted and Reflected Light Mineral Petrography*  
Whole Rock Geochemistry  
28
2. Geological Setting

2.1. Introduction to the Bushveld Complex, South Africa 34

2.2. Regional and Tectonic Setting 37

2.3. General Stratigraphy of the Transvaal Supergroup and the Bushveld Complex 41

*Transvaal Supergroup* 41

*Rooiberg Group* 42

*Bushveld Complex* 45

  *Rashoop Granophyre Suite* 48
  *Rustenburg Layered Suite* 51
  *Lebowa Granite Suite* 52

2.4. Mineral Deposits of the Bushveld Complex 56

*Vergenoeg Exogranitic Fe-F Pipe* 57

*Phalaborwa Craton-Margin Carbonatite-hosted Mg-Cu-P-REE Deposit* 62

*Other Examples from the Bushveld Complex* 65

  *Albert Endogranitic Ag-(Cu-U) Deposit* 65
  *Rooibokkop-Boschhoek Endogranitic Fracture-Hosted Cu Deposit* 67
  *Zaaiplaats Endogranitic Sn Deposit* 68
  *Rooiberg Exogranitic Sn Deposit* 69
3. Local Geology of the Study Area

3.1. Geological Characteristics of the Lebowa Granite Suite in the Rooiberg District of the Western Bushveld Complex

*Detailed Geology of the Study Area*

*Field Descriptions of Main Rock Types*

*Nebo Granite*

*Rashoop Granophyres*

*Rooiberg Rhyolites, Agglomerates and Pseudogranophyres*

*Quartzite xenoliths, Leptites and other Sedimentary Lithologies*

*Field Descriptions of Styles of Alteration*

*Structural Considerations in the Rooiberg District of the Western Bushveld Complex*

*Geophysical Considerations in the Rooiberg District of the Western Bushveld Complex*

4. Silicate & Opaque Mineral Petrography

4.1. Petrographic Descriptions of the Main Rock Types

*Nebo Granite*

*Rashoop Granophyres*

*Rooiberg Rhyolites, Pseudogranophyres and Agglomerates*

*Quartzitic xenoliths*

4.2. Petrographic Descriptions of the Mineralised and Ore Zone Rock Types

*Ferroactinolite Britholite Rock*

*Massive Iron Oxide-Quartz-Fluorite Assemblage*

*Chlorite-Fluorite-Sulphide Ore*

*Silicified Core Assemblage*

*REE-enriched Sediments*
4.3. Alteration Assemblages & Temporal Relations to the Mineralising Event

Deuteric

Sodic (±Calcic) Alteration

Potassic Alteration / K⁺-Metasomatism

Sericitisation / H⁺ Metasomatism / Hydrolysis

Silicification

Chloritisation

Hematisation

4.4. Paragenetic Sequence

5. Whole Rock Geochemistry

5.1. Geochemistry of Granites

5.2. Chemical Variation in the Bushveld Granites

5.3. Geochemistry of Weathering and Hydrothermal Alteration

Weathering

Hydrothermal Alteration

Bivariate Major Element Analysis

Composition-Volume Relations in Altered Rocks of the Study Area

Trace Element Geochemistry with respect to Crystal Fractionation
6. Fe-F (Cu-Au-REE) Mineralisation in the Bushveld Granites

6.1. Locality Descriptions of Mineral Occurrences in the Western Bushveld Granites near the farm Ruigtepoort

Ruitgepoort Fe-F (-Cu-Au) Deposit
Slipfontein Fe-F (-Cu-Mo) Deposit
Blokspruit Fe-F (-REE-Cu-Au) Prospects
Elandslaagte Fe-REE (-F-Cu-Sn-Mo) Occurrences
Doornfontein Fe-F (-REE-Au-Cu-U) Prospects

6.2. Summary of Characteristic Features of Mineral Occurrences in the Western Bushveld Granites near the farm Ruigtepoort

6.3. Discussion on the Longevity of Hydrothermal Mineralisation in the Bushveld Complex

7. Discussion on Aspects of Mineralisation of the Bushveld Granites

7.1. Comparison of Bushveld-type mineralisation to Olympic Dam & Salobo

Geological Models for Bushveld-type Mineralisation
Discussion on Mineral Assemblages
Discussion on Alteration Patterns and Sources

7.2. General Discussions on Aspects of the Mineralisation

Hematite Stage vs. Magnetite Stage
The Role of Fluorine
Carbonatite Association

7.3. Summary and Conclusions
References

APPENDIX I : Sample numbers, rock type descriptions and co-
ordinates of all samples.

APPENDIX II : Major, trace and REE analyses used in this study
from Blokspruit 157JQ, Ruigepoort 162JQ and other surrounding
farms.

APPENDIX III : Abstracts

APPENDIX IV : Map Layers
List of Figures

Figure 1.1. Distribution of some recognised IOCG deposits worldwide. (modified after Hitzman, 2000).

Figure 1.2. Tectonic setting of iron oxide-Cu-Au deposits (taken from Hitzman, 2000).

Figure 1.3. Schematic illustration of flow paths and hydrothermal features for alternative models for IOCG deposits. Shading in arrows indicates predicted quartz precipitation (veining) for different paths in different quartz-saturated rocks which provides a useful first-order indication of path (cf. Table 1.2.) (modified from Barton & Johnson, 2004).

Figure 1.4. Regional geological map of the interpreted subsurface geology of the Gawler Craton. Olympic Dam located top right (from Reynolds, 2000).

Figure 1.5. Simplified geological plan of the Olympic Dam Breccia Complex (ODBC) showing the general distribution of the major breccia types. Note the broad zonation from the host granite at the margins of the breccia complex to progressively more hematite rich lithologies in the centre (from Reynolds, 2000).

Figure 1.6. Schematic E-W cross section through the ODBC, showing generalised lithological relationships and the location of the bn-cp interface (from Reeve et al., 1990).

Figure 1.7. Generalised alteration and mineralisation patterns within the ODBC with some typical mineral assemblages. More common components of the ODBC shown in solid lines; neither absolute nor relative abundances are implied. mt=magnetite; hem=hematite; ser=sericite; chl=chlorite; sid=siderite; flu=fluorite; bar=barite; sil=silicification; py=pyrite; cp=chalcopyrite; bn=bornite; cc=chalcocite; Cu_o=native copper; Au_o=free gold; ura=uraninite; bra=brannerite; cof=coffinite; REE=lanthanum and cerium (from Reynolds, 2000).

Figure 1.8. Schematic cross section of an Olympic Dam style hydrothermal system, showing Cu-U-Au mineralisation associated with hematite-sericite-chlorite-carbonate alteration (HSCC). Deeper level and/or distal calcisilicate-alkali feldspar-magnetite alteration (CAM), and alternative fluid types that may have been active in the system, are also shown. The interface between chalcopyrite-pyrite (cpy-py) and bornite-chalcocite (bn-cc) assemblages is indicated. Geology based on Reeve et al. (1990) and Haynes et al. (1995). (from Skirrow, 1999; Skirrow et al., 2000).

