PLATINUM-GROUP MINERALS FROM THE PALEOPROTEROZOIC CHROMITITE, OUTOKUMPU OPHIOLITE COMPLEX, EASTERN FINLAND

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ABSTRACT

This paper describes the presence of platinum-group minerals in the Vasarakangas chromitite from the 1.97 Ga Outokumpu ophiolite complex in eastern Finland. The platinum-group mineral assemblages as well as the compositions of laurite, irarsite and orarsite, and also the chondrite-normalized platinumgroup element patterns are compatible with those described in younger Mesozoic ophiolitic chromitites. In contrast to these younger chromitites, where Irgroup minerals occur mainly as inclusions in chromite, the platinum-group minerals at Vasarakangas are principally found as enclosed minor grains in euhedral matrix gersdorffites. The PGE distribution between separated chromite and gersdorffite fractions is in accordance with the observed exceptional mode of PGM occurrence.

INTRODUCTION

In ophiolitic chromitites and also in mafic layered intrusions, platinum group minerals (PGM) such as laurite (Ru,Os,Ir)S₂, irarsite (Ir,Ru)AsS, and osarsite (Os, Ru)AsS are principally found as inclusions within chromite grains (e.g., Augé, 1985; 1986; Legendre and Augé, 1986; Stockman and Hlava, 1984; McElduff and Stumpfl, 1990). In some cases, these minerals can also occur in the silicate matrix, but most commonly, the matrix platinum-group minerals are represented by arsenides, sulfarsenides, antimonides and alloys of Rh, Pt and Pd, and are accompanied by base metal sulfides and nickel arsenides (Prichard and Tarkian, 1988; Thalhammer et al., 1990; Mondal and Baidya, 1997). This paper describes an exceptional mode of occurrence of platinum-group minerals in a chromitite from the 1.97 Ga Outokumpu ophiolite complex.

GEOLOGICAL SETTING

The Paleoproterozoic Outokumpu ophiolite complex with an age of 1972±18 Ma (Huhma, 1986), is located in eastern Finland. The ophiolite consists of dismembered ultramafic serpentinite and soapstone massifs that vary greatly in size and shape, and occurs in a zone that can be traced for a distance of some 260 km. The largest massifs have a longitudinal axis of several kilometers and reach a thickness of a few hundred meters, whereas the smallest ones are only a few tens of meters long (Fig. 1).

The ultramafic massifs of the Outokumpu ophiolite complex represent a deep section in an ancient oceanic crust and upper mantle. The mantle rocks were originally dunites and harzburgites, and the cumulates from the oceanic crust were dunites, wehrlites and lherzolites (Liipo et al., 1995). The massive Cu-Zn-Co sulphide ores of the complex are hosted by quartz- and calc-silicate rocks closely associated with ophiolitic serpentinites (e.g., Gaál and Parkkinen, 1993).

PETROGRAPHY AND MINERALOGY OF THE CHROMITITE

All the samples examined in this study were collected

from the tailings of the closed Vasarakangas talc quarry. Despite the intense penetrative deformation of the host rocks, the chromitite samples display typical structures of ophiolitic chromitites, such as massive and nodular-like textures. The nodular-like chromitite comprises subrounded, coarse grains while the massive type is dissected by sets of fractures. The chromite grains vary in shape from euhedral to rounded and are up to 40 mm in size, though the largest grains are commonly cataclastic. The grains are very fresh and have retained their primary chemical composition. Only narrow rims of opaque ferritchromite have developed at the margins of the chromites and along the cross-cutting fractures. Both the Cr/(Cr+AI) and $Mg/(Mg+Fe^{2+})$ values of the chromites range from 0.55 to 0.63 (Vuollo et al., 1995; Lijo et al., 1995).

In contrast to chromite, primary silicate minerals are not preserved in the chromitite. The fracture network and interstitial silicate matrix are composed of Cr-chlorite and magnesite. Accessory nickeline (NiAs) and compositionally heterogeneous gersdorffite (NiAsS) occur predominantly in secondary silicates as anhedral to euhedral grains from 2 to 100 μ m in size and are only occasionally found in the ferritchromite rims as small, anhedral inclusions less than 10 μ m in diameter. Small grains of Os-poor laurite, isarsite and osarsite occur commonly as inclusions in matrix gersdorffite. One exceptionally large (100 μ m) laurite grain was discovered outside gersdorffite in matrix chlorite (Figs. 2 and 3).

