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MINERALISATION OF THE PHALABORWA COMPLEX AND THE CARBONATITE CONNECTION IN IRON OXIDE-Cu-Au-U-REE DEPOSITS

Robin E Harmer

Economic Geology Unit, Council For Geoscience, Pretoria, South Africa.

Abstract – The family of Proterozoic iron-oxide copper-gold deposits have as a unifying characteristic mineralisation which is dominated by titanium-poor iron oxides in which the total rare earth elements (REE) are enriched. The REE are typically LREE enriched and are concentrated in apatite and/or discrete REE phases. Carbonatites typically contain low-TiO_2 magnetite and apatite as minor phases and are characterised by elevated total REE with extreme enrichment of LREE over HREE. Copper and gold are not, however, commonly associated with carbonatites.

The 2060 Ma Phalaborwa Complex in South Africa is unusual in having economic concentrations of copper sulphides in a plug of magnetite-rich foskorite and carbonatite. The maximum enrichment in copper is found in the transgressive carbonatite, the last phase of intrusion in the Complex. Bornite is the major copper sulphide in the banded carbonatite whereas chalcopyrite predominates in the transgressive carbonatite ore body. Apatite, noble metals (PGE and gold) and uranium are also beneficiated. Copper and gold have been reported from other southern African carbonatites but economic levels of these metals have not been identified. In addition to containing anomalous concentrations of copper, the carbonatites at Phalaborwa are also anomalous with respect to their isotopic compositions. With few exceptions carbonatites are characterised by ε_{Sr} and ε_{Nd} values indicating derivation from mantle sources - Phalaborwa has elevated ε_{Sr} and negative ε_{Nd} suggesting substantial inputs from old crustal reservoirs. It is argued that these anomalies are possibly related and that the copper mineralisation and crustal isotopic signatures were introduced by fluids evolved from the crystallising carbonatite magma. These fluids would be capable of leaching metals from surrounding country rocks during fenitisation and cycling them into the solidifying body of carbonatite.

The presence of carbonatite-sourced fluids have been identified or suspected in a few of the iron oxide copper-gold deposits. Carbonatites are small igneous bodies whereas iron oxide-copper-gold deposits are typically of enormous size and so carbonatites are unlikely to play a significant role in their genesis. It is argued, however, that studies of carbonatite complexes - in particular where high level fenitisation zones are exposed – might provide useful analogues for understanding the mineralising processes which have produced the large iron oxide-Cu-Au-U-REE deposits.

Introduction

Hitzman *et al.* (1992) originally proposed that several Proterozoic iron-oxide copper-gold deposits - including Olympic Dam, Kiruna and Bayan Obo - shared sufficient age, mineralogical and broad geological features to be considered a distinct class of ore deposit. Mineralogically, the ores in these deposits are dominated by iron oxides (magnetite and/or hematite) which are characterised by low concentrations of titanium - generally less than 0.5% TiO_2 and rarely above 2% TiO_2. While the metal suite distinguishing this family, Fe-Cu-U-Au-REE, is usually found in each deposit not all of the metals are necessarily present in economically significant concentrations. Rare earth elements are enriched in the light elements (LREE) and occur in apatite or a REE phase. Enrichments in fluorine, barium and phosphorous are also noted.

Carbonatites have as characteristic (ubiquitous?) minor phases magnetite and apatite and are characterised by high levels of total REE having extreme enrichment of the LREE over HREE. Hematite carbonatite dykes are common late stage features in many carbonatite complexes and these are usually enriched in REE relative to earlier phases of carbonatite (e.g. Le Bas, 1977). Carbonatite magnetites are characterised by very low TiO_2 concentrations (Mitchell, 1979). Copper and gold are, however, not commonly associated with carbonatites. The Phalaborwa Igneous Complex is unusual in having a carbonatite phase in which copper reaches economic concentrations. Phalaborwa is not the only carbonatite which contains copper mineralisation - some other South African carbonatites contain copper but not at economic grades.

