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Introduction and Research Overview

1.1. Introduction to Iron Oxide-Copper-Gold Mineralisation

The class of deposits known as iron oxide-copper-gold (IOCG) is associated with felsic igneous rocks in most cases, commonly potassic igneous magmatism, with the deposits being commonly ~2.2 –1.5 Ga in age. They tend to be enriched in Ca, Fe, Mn and P, with a large number of deposits exhibiting an additional distinctive enrichment in F. The group as a whole is variably enriched to economic levels of Fe, Cu, Zn, Nb, Ag, Rare Earth Elements (REE), Au, Pb and U. They occur in a range of tectonic settings, such as along subduction-related continental margins, regions of orogenic basin collapse, or regions of anorogenic magmatism, and have been recognised in many localities around the world (Figure 1.1).

The IOCG class of deposits represents a family of loosely related ores that share a pool of common characteristics, controlled principally by chemical affinities; but for these similarities there are as many differences, which have led to contention in the past as to which deposits should be included in this class.

From an ore genesis perspective, IOCG deposits and their associated polymetallic mineralisation are poorly understood. Which deposits belong in this class and how they are related remains controversial. However, they are highly significant as they represent a dominant source of iron ore, for example in Chile and Mexico,

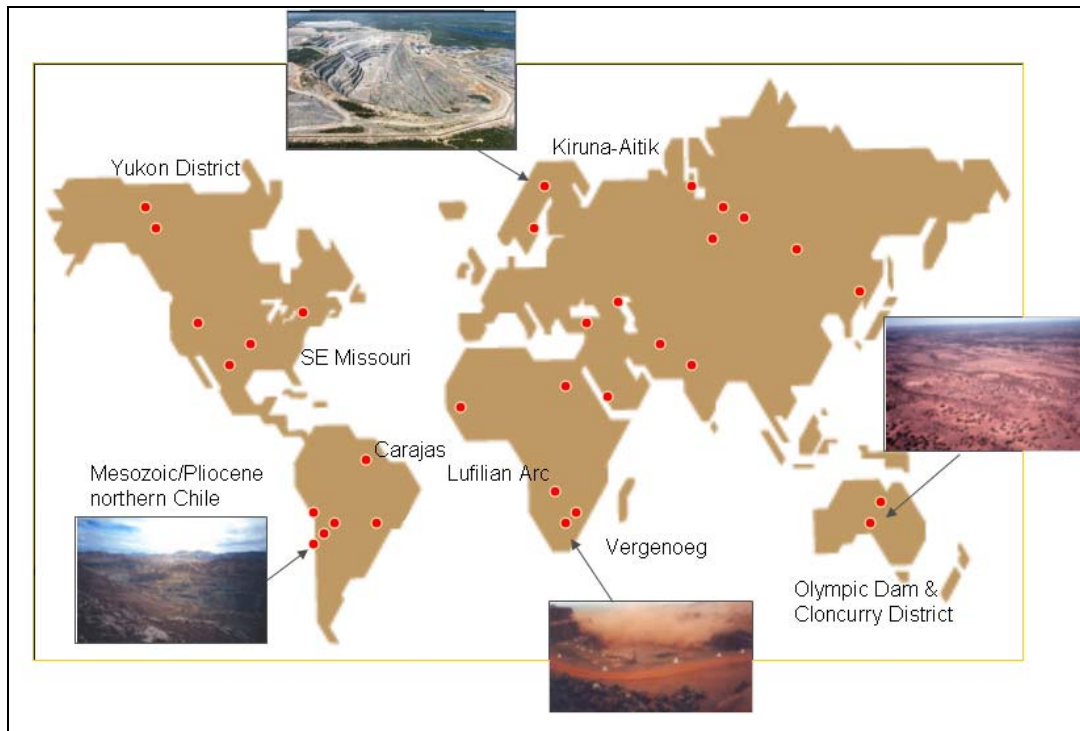


Figure 1.1. Distribution of some recognised IOCG deposits worldwide. (modified after Hitzman, 2000)

as well as in Sweden where deposits, such as those found at Kiruna-Aitik, have formed the basis of industrial development. The discovery of the giant Olympic Dam deposit - at Roxby Downs, South Australia, in 1975, attested to the greater potential of this style of mineralisation. Olympic Dam is host to a voluminous polymetallic suite of Fe-Cu-U-(Au-Ag) with approximately 2 billion tonnes of ore at 2.5 % Cu, as well as 0.6 g/t Au, 0.02 % Co, 6 g/t Ag, 0.5 % LREE, and 0.8 kg/t U_3O_8 , (Williams 1999), and it is currently the fifth largest low-grade copper producer in the world. The deposit was concealed underneath 300 m of post-Proterozoic sedimentary cover and was discovered during an exploration program for sedimentary-hosted stratiform copper mineralisation. It was only through somewhat predictive geological techniques that it was identified. With regard to these sorts of ore-bearing systems it should be borne in mind that the *economic* portions may have highly subdued, or even no geophysical signatures.

A magmatic-hydrothermal continuum has been suggested for IOCG mineralisation with Williams and Blake (1993) proposing two broad groups for these mineralisation styles based on their detailed host rock and geochemical associations. One of these groups may be referred to as Olympic Dam-type, which exhibits an Fe (-oxide) $\pm$ REE $\pm$ U $\pm$ Au $\pm$ Cu association. According to Hitzman *et al* (1992), deposits of this association may be quite diverse in detail but are linked by similar processes and tectonic setting with the differences controlled by local wall rock and structural controls. Other world-class polymetallic deposits that may belong to this class of deposits include Carajás, northern Brazil; Cloncurry, Australia; Pea Ridge, Missouri; Cerro Mercado, Mexico; Bayan Obo, Mongolia; Crixas, Brazil; and Vergenoeg in South Africa (Pollard & Williams, 1999). The other group, which may be referred to as Broken Hill-type, has a Pb-Zn-Ag association distinguished by Fe/Mn silicate and calc-silicate host rocks.

Many of these deposits exhibit intermediate characteristics of this continuum. These deposits characteristically contain anomalous amounts of Rare Earth Elements (REE), copper, gold, silver, cobalt and uranium with associated iron oxides and commonly associated fluorite.

A characteristic feature of all IOCG districts is the abundant occurrence of barren ironstones, dominated by large accumulations of magnetite or hematite that only contain anomalous amounts of the associated metals (e.g. Kiruna barren ironstones) (Barton & Johnson, 2004). The number of barren Fe-oxide-rich occurrences exceeds the Cu (-Au) ones by many times. The absence of metals in these instances may in fact provide insight into the formative processes required to produce large polymetallic deposits, representing variable conditions of the system or unsatisfied conditions relating to metal trap sites. Economic copper-gold mineralisation is thought to be a later feature in the regional development of these deposits (Barton & Johnson, 2004). It is generally considered that in IOCG formation an early sulphide-poor magnetite stage precedes a subsequent metal-bearing hematite stage. It appears that a necessary requirement for the formation

of large polymetallic deposits is the presence of sulphur during the latter stage, in spite of the sulphur-poor characteristics of the system, such that metals may be precipitated. This will be considered in greater detail later. Regardless, the presence of these barren ironstones becomes an important indicator of prospective terranes for IOCG mineralisation.

The realisation within economic geology discussions that most deposits do not, in fact, satisfy all conditions of any given ore model, and that most deposits have been affected episodically by multiple processes over longer periods of time, tends to be the rule and not the exception. This consideration is important when dealing with the IOCG continuum where a great many more factors appear to be influential in the formation of its deposits.

Characteristics of IOCG Mineralisation and Proposed Models

With the recognition of IOCG deposits as a separate class of deposits, it was quickly determined that no simple descriptive model would adequately encapsulate the diversity of the systems included in this family. However, a number of features are common to most descriptions of IOCG and related systems, and a number of other characteristics appear to be recurrent, although not necessarily universally present (Table 1.1).

Three tectonic settings have been identified in which IOCG deposits occur. These relate to regions of extension along subduction-related continental magmatism, intra-continental orogenic basin collapse or intra-continental anorogenic magmatism (Figure 1.2). All of these are likely to have relatively oxidised source rocks, igneous activity related to mantle underplating, and high heat flow (Hitzman, 2000). The presence of evaporites in some districts may have been important in the formation of saline brines, which are commonly associated with IOCG mineralisation (Barton & Johnson (2000). The combination of tectonic

setting and host lithology affect the geological signatures relating to alteration and mineralisation.

Table 1.1. Characteristics of IOCG Systems (after Barton & Johnson, 2004).

Generally accepted distinguishing characteristics

- an abundance of Cu and Au
- extensive alkali-rich alteration of both sodic-calcic [Na(Ca)] and potassic [K] types (Hitzman *et al.* 1992; Barton & Johnson, 1996)
- voluminous low-Ti magnetite and/or hematite
- a distinctive suite of minor elements, i.e. REE, Co, Ag, $\pm$ U, $\pm$ P
- prominent structural control including localisation along high- to low-angle faults, generally splays off major crustal scale faults (Hitzman, 2000)

Potentially key characteristics

- adjunct coeval magmatism
 - associations with distinctive magmas, e.g. high-K granitoids (Pollard, 2000) or alkaline magmatism (Meyer, 1988)
 - non-magmatic brines, e.g. evaporitic fluids or basinal brines (Barton & Johnson, 1996; Haynes, 2000)
 - distinctive tectonic environments, e.g. extensional or compressional settings (Hitzman, 2000)
 - distinctive ages of formation, e.g. Mesoproterozoic (Meyer, 1988)
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Significant and extensive hydrothermal alteration is evident in all IOCG terranes. This manifests predominantly as alkali-rich alteration of both sodic-calcic/albitic [Na (Ca)] and potassic [K] types (Hitzman *et al.* 1992; Barton & Johnson, 1996) on a regional scale, and is commonly of the order of 10s to 100s of km².

Sodic-calcic alteration tends to occur in the deeper and more peripheral zones and its affects may be on the order of 100s of km². It typically removes base metals and ferrous metals (Dilles & Einaudi, 1992; Williams, 1994; Johnson, 2000).

