View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Constellation

PETROGENESIS OF CU-NI SULPHIDE ORES FROM O'OKIEP AND KLIPRAND, NAMAQUALAND, SOUTH AFRICA: CONSTRAINTS FROM CHALCOPHILE METAL CONTENTS

W.D. MAIER
Department of Geosciences, University of Oulu 90014, Finland
e-mail: wolfgang.maier@oulu.fi

M.A.G. ANDREOLI
South African Nuclear Energy Corporation, South Africa; School of Geosciences, University of the Witwatersrand, Johannesburg 2000, South Africa
e-mail: marco.andreoli@necsa.co.za

D.I. GROVES
Centre for Exploration Targeting, University of Western Australia, Crawley 6009, Australia
e-mail: di_groves@hotmail.com

S.-J. BARNES
Department of Sciences de la Terre, Université du Québec à Chicoutimi, Chicoutimi G7H 2B1, Canada
e-mail: sjbarnes@uqac.ca

© 2012 December Geological Society of South Africa

ABSTRACT

The petrogenesis of sulphide ores in the O'okiep district has remained controversial. Based mainly on the concentration of chalcophile metals (PGE, Cu, Ni), it is proposed that the sulphides segregated from a basaltic magma generated during melting of sub-continental lithospheric mantle. Sulphide saturation of the magma was delayed due to relatively high fO_2 until crustal contamination occurred during the advanced stages of differentiation. The immiscible sulphide melt was entrained and fractionated in dynamic magma conduits. Sulphides enriched in monosulphide solid solution (mss) component precipitated at depth in the Kliprand area of southern Namaqualand to form the Hondekloof deposits, whereas the O'okiep ores crystallised at shallower levels from highly fractionated residual sulphide liquids enriched in intermediate solid solution (iss). Sulphides of intermediate composition occur at Ezelsfontein. In the context of this model, the O'okiep intrusions could represent the proximal magmatic members of an IOCG suite of deposits, raising the prospect for additional IOCG deposits elsewhere in southern Africa. The model also predicts an enhanced potential at O'okiep for undiscovered Ni sulphide ores at depth.

Introduction

Since the middle of the 19th Century and until the recent closure of the Carolusberg mine, the sulphide ores in the Springbok area of Namaqualand, also known as the O'okiep Copper District (Figure 1), have been a major source of copper for South Africa (cf. McIver et al., 1983; Lombaard et al., 1986; Schoch and Conradie, 1990; Cawthorn and Meyer, 1993; Clifford et al., 1995; 2012; Van Zwieten et al., 1996; 2004; Robb et al., 1999; Duchesne et al., 2007). The mineralisation is hosted by the orthopyroxenitic and, to a lesser extent, noritic and dioritic portions of composite mafic-ultramafic pipe- and dyke-like bodies of the Koperberg Suite. One of the main reasons for the profusion of research papers written on the Koperberg Suite is the atypical nature of the ores compared to most magmatic sulphide ores from elsewhere, namely their unusually high Cu/Ni and Cu/S ratios, and the abundance of bornite among the sulphide minerals. This has led to controversy on the origin of the Koperberg suite and its ores, with some authors calling for a crustal progenitor (Clifford et al., 1995; 2004; Maier, 2000; Duchesne et al., 2007), whereas most others invoke contamination of mantle magmas by crustal anatectic melts (McIver et al., 1983; Cawthorn and Meyer, 1993; Van Zwieten et al., 1996; Robb et al., 1999).

In the present study, aimed at providing some further constraints on the genesis of the Koperberg suite, noble metal data are presented from several deposits in the Springbok area, including Cu-rich ores from Carolusberg, East O'okiep, West O'okiep, Rietberg, Spektakel, Hoits, Homeep, Jubilee, and Nigramoep (Figure 1). New geochemical data are also presented from more Ni-rich ores at Ezelsfontein, also in the Springbok area, and from the apparently co-genetic Hondekloof deposit, situated near the village of Kliprand, ca. 120 km southeast of the O'okiep district (Figure 1; Taylor 1990; Andreoli and Moore 1991; Hamman et al., 1995; Andreoli et al., 2006).

The Koperberg Suite

Geographic distribution and emplacement age

For more than a century the predominantly mafic bodies of the Koperberg Suite were thought to occur only in the

SOUTH AFRICAN JOURNAL OF GEOLOGY, 2012, VOLUME 115.4 PAGE 499-514
doi:10.2113/gssajg.115.4. 499

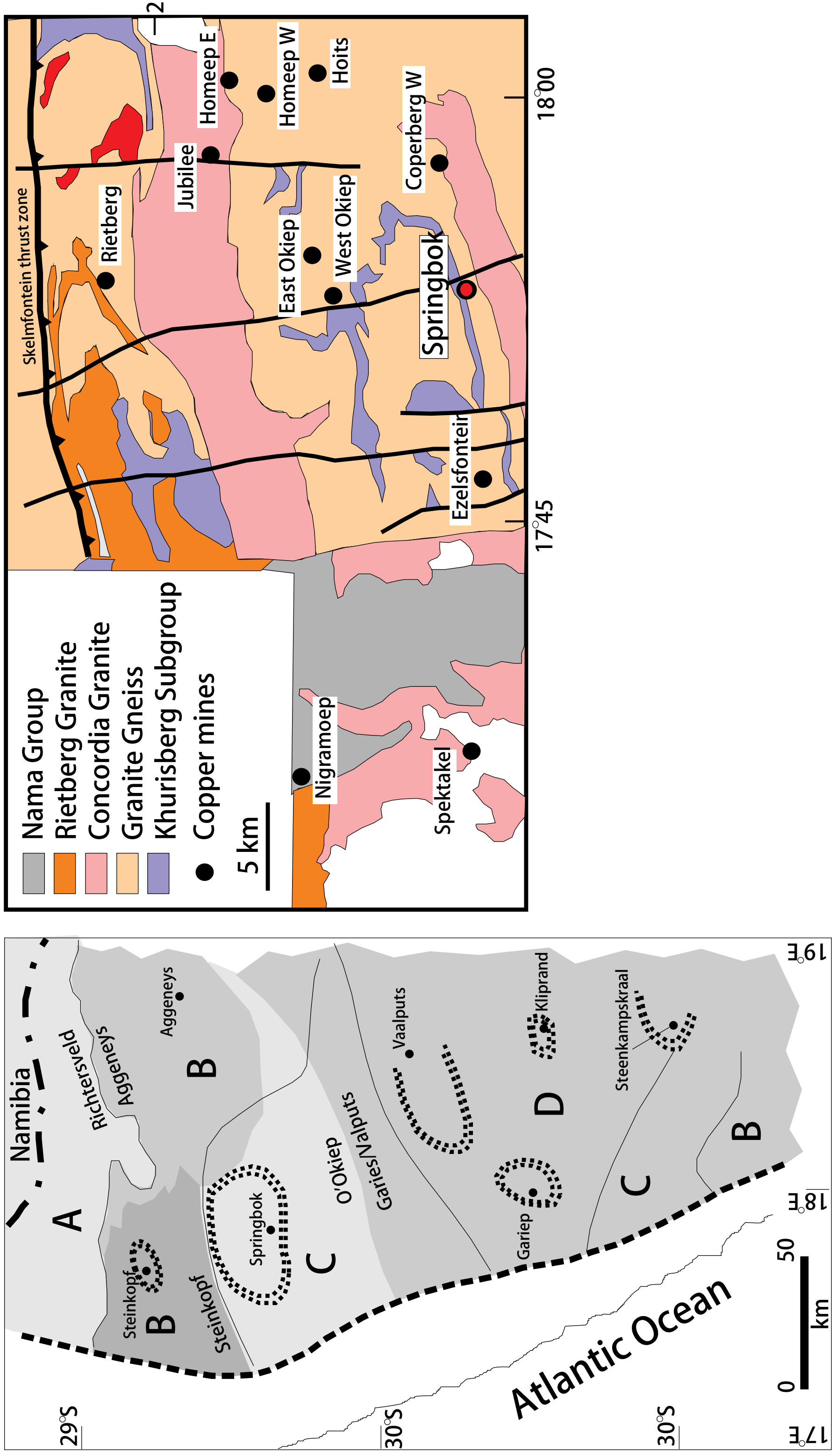

Figure 1. (***a***) *Geological sketch of western Namaqualand showing localities mentioned in the text (modified after Waters, 1989; Andreoli et al., 2006). Tectonic terranes are shown in variable shade, double dotted lines indicate clusters of Koperberg suite and related rocks, and solid lines show metamorphic facies boundaries (A: greenschist, B: amphibolite, C: low-T granulite, D: high-T granulite), short broken line near coastline: staurolite zone (Pan African overprint)* (***b***) *Geology and locality map of the O'okiep area.*

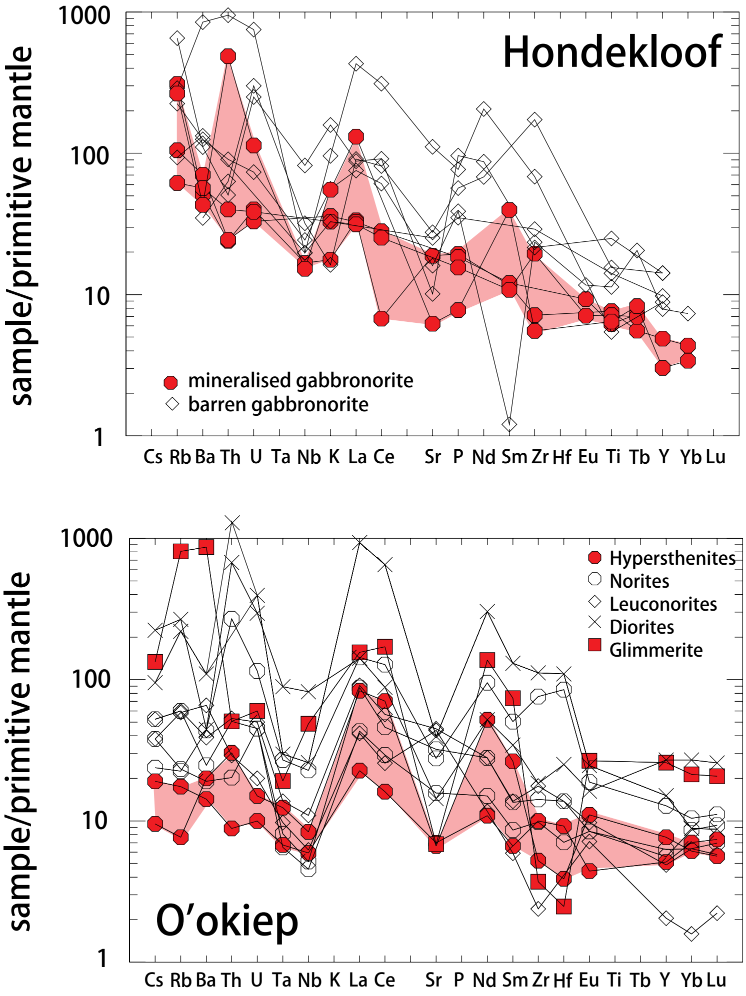

Figure 2. *Mantle normalised multi-element diagram of incompatible trace elements, for rocks from (**a**) Hondekloof, and (**b**) O'okiep (data from Duchesne et al., 2007). Normalization values from Sun and McDonough (1989).*