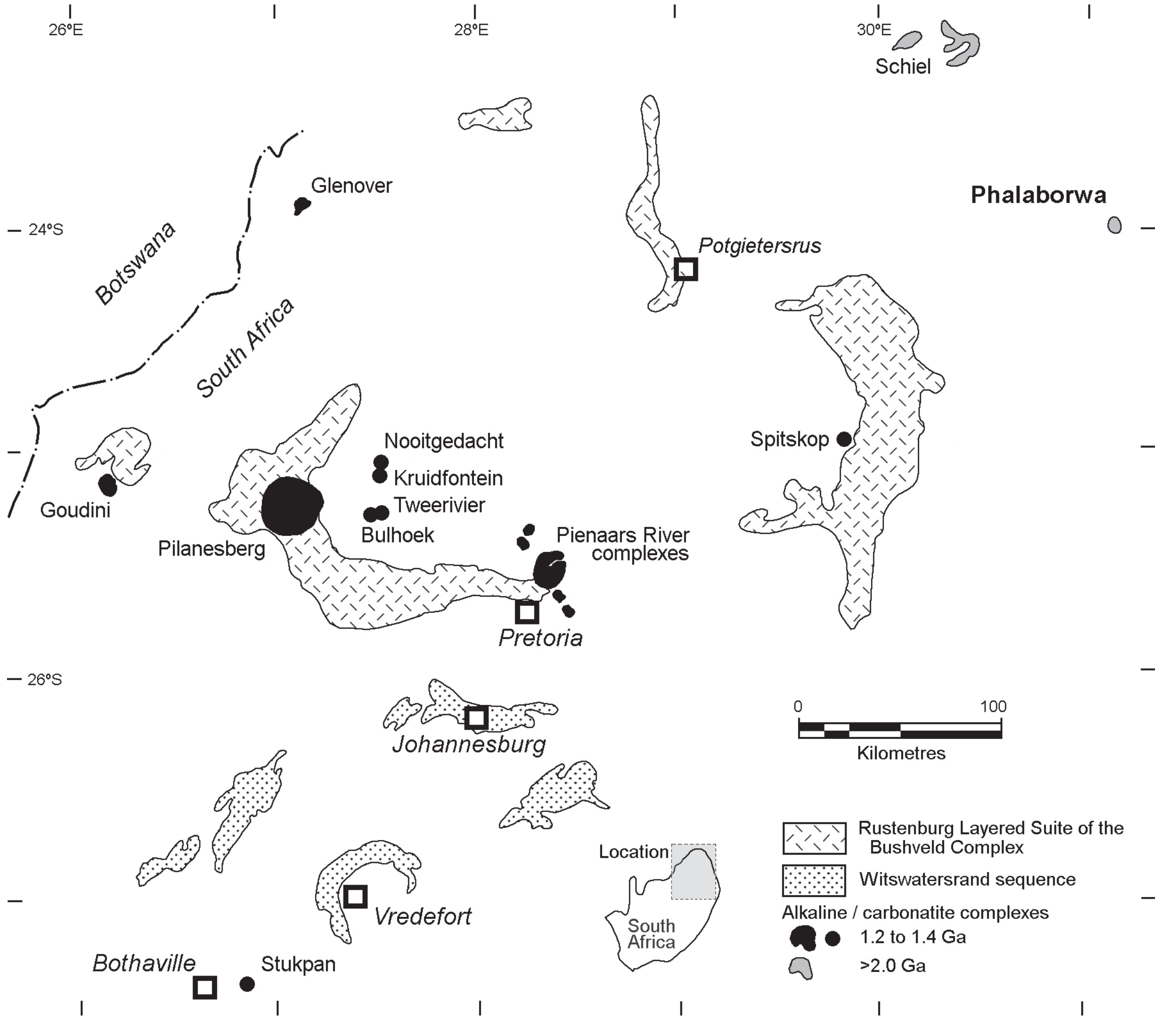

Figure 1: Map showing location of carbonatite and alkaline complexes on the Kaapvaal Craton of southern Africa.

In this paper the mineralisation at Phalaborwa will be reviewed in some detail followed by a discussion of other carbonatites in which metal mineralisation has been noted. A possible "carbonatite connection" in the mineralisation at other iron-oxide copper-gold deposits will then be discussed. Current thinking on the nature of carbonatite magmatism will be briefly reviewed and the importance of late stage fluid activity highlighted and its potential role in the mineralisation of Phalaborwa evaluated.

Phalaborwa

The Archaean Kaapvaal Craton of South Africa was subjected to two episodes of alkaline and carbonatitic magmatism during the Proterozoic (Fig. 1): an earlier event at ~2 Ga during which the Phalaborwa and Schiel Complexes were intruded and a later episode at 1.4 to 1.3 Ga when a number of carbonatite and syenite complexes were emplaced (Harmer, 1992; Verwoerd, 1993).

The Phalaborwa Igneous Complex is predominantly composed of a pipe-like body of pyroxenite with a smaller, oval body of foskorite[1] (olivine/serpentine-magnetite-apatite-calcite rock) and carbonatite (see Fig. 2). Phalaborwa is commonly referred to as a "carbonatite complex" despite the fact that carbonatite accounts for less than 6% of the surface area of the complex!

Phalaborwa intrudes Archaean basement gneisses and has been dated at 2060.6±0.5 Ma (U-Pb on baddeleyite: Reischmann, 1995) and so is marginally older than the mafic magmatism of the Bushveld Complex dated at 2054.5±1.5 Ma (uranium-lead on zircon: Armstrong *et al.*, submitted). The complex occurs some 20 km southeast of the Murchison greenstone belt which lies along the trace of the "Thabazimbi-Murchison Lineament", a zone of crustal weakness that has been repeatedly re-activated over time. There are no obvious tectonic features controlling the site of emplacement of the complex.

Geology

Details of the geological make up of the Phalaborwa Complex have been provided by Hanekom *et al.* (1965) and staff of the Palabora Mining Company (PMC, 1976). The pyroxenites are composed of varying proportions of

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[1] This rock was first named at Phalaborwa by Russell *et al.* (1954) as "phoscorite" after the name of the company responsible for mining apatite from the pyroxenite: the "Phosphate Development Corporation" (abbreviation "Phoscor"). Since inception, this corporation has been known exclusively as "Foskor" the abbreviation of the Afrikaans version of its name - "Fosfaat-Ontginningskorporasie". As a consequence, "foskorite", as originally used by Hanekom *et al.* (1965) and most South African geologists since then, is preferred for the rock name in preference to "phoscorite" as is often seen in foreign publications and in Le Maitre *et al.* (1989).