Figure 1.9. Location of the Carajás Mineral Province on the margin of the Southern Amazonian Craton (from Groves, 2004).

Figure 1.10. Simplified Geological Map of the Itacaiúnas Belt of the Carajás Mineral Province, northern Brazil (from Groves, 2004).

Figure 1.11. Paragenetic sequence of the Salobo deposit, Carajas District, northern Brazil (Requia & Fontboté, 2000).

Figure 1.12. Schematic model of the Carajás Mineral Province indicating the relationships between major deposits in the region, including Salobo. Grades are indicated for each deposit, corresponding to wt % Cu and g/t Au, respectively (Groves, 2004).
Figure 2.1. Distribution and Stratigraphy of the Bushveld Complex, South Africa.

Figure 2.2. Simplified map of the central and eastern Bushveld Complex, with an enlarged plan showing the exposed Lebowa Granite Suite (LGS) and Rooiberg Group in the eastern section of the Complex and the widespread distribution of granite-related polymetallic ore deposits (modified from Robb et al. 2000).

Figure 2.3. Proposed cratonic architecture as suggested by terrane boundaries within the Kaapvaal Craton. Thick dashed line delineates the geophysical boundary of the Kaapvaal Craton, with terrane boundaries chosen to coincide with the Colesberg lineament, the Thabazimbi-Murchison lineament (TMZ), the Hout River Shear Zone (HRSZ), the Palala shear zone (PSZ) and a south-westerly extension of the Inyoka Fault (reproduced from Eglington & Armstrong, 2004).

Figure 2.4. Lineaments traversing the Bushveld Complex shown in relation to older megalineaments of the Kaapvaal and Zimbabwe Cratons (see inset) (Davies et al., 1970; Wilson, 1977, 1979) and radiometric anomalies over the Lebowa Granite Suite denoted by black dots. The megalineaments are as follows: A) Great Dyke, B) Losburg-Trompsburg, C) Murchison, D) Koppies continental arch, E) Ushushwana. The corresponding Bushveld lineaments are as follows: 1) Fransoort Zone, 2) Grobbelaars Hoek-Hlabisa Zone, 3) Soutpan-Spitskop Zone, 4) Murchison Zone, 5) Glenover-Grobbelaars Hoek Zone. All known deposits of fluor spar and tin and eighty-five percent of the radiometric anomalies are confined within these zones. Some of the radiometric anomalies are so closely spaced that they are not individually represented here (taken from Simpson & Hurdley, 1985).

Figure 2.5. Distribution of Rooiberg Group rocks (taken from Crocker et al., 2001).

Figure 2.6. Variation in the lithostratigraphic succession of Rooiberg Group rocks between the eastern and western lobes of the Bushveld Complex. Red bar indicates litho-types that have been potentially identified within the study area, corresponding to the Damwal Formation in the eastern Bushveld but largely undeveloped in the western Bushveld (taken from Crocker et al., 2001).

Figure 2.7. The Acid Rocks of the Lebowa Granite Suite (taken from Crocker et al., 2001).

Figure 2.8. Distribution of the Rashoop Granophyre Suite (taken from Crocker et al., 2001).

Figure 2.9. Distribution of the Lebowa Granite Suite (taken from Crocker et al., 2001).

Figure 2.10. Distribution of fluorite occurrence in the Bushveld Complex (numbered squares – refer to source). Vergenoeg Fe-F mine is located in the near geographic centre of the Complex. The detailed study area is indicated by the black frame to the left of the picture. (taken from Crocker et al. 2001).

Figure 2.11. Surface geology of the Vergenoeg mine breccia pipe orebody. (taken from Crocker, 1985).

Figure 2.12. Simplified schematic cross-section of the Vergenoeg Fe-F breccia pipe showing clear vertical zonation with respect to mineralisation assemblages. Z = mean height above sea level. (modified after Crocker, 1985; Fourie, 2000).

Figure 2.13. Mineral paragenesis of Vergenoeg Fe-F deposit (from Borrok et al., 1998).
Figure 2.14. Simplified schematic geological plan of the centrally-intruded Loolekop pipe of the Phalaborwa Complex.

Figure 3.1. Inferred limit of the Bushveld Complex showing the west, east, north and south lobes. The granites of the Lebowa Granite Suite (LGS) are indicated with crosses. Vergenoeg Fe-F mine is located in the near geographic centre of the Complex. The detailed study area is indicated by the black frame to the left of the picture.

Figure 3.2. Geological sketch map of the area near Rooiberg. The detailed study area of this report is marked by the black frame, including the mineral occurrences at Ruigtepoort, Blokspruit, Slipfontein and Elandslaagte. Fluorite occurrences, as identified by Crocker et al. (1988), are denoted by black dots.

Figure 3.3. Farm boundaries and the area mapped in this study.

Figure 3.4. Geological outcrop map with interpretation of the farms near Ruigtepoort.

Figure 3.5. Regional sketch map of the area around the Rooiberg fragment depicting the principal regional structures. (modified from Crocker et al., 2001).

Figure 3.6. Structural traces and principal lineaments of the farms near Ruigtepoort with frequency azimuth rose plots calculated per farm.

Figure 3.7. Regional airborne radiometric survey of the Rooiberg fragment and surrounding Bushveld granites. Area of study indicated by white square (image reproduced courtesy of Rio Tinto Exploration Africa).

Figure 3.8. Total Count radiometrics for the farms near Ruigtepoort Mine (image reproduced courtesy of Rio Tinto Exploration Africa).

Figure 3.9. Airborne magnetic survey of the farms near Ruigtepoort mine (image reproduced courtesy of Rio Tinto Exploration Africa).

Figure 4.1. Na-K activity-activity diagram, constructed for the P-T condition indicated. The starting fluid is marked by the closed black dot derived from fluid inclusion data for Mount Angeley two-feldspar quartz monzonite. The open circle represents the fluid after albitisation of calc-silicate country rocks with the solid arrow tracing the path of intermediate experimentally derived results. Dotted lines trace hypothetical path of projected fluid evolution producing corresponding K-metasomatism and sericitisation (after Oliver et al., 2004).

Figure 4.2. Models by Oliver et al. (2004) portraying progressive infiltration of fluids through a rock column. Fluid of the same composition is added from the left and allowed to react. On completion of each reaction step (ticks on x-axis) the fluid is displaced to the next block of rock and new fluid added as before. The bottom portion of each diagram shows the calculated molalities of the indicated fluid species. a) Isothermal infiltration of calc-silicate rock with conditions as indicated. b) Retrograde (down P-T) infiltration of calc-silicate rocks from 550°C and 350 MPa to 400°C and 200 MPa (after Oliver et al., 2004).

