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The Distribution of Platinum and Palladium Metals in Iron Meteorites and in the Metal Phase of Ordinary Chondrites[1]

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Abstract. The concentrations of Ru, Rh, Pd, Ir, and Pt have been determined spectrographically in twenty-four iron meteorites and in the metal phase of five ordinary chondrites. It was found that most iron meteorites fall into three distinct groups with regard to the Ru and Rh concentrations and into three groups with regard to the Ir and Pt concentrations, each Ir-Pt group corresponding to one of the Ru-Rh groups. Correlations are observed between these Ir-Pt and Ru-Rh groups on the one hand, and the Ga-Ge groups found by previous workers on the other, but the relationships are by no means clear-cut. Compared with Ru, Ir, and Pt, Pd was found to vary over a relatively small range. The metal phases of all chondrites studied are chemically identical with the iron meteorites of the largest Ru-Rh and the largest Ir-Pt group, namely the Ru-Rh group which contains about 6 ppm Ru and 1.5 ppm Rh, and the Ir-Pt group which contains about 2 ppm Ir and 7 ppm Pt. The following atomic abundances (Si = 10^6) of Ru, Rh, Pd, Ir, and Pt have been derived from our data:

	Ru	Rh	Pd	Ir	Pt
Based on metal phase of high-iron-group chondrites	1.66	0.27	1.05	0.40	1.22
Based on iron meteorites, assuming they constitute 10% of mean meteoritic matter	1.44	0.23	0.52	0.31	0.89

These values generally agree within a factor of less than 2 with the abundances calculated by recent workers.

INTRODUCTION

Pt and Pd metals are concentrated almost entirely in the metal phase[2] of meteoritic matter. In view of this, it is desirable that accurate determinations of their distribution in iron meteorites and in the metal phase of chondrites be obtained. Abundances of these elements have been determined spectroscopically in iron meteorites by *Noddack and Noddack* [1930] and also by *Goldschmidt and Peters* [1932], but the estimates are only approximate [*Suess and Urey,* 1956]. *Goldschmidt* [1938] averaged these analyses and *Suess and Urey* [1956] reported interpolated values. Table 1 lists the average concentrations of Pt and Pd metals in iron meteorites selected by previous investigators.

Brown and Goldberg [1949] and *Goldberg et al.* [1951] have determined Pd in forty-five iron meteorites by neutron activation, and *Hara and Sandell* [1960] have determined Ru in seventeen iron meteorites and in the metal phase of two pallasites by absorption spectrophotometry. *Herr et al.* [1958] have also determined Ru in the Carbo iron meteorite by neutron activation. The ranges of concentration obtained by all these workers are shown in Table 2 and compared with the ranges of concentration observed in this study.

The averages and the precision of the data of Goldberg et al. for Pd are respectively 3.7 ppm and approximately 10%, and those of the data of Hara and Sandell for Ru are respectively 6.6 ppm and about 5%.

As we shall see, the ranges of concentration observed in this study of Ir, Pt (see also *Nichiporuk and Brown* [1962]), and Rh in iron meteorites are just as large as if not larger than

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[2] We thank Dr. Goles for pointing out to us that the metal phase as used in this paper is not a phase in the strict sense but rather is a mixture of true phases, kamacite and taenite, which were not separated in this investigation.

TABLE 1. Abundances of Pt and Pd Metals in Iron Meteorites Selected by Previous Investigators

Metals	*Goldschmidt* [1938]	*Brown* [1949]	*Suess and Urey* [1956]
Ru, ppm	10	10.6	10
Rh, ppm	5	4.1	1 44
Pd, ppm	9	3.7*	5.7
Os, ppm	8	7.6	12.2
Ir, ppm	4	3.0	10 1
Pt, ppm	20	19	20 2

*The average of determinations by *Brown and Goldberg* [1949].

the ranges of concentrations of Pd and Ru. By comparison, the ranges of concentration of Pt and Pd metals in the metallic-iron phase of ordinary, high-iron-group chondrites were found to be very small.

ANALYTICAL METHODS

Pt and Pd metals were isolated from iron meteorites and the metal phase of chondrites by precipitation as sulfides and were determined spectrographically.

Samples ranging in weight from 8 to 20 g were cut from larger portions of iron meteorites, care being taken to avoid discernible inclusions of troilite, schreibersite, and cohenite. Samples of Huizopa, Indian Valley, and Tazewell were in the form of fine sawings and were residues from other work. All samples were washed in 6 N HCl, quadruply distilled water, and ethyl alcohol to remove surface impurities.

Specimens of chondrites weighing 70 to 90 g were crushed in a Plattner mortar to about 100 mesh and separated into 'magnetic' and 'nonmagnetic' fractions with a hand magnet. The 'magnetic' fractions used in this work were composed of metallic grains with inclusions of fine silicate and troilite particles which were embedded in the grains during the crushing process. The 'magnetic' fractions ranged in weight from 7 to 13 g.

All chemistry was performed in pyrex glassware which before use had been thoroughly washed and kept for at least 2 hours in hot, concentrated, reagent grade HNO_3. The samples were brought into solution in 400-ml beakers in a mixture of hot, concentrated HCl and HNO_3. The HCl was obtained by bubbling tank HCl gas into distilled water in a flask. HNO_3 was distilled under vacuum in a quartz still. The residue was filtered, dried, and weighed; nitrate was destroyed by evaporation with HCl. The solution was made 8.1 N in HCl, then transfered into a 1-liter separatory funnel. This solution contained all Pt and Pd metals except Os.