Potassic alteration/metasomatism manifests as two broad types. The first type contains secondary biotite or K-feldspar, and commonly with associated calcic phases such as amphibole or clinopyroxene. This type is typically associated with the introduction of magnetite or hematite and any of copper, gold, REE, and other

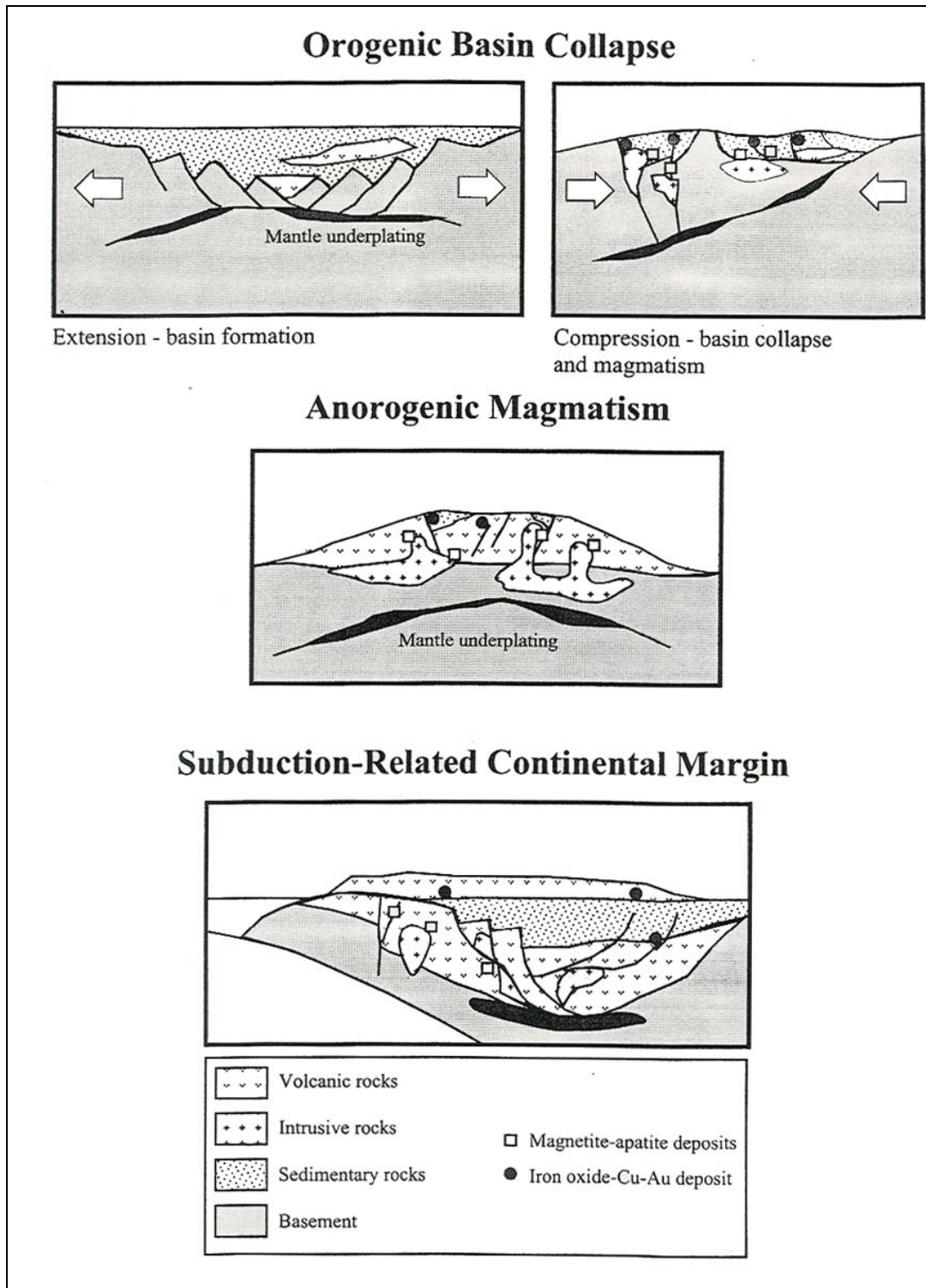


Figure 1.2. Tectonic setting of iron oxide-Cu-Au deposits (taken from Hitzman, 2000)

elements (Barton & Johnson, 2004). It forms in inferred upflow zones of a maximum dimension of a few kilometres or less (Barton & Johnson, 2004). The second type is associated with recharge zones of certain continental and transitional marine settings (Barton & Johnson, 2000) which tend to be oxidised (hematite stable), K-feldspar dominated (with typically >8 % K₂O), and more laterally extensive on a scale of 10s of km² (Barton & Johnson, 2004).

Acid alteration, consisting of sericitic or chloritic alteration with accessory hydrothermal quartz, is common but tends to occur in closer proximity to mineralisation, of a few kilometres in extent.

Copper-gold mineralisation (chalcopyrite ± bornite) occurs within or near iron-oxide accumulations, of both hematite and magnetite character; where the hematite-dominated mineralisation is distal and shallow, and the magnetite-dominated mineralisation is deeper and earlier.

All IOCG models recognise the iron-oxide rich, sulphur-poor nature of the systems responsible for the formation of these deposits. It thus follows that fluids are requisitely saline, sulphide-poor, and relatively oxidised and may have been of either magmatic or non-magmatic derived sources (Figure 1.3, Barton & Johnson, 2004). In truth, it is likely often a variable combination of the two (see Table 1.2 for a synopsis of these differing genetic models). These characteristics may be extrapolated and used to evaluate Fe-oxide (-Cu-Au) bodies in the Bushveld Complex.

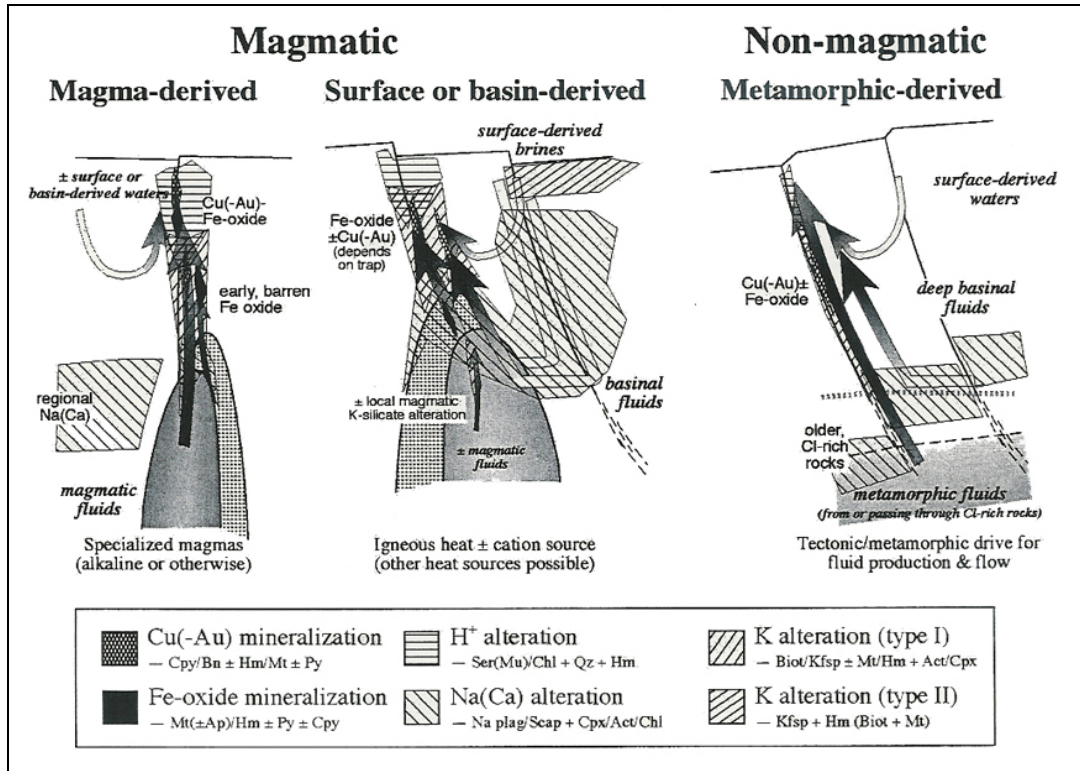


Figure 1.3. Schematic illustration of flow paths and hydrothermal features for alternative models for IOCG deposits. Shading in arrows indicates predicted quartz precipitation (veining) for different paths in different quartz-saturated rocks which provides a useful first-order indication of path (*cf.*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

Table 1.2. Synopsis of alternative genetic models for IOCG systems (*cf.* Figure 1.3.) (taken from Barton & Johnson, 2004).

Fluid Source	Magmatic	Non-magmatic	
		Basin/Surface	Metamorphic
Fundamental Process	• Release of S²⁻-poor metal-bearing brine from magma; rise of buoyancy • Cooling, wall-rock reaction $\pm$ fluid mixing provide trap	• Thermal convection of non-magmatic brines; wall rock reaction provides metals • Cooling, wall-rock reaction or fluid mixing provide trap; second fluid may provide metals	• Metamorphic release of brine components by devolatilisation or reaction with other aqueous fluids; rise by buoyancy • Cooling, wall-rock reaction $\pm$ fluid mixing provide trap
Igneous Associations	• High-K, oxidised suites ranging in composition from diorites to granites • Carbonatite and strongly alkaline connections proposed by some	• Igneous rocks diverse (gabbro to granite); non-magmatic examples known • Key heat source in most • Material source, diversity reflected in geochemistry	• No necessary connection, though commonly present • Could be heat source in some settings • Can be material source
Hydrothermal alteration in feldspathic hosts	• Na(Ca) and other types (K, H⁺) link to magmas • Regional Na(Ca) coincident but not directly related to Cu(-Au)	• K (type I), H⁺ $\pm$ Na(Ca) in upwelling zones • Na(Ca) $\pm$ K (type II) in recharge zones	• Primarily K and H⁺ alteration associated with deposits • Regional Na(Ca) association reflects sources
Relationship of Fe-oxides to Cu(-Au)	• Some Fe-oxides with Cu(-Au), may be deeper or higher-T equivalents • Barren Fe-oxides may form from distinct fluids and commonly older hydrothermal systems in same area	• Mt-rich are deeper, earlier, higher T parts of ore-forming; Mt or Hm also typical with Cu • Barren Fe-oxides represent lack of S trap for Cu or lack of second Cu-bearing fluid	• Fe-oxides present, but relatively minor (Bi or Chl common); Fe-oxides commonly generated by breakdown of mafic minerals rather than Fe introduction
Local setting: depth/ structure	• Shallow to mid-crustal levels; commonly along regional structures but near causative intrusions	• In (mainly) brittle upper crust; plumbing provided by regional or volcano-tectonic structures	• Mid- to shallow crustal levels near or on major structures; surface fluids require shallow levels
Global setting	• Arcs or extensional environments that produce characteristic magmas (oxidised high-K or alkaline)	• Regions with appropriate brine sources (arid settings or older Cl-rich materials), plumbing systems, and thermal drives	• Regions with Cl-rich low- to intermediate-grade source rocks; compressional setting (e.g. basin collapse) or prograde metamorphism
Key references	• Hauck (1989), Pollard (2000), Groves & Vielreicher (2001)	• Barton & Johnson (1996, 2000), Haynes <i>et al.</i> (1995), Haynes (2000)	• Williams (1994), De Jong <i>et al.</i> (1998), Hitzman (2000)

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

The general characteristics of IOCG deposits were introduced above. A spectrum of deposits was identified, linked principally by a common chemical affinity. Deposits may differ slightly in host rocks, metallogeny, fluid compositions, depth of formation or any number of other features.

