David I. Groves · Noreen M. Vielreicher

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?

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Abstract Olympic Dam-type iron-oxide copper–gold deposits are widely recognised in terrains with significant Palaeoproterozoic to Mesoproterozoic granitic magmatism. Most researchers favour a magmatic association for these deposits, but none of the 100–200 Mt recognised copper-bearing deposits has a spatial and/or temporal relationship to an intrusive body of sufficient dimensions to produce the hosting giant breccia and/or hydrothermal systems. In other words, if the recognised ore-bodies are magmatic-hydrothermal, they must be classified as distal deposits. The magnetite–copper–phosphate–rare earth element pipe-like carbonatite-hosted orebody at Loolekop, within the larger Phalaborwa Carbonatite Complex, has many features to suggest that it represents an end member of the Olympic Dam-type deposit class hosted within its magmatic source rock. It (1) falls broadly within the appropriate age range, (2) has a similar giant size and low copper grade, (3) is dominated by magnetite, (4) has sulfur-poor copper-sulfide minerals and lacks iron sulfides, (5) is silica-poor, and (6) is enriched in REE, particularly LREE, as well as P, F, U and Th. As an end member of the Olympic Dam-type deposits, the Loolekop orebody can help explain the common siting of the deposits at craton edges or other lithospheric boundaries, where decomposition melting of metamorphosed mantles can produce volatile-rich alkaline melts (rich in RIEE, P, F, etc.). Such melts are capable of generating sulfur-deficient volatiles enriched in copper and gold, among other elements, as well as phreatic breccia pipes and associated intense metasomatism, the most common features of the Olympic Dam-type deposits.

Introduction

The iron-oxide copper–gold Olympic Dam-type deposit group is now recognised worldwide, with world-class Proterozoic examples discovered in the Stuart Shelf (e.g. Olympic Dam) and Cloncurry (e.g. Ernest Henry) districts of central Australia and the Carajas Region of northeastern Brazil (e.g. Igarape Bahia–Alemao, Salobo), and other less important 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 as discussed below, most authors favour an association between the clearly epigenetic, commonly breccia-hosted mineralisation and widespread, commonly anorogenic, igneous intrusive activity. However, nowhere are the orebodies sited in major intrusive rock-bodies considered to be both coeval and cognetic with the mineralisation. In this short paper, attention is drawn to the Phalaborwa (Palabora) magnetite-copper (plus minor gold) deposit hosted within a pyroxenite-carbonatite complex near the eastern margin of the Kaapvaal Craton of South Africa (Fig. 1). The deposit is enriched in many of the minor elements (e.g. REE, F, P, U, Th) that typify the iron-oxide copper–gold deposit group and, as such, is a possible end-member of this group, showing a closer association with its igneous source.

The discussion of the similarities of the Phalaborwa deposit to the Olympic Dam-type iron-oxide copper–gold group of deposits follows a brief summary of their general characteristics. It is realised that there are variations within the group, and emphasis has been placed on the larger, more economically significant, examples. The implications of this association are then briefly discussed in terms of alternative genetic models proposed for the deposit group. The short paper conveys a concept, and is not intended to be an exhaustive review of either copper–gold deposits or Phalaborwa.

