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The Petrography and Chemical Composition of the Ogi Meteorite, from Ogi-machi, Ogi-gun, Saga-ken, Japan

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I. Introduction

The Ogi meteorite fell about 11 o'clock in the morning on June 8, 1741 in Ogi-machi, Ogi-gun, Saga-ken, Japan at 33°18′N, 130°12′E. It consists of four stones which weigh approximately 5.6, 4.6, 2 and 2 kg, respectively. In 1882, a brief description on the appearances and overall chemical composition of the larger two stones reported by DIVERS (analyst Shimizu). Other two fragments had been lost prior to this by somewhat reason. The largest stone, which had long been the property of Nabeshima's family, was unfortunately destroyed by American incendiary bombs in the World War II. The second largest one is the only specimen remained at present of the Ogi meteorite, which was previously brought into the British Museum. MASON (1963) determined the olivine composition by X-ray procedure, and VAN SCHMUS and WOOD (1967) classified Ogi as an H6 chondrite. However, reports on petrography, mineralogy and further precise chemical composition of this meteorite have apparently not been published to date. In this paper, we report the petrography and chemical composition of the chondrite Ogi, a small chip of which was recently provided from Dr. R. HUTCHISON, the British Museum to us.

II. Petrography

The interior of the stone is rather friable but looks still fresh showing light gray color, as described a hundred years ago (DIVERS, 1882), though it has been partly colored light-brownish by atmospheric weathering. Microscopic observation of thin sections reveals that this meteorite consists essentially of a compact assemblage of various sized grains of ferromagnesian silicates and opaque minerals. Though Ogi exhibits a highly crystalline granular matrix, the texture composed of microcrystalline matrix and medium sized phenocrysts is still noticed throughout the whole mass (Fig. 1).

Olivine and orthopyroxene are dominant as transparent minerals, and plagioclase and calsic pyroxene come next. Phosphate minerals are fairly rare. The opaque phase is metallic nickel-iron, troilite, chromite and a trace amount of native copper. The phase composition of the Ogi meteorite determined by planimetric integration is expressed as weight percent in Table 1. The abundances obtained for the constituent mineral phases in Ogi are almost in the range of average recrystallized H-group chondrites according to the summarized data by VAN SCHMUS and WOOD (1967).

Table 1. Phase composition of the Ogi meteorite.

Constituents	Weight percent
Olivine	39
Orthopyroxene	24
Clinopyroxene	4
Plagioclase	9
Apatite	<0.1
Nickel-Iron	17
Troilite	6
Chromite	1
Native Copper	<0.1
Total	100

Because of the restricted quantity of available samples, the total area scanned was only ca. 1.0 cm^2, which may not be enough to estimate accurate modal abundances for the whole stone. The Ogi meteorite shows the structure characteristics of chondrites subjected to the advanced recrystallization due to thermal metamorphism. Chondrules are scarce and the chondrule-matrix boundary is usually obliterated. Secondary feldspar is common as well-developed crystals, and clinobronzite and glassy material are absent in thin sections.

In crossed polarized light, wavy extinction is observed in every silicate grain, and extinction bands due to kinking in crystals are recognizable in several olivine and orthopyroxene grains (Fig. 2). Some grains of olivine exhibit a set of cleavage lines in them. These features are considered to be ascribable to light to moderate shock of 150–200 kb, according to the shock loading experiment of CARTER *et al.* (1968). Ogi, however, exhibits only to a minor extent the veining or fracturing which usually attributed to a shock of lower intensity. The presence of metal grains as buffer to a mechanical shock may be a cause of this conflict. Textural evidences supporting this hypothesis, e.g. anisotropically strained features around metal grains, could not be observed in the thin sections studied. Moreover, no evidence of blacking nor maskelynitization could be seen in this chondrite.

