Mineralogical and Petrographical Study of the Zaisho Meteorite, a Pallasite from Japan

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Dedicated to Prof. Dr. H. Hintenberger on the occasion of his 70th birthday

The Zaisho meteorite, a pallasite from Japan, is primarily composed of nickel-iron and olivine, and contains minor amounts of troilite, schreibersite, chromite and farringtonite. The olivine of this meteorite is $Fa_{18.6}$ in molar composition, and exhibits non-rounded morphology. About 17% of the olivines are kinked crystals. The formational temperature was estimated to be 1220 °C from the Mg-Fe^{2+} distribution coefficient in the coexisting olivine-chromite pair.

1. Introduction

The pallasite consisting primarily of nickel-iron and olivine is a rare type of meteorite and provides significant information on the deep-seated material in asteroidal bodies of the solar system. According to Hutchison et al. [1], fifty one listed pallasites did exist in 1977. One pallasite has recently been identified among Antarctic meteorites [2]. The Zaisho meteorite, the only pallasite from Japan, is one of the rare samples of pallasite which were observed to fall [3].

This meteorite was seen to fall at Zaisho, Kami-gun, Kochi-ken, about 5 a.m. on February 1, 1898, and was reported to be 0.33 kg in original weight. The main mass of the Zaisho meteorite is now in the possession of Mr. S. Goto, and a part is kept in the meteorite collection of the National Science Museum, Tokyo, Japan. On this meteorite, the olivine composition [4] and classification [5] were reported in the past, but no further scientific investigations on mineralogy, petrology and chemistry have been done for a long time. Recently, Mr. S. Goto kindly allowed us to use a chip of the meteorite for scientific work. This paper presents the result of the mineralogical and petrographical investigation of the Zaisho meteorite.

2. Experimental Method

A polished section of the meteorite specimen was prepared for microscopic study, and the structure and mineral species were investigated with a polarizing microscope in the reflecting light. A few pieces of polished sections and thin sections of individual mineral phases were also prepared both for microscopic examination and for electron probe microanalysis. Optic axial angle and optical orientation of transparent minerals in the thin section were measured using a universal stage fixed on the microscope stage. Measurement of refractive indices of olivine and phosphate mineral was carried out by the oil-immersion method under the polarizing microscope. In order to certify the mineral identification, X-ray powder patterns of individual minerals which were picked out from the microscopically examined polished sections were taken with a Debye-Scherrer camera under either Fe Kα or Cu Kα radiation. Precise lattice constants of olivine were calculated from X-ray powder patterns taken with a D-9C X-ray diffractometer made by Rigaku Electric Co. The diffraction angle of each peak was corrected by comparison with that of pure silicon standard. Chemical compositions of several minerals, kamacite, schreibersite, olivine, chromite and farringtonite, were determined using a computer-controlled JOEL 733 electron probe microanalyzer. The instrument was operated at 15-kV and 0.04-μA probe current. In all analyses, a focussed electron beam, 10 μm in diameter, was bombarded on the surface of mineral grains in the carbon-coated polished section. The intensity of the resultant characteristic X-ray emission of each element of the sample was compared with that of the well-analyzed standard material, and corrections of atomic number, absorption and fluorescence effects were carried out.

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3. Petrography and Mineralogy

The Zaisho meteorite of Mr. S. Goto's collection is shown in Figure 1. It is approximately 3.5 cm × 4.5 cm × 5.5 cm in size, and weights about 300 grams. The outer surface is bumpy in appearance. The protuberant metallic parts are covered with a thin, black crust and the silicate parts exhibit a dull, glassy luster tarnished by weathering products. Metallic nickel-iron and troilite are partly oxidized on their surfaces from moderate weathering in the terrestrial environment.

Fig. 1. A section of the Zaisho meteorite.

On the cut section of the main mass, 11.8 cm^2 in area, metallic and silicate phases occupy 15.5% and 85.5%, respectively, of the total area, indicating that about 30 wt.% of the total mass of the Zaisho meteorite is metallic. Macroscopically, nickel-iron forms a continuous network structure, and fairly angular and subangular olivines fill the interstices of the metallic phase. In the nickel-iron phase, kamacite adjoining the silicate phase and plessite surrounded by the nickel-rich rim (taenite) are clearly discernible in the polished section. Olivine grains are easily scraped off from the meteorite mass owing to the loose contact with the metallic phase and the prevalence of fracturing. They are usually olive-yellow in color in fresh grains, but some grains are brown and dark brown in appearance, because iron oxide produced by weathering covers the surface and spreads into the interior along the fractures and cleavages.

