

PALLADIUM, PLATINUM, RHODIUM, IRIDIUM AND RUTHENIUM IN CHROMITE-RICH ROCKS FROM THE SAMAIL OPHIOLITE, OMAN

NORMAN J PAGE

*U.S. Geological Survey, 345 Middlefield Road,
Menlo Park, CA 94025, USA*

JOHN S. PALLISTER

*Department of Geological Sciences, University of California,
Berkeley, CA 93106, USA*

MICHAEL A. BROWN AND JOHN D. SMEWING

*Department of Earth Sciences, The Open University, Walton Hall,
Milton Keynes MK7 6AA, England*

JOSEPH HAFFTY

*U.S. Geological Survey, Denver Federal Center, Box 25046,
Denver, CO 80225, USA*

ABSTRACT

Platinum-group element (PGE) distributions, contents, and ratios have been determined in chromitite and chromite-rich rocks from two stratigraphic sections, 250 km apart, through the basal ultramafic member of the Samail (Oman) ophiolite. Chromitite occurs, either as pods and lenses in dunite hosts within foliated harzburgite and subordinate lherzolite of mantle origin, or as discontinuous layers at the base of the overlying cumulus sequence. Both sections show similar abundances of the PGEs, whose average contents in chromite-rich rocks for both sections are, in parts per billion: Pd 8, Pt 14, Rh 6, Ir 48 and Ru 135. The PGE data, combined with major-element and petrographic data on the chromitite, suggest the following tentative conclusions: (1) The middle part of each section contains the highest amount of total PGEs, and has relatively larger contents of Ir and Ru. (2) PGE concentrations and ratios in either section do not correlate with coexisting silicate and chromite abundances and chromite compositions; these differences suggest that the PGEs occur in discrete sulfide or alloy phases rather than in the crystal structure of major oxides and silicates. (3) The Pd/PGE ratio, on average, increases upward in each section. (4) The Samail PGE concentrations, particularly Rh, Pt and Pd, are lower than the average values for chromite-rich rocks in stratiform intrusions; these low concentrations suggest that chromite-rich rocks from the oceanic upper mantle are depleted in PGE with respect to chondrites.

Keywords: Samail ophiolite, platinum-group elements, chromitite, platinum, palladium, rhodium, iridium, ruthenium, Oman.

SOMMAIRE

On a déterminé la distribution, le contenu et les rapports d'éléments du groupe du platine (PGE) dans la chromitite et les roches à chromite abondante le long de deux coupes, séparées de 250 km, dans le membre inférieur ultramafique de l'ophiolite de Samail (Oman). La chromitite forme soit des poches et des lentilles dans des niveaux de dunite au sein d'une harzburgite et d'une lherzolite subordonnée, roches feuilletées d'origine mantellique, soit des couches discontinues à la base d'une séquence cumulus qui les recouvre. Dans les deux cas, les teneurs en PGE sont semblables: en moyenne, les roches riches en chromite contiennent (en milliardièmes): 8 Pd, 14 Pt, 6 Rh, 48 Ir et 135 Ru. Ces données, vu la composition (éléments majeurs) et pétrographie de la chromitite, permettent les conclusions suivantes: (1) La partie centrale de chaque section contient les teneurs globales les plus élevées des PGE, ainsi que des teneurs relatives plus grandes en Ir et Ru. (2) Les concentrations et les rapports des PGE dans chacune des sections ne montrent de corrélation ni avec la distribution des silicates ou de la chromite, ni avec la composition de celle-ci. Ceci fait penser que ces éléments se trouvent répartis plutôt dans des phases sulfurées ou des alliages métalliques que dans la structure des cristaux de silicates ou d'oxydes. (3) Le rapport Pd/PGE, en moyenne, augmente vers le haut dans chaque section. (4) Les concentrations des PGE, dans l'ophiolite Samail, surtout celles de Rh, Pt et Pd, sont ici inférieures aux valeurs moyennes pour les roches à chromite des complexes intrusifs stratiformes. Ces concentrations anormalement basses font supposer que le manteau supérieur subocéanique est appauvri en PGE en comparaison des chondrites.

(Traduit par la Rédaction)

Mots-clés: ophiolite de Samail, éléments du groupe du platine, chromitite, platine, palladium, rhodium, iridium, ruthénium, Oman.

INTRODUCTION

Estimates of platinum-group element (PGE) abundances and ratios in the mantle (Naldrett & Cabri 1976, Crocket 1979, Naldrett & Duke 1980) have been based on a limited number of analyses of presumed mantle-type rocks, including ophiolite sequences (Loney *et al.* 1971, Crocket & Chyi 1972, Crocket & Teruta 1977, Page 1969, Page *et al.* 1979, 1980, Constantinides *et al.* 1980) and ultramafic nodules from kimberlites and basalts (Paul *et al.* 1977, Jagoutz *et al.* 1979, Morgan & Wandless 1979). The paucity of data greatly affects modern discussions on modeling the derivation from the mantle of those magmas that produced economic concentrations of PGE in stratiform ultramafic complexes, the nickel deposits associated with komatiitic and tholeiitic rocks in greenstone belts, and Sudbury-type Ni and Cu deposits. Studies of the PGEs in large stratiform complexes dominated by cumulus processes, such as

the Bushveld, Stillwater and Fiskenaasset, show that Pt and Pd are concentrated with respect to Os, Ir, Rh and Ru. Similarly, a comparison of the average PGE contents of mafic and ultramafic rocks suggests that Pt and Pd are preferentially concentrated in the melt, whereas Ir is retained in the residuum during partial melting in the mantle. Ultramafic rocks (peridotites) that represent both the depleted residuum of partial melting and the products of cumulus crystallization from mantle melts have been recognized in ophiolites (Greenbaum 1972, Glennie *et al.* 1974, Coleman 1979), including the Samail (Hopson *et al.* 1979, Boudier & Coleman 1981). Chromitite generally contains higher PGE concentrations than the enclosing rocks (Page 1969, Page *et al.* 1975, 1979, 1980); it is found within both types of peridotite in the Samail ophiolite. These include layered lensoidal chromitite from the base of the cumulus suite of the ophiolite (Pallister & Hopson 1981) and podiform chromitite from the underlying peridotite tectonite of the mantle suite. Thayer (1969, 1980) has presented arguments that cumulus processes may also have been the major process in the origin of podiform chromitite and the enclosing ultramafic rocks, no matter where they occur in the ophiolite sequence. Brown (1980, 1981) has presented textural and geochemical data in support of the argument that chromitite and dunite bodies in the Samail ophiolite were formed by cumulative processes, even though they differ in many respects from cumulates in stratiform intrusions. The harzburgite host rocks of the chromitite and dunite, on the other hand, bear characteristics thought to indicate a residue of partial melting. A study of the PGE distribution and ratios in ophiolites might be able to distinguish rocks formed by cumulus processes from residual rocks left over from the process of partial melting. The PGE data from the Samail ophiolite definitely bear on this problem.