Olivine occurs in various sizes from a few micrometer up to 0.9 mm across. Porphyritic texture consisting of subrounded grains of olivine and interstitial feldspar is sporadically seen in thin sections. Most common phenocrysts enclosed by microcrystalline matrix are elongated olivine, whose margine is always corroded to various

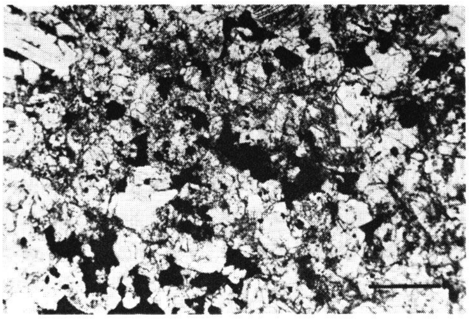


Fig. 1. Photomicrograph of a thin section of the Ogi meteorite. It shows highly recrystallized texture. Plane polarized light. Scale bar in the photograph is 0.5 mm in length.

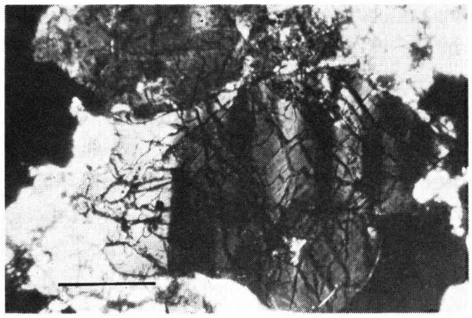


Fig. 2. Extinction bands in olivine due to plastic bending of the crystal structure. Crossed polarized light. Scale bar is 0.1 mm in length.

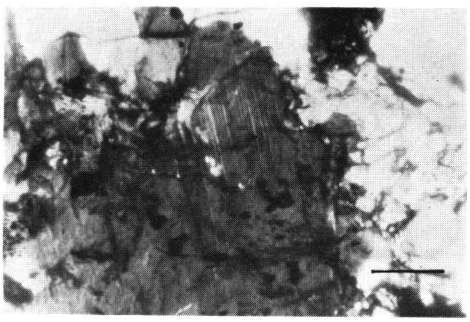


Fig. 3. Thin exsolution lamellae of clinopyroxene in an orthopyroxene grain. Crossed polarized light. Scale bar is 0.1 mm in length.

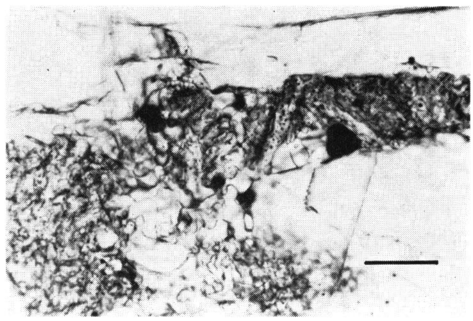


Fig. 4. Microcrystalline matrix in an olivine chondrule. Some elongated crystals of clinopyroxene are noticeable among fine granular grains. Plane polarized light. Scale bar is 0.05 mm in length.

degrees. The chemical composition of olivine analysed by electron microprobe is rather uniform grain by grain, and the average fayalite mole percent is 19.9 ± 0.2 (Table 2). The olivine composition was also determined by X-ray diffraction, using the method of YODER and SAHAMA (1957). Spacing d_{130} corresponds to about 20 mole percent fayalite, which is in accordance with EPMA data and also with Mason's measurement by X-ray diffraction procedure (1963). Refractive indices of olivine are $\alpha =$ 1.668 and $\gamma = 1.711$, which also indicate about 20 mole percent Fe_2SiO_4 according to the work of DEER *et al.* (1962).