Figure 4.3. Plot of log $a_{K^+}/a_{H^+}$ vs. temperature at 1 kb showing the temperature ranges of alteration assemblages associated with mineralisation. Point 1 marks the original fluid. Point 2 marks the position of the fluid equilibrated with the hornblende-bearing magma. Various paths may be taken by the fluid on cooling with deuteric alteration being followed by potassic alteration and phyllic alteration (after Burnham & Ohmoto, 1980).
**Figure 4.4.** Comparisons of the Fe$^{2+}$ contents of typical submarine hydrothermal fluids (A), typical subaerial geothermal fluids (B), and the fluids in equilibrium with the magnetite-hematite assemblage (solid and dashed line). The equilibrium Fe$^{2+}$ values are estimated for the most common pH value of hydrothermal fluid at each temperature (cf. Ohmoto and Goldhaber, 1997). Note the reaction between hematite and hydrothermal fluid A will transform the hematite to magnetite (path 3f), whereas the reaction between magnetite and hydrothermal fluid B will transform the magnetite to hematite (path 3r). Taken from Ohmoto (2003).

**Figure 5.1.** Generalised scheme that links granite compositions and magmatic oxidation stae to metal associations and intrusion-related ore deposit types (modified after Barton, 1996). Metals shown in bold reflect the more important associations (taken from Robb, 2005).

**Figure 5.2.** Ternary diagram of Al$_2$O$_3$-(CaO + Na$_2$O)-K$_2$O demonstrating common alteration trend of an average granitic composition. Data from this study follow a discrete trend which tends to the potassium end-member and reflects K-metasomatism of granitic host rocks (modified after Nesbitt and Young, 1984; 1989).

**Figure 5.3.** Ternary Q-Ab-Or demonstrating alteration trends in terms of normative values of quartz, albite plagioclase and K-feldspar.

**Figure 5.4.** Ternary SiO$_2$-(K$_2$O + Na$_2$O)-Fe$_2$O$_3$ demonstrating the strong ferric component that accompanies mineralisation.

**Figure 5.5.** K$_2$O vs. SiO$_2$ plot for samples demonstrating variation in potassium with respect to different styles of alteration.

**Figure 5.6.** Fe$_2$O$_3$ vs. SiO$_2$ plot demonstrating variation in iron with respect to alteration.

**Figure 5.7.** Al$_2$O$_3$ vs. SiO$_2$ plot demonstrating variation in aluminium with respect to alteration.

**Figure 5.8.** CaO vs. SiO$_2$ plot demonstrating variation in calcium with respect to alteration.

**Figure 5.9.** Na$_2$O vs. SiO$_2$ plot demonstrating variation in sodium with respect to alteration.

**Figure 5.10.** Isocon plots of averaged altered granite types with respect to averaged least altered granites. Thin line reproduced in plots (b)-(f) corresponds to the reference deuteric isocon in (a).

a) Deuterically altered granites with good isocon for most components, with slight mass loss with respect to the least altered granites. b) K-metasomatic alteration with slight mass change and some concentration variation for components related to K-feldspar, in particular. c) Prolonged or intense K-metasomatism resulting in microclinised granite with relative mass gain. Potassium strongly enriched at the expense of sodium and calcium. d) Sericitic alteration with mass loss; aluminium expectedly involved in a one-for-one transformation from feldspar to sericite with no resultant concentration change. e) Silicic-hematitic alteration exhibiting large mass loss and broad component concentration variation. f) Chloritic alteration exhibiting large mass loss with significant increased concentrations of base metals, Rare Earths and iron.
**Figure 5.11.** a) Bivariate plot of Rb vs. Sr with indicated crystal fractionation trends and alteration trends. b) Bivariate plot of Rb vs. Ba with indicated crystal fractionation trends and alteration trends.

**Figure 5.12.** LILE covariation in Ruigtepoort granites with indicated crystal fractionation trends and alteration trends. a) Bivariate plot of Rb/Sr vs Sr b) Bivariate plot of Rb/Sr vs Ba (after Inger and Harris, 1993).

**Figure 6.1.** Geological Interpretation of the geology around the Ruigtepoort Fluorspar mine. Scale 1:14 285.

**Figure 6.2.** The Ruigtepoort fluorspar mine map and sections (from Crocker et al. 2001).

**Figure 6.3.** Geological Interpretation of the geology around the Slipfontein Fluorspar mine. Scale 1:14 285.

**Figure 6.4.** The Slipfontein fluorspar mine map and section (from Crocker et al. 2001).

**Figure 6.5.** Geological Interpretation of the geology around the Ysterkop prospects on Blokspruit 157JQ. Scale 1:16 667.

**Figure 6.6.** The Blokspruit or Ysterkop North actinolite-fluorspar prospect (from Crocker et al. 2001).

**Figure 6.7.** The distribution and locations of the numerous iron oxide–fluorite occurrences on the Blokspruit and Ruigtepoort farms (from Crocker et al. 2001).

**Figure 6.8.** Geological Interpretation of the geology around the Elandslaagte REE occurrence. Scale 1:14 285.

**Figure 6.9.** Geological Interpretation of the geology around the Elandslaagte Central REE occurrence. Scale 1:14 285.

**Figure 6.10.** Geological Interpretation of the geology around some mineralised bodies on the farm Doornfontein 155JQ. Scale 1:14 285. a) The prospect in the southeast corner of the farm is of a large massive iron oxide-quartz plug, approximately 100 m in diameter, which forms a low hill 20-30 m above the otherwise flat granitic plain. b) A number of small diggings located on the western side of the farm intersect chloritised granites, sedimentary xenoliths and thin magnetite-hematite veins.

**Figure 6.11.** Frequency histogram of age determinations from the LGS and Rooiberg Group from 2100 Ma to 950 Ma (taken from Robb et al. 2000).


**Figure 6.13.** 207Pb/206Pb versus 238U/206Pb plot (Tera-Wasserburg concordia) for analyses of authigenic zircons associated with late hydrothermal quartz in the Spoedwel mine (taken from Robb et al. 2000, for data see same reference).

**Figure 6.14.** Frequency histogram showing ages for the LGS selected on the basis of accuracy and precision (i.e. single or small grain population U-Pb zircon or monazite ages or reasonably well-constrained Rb-Sr and Pb-Pb isochrons). Also shown are presently available age constraints for the Kheis orogeny (Kruger et al., 1999), Soutpansberg/Waterberg deposition (SACS, 1980), and the Kibaran and Namaquan orogenies (Robb et al., 1999). (taken from Robb et al. 2000).
Figure 7.1. Location of three major IOCG deposits at Olympic Dam, Carajás and Vergenoeg. Proterozoic crust shown in dark grey, Phanerozoic rocks in medium grey and light grey (from Groves, 2004).