ANALYTICAL METHODS

Polished sections and resin mounts of different fractions of chromitite were systematically studied under reflected light and with a JEOL JXCA 733 electron microprobe equipped with a LINK AN 10000 at the Institute of Electron Optics, University of Oulu. The acceleration voltage was 20 kV, the sample current 15 nA, and the spot size used was between 2 and 10 μ m depending on the size of the analyzed grain. Pure metals and synthetic sulfides were used as standards. Both, the wave length-dispersion (WDS) and energydispersion (EDS) methods were used. Results were corrected with an on-line ZAF program. The small size of the PGM grains and their occurrence as inclusions in gersdorffite grains explain the low analytical totals in some cases, as



Fig. 1 - Geologic sketch map of the Outokumpu ophiolite complex, showing location of the chromitite occurrence at Vasarakangas. Legend: 1-Kalevian mica schists; 2-Jatulian and Sariolian quartzites; 3- Ophiolite assemblage; 4- Archean basement. Modified after Liipo et al. (1995).



Fig. 2 - a) Occurrence of euhedral gersdorffite (grs) intersticially and in the fractures of chromite (chr), scale bar 1000 μ m; b) occurrence of laurite (lau) as an inclusion in gersdorffite, scale bar 10 μ m.



Fig. 3 - a) Laurite (lau) inclusion in gersdorffite (grs) - nickeline (nic) grain, scale bar 10 µm; b) irarsite (irar) inclusions in gersdorffite, scale bar 10 µm.

well as the additional contents of Ni, Co and Fe, which apparently came from the gersdorffite hosts.

During the Os isotopic study of the Vasarakangas chromitite (Walker et al., 1996), selected chromitite samples were crushed and chromite was separated using heavy liquids and purified magnetically. Magnetic separation yielded gersdorffite and nickeline (GN) fractions as by-products. To confirm the mode of PGM occurrence, two GN fractions and one chromite fraction were analyzed for PGE and Au at the Geological Survey of Finland by using an inductively coupled mass spectrometer (ICP-MS) and nickel fire assay preconcentration (Juvonen et al., 1994).

PLATINUM-GROUP ELEMENT DISTRIBUTION

The results of PGE analyses of chromite and GN fractions together with the bulk analyses of chromitite are presented in Table 1. The average bulk PGE grades are 60 ppb Os, 36 ppb Ir, 108 ppb Ru, 10 ppb Rh, 7.2 ppb Pt, 2.4 ppb Pd and 8 ppb Au (Vuollo et al., 1995), while in the GN and pure chromite fractions the concentrations of PGE are several orders of magnitude higher and lower, respectively.

The PGE assays of the GN and chromite fractions display (Fig. 4) a classic chondrite-normalized PGE pattern with a steep, negative slope, typical for podiform chromitites in ophiolites (e.g., Page et al., 1982). The high PGE quantities in the GN fractions indicate that the bulk PGE

Table 1 - GE and gold contents in chromitite. Minimun and maximum PGE values are based on PGE analyses of six (6) chromitite samples (Vuollo et al. 1995).

Sample	POL-15	POL-15	POL-8	POL-8		
Fraction	Chr	Grs	Bulk	Grs	Bulk min.	Bulk max.
ppb						
Os	24.8	712.0	118.0	6690.0	29.0	118.0
Ir	14.0	415.0	74.0	4680.0	20.0	74.0
Ru	26.0	1060.0	125.0	14600.0	84.0	125.0
Rh	2.0	76.0	9.0	1140.0	8.0	11.0
Pt	1.4	10.4	8.0	738.0	6.0	27.0
Pd	3.0	16.6	2.0	338.0	2.0	5.0
Au	2.7	13.9	5.0	1380.0	5.0	14.0
Total PGE	71	2290	336	28186		

Chr = chromite fraction, Grs = gersdorffite fraction



Fig. 4 - Chondrite-normalized plots of PGE and gold for a) chromitite and gersdorffite fractions and b) bulk PGE and gold (Vuollo et al. 1995). In Fig. 2a chr denotes to chromitite, grs to gersdorffite fraction and b to bulk sample.

concentrations are controlled mainly by the PGM inclusions within the matrix gersdorffites. The bulk assay is comparable to those reported earlier by Vuollo et al. (1995).