Orthopyroxene mostly shows irregular outline in this chondrite and crystals elongated to c-axis are rather rare. Some orthopyroxene grains contain thin exsolution lamellae of clinopyroxene sharing a common (100) plane and [001] axis (Fig. 3). Clinopyroxene usually occurs as elongated crystals around orthopyroxene or sometimes next to olivine, and it is thought to be a secondary member probably crystallized as a reaction rim of the other mafic minerals during thermal metamorphism. Though olivine is the most common constituent of the fine-grained crystals in matrix, fine isolated grains of clinopyroxene exhibiting thin twinning lamellae are also present among them. The crystallization trend of diopsidic clinopyroxene is clearly seen in the microcrystalline matrix in olivine chondrules or their relicts. In these parts, some elongated crystals with high birefringence and oblique extinction ($Z \wedge C = 40°$) are enclosed among fine granular mafic grains and plagioclase (Fig. 4). Some chondrules are composed of irregular shaped fine crystals of orthopyroxene, clinopyroxene and some plagioclase, which are arranged in preferred orientation as in flow texture (Fig. 5). It is noteworthy that opaque minerals (metal and sulphide) in these chondrules are often idiomorphic and are arranged parallel to silicate crystals. Average

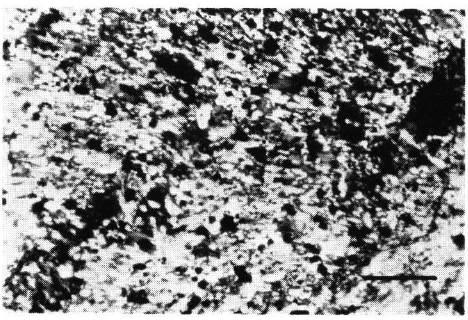


Fig. 5. Magnified view of the inner part of a pyroxene chondrule. It consists of orthopyroxene, clinopyroxene, some plagioclase and opaque phases and they are arranged in a preferred orientation as in flow structure. Crossed polarized light. Scale bar is 0.1 mm in length.

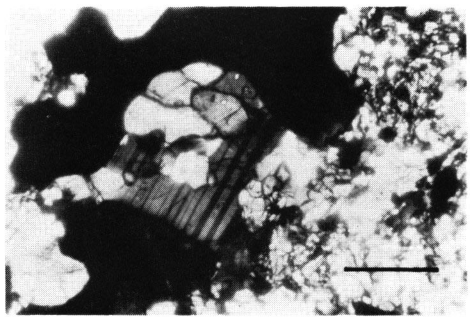
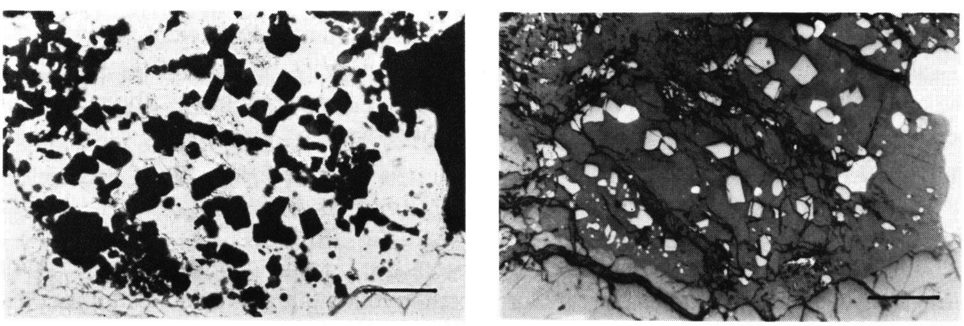


Fig. 6. Ogi contains a considerable amount of plagioclase. Many of the coarser plagioclase crystals exhibit twinning lamellae of Albite type. Crossed polarized light. Scale bar is 0.1 mm in length.



(a) (b)

Fig. 7. Idiomorphic crystals of chromite enclosed in plagioclase. (a) Plane polarized light. (b) Reflected light. Scale bar is 0.05 mm in length.

Table 2. Chemical composition of olivine in the Ogi meteorite.

