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SPECTRAL COMPARISON BETWEEN OLIVINE-RICH ASTEROIDS AND PALLASITES

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Abstract: Reflectance spectra of two pallasites were measured and compared with four reflectance spectra of olivine-rich asteroids. Bidirectional reflectance spectra (0.3–2.6 μm) were measured at several different points on chips of Yamato-8451 (Y-8451) and Imilac pallasite. A metal-rich part of Y-8451 showed a reflectance spectrum very similar to 113 Amalthea. Other olivine-rich asteroids could not be fit well even by combining all the measured reflectance spectra of those two pallasites. Some kind of regolith process seems to be important in producing those reflectance spectra. Y-8451 is unusual as a pallasite. Its olivine grains are much smaller than usual pallasites, the Fa value is the lowest, and both orthopyroxene and inverted protoenstatite are present. Their Fe/(Fe+Mg) ratios correspond to the formation temperature of 1135°C. Y-8451 is rather similar to metal-rich primitive achondrites such as Y-791058, which is, therefore, also examined in this study. 113 Amalthea is another example of the S asteroids whose reflectance spectra can be approximated with a stony-iron model.

1. Introduction

The similarity of reflectance spectra between olivine-rich asteroids and pallasites is one of the clearest understandings about the relationship between asteroids and meteorites together with the one between Vesta-like asteroids and HED achondrites. Two asteroids (246 Asporina and 289 Nenetta) in the main belt were the first ones that were found to be olivine-rich by high resolution near-infrared reflectance spectra, and their similarity to Chassigny and Brachina were pointed out (CRUIKSHANK and HARTMANN, 1984). Another asteroid (446 Aeternitas) was also found to be olivine-rich (BELL *et al.*, 1984a). The spectral similarity between those olivine-rich asteroids and pallasites was shown by simulating the pallasite assemblage with some combinations of metallic iron and powder olivine (BELL *et al.*, 1984b, c). An olivine-rich asteroid (3199 Nefertiti) was later found also in Earth-crossing orbits (CRUIKSHANK *et al.*, 1985), which increased our expectation to find their counterparts among our meteorite collections.

There can be more olivine-rich asteroids in Earth-crossing orbits (VEEDER *et al.*, 1990).

Recent 52-color near-infrared measurements (BELL *et al.*, 1988) found two more olivine-rich asteroids (113 Amalthea and 354 Eleonora) in the main belt. Those two asteroids show S-type feature around the visible wavelength range but are olivine-rich in their overall spectral features. It supports the idea that those asteroids are olivine-rich end members of the S asteroids (GAFFEY *et al.*, 1990). Therefore, the term "olivine-rich asteroids" is used instead of the A or S asteroids.

In this paper, reflectance spectra of four olivine-rich asteroids in the main belt are compared with those of two pallasites (Y-8451 and Imilac) newly measured in this

