

Platinum-group elements as petrological indicators in mafic–ultramafic complexes of the central and southern Urals: preliminary results

G. Garuti ^{a,*}, G. Fershtater ^b, F. Bea ^c, P. Montero ^c, E.V. Pushkarev ^b, F. Zaccarini ^a

^a Department of Earth Sciences, University of Modena, Via S. Eufemia 19, 41100 Modena, Italy

^b Institute of Geology and Geochemistry, Ural Branch, Ekaterinburg, Russia

^c Department of Mineralogy and Petrology, University of Granada, Granada, Spain

Received 30 April 1996; accepted 25 October 1996

Abstract

Platinum-group elements (PGE) and gold were analyzed by ICP-MS after the Ni-sulphide fire assay pre-concentration step in 44 rocks from 5 orogenic mafic–ultramafic massifs of the central and southern Urals. They comprise: (a) ring-zoned, Ural–Alaskan type bodies of the ‘Pt-bearing belt’ (Kachkanar, Tagil, Uktus); and (b) lherzolite–harzburgite complexes overlain by layered wehrlite, gabbro, and diorite (Nurali, Mindyak) supposed to be ophiolite-type suites.

Total PGE and Au contents are generally higher in Ural–Alaskan type complexes compared with lherzolite–harzburgite complexes. Mantle-normalized PGE patterns range from nearly unfractionated in the dunites ($Pd/Ir = 0.57–3.68$) to mildly and strongly fractionated in wehrlite, clinopyroxenite, and gabbro ($Pd/Ir = 9.1–187$). Exceptionally high values of Pd/Ir (761–2622) are observed in amphibole-rich lithologies at Kachkanar, possibly indicating a relationship between fractionation of the less refractory Pd and increased fluid activity in the parental magma. Pronounced, positive Pt-anomalies, up to 20 times the mantle estimate, distinguishes the Ural–Alaskan type dunites, and progressively reduces in pyroxenites and gabbros. In the lherzolite–harzburgite complexes of Mindyak and Nurali, layered wehrlites and pyroxenites, as well as rocks from the gabbro–diorite units have fractionated PGE patterns ($Pd/Ir = 2.94–92.39$) and positive Pt-anomaly as in the Ural–Alaskan complexes. Conversely, the Pt-anomaly is negative in the peridotites, and increases from lherzolites and harzburgites, to dunites, similarly to residual mantle from alpine-type orogenic massifs. The Pd/Ir (0.71–3.7) is higher than in ophiolites, and resembles that of lherzolite massifs of the western Mediterranean, representing sub-continental mantle.

Variation of the Pt-anomaly versus Pd/Ir in Ural–Alaskan type complexes and in the layered sequences overlaying lherzolite–harzburgite mantle suites is consistent with magmatic fractionation, in which Pt behaves as a compatible element. It reflects a progressive depletion by partial melting in mantle peridotites, the Pt becoming incompatible in the last stage of melting in which Pt-poor residual dunites are formed. The positive Pt-anomaly in Ural–Alaskan type complexes is striking, and would appear as a distinctive feature of the parent magma, probably inherited from its mantle source.

Keywords: platinum; elements; ultramafics; Urals

1. Introduction

Platinum-group elements (PGE) have long been considered as a major target for mining exploration,

but due to developments in analytical techniques and increasing available data, their potential as petrological indicators of the evolution of ultramafic–mafic rocks was soon recognized and emphasized in many natural examples (Naldrett and Cabri, 1976; Crocket, 1981; Barnes et al., 1985, 1988; Lorand, 1989; Leblanc, 1991; Garuti et al., 1984, 1995). Be-

* Corresponding author. Tel.: +39 (59) 417225; Fax: +39 (59) 417292; E-mail: garutig@unimo.it

cause of their siderophile nature, PGE concentrated in the earth's core and mantle during early history of the planet (Jagoutz et al., 1979; Arculus and Delano, 1981; O'Neill, 1991), and consistently with this geochemical behaviour, their crustal 'clarke' values are remarkably low, frequently close to the detection limits. Transfer of PGE from the mantle into the crust is confined to specific geodynamic areas in which important mantle–crust interactions (obduction of mantle fragments, injection of mantle-derived melts; Naldrett, 1981) occur. PGE are geochemical monitors of these geological processes, and able to give information about the petrological nature and evolution of the mantle source from which they were derived.

In the Ural orogen, Palaeozoic collision between the East European continental platform to the west and the Asian plate to the east, brought to the surface suites of ultramafic–mafic complexes which now are located along the Main Uralian Fault (Fig. 1) in the

Suture Megablock Zone (Fershtater et al., 1997). The ultramafic–mafic complexes can be divided into three types: (1) harzburgite–dunite–volcanics associations representing sections through the upper mantle–crust transition in sub-oceanic areas (ophiolites); (2) concentrically zoned dunite–clinopyroxenite–gabbro intrusions derived from magmatic activity in ocean–continent collision areas (Ural–Alaskan type complexes); (3) lherzolite–harzburgite complexes considered as weakly depleted ophiolite suites constituting the floor for overthrusting, allochthonous, huge ophiolite massifs (Kraka, Khabarny) representing true oceanic crust (Savelieva, 1987; Saveliev and Saveliev, 1992). Secondary PGE-deposits of economic importance were known to occur in some of these complexes, being genetically related with primary proto-concentrations in mineralized magmatic rocks (Betchtin, 1961; Razin, 1976). It has recently been recognized that distinctive PGE assemblages are related to different magmatic associations: (a) Ir–

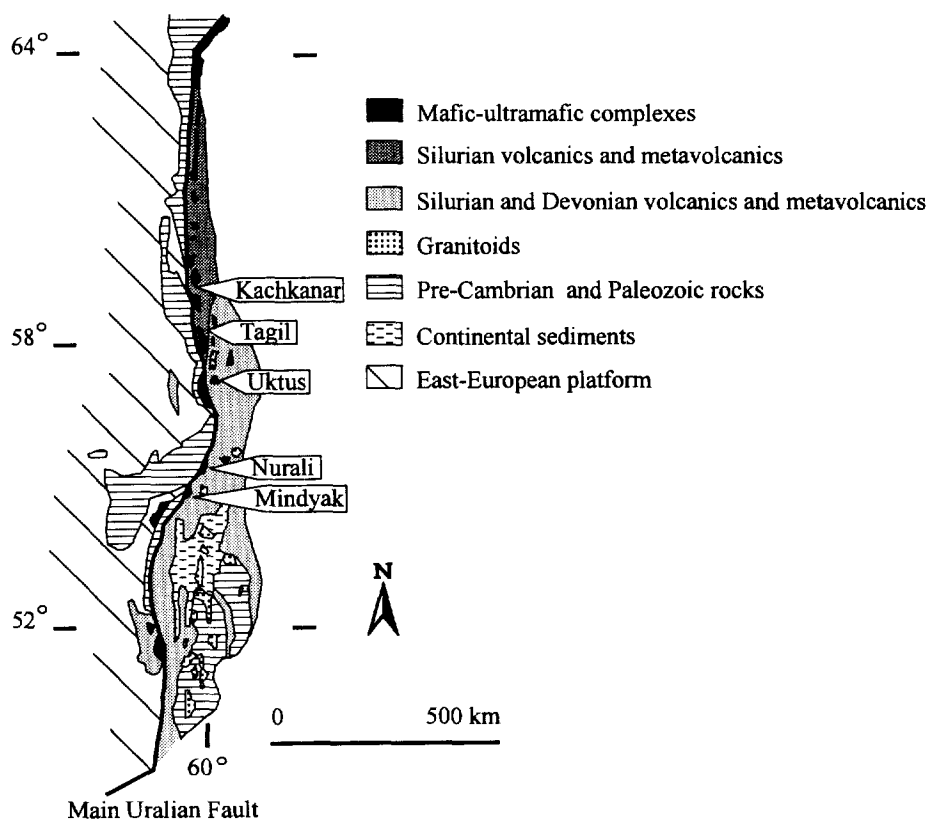


Fig. 1. Geological scheme of the Urals and location of the complexes studied (modified after Ivanov et al., 1975; Efimov et al., 1993).

