

THE PHALABORWA (PALABORA) DEPOSIT AND ITS POTENTIAL CONNECTION TO IRON-OXIDE COPPER-GOLD DEPOSITS OF OLYMPIC DAM TYPE

Noreen M. Vielreicher, David I. Groves and Richard M. Vielreicher

Centre for Global Metallogeny, Department of Geology and Geophysics, The University of Western Australia

Abstract - Phalaborwa was the second largest copper mine in the world in 1999, and the largest in Africa. The orebody is hosted by the Loolekop pipe within the Phalaborwa Complex, and is also mined for magnetite, apatite, vermiculite with a large array of by-products including gold, silver, phosphate, rare earth elements and uranium. The Phalaborwa Complex intruded Archaean basement at the edge of the Kaapvaal Craton in early Proterozoic times (2060±1 Ma) and consists of concentrically zoned, multiple intrusions which decrease in age from the margin to the core. The outer parts are predominantly clinopyroxenites, which have been variably metasomatised. Younger pegmatoidal pyroxenites intruded at three centres, including Loolekop, where foskerite and a banded carbonatite were also emplaced, followed by a transgressive carbonatite that intruded as the last magmatic phase along fracture and shear zones. Economic copper mineralisation is hosted predominantly within the transgressive carbonatite as disseminated grains and veinlets of chalcopyrite, with lesser bornite and cubanite. Magnetite is a primary igneous phase in all rocks and is paragenetically earlier than the copper sulphides. The quality and quantity of magnetite is zoned and its distribution is antithetic to that of copper. Ore fluids are high temperature, highly saline, CO₂-rich, magmatic-water dominated brines. The Complex and the mineralisation are interpreted to be products of the interaction of multiple pyroxenitic to carbonatitic magmas and their volatiles, which were ultimately derived from decompression melting of metasomatised mantle during extension at a transition from thick Archaean to thinner post-Archaean lithosphere. The orebody at Loolekop has many features including its age, giant size, pipe-like form, low ore grade, minor and major element associations and ore-fluid properties that are consistent with it being a proximal end member of the widely recognised iron-oxide copper-gold deposit group. As such it helps explain characteristics such as the pipe-like brecciation as well as the common siting of these deposits at craton edges or other lithospheric boundaries.

Introduction

The iron-oxide copper-gold deposit group is now recognised worldwide, with world-class or giant Proterozoic examples discovered in the Stuart Shelf and Cloncurry districts of central Australia and the Carajas Region of northeastern Brazil, and other Proterozoic to Phanerozoic examples in North and South America (e.g., Hauck, 1990; Hitzman *et al.*, 1992). Although there is some controversy regarding their genesis, most authors favour an association between the clearly epigenetic, commonly breccia-hosted mineralisation and igneous intrusive activity, commonly anorogenic, which is widespread in mineralised regions. However, nowhere are the orebodies sited in major intrusive rock-bodies considered to be both coeval and cogenetic with the mineralisation. Attention is drawn here to the Phalaborwa (Palabora) deposit as a possible end-member of this group.

The Phalaborwa Complex, located in the Mpumalanga province in northeast Transvaal Province of the Republic of South Africa (Figure 1) at latitude 24° 00'S and longitude 31° 07'E, represents the oldest known carbonatite complex of the southern African continent and is host to one of the

world's major copper deposits. Copper is currently mined by open cut, and it is planned to continue mining to an approximate depth of 775 m before going underground in 2002. By this time, an estimated 3.4 Mt of copper metal will have been extracted, along with millions of tons of titaniferous magnetite and significant amounts of nickel, uranium, thorium, zirconium, baddeleyite, gold, silver, rare-earth elements and platinum-group metals, as well as sulphuric acid, sulphate-monohydrate and -hexahydrate. In addition, it is estimated that the Complex contains 298 Mt of merchant grade phosphate (in the form of apatite) per 100 m of depth; it is also the world's largest resource of high-grade vermiculite. Thus, it is enriched in many elements (e.g., Fe, Cu, Au, REE, P, F, U, Th) that typify the iron-oxide copper-gold deposit group.

The hosting Phalaborwa Complex is mainly composed of ultramafic rocks, largely dunite and pyroxenite, with a core of carbonatite. Minor rock types include glimmerite, foskorite, syenite, and fenite (Verwoerd, 1993). Importantly, it is a dense, magnetic body, producing a coincident gravity and magnetic anomaly of regional magnitude, such as that which led to the exploration drilling for the Olympic Dam deposit (e.g., Reeve *et al.*, 1990).