PLATINUM-GROUP MINERALS AND GOLD

Nine laurite, one osarsite and four irarsite grains have been found and identified in this investigation from 17 thin sections and resin mounts (Table 2, Figs. 2 and 3). Within gersdorffite, irarsite, osarsite and laurite occur mostly as subhedral to anhedral inclusions with a maximum dimension of only 10 μ m. However, one exceptionally large Osrich laurite grain with a diameter of 100 μ m was discovered. Native gold was encountered as rare subhedral inclusions within nickeline, but in contrast to gersdorffite, no PGM has been discovered in nickeline.

Individual grains of laurite are rather homogeneous but considerable variation exists between discrete laurite grains. The composition of laurite ranges from $(Ru_{0.93}Ir_{0.13})_{\Sigma 1.06}S_2$ to $(Ru_{0.63}Os_{0.43}Ir_{0.01})_{\Sigma 1.08}$ (As_{0.03}S_{1.97})_{$\Sigma 2$}. Laurite is also marked by a significant enrichment in Os (up to 39.06 wt%), most prominent in the largest 100 µm matrix grain, whereas the Os content in the smallest grains entrapped in gersdorffite is clearly lower, ranging from 23.5 wt% Os to below the detection limit. As the Os content of laurite decreases, the Ir

Sample POL-7N Mineral Laurite size/µm 100x100 method wds Ru 29.7 Os 38.1 Ir 1.3 As 1.0 As 29.6 Fe 0.0 Co 0.0 Ni 0.2 Total 100.2 Ru 20.3 S 29.6 Fe 20.0 Ni 70tal 100.2 Ni 0.2 Ni 0.2 Ni 0.2 Ni 0.2 Ni 0.0 Ni 0.2 Ni 0	POL-7N wds 9 28.43 0 39.06 0 39.06 2 232 6 29.38 0 0.01 2 0.04 2 0.07 6 100.64 6 100.64 6 100.64 8 21.38 8 21.38 8 21.38	POL-8L Laurite 6x3 6x3 eds 23.50 23.50 33.36 -	POL-7N Laurite 6x3 wds 44.45 5.64	POL-7 Laurite 4x3 eds	POL-7N Irarsite	POL-7 Irarsite	POL-8A Irarsite	POL-8L Irarsite	POL-7 Osarsite	POL-7 Gersdorffite	POL-7 Nickeline
method weight per cent Ru 29.7 Os 38.1 Ir 1.3 As 1.0 S 29.6 Fe 0.0 Co 0.0 Ni 0.2 Total 100.2 Ru 20.3 Os 0.0 S 29.6 Fe 0.0 Co 0.0 Ni 0.2 Total 100.2 Ru 20.3 Os 13.8	wds 9 28.43 9 28.43 0 39.06 4 0.72 6 2.32 6 2.32 9 0.01 10 0.02 12 0.04 12 0.04 12 0.06 100.64 0.01 6 100.64 6 100.64 6 101.64 6 101.64 14.16 5	eds 41.78 23.50 33.36 33.36	wds 44.45 5.64	eds	CXU1	8x3	3x2	5X4	3x2	100x100	100x100
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Ir 1.3 As 1.0 S 29.6 Fe 0.0 Fe 0.0 O 0.0 Co 0.0 Ni 0.2 Total 100.2 Ru 20.3 Os 13.8	4 0.72 6 2.32 6 29.38 9 0.01 2 0.04 2 0.04 .6 100.64 .6 100.64 oortions 8 .5 14.16	33.36		0.00	0.00	0.27	I	I	59.21	0.01	0.62
As 1.0 S 29.6 Fe 0.0 Co 0.0 Ni 0.2 Total 100.2 Ru 20.3 Os 13.8	6 2.32 6 2.33 9 0.01 2 0.04 2 0.67 6 100.64 8 21.38 5 14.16	33.36	3.85	13.35	56.85	61.17	52.14	60.85	I	0.35	00.00
S 29.6 Fe 0.0 Co 0.0 Ni 0.2 Total 100.2 Ru 20.3 Os 13.8	6 29.38 9 0.01 2 0.04 6 100.64 6 100.64 8 21.38 5 14.16	33.36	6.54	·	23.98	24.10	25.70	22.17	24.81	48.70	53.23
Fe 0.0 Co 0.0 Ni 0.2 Total 100.2 Ru 20.3 Ru 20.3 Os 13.8	9 0.01 2 0.04 6 100.64 8 21.38 5 14.16		31.67	34.88	11.90	11.46	12.10	11.20	10.03	15.06	0.21
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Ni 0.2 Total 100.2 Ru Atomic prop Os 13.8	2 0.67 6 100.64 oortions 8 21.38 5 14.16	-	0.20	ı	0.03	0.02	ı	I	ı	3.85	0.02
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Atomic prop Ru 20.3 Os 13.8	ortions 8 21.38 5 14.16	98.64	96.86	99.48	98.43	101.28	95.33	97.10	66.66	99.34	99.37
Ru 20.3 Os 13.8	8 21.38 5 14.16										
Os 13.8	5 14.16	22.38	23.38	30.47	3.58	2.08	2.73	1.02	5.80	0.00	0.00
		7.83	1.80	0.00	0.00	0.14	0.00	00.0	30.70	0.00	0.22
Ir 0.4	8 0.26	0.00	1.22	4.17	27.98	30.15	25.53	31.54	0.00	0.11	0.00
As 0.9	7 2.14	0.00	5.30	0.00	30.29	30.47	32.28	29.49	32.66	37.76	47.62
S 63.9.	4 63.19	65.96	60.05	65.36	35.11	33.86	35.52	34.81	30.85	27.29	0.43
Fe 0.1	1 0.02	0.00	0.28	0.00	0.07	0.08	0.00	0.00	0.00	0.52	0.03
Co 0.0	0.05	0.00	0.21	0.00	0.05	0.03	0.00	0.00	0.00	3.80	0.02
Ni 0.2	5 0.79	0.00	4.40	0.00	2.92	3.19	3.93	3.14	0.00	30.53	51.68
Mineral form	nlae										
Ru 0.6	3 0.65	0.68	0.72	0.93	0.11	0.06	0.08	0.03	0.17	0.00	0.00
Os 0.4	3 0.43	0.24	0.06	0.00	0.00	0.00	0.00	0.00	0.92	0.00	0.00
Ir 0.0	0.01	0.00	0.04	0.13	0.84	06.0	0.77	0.95	0.00	0.00	0.00
Fe 0.0	0.00	0.00	0.00	00.0	0.00	0.00	0.00	0.00	0.00	0.02	0.00
Co 0.0	0.00 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00
Ni 0.0	0 0.01	0.00	0.07	0.00	0.09	0.10	0.12	0.09	0.00	0.92	1.08
Σ 1.0	8 1.11	0.92	0.88	1.06	1.04	1.07	0.97	1.07	1.09	1.05	1.08
S 1.9	7 1.93	2.00	1.84	2.00	1.05	1.02	1.07	1.04	0.93	0.82	0.01
As 0.0	0.07	0.00	0.16	0.00	0.91	0.91	0.97	0.88	0.98	1.13	0.99
Σ 2.0	0 2.00	2.00	2.00	2.00	1.96	1.93	2.03	1.93	1.91	1.95	1.00

