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The Pallasites

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INTRODUCTION

The pallasites are a comparatively rare type of meteorite, but are remarkable in several respects. Historically, it was a pallasite for which an extraterrestrial origin was first postulated because of its unique compositional and structural features. The Krasnoyarsk pallasite was discovered in 1749 about 150 miles south of Krasnoyarsk, and seen by P. S. Pallas in 1772, who recognized these unique features and arranged for its removal to the Academy of Sciences in St. Petersburg. Chladni (1794) examined it and concluded it must have come from beyond the earth, at a time when the scientific community did not accept the reality of stones falling from the sky. Compositionally, the combination of olivine and nickel-iron in subequal amounts clearly distinguishes the pallasites from all other groups of meteorites, and the remarkable juxtaposition of a comparatively light silicate mineral and heavy metal poses a nice problem of origin. Several theories of the internal structure of the earth have postulated the presence of a pallasitic layer to account for the geophysical data. No apology is therefore required for an attempt to provide a comprehensive account of this remarkable group of meteorites.

Some 40 pallasites are known, of which only two, Marjalahti and Zaisho, were seen to fall (table 1). Of these, some may be portions of a single meteorite. It has been suggested that the pallasite found in Indian mounds at Anderson, Ohio, may be fragments of the Brenham meteorite,

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TABLE 1

THE PALLASITES

	Date of Find or Fall	Weight in Kilograms
Admire (United States)	1881	50
Ahumada (Mexico)	1909	53
Albin (United States)	1915	37
Anderson (United States)	Prehistoric	1.5
Antofagasta (Chile)	1936	14
Argonia (United States)	Before 1940	34
Bendock (Australia)	1898	27
Bitburg (Germany)	Before 1805	1600
Brahin (Soviet Union)	1810	700
Brenham (United States)	1882	2500
Calderilla (Chile)	Fell 1883?	0.02
Cold Bay (Alaska)	1921	0.32
Eagle Station (United States)	1880	36
Finmarken (Norway)	1902	77.5
Giroux (Canada)	1954	4.7
Glorieta Mountain (United States)	1884	146
Gran Chaco (Argentina)	1811	1.6
Huckitta (Australia)	1924	1415
Ilimaes (Chile)	1874	95
Imilac (Chile)	1822	240
Itzawisis (Southwest Africa)	1946	0.35
Krasnoyarsk (Soviet Union)	1749	687
Lipovskii (Soviet Union)	1904	3.8
Marjalahti (Finland)	Fell 6/1/1902	45
Molong (Australia)	1912	105
Mt. Dyrring[a] (Australia)	1903	11
Mt. Vernon (United States)	1868	160
Newport (United States)	1923	5.6
Ollague (Bolivia)	1924	6.7
Pavlodar (Soviet Union)	1885	4.5
Phillips County (United States)	1935	1.3
Pojoaque (United States)	Before 1931	0.08
Port Orford (United States)	1859	0.03
Salta (Argentina)	Before 1940	27.1
Santa Rosalia (Mexico)	Before 1950	1.6
Singhur (India)	1847	14.2
Somervell County (United States)	1919	12
South Bend (United States)	1893	2.5
Springwater (Canada)	1931	67
Sterling (United States)	1900	0.7
Thiel Mountains (Antarctica)	1962	31.7
Zaisho (Japan)	Fell 2/1/1898	0.33

[a] The unlocalized Australia pallasite resembles Mt. Dyrring in all respects, and can be considered a fragment of this meteorite, as suggested by Hodge-Smith (1939).