The two deposits assessed in this chapter were chosen for likenesses to the Bushveld-type mineralisation discussed in this study. The Olympic Dam deposit, South Australia, is considered the type-deposit for the IOCG class of deposits and shares a great many common characteristics. The Carajás district of northern Brazil contains many deposits of differing characteristics (as in the Bushveld granites), and focus will be made on deposits, such as Salobo, that most closely resemble other members of the IOCG class of deposits.

Olympic Dam Cu-U-Au-Ag-REE Deposit, South Australia

The Olympic Dam Cu-U-Au-Ag-REE deposit is located approximately 520 km NNW of Adelaide, South Australia (lat. 30° 27' S, lon. 136° 53' E) (Figure 1.4). It is hosted by the Roxby Downs granite that is Mesoproterozoic in age ($1\,588 \pm 4$ Ma; Creaser & Cooper, 1993) and is a coarse-grained, A-type syenogranite. Iron-rich breccias host mineralisation that closely followed the emplacement and cooling of the Roxby Downs granite (Johnson & Cross, 1995).

The deposit is concealed beneath 300 m of Neo-Proterozoic and Cambrian sedimentary cover of the Stuart Shelf Sequence, and was discovered during an exploration program for sedimentary-hosted stratiform copper mineralisation using the integration of geology, magnetic and gravity data and the delineation of

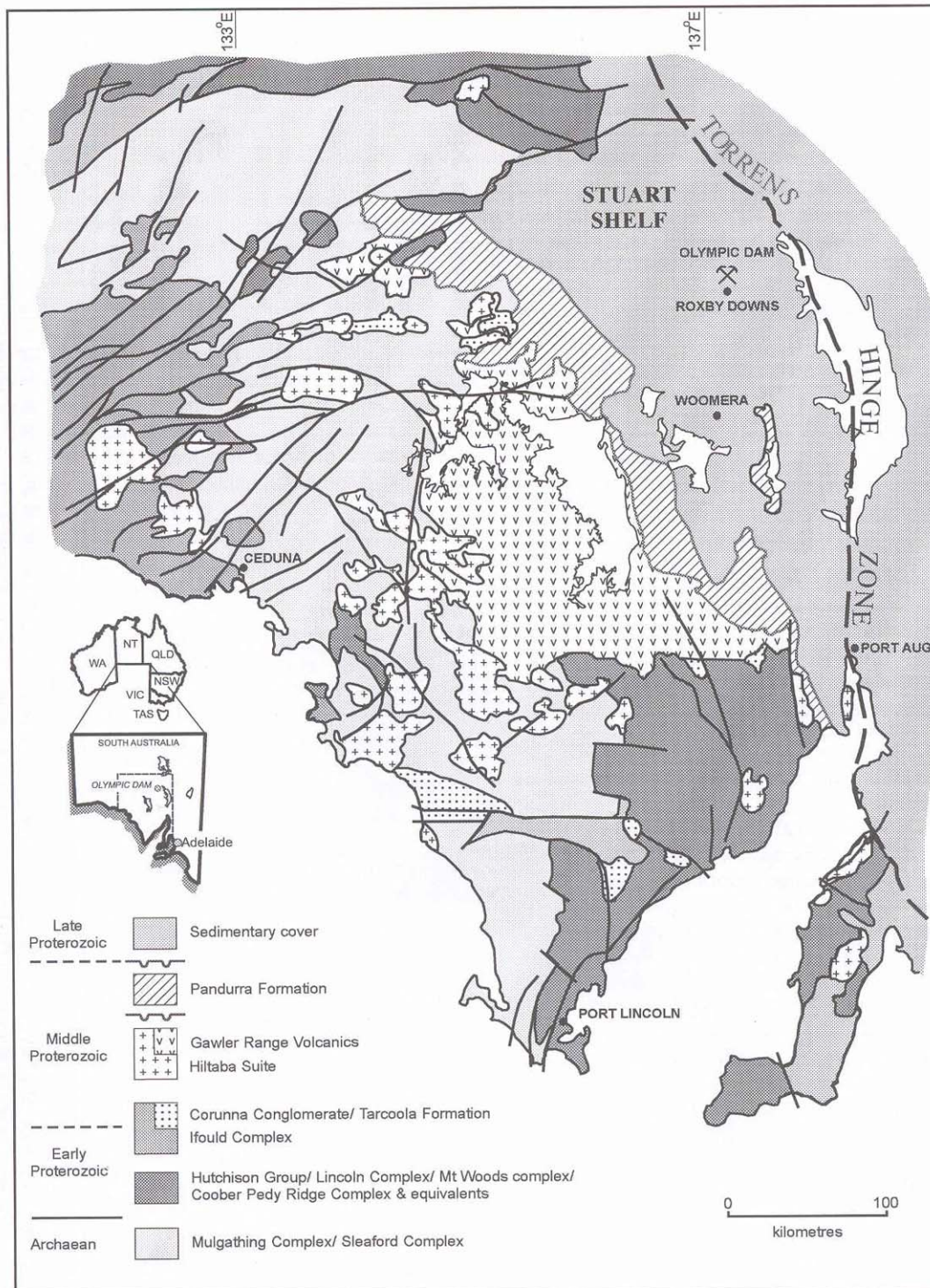


Figure 1.4. Regional geological map of the interpreted subsurface geology of the Gawler Craton. Olympic Dam located top right (from Reynolds, 2000).

well-defined structural corridors (Pirajno, 2000). The deposit is located on the eastern margin of the Gawler Craton. The oldest basement rocks are the metasedimentary rocks of the Palaeoproterozoic Hutchison Group and deformed granites of the Lincoln Complex (Figure 1.4). These rocks are intruded by Mesoproterozoic granitoids of the Hiltaba Suite and subsequently by the bimodal volcanics of the Gawler Range Volcanics of the same age (Flint, 1993).

Mineralisation is characterised by hydrothermal hematite-quartz breccia that is somewhat dyke-like in occurrence, up to 100 m wide; known as the Olympic Dam Breccia Complex (ODBC) (*c.f.* Oreskes & Einaudi, 1990; and Reeve *et al.* 1990). The breccia complex forms an elongate zone approximately 5 km long and 1.5 km wide (Figure 1.5), and is loosely zoned from granite breccia on the periphery of

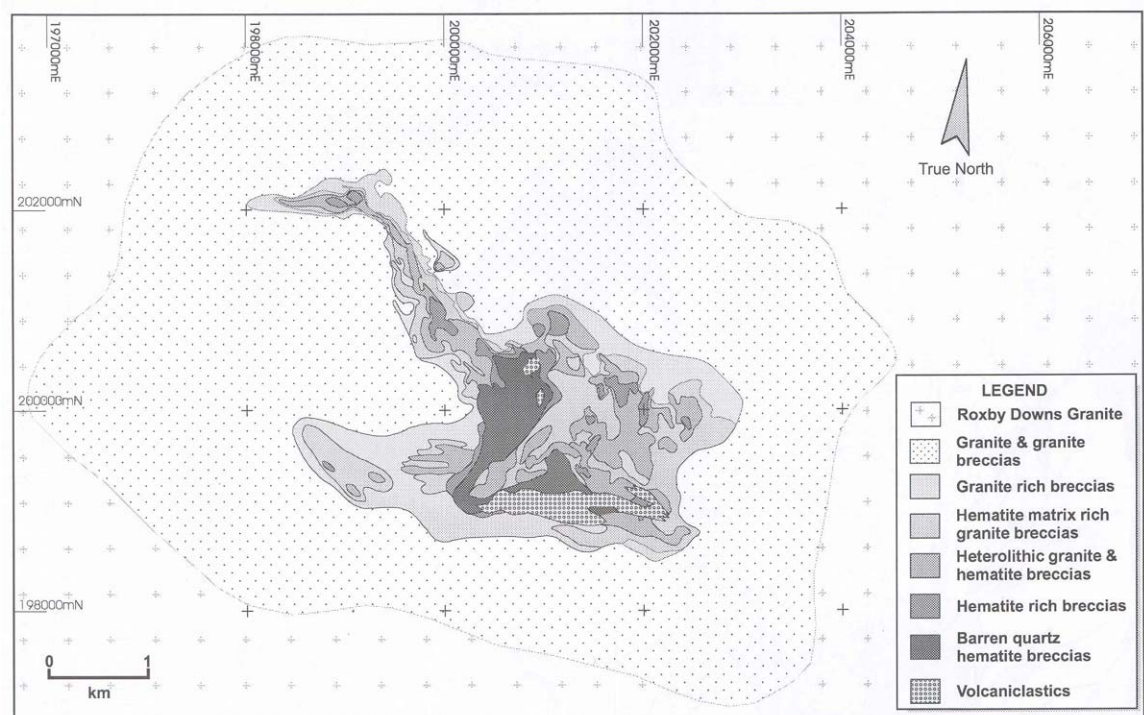


Figure 1.5. Simplified geological plan of the Olympic Dam Breccia Complex (ODBC) showing the general distribution of the major breccia types. Note the broad zonation from the host granite at the margins of the breccia complex to progressively more hematite rich lithologies in the centre (from Reynolds,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

the deposit (Plate 1.1 (a)), passing into a heterolithic breccia (Plate 1.1 (b)), hematite-quartz microbreccia (Plate 1.1 (c)) and fine-grained massive hematite-quartz in the central portions. The central hematite-quartz breccia zone is noted as being essentially barren of copper-uranium mineralisation (Reynolds, 2000). The heterolithic microbreccia consists of fragments of hematite and altered granite in a matrix of quartz-hematite-sericite-siderite-chlorite (Pirajno, 2000).