Nickel-Iron

The metal area of the Zaisho meteorite consists of three phases, kamacite, taenite and plessite. Plessite rimmed by nickel-rich taenite is immutably situated in the inside of the metal area, and kamacite surrounding plessite and taenite is generally adjacent to olivine and phosphate grains. Figure 2 shows a metal area of this meteorite, in which swathing kamacite bands sandwich plessite. There is no evidence of Neumann structure in the kamacite, although this structure is found in many

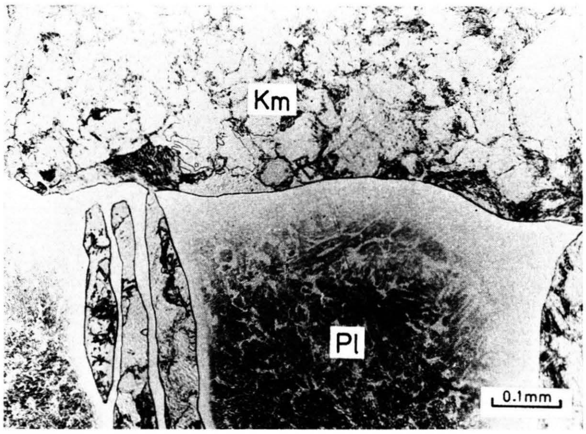

Fig. 2. Nital-etched nickel-iron phase of the Zaisho meteorite. The kamacite area (Km) shows a granular structure, and the plessite field (Pl) is surrounded by a nickel-rich rim.

pallasites [6]. Chemical etching by 5% nital solution reveals that the kamacite phase has a granulated structure. Laue photograph of the kamacite phase does not show any evidence of preferred orientation of kamacite grains. Chemical composition of kamacite determined by electron probe microanalysis is Fe: 92.0%, Ni: 7.16% and Co: 0.84%.

Schreibersite

Schreibersite is always associated with kamacite. It is commonly present as inclusions in kamacite, and often occurs on the border between kamacite and silicate or phosphate grains. Figure 3 shows the occurrence of schreibersite which is adjacent to kamacite, troilite and farringtonite. The composition is Fe: 43.5%, Ni: 41.1%, Co: 0.20% and P: 15.7%.

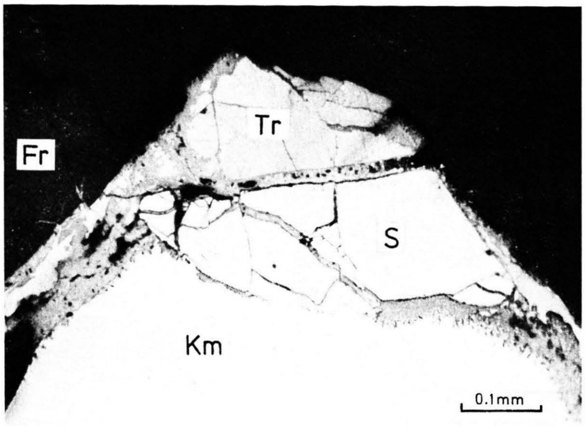

Fig. 3. Troilite (Tr), schreibersite (S), kamacite (Km) and farringtonite (Fr) occurring adjacent to one another.

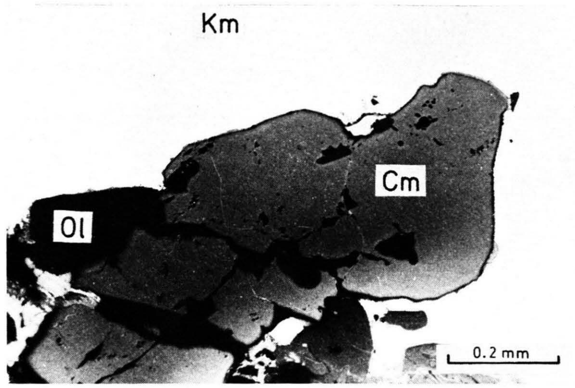

Fig. 5. Chromite (Cm) occurring adjacent to kamacite (Km) and olivine (Ol).

Troilite

Troilite grains are commonly present adjacent to olivine and farringtonite, and occur as single crystals with well-developed cleavages. Narrow veinlets of troilite widely spread through the fractures, cleavages and grain boundaries of olivines and farringtonites (Figure 4). Under crossed nicols it is noticed that some of the veinlets are composed of polycrystalline aggregate of minute troilite crystals.