diopside, phlogopite and apatite and range in texture from fine- and medium-grained varieties to pegmatoidal zones in which individual pyroxene and mica crystals of 10 to 20 cm are common. A feldspathic pyroxenite facies is developed along most of the outer contact as a result of assimilation of gneissic material. Fenitisation of the country rock gneisses to syenitic assemblages is noted and involves K-Na-Fe metasomatism. Foskorite and carbonatite form a vertical, oval-sectioned pipe intrusion in the west-central part of the complex and the body is surrounded by pegmatoidal pyroxenite (Figs. 2 and 3). Along the outer margin foskorite occurs interleaved with pyroxenite in a series of concentric septa and is itself concentrically interleaved with the banded carbonatite. Contacts between the foskorite and banded carbonatite vary from sharp to gradational and, where planar fabrics are apparent in the foskorite, they tend to parallel the near-vertical concentric banding in the adjacent banded carbonatite. The elliptical-concentric fabric of the foskorite-banded carbonatite body is cut across at sharp angles by the later transgressive carbonatite suggesting a significant time lapse, and possibly a change of stress regime, prior to intrusion of the transgressive carbonatite. In addition to the main, central intrusive body, many discontinuous dykes and veinlets of transgressive carbonatite - ranging from 1 cm to 10 m in width - are found cutting foskorite and banded carbonatite.

Deep drilling has proved the continuity of the foskorite-carbonatite body over a vertical distance of over 1500 m. Foskorite is a texturally variable assemblage of coarse olivine (usually serpentinised), magnetite, apatite and phlogopite with irregularly distributed interstitial patches and blebs of calcite. Baddeleyite is a common accessory. Both carbonatites are magnesian calcite varieties with variable, though always significant, quantities of magnetite, subordinate apatite and accessory amounts of silicates such as phlogopite, chondrodite and olivine. Calcite is less magnesian in the banded variety and the distinguishing banded texture is imparted by alignment of layers, individual grains, or clots of the magnetite component. The transgressive carbonatite is generally coarser-grained with the magnetite often forming prominent euhedral grains.

Mineralisation

Copper - Copper sulphides occur in the foskorite and both phases of carbonatite but are most concentrated in the transgressive carbonatite and it is this unit that is targeted for exploitation. Bornite is the principle sulphide phase present in foskorite and the banded carbonatite where it occurs as small scattered blebs. Chalcocite is found in the foskorite, graphically intergrown with bornite. In the banded carbonatite the sulphide grains may be aligned along with the other fabric defining phases (magnetite, apatite, silicates). Chalcopyrite predominates in the transgressive carbonatite but bornite and minor cubanite are also noted. In contrast to the random distribution of the sulphides in the earlier units, the chalcopyrite occurs in stringers and veinlets which are thought to represent fillings in annealed fractures within the transgressive carbonatite. The contrast in textural occurrence between the bornite-dominated mineralisation in the foskorite - banded carbonatite and the chalcopyrite-dominated mineralisation in the transgressive carbonatite has been regarded as evidence of two discrete mineralising events (PMC, 1976; Wilson, 1998). Both chalcopyrite and bornite are seen to replace magnetite. Palmer (1998) described localised dolomitisation of calcite and deposition of a second generation of magnetite associated with chalcopyrite.

In a much later phase of mineralisation valleriite was deposited at low temperature along shear zones, fractures and mineral cleavages and affects magnetite, carbonate and silicates as well as the sulphides. This phase of mineralisation is described by PMC (1976) as “an overall steaming of the orebody”.

Apatite: Phosphate and REE - Apatite is, after copper, the major economic resource at Phalaborwa. While apatite is a common constituent in all the components of the complex, it attains economic quantities in the foskorite and in parts of the pyroxenite. FOSKOR recovers apatite from their operating pit in the pyroxenite (~3 km NNW of the carbonatite body: see Fig. 2) and from foskorite ore and apatite-rich tailings from the copper mining operation.

Magnetite - Magnetite is an essential, and abundant, component of foskorite and both phases of carbonatite whereas the pyroxenite is essentially free of magnetite. Both the quantity and titanium composition of the magnetite varies substantially between the different units. Magnetite is most abundant in the foskorite where it is titaniferous (~4% TiO_2) and constitutes up to 50 wt.% of the rock. The carbonatites together (as mined) contain about 27 wt.% of magnetite of lower TiO_2 content (PMC, 1976). Magnetite from the banded carbonatite has TiO_2 contents in the range 0.1 to 1.0% whereas magnetite in the transgressive carbonatite has TiO_2 contents below 0.1% (Verwoerd, 1986).

Uranium - Uranothorianite occurs in the transgressive carbonatite and is recovered and processed as a uranium oxide resource. It is only the huge scale of the Palabora operation that renders this economically viable as actual U_3O_8 concentrations in the ore body are only ~30 ppm (Verwoerd, 1986). Levels of thorium are approximately twice those of uranium.

Precious Metals - Precious metals gold, silver and the PGE occur in minute quantities and it is only the scale of the mining operation that allows these to be beneficiated. The metals are recovered from the anode slimes in the electrolytic purification of the copper where gold averages 3.5 kg/t of slime, platinum and palladium approximately 0.5 kg/t and silver 85 kg/t. Precious metals have not been detected in untreated samples although Rudashevsky *et al.* (2000) succeeded in recovering minerals of these metals from the heavy fractions by sulphide flotation. These minerals are found to be in intimate association with the major copper sulphide minerals and these authors conclude that they exsolved from the primary sulphide solid solution at temperatures of 350 to 400°C.

