Possible platinum-group element (PGE) oxides in the PGE-mineralized chromitite from the Northern Oman Ophiolite

Ahmed H. AHMED*, Shoji ARAI** and Kazuyuki KADOSHIMA**

* *Central Metallurgical Research and Development Institute, P.O. Box 87, Helwan, Cairo, Egypt*

** *Department of Earth Sciences, Kanazawa University, Kakuma, Kanazawa 920-1192, Japan*

A number of platinum-group mineral (PGM) grains with characteristic optical and geochemical properties are found in the recently discovered PGE-mineralized chromitite at Wadi Hilti in the deeper mantle section of the northern Oman ophiolite. They usually occur as polygonal inclusions within fresh chromian spinel. They have exclusively Ru-Os-Ir compositions with low totals on conventional microprobe analysis and show the same Ru-Os-Ir ratios as Os-rich laurite, (Ru, Os, Ir)₂S₃, commonly found in the chromitite. Qualitative and quantitative analyses show that oxygen is one of major constituents of these PGM grains, and they are Ru-Os-Ir oxides. They are characteristically lower in Fe-Ni contents than Ru-Os-Ir oxides ever reported. The characteristic radial-fibrous textures as well as a hollow space around the polygons possibly mean their secondary origin with significant volume reduction. The similarity of element ratios and mode of occurrence between the PGE oxides and laurite indicates that the former have been produced by desulfurization/oxidation of the latter. Formation of the PGE oxides from Oman has been performed with an increase of Eh at a very early stage of serpentinization

Introduction

It is well established now that platinum-group element (PGE) oxides occur in the PGE mineralized portions of ultramafic or ophiolitic complexes although their natural occurrences had been suspected (e.g., Cabri, 1981). Only limited reports, however, have been available to date from Shetland (Ixer and Prichard, 1989; Prichard et al., 1994), Pirogues, New Caledonia (Auge and Legendre, 1994), Vourinos, Greece (Garuti and Zaccarini, 1997), Nurali, Southern Urals, Russia (Garuti et al., 1997), and Western Andriamena, Madagascar (McDonald et al., 1999). These PGE oxides are occasionally marked by low reflectance and unusual textures under the microscope compared with the other platinum-group mineral (PGM) phases (e.g., sulphides and alloys). Further information on PGE oxides can be obtained from the experimental or theoretical works (e.g., Westland, 1981; Griffith, 1989; Capobianco and Drake, 1990). PGE oxides have been interpreted as alteration products of preexisting PGM: desulfurization/oxidation of PGE sulphides (e.g., Garuti and Zaccarini, 1997) or weathering of PGE alloys (e.g., Auge and Legendre, 1994).

PGE-mineralized chromitite has been recently discovered in the deeper mantle section of the northern Oman ophiolite (Ahmed and Arai, 2002). A few PGM grains with low reflectance and characteristic textures

have been found both in the PGE-rich and PGE-poor chromitites of Wadi Hilti, northern Oman ophiolite. The presence of appreciable amount of oxygen was confirmed by the qualitative and semi-quantitative analyses. Origin of PGE oxides is important to understand the behaviour of PGM, including mobility of PGE, at low temperature conditions. This is the first report on PGE oxides from the Oman ophiolite, and will contribute to further understanding of the general characteristics and origin of PGE oxides.

Geological setting and chromian spinel chemistry

In the northern part of the Oman ophiolite of Cretaceous age a complete ophiolite sequence is well preserved and exposed from the upper crust to the upper mantle (Lippard et al., 1986). Wadi Hilti provides us with one of the best profiles of the whole ophiolite section (Fig. 1). The mantle sequence there consists mainly of harzburgite with minor amounts of lherzolite and dunite, which is sometimes gradational through chromitiferous dunite to chromitite. Chromitite pods are occasionally surrounded by envelopes of dunite varying from few centimeters to few meters in thickness but are not necessarily related to the size of chromitite body. The host harzburgite and dunite envelopes are relatively fresh; the degree of serpentinization is very low, occasionally less than 15 % (Ahmed, 2001). As observed in other ophiolites, chromitite pods are usually located within the Moho transition zone above mantle