O'okiep Copper District, a relatively restricted area in northern Namaqualand where they intrude the orthogneisses, granitoids and granulites of the 1200 to 1000 Ma Namaqualand Metamorphic Complex (McIver et al., 1983; Lombaard et al., 1986; Cawthorn and Meyer 1993; Van Zwieten et al., 1996; Clifford et al., 1995; 2004; 2012). The emplacement age has consistently been difficult to resolve from the age of regional metamorphism, with recent work establishing a range between ~1040 and ~1020 Ma, indistinguishable from a lower granulite facies metamorphic peak dated at ~1030 Ma (P ~5 kbars, T ~750 to 800°C; Robb et al., 1999; Clifford et al., 1995; 2004 and references therein).

Since the late 1980s, detailed mapping in central and southern Namaqualand brought to light other clusters of intrusive rocks with many of the lithological, geochemical, emplacement age, and structural features distinctive of the Koperberg Suite near Springbok (Figure 1; Andreoli et al., 1986; 1994; 2006; Hamman et al., 1996; Read et al., 2002). This southern region experienced upper granulite facies conditions characterized by the stability of such rare minerals like osumilite, as well as spinel + quartz (P >5 kbars, T ~860 to 1000°C; Mouri et al., 2003; Robb et al., 1999). These articles also note some significant differences between clusters, namely in their Sm-Nd model ages, in the relative proportions of rock types, and their metallogenic signature. Copper was the main resource in the O'okiep District, replaced respectively by magnetite/ilmenite near Vaalputs, monazite + copper at Steenkampskraal, and nickel near Kliprand.

Field relations and lithologies

The Koperberg Suite in the Springbok area is represented by more than 1700 irregular and discontinuous sheet-, plug-, pipe- and dyke-like intrusive

Table 1. Compositional data from Okiep district and Hondekloof.

	Rocktype	**Ba**	**Sr**	**Y**	**Cr**	**Ni**	**V**	**Cu**	**S**	**Ru**	**Rh**	**Pd**	**Ag**	**Os**	**Ir**	**Pt**	**Au**
Cu-rich ores																	
Carolusberg																	
cw1905	Orthopyroxenite	59	24	14	3534	791	358	48796	1.27			93.0			1.7	96.0	173.0
cw2662	Norite	108	471	48	692	241	280	18508	0.88			44.0			0.5		76.3
cw271	Norite	117	381	64	1125	331	445	23904	0.82	2.0	0.6	29.0			0.2	13.2	50.5
cw276	Norite	106	292	85	1413	382	508	31386	0.80	2.4	1.0	44.8			0.3	19.8	60.6
cw293	Norite	197	687	48	595	171	281	13407	0.36			25.0			<0.05		74.4
cw508	Orthopyroxenite	20	10	14	3210	767	256	55470	1.78						0.8		285.0
East Okiep																	
e02	Leuconorite	992	699	23	34	172	216	10225	1.25	2.5		5.9			0.1		20.9
e03	Leuconorite	867	746	17	45	100	227	9990	1.12	3.5					0.1		21.4
e06	Leuconorite	242	629	35	38	83	248	12264	1.26	3.4		5.4			<0.05	9.0	23.2
e08	Leuconorite	256	650	31	29	83	210	13294	1.47			7.0			<0.05		27.5
Jubilee																	
j102	Pyroxene diorite	177	476	42	1568	457	185	22600	0.81	3.8	1.1	36.9			0.5	34.3	55.2
j186	Mica diorite	1192	787	13	0	38	333	100	0.00	4.8		5.6			0.1		1.6
j23	Pyroxene diorite	367	349	70	909	233	157	5300	0.32	4.3	0.5	20.5		0.6	0.2	12.6	16.3
j28	Mica diorite	725	698	58	31	16	176	500	0.01	5.4		2.8			<0.05		0.3
j53	Pyroxene diorite	264	765	10	488	215	294	12800	0.46	3.1	0.5	8.0			0.1	10.1	9.4
j64	Pyroxene diorite	199	673	11	21	58	275	600	0.11	2.9	0.3				<0.05	1.3	0.5
West Okiep																	
w02	Leuconorite	293	626	50	324	396	711	41663	1.12		1.0				0.1		177.8
w04	Leuconorite	251	667	37	436	434	572	42628	1.40	6.7	4.9				1.6		157.4
w06	Leuconorite	252	644	54	371	209	863	9140	0.30	2.1		2.5			<0.05	6.4	21.4
Hoits																	
U-190-275	Leuconorite	455	126	60	191	224	597	24960	2.56	3.3		10.0			0.1		36.0
U-II-230	Leuconorite	1811	365	43	178	174	623	20750	1.17	4.0	0.5	6.0			0.1		24.0
Spektakel																	
NW 103 124	Norite	32	156	25	396	347	438	39820	3.66	2.0	0.8	22.0		1.1	0.2	13.0	1.5
NW 103 103	Norite	102	130	20	163	108	337	9261	0.87	1.7		5.0			<0.05	3.0	1.9
Rietberg																	
R-1	Mica diorite	233	85	41	1165	490	673	64830	3.18	23.9	0.9	34.4	29.0		0.2	57.0	151.9
R-2 shaft	Mica diorite	1045	161	145	5297	582	1098	42230	1.49	5.0		37.0	11.0		0.3	14.0	92.5
Homeep																	
Homeep east u-86	Leuconorite	1494	211	135	1196	164	632	13900	0.76	4.5	0.5	33.0			0.4	57.2	
Homeep west 2	Cu-ore	72	374	0	65	1175	21	118700	7.30	33.1	0.4	331.0	92.0		0.2	686.0	233.2
Homeep west 1	Leuconorite	167	172	576	3579	1375	1517	67280	5.73	9.2		63.0	4.0		0.1	62.0	143.8
Nigramoep																	
D1	Semi-massive Cu ore	165	370	17	5040	512	1578	142400	6.52	17.0		22.0	106.0		0.1	115.0	251.8
286 51.8	Semi-massive Cu ore	67	316	12	1088	362	948	160900	8.52	20.8		30.0	28.0		0.2	32.0	5.7
8 164.3	Leuconorite	1865	500	17	172	73	260	11950	0.50	3.0		9.0			0.1		12.3
8 177	Norite	170	463	11	827	224	352	11180	0.91	4.0	0.6	33.0		0.5	0.1		33.9
KNU286 48	Semi-massive Cu ore	235	232	8	1335	564	1474	92550	4.23	10.0		40.0	7.0		0.2		30.8
Intermediate ores																	
Ezelsfontein																	
i-26	Plag-mica-ap-sulf rock	33	105	170	1516	1882	935	12700	15.20	1.9	1.8	16.0			0.7		82.4
I-35	Plag-mica-ap-sulf rock	111	95	143	1876	1219	1169	2172	11.10	0.0	0.8	30.0			0.6		15.5
Ni rich ores																	
Hondekloof																	
14-19	gabbronorite	5	263	20	180	9885	186	2793	15.00	2.3	0.9	8.0	3.0	0.5	0.3	3.0	20.8
14-30	semi massive Ni-Cu ore	22	138	15	229	17450	141	1085	24.00	0.0	2.5	35.0	6.0		0.9		20.6
14-31.7	gabbronorite	284	184	19	988	3104	255	544	3.69	2.9	0.0	1.0			0.1		4.9

bodies comprising, in order of decreasing abundance, quartz-bearing anorthosite, various types of diorite and norite, and orthopyroxenite. Rocks of more alkaline affinity, such as glimmerite and syenite (often refererred as shonkinite in the literature) are less abundant (Conradie and Schoch 1986). The mineralisation in the Springbok area consists essentially of copper sulphides. Although mining has now come to an end, the sulphide mineralization produced and in reserve between 1939 and 1986 amounted to 94 million tons averaging 1.75% Cu (Lombard et al., 1986). The mineralization is mainly hosted by the more mafic members of the suite, namely orthopyroxenite, norite, and, to a lesser extent, biotite-bearing norite and diorite. Most economic bodies are 60 to 100 m wide and taper out at depth (Lombaard et al., 1986). Within the pipes, the more leucocratic phases (anorthosite-biotite diorite) are generally concentrated at higher levels and are interpreted to have intruded first**,** whereas the orthopyroxenites are more commonly located in the deeper levels and are interpreted to have intruded last (McIver et al., 1983; Van Zwieten et al., 1996; Clifford et al., 1995, and references therein). The richest ore tends to occur in the lower portions of the orthopyroxenites, such as at Carolusberg and Nigramoep mines (Potgieter 1996). The intrusions are generally associated with so-called "steep structures". These are narrow, "D_4" deformation zones along which the regional sub-horizontal planar fabric established during the "D2" regional deformation has been upturned into an antiformal cusp-like shape (Watkeys 1996; Kisters et al., 1996), possibly formed in a transpressional/dilatational regime (Lombaard and Schreuder 1978, Watkeys 1996). In addition, occasional copper-bearing, high-Th-U glimmerite intrusions with Koperberg Suite affinities were observed well to the north of the Springbok copper district, in the Steinkopf area (Andreoli et al., 2006).