The Fe (as $HFeCl_4$) was extracted twice with 600-ml portions of redistilled isopropyl ether [*Dodson et al.*, 1936; *Nachtrieb and Fryxell*, 1948], and the aqueous HCl layer containing the metals was drawn off into a 200-ml Berzelius beaker. After the addition of 40 mg of Cu as a carrier and 0.5 mg of Mo as an internal standard, the aqueous layer was evaporated to about 20 ml and then saturated with Cl_2 gas to oxidize all Mo to the +6 state. The solutions were evaporated to dryness and the solids were dissolved in 20 ml of 1.5N HCl which contained $AlCl_3 \cdot 6H_2O$ as a coagulant for Ir sulfide. The Ru, Rh, Pd, Ir, and Pt sulfides were precipitated with Cu and Mo sulfides by bubbling H_2S gas into warm solutions in 200-ml beakers for 3 hours and allowing the precipitates and supernates to stand for 48 hours. The sulfides were collected in sintered glass crucibles, and the precipitation was repeated. The two precipitates were thoroughly mixed in dilute HCl and ethyl alcohol and dried at 100°C; their weights ranged from 120 to 130 mg for all samples analyzed.

All compounds and metals used in this work were 'specpure' grade, obtained from Johnson, Matthey and Co., Ltd. A series of standards was prepared containing from 15 to 4000 ppm of each metal and 1.0 mg of Mo as an internal standard. The metals were present in a matrix of 120 to 130 mg of CuS. The standard solutions composed of 15 g of Fe, 1.4 g of Ni, and 0.08 g of Co were converted into Cu-Mo sulfides in the same manner as the meteorite solutions, thus

TABLE 2. Ranges of Concentration of Pd and Ru in Iron Meteorites As Found by Previous Workers and in This Study

Investigators	Ru, ppm	Pd, ppm
Goldbert et al. [1951]		1.44–9.88
Herr et al. [1958]	52.4 ± 1.5	
Hara and Sandell [1960]	0.8–14.8	
This work	0.5–23.7	1.45–6.47

ensuring close physical and chemical resemblence of both samples and standards. Inasmuch as iron meteorites contain about 10 ppm Mo [*Kuroda and Sandell,* 1954], an equivalent amount of the element (0.17 mg) was added to each standard solution before its extraction with ether.

To establish whether significantly variable yields of the investigated metals might have been obtained, minute quantities of Os^{191} (β-particle emitter 0.18 Mev, 15 days half-life) tracer were added to three HCl solutions of Fe, each of which contained Ni and Co, and the measured traces of all Pt and Pd metals. Within a counting accuracy of 5%, the yields of Os^{191}, corrected for absorption and scattering effects in a matrix of Cu and Mo sulfides, were found to be constant.

As ions of all Pt and Pd metals are expected to behave similarly, it appears reasonably certain that the yields of Ru, Rh, Pd, Ir, and Pt, like the yields of Os, which were not determined in this study, did not vary appreciably under the conditions of the enrichment procedures described.

The standards and samples were exposed using the following equipment and methods:

Spectrograph. Jarrell-Ash 3.4-m grating instrument with 15-thousand-lines-per-inch grating; Wadsworth mount, dispersion 5.2 A/mm in first order.

Electrodes. High-purity ¼-in. graphite rods as anode. Pointed ⅛-in. rods as cathode.

Excitation. 10-amp dc arc (13-amp short circuit) from a Jarrell-Ash Uni-source. Sample as anode. Analytical gap 4 mm magnified 5× and focused on the slit. Central 2 mm used with a slit width of 10 μ. Samples and standards ground with pure quartz in proportions of 1 to 0.5, and 25-mg portions burned to completion after an initial pre-arcing at 2.5 to 3.0 amp; total time of burning 4 min. Total energy method with internal standardization.

Wavelengths. The analytical lines used were Ru 3436.737 A, Rh 3396.85 A, Pd 3421.24 A, Ir 2543.971 A, Ir 2849.725 A, and Pt 2659.454 A. The internal standard line was Mo 2816.154 A (singly ionized molybdenum).

Plates. Eastman Kodak III-0 developed for 4 min at 20°C in DK-50 developer, 30 sec in short stop, 10 min in acid fix, and 20 min wash.

Plate calibration. Thirteen selected iron lines. Each plate was calibrated, and standards, including a blank, were exposed on each plate.

Densitometer. Jarrel-Ash model 2100.

Sensitivity. Ru 30 ppm; Rh 10 ppm; Pd 10 ppm; Ir (Ir 2849.725 A) 30 ppm; Pt 15 ppm; in a matrix of copper and molybdenum sulfides corrected for quartz dilution and assuming 100% precipitation yields of the metals.

PRECISION AND ACCURACY

The concentration of Ir in the Bear Creek, Sandia Mountains, and Sikhote-Alin meteorites was somewhat below the sensitivity limits of the element in the enriched samples under the conditions described. All samples were exposed between two and four times, and the arithmetic mean is reported.

An indication of the precision of the method may be obtained from the data on six iron meteorites shown in Table 3. The duplicate samples were of approximately equal size and were taken from either adjoining or separated locations of each of the six meteorites listed.