Table 2 - Selected compositions of platinum-group minerals and representative analysis of gersdorffite and nickeline.

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content increases and reaches 13.35 wt%. Walker et al. (1996) analyzed large matrix laurite for Re-Os isotopes and obtained a near chondritic initial γ_{Os} value of -1.6.

Irarsite varying in composition from $(Ir_{0.90}Ru_{0.06}Ni_{0.10})_{\Sigma 1.07}As_{0.91}S_{1.02}$ to $(Ir_{0.77}Ru_{0.08}Ni_{0.12})_{\Sigma 0.97}As_{0.97}S_{1.02}$ occurs as anhedral to subhedral inclusions in gersdorffite. Only one anhedral osarsite grain with a composition of $(Os_{0.92}Ru_{0.17})_{\Sigma 1.09}As_{0.98}S_{0.93}$, has been found enclosed in gersdorffite.

Small amounts of PGE were also detected from gersdorffite, at maximum 1.2 wt% Ru and 4.6 wt% Os. Either these values originate from minor invisible PGM grains or PGE occur as a solid solution in gersdorffite as suggested by Leblanc et al. (1990).

DISCUSSION

The PGE content and distribution in chromitites from ophiolites of the Mesozoic, Paleozoic and Neoproterozoic ages are comparable (e.g., Leblanc 1991), and the close relationship between chromite and the Ir-group elements (Ir, Os, Ru) is well-documented. Compared with the occurrence of PGM in these younger podiform chromitites (e.g., Augé 1985; 1986, McElduff and Stumpfl 1990), the Paleoproterozoic chromitite from Vasarakangas is exceptional in at least two distinct ways. Firstly, instead of chromite interiors, PGMs are most frequently enclosed in gersdorffites located in the altered silicate matrix. Secondly, in most podiform chromitites matrix-hosted PGMs are Pt-, Pd-, and Rh-rich, whereas in the Vasarakangas chromitite, these minerals are dominated by laurite with some osarsite and irarsite. It is also noteworthy that the large laurite grain that was found in the matrix, has the highest Os content, up to 39.1 wt%. Usually rare matrix laurites in Mesozoic chromitites are low or devoid of Os, which reflects osmium's property to be more prone than Ru to remobilization from laurite (e.g., Garuti and Zaccarini, 1987).