Textural evidence indicates polycyclic alteration and brecciation events (Reynolds, 2000). The variation in breccia nature and composition is attributed to the proposed processes responsible for their formation: hydraulic fracturing, tectonic faulting, chemical corrosion, phreatomagmatism and gravity collapse (Reeve *et al.*, 1990). Margins between breccia types may be gradational on the scale of metres to tens or hundreds of metres or may be abrupt (Reynolds, 2000). The ODBC is considered to have formed by the progressive hydrothermal brecciation and iron metasomatism of the Roxby Downs host granite (Oreskes & Einaudi, 1990). The Complex represents a pipe-like structure that dips steeply to sub-vertical. Drilling has indicated that it extends to a depth in excess of 1 400 m (the limits of drilling).

Alteration

Alteration around the deposit is dominated by a sericite-hematite mineralogy with lesser amounts of chlorite, silica, carbonate (siderite) and magnetite and is not associated with any sodic metasomatism (Reynolds, 2000). Like the brecciation episodes, hydrothermal alteration appears to be polycyclic in nature, but zonation patterns may be developed around the deposit and around individual breccia zones; the intensity of the alteration being directly proportional to the amount of brecciation. That is, the granite and granite breccia halo that surrounds the ore zone (Figure 1.5) is characterised by weak, highly variable sericite-

hematite-chlorite-carbonate alteration, with intensity increasing towards the centre.

Sericitic alteration of feldspars is widespread, and where locally intense may be texturally destructive of affected grains (Plate 1.1 (d)-(e)). Intense Fe-metasomatism may cause significant volume changes in affected granites where a substantial proportion of the feldspathic components are leached out during hydrothermal alteration (Plate 1.1 (f)).

Sericite and Fe-metasomatism occur weakly in the fractured granite and become more intense towards breccia bodies, where sericite, hematite, chlorite and epidote become dominant. Towards the centre of the breccia bodies hematite becomes abundant and overprints all other styles of alteration. Chlorite alteration of the Roxby Downs granite is patchy but widespread and tends to be pseudomorphic of the feldspar grains (Reynolds, 2000). Chlorite alteration, together with siderite alteration, is more abundant at depth and on the peripheries of the deposit and appears to be associated with magnetite-dominated alteration and chalcopyrite mineralisation (Reynolds, 2000). Silicification occurs throughout the breccia complex but is most intense around the margins of the central hematite-quartz breccias. These zones are prospective for gold mineralisation.

Veinlets occur throughout the Complex and the granite country rocks and may be composed of one or any of the components in a variety of combinations: hematite, sericite, chlorite, siderite, barite, fluorite, quartz, sulphides or pitchblende and only rarer tourmaline and dolomite (Reynolds, 2000). A late-stage overprint of the Complex, extending into the roof-rocks, produces barite-fluorite-siderite-sulphide veins up to several metres across, but despite their similar assemblage, are not considered to be associated with the development of the ODBC (Reynolds, 2000).

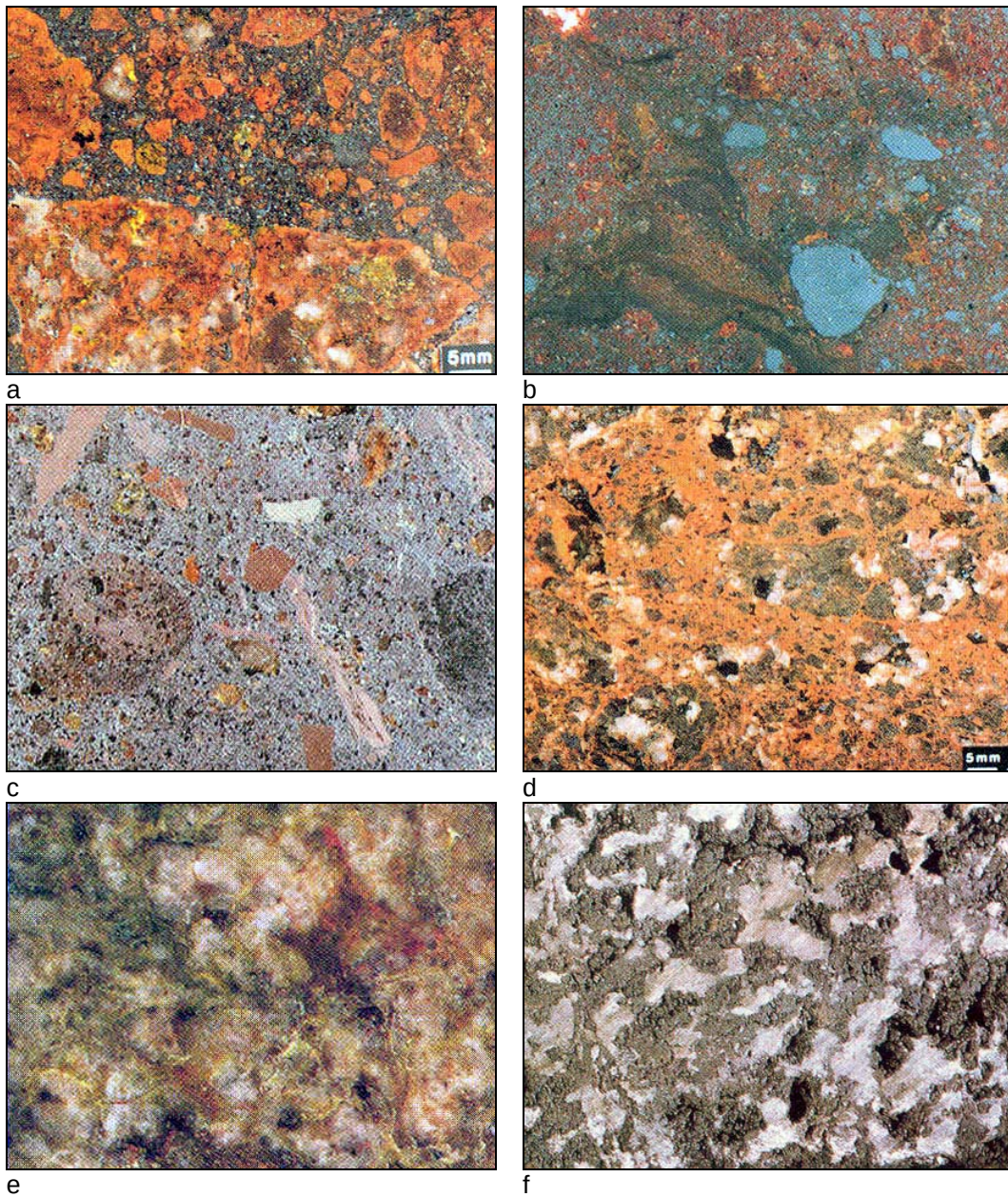


Plate 1.1. All photographs and descriptions from Reeve *et al.*, (1990). a) Granitic breccia with abundant hematite-rich matrix. Fine-grained orange clasts in the upper half largely consist of fine-grained felted sericite, which are presumably products of extreme alteration of intensely brecciated granite. 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.

Mineralisation

Olympic Dam is host to a voluminous polymetallic suite of Fe-Cu-U-(Au-Ag) with approximately 2 billion tonnes of ore at 2.5 % Cu, as well as 0.6 g/t Au, 0.02 % Co, 6 g/t Ag, 0.5 % LREE, and 0.8 kg/t U₃O₈, (Williams 1999), and it is currently the fifth largest low-grade copper producer in the world. Ore grades are represented in Table 1.3. The ore zones account for only a small portion of the ODBC volume but background levels of all mineralisation components are widespread, typically up to 0.5 % Cu, 0.2 kg/t U₃O₈, 0.5 g/t Au and 1 g/t Ag (Reeve *et al.* 1990).

Table 1.3. Ores Grades of the Olympic Dam Cu-U-Ag-Ag-REE deposit, South Australia.

Deposit (Williams, 1999)	Reserve (Reynolds, 2000)	Resource (Reynolds, 2000)
2000 Mt	> 600 Mt	
2.5 % Cu	1.8 % Cu	30 Mt Cu
0.8 kg/t U ₃ O ₈	0.5 kg/t U ₃ O ₈	930 Kt U ₃ O ₈
0.6 g/t Au	0.5 g/t Au	1200 t Au
6 g/t Ag	3.6 g/t Ag	6700 t Ag
0.5% LREE	26 % Fe	10 Mt REE

The principal copper-bearing minerals are cogenetically-precipitated chalcopyrite, bornite and chalcocite (Plates 1.2 (a)-(c)) (Johnson & McCulloch, 1995) with minor native copper. Bornite and chalcocite often occur as exsolution intergrowths of each other (Plate 1.2 (d)-(e)). Minor gold and silver is intimately associated with the copper sulphides.

Sulphides occur as disseminated grains or as veinlets with massive ore rare. The principal uranium mineral is uraninite with lesser coffinite, pitchblende and brannerite (Plate 1.2 (c)), and the REEs contained in bastnaesite, monazite, xenotime and florencite (Oreskes & Einaudi, 1990).

High-grade copper-uranium mineralisation generally correlates to more hematite altered rocks (Fe-metasomatised) and may be accompanied by fluorite, barite and REE phases. The exception is the central hematite-quartz breccia, which appears to be a final stage hydrothermal reworking of earlier generations of mineralisation. High-grade gold zones occur as narrow, complex zones around the silicified margins of the hematite-quartz core.