Figure 7.2. Schematic model of level of formation for some Bushveld-type Fe-F deposits (from Crocker et al., 1988).

Figure 7.3. Generalised distribution of styles of alteration about a mineralised vein or body, with intense chloritisation, hematisation and silicification occurring closest to the vein (<2 m), sericitic alteration in close proximity (<5 m) which may possess an epidote and/or silicic component, K-metasomatism in a more broad pattern around the vein (100s of m), and albitisation occurring on a regional scale.

Figure 7.4. Schematic cross section representing proposed relationships of alteration zoning in iron oxide (-Cu-U-REE-Au) deposits, drawn to represent examples in volcanic and plutonic host rocks (from Hitzman et al., 1992).

Figure 7.5. Schematic cross-section of the Eastern Mt. Isa Block Succession explaining the distribution and generation of IOCG deposits and the likely chemical reaction paths between source rocks, albitisation and ore deposits. Black arrows are inferred pathways of brines, white arrows are speculated sulphur-bearing fluids. Fluid modification from albitisation indicated by the variable grey shading (reproduced from Oliver et al., 2004).

Figure 7.6. Distribution of alkaline rocks and carbonatite around the Bushveld Complex (after Woolley, 2001; Crocker et al., 2001). Bushveld-age alkaline intrusives shown in red, Pilanesberg-age alkaline intrusives shown in green and undated alkaline intrusives shown in blue.

Figure 7.7. Distribution of some carbonatite and alkaline intrusions near the study area. Base map is taken from 1:250 000 Geological Sheet, South African Council for Geoscience.

Figure 7.8. Schematic model of level of formation for some Bushveld-type Fe-F deposits in conjunction with alteration and fluid characteristics of an IOCG model where magmatic fluids dominated (c.f. Figure 1.3) (modified after diagrams of Crocker et al., 1988; and Barton & Johnson, 2004).

APPENDIX IV (i). Geological Outcrop map of distribution of Nebo granites of the farms near Ruigtepoort mine, Rooiberg District.

APPENDIX IV (ii). Geological Outcrop map of distribution of Klipkloof granites of the farms near Ruigtepoort mine, Rooiberg District.

APPENDIX IV (iii). Geological Outcrop map of distribution of Roof-rocks to the granites of the farms near Ruigtepoort mine, Rooiberg District.

APPENDIX IV (iv). Geological Outcrop map of distribution of massive iron oxide ironstones of the farms near Ruigtepoort mine, Rooiberg District.

APPENDIX IV (v). Geological Outcrop map of distribution of pronounced sericite alteration of the farms near Ruigtepoort mine, Rooiberg District.

APPENDIX IV (vi). Geological Outcrop map of distribution of structural lineaments of the farms near Ruigtepoort mine, Rooiberg District.

APPENDIX IV (vii). Geological Outcrop map of distribution of alluvium and grits of the farms near Ruigtepoort mine, Rooiberg District.
List of Tables

Table 1.1. Characteristics of IOCG Systems (after Barton & Johnson, 2004).
Table 1.2. Synopsis of alternative genetic models for IOCG systems (cf. Figure 1.3.) (taken from Barton & Johnson, 2004).
Table 1.3. Ores Grades of the Olympic Dam Cu-U-Ag-Ag-REE deposit, South Australia.
Table 2.1. Lithostratigraphic subdivisions of the Bushveld Complex according to SACS (1980). Ages in bold print represent best current age estimates according to Walraven (1997) and Harmer & Armstrong (2000).
Table 2.2. General trends in Nebo granite from base to roof (Gain & Twist, 1995).
Table 2.3. Typical three-fold subdivision of the Lebowa Granite Suite (Crocker et al. 2001).
Table 2.4. Types of mineralisation in the Bushveld granites (Bailie & Robb, 2004).
Table 3.1. Representation of principal structural orientations on the farms Slipfontein 551KQ, Blokspruit 157JQ and Ruigtepoort 162JQ.
Table 4.1. Effects of Secondary alteration of granites (after Stemprok & Skvor, 1974).
Table 4.2. Generalised paragenetic sequence of Ruigtepoort mine and satellite occurrences, with dominant style of alteration.
Table 5.1. Characteristics of S-type, I-type, and A-type granites (Chappell & White, 1974).
Table 5.2. Geochemical analyses for least-altered Bushveld Nebo granites from Ruigtepoort area and comparisons with analyses of unaltered Nebo granites from elsewhere in the Bushveld.
Table 5.3. Average geochemical analyses for differentiated granite types and altered Nebo granites from Ruigtepoort area.
Table 5.4. Scaling factors used in construction of isocon diagrams.
Table 5.5. Mineral/melt partition coefficients for rhyolitic melts (after Rollinson, 1993).
Table 5.6. Average values of selected trace elements for coarse-grained granites with respect to alteration and mineralisation.
Table 6.1. Base and precious metal contents for the mineral occurrences of the Western Bushveld Complex near the farm Ruigtepoort 162JQ.
Table 6.2. Summary of Characteristic Features of Mineral Occurrences in the Western Bushveld Granites near the farm Ruigtepoort.
Table 7.1. Synopsis of characteristics of IOCG deposits considered in this study.
Table 7.2. Characteristics of deposits from systems dominated by magmatic fluid and non-magmatic fluids (reproduced from Barton & Johnson, 2000).
List of Plates

Plate 1.1. All photographs and descriptions from Reeve et al., (1990). a) Granitic breccia with abundant hematite-rich matrix. Fine-grained orange clasts in the upper half largely consist of fine-grained felted sericite, which are presumably products of extreme alteration of intensely brecciated granite. Chalcopyrite (tan & brass colour) disseminated throughout clasts and matrix. b) Heterolithic matrix-rich breccia with subequal proportions of sericite clasts (orange-brown) and steely grey hematite clasts. Abundant quartz fragments. c) Heterolithic hematite breccia. Hematite clasts include a variety of red-brown, purplish and black types, many of which are fragments of pre-existing breccias. Subordinate clasts of sericitised granite breccia and hematite-quartz breccia also present. Chalcopyrite and bornite occur as non-visible disseminations. Fluorite present (jet-black) d) Sericite-chlorite altered granite clasts in orange brown network of very fine-grained sericite, ultra-fine iron oxide and angular relict quartz fragments. e) Intensely sericitised granite breccia in which original granite texture preserved. f) Intensely Fe-metasomatised granite in which primary feldspars and ferromagnesian minerals totally replaced by vuggy hematite.