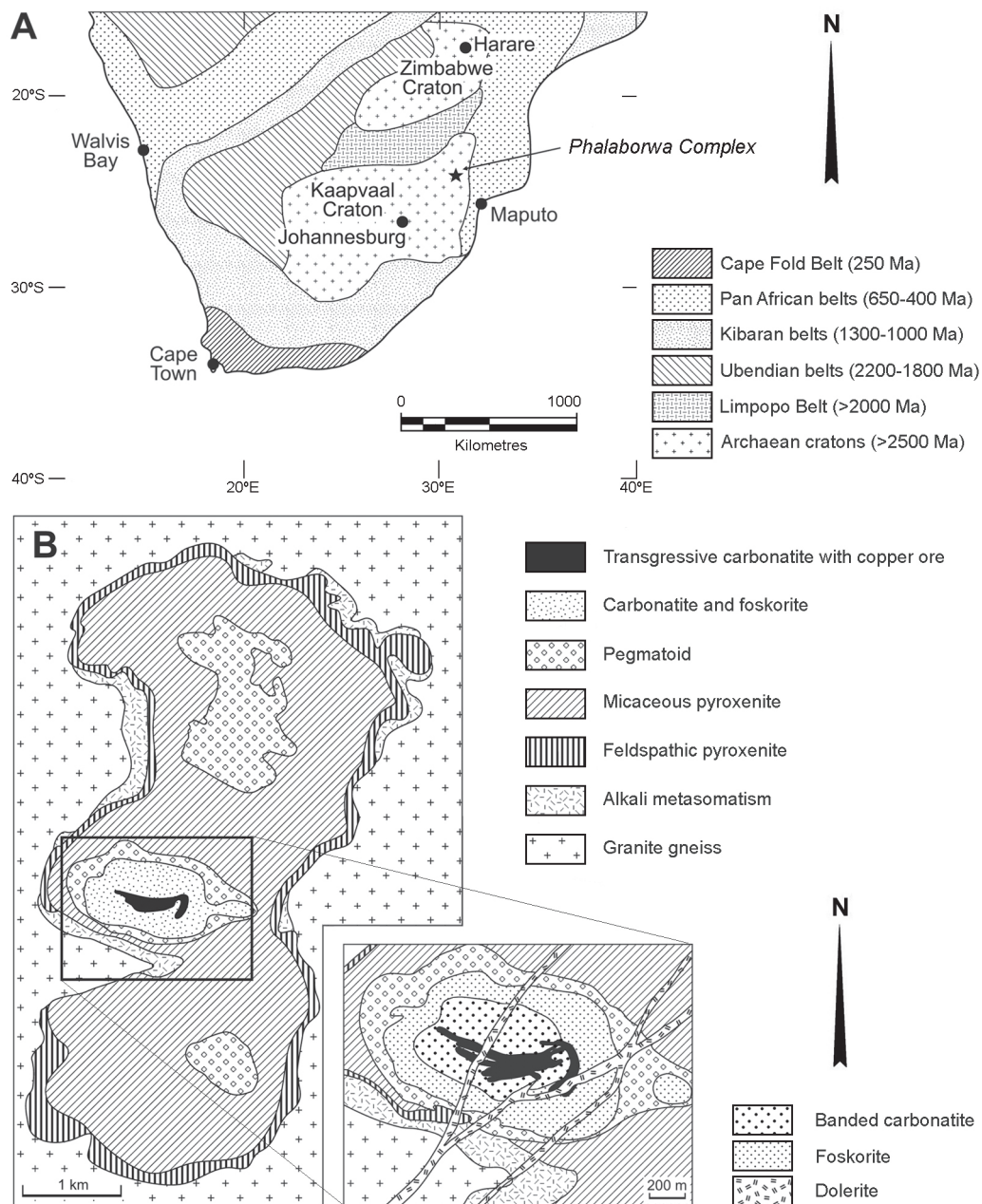


Figure 1: Geological setting of the Phalaborwa orebody. A) Generalised map of southern Africa showing position of Phalaborwa in relation to the edge of the Kaapvaal Craton (simplified from Reeve et al., 1990). B) Simplified maps of the Phalaborwa Complex with an enlargement of the Loolekop pipe (modified after Hanekom et al., 1965 and Palabora Mining Company, 1976).

Regional Geology

The Palaeoproterozoic Phalaborwa Complex is the result of multi-stage (Table 1), ultramafic to peralkaline magmatic and metasomatic activity around three centres within Archaean granites, gneisses, quartzites, granulites, amphibolites and talc- and serpentine-schists, at the eastern margin of the Kaapvaal Craton. This igneous complex is a large elongate, irregularly shaped body (Figure 1), comprising clinopyroxenites and syenites and is described in detail by the Palabora Mining Company Ltd Mine Geological and Mineralogical Staff (Palabora Mining Company; 1976), Verwoerd (1986) and Eriksson (1989). The earliest recognised intrusion is a vertically extensive, pipe-like body of pyroxenite (diopside-phlogopite-apatite rock), which was accompanied by localised fenitisation of the Archaean country rocks to produce feldspathic

pyroxenites. The pyroxenites now make up about 70% of the main Phalaborwa Complex and, as a result of flow differentiation, vary in composition from massive pyroxenite to glimmerite. Mineralogical relationships and textures indicate that clinopyroxene, phlogopite and apatite crystallised simultaneously. Local crystal settling resulted in monomineralic assemblages of each of these minerals (Eriksson, 1989). Subsequent intrusion of syenitic plugs and dykes at the periphery of the pyroxenite was associated with intense brecciation of the pyroxenite. This dynamic intrusive phase was followed by more passive metasomatism and formation of ultramafic pegmatoids at three igneous centres, north Phalaborwa, south Phalaborwa and at Loolekop. A magnetite-olivine-apatite rock, known as foskorite, and banded carbonatite are also interpreted to have been emplaced at this time at the Loolekop pipe. Field evidence suggests that the foskorite is extremely

heterogeneous and may, at least in part, be the result of metasomatism of pre-existing rocks during carbonatite emplacement. The two intrusive cycles culminated in the emplacement of the economically most important, transgressive carbonatite into the core of the Loolekop pipe along fractures and shear zones. These multiple surges of igneous activity have resulted in complex cross-cutting and gradational (probably in part metasomatic) contacts between the lithologies (Fourie and De Jager, 1986; Eriksson, 1989).