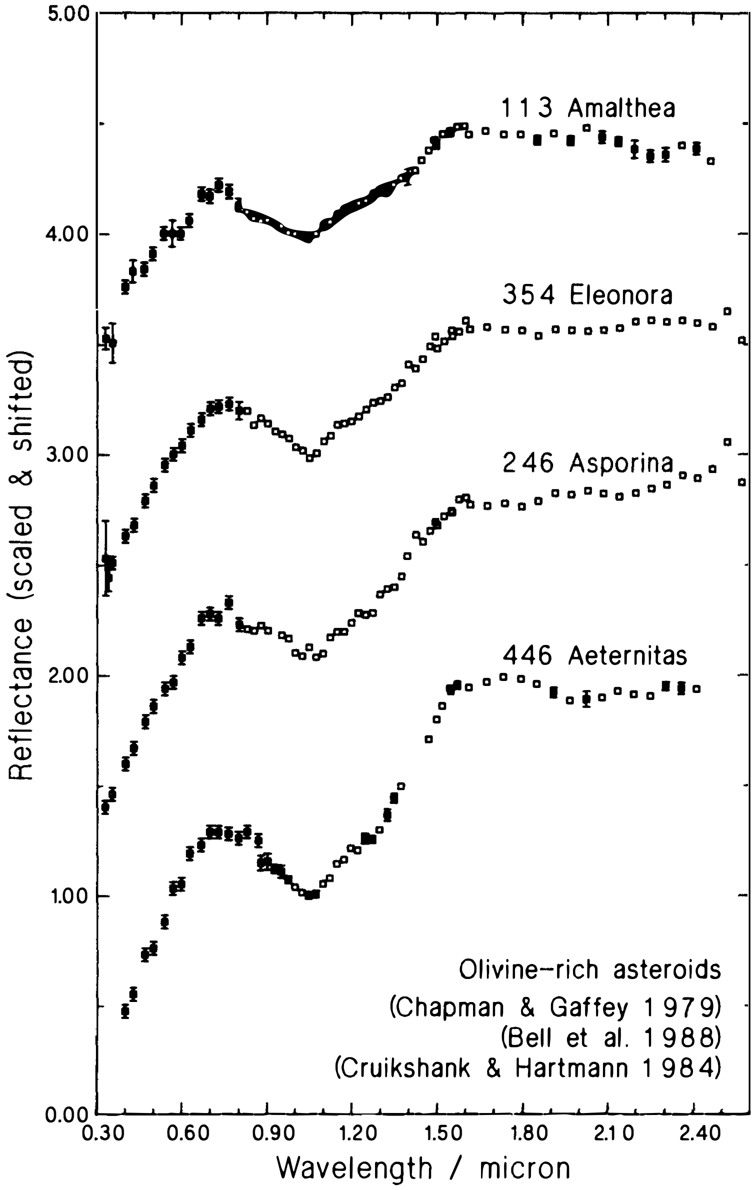

Fig. 1. Reflectance spectra of four olivine-rich asteroids. Ultraviolet and visible (CHAPMAN and GAFFEY, 1979) and near-infrared (BELL et al., 1988; CRUIKSHANK and HARTMANN, 1984) data were connected at 0.8 μm with a least-square fitting for each asteroid.

study. Because of the affinity of Y-8451 pallasite to metal-rich primitive achondrites, a metal-rich primitive achondrite Y-791058 was also studied for comparison. However, reflectance spectrum of Y-791058 is not given in this paper because it had so much rust.

2. Measurements of Reflectance Spectra

Four olivine-rich asteroids 113 Amalthea, 354 Eleonora, 246 Asporina, and 446 Aeternitas were chosen for this study. Ultraviolet-visible (0.3–1.1 μm) reflectance spectra of the above asteroids were measured by CHAPMAN and GAFFEY (1979). Their near-infrared (0.8–2.6 μm) reflectance spectra were measured by BELL *et al.* (1988) except for 246 Asporina measured by CRUIKSHANK and HARTMANN (1984). Visible and near-infrared reflectance spectra were combined by a scaling factor derived by applying the least-square method to the data in the overlapping wavelength range (0.8–1.1 μm). The connected reflectance spectra are shown in Fig. 1.

Pallasites contain large amount of metallic iron, whose reflectance spectrum largely

Fig. 2. Y-8451,20 chip. Both side 1 and 2 are cut surfaces. Brighter parts are metallic irons. Circles specify the spots whose reflectance spectra (Fig. 4a) were measured. Diameter of each circle is 6 mm.

depends on the surface condition and viewing geometry not only on its chemical composition (Fe/Ni ratio). Therefore, different viewing geometries and surface conditions were chosen for measurements when possible. Bidirectional reflectance spectra (0.3–2.6 μm) of pallasites in this study were measured at RELAB in Brown University. The incident light had a round shape of 6 mm in diameter. Pressed halon was used as the standard material, and the measured reflectance spectra relative to halon were corrected based on the absolute reflectance data of halon by National Bureau of Standard. The details of RELAB are described in PIETERS (1983) and in the RELAB User's Manual.

Y-8451,20 chip was cut by National Institute of Polar Research, and three different spots on the chip were chosen for measurement (Fig. 2). Reflectance spectra of all three spots were measured at the diffuse geometry (30° incidence and 0° emergence), and one of them (spot 2) were measured also at the specular geometry (15° incidence and $-15°$ emergence). Those measured reflectance spectra are shown in Fig. 4a. Because halon has near-isotropic diffuse reflectance, a flat metallic-iron surface can reflect much more

Fig. 3. Imilac chip. Side 1 was polished with No. 60 sandpaper for reflectance measurements. Side 2 was a near-mirror surface and was used for reflectance measurements as it was. It was later polished with No. 60 sandpaper for taking the photograph. Brighter parts are metallic irons, and darker ones are olivine grains. Circles specify the spots whose reflectance spectra (Fig. 4b) were measured. Diameter of each circle is 6 mm.