Other - Baddeleyite occurs as a minor accessory constituent in the foskorite and carbonatite and is recovered from the copper flotation tailings.

The Phalaborwa Deposit as a Member of the Iron Oxide-Cu-Au-U-REE "Clan"?

Hitzman *et al.* (1992) pointed out that, while they regarded the similarities between the different iron oxide deposits they reviewed to be sufficient for them to be considered part of a "clan", significant differences clearly exist between individual deposits. Superficially, Phalaborwa certainly does produce Fe, Cu, U and precious metals and the REE's in the apatite processed from the complex could be regarded as a REE resource. However, as emphasised above, only iron and copper occur in above average abundances. It is only the huge tonnages processed that allow uranium and the precious metals to be economically retrieved – average abundances of uranium in the mined ore are no more than 35 ppm whereas PGE and gold are below detection.

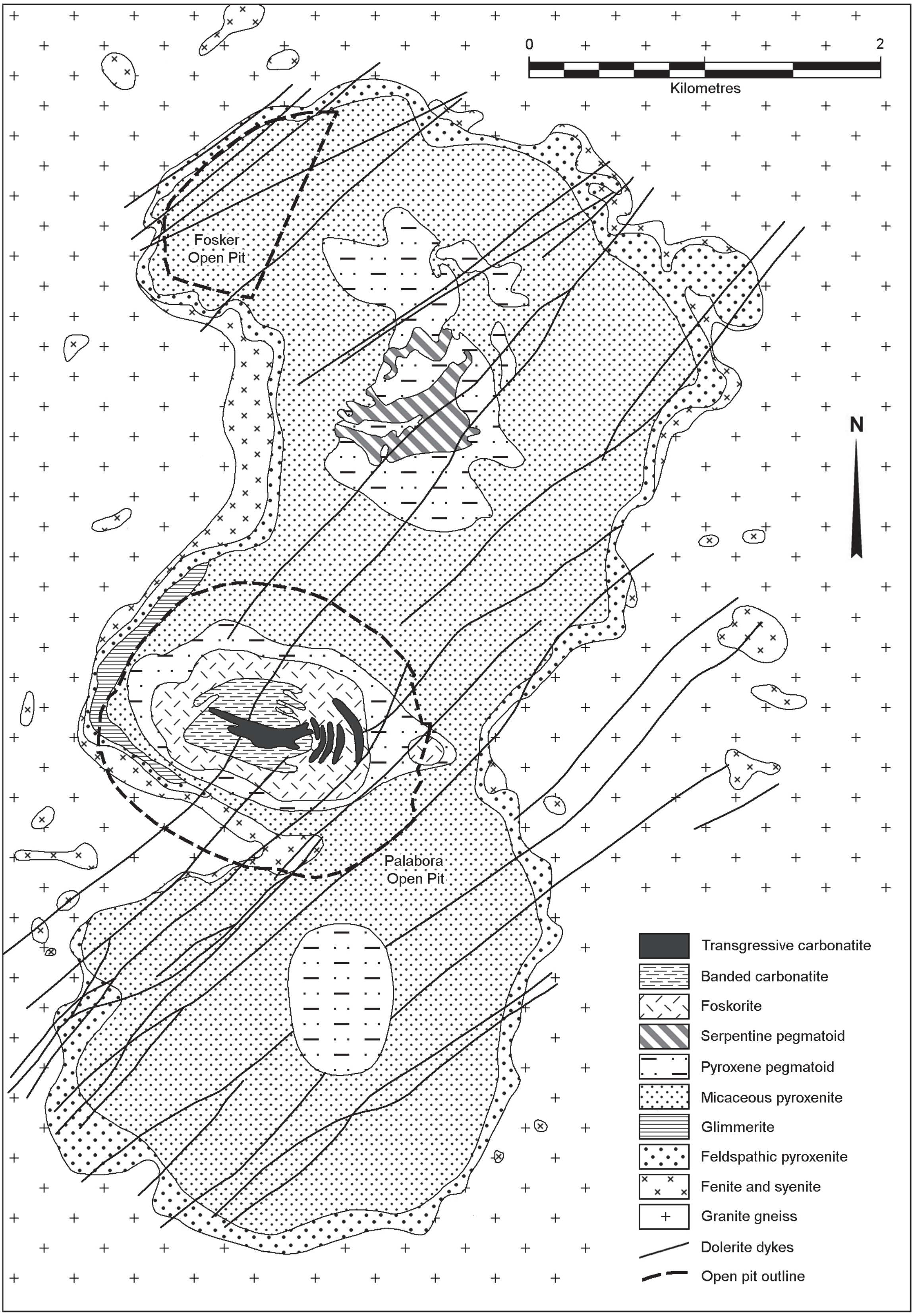

Figure 2: Geological map of the Phalaborwa Igneous Complex (after Wilson, 1998)

Other Metal-bearing Carbonatites in Southern Africa

While Phalaborwa remains the only carbonatite with *economic* concentrations of copper, copper sulphides are known to occur in the Glenover and Nooitgedacht carbonatites as well. High gold concentrations have been found in the Kruidfontein Complex. These complexes form part of the younger group of Proterozoic carbonatite and alkaline complexes (Fig. 1).

