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Abundance and ranges of composition of the platinum metals in various rocks and meteorites are summarized from the literature

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GEOCHEMISTRY OF THE PLATINUM METALS

By THOMAS L. WRIGHT and MICHAEL FLEISCHER

ABSTRACT

This paper summarizes the literature pertaining to the geochemistry of the platinum metals. The platinum metals—platinum, iridium, osmium, palladium, rhodium, and ruthenium—occur as alloys of metals, as intermetallic compounds, and as compounds with oxygen, sulfur, tellurium, arsenic, antimony, tin, and bismuth. The synonomy and known ranges of composition of platinum-metal compounds are summarized in tables. Platinum metals also occur as trace constituents of rock-forming minerals, in amounts as much as 10 ppm, although commonly less than 1 ppm. The form in which platinum metals occur in these minerals is imperfectly known.

Platinum metals are unevenly distributed throughout rock masses, probably in the form of pure metals or alloys. Data for content of platinum metals in rocks are of uncertain reliability owing to inherent sampling difficulties and to errors in the analytical procedures. The following abundances are estimated to within one order of magnitude: Ultramafic rocks (0.05 ppm); mafic igneous rocks (0.02 ppm); silicic and intermediate igneous rocks (0.005 ppm). In general, data are insufficient to give estimates for metamorphic and common sedimentary rocks. Some uncommon sediments—for example, copper-bearing shale, coal ash—have platinum-metal contents as high as 1 ppm.

Recent estimates of crustal abundances of the platinum metals are as follows (all values in ppm): Palladium, 0.01–0.02; platinum, 0.005; iridium, osmium, rhodium, and ruthenium, all less than 0.001. Data for industrial recovery of platinum metals indicate a much greater recovery of platinum than of palladium, which suggests that the crustal abundance figures for platinum and palladium should be reversed.

Meteorites contain more platinum metals than crustal rocks; siderites contain, on the average, 30 ppm total platinum metals compared with 4 ppm in chondrites. In individual meteorites, platinum and iridium are largely concentrated in the iron phase, whereas osmium, iridium, ruthenium, and rhodium are also present in significant amounts in the troilite (sulfide) phase. The following average contents of the platinum metals in meteorites have been calculated from data in the literature (all values in ppm): Platinum, 2.3; osmium, 1.7; ruthenium, 1.6; palladium, 1.4; iridium, 0.7; rhodium, 0.6.

The cosmic abundances of the platinum metals, as summarized from the recent literature, are as follows (atoms per 10^6 atoms silicon): platinum, 1.3–1.6; ruthenium, 1.5–0.9; osmium, 1.0–0.6; iridium, 0.8–0.5; palladium, 0.7–0.6; rhodium, 0.2.

GENERAL GEOCHEMICAL CONSIDERATIONS

The platinum metals comprise the six heavier metals of group VIII of the periodic table of the elements. They are conventionally separated into two subgroups: the light platinum metals (of lower atomic weights) ruthenium (Ru), rhodium (Rh), and palladium (Pd) and the heavy platinum metals osmium (Os), iridium (Ir), and platinum (Pt). Atomic weights and metallic and covalent radii of the platinum metals are given in table 1 and isotopic abundances are summarized in table 2. Solid solution among the platinum metals is extensive, because of the similarity in their metallic radii. These metals also combine with or can be replaced in part by significant amounts of Fe (radius 1.27 A.), Ni (radius 1.24 A.), and Cu (radius 1.28 A.).

The platinum metals are strongly siderophilic and chalcophilic—that is, they occur predominantly as pure metals and alloys and to a much lesser extent combined with sulfur, tellurium, and arsenic. They occur in rock-forming silicates in small to negligible amounts. For the most part the platinum metals are concentrated in the early stages of magmatic differentiation and consequently are most abundant in magmatic mafic and ultramafic bodies and associated ore deposits. Under certain conditions, as yet imperfectly known, the platinum metals are carried through the differentiation process because of their lack of affinity for the silicate minerals and are then concentrated in the products of late hydrothermal solutions.

Economically valuable deposits of the platinum metals are restricted almost entirely to areas within or near masses of mafic and ultramafic rocks. The platinum metals in the primary deposits are closely associated with sulfides—especially of the chalcopyrite-pyrrhotite-pentlandite assemblage—or with chromite, but much of the world's supply has come from placer deposits derived from ultramafic rocks in which traces of platinum metals were originally disseminated.

Previous reviews of the geochemistry of the platinum metals may be found in Goldschmidt (1954, p. 677–695), Rankama and

TABLE 1.—*Atomic properties of the platinum metals*

	Ru	Rh	Pd	Os	Ir	Pt
Atomic No.	44	45	46	76	77	78
Atomic weight [1]	101.07	102.05	106.4	190.2	192.2	195.09
Metallic radius, A	1.34	1.34	1.37	1.35	1.35	1.38
Octahedral covalent radius, A	1.33	1.32	1.31	1.33	1.32	1.31

[1] 1961 scale based on carbon-12.

TABLE 2.—*Isotopic composition, in percent, of the platinum metals*

1. Ruthenium

Reference	Abundance (percent) for indicated mass No.—											
	94	95	95	97	98	99	100	101	102	103	104	105
Seaborg and Perlman (1948)	------	------	5.68	------	2.22	12.81	12.70	16.98	31.34	--------	18.67	--------
Friedman and Irsa (1954)	------	------	5.50	------	1.91	12.70	12.69	17.01	31.52	--------	18.67	--------
White, Collins, and Rourke (1956)	<0.01	<0.01	5.57	<0.01	1.86	12.7	12.6	17.1	31.5	<0.0001	18.5	<0.0007
Feitknecht, Herr, and Hoffmeister (1962)	------	------	5.52	------	1.85	12.72	12.53	17.09	31.54	--------	18.74	--------
Do	------	------	5.52	------	1.84	12.74	12.61	17.07	31.60	--------	18.62	--------

2. Rhodium

[Rh_{103}=100.0 (Reference: Seaborg and Perlman, 1948)]

3. Palladium

Reference	102	104	105	106	108	110
Seaborg and Perlman, 1948	0.8	9.3	22.6	27.2	26.8	13.5
Sites, Consolazio, and Baldock (1953)	.96	10.97	22.23	27.33	26.71	11.81

4. Osmium

Reference	184	186	187	188	189	190	192
Seaborg and Perlman (1948)	0.018	1.59	1.64	13.3	16.1	26.4	41.0

