REFLECTANCE SPECTROSCOPY OF LUNAR METEORITE YAMATO-791197: RELATION TO REMOTE SENSING DATA BASES OF THE MOON

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Abstract: The major mineralogical components of Yamato-791197 determined from reflectance spectra are calcium-rich clinopyroxene, plagioclase, and $<30\%$ olivine. These results are determined from visual examination of spectra in 1.0-μm region, with continuum removed and using a multiple-order derivative analysis to detect band positions. Geochemical constraints on the provenance of Y-791197 provided by the Apollo orbital X-ray and γ-ray spectrometers indicate that areas with a surface chemistry like that measured in geochemical analysis of Y-791197 are extremely limited on the central nearside. Only 25% of highland craters spectrally measured on the nearside consist of high-calcium pyroxene. Only one crater, Eimmart A, located on the eastern limb close to Mare Crisium, consists of moderately calcium-rich pyroxene, plagioclase and a significant olivine component.

1. Introduction

Yamato-791197 was found on the bare ice fields near the Yamato Mountains, Antarctica during the 20th Japanese Antarctic Research Expedition in 1979 (Yanai and Kojima, 1985). At the time of curation, it was the second known meteorite from the Moon. The first, ALHA81005 was found near the Allan Hills mountains located about 4000 km from the Yamato Mountains. A consortium was organized by the National Institute of Polar Research to study the chemistry, mineralogy, petrography and age of this meteorite. One objective was to determine its relationship to ALHA-81005, that is, whether or not it came from the same fall and/or from the same impact event on the Moon. The consortium is also interested in determining where on the Moon the impact(s) occurred.

Reflectance spectroscopy is currently the major remote sensing technique used to determine the mineralogy of the front side of the moon. By measuring the reflectance

of Y-791197, specific mineral constituents can be identified. This indirectly inferred mineralogy and petrology can thus be related to that of different regions of the front side derived from spectra obtained with ground-based telescopes. The ground-based reflectance data base includes more than 200 areas on the nearside and represents a larger-sampled region than the returned Apollo samples. We present the results of the reflectance measurements for Y-791197 and discuss their implications for determining the relationship to ALHA81005 and the location of the impact event.

2. Experimental Procedures

The spectrum of a 1 cm^2 cut surface slab of Y-791197,72 was measured with the Reflectance Experiment Laboratory (RELAB) at Brown University (PIETERS, 1983a). The surface of the meteorite slab, shown in Fig. 1a, exhibits many medium-sized, light clasts set in a darker matrix. For the spectral measurements the incident light beam was approximately 6 mm in diameter and was positioned to exclude the portion of a fusion crust in the upper right corner of the slab. The entire rear portion of this meteorite slab displays a well-developed fusion crust (Fig. 1b). A spectrum of the fusion crust was measured under the same configuration as the slab surface. The incident beam which has an approximate 2 nm bandpass, was sampled every 10 nm from 0.6 to 2.6 μm for the slab measurements. Three runs of the slab were averaged to measure experimental error. Only one run of the fusion crust was made before the sample was returned.

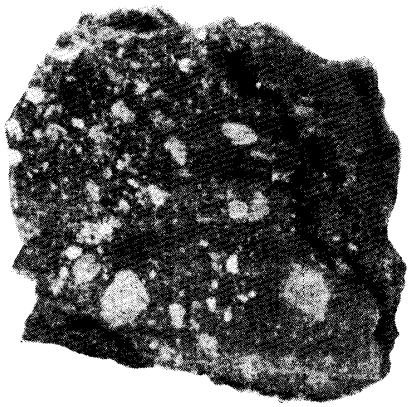

Fig. 1a. Interior surface of Y-791197,72 enlarged 4×.