A sulphide zonation has been identified laterally and vertically from pyrite-chalcopyrite at depth and towards the periphery of the deposit, grading inwards and upwards to bornite and the chalcocite (Reeve *et al.*, 1990; Oreskes & Einaudi, 1990) and may be hypogene in origin suggesting multi-stage introduction of fluids (Reeve *et al.*, 1990). A distinct boundary is identified between chalcopyrite and bornite mineralisation (Figure 1.6)

Fluorite mineralisation occurs together with sulphides in the mineralised breccias as disseminations, clasts and veins that may comprise up to 1-2 % of the rock. Barite characteristically occurs in the hematite-granite breccia and central hematite-quartz breccia core of the deposit, which contain lesser amounts of sulphide mineralisation.

Magnetite generally only occurs at depth or in less evolved breccia systems in the periphery of the deposit, however, relict magnetite is commonly found in the cores of hematite grains (Plate 1.2 (f)) implying that magnetite was the earliest phase of iron oxide mineralisation, and had been subsequently overprinted by widespread hematite alteration. Hematite alteration tends to be more abundant and intense towards the centre of the rock and affects virtually any of the primary granitic components or vein minerals.

Secondary barite and hematite in the upper portions of the deposit indicate surface or near-surface exhalative activity (Pirajno, 2000). Generalised alteration and mineralisation patterns are shown in Figure 1.7.

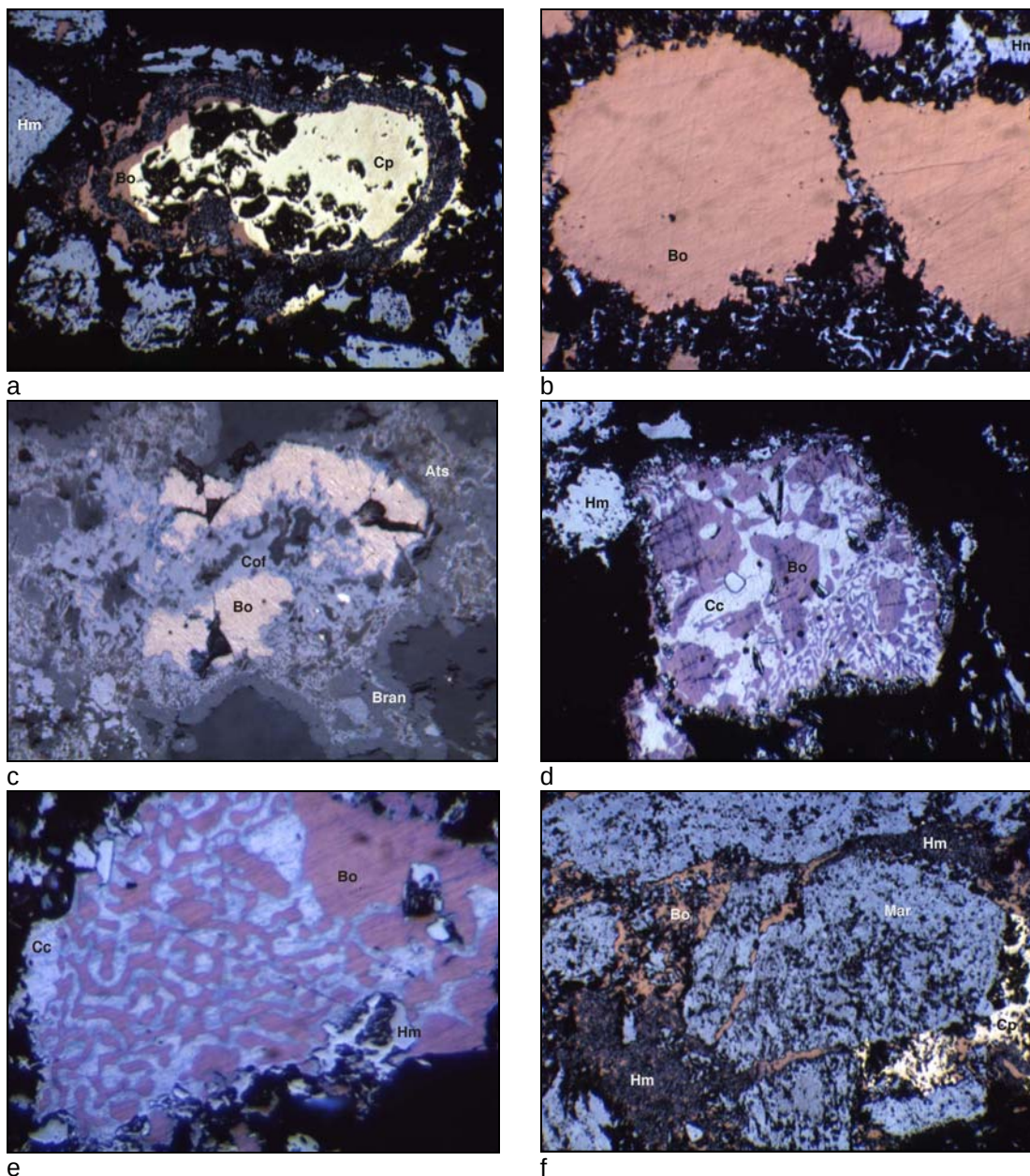


Plate 1.2. All photomicrographs and descriptions from (Hagni, *unpubl.*) a) Rounded chalcopyrite with coating of bornite then partial coating of later chalcopyrite. Subsequent fine-grained hematite has preferentially replaced parts of the bornite layer. Reflected light x 150; oil immersion. b) Rounded 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.

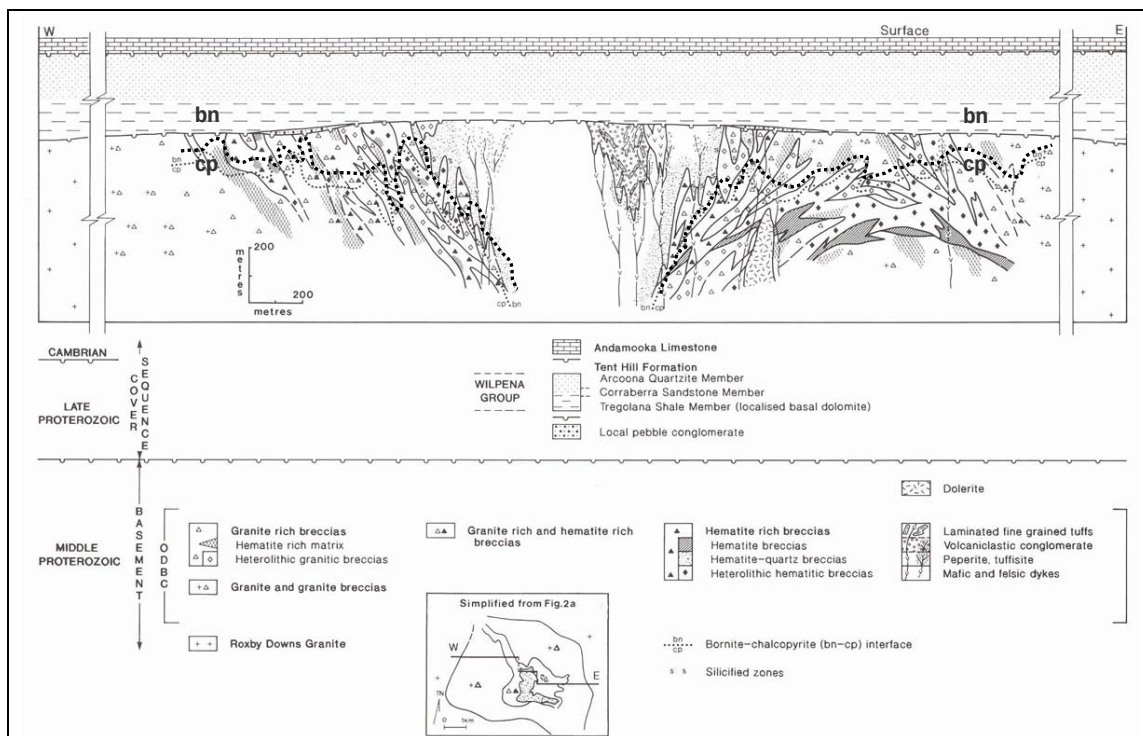


Figure 1.6. Schematic E-W cross section through the ODBC, showing generalised lithological relationships and the location of the bn-cp interface (from Reeve *et al.*, 1990).

ODBC LITHOLOGY	ALTERATION	MINERALISATION	TYPICAL ASSEMBLAGES
HEMATITE - QUARTZ BRECCIA CORE			hem + sil + bar + REE
CORE MARGINS			hem + sil + ser + Au ⁰
HEMATITE - GRANITE BRECCIAS			hem + ser + flu + bn + cc hem + ser + flu + bn + cp hem + ser + flu + sid + chl + cp + (py)
PERIPHERAL/DEEP BRECCIAS			mt + (hem) + chl + sid + flu + py + (cp)
	mt hem ser chl sid flu bar sil	py cp bn cc Cu ⁰ Au ⁰ ura bra cof REE	

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; Cu⁰=native copper; Au⁰=free gold; ura=uraninite; bra=brannerite; cof=coffinite; REE=lanthanum and cerium (from Reynolds, 2000).

Fluid Characteristics

Two fluid sources were recognised based on fluid inclusions and stable isotopes (Oreskes & Einaudi, 1992). The first fluid was of magmatic origin (high-temperature) and characterised by high $\delta^{18}\text{O} = \sim 10\text{‰}$, and a homogenisation temperature of $\sim 400\text{ °C}$. The production of the abundant magnetite is attributed to this fluid. The second fluid was found to be lower temperature (200-400 °C) with $\delta^{18}\text{O} < 9\text{‰}$. Salinities for these fluids ranged from 7 wt% to 42 wt% NaCl equivalent. It is presumed that this fluid contained some meteoric component and was implicated in the hematization overprint, similar to that in the Bushveld granites.

Deposit Model

The ODBC is considered to have formed in a high-level environment, which may have formed a phreatomagmatic volcanic structure at surface (Figure 1.8) (Reeve *et al.*, 1990). Brecciation initiated at structurally determined position within the Roxby Downs granite and was accompanied by alteration, veining, phreatomagmatic activity and mineralisation that occurred polycyclically (Reynolds, 2000).