Based on the wholerock PGE patterns, the ultimate origin of the PGMs of the Vasarakangas chromitite is evidently magmatic, but the reason for the exceptional mode of PGM occurrence is unclear. The most probable reason is that the PGMs were originally entrapped in olivine grains, as proposed by McElduff and Stumpfl (1990) for a large matrix laurite in a chromitite from the Troodos ophiolite.

The gersdorffite and nickeline grains occurring in the cracks and rims of chromite and in the matrix as well as osarsite, irarsite and laurite grains occurring as inclusions in gersdorffite, have been interpreted as alteration products of alloys resulting from the introduction of As by late magmatic fluids or during serpentinization processes (e.g., Prichard and Tarkian, 1988; Burkhard, 1989). Based on its occurrence within the matrix and not within gersdorffite, coupled with its high Os content and close to chondritic γ_{Os} value, the large matrix laurite is interpreted to represent a relict of a primary magmatic assemblage.

Several recent studies have confirmed that the modification and alteration of PGMs can result from the involvement of late-magmatic or relatively low-temperature hydrothermal fluids in processes leading either to concentration or remobilization of PGEs (Ballhaus and Stumpfl, 1986; Nilsson 1990; Mogessie et al., 1991; Chen et al., 1993; Caruti and Zaccarini, 1997). Though the subsequent hydrothermal alteration has modified the PGMs, the total PGE content has remained unchanged. At Vasarakangas, the modification of PGMs and the genesis of the gersdorffite-nickeline assemblage are related to the polyphase steatitization processes post-dating the regional amphibolite-facies metamorphism which took place at about 650°C and 3.5 ± 1 kbar (Treloar et al. 1981; Kuronen, 1995). The P-T conditions of late hydrothermal alteration are poorly constrained due to the lack of well-calibrated geothermobarometers. According to the calibration of Kranidiotis and Maclean (1987), the chemical composition of chlorite yielded a temperature range of 226 - 336°C, with an average value of about 300 °C. In the CoAsS-NiAsS-Fe-AsS system (Klemm, 1965), gersdorffite analyses plot in the low temperature region (T < 300°C).

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REFERENCES

- Augé T., 1985. Platinum-group-mineral inclusions in ophiolitic chromitite from the Vourinos complex, Greece. Can. Min., 23: 163-171.
- Augé, T., 1986. Platinum-group mineral inclusions in chromitites from the Oman ophiolite. Bull. Minéral., 109: 301-304.
- Ballhaus C.G. and Stumpfl E.F., 1986. Sulfide and platinum mineralization in the Merensky Reef: evidence from hydrous silicates and fluid inclusions. Contrib. Mineral. Petrol., 94: 193-204.
- Burkhard D.J.M. 1989. Co-Ni-As sulphides in serpentinites of different metamorphic grade in the eastern central Alps (Switzerland and Italy). Mineral Petrol., 41: 65-71.
- Chen Y., Fleet M.E. and Pan Y., 1993. Platinum-group minerals and gold in arsenic-rich ore at the Thompson mine, Thompson nickel belt, Manitoba, Canada. Mineral Petrol., 49, 127-146.
- Gaál G. and Parkkinen J., 1993. Early Proterozoic ophiolite-hosted copper-zinc-cobalt deposits of the Outokumpu type, In: R.V. Kirkham, W.D. Sinclair, R.I. Thorp and J.M. Duke (Eds.), Mineral deposits modeling, Geol. Ass. Can. Paper, 40: 335-341.
- Garuti G. and Zaccarini F., 1997. In situ alteration of platinumgroup minerals at low temperature: Evidence from serpentinized and weathered chromitite of the Vourinos complex, Greece. Can. Min., 35: 611-26.
- Huhma H., 1986. Sm-Nd, U-Pb and Pb-Pb isotopic evidence for the origin of the Early Proterozoic Svecokarelian crust in Finland. Geol. Surv. Finland Bull., 337, 48 p.
- Juvonen R., Kallio E. and Lakomaa T., 1994. Determination of precious metals in rocks by inductively coupled plasma mass spectrometry using nickel sulfide concentration. Comparison with other pre-treatment methods. Analyst, 119: 617-21.
- Klemm D., 1965. Synthesen und analysen in den dreiecksdiagrammen FeAsS- CoAsS-NiAsS und FeS₂-CoS₂-NiS₂. N. Jb. Miner. Abh., 103: 205-255.
- Kranidiotis P. and Maclean W.H., 1987. Systematics of chlorite alteration at the Phelp Dodge massive sulfide deposite, Matagami. Quebec. Econ. Geol., 82: 1898-911.
- Kuronen E., 1995. The Lahnaslampi Soapstone Massif: Its genesis, evolution and present composition as resulting from polyphase metamorphism and deformation. Unpubl.M. Sci. Thesis, University of Oulu, 116 p. (in Finnish).
- Leblanc M., 1991. Platinum-group elements and gold in ophiolitic complexes: Distribution and fractionation from mantle to oceanic floor. In: Peters Tj. et al. (Eds.), Ophiolite genesis and evolution of oceanic lithosphere., Ministry of Petroleum and Minerals, Sultanate of Oman, p. 231-260.