Plate 1.2. All photomicrographs and descriptions from (Hagni, unpubl.) a) Rounded chalcopyrite with coating of bornite then partial coating of later chalcopyrite. Subsequent fine-grained hematite has preferentially replaced parts of the bornite layer. Reflected light x 150; oil immersion. b) Rounded bornite in matrix of hematite. Reflected light x 150; oil immersion. c) Bornite partially replaced by subsequent uranium-bearing fluids. Bluish tinted coffinite with fine-grained disseminations of covellite. Brannerite is locally formed in association with the abundant anatase. Although U mineralization shown here formed late, uranium was present in the early ore fluids indicated by the presence of trace amounts of uranium in hematite. Reflected light x 500; oil immersion. d) Exsolution intergrowth of bornite and chalcocite. Reflected light x 150; oil immersion. e) Exsolution intergrowth between bornite and chalcocite showing smooth boundaries between the two minerals that are typical for such exsolution intergrowth. Hematite occurs especially along the margins of the sulphide grain and probably occurs as a partial replacement of the sulphide grain. Reflected light x 500; oil immersion. f) Large pseudomorphic crystal of martite after magnetite, characterized by its fine-grained polycrystalline nature. Small remnants of magnetite remain in most martite grains. Bornite and chalcopyrite occur as veins and along the martite grain boundaries Finer grained hematite occurs in the groundmass between the martite. Reflected light x 150; oil immersion.

Plate 2.1. Mineralised Fe-F breccia from Vergenoeg mine, South Africa. a) Hematite-fluorite ore sample from Vergenoeg mine. b) Thin section photomicrograph of typical magnetite-hematite-fluorite ore. Plane polars x 4; field of view is 2.75 mm wide; Photo ID: PO1-A. c) Hematite breccia with abundant sedimentary-derived fragments. Plane polars x 4; field of view is 2.75 mm wide; Photo ID: PO2-A. d) Hematite breccia with abundant sedimentary-derived fragments. Crossed polars x 4; field of view is 2.75 mm wide; Photo ID: PO2-B.
Plate 3.1. a) Flat, outcrop-poor weathered surface of Bushveld granites in the north, central and eastern portions of the area. b) Low hills and outcrops, often wooded, of the southern and western portions of the area. Fracture related depressions and drainage features tend to be more prominent. c) Rounded-boulder granite outcrop of the southern portion of the area, usually well-vegetated. d) Typical dull-pink perthitic Nebo granite from Blokspruit 157JQ; Sample #ID 11120. e) Grey hornblende-rich Nebo granite representing least differentiated material. Sharp contact with aplite (Klipkloof) phase. From Paalkraal 556KQ. f) Porphyritic variety Nebo granite from Ruitgepoort 162JQ; Sample #ID 11141.

Plate 3.2. a) Weathered surface of Nebo and Klipkloof granites. Coarse quartz grains in the Nebo granite weather prominently forming a rough, pitted surface; by contrast, the Klipkloof is smooth and even. b) Outcrop of Bobbejaankop granite with characteristic quartz chains weathering prominently. c) Red Nebo granite common throughout the area. The mafic phase is dominantly biotite, which is commonly chloritised. From Blokspruit 157JQ; Sample #ID 11103. d) Bobbejaankop variety Nebo granite from type-locality in the eastern Bushveld e) Klipkloof variety Nebo granite from Ruitgepoort 162JQ.

Plate 3.3. a) Spherulitic rhyolite with greenish nodules from Slipfontein 551KQ; Sample #ID 11194. b) Heavily weathered spherulitic rhyolite from Blokspruit 157JQ; Sample #ID 11153. c) Typical fine-grained red pseudogranophyre from Ruitgepoort 162JQ; Sample #ID 11070. d) Purplish-brown Rooiberg agglomerate from Elandslaagte 154JQ; Sample #ID 11076. e) Yellowish-brown silicified Rooiberg agglomerate with rhyolitic shards, from Elandslaagte 154JQ; Sample #ID 11202.

Plate 3.4. a) Clean, highly-recrystallised meta-quartzitic xenolith consisting of up to 99 % quartz from Elandslaagte 154JQ; Sample #ID 11146. b) Finely-laminated, hematite-rich sediment. c) Massive, fine-grained leptite from Ruitgepoort 162JQ. d) Iron oxide-rich grit of possible Karoo age, from Ruitgepoort 162JQ; Sample #ID 11081.

Plate 3.5. a) Exaggerated reddening of Bobbejaankop granite due to K-metasomatism from Blokspruit 157JQ. K-feldspar grains appear to be annealing. Sample #ID 11105. b) Episyenitic granite where quartz comprises less than 10 % of the rock from Ruitgepoort 162JQ. Sample #ID 11177. c) Myrialitic episyenite with hematite cavity fill and anomalous metal contents from Blokspruit 157JQ. d) Sericitised fine-grained granite from Elandslaagte 154JQ. Sample #ID 11060. e) Intensely sericitised fine-grained granite from Elandslaagte 154JQ. Sample #ID 11201. f) Silicified-sericitised medium-grained granite from Elandslaagte 154JQ with yellow-green colouration. Sample #ID 11145.

Plate 3.6. a) Intensely haematised coarse Nebo granite from Ruitgepoort 162JQ. Sample #ID 11068. b) Intensely and pervasively chloritised medium-grained granite from Doornfontein 155JQ. Late fracture has introduced oxidised iron oxides and caused local overprinting. Sample #ID 11089. c) Alteration front between earlier sericitisation-silicification of fine-grained granite from Blokspruit 154JQ, with later hematite overprint. Hm=hematite, Ser-Sil=sericitised-silicified. Sample #ID 11187. d) Compounded alteration overprinting of early sericitisation by intense haematisation, presumably followed
by intense chloritisation; from Blokspruit 154JQ. Hm=hematite, Ser=sericitised, Chl=chloritised. Sample #ID 11122. e) Coarse granite country rock to the Ruigtepoort fluorspar mine; sample taken approximately 10 m from orebody contact. Intense hematisation developed away from the orebody and overprinted by intense chloritisation developed closer to the orebody. Hm=hematite, Chl=chloritised. Sample #ID 11067. f) Sericitised-silicified actinolite rock overprinted by gossanous hematite from Blokspruit 154JQ. Hm=hematite, Ser-Sil=sericitised-silicified.

Plate 4.1. a) Typical hypersolvus, perthitic granite comprising perthite and quartz. Accessory phases not visible in this photograph. Crossed polars x4; field of view is 2.75 mm wide; Photo ID: 11097-F. b) Typical subsolvus Klipkloof granite with plagioclase needles, indicative of super-cooling. Plane polars x10; field of view is 0.85 mm wide; Photo ID: 11212-B. c) Transsolvus granite as defined by the occurrence of both albite plagioclase and perthite. Crossed polars x4; field of view is 2.75 mm wide; Photo ID: 11103-H. d) Anhedral comagmatic perthite and quartz, with quartz completely enclosing an albite plagioclase grain. Crossed polars x10; field of view is 0.85 mm wide; Photo ID: 11193-G. e) Anhedral perthitic K-feldspar. Plane polars x10; field of view is 0.85 mm wide; Photo ID: 11194-C. f) Anhedral perthitic K-feldspar. Crossed polars x10; field of view is 0.85 mm wide; Photo ID: 11194-D.