An estimated 500 m of the ODBC is considered to have eroded during Meso- to Neoproterozoic glaciations to the present unconformity level. Subsequent deposition of the overlying Stuart Shelf Sequence occurred at around 700 Ma (Pirajno, 2000), with little subsequent geological modification of the deposit taking place.

Haynes *et al.*, (1995) proposed a fluid-mixing model as the dominant process responsible for the generation of the ores. The model suggests the occurrence of three distinct fluid sources: magmatic, deep meteoric and near-surface oxidised meteoric fluids. Cu-Au-U mineralisation was thought to have occurred in a saline

groundwater reservoir, which introduced Cu, Au, U and S and mixed with hotter fluids, which introduced Fe, F, Ba and CO₂. The model relies on sulphate reduction and ferrous iron oxidation ($\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$) for the precipitation of iron oxides and sulphides. Barton & Johnson (1996) invoked an evaporitic source for saline fluids in a similar model.

Oreskes & Einaudi (1992) proposed a two-stage model involving an early fluid, likely of magmatic origin, responsible for abundant magnetite production, and a significantly later fluid of lower temperature, responsible for ore mineralisation and Fe-metasomatism, which destructively overprinted the earlier magnetite generation. This fluid is proposed to have had some meteoric component.

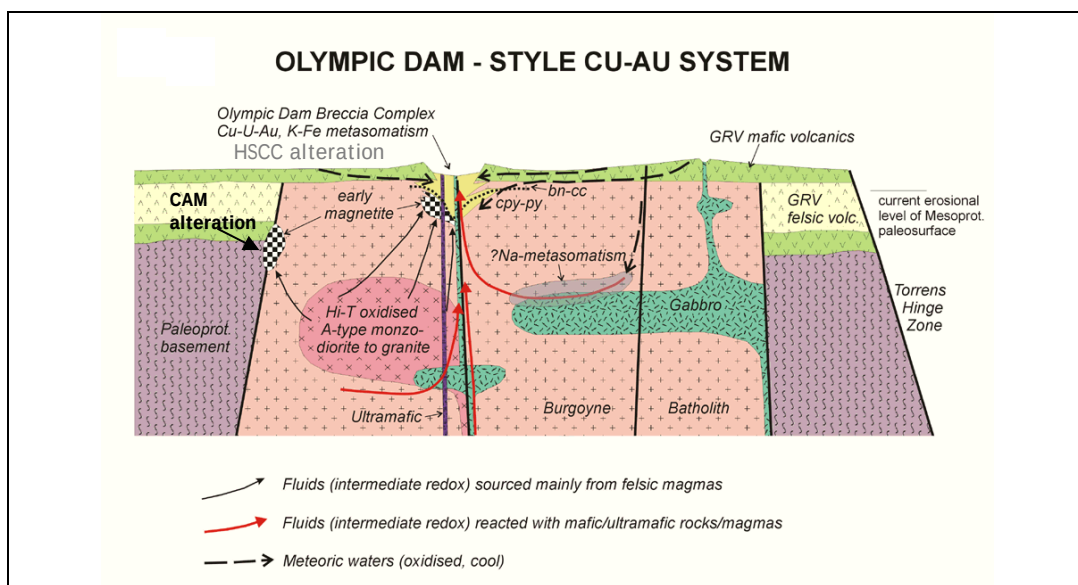


Figure 1.8. Schematic cross section of an Olympic Dam style hydrothermal system, showing Cu-U-Au mineralisation associated with hematite-sericite-chlorite-carbonate alteration (HSCC). Deeper level and/or distal calcsilicate-alkali feldspar-magnetite alteration (CAM), and alternative fluid types that 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).

Carajás District, Northern Brazil – Salobo Deposit

The Carajás Mineral Province (CMP) of northern Brazil is one of the most endowed mineral districts in the world and hosts a diverse suite of commodities including iron, copper, manganese, gold, nickel, bauxite and PGEs. The iron deposits are some of the largest in the world are reported to contain on the order of 18 Gt of high grade hematite ore at an average grade of 67 % Fe (Dalstra & Guedes, 2004). The CMP is situated on the southeastern margin of the Southern Amazonian Craton in the Brazilian Central Shield in possibly the largest A-type granitoid province in the world (Figure 1.9).

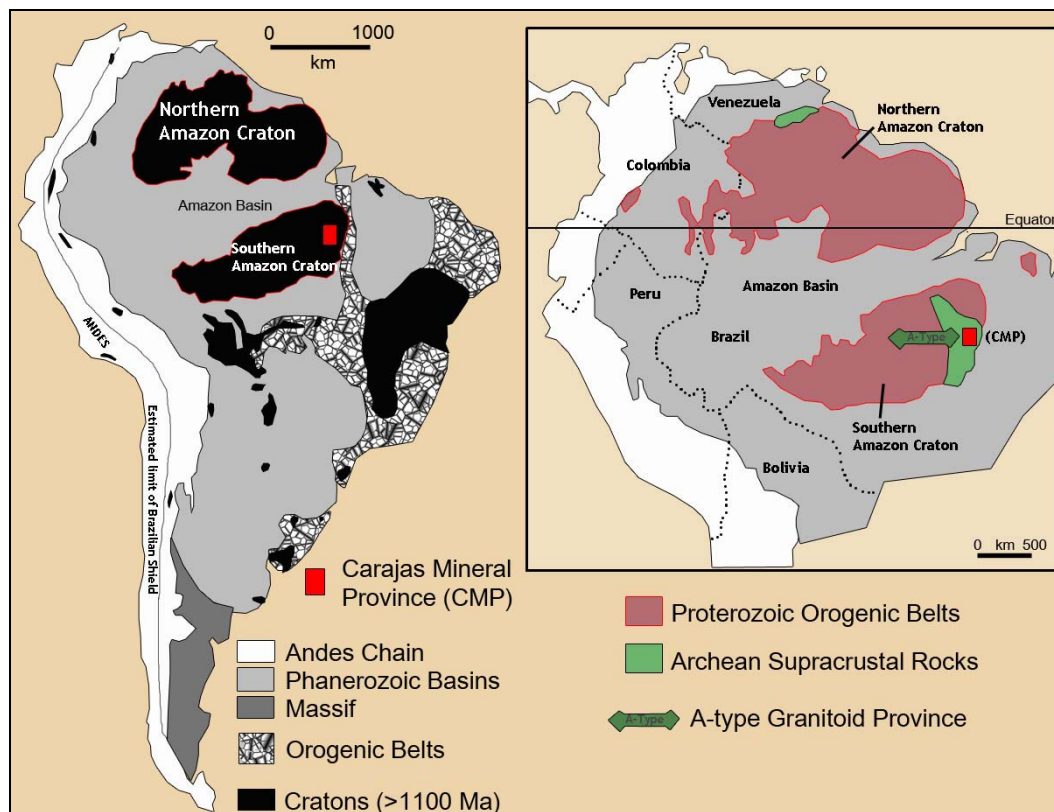


Figure 1.9. Location of the Carajás Mineral Province on the margin of the Southern Amazonian Craton (redrawn from Groves, 2004).

IOCG mineralisation is contained in various supercrustal sedimentary and volcanic assemblages that compose the Itacaiúnas Belt formed on the Archean granite-gneiss basement (Figure 1.10). These rocks belong to the 2.76 – 2.6 Ga Itacaiúnas Supergroup (consisting of the Igarapé Salobo Group, Salobo-Pojuca Group, Grão Pará Group and Igarapé Bahia Group) (Souza & Viera, 2000). Deposition of these groups is considered to have taken place within a tectonic environment of extensional continental crust, accompanied by ocean basin formation (Wirth *et al.*, 1986) that has been further described as a pull-apart rift basin (Pinheiro *et al.*, 1991; Araújo & Maia, 1991).

The supercrustal rocks were intruded by granitoids of the $2\,573 \pm 2$ Ma Granito Estrela Complex and by the 1 800 – 1 900 Ma A-type Central Granite of the Carajás Suite (Machado *et al.*, 1991). Gabbros of various ages (2.6 Ga and younger) and numerous Proterozoic-Phanerozoic dykes also cut the sequence.

A number of important deposits (>100 Mt) are located in the Itacaiúnas Belt including Salobo, Igarapé Bahia, Alemão and Serra Pelada. The Salobo IOCG deposit is located on the north-western end of the Belt, and is developed among a sequence of amphibolites, banded iron formations, metagreywackes and quartzites belonging to the Salobo-Pojuca Group (Farias & Saueressig, 1982; Lindenmayer, 1990), which ranges in thickness from 300 to 600 m. Shearing is observed along the basal contact with underlying basement gneisses. The lower portion of the Salobo Group, consisting of metagreywackes and amphibolite layers and lenses (originally of tholeiitic basaltic composition, Requia & Fontboté, 1999), is host to the mineralisation. The upper portion of the Group consists entirely of quartzites. The Salobo rocks underwent amphibolite facies metamorphism at 2763 – 2759 Ma, with a peak metamorphism at 650 °C and 3 kbar, with subsequent retrograde greenschist facies metamorphism with a temperature of 350 °C (Requia *et al.*, 1995).

According to Machado *et al.*, (1991), the Salobo deposit is situated in a duplex structure bounded by two convergent shear zones. These shears developed a sub-vertical mylonitic fabric that affected all lithologies except the younger intrusives.