Other mafic rocks relevant to our study that occurr in the Springbok area include hornblende-two-pyroxene±biotite granulites of the Oorkraal Suite (formerly known as the Nuwefontein Suite: Hamman et al., 1996; C DeBeers, personal communication 2000) which are foliated and deformed by a "pre-D_3" tectonic event. They occur as raft-like inclusions/sills in the ~1200 Ma Nababeep orthogneiss and yield an emplacement age of 1168 ± 9 Ma by U-Pb SHRIMP on zircons (Lombaard et al., 1996; Robb et al., 1999; K. Beukes, personal communication 1994). These mafic granulites are compositionally distinct from the more rare, hornblende-free gabbroic rocks referred to as jotunite (Clifford et al., 2004; Duchesne et al., 2007). The latter were dated at 1035 ± 13 Ma and were proposed to represent a parental "chilled" melt from which the rocks and ores of the coeval (see above) Koperberg Suite were derived by fractionation.

The geology of the Hondekloof deposits near Kliprand (Figure 1) was investigated by Taylor (1990), Andreoli and Moore (1991), and Hamman et al. *(*1996) from whom the following description has been taken. The Kliprand area falls within the spinel+quartz upper granulite facies domain (D, Figure 1; Waters 1991) and thus represents a deeper crustal level than the Springbok area. In this area there are large bodies of megacrystic charnockite and charnockitic orthogneiss, mafic two-pyroxene granulites of the Oorkraal Suite (Table 1; cf. De Beer, 2000) and an easterly-trending belt of predominantly supracrustal rocks (Albat 1984; Moore 1989). The latter represents a zone of monoclinal steepening and local shearing. It consists of calcsilicate rocks, metapelites, biotite-garnet gneisses, quartzite and ferruginous rocks belonging to the de Beer Kamiesberg Subgroup of the Bushmanland Group (de Beer 2000). Scattered within the belt are lenticular to irregularly-shaped bodies/sheets of melanocratic to mesocratic biotite granulites/gneisses of the pre-to early syntectonic Oorkraal Suite (Table 1; cf. de Beer, 2000) and less deformed lenses/sheets/outcrops of mafic biotite-hornblende-metagabbro, orthopyroxenite, gabbronorite, leuconorite, anorthosite, diorite and glimmerite with the characteristics of the Koperberg Suite (Table 2).

The nickel deposits occur as small lenticular gossans along the basal contacts between poorly-banded, granulitic gabbronorite and banded migmatitic biotite-garnet paragneiss. Many lenses occupy fold hinges and are strung within a 1200 m wide, 3.5 km long belt of steepened foliation. Hamman et al. *(*1996) reported gradational contact relationships between sulphide-rich and sulphide-poor mafic lithologies (Table 2) and interpreted these bodies to be syn- to late tectonic and co-genetic with the Koperberg Suite. In their model, the sulphides were mobilized and concentrated during tectonism (accompanied by pervasive shearing) to sites of reduced strain represented by the fold hinges. This resulted in thick sulphide-enriched crests with long and thin attenuated, often disrupted fold limbs. The lateral and vertical discontinuity of the sulphide bodies, and possibly also that of the gabbronorite host, is attributed to this deformational event (J. Hattingh, personal communication 2008). Shallow drilling in the early 1980s defined *in situ* ore resources totalling 2 Mt at 0.88% Ni and 0.2% Cu. More recently, however, renewed drilling has significantly extended the reserves (J. Hattingh, personal communication).

Mineralogy and Petrology

Most of the basic bodies in the Springbok/O'okiep area are relatively unaltered and are essentially composed of plagioclase (An_{32-74}) and orthopyroxene (En_{58-68}). In most bodies, orthopyroxene is significantly more primitive than plagioclase (van Zwieten et al., 1996). Phlogopite, quartz, magnetite, spinel (hercynite) and sulphides are additional common minerals, whereas clinopyroxene is rare (McIver et al., 1983; Conradie and Schoch 1986; Brandriss and Cawthorn 1996). Apatite and zircon are abundant trace phases and may be locally highly enriched (e.g. at Ezelsfontein). Allanite or monazite are

Table 2. Koperberg Suite meta-gabbronorites.

Column	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	ore			**low grade ore**	**Non mineralized**				**jotunite**	
N=	**1**	**1**	**1**	**1**	**1**	**1**	**5**	**1**	**1**	**2**
SiO_2	20.41	25.08	36.05	39.68	43.12	49.88	53.58	55.43	56.01	52.86
TiO_2	1.35	1.6	1.3	1.5	5.24	2.38	2.97	3.26	1.14	2.40
Al_2O_3	7.46	6.3	9.11	6.57	14.57	15.5	15.72	14.29	13.76	13.85
Fe_2O_3 tot	53.31	43.89	35.96	32.7	12.62	11.17	11.2	9.86	7.9	13.98
MnO	0.05	0.13	0.08	0.26	0.09	0.11	0.15	0.12	0.08	0.20
MgO	4.87	4.98	3.91	10.83	7.93	7.96	5.06	2.47	5.87	4.12
CaO	1.75	3.02	3.51	3.24	5.26	5.59	7.02	6.66	5.31	8.24
Na_2O	0.71	0.02	0.66	0.54	1.38	1.93	2.28	3.23	1.8	2.70
K2O	1.6	0.51	1.04	0.95	4.59	1.62	0.95	0.47	2.77	1.49
P_2O_5	0.16	0.4	0.38	0.32	1.98	0.8	0.72	1.17	1.58	0.73
LOI	9.02	12.85	6.91	2.84	1.98	2.1	0.52	3.44	2.1	
Total	100.69	98.78	98.91	99.43	97.82	99.04	100.17	101.32	98.23	100.57
Rb	159	186	63	37	392	135	56		173	47
Sr	124	375			201	319	502	548	2211	197
Ba	285	336	465	375	730	828	875	230	5604	840
Y	13	21			61	34	42	61	38	71
Zr	58	75		205	226	247	305	1814	717	418
Nb	10	11			54	16	13	21	13	22
La	85.1	21.8	21.2	20.4	57	48.85		59	279	57
Ce		11.3	47.0	42.3	153	102.3		136	520	124
Nd					109			85	257	65
Sm	16.2	4.8	4.9	4.4		0.5				13
Eu			1.4	1.1		1.8				3
Tb	0.8	0.6	0.7	0.7		2.0				3
Yb	1.5	1.9				3.2				6
Th	38.4	1.9	1.9	3.2	4	7.2		5	75	1
U	2.3	0.8	0.7	0.8	5	1.5		6	15	1
Co	1016	947		320	45	34	26			321
Ni	16966	17195	12432	6520	101	92	128	66	330	41
Cu	582	2720			42	18	42	147	170	165
V	104	49	149		398	179	196	172	110	38
Cr	487	140	318	676	133	609	173	17	156	72
Zn	158	267			242	257	142	172	118	143

Col. 1	HKF 14-46				
Col. 2	HKF 14-23.6				
Col. 3	HKF 14 B				
Col. 4	HKF 14 C				
Col. 5	HKF 15-11				
Col. 6	HKF 15-23.6				
Col. 7	NAM 543	NAM 900	NAM 902	ET 1	ET 11
Col. 8	HKF 26-15				
Col. 9	HKF 26-19				
Col. 10	Samples 35, 36 (Duchesne et al., 2007)				

also occasionally present in cupriferous biotite norite ore (Andreoli et al., 2006). The rocks have highly equilibrated textures, indicative of metamorphic recrystallisation at granulite facies conditions. Together with the age data summarized above this suggests intrusion of the Koperberg Suite shortly before or during peak metamorphic conditions (Robb et al., 1999; Clifford et al., 2004; Andreoli et al., 2006), unlike many other magmatic Ni-Cu deposits on Earth that formed in extensional, rift related settings (Barnes and Lightfoot, 2006).

Opaque minerals in the mineralized rocks comprise approximately 50% magnetite (Cawthorn and Meyer 1993), unusually high for magmatic ores where magnetite generally constitutes between 5 and 10% of the total opaque component (Naldrett 1989). In most bodies, the sulphide assemblage is dominated by bornite and chalcopyrite (Carolusberg-type ore, e.g.

at Carolusberg, Rietberg, and Homeep), but in some deposits, such as East O'okiep, Narrap, and Ezelsfontein, pyrrhotite is abundant, minor pentlandite is present, whereas bornite is absent (Narrap-type ore). At several deposits, including Hoits, Nigramoep, Jan Coetzee, and Spektakel, younger (600 to 500 Ma) metamorphic and meteoric fluids have remobilized Cu to form sulphides such as chalcocite and covellite, as well as abundant sericite, epidote and chlorite (Hoits-type ore, Clifford et al., 2012). In all deposits, the sulphides are mainly disseminated, but may locally occur as massive pods and as veinlets and veins, reflecting remobilization. All rock types in the O'okiep district have a strong crustal signature ($_{\varepsilon}$Nd around -9; Sr_i 0.7061 to 0.7272, $\delta^{34}S$ -4 to +4, and high μ values; von Gehlen et al., 1990; Boer et al., 1994; Clifford et al., 1995; Van Zwieten et al., 1996; Brandriss and Cawthorn 1996). The frequent, at times even extraordinary enrichment of members of the Koperberg Suite in U, Th and the REE (hosted by accessory minerals such as zircon, monazite, allanite, etc.) well above world averages for mafic rocks and granulites, is also notable (Andreoli et al., 1994; 2006, and references therein).