5. Iridium

[Ir_{191}=38.5; Ir_{193}=61.5 (Reference: Seaborg and Perlman, 1948)]

6. Platinum

Reference	188	189	190	191	192	193	194	195	196	197	198	199	200
Seaborg and Perlman (1948)	--------	--------	------	--------	0.78	--------	32.8	33.7	25.4	--------	7.23	-------	--------
Leland (1949)	--------	--------	0.012	--------	----	-------	----	----	----	--------	----	--------	--------
Duckworth and others (1952)	<0.002	<0.002	------	<0.004	----	<0.009	----	----	----	<0.010	----	<0.008	<0.007
Lopez de Azcona (1955)	--------	--------	.06	--------	.78	--------	32.8	33.7	25.4	--------	7.23	-------	--------
White, Collins, and Rourke (1956)	<.0013	<.0005	.0127	<.0005	.78	<.001	32.9	33.8	25.2	<.001	7.19	<.001	<.001

Sahama (1950, p. 688–694), Zvyagintsev (1946), Zvyagintsev (1950), Quiring (1962), and Gmelin (1938).

MINERALOGY OF THE PLATINUM METALS

This section summarizes the chemical composition of the minerals in which the platinum minerals occur. The minerals are divided into three groups: Alloys of metals, and intermetallic compounds; compounds of platinum metals with oxygen, sulfur, tellurium, arsenic, antimony, bismuth, and tin; and minerals that contain the platinum

metals as trace constituents. It is possible that some of the compounds placed in the second group, especially those with bismuth and tin, should properly be classed as intermetallic compounds, but more data on the crystal structures of the compounds are needed for certain classification.

ALLOYS AND INTERMETALLIC COMPOUNDS

The alloys and intermetallic compounds of the platinum-group metals are listed alphabetically in table 3 and the ranges of chemical composition reported for them are given in table 4. Synonymy is indicated in table 3; names that are italicized are considered to rank as species.

The nomenclature of the alloys of the platinum metals has been confused and has not been consistent, even in the major reference books on mineralogy. This is especially true of the iridium-osmium alloys, which form two distinct series of alloys, cubic and hexagonal. In much of the literature, and particularly in commercial work, the two series have not been separated, and it is commonly impossible to be sure whether material referred to as iridosmine or osmiridium was actually the cubic phase, the hexagonal phase, or mixtures of the two. The nomenclature used in table 3 is that recommended by Hey (1963).

The cubic alloys include species with platinum, iridium, and palladium dominant; the natural alloys in which platinum is dominant are by far the most abundant. Platinum-iridium and platinum-palladium are reported to form complete series of cubic solid solutions at high temperatures, but the solubility at low temperatures may be limited (Hansen and Anderko, 1958, p. 871, 1121). Platinum also forms complete series of cubic solid solutions at high temperatures with iron, nickel, and copper (Hansen and Anderko, 1958, p. 616, 698, 1031), but complex exsolution and reaction phenomena occur on cooling, and the limits of solubility of these elements in platinum at low temperatures have not yet been determined accurately.

A cubic phase, corresponding to osmiridium of table 3, is stable in the system iridium-osmium in the composition range Ir 100–68, Os 0–32 percent. A hexagonal phase, corresponding to the series iridosmine-osmium of table 3, is stable in the system iridium-osmium in the composition range Ir 68–0, Os 32–100 percent. It may be expected that the position of the boundary between cubic and hexagonal phases will be shifted by the presence of other metals; thus the presence of ruthenium, which crystallizes in the hexagonal system, would probably favor the formation of the hexagonal phase. Data are not yet available on the ternary systems.

The hexagonal iridosmine series appears to be much more abundant in natural occurrences than the cubic osmiridium. Recent analyses

TABLE 3.—*Glossary of names of alloys and intermetallic compounds of the platinum metals*

[Names in italic are considered to rank as species]

Mineral	*Description*
Allopalladium	Hexagonal. Pd, with some Pt, Ru, and Cu, and traces of Ir, Rh, Ag, Hg.
Aurosmirid	Aurian osmiridium. Cubic. Au 19.3 percent.
Avaite	Synonym of platiniridium.
Cuproplatinum	Cuprian platinum.
Eugenesite	Synonym of allopalladium.
Ferroplatinum	Ferrian platinum.
Gold	Reported to contain Pd (see porpezite), Rh (see rhodite), Ir, Pt.
Iridium	Pure iridium has not yet been reported. See platiniridium and osmiridium.
Iridosmine-osmium series	Hexagonal. A single series, divided arbitrarily for convenience into iridosmine, with Ir 68–20, Os 32–80 percent, and osmium, with Ir 20–0, Os 80–100. Iridosmine is divided by some authors into the varieties nevyanskite with Ir>Os, Ir 68–50 percent, and sysertskite with Os>Ir, Ir 20–50 percent.
Iridosmium	Synonym of iridosmine.
Nevyanskite. See Iridosmine.	
Nickel-platinum	Nickelian platinum.
Norilskite (Pt, Fe, Ni, Cu)	A mixture(?).
Osmiridium	Cubic. (Ir, Os) with Os up to 32 percent. The name is also used, especially commercially, to include the hexagonal alloys (iridosmine).
Osmite	Synonym of iridosmine.
Osmium. See iridosmine-osmium series.	
Palladium	Cubic. Pd, with some Pt, Rh, Ir, Ru, Os, Pb.
Palladium-amalgam	Synonym of potarite.
Palladiplatinum	Cubic. Approximately equal amounts of Pd and Pt.
Platiniridium	Cubic. (Ir, Pt).
Platinum	Cubic. Pt, with Ir, Pd, Rh, Os, Au(?), Cu, Fe, Ni. See also norilskite, Palladiplatinum.
Platinum-nevyanskite	Platinian osmiridium or Iridosmine.
Polyxene	Synonym of platinum.
Porpezite	Palladian gold (up to 10 percent Pd).
Potarite	Pd_3Hg_2(?) or PdHg(?). Cubic(?).
Rhodite	Rhodian gold (up to 43 percent Rh(?)).
Rhodium-nevyanskite	Rhodian osmiridium or iridosmine.
Ruthenium-nevyanskite Ruthenosmiridium Ruthenium-sysertskite	Ruthenian Iridosmine. (up to 21.1 percent Ru).
Selenpalladium	Synonym of allopalladium (erroneously thought to contain Se).
Siserskite, sisserskite, sysertskite. See Iridosmine.	
Unnamed Mineral A	Pd_4Pb. Borovskii and others (1959).