The Samail ophiolite has been studied extensively in two transects separated by about 250 km (Fig. 1), one near Ibra in the south (Fig. 2A), the other in the Wadi Rajmi and Wadi Rayy to Wadi Jizi in the northern Oman Mountains (Fig. 2B). Two suites of chromite-bearing rocks from the two areas, totaling 30 samples, were collected from the basal ultramafic member (predominantly harzburgite and dunite tectonite) and from near and below the base of the cumulus members. The samples from both areas are referred to the mapped horizon at the base of the cumulates.

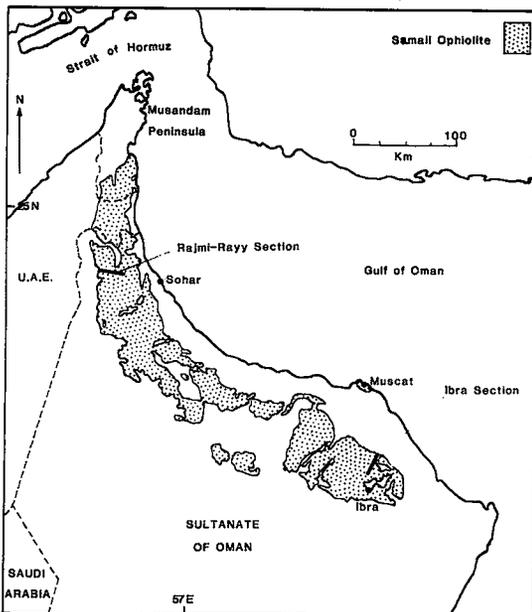
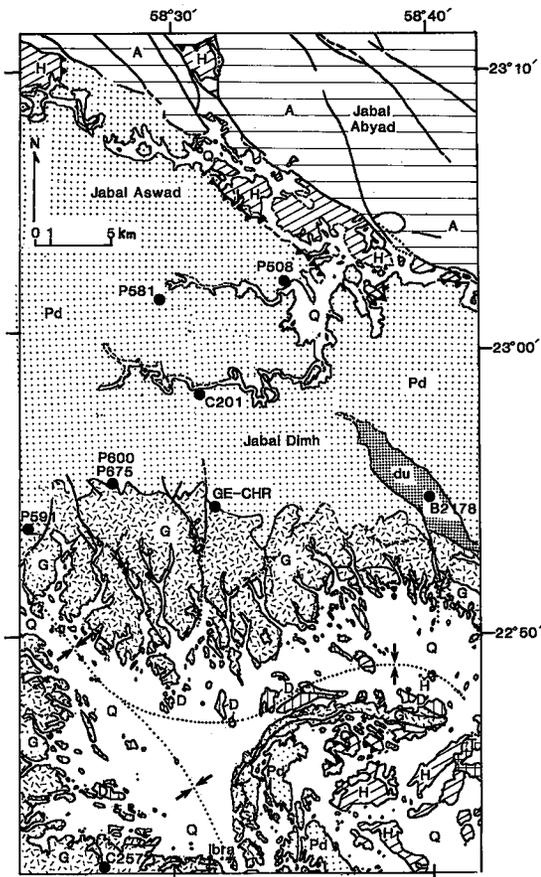


FIG. 1. Location map showing the Ibra and Rajmi-Rayy areas; modified from Glennie *et al.* (1974).



EXPLANATION

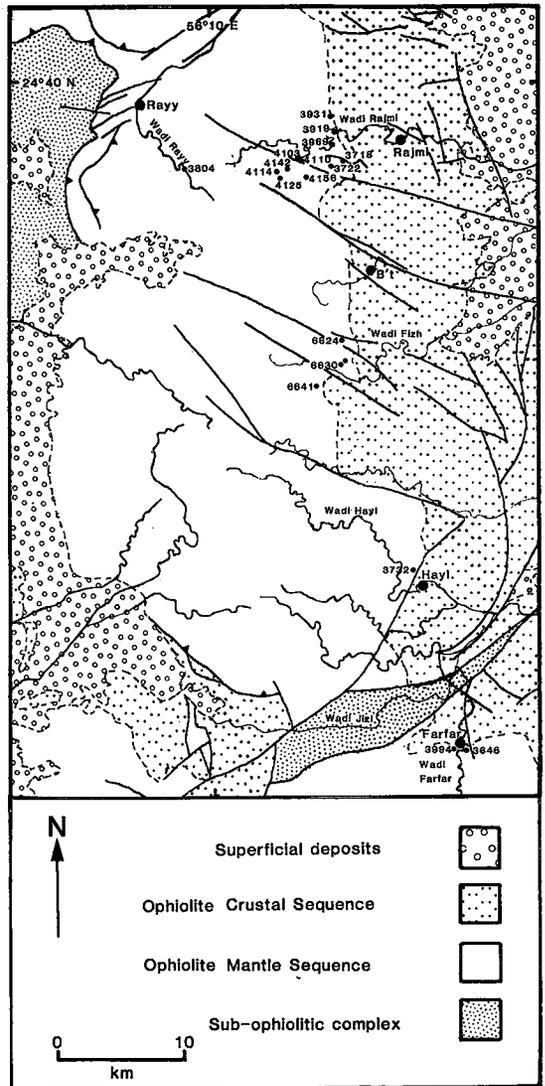
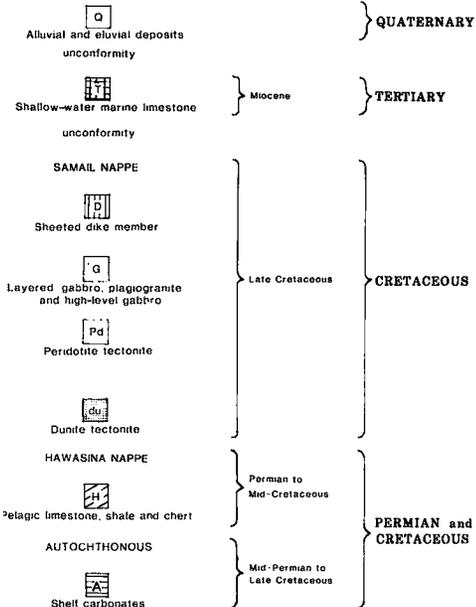


FIG. 2. Locations of chromite samples and their relation to geological units. A. (left) Map of Ibra, modified after Hopson *et al.* (pers. comm. 1981). B. (right) Map of Ramjii-Rayy area, modified from Smewing (1980).