Nature of iron oxide copper–gold deposits

Olympic Dam-type iron oxide copper–gold deposits (Oreskes and Einaudi 1990; Reeve et al. 1990) are now a widely recognised class of structurally controlled, epigenetic ore deposits (e.g. Hauck 1990; Hitzman et al. 1992; Huhn and Nascimento 1997; Williams 1998). Although they have different characteristics in detail, the larger ore deposits of this group have a number of common features including (1) high tonnage (>100 Mt) and low copper (<2.0% Cu) and gold (<0.8 g/t Au) grades, (2) a dominance of iron-oxides, magnetite and/or haematite, (3) low content (<5%) of relatively low-sulfur copper minerals, commonly chalcopyrite, bornite and/or chalcocite, (4) a low SiO₂ content, particularly a lack of quartz veins, (5) pervasive, commonly texture-destroying alteration, (6) a characteristic metal association of Fe–Cu–Au, commonly with anomalous LREE, F and P, with variable enrichments in Ag, As, Ba, Bi, Co, Mo, Nb, Ni, Th and/or U in places, (7) high Cu/Cu + Zn + Pb ratios (>0.9), and (8) restricted range of Cu/Au ratios (15–30 × 10⁻⁴). Although there are exceptions, the early paragenesis is, in most cases, dominated by iron-oxides followed by a later paragenesis dominated by copper sulfide minerals and gold. Commonly, the nature of mineralisation also changes, with an early, disseminated style generally giving way to more fracture/shear-zone-controlled
mineralisation style later in the paragenesis. Carbonate alteration is generally not significant, but, where present, is generally early in the paragenesis, with carbonate minerals replaced by sulfide minerals. Temperatures are estimated to range from ~600 °C for deposition of the early iron-oxide and/or silicate minerals to 200–500 °C for the copper-gold mineralisation (e.g. Hitzman et al. 1992; Twyerould 1997; Davidson and Large 1998). The ore fluids are highly saline (as much as 50 wt% NaCl equivalent, Reeve et al. 1990; Johnson 1990; Davidson and Large 1998), acidic and oxidising, with fO2, generally increasing with higher crustal level of formation (e.g. Hauck 1990; Reeve et al. 1990; Hitzman et al. 1992). Interestingly, CO2 is a common component of the ore fluids (e.g. Conan-Davies 1987; P. Williams personal communication 2000).

Zoning of metals can be recognised at some of these deposits, with iron-, copper- and gold-bearing assemblages forming discrete zones (e.g. Olympic Dam). There also appear to be significant variations in the associated alteration mineralogy with depth of formation, estimated to be from ~1 km to a minimum of 6 km below surface (e.g. Hitzman et al. 1992). There is a general trend with inferred depth of formation from dominantly haematite (e.g. Olympic Dam) to magnetite (e.g. Ernest Henry, Carajas deposits), with a corresponding broad change in associated iron carbonate and silicate minerals from shallow-level carbonate phases through actinolite to deeper-level grunerite and even fayalite (e.g. Salobo: Lindemayer 1998). There is also a suggestion of a change from sericitic through potassic to plagioclase feldspar alteration with depth (e.g. Hitzman et al. 1992), with quartz generally more common at inferred shallower crustal levels of formation (e.g. silification at Carajas and haematite-quartz breccias at Olympic Dam), although this is poorly constrained. This depth zonation broadly corresponds to that in some porphyry-copper systems such as Yerrington, Nevada (e.g. Dilles and Finaudi 1992), although none of the recognised iron-oxide copper-gold deposits are sited in, or adjacent to, a recognisable intrusion large enough to be the source of the ore fluids.

Typically, large deposits of Olympic Dam-type contain >100 Mt at 0.8–2.0% Cu and 0.2–0.8 g/t Au, with Cu/Au ratios in the order of 18,000/1 to 27,000/1. According to Hitzman et al. (1992), the giant phosphorus-bearing iron ores of Kiruna, Sweden, and the iron-rich rare earth element ores of Bayan Obo, Inner Mongolia, may be part of an even more extensive class of deposits, termed iron-oxide copper–rare earth element deposits.

Most world-class iron-oxide copper–gold deposits are Palaeoproterozoic to Mesoproterozoic in age, with the type example being the Olympic Dam deposit (2,000 Mt at 1.6% Cu and 0.6 g/t Au), which formed at about 1.590 Ma in the Stuart Shelf area of South Australia (e.g. Campbell et al. 1998). Another large central Austra-

lilian deposit is Ernest Henry (167 Mt at 1.1% Cu and 0.5 g/t Au), which formed at about the same time as a suite of 1,530–1,500 Ma granitoids (e.g. Pollard et al. 1998). Other deposits that most likely belong to this class (e.g. Huhn and Nascimento 1997; Tasava 1999), include Salobo (1,000 Mt at 0.85% Cu and 0.4 g/t Au) and Igarape–Bahia/Alemao (140 Mt at 1.5% Cu and 0.8 g/t Au in primary ore at Alemao; Tazara 1999). However, other authors have suggested other classifications (e.g. volcanogenic massive sulfide, porphyry copper-gold) for these deposits (see discussion in Requia and Fontboté 2000). The age of the Carajas deposits is not known, although there are several 1,800 ± 100 Ma anorogenic granitoids in the region (Machado et al. 1991). The Mesozoic Candelaria deposit in the Chilean Andes (366 Mt at 1.08% Cu and 0.26 g/t Au: Ryan et al. 1995) has been associated with the Olympic Dam-type deposits, but is different in tectonic setting, the presence of significant pyrite, the lack of characteristic minor-element concentrations, and the occurrence of a typical skarn paragenesis. Only the Proterozoic examples are discussed further below.