Plate 4.2. a) Embayed and resorbed quartz grains intergrown with K-feldspar. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11121-C. b) Embayed and resorbed quartz grains intergrown with K-feldspar. Crossed polars x4; field of view is 2.75 mm wide; Photo ID: 11049-M. c) Biotite-quartz symplectite. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11023-K. d) Biotite-quartz symplectite. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11034-A. e) Cluster of accessory phases including zircons, chloritised biotite, magnetite and other iron oxides. Crossed polars x20; field of view is 0.45 mm wide; Photo ID: 11067-L. f) Interstitial biotite with subsolidus hydrothermal magnetite developed along cleavage planes demonstrating the relationship between K- and Fe- metasomatism. Crossed polars x10; field of view is 0.85 mm wide; Photo ID: 11193-F.

Plate 4.3. a) Granophyric texture of typical granophyre. Crossed polars x4; field of view is 2.75 mm wide; Photo ID: 11102-A. b) Granophyric texture with no discernible nucleation point Crossed polars x4; field of view is 2.75 mm wide; Photo ID: 11102-B. c) Typical massive Rooiberg rhyolite consisting of quartz, feldspar and minor biotite. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11049-J. d) Coarse pseudgranophyre from Elandslaagte 154JQ. Fine stringy quartz-feldspar symplectic intergrowth nucleating off the side of K-feldspar grain. Crossed polars x4; field of view is 2.75 mm wide; Photo ID: 11058-A. e) Donut graphic texture of pseudogranophyre. Plane polars x10; field of view is 0.85 mm wide; Photo ID: 11213-H. f) Streaky texture of pseudogranophyre. Crossed polars x4; field of view is 2.75 mm wide; Photo ID: 11213-I.

Plate 4.4. a) Spotted texture of pseudogranophyre. Crossed polars x10; field of view is 0.85 mm wide; Photo ID: 11213-E. b) Agglomerate groundmass composed of chalcedonic quartz and sericite. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11076-E. c) Agglomerate groundmass composed of
chalcedonic quartz and sericite. Crossed polars x4; field of view is 2.75 mm wide; Photo ID: 11076-F. d) Fine needles, altered and obscured by ferrohydroxides, in agglomerate possibly indicative of supercooling. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11088-A. e) Angular fragment in agglomerate with relict faces of feldspar crystal; completely altered. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11076-A. f) Subhedral lathlike fragments in agglomerate, presumably feldspar crystals, completely obscured by hematite and other ferrohydroxides. Plane polars x10; field of view is 0.85 mm wide; Photo ID: 11076-G.

Plate 4.5. a) Quartzitic xenolith near granite roof principally composed of mosaic textured quartz, with iron oxides along grain boundaries and microfractures. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11072-A. b) Quartzitic xenolith near granite roof principally composed of mosaic textured quartz, with iron oxides along grain boundaries and microfractures. Crossed polars x4; field of view is 2.75 mm wide; Photo ID: 11072-B. c) Annealed quartz of sedimentary xenolith. Minor phases include sericite and iron oxides. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11150-A.

Plate 4.6. a) Fresh yellowish-green ferroactinolite. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11091-A. b) Colourless to pale green, unaltered actinolite with rounded oxide grains. The brownish phase along grain margins and in fractures may be nontronite. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11139-D. c) Pervasive chloritisation alteration front over actinolite. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11139-C. d) Hematite replacement of actinolite. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11139-F. e) Silica-hematite pseudomorph after actinolite. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11046-A. f) Yellowish brown Y-britholite. Plane polars x4; field of view is 2.75 mm wide; Photo ID: 11091-E.

Plate 4.7. a) Euhedral magnetite in quartz partially oxidised to hematite. Mt=magnetite, Hm=hematite. Reflected light x50; field of view is 0.16 mm; Photo ID: 11194-N. b) Gossanous iron oxide of hematite with relict magnetite. Mt=magnetite, Hm=hematite. Reflected light x80; field of view is 0.10 mm; Photo ID: 11079-A. c) Specularite flakes from Ruitgepoort contact granite. Reflected light with Plane polars x4; field of view is 2.75 mm; Photo ID: 11067-Q. d) Quartz-hematite vein demonstrating multiple episodes of quartz growth. Plane polars x4; field of view is 2.75 mm; Photo ID: 11074-J. e) Hematite gossan. Rhombic forms may be indicative of primary siderite-magnetite in ore. Reflected light x4; field of view is 2.75 mm; Photo ID: 11055-A. f) Hematite gossan from Elandslaagte 154JQ with pyrite in cores of gossan lattice. Py=pyrite, Hm=hematite. Reflected light x4; field of view is 2.75 mm; Photo ID: 11074-E.

Plate 4.8. a) Hematite gossan. Primary fluorite still contained in some partitions. Hm=hematite, Fl=fluorite. Reflected light x20; field of view is 0.45 mm; Photo ID: 11055-A. b) Multiple growth phases of quartz associated to hematite ores. Plane polars x10; field of view is 0.85 mm; Photo ID: 11143-F. c) Quartz growth terminating in triple junction with hematite in final pore space. Qtz=quartz. Plane polars x4; field of view is 2.75 mm; Photo ID: 11055-H. d) Octahedral growth planes in high temperature fluorite. Plane polars x20; field of
view is 0.45 mm; Photo ID: 11068-G. e) Pseudomorphed quartz after actinolite needles with fine inclusions of hematite. Matrix is quartz. Plane polars x4; field of view is 2.75 mm; Photo ID: 11037-F. f) Pseudomorphed hematite after actinolite with crystalline quartz matrix. Plane polars x4; field of view is 2.75 mm; Photo ID: 11037-C.

**Plate 4.9.** a) Pseudomorphed quartz after actinolite needles with larger aggregates of hematite. Plane polars x4; field of view is 2.75 mm; Photo ID: 11017-F. b) Chloritized granite with iron oxides developed within perthite and along grain boundaries. Plane polars x10; field of view is 0.85 mm; Photo ID: 11008-P. c) Iron oxides occurring as veins and stringers in actinolite rock. Plane polars x4; field of view is 2.75 mm; Photo ID: 11056-A. d) Granite breccia with hematite fill. Plane polars x4; field of view is 2.75 mm; Photo ID: 11149-B.