Figure 1. Geological sketch map of the Wadi Hilti area of northern Oman ophiolite, showing the location of PGE-mineralized chromitite in the deeper mantle section.

harzburgite in Oman (Nicolas and Azri, 1991). Recently large-scale chromitite pods were also described additionally from the deeper mantle section at Wadi Hilti, northern Oman ophiolite (Ahmed, 2001; Ahmed and Arai, 2002). Two types of chromitites, based on the mode of occurrence and PGE contents, are described in the deeper mantle of the northern Oman ophiolite: PGE-poor chromitite found as lensoidal bodies concordant with the host harzburgite foliation, and PGE-rich chromitite discordant with the host harzburgite foliation (Ahmed and Arai, 2002). Massive chromitite is composed of coarse aggregates of chromian spinel which is usually fractured. The fracture network is composed mainly of serpentine minerals, while chlorite is occasionally absent.

Based on chromian spinel chemistry, two compositionally distinctive types of chromitite are recognized in the deeper part of the mantle section of the northern Oman ophiolite: high- and intermediate-Cr# types (Fig. 2). The former has spinel high in Cr#, > 0.7, and is usually PGE-rich, whilst the latter has intermediate Cr# (~0.6) spinel, and is PGE-poor (Ahmed and Arai, 2002). Chromian spinel has low TiO₂ contents, usually < 0.3 wt%, both in chromitites and associated peridotites (harzburgite and dunite) (Ahmed, 2001).

Figure 2. Variation of Cr/(Cr + Al) atomic ratio versus Mg/(Mg + Fe²⁺) atomic ratio of chromian spinel in both PGE-rich and PGE-poor chromitites from the deeper mantle section at Wadi Hilti, northern Oman ophiolite.

Methods of investigation

Chromitite samples have been examined firstly on polished thin sections by reflected light at high magnifications to detect very small PGM grains down to 1 µm across. Colour and reflectance under the microscope enables us to discriminate the PGE oxides from the other PGM and base-metal sulphides on the same section.

PGM analyses were carried out using a JEOL electron-probe microanalyser JXA-8800 at the Center

Figure 3. BSE images of the PGE oxides in the PGE-mineralized chromitite of the northern Oman ophiolite. A) & B), PGE oxide grains with perfect euhedral shapes hosted by fresh chromian spinel. C) Close up of image A, showing the radial cracks within the PGM grain which are partly continuous to those in the host spinel. D) Close up of image B, showing a hollow space around the PGM.

for Co-operative Research of Kanazawa University. Analytical conditions were 25-kV accelerating voltage, 20-nA probe current in case of all elements except oxygen. Oxygen analysis was conducted at 10 kV and 50 nA in a separate run using LDE analyzing crystals. Oxygen was analysed both qualitatively and semi-quantitatively using the wavelength dispersive spectroscopy (WDS) mode. Counting time was 10 seconds for all elements. The standard used was pure metal for the elements Os, Ir, Ru, Rh, Pt, Pd, Cu, Ni, Fe and Cr, while gallium arsenide for As and pentlandite for S. Two oxide standards, Fe_2O_3 and Al_2O_3 , were used for the oxygen analysis. $K\alpha$ X-ray line was used for the elements Ni, S, Fe, Cr and O, $L\alpha$ line for Os, Ir, Ru, Rh, Pt and Cu, and $L\beta$ lines for Pd and As.