At Hondekloof, the host rock is mainly a medium-grained gabbronorite consisting, on average, of plagioclase (64%), orthopyroxene (14%), clinopyroxene (11%), and phlogopitic mica (7%) with minor quartz and accessory apatite and opaque minerals. Where clinopyroxene is absent the rocks hold less phlogopite and have a noritic composition; and where hypersthene is less prominent, dioritic (sulphide-bearing) compositions predominate. The plagioclase has An_{45-55} and orthopyroxene has En_{53-62}. Chadacrysts of plagioclase, clinopyroxene, phlogopitic mica, apatite and opaque minerals occur in some of the hypersthene grains. The clinopyroxene is colourless to pale green and has a salite composition. It poikiloblastically encloses most of the other minerals suggesting simultaneous growth during recrystallization (J. Hattingh, personal communication). The concentration of phlogopitic mica is extremely variable, from an average of 7 up to 90 modal per cent in the glimmeritic rocks. Surprisingly, monazite and fluorspar were found as accessories in low grade dioritic – glimmeritic ore rocks. In contrast to the Cu-rich nature of the O'okiep sulphide assemblages, the Hondekloof sulphides consist largely of pyrrhotite, containing pentlandite flames and blebby chalcopyrite. The $\delta^{34}S$ of the sulphides is -2.2 to -3.6, overlapping with the sulphur isotopic signature of sulphides at O'okiep.

The available data suggest that the felsic members of the Koperberg Suite were derived from protoliths that were isotopically heterogeneous at the regional scale. The intrusions in the O'okiep district have εNd significantly lower (range: -8 to -10; T_{CHUR} ~1800 Ma) than the monazite-bearing intrusive at Steenkampskraal (ca. -1.8 to -1.3; T_{CHUR} ~1050 to 1160 Ma; Andreoli et al., 2006)

New results

In the present study we determined the platinum-group elements (PGE), Cu, Ni, S, and some selected other elements in 28 samples from the O'okiep copper district and from Hondekloof. The data are presented in Table 1, together with data from ten samples from Carolusberg and East O'okiep presented previously (Maier, 2000). All analyses were carried out at the University of Quebec at Chicoutimi, Canada. The PGE and Au were determined by Ni-sulphide fire assay followed by instrumental neutron activation analysis (INAA), using the method described in Maier and Barnes (1999). Nickel and Cu were determined by Atomic Absorption (AA) spectroscopy, S by LECO titration, the remaining elements were determined by INAA using the method of Bédard and Barnes (2002). Copper, Ni and S contents in the samples from Carolusberg, East and West O'okiep, and Jubilee are given in Cawthorn and Meyer (1993).

Bulk PGE contents in the samples are highly variable, from below detection limit to about 1 ppm. The bulk of the PGE component consists of Pt and Pd. Iridium contents are generally below 2 ppb. The lowest PGE contents occur in the Ni-rich ores from Hondekloof and Ezelsfontein, and in some Cu-rich ores, notably from East O'okiep and West O'okiep. The most PGE-enriched ores occur at Homeep, Carolusberg West, and Nigramoep. The PGE tenors of the sulphides are highly variable: at Carolusberg and Homeep the Pt+Pd contents in 100% sulphide reach approximately 1 to 4 ppm, but at most of the other localities the tenors are much lower, notably in the Ni rich ores from Ezelsfontein and Hondekloof.

Compared to most other magmatic sulphide ores, the Au contents are relatively high, exceeding PGE contents in most samples. The average Au content of all samples is 69 ppb, compared to 29 ppb Pd and 31 ppb Pt. Similarly high Au/PGE ratios were recorded at Caraiba, Brazil (Maier and Barnes, 1999) and in some of the Sudbury mines (e.g. Cu-rich sulphide stringers at Little Stobie; Hoffman et al., 1979).

The metals correlate with S in individual deposits, but the total sample population shows unsystematic scatter in binary metal/S plots (Figure 3). The least scatter is found in Cu/S and Ni/S.

The mantle-normalised PGE patterns are strongly fractionated (Pd/Ir up to 100) with negative Ir anomalies and a progressive increase in concentration from Ir to Cu (Figure 4). The lowest Pd/Ir occurs in the Ni-rich ores, at Ezelsfontein (average 37) and Hondekloof (average 27). The Pd/Ir ratios in the Cu-rich ores are higher than those of most other sulphides hosted by differentiated gabbroic rocks. The closest analogies are again the Caraiba norites-pyroxenites in Brazil (Pd/Ir 72; Maier and Barnes 1996, 1999) and Cu-rich ores at Sudbury (Naldrett et al., 1982).

Some new lithophile whole rock-data from the Hondekloof gabbronorites in the Kliprand area are given in Table 2. The bulk major-, minor and trace element

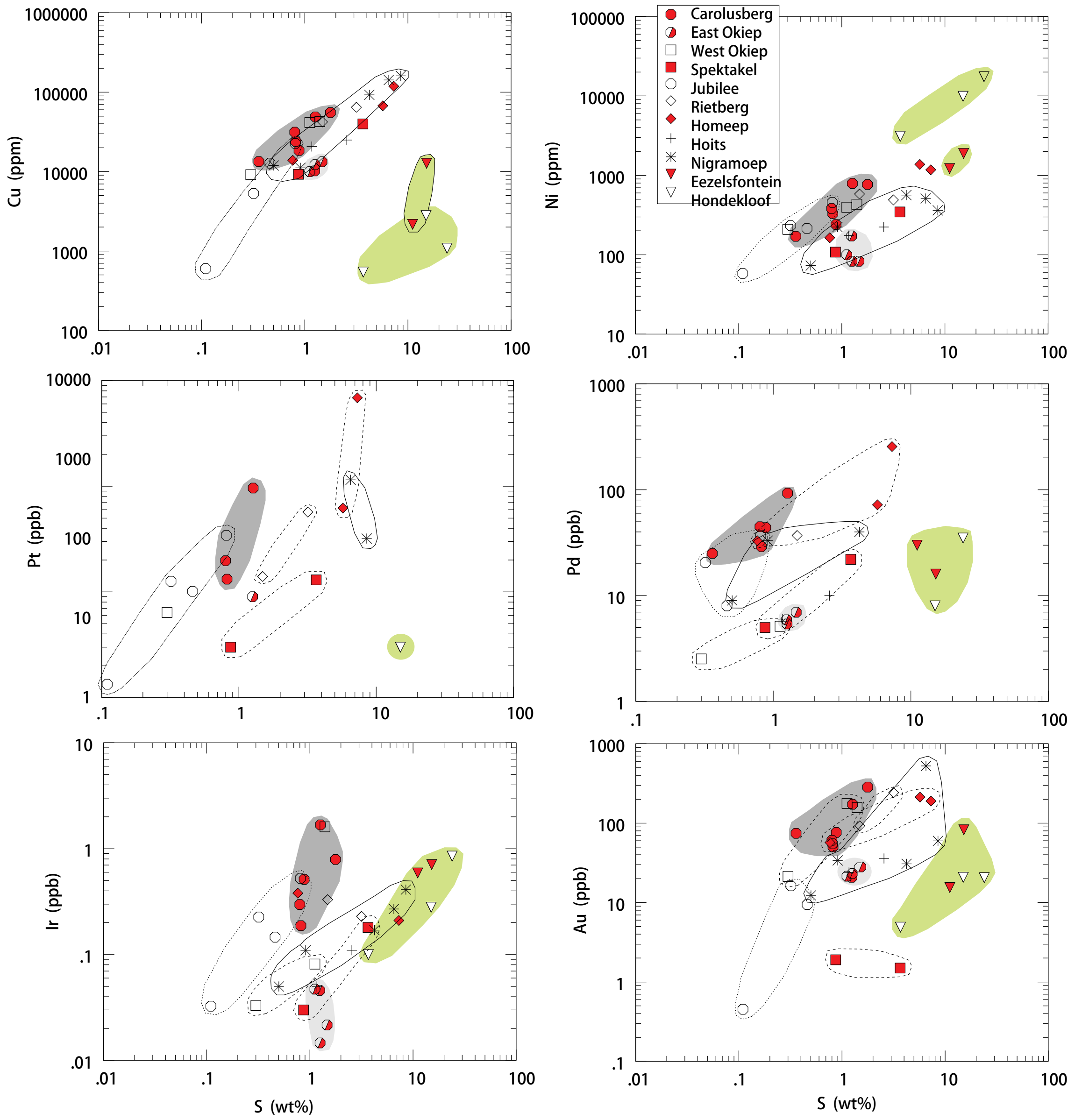

Figure 3. *Binary variation diagrams vs S of (i) Cu, (ii) Ni, (iii) Pt, (iv) Pd, (v) Ir, and (vi) Au. Note that most of the data correlate positively with S, but individual deposits define distinct fields.*

composition of the rocks bears some similarities to the Koperberg Suite Table 2), but also to the mafic-intermediate granulites and gneisses of the Oorkraal Suite (Table 3) and the two-pyroxene granulite (jotunite) of the Springbok area (cf. Table 2; Hamman et al., 1996; Duchesne et al., 2007). The rocks have distinct crustal signatures, with strong, but variable relative enrichment in LIL and HFS elements, and negative Nb-Ta, Sr, and Ce anomalies (Figure 2). In both the Hondekloof gabbronorites and the Koperberg Suite in the Springbok area the mineralised samples tend to contain lower concentrations of incompatible trace elements than the unmineralised samples. This trend appears nevertheless reversed in the case of the monazite-chalcopyrite ore at Steenkampskraal (Andreoli et al., 1994), certain monazite/allanite-Cu sulphides ores in the O'okiep District (Andreoli et al., 2006) and of the monazite-fluorspar-mica-sulphide bearing diorite (low grade ore) at Hondekloof (cf. Column 4, Table 2).

Discussion

Unbundling the nomenclature knot.