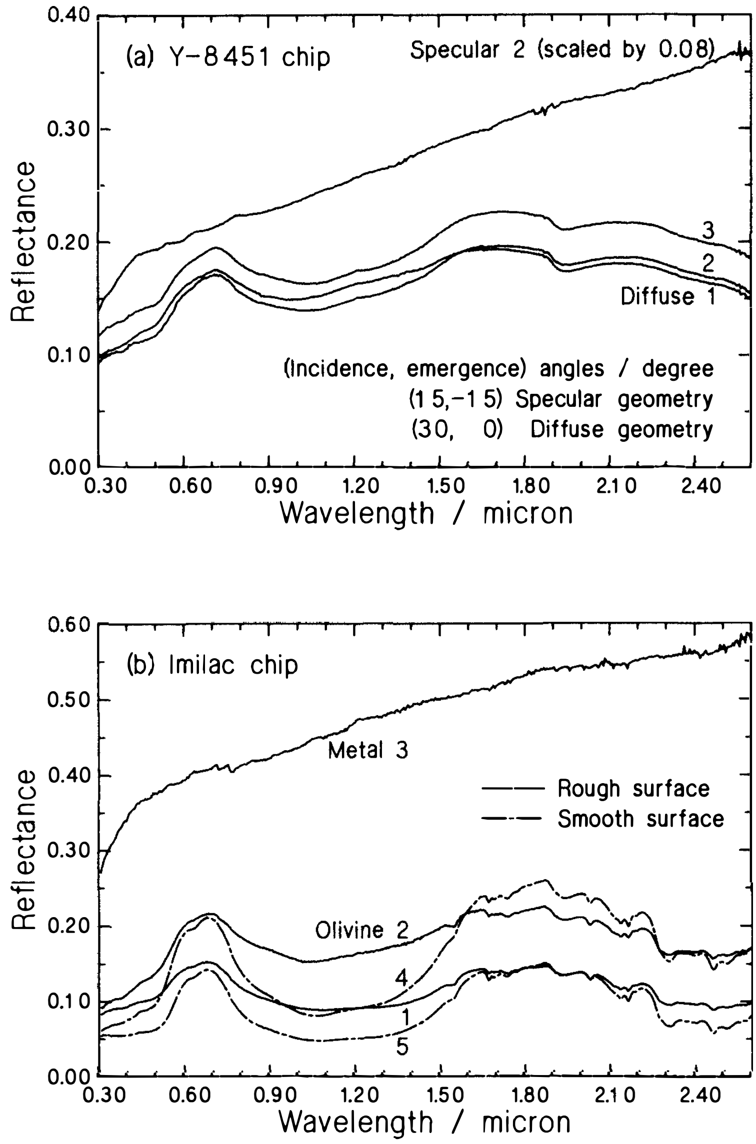

Fig. 4. Bidirectional reflectance spectra of two pallasite chips. Numbers correspond to the spots on Figs. 2 and 3. (a) Y-8451 chip. Actual reflectance of the specular-geometry measurement is 100/8 times higher than is shown. (b) Imilac chip. Three measurements on the rougher side (side 1) are shown in solid lines, and two measurements on the smoother side (side 2) are shown in broken lines. All measurements were at the diffuse geometry.

light than halon at the specular geometry. Spot 2 has about 460% reflectance at 2.6 μm.

Imilac pallasite was cut into a flat chip (Fig. 3). The fresher side (side 1) was polished with No.60 sandpaper to roughen the surface and obtain diffuse reflection of light. Side 1 had a surface texture on the scale of 400 μm after the treatment. The other side (side 2) was much smoother with some rusts. A metallic-iron-rich part (spot 3) and two olivine grains on the rougher side (side 1), and two olivine grains on the smoother side (side 2), were chosen for reflectance spectral measurements at the diffuse geometry (30° incidence and 0° emergence). Spot 2 actually contained some metallic iron. Those measured reflectance spectra are shown in Fig. 4b.