The differences between two samples could arise in part from possible variations in chemical yields, from spectrographic errors (e.g., due to self-absorption in the analytical lines at higher concentrations of the metals), from the inhomogeneity of the samples, and from con-

TABLE 3. Concentrations of Five Pd and Pt Metals in Duplicate Samples of Six Iron Meteorites

Name of Meteorite	Ru, ppm	Rh, ppm	Pd, ppm	Ir, ppm	Pt, ppm
Arispe I	15.1	1.7		7.3	
Arispe II	12.3	1.7	3.1	7.9	17.2
Canyon Diablo I	5.9	1.5		1.6	6.6
Canyon Diablo II	6.9	1.5	3.6	1.9	8.1
Henbury I	6.5	1.4	4.4	2.7	6.4
Henbury II	5.6	1.1	3.4	1.9	4.9
Mount Tabby I	17.6	2.2	2.8	10.5	25.2
Mount Tabby II	15.6	2.3	3.3	7.6	21.9
Odessa I	6.0	1.3		1.9	8.9
Odessa II	6.0	1.4	3.7	1.8	8.1
Toluca I	4.9	1.0		1.9	7.5
Toluca II	5.7	1.2	4.0	2.2	5.6

TABLE 4. Ru and Pd Contents of Iron Meteorites Determined by Different Methods of Analysis*

		Ru, ppm		Pd, ppm	
Name of Meteorite	Class	Photometric, *Hara and Sandell* [1960]	Spectrographic, This Work	Neutron Activation, *Goldberg et al.* [1951]	Spectrographic, This Work
Altonah	Of	3.6	4.7	4.45	4.2
Arispe	Og	10.0	13.7	2.69	3.1
Bear Creek	Om			5.57	5.4
Bristol	Of			4.36	3.9
Canyon Diablo	Og	5.9	6.4	3.98	3.6
Cape of Good Hope	D			7.07	4.1
Coahuila	H			1.44	2.0
Costilla Peak	Om	12.4	13.4	2.02	2.5
Coya Norte	H	14.8	15.2		
Edmonton	Of	0.8	0.5	5.97	6.5
Goose Lake	Om	4.6	6.4	3.34	3.9
Henbury	Om	3.6	6.0	2.02	3.9
Indian Valley	H			1.54	1.5
Odessa	Og			4.15	3.7
Sandia Mountains	H	7.5	7.2	2.24	2.1
Spearman	Om	4.8	4.6	3.67	2.9
Tazewell	Off			7.73	5.7
Toluca	Om			4.72	4.0

* Most of the specimens for which comparisons are made in this table are from the original collection used by *Goldberg et al.* [1951].

tamination of the samples with troilite or schreibersite.

The average deviation from the mean is estimated to be 8% for Ru, 10% for Rh, 9% for Pd, 17% for Ir, and 12% for Pt.

To obtain an indication regarding the accuracy of the spectrographic method a comparison was made of the Pt and Pd metal results in this work with the results obtained by *Goldberg et al.* [1951], by *Hara and Sandell* [1960], and by *Yavnel'* [1950]. Further, the Ir results on the metal phase of several chondrites were compared with those obtained by *Rushbrook and Ehmann* [1962].

From the comparisons presented in Table 4 it can be seen that spectrographic Ru determinations are generally about 20 to 30% higher than those determined by absorption spectrophotometry. Pd determined spectrographically actually shows two trends. At concentrations below about 3 ppm spectrographic Pd determinations tend to be higher than Pd determined by neutron activation; above the 3-ppm level they tend to be lower. The more serious discrepancy, lying outside the limits of reproducibility (Table 3) of the spectrographic method, is in the analyses of the Henbury meteorite. As all determinations were made on the meteorite specimen used by *Goldberg et al.* [1951], the observed discrepancy would appear to indicate that appreciable fluctuation exist in the chemical composition of the meteorite. It is possible, however, that samples of this meteorite might have been accidentally mixed with another.

The comparison presented in Table 5 shows that whereas the three sets of the determined Ru, Rh, Pd, and Pt values of *Yavnel'* [1950] are generally of poor precision, his selected values, except that for Pd, agree closely with our values.

As for Ir, it is clear from Table 6 that the spectrographic method yields values that are in good agreement with those obtained by neutron activation. The fact that *Yavnel'* [1950] did not detect Ir in the Sikhote-Alin iron meteorite spectrographically (footnote, Table 5) provides an independent check, even though only qualitative, on those of our spectrographic Ir values which are lower than 0.5 ppm (Table 7).

RESULTS

The concentrations of Ru, Rh, Pd, Ir, and Pt in twenty-four iron meteorites are given in

TABLE 5. Ru, Rh, Pd, and Pt Contents of the Sikhote-Alin Meteorite

	Ru, ppm	Rh, ppm	Pd, ppm	Pt, ppm
Yavnel' (1950)*				
Sample 1	0.4	0.2	2.8	2.4
Sample 2	5.7	0.9	6.9	4.6
Sample 3	3.4	0.8	2.0	2.7
Accepted contents	5.7	0.9	6.9	4.6
This work	5.0 ± 0.1	1.6 ± 0.1	<1 (estimated)	3.9 ± 0.3

* High-temperature extraction of the metals into a lead globule followed by spectrographic determination. The highest of the three sets of values selected because the low values are believed to be the result of probable high-temperature volatilization losses of the metals. Analytical error is estimated to be about 20%. Ir and Os have not been detected. Sample sizes in the range of 25 g.

Table 7. The corresponding concentrations in the metal phases of five ordinary chondrites, together with the observed proportions of these phases, are given in Table 8.