Swarms of northeast-striking dolerite dykes cut all rocks within the Phalaborwa Complex and its vicinity. The dykes are interpreted to be late-Palaeoproterozoic in age and do not appear to have had any thermal effect. As described by Eriksson (1989), an early phase of dolerite magmatism, prior to intrusion of the Complex, is evident as xenoliths in the main pyroxenite, as well as truncated dolerite dykes. The Phalaborwa Complex covers an area of some 16 km² and gravity data indicate that it is a pipe-like body, plunging 76 to 80° to the east, to a depth of at least 5 km (Hanekom *et al.*, 1965). Isotopic dating, using Rb-Sr in phlogopite, indicates an age of 2012±19 Ma for the emplacement of the Phalaborwa Complex (Eriksson, 1989). However, an isochron age of 2047±11 Ma (Eriksson, 1984) from uranothorianites and baddeleyites in foskorite and carbonatite was considered a better estimate (Palabora Mining Company, 1976; Eriksson, 1989; Verwoerd, 1993). Conventional U-Pb analyses of the baddeleyites using thermal ionisation mass spectrometry (TIMS) indicates an age of 2060±1 Ma (Heaman and Le Cheminant, 1993), which has been subsequently supported by U-Pb analyses using SHRIMP (Wingate, 1997). Palaeomagnetic data of several syenite pipes peripheral to the main Complex reveal ages ranging from 2047 to 1950 Ma (Meier and Klemd, 1997).

Local Geological Setting

The Loolekop pipe, within the larger Phalaborwa Complex (Figure 1), hosts the majority of the economic iron-oxide copper-(gold) mineralisation, and is an elliptical (1.4 × 0.8 km), vertical pipe, elongated in an east-west direction. The Loolekop pipe comprises a core of carbonatite surrounded by foskorite (a metasomatic halo?) within pegmatoidal phlogopite-apatite-bearing pyroxenite. Drilling by Palabora Mining Company indicates that the carbonatite reaches a depth of at least 1500 m (Eriksson, 1989).

The foskorite is a coarse-grained, basic/ultrabasic rock composed of variably serpentinised olivine, magnetite (up to 50 wt.%), apatite (up to 25 wt.%), carbonate (~6 wt.%) and phlogopite, which decreases inwards towards the contact with the banded carbonatite (Palabora Mining Company, 1976; Eriksson, 1989). Minerals form roughly vertical bands sub-parallel to the overall shape of the body, and modal variations vary considerably from 100% magnetite to 100% olivine. Locally, fluor-silicates of magnesium, including chondrodite and clinohumite, occur. There are carbonatite patches, or lenses, within the foskorite, and their size and abundance increase towards the centre of the pipe. The contacts of foskorite with the host pyroxenite and inner banded carbonatite vary from sharp to gradational and are concentrically interbanded, possibly indicating a passive emplacement (Eriksson, 1989) or metasomatic replacement.

The inner zone of carbonatite comprises two phases:

- (1) an outer, elliptical, concentrically zoned, medium- to coarse-grained carbonatite comprising various proportions of magnetite-bornite-carbonate

Table 1: Simplified geological history of the Phalaborwa Complex (data from Palabora Mining Company, 1976 and Fourie and De Jager, 1986). Note that magmatism related to cycle 1 was more extensive and voluminous than cycle 2 which was focussed along a network of fractures and shears formed during the first cycle.

Cycle	Stage	Event	Associated Mineralisation
1	1	Intrusion of apatite-poor pyroxenite along same conduit as dunite, followed by glimmerite	
	2	Three intrusion centres including emplacement of two pipes of apatite-rich pyroxenite in south of complex and at Loolekop, plus ring-like intrusion to the north. Local pegmatoids.	Apatite
	3	Syenite plugs controlled by fractures formed during earlier magmatism	
	4	Crystallisation of foskorite and banded carbonatite as last magmatic phase within central conduit at Loolekop.	Main magnetite mineralisation; Cu-sulphides, mainly bornite; Apatite
2	1	Apatite-poor, phlogopite-pyroxene pegmatoid dykes intruded in north of complex	
	2	Intrusion of apatite-phlogopite-pyroxene dykes throughout complex	Apatite
	3	Intrusion of syenite dykes	
	4	Emplacement of transgressive carbonatite at intersection of shear zones and stockwork of transgressive carbonatite veinlets along preferred trends in older rocks	Uraniothorianite; Minor magnetite; Major Cu-mineralisation including chalcopyrite with bornite & cubanite
		Infiltration of late fluids along fracture network (most intense in core of intrusion)	Valleriite; Vermiculite after phlogopite

(Mg calcite-dolomite) \pm olivine, which is only weakly serpentinised. Olivine is fractured and partially replaced by phlogopite, monazite or clinohumite. There are traces of chondrodite and biotite. Lombaard *et al.* (1964) recognised two generations of banded carbonatite distinguishable only in the orientation of the banding.

- (2) an inner, younger, transgressive, dyke-like, carbonate (Mg calcite \pm dolomite) – phlogopite – apatite – magnetite – bearing carbonatite that is located centrally in northwest- (290°) and northeast- (070°) striking fracture sets, as well as veins in banded carbonatite, foskorite and massive mica-feldspar pyroxenite. Two curvilinear, vertically extensive, mica-rich carbonatitic intrusions are also sited within the eastern portion of banded carbonatite (Fig. 1). Grain-size varies from coarse-grained in the central parts of the main body to very fine-grained and sugary in narrow veins (Palabora Mining Company, 1976; Eriksson, 1989). Banding is not evident within the transgressive carbonatite unlike the foskorite and the banded carbonatite, which both display crude vertical, elliptical mineralogical banding sub-parallel to the lithological contacts, due to the alignment of magnetite/phlogopite/apatite-rich zones.

Northeast-striking, steeply dipping, anastomosing dolerite dykes cut the complex and are interpreted to be Palaeoproterozoic in age ($\sim 1880 \pm 25$ Ma; Palabora Mining Company, 1976). They are interpreted to be genetically unrelated to the carbonatite (Verwoerd, 1993).

Nature and Distribution of Mineralisation

Both the foskorite and carbonatite host economic copper in chalcopyrite, bornite, cubanite, and chalcocite, phosphorus in apatite, and iron-oxide as magnetite mineralisation. Other sulphides that have been reported from rocks in the Loolekop pipe include pyrrhotite, pentlandite, millerite, bravoite, linnaeite, violarite, covellite, tetrahedrite, sphalerite, galena, pyrite, marcasite and molybdenite. In addition to copper and iron-oxide, minor gold, silver, platinum and palladium are produced (Palabora Mining Company, 1976; Eriksson, 1989; Verwoerd, 1993).