### Tectonic, magmatic and structural associations of deposit group

The Proterozoic deposits are all spatially associated with felsic igneous rocks, mainly A-type to shoshonitic intracratonic granitoids (e.g. Pollard et al. 1998), with or without bimodal volcanism, and are normally sited close to the margins of Archean cratons (e.g. Hitzman et al. 1992). The Olympic Dam deposit, for example, is sited within 50 km of the eastern margin of the Archean Gawler Craton in South Australia (e.g. Reeve at al. 1990). The Carajas deposits are also sited close to the eastern margin of the only remnant of a once-extensive Archean craton now represented by one of the most extensive anorogenic terranes on Earth (e.g. Santos et al. 2000). The tectonic setting of the Ernest Henry deposit is not as clear, although, from gravity data, it does appear to lie close to a boundary between thick Archean lithosphere and post-Archean thinner lithosphere.

At the regional scale, the deposits lie proximal to, or along, crustal-scale faults or shear zones, or lineaments defined from airborne geophysical surveys. At the deposit scale, there is also structural control by faults and shear zones or geological contacts. The ore bodies have a steep dip or plunge. Some of the deposits have a classic pipe-like form (e.g. Olympic Dam), others resemble ring-dikes in their overall shape (e.g. Igarape Bahia/Alemao and Sossego at Carajas), and yet others (e.g. Ernest Henry) may be more irregular, but essentially have a dipping pipe morphology. Figure 2A, B shows the shape and size of the Olympic Dam and Igarape Bahia/Alemao deposits, respectively. Most large deposits of this group consist, at least in part, of breccias, particularly in the centre of the deposit, with variable volumes of replaced fragments. Replacement is also evident at the edges of pipes. The deposits are everywhere breccia-hosted irrespective of the host rocks, which can range from broadly coeval anorogenic granitoids (e.g. Olympic Dam), to older metavolcanic or metasedimentary rocks (e.g. Ernest Henry), to much older terranes of gneiss, granitoids or metavolcanic rocks (e.g. Carajas).

Fig. 2 Simplified maps (at the same scale) of: A Olympic Dam, B Igarape Bahia/Alemao and C Phalaborwa Complex, showing overall similarity of scale and broadly pipe-like morphologies. All pipe-like bodies are steeply-dipping to vertical in cross section. D Simplified map of the Loolekop pipe at Phalaborwa as shown in C. A is simplified from Reeve et al. (1990) and Haynes et al. (1995). B is a schematic plan based on Zang and Fyfe (1995) and unpublished data from DOCEGEO. C and D are simplifications from Hanekom et al. (1965) and Phalabora Mining Company (1976)
Comparison of Phalaborwa with the Olympic Dam Deposit Group

The Phalaborwa magnetite-copper ore is well described by Palabora Mining Company Staff (1976), Verwoerd (1986, 1993), and Eriksson (1989) as a magmatic-hydrothermal deposit. Only a brief discussion of those features critical to its comparison to the iron-oxide copper–gold deposit group is provided here. Comparisons are summarised in Table 1.

Alkaline magmatism has been discontinuous and episodic through geological time (Verwoerd 1993). In comparison to other carbonatite complexes of southern Africa, Verwoerd (1993) includes the Phalaborwa Complex, dated at ~2,060 Ma (Eriksson 1989), within a widespread Protoprotrozoic (2.5–1.6 Ga) event. This time frame overlaps with the ca. 1.9–1.4 Ga time frame for formation of iron-oxide copper–gold deposits globally. Also, in terms of tectonic setting (Fig. 1), Phalaborwa lies close to the eastern margin of the Kaapvaal Craton of South Africa (e.g., Sohng 1986), and hence has a similar tectonic position to the iron-oxide copper–gold deposits. It was certainly emplaced in an anorogenic setting with an associated swarm of xenites. The size of the magnetite–copper mineralised carbonatite at Loolekop, within the larger Phalaborwa Complex (Fig. 2C), is of the same order as some world-class iron-oxide copper–gold deposits, within larger breccia bodies, as shown by comparison of Fig. 2D with Fig. 2A, B. Its total resource of about 850 Mt at about 0.5% Cu (Leroy 1992) is also in the same range as world-class deposits of the iron-oxide copper–gold group of deposits. Its near vertical pipe-like shape also matches that of several of the world class deposits of this group.