Ru-Rh and Ir-Pt groups. The Ru contents of the iron meteorites are plotted against the Rh contents in Figure 1, and the Ir contents of the meteorites are plotted against the Pt contents in Figure 2. Inspection of the figures shows that the Ru and Ir levels are concentrated in three well-separated and mutually corresponding regions which for convenience we called Ru-Rh groups I, II, and III and Ir-Pt groups I, II, and III. The ranges of concentration associated with each of the groups are as follows:

	Ru-Rh Groups		Ir-Pt Groups	
	Ru, ppm	Rh, ppm	Ir, ppm	Pt, ppm
Group I	11.9–21.5	1.7–2.5	7.6–15.3	11.8–29.3
Group II	4.6– 7.2	0.7–1.6	1.4– 3.2	4.4– 8.5
Group III	<1.0	<0.5	<0.5	2.4– 9.8

Only one of the meteorites studied (Bear Creek) was found to have a Ru content and two (Edmonton and Tazewell) to have a Pt content lying outside these rather narrow limits. The remaining twenty-one meteorites are divided among the different groups in the following manner:

Of the nine meteorites belonging to Ru-Rh group I, six belong to Ir-Pt group I; one belongs to Ir-Pt group III; and two belong to Ir-Pt group I on the basis of their Pt contents and to Ir-Pt group II on the basis of their Ir contents.

Of the twelve meteorites which belong to Ru-Rh group II, as many as nine belong to Ir-Pt group II; the remaining three belong to Ir-Pt group III.

The only two meteorites which are in Ru-Rh group III do not belong to any of the Ir-Pt groups.

It is of interest that the Ru/Rh ratio varies only from 5.7 to 10.3 for the meteorites of Ru-Rh group I, from 3.1 to 6.7 for those of group II, and from 1.6 to 3.2 for those of group III; the Pt/Ir ratio varies from 1.2 to 3.7 for the meteorites of Ir-Pt group I, from 1.8 to 4.7 for those of group II, and from 6.0 to 33.8 for those of group III.

Structures and nickel contents. When the structures and the known Ni contents (Table 7) of the meteorites belonging to each Ru-Rh and Ir-Pt group are examined, it is found that the meteorites of Ru-Rh group I and Ir-Pt group I have Ni contents lying between 5.5 and 16.5% and embrace hexahedrites, coarse and medium

TABLE 6. Ir Content of the Metal Phase of Ordinary Chondrites by Different Methods of Analysis

Name of Meteorite	Ir, ppm, Neutron Activation,* *Rushbrook and Ehmann* [1962]	Name	Ir, ppm, Spectrographic, This Work
Elenovka	3.0	Alamogordo	3.0 ± 0.3
Forest City	2.7	Gilgoin Station	2.6 ± 0.3
Okhansk	3.0	Okhansk	2.9 ± 0.4
Plainview	3.0	Plainview	3.2 ± 0.6
Pultusk	2.4	Gladstone	2.1 ± 0.2
Average value	2.85	Average value	2.8 ± 0.4

* Complete samples of the chondrites were analyzed for Ir and the results normalized to the known metal phase content, assuming 100% siderophile character of the element.

TABLE 7. Ru, Rh, Pd, Ir, and Pt Contents of Iron Meteorites

Name of Meteorite	Type*	Ni,† %	Ru, ppm	Rh, ppm	Pd, ppm	Ir, ppm	Pt, ppm
Altonah	Of	8.56	4.7 ± 0.1	0.7 ± 0.1	4.2 ± 0.1	1.6 ± 0.2	5.1 ± 0.6
Arispe	Og	6.77	13.7 ± 1.5	1.7 ± 0.1	3.1 ± 0.2	7.6 ± 0.3	17.2 ± 0.1
Bear Creek	Om	10.14	2.5 ± 0.4	1.5 ± 0.3	5.4 ± 0.6	<0.4	2.4 ± 0.1
Bendego	Og	6 8	11.9 ± 0.7	2.1 ± 0.4	2.7 ± 0.9	0.3 ± 0.1	9.8 ± 1.0
Bristol	Off	8.15	5.1 ± 1.2	0.8 ± 0.1	3.9 ± 0.3	1.7 ± 0.4	5.0 ± 0.6
Canyon Diablo	Og	7 18	6.4 ± 0.4	1.5 ± 0.1	3.6 ± 0.2	1.8 ± 0.2	7.4 ± 0.7
Cape of Good Hope	D_1	16.48	13.3 ± 0.2	1.7 ± 0.3	4.1 ± 0.1	8.5 ± 2.1	11.8 ± 0.2
Coahuila	H	5.65	23.7 ± 2.5	2.3 ± 0.1	2.0 ± 0.1	14.8 ± 0.1	24.2 ± 0.1
Costilla Peak	Om	7.59	13.4 ± 0.2	1.7 ± 0.1	2.5 ± 0.2	15.3 ± 2.3	17.7 ± 3.3
Coya Norte	H	5.5	15.2 ± 2.0	2.5 ± 0.2	1.8 ± 0.3	3.3 ± 0.5	21.9 ± 5.6
Edmonton	Off-Of	12.66	0.5 ± 0.1	0.3 ± 0.0	6.5 ± 0.8	0.6 ± 0.1	0.5 ± 0.1
Goose Lake	Om	8.46	6.4 ± 0.5	1.2 ± 0.1	3.9 ± 0.5	2.2 ± 0.3	6.8 ± 0.7
Henbury	Om	7.66	6.0 ± 0.1	1.2 ± 0.2	3.9 ± 0.5	2.3 ± 0.4	5.6 ± 0.8
Huizopa	Of	7 81	5.7 ± 0.5	0.9 ± 0.1	4.8 ± 0.2	2.5 ± 0.1	4.4 ± 0.3
Indian Valley	H; D_2gr-H	5.64	21.0 ± 1.2	2.1 ± 0.1	1.5 ± 0.1	7.9 ± 1.7	29.3 ± 2.6
Moonbi	Om-Of	7.99	6.3 ± 0.1	1.3 ± 0.1	3.5 ± 0.1	1.4 ± 0.1	9.2 ± 0.7
Mount Tabby (?)	Og	6.82	16.6 ± 1.0	2.2 ± 0.1	3.0 ± 0.2	9.1 ± 1.4	23.5 ± 1.6
Odessa	Og-Ogg	7.40	6.0 ± 0.1	1.4 ± 0.1	3.7 ± 0.2	1.8 ± 0.1	8.5 ± 0.4
Rio Loa	H	5.70	21.5 ± 2.4	2.5 ± 0.6	2.2 ± 0.5	3.4 ± 0.6	26.9 ± 4.6
Sandia Mountains	Hgr	5.94	7.2 ± 1.0	1.5 ± 0.3	2.1 ± 0.4	<0.4	9.0 ± 1.0
Sikhote-Alin	Hgr-Ogg	5 68	5.0 ± 0.1	1.6 ± 0.1		<0.3	3.9 ± 0.3
Spearman	Om	8.39	4.6 ± 0.1	1.2 ± 0.1	2.9 ± 0.2	0.4 ± 0.1	6.7 ± 0.2
Tazewell	Off	16.69	0.5 ± 0.1	0.14 ± 0.01	5.7 ± 0.8	0.3 ± 0.1	0.5 ± 0.1
Toluca	Om	8.31	5.3 ± 0.4	1.1 ± 0.1	4.0 ± 0.2	2.0 ± 0.1	6.5 ± 0.9