This horizon represents the division between ultramafic upper-mantle rocks and the cumulate gabbroic and basaltic crustal components of the ophiolite. It is termed the "petrologic Moho." Locations of samples selected from the Ibra area are shown in Figure 2A. These samples contain significant amounts of partly to com-

TABLE 1. PALLADIUM, PLATINUM, RHODIUM, IRIIDIUM, AND RUTHENIUM ANALYSES AND SELECTED SEMIQUANTITATIVE SPECTROGRAPHIC ANALYSES OF CHROMITITES FROM THE SAMAIL OPHIOLITE, Cr/Cr+Al AND Mg/Mg+Fe²⁺ RATIOS AND TiO₂ CONTENTS OF CHROMITE AND DISTANCE BELOW THE BASE OF THE CUMULATES

Sample number	Pd	Pt	Rh	Ir	Ru	Co	Cu	Ni	V	Cr/Cr+Al	Mg/Mg+Fe	TiO ₂	Distance (km)
	(parts per billion)					(parts per million)						(weight percent)	
Ibra area													
P-508-1	5	tr	6	30	<100	150	30	1,000	700	0.599	0.736	0.38	8.2
P-581	<4	12	14	50	<100	1560	7	1,500	1,000	0.505	0.736	0.43	7.1
C-201	<4	<10	16	43	150	150	10	1,500	700	0.632	0.730	0.51	3.9
C-201X	<4	<10	13	tr	100	150	50	1,000	1,000	0.597	0.662	0.40	3.9
B-2178	6	<10	<5	30	<100	150	70	1,500	1,500	0.530	0.600	-	1.2
C-257-1	<4	<10	12	32	170	200	2	1,000	1,500	0.533	0.656	0.68	0
C-257-2	<4	<10	<5	30	<100	150	70	1,500	1,000	0.530	0.600	0.67	0
P-591	13	21	tr	<30	<100	150	50	1,500	700	0.538	0.719	0.51	0
P-600-1	<4	<10	<5	<30	<100	150	50	1,000	700	0.574	0.613	0.62	0
P-675-3	<4	<10	<5	<30	<100	100	1.5	1,000	700	0.517	0.677	0.39	0
GE-chr	10	<10	<5	<30	<100	200	15	1,500	1,000	0.471	0.688	0.45	0
NAKHL	4	<10	11	<30	<100	150	7	1,000	1,000	0.457	0.691	0.45	0
Rajmi-Rayy area, Wadi Fizh, Farfar and Hayl areas													
3804	<4	18	10	<36	<120	200	5	1,500	1,000	0.739	0.655	0.13	12.4
4114	5	15	9	160	180	200	7	1,000	1,000	0.623	0.656	0.17	5.2
4125	5	22	tr	67	170	200	10	1,500	1,000	0.672	0.654	0.20	5.0
4142	tr	14	<5	<30	<100	200	70	1,500	1,000	0.575	0.641	0.19	4.3
4103	tr	<10	tr	53	tr	200	70	1,500	1,000	0.656	0.639	0.231	3.8
4110	6	10	tr	65	<200	200	200	1,500	1,500	0.596	0.597	0.17	3.7
4156	71	29	tr	51	tr	200	15	1,000	1,500	0.644	0.631	0.26	2.8
3722	tr	tr	tr	31	tr	150	7	1,500	700	0.656	0.662	0.41	1.5
3969	<4	tr	tr	31	<100	300	7	1,500	1,500	-	-	-	0.8
6624	4	11	tr	<130	<450	200	1.5	1,500	1,000	-	-	-	0.8
6630	4	13	tr	<59	<200	200	3	1,500	1,500	-	-	-	0.8
6641	5	20	tr	<94	<350	200	5	1,500	1,000	0.662	0.669	0.19	0.8
3718	5	13	6	44	120	150	3	1,500	1,500	0.534	0.634	1.06	0.6
3646	tr	22	<5	<30	400	100	5	700	700	0.586	0.670	0.09	0.3
3919	5	tr	tr	39	<100	150	30	1,500	1,000	0.524	0.648	0.25	0.2
3994	<4	13	tr	<30	<100	150	15	1,000	700	-	-	0.14	0.2
3931	<4	tr	tr	35	<100	200	3	700	700	-	-	-	0.05
3732	tr	tr	tr	<30	<100	150	150	1,500	1,000	-	-	-	unknown

Fire assay-emission spectrographic analyses of Pd, Pt, Rh, Ir, Ru analyzed by J. Haffty and A. W. Haubert; six-step semiquantitative analyses for Co, Cu, Ni, and V by L. A. Bradley; chromite analyses by M. A. Brown and J. S. Pallister; tr = trace; - = no data.

pletely serpentinized olivine, altered pyroxene and altered plagioclase. They range from 40 to 95 volume % chromite, and most have cumulus textures. Dots in Figure 2B show the approximate locations of samples of the Rajmi-Rayy and Wadi Jizi chromitites. These samples consist of 90 to 95 volume % chromite. Both sets of samples represent lenses of chromite in dunite pods in harzburgite or layers of chromite in dunite at or near the base of the cumulates.

ANALYTICAL METHODS AND RESULTS

Analytical information, including PGE contents, results of selected semiquantitative spectrographic analyses and of microprobe analyses of the samples from Ibra and Rajmi-Rayy

areas, is given in Table 1. The analyses for platinum, palladium and rhodium were performed by the method of Haffty & Riley (1968), and those for iridium and ruthenium by the method of Haffty *et al.* (1979). Both methods involve a fire-assay preconcentration step described by Haffty *et al.* (1977). Sample size and the methods used define the detection limits for individual elements; these limits, under the best conditions, are less than 4, 10, 5, 30 and 100 parts per billion (ppb) for Pd, Pt, Rh, Ir and Ru, respectively. Smaller-sized samples result in higher reported limits of detection. Sample with "less than" values in Table 1 were not used in the numerical treatments, but are illustrated in the figures by arrows; samples with a trace value (tr) were assigned values of

2, 7, 3, 27 and 97 ppb for Pd, Pt, Rh, Ir and Ru, respectively, and were used in the calculations. The TiO_2 contents, $\text{Cr}/(\text{Cr}+\text{Al})\times 100$, and the $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})\times 100$ ratios of the chromites are derived from microprobe results described by Brown (1981) for the Rajmi-Rayy area and by J.S. Pallister (unpubl. data, 1980) for the Ibra transect. All the rock samples were analyzed for 33 elements by a semiquantitative six-step spectrographic method, and only the more significant elements are shown in the table.

INTERPRETATION AND ANALYSIS OF VARIATIONS OF THE PLATINUM-GROUP ELEMENTS

In chromite-rich rocks from the Samail ophiolite (Table 1), palladium attains values of 71 ppb and averages 8 ± 15 ppb (\pm value is one standard deviation) for the 19 detectable concentrations; platinum attains a maximum of 29 ppb and averages 14 ± 6 ppb for the 20 detectable concentrations, rhodium attains a value of 16 ppb and averages 6 ± 4 ppb for the 23 detectable concentrations, iridium attains 160 ppb and averages 48 ± 31 ppb for the 17 detectable concentrations, and ruthenium attains 180 ppb and averages 135 ± 36 ppb for the 8 detectable concentrations. If these averages are compared to average values derived from Morgan & Wandless (1979) for ultramafic nodules, 4.5 ppb Pd and 4.2 ppb Ir based on 20 and 11 analyses, respectively, then the higher Pd and Ir content of the chromite-rich rocks is demonstrated. Figures 3A and 3B illustrate the concentration levels of PGE in both the Ibra and Rajmi-Rayy chromitites. The lowest concentration levels of PGE occur about 0.25 km below the base of the cumulates in the Rajmi-Rayy section (Fig. 3B); no samples from this interval are available for the Ibra area. The ratios of an individual PGE to the sum of the five PGEs for the Ibra section suggest that Pd and Pt increase upward in section and Ir decreases, whereas in the Rajmi-Rayy area, Pd tends to increase upward. Of course, these trends are not statistically valid, given the variation in the data.