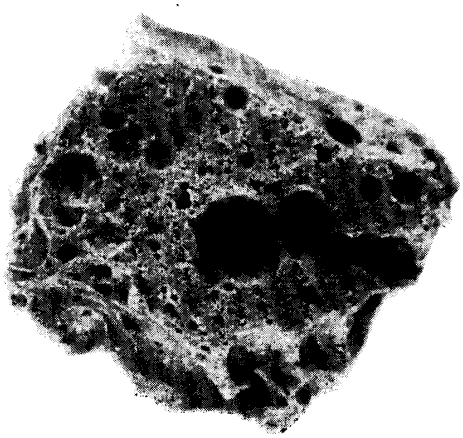

Fig. 1b. Fusion crust on back side of Y-791197,72, enlarged 4×.

A second sample of the meteorite, Y-791197,90 consisting of mm-sized chips was made available for study. These chips, with a total weight of 0.109 g are shown in Fig. 2. After a spectrum of the chips was measured, the sample was crushed to a powder and passed through a 250 μm sieve. A spectrum of the powder was then measured. The spectral range covered for chips and powder was 0.4 to 2.6 μm.

For all measurements, the angle of incidence was $i=30°$ and the angle of emission was $e=0°$. Signal intensity was measured at each wavelength alternately for the sample and a halon standard, and back-ground intensity was subtracted from each. Reflectance was calculated as the ratio of sample to halon, multiplied by the National Bureau

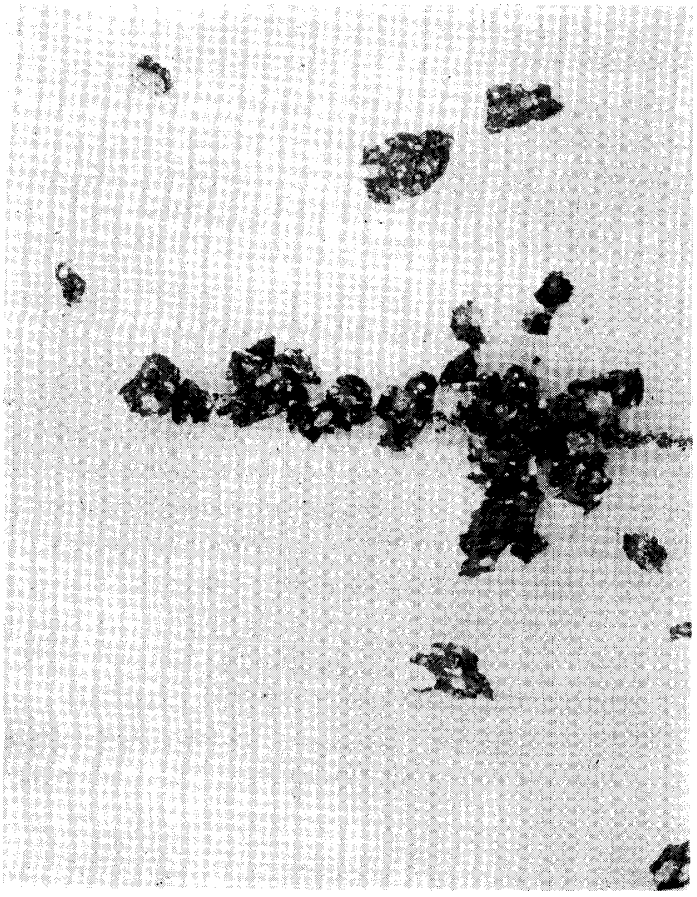

Fig. 2. Chips of Y-791197,90 enlarged 4×.