The ore comprises 25–30 wt% magnetite with >1% copper sulfide minerals, which comprise chalcopyrite and bornite with minor chalcocite and digenite. As in many of the iron-oxide copper–gold deposits, (1) the sulfide minerals replace magnetite and hence are paragenetically late; (2) carbonate (carbonatite?) alteration is minor and is paragenetically early and, in places, is replaced by bornite; and (3) mineralisation changes in style from disseminated to fracture-controlled later in the paragenesis. The metal distribution is also zoned with higher copper grades in the centre of the deposit and magnetite in peripheral locations. Mineralisation at Phalaborwa is also accompanied by high, but erratic, P and F concentrations, and anomalous (also erratic) U, Th and REE, especially LREE, concentrations. Such enrichments are related to the occurrence of fluorapatite, uranothianate, hydroxypatite and carbonate. Hence, the same minor elements are concentrated at Loolekop as in the iron-oxide copper–gold deposit group. The ore also contains significant Au, Ag, Pt and Pd values (typical production per year of ~15 t, of which ~641 kg is Au: Verwoerd 1986), but the Cu/Au ratio at Loolekop is about 200,000/1; an order of magnitude greater than those of the iron-oxide copper–gold group. Thus, relatively low gold is the main anomaly, and this is discussed in the genetic section below. Despite this, it must be concluded that the Loolekop deposit at Phalaborwa shows a significant number of similarities to the Olympic Dam-type iron-oxide copper–gold deposit group.

Genetic models and significance of Phalaborwa deposit

Genetic models for the iron-oxide copper–gold deposit group are briefly reviewed, and the significance of the Phalaborwa deposit then discussed.

Available fluid-inclusion, mineral-stability and other thero-metamorphic data from a number of the deposits indicate that the copper–gold mineralisation formed from variable, but generally high salinity, low pH and oxidising aqueous fluids, with co-existing CO₂-rich fluids, at 200–500 °C (Hitzman et al. 1992; Twyford 1997; Davidson and Large 1998). The available oxygen and carbon isotopes data are consistent with involvement of a deep magmatic or metamorphic fluid, at least for the early stages of mineralisation, including at least some sulfides (Hitzman et al. 1992), with some meteoric water influx in the later stages (e.g. Gow et al. 1994), and some evidence for fluid mixing at shallow crustal levels (e.g. Haynes et al. 1995). The ultimate source of the deep fluid has been hotly debated. Most authors favour an ultimate magmatic source, with exsolution from either alkaline magmas (e.g. Meyer 1988; Hauck 1990) or specific granitoid suites (e.g. Wyborn 1998). Alternatively, connate basinal brines, perhaps derived from older evaporites, have been suggested as the source (e.g. Barton and Johnson 1996).

Numerous lines of evidence support a magmatic source, particularly an alkaline source, despite the lack of a specific spatial relationship to potential igneous source-bodies in the classic examples of the deposit group. This evidence includes (1) the high temperature (600 °C) and magmatic/metamorphic signature of at least the early fluid; (2) the high salinity fluid that argues against a