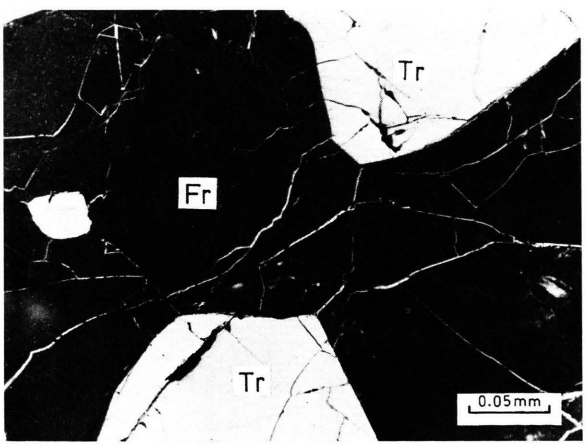

Fig. 4. Troilite (Tr) and troilite veins in the farringtonite (Fr).

Chromite

In the silicate phase consisting of olivines, angular and irregular-shaped chromite crystals occur in the interstices along the grain boundaries of olivine crystals. Figure 5 shows somewhat rounded crystals of chromite occurring in contact with kamacite and olivine grains. The average composition of three grains is Cr_2O_3: 68.6%, Al_2O_3: 0.58%, TiO_2: <0.05%, FeO: 26.1%, MgO: 3.36% and MnO: 0.82%; also vanadium is present.

Olivine

The silicate phase of the Zaisho meteorite is composed of non-rounded olivine crystals of homogeneous chemical composition. The average composition is MgO: 43.2%, FeO: 17.6%, MnO: 0.38%, SiO_2: 38.8%, Al_2O_3, Cr_2O_3, TiO_2, NiO and CaO: <0.01%, respectively. The atomic ratio of $Fe^{2+}/(Mg+Fe^{2+})$ is 0.186. The optical properties and cell constants are as follows.

Refractive indices: $\alpha = 1.671$, $\gamma = 1.712$;
Optic axial angle: $2V = -89°$;
Cell constants: $a = 4.771$ Å, $b = 10.25$ Å, $c = 6.006$ Å.

A conspicuous characteristic of the olivine crystals is the presence of kink bands (Fig. 6), although the olivines in this meteorite show neither undulatory extinction under crossed nicols nor asterism in the single crystal Laue photograph. In the thin section of olivine grains, which were randomly picked up from the meteorite specimen, four of twenty four grains exhibit kink bands under crossed nicols. Examination of the optical orientation of kinked crystals using a universal stage showed that the boundary of the kink band and the axis of external rotation are parallel to the (100)

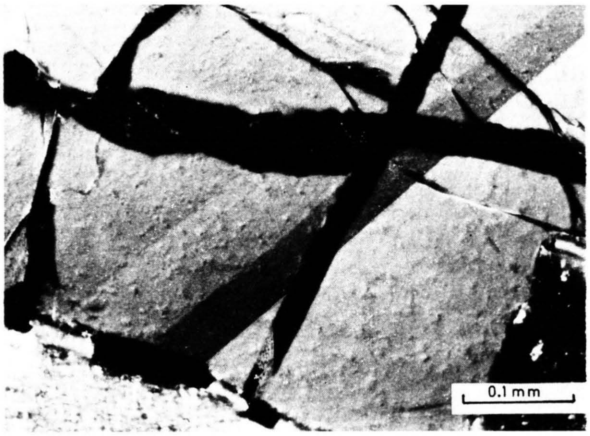

Fig. 6. Multiple kink bands in the olivine crystal. Nicols crossed.

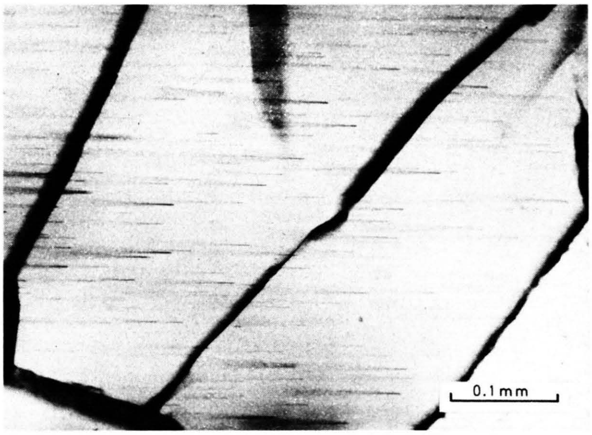

Fig. 8. Thin, straight form of tubular inclusions in the olivine crystal.

plane. The same result is seen in other pallasitic olivines [7]. The olivines of pallasites commonly contain rounded inclusions and tubular ones [6]. Both of them are observed in the olivine crystals of this meteorite. Figure 7 shows minute, opaque inclusions spreading along the fracture of olivine, and they are composed of small grains of troilite, nickel-iron and chromite. Olivine crystals containing numbers of straight tubes, less than 1 μm in diameter and arranged in parallel, are commonly found in this meteorite (Figure 8). These tubes appear apparently hollow, but some of them are filled with troilite and chromite.