Optical properties

While studying the PGE mineralogy in the mineralized chromitite that has been recently discovered in deeper part of the mantle section, northern Oman ophiolite (Ahmed and Arai, in prep.), some PGM grains with low reflectance and characteristic textures, compared with the associated other PGM, were found as inclusions within unaltered chromian spinel. These grains have attracted our attention due to their appearance and low analytical totals for conventional microprobe analysis of PGM (mainly sulphides and alloys). They were later interpreted as PGE oxides. They show yellowish-white colours and range from 15 up to 50 μm in size with perfect polygonal shapes (Fig. 3A, B) within chromian spinel grains that are cracked but chemically intact. In

Figure 4. BSE images of PGE oxides and primary laurite in the PGE-mineralized chromitite, northern Oman ophiolite. A) Radial and fibrous cracks in a PGE oxide grain within unaltered chromian spinel. B) Ragged surface due to cracking of a PGE oxide grain within unaltered chromian spinel. C) Enlargement of the periphery of a PGE oxide grain in A, showing cracks with various dimensions. D) Homogeneous appearance of Os-rich laurite in the same PGE-mineralized chromitite of the northern Oman ophiolite. Note the absence of the internal textures and smooth surface.

most cases the grains show characteristic radial cracks, which are usually continuous to the cracks of the host chromian spinel (Fig. 3C). PGM grains composed of PGE oxides usually have a hollow space around them (Fig. 3C, D). It is noteworthy that the polygonal PGM (oxides) have cracks, sometimes radiating, with various dimensions (Fig. 4A, C). These features indicate a significant volume decrease on formation of the PGE oxides. Similar cracking was also reported from PGE oxides in chromitites and related alluvium of the New Caledonian ophiolite (Auge and Legendre, 1994) and the Nurali Ultramafic complex, southern Urals (Garuti et al., 1997). The hollow space around PGE oxides was recognized in chromitite from the Vourinos ophiolite (Garuti and Zaccarini, 1997).

These PGE oxides have lower reflectance than the associated PGM like Os-rich laurite, the most common PGM in northern Oman chromitite, which has higher

reflectance and smoother surface under the microscope. Laurite and other PGM are free of radial cracking and usually show homogeneous appearance (Fig. 4D).

Chemical properties

The weight percent totals of these PGM (oxides) are far lower than 100 wt %, occasionally around 80 wt % (Table 1) which was ascribed to the possible presence of some light elements not detected by conventional electron microprobe analysis. Their chemical analysis demonstrates exclusive presence of Ru, Os and Ir as major constituents with a considerable amount of Fe, around 4 wt %, and traces of Ni and Rh, around 1.5 and 1.1 wt %, respectively (Table 1). Suspected anions such as S, As, Te, Bi and Sb are practically absent. The amount of Cr, up to 3 wt %, may be attributed to the excitation of the host chromian spinel, and all Cr was

Figure 5. Wavelength dispersive X-ray spectra on analyzing crystals LDE1, LDE2, LIF and PETJ, from top to bottom, showing the major constituent elements of a PGE oxide grain (Fig. 3D) in the PGE-mineralized chromitite, northern Oman ophiolite. Peaks for C and Cr are from carbon coating and chromian spinel host, respectively.

neglected in calculation of atomic ratios (Table 1). Mg, Si and Al are also detected in some analyses probably due to the excitation of the associated silicates.

Wavelength dispersive spectroscopy (WDS) clearly shows that oxygen is one of the major constituents in these PGM (Fig. 5). Semi-quantitative analysis was carried out to determine the oxygen content, yielding 2.5 to 10.3 wt % (Table 2). Detection of oxygen was not ascribed to excitation from the surrounding oxide (chromian spinel), judging from line profiles for oxygen content across the suspected PGE oxide grains. Weight percent of metals have also recalculated as ideal oxides considering the valence of 3+ for Ru, Rh, Cr and Fe, 4+ for Os and Ir, and 2+ for Ni, yielding analytical totals usually less than 100 wt % in most cases (Table 2),

which is partly due to the roughness of the surface with cracks (Fig. 4). The possibility of the presence of hydroxyl (OH) can not be eliminated. The oxygen content of the associated laurite, on the other hand, is usually less than 0.2 wt % (Table 2).