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TABLE 4.—*Ranges of chemical composition of alloys and intermetallic compounds of the platinum metals*

[In weight percent]

Element	Auros-mirid[1]	Gold	Irido-mine-os-mium series	Noril-skite[1]	Osmiri-dium	Pallidi-plati-num[1]	Palla-dium	Platin-iridum[1]	Platinum	Un-named mineral A[1]
Pt		[2]10.5	0.2–13.6	35.5	0–11.3	48.9	[2]1.6	19.6	55.4–87.2	
Ir	51.7	[2]30.4	64.5–3.7		51.7–72.5		2.2	76.9	Usually 1.0–10.4, [2]27.8.	
Os	25.5		22.9–98		31.2–10		2.7		0–0.5	
Pd		[2]11.6	0–.6	3.6	0–.6	51.1	86–100	9.9	Usually 0–2, [2]37.	≈70
Rh		[2]43?	0–7.7		0–11.3		[2]3.0		0.4–6.9	
Ru	3.5		0–18.3		0–4		2.2			
Au	19.3	Major	0–.9						[2]3.0	
Fe	Trace	[2].6	0–2.6		0–2.3				2.6–28.0	
Cu		[2].9	0–.1	25.3				1–8	0–13	
Ni				9.3					0–4	
Pd				25.6			[2]8.1			≈30
Sn										≈1
Ag									0–8	

[1] One analysis.
[2] Maximum content reported.

by Levy and Picot (1961) on material checked by X-ray study show that the series covers nearly the entire composition range found in the iridium-osmium system. The hexagonal minerals allopalladium and potarite are very rare.

The limits of composition of the natural alloys are poorly known, but the available data are summarized in table 4, which is based on analyses of minerals. Analyses of commercial concentrates of undetermined mineralogy have not been included. The compositional ranges indicated for the minerals must be considered to be uncertain, partly because of the formidable difficulties of analysis of the platinum metals, but mainly because of doubt as to the homogeneity of the material analyzed. The alloys of the platinum metals, as well illustrated by Ramdohr (1960, p. 322, 335), Borovskii and others (1959), Genkin (1959), and Genkin and others (1962, 1963), commonly occur as complex intergrowths of minute grains. It is therefore likely that many of the available analyses were made on concentrates that may not have been single phases. Much of, and possibly all, the gold reported in the analyses was probably present as native gold. Some of the copper, iron, and nickel reported was probably present as chalcopyrite, bornite, pentlandite, native copper, and other admixtures. Much work is needed, especially analyses of mineral grains proved to be homogeneous by optical and X-ray study, to improve our knowledge of the compositional limits of these alloys. Especially promising is the application of electron-probe analysis, which makes it possible to determine the composition of grains as small as 10 microns in diameter.

The use of this method in the past few years has added to our knowledge of the series iridosmine-osmium (Levy and Picot, 1961) and has resulted in the discovery of many new minerals—listed in tables 3 and 6 (Borovskii and others, 1959; Genkin, 1959; Genkin and others, 1962, 1963; and Stumpfl, 1961).

COMPOUNDS WITH OXYGEN, SULFUR, TELLURIUM, ARSENIC, ANTIMONY, BISMUTH AND TIN

The compounds of the platinum metals are listed alphabetically in table 5 and are grouped by anions in table 6. Names that are italicized in table 5 are considered to rank as species. The ranges of chemical compositions are given in table 7. It will be noted (table 5) that many of these minerals have been found recently. The minerals of this group are all rare and very few analyses have been made—only one for many of them—so that relatively little is known of the possible ranges in composition.

TABLE 5.—*Glossary of names of compounds of the platinum metals with oxygen, sulfur, tellurium, arsenic, antimony, bismuth, and tin*

[Names in italic are considered to rank as species]

Mineral	Composition	System	Reference	Remarks
Arsenopalladinite	Pd_3As			
Braggite	(Pt, Pd, Ni)S	Tetragonal		
Cooperite	(Pt, Pd)S	do		
Froodite	$PdBi_2$	Monoclinic		
Geversite	$PtSb_2$	Cubic	Stumpfl (1961)	
Kotulskite	$Pd(Te, Bi)_{1.2}$	Hexagonal	Genkin and others (1963).	
Laurite	$(Ru, Os)S_2$	Cubic		
Michenerite	$PdBi_2$	do		From Sudbury, Ontario.
	(Pd, Pt)BiTe	do		From Monchegorsk, U.S.S.R.
Moncheite	$(Pt, Pd)(Te, Bi)_2$	Hexagonal	Genkin and others (1963).	
Niggliite	PtSn(?)			Possibly PtTe(?).
Palladinite	PdO(?)			Uncertain.
Sperrylite	$PtAs_2$	Cubic		
Stannopalladinite	$(Pd, Pt)_3Sn_2$			
Stannoplatinite	Pt_3Sn_2(?)			No analysis.
Stibiopalladinite	Pd_3Sb			
Vysotskite	(Pd, Ni, Pt)S	Tetragonal	Genkin and Zvyagintsev, (1962).	
Unnamed new minerals:				
B	$(Pt, Ir)As_2$	Cubic	Stumpfl (1961)	Perhaps iridian Sperrylite(?).
C	$Pt(Ir, Os)As_4$	do	do	
D	$PtMAs_2$		Borovskii and others (1959).	M=Os(?).
E	PtSb	Hexagonal	Stumpfl (1961)	
F	Pt(Sb, Bi)	do	do	Bismuthian variety of E(?).
G	Pd(Sb, Bi)		do	
H	Pd-Bi mineral		Hawley (1962, p. 95–96).	From Sudbury. Not froodite or michenerite.
I	Pd_2CuSb		Stumpfl (1961)	
J	Pd_3CuSb_3		do	
K	$Pt_4Cu_4Sn_3$		do	
L	PtPdSn		Borovskii and others (1959).	