Os–Ru specialized ores in ophiolite-type complexes; and (b) Pt–(Ir) ores in Ural–Alaskan type complexes (Volchenko et al., 1995). Very little information, however, is available concerning the PGE contents of barren lithotypes within the same complexes (Fominykh and Kvostova, 1970), although they would be of great importance in better understanding and modelling the generation of PGE-bearing magmas, as well as evolution of their mantle source. This paper reports preliminary results of the systematic geochemical investigation of PGE distribution in rocks from five ultramafic complexes in the central and southern Urals pertaining to the Ural–Alaskan type (Kachkanar, Tagil, Uktus), and the Iherzolite–harzburgite type (Nurali, Mindyak). Significant differences in PGE distribution patterns exist between the two associations, reflecting different petrological evolution of the ultramafics. Problems relevant to the origin of these variations are presented and briefly discussed.

2. Geological setting

Geological sketches showing internal lithology and country rock relationships for the investigated Ural–Alaskan type complexes and Iherzolite–harzburgite massifs are presented in Figs. 2 and 3, respectively.

2.1. Ural–Alaskan type complexes

The complexes of Kachkanar and Tagil are two of the fourteen huge, concentrically zoned massifs belonging to the ‘Platinum-bearing Belt’, which extends over more than 1000 km in the central and northern Urals (lat. 58° to 68°N), between the Main Uralian Fault to the west and the Silurian island arc volcanic belt to the east (Efimov et al., 1993). These massifs are similar to those of southeastern Alaska and are characterized by the association

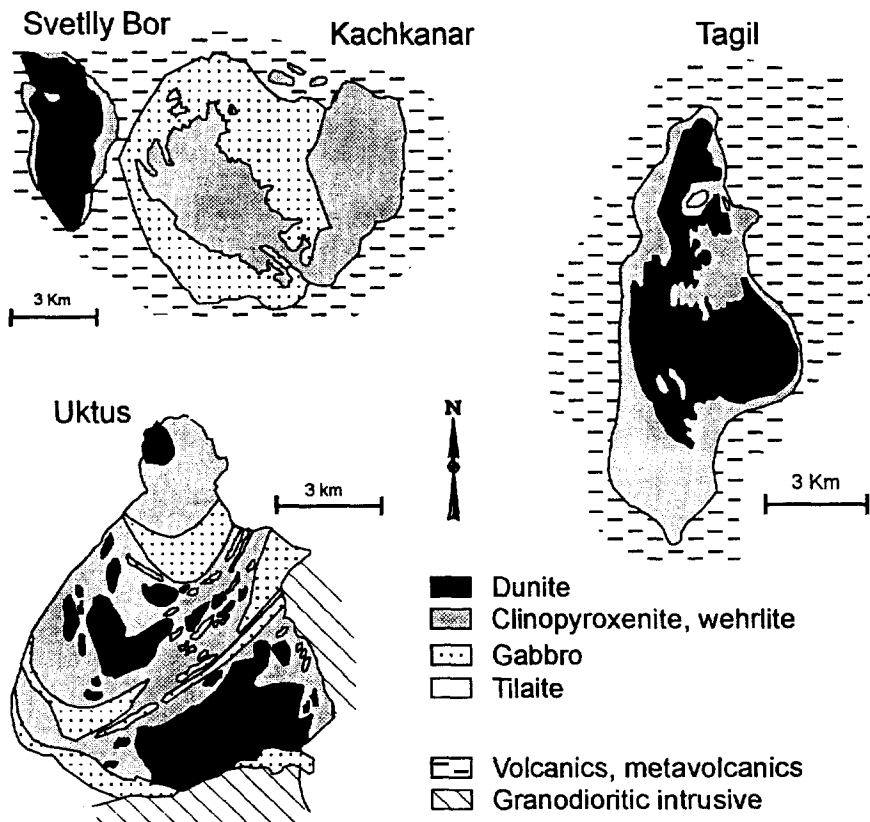


Fig. 2. Geological sketch map of the Ural–Alaskan type complexes Uktus, Tagil and Kachkanar (modified after Malachov and Malachova, 1970; Efimov et al., 1993).

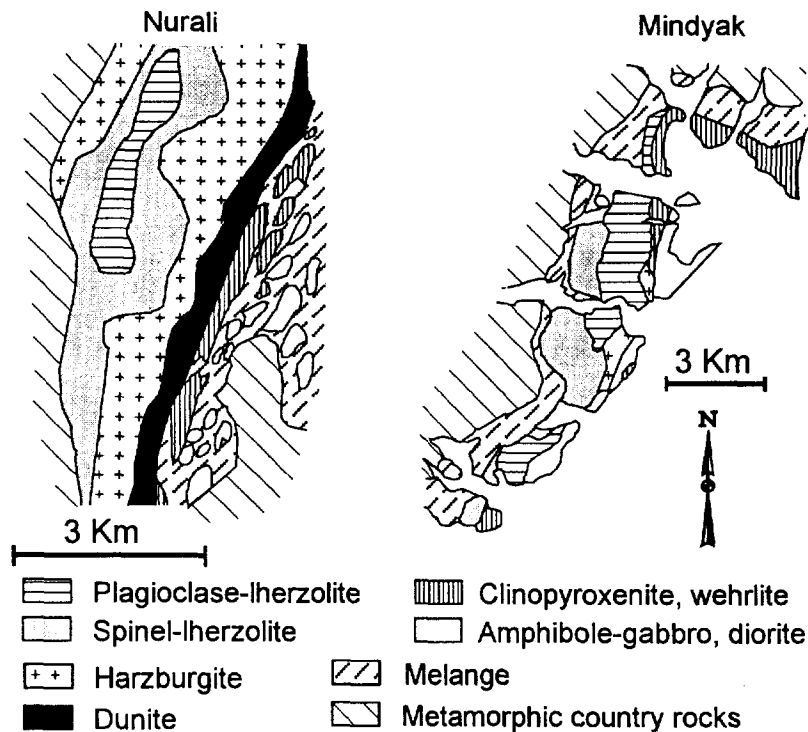


Fig. 3. Geological sketch map of the lherzolite–harzburgite complexes Nurali and Mindyak (modified after Denisova, 1984; Savelieva, 1987).

dunite–clinopyroxenite–gabbro. Typically they contain substantial amphibole and display a concentric setting, with the dunite being at the core of the intrusive bodies. The origin of their parental magmas and mode of emplacement are still a matter of discussion, although trace element geochemistry in the Ural occurrences (Fershtater and Bea, 1996) strongly suggests that the mantle source probably underwent secondary enrichment in incompatible elements (Sr, Rb, LREE and others).

The Kachkanar complex consists of three bodies separated by amphibolite terrain: the proper Kachkanar clinopyroxenite–gabbro massif (clinopyroxenite, amphibole–clinopyroxenite, olivine- and amphibole-gabbro, hornblende) with titanomagnetite ore-deposits, and two dunite–clinopyroxenite bodies, Svetlyy Bor and Veresoviy Bor to the west. K–Ar age determination gave 432–475 Ma for phlogopite in the clinopyroxenite of Veresoviy Bor (Ivanov and Kaleganov, 1993).

The Tagil complex is composed of a dunite core enveloped with a narrow rim comprising clinopyrox-

enite, wehrlite, and ‘tilaite’ (plagioclase- and pseudoleucite-bearing olivine–clinopyroxenite with porphyritic texture). This rock represents a subvolcanic evolved variety of the Tagil clinopyroxenite magma (Fershtater and Pushkarev, 1992). Dunite is remarkably homogeneous, mainly consisting of olivine (91–92% Fo) and chromite ($Cr/(Cr + Al) > 0.7$) with frequent chromitite segregations and veins (Solovieva Mountain) and probably represents the source rocks of the well known Pt-placers in the area.