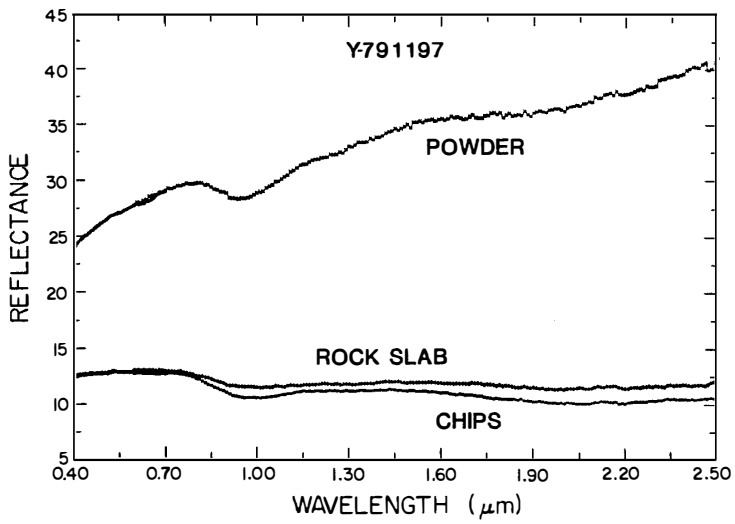

Fig. 3. Reflectance spectra of Y-791197,72 (slab) and Y-791197,90 (chips and powder) from 0.4–2.6 μm. Reflectance is relative to halon in percentage units.

of Standards (NBS) calibration of halon. A more detailed description of the RELAB characteristics is available as a handbook on request.

Reflectance spectra of the Y-791197 rock slab, rock chips, and powder are shown

in Fig. 3. In order to compare the nature of absorption features near 1.0 μm, a straight line was fit to two points of maximum reflectance on either side of the 1-μm band. This line represents the continuum spectrum. The absorption bands are isolated for study by dividing the spectrum by the continuum. Such spectra are shown in Fig. 4 for all Y-791197 spectra as well as for the composite ALHA81005 spectrum (from PIETERS *et al.*, 1983) for comparison. The measurement configuration of the RELAB spectrometer was slightly different for the reflectance measurements of the slab surface of ALHA81005 (PIETERS *et al.*, 1983). The projected beam width used for ALHA81005 was about 2 mm, which allowed small areas of the sample to be measured separately. In order to represent the average spectral properties of the ALHA81005, a single composite spectrum for ALHA81005 was prepared by averaging separate spatial measurements of the slab.

3. Interpretive Approach

Mineralogical information is predominantly contained in the fundamental parameters of absorption bands: their presence, position, width and strength. The presence of specific minerals is inferred from absorptions due to interelectronic transitions of cations in their crystal structure. In spite of the fact that the albedo, continuum and spectral contrast (referring to the strength of the spectral features) of spectra of Y-791197 (Fig. 3) are different when measured in different physical forms (slab, chips, and powder), information about the major mineral components is contained in all three types of spectra. We have used two independent techniques to analyze these spectra. The first consists of visual examination of the spectra to determine the existence and approximate positions of absorption bands. This process also involves calculating a straight line continuum between one or two absorptions, dividing the spectrum by this continuum and examining the residual spectrum for position and strength of the absorption bands. This approach has been used most frequently for interpreting laboratory and telescopic spectra (*e.g.* PIETERS, 1983b, 1985). Continuum removal cannot routinely be applied to the 2-micron region for the remote measurements because a small ($<10\%$) thermal component is often present in lunar reflectance measurements beyond 2 μm. Close examination of the 1.0 μm region with a continuum removed allows the determination of the existence, if any, and approximate position of composite absorption bands.

The widely varying albedo and spectral contrast of the spectra of the slab, chips and powder is controlled by the average particle size and size distribution of each sample. Understanding the nature and differences of photon interactions within the same sample of different physical form is important for the interpretation of reflectance spectra, but is beyond the scope of this study.

The second analysis technique is based on a multiple, high-order derivative algorithm that extracts absorption band positions from reflectance spectra (HUGUENIN and JONES, 1985a). Estimated half-widths of absorption bands control the interval for smoothing the spectrum and fitting it to a polynomial function. Derivatives are calculated from the polynomial approximation of the curve. Bands are positioned at the wavelengths at which all three of the following conditions are met: the fifth deriv-

ative of the spectrum equals zero, the fourth derivative has positive sign, and the second derivative is negative. This analysis was performed on spectra of Y-791197,90 of both chips and powder. Successful application of this algorithm to laboratory and telescope reflectance spectra of moderate resolution and quality is presented in HUGUENIN and JONES (1985a, b).