3. Comparison of Reflectance Spectra between Olivine-Rich Asteroids and Pallasites

Between reflectance spectra of four olivine-rich asteroids (Fig. 1) and seven olivine-rich spots on pallasites (Fig. 4), only 113 Amalthea and Y-8451 (diffuse 3) matche well each other as shown in Fig. 5. Absorption bands of Y-8451 at 0.5 μm, 1.95 μm, and beyond 2.6 μm are likely due to rusts and other hydroxides. The match between those two spectra is excellent except for the shortest wavelength range ($<0.4\,\mu$m). Olivines in Imilac show not only absorption features of rusts but also many unknown absorption bands at wavelengths longer than 1.6 μm, which are likely due to weathering. Side 2 of Imilac (broken curves in Fig. 4b) are more rusted than side 1 (solid curves). Olivine-rich asteroids also show weak absorption bands around the same wavelength range, but they do not correspond to those of Imilac in wavelength position. Those small bands can be artifacts of the Earth's atmospheric effects because those wavelength positions are common for many asteroidal reflectance spectra.

As an attempt to characterize olivine-rich asteroids in terms of pallasites in this study, linear spectral fittings of olivine-rich asteroids were performed with all the nine spectra of two pallasites (Fig. 4) as the end members because each of them had its own character. The method is the same with our previous work (HIROI *et al.*, 1992) that assumes the asteroidal surfaces are some kind of regional mixtures of meteorites. Reflectances of those spots were simply combined linearly at each wavelength, where the absolute reflectance of the target asteroid at 0.55 μm (c_0) and the linear combination coefficients (c_1, c_2, $\cdots$, c_9) of those 9 spots were optimized to give the following relationship as closely as possible:

$$c_0 R_S = \sum_{i=1}^{9} c_i R_{Ai}\,, \qquad \sum_{i=1}^{9} c_i = 1\,, \quad c_i \geq 0\,, \tag{1}$$

where R_S and R_{Ai} indicate the scaled reflectance of the target asteroid and the absolute

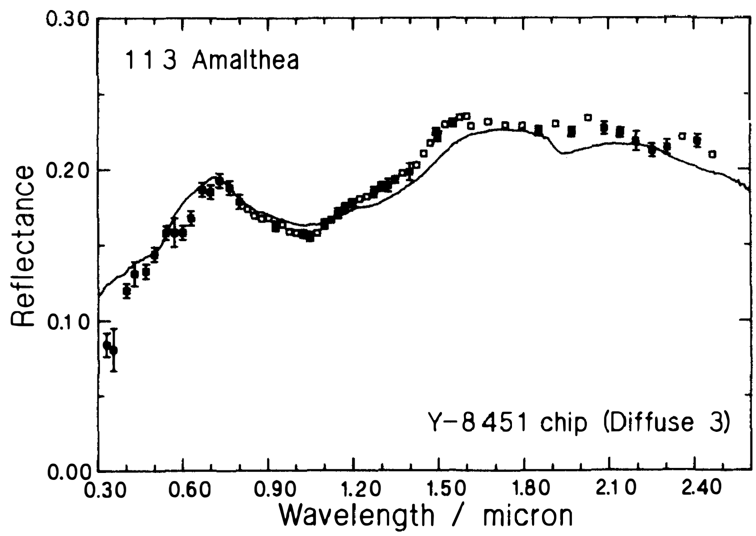

Fig. 5. A comparison of reflectance spectra of 113 Amalthea and Y-8451 (spot 3). Spot 3 is the metal-rich end of Y-8451 chip (Fig. 2). Reflectance spectrum of Amalthea is scaled.

reflectance of the spot i, respectively. By dividing eq. (1) by c_0

$$R_S = \sum_{i=1}^{9} C_i R_{Ai}\,, \qquad \sum_{i=1}^{9} C_i = 1/c_0\,, \quad C_i = c_i/c_0 \geq 0\,. \tag{2}$$