The Uktus complex has structural and lithological characteristics in common with the other Ural–Alaskan type complexes, although it is located 50–60 km east of the Platinum-bearing Belt, at the convergence of the Verkhisetck and Sisert anticline with the Sverdlovsk syncline structures (Fershtater et al., 1997) in tectonic contact with mafic volcanics to the west, and cut by Lower-Carboniferous (Shteinberg et al., 1988) granodiorite to the south and east. Younger lamprophyric dykes (370 Ma) are emplaced into the Uktus body, marking the upper age-limit for

the intrusion (Kaleganov and Pushkarev, 1992). The complex consists mainly of dunite, clinopyroxenite (containing olivine and accessory hornblende and magnetite), and gabbro (containing olivine and/or amphibole), along with minor wehrlite formed by modal increase of olivine in clinopyroxenite at the contact with dunites, which in their turn are enriched in iron. Dunites contain accessory chromite and minor chromitite segregations characterized by lower $\text{Cr}/(\text{Cr} + \text{Al}) = 0.45\text{--}0.75$ and $\text{Mg}/(\text{Mg} + \text{Fe}^{2+}) = 0.2\text{--}0.5$ than the other Ural–Alaskan type complexes (Pushkarev et al., 1994). Serpentinization affects the dunites up to 70% by volume.

2.2. *Lherzolite–harzburgite complexes*

The Nurali and Mindyak massifs are situated in the ‘melange unit’ of the Main Uralian Fault (Suture Megablock Zone) in between Beloretsk and Miass (South Urals, Bashkortostan). Both complexes consist of a lower mantle tectonic unit (plagioclase–lherzolite, spinel–lherzolite, harzburgite, dunite characterized by high P – T plastic flow structure) and pyroxenite and gabbro dykes, overlain by layered cumulates (dunite–wehrlite, clinopyroxenite, websterite), and upper amphibole–gabbro and diorite (Denisova, 1984; Savelieva, 1987). Some geochemical and petrographic features distinguish these complexes from the ophiolites of the Ural oceanic crust. Gabbros and diorites have REE distribution patterns compatible with differentiation of MORB-like magma, although both are distinguished from N-MORB analogues by enrichment in Rb, Sr, P, and K (Fershtater and Bea, 1996). Garnet-bearing websterite and pyroxenite occur at Mindyak, suggesting that the complex might have undergone high-pressure equilibration at some stage of its evolution. In addition, petrography and structural zoning of the mantle suite in both Nurali and Mindyak recall those of orogenic lherzolites in the western Mediterranean province (Betic–Rifean Cordillera, Pyrenees, and Ivrea Zone, western Alps) related with granulitic terrains, and interpreted as lithospheric mantle stabilized at the base of the continental crust (Nicolas and Jackson, 1972; Menzies and Dupuy, 1991). These observations confirm that the Nurali and Mindyak mantle massifs cannot be strictly interpreted as mature, sub-oceanic ophiolitic mantle. Actually, they might represent weakly depleted

oceanic upper mantle (Savelieva, 1987; Savelieva and Saveliev, 1992), but the possibility that they originated from the lithosphere below the continent–ocean transition zone, or even below the continental margin, has to be taken into account.

3. Analytical methods

The PGE (Os, Ir, Rh, Pt, Pd) and Au were analyzed at the University of Granada by ICP-MS, after the Ni-sulphide fire assay pre-concentration step carried out at the University of Modena. Ni-sulphide beads (stoichiometric Ni_3S_2) varying from 4 to 6 g in weight were obtained from 10 to 20 g of sample, previously powdered in agate mill, by fusion at 1000°C and then dissolved in hot aqua regia. Spectrometric analysis was performed directly on the obtained solution after appropriate dilution. The Ru determination was strongly affected by fluctuating interference from Ni, therefore this element was omitted in the graphics and not taken into account for discussion. Precision and accuracy of PGE determination are less than 10% based on repeated analyses of the UMT-1 international standard. Limits of detection are 0.05 ppb for Os, Rh, Pt and Pd, and 0.005 ppb for Ir and Au. Nickel and Cu were also analyzed by ICP-MS on solution obtained by direct, hot acid attack of the sample.

4. Distribution of PGE, Au, Ni, and Cu

Concentrations of PGE, Au, Ni, and Cu are reported in Table 1, together with the relevant parameters Pd/Ir, Ni/Cu, and Pt-anomaly. The estimated composition of asthenospheric mantle according to Barnes et al. (1988) together with data relative to peridotites from orogenic lherzolite massifs and Mesozoic ophiolites of the Mediterranean basin, as well as concentrically zoned complexes of Asia and America are listed in Table 2 for comparison. Data normalized to the asthenospheric mantle estimate are illustrated in Figs. 4 and 5. Barnes et al. (1988) have shown the advantages to use mantle normalization instead of the conventional normalization to C1 chondrite, when transition metals highly concentrated in chondrites, such as Ni and Cu, are plotted on the same diagram as the PGE and Au. In addition, PGE and Au concentrations in the reference astheno-

Table 1
Lithology and metal concentrations of the analyzed samples

Sample	lithology	Ni	Os	Ir	Rh	Pt	Pd	Au	Cu	Pd/Ir	Ni/Cu	Pt/Pt*
<i>Ural-Alaskan type complexes</i>												
UK4	dunite	1528	1.5	2.0	0.4	13	2.0	3.8	1.1	1.0	1389	4.63
UK1	dunite	952	1.0	6.5	1.1	70	3.7	16	8.0	0.6	119	10.98
UK2	dunite	887	5.7	8.8	2.6	163	16	32	3.4	1.8	261	8.08
UK9	ol-clinopyroxenite	206	2.1	0.4	0.4	24	8.8	9.1	4.0	22	51	4.11
UK7	ol-gabbro	85	0.6	0.3	0.2	18	18	10	7.7	57	11	3.46
UK8	gabbro	85	4.2	1.4	1.2	50	48	6.5	67	34	1	2.05
SL21	dunite	1112	0.5	0.7	1.4	26	2.0	6.2	5.0	2.8	222	4.92
SL25	dunite	932	1.3	0.7	1.2	22	2.7	5.3	7.7	3.7	121	3.84
SL24	wehrlite	381	2.2	0.5	0.3	33	7.6	2.4	3.2	16	119	6.71
SL22	clinopyroxenite	208	0.9	0.1	2.8	26	4.3	1.9	3.9	30	53	2.36
SL23	tilaite	214	0.4	0.2	1.8	11	5.0	5.3	86	23	2	1.21
KK10	clinopyroxenite	64	0.7	0.1	1.2	1.5	7.4	4.5	168	74	0.4	0.16
KK12	amph-clinopyroxenite	73	0.3	0.1	0.3	38	157	8.5	42	26	222	1.66
KK14	gabbro	0.1	0.2	0.1	2.5	0.8	13	15	463	186	0.0002	0.05
KK11	amph-gabbro	0.1	0.4	0.1	2.7	0.6	5.3	6.4	416	49	0.0002	0.05
KK13	hornblendite	59	0.3	0	0.1	23	30	2.1	12	760	5	4.20
<i>Lherzolite-harzburgite complexes</i>												
MY30	plg-lherzolite	2140	7.0	3.1	0.7	7.3	7.5	4.4	12	2.4	186	1.06
MY31	plg-lherzolite	2041	4.9	3.3	1.0	6.6	4.7	5.3	27	1.4	75	0.96
MY37	lherzolite	2037	2.7	2.1	0.5	3.7	1.5	3.5	15	0.7	139	1.30
MY33	harzburgite	2157	16	12	3.1	34	27	119	16	2.2	136	1.19
MY27	harzburgite	2062	2.2	1.6	1.5	4.2	2.2	4.0	5.7	1.4	362	0.73
MY29	harzburgite	2052	4.4	3.3	0.6	6.1	6.9	3.5	12	2.1	174	0.95
MY28	gabbro dyke	63	2.3	0.5	0.4	7.0	14	3.0	19	31	3.3	0.90
MY32	gabbro dyke	26	0.5	0.1	0.7	6.6	12	5.8	52	101	0.5	0.73
MY39	wehrlite	223	0.2	0.2	0.3	44	7.7	2.4	3.7	48	60	9.32
MY40	clinopyroxenite + mgn	143	0.3	0.3	0.6	33	29	3.7	24	92	6	2.62
MY38	clinopyroxenite	1119	1.0	0.7	1.1	14	12	9.4	104	18	11	1.19
MY35	gabbro	13	0.2	0.1	1.1	7.7	2.9	5.1	134	36	0.1	1.38
MY34	amph-gabbro	0.1	0.4	0.1	1.0	29	4.9	5.7	114	70	0.0009	4.18
MY36	diorite	11	0.2	0.1	0.5	3.3	6.5	5.9	47	72	0.2	0.56
NU59	lherzolite	2070	2.4	1.5	0.4	6.0	4.0	4.8	4.2	2.6	493	1.64
NU62	harzburgite	2279	6.6	4.6	0.7	4.8	5.0	5.7	2.3	1.1	991	0.80
NU61	harzburgite	2110	5.1	3.6	0.8	8.0	13	17	10	3.7	209	0.80
NU60	dunite	2340	4.9	3.5	1.2	1.0	3.8	5.7	9.7	1.1	241	0.14
NU64	dunite	2353	5.1	3.5	1.2	1.0	3.8	6.2	2.8	1.1	840	0.15
NU57	clinopyroxenite dyke	2115	0.6	0.7	0.5	3.1	5.8	4.5	3.9	8.6	542	0.58
NU47	wehrlite	196	0.1	0.2	0.3	4.1	6.9	2.2	7.2	33	27	0.93
NU48	wehrlite	1722	4.4	3.5	0.7	9.5	10	3.0	17	2.9	103	1.12
NU51	wehrlite	316	0.3	0.4	1.0	21	16	4.3	5.3	38	60	1.63
NU52	melanogabbro	0.1	0.1	0	0.5	0.4	2.2	3.3	59	45	0.002	0.14
NU55	gabbro	0.1	0.1	0.1	0.1	0.1	1.4	4.4	19	16	0.005	0.10
NU53	amph-gabbro	194	0.1	0.2	0.2	1.7	4.9	3.8	8.8	31	22	0.61
NU54	amph-gabbro	0.1	0.1	0	0.4	0.6	2.4	4.2	40	81	0.003	0.20
NU56	diorite	3	0.1	0.1	0.2	0.6	3.2	4.0	41	53	0.1	0.24