At the 97.5% confidence level, the means of the detectable concentrations of Pd, Pt, Rh, Ir and Ru for the Ibra sections show no significant difference from the means for the Rajmi-Rayy section. Because of this similarity, together with the similar patterns of distribution with regard to stratigraphic position and the overall similarity of the geology, petrology and major-element chemistry, the data for both sections were combined. These data are as-

sumed to represent the overall generalized pattern of distribution with regard to stratigraphic position for chromite-rich rocks in the ultramafic member of the Samail ophiolite. In Figure 4, the concentration data were combined as averages; calculated ratios for each individual metal illustrate the generalized pattern and the changes of the ratios with distance below the base of the cumulates. This figure demonstrates that the highest concentration of platinum-group elements (Pd+Pt+Rh+Ir+Ru) occurs between 2 and 6 km from the base of the cumulates and suggests that the platinum-group elements ratios vary widely through the section.

Using the Spearman rank-correlation technique and *t* tests of significance of the correlations, various properties of the samples were tested for correlations with the PGE concentrations and ratios. These properties include % spinel, $\text{Cr}/(\text{Cr}+\text{Al})$ and $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ in chromite, TiO_2 content of chromite, and semiquantitative trace-element content of the rock samples (specifically Co, Cu, Ni and V). The Ibra and Rajmi-Rayy sections were tested separately and then in combination to determine whether any correlations exist. Very few correlations were found with a coefficient greater than 0.5 and greater than a 95% confidence level. Those significant correlations for the combined sections that have correlation coefficients between 0.5 and 0.75 are for (a) $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ in chromite with the Rh/PGE ratio, (b) $\text{Cr}/(\text{Cr}+\text{Al})$ with Rh/PGE and Ir/PGE ratios, and (c) Ir with the concentration of TiO_2 in chromite. The scatter diagrams also demonstrate that few correlations exist, and those that have statistical significance may or may not have any geological or geochemical significance. No correlations of the trace elements with PGE concentrations or PGE ratios were found. The net result of this analysis is that coexisting silicate and chromite abundances, chromite composition and chromitite trace-element concentrations show little correlation with platinum-group element concentrations and ratios. It follows that the majority of the platinum-group elements probably occur as discrete platinum-group metal sulfide or alloy phases, rather than in specific structural sites in the oxides and silicates. In fact, osmium- and iridium-bearing laurite ($\text{Ru}, \text{Os}, \text{Ir}$) S_2 and iridium- and ruthenium-bearing erlichmanite ($\text{Os}, \text{Ir}, \text{Ru}$) S_2 have recently been identified in chromitite from the Kokkinorotsos chrome mine in the Troodos ophiolite at Cyprus (Constantinides *et al.* 1980), a discovery that suggests that such

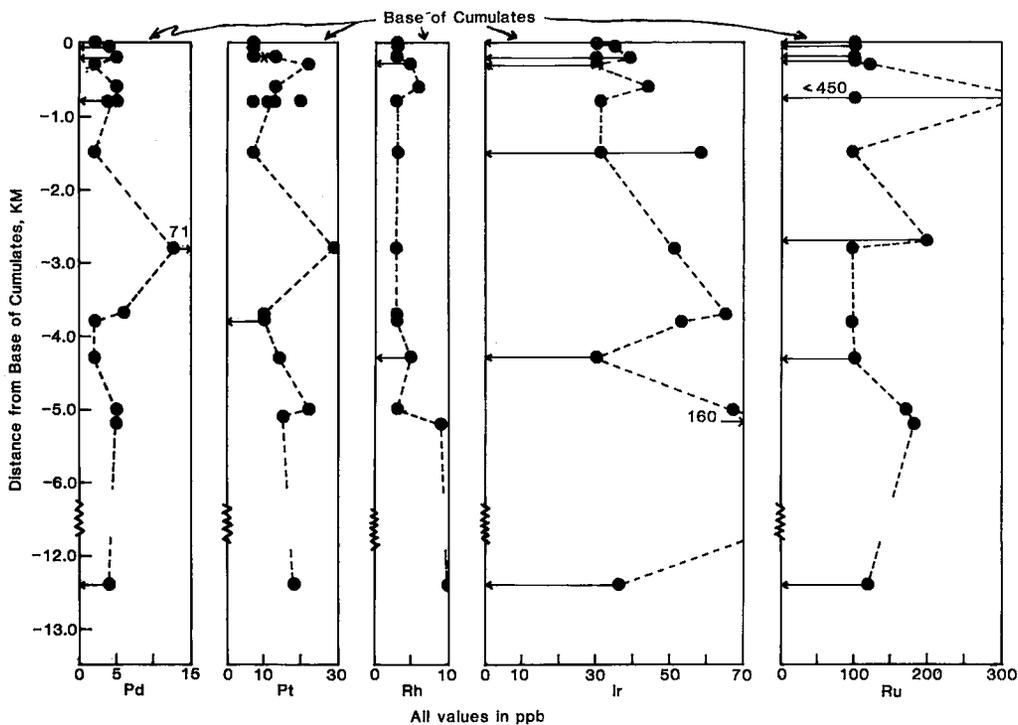
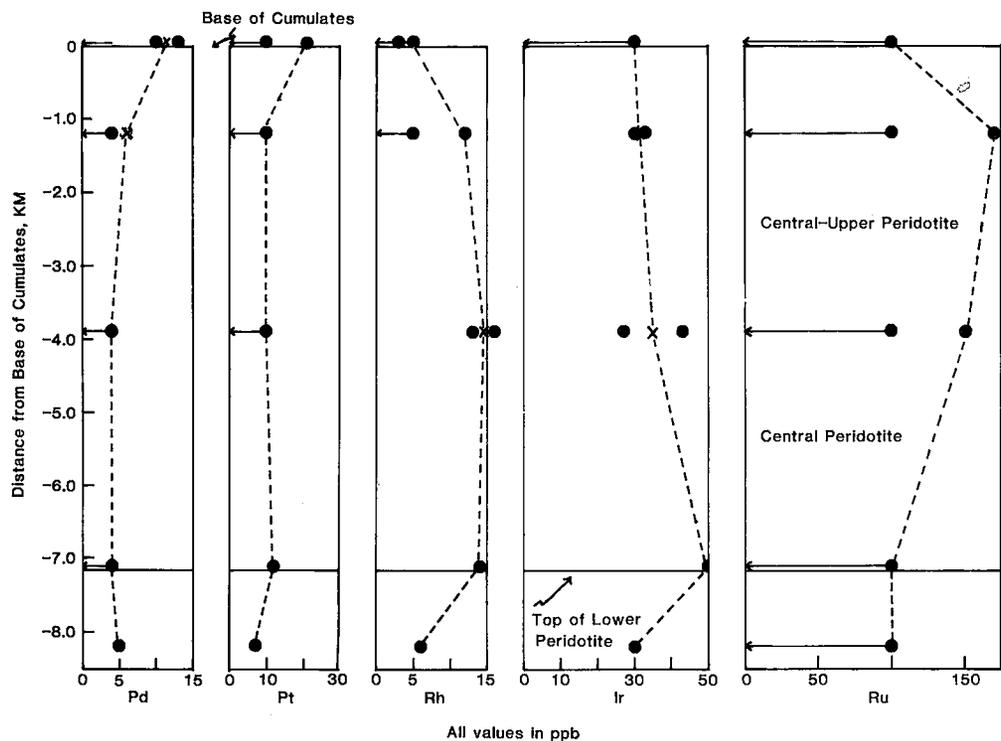


FIG. 3. Variation in PGEs with stratigraphic distance below the base of the cumulates. A. Ibra area, B. Rajmi-Rayy area.