Copper

Distribution: The transgressive carbonatite is richest in copper with a consistent grade of about 1 wt.% copper, compared to an average grade of 0.5 wt.% over the whole orebody (Leroy, 1992). Chalcopyrite is the major sulphide in transgressive carbonatite as disseminated grains as well as massive blebs along fractures. Locally, there are exsolution lamellae of bornite and cubanite and pyrrhotite is present in places. Like the transgressive carbonatite itself, lenses of copper mineralisation are strongly controlled by the NW- and NE-striking fracture sets. Mineralisation zones comprise sulphide veinlets, up to 1cm wide, which are discontinuous along strike and down dip. These zones can be up to 10m apart (Eriksson, 1989), and are commonly associated with thin coatings of late-stage valleriite which

significantly reduce the recovery of Cu from the ore (Verwoerd, 1986; Eriksson, 1989).

The banded carbonatite contains less sulphides than the transgressive carbonatite, but copper recovery is good due to the low valleriite content (Verwoerd, 1986). Bornite is the dominant sulphide phase and forms disseminated grains, droplet-like inclusions within olivine, magnetite and calcite (Van Rensburg, 1965), as well as massive patches and lenses which are, in places, parallel to primary mineralogical bands defined by magnetite, apatite and silicates (Eriksson, 1989).

The foskorite contains sulphides, mainly bornite and minor late-stage chalcocite, as randomly disseminated grains that locally appear to replace earlier minerals such as interstitial calcite (Verwoerd, 1986; Eriksson, 1989). Locally, minute elongate sulphide inclusions are aligned parallel to elongation axis of apatite. Such crystallographic control of bornite-chalcopyrite intergrowths suggests exsolution in apatite within a copper- and sulphur-rich environment (Aldous, 1980). Bornite, chalcopyrite and pentlandite also occur as small inclusions, as well as in fluid inclusions in pyroxenes, and are interpreted to be products of early sulphide-rich melts (cf Aldous, 1986). In turn, olivine is also enclosed within chalcopyrite and bornite (Eriksson, 1989).

Paragenesis: Three generations of copper mineralisation are recognised at Loolekop (Verwoerd, 1986): i) early stage of orthomagmatic disseminated grains of sulphides in foskerite and banded carbonatite, associated with early sulphide-bearing magmas (Aldous, 1965); ii) main stage of postmagmatic sulphide veinlets associated with the emplacement of the transgressive carbonatite; and, iii) late stage films of valleriite on mineral cleavage planes, grain boundaries, fracture surfaces and shear planes of broad, cross-cutting shear zones.

Iron Oxide

Distribution: Economically, magnetite is the most important co-product of the copper mining from the Loolekop pipe. The average magnetite content of the ore is in the order of 27 wt.%. It is invariably Ti-bearing, but, overall, contents of Cr₂O₃ and TiO₂ are low. However, the distribution of magnetite is zoned, both in quality and quantity. Essentially the TiO₂ content in the magnetites decreases inwards from up to 4 wt.% TiO₂ in the magnetite in foskorite, to <1wt.% TiO₂ in magnetite in the transgressive carbonatite. However, additional isolated ilmenite grains also occur in the carbonatite phases (Eriksson, 1989). The magnesium contents of magnetite also vary from up to 1.5 wt.% MgO in magnetite in foskorite to about 0.3 wt.% in magnetite in carbonatite (Eriksson, 1989). Similarly, the abundance of magnetite decreases from up to 50 wt.% magnetite in foskerite to 15 to 30 wt.% in carbonatite (Eriksson, 1989). However, the grades of magnetite are very erratic within each rock type and can vary from <1 to >90% of rock over as little as a 1m interval. Magnetite forms disoriented clots and lenses with silicate phases in the transgressive carbonatite, and also as disseminated idomorphic crystals

(mm- to cm-scale) that locally contain exsolution lamellae of ilmenite. There is virtually no magnetite in the surrounding pyroxenite (Eriksson, 1989).

Paragenesis: Two generations of magnetite can be distinguished in foskorite. First, there is primary magnetite which forms anhedral to euhedral grains (<1 to 10 mm), with the development of ilmenite-rich rims on some of the magnetite grains (Eriksson, 1989); in places, ulvospinel and ilmenite also formed as exsolution products in magnetite. In the banded carbonatite, primary igneous magnetite forms discrete idiomorphic grains, which are aligned parallel to the outer contact of the carbonatite, giving it the banded appearance. A later generation of magnetite, locally replacing baddeleyite, forms rims on sulphide minerals and also along cleavage planes in phlogopite (Eriksson, 1989).

Phosphate and REE

Apatite is the only phosphate ore mineral at Phalaborwa and occurs as a primary igneous phase in all rock types. However, at Loolekop, the highest phosphate grade is found in foskerite where apatite can constitute up to 56% of the rock as disseminated grains or in vertical bands with sharp, centimetre-scale variations in grade (Eriksson, 1989). There is an overall positive correlation between phosphate and phlogopite distribution, and although magnetite is generally enriched in apatite-rich zones, there is no consistent relationship between apatite and magnetite distribution (Fourie and De Jager, 1986). Apatite also controls the total rare earth element (REE) concentration which has a resource in excess of >1.6 Mt. Concentrates are unusually rich in europium, and to a lesser extent, cerium, neodymium and samarium. Apatite within the carbonatite contains the highest total REE, in particular LREE, concentrations (up to 1% REE oxides), which progressively decrease to pyroxenite and foskorite. In contrast, the fluorine contents increase and fluorapatite predominates in the foskerite with only minor hydroxyapatite and rare chlorapatite (Verwoerd, 1986). Phosphate mineralisation extends to at least 1000 m in depth but grades are very erratic. There is little to no apparent structural control, but the ore distribution reflects the overall pipe-like structure.