First C_i's in eq. (2) were optimized independently by the least-square method with the constraint of $C_i \geq 0$, and then c_i's were calculated by

$$c_0 = 1\Big/\sum_{i=1}^{N} C_i\,, \qquad c_i = c_0 C_i\,. \tag{3}$$

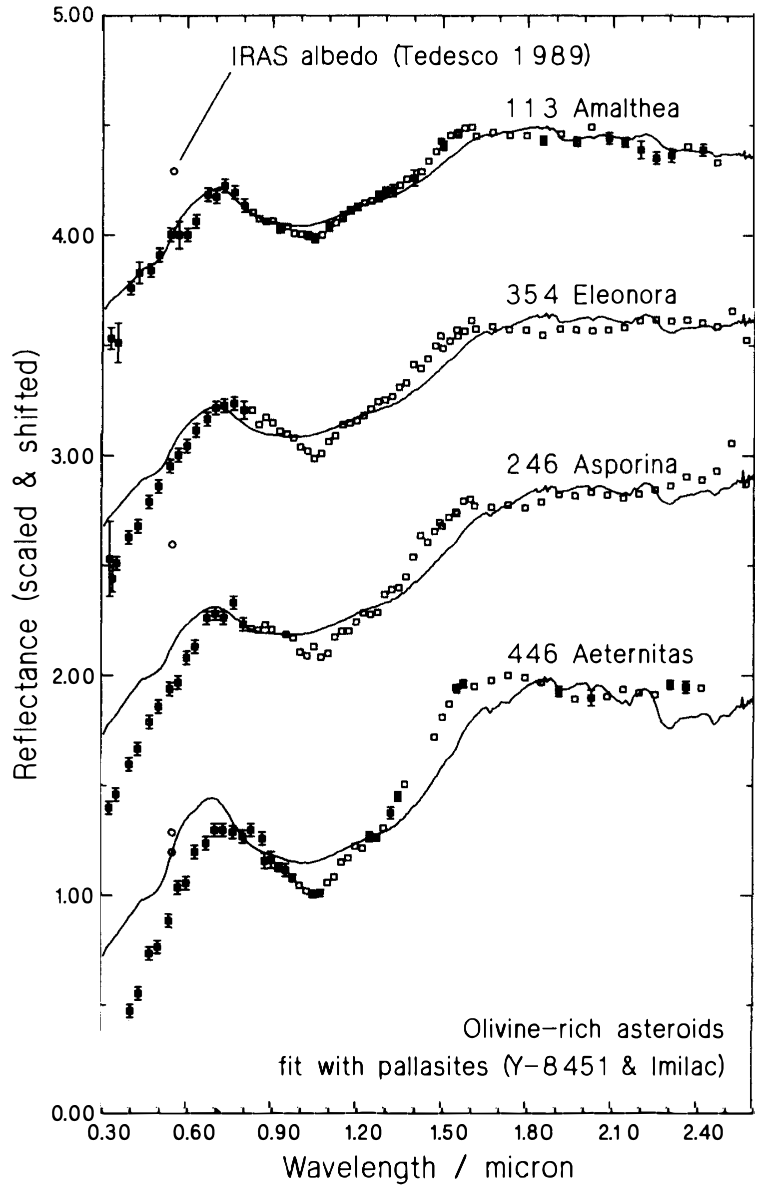

Fig. 6. Linear spectral fits of four olivine-rich asteroids (Fig. 1) with pallasites Y-8451 and Imilac (Fig. 4). All the reflectance spectra are scaled to 100% at 0.55 μm and shifted by 100% from one another. The IRAS albedoes (TEDESCO, 1989) are plotted with open circles at 0.55 μm.

Table 1. The results of spectral fits of olivine-rich asteroids with two pallasites.

	Modal abundances (area %)			Albedo %		Relative error %
	Y-8451 specular 2	Y-8451 diffuse 1	Imilac olivine 4	Optimized	IRAS*	
113 Amalthea	2.9	76.4	20.6	21.0	27	5.8
354 Eleonora	8.0	47.1	45.0	31.8	19	8.8
246 Asporina	15.7		84.3	45.3	13	12.5
446 Aeternitas	8.7		91.3	29.3	35	15.8

* TEDESCO (1989).

The results are shown in Fig. 6 and listed in Table 1. Only three spots (Y-8451 specular 2, Y-8451 diffuse 1, and Imilac olivine 4) had non-zero coefficients after calculation of all four olivine-rich asteroids. The relative error in Table 1 is the root mean square error divided by the optimized reflectance at 0.55 μm (c_0). While 113 Amalthea is fit even better, the others are not fit well in terms of absorption band shapes and positions. The optimized albedoes are similar to the IRAS albedoes (TEDESCO, 1989) except for 246 Asporina.