* According to *Prior* [1953] and *Lovering et al.* [1957].

† According to *Goldberg et al.* [1951], *Lovering et al.* [1957], and *Yavnel'* [1954].

octahedrites, according to the classification proposed by *Lovering et al.* [1957], and also a Ni-rich ataxite. The former group contains about 70% and the latter about 30% of the hexahedrites studied. The lower Ni boundaries of the two groups appear to lie in the neighborhood of 5.5%.

The meteorites of Ru-Rh group II and Ir-Pt group II, each of which contains about one-half of the meteorites studied, range in Ni content

TABLE 8. Ru, Rh, Pd, Ir, and Pt Contents of the Metal Phase of Chondrites

Name of Meteorite	Class	Metal Phase, %	Ru, ppm	Rh, ppm	Pd, ppm	Ir, ppm	Pt, ppm
Alamogordo	Crystalline spherical chondrite	13.5	6.1 ± 0.8	0.9 ± 0.1	4.2 ± 0.6	3.0 ± 0.3	7.9 ± 0.4
Gilgoin Station	Crystalline bronzite chondrite	19.6	5.4 ± 0.2	1.0 ± 0.2	3.7 ± 0.3	2.6 ± 0.3	8.0 ± 1.6
Gladstone	Black-veined crystalline spherical chondrite	15.4	5.9 ± 0.3	1.0 ± 0.1	3.9 ± 0.2	2.1 ± 0.2	8.5 ± 1.4
Okhansk	Polymict brecciated spherical bronzite chondrite	20.8	6.2 ± 0.6	1.1 ± 0.1	3.7 ± 0.1	2.9 ± 0.4	9.1 ± 1.7
Plainview	Polymict brecciated veined intermediate chondrite	15.0	6.5 ± 0.4	1.0 ± 0.1	4.7 ± 0.3	3.2 ± 0.6	9.0 ± 0.9

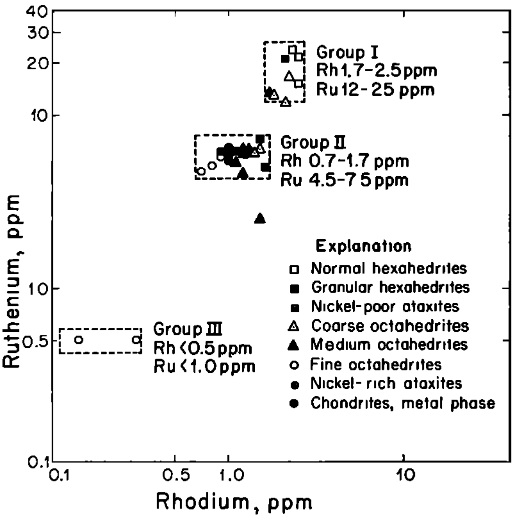

Fig. 1. Relation between Ru and Rh contents of meteorites.

from 5.5 to 9.0% and consist chiefly of medium and fine octahedrites.

The two meteorites of Ru-Rh group III have Ni contents of 12.7 and 16.7% and are fine octahedrites; the five meteorites of Ir-Pt group III range in Ni content between 5.7 and 10.1% and encompass hexahedrites and medium and coarse octahedrites.

CORRELATIONS

Ga-Ge groups. It will be recalled that the ranges of concentration in the four known Ga-Ge groups are as follows:

	Ga, ppm	Ge, ppm
Group I	80–100	300–420
Group II	40–65	130–230
Group III	8–24	15–80
Group IV	1–3	<1–1

Of these four groups, Ga-Ge groups II, III, and IV, which comprise twenty out of the twenty-four meteorites examined in this study, are represented in the correlations shown in Table 9. It is interesting to note that the meteorites of Ru-Rh group I and Ir-Pt group I without exception belong to Ga-Ge group II, whereas the meteorites of Ru-Rh group II and and Ir-Pt group II can belong to either Ga-Ge group II or group IV. Since there are no meteorites among those listed in the table which belong to both Ru-Rh group III and Ir-Pt group III, the relationships, if any, between these groups and Ga-Ge groups, in particular Ga-Ge group III, are not completely clear.