4. Results

4.1. *Whole rock slab*

The spectrum of the whole rock slab (Fig. 3) has an albedo of 0.125 at 0.60 μm. Weak absorptions at 1.0 and 2.0 μm are observed. The reflectance decreases with wavelength, a characteristic of whole rock spectra (SINGER and BLAKE, 1983) that has not been fully modelled by quantitative theory to date. For slab sample measurements, there is very low spectral contrast and also generally low overall albedo. The presence of a 1.0 and 2.0 μm band is due to spin-allowed crystal field transitions of Fe^{2+} and is diagnostic of the existence of pyroxenes (*e.g.* ADAMS, 1974). The Y-791197 slab spectrum with continuum removed (the second from the top in Fig. 4), exhibits an asymmetry of the 1.0 μm absorption which suggests the presence of additional components. This asymmetry may be attributed to either olivine, plagioclase or both. Subsequent analysis and discussion will address these possibilities.

4.2. *Chips*

The spectrum of mm-sized chips of Y-791197,90 (Figs. 3 and 4) exhibits an albedo of 0.13 at 0.60 μm. Because of the limited sample size for the chips, the reflectance measurement may have included some of the black teflon sample dish (albedo about 3%, spectrally flat). The albedo value measured for the chips is thus a lower limit. The apparent band center is near 0.96 μm implying an average pyroxene composition

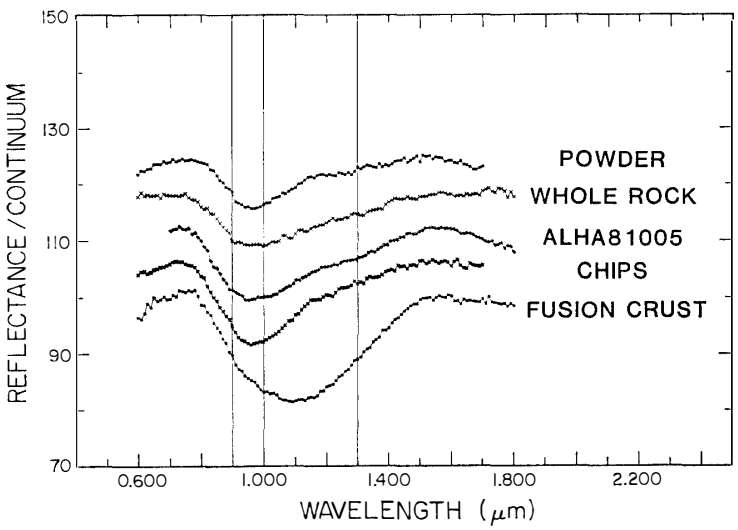

Fig. 4. Spectra of the 1.0 μm region for Y-791197 in four different forms: powder, whole rock, chips and fusion crust. The spectrum labelled ALHA81005 is an average of all measured areas of the whole rock slab, from PIETERS *et al. (1983). Each spectrum is offset 10% from the one below it.*

that is moderately calcium-rich falling in the pigeonite or sub-calcic augite field on the pyroxene quadrilateral. Both the 1.0 and 2.0 μm absorption bands are stronger than the spectrum of the rock slab. This could be due to the presence of a larger surface area of crystalline pyroxene compared to the slab, or the presence of more pyroxene-rich clasts in this sample relative to the slab sample (which came from a different portion of the meteorite). The decreased slope beyond 0.60 μm, toward longer wavelengths is similar to that observed for the rock slab (Fig. 3). This serves as a reminder that the chips are smaller pieces of whole rock. The UV charge-transfer absorptions at wavelengths shortward of 0.60 μm are not as strong in this spectrum as they are in the spectrum of powdered sample (the change in reflectance of the chips between 0.565 and 0.400 μm is $\sim$3%). The presence of an absorption due to Fe^{2+} in plagioclase near 1.3 μm (Fig. 4) is evident from the flattening of the spectrum (CROWN and PIETERS, 1985; KING *et al.*, 1981). Such a prominent feature suggests that plagioclase is a major mineral present in this assemblage, and/or is present as large grains. The strength of the absorption also attests to the ferroan (>0.1% FeO) nature of the plagioclase (ADAMS and GOULLAUD, 1978).