TABLE 6.—*Compounds of the platinum metals grouped by anions*

[The metal listed is the dominant one]

Oxides	Pd (palladinite) (?)
Sulfides	Pt (braggite, cooperite)
	Pd (vysotskite)
	Ru (laurite)
Tellurides	Pt (moncheite, niggliite) (?)
	Pd (kotulskite)
Arsenides	Pt (sperrylite, unnamed B, C, D)
	Pd (arsenopalladinite)
Antimonides	Pt (geversite, unnamed E, F)
	Pd (stibopalladinite, unnamed G, I, J)
Bismuthides	Pt (moncheite, unnamed F)
	Pd (froodite, kotulskite, michenerite, unnamed G, H)
Stannides	Pt (niggliite(?), stannoplatinite, unnamed K, L)

TABLE 7.—*Chemical composition of compounds of the platinum metals*

[In weight percent]

Element	Braggite	Cooperite	Geversite[1]	Kotulskite[1]	Laurite	Michenerite	Moncheite	Sperrylite	Stannopalladinite
Pt	59	80.3–82.5	45			8.4– 9.3	22.3–30.8	52.6–63	15–20
Ir	Present	Present							
Os					[2]3.0				
Pd	18–20.9	0– 4.3		31.1		11.7–16.9	4.6– 9–2	Trace	40–45
Rh	Present							0– 1.7	
Ru	Present				65–67				
Au									
Fe								0– .7	0.3–2.3
Cu								0– .7	5–12
Ni	2.8– 4.7	0– .1							0.1– .7
Pd									
S	16.8–19.0	14.3–17.5			31.8–33				
Te				44.0		28.8–37.6	33.5–55.4		
As								39.9–41.9	
Sb			51.5					0– .5	
Bi				24.9		42.3–45.0	9.2–31.7		
Sn								0–4	28–33

Element	Stibiopalladinite	Vysotskite	Unnamed mineral [based on one analysis each]									
			B	C	D	E	F	G	I	J	K	L
Pt		4.1– 5.5	47.0	22.0	≈36	50.5	50.5			6.0	51.7	≈50
Ir			5.0	Major								≈2.5
Os				Major								
Pd	70.4–73	57.1–61.9						43.6	53.5	62.0		28
Rh												
Ru					≈3							
Au												
Fe												
Cu									16.0	5.0	16.8	
Ni		14.2–16.6										
Pd												
S												
Te												
As			46.8	32.5	≈28							
Sb	25–28					34.7	26.4	25.2	31.3	30.0		
Bi							15.3	32.2				
Sn											22.0	≈30

[1] One analysis.
[2] Maximum content reported.

MINERALS THAT CONTAIN PLATINUM METALS AS TRACE CONSTITUENTS

The platinum metals have been reported to occur as trace constituents in members of all mineral groups except the carbonates and nitrates, and especially in sulfides, selenides, tellurides, and arsenides. The microscopic features of the minerals analyzed are not described in most of the papers; it is probable that at least part of the platinum metals reported were present as discrete minerals rather than as solid solutions. Additional uncertainty is caused by the difficulties of analysis; for example, it is known that osmium and rhodium are likely to be lost in part during cupellation and are therefore likely to be low in analyses made by first collecting the platinum metals in assay beads. Analyses of more than 200 minerals and rocks for all 6 platinum metals are given by Noddack and Noddack (1931); mentioned here are those minerals that contained more than 1 ppm total platinum metals.

Such data as are available on sulfides and arsenides are given in table 8. It is evident that precise analyses on material of known homogeneity are badly needed. Many additional determinations are given by Hawley and Rimsaite (1953) from Canadian ore deposits and by Schneiderhöhn and Moritz (1931) for sulfides of the Merensky Reef of the Bushveld complex, South Africa; the maximum contents

TABLE 8.—*Total platinum-metals content, in parts per million, reported in sulfides, selenides, tellurides, and arsenides*

[See also tables 9 and 10]

Mineral and locality	Total platinum metals	Reference
Hessite, Altai, U.S.S.R.	137	Noddack and Noddack (1931).
Argentite, Freiberg, Germany	16	Do.
Berzelianite, Skrikerum, Sweden	15.6	Do.
Galena	1, 2, 5	Gmelin (1938).
Clausthalite, Tilkerode, Germany	135	Noddack and Noddack (1931).
Altaite, Altai, U.S.S.R.	44	Do.
Sphalerite	1.5, 7	Gmelin (1938).
Chalcopyrite	1	Do.
Pyrrhotite, Evje, Norway	7.8	Noddack and Noddack (1931).
Pyrrhotite, Froyssa, Norway	5.3	Do.
Pyrrhotite, Sulitelma, Norway	1	Do.
Pentlandite, Espedalen, Norway	7.2	Do.
Molybdenite	1.7	Gmelin (1938).
Cobaltite, Skutterud, Norway	2	Noddack and Noddack (1931).
Gersdorffite, Loos, Sweden	8	Do.
Niccolite, Mansfeld, Germany	4	Do.
"Arsensilber," Andreasberg, Germany	24	Do.
Domeykite, Paracatas, Mexico	5	Do.

TABLE 9.—*Maximum contents of total platinum metals in minerals*

[In ppm]

Location	Pyrite	Pyrrhotite	Chalcopyrite	Pentlandite	Mixed arsenides	Nickel pyrite	Reference
Canadian ore deposits:							
Nickeliferous sulfide ores	0.7	9.8	35.8	4.8	[1] 247	50	Hawley and Rimsaite (1953).
Nonnickeliferous sulfide ores	.012	.056	1.12	-------	.11	-------	Do.
Creighton Mine, Sudbury, Ontario	-------	[2] .59	[3] .77	[4] 6.6	-------	------	Morris, Hill and Smith (1963).
Merensky Reef Bushveld complex S. Africa.	-------	50	-------	50	-------	50	Schneiderhöhn and Moritz (1931).

[1] Nearly all palladium, with trace of platinum.
[2] Pt, 0.50; Pd, 0.09.
[3] Pt, 0.76; Pd, 0.011.
[4] Pt, 6.3; Pd, 0.3.

given are listed in table 9. For comparison, recent data by Morris, Hill, and Smith (1963) are given. These were made by neutron-activation analysis; all others are spectrographic analyses. The data for the Canadian deposits show much higher content of total platinum metals in nickeliferous ores than in nonnickeliferous ores.

Averages of analyses for platinum, palladium, and rhodium for ores from Sudbury, Ontario, and from Noril'sk, U.S.S.R., are given in table 10. The ratios of the three elements in the two deposits are very different, but both sets of data show much higher relative contents of rhodium in pyrrhotite than in chalcopyrite.

Oxide minerals that have been reported to contain more than 1 ppm of total platinum metals are pyrolusite (14 ppm), psilomelane (4.9 ppm), cassiterite (1 ppm), columbite (3.45, 3 and 1.9 ppm), and chromite (2.35, 4.4 ppm, Noddack and Noddack, 1931). Up to 20 ppm total platinum metals was found in chromites from the South African platinum deposits (Schneiderhöhn and Moritz, 1931); chromite from eclogite pegmatite contained 0.24 to 1.15 ppm (Lunde and Johnson, 1928).