A more comprehensive picture of the general relationships between the groups, structural classes, and Ni contents of the meteorites is shown in Figure 3, where Ni concentration is plotted against kamacite bandwidth in order of decreasing coarseness. The Ru-Rh, Ir-Pt, and Ga-Ge groups are found to be only nonuniquely associated with the well-defined structural fields, as shown in Figure 3. Meteorites lying within any of these fields will with high probability have Ru, Rh, Ir, Pt, Ga, and Ge contents corresponding to any of the three Ru-Rh, Ir-Pt, and Ga-Ge groups, thus making it appear that there is little or no immediately discernible relationship between structure and Ga-Ge, Ru-Rh, and Ir-Pt groups.

Palladium. The behavior of Pd was found to be quite different from that of Ru, Rh, Ir, and Pt. While the Ru, Rh, Ir, and Pt concentrations generally increase with increasing concentration of one another, the Pd concentration, which varies only over the relatively narrow range of 1.45 to 6.47 ppm, decreases with increasing concentration of each of these metals. Although the Ru, Rh, Ir, and Pt concentrations generally decrease with increasing Ni concentration and decreasing kamacite bandwidth, the Pd concentration increases.

Goldberg et al. [1951] pointed out that Pd

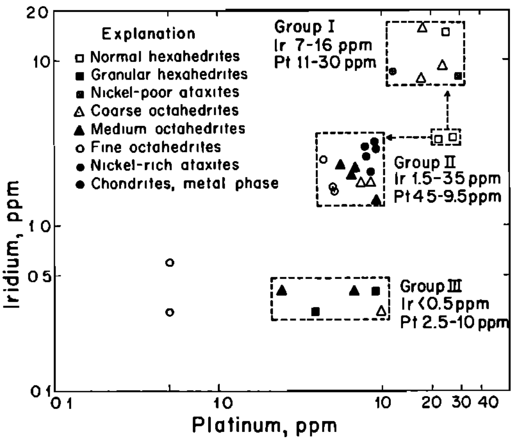

Fig. 2. Relation between Ir and Pt contents of meteorites.

TABLE 9. Correlations between Ru-Rh, Ir-Pt, and Ga-Ge Groups [*Lovering et al.*, 1957]

Name of Meteorite	Type	Ru-Rh Group	Ir-Pt Group	Ga-Ge* Group
Altonah	Of	II	II	IV
Arispe	Og	I	I	II
Bear Creek	Om	Anomalous	III	III
Bendego	Og	I	III	II
Bristol	Off	II	II	IV
Canyon Diablo	Og	II	II	Anomalous
Cape of Good Hope	D_1	I	I	Not determined
Coahuila	H	I	I	II
Costilla Peak	Om	I	I	Not determined
Coya Norte	H	I	I-II	II
Edmonton	Off-Of	III	Anomalous	III
Goose Lake	Om	II	II	II
Henbury	Om	II	II	II
Huizopa	Of	II	II	IV
Indian Valley	D_2gr-H	I	I	II
Moonbi	Om-Of	II	II	Anomalous
Mount Tabby	Og	I	I	II
Odessa	Og	II	II	Not determined
Rio Loa	H	I	I-II	II
Sandia Mountains	Hgr	II	III	II
Sikhote-Alin	Hgr-Ogg	II	III	Not determined
Spearman	Om	II	III	III
Tazewell	Off	III	Anomalous	IV
Toluca	Om	II	II	II

* None of the eight meteorites belonging to Ga-Ge group I has been examined for Ru, Rh, Ir, and Pt in this study.

concentration increases with increasing Ni concentration but decreases with increasing Ga concentration. They showed that for a given Ni content, the meteorites belonging to Ga class II have lower Pd contents than the meteorites belonging to Ga classes I and III. More recently *Hara and Sandell* [1960], in a paper on the meteoritic abundance of Ru, have concluded independently on the basis of their own Ru determinations on thirteen iron meteorites and the Pd values of Goldberg et al. for these same meteorites that Pd concentration generally decreases with increasing Ru concentration.

In general, whereas hexahedrites and coarse octahedrites have the highest Ru, Rh, Ir, and Pt contents and fine octahedrites have the lowest, the same hexahedrites have the lowest Pd content and the fine octahedrites have the highest. A significant exception to these trends is Cape of Good Hope. This is a meteorite of very fine structure; yet the Ru, Rh, Ir, and Pt contents appear much too high, considering the trends observed. The Pd content of this meteorite appears much too low considering these same trends. The behavior of Pd and that of Ru, Rh, Ir, and Pt in relation to one another and also in relation to Ni is illustrated diagramatically in Figures 4 through 6.

In general, meteorites of low Pd content (1.5 to 3.5 ppm) tend to fall into Ru-Rh group I,

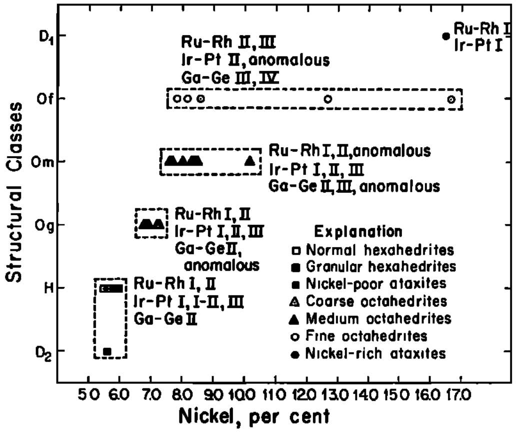

Fig. 3. Relation between structural classes, Ni content and Ru-Rh, Ir-Pt, and Ga-Ge groups.