**Plate 4.10.** a) Chlorite-specularite-fluorite ore of Ruigtepoort Mine with fragmented pyrite grains and bright red iron oxides. Reflected with Plane polars x10; field of view is 0.85 mm; Photo ID: 11001-ZG. b) Chlorite and ferrohydroxides after actinolite in radiating growths. Plane polars x20; field of view is 0.45 mm; Photo ID: 11611-D. c) Chlorite groundmass with fluorite and minor sulphides. Black spots are radiation damage around thorium-rich minerals. Reflected with Plane polars x4; field of view is 2.75 mm; Photo ID: 11001-R. d) Iron oxide staining within the chlorite groundmass. Euhedral pyrite grain in bottom field of view with small pyrite grains above. Reflected with Plane polars x80; field of view is 0.10 mm; Photo ID: 11001-ZC. e) Heavily-pitted, euhedral pyrite crystal with pyritohedral habit; predates fluorite and chlorite. Reflected with Plane polars x4; field of view is 2.75 mm; Photo ID: 11001-E. f) Pyritohedral pyrite with chalcopyrite core and small angular fluorite inclusion. Fine exsolution-type lamellae unidentified. Reflected with Plane polars x4; field of view is 2.75 mm; Photo ID: 11001-X.

**Plate 4.11.** a) Inclusions in pyrite of earlier-formed ore phases magnetite. Reflected x40; field of view is 0.20 mm; Photo ID: 11160-T. b) Inclusions in pyrite of earlier-formed ore phase, possibly ilmenite. Reflected x80; field of view is 0.10 mm; Photo ID: 11160-J. c) Sub-euhedral pyrite enclosed by later-formed fluorite. Reflected with Plane polars x4; field of view is 2.75 mm; Photo ID: 11001-G. d) Pyrite with flame-like chalcopyrite in chlorite-iron oxide groundmass. Reflected with Plane polars x80; field of view is 0.10 mm; Photo ID: 11001-ZF. e) Chalcopyrite with reddish brown alteration/exsolution in pyrite. Reflected with Plane polars x20; field of view is 0.45 mm; Photo ID: 11001-U. f) Fine chalcopyrite and pyrite fragments in coarse fluorite. Reflected with Plane polars x10; field of view is 0.85 mm; Photo ID: 11002-C.

**Plate 4.12.** a) Multiple growth quartz of sinter. Plane polars x4; field of view is 2.75 mm; Photo ID: 11159-E. b) Mosaic textured epithermal quartz. Crossed polars x4; field of view is 2.75 mm; Photo ID: 11159-D. c) Highly-pitted and fractured pyrite grain. Reflected light x4; field of view is 2.75 mm; Photo ID: 11159-A. d) Highly-fragmented arsenopyrite and pyrite. Reflected light x4; field of view is 2.75 mm; Photo ID: 11159-B. e) Gold grain in quartz 0.01 mm (10 µ) in size. Reflected light x80; field of view is 0.10 mm; Photo ID: 11160-ZT. f) Multiple gold grains in quartz approximately 0.015 mm (15 µ) in length. Reflected light x80; field of view is 0.10 mm; Photo ID: 11001-Y.
Plate 4.13.  a) Tightly packed metaquartzitic rock with interstitial hematite. Small quartz grains included in larger grains (centre left) evidence for recrystallisation. Qtz=quartz, Hm=hematite. Crossed polars x4; field of view is 2.75 mm; Photo ID: 11150-D. b) Quartzitic xenolith where 40-50 % of field of view is replacement hematite. Plane polars x4; field of view is 2.75 mm; Photo ID: 11087-C. c) Specularitic hematite replacement in sedimentary xenolith. Reflected light x4; field of view is 2.75 mm; Photo ID: 11150-E. d) High-relief rare earth mineral bastnaesite. Qtz=quartz, FeOx=iron oxide, Bast=bastnaesite. Plane polars x20; field of view is 0.45 mm; Photo ID: 11087-E. e) Sericite clot in sedimentary xenolith. Plane polars x4; field of view is 2.75 mm; Photo ID: 11150-F. f) High birefringence of sericite clot in sedimentary xenolith. Crossed polars x4; field of view is 2.75 mm; Photo ID: 11150-G.

Plate 4.14.  a) Deuterically altered, reddened K-feldspar with interstitial symplectic biotite. Plane polars x4; field of view is 2.75 mm; Photo ID: 11023-G. b) Deuteric chloritised symplectic biotite. Plane polars x4; field of view is 2.75 mm; Photo ID: 11023-I. c) Microclisinisation of albite feldspar. Crossed polars x4; field of view is 2.75 mm; Photo ID: 11120-D. d) Microclisinisation of granite; new K-feldspar growth at the expense of quartz. Plane polars x4; field of view is 2.75 mm; Photo ID: 11004-J. e) Microclisinisation of granite; new K-feldspar growth at the expense of quartz. Plane polars x4; field of view is 2.75 mm; Photo ID: 11177-B. f) Growth of secondary biotite related to K-metasomatism; growing at expense of pre-existing feldspar. Crossed polars x4; field of view is 2.75 mm; Photo ID: 11120-H.

Plate 4.15.  a) Sericite replacement of perthite K-feldspar. Crossed polars x4; field of view is 2.75 mm; Photo ID: 11125-B. b) Sericitisation of K-feldspar; quartz grains unaffected. Crossed polars x10; field of view is 0.85 mm; Photo ID: 11115-A. c) Near-complete replacement of K-feldspar in intensely altered zone. Crossed polars x4; field of view is 2.75 mm; Photo ID: 11078-D. d) Intensely sericitised K-feldspar exhibiting primary crystal habit; associated quartz and hematite. Crossed polars x4; field of view is 2.75 mm; Photo ID: 11201-E. e) Intensely sericitised granite; biotite replaced by muscovite with magnetite symplectic banding still apparent. Plane polars x10; field of view is 0.85 mm; Photo ID: 11111-D. f) Intense muscovite replacement of feldspars with associated iron oxides, possibly liberated from feldspar with alteration. Crossed polars x4; field of view is 2.75 mm; Photo ID: 11078-F.

Plate 4.16.  a) Quartz rim developed around K-feldspar grain likely derived from sericitisation. Abundant iron oxides. Plane polars x4; field of view is 2.75 mm; Photo ID: 11014-G. b) Epithermal sinter of Ruigtepoort mine where a quartz-sulphide assemblage has wholly replaced the original chlorite ore assemblage. Crossed polars x4; field of view is 2.75 mm; Photo ID: 11159-D. c) Intensely chloritised feldspar with iron oxide staining. Plane polars x4; field of view is 2.75 mm; Photo ID: 11066-B. d) Mattted chlorite fans. Plane polars x4; field of view is 2.75 mm; Photo ID: 11067-F. e) Chlorite replacing quartz. Plane polars x4; field of view is 2.75 mm; Photo ID: 11059-A. f) Chlorite alteration of ferroactinolite. Plane polars x4; field of view is 2.75 mm; Photo ID: 11139-C.