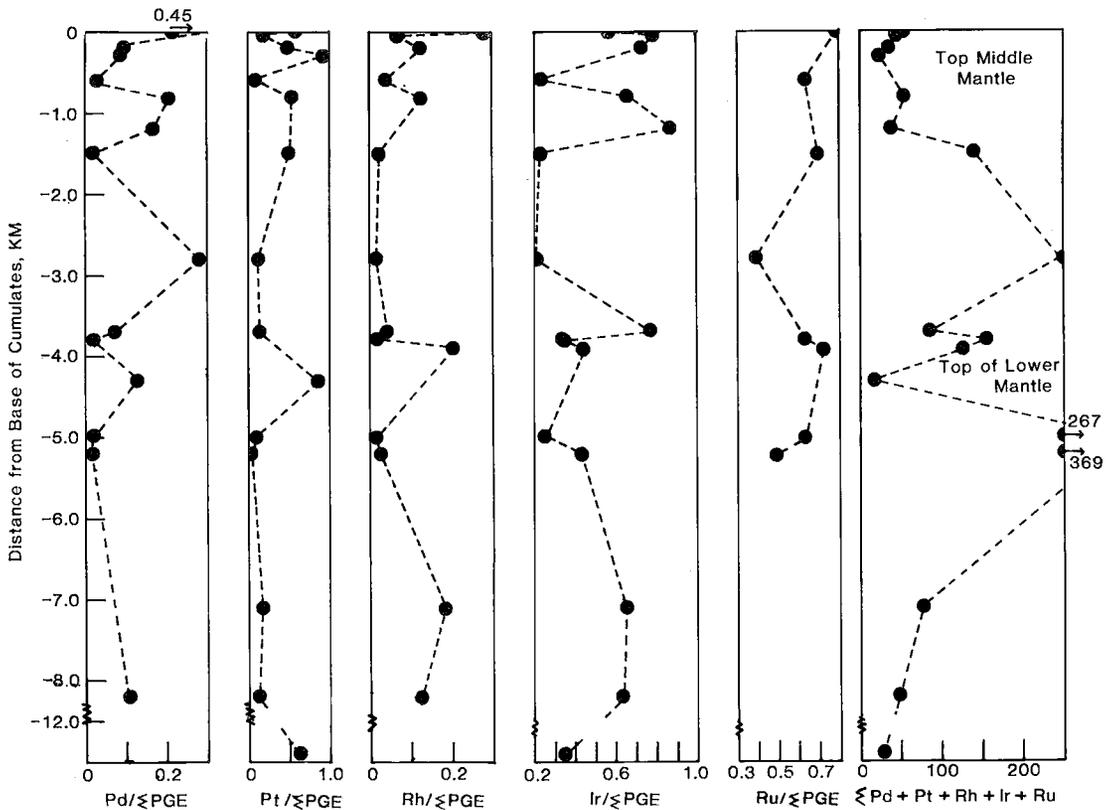


FIG. 4. Variation in the ratio of Pd, Pt, Rh, Ru and Ir to the sum of PGEs ($Pd+Pt+Rh+Ir+Ru$) with stratigraphic distance below the base of the cumulates for the combined Ibra and Rajmi-Rayy areas of the Samail ophiolite.

phases may be eventually identified in Oman. The paucity of correlations also suggests that the phases into which the PGEs partition react independently to mantle processes from the silicates and oxides. The exceptions to these generalizations are that the Rh/PGE and Ir/PGE ratios may be related in some way to chromite compositions; the relation is suggested by a weak correlation. That is, Rh may be present in the structure of the chromite (Grimaldi & Schnepfe 1969); such presence would account for the better correlation obtained. Ross & Keays (1979) reported that in olivine from komatiites of western Australia, Ir occurs in concentrations of about 5.68 ppb and Pd in concentrations below 0.21 ppb; those data can be interpreted to suggest that in olivine of mantle rocks, Ir occurs in lattice sites. That interpretation is not supported here because of the absence of correlations in the more silicate-rich chromitites from the Samail ophiolite.

Limited data suggest that the distributions,

concentrations and ratios of the platinum-group elements in chromitites from the Samail ophiolite are similar to those in other ophiolites. Because analyses of Ir and Ru from other occurrences are sparse, Figure 5 compares only Pd, Pt and Rh ratios. Analyses of ophiolites from Turkey and Iran (Page *et al.* 1979), from Pakistan (Page *et al.* 1980), the United States (Page *et al.* 1975, Page 1969, Loney *et al.* 1971, Keith & Foster 1973, Clark & Greenwood 1972) and from the Urals (Fominykh & Khvostova 1970) are included as average ratios in Figure 5. Examination of the distribution patterns of the Ibra and Rajmi-Rayy ratios shown in Figure 5 and comparison of these with average ratios from other ophiolites show no discernible differences or similarities.

Another way of examining the data from Oman is to normalize the data with respect to chondrite averages and to plot the data on diagrams similar to those used for the rare-earth elements. This method has been used