Uranium

Uranium oxide is recovered from uranothorianite, a minor accessory phase in the transgressive carbonatite, and from thucholite, a mixture of hydrocarbon, uraninite and sulphides, which is present along shears and fractures in the centre of the transgressive carbonatite. At about 30 ppm U₃O₈, the grades at Loolekop are the lowest of any uranium orebody in the world. However, tonnages are high and up to 258 t of uranium oxide is produced annually (Verwoerd, 1986).

Zirconium

Baddeleyite is the main zirconium mineral at Loolekop where it is an accessory phase in all rock types. It is most abundant in the foskerite but is also recovered from the carbonatites (Verwoerd, 1986; Eriksson, 1989). Baddeleyite in the carbonatites has a higher uranium content compared

to that in the foskorite (Eriksson, 1984), but baddeleyite in the foskorite is particularly enriched in Fe and is locally replaced by magnetite (Eriksson, 1989). Total annual production of baddeleyite is typically in the order of 15 000 to 20 000 t (Verwoerd, 1986).

Gold, Silver and Platinum Group Metals

Over the past 20 years, the second-biggest profit at Loolekop next to copper has been from the combined output of gold, silver and platinum group elements (PGE), which are by-products of the copper mining. These precious metals are present in the anode sludge from electrolytic refining of copper ore, and grades vary with copper content. The typical annual production of precious metals is in the order of 20 t, containing Ag, Au and PGE at a ratio of approximately 50:2:1 respectively (Verwoerd, 1986).

Others

The Phalaborwa Complex supports the world's second largest vermiculite mine. Approximately 180 000 t of vermiculite concentrate are produced per annum from the mining of two pegmatoidal pyroxenite bodies, which contain an average grade of 22% vermiculite. The two pyroxenites, in the north and south of the Complex (Fig. 1B), were emplaced late during the first magmatic cycle (Table 1), and vermiculite is interpreted to be the alteration product of phlogopite due to circulation of ground water. (Verwoerd, 1986). Other by-products of the copper mining at Phalaborwa include:

- (1) nickel, which is associated with sulphide minerals, including pentlandite, cubanite, millerite, bravoite, violarite, siegenite and talnakhite (Verwoerd, 1986);
- (2) lead, selenium, tellurium, arsenic, antimony and bismuth, which are present in minute quantities together with precious metals in the electrolytic refinery sludge (Verwoerd, 1986); and
- (3) sulphuric acid.

Formation of Iron Oxide

There are two generations of magnetite recognised in the Loolekop orebody. As described above, both generations are intimately intergrown and form bands with primary olivine, apatite and carbonate in the foskerite-banded carbonatite and in the younger transgressive carbonatite. Moore (1984) proposed that this banding was the result of a diffusion-controlled mechanism around crystal nuclei in a non-turbulent magma. However, Eriksson *et al.* (1985) suggested in-situ accumulation of crystals, maybe under-cooled and accompanied by gravity slumping and sheath folds was the cause. Either way, magnetite is interpreted to be the result of orthomagmatic differentiation processes in each of the magmatic cycles (Table 1). The chemical variations observed in the magnetite generations (e.g., titanium and magnesium concentrations) can be explained in terms of changes in the depth of emplacement, bulk chemistry and/or oxygen fugacity of the respective magma (Eriksson, 1989).

Relationship of Iron Oxide to Copper Mineralisation

Iron-oxides (magnetite) and copper-sulphides are concentrated in the last phases of each of the two magmatic cycles, i.e., the foskerite - banded carbonatite and in the transgressive carbonatite (Table 1). In both instances, the copper sulphides are paragenetically later than the magnetite (Eriksson, 1989) and the first cycle is characterised by relatively higher concentrations of magnetite than copper, whereas cycle two is more enriched in copper. Hence, there is an overall antithetic relationship between the distributions of magnetite and copper mineralisation (Leroy, 1992).

Although magnetite mineralisation is generally accepted to be orthomagmatic, the paragenetically later copper-sulphides have been interpreted to be either introduced by hydrothermal solutions (Park and MacDiarmuid, 1970), or the result of magmatic segregation (Aldous, 1986). However, the presence of chalcopyrite in primary fluid inclusions in the neighbouring pyroxenite (Aldous, 1986) indicates that copper was an intrinsic early phase in the magmatic cycle and is strong support for a magmatic origin of the copper mineralisation whereby magnetite and copper-sulphides were segregated into different phases in a parental magma. Redistribution of some of the sulphides during late magmatic fracturing, brecciation and recrystallisation (Eriksson, 1989) may also have taken place. In addition, the formation of valleriite along fractures and shear zones is interpreted to be the result of infiltration of late oxidising fluids after the cessation of magmatism.

P-T Conditions during Emplacement

The depth of emplacement of the Phalaborwa Complex is estimated to be at a maximum of about 12 km (Button, 1976). Eriksson (1982) estimated pressures in the order of 450 MPa, consistent with the lack of extensive metasomatism around the main Complex. Geothermometry using non-sulphide assemblages yield a wide spread of temperatures between 150 to 800°C, which has been interpreted by Eriksson (1989) to reflect re-equilibration at lower temperatures. Geothermometrical studies based mainly on sulphide and phlogopite compositions suggest temperatures in excess of approximately 1000°C, consistent with what can be expected for the high-potassic, ultrabasic, and carbonatitic liquids at Phalaborwa (cf Eriksson, 1989).