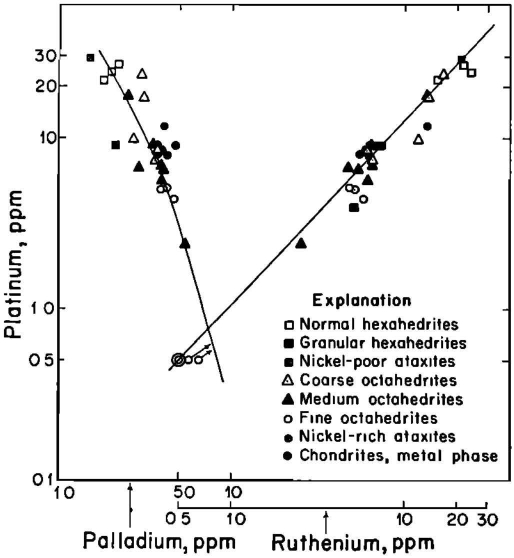

Fig. 4. Relations between Pd and Pt and between Ru and Pt contents of meteorites.

Ir-Pt group I, and Ga-Ge group II; meteorites with intermediate Pd contents (3.5 to 5.0 ppm) tend to fall into Ru-Rh group II, Ir-Pt group II, and Ga-Ge group II or IV; and meteorites with high Pd contents (greater than 5.0 ppm), of which only three are represented here, tend to fall into Ga-Ge group III or IV and into Ru-Rh group III or Ir-Pt group III.

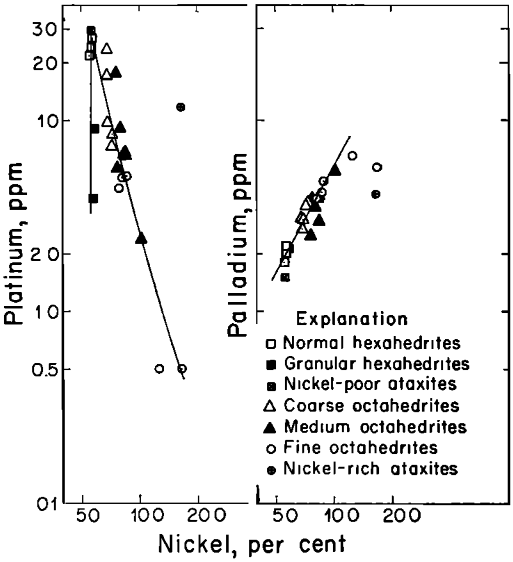

Fig. 5. Variation of Pd and Pt contents of meteorites with Ni content.

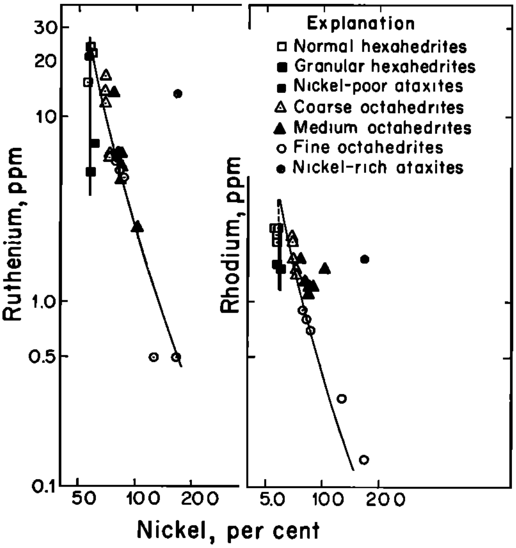

Fig. 6. Variation of Ru and Rh contents of meteorites with Ni content.

Similarity of Canyon Diablo and Odessa. Goldberg et al. observed that three pairs of meteorites, namely Canyon Diablo–Odessa, Henbury–Costilla Peak, and Altonah–Bristol, have compositions and structures which are quite close to each other. They pointed out that of these pairs only Canyon Diablo–Odessa is made up of meteorites which lie close to each other geographically. The Odessa craters lie about 600 miles east-southeast of Meteor Crater, Arizona. It is apparent also from this work that Canyon Diablo and Odessa are very similar in composition, as shown in Table 10, where these two meteorites are listed along with two other pairs of very similar meteorites.

TABLE 10. Pairs of Meteorites of Similar Compositions

Name of Meteorite	Class	Ni, %	Ru, ppm	Rh, ppm	Pd, ppm	Ir, ppm	Pt, ppm
Canyon Diablo	Og	7.18	6.4	1.5	3.6	1.8	7.4
Odessa	Og	7.24	6.0	1.4	3.7	1.8	8.5
Goose Lake	Om	8.46	6.4	1.2	3.9	2.2	6.8
Henbury	Om	7.66	6.0	1.2	3.9	2.3	5.6
Altonah	Of	8.56	4.7	0.7	4.2	1.6	5.1
Bristol	Of	8.15	5.1	0.8	3.9	1.7	5.0

TABLE 11. Dissimilar Pt and Pd Metal Contents of Hexahedrites

Name of Meteorite	Ni, %	Ru, ppm	Rh, ppm	Pd, ppm	Ir, ppm	Pt, ppm
Coahuila	5.56	23.7	2.3	2.0	14.8	24.2
Coya Norte	5.5	15.2	2.5	1.8	3 3	21.9
Indian Valley	5 64	21.0	2.1	1.5	7.9	29 3
Rio Loa	5 70	21.5	2.5	2.2	3.4	26.9
Sandia Mountains	5.94	7.2	1.5	2.1	<0.4	9.0
Sikhote-Alin	5.68	5 0	1 6		<0.3	3.9

It is interesting to note that the date of fall of Canyon Diablo has been estimated [*Anders*, 1963] at ≥2700 years ago and that of Odessa at ≥1400 and even at ≥2900 years ago. These estimates are based on the content of the cosmic-ray-produced Ar^{39} (325 years half-life) and Cl^{36} (308,000 years half-life), as reported by various investigators. The C^{14} content of Odessa, as determined by *Goel and Kohman* [1962], gives a date of fall more than 11,000 years ago. From the chemical similarities given above and these limiting dates of fall, it appears that the final proof as to whether Canyon Diablo and Odessa are really fragments of the same shower of irons will depend upon further measurements of the cosmic-ray-induced activities.