Glenover: Cu, P and REE

Glenover is a poorly-exposed, and under-studied, pyroxenite-carbonatite complex that intrudes into Proterozoic clastic deposits of the Waterberg Group (Verwoerd, 1967). Glenover comprises a plug of micaceous pyroxenite which is cut by a central plug and several arcuate sheeted intrusions of carbonatite. The carbonatite is multi-phase with cross-cutting relationships clearly evident in the few exposed pavements. Magnetite and apatite are conspicuous constituents of both carbonatite and pyroxenite components.

A body of phosphate-rich breccia was quarried for many years but little exploration activity was focussed beyond the bounds of this breccia. Verwoerd (1967) inferred the breccia to be of volcanic origin (in the author's opinion it is more likely to be a karst feature developed in the central carbonatite plug).

Sulphides, including chalcopyrite, occur most commonly near the margins of intrusive carbonatite veinlets - commonly where these are juxtaposed against micaceous pyroxenite.

Kruidfontein: Au, REE and Fluorite

The Kruidfontein complex is a remarkably well-preserved (given its ~1300 Ma age) caldera volcanic structure composed of silicate and carbonatitic eruptives and intrusives. Kruidfontein is emplaced into the "Crocodile River Fragment" – an inlier of highly deformed sedimentary rocks of the lower Transvaal Supergroup succession projecting through the mafic and granitic intrusive units of the 2054 Ma Bushveld Complex. The caldera system was built in two discrete stages: (1) an initial cone-building phase of predominantly nephelinitic pyroclastics and ignimbrites followed by cauldron subsidence and (2) a dominantly carbonatitic phase also terminating in cauldron subsidence (Schürmann, 1999a). Kruidfontein is currently composed of two concentric quasi-circular zones: an outer ring of silicate pyroclastics and a core of bedded to massive tuffaceous units, pyroclastic breccia units and intrusive carbonatite. Extensive alteration has affected

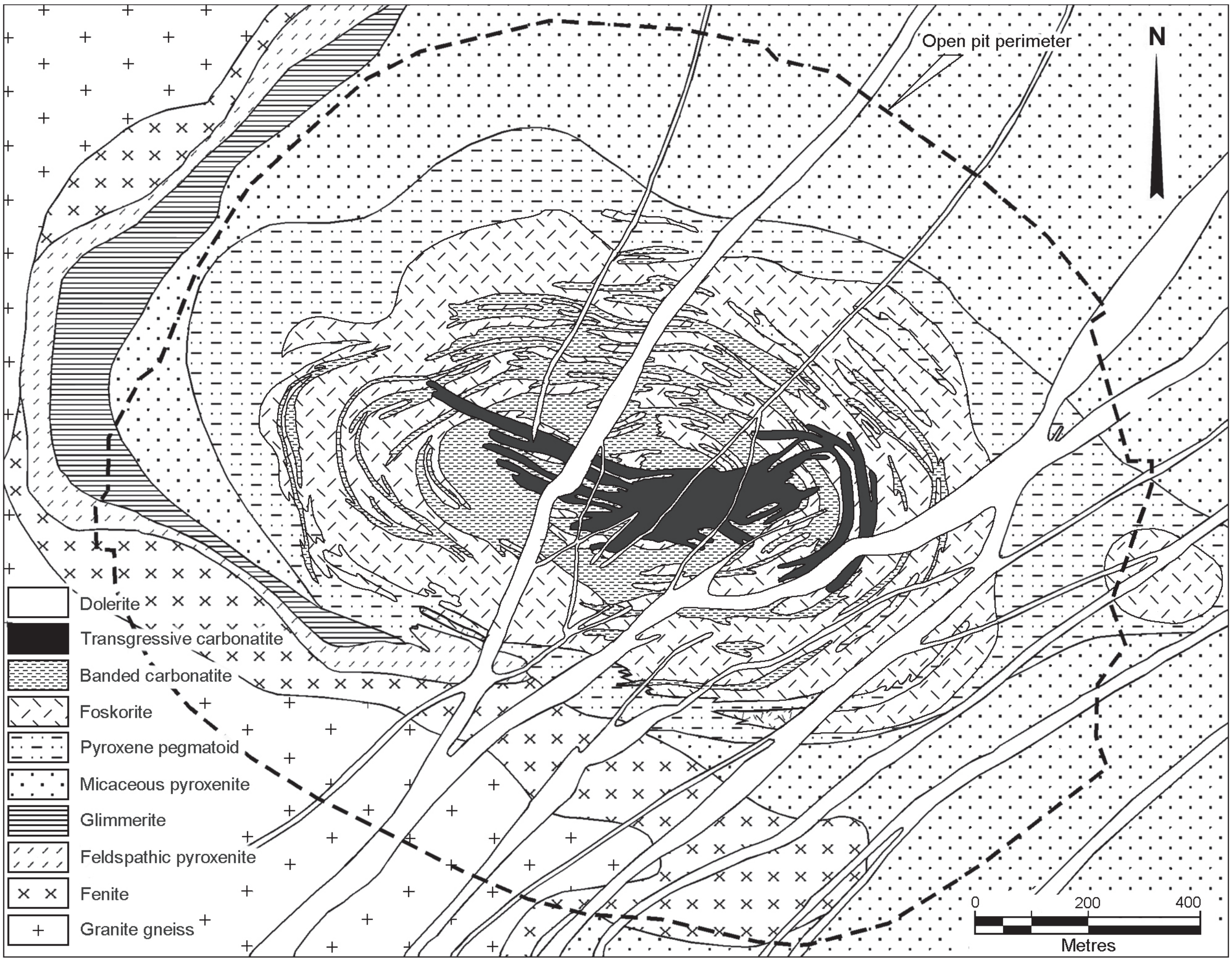

Figure 3: Geological map of the foskorite-carbonatite component of the Phalaborwa Igneous Complex (after Wilson, 1998).

the central zone and includes fenitisation (essentially feldspathisation), chloritisation and ferruginisation.