Traces of platinum metals were reported in sylvite (0.0007–0.0034 ppm) and in carnallite (0.0001–0.003 ppm) from German salt deposits (Goubeau and Birkenbach, 1938).

Contents of more than 1 ppm of total platinum metals have been reported for the following silicates: zircon, variety alvite, 10.4 ppm; gadolinite, 2.9, 8.4 ppm; and thortveitite, 8.3 ppm (Noddack and Noddack, 1931). These, as well as columbite of the oxide minerals, are formed in late stages of granitic pegmatites, which suggests that small amounts of the platinum metals remain in solution throughout the cycle of igneous differentiation, and precipitate in the final stages.

TABLE 10.—*Average content of platinum, palladium, and rhodium in sulfide minerals*

Mineral	Number of samples	Total platinum metals (ppm)	Pt	Pd	Rh
			Percent of total platinum metals		
Sudbury, Ontario [1]					
Pyrite	4	2. 60	54. 9	41. 6	3. 5
Pyrrhotite	17	1. 50	46. 0	42. 4	11. 6
Pentlandite	4	6. 70	31. 0	60. 8	8. 2
Chalcopyrite	8	7. 74	19. 0	80. 2	. 8
Noril'sk, U.S.S.R. [2]					
Pyrrhotite (veins)	----------	19	10. 6	52. 5	36. 9
Pyrrhotite (incrustations)	----------	20. 6	12. 6	72. 7	14. 5
Chalcopyrite (veins)	----------	4. 5	17. 0	83. 0	------
Chalcopyrite (incrustations)	----------	5. 14	9. 7	89. 5	. 8

[1] Summarized from Hawley (1962), tables 16–17, p. 124–125.
[2] Summarized from Ginzburg and Rogover (1961).

Rock-forming silicates reported to contain small amounts of platinum metals include olivine (0.19 ppm), pyroxene (0.03 ppm), serpentine (0.05, 0.18 ppm), hornblende (0.03 ppm), garnet (0.01 ppm), and orthoclase (0.03 ppm, Noddack and Noddack, 1931). Eclogite minerals reported to contain platinum metals are pyroxene (0.01, 0.07 ppm), and garnet (0.02, 0.02 ppm, Lunde and Johnson, 1928). As no microscope observations are given, the form of occurrence in these minerals is not known.

OCCURRENCE AND ABUNDANCE OF PLATINUM METALS IN ROCKS

UNCERTAINTIES IN THE DATA

Published analytical data for platinum metals in rocks are subject to errors derived from inherent sampling difficulties and from analytical uncertainties. Platinum metals are distributed nonuniformly throughout rock masses because of their tendency to crystallize as pure metals and alloys instead of as substituting ions in the lattices of rock-forming silicates. Hence, it is difficult to obtain representative samples of rock for analysis. Lunde and Johnson (1928, p. 190) analyzed seven samples of a single body of peridotite and found platinum-metal contents ranging from 0.075 ppm to 0.74 ppm and differing by a factor of nearly 10. Hahn-Weinheimer and Rost (1961, p. 175) found a similar scatter in analyses of five samples of a single body of serpentine; palladium ranged from 0.06 to 0.83 ppm, platinum from 0 to 0.22 ppm, and the sum of platinum and palladium

ranged from 0.11 to 1.05 ppm making a total difference of nearly an order of magnitude. Hagen,[1] in 1954, reported analyses of composite samples of Deccan plateau basalts which differed for palladium by a factor of two and for platinum by a factor of four.

Analytical uncertainties in the method of fire assay are discussed by Hagen, including a lengthy treatment of the corrections for losses during analysis. Corrections used by Hagen were large (as much as a factor of two) and were based on composite samples, thereby reducing the precision of data for individual samples. Vincent and Smales (1956) analyzed by neutron activation the same sample of Mooihoek dunite that Hagen analyzed spectrographically. Vincent and Smales' value of 0.125 ppm Pd differs from Hagen's value of 0.065 ppm Pd by a factor of two. This difference may reflect both sample inhomogeneity and analytical errors.

Because of the uncertainties involved, the platinum metal contents cited in table 11 and discussed in the following section should not be accepted as having an accuracy of greater than one order of magnitude.

IGNEOUS ROCKS

Data on the content of platinum metals in igneous rocks are scanty and scattered through a wide literature. Most of the data pertain to ultramafic rocks, the silicic and intermediate rocks having been almost completely ignored. Hagen[1] reports spectrographic analyses, after concentration by fire assay, of Pt and Pd in 77 igneous rocks samples, 35 of which are from the Bushveld complex (Transvaal). Because of the large number of samples and the recent date of the study, Hagen's data form the basis for much of the discussion in this section. His results are summarized in table 11.

Economically valuable deposits of platinum metals have been universally found associated with mafic and ultramafic rocks. As a result the data on abundance are heavily weighted in favor of these rocks to the virtual exclusion of more silicic igneous rocks and sediment and metamorphic rocks. The abundance of platinum metals in a single ultramafic rock unit or ultramafic rocks within a single petrologic province is given by Hagen[2] in 1954, Lunde (1927), Lunde and Johnson (1928), Schneiderhöhn and Moritz (1931), Cotelo Neiva (1949), Hahn-Weinheimer (1959), and Hahn-Weinheimer and Rost (1961). Additional values for miscellaneous ultramafic rock units are given by Leutwein (1939), Du Rietz (1956), Vincent and Smales (1956), and Hagen.[3] The maximum contents of platinum-group metals reported for ultramafic rocks other than those cited in

[1] Hagen, J. C., 1954, Some aspects of the geochemistry of platinum, palladium, and gold in igneous rocks with special reference to the Bushveld complex, Transvaal: Massachusetts Inst. Technology, [Cambridge], unpub. Ph. D. thesis.
[2] Hagen, op. cit.
[3] Hagen, op. cit.