Elements	1	2	3	4	Average
SiO_2	38.81	39.04	38.52	38.91	38.82
TiO_2	0.00	0.00	0.00	0.02	0.01
Al_2O_3	0.00	0.00	0.01	0.01	0.01
FeO	18.22	19.07	18.63	18.93	18.71
MnO	0.43	0.42	0.44	0.49	0.45
MgO	42.11	42.12	42.01	42.30	42.14
CaO	0.00	0.02	0.01	0.01	0.01
Na_2O	0.00	0.00	0.00	0.01	0.00
K_2O	0.01	0.00	0.01	0.00	0.01
Cr_2O_3	0.06	0.01	0.00	0.03	0.03
Total	99.64	100.70	99.63	100.71	100.19
Fo	80.5	79.8	80.1	79.9	80.1
Fa	19.5	20.2	19.9	20.1	19.9

Table 3. Chemical composition of orthopyroxene in the Ogi meteorite.

Elements	1	2	3	4	Average
SiO_2	55.86	55.87	55.85	56.06	55.91
TiO_2	0.17	0.19	0.21	0.19	0.19
Al_2O_3	0.15	0.18	0.17	0.18	0.17
FeO	11.65	11.48	11.35	11.98	11.62
MnO	0.52	0.47	0.46	0.49	0.49
MgO	30.53	30.28	30.35	30.01	30.29
CaO	0.79	0.75	0.87	0.91	0.83
Na_2O	0.01	0.00	0.03	0.02	0.02
K_2O	0.02	0.01	0.02	0.00	0.01
Cr_2O_3	0.17	0.15	0.08	0.21	0.15
Total	99.87	99.38	99.41	100.05	99.68
Wo	1.5	1.4	1.7	1.7	1.6
En	81.1	81.3	81.3	80.3	81.0
Fs	17.4	17.3	17.1	18.0	17.4

molar composition of orthopyroxene determined by EPMA is $Wo_{1.6}En_{81.0}Fs_{17.4}$ and the variation in chemical composition seems to be small (Table 3). The refractive indices $\alpha=1.673$, $\gamma=1.686$ correspond to about 17–19 mole percent ferrosilite, according to the determinative curve of KUNO (1954).

Secondary feldspar is one of the principal silicate phases in this chondrite. Clear plagioclase crystals sometimes reach up to 0.2 mm in size. They often show twinning of Albite type (Fig. 6). Plagioclase also occurs as fine interstitial grains among mafic minerals in the matrix and in chondrules. The refractive indices of plagioclase are $\alpha=1.533$, $\gamma=1.542$, indicating high-temperature type oligoclase of approximately 11–12 mole percent anorthite, according to the determinative curve of SMITH (1958). Electron microprobe yields, on the other hand, the average composition of

Table 4. Chemical composition of plagioclase in the Ogi meteorite.

Elements	1	2	3	4	Average
SiO_2	64.54	63.51	64.51	64.37	64.23
TiO_2	0.03	0.05	0.03	0.04	0.04
Al_2O_3	20.46	21.14	21.28	20.86	20.94
FeO	0.32	0.33	0.69	0.48	0.46
MnO	0.05	0.04	0.02	0.00	0.03
MgO	0.00	0.00	0.00	0.01	0.00
CaO	2.39	2.41	2.43	2.36	2.40
Na_2O	9.65	10.00	10.16	9.36	9.79
K_2O	1.25	0.83	0.84	1.56	1.12
Cr_2O_3	0.00	0.00	0.00	0.00	0.00
Total	98.69	98.31	99.96	99.04	99.01
Or	7.0	4.6	4.6	8.7	6.2
An	11.2	11.2	11.1	11.2	11.2
Ab	81.8	84.2	84.5	80.1	82.6

$Or_{6.2}An_{11.2}Ab_{82.6}$ (Table 4). Opaque minerals are mostly xenomorphic, but minute grains with idiomorphic outline are also present in some parts of thin sections. Especially fine chromites mainly enclosed in feldspar (Fig. 7), or metal grains in pyroxene chondrules are often angular to subangular, indicating probably earlier crystallization of opaque phases than of silicates. Chromite included in olivine or orthopyroxene grains are, on the other hand, always an aggregate of fine to very fine grains with the feature of a swarm or thin plate (Fig. 8). In most cases, they are arranged in preferred orientation probably along veins most of which are now already healed. Consequently, they sometimes appear to be a long thin plate or broken line on a cross section