Fluorite occurs as primary concentrations in many of the dykes of fine-grained calcite carbonatite where it occurs as disseminated grains. A major fluorite ore body (2.5 Mt @ 28%; 30 Mt @ 15% CaF_2) has been proven at the south-western boundary of the inner zone where fluorite has extensively replaced pyroclastic material (Schürmann, 1999a).

Anomalous gold values were found in the north eastern part of the inner ring during a soil geochemistry survey and drilled. Ore grades were found over a 10 m interval, with values of 3.8 g/t Au found over a 1m section (Pirajno *et al.,* 1995). The anomaly coincides with a region of intense potassic fenitisation of the pyroclastics and the elevated gold values occur in a shallower (<150 m below surface) zone where oxidation and ferruginisation has overprinted the fenitised pyroclastics. Ore grades coincide with the zone of highest Fe and Mn enrichment (at ~50 m). Gold occurs as 1 to 8 mm particles enclosed or intergrown with iron oxyhydroxides and is silver-poor. Gold (and barium, manganese and yttrium) are strongly depleted from the fenites below the oxidised zone reflecting leaching by the fenitising fluids. That these fluids transported gold is also evidenced by the observation of gold grains within fluorite and barite. Both supergene and hypogene models for the concentration of gold were considered by Pirajno *et al.* (1995) who tentatively favour leaching and transport of the gold by hydrothermal/fenitising fluids and precipitation under oxidising conditions in the Fe-Mn-enriched weathered profile of the carbonatitic pyroclastics.

Nooitgedacht: Cu

The Nooitgedacht complex intrudes the Crocodile River fragment 5 km to the north of Kruidfontein. Unlike Kruidfontein, Nooitgedacht is deeply eroded and has little topographic expression. As a consequence outcrops are poor and most data on the complex has been gained from drill holes. Essentially Nooitgedacht comprises a plug of pyroxenite and ijolite intruded by carbonatite of different types emplaced in several distinct phases (Schürmann, 1999b):

(1) cone sheets and ring dykes of phlogopite and magnetite bearing calcite carbonatite. The non-carbonate constituents are flow aligned into a foliation. Apatite is a common accessory and pyrochlore and pyrite are also present. Sheets range in size from 1 to over 150 m in width.
(2) centrally-placed plug-like body of quartz-ankerite-calcite carbonatite in which flow banding is noted and has a finer-grained chilled margin.
(3) stockwork of porphyritic dolomite calcite carbonatite (dolomite forming the phenocrysts)
(4) radial dykes of dolomite carbonatite.

Sulphides reported are galena, pyrite, pyrrhotite and chalcopyrite and these commonly replace primary magnetite. Although little chalcopyrite is noted in samples studied thus far, soil geochemistry has revealed several substantial copper anomalies suggesting that copper-enriched phases of the carbonatite are to be found at depth.

Possible Carbonatite Connection in Other Iron oxide-Cu-Au Deposits

Hitzman *et al.* (1992) recognized several similarities between the suite of metals characterising the iron oxide-copper-gold deposits and those found in carbonatites but argued that none of these deposits were known to be associated with carbonatitic magmatism. The Proterozoic Bayan Obo Fe-REE deposit of Inner Mongolia, China was one of the "type" deposits discussed by Hitzman *et al.* (1992).

The mineralisation at Bayan Obo is hosted in a succession of dolomitic carbonates the origin of which is disputed. While many regard these metamorphosed carbonates ("marbles") as sedimentary, other authors have argued that they represent metamorphosed carbonatite intrusives and extrusives. Mariano (1989) considered the chemistry and mineralogy of the deposit as supporting a mantle-derived, carbonatitic origin for the ore-depositing fluids. Undeniable carbonatite dykes are known within the province (Le Bas *et al.*, 1992). Samples analysed by Le Bas *et al.* (1997) certainly do appear to have isotopic ($^{87}Sr/^{86}Sr$ of 0.702 to 0.705 - significantly lower than estimated Proterozoic seawater of 0.705 to 0.706 and sampled sedimentary carbonates at Bayan Obo of >0.720) and chemical (Sr and Nb contents of 890 and 40 ppm to over 7700 and 3800 ppm, respectively) signatures which would be regarded as typical of carbonatites. While Campbell *et al.* (1997) concede this fact, they consider that these samples relate to relatively small intrusions of carbonatite into a dominantly sedimentary carbonate succession. They consider these sediments to have been altered by "deep-sourced, fluorine-enriched hydrothermal fluids" without indicating the source of these fluids. The current author regards the evidence for the presence of carbonatites in the Bayan Obo succession persuasive and would suggest that the "deep seated fluids" are most likely sourced from these intrusive bodies.