One of the spectral differences between three not-well-fit asteroids and pallasites, is the absorption band depth. In order to produce their reddened profiles, much metallic irons must be mixed, which decreases the absorption band depth around 1 μm due to olivines. This difference may be solved by grinding olivine grains in pallasites into powder (BELL *et al.*, 1984b, c) because they give brighter but deeper absorption bands. Another difference is that those asteroids have linear steep slopes in visible range (0.3–0.7 μm), which may be difficult to produce by any combination of metallic irons and olivines.

There is a possibility that the assumption of regional mixing of metallic iron and olivine grains is not valid for olivine-rich asteroids in this study. Simulating asteroidal regolith processes by grinding pallasites into several grain-size fractions, would be the best effort to clarify if there is any real difference between olivine-rich asteroids and pallasites. We expect that asteroidal surface materials are not so much altered mineralogically from those found in our meteorite collections because of their small sizes compared with major planets and satellites. The unknown process that produced spectral reddening of lunar soils (PIETERS *et al.*, 1992) would be an extreme case of the alteration due to regolith processes and space weathering.

4. Mineralogy of Y-8451 and Primitive Achondrites and Their Relationship with the S Asteroids

Because Y-8451 is very similar to 113 Amalthea in terms of their reflectance spectra, it will be meaningful to describe some mineralogical characteristics of Y-8451 and its relationship with primitive achondrites used in our stony-iron model for the S asteroids (HIROI and TAKEDA, 1991; HIROI *et al.*, 1992, 1993). 113 Amalthea and 354 Eleonora are usually classified as S asteroids.

Y-8451,61-1 polished thin section we examined, is composed of interconnected rounded crystals of olivine filled with thick bands of metals. The grain boundaries between olivine and metal and between olivine grains in a few cases are filled with thin films of Ni-containing iron hydroxides, and a few boundaries are intruded by thin tongue of metals. Olivine crystals have numerous fractures and are fragmented into small pieces at some olivine-olivine boundaries, and a few metal-olivine boundaries show slight dislocations, which indicates shock deformations. The crystal sizes of olivine are 3 mm or less in diameters, which are smaller than those of common pallasites such as Imilac.

The chemical compositions of pyroxenes in Y-8451 are plotted in Fig. 7 with other primitive achondrites and ureilites. At one corner of an olivine crystal facing to metal, one subrounded orthopyroxene ($Ca_{2.1}Mg_{88.9}Fe_{9.0}$) crystal is present. In another olivine, two joined elongated petal-shaped pyroxenes with very low Ca concentration ($Ca_{0.6}Mg_{90.7}Fe_{8.7}$) are present. The composition is uniform within the grains and distinctly lower in Ca than the orthopyroxene. Their compositional relation (a small difference in Ca contents and higher Fe/Mg ratios) indicates that those pyroxenes with very low Ca may be inverted protoenstatites. The absence of twinning of clinoenstatite common for such pyroxene, suggests that it was mostly inverted to orthopyroxenes. The coexisting inverted protoenstatite and orthopyroxene in meteorites have been found in Steinbach (REID *et al.*, 1974), and this is the second example. By applying temperature-composition (Fe/Fe + Mg ratio) diagram of REID *et al.* (1974) for Steinbach, one can obtain 1135°C as their formation temperature. The presence of protoenstatite suggests that the pressure was not as high as that of a large planetary interior. The diameter of Amalthea estimated by IRAS survey, is about 48 km (TEDESCO, 1989),