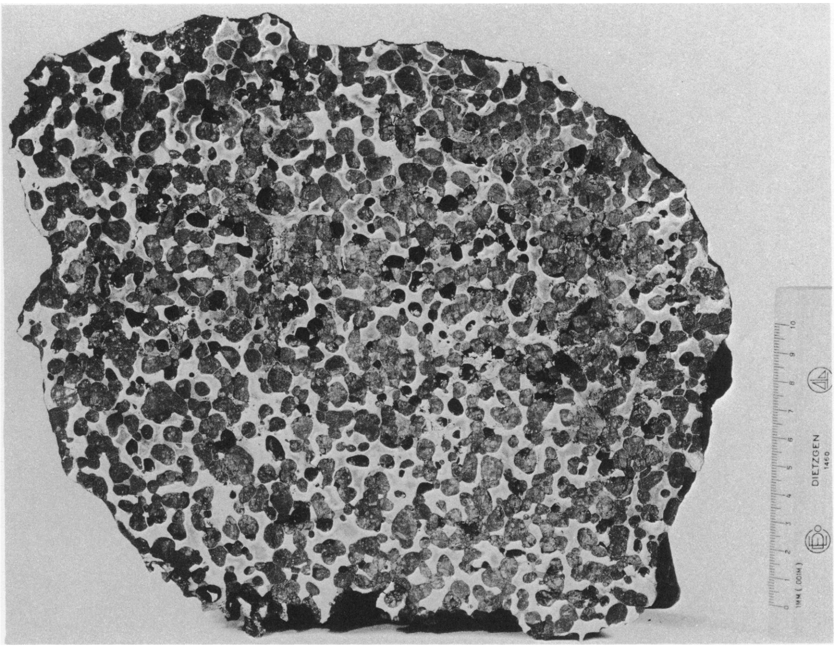

FIG. 1. Polished surface of the Brenham pallasite, showing rounded crystals of olivine (gray to black) in a matrix of nickel-iron (white).

carried thence by the Indians; and Pojoaque is almost certainly a transported fragment of Glorieta Mountain, as suggested by Nininger (1940). The rarity of pallasites as observed falls indicates that they are actually a very rare type of meteorite. They are comparatively common as finds, because the metal phase renders them quite resistant to weathering and also makes them easily recognizable even to inexperienced finders as meteorites or at least as stones worthy of preservation and record.

STRUCTURE

The structure of the pallasites is determined by two apparently unrelated factors—the relative amounts of olivine and nickel-iron, and the form of the olivine grains. The nickel-iron usually forms a continuous network, in which the olivine sits as discrete grains (e.g., Brenham, fig. 1). In the few pallasites with comparatively little nickel-iron (e.g., Eagle Station, fig. 2), the continuity of the nickel-iron network may be interrupted in places. Meteorites transitional between a pallasite like Eagle Station and the true achondrites, in which nickel-iron is practically

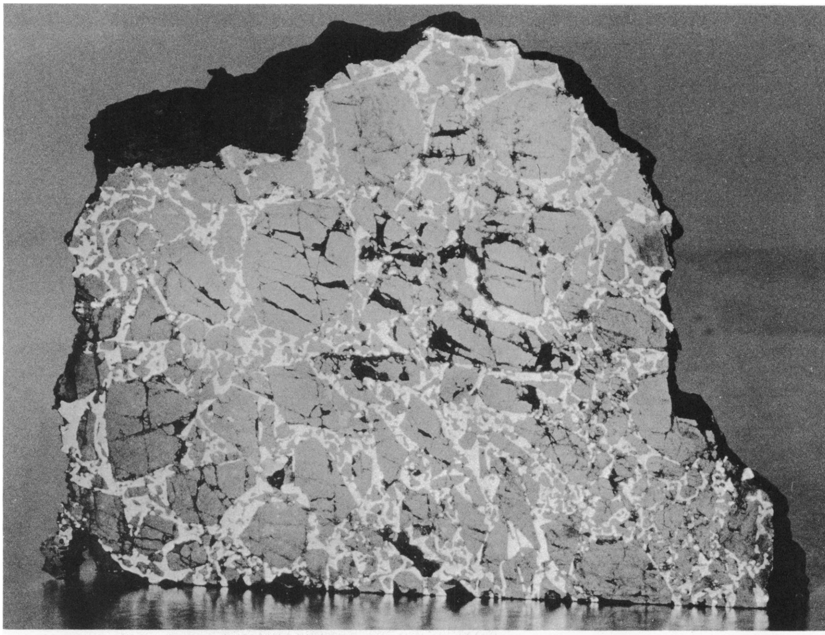

FIG. 2. Polished surface of the Eagle Station pallasite, showing angular and brecciated grains of olivine (gray) in a matrix of nickel-iron (white).

absent, have not so far been recognized. However, pallasites transitional to siderites are known: most specimens of Brenham, for example, are typical pallasites, but some show large patches of pure nickel-iron (fig. 3); and the Glorieta Mountain meteorite, normally classified as an octahedrite, shows occasional patches of pallasitic structure and composition.

Brezina (1904) divided the pallasites into four classes on the basis of the form of the olivine grains. The extremes in structural type are exemplified by Brenham, with rounded olivine grains, and Huckitta (fig. 4) and Eagle Station, in which the olivine is present as angular fragments; but intermediate types are common, and both angular and rounded olivines may be present in the same pallasite. In most of these meteorites the olivine is present as individual crystals with polyhedral form, the edges and corners being rounded; the individual crystals are commonly about 5–10 mm. in diameter, but may be considerably larger. The form and size of the olivine crystals are not dependent on the composition of the meteorite, and the Brezina classification is of doubtful utility. If this small group of meteorites is to be subdivided, a better basis is the composition of the olivine, as will be seen in a later section.