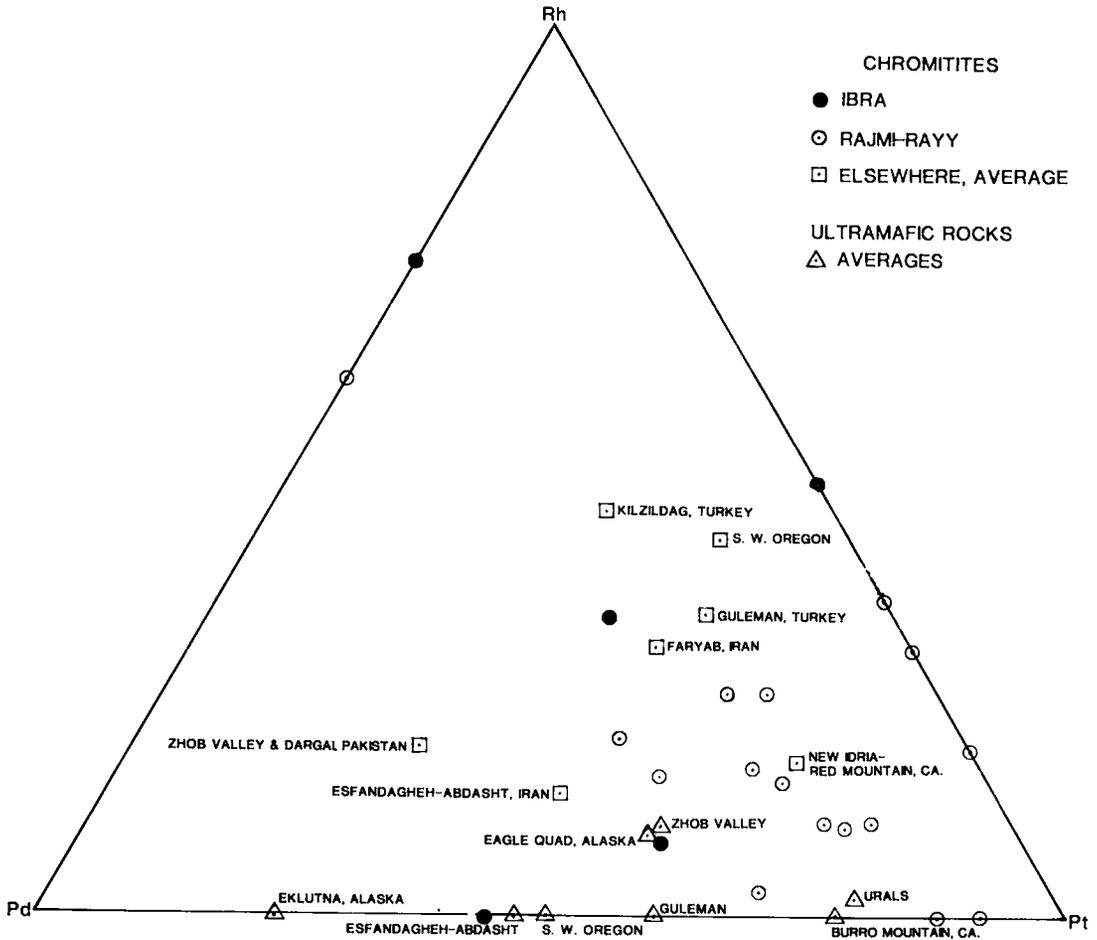


Fig. 5. Palladium, platinum and rhodium ratios of the chromitite from the Samail ophiolite compared with average data from other ophiolites.

by Naldrett *et al.* (1979) for nickel sulfide deposits of the Sudbury district and those associated with komatiites. Chondrite concentrations used in normalizing (in ppb) are: Pd 1,200, Pt 1,500, Rh 200, Ru 1,000 and Ir 500; these are the average values given by McBride (1972). In Figure 6, the results for each are split into two groups: chromitite at or near the base of the cumulates (for Ibra, all samples between 0 and 1.2 km, for the Rajmi-Rayy, all samples between 0 and 1.5 km) and chromitite from deeper in the section. The lines or boundaries for each grouping represent samples with maximum and minimum contents; all other samples fall between these boundaries. In both areas, from both near the base of the cumulates and deeper in the harzburgite section, chromitite is

more depleted with respect to chondrite in Rh, Pt and Pd than in Ru and Ir, in comparison, with respect to chondrite. The diagrams also demonstrate that the chromitite at or near the base of the cumulates tends to be more depleted with respect to chondrite than are the chromitites from deeper in the section.

The pattern of chondrite-normalized PGE contents in chromite of the Samail ophiolite differs strikingly from that in stratiform ultramafic complexes derived from the differentiation of basaltic and komatiitic magmas (Fig. 7). The values for the Stillwater complex represent averages of the Ir, Ru, Pt, Pd and Rh chondrite-normalized ratios calculated from the concentration data for chromitite, ultramafic and mafic rocks given by Page *et al.* (1976,

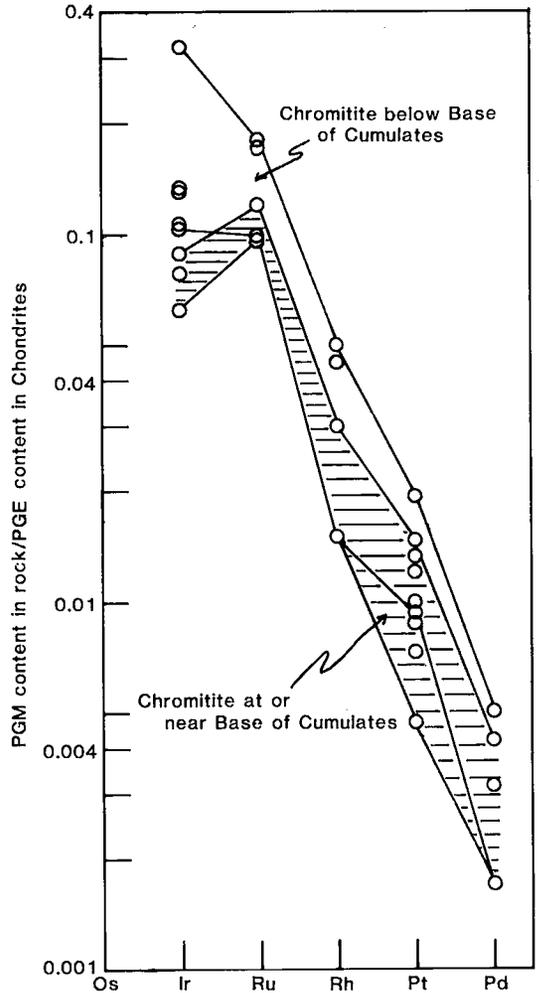
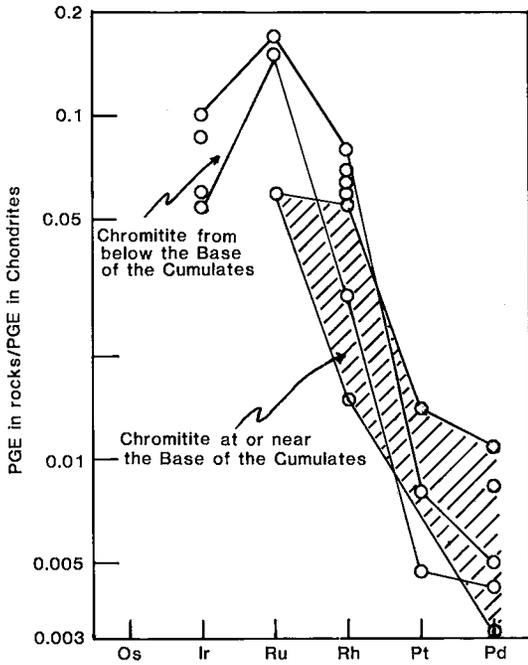


FIG. 6. Chondrite normalized PGE data for the chromitite from the Samail ophiolite. A. Ibra section, (above) B. Rajmi-Rayy section.