TABLE 11.—*Summary of abundance data (ppm) on platinum metals in rocks* [1]

Rock type	Number of samples	Pt	Pd	Reference
Bushveld silicic rocks	4	0.003	0.005	Hagen, 1954.
U.S.A. silicic rocks	2	.003	.003	Do.
Westerly, R.I., granite (G–1).	----------	----------	[2] .01	Ahrens and Fleischer, 1960. Fleischer and Stevens, 1962.
Basalts	15	.026	.041	Hagen, 1954.
Diabases	5	.037	.016	Do.
Centerville diabase (W–1).	----------	----------	.20 .017	Ahrens and Fleischer, 1960. Fleischer and Stevens, 1962.
Bushveld gabbros	4	.021	.031	Hagen, 1954.
Other gabbros	4	.019	.020	Do.
Skaergaard (chilled marginal gabbro).	2	.018	.018	Vincent and Smales, 1956.
Bushveld norites	7	.038	.015	Hagen, 1954.
Sudbury norites	2	.011	.006	Do.
Bushveld peridotites	2	.017	.012	Do.
Other peridotites	3	.018	.011	Do.
Bushveld pyroxenites	7	.048	.059	Do.
U.S.A. pyroxenites	2	.009	.003	Do.
Onverwacht (Bushveld) dunites:				
Olivine (outer)	----------	.018	.004	Do.
Hortonolite (inner).	----------	3.17	.013	Do.
Mooihoek (Bushveld) dunites:				
Olivine (outer)	----------	.066	.065	Do.
Hortonolite (inner).	2	12.3, .26	.26, .023	Do.
Bushveld anorthosites	2	.075	.032	Do.
Essex anorthosite	1	.004	.003	Do.
Igneous rocks	27	.011	.017	Do.
Igneous rocks [3]	----------	.005	.02	Vinogradov, 1956.

[1] Table modified and enlarged from Hagen (1954) table 2–24, p. 103.
[2] Also contains Ir=0.0063 ppm.
[3] 2 parts acidic to 1 part basic. Qualitative estimates of abundance for the other platinum-group metals as follows: Ru=0.0001; Rh=.001; Os=.0001; Ir=.001.

table 11 are as follows: dunite (30 ppm); peridotite (0.74 ppm); pyroxenite (0.6 ppm); serpentinite (1.05 ppm).

The contents of platinum metals in igneous rocks other than ultramafic are given by Hagen[4] and Noddack and Noddack (1931). Hagen's data for palladium and platinum are summarized in table 11. Data on three different basalts presented by the Noddacks are as follows: 0.21 ppm, 0.03 ppm, and 0.05 ppm total platinum metals. These values are consistent with Hagen's average for basalt (Pt+Pd =0.067 ppm) and the Pd content of W–1 (0.02 ppm) reported in table 11. The Noddacks also report values of 0.02, 0.01, and 0.05 ppm in 3 different granites. The Pd content of G–1 is reported as

[4] Hagen, op. cit.

less than 0.01 ppm (table 11). No quantitative determinations of platinum metals in intermediate rocks exist.

SEDIMENTARY ROCKS

Determinations of platinum metals in sedimentary rocks are few and are mostly from unusual or uncommon rock types; none is from sandstone, limestone, or ordinary shale. During the weathering cycle the platinum metals, by virtue of their high specific gravity and low solubility, are largely concentrated as placer deposits, and therefore their abundance in ordinary sedimentary rocks is quite low. The abundances of platinum metals in sedimentary deposits are summarized in table 12. The highest contents of Pt and Pd are found in the Mansfeld copper-bearing shale of Germany (0.02–0.05 ppm), where these metals may be associated with sulfides, and in coal ash (up to 0.5 ppm).

TABLE 12.—*Platinum metals in sedimentary rocks*

[D, detected, no value given]

Rock type	Abundance (ppm) for indicated element						Reference
	Pt	Ir	Os	Pd	Rh	Ru	
Copper-bearing shale (Mansfeld).	0.0001	0.0001		0.0001			Cissarz and Moritz, 1933.
Do	.05	.004	0.003	.02	0.0002	0.003	Noddack, 1936.
Black shale—	.05			<.05	<.01	.06	Tischendorf, 1959.
	.05			<.05	.02	.08	
	.01			<.05	.01	.04	
Bleached shale	.05			<.05	.02	.04	Do.
	.05			<.05	<.01	.005	
	.01			<.05	<.01	.02	
Sand	.007						Quiring, 1962.
	.04						
	.01						
Loam	.02						Do.
Coal (clarite) (in ash)	.2						Goldschmidt and Peters, 1933.
Coal (Steinkohle) (in ash)	.1–.5		.05–.5	.02			Do.
Fine potter's clay	.2–.5		.2–.5				Goldschmidt and others, 1948.
Marine sapropel—	.2–.5	<.5(?)	<.2				Do.
Hematitic flint clay			D				Ahrens, 1945.
Recent montmorillonite clay			D				Do.
Pink kaolin				D	D		Iimori and Yoshimura, 1929.
Globigerina ooze			D				Smales and Wiseman 1955.
	Total platinum metals						
German K-salt deposits, saline clays.	0.0009–0.092						Goubeau and Birkenbach, 1938.
Rock surrounding the saline layers.	0.0006–.174						Do.

METAMORPHIC ROCKS

Determinations of platinum-metal content of metamorphic rocks are scarce, and where such measurements are reported they are invariably given for rocks in a generally ultramafic terrain—either

metamorphosed ultramafics or contact rocks adjacent to an ultramafic massif. The platinum-metal content of a pyroxene-calcite rock (sagvandite) listed by Lunde and Johnson (1928) is as follows:

	Content (ppm)
Sample 1	
Fresh sagvandite	0.73
Amphibole-garnet-bearing contact zone	1.22
Sediments (outside contact aureole)	<.01
Sample 2	
Decomposed sagvandite	.65
Hydrothermal contact zone	1.24
Chlorite schist in contact zone	<.01

Eclogites have been reported with 0.077 ppm platinum metals (Lunde and Johnson, 1928) and with 0.01 ppm Pt (Noddack and Noddack, 1931). Platinum of 0.08–0.5 ppm and Pd of 0.08–0.1 ppm are reported for four garnet-bearing amphibolites (Leutwein, 1939).

AVERAGE ABUNDANCES

It is difficult at present (1964) to cite meaningful figures for the abundance of platinum metals in different rock types. In addition to sampling and analytical uncertainties there probably are real variations of platinum metals in different geologic provinces. For example, comparing two mafic intrusives, the Bushveld is rich in platinum metals in relation to the Skaergaard. The average abundances of platinum and palladium for igneous rocks given at the bottom of table 11 are probably of the correct order of magnitude, but many more and better data are needed before the abundances can be established with certainty. Data are insufficient to permit estimates of average abundances for sedimentary or metamorphic rocks.

IN THE EARTH'S CRUST

Estimates of the crustal abundance of platinum metals are summarized in table 13. The later estimates are probably within one order of magnitude of the true abundance. Better estimates of crustal abundance will not be possible until more data are obtained on platinum-metal content of granitic rocks which make up the bulk of the crust.