Plate 4.17.  a) Hematisation of chloritised granites adjacent to Ruigtepoort mine; iron oxides distributed along fractures and between grains. Plane polars x20; field of view is 0.45 mm; Photo ID: 11066-E. b) Hematisation alteration front
consisting of fine stringer veins of hematite in fine-grained granite. Left portion of photograph unaltered assemblage. Plane polars x4; field of view is 2.75 mm; Photo ID: 11187-D. c) Iron oxides precipitated along grain boundaries in chloritised granite. Plane polars x10; field of view is 0.85 mm; Photo ID: 11008-P. d) Iron oxides precipitated along grain boundaries. Plane polars x10; field of view is 0.85 mm; Photo ID: 11008-Q. e) Hematite precipitated in a patchwork pattern in coarse Bobbejaankop granite. Plane polars x4; field of view is 2.75 mm; Photo ID: 11068-C. f) Bands of hematite in intensely sericitised feldspar; may be consequence of iron liberation during alteration. Plane polars x4; field of view is 2.75 mm; Photo ID: 11082-A.

Plate 6.1. a) Defunct Ruigtepoort Fluorite Mine 100 m long by 40 m wide; person in blue for scale. b) Contact between Bobbejaankop granite country rock and Ruigtepoort Mine ore body. The granites to the left of the contact are chlorite altered nearest the contact, grading into pervasive hematite alteration, grading to common deuterically altered granite. The contact is steeply dipping (~80°), with numerous parallel fractures, and strikes N-S. FeOx=iron oxide, Chl=chlorite. c) Chlorite rock of the Ruigtepoort ore zone, consists of chlorite, fluorite with minor sulphides and quartz; here with large euhedral fluorite and abundant sulphides. The sulphides visible in the photograph are dominated by pyrite with minor chalcopyrite; Chl=chlorite, Py=pyrite, Fl=fluorite. Sample #ID 11215. d) Chlorite rock with milky quartz and chalcopyrite in abundance, oxidised to bornite and covellite. Chl=chlorite, Cp=chalcopyrite, Bn=bornite, Cv=covellite, Qtz=quartz. e) Kaolinite and halloysite associated with the chlorite rock is likely an alteration product after actinolite. f) Vermiform quartz chains in the chlorite rock.

Plate 6.2. a) Specularitic hematite with milky quartz and occasional prismatic quartz crystals, and abundant iron oxides; Sample #ID 11013. b) Hematite-chlorite altered country granite with specularitic vein. Hm=hematite, Chl=chlorite, Spu=specularite. c) Chlorite alteration overprinting earlier hematite alteration of country granite, where the chlorite alteration exists closest to ore body. The hematite alteration will grade into fresh country rock over a few 10’s of metres; Hm=hematite, Chl=chlorite. Sample #ID 11067. d) Sectioned country granite near Ruigtepoort mine; quartz chains and deep red colour indicative of Bobbejaankop variety and suggest close proximity to intrusion roof. Chlorite developed along fine fracture in rock; Sample #ID 11089. e) Contact between altered country granite and chlorite rock ore zone. Chlorite altered to chlorite and sericite; Sample #ID 11004. f) Contact between chlorite rock and high-sulphidation quartz-pyrite-arsenopyrite sinter with conspicuous dividing oxidation front. Qtz=quartz, Py=pyrite.

Plate 6.3. a) Quartz-pyrite-arsenopyrite sinter. Sulphides pseudomorph after actinolite blades with milky vein quartz filling pore spaces; Qtz=quartz, Flu=fluorite, Py + Apy=pyrite + arsenopyrite Sample #ID 11159. b) Quartz-pyrite-arsenopyrite sinter. Minor late generation purple and colourless fluorite; Sample #ID 11159. c) Hand specimen of scoria-like material from Ruigtepoort mine, composed of abundant iron oxides and quartz. d) Scoria-like material in section showing gossanous hematite, limonite and other iron oxides and brecciated vein quartz fragments. FeOx=iron oxide, Hm=hematite, Qtz=quartz. e) Specularite-quartz vein in Bobbejaankop granite, near Ruigtepoort mine;
Sample #ID 11181. f) Hydrothermal granite breccia with hematite-magnetite-quartz vein fill. Granite clasts affected by sericite alteration; Sample #ID 11178.

Plate 6.4. a) Hematite-quartz-fluorite vein-fill of brecciated quartz blocks. b) Flat-lying manto-shaped orebody with pegmatite sill base. c) Sericite-epidote altered granite near mineralised aplitic dykes; Sample #ID 11015. d) Gossan of hematite quartz and minor sulphides; Sample #ID 11217. e) Brecciated vein quartz with hematite-quartz-fluorite-sulphide vein fill. f) Siderite-magnetite ore in breccia vein fill; Sample #ID 11216. g) Coarse molybdenite flakes in pegmatitic quartz.

Plate 6.5. a) Example of hematite-quartz pseudomorphed actinolite crystals with fluorite filling the residual vug. Fl=fluorite. b) Actinolite blades range in size from less than 1 cm to in excess of 10 cm. c) Actinolite rock in outcrop from the Ysterkop North prospect. d) Fresh ferroactinolite blades from Ysterkop North with pink britholite euhedral. In weathered examples the ferroactinolite may alter to lime-green nontrite and the britholite to goethite (Crocker et al., 2001); Act=actinolite, Brith=britholite. Sample #ID 11091. e) Mega-breccia of sub-rounded and angular granite blocks set in dissociated ferroactinolite matrix, from Ysterkop North. f) Mega-breccia from Ysterkop North of granite blocks in ferroactinolite matrix. Field of view approximately 4 m.

Plate 6.6. a) Massive hematite with intermingled white adularia, from Blokspruit 157JQ. b) Black hematite veining in fine-grained granite episyenite, the granite taking a deep red to purplish hue; Sample #ID 11057. c) Hematite infilling pore-spaces of granite episyenite. Fe₂O₃ now accounts for 26 wt% of bulk rock; Sample #ID 11053.

Plate 6.7. a) Hydrothermal granite breccia with hematite-quartz fracture fill associated with several mineralised occurrences on Elandslaagte 154JQ; Sample #ID 11147. b) Siliceous host rock to hematite-REE mineralisation, possibly bastnaesite-bearing; from Elandslaagte 154JQ; Sample #ID 11150. c) Siliceous host rock with abundant purplish hematite and fine specularite; Sample #ID 11152. d) White, crystalline quartzitic xenolith found in association with centres of hydrothermal activity; Sample #ID 11146. e) Intensely sericite-epidote altered granite country host rock; Sample #ID 11145. f) Massive hematite-quartz veins; Sample #ID 11079.

Plate 6.8. a) Chlorite-altered granite from Doornfontein 155JQ; Sample #ID 11085. b) Breccia of gossanous hematite after amphibole and chalcedonic quartz; Sample #ID 11073. c) Intense kaolinitisation of granite country rocks in immediate vicinity to mineralisation; Sample #ID 11083. d) Hydrothermal breccia with fragments of hematite-quartz gossan and granitic rocks; Sample #ID 11203.