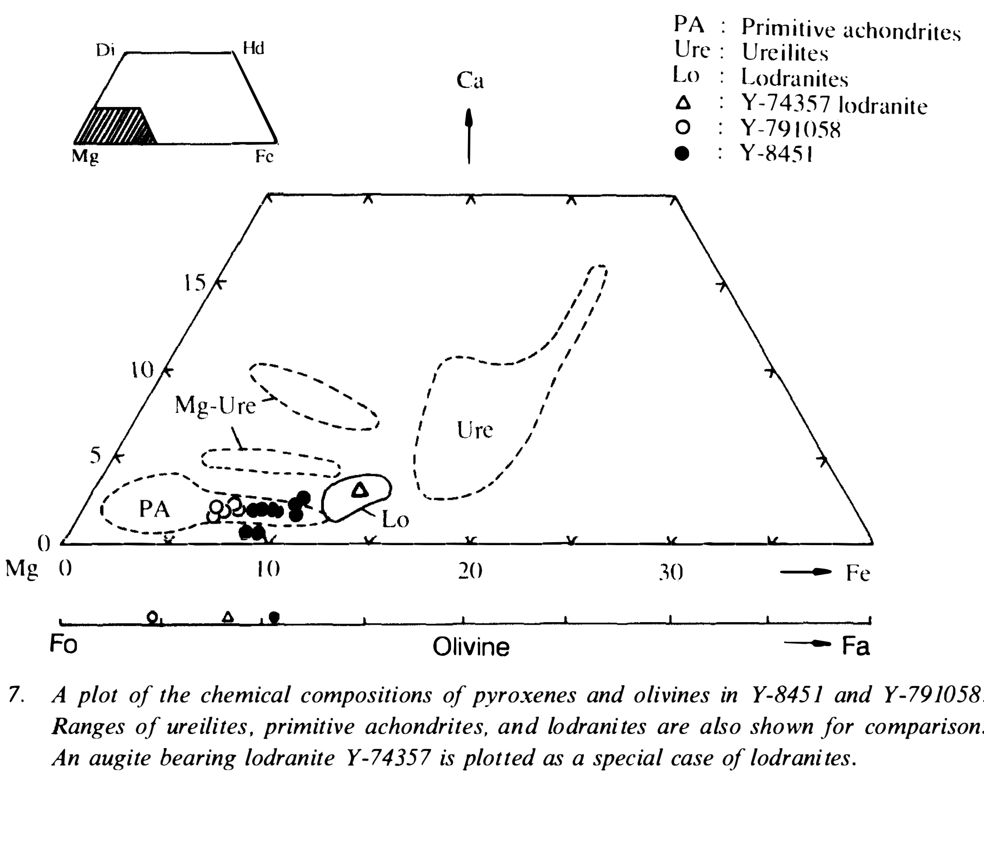

Fig. 7. A plot of the chemical compositions of pyroxenes and olivines in Y-8451 and Y-791058. Ranges of ureilites, primitive achondrites, and lodranites are also shown for comparison. An augite bearing lodranite Y-74357 is plotted as a special case of lodranites.

although this asteroid could have come from the surface portion of a larger body.

The chemical compositions of olivines in Y-8451 (Fa_{10-11}) are more Mg-rich than common pallasites (*e.g.*, Imilac $Fa_{12.5}$) (BUSECK, 1977). The modal abundances of minerals are: olivine 63%, metal-sulfide 30%, orthopyroxene 3%, protopyroxene 0.1%, and oxide vein 4% in volume. The small sizes and Mg-rich compositions of olivine crystals in Y-8451 imply its affinity to primitive achondrites (HIROI and TAKEDA, 1991). Further determination of the oxygen isotopes is required to be sure of its classification as a pallasite.

Because of the affinity of Y-8451 to metal-rich primitive achondrites, Y-791058 was studied for comparison. Y-791058,51-2 polished thin section we examined, contains a large amount of metallic iron (82 vol%) with dispersed subrounded silicate grains up to about 1 mm in diameter. The distribution of silicate grains are not uniform but silicate-rich regions are separated from metal-rich regions. The metal parts are partly converted into iron hydroxides. The modal abundances of minerals are: metal-sulfide-Fe-hydride 82%, olivine 4%, orthopyroxene 8%, plagioclase 6%, and augite 0.1%. The plagioclase is more abundant than other meteorites with this kind of mineral assemblage. Reflectance spectrum of Y-791058 is not given here because of the presence of much rust due to heavy terrestrial weathering of this meteorite.

The chemical compositions of olivine ($Fa_{4.6}$) and pyroxene ($Ca_{1.8}Mg_{91.5}Fe_{6.7}$) of Y-791058 are located at the reduced end of Y-74357, an augite-bearing lodranite (Fig. 7), but are not as reduced as some of primitive achondrites such as Y-8002 and Y-75274. The chemical compositions of plagioclases in Y-791058 are plotted in Fig. 8 with ordinary chondrites (H, L, LL, and Y-74160). The plagioclase compositions range from An_{12} to An_{20} and distribute towards more An-rich side of plagioclases of ordinary chondrites. The plagioclase crystals are zoned within a grain, but their ranges are less than those of an LL7 chondrite (Y-74160). Silicates in Y-791058 is mineralogically similar to primitive achondrites, especially in iron meteorites with silicate inclusions.