Even a cursory appraisal of the literature on the O'okiep copper district reveals that the origin of these mineral deposits remains highly controversial. Because most publications focused on the Springbok area, we contend that at least some of the issues may be cleared by considering the wider geographic perspective of central-southern Namaqualand. For instance, our observations, both at Okiep and at Vaalputs and Kliprand, severely constrain Duchesne et al.'s (2007) model which derives the Koperberg Suite via the fractionation of jotunite, because field exposures of such rocks appear to be much rarer than suggested by these authors. Duchesne et al. (op. cit.) equated an occurrence of 1035 ± 15 Ma (Clifford et al., 2004) unmetamorphosed jotunite to the extensive sheets of Oorkraal Suite mafic (two-pyroxene, hornblende granulites found in the same area (cf. Lombaard et al., 1986). However, these rocks *[that is the two-pyroxene granulites in the Springbok area]* are older, yield a 1168 ± 9 Ma emplacement age, and a 1063 ± 16 Ma metamorphic age (Robb et al., 1999) and have a sub-alkaline, high-Mg tholeiitic basalt composition (cf. Table 1; Reith and Meisel, 2001). A comparable confusion was seemingly repeated in the Kliprand area, where Hamman et al. (1996) attributed to the Nuwefontein Suite both the regionally extensive sheets of two-pyroxene granulites and a string of less

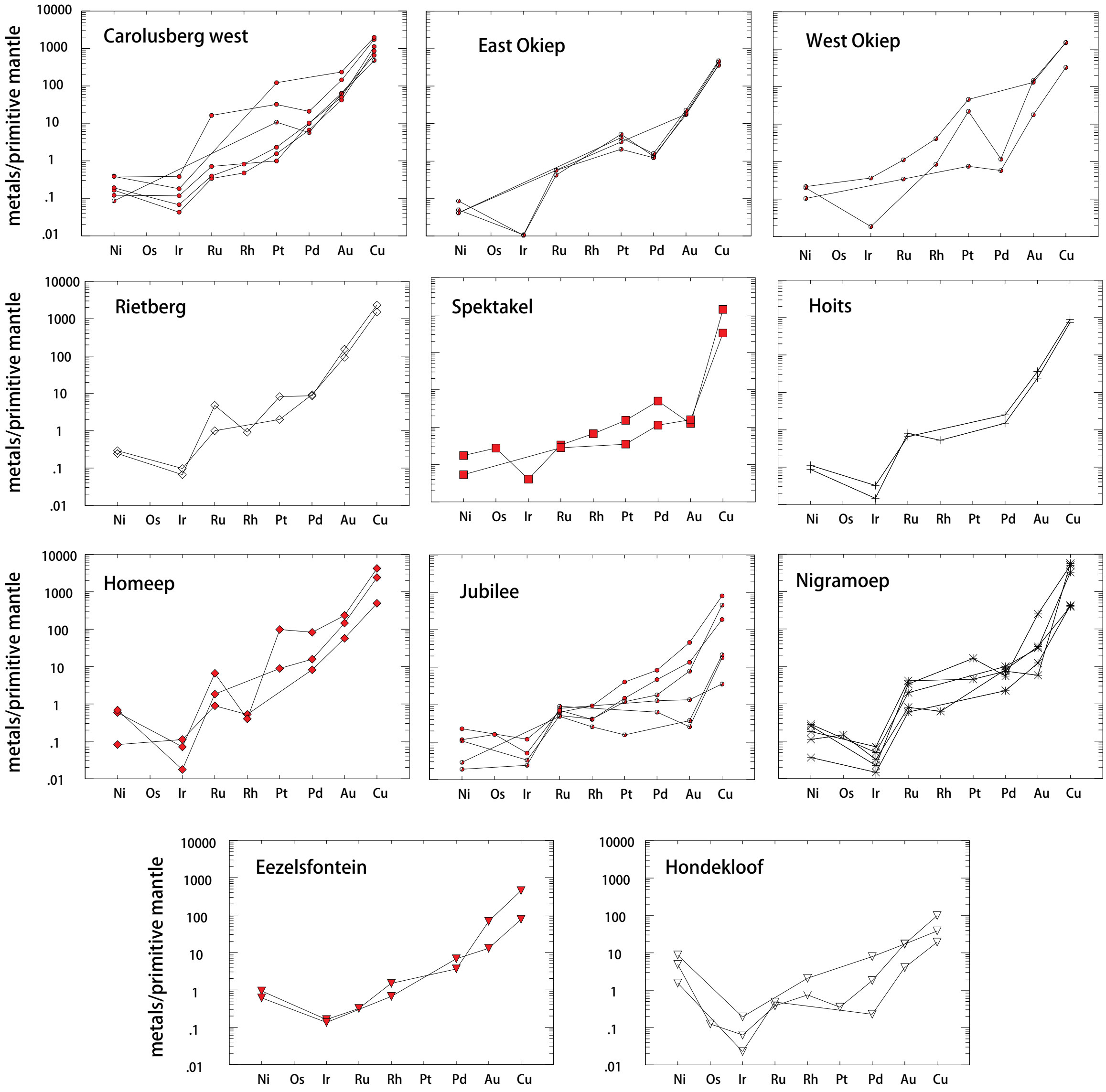

Figure 4. *Mantle-normalised metal plots for the O'okiep and Hondekloof ores. Primitive mantle normalization values are from Barnes and Maier (1999).*

Table 3. Whole-rock compositions of selected metagabbro and mafic to intermediate granulites of the Oorkraal suite

	Nuwefontein					Vaalputs	O'okiep	
	Metagabbro		mafic granulite	meta-dior		biotite granulite	2 pyrox gran	
Column	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
N	**1**	**2**	**7**	**1**	**2**	**7**	**3**	**2**
SiO_2	44.28	47.03	52.04	53.09	59.46	58.83	47.08	52.86
TiO_2	1.21	1.12	2.55	2.73	2.26	1.83	1.52	2.40
Al_2O_3	9.27	11.27	15.56	15.37	14.85	15.05	14.22	13.85
Fe_2O_3 tot	13.31	12.60	11.45	9.77	9.13	8.56	13.17	13.98
MnO	0.18	0.18	0.14	0.12	0.07	0.13	0.19	0.20
MgO	22.42	18.98	6.28	3.72	2.55	2.56	0.41	4.12
CaO	5.05	6.42	6.99	5.81	4.78	4.62	9.08	8.24
Na_2O	1.6	1.48	1.65	3.05	3.28	3.63	1.75	2.70
K_2O	1.09	0.66	1.62	4.09	2.27	2.89	0.83	1.49
P_2O_5	0.32	0.17	0.7	1.02	0.86	0.73	0.27	0.73
LOI	1.41	0.34	0.71	0.54	1.07	0.50	1.69	
Total	100.14	100.23	99.69	99.31	100.55	99.33	99.22	100.57
Rb	35	18	74		136	227	31	47
Sr	446	186	723		333	475.0	203	197
Ba	839	270	1402		977	1572.0	226	840
Y	23	25	39		56	53.0	35	71
Zr	175	117	317		804	705.0	138	418
Nb	5	3	9		25	18.0	7	22
Co	90	74	33		15	16	51	321
Ni	549	433	93		22	13	166	41
Cu	37	33	23		8	21	91	165
V	147	183	199		114	98	297	38
Cr	791	2035	196		155	39	479	72
Zn	105	93	125		157	131	109	143
K/Rb	258	304	182		139	106		263

Col. 1 ET 23 opx+cpx+oli+plg+bio
Col. 2 ET 51 NAM 541 hor+opx+cpx+plg+oli>bio
Col. 3 ET 10 ET 13 ET 46 ET 47 ET 48 NAM 538 NAM 539
Col. 4 NAM 533
Col. 5 NAM 539A NAM 542A
Col. 6 KAPKAP KAPKAP 2 R 20 PL 20 R 9 DH1-703 DH1-856.8
Col. 7 NA 278-2 NA 278-3 NAM 222 NA-278 samples: Reith and Mesel, 2001
Col. 8 Jotunite samples 35, 36 (Duchesne et al., 2007)

deformed Koperberg Suite bodies structurally confined to an easterly-trending monoclinal, sheared structure (Taylor, 1991; Andreoli and Moore, 1991). Our new data, complemented by mapping by Taylor (1991), the Council for Geoscience (C. de Beer, personal communication, 2008) and, most recently, by prospecting activities for nickel (Johann Hattingh, personal communication 2008) correlate the barren two-pyroxene granulites of the Nuwefontein Suite to the Oorkraal Suite, and the nickeliferous gabbronorites and related rocks (anorthosite, diorite, glimmerite) to the younger Koperberg Suite. On this basis we propose to discontinue the use of the term "Nuwefontein Suite".

Magmatic lineage of the mineralised rocks.

Previous workers suggested that the Koperberg sulphides crystallized from sulphide melt that segregated from an alkaline basaltic or anorthositic magma, in response to contamination with peraluminous granitic country rocks (McIver et al., 1983; Schoch and Conradie 1990; Boer et al., 1994; Van Zwieten et al., 1996). Probably the main argument is the unusual combination of differentiated silicate phases, enrichment in incompatible elements (including LILE and HFSE), and crustal Nd isotope signatures on the one hand, with elevated Cr and Ni contents on the other hand.

An anorthositic - jotunitic lineage might be consistent with the rare dykes of jotunite in the O'okiep Copper district (Clifford et al., 2004; Duchesne et al., 2007) and the observed enrichment in magnetite, apatite, relatively sodic plagioclase, and ferrous orthopyroxene in the Koperberg Suite. The hyper-enrichment of certain sulphide-bearing members of the same suite in Large Ion Lithophile (LIL) and High Field Strength (HFS) elements, as exemplified by the ~5 x 10^5 tonnes of monazite-chalcopyrite concentrate once mined from the

Steenkampskraal thorium mine (Andreoli et al., 1994; 2006; Schoch and Conradie, 1990) would have to be explained by a highly trace element-enriched contaminant, such as a small-degree melt of the country rocks, or a sub-continental lithospheric mantle (SCLM) component (see below).

Evidence for an alkaline signature is ambiguous. This is because the compositional characteristics of alkaline magmas resemble those of crustally contaminated magmas in many regards (i.e. fractionated incompatible element patterns, volatile enrichment, negative $_{\varepsilon}$Nd, high initial Sr isotope ratios, etc.) which in turn reflects the derivation of many alkaline magmas from refractory SCLM refertilised by crustally-derived fluids and melts (Francis and Ludden, 1995). Partial melts of the SCLM can be alkaline if derived by small degree of melting (e.g. kimberlites and many alkali basalts) or tholeiitic if derived by larger degrees of melting (e.g. Bushveld magmas; Harmer and Sharpe, 1985; Richardson and Shirey, 2009). Therefore, all that can be said at present on the petrogenesis of the parental magmas to the O'okiep and Hondekloof deposits is that they are derived from a relatively differentiated mafic magma of basaltic lineage, containing a large HFSE/lithophile element component, either derived from metasomatised mantle and/or via contamination of asthenospheric mantle melt by crust (cf Andreoli et al., 2006).