The PGE oxides are within the compositional range of primary Os-bearing laurite in terms of Ru-Os-Ir ratio (Fig. 6). Ru-Os-Ir oxides similar to the Oman ones were reported by Garuti and Zaccarini (1997) and Garuti et al. (1997) from altered or weathered chromitites. The PGE

Figure 6. Compositional variations of Ru-Os-Ir (in atomic ratios) of PGE oxides in the PGE-mineralized chromitite, northern Oman ophiolite, in comparison with (A) the compositional field of primary Os-rich laurite from the same PGE-rich chromitite, northern Oman ophiolite (Ahmed and Arai, in prep.) and (B) the compositional ratios of PGE oxides from the Nurali ultramafic complex, southern Urals, Russia (Garuti et al., 1997) and laurite from Vourinos complex (Garuti and Zaccarini, 1997). Note the similarity of the Ru-Os-Ir ratios between the PGE oxides and laurite (A).

oxides in the present study are distinctly lower in Fe and Ni than those reported by Garuti and co-workers (Fig. 7).

Discussion

The PGE oxides/hydroxides ever documented are mostly enriched with Pt and Pd that are more mobile than Ru, Os and Ir, and were found mainly from alluvial occurrences (e.g., Auge and Legendre, 1994). However, in-situ PGE oxides or hydroxides of Ru-Os-Ir compositions have been recently described from chromitite (e.g., Auge and Legendre, 1994; Garuti and Zaccarini, 1997; Garuti et al., 1997). The reported PGE oxides in this study are similar both in composition and

Table 1. Selected microprobe analysis of the oxygen-bearing Ru-Os-Ir compounds from the PGE-mineralized chromitite, northern Oman ophiolite. * Os-rich laurite grain

	18-1	18-6	18-7	6-1	6-2	6-3	6-4	10	18-5*
Elements	wt %								
S	0.00	0.02	0.00	0.02	0.02	0.06	0.00	0.07	32.12
Os	25.46	25.75	25.74	11.44	15.35	14.07	13.48	18.94	22.07
Ir	12.30	11.71	12.02	5.14	6.76	5.75	6.12	11.92	11.83
Ru	34.40	34.57	34.13	30.74	42.97	33.71	31.24	36.33	28.03
Rh	1.26	1.10	1.04	1.05	1.37	1.07	1.02	0.65	0.70
Pt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.00
Pd	0.13	0.12	0.00	0.15	0.11	0.12	0.00	0.72	0.01
As	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	1.72	1.19	2.03	0.09	0.18	0.11	0.12	1.19	0.09
Cu	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Fe	4.12	4.31	3.39	5.80	6.39	5.62	5.26	6.15	0.52
Cr	2.53	3.23	1.98	1.19	1.53	1.23	1.14	0.92	1.72
Total	81.92	82.00	80.23	55.62	74.68	61.75	58.38	77.34	97.09
Atomic ratio									
S	0.00	0.09	0.00	0.12	0.09	0.35	0.00	0.31	67.94
Os	20.46	20.91	20.80	11.84	12.00	13.38	13.70	14.90	7.88
Ir	9.77	9.40	9.60	5.26	5.23	5.41	6.15	9.27	4.17
Ru	51.96	52.75	51.82	59.77	63.14	60.22	59.67	53.72	18.80
Rh	1.86	1.64	1.55	2.01	1.97	1.88	1.92	0.94	0.46
Pt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00
Pd	0.19	0.17	0.00	0.27	0.14	0.21	0.00	1.01	0.01
As	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	4.48	3.12	5.31	0.30	0.46	0.34	0.40	3.03	0.10
Cu	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00
Fe	11.27	11.92	10.92	20.42	16.99	18.18	18.17	16.46	0.63

Table 2. Quantitative microprobe analysis, including oxygen, of some oxygen-bearing Ru-Os-Ir grains and calculated compositions as oxides in the PGE-mineralized chromitite, northern Oman ophiolite. * Os-rich laurite grain. n.cal., not calculated