UK = Uktus; SL = Tagil; KK = Kachkanar; MY = Mindyak; NU = Nurali. ol = olivine; amph = amphibole; plg = plagioclase; mgn = magnetite; Pt/Pt* = $(Pt/8.3)/\sqrt{(Rh/1.6) \cdot (Pd/4.4)}$. Concentrations of Ni and Cu are in ppm, of PGE and Au in ppb.

sphere are assumed to be $0.00815 \times C1$ chondrite values (Naldrett, 1981); therefore reciprocal relations among noble metals are not modified, and the

PGE–Au section of mantle-normalized patterns has the same shape as in C1 chondrite-normalized patterns. PGE are listed in order of decreasing melting

Table 2

Provenance, lithology, and metal concentration of peridotites from upper mantle and concentrically zoned complexes from literature

	Lithology	Os	Ir	Ru	Rh	Pt	Pd	Au	Pt/Pt*	Pd/Ir	Ref.
Primitive mantle		4.2	4.4	5.6	1.6	8.3	4.4	1.2	1.00	1.00	(I)
<i>Orogenic lherzolite massifs (40)</i>											
Pyrenees	Lhz	5.0	4.9	7.6	2.4	7.0	14.0	n.d.	0.39	2.83	(II)
Ivrea Zone	Lhz	8.5	3.3	6.6	3.2	10.7	10.8	16.1	0.59	3.29	
Beni Bouzera	Lhz	4.2	2.0	8.1	1.3	2.4	6.9	2.7	0.26	3.39	
Ronda	Lhz	5.5	3.0	5.0	1.3	6.7	7.2	19.2	0.70	2.43	
Ivrea Zone	Hlz	6.4	3.1	3.8	1.4	3.7	5.7	43.0	0.41	1.82	
Beni Bouzera	Hlz	5.5	3.8	5.9	1.9	3.2	5.7	3.7	0.31	1.50	
Ronda	Hlz	7.2	3.7	5.4	1.4	5.4	6.3	15.1	0.57	1.71	
Ronda	Dn	7.8	2.5	4.6	1.6	1.9	3.6	7.8	0.25	1.44	
<i>Mesozoic ophiolites (15)</i>											
Vourinos	Dn	6.4	2.5	8.7	2.6	1.6	1.4	1.7	0.27	0.55	(III)
Liguria (*)	Dn	4.0	2.1	2.0	1.0	4.0	2.0	2.0	0.90	0.95	
Vourinos–Troodos	Hlz	5.0	3.9	6.4	3.0	5.3	4.3	1.4	0.47	1.10	
Liguria (*)	Lhz	3.0	2.9	3.0	2.8	6.8	3.3	6.0	0.71	1.13	
<i>Ural–Alaskan type complexes (25)</i>											
Urals	Dn	3.7	9.6	0.6	4.4	82.0	32.0	n.d.	2.21	3.33	(IV)
N. Tagil	Dn	5.6	7.8	0.8	8.1	93.0	38.0	n.d.	1.69	4.87	
Kyrlyn (Urals)	Dn	0.8	6.6	0.7	3.6	89.0	54.0	n.d.	2.04	8.18	
Konder (Aldan S.)	Dn	3.0	6.0	4.0	10.0	78.0	28.0	31.0	1.49	4.67	
Feklistovsky	Dn	3.8	3.8	2.8	6.3	84.3	48.1	4.2	1.55	12.66	
Tulameen	Dn	n.d.	0.5	n.d.	1.2	48.0	n.d.	0.3			
Tulameen	Dn	2.7	2.1	n.d.	1.9	180.0	n.d.	4.1			
Condoto	Dn	3.0	2.7	4.4	2.3	38.0	1.8	2.0	5.97	0.67	

Ref.: (I) = Barnes et al. (1988); (II) = Lorand (1989); Garuti et al. (1995); (III) = Leblanc (1991); Kostantopoulou and Economou-Eliopoulos (1991); Prichard and Lord (1990); unpublished data from the author G.G. (*); (IV) = Fominykh and Kvostova (1970); Malich (1990); Lazarenkov and Malich (1991); Tistl (1994). Concentrations of PGE and Au are in ppb. Total number of samples considered in brackets.

point, while the Ni value and the pair Au–Cu have been placed to the left of Os and to the right of Pd, respectively, following their decreasing order of compatibility (Barnes et al., 1988).

The PGE can be divided into two groups: the Ir-group PGE (IPGE = Os, Ir, Ru), and the Pd-group PGE (PPGE = Rh, Pt, Pd). The two groups are characterized by different solubilities in silicate magmas, the IPGE being more refractory and compatible than the low-melting PPGE (Barnes et al., 1985). This distinct geochemical behaviour is emphasized by the Pd/Ir ratio considered as ‘index of fractionation’ of the PGE during petrological processes. Since Pd and Ir are concentrated at the same level in asthenosphere (and C1 chondrite), unfractionated materials should have Pd/Ir close to 1. The Pd/Ir increases with differentiation in magmatic fractionation processes, and should be lower

than unity in residual mantle material, decreasing with increasing degree of partial melting. The Ni/Cu displays opposite behaviour. Primitive mantle has Ni/Cu = 71.4, the value increasing with partial melting and decreasing at increasing degree of fractionation during magmatic crystallization. The Pt-anomaly ($Pt/Pt^* = Pt_N / \sqrt{Rh_N \cdot Pd_N}$) gives a measure of the deviation of Pt from the general trend of the normalized pattern of a sample. It is $Pt/Pt^* = 1$ in the reference material (primitive asthenosphere), and it significantly varies from positive ($Pt/Pt^* > 1$) to negative ($Pt/Pt^* < 1$) in the analyzed samples as a consequence of different petrological processes.