Stumpfl et al. (1976) also envisaged a broadly basaltic lineage for the deposits, but in most other aspects their model is radically different from that of other authors in that they suggested anatexis of a lower crustal mafic protolith and ascent and intrusion of felsic partial melt entraining restitic material. This model would be consistent with the high-grade metamorphic setting of both the Curaca Valley and O'okiep ores. In the case of a gabbroic to dioritic protolith, the restitic phases may consist mainly of pyroxenes (Osborn, 1978). Crustal anatexis of a dioritic protolith would probably yield dry melts with silica activities equal to unity, and such melts would not be able to dissolve much P_2O_5, Zr, or Fe^{3+}, resulting in refractory behaviour of magnetite, apatite, and zircon. Segregation of these residual phases during ascent and intrusion may yield the unusual ultramafic assemblages predominantly observed in the lower portions of pipes in the O'okiep district, namely orthopyroxene-magnetite (+apatite) (Maier, 2000).

Models of ore formation

Past workers have modelled the O'okiep ores by various processes, none of which is considered entirely

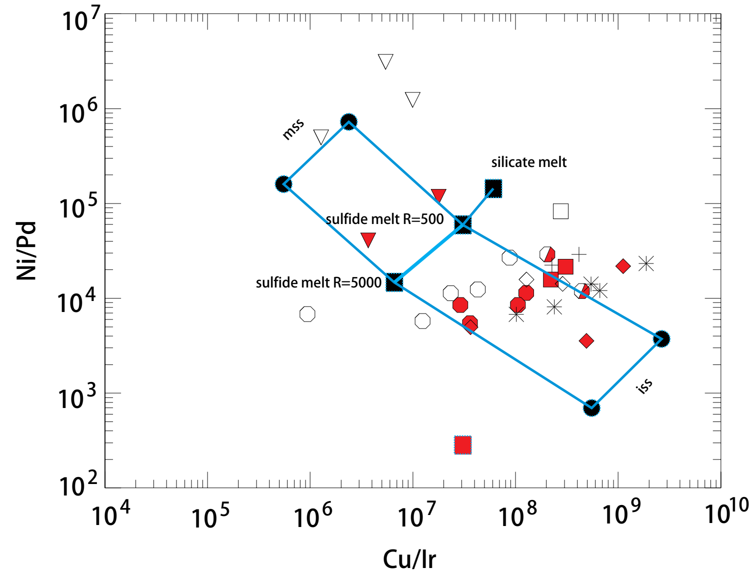

Figure 5. *Plot of Ni/Pd vs Cu/Ir. O'okiep and Hondekloof ores can theoretically be modeled by a multistage process, involving sulphide segregation from differentiated magma of picritic lineage (150 ppm Cu, 40 ppm Ni, 0.35 ppb Pd, 0.0025 ppb Ir), followed by sulphide fractionation and separation of mss (F=0.9, D of 0.22 for Cu, 2 for Ni, 0.15 for Pd and 3 for Ir) and iss (F=0.2) components. However, ores with Cu/Ni ratios as high as observed at O'okiep have not yet been observed elsewhere. See text for discussion, and Figure 1 for symbols.*

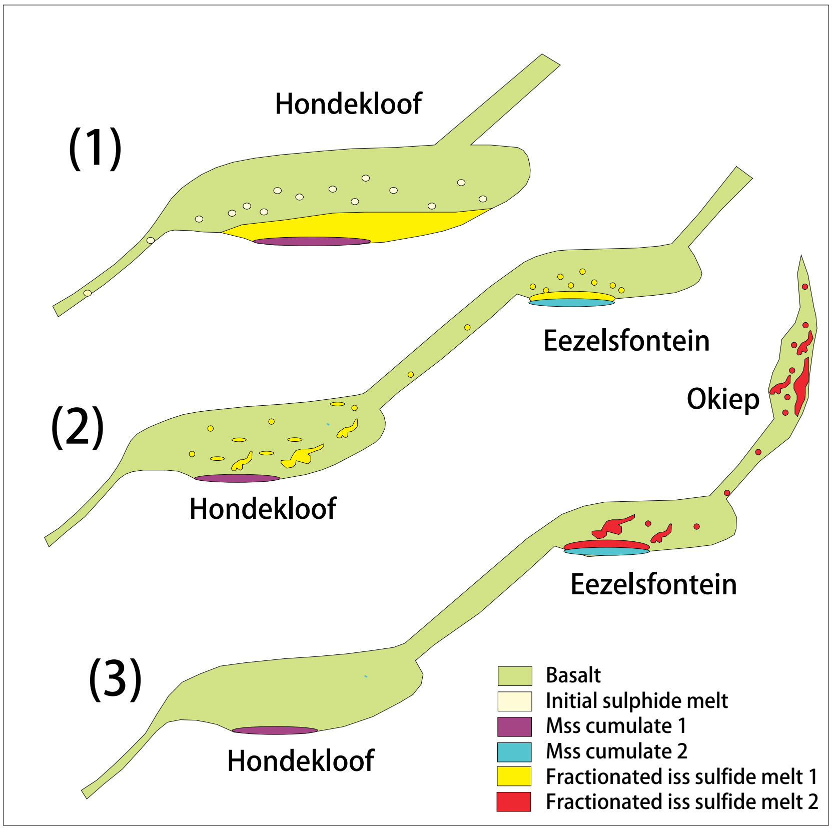

Figure 6. *Schematic model of ore formation at O'okiep and Hondekloof. Basaltic, relatively Cu-rich and PGE-poor magma was generated through low-degree partial melting in the sub-continental lithospheric mantle. The magma differentiated during ascent through the crust. Sulphide saturation was triggered by contamination. Continued ascent in dynamic magma conduits led to extensive fractionation of the sulphide liquid.* ***(1)*** *Relatively Ni-rich cumulate ores formed by mss fractionation in deep intrusions such as Hondekloof.* ***(2)*** *Residual sulphide liquid was entrained and re-deposited at Eezelsfontein. Renewed mss fractionation produced relatively Ni-rich cumulates and Cu-rich residual liquid.* ***(3)*** *Continued magma flux led to entrainment of highly fractionated sulphide melt to shallowest intrusions at O'okiep. See text for explanatio*

satisfactory to explain all the characteristics of the deposits:

i. Based on the unusual sulphide assemblage in the Koperberg Suite, particularly the abundance of bornite, Cawthorn and Meyer (1993), Boer et al. (1994), and Van Zwieten et al. (1996) proposed that the ores formed by metamorphic oxidation and desulphidization of a primary magmatic sulphide assemblage derived from mantle basalt, dominated by pyrrhotite and chalcopyrite, to an assemblage consisting of chalcopyrite, bornite, and Ti-free magnetite:

$$\underset{\text{cp}}{5CuFeS_2} + \underset{\text{po}}{5FeS} + 6H_2O + [8O_2] = \underset{\text{bn}}{Cu_5FeS_4} + \underset{\text{mag}}{3Fe_3O_4} + 6H_2S + 5SO_2$$

The model would provide an explanation for the abundance of bornite and magnetite in the most Cu-rich ores. Similarly Cu-rich ores in other metamorphic terrains (e.g. at Caraiba) also are characterised by abundant bornite and magnetite (Maier and Barnes, 1999). However, the model provides no explanation for the extremely high Cu/Ni ratios of the O'okiep ores, and the low Cu/Ni at Hondekloof. Therefore, an additional or alternative mechanism is required.

ii. The high Cu/Ni ratios and the abundance of mica in the mineralized rocks of the Koperberg Suite could suggest *in situ* hydrothermal or metamorphic remobilization or introduction of Cu to the mafic rocks via an aqueous fluid phase, but this model is considered unlikely as the mineralization is exclusively associated with the mafic-ultramafic rocks within a high-T, low-a_{H2O} granulite facies environment (Waters, 1986; Clifford et al., 1994; Andreoli et al., 2006).

iii. The ascending basic magma may have assimilated Cu from deep-seated Cu-bearing country rocks, for example porphyry copper deposits within the Eburnian-aged basement rocks to the north of the O'okiep district (Minnitt, 1986). Copper porphyries can contain significant Au and, in some cases, also PGE (Economou-Eliopoulos, 2005). The O'okiep and Hondekloof rocks have distinct crustal isotope signatures consistent with significant crustal contamination (van Zwieten et al., 1996; Brandriss and Cawthorn, 1996). However, the model is unsatisfactory as presently it cannot be directly constrained.

iv. Based on the common high-grade metamorphic setting of the Caraiba and O'okiep ores, Maier and Barnes (1999) and Maier (2000) suggested that the Cu-rich sulphides formed by partial melting of lower crustal rocks containing Cu-rich proto sulphides (see also Stumpfl et al., 1976; Clifford et al., 1995; 2004; 2012; Duchesne et al., 2007), followed by entrainment and fractionation of sulphide melt in slurries of anatectic melt and restite. The model is consistent with the crustal signature of the silicate and sulphide minerals, the disequilibrium compositions of, e.g., plagioclase and orthopyroxene, and potentially the low PGE contents and high Au/PGE ratios of the sulphides. However, the model is more difficult to apply to the relatively Ni-rich Hondekloof ores as any sulphide melts that formed during partial melting of crust might be expected to equilibrate with residual mafic components, resulting in compatible behaviour of Ni. Hondekloof would thus have to represent a relatively more restitic component, inconsistent with the composition of the silicates.