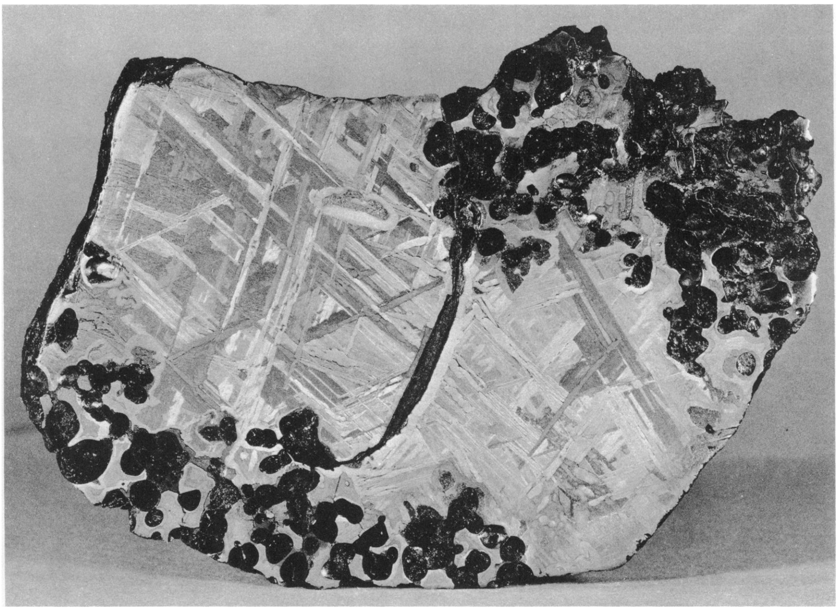

FIG. 3. Polished surface of the Brenham meteorite. Most specimens of Brenham are typical pallasite, but this shows a large patch of nickel-iron with Widmanstatten structure. The specimen is 18 cm. long.

The structure of the nickel-iron in pallasites has been well summarized by Lovering and others (1957), as follows:

The etched surfaces of the metal phases of the stony-iron meteorites investigated in this study show structures which depend upon the size of the surface area. Although it was not possible to draw a clear distinction between the small and large surface areas, it appeared certain that the areas measuring 3 mm. across or less, are very abundant. The patterns brought out by etching show zonal arrangement of the structural components, the outlines of each being roughly parallel to the boundaries of the metal areas. The arrangement is as follows: (1) grey border of kamacite adjoining the silicate (0.5 mm or more); (2) a very thin zone of silvery taenite; (3) a usually large, dark grey, core of dense plessite.

The pallasites which have metal areas two or more centimeters across (e.g., Newport) or which grade into octahedrites (e.g., Brenham and Glorieta Mountain) show structures that are essentially similar to those possessed by medium octahedrites. The plessite occurs in the form of trapeze-like or rectangular elongated areas (the Newport pallasite) bounded by a thin border of taenite, and which are scattered on the background of a medium Widmanstätten structure.

Zavaritskii and Kvasha (1952) while studying the structure of the Pallas Iron, observed metal sites which show either concentric or the usual octahedral arrangement of the structural components. In the concentric arrangement the thickness of the olivine-adjacent border of kamacite is of the order of tenths of a millimetre,

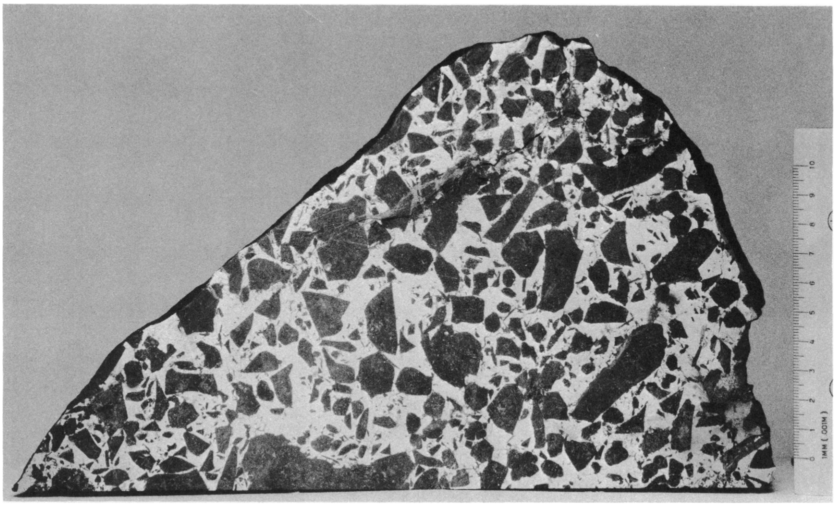

FIG. 4. Polished surface of the Huckitta pallasite, showing angular fragments of olivine (black) up to 6 cm. long in a matrix of nickel-iron (white).

and that of the plessite-surrounding rim of taenite is of the order of hundredths of a millimetre. In the usual octahedral arrangement the width of the kamacite bands is from 0.01 to 0.02 mm, although in some metallic sites the structure becomes still finer, and slowly grades into plessite with micro-octahedral or even submicroscopic cryptocrystalline (felsitic) structure.