	18-1	18-6	18-7	6-1	6-2	6-3	6-4	10	18-5*
Elements	Wt %								
S	0.00	0.02	0.00	0.02	0.02	0.06	0.00	0.07	32.12
O	8.95	10.32	7.65	5.52	6.14	2.57	3.47	9.25	0.20
Os	25.46	25.75	25.74	11.44	15.35	14.07	13.48	18.94	22.07
Ir	12.30	11.71	12.02	5.14	6.76	5.75	6.12	11.92	11.83
Ru	34.40	34.57	34.13	30.74	42.97	33.71	31.24	36.33	28.03
Rh	1.26	1.11	1.04	1.05	1.37	1.07	1.02	0.65	0.70
Pt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.00
Pd	0.13	0.12	0.00	0.15	0.11	0.12	0.00	0.72	0.01
As	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	1.72	1.19	2.03	0.09	0.18	0.11	0.12	1.19	0.09
Cu	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Fe	4.12	4.31	3.39	5.80	6.39	5.62	5.26	6.15	0.52
Cr	2.53	3.23	1.98	1.19	1.53	1.23	1.14	0.92	1.72
Total	90.87	92.33	88.56	61.14	80.79	64.31	61.83	86.58	97.27
Oxides	Wt %								
OsO ₂	29.74	30.08	30.07	13.36	17.93	16.44	15.74	22.13	n.cal.
Ru ₂ O ₃	42.57	42.77	42.23	38.03	53.17	41.69	38.65	44.95	n.cal.
IrO ₂	14.34	13.66	14.02	5.99	7.89	6.71	7.13	13.90	n.cal.
Rh ₂ O ₃	1.55	1.35	1.29	1.31	1.68	1.32	1.26	0.80	n.cal.
Fe ₂ O ₃	5.91	6.17	5.68	8.31	9.13	8.03	7.51	8.79	n.cal.
NiO	2.19	1.51	2.58	0.11	0.23	0.14	0.15	1.51	n.cal.
Total	96.29	95.53	95.86	67.11	90.03	74.34	70.45	92.09

Figure 7. Relationship between Fe and Ni contents in PGE (Ru-Os-Ir) oxides in chromitites and related alluvium from Oman (this study), Vourinos ophiolite (Garuti and Zaccarini, 1997) and Nurali complex (Garuti et al., 1997). Note that the relatively low Fe-Ni contents of the PGE oxides from Oman (see text).

texture to those described by Garuti et al. (1997) in the Nurali ultramafic complex, southern Urals, Russia. They are partly similar to those reported by Garuti and Zaccarini (1997) from Vourinos ophiolite, Greece. The O-bearing PGM from weathered (lateritized) samples, in which limonite and other Fe-hydroxides are abundant, are possibly mixtures of PGE alloys and Fe hydroxides (e.g., Garuti and Zaccarini, 1997). The relatively low content of Fe in the Oman PGM (Fig. 7) may indicate that their oxygen detected was not derived from mixed Fe-hydroxides.

The PGE oxides from the Oman ophiolite were possibly formed at very low temperature conditions, where chromian spinel can remain intact. At higher temperatures chromian spinel in chromitite is not stable, being converted to Fe-rich phases, ferritchromite or Cr-bearing magnetite (e.g., Ahmed et al., 2001). In addition the PGE oxides formation has been performed at an early stage of serpentinization because peridotites surrounding the chromitite pods are relatively fresh. This situation is confirmed by the relatively low contents of Fe and Ni (Fig. 7): Fe and Ni are supplied from olivine on serpentinization, also by the abundance of serpentine minerals in the fractures network. Ni-Fe alloys are quite commonly associated with PGM in highly altered chromitites (e.g., Garuti and Zaccarini, 1997; Arai et al., 1999). Stockman and Hlava (1984) concluded that Ru-rich alloys were formed by desulfurization from primary laurite with significant addition of Fe-Ni during serpentinization. In the Nurali complex of the southern Urals the Fe-rich Ru-Os-Ir oxide grains (Fig. 7) are solely associated with altered chromian spinel (ferritchromite) (Garuti et al., 1997).