Farringtonite

Phosphate minerals are common in pallasites, and whitlockite, stanfieldite and farringtonite are primary phosphate species [8, 9, 10]. In the present specimen of the Zaisho meteorite, only farringtonite was observed (Fig. 3 and 4), and was also identified by the Debye-Scherrer photograph. It occurs invariably at the contact of the metallic with the silicate parts. The composition is MgO: 41.1%, FeO: 3.87%, MnO: 0.26%, CaO: 0.07% and P_2O_5: 54.7%. The optical properties are as follows.

Refractive indices: $\alpha = 1.542$, $\gamma = 1.560$;

Optic axial angle: $2V = +55°$.

In the farringtonite, fragments and shards of olivine grains are frequently present (Figure 9).

Fig. 7. Minute opaque inclusions occurring along the fratures of the olivine crystal.

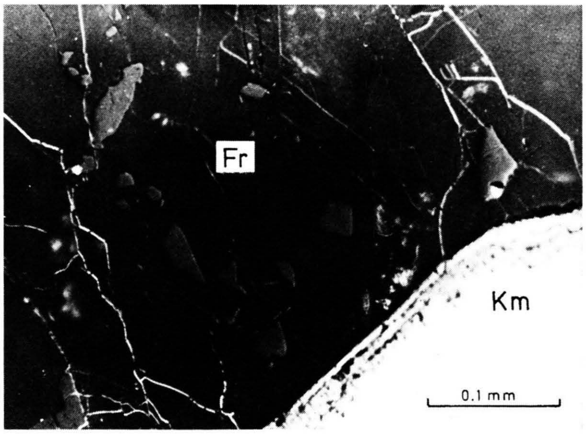

Fig. 9. Olivine fragments in the farringtonite (Fr) occurring adjacent to kamacite (Km).

4. Discussion

Recent studies of pallasitic olivines revealed that the pallasites are divided into two groups. The one consists of Fa 10.5—13.5 olivines, and the other comprizes Fa 16.5—20.5 olivines [4, 11]. On the other hand, Scott [12] showed from the study of nickel and minor element abundances of metallic phase that there are two distinctive groups having Fa 10.5—13 and Fa 19—20 olivines. The molar composition of olivine (Fa 18.6) indicates that the Zaisho meteorite belongs to the fayalite-rich group. As to the morphology of olivine crystals, there are two categories, pallasites having angular olivines and those having rounded ones [5, 13]. The Zaisho meteorite is assigned to the former, and this is corresponding to the fact that kinked crystals are present in the olivines of this meteorite [7]. In order to estimate the formational temperature of pallasites, Jackson's method [14] using olivine-chromite equilibration was applied. This method uses the Mg and Fe^{2+} fractions in the olivine and chromite, and the Cr, Al and Fe^{3+} fractions in the chromite. In this meteorite, $Mg/(Mg+Fe^{2+})$ and $Fe^{2+}/(Mg+Fe^{2+})$ in the olivine are 0.814 and 0.186, respectively, and $Mg/(Mg+Fe^{2+})$, $Fe^{2+}/(Mg+Fe^{2+})$, $Cr/(Cr+Al+Fe^{3+})$ and $Al/(Cr+Al+Fe^{3+})$ in the chromite are 0.187, 0.813, 0.988 and 0.012, respectively. The Mg-Fe^{2+} distribution coefficient ($K_{D_{Mg-Fe^{2+}}} = 19.03$) in the chromite-olivine pair shows that the formational temperature is 1220 °C. The result is in good agreement with the temperature range of nine pallasites, 1143—1359 °C [15]. From the petrographical aspect, the minerals of the Zaisho meteorite show no sign of the shock deformation. The olivines are free from undulatory extinction and mosaicism, the Neumann structure is absent in the kamacite, and no evidence of shock-induced vitrification and melting is observed in the thin section and polished section. However, the occurrence of kinked crystals which are noticed in about 17% of the olivines and the presence of fragmented olivines in the farringtonite indicate that the Zaisho meteorite was subjected to a post-formational deformation [6, 7]. The melting temperature of the farringtonite, 1180 °C at 1 atm, is much lower than that of the olivine, 1680—1840 °C at 1 atm. This fact suggests that the fragmentation of olivine crystals was caused before the crystallization of the farringtonite, and that the fragments were included in the farringtonite by its solidification.

5. Summary

The Zaisho meteorite is primarily composed of nickel-iron and olivine and contains minor amounts of troilite, schreibersite, chromite and farringtonite. The olivines are $Fa_{18.6}$ in molar composition and exhibit non-rounded morphology. About 17% of the olivines are kinked crystals. The formation temperature was estimated to be 1220 °C from the Mg-Fe^{2+} distribution coefficient in the coexisting olivine-chromite pair.

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