<table>
<thead>
<tr>
<th>Feature</th>
<th>Iron-oxide Cu–Au deposits</th>
<th>Loolekop Pipe, Phalaborwa</th>
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</thead>
<tbody>
<tr>
<td>Age range</td>
<td>Mostly 1900–1400 Ma</td>
<td>~2000 Ma</td>
</tr>
<tr>
<td>Tectonic setting</td>
<td>Adjacent to craton margins and/or lithospheric boundaries</td>
<td>Close to eastern margin of Archean Kaapvaal Craton</td>
</tr>
<tr>
<td>Mineralisation style</td>
<td>Commonly pipe-like to ring-like, near vertical pipes of brecciated country rock</td>
<td>Near-vertical pipe-like carbonatite body with concentric zoning (ring-like form)</td>
</tr>
<tr>
<td>Dimensions of Breccias</td>
<td>1–20 km&lt;sup&gt;3&lt;/sup&gt;</td>
<td>~16 km&lt;sup&gt;3&lt;/sup&gt; for whole pipe</td>
</tr>
<tr>
<td>Host rocks</td>
<td>Archean gneisses and granitoid, greenstones, metamorphosed Protoprozoic rocks, anorogenic granitoids</td>
<td>Pyroxene–carbonatite complex intruding Archean granitoids, gneisses, granulites, amphibolites and talc-serpentinite schists</td>
</tr>
<tr>
<td>Alteration</td>
<td>Intense, texture-destructive alkalii and iron metasomatism, normally haematite and magnetite, but also iron silicates</td>
<td>Intense alkalii metasomatism in country rocks spatially associated with carbonatite pipes. Abundant magnetite</td>
</tr>
<tr>
<td>Opaque phases</td>
<td>Magnetite and/or haematite</td>
<td>Magnetite</td>
</tr>
<tr>
<td>Major</td>
<td>Chalcopyrite ± bornite ± chalcocite ± pyrrhotite ± pyrite</td>
<td>Chalcopyrite-borne ± chalcocite ± cubanite</td>
</tr>
<tr>
<td>Minor</td>
<td>Cu–REE ± Ag, As, Ba, Co, F, Fe, Mo, Nb, Ni, P, Th, U</td>
<td>Cu–REE–P–Fe–U–Th (minor Au and PGE)</td>
</tr>
<tr>
<td>Element associations</td>
<td>~18,000/1 to 27,000/1</td>
<td>~200,000/1</td>
</tr>
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normal metamorphic source, combined with the presence of CO\textsubscript{2}, which could indicate an unusual magmatic source; (3) the oxidising nature of the ore fluid, together with a low pH; (4) the distinctive ore association of both compatible and incompatible elements, which is similar to that of alkaline rocks, as first recognised by Meyer (1988); (5) the pipe to ring-like forms of some of the breccia pipes, which resemble those of explosive alkaline intrusions; for example, a cross section through Olympic Dam (e.g. Reeve et al. 1990) resembles that of the Argyle diamond-rich lamproite pipe of the Kimberley region of Western Australia (e.g. Drew and Cowan 1994); (6) the complex and repetitive nature of the ore-paragenesis, reflecting a prolonged but discrete hydrothermal event, reminiscent of the multiple phases of intrusion common to alkaline magmatism; (7) the broadly similar timing of formation of the Olympic Dam ore body with anorogenic magmatism (Johnston and Cross 1995); and (8) the depletive mantle-like Nd isotope signature of the Olympic Dam deposit, combined with the presence of hydrothermally altered lamprophyre dykes containing high-chrome chromites in the Olympic Dam breccia body (Campbell et al. 1998), and coincident magnetic and gravity anomalies (Reeve et al. 1990), consistent with an alkaline mafic body at depth (Campbell et al. 1998). Evidence specifically against the connate-fluid model as a generally applicable model is the occurrence of iron-oxide copper-gold ores in Archean gneisses and granitoid-greenstones in Carajas, Brazil, rather than in coeval rocks in extensional basins, as expected from the model.

The notion that the Phalaborwa deposit represents an example of the deposit class proximal to the parent igneous body fits very well with all of these broad constraints. The Loolekop body itself lies within a larger plug of dense carbonatite and ultramafic rocks with high magnetite contents that define coincident gravity and magnetic highs. The body has a depletive mantle-like Nd isotope signature (Eriksson 1989) similar to that of Olympic Dam (Campbell et al. 1998), and is sited in an area where there is abundant, intense, texture-destructive alkali metasomatism. The specific sitting of the iron-oxide copper-gold deposits near craton margins (or changes in lithosphere thickness) is also consistent with an alkaline magmatic association. Extensional boundaries where there is a transition from thick Archean to thinner post-Archean mantle lithosphere will lead to decompressional melting of metasomatized domains of mantle lithosphere (Wyllie 1989; Bell et al. 1999), and, in turn, will produce alkaline magmatism characterised by enrichment of incompatible and compatible elements (e.g. Meen 1987; Harmer 1999). The temporal association of deposit formation with the emplacement of alkaline magmas, such as at Phalaborwa, also explain the near-vertical pipe-like nature of many of the iron-oxide copper-gold orebodies and the abundance of breccias within them, as such magmas are volatile rich and are commonly associated with phreatic explosive emplacement (Heinrich 1966).