Genesis of Ore System

Both the magnetite and copper mineralisations are products of multiple pulses of oxidised, halogen-rich pyroxenitic and carbonatitic magmas which differentiated due to liquid immiscibility early from a residual melt that was left after a syenitic fraction separated from a mantle-derived parent alkalic peridotite magma (Fourie and de Jager, 1986; Mutschler *et al.*, 1994). It has been proposed that the parent alkalic magma was the product of decompression melting of metasomatised mantle (e.g., Mutschler *et al.*, 1994) resulting from extension at boundaries where there is a transition from thick Archaean to thinner post-Archaean

mantle lithosphere (Groves and Vielreicher, 2001). Such processes would produce alkaline magmatism enriched in incompatible and compatible elements (e.g., Meen 1987; Harmer 1999). Further crustal level fractionation could account for the formation of several magmas including a generally undifferentiated silicate, carbonate and sulphide-bearing fractions which interacted with each other and their derived fluids to produce the mineralisation at Phalaborwa. The depleted initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratio values of the carbonatites support this interpretation and characterise the source to the carbonatites as enriched in light ion lithophile elements (LILE) relative to bulk earth (Eriksson, 1989). Processes such as flow differentiation, *in situ* accumulation and gravitational settling are also evident by textures in the main pyroxenite intrusion and in the magnetite ore. Complex cross-cutting relationships within and between the pyroxenite and carbonatites, as well as the spatial variation in magnesium and titanium contents of the magnetite ore support multiple pulses of magma. However, the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the carbonatites differ significantly from those of the pyroxenites, suggesting a complex magmatic history rather than differentiation alone to form the carbonatites (Eriksson, 1989). Intense texture-destructive fenitisation and other metasomatic effects indicate that the magmas were volatile rich. Mineralisation styles include orthomagmatic sulphides, late-magmatic-pneumatolytic sulphides in veinlets and fracture fills. Ore fluids were high temperature (~1000°C), highly saline, CO₂-rich and magmatic water-dominated chloride brines. Retrograde meteoric water-dominated fluids infiltrated fracture networks after magmatism, and resulted in the formation of valleriite as well as potentially causing some redistribution of sulphides and gold (e.g., Mutschler *et al.*, 1994).

Connection to Iron-Oxide Copper-Gold Deposits

The group of structurally controlled, epigenetic, iron-oxide copper-gold deposits typically includes deposits which contain >100 Mt of ore at 0.8 to 1.6% Cu and 0.2 to 0.8 g/t Au. The type example is the Olympic Dam deposit which formed at about 1590 Ma in the Stuart Shelf area of South Australia (e.g., Campbell *et al.*, 1998; Reeve *et al.*, 1990). Other examples of this type include Ernest Henry, Australia (e.g., Pollard *et al.*, 1998) and Carajas, Brazil (e.g., Huhn and Nascimento, 1998). Although deposits of this class have different characteristics in detail, the larger deposits have many similarities (Table 2; e.g., Hitzman *et al.*, 1992; Hauck, 1990; Williams, 1998; Huhn and Nascimento, 1998). Some features such as the distribution of metals, alteration mineralogy, as well as $f\text{O}_2$ of the ore-fluid can be zoned laterally and/or vertically (Hitzman *et al.*, 1992; Hauck, 1990; Groves and Vielreicher, 2001).

A number of such features also characterise the orebody at Loolekop in the Phalaborwa Complex (Table 2; Groves and Vielreicher, 2001), including:

- (1) the age of mineralisation (2060 Ma), classified as part of a more widespread Palaeoproterozoic magmatic event in Africa (2.5 to 1.6 Ga; Verwoerd, 1993);

- (2) the tectonic setting at the edge of a stable Craton in an anorogenic setting associated with syenitic magmatism;
- (3) the dimensions of the orebody (about 1 km²), its low ore grade and high tonnage (approximately 850 Mt @ 0.5% Cu; Leroy, 1992);
- (4) the overall pipe-like shape and iron oxide-copper zonation, with higher copper grades in the centre of the deposit and magnetite in distal parts;
- (5) multiple phases of mineralisation, with copper sulphides paragenetically later than magnetite, and carbonate is early and is, in places, replaced by bornite;
- (6) the style of mineralisation, characterised by a dominance of iron-oxide in the form of magnetite, together with relatively low-sulphur copper minerals, including chalcopyrite and bornite, and a lack of quartz;
- (7) the mineralisation changes in style from disseminated to fracture-controlled with time;
- (8) the characteristic mineral and element associations (Table 2), in particular the high, but erratic, P and F concentrations, and anomalous (also erratic) U, Th and REE, especially LREE, concentrations, also significant concentrations of Au, Ag, Pt and Pd (typical production per year of about 15 t, of which approximately 641 kg is gold: Verwoerd 1986), as well as a lack of base-metals, (i.e., high Cu/Cu+Zn+Pb ratio);
- (9) the nature of the ore fluids as hot, saline, oxidising, and CO₂-and magmatic-water bearing brines.

However, there are two major differences between Phalaborwa and the recognised group of iron-oxide copper-gold deposits. Firstly, the mineralisation at Phalaborwa is intimately associated with, and hosted in, an igneous intrusion, whereas none of the typical iron-oxide copper-gold deposits are sited in, or adjacent to, a recognisable intrusion large enough to be the source of the fluids. However, available fluid inclusion, isotope, mineral-stability and other thermodynamic data support the involvement of a hot, deep, CO₂-bearing, oxidising, acidic, aqueous ore-fluid, at least for the early stages of mineralisation. The exact nature of the fluid is controversial, although all the characteristics of the fluid and the style of mineralisation (e.g., pipe-like shape, repetitive nature of ore paragenesis, distinctive association of both compatible and non-compatible elements) are consistent with a magmatic origin of mineralisation, in particularly an alkaline source (Meyer, 1988; Hauck, 1990; Campbell *et al.*, 1998; Groves and Vielreicher, 2001). As such, it is proposed that Phalaborwa represents a proximal end member of this deposit class (Groves and Vielreicher, 2001).