A "deep seated" source has also been advocated for the mineralising fluids at Olympic Dam. Johnson and McCulloch (1995) showed that the sulphide-poor hematitic breccias and sulphide ores at Olympic Dam have identical ε_{Nd} values (around -2.5 units) which are different to those in the Roxby Downs granite that hosts the deposit. These authors argue that the ε_{Nd} value of the ores is too high to have been derived solely from pre-existing crustal rocks and that a mantle-derived rock or magma must have contributed to the ore forming process. Johnson and McCulloch (1995) suggest that fluids derived from altered mantle-derived alkaline mafic/ultramafic dykes which cut the ore body were the source of the more positive ε_{Nd} in the ores. Carbonatite and alkaline ultramafic magmatism is commonly spatially related (e.g. Phalaborwa) and so it is not impossible that deeper carbonatite intrusions contributed to the mineralisation here as well.

Discussion

Origin of Cu Mineralisation at Phalaborwa

As mentioned, Phalaborwa is the only carbonatite-bearing complex containing *economic* quantities of copper – it is not the only carbonatite containing copper sulphides. However, the high concentration of copper sulphides *is* an anomaly. Most of the other geological features of the complex are shared to varying degrees by other complexes but there is one other highly anomalous feature of Phalaborwa – its isotopic composition.

A striking feature shared by most of the world's carbonatites is that they exhibit relatively little variation in their Sr and Nd isotopic compositions (e.g. Bell and Blenkinsop, 1989; Harmer and Gittins, 1998) - young carbonatites (ca <200 Ma) exhibit less variability than is encountered in oceanic island basalts. As a consequence, it is widely accepted that carbonatites must ultimately be derived from mantle melts – either indirectly, through immiscibility or fractionation from a silicate parent (e.g., Kjarsgaard and Hamilton, 1989) or directly as near-solidus melts of carbonated mantle peridotite (Sweeney, 1997; Harmer and Gittins, 1998).

By contrast Phalaborwa has Sr and Nd isotopic signatures (Fig. 4) which are highly anomalous (Eriksson, 1989) and reflect contributions from sources having long lived (>1 Ga) enrichments in Rb/Sr and LREE/HREE – values that conventionally are attributed to crustal rather than mantle reservoirs. The only known carbonatite complex with similar enriched isotopic signature is the Ihouhaouene complex in Algeria which, coincidentally, at 2.0 Ga is similar in age to Phalaborwa. While it is possible that the high ε_{Sr} values could be derived from mantle sources (diamond-bearing lamproites from Western Australia have similar signatures) it is more likely that they reflect the involvement of crustal material.

In addition to the enriched isotopic signatures in the complex as a whole, significant differences exist between the carbonatites and the pyroxenites which precludes the possibility that the carbonatites evolved, in a closed system, from the same magma as that producing the pyroxenites (Eriksson, 1989). Eriksson also identified significant variability in $^{87}Sr/^{86}Sr$ between individual mineral phases in the carbonatite and pyroxenite.

The Nature of Carbonatite Magmatism

Carbonatites, literally igneous rocks in which carbonate minerals comprise more than half the rocks by volume, in most instances do not represent liquid compositions and should rather be considered as *cumulates* (the term is here used in the non-genetic sense of Irvine (1982) implying the *accumulation* of phases but with no process implied). Neither calcite nor dolomite, the predominant carbonate phases in most common carbonatites, are able to exist as melts at geologically reasonable temperatures at crustal pressures – at 1 kbar $CaCO_3$ only melts at 1330°C whereas dolomite dissociates (into calcite, MgO and CO_2) at temperatures above 815°C. It was observations such as these that influenced petrologists like Shand and Bowen to long deny the possibility of carbonatites being igneous rocks. Additional *fluxing* components (Bailey, 1993) are needed for carbonate-rich melts to exist. Early experiments (Wyllie and Tuttle, 1960) demonstrated that a calcite-precipitating melt can exist at geologically reasonable temperatures in the presence of H_2O but little evidence exists in real carbonatites to support a significant role for water. Other effective fluxing components which work

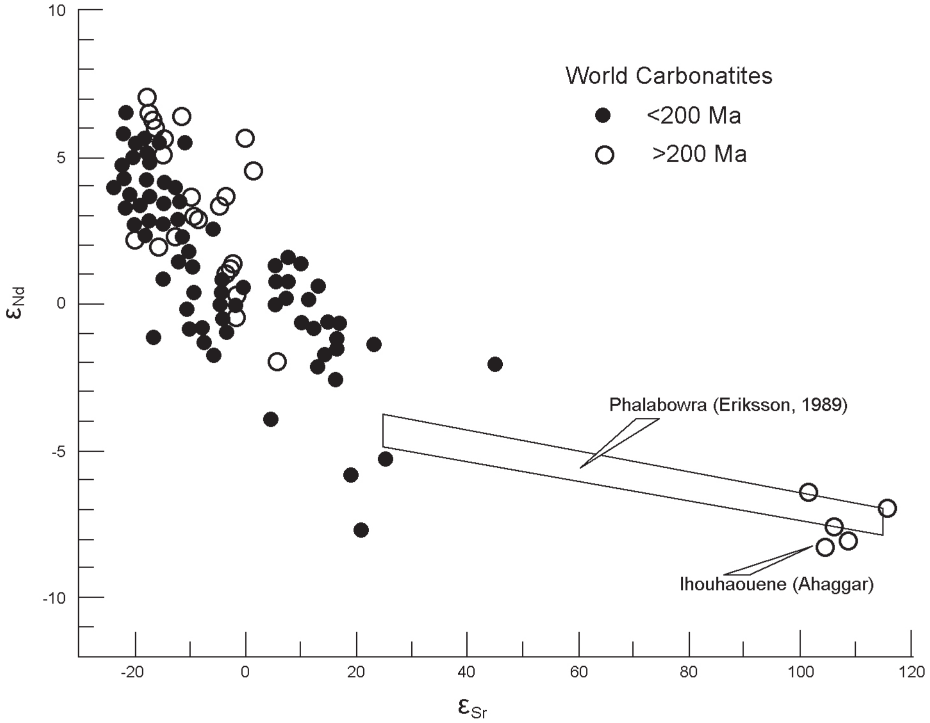

Figure 4: Plot of ε_{Nd}- ε_{Sr} values for world carbonatites. Epsilon values are calculated for the time of intrusion of each complex