Table 1, p. 1355). These values are strongly weighted by compositions of chromitite samples from the ultramafic zone. Concentration data (Naldrett & Cabri 1976, Table 5D) were used to calculate chondrite-normalized PGE contents for the Merensky Reef of the Bushveld complex and for the Sudbury deposits, whereas PGE proportions from Smirnov (1977) were combined with the data of Naldrett & Cabri (1976, Table 5D) to arrive at a pattern representing deposits of the Noril'sk (U.S.S.R.) type. The Noril'sk, Sudbury and Merensky Reef PGE contents resemble those of materials more sulfide-enriched than rocks of the Stillwater complex and the Samail ophiolite. All the average patterns obtained from rocks of stratiform basaltic-magma systems, whether derived from chromitite or sulfide-enriched materials, show relative enrichment in Rh, Pt and Pd relative to Ir, Ru and Os. All of the chondrite-normalized patterns show positive slopes. Patterns for nickel-copper deposits associated with komatiitic rocks (Naldrett *et al.* 1979, Naldrett 1981) also slope positively, but they have

lesser slopes than those shown in Figure 7. However, chondrite-normalized PGE data from the Samail ophiolite have a negative slope, which emphasizes the relative enrichment in Ir and Ru relative to Pt and Pd for the ophiolite. These features suggest that either the PGEs in the ultramafic section of the ophiolite do not show or retain evidence for such cumulus processes as those observed in the Stillwater complex or, possibly, the magma from which the Samail chromitite originated was derived from a mantle previously depleted in Pt and Pd.

CONCLUSIONS

Estimates of average PGE concentrations in chromite-rich rocks of the harzburgite tectonite portions of oceanic mantle may be in the range of 8 ppb for Pd, 14 ppb for Pt, 6 ppb

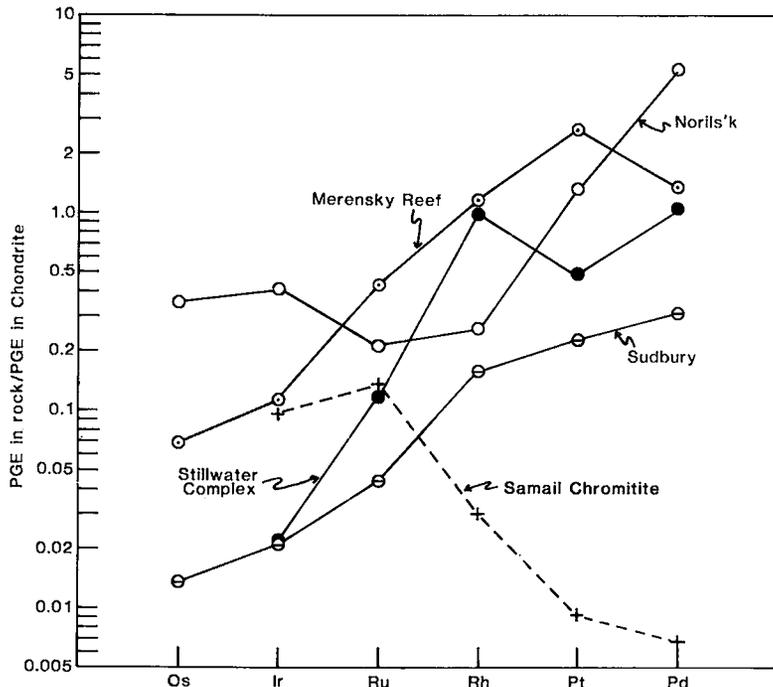


FIG. 7. Chondrite-normalized PGE patterns from the Samail ophiolite complex compared with those from the Stillwater complex, Merensky Reef of the Bushveld complex, Sudbury and Noril'sk.

for Rh, 48 ppb for Ir and 135 ppb for Ru. The actual values are probably lower, because samples containing less than detectable concentrations were not included in the average. Data for the peridotite tectonite parts of ophiolites from Pakistan, Turkey, Iran, Oregon, California, Eagle quadrangle (Alaska) and Mt. Albert (Quebec), used to construct Figure 5, support the argument for lower PGE concentrations in the harzburgite portions of the oceanic mantle than in the chromitites. Averages for alpine-type complexes in the Urals (Naldrett & Cabri 1976, Table 5A) are 18 ppb Pd and 73 ppb Pt, with low values for Os, Ir, Ru and Rh; these data perhaps suggest a different mantle composition than in Oman. More analytical studies of PGE in mantle-type rocks are needed in order to characterize different types of mantle. However, the limited data suggest that most of the tectonic parts of ophiolites represent oceanic mantle that is depleted in PGE with respect to chondrite, especially in Rh, Pt and Pd.

Specific conclusions concerning the PGEs in the chromitite of the Samail ophiolite are: (1) the middle parts of both Ibra and Rajmi-Ray

sections contain the highest concentrations of total PGEs and are slightly enriched relatively in Ir and Ru. (2) All PGE concentrations in Oman show opposite enrichment patterns to those of stratiform intrusive complexes when normalized to chondrite ratios. (3) PGE contents and ratios are not correlated with properties of the silicates and chromites; they appear to have responded differently to processes that affected the major part of the rocks. These differences suggest that the PGEs occur in discrete sulfide or alloy phases. (4) In general, in the Samail ophiolite the Pd/PGE ratio tends to increase upward. (5) The cumulus history of the chromitite in dunite pods in the Samail ophiolite may have differed from that of stratiform intrusions in its effect on concentrations, ratios and distributions of platinum-group elements.

REFERENCES

- BOUDIER, F. & COLEMAN, R.G. (1981): Cross section through the peridotite in the Samail ophiolite, southeastern Oman Mountains. *J. Geophys. Res.* 86, 2573-2592.