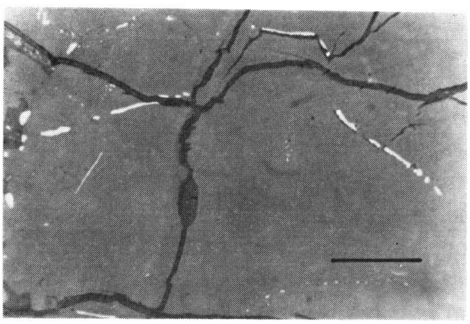


Fig. 8. The occurrence of chromite as an inclusion in olivine grains. It shows a feature of a fine plate of irregular outline, probably crystallized filling veins, most of which are now already healed. Plane polarized light, Scale bar is 0.03 mm in length.

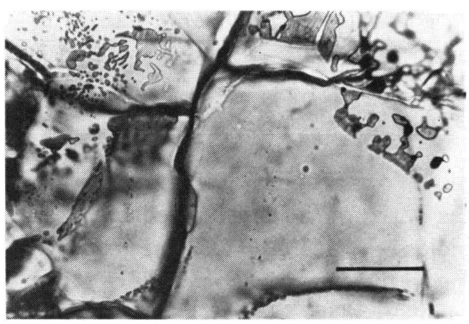


Fig. 9. The same part as in Fig. 8, taken with reflected light. The occurrence of chromite as thin plate sometimes exhibits a feature of a long thin line or broken line on a cross section. Scale bar is 0.03 mm in length.

(Fig. 9). Metallic nickel-iron, troilite, and chromite reach up to about 0.8, 0.5, and 0.3 mm in size, respectively. Most of metal phase is kamacite, but taenite is also recognized intimately intergrown with kamacite. Fine grains of native copper are rarely included in coarser metal grains intergrowing with troilite fragments. A considerable amount of titanium was detected in chromite grains by EPMA, but ilmenite could not be noticed as a distinct phase in thin sections studied.

III. Chemical Composition

The chemical composition of Ogi was determined by the method similar to that described in our previous papers (SHIMA *et al.*, 1979, OKADA *et al.*, 1979, YABUKI and SHIMA, 1980, SHIMA, 1980). Table 5 shows the results of chemical fractional dissolution. The obtained chemical compostion of the Ogi meteorite is given in Table 6 in

Table 5. Relative elemental abundances in separated phases of the chondrite Ogi.

Element	Whole meteorite (%)	Fraction (%)			
		$CuCl_2$–KCl	EDTA	Br_2-aqua regia	Residue
Si	18.571				
Mg	15.025	1.16	1.04	59.31	38.48
Fe	22.927	59.86	0.70	36.17	3.27
Al	1.084	0.73	1.59	1.39	96.29
Ca	1.259	5.45	3.37	13.03	78.15
Na	0.849				
K	0.100				
Cr	0.398	~0	~0	0.65	99.35
Mn	0.235	1.93	1.02	57.28	39.77
Ti	0.083	~0	~0	~0	100
P	0.097	~0	45.83	54.17	~0
Ni	2.070	91.30	0.41	8.29	~0
Co	0.099	92.47	0.82	6.71	~0
S	2.139				

a conventional format. The amount of iron in the sulphide phase was calculated as an equimolar ratio of the total sulphur, and metallic iron was calculated from the results of the stepwise fractional dissolution experiment. The normative abundances calculated on the basis of the analytical data are also listed in Table 6. The normative composition agrees rather well with the phase abundances determined by planimetric integration (Table 1) except that the ratio of olivine to orthopyroxene is smaller in the former result, and ilmenite is not present as a single phase in thin sections, as previously noted. In Table 7, the ratios of Fe_{total}/SiO_2, Fe_{metal}/Fe_{total}, SiO_2/MgO and fayalite mole percent in olivine are tabulated for the classification of the chemical group of this chondrite. These values, except Fe_{metal}/SiO_2, indicate that the chondrite

Table 6. Chemical composition and CIPW norm of the chondrite Ogi.