Mineralogical and Chemical Composition

The essential minerals of all pallasites are olivine and nickel-iron. Accessory minerals, probably present in all of them, are troilite, schreibersite, and chromite. Lawrencite has been recorded from some of them, and a new mineral, farringtonite, was recently described from one of them (Springwater). Trace amounts of graphite have been recorded in Krasnoyarsk and Brenham, and this mineral is probably present in other pallasites. Weathering results in the formation of a variety of iron oxides and sometimes of secondary nickel minerals.

Nickel-iron is present as the two distinct phases, kamacite and taenite, and their eutectoid intergrowth, plessite. The amount and composition of the nickel-iron are different in different pallasites. Many contain approximately equal amounts by weight of nickel-iron and olivine, but nickel-iron contents as high as 80 per cent (in Marjalahti) and as low as 30 per cent (in Eagle Station) have been recorded.

Chemical analyses of the metal phase of pallasites are given in table 2.

The principal components are iron and nickel, iron ranging from 80 per cent to 92 per cent and nickel from 8 per cent to 14 per cent. Most of these meteorites have nickel content near 10 per cent, corresponding to the octahedrites among the iron meteorites. Prior (1916) observed a correlation between the composition of coexisting nickel-iron and olivine in meteorites, higher nickel content of the nickel-iron being associated with higher FeO/MgO ratio in the olivine, and this rule is generally followed in the pallasites. Springwater, Itzawisis, and Eagle Station,

TABLE 2
COMPOSITION OF NICKEL-IRON IN PALLASITES

Meteorite	Fe	Ni	Co	Reference
Admire	—	12.45	0.50	Lovering *et al.*, 1957
Albin	—	10.43	0.57	Lovering *et al.*, 1957
Anderson	89.00	10.65	0.45	Kinnicutt, 1884
Bendock	—	9.20	0.58	Lovering *et al.*, 1957
Brenham	—	10.98	0.60	Lovering *et al.*, 1957
Eagle Station	79.94	13.98	1.04	Prior, 1918
Glorieta Mountain	87.06	11.79	0.42	Henderson, 1941; also P, 0.37
Huckitta	89.36	8.98	0.45	Madigan, 1939; also S, 0.02; C, 0.13
Imilac	—	11.32	0.47	Lovering *et al.*, 1957
Itzawisis	83.9	14.9	0.93	Nel, 1949; also S, 0.06; P, 0.06
Marjalahti	91.59	8.16	0.57	Wiik, unpublished; also Ti, 0.013; Mn, 0.000
Molong	87.35	8.30	0.62	Mingaye, 1916; also S, 0.43; P, 0.16; C, 0.11
Newport	—	10.83	0.58	Lovering *et al.*, 1957
South Bend	90.22	9.35	0.26	Farrington, 1906; also Cu, 0.11; P, 0.05; S, 0.05
Springwater	85.47	13.65	0.66	Wiik, unpublished; also Ti, 0.021; Mn, 0.000

with nickel contents of 13.65 per cent, 14.9 per cent, and 13.98 per cent, respectively, have olivine with 18–20 mole per cent Fe_2SiO_4; the remaining pallasites have olivine with 11–13 mole per cent Fe_2SiO_4. The Admire pallasite, with nickel content of 12.45 per cent, has olivine with 11 mole per cent Fe_2SiO_4, which appears anomalous; however, an earlier analysis of Admire (Merrill, 1902) shows a considerably lower nickel content.

Lovering and his co-authors (1957) measured the contents of Cr, Cu, Ga, and Ge, as well as Ni and Co, in several pallasites. Their results are given in table 3. Cobalt varies over a narrow range, 0.47 per cent to 0.60 per cent, which is confirmed by other analyses cited in table 2.