4.1. Ural–Alaskan type complexes

With a few exceptions, the rocks from Ural–Alaskan type complexes display enrichment in Pt

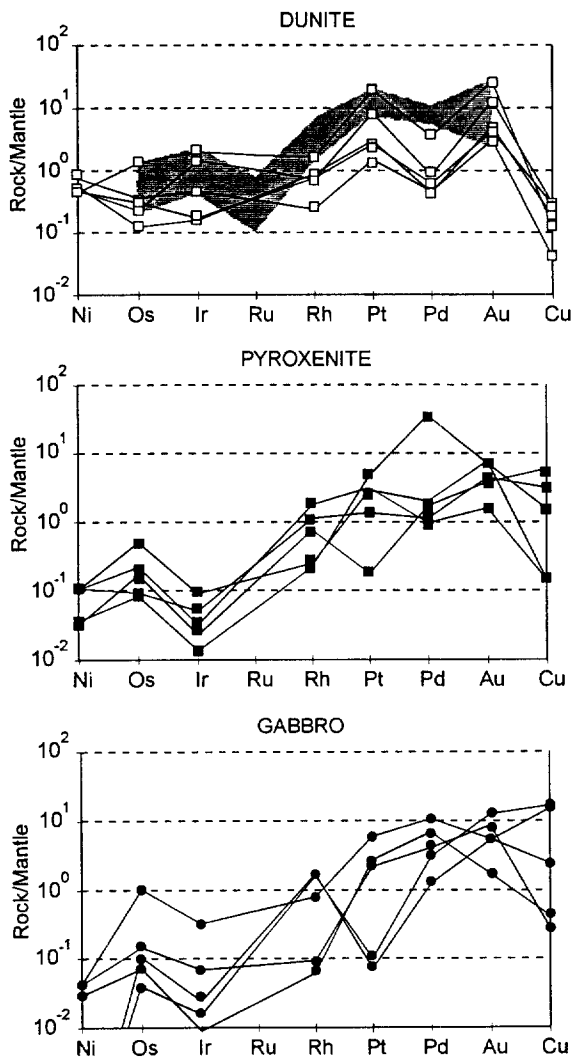


Fig. 4. Mantle-normalized patterns for rocks from the Uktus, Tagil and Kachkanar Ural–Alaskan type intrusions. In the dunite diagram the field of dunites from Aldan–Shield, Urals and Tulaheen is reported for comparison (see Table 2 for the data source reference group IV).

and Au, and depletion in Ni, Os, and Ir with respect to pristine mantle, while Pd, Rh and Cu vary from enriched to strongly depleted. The refractory Ni and Ir progressively decrease from dunites to pyroxenites and gabbros, whereas the variation of Pd and Cu with lithology is reversed. A major consequence is that the PGE patterns range from nearly unfractionated in the dunites ($Pd/Ir = 0.57\text{--}3.68$) to mildly and

strongly fractionated in pyroxenite, wehrlites ($Pd/Ir = 9.11\text{--}74.1$) and gabbroic rocks ($Pd/Ir = 34.4\text{--}2622$), while the Ni/Cu ranges 1389–119 in dunite and wehrlite, and 53 to near zero in pyroxenites and gabbros. Remarkable enrichment in Pd and Cu with respect to primitive mantle resulting in extremely high Pd/Ir and low Ni/Cu, are observed at Kachkanar, where pyroxenite and gabbro always contain substantial amounts of hornblende. Marked positive Pt-anomalies are present in the dunites, and progressively reduce in pyroxenites and gabbros. Some amphibole gabbros and magnetite-rich pyroxenites from Kachkanar, are particularly depleted in PGE, and display extremely negative Pt-anomalies.

4.2. Lherzolite–harzburgite complexes

Peridotites from the lherzolite–harzburgite complexes of Mindyak and Nurali are enriched in Ni, Os, and Au, and depleted in Cu, Ir, Rh and Pt compared with pristine mantle, while Pd ranges from depleted to enriched. Lherzolites and harzburgites have flat, unfractionated PGE patterns ($Pd/Ir = 0.7\text{--}3.7$) and Ni/Cu in the range 991–75. The value of the Pt-anomaly varies from negative to positive in the range 0.73–1.6. One sample from Mindyak (MY 33) exhibits enrichment of all PGE, but it was collected in a fault-zone, and probably above the so-called petrologic Moho. Dunites have Pd/Ir (1.1) and Ni/Cu (840–241), respectively, lower and higher than the average of lherzolite and harzburgite, and in contrast with Ural–Alaskan type dunite, they exhibit general depletion in PGE and distinctive negative Pt-anomaly (0.15). Wehrlites, pyroxenites and gabbros associated with the lherzolite–harzburgite complexes have PGE distribution similar to that of the Ural–Alaskan type complexes. In comparison with the primitive mantle, they are depleted in Ni, Os, Ir, Rh, are enriched in Au, and vary from enriched to depleted in Pt, Pd, and Cu. The PGE patterns generally have a positive slope with a degree of fractionation increasing from wehrlite ($Pd/Ir = 2.9\text{--}48.4$) to pyroxenite ($Pd/Ir = 8.6\text{--}92.4$) and gabbroic rocks ($Pd/Ir = 15.7\text{--}101$). This is consistent with a trend of magmatic fractionation that is well illustrated by the layered wehrlite of Nurali where Pd/Ir increases from 2.9 up to 33.2 over a stratigraphic distance of about 25 m. The Pt-anomaly is generally posi-

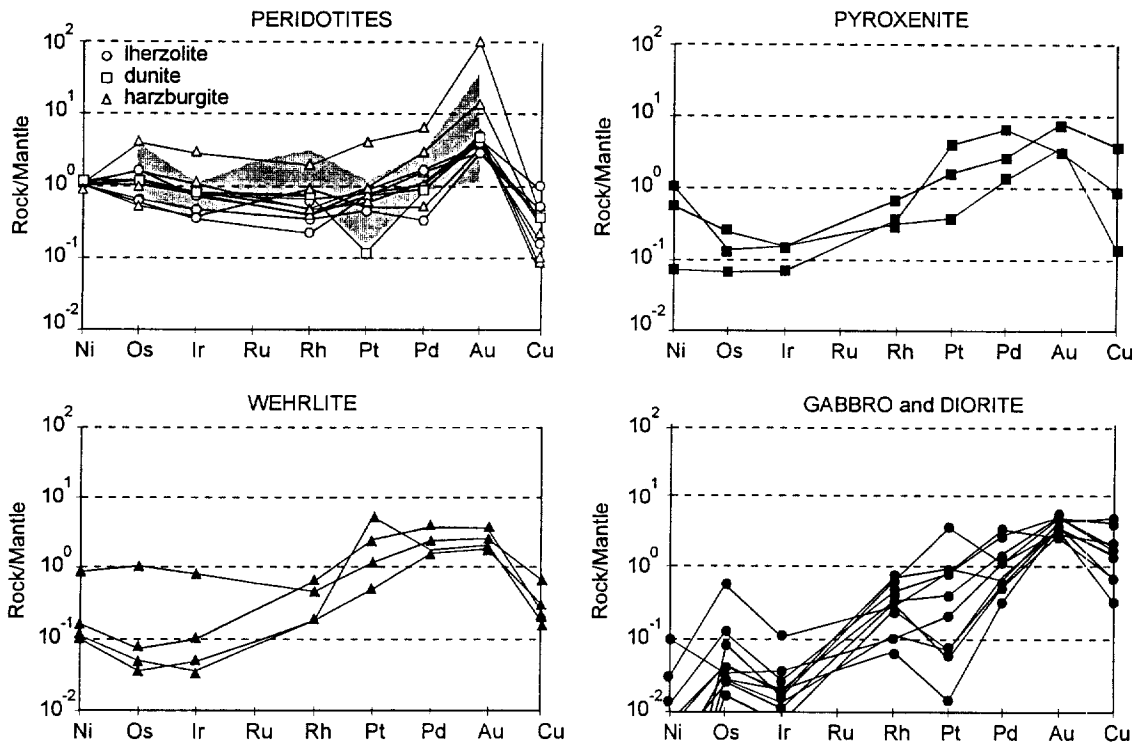


Fig. 5. Mantle-normalized patterns for rocks from the Nurali and Mindyak lherzolite–harzburgite complexes. In the peridotites diagram, the field of peridotites from Troodos, Vourinos, and Liguria (Mesozoic ophiolites) and Betic–Rifean Cordillera, Pyrenees and Ivrea-Zone (orogenic lherzolite massifs) is reported for comparison (see Table 2 for the data source reference groups II and III).

tive in rocks from Mindyak, except for the gabbro dykes within the mantle lherzolite, whereas it varies from positive to negative from wehrlite to gabbro at Nurali.