The PGE (Ru-Os-Ir) oxides from Oman were most probably transformed from primary laurite by desulfurization/oxidation with volume reduction. The polygonal shape and mode of occurrence as inclusion within chromian spinel are exactly the same as laurite (Figs. 3 and 4). The Ru-Os-Ir ratio has been almost unchanged during the desulfurization/oxidation process (Fig. 6).

A) Primary magmatic phases

B) Early stage serpentinization

Figure 8. Cartoon showing the genetical formation of PGE oxides in the PGE-mineralized chromitite, northern Oman ophiolite via desulfurization of primary Os-rich laurite. (A) Primary magmatic laurite grain (white) enclosed within chromian spinel. (B) Radial cracks developed within chromian spinel and continuously extended to the enclosed PGM resulted in the formation of PGE oxides.

Preservation of Ru-Os-Ir ratios on transformation from laurite to PGE oxides was also reported from Vourinos ophiolite (Garuti and Zaccarini, 1997). The primary laurite as a precursor for PGE oxides is also suggested by the occurrence of the Nurali complex: primary magmatic laurite is included only by fresh chromian spinel while the oxides by ferritchromite (Garuti et al., 1997). Due to the brittle failure of chromite grains, radial cracks are developed through chromite grains and continuously extended to some of the enclosed PGM (Fig. 8). As a result, some of the primary magmatic laurite grains were exposed to the oxidative weathering and; therefore desulfurated to the Ru-Os-Ir oxides with a significant volume reduction (Fig. 8). The absence of chlorite minerals within the fractures network of spinel and PGE oxides and the only presence of serpentine minerals suggested that chromian spinel is not involved in the alteration product at least in the stage of PGE oxides formation.

As suggested by Garuti et al. (1997) Eh rather than temperature has possibly controlled the formation of PGE oxides in Oman. Westland (1981) suggested that PGE sulphides can be transformed into PGE alloys or PGE oxides depending on the Eh-pH change in the system PGE-S-H₂O. Bowles (1981) either laurite or Ru-rich alloys can be precipitated in lateritic environment depending on Eh-pH conditions. According to Brookins (1987) laurite is converted to RuO₂ via Ru metal with an increase of Eh at a given pH in the system Ru-O-H-S at low temperature, low pressure conditions. It is suggested, therefore, Eh enhancement on invasion of aqueous fluid has converted primary Os-bearing laurite to Ru-Os-Ir oxides through alloys in the chromitite of Oman.

Summary and conclusions

1. PGE oxides are described from podiform chromitite of the Oman ophiolite for the first time. They form polygonal inclusions with radial cracks within unaltered chromian spinel.
2. They are composed of Ru, Os, Ir and O with small amount of Fe. Their Ru-Os-Ir ratio is almost similar to that of primary Os-bearing laurite (Ru-Os-Ir sulphide), the most common PGM in the Oman chromitite.
3. The oxides have been formed by desulfurization/oxidation from the laurite with appreciable volume reduction at very low-temperature conditions where chromian spinel remained chemically intact. Increase of Eh possibly has promoted the transformation of laurite to PGE

oxides via alloys.

4. The formation of the PGE (Ru-Os-Ir) oxides has been performed at an early stage of serpentinization. Fe-Ni contents of the PGE oxides may increase with a progress of serpentinization.

Acknowledgments

The authors greatly appreciate H. Watanabe, Kanazawa University, for his assistance in observing the back-scattered electron images on SEM. Suggestion on oxygen analysis by N. Nishida, University of Tsukuba, was greatly acknowledged. Comments of the referees were very helpful to improve the manuscript.