v. The Cu- and Ni-rich ores could have formed through extreme fractionation of a magmatic sulphide liquid. The main challenge for this model is to explain the relatively Ni-rich Hondekloof ores. The mineral chemistry of the Hondekloof biotite gabbros and norites is as evolved as that of the O'okiep intrusions, consistent with a differentiated basaltic parent melt in both districts, but Ni contents and Ni/Cu ratios of the Hondekloof sulphides are much higher than at O'okiep. Compositional ranges of potential sulphide liquids can be evaluated by simulating fractional crystallization of basaltic-picrite magma using thermodynamic modelling software such as PELE. Assuming a picritic starting composition (e.g., olivine-phyric basalt from Cape Smith; Barnes and Picard, 1995) and lower- to mid-crustal pressure, residual basalt crystallizes pyroxene and plagioclase of the composition recorded at Hondekloof after approximately 50% fractional crystallization (in detail, the modelling is dependent on H_2O content and fO_2, but generalized trends are sufficient for the present purpose). At this stage of solidification, the magma would have 3 to 4% MgO, 45 ppm Ni, and several hundred ppm Cu as long as the magma was sufficiently oxidized so that large-scale sulphide saturation was not achieved. Assuming R factors between 500 and 5000, the sulphide melt has about 5 to 7.5% Cu, 1 to 1.3% Ni, and Cu/Ni ratios of at least 5, an order of magnitude higher than Hondekloof sulphides. To produce ores with 1.5 to 2% Ni and Cu/Ni 0.2 to 0.5, as at Hondekloof, the crystallizing mss needs to fractionate from the residual sulphide melt after as little as 10% crystallization. The Cu-rich O'okiep ores may theoretically be produced by fractionation of *iss* after advanced crystallization of the sulphide liquid (F = 0.2) (Figure 5). A concern with this model is that Cu/Ni ratios as high as at O'okiep have not yet been recorded in magmatic ores elsewhere. Another problem is that the metal-rich nature of the O'okiep sulphides requires the magma to remain undersaturated in sulphide melt during advanced differentiation. This is difficult to reconcile with the low PGE contents of the ores. One could argue that the magma merely attained temporary sulphide saturation. This resulted in segregation of only a small amount of sulphide melt that failed to deplete Cu in the magma, whereas the highly chalcophile PGE were effectively stripped from the magma. However, due to the homogenous PGE depletion of all deposits in the district, this model seems implausible.

In view of the above considerations, we presently favour a composite model incorporating new ideas as well as elements of some of the above models, as discussed below.

Genetic links to the IOCG group of deposits.

The O'okiep deposits bear certain similarities to the Caraiba copper deposits of Brazil (Oliveira and Tarney, 1995; Maier and Barnes, 1996, 1999). In a global context, the O'okiep, Caraiba and Phalaborwa copper deposits may be rare magmatic end-members of the IOCG class of deposits (Andreoli et al., 2006, Groves and Vielreicher, 2001). A related deposit may be the occurrence at Otjisuzubin in the Damara belt of Namibia, where anomalous copper is associated with apatite in an alkaline complex comprising alkali pyroxenite, sövite, mafic pegmatoids and syenite (Gunthorpe and Burger, 1986). Another unique deposit, i.e. the Vergenoeg pipe of fayalite-magnetite-fluorite probably represents a Cu-poor variant sited in the centre of the Kaapvaal Craton (Goff et al. 2004). This array of unique deposits suggests that the SCLM under southern Africa was anomalously fertile and raises the possibility of magmatic-hydrothermal IOCG deposits in the southern African terranes. One such deposit, previously unrecognised as a variant of IOCG, may be the Messina copper deposit in high-grade metamorphic rocks of the

Central Limpopo belt. At Messina, anomalously S-poor assemblages of chalcopyrite, bornite and hypogene chalcocite and native copper, associated with hematite, occur in large breccia pipes (Jacobsen, 1974). The deposit occurs close to known diamondiferous kimberlite pipes at River Ranch and Venetia, and Jacobsen and McCarthy (1975, 1976) have suggested a genetic association with deep alkaline intrusions. It is suspected that the potential for IOCG deposits in southern Africa may not have been realised because of the anomalous nature of the deposits discovered to date, including the O'okiep deposits discussed here.

In the context of the IOCG model, the O'okiep magmatism would have been triggered by crustal extension, for example in response to orogenic collapse caused by extreme radiogenic heating at mid- to lower crustal depths (Mouri et al., 2003; Andreoli et al., 2006). As a result of this event, small-degree partial melting of the SCLM produced magmas that are variably enriched in volatiles, CO_2, LILE, HFS, Au, Cu, P, but also SiO_2, Cr, MgO and other compatible elements. In contrast, PGE contents of the magma were low, analogous to many alkaline magmas elsewhere (Maier and Barnes, 2004). The magma ascended rapidly into the crust due to its high volatile content. In the oxygenated magmas S was stable as sulphate (Mungall et al., 2006) preventing early sulphide saturation and allowing Cu and Au to be concentrated in the magma until the advanced stages of differentiation (Campbell et al., 1998, and references therein). Sulphide saturation was eventually triggered by contamination and addition of external S, causing low $_{\varepsilon}$Nd and δ^{34}S values. The sulphides underwent extensive fractionation during continued magma ascent in dynamic magma conduits, possibly favoured by oxidation (cf Wohlgemuth-Überwasser et al., 2012). This resulted in deposition of relatively Ni-rich ores in deep intrusions such as Hondekloof, and progressively more Cu-rich ores with decreasing depth of emplacement (Figure 6). Because PGE and Au are incompatible into mss, they are enriched in the most Cu-rich deposits. The relatively high Au/PGE ratios of the ores mirror those of the SCLM (Maier et al., 2012).

Conclusions

The genesis of the Namaqualand Cu-Ni ores can be linked to other Cu-Au-P-LREE enriched systems, such as Caraiba and the IOCG group of deposits. Key components of the model include magma generation at craton margins, in response to melting of metasomatised SCLM in a back arc environment. The volatile-rich, oxidized magmas formed through relatively small degrees of partial melting, resulting in low PGE contents. The magmas ascend rapidly into the crust through trans-lithospheric structures, delaying sulphide saturation until relatively advanced stages of differentiation, thus causing pronounced enrichment in Cu, and incompatible lithophile elements.

Sulphide-bearing silicate rocks at O'okiep and Hondekloof show remarkable similarity in terms of petrography and composition of silicate minerals, leaving little doubt that they are co-genetic. In contrast, the sulphide ores at the two localities are of a distinctly different composition. At O'okiep there occur mainly Cu-rich sulphide minerals, dominated by bornite and chalcopyrite, with Cu/Ni ratios reaching >100. At Hondekloof there occur Ni-rich ores dominated by pyrrhotite with Cu/Ni ratios between 0.1 and 0.5. Ores of intermediate composition occur at Ezelsfontein. The range of compositions can be explained by fractionation of magmatic sulphide melt during magma ascent and emplacement in dynamic conduit systems. This is particularly clear at Hondekloof because these ores are too Ni-rich to represent unfractionated primary magmatic sulphides segregated from their relatively differentiated host rocks. The model has potential exploration implications as it suggests potential in Namaqualand for more Ni-rich ores of the Hondekloof type. The Ni-rich ores would be expected to occur at deeper crustal levels than the Cu-rich ores, consistent with the emplacement of the Kliprand intrusion in upper (T ~860°C) granulite facies rocks relative to the O'okiep ores in lower granulite (T ~750°C) facies.

Acknowledgements

We thank Gold Fields of South Africa, the O'okiep Copper Company, and the Foundation for Research Development of South Africa for financial support. Leslie Terreblanche, Koos Beukes, and several other staff at Nababeep mine offices guided WD Maier during fieldwork and mine visits at Carolusberg and Nigramoep mines. Rodger Hart (iThemba Labs Gauteng) kindly provided neutron activation analyses. Reviews by E Ripley and S Prevec helped to improve the paper.

References

Andreoli, M.A.G. and Moore, J., 1991. Geology and mineralogy of the Hondekloof nickel prospect, Kliprand, Cape Province. Atomic Energy Corporation of South Africa Internal Report GEA-968, 32pp. (2 unbound maps).

Andreoli, M.A.G., Smith, C.B., Watkeys, M., Moore, J.M., Ashwal, L.D. and Hart, R.J., 1994. The geology of the Steenkampskraal monazite deposit, South Africa: implications for REE-Th-Cu mineralization in charnockite-granulite terranes. Economic Geology, 89, 994-1016.

Andreoli M.A.G., Hart R.J., Ashwal L.D. and Coetzee H., 2006. Correlations between U, Th content and metamorphic grade in the western Namaqualand belt, South Africa, with implications for radioactive heating of the crust. Journal of Petrology, 47, 1095-1118.

Barnes, S.-J. and Maier, W.D., 1999. The fractionation of Ni, Cu and the noble metals in silicate and sulphide liquids. In: R.R. Keays, C.M. Lesher, P.C. Lightfoot, C.E.G. Farrow (Editors), Dynamic processes in magmatic ore deposits and their application to mineral exploration. Geological Association of Canada, Short Course Notes, 13, 69-106.

Barnes, S.-J. and Picard, C.P., 1995. The behaviour of platinum-group elements during partial melting, crystal fractionation, and sulphide segregation: an example from the Cape Smith Fold Belt, northern Quebec. Geochimica et Cosmochimica Acta, 57, 79-87.

Boer, R.H., Meyer, F.M. and Cawthorn, R.G., 1994. Stable isotopic evidence for crustal contamination and desulfidation of the cupriferous Koperberg Suite, Namaqualand, South Africa. Geochimica et Cosmochimica Acta, 58, 2677-2687

Brandriss, M.E. and Cawthorn, R.G., 1996 Formation of anorthosite and leucotonalite during magma hybridization in the Koperberg Suite of Namaqualand, South Africa. South African Journal of Geology, 99, 135-151

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, the Tennant Creek district and Yilgarn Craton. Austrailian Journal of Earth Science, 45, 201-218.

Cawthorn, R.G. and Meyer, F.M., 1993. Petrochemistry of the O'okiep copper district basic intrusive bodies, northwestern Cape Province, South Africa. Economic Geology, 88, 590-605.