TABLE 3

CONTENT OF NICKEL, COBALT, CHROMIUM, COPPER, GALLIUM, AND GERMANIUM IN THE METAL PHASE OF PALLASITES (LOVERING AND OTHERS, 1957)

Name	Ni, in per Cent	Co, in per Cent	Cr, in Parts per Million	Cu, in Parts per Million	Ga, in Parts per Million	Ge, in Parts per Million
Admire	12.45	0.50	8.3	233	18	34
Albin	10.43	0.57	4.5	223	23	30
Bendock	9.20	0.58	< 1	143	16	40
Brenham	10.98	0.60	< 1	168	19	63
Glorieta Mountain	11.79	0.54	2.7	217	12	18
Imilac	11.32	0.47	< 1	190	19	41
Newport	10.83	0.58	< 1	240	17	29
Springwater	13.16	0.60	< 1	174	15	38

TABLE 4

ANALYSES OF PALLASITE OLIVINE

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	40.40	40.70	40.26	40.24	39.61	40.24	40.79	40.21	38.69	38.3	39.22
TiO_2	—	—	0.36	0.00	—	—	—	0.00	0.04	—	—
Al_2O_3	0.17	—	0.53	0.01	0.21	0.06	0.02	—	0.1–0.01	—	—
Fe_2O_3	0.45	0.18	—	0.68	—	—	—	—	0.0	—	—
FeO	9.59	10.79	11.33	10.92	11.88	11.80	12.10	12.57	17.10	17.8	18.83
MnO	0.20	0.14	0.25	0.28	0.19	0.29	—	—	0.34	—	—
MgO	47.70	48.02	47.21	48.08	48.29	47.41	47.05	47.49	43.51	43.1	42.31
CaO	Trace	—	0.00	0.00	—	—	—	0.20	0.0	—	—
	100.24	99.85	99.97	100.32	100.18	99.80	99.96	100.47	100.08	99.23	100.36
Fa[a]	10.7	11.5	11.9	12.1	12.3	12.5	12.6	12.9	18.4	18.8	19.7
D	3.357	3.376		3.378	3.37			3.38			

1 Molong: NiO + CoO, 0.06; Na_2O, 0.03; K_2O, trace; H_2O+, 1.52; H_2O-, 0.12; Mingaye, 1916
2 Brenham: NiO, 0.02; Kunz, 1890
3 Admire: Na_2O; 0.00; K_2O, 0.00; P_2O_5, 0.03; Lovering, 1962
4 Marjalahti: H_2O+, 0.00; H_2O-, 0.04; F, n. d.; Cr_2O_3, 0.07; P_2O_5, n. d.; Na_2O, 0.00; K_2O, 0.00; NiO, n. d.; CoO, n. d.; Yoder and Sahama, 1957
5 Brahin: Inostranzeff, 1869
6 Krasnoyarsk: Kokscharov, 1870
7 Imilac: Kobell, 1851
8 Huckitta: Madigan, 1939
9 Springwater: NiO, 0.00; P_2O_5, 0.20; H_2O, 0.20; Wiik, unpublished
10 Itzawisis: Cr_2O_3, 0.03; Ni, 0.00; Nel, 1949
11 Eagle Station: Prior, 1918
[a] Fa = 100 $(Fe^{II} + Fe^{III} + Mn)/(Fe^{II} + Fe^{III} + Mn + Mg)$.

Values much outside this range, such as Eagle Station (1.04%) and South Bend (0.26%), are probably erroneous. Chromium is consistently low, a fact that agrees with the observation that chromium in the pallasites is present as the mineral chromite. Copper ranges from 143 to 240 parts per million, comparable to the amounts found in iron meteorites. In the gallium and germanium contents the nickel-iron from pallasites falls in Group III of Lovering and others (1957), a group that also includes most of the octahedrites among the irons.

Some other data on minor and trace elements in pallasitic nickel-iron are included in table 2. The small amounts of P and S are probably to be ascribed to inclusions of schreibersite and troilite. Carbon is probably present as graphite. Wiik (personal communication) has carefully analyzed the metal from Marjalahti and Springwater for Ti and Mn; a small amount of Ti (0.01%–0.02%) was found, but no Mn could be detected.

Olivine: The olivine in these meteorites may be present as rounded grains, polyhedral crystals with rounded corners, or angular fragments. The size of the individual grains is usually about 5–10 mm. across, but pieces as large as 6 cm. long have been recorded in the Huckitta pallasite. The grains are normally single crystals or fragments of single crystals. The polyhedral grains show a combination of crystal faces, and indeed the goniometric data on olivine are largely based on measurements of crystals extracted from pallasites. The color of the fresh olivine is usually pale yellow. However, in many pallasites it is tinged red or brown by the presence of iron oxides formed by weathering.