Dissimilarities among hexahedrites. Henderson [1941] noted that hexahedrites found in widely separated areas of the world are frequently indistinguishable from one another on the basis of their Ni contents. *Goldberg et al.* [1951] confirmed the earlier observation on the hexahedrites and stated further that individual hexahedrites are frequently identical with respect to their trace constituents.

In this work, hexahedrites were frequently found to be dissimilar in trace element contents, as can be seen from inspection of Table 11. The greatest of these dissimilarities appears to be related to the physical structures of the hexahedrites. The normal hexahedrites (Coahuila, Coya Norte, Rio Loa), which are made up of a uniform kamacite phase, have high concentrations of Ru, Ir, and Pt; whereas the granular hexahedrites (Sandia Mountains, Sikhote-Alin), which are made up of separate crystals of kamacite, have low concentrations of these elements, in particular markedly low concentrations of Ir. These relationships between the structures of the hexahedrites and their trace constituents can be found from the graphs in Figures 5 and 6, where all hexahedrites lie on separate branches of the curves representing the behavior of Pt and Pd metals as a function of Ni content.

Chondrites. The five chondrites examined in this study contain 13 to 21% metallic phase and are classified as belonging to the high-iron group of *Urey and Craig* [1953]. With the exception of Okhansk, which has been previously classified by *Wiik* [1956], these classifications are new and are taken from analyses of stony meteorites by X-ray fluorescence [*Nichiporuk et al.*, 1965].

It is evident that the metal phases of the high-iron-group chondrites, unlike the highly variable metal phases of all iron meteorites studied, are nearly identical in Pt and Pd metal contents and are quite similar in these contents to the large group of coarse, medium, and fine octahedrites belonging to our Ru-Rh group II and Ir-Pt group II. Furthermore, with respect to Ru, the metal phases of the high-iron-group chondrites are decidedly similar to the granular hexahedrites belonging to Ru-Rh group II.

This rather clear connection between high-iron-group chondrites and the two mutually interlinked groups of iron meteorites suggests that perhaps other groups of chondrites, namely

TABLE 12. Average Concentrations of Five Pt and Pd Metals

Group	Ru, ppm	Rh, ppm	Pd, ppm	Ir, ppm	Pt, ppm
High-iron-group chondrites, metal phase, 5 samples	6.0 ± 0.5	0.98 ± 0.10	4.1 ± 0.3	2.8 ± 0.4	8.5 ± 1.2
Iron meteorites, 24 samples	9.2 ± 0.8	1.47 ± 0.15	3.5 ± 0.6	3.7 ± 0.6	11.0 ± 1.3

TABLE 13. Abundances of Pt and Pd Metals, Si = 10^6

Investigators	Ru	Rh	Pd	Ir	Pt
This work, based on metal phase of high-iron-group chondrites	1.66	0.27	1.05	0.40	1.22
This work, based on iron meteorites	1.44	0.23	0.521	0.31	0.89
Hara and Sandell [1960], chondrites	1.5				
Bate and Huizenga [1963],					
low-iron-group chondrites	1.10				
high-iron-group chondrites	1.63				
Schindewolf and Wahlgren [1960],					
low-iron-group chondrites		0.23			
high-iron-group chondrites		0.33			
Hamaguchi et al. (1961), chondrites			1.26	0.27	0.80
Rushbrook and Ehmann [1962], chondrites				0.38	
Suess and Urey [1956], interpolated iron meteorite values of *Goldschmidt* [1938]	1.49	0.214	0.675*	0.821	1.625
Cameron [1959], nucleosynthesis and *Suess and Urey* [1956]	0.87	0.15	0.675	0.494	1.28
Clayton and Fowler [1961], nucleosynthesis	0.83	0.13	0.601	0.39	0.80

* Based on analyses of 45 iron meteorites by *Goldberg et al.* [1951].

low-iron-group and enstatite chondrites, are also chemically connected to particular groups of iron meteorites. It should be noted in this context that in the previous work [*Lovering et al.*, 1957] the stony-iron meteorites, specifically the pallasites, were found to be very clearly linked in their Ga and Ge contents to a large group of iron meteorites composed mainly of medium octahedrites and belonging to Ga-Ge group III.

Abundances of Pt and Pd metals. It is convenient at this point to calculate from the above data the atomic abundances of Pt and Pd metals and see how they compare with the abundances calculated by recent workers. The average values we have used are shown in Table 12. All average Pd values and the averages of the metal phase of chondrites are from quite uniformly distributed individual values and are straightforward. The averages of the iron meteorites are the summed-up proportionately weighted averages of each Ru-Rh and each Ir-Pt group. Entries in Table 13 are in atomic abundances, and the calculations have been made assuming in the case of the iron meteorites a contribution to mean meteoritic matter of 10% [*Suess and Urey,* 1956; *Ehmann,* 1961] and in the case of the chondrites the contribution of the metal phase equal to the actually determined proportions by weight of that phase as listed in Table 8. The abundances are relative to Si taken as 10^6, and the calculations are based on an amount of Si of 17.2% by weight [*Urey,* 1964] for the high-iron-group chondrites and an average amount between that percentage and the 18.6% [*Urey,* 1964] in the low-iron-group chondrites for the iron meteorites after normalization to mean meteoritic matter. The results are shown in Tables 12 and 13.

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