5. Discussion

Peridotites from both Ural–Alaskan type and lherzolite–harzburgite complexes display a variable degree of serpentinization, although primary silicates and oxides usually are well preserved indicating that alteration was largely incomplete. The secondary silicate assemblage mainly consists of pseudomorphic lizardite indicating low temperatures (<200°C), possibly corresponding to late-stage hydrothermal or supergene alteration. It has been shown that Pt, Pd, and Au can move through soils in aqueous solutions (Cook and Fletcher, 1992; Cook et al., 1992); however, under conditions of incipient to partial serpentinization the PGE and, to a lesser extent, Au are expected to behave inertly (Barnes et al., 1985).

In addition, the analyzed peridotites display absolute concentrations and distribution patterns of PPGE and Au comparable with peridotites from other complexes (see Table 2 and Figs. 4 and 5) where effects of serpentinization are negligible (Garuti et al., 1995). Therefore, the observed variations, in metal distribution patterns are ascribed to high-temperature processes such as partial melting or crystal fractionation, although with some caution for Au.

According to Barnes et al. (1988) the effects of partial melting and crystal fractionation processes on PGE fractionation are emphasized by plotting Pd/Ir versus Ni/Cu. Reciprocal variation of these parameters defines a negative correlation trend, having the most residual mantle material and the most evolved products of fractionation at the opposite ends. The Ural samples conform to this trend, although Ural–Alaskan type dunites overlap the mantle field in spite of the fact that they probably were originated by crystal fractionation and are not mantle residuum after partial melting. This is due to the general de-

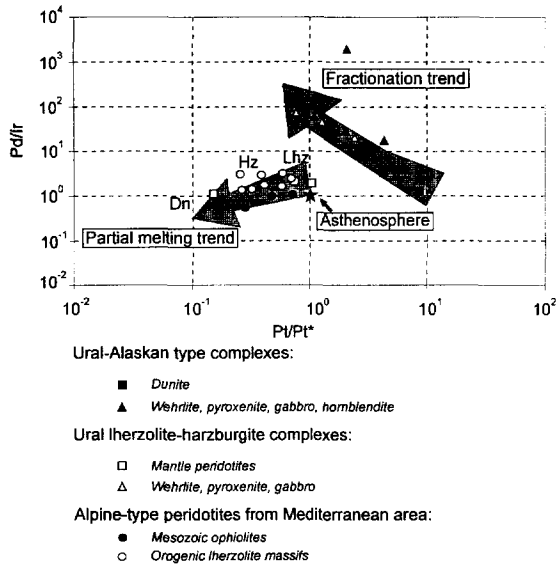


Fig. 6. Plot of Pd/Ir versus Pt/Pt* for average compositions of rocks from the investigated Ural–Alaskan type complexes and Ural lherzolite–harzburgite massifs. Average compositions of Alpine-type peridotites (Mesozoic ophiolites and orogenic lherzolites) from the Mediterranean area are reported for comparison (see Table 2 for the data source reference groups II and III). Abbreviations: Lhz = lherzolite; Hz = harzburgite; Dn = dunite. The Pt anomaly is calculated as follows: $Pt/Pt^* = (Pt/8.3) \sqrt{[(Rh/1.6) \times (Pd/4.4)]}$.

pletion of both Ni and Cu in these rocks, the Ni/Cu being around the mantle value.

Discrimination between residual mantle material and crystal-fractionation products is effectively made clear by plot of Pt/Pt* versus Pd/Ir (Fig. 6). Mantle rocks of the Nurali and Mindyak lherzolite massifs define a trend of increasing negative Pt/Pt* at decreasing Pd/Ir from lherzolites and harzburgites to dunites, apparently consistent with literature data concerning lherzolite–harzburgite–dunite mantle suites from Mesozoic ophiolites (Vourinos, Troodos, Liguria) and orogenic lherzolite massifs (Ivrea-Zone, Pyrenees, Betic Cordillera) in the western Mediterranean. The trend shows that both Pt and Pd behave as incompatible elements during mantle partial melting, although they are depleted to an appreciable extent only at relatively high degrees of melting when residual dunites are produced. Fig. 6 also shows that the Nurali and Mindyak tectonites are similar to the orogenic lherzolites, being char-

acterized by Pd/Ir slightly higher than the primitive asthenosphere and the ophiolitic mantle. Comparison between data listed in Tables 1 and 2 reveals that the higher Pd/Ir is mainly due to Pd enrichment. This feature, apparently not consistent with the residual nature of these mantle materials, is not yet completely explained for the samples of Nurali and Mindyak, but in the other orogenic lherzolites (Lorand, 1989; Garuti et al., 1995), it was attributed to reaction with upwards-percolating basaltic melts and might represent a distinctive character of the subcontinental lithospheric mantle compared with primitive asthenosphere and mature sub-oceanic mantle. The clear Au anomaly in peridotites of Nurali and Mindyak (Fig. 6) is similar to that observed in Ronda and Ivrea Zone (Garuti et al., 1995), and like the Pd re-enrichment it might be interpreted in terms of percolating-melt metasomatism, although the possible remobilisation of Au during serpentinization prevents any conclusive consideration in this respect.

In contrast with the mantle material, most rocks formed by crystal fractionation, including wehrlite and pyroxenite cumulates from Nurali and Mindyak, have a positive Pt-anomaly with respect to primitive mantle and define a clear negative trend of decreasing Pt/Pt* at increasing Pd/Ir. This trend is particularly exemplified by Ural–Alaskan type complexes where it clearly reflects magmatic fractionation (Fig. 6). The positive Pt-anomaly is conspicuous in cumulate dunites and decreases at increasing Pd/Ir, throughout the fractionation of wehrlite, clinopyroxenite and pyroxenite up to advanced stages of crystallization. Amphibole-rich rocks from Kachkanar exhibit anomalous Pd/Ir at given Pt/Pt*, possibly reflecting the tendency of Pd to concentrate in volatile-rich differentiated liquids. The opposite Pt/Pt* vs Pd/Ir variation trend emphasizes the differential behaviour of Pt that changes from incompatible during mantle partial melting, into compatible in the early stage of crystal fractionation of Ural–Alaskan type magmas.

As mentioned above, Pt belongs to the incompatible PPGE group characterized by relatively high solubility in mafic silicate magmas (Barnes et al., 1985). During early stages of crystallization, Pt together with Pd and Rh should tend to remain in the silicate melt unless immiscible sulphide liquid appears, acting as the collector for all the PPGE. Present data, on the contrary, indicate that large

amounts of Pt (but not Rh and Pd) are extracted from the magma, during the early stages of crystal fractionation giving rise to the observed positive Pt-anomaly in cumulate dunites of Ural–Alaskan type complexes. The dominant Pt-mineralogy in primary dunite mineralization and associated placer deposits (Betehtin, 1961; Razin, 1976; Volchenko et al., 1995) would indicate that Pt was precipitated as alloys, mainly Pt–Fe and Pt–Ir, along with Ir–Os and apparently in the absence of a sulphide liquid as deduced from the scarcity of sulphides in dunites. The relative increase of chalcophile metals Cu, Pd, and Rh in clinopyroxenites and gabbros (Table 1) would suggest that sulphur saturation of the magma, causing the precipitation of sulphides, was probably achieved only in late stages of fractionation. As PGE have partition coefficients (D) between silicate and sulphide liquids varying from 10^3 to 10^6 (Peach et al., 1990; Bezmen et al., 1994), they concentrated into the sulphide liquid, and were either precipitated as chalcogenides or retained in solid solution into Fe–Cu–Ni sulphides during crystallization of the sulphide liquid. In particular, Fleet et al. (1991) showed that D_{Pd} and D_{Pt} are of the same order ($\sim 2 \times 10^4$), therefore no substantial fractionation should have been produced between Pt and Pd during the late fractionation stages.