The composition of the olivine is quite uniform within a single pallasite, but in the pallasites as a whole it shows a restricted and discontinuous distribution pattern. The composition of the olivine, as determined by the X-ray diffraction technique of Yoder and Sahama (1957), with Fa equal to mole per cent Fe_2SiO_4, in various pallasites is as follows:

Fa_{11}: Admire, Ilimaes, Ollague, South Bend, Gran Chaco
Fa_{12}: Ahumada, Albin, Antofagasta, Argonia, Brahin, Brenham, Giroux, Thiel Mountains, Huckitta, Imilac, Marjalahti, Molong, Mt. Vernon, Newport, Port Orford, Santa Rosalia, Somervell County
Fa_{13}: Anderson, Finmarken, Glorieta Mountain, Krasnoyarsk, Mt. Dyrring, Pavlodar, Pojoaque, Salta
Fa_{17}: Phillips County
Fa_{18}: Springwater
Fa_{19}: Itzawisis, Zaisho
Fa_{20}: Cold Bay, Eagle Station

Olivine with less than 11 mole per cent Fe_2SiO_4 (Fa) or more than 20 mole per cent is not known from these meteorites. Most of them have olivine with between 11 per cent and 13 per cent of Fa; a few have olivine between 17 per cent and 20 per cent of Fa. Whether these different amounts indicate two distinct groups of pallasites, as Yavnel (1958) has postulated, or whether we are dealing with a single group with an olivine composition peak at about 12 per cent of Fa and tailing off to 20 per cent of Fa, is not obvious. The rarity of the pallasites makes a statistical analysis of this sort somewhat venturesome.

There are a considerable number of analyses of pallasite olivine in the literature, but some of these are certainly erroneous, since they are inconsistent with the composition as established by refractive index or X-ray diffraction methods. A selection of analyses consistent with the physical data is given in table 4. These analyses show that pallasite olivine is remarkably pure magnesium-iron silicate, the only other element normally present in amounts greater than 0.1 per cent being manganese. Titanium, when determined, is absent or extremely low, except for 0.36 per cent of TiO_2 recorded in the Admire olivine; however, this figure is contradicted by a record of 20 parts per million of Ti determined spectrographically in Admire olivine (Lovering, 1957). Alumina is also low, mostly in the range of 0.01 per cent to 0.1 per cent; the high figure of 0.53 per cent for Admire is certainly suspect. The records of Fe_2O_3 are probably the result of weathering or of oxidation during analysis. The highly reducing environment in which the pallasites crystallized would seem to insure that essentially all the iron in the olivine is in the ferrous state. The analyses indicate that manganese is universally present as a minor constituent in pallasite olivine, in amounts of 0.2 per cent to 0.4 per cent of MnO, which is confirmed by spectrographic analyses, which show 1500 to 2000 parts per million of Mn (Lovering, 1957). Only one analysis, that of Huckitta, shows a determinable amount of calcium.

It is particularly noteworthy that careful modern analyses have failed to detect any nickel in the olivine from pallasites, in spite of the presence of considerable nickel in the nickel-iron. Lovering (1957), using spectrographic analysis, records 150–350 parts per million nickel in olivine from four pallasites, with a mean of 250 parts per million. This is in marked contrast to the nickel content of olivine from terrestrial ultrabasic rocks, which is of the order of 3000 parts per million (Ross, Foster, and Myers, 1954).

Wiik's analysis of olivine from the Springwater meteorite shows 0.20 per cent of P_2O_5. This olivine was very carefully purified, special care being taken to separate it completely from admixed farringtonite, and it seems certain that the phosphorus is in the olivine structure, substituting for silicon.

The trace-element distribution in pallasite olivine has been extensively studied by Lovering (1957), whose results are reproduced in tables 5 and 6. These figures further confirm the paucity of minor and trace elements in this material. Crystallochemically olivine is a close-packed structure and in general has little tolerance for the substitution of elements other than those closely related to the essential elements in its composition.

TABLE 5
TRACE-ELEMENT DISTRIBUTION IN OLIVINE FROM PALLASITES,[a] IN PARTS PER MILLION (LOVERING, 1957)[b]

	Ba	Co	Cr	Cu	Ga	Ge	Mn	Ni	Sn	Ti	V	Zr
Admire	<1	15	250	~1	<2	<20	2000	150	<10	20	15	<4
Albin	2	15	150	2	<2	<20	2000	150	~10	60	15	~10
Brenham	<1	80	100	5	<2	<20	1500	350	<10	10	17	<4
Springwater	<1	30	100	8	<2	<20	2000	350	<10	10	10	<4
Mean	*<1*	*35*	*150*	*4*	*<2*	*<20*	*1900*	*250*	*<10*	*25*	*15*	*<4*

[a] Mean of two analyses for each olivine.
[b] The following elements occur in concentrations less than the sensitivities reported in table 6: Ag, As, Au, Be, Bi, Cd, In, La, Mo, Nb, Pb, Pt, Sb, Sr, Ta, Th, Tl, U, W, Y, Yb, and Zn.