4.3. Powder

The spectrum of the powder prepared from the chips of sample Y-791197,90 is more comparable to most published spectra of lunar samples. At 0.60 μm the albedo of the powder is 0.28, more than twice as bright as the chips and whole rock slab. The 1.0 and 2.0 μm pyroxene bands are prominent, although proportionally weaker than those of the parent chips (see Fig. 4). The slope between 0.565 and 0.400 μm is $\sim$14%. A 1.3 μm plagioclase feature is indicated by two inflection points near 1.17 and 1.52 μm. These absorptions are superimposed on a continuum that increases with increasing wavelength, a characteristic feature of all lunar sample spectra (MCCORD and ADAMS, 1973; ADAMS and GAFFEY, 1976).

4.4. Multiple order derivative analysis

The band positions found by the multiple-order derivative analysis for spectra of the chips and powder are indicated in Figs. 5 and 6 respectively. The spectra are plotted at expanded and unequal scales. The analysis was performed on spectra with and without a continuum removed. The resulting band positions are consistent to within 2%. The differences in band positions found in spectra of powder and chips averages 2.6%. A reasonable accuracy for these band positions is therefore 3%. There are three absorptions at 0.471, 0.846 and 2.439 μm that were detected in the spectrum of the chips but not of the powder. Their absence in the powder spectrum is probably related to scattering effects that are prominent in interactions of photons with powder. The coincidence of band positions with noise features cannot be verified without band width and depth information. Subsequent development of this technique aimed at extracting a measure of the band widths will clearly indicate if noise features are erroneously identified as absorption bands.

The derivative analysis locates two band positions in the 1.0-μm region. The band at approximately 0.94 μm is at only slightly shorter wavelength than the band center located by eye from Fig. 4. This band and the bands located between 2.0 and