The observed decoupling of Pt from the other PPGE, and its precipitation with the refractory Ir and Os in dunites of Ural–Alaskan type complexes is not completely understood. Clearly, it requires a sudden decrease of Pt-solubility in the silicate magma that, apparently, is determined by the stabilization of Pt–Fe alloys in the system. Stability conditions of Pt–Fe alloys are largely unknown. Amossé et al. (1990) have shown experimentally that, at temperature of 1430°C, and below the FMQ buffer, Pt-solubility in mafic melts negatively correlates with f_{O_2} , but is considerably increased by increasing f_{S_2} (although keeping below the sulphur saturation condition). Formation of Pt–Fe alloys was observed in the experiments at $f_{S_2} = 0$, and f_{O_2} in the range of values compatible with the precipitation of chromite from basaltic melts (Hill and Roeder, 1974). Using these concepts, Tistl (1994) ascribed the crystallization of Pt–Fe alloys in dunites of the Condoto zoned complex (Colombia) to rapid pressure drop causing sudden increase of f_{O_2} and shift of the system to-

wards the PGE-alloy, olivine, chromite stability field. Present data, relative to zoned ultramafic complexes of the Urals, are in agreement with this interpretation, and support the conclusion that the compatible behaviour of Pt, similar to Ir and Os, probably was determined by low f_{S_2} and high f_{O_2} leading to the formation of alloys. Conditions leading to the stabilization of alloy phases in magmatic systems seem to play a special role in controlling the behaviour of PGE in general, and of Pt in particular. Experimental study of PGE partitioning between alloys and sulphides in the Fe–Ni–S system (Fleet and Stone, 1991) has revealed a more siderophile tendency of the heavy triade Os–Ir–Pt, which preferentially concentrates in alloy phases, compared with the light Ru–Rh–Pd, which partitions in the coexisting sulphide. This differential behaviour is not consistent with the previously accepted subdivision into PPGE and IPGE based on different melting point, but apparently is in agreement with natural observations and accounts for PGE fractionation in Ural–Alaskan type complexes.

On the other hand, the remarkable Pt-specialization observed in Ural–Alaskan type complexes all over the world, might not be a simple effect of fractionation under particular chemical–physical conditions. Actually, similar f_{S_2} conditions, although at relatively lower f_{O_2} , are observed even in the chromitite-forming system of ophiolites, but generally they lead to the precipitation of Ir–Os–Ru alloys, and not necessarily Pt. The possibility exists therefore that formation of Pt–Fe alloys is related with the positive Pt-anomaly, possibly reflecting an original feature of the parent magma of these intrusions. The question is, which mechanism is able to selectively enrich Pt and not the other PGE in a mafic magma? Sulphide segregation during uplift is unlikely as decoupling mechanism because of the mentioned similarity of PGE partition coefficients between silicate and sulphide liquids. In addition, it is difficult to explain how Pt can be enriched in the liquid relative to Pd during any partial melting process involving a sulphide phase (Peach et al., 1990). The only possibility is, therefore, that Ural–Alaskan type magmas inherited this feature from their mantle source. It has been proposed that selective Pt-enrichment can be produced in the mantle by early extraction of melts leaving refractory Pt-

alloys in the residuum (Garuti et al., 1995). Small volumes of Pt-rich ultramafic liquids petrologically similar to the parent magmas of Ural–Alaskan type complexes can be produced by late-stage re-melting of such residual mantle, probably enhanced by re-influx of fluids from an external source (underlying asthenosphere or crust?). Re-introduction of fluids would also account for the secondary enrichment in incompatible trace elements (Sr, Rb, LREE and others) proposed for the mantle source of these complexes (Fershtater and Bea, 1996). If confirmed, this preliminary conclusion poses important questions concerning the evolution of mantle from which the investigated ultramafic complexes of the Urals originated.

6. Concluding remarks

Comparative study of the distribution of PGE, Au, Ni, and Cu in five ultramafic massifs of the central and southern Urals allow the following preliminary conclusions to be drawn:

(1) PGE variations in Ural–Alaskan type complexes of Kachkanar, Tagil, and Uktus can generally be explained by magmatic fractionation processes, emphasized by progressive increase of the Pd/Ir ratio, and decrease of the Pt-anomaly. This is consistent with compatible behaviour of both Ir and Pt with respect to Pd, during fractionation. Unusual decoupling of Pt from the PPGE is evident.

(2) The positive anomaly of Pt in Ural–Alaskan type rocks is striking. This would appear as a distinctive feature of the parent magmas, probably inherited from their mantle source. If confirmed this conclusion poses a problem concerning the origin of Pt-enrichment in the upper mantle.

(3) PGE variations indicate that lherzolites and harzburgites from Nurali and Mindyak are residual mantle after limited extraction of basaltic melts, or depleted mantle which underwent some re-enrichment of less refractory PGE (mainly Pd) and Au during lithospheric evolution. The character of PGE distribution is similar to orogenic lherzolites rather than ophiolitic mantle, possibly suggesting that lithosphere below the continental margin was the source region of the mantle protolith at Nurali and Mindyak.

(4) The cumulate rocks of Nurali and Mindyak have some characteristics in common with Ural–

Alaskan type wehrlites, clinopyroxenites, and gabbros. Their parental magmas do not appear to be genetically related to the underlying residual mantle.

Acknowledgements

This paper was carried out thanks to the analytical facilities of the ICP-MS laboratory of the Granada University. We would like to thank Dr. D. Brown, Prof. A.A. Efimov, and two unknown referees who improved the paper with their constructive criticisms. The authors are grateful to the 'Europrobe' programme for the financial support during the Uralides and Iberia Workshop held in Granada on 23rd–29th March 1996. This is Europrobe Publication Nr. 107. Partial financing for the project was provided by the INTAS 94-1857 grant, and Italian MURST grant 1994.

References

- Amossé, J., Allibert, M., Fisher, W., Piboule, M., 1990. Experimental study of the solubility of platinum and iridium in basic silicate melts — Implications for the differentiation of platinum-group elements during magmatic processes. *Chem. Geol.* 81, 45–53.
- Arculus, R.J., Delano, J.W., 1981. Siderophile element abundances in the upper mantle: Evidence for a sulfide signature and equilibrium with the core. *Geochim. Cosmochim. Acta* 55, 1159–1172.
- Barnes, S.J., Naldrett, A.J., Gorton, M.P., 1985. The origin of the fractionation of platinum-group elements in terrestrial magmas. *Chem. Geol.* 53, 303–323.
- Barnes, S.J., Boyd, R., Korneliussen, A., Nilsson, L.P., Often, M., Pedersen, R.B., Robins, B., 1988. The use of mantle normalization and metal ratios in discriminating between the effects of partial melting, crystal fractionation and sulphide segregation on platinum-group elements, gold, nickel and copper: examples from Norway. In: H.M. Prichard, P.J. Potts, J.F.W. Bowles, S.J. Cribb (Eds.), *Geo-Platinum 87*. Elsevier, London, pp. 113–143.
- Betechtin, A.G., 1961. Mikroskopische Untersuchungen an Platinerzen aus dem Ural. *Neues Jahrb. Mineral. Abh.* 97 (1), 1–34.
- Bezmen, N.I., Asif, M., Brüggmann, G.E., Romanenko, I.M., Naldrett, A.J., 1994. Distribution of Pd, Rh, Ru, Ir, Os, and Au between sulfide and silicate melts. *Geochim. Cosmochim. Acta* 58, 1251–1260.
- Cook, N.J., Fletcher, W.K., 1992. Distribution and behaviour of platinum in soils of the Tulameen ultramafic complex, southern British Columbia. *British Columbia Mineral Resources Division (Geological Survey Branch)*, 1992-6, 94 pp.
- Cook, N.J., Wood, S.A., Yingsu Zhang, 1992. Transport and