Species	Weight percent	Species		Weight percent
SiO_2	39.729	Olivine	Fo	22.93
MgO	24.916		Fa	7.29
FeO	7.046	Hypersthene	En	26.95
Al_2O_3	2.048		Fs	3.06
CaO	1.761		En	2.39
Na_2O	1.145	Diopside	Fs	0.27
K_2O	0.120		Wo	3.00
Cr_2O_3	0.581		Or	0.71
MnO	0.304	Plagioclase	Ab	9.69
TiO_2	0.139		An	0.09
P_2O_5	0.223	Apatite		0.52
H_2O	0.113	Chromite		0.86
Metal		Ilmenite		0.26
Fe	13.724	Nickel-Iron		15.89
Ni	2.070	Troilite		5.86
Co	0.099	Water		0.11
Sulphide				
Fe	3.726			
S	2.139			
Sum	99.883			99.88
Total Fe	22.927			

Table 7. Identification of chemical group by some parameters.*

	Ogi	H	L	LL
Fe_{total}/SiO_2	0.577	0.77 ± 0.07	0.55 ± 0.05	0.49 ± 0.03
Fe_{metal}/Fe_{total}	0.599	0.63 ± 0.07	0.33 ± 0.07	0.08 ± 0.07
Fa**	18.0 19.9***	18 ± 2	24 ± 2	29 ± 2
SiO_2/MgO	1.595	1.55 ± 0.05	1.59 ± 0.05	1.58 ± 0.05

* Classification. After VAN SCHMUS and WOOD (1967).
** Mole percent fayalite in olivine.
*** Obtained by EPMA.

Ogi belongs to H-group, when compared with indicator values of chemical classification of chondrites by VAN SCHMUS and WOOD (1967). The total amount of iron in Ogi, 22.927 wt.%, is fairly small for an H-group chondrite and is more in the range found for L chondrites (Table 6). As a consequence, the ratio of Fe_{metal}/SiO_2 is low, and the calculated normative abundance of metallic iron is also small compared with usual H-group chondrites. The presence of pyroxene chondrules in the sample used in wet chemical analyses may be the most probable cause of this low iron content. Pyroxene chondrules are usually large in size (sometimes greater than 1.5 mm across) and contain much smaller amount of matals than the surrounding matrix, as is seen in studied thin sections. It may be due to this same factor that the calculated mineral content in the CIPW norm is unusually rich in pyroxene (Table 6). Shimizu obtained

26.13 wt.% of total iron by wet chemical analysis by using much larger amount of samples (DIVERS, 1882). This difference between the two analytical results may be also due to a sampling effect.

IV. Sammary

The Ogi meteorite is a white olivine-bronzite chondrite, according to the petrography and the chemical analysis data, especially the values of Fe_{metal}/Fe_{total} (0.599), SiO_2/MgO (1.595) (VAN SCHMUS and WOOD, 1967), and the composition of olivine (Fa 18 by chemical analysis and Fa 20 by EPMA and optics) and orthopyroxene (Fs 17) (MASON, 1963, KEIL and FREDRIKSSON, 1964). The toatl amount of iron, 22.927 wt.%, is however rather low for an H-group chondrite. This is considered to be due to a sampling effect, probably the presence of some coarse pyroxene chondrules in the specimen used for chemical analyses. Advanced recrystallized texture, absence of igneous glasses and clinobronzite, and presence of well-developed plagioclase crystals indicate the petrologic type of this chondrite to be 6 (VAN SCHMUS and WOOD, 1967). In addition, the chemical compositions of coexisting olivine and orthopyroxene are rather homogeneous, which is also supported by the fact that their dominant peaks in X-ray diffraction are fairly sharp. Ogi shows some features probably induced by a shock of about 150–200 kb, such as prevalent undulatory extinction in silicates, and some kink bands in mafic minerals (CARTER *et al.*, 1968). However, veining or fracturing of mafic minerals is not prominent in this chondrite and further shocked features of similar or higher grade, e.g. maskelynitization or mosaicism are completely absent in thin sections.

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