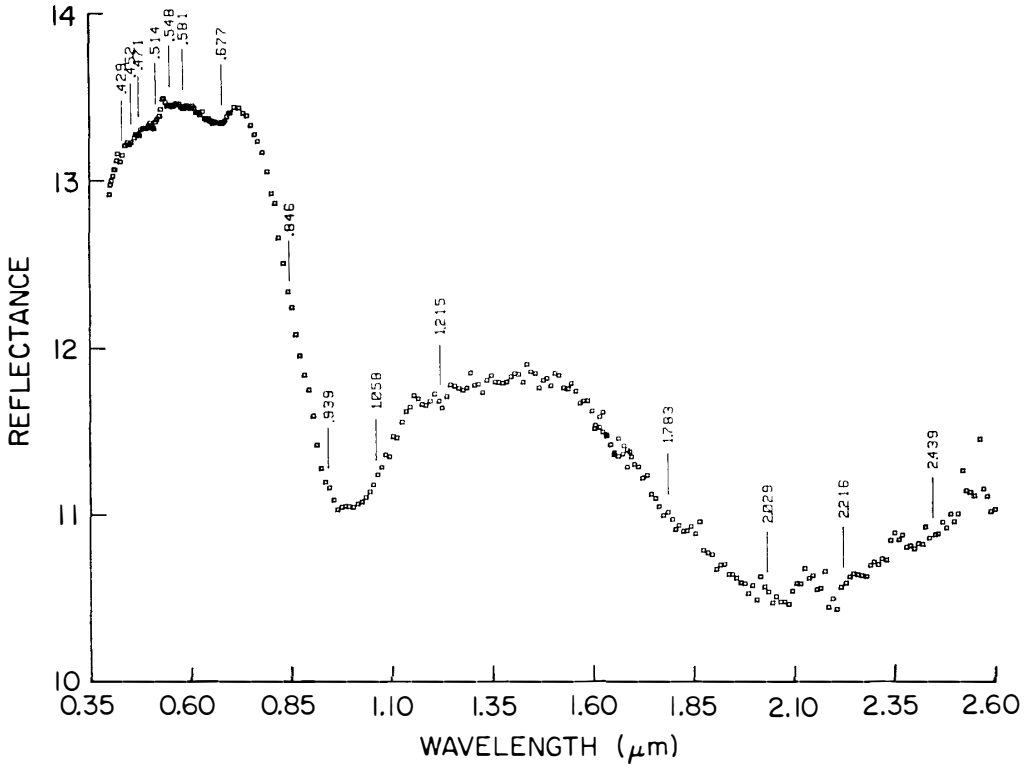

Fig. 5. Expanded-scale spectrum in units of percent of Y-791197,90 chips with positions of absorption bands located by multiple-order derivative analysis indicated.

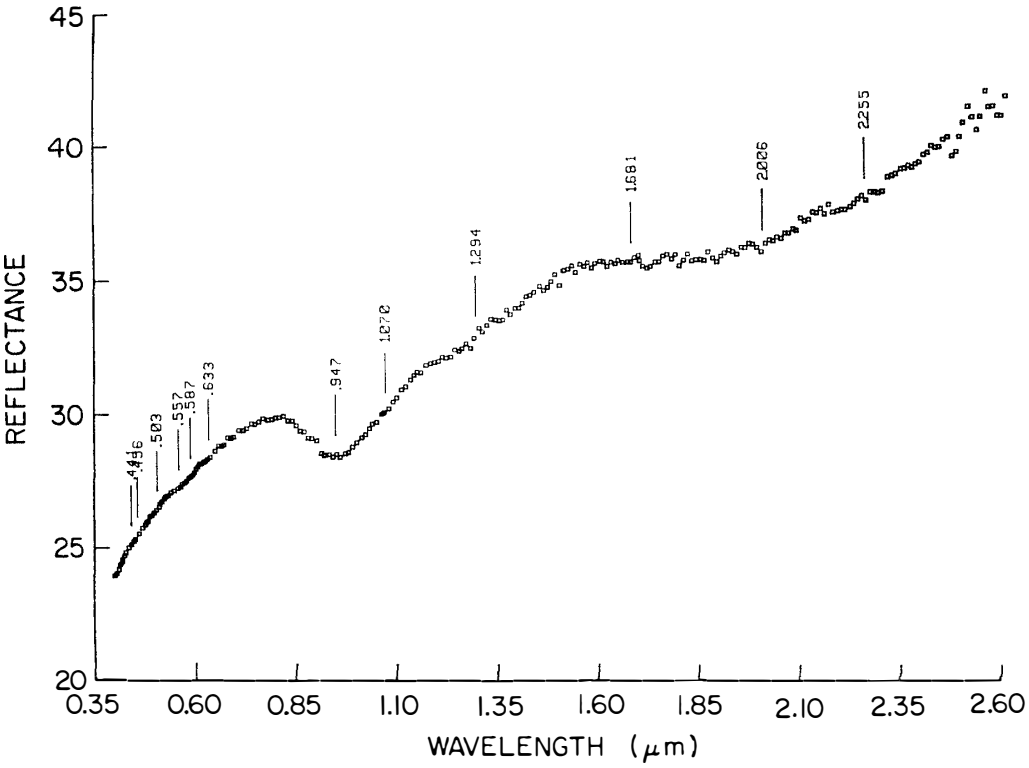

Fig. 6. Same as Fig. 5 but for Y-791197,90 powder. Expanded scale is different.