- fixation of Au, Pt and Pd around the Lac Sheen Cu–Ni–PGE occurrence in Quebec, Canada. *J. Geochem. Explor.* 46, 187–228.
- Crocket, J.H., 1981. Geochemistry of the platinum-group elements. In: L.J. Cabri (Editor). *PGE Mineralogy, Geology, Recovery*. Can. Inst. Min. Metall., Spec. Vol. 23, 47–64.
- Denisova, E.A., 1984. The internal structure of the Mindyak ultramafic massif (South Ural). *Dokl. Acad. Nauk SSSR* 274(2), 382–387 (in Russian).
- Efimov, A.A., Efimova, L.P., Mayegov, V.I., 1993. The tectonics of the Platinum-Bearing Belt of the Urals: Composition and mechanism of structural development. *Geotectonics* 27, 197–207.
- Fershtater, G.B., Bea, F., 1996. Geochemical typification of the Ural ophiolites. *Geochemistry* 3, 195–218.
- Fershtater, G.B., Pushkarev, E.V., 1992. Nephelin-bearing tilaite from dunite–clinopyroxenite–gabbro association of the Ural Platiniferous Belt. *Izv. Acad. Nauk SSSR, Ser. Geol.* 4, 74–84 (in Russian).
- Fershtater, G.B., Bea, F., Borodina, N.S., Montero, M.P., Smirnov, V.N., Pushkarev, E.V., Rappaport, M.S., Zinger, T.F., 1997. Magmatism as a key to the deep Urals. In: Pérez-Estaún, A., Brown, D., Gee, D. (Eds.) *EUROPROBE'S Uralides Project*. *Tectonophysics* 276, 87–102.
- Fleet, M.E., Stone, W.E., 1991. Partitioning of platinum-group elements in the Fe–Ni–S system and their fractionation in nature. *Geochim. Cosmochim. Acta* 55, 245–253.
- Fleet, M.E., Stone, W.E., Crocket, J.H., 1991. Partitioning of palladium, iridium, and platinum between sulfide liquid and basalt melt: Effects of melt composition, concentration, and oxygen fugacity. *Geochim. Cosmochim. Acta* 55, 2545–2554.
- Fominykh, V.G., Kvostova, V.P., 1970. Platinum content of Ural dunites. *Dokl. Akad. Nauk SSSR* 191, 443–445 (in Russian).
- Garuti, G., Gorgoni, C., Sighinolfi, G.P., 1984. Sulfide mineralogy and chalcophile and siderophile element abundances in the Ivrea–Verbano mantle peridotites (western Italian Alps). *Earth Planet. Sci. Lett.* 70, 69–87.
- Garuti, G., Oddone, M., Torres-Ruiz, J., 1995. Platinum-group element in upper mantle rocks from the Ivrea Zone (Italy) and the Betic–Rifean Cordillera (Spain, Morocco). *Proc. Int. Field Conf. Symp. Petrology and Metallogeny of Volcanic and Intrusive Rocks of the Midcontinent Rift System, Duluth, Minn., August 19–September 1*, pp. 53–54.
- Hill, R., Roeder, P., 1974. The crystallization of spinel from basaltic liquid as a function of oxygen fugacity. *J. Geol.* 82, 709–729.
- Ivanov, O.K., Kaleganov, B.A., 1993. New data about age of the concentric–zonal dunite–pyroxenite massifs of the Ural Platiniferous Belt. *Dokl. Acad. Nauk* 328(6), 720–724 (in Russian).
- Ivanov, S.N., Perfiliev, A.S., Efimov, A.A., Smirnov, G.A., Necheukhin, V.M., Fershtater, G.B., 1975. Fundamental features in the structure and evolution of the Urals. *Am. J. Sci.* 275, 107–130.
- Jagoutz, E., Palme, H., Baddenhausen, H., Blum, K., Cendales, M., Dreibus, G., Spettel, B., Lorenz, V., Wanke, H., 1979. The abundance of major, minor and trace elements in the earth's mantle as derived from primitive ultramafic nodules. *Proc. 10th Lunar Planet Science Conference*, pp. 2031–2050.
- Kaleganov, B.A., Pushkarev, E.V., 1992. Potassium–Argon dating of gabbro of the Uktus and Shabrovsky massif. In: *Geology and Geochemistry, Ural Branch, RAS, YearBook-91, Ekaterinburg*, pp. 62–64 (in Russian).
- Kostantopoulou, G., Economou-Eliopoulos, M., 1991. Distribution of platinum-group elements and gold within the Vourinos chromite ores, Greece. *Econ. Geol.* 86, 1672–1682.
- Lazarenkov, V.G., Malich, K.N., 1991. Geochemistry of the Ultrabasites of the Konder Platiniferous massif. *Geokhimiya* 10, 1406–1418 (in Russian).
- Leblanc, M., 1991. Platinum-group elements and gold in ophiolitic complexes: distribution and fractionation from mantle to oceanic floor. In: Tj. Peters et al. (Editors), *Ophiolite Genesis and Evolution of the Oceanic Lithosphere, Oman*. Kluwer, Dordrecht, pp. 231–260.
- Lorand, J.P., 1989. Abundance and distribution of Cu–Fe–Ni sulfides, sulfur, copper and platinum-group elements in orogenic-type spinel lherzolite massifs of Ariège (Northeastern Pyrenees, France). *Earth Planet. Sci. Lett.* 93, 50–64.
- Malachov, I.A., Malachova, L.V., 1970. The Nizhne–Tagilskiy pyroxenite–dunite massif and its environment. *Sverdlovsk Institute of Geology and Geochemistry*, 167 pp. (in Russian).
- Malich, K.N., 1990. Distribution of Platinum-Group Elements in Aldan–Shield ultrabasic intrusions. *Geokhimiya* 3, 425–429 (in Russian).
- Menzies, M.A., Dupuy, C., 1991. Orogenic massifs: protolith, process and provenance. *J. Petrol., Special Lherzolites Issue*, pp. 1–16.
- Naldrett, A.J., 1981. Platinum-group element deposits. In: L.J. Cabri (Ed.), *PGE Mineralogy, Geology, Recovery*. Can. Inst. Min. Metall., Spec. Vol. 23, 197–231.
- Naldrett, A.J., Cabri, L.J., 1976. Ultramafic and related rocks: their classification and genesis with special reference to the concentration of nickel sulfides and platinum-group elements. *Econ. Geol.* 71, 1131–1158.
- Nicolas, A., Jackson, E.D., 1972. Repartition en deux provinces des péridotites des chaînes alpines longeant la Méditerranée: implications géotectoniques. *S.M.P.M.* 52, 479–495.
- O'Neill, H.St.C., 1991. The origin of the Moon and the early history of the Earth. A chemical model, part 2. *The Earth. Geochim. Cosmochim. Acta* 55, 1159–1172.
- Peach, L.C., Mathez, E.A., Keays, R.R., 1990. Sulfide melt–silicate melt distribution coefficients for noble metals and other chalcophile elements as deduced from MORB: Implication for partial melting. *Geochim. Cosmochim. Acta* 54, 3379–3389.
- Prichard, H.M., Lord, R.A., 1990. Platinum and Palladium in the Troodos ophiolite complex, Cyprus. *Can. Mineral.* 28, 607–617.
- Pushkarev, E.V., Gulyaeva, T.Y., Palueva, G.V., Petrisheva, V.G., Sherstobitova, L.A., 1994. Dunite of the Uktus massif. In: *Geology and Geochemistry, Ural Branch, RAS, YearBook-93, Ekaterinburg*, pp. 73–80 (in Russian).
- Razin, L.V., 1976. Geological and genetic features of forsterite dunites and their Platinum-group mineralization. *Econ. Geol.* 71, 1371–1376.

- Savelieva, G.N., 1987. Gabbro–Ultrabasite Assemblage of Ural Ophiolites and their Analogues in Recent Oceanic Crust. Nauka, Moscow, 245 pp. (in Russian).
- Savelieva, G.N., Saveliev, A.A., 1992. Relationship between peridotites and gabbroic sequence in the ophiolites of the Urals and the Lesser Caucasus. *Ofioliti* 17, 117–137.
- Shteinberg, D.S., Ronkin, Y.L., Kurulenko, R.S., Lepikhina, O.P., Berseneva, N.P., 1988. Rb–Sr age of the rocks of the Shartash intrusive-dykes complex. In: *Geology and Geochemistry, Ural Branch, RAS, Ekaterinburg*, pp. 110–112 (in Russian).
- Tisl, M., 1994. Geochemistry of platinum-group elements of the zoned ultramafic Alto Condoto complex, Northwest Colombia. *Econ. Geol.* 89, 158–167.
- Volchenko, Y.A., Zoloev, K.K., Koroteev, V.A., Mardirosoyan, A.N., 1995. The types of the platinum deposits and their genetical essence. Actual problems of magmatic geology petrology and ore formation. *Uralgeolcom*. In: *Geology and Geochemistry, Ural Branch, RAS, Ekaterinburg*, pp. 38–55 (in Russian).