Edwards (1955) has reported sodium and potassium in pallasite olivine, as follows: Na, 0.05 per cent (Admire, Brenham, Finmarken), 0.04 per cent (Mt. Vernon); K, 0.009 per cent (Admire, Brenham, Finmarken), 0.011 per cent (Mt. Vernon). Harder (1961) reported 5 parts per million of boron in olivine from Brenham.

TROILITE: This mineral is probably present in accessory amounts in all pallasites. The amount is usually about 1 per cent, and it commonly occurs as small grains at the boundary between olivine and nickel-iron, although it may be present within these phases. Borgström (1903) carefully extracted and analyzed the troilite from the Marjalahti meteorite and found that it corresponded to the formula FeS; he found no detectable nickel in it. However, Nichiporuk and Chodos (1959) report the following concentrations (in parts per million) in troilite from the Brenham pallasite: V, 24; Cr, 1600; Co, 2000; Ni, 5400; Cu, 206; Zn, 63; As, <50. There is a clear discrepancy here; it is improbable that an analyst as experienced as Borgström would have failed to detect 0.5 per cent of nickel. Either the nickel content of pallasite troilite varies from one meteorite to another, or the Brenham troilite analyzed by Nichiporuk and Chodos had inclusions of nickel-iron (or schreibersite or both). The latter explanation seems feasible, since the presence of 5 per cent of

TABLE 6

Approximate Sensitivities (in Parts per Million) of Elements in the Spectrographic Analytic Techniques Described (Lovering, 1957)

Element	Sensitivity
Ag	0.5
As	200
Au	20
Be	0.8
Bi	10
Ca	1
Cd	20
Ga	1
In	10
La	100
Li	30
Mo	2
Nb	20
Pb	10
Pt	50
Sb	200
Sc	5
Sr	1
Ta	200
Th	200
Ti	1
Tl	50
U	500
W	100
Y	10
Yb	1
Zn	100
Zr	2

nickel-iron or 2 per cent of schreibersite would wholly account for the recorded nickel content of the troilite. Lovering (1957), using spectrographic analysis, reported the trace-element distribution in troilite from the Brenham (B) and Springwater (S) meteorites as follows (in parts per million): Co, 130 (B), 180 (S); Cr, 1400 (B), 900 (S); Cu, 960 (B), 500 (S); Ge, 10 (B), 6 (S); Mn, 320 (B), 320 (S); Ni, 10,000 (B), 3000 (S); V, 8 (B), 9 (S). The figures for Brenham do not agree very well with those given by Nichiporuk and Chodos. Some of the discrepancies can perhaps be ascribed to the difficulty in preparing a pure sample of troilite from these meteorites.

SCHREIBERSITE: This mineral has been recorded from several pallasites and is probably present in all of them; the amount recorded is 1 per cent to 2 per cent. It occurs as small grains, usually at the borders between nickel-iron and olivine, or within the nickel-iron. An analysis of schreibersite from the Marjalahti meteorite gave: Fe, 55.15 per cent; Ni, 29.15 per cent; Co, 0.21 per cent; P, 14.93 per cent, corresponding to the accepted formula $(Fe,Ni)_3P$ (Borgström, 1903).

CHROMITE: This is a common accessory mineral of the pallasites, being present as small grains in amounts up to about 1 per cent. Chromite from the Admire pallasite gave an analysis corresponding to pure $FeCr_2O_4$ (Merrill, 1902), but that from the Mt. Vernon pallasite gave the following analysis (Tassin, 1905): Cr_2O_3, 64.91 per cent; Al_2O_3, 9.85 per cent; MgO, 4.96 per cent; FeO, 17.97 per cent; SiO_2, 1.38 per cent (the SiO_2 and some of the MgO and FeO were presumably present as admixed olivine).

LAWRENCITE: The presence of this mineral in some pallasites has been established by the exudation, from freshly cut surfaces, of a greenish solution reacting for chloride and iron. Meteorites containing this mineral are subject to rapid oxidation and disintegration; the Admire pallasite is particularly notorious in this respect. Other pallasites are evidently free of lawrencite, since they remain unaffected by the normal humidity of the atmosphere.

FARRINGTONITE: This mineral, $Mg_3(PO_4)_2$, was discovered by DuFresne and Roy (1961) in the Springwater pallasite. It occurs in accessory amounts (1%–2%) peripheral to the olivine grains. The color is yellow, resembling that of olivine, but farringtonite has a well-marked cleavage which serves to distinguish it from olivine on a polished surface of the meteorite. It has not so far been recognized in any other meteorite.