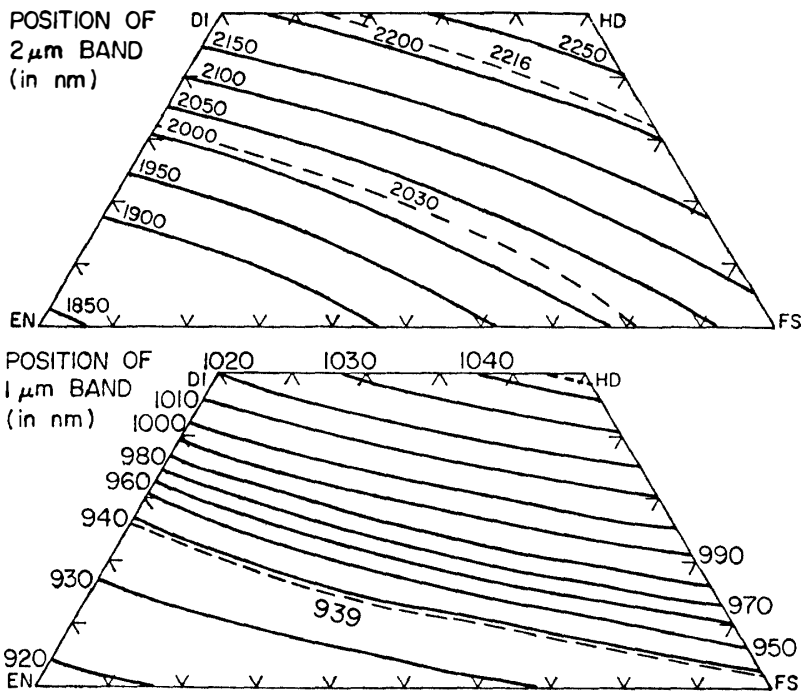

Fig. 7. Projection of 1.0 and 2.0 μm pyroxene bands on the pyroxene quadrilateral. Solid lines are the calibration of HAZEN *et al. (1978). Broken lines are the bands found in this work in the spectrum of Y-791197,90 chips.*

2.2 μm are consistent with the presence of an average pyroxene composition with up to 30% Ca/Ca+Mg+Fe (Fig. 7). The band at 1.05–1.07 may be the strongest of the three overlapping bands attributable to olivine (*e.g.* SINGER, 1981). Because the other two bands associated with olivine are not detected (the band at 0.846 may be one of them), we conclude that there is $\leq$30% modal olivine in our measured sample. Laboratory studies (CLOUTIS *et al.*, 1985; SINGER, 1981) have shown that up to 30% olivine can be present in particulate mixtures with orthopyroxene before the olivine signature is detected. The band at 1.215–1.294 μm is consistent with a plagioclase component (ADAMS and GOULLAND, 1978).

The absorption bands located in the visible region of the spectrum are spin forbidden crystal field bands controlled mostly by Fe^{2+} cations in pyroxene (*e.g.* HAZEN *et al.*, 1978) and possibly olivine (HAZEN *et al.*, 1977). These bands are weak and narrow and their systemmatics have not been worked out. We attempted to identify an olivine signature based on the positions of these absorptions between 0.4 and 0.7 μm, but five of the seven band positions are consistent with absorptions found in spectra of olivines as well as pyroxenes. Similar absorption bands have been located in spectra of diogenite meteorites using gaussian band analysis (MCFADDEN *et al.*, 1982). Even though some of the bands are difficult to discriminate in the spectra by eye, their existence is probably real, since they have been detected in spectra of other material and their positions are consistent with the presence of additional diagnostic absorptions due to pyroxene in the 1- and 2-micron regions. Therefore we cannot uniquely identify olivine from these bands alone.

The multiple-order derivative analysis resolves both a plagioclase and probably

an olivine signature which could not be done by eye. The resultant pyroxene composition is consistent with that determined from inspection of the continuum-removed spectra. With the additional capabilities of extracting band widths and depths, we expect to be able to identify the species responsible for the other absorptions.