The relative abundances of the platinum metals in the later estimates (table 13) are as follows:

$$Pd > Pt \gg Ir \geqq Os \geqq Rh \approx Ru.$$

Another figure for the relative abundance among the platinum metals can be obtained from the amounts recovered for industrial use. In table 14, production data from several sources are compared with estimates of relative abundance computed from the abundance figures

TABLE 13.—*Estimated abundance (ppm) of platinum metals in the earth's crust*

[n, significant but unknown integer]

	Ir	Os	Pd	Pt	Rh	Ru	Source
1	0.000n	0.000n	0.000n	0.000n	0.000n	0.000n	Clarke and Washington, 1924.
2	.0005	.0009	.6	1.2	.01	.0036	Berg, 1929.
3	.01	.05	.08	.05	.01	.05	Fersman, 1933.
4	.02	.04	.05	.05	.01	.04	Schneiderhöhn, 1934.
5	.001	----------	.01	.005	.001	----------	Goldschmidt, 1937, 1954 and Rankama and Sahama, 1950.
6	.01	.05	.05	.05	.01	.05	Anderson, 1945.
7	.001	.01	.01	.005	.001	.02	Polanski, 1948.
8	.001	.001(?)	.01	.005	.0001	.00001(?)	Mason, 1952.
9	.001	.0001(?)	.02	.005	.001(?)	.0001(?)	Vinogradov, 1956.
10	.001	.001	.01	.005	.001	.001	Mason, 1958.
11	----------	----------	.00n	----------	----------	----------	Turekian and Wedepohl, 1961.
12	----------	----------	.013	----------	----------	----------	Vinogradov, 1962b.

TABLE 14.—*Comparison of the relative amounts of platinum metals recovered by industrial processes with that computed from their natural abundance*

[All values in percent of total platinum metals]

Source	Ru	Rh	Pd	Os	Ir	Pt
Vinogradov, 1956 [1]	0.4	3.7	73.5	0.4	3.7	18.3
Mason, 1958 [1]	5.2	5.3	52.6	5.2	5.3	26.4
United States production, 1956–60:[2]						
Range	.7–3.1	.6–4.8	7.5–18.8	.8–2.9	3.4–6.5	68.5–86.2
Average	1.8	2.4	12.4	1.7	5.0	76.7
World production, 1735–1940 [3]	.4	.7	7.3	1.8	3.4	86.4
Sudbury Ontario, production, 5 years [4]	9.9	8.8	40.0	----------	4.7	36.6
Various deposits [5]	.05–.1	.3–.5	.3–23.0	.3–1.7	1.1–3.4	70–84.5

[1] Computed from abundance figures.
[2] Calculated from table 2, U.S. Bur. Mines Yearbook, 1960, v. 1, p. 889.
[3] Calculated from Quiring, 1962, table 16, p. 84–85.
[4] Quoted in Hawley, 1962, p. 122.
[5] Quiring, 1962, tables 17–20, p. 86–89.

of Vinogradov (1956) and Mason (1958). The tabulation shows that industrial recovery of platinum far exceeds the recovery of palladium, whereas the relative-abundance estimates would suggest the reverse. Probably the relative-abundance figures are in error, because most of the analytical data summarized in the present paper indicate that palladium is not as abundant as platinum in the earth's crust. Among the minor platinum metals, iridium is generally recovered in greater quantities than rhodium, ruthenium, or osmium. This order is consistent with the abundance figures.

IN METEORITIC MATTER

Information on the abundance of platinum metals in meteorites is more complete than in any other natural materials. Analyses of individual metals by neutron-activation and by improved wet chemical techniques are available for a variety of meteorites. Because of their siderophile and chalcophile character, the platinum metals are preferentially concentrated in siderites and the nickel-iron and troilite phases of chondrites. The ranges of platinum-metal content of siderites and chondrites are summarized in table 15. The distri-

TABLE 15.—*Platinum metals in individual meteorites*

Element	Range (ppm)		Average (ppm)	References
	From—	To—		
Siderites				
Ru	1	15	7	Hara and Sandell (1960).
	2	9.4	5.5	Sen Gupta and Beamish (1963).
	5.7			Yavnel (1963).
Overall average			6.2	
Rh	1			Schindewolf and Walgren (1960).
	2.12	4.1	3.0	Sen Gupta and Beamish (1963).
	.9			Yavnel (1963).
Overall average			3.0	
Pd	1	10	3.7	Goldberg, Uchiyama, and Brown (1951).
	3.4	3.7	4.3	Hamaguchi, Nakai, and Kamemoto (1961).
	1.20	6.6	3.2	Sen Gupta and Beamish (1963).
	6.9			Yavnel (1963).
Overall average			3.7	
Os	.58	3.22	2.03	Herr, Hoffmeister, and Langhoff (1960).
	2.4	17	6.6	Sen Gupta and Beamish (1963).
Overall average			4.3	
Ir	.33	3.3	1.7	Hamaguchi, Nakai, and Kamemoto (1961).
	.3	10.3	3.7	Nichiporuk and Brown (1962).
	1.3	6.85	3.0	Sen Gupta and Beamish (1963).
Overall average			2.8	
Pt	4	142	38	Hawley (1939).
	9.9	30	17	Hamaguchi, Nakai, and Kamemoto (1961).
	.5	29.3	11.0	Nichiporuk and Brown (1962).
	1.86	11.4	7.5	Sen Gupta and Beamish (1963).
	4.6			Yavnel (1963).
Overall average			11.8	
Chondrites				
Ru	0.4	0.5	0.4	Hagen,[1] in 1954.
	.7	1.2	1.0	Hara and Sandell (1960).
	.6	1.44	.89	Bate and Huizenga (1963).
Overall average			0.8	
Rh	.1	.7	0.15	Hagen (1954).
	.15	.21	.19	Schindewolf and Walgren (1960).
Overall average			0.2	
Pd	.5	3.9	1.0	Hagen (1954).
	.73	1.0		Hamaguchi, Nakai, and Kamemoto (1961).
	1.7	5.2		Reed (1963).
Overall average			1.0	
Os	.52	1.24	0.91	Bate and Huizenga (1963).
Overall average			0.9	
Ir	.3	.6	0.4	Hagen (1954).
	.4	.25		Hamaguchi, Nakai, and Kamemoto.
	.32	.57	.48	Rushbrook and Ehmann (1962).
Overall average			0.4	
Pt	1	10	2.7	Hawley (1939).
	.2	5.6	.4	Hagen (1954).
	1.0	1.0		Hamaguchi, Nakai, and Kamemoto (1961).
Overall average			0.7	

[1] Hagen, J. C., 1954, Some aspects of the geochemistry of platinum, palladium, and gold in igneous rocks with special reference to the Bushveld Complex, Transvaal: Massachusetts Inst. Technology [Cambridge], unpublished Ph. D. thesis.

bution of platinum metals in the coexisting phases in chondrites are listed in table 16. The data show that platinum, iridium, and rhodium are dominantly siderophile, and that the remaining metals are almost equally chalcophile and siderophile.