References

- Ahmed, A.H. (2001) Platinum-group elements and chromitite deposits in two ophiolite suites: Proterozoic ophiolite, Eastern Desert, Egypt, and Phanerozoic ophiolite, northern Oman. Unpublished PhD Thesis, Kanazawa University, Japan.
- Ahmed, A.H., Arai, S. and Attia, A.K. (2001) Petrological characteristics of the Pan African podiform chromitites and associated peridotites of the Proterozoic ophiolite complexes, Egypt. *Mineralium Deposita*, 36, 72-84.
- Ahmed, A.H. and Arai, S. (2002) Unexpectedly high-PGE chromitite from the deeper mantle section of the northern Oman ophiolite and its tectonic implications. *Contributions to Mineralogy and Petrology*, 143, 263-278.
- Arai, S., Prichard, H.M., Matsumoto, I., and Fisher, P.C. (1999) Platinum-group minerals in podiform chromitite from the Kamuikotan zone, Hokkaido, northern Japan. *Resource Geology*, 49, 39-47.
- Auge, T. and Legendre, O. (1994) Platinum-group element oxides from the Pirogues ophiolitic mineralization, New Caledonia: origin and significance. *Economic Geology*, 89, 1454-1468.
- Bowles, J.F.W. (1986) The development of platinum-group minerals in laterites. *Economic Geology*, 81, 1278-1285.
- Brookins, D.G. (1987) Platinoid element Eh-pH diagrams (25°C, 1bar) in the systems M-O-H-S with geochemical applications. *Chemical Geology*, 64, 17-24.
- Cabri, L.J. (1981) Platinum-group elements: Mineralogy, geology, recovery. CIM Special Volume 23, pp. 267, The Canadian Institute of Mining and Metallurgy, Montreal.
- Capobianco, C.J. and Drake, M.J. (1990) Partitioning of ruthenium, rhodium, and palladium between spinel and silicate melt and implications for platinum group elements fractionation trends. *Geochimica et Cosmochimica Acta*, 54, 869-874.
- Garuti, G. and Zaccarini, F. (1997) In situ alteration of platinum-group minerals at low temperature: evidence from serpentinized and weathered chromitite of the Vourinos complex, Greece. *Canadian Mineralogist*, 35, 611-626.
- Garuti, G., Zaccarini, F., Cabella, R. and German, F. (1997) Occurrence of unknown Ru-Os-Ir-Fe oxide in the chromitites of the Nurali ultramafic complex. *Canadian Mineralogist*, 35, 1431-1440.
- Griffith, W.P. (1989) Ruthenium and osmium oxo complexes as

- organic oxidants. *Platinum Metals Review*, 33, 181-185.
- Ixer, R and Prichard, H.M. (1989) The mineralogy and paragenesis of Pt, Pd, Au and Ag bearing assemblages at Cliff, Shetland. pp. 40, *Geological Survey of Finland Bulletin* 61.
- Lippard, S.J., Shelton, A.W. and Gass, I.G. (1986) The ophiolite of northern Oman. *The Geological Society Memoir* No. 11, pp. 178, Blackwell Scientific Publications, Oxford.
- McDonald, I., Ohnenstetter, D., Ohnenstetter, M. and Vaughan, D.J. (1999) Palladium oxides in ultramafic complex near Lavatrafo, Western Andriamena, Madagascar. *Mineralogical Magazine*, 63, 345-352.
- Nicolas A and Al Azri H (1991) Chromite-rich and chromite-poor ophiolites: the Oman case. In *Ophiolite Genesis and Evolution of the Oceanic Lithosphere* (Peters, Tj. et al. Eds.), pp. 903, Kluwer Academic Publishers, Dordrecht, 261-274.
- Prichard, H.M., Ixer, R.A., Lord, R.A., Maynard, J., and Williams, N. (1994) Assemblages of platinum-group minerals and sulfides in the silicate lithologies and chromite-rich rocks within the Shetland ophiolite. *Canadian Mineralogist*, 32, 271-294.
- Stockman, H.W. and Hlava, P.F. (1984) Platinum-group minerals in Alpine chromitites from south-western Oregon. *Economic Geology*, 79, 491-508.
- Westland, A.D. (1981) Inorganic chemistry of the platinum-group elements. In *Platinum-Group Elements: Mineralogy, Geology, Recovery* (Cabri, L.J. Ed.), pp. 267, The Canadian Institute of Mining and Metallurgy, Montreal, 5-18.

Manuscript received; 31 March, 2002

Manuscript accepted; 31 July, 2002