The second major difference is that the Cu/Au ratio at Loolekop is about 200,000/1, an order of magnitude greater than at deposits included in the iron-oxide copper-gold group. This is discussed by Groves and Vielreicher (2001) who concluded that the low gold concentrations at Loolekop are a consequence of the deep crustal level of formation and the proximity to the causal intrusion.

Table 2: Comparison between general characteristics of Proterozoic iron-oxide Cu-Au deposits and those of the Loolekop magnetite-copper deposit at Phalaborwa.

Feature	Iron-Oxide Cu-Au Deposits	Loolekop Pipe, Phalaborwa
Age Range	Mostly 1900 to 1400 Ma	~2000 Ma
Tectonic Setting	Adjacent to craton margins and/or lithospheric boundaries	Close to eastern margin of Archaean Kaapvaal Craton
Mineralisation Style	Commonly pipe-like to ring-like, near vertical pipes of brecciated country rock	Near-vertical pipe-like carbonatite body with concentric zoning (ring-like form)
Dimensions of Breccias	1 to 20 km ²	~16 km ² for whole complex ~1 km ² for orebody - Loolekop pipe
Host Rocks	Archaean gneisses and granitoid, greenstones, metamorphosed Proterozoic rocks, anorogenic granitoids	Pyroxenite-carbonatite complex intruding Archaean granitoids, gneisses, granulites, amphibolites and talc-serpentine schists
Alteration	Intense, texture-destructive alkali and iron metasomatism, hematite and/or magnetite, also iron silicates	Intense alkali metasomatism in country rocks spatially associated with carbonatite pipes. Abundant magnetite
Opaque Major	Magnetite and/or hematite	Magnetite
Phases Minor	Chalcopyrite ± bornite ± chalcocite ± pyrrhotite ± pyrite	Chalcopyrite - bornite ± cubanite ± chalcocite ± pyrrhotite
Element Associations	Cu-Au-REE±Ag, As, Ba, Co, F, Fe, Mo, Nb, Ni, P, Th, U	Cu-Fe-P-REE-F-U-Th-Au-Ag-Ni-PGE±Mo

Concluding Statement and Implication for Exploration

The interpretation that the orebody at Loolekop within the Phalaborwa Igneous Complex belongs to the iron-oxide copper-gold deposit group is consistent with most of its characteristics including age, size and shape, grade, as well as mineral and element associations. This style of deposit can be explained by decompression melting of metasomatised mantle at a lithospheric boundary to produce volatile rich alkaline melts, enriched in compatible and incompatible elements. The volatiles generated from such melts can be deficient in sulphur, enriched in copper and gold, amongst other elements and capable of causing intense metasomatism and pipe-like phreatic brecciation, the most common features of the iron-oxide copper-gold deposit group. Such a tectonic setting is also compatible with that of the majority of Proterozoic iron-oxide copper-gold deposits. The alkaline association also fits well with the available constraints on the genesis of this deposit type, and can explain the coincident gravity and magnetic anomalies at Olympic Dam, which first led Western Mining Corporation to explore the area. The interpretation that Phalaborwa represents a proximal example of the iron-oxide copper-gold deposit group implies that there could be more conventional, distal Olympic Dam type deposits elsewhere around the margin of the Kaapvaal Craton. Vergenoeg may indeed be another example of this deposit type, hence supporting the prospectivity for such deposits at Craton margins.

References

- Aldous, R., 1980 - Ore genesis in copper bearing carbonatites: a chemical, mineralogical and fluid inclusion study; Unpublished PhD thesis, *Imperial College, University of London*.
- Aldous, R., 1986 - Copper-rich fluid inclusions in pyroxenes from the Guide Copper Mine, a satellite intrusion of the Palabora Igneous Complex, South Africa; *Economic Geology*, v. 81, pp. 143-155.
- Bell, K., Kjarsgaard, B.A. and Simonetti, A., 1999 - Carbonatites – into the twenty-first century; *Journal of Petrology*, v. 39, pp. 1839-1845.
- Button, A., 1976 - Stratigraphy and relations of the Bushveld floor in the eastern Transvaal; *Transactions of the Geological Society of South Africa*, v. 79, pp. 3-12.
- Campbell, I.H., Compston, D.M., Richards, J.P., Johnson, J.P. and Kent, A.J.R., 1998 - Review of the application of isotopic studies to the genesis of Cu-Au mineralisation at Olympic Dam and Au mineralisation at Porgera, Tennant Creek district and Yilgarn Craton; *Australian Journal of Earth Sciences*, v. 45, pp. 201-218.
- Eriksson, S., C., 1982 - Aspects of the petrochemistry of the Phalaborwa Complex, northeastern Transvaal, South Africa; Unpublished PhD thesis, *University of the Witwatersrand, Johannesburg*.
- Eriksson, S.C., 1984 - Age of carbonatite and phoscorite magmatism of the Phalaborwa Complex (South Africa); *Isotope Geoscience*, v. 2, pp. 291-299.
- Eriksson, S.C., 1989 - Phalaborwa: a saga of magmatism, metasomatism and miscibility; in Bell, K. (ed) Carbonatites, Genesis and Evolution, *Unwin Hyman, London*, pp. 221-254.
- Eriksson, S.C., Fourie, P.J. and de Jager, D.H., 1985 - A cumulate origin for the minerals in clinopyroxenites of the Phalaborwa complex; *Transactions of the Geological Society of South Africa*, v. 88, pp. 207-214.
- Fourie, P.J. and de Jager, D.H., 1986 – Phosphate in the Phalaborwa Complex; in Anhaeusser, C.R. and Maske, S. (eds.), Mineral Deposits of Southern Africa, *Geological Society of South Africa*, v. 2, pp. 2239-2253.
- Groves, D.I. and Vielreicher, N.M., 2001 - The Phalaborwa (Palabora) carbonatite-hosted magnetite-copper sulfide deposit, South Africa: an end-member of the iron-oxide copper-gold-rare earth element deposit group?; *Mineralium Deposita*, v. 36, pp. 189-194.
- Hanekom, H.J., van Staden, C.M., Smit, P.J. and Pike, D.R., 1965 - The geology of the Palabora Igneous Complex; *South Africa Geological Survey Handbook*, Memoir 54.
- Harmer, R.E., 1999 - The petrogenetic association of carbonatite and alkaline magmatism: constraints from the Spitskop complex, South Africa; *Journal of Petrology*, v. 40, pp. 525-548.
- Hauck, S.A., 1990 - Petrogenesis and tectonic setting of middle Proterozoic iron-oxide-rich deposits: An ore deposit model for Olympic Dam-type mineralisation; *United States Geological Survey, Bulletin* 1932, pp. 4-39.
- Heaman, L.M. and le Cheminaunt, A.N., 1993 - Paragenesis and U-Pb systematics of baddeleyite (ZrO₂); *Chemical Geology*, v. 110, pp. 95-126.
- Hitzman, M.W., Oreskes, N. and Einaudi, M.T., 1992 - Geological characteristics and tectonic setting of Proterozoic iron oxide (Cu-U-Au-REE) deposits; *Precambrian Research*, v. 58, pp. 241-287.
- Huhn, S.R.B. and Nascimento, J.A.S., 1997 - São os depósitos cupríferos de Carajás do tipo Cu-Au-U-ETR?; in Costa, M.L., Angélica, R.S. (eds.), Contribuições a Geologia da Amazônia, Belém, *FINEP/Sociedade Brasileira de Geologia-Núcleo Norte*, pp. 143-160.
- Leroy, A. J., 1992 - Palabora - not just another copper mine; *Minerals Industry International*, v. 1005, pp. 14-19.