The most recent abundance estimates for meteoritic matter as a whole are listed in table 17. The disparity between estimates by different authors is due largely to their respective assumptions regarding the relative proportions of silicate, sulfide, and metal phases, although many of the basic analytic data used by the authors are the same. The averages calculated by the present authors are based on the most recent abundance values (table 15) using a ratio, chondrite: siderite=6:1 (Levin and others, 1956).

TABLE 16.—*Distribution of the platinum metals in* Fe, S, *and* Si *phases of chondrites*

[Results given in ppm]

Element	Goldschmidt (1954)		Levin and others (1956)		Hara and Sandell (1960)		Bate and Huizenga (1963)		
	Fe	S	Fe	S	Fe	S	Fe	S	Si
Ru	10	9	11	4.2	[1] 4.3 [3] 5.3	[1] 6.3 [3] 5.2	[2] 3.11 [4] 2.33	--- --- [5] 0.0323	[2] 0.224 [4] .222 ---
Rh	5	.4	4.1	1.0	---	---	---	---	---
Pd	9	2	3.7	.45	---	---	---	---	---
Os	8	9	8.0	10.0	---	---	[2] 1.76 [4] 1.24	--- --- [5] .0051	[2] .170 [4] .157 ---
Ir	4	.4	4.0	.4	---	---	---	---	---
Pt	20	2	2.0	2	---	---	---	---	---

[1] Composite Ru for 6 chondrite "finds".
[2] Forest City chondrite.
[3] Composite Ru for 9 chondrite "finds".
[4] Ochansk chondrite.
[5] Canyon Diablo meteorite.

TABLE 17. *Recent estimates of the average content (ppm) of platinum metals in meteorites*

Source [1]	Ru	Rh	Pd	Os	Ir	Pt
Goldschmidt, 1954	2.2	0.8	1.5	1.9	0.65	3.2
Brown, 1949	4.2	1.6	1.5	3.0	1.2	7.6
Suess and Urey, 1956	1.35	.5	.9	1.2	.4	1.9
Levin, Kozolovskaya, and Starkova, 1956	2.0	.6	.5	1.1	.3	3.0
Present study	1.6	.6	1.4	1.7	.7	2.3

[1] Assumed composition, in percent, of meteoritic material, as follows:

[Present, study, computed from table 14, using chondrite : siderite=6:1]

Source	Silicate	Nickel-iron	Troilite
Goldschmidt	78	15	7
Brown	60	40	Negligible
Suess and Urey, average chondrite	85	9	6
Levin, Kozolovskaya, and Starkova, chondrite: siderite=6:1	80	14.5	5

In individual siderites, platinum and palladium increase with increasing nickel content (Hawley, 1939; Goldberg, Uchiyama, and Brown, 1951), whereas ruthenium decreases with increasing nickel content (Hara and Sandell, 1960).

Variation in concentration of various elements with gallium content and classification according to gallium groups has been discussed by Goldberg, Uchiyama, and Brown (1951) and by Lovering and others (1957). Using Lovering's classification for meteorites of similar nickel content, the highest contents of palladium are reported in meteorites falling in group I (very high gallium), whereas the lowest values are reported in those of group III (intermediate gallium). Hawley's data on platinum follow a similar trend. No data are reported on meteorites of group III, but those of groups I and II (high gallium) have slightly higher Pt contents than those of group IV (low gallium) for constant nickel content. Ruthenium shows no consistent variation as a function of gallium content (Hara and Sandell, 1960).

COSMIC ABUNDANCE

Recent estimates of the cosmic abundance of the platinum metals are summarized in table 18. All estimates are given relative to $Si=10^6$ atoms rather than in parts per million, and are based on data from meteorites and the sun. Brown (1949) computes the cosmic abundances directly from these data. Brown's values for meteoritic matter (see table 17) disagree with those of other authors, because his assumptions regarding the composition of meteoritic matter are so different from those of other authors. Other authors, using essentially the same data, have modified the estimates of cosmic abundance to fit various theories of nucleogenesis. A good discussion of the assumptions that go into the modified estimates is given by Cameron (1959). There is generally good agreement among the three most recent estimates which indicate that the platinum metals fall in the following order of decreasing cosmic abundance:

$$Pt > Ru > Pd \approx Os > Ir > Rh$$

Table 18.—*Recent estimates of cosmic abundance of the platinum metals*

[Atoms per million atoms of Si]

Reference	Ru	Rh	Pd	Os	Ir	Pt
Brown (1949) [1]	9.3	3.5	3.2	3.5	1.4	8.7
Suess and Urey (1956) [2]	1.5	.2	.7	1.0	.8	1.6
Cameron (1959) [2]	.9	.15	.7	.6	.5	1.3
Aller (1961) [2]	.9	.2	.6	.8	.5	1.6

[1] Data from meteorites and sun.
[2] Values obtained by adjusting empirical solar and meteoritic abundances to conform to various theories of nucleogenesis.

SUGGESTIONS FOR FUTURE STUDY

It is evident in the preceding that many more data are needed to understand adequately the geochemistry of the platinum metals. Platinum-metal contents of abundant rock types, particularly granites, are needed to improve the estimates of crustal abundance. Because of the uneven distribution of platinum metals in rocks, future analyses should be based on samples of large masses of rock. Complete analyses for six platinum metals are badly needed to estimate accurately the relative abundances of platinum metals in the crust. Detailed study of the mineralogy of the platinum metals is just now beginning. The electron microprobe should be used to determine the limits of solid solution of platinum metals in natural alloys, the composition variations in platinum-metal compounds, and the extent to which trace amounts of platinum metals in rock-forming minerals are present as discrete inclusions or as substituting ions. Finally, we know little about the actual behavior of the platinum metals in magmatic processes. Experimental work on solubilities of platinum metals and platinum-metal complexes is needed to understand the mode of transport of platinum metals in ore-forming solutions and the role played by the platinum metals in magmatic crystallization.

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