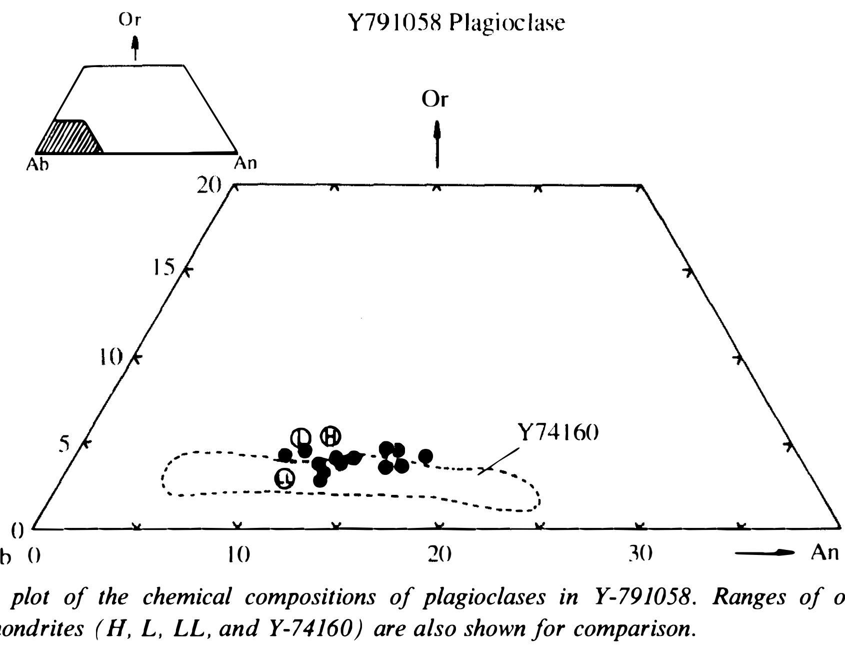

Fig. 8. A plot of the chemical compositions of plagioclases in Y-791058. Ranges of ordinary chondrites (H, L, LL, and Y-74160) are also shown for comparison.

Y-791058 is similar to silicate inclusions in iron meteorites such as San Cristobal (SC), in that the amounts of iron and plagioclase are larger than other primitive achondrites, but SC is also rich in phosphates such as brianite (PRINZ *et al.*, 1983). The occurrence of plagioclase-rich primitive achondrites is very significant with respect to the origin of primitive achondrites and to our model of the S-asteroid surface materials (TAKEDA *et al.*, 1992) as explained below.

Our model of generating lodranite-like mafic-silicate-rich materials from chondrite-like source materials involves partial melting and removal of Ca-Al-rich melt and Fe-Ni-S eutectic melts. It is expected that such materials rich in Ca-Al and Fe-Ni-S will crystallize plagioclase and metal-troilite when they are concentrated elsewhere. If these melts are brought near surface, they will be lost into space by eruption. Patches of silicate-rich portions embedded in metal-rich portion as observed in Y-791058, can be produced if Fe-Ni-S eutectic melt is brought into certain areas through grain boundaries. The pallasite textures will be produced if such metal-rich melt is added to olivine cumulate crystals through grain boundaries. Our model of S-asteroid surfaces also assumes that a few domains of silicate-rich areas are distributed in the matrices of metallic irons. However, oxygen isotopes and trace element abundances must be also measured and taken into account.

5. Conclusions

(1) An olivine-rich asteroid 113 Amalthea is likely to have surface material similar to a unique pallasite Y-8451 as a result of comparison of their reflectance spectra. Amalthea is another example of the S asteroids that can be well approximated with a stony-iron model composed of primitive achondrites and various amounts of metallic-iron.

(2) Mineralogy of Y-8451 suggests that it was formed at a temperature 1135°C and did not experience so high a pressure as in planetary interiors. The formation process of Y-8451 may be similar to that of Y-791058, which is likely to be a common process for primitive achondrites.

(3) Other olivine-rich asteroids are likely to have some kind of regolith composed of pallasite-like materials. More measurements of reflectance spectra of pallasites ground into several sizes of powders, can clarify if there is any real difference between the olivine-rich asteroids and pallasites.

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