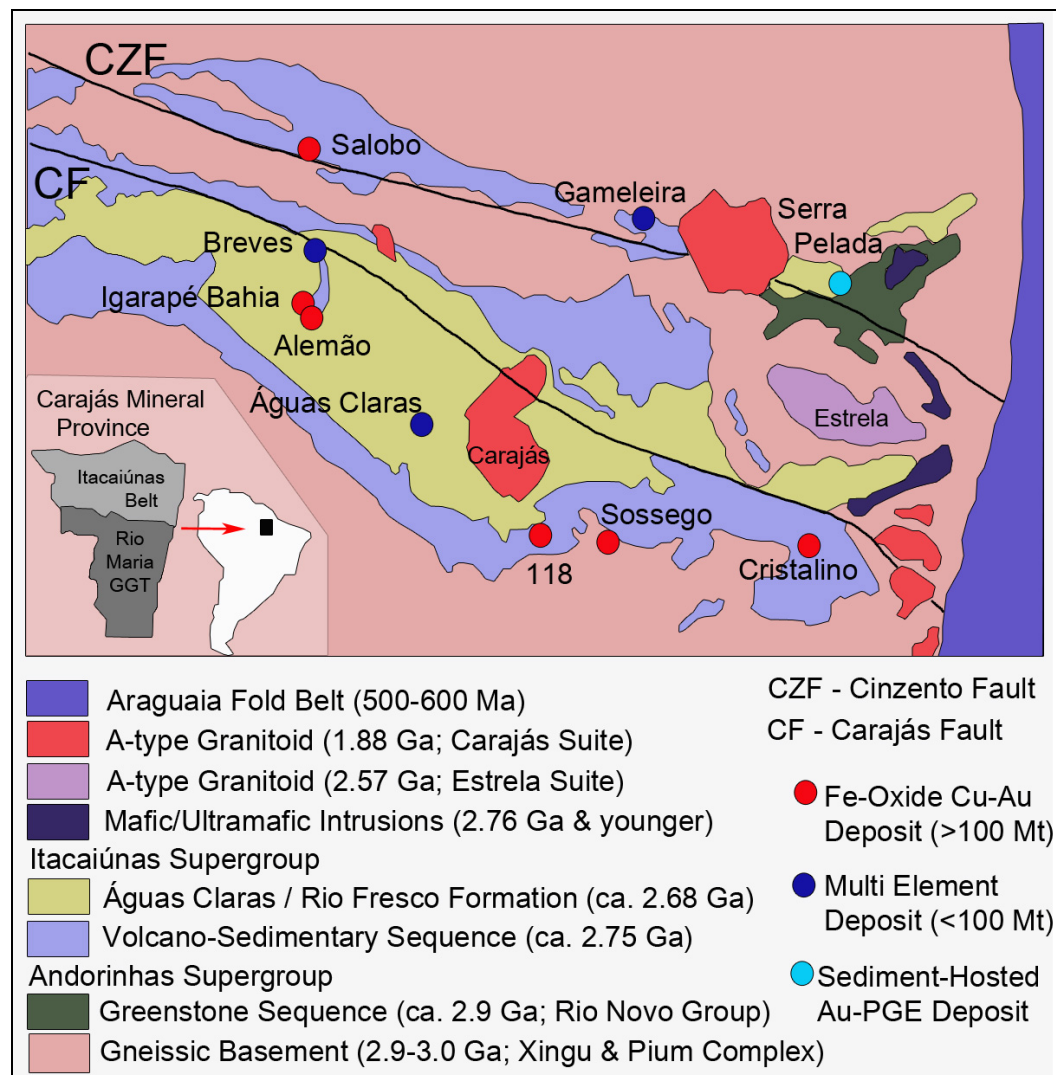


Figure 1.10. Simplified Geological Map of the Itacaiúnas Belt of the Carajás Mineral Province, northern Brazil (redrawn from Groves, 2004).

Alteration

Alteration effects were determined from amphibolite precursors, composed primarily of Ca-amphibole and plagioclase, with subordinate biotite, cummingtonite, quartz and chlorite, and minor tourmaline, titanite, stilpnomelane, epidote, sericite and calcite (Requia & Fontboté, 1999).

Alkali metasomatism predominates with an initial event of Na-metasomatism indicated by albitisation of Ca-plagioclase. This was followed by extensive K-metasomatism resulting in replacement of plagioclase by K-feldspar or by the formation of biotite, in the absence of K-feldspar. Intense potassic alteration was observed spatially related to mineralisation suggesting a link (Requia & Fontboté, 1999). Alkali metasomatism appears to be post-dated by sericitisation and propylitisation, which occur among all alteration types.

Chloritisation of mafic minerals is widespread throughout the Carajás region and is likely a regional metamorphic background effect (Requia & Fontboté, 2000).

Mineralisation

The Salobo IOCG deposit represents the largest Brazilian copper deposit with a resource of 1 200 Mt @ 0.86 % Cu and an included reserve estimated at 450 Mt @ 1.15 % Cu and 0.5 g/t Au (Requia & Fontboté, 2000).. The deposit extends approximately 4 000 m along strike and is between 100 – 600 m in width (Souza & Viera, 2000). It is recognised to depths of 750 m below surface from drilling.

The principal ore assemblages are magnetite-bornite-chalcocite and magnetite-bornite-chalcopyrite. Magnetite dominates both assemblages with variable amounts of sulphides; accessory phases include hematite, molybdenite, ilmenite, uraninite, graphite, digenite and covellite. Native gold may occur as small inclusion less than ~10 µm in copper sulphides or interstitially between magnetite and chalcopyrite (Requia & Fontboté, 2000). The paragenetic sequence of the Salobo deposit is given in Figure 1.11.

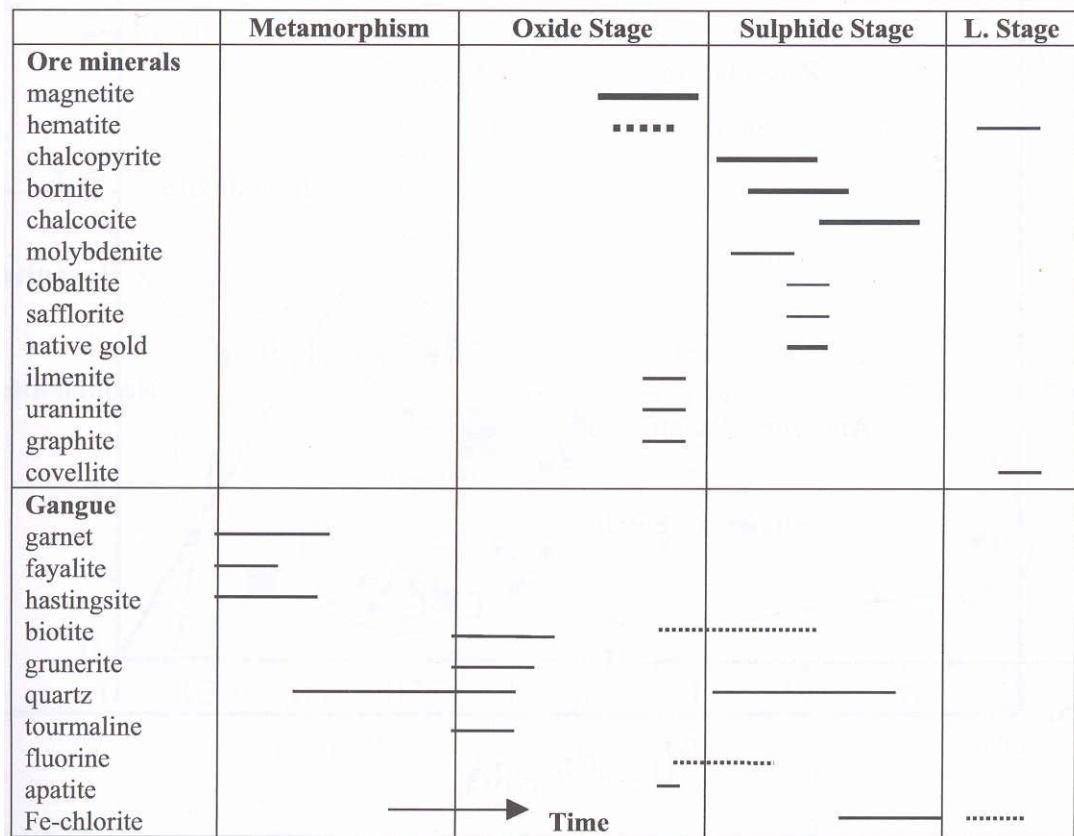


Figure 1.11. Paragenetic sequence of the Salobo deposit, Carajas District, northern Brazil (Requia & Fontboté, 2000).

Fluid Characteristics & Sulphur Isotopes

Two fluids were recognised from the Salobo deposit (Requia *et al.*, 1995, Requia, 1995). The first fluid was found to homogenise at a temperature of 360 °C and contained salinities of up to 58 wt % NaCl equivalent. The other fluid homogenised at a range of temperatures with a tendency towards 195 °C with much lower salinities of between 1-29 wt % NaCl equivalent. The interpreted source of these fluids is a deeper brine of magmatic-connate derivation, and an upper oxidised fluid probably of meteoric derivation (Requia *et al.*, 1995, Requia, 1995).

Sulphur isotopes indicate a magmatic sulphur source for chalcopyrite and bornite from low $\delta^{34}\text{S}$ values, ranging from 0.2 ‰ – 1.6 ‰, with an average of 1.0 ‰

Deposit Model

Ore formation has been shown to be related to the 2.573 Ga alkaline Granito Estrela Complex (Requia & Fontbote, 2000), with clear distinction evident between Cu-Au-Ag-U-F-Mo-Co-LREE enriched ironstones and depleted banded iron formation, indicating a hydrothermal origin. The alteration types (alkali metasomatism), and their distribution and the ore and fluid chemistry are consistent with IOCG-type deposits. The extremely low sulphur isotope values indicate a magmatic source. Figure 1.12 is a schematic model of the Itacaiúnas Belt showing the proposed genetic relationship of some of the principal deposits of the CMP, and the influence that the steeply-dipping shears may have had on ore development.