- BROWN, M.A. (1980): Textural and geochemical evidence for the origin of some chromite deposits in Oman ophiolite. In *Ophiolites*, Proc. Int. Ophiolite Symp. 1979 (A. Panayiotou, ed.). *Geol. Surv. Cyprus*, 714-721.
- (1981): *Chromite Deposits and Ultramafic Host Rocks in the Oman Ophiolite*. Ph. D. thesis, Open Univ., Milton Keynes, U.K.
- CLARK, A.L. & GREENWOOD, W.R. (1972): Geochemistry and distribution of platinum-group metals in mafic to ultramafic complexes of southern and southeastern Alaska. *U.S. Geol. Surv. Prof. Pap.* 800-C, 157-160.
- COLEMAN, R.G. (1979): *Ophiolites, Ancient Oceanic Lithosphere?* Springer-Verlag, New York.
- CONSTANTINIDES, C.C., KINGSTON, G.A. & FISHER, P.C. (1980): The occurrence of platinum-group minerals in the chromitites of the Kokkinorotsos chrome mine, Cyprus. In *Ophiolites*, Proc. Int. Ophiolite Symp. 1979 (A. Panayiotou, ed.). *Geol. Surv. Cyprus*, 93-101.
- CROCKET, J.H. (1979): Platinum-group elements in mafic and ultramafic rocks: a survey. *Can. Mineral.* 17, 391-402.
- & CHYI, L.L. (1972): Abundances of palladium, indium, osmium and gold in an Alpine ultramafic pluton. *Int. Geol. Congr.* (24th) 10, 202-209.
- & TERUTA, Y. (1977): Palladium, iridium, and gold contents of mafic and ultramafic rocks drilled from the mid-Atlantic ridge, Leg 37, Deep Sea Drilling Project. *Can. J. Earth Sci.* 14, 777-784.
- FOMINYKH, V.G. & KHVOSTOVA, V.P. (1970): Distribution of platinum metals in rock-forming minerals of the Gusevogorskoye deposit. *Dokl. Acad. Sci. USSR, Earth Sci. Sect.* 200, 182-183.
- GLENNIE, K.W., BOEUF, M.G.A., CLARKE, M.W., MOODY-STUART, M., PILAAR, W.F.H. & REINHARDT, B.M. (1974): Geology of the Oman Mountains, Arabia. *Yerh. Koninkl. Ned. Geol. Mijnbouwkd. Genoot., Geol. Ser.* 31.
- GREENBAUM, D. (1972): Magmatic processes at ocean ridges: evidence from the Troodos massif, Cyprus. *Nature Phys. Sci.* 238, 18-21.
- GRIMALDI, F.S. & SCHNEFFE, M.M. (1969): Mode of occurrence of platinum, palladium, and rhodium in chromitite. *U.S. Geol. Surv. Prof. Pap.* 650-C, 149-151.
- HAFFTY, J., HAUBERT, A.W. & PAGE, N.J. (1979): Determination of iridium and ruthenium in geological samples by fire assay and emission spectrography. *U.S. Geol. Surv. Prof. Pap.* 1129-G.
- & RILEY, L.B. (1968): Determination of palladium, platinum, and rhodium in geologic materials by fire assay and emission spectrography. *Talanta* 15, 111-117.
- , ——— & GOSS, W.D. (1977): A manual on fire assaying and determination of the noble metals in geological materials. *U.S. Geol. Surv. Bull.* 1445.
- HOPSON, C.A., PALLISTER, J.S. & COLEMAN, R.G. (1979): Petrologic processes at oceanic crust-mantle boundary, southeastern Samail ophiolite, Oman. *Amer. Geophys. Union Trans.* 60, 962 (abstr.).
- JAGOUTZ, E., PALME, H., BADDENHAUSEN, H., BLUM, K., CENDALES, M., DREIBUS, G., SPETTEL, B., LORENZ, V. & WAENKE, H. (1979): The abundances of major, minor, and trace elements in the earth's mantle as derived from primitive ultramafic nodules. *Lunar Planet. Sci.* 10, 610-612.
- KEITH, T.E.C. & FOSTER, H.L. (1973): Basic data on the ultramafic rocks of the Eagle quadrangle, east-central Alaska. *U.S. Geol. Surv. Open-File Rep.* 73-581.
- LONEY, R.A., HIMMELBERG, G.R. & COLEMAN, R.G. (1971): Structure and petrology of the Alpine-type peridotite at Burro Mountain, California, U.S.A. *J. Petrology* 12, 245-309.
- MCBRIDE, W.A.E. (1972): Platinum metals. In *The Encyclopedia of Geochemistry and Environmental Sciences* (R. W. Fairbridge, ed.). Van Nostrand Reinhold, New York.
- MORGAN, J.W. & WANDLESS, G.A. (1979): Terrestrial upper mantle: siderophile and volatile trace element abundances. *Lunar Planet. Sci.* 10, 855-857.
- NALDRETT, A.J. (1981): Nickel sulfide deposits: classification, composition and genesis. *Econ. Geol., 75th anniv. vol.*, 628-685.
- & CABRI, L.J. (1976): Ultramafic and related mafic rocks: their classification and genesis with special reference to the concentration of nickel sulfides and platinum-group elements. *Econ. Geol.* 71, 1131-1158.
- & DUKE, J.M. (1980): Platinum metals in magmatic sulfide ores. *Science* 208, 1417-1424.
- , HOFFMAN, E.L., GREEN, A.H., CHOU, CHEN-LIN, NALDRETT, S.R. & ALCOCK, R.A. (1979): The composition of Ni-sulfide ores, with particular reference to their content of PGE and Au. *Can. Mineral.* 17, 403-415.

- PAGE, N.J. (1969): Platinum content of ultramafic rocks. *U.S. Geol. Surv. Circ.* 622.
- , ENGIN, T. & HAFFTY, J. (1979): Palladium, platinum, and rhodium concentrations in mafic and ultramafic rocks from the Kizildag and Guleman areas, Turkey, and the Faryab and Esfandagheh-Abdasht areas, Iran. *U.S. Geol. Surv. Geol. Surv. Open-File Rep.* 79-340.
- , HAFFTY, J. & AHMAD, Z. (1980): Palladium, platinum, and rhodium concentrations in mafic and ultramafic rocks from the Zhob Valley and Dargai complexes, Pakistan. *U.S. Geol. Surv. Prof. Pap.* 1124-F, 1-6.
- , JOHNSON, M.G., HAFFTY, J. & RAMP, L. (1975): Occurrence of platinum group metals in ultramafic rocks of the Medford-Coos Bay 2° quadrangles, southwestern Oregon. *U.S. Geol. Surv. Misc. Field Stud. Map* MF-694.
- , ROWE, J.J. & HAFFTY, J. (1976): Platinum metals in the Stillwater complex, Montana: *Econ. Geol.* 71, 1352-1363.
- PALLISTER, J.S. & HOPSON, C.A. (1981): Samail ophiolite plutonic suite: field relations, phase variation, cryptic variation and layering; and a model of a spreading ridge magma chamber. *J. Geophys. Res.* 86, 2593-2644.
- PAUL, D., CROCKET, J.H. & NIXON, P. (1977): Abundances of palladium, iridium, and gold in kimberlites and associated nodules. *Ext. Abstr., 2nd Int. Kimberlite Conf.* (Santa Fe), 272-279.
- ROSS, J.R. & KEAYS, R.R. (1979): Precious metals in volcanic-type nickel sulfide deposits in western Australia. I. Relationship with the composition of the ores and their host rocks. *Can. Mineral.* 17, 417-435.
- SMEWING, J.D. (1980): An Upper Cretaceous ridge-transform intersection in the Oman ophiolite. In *Ophiolites: Proc. Int. Ophiolite Symp. 1979* (A. Panayiotou, ed.). *Geol. Surv. Cyprus*, 407-413.
- SMIRNOV, V.I., ed. (1977): *Ore Deposits of the USSR. III.* Pitman Publ., San Francisco.
- THAYER, T.P. (1969): Gravity differentiation and magmatic re-emplacment of podiform chromite deposits. *Econ. Geol. Mon.* 4, 132-146.
- (1980): Syncrystallization and subsolidus deformation in ophiolitic peridotite and gabbro. *Amer. J. Sci.* 280-A, 269-283.

Received March 1982, revised manuscript accepted May 1982.