The bulk composition of a pallasite is seldom determined directly by chemical analysis, because of the difficulty in preparing a representative sample. Usually the composition of the nickel-iron and the olivine are determined separately, and the proportions of those two phases determined by planimetric measurements on a polished surface or from a measurement of the density of a sufficiently large piece. From the percentages of the olivine and nickel-iron and their composition, the bulk composition can be calculated; this has been done for many pallasites by Chirvinsky (1949).

THEORIES OF ORIGIN

The problem of the origin of the pallasites has intrigued investigators for many years, and numerous theories have been advanced to explain their mode of formation. Previous theories were carefully described and discussed by Nel (1949), in a paper which unfortunately is not readily available.

Merrill, in his description of the Admire pallasite (1902), argued from the structural relationship that the metal phase was introduced after crystallization of the olivine. He maintained, however (Merrill, 1928), that the nickel-iron was introduced not as the molten metal but in the form of troilite and lawrencite which were subsequently reduced, probably in an atmosphere of hydrogen, to the metal phase.

Lord Rayleigh (1942, 1944) discussed the origin of the pallasites and simulated their structure with mixtures of molten solder and fragments of steatite. He agreed with Merrill that the olivine and the nickel-iron had originated independently of each other. However, Rayleigh believed that the olivines in the pallasites were fragments from some pre-existing material which had become immersed in molten nickel-iron.

Prior (1916) pointed out that the pallasites obeyed the rule that he had established earlier for the chondrites, viz., that the greater richness in nickel of the nickel-iron is accompanied by a correspondingly greater richness in ferrous oxide of the olivine. This rule, which is further confirmed by additional data in the present paper, is highly significant in establishing a compositional relationship between the olivine and the metal phase—a relationship that contradicts Merrill's and Rayleigh's views as to independent origins for these two phases and their subsequent chance association. Prior explained this relationship as the result of the partial oxidation of a magma containing free silicon, magnesium, iron, and nickel. Other explanations are, however, feasible. Nel (1949) agreed with Prior as to the compositional relationship between the nickel-iron and the olivine, but ascribed it to some process of magmatic differentiation. He showed that the amounts and compositions of the metal and silicate phases in pallasites, chondrites, and achondrites, when plotted on a variation diagram, give a pattern similar to that observed in variation diagrams for a sequence of magmatically differentiated igneous rocks such as the Bushveld complex.

Ringwood (1961) has discussed the origin of the pallasites in a general paper on the chemical and genetic relationships among meteorites. He marshaled evidence for their formation by the melting and differentiation of chondritic material, specifically material corresponding to the olivine-bronzite chondrites. These ideas have been further developed by Lovering (1962), who wrote:

A detailed examination of the pallasite meteorites has indicated that these meteorites represent accumulations of olivine crystals intruded by a liquid iron-nickel melt which also contained a considerable proportion of iron sulphide. . . . The nickel, cobalt, gallium, and germanium contents of the metal phase in pallasites are remarkably constant and these and other data have been used to show that the metal phase of pallasites represent samples of the parent metal melt from which all the various types of iron meteorites have differentiated. . . . It is suggested here that the achondrites and the iron meteorites have differentiated from the silicate and metal fractions respectively of average "normal" chondritic material which has been completely melted in the parent meteoritic body.

It thus appears to be well established that the pallasites represent the product of melting and differentiation of chondritic material. A melt of such material would consist of two immiscible liquids, nickel-iron and silicate (with possibly a small amount of a third liquid of troilite composition). From the silicate melt, the first phase to crystallize would be olivine. In the Fe_2SiO_4-Mg_2SiO_4 system (Bowen and Schairer, 1935), olivine of composition Fa_{12} (that of the major group of pallasites) would crystallize at about 1750° C. However, a chondritic melt is considerably more complex than the simple Fe_2SiO_4-Mg_2SiO_4 system, and it is conceivable, indeed probable, that the crystallization temperature of the olivine could be 1500° C. or lower. Nevertheless, the olivine was evidently solid while the nickel-iron was still molten, since in some pallasites the olivine is present as euhedral crystals and in others it occurs as sharply angular fragments. The consistent relationship between the composition of the olivine and the composition of the nickel-iron, exemplified by Prior's rules, shows that the two phases crystallized in equilibrium, presumably from a common source material. One feature of pallasite structure that has caused much discussion is the presence in juxtaposition of light olivine and heavy nickel-iron; this has been cited as evidence that the parent body in which the pallasites were formed had only a feeble gravitational field and hence was very small. However, as Wood (1963) has pointed out, the olivine crystals may have been prevented from leaving the liquid iron system by some form of solid boundary or ceiling, against which they accumulated.

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