- Lombaard, A.F., Ward-Abls, N.M. and Bruce, R.W., 1964 - The exploration and main geological features of the copper deposit at Loolekop, Palabora Complex; in Haughton, S.E. (ed.), *The Geology of Some Ore Deposits in Southern Africa*, *Geological Society of South Africa*, v. 2, pp. 315-337.
- Meen, J. K., 1987 - Mantle metasomatism and carbonatites; An experimental study of a complex relationship; *Geological Society of America*, Special Paper 215, pp. 91-100.
- Meier, S. and Klemd, R., 1997 - Cooling and uplift history of selected syenite pipes of the Phalaborwa Igneous Complex, South Africa: evidence from microthermometry and petrography; *Proceedings of The XIV European Current Research on Fluid Inclusions (ECROFI)*, Nancy, France, pp. 205-206.
- Meyer, C., 1988 - Ore deposits as guides to geologic history of the Earth; *Annual Reviews in Earth and Planetary Science*, v. 16, pp. 147-171.
- Moore, A.C., 1984 - Orbicular rhythmic layering in the Palabora carbonatite, South Africa; *Geological Magazine*, v. 121, pp. 53-60.
- Mutschler, F.E., Aziz, N.M. and Readdy, L.A., 1994 - Gold and alkaline igneous rocks: a cornucopia of deposit models, porphyry to epithermal, magmatic to meteoric; *Geological Society of America*, Abstracts with Programs v. 26/7, p. 139.
- Palabora Mining Company Limited Mine Geological and Mineralogical Staff, 1976 - The geology and economic deposits of copper, iron, and vermiculite in the Palabora Igneous Complex: A brief review; *Economic Geology*, v. 71, pp. 177-192.
- Park, C. F. and MacDiarmuid, R. A., 1970 - Ore Deposits; 2nd edition, *Freeman, San Francisco*, 522p.
- Pollard, P.J., Mark, G. and Mitchell, L.C., 1998 - Geochemistry of post -1540 Ma granites in the Cloncurry District, northwest Queensland; *Economic Geology*, v. 93, pp. 1330-1344.
- Reeve, J.S., Cross, K.C., Smith, R.N. and Oreskes, N., 1990 - The Olympic Dam copper-uranium-gold silver deposit, South Australia; in Hughes, F.E., (ed.), *Geology of Mineral Deposits of Australia and Papua New Guinea*, *The Australasian Institute of Mining and Metallurgy, Melbourne*, Monograph 14, v. 2, pp. 1009-1035.
- Verwoerd, W.J., 1986 - Mineral deposits associated with carbonatites and alkaline rocks; in Anhaeusser, C.R. and Maske, S. (eds.), *Mineral Deposits of Southern Africa*, *Geological Society of South Africa*, v. 2, pp. 2173-2191
- Verwoerd, W.J., 1993 - Update on carbonatites of South Africa and Namibia; *South African Journal of Geology*, v. 96, pp. 75-95.
- Williams, P.J., 1998 - Metalliferous economic geology of the Mt Isa Eastern Succession, Queensland; *Australian Journal of Earth Sciences*, v. 45, pp. 329-341.
- Wingate, M.T.D., 1997 - Testing Precambrian continental reconstructions using ion microprobe U-Pb baddeleyite geochronology and paleomagnetism of mafic igneous rocks; Unpublished Ph.D. thesis, *Australian National University, Canberra*, 236p.
- Wyllie, P.J., 1989 - Origin of carbonatites: evidence from phase equilibrium studies; in Bell, K. (ed), *Carbonatites Genesis and Evolution*, *Unwin Hyman, London*, pp. 500-545.