The relatively low gold concentrations in the Phalaborwa system could be seen as conflicting with this model. A semi-quantitative analysis indicates that this need not be the case. For example, if gold is carried as a chloride complex, as would be the case in a hot (>300 °C), high-salinity, relatively oxidising, low sulfur ore-fluid (Hayashi and Ohmoto 1991; Large et al. 1989; Murphy et al. 1999) that is proposed for these deposits, gold solubility will be temperature dependent, with declining solubility at lower temperature (e.g. Seward and Barnes 1997; Loucks and Mavrogenes 1999). Thus, higher temperature deposits more proximal to the parent intrusion will contain more gold relative to deposits more distal to it. There are few data on metal zoning for the Proterozoic examples. However, Olympic Dam (0.6 g/t Au and Alemao (0.8 g/t Au), which are interpreted to be relatively shallow-level and hence potentially more distal, deposits, on the basis of their alteration mineralogy, are, on average, more gold-rich than Ernest Henry (0.5 g/t Au) and Salobo (0.4 g/t Au), which are interpreted to be hotter, deeper, and hence potentially more proximal, ore bodies (e.g. Hitzman 1992; Huhne and Nascimento 1997). In fact, at Olympic Dam, there is an incomplete but apparent zoning whereby gold is preferentially enriched in the upper parts of the system relative to copper below (Fig. 3; Reeve et al. 1990).

Fig. 3 Cross section from Olympic Dam (Mine Section V527-17) showing a locally well-developed example of the broad relationships between higher grade gold mineralisation and copper-uranium mineralisation. Note the downward zonation from largely discrete zones of gold mineralisation, through higher copper grade bornite-chalcocite mineralisation, to lower grade chalcopyrite (pyrite) mineralisation (Reeve et al. 1990)

**Concluding statement**

The inclusion of the Phalaborwa magnetite-copper (+ P ± F ± U) deposit in the Olympic Dam-type iron-oxide copper-gold group of deposits is compatible with most of its characteristics, including age, giant size, low ore grade, minor-element associations, high Cu/Cu + Zn + Pb ratio and pipe-like form. Its tectonic setting, close to a lithospheric boundary, is compatible with that of the majority of Proterozoic iron-oxide copper-gold deposits. This style of deposit can be explained by decomposition melting of metasoamatised mantle to produce volatile-rich alkaline melts capable of generating phreatic brecciation, intense alteration and the associated mineralisation. Campbell et al. (1998) argue that magmas of this type will become saturated in volatiles before they are saturated in sulfides, and hence copper and gold will partition into the hydrothermal fluid rather than be lost to that fluid by partition into immiscible sulfide liquids. The alkaline association best fits the available constraints on genesis of the iron-oxide copper-gold deposits, and can explain the as-yet-unexplained co-incident gravity and magnetic anomalies at Olympic Dam, which first led Western Mining Corporation to explore the area. The interpretation of the Phalaborwa deposit as the proximal end-member of the iron-oxide copper-gold deposits makes good sense, and points to the possibility of more conventional, distal deposits of this type around the margin of the Kaapvaal Craton.

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References

Conan-Davies MSM (1987) A sheet silicate and fluid inclusion study of the mine area DNW, Olympic Dam, South Australia. BSc Thesis, Australian National University
Drew GJ, Cowan DR (1994) Geophysical signature of the Argyle lamproite pipe, Western Australia. In: Dentith MC, Frankcombe RF, Ho SE, Shephard JM, Groves DI, Trench A (eds) Geophysical signatures of Western Australian mineral deposits. Geology and Geophysics Department (Key Centre) and University Extension, University of Western Australia, Publication 26, pp 393–402
Heimrich EW (1966) The geology of carbonatites. Rand and McNally, Chicago, p 555