- Leblanc M., Gervilla F. and Jedwab J., 1990. Noble metals segregation and fractionation in magmatic ores from Ronda and Beni Bousera lherzolite massifs (Spain, Morocco). Mineral Petrol., 42: 233- 48.
- Legendre, O. and Augé, T., 1986. Mineralogy of platinum-group mineral inclusions in chromites from different ophiolitic complexes, In: M.J. Gallagher, R.A. Ixer, C.R. Neary and H.M. Prichard (Eds.), Metallogeny of basic and ultrabasic rocks., Inst. Mining Metallurgy, London, p. 361-372.
- Liipo J., Vuollo J., Nykänen V., Piirainen T., Pekkarinen L. and Tuokko, I., 1995. Chromites from the early Proterozoic Outokumpu-Jormua ophiolite belt: a comparison with chromites from Mesozoic ophiolites. Lithos, 36: 15-27.
- McElduff B. and Stumpfl E.F., 1990. Platinum-group minerals from the Troodos ophiolite, Cyprus. Mineral Petrol., 42: 211-32.
- Mogessie A., Stumpfl E.F., Weiblen P.W., 1991. The role of fluids in the formation of platinum-group minerals, Duluth Complex, Minnesota: Mineralogic, textural and chemical evidence. Econ. Geol., 86: 1506-18.
- Mondal S.K. and Baidya T.K., 1997. Platinum-group minerals from the Nuasahi ultramafic-mafic complex, Orissa, India. Min. Mag., 61: 902-6.
- Nilsson L.P., 1990. Platinum-group mineral inclusions in chromitite from the Osthammeren ultramafic tectonite body, south central Norway. Mineral. Petrol., 42: 249-63.
- Page N.J., Cassard D. and Haffty J., 1982. Palladium, platinum,

rhodium, ruthenium and iridium in chromitites from the Massif du Sud and Tiébaghi Massifs, New Caledonia. Econ. Geol., 77: 1571-77.

- Prichard H.M. and Tarkian M., 1988. Platinum and palladium minerals from two PGE-localities in the Shetland ophiolite complex. Canad. Min., 26: 979-90.
- Stockman H.W. and Hlava P.F., 1984. Platinum-group minerals in alpine chromites from south-western Oregon. Econ. Geol., 79: 491-508.
- Treloar P.J., Koistinen T.J. and Bowes D.R., 1981. Metamorphic development of cordierite-amphibole rocks and mica schists in the vicinity of the Outokumpu ore deposit, Finland. Trans. R. Soc. Edinb. Earth Sci., 72: 201-15.
- Thalhammer O.A.R., Prochaska W. and Mühlhans H.W., 1990. Solid inclusions in chrome-spinels and platinum-group element concentrations from the Hochgrössen and Kraubath ultramafic massifs (Austria). Their relationship to metamorphism and serpentinization. Contrib. Mineral. Petrol., 105: 66-80.
- Vuollo J., Liipo J., Nykänen V., Piirainen T., Pekkarinen L., Tuokko I and Ekdahl E., 1995. An early Proterozoic podiform chromitite in the Outokumpu ophiolite complex. Econ. Geol., 90: 445-52.
- Walker R.J., Hanski E.J., Vuollo J. and Liipo J., 1996. The Os isotopic composition of Proterozoic upper mantle: evidence from the Outokumpu ophiolite, Finland. Earth Planet. Sci. Lett., 141: 161-74.

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