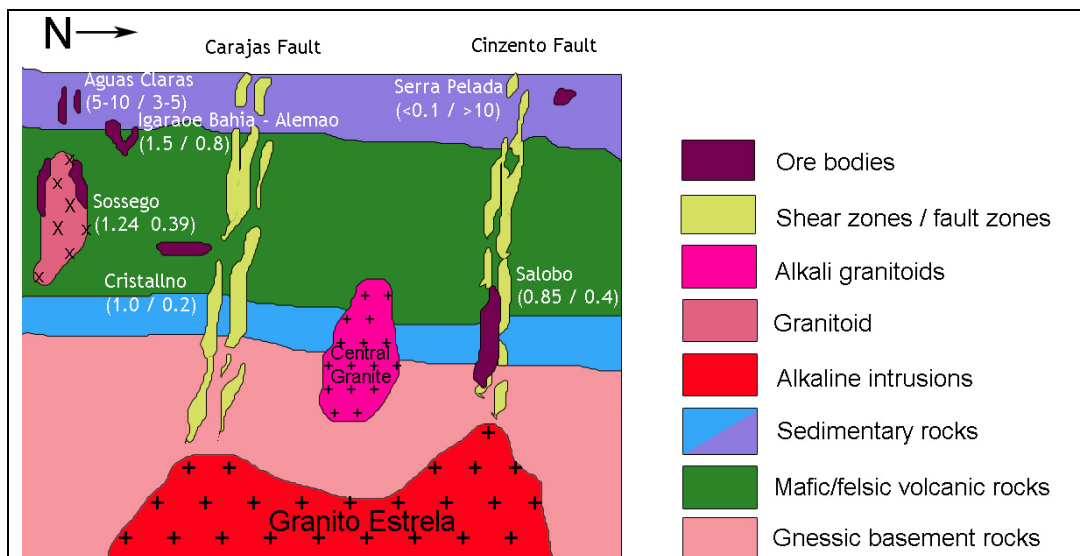


Figure 1.12. Schematic model of the Carajás Mineral Province indicating the relationships between major deposits in the region, including Salobo. Grades are indicated for each deposit, corresponding to wt % Cu and g/t Au, respectively (redrawn from Groves, 2004).

1.3. Previous Work & Research Objectives

This study is a co-operative effort between the University of the Witwatersrand and Rio Tinto Exploration Ltd. It forms part of a much larger exploration and research program undertaken by Rio Tinto to re-evaluate known mineral deposits, primarily in the context of massive iron oxide-polymetallic mineralisation, and to identify new mineral occurrences of economic significance within the mineralised rocks of the Bushveld Complex. In this study, specific attention has been focused on the alteration and associated Fe-Cu-Au-F mineralisation in the western Bushveld granites. The chosen study area is located southeast of the town of Rooiberg, adjacent to the Rooiberg fragment; a sedimentary inlier to the Bushveld Complex consisting of Transvaal Supergroup sediments.

Several models have been generated to explain the origin and characteristics of ore deposits found within the acid phase of the Bushveld Complex. The principal aim of the greater study is to resolve whether these deposits formed from an immiscible, iron-rich magma (Crocker, 1985) or an unusual, low-sulphur, iron-rich hydrothermal fluid (Borrok *et al*, 1998), as well as determining the source of these fluids.

To determine the origin of these deposits, we need to know:

- the nature of the mineralising fluids (orthomagmatic versus hydrothermal)
- the composition and temperature of the fluid from which these massive iron oxide deposits formed
- the source of the fluids (magmatic versus meteoric), and
- the relation between these deposits and the evolution of genetically related silicic magmas

Extensive research was carried out by Crocker (1976; 1977; 1979; and 1985) and Crocker *et al* (1988, 2001) in the region in establishing an inventory of the numerous fluorite occurrences. Crocker favoured a magmatic origin for these

deposits, although, the relationship between mineralisation and alteration has not been satisfactorily addressed. A detailed understanding of this relationship is imperative for the development of an effective exploration model, and critical in the search for new deposits of similarly styled mineralisation.

Freeman (1998) examined fluids from several polymetallic-type deposits in the eastern Bushveld granites in comparison to the barren granites, to establish the characteristics of the mineralising fluid, and also attempted to place a relative temporal constraint on the mineralising event. It was determined that two distinct populations of fluids existed, namely a high temperature magmatic fluid and a lower temperature meteoric/connate derived fluid, with mineralisation occurring in the zone of fluid-mixing. These results favoured a magmatic-hydrothermal model for mineralisation over an immiscible iron-rich magmatic fraction model.

A study by Borrok *et al* (1998) performed a comprehensive fluid inclusion stable isotope assessment of Vergenoeg to constrain primary mineral assemblages, temperatures of formation, and genetic source of mineralising fluids. It too established a clear magmatic-hydrothermal origin of formation. These results were supported by the isotopic studies of Ogilvie (1998), which demonstrated contaminated Sr isotopic ratios suggestive of the assimilation of country rocks; and fluid studies, which again demonstrated the presence of distinct meteoric and magmatic fluid populations.

Another study by Bailie (1997) and Bailie & Robb (2004) looked regionally at the mineral occurrences of the eastern Bushveld granites and attempted to constrain these occurrences within a genetic model applicable to a broader exploration program. The study evaluated the Bushveld granites in terms of lithology, morphology, mineralogy, relation to host rock and trace element indices for identifying and prioritising targets of mineralisation. Four main types of deposits were identified based upon mineral associations.

Research Aims

This study attempts to:

- map in detail the distribution of mineralised bodies and describe the associated alteration patterns in the Rooiberg district of the western Bushveld Complex, near the Ruigtepoort Fluorspar mine.
- compliment and apply existing regional results to the geology of more localised targets.
- establish the relationship between mineralisation and alteration using petrographical and geochemical observations, and to determine whether alteration assemblages can be used as an effective tool for vectoring towards mineralisation.
- construct a model to explain the origin and characteristics of these deposits.
- re-evaluate the small iron oxide-fluorite deposits of the western Lebowa Granite Suite in the context of an IOCG magmatic-hydrothermal continuum framework.
- identify new occurrences of potential economic significance.
- establish the relationship and similarities, if any, between the Lebowa Granite Suite polymetallic deposits and Olympic Dam-type Fe-Cu-U-(Au-Ag) mineralisation.

Significance of the Research

The significance of the research can be categorised from an economic geology perspective as follows:

- Massive iron oxide deposits have only recently been established as a separate class of ore deposits, in spite of a long history of exploitation throughout the world. These deposits as a separate class of ore deposits are not yet properly understood.

- Massive iron oxide deposits represent a considerable resource of a multitude of commodities and include several major world-class ore deposits:
 - the numerous Australian Proterozoic Fe-oxide-(Cu-Au) deposits such as Olympic Dam (450 Mt @ 2.5% Cu, 0.6 g/t Au) and Cloncurry District deposits (195 Mt @ mean 1.3% Cu, 0.7 g/t Au) (Williams, 1999)
 - Vergenoeg, South Africa, one of the largest, single fluorite deposits in the world (178 Mt @ 28.1% CaF₂, 195 Mt @ 42 % Fe) (Fourie, 2000)
 - the iron ore deposits of the Carajás Mineral Province, northern Brazil, including the Salobo copper-gold deposit with a resource of 1200 Mt @ 0.86% Cu and reserves estimated at 450 Mt @ 1.15% Cu and 0.5 g/t Au (Souza & Viera, 2000)
 - the iron ore deposits of the Chilean Coastal Belt such as La Candelaria copper-gold deposit (366 Mt @ 1.1% Cu, 0.26 g/t Au), the Manto Verde copper deposit (120 Mt @ 0.72% Cu, 0.1 g/t Au) and the Andacollo copper-molybdenum deposit (300 Mt @ 0.7% Cu, 0.25 g/t Au) (Williams, 1999)
 - the iron ore deposits of the Nörbotten terrane, Sweden, which have formed the basis of Swedish industrial development. These include Aitik (450 Mt Fe-oxide @ 0.4% Cu, 0.2 g/t Au), Viscaria (25 Mt @ 2.9% Cu), Pahtohavare (5.4 Mt @ 2.18 % Cu, 1.28 g/t Au), and Kiruna (2 000 Mt Fe-oxide @ 60% average Fe content, 0.9% REE) (Blake, 1999)
 - the Bayan Obo rare-earth deposit, Inner Mongolia, one of the largest rare earth element deposits in the world (1.5 Mt @ mean 6% REE, 0.13% Nb) (Williams & Blake, 1993)
- The Bushveld Complex is still an unknown entity in terms of the characteristics that define IOCG deposits and whether the numerous polymetallic deposits located in the upper portions of the granite and the roof rocks correspond to mineralisation of this type.

Methodology

Basic Field Mapping

The study area was mapped from 1:10 000 orthophotos with emphasis being given to the recognition of zonation patterns in the alteration assemblages associated with fluorite-hematite (-gold) mineralisation. Consideration was given to litho-types, structural control on mineralisation, and mineralisation in terms of depth of emplacement. Textural variation, as well as mineralogical changes in the various granitic lithologies was also mapped. Samples were taken of both altered and background “least altered” material. Known mineral occurrences were revisited and new mineral occurrences identified. Comparative samples were taken of variously mineralised and background unmineralised material. A geological outcrop map illustrating these features was prepared and is included in this volume.

Transmitted and Reflected Light Mineral Petrography

Polished thin sections were prepared from over 100 samples to study the silicate and opaque mineral petrography of the various lithologies, styles of alteration and mineralisation. Sections were described in terms of primary assemblages and alterations thereof, and related to mineralisation. Alteration assemblages were considered and evaluated in terms of IOCG deposits. Digital photographs used in this study were taken at the University of the Witwatersrand.

Whole Rock Geochemistry

Major and trace element whole rock geochemistry was determined for a representative suite of 82 altered, background and mineralised samples, using a Phillips 1400 X-ray fluorescence (XRF) spectrometer at the University of the

Witwatersrand. A suite of 58 mineralised and background samples were fire assayed for Au and Ag contents by Bergström and Bakker Laboratories, South Africa. LREE and rare metals (Sn, Mo, U, Th, Pb, As and W) analyses for a selected suite of samples were also determined by XRF by Bergström and Bakker Laboratories, South Africa.

Results of these analyses were compiled and modelled in the context of IOCG deposits, with emphasis on styles of alteration. Well-documented crystal fractionation trends in the Bushveld granites were considered and related to observed alteration and mineralisation trends.

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This chapter presented a brief overview of the prominent characteristics of IOCG-type mineralisation in a global context, including reviews of the Olympic Dam and Salobo deposits. Key similarities have been identified amongst IOCG deposits with respect to tectonic settings, associations with potassic magmatism, characteristic fluids of highly-saline magmatic character which mix with oxidised surficial fluids, extensive alkali-rich alteration of both sodic-calcic and potassic types, voluminous Fe-oxides and a distinctive suite of minor polymetallic elements. The next chapter will present a geological overview of the Bushveld Complex and its related mineralisation, with particular attention to the acid phase, and will draw attention to the above characteristics.