Clifford, T.N., Barton, E.S., Retief, E.A., Rex, D.C. and Fanning, C.M., 1995. A crustal progenitor for the intrusive anorthosite-charnockite kindred of the cupriferous Koperberg Suite, O'okiep District, Namaqualand, South Africa; New isotope data for the country rocks and intrusives. Journal of Petrology, 36, 231-258.

Conradie, J.A. and Schoch, A.E., 1986. Petrographical characteristics of the Koperberg Suite, South Africa - an analogy to massif-type anorthosites? Precambrian Research, 31, 157-188.

Duchesne, J.-C., Vander Aurewa, J., Liegeois, J.-P., Barton, E.S. and Clifford, T.N., 2007. Geochemical constraints of the petrogenesis of the O'okiep Koperberg Suite and granitic plutons in Namaqualand, South Africa: a crustal source in Namaquan (Grenville) times. Precambrian Research, 153, 116-142.

Economou-Eliopoulos, M., 2005. PGE potential of porphyry deposits. In: J.E. Mungall (Editor), Exploration for platinum-group elements, Mineralogical Association of Canada, Short Course Series V 35.

Fraser, K.J., Hawkesworth, C.J., Erlank, A.J., Mitchell, R.H. and Scott-Smith, B.H., 1985. Sr, Nd and Pb isotope and minor element geochemistry of lamproites and kimberlites. Earth and Planetary Science Letters, 76, 57-70.

Gibson, R.L., Robb, L.J., Kisters, A.F.M., and Cawthorn, R.G., 1996. Regional setting and geological evolution of the O'okiep Copper District, Namaqualand, South Africa. South African Journal of Geology, 99, 107-120.

Goff, B.H., Weinerg, R., Groves, D.I., Vielreicher, N.M. and Fourie, P.J., 2004. The giant Vergenoeg fluorite deposit in a magnetite-fluorite-fayalite-REE pipe: a hydrothermally altered carbonatite-related pegmatoid? Mineralogy and Petrology, 80, 173-199.

Groves, D.I. and Vielreicher, N.M., 2001. The Phalaborwa (Palabora) carbonatite-hosted magnetite copper sulphide deposit, South Africa: an end-member of the iron-oxide copper gold rare-earth element deposit group?. Mineralium Deposita, 36, 189-194.

Gunthorpe, R.J. and Burger, A.D., 1986. Geoogy and economic evolution of the Otjisazu alkaline igneous complex, central South West Africa/ Namibia, In: C.R. Anhaeusser S. Marke (Editors), Mineral Deposits of Southern Africa. Geological Society of South Africa, 2255-2260.

Hamman, J.N., Rozendaal, A. and Jordaan, W., 1996. Gabbro norite hosted Ni-Cu-(Co) sulphide mineralization in southern Namaqualand and its relationship to the cupriferous Koperberg Suite of the O'okiep Copper District, South Africa. South African Journal of Geology, 99, 153-167.

Hronsky, J.M.A. and Groves, D.I., 2009. Towards a Unified Model for Magmatic-Hydrothermal Gold Metallogeny with Implications for Orogenic Gold. Abstr., Proc 10th SGA meeting, Townsville, Australia.

Jacobsen, J.B.E., 1974. Structure of the copper ore bodies and country rocks at Artonvilla mine, South Africa. Transactions of the Institute for Mining and Metallurgy, 83, B60-B64.

Jacobsen, J.B.E. and McCarthy, T.S., 1976. Possible late Karoo carbonatite and basalt intrusions at Messina, Transvaal. Transactions of the Geological Society of South Africa, 78, 153-159.

Jacobsen, J.B.E. and McCarthy, T.S., 1976. An unusual hydrothermal copper deposit at Messina, South Africa. Economic Geology, 71, 117-130.

Jana, D. and Walker, D., 1997. The influence of sulphur on partitioning of siderophile elements: Geochimica et Cosmochimica Acta, 61, 5255-5277.

Kisters, A.F.M., Charlesworth, E.G., Gibson, R.L., and Anhaeusser, C.R., 1996. The relationship between antiformal and monoclinal steep structures in the O'okiep Copper District, Namaqualand: a case study. South African Journal of Geology, 99, 185-195.

Lombaard, A.F. and Schreuder, F.J.G., 1978. Distribution pattern and general geological features of steep structures, megabreccias and basic rocks in the O'okiep Copper District. In: Verwoerd WJ (ed.) Mineralization in metamorphic terranes. Special Publication of the Geological Society of South Africa, 4, 269-295.

Lombaard, A.F. and the Exploration Department staff of the O'okiep Copper Company Ltd., 1986. The copper deposits of the O'okiep Copper District. In: C.R. Anhaeusser and S. Maske (Editors), Mineral deposits of Southern Africa. Geological Society of South Africa, 1421-1445.

Maier, W.D., 2000. Platinum-group elements in Cu-sulphide ores at Carolusberg and East O'okiep, Namaqualand, South Africa. Mineralium Deposita, 35, 422-429.

Maier, W.D. and Barnes, S.-J., 1996. Unusually high concentrations of magnetite at Caraiba and other Cu-sulphide deposits in the Curaça valley, Bahia, Brazil. Canadian Mineralogist 34, 717-731.

Maier, W.D. and Barnes, S.-J., 1999. The origin of Cu sulphide deposits in the Curaca Valley, Bahia, Brazil: Evidence from Cu, Ni, Se, and platinum-group element concentrations. Economic Geology, 94, 165-183.

Maier, W.D. and Barnes, S.-J., 2004. Pt/Pd and Pd/Ir ratios in mantle-derived magmas: a possible role for mantle metasomatism. South African Journal of Geology, 107, 333-340.

Maier, W.D., Peltonen, P., McDonald, I., Barnes, S.J., Barnes, S.-J., Hatton, C. and Viljoen, F., 2011. The concentration of platinum-group elements and gold in southern African and Karelian kimberlite-hosted mantle xenoliths: Implications for the noble metal content of the Earth's mantle. Chemical Geology, 302-303 (2012), 119-135.

Marsh, J.S., Ewart, A., Milner, S.C., Duncan, A.R. and Miller, R.M., 2001. The Etendeka igneous province: magma types and their stratigraphic distribution with implications for the evolution of the Parana-Etendeka flood basalt province. Bulletin of Volcanology, 62, 464-486.

McIver, J.R., McCarthy, T.S. and Packham, B. de V., 1983. The copper-bearing basic rocks of Namaqualand, South Africa. Mineralium Deposita, 18, 135-160.

Minnitt, R.C.A., 1986. Porphyry copper-molybdenum mineralization at Haib River, South West Africa/Namibia. In: C.R. Anhaeusser and S. Maske (Editors), Mineral Deposits of Southern Africa. Geological Society of South Africa, 1567-1585.

Mungall, J.E., Hanley, J.J., Arndt, N.T. and Debecdelievre, A., 2006. Evidence from meimechites and other low-degree mantle melts for redox controls on mantle-crust fractionation of platinum-group elements, Proceedings of the National Academy of Science, 103, 12695-12700.

Naldrett, A.J., 1989. Sulphide melts - crystallization temperatures, solubilities in silicate melts, and Fe, Ni, and Cu partitioning between basaltic magmas and olivine. In: J.A. Whitney and A.J. Naldrett (Editors), Ore deposits associated with magmas, Reviews in Economic Geology, 4, 5-20.

Naldrett, A.J., Innes, D.G., Sowa, J. and Gorton, M.P., 1982. Compositional variation within and between five Sudbury ore types. Economic Geology, 77, 1519-1534.

Oliveira, E.P. and Tarney, J., 1995. Genesis of the Precambrian Cu-rich Caraiba hypersthenite-norite complex, Brazil: Mineralium Deposita, 30, 351-373.

Potgieter, J.E., 1996. Exploration in the O'okiep Copper District, Northern Cape Province, South Africa: an overview. South African Journal of Geology, 99, 209-220.

Read, D., Jarvis, N.V., Williams, T., Knoper, M. and Andreoli, M.A.G., 2002. The degradation of monazite: implications for the mobility of rare-earth and actinide elements during low-temperature alteration. European Journal of Mineralogy, 14, 487-498.

Robb, L.J., Armstrong, R.A. and Waters, D.J., 1999. The history of granulite-facies metamorphism and crustal growth from single-zircon U-Pb geochronology: Namaqualand, South Africa. Journal of Petrology, 40, 1747-1770.

Schoch, A.E. and Conradie, C.A., 1990. Petrochemical and mineralogical relationships in the Koperberg Suite, Namaqualand, South Africa. American Mineralogist, 75, 27-36.

Stumpl E.F., Clifford T.N., Burger A.J., Zyl V (1976) The copper deposits of the O'Okiep district, South Africa: new data and concepts: Mineral Deposita 11, 46-70

Sun, S.-S. and McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: A.D. Saunders and M.J. Norry (Editors), Magmatism in the Ocean Basins, Geological Society, Special Publication 42, 313-345.

Taylor, E., 1990. The geology and Ni-metallogenesis in the Namaqualaand Movile Belt, Kliprand, North-West Cape, South Africa. Unpublished BSc. (Honours) Project, University of the Witwatersrand, South Africa, 69pp.

Van Zwieten, A.J.M., McCarthy, T.S. and Cawthorn, R.G., 1996. A petrogenetic model for the Koperberg Suite: evidence from the Jubilee Mine, Namaqualand, South Africa. South African Journal of Geology, 99, 121-134.

Von Gehlen, K., Nielsen, H., Rozendaal, A. and Jensen, M.L., 1990. Sulfur isotopes indicate a homogenous, probably mantle source for the O'okiep copper ores, Namaqualand. Abstract Geocongress '90, Geological Society of South Africa, Cape Town, 582-585.

Watkeys, M.K., 1996. The Klondike steep structure, O'okiep Copper District, South Africa. South African Journal of Geology, 99, 169-183.

Woodland, S.J., Pearson, D.G. and Thirlwall, M.F., 2002. A platinum-group element and Re-Os isotope investigation of siderophile element recycling in subduction zones: comparison of Grenada, Lesser Antilles Arc, and the Izu-Bonin Arc. Journal of Petrology., 43, 121-198.

Editorial handling: S. Prevec.