experimentally and are consistent with field and petrological observations in carbonatites include fluorine (Gittins and Tuttle, 1964; Jago and Gittins, 1991) and alkalis (Cooper *et al.*, 1975; Beckett, 1989: referenced and discussed in Harmer and Gittins, 1997). The common non-carbonate components in carbonatites provide support for the presence of these fluxes in the original carbonate magma: the most common silicates found in carbonatites are all alkalic (phlogopite, alkali amphiboles, aegirine); apatite is usually fluorapatite; micas and amphiboles commonly have much of the volatile radical as fluorine and not hydroxyl ion. Harmer and Gittins (1997) have reviewed the effectiveness of alkali carbonate as a flux in dolomitic systems. It was demonstrated that in the presence of small amounts of alkali carbonate, calcite is the high temperature liquidus phase of a magnesian carbonate melt and that dolomite crystallises only at lower temperatures. This system shows that calcite carbonatites (sövites) may develop as cumulates from a melt of essentially dolomite composition. It is interesting that calcite carbonatites containing abundant phlogopite and alkali amphibole are common – again testifying to the fact that the parental magma must have contained significant quantities of magnesium and alkalis.

Perhaps the most compelling evidence that carbonatite magmas lost material to a fluid phase during crystallisation is the fact that carbonatite intrusions are characteristically surrounded by fenite aureoles – zones in which the immediate country rocks have been subjected to extensive metasomatic alteration. Typically, this metasomatism consumes quartz, converting granitic protoliths to undersaturated syenitic and nepheline syenitic assemblages. Studies of fenite zones reveal massive introduction of alkalis as well as Fe, Mg, Ca and trace elements like Sr, Nb and the REE. Economic deposits of fluorite are commonly developed in fenites at the margins of carbonatite intrusions and testify to the high halogen content of carbonatite magmas: examples listed in Mariano (1989; Table 7.1) include Okorusu (7 to 10 Mt), Amba Dongar (12 Mt) and Mato Preto (4.5 Mt). Carbonatite magmas must have had far higher concentrations of these elements than are found in crystalline carbonatites.

Studies of chemical changes during fenitisation show both losses and gains of elements during metasomatism – elements are dissolved and removed as well as being deposited. Fluids of appropriate composition would thus be capable of leaching metals from country rocks and cycling these back into the crystallising carbonatite.

Could the anomalous isotopic patterns in Phalaborwa and the anomalous copper content of the carbonatite be related?

If one accepts that the isotopic and copper anomalies at Phalaborwa may be related then one might speculate whether the elevated concentration of copper sulphides in these carbonatites are enrichments of the primary copper content of the parental carbonatite magma during essentially closed system evolution, or whether excess copper was introduced from an external crustal source - such as one of the greenstone belts which are common in the gneissic terrain around Phalaborwa. Given the inherently high Sr content of carbonatite magmas it is unlikely that bulk assimilation of basement rocks could have occurred. It is more likely that the anomalies result from material exchanged by circulating fenite fluids at a late stage in the solidification of the carbonatite (this would also be consistent with the observed disequilibrium in isotopic composition between phases).

A detailed study of the isotopic relationships between different mineral phases in the Phalaborwa carbonatites (including magnetite and chalcopyrite) is currently underway to investigate the implications of this apparent disequilibrium to the copper mineralisation.

To Conclude

Some of the unifying features of the iron oxide-Cu-Au-U-REE family of ore deposits are characteristic *primary* features of carbonatites: abundant low-TiO_2 iron oxide phases and apatite, enrichment in total REE and the LREE. In addition, the nature of the alteration zoning in these deposits is similar to that encountered in the fenitisation aureoles around carbonatite intrusions: potassic metasomatism (and chloritisation/hematisation) at low temperature and/or low pressures; sodic metasomatism at higher temperatures and/or pressures. The fluids liberated from crystallising carbonatite magmas will be alkali and halide rich and capable of mobilising metals from surrounding country rocks and earlier phases of the carbonatite complex itself. It is argued that copper and gold could be enriched in carbonatites in this way.

A characteristic of iron oxide-Cu-Au-U-REE deposits are their enormous size, typically 10^7 to 10^8 tons of mineralised rock: carbonatite complexes are characteristically small, surface areas seldom more than 1 to 10 km^2. Even though carbonatite magmas will generate more hydrothermal (carbonothermal?) fluids than equal volumes of most other igneous rocks, the scales remain prohibitive.

The similarities highlighted in this paper do suggest, however, that studies of carbonatite complexes – in particular high level fenitisation zones – might provide useful analogues for understanding the mineralising processes which have produced the large iron oxide-Cu-Au-U-REE deposits.

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