5. Discussion

A number of geochemical studies of Y-791197 have provided strong evidence that this meteorite was derived from the surface of the Moon (*e.g.*, LINDSTROM *et al.*, 1985; OSTERTAG *et al.*, 1985; FUKUOKA *et al.*, 1985; WARREN and KALLEMEYN, 1985). We have summarized geochemical data for Y-791197 in Table 1 for comparison with similar data derived from the orbital X-ray and γ-ray spectrometers of Apollo 15 and 16 as well as the composition of ALHA81005. The bulk composition of Y-791197 has slightly more FeO and Al_2O_3 and slightly less MgO than ALHA81005. As noted by

Table 1. Geochemical data for Y-791197, ALHA81005, Apollo 15 and 16.

	ALHA81005 wtd. mean A	Y-791197 wtd. mean	Y-791197 whole-rock	Y-791197 bulk	Y-791197 wtd. av. bulk	High-land wtd. crustal mean B compo-sition	Typical wtd. high-lands mean compo-sition	Average whole-rock near-side high-land	Average farside high-lands
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Al_2O_3	25.1	—	26.8	—	26.8	24.6	—	—	—
MgO	8.8	—	6.5	—	5.4	6.8	5.4	—	—
FeO	5.5	6.1	5.7	6.5	6.8	6.6	6.2	10.0	6.5
TiO_2	0.23	—	0.27	—	0.31	0.56	1.5	2.1	1.5
K_2O	<0.04	0.025	0.028	0.035	0.027	0.075	0.076	—	—
Th	0.20	0.33	0.28	0.45	—	0.9	0.50	1.3	0.54

(1) KOROTEV *et al.* (1983), (2) LINDSTROM *et al.* (1985), (3) WARREN and KALLEMEYN (1985), (4) OSTERTAG *et al.* (1985), (5) FUKUOKA *et al.* (1985), (6)–(9) Same as in the PIETERS *et al.* (1983) GRL paper.

LINDSTROM *et al.* (1985), these compositional differences would be expected based on the differences in clast proportions exhibited by the two lunar meteorites. While Y-791197 is slightly enriched in TiO_2, K_2O and Th relative to ALHA81005, it is more significant that these elemental abundances for both meteorites are markedly lower than either the average or the "typical" highlands values determined by TAYLOR (1982) and KOROTEV *et al.* (1980) (see Table 1). If the compositions of ALHA81005 and Y-791197 are representative of their source regions, then these regions must be depleted in KREEP-rich lithologies (which contain relatively high abundances of K_2O, TiO_2 and Th). A synthesis of the X-ray and γ-ray results suggests that the entire Apollo ground track on the central lunar nearside can be ruled out as a likely source region for either of the meteorites. The Th data alone rule out most regions. The Th distribution map prepared by METZGER and co-workers (Plate 2.2, BASALTIC VOLCANISM STUDY PROJECTS, 1981) shows that nearside Th abundances rarely even approach the low values determined for ALHA81005 and Y-791197. On the other hand, METZGER *et al.* (1977)

determined that the average Th values in the farside highland regions range from 0.24–0.84 ppm and exhibit an average concentration of 0.5 ppm. Low Th regions are also shown to be widespread on the western limb.

The spectrally dominant mafic silicate in our samples of Y-791197 is a clinopyroxene of pigeonite to sub-calcic augite composition. Abundant ferroan plagioclase and up to 30% olivine (which is barely detected in the spectra) are present. These same minerals were spectrally detected in the measured slab of ALHA81005 (PIETERS *et al.*, 1983). There is a greater contribution of olivine in the spectrum of ALHA81005 than in that of Y-791197 (the ratio of ALHA81005 1.0-μm band area to that of Y-791197 is 1.5) implying more olivine in ALHA81005. On this basis, if the two rocks are representative of the region from which they were ejected, they are different. However, because we cannot judge how representative our sample is of the whole meteorite nor of the region from which it originated because of its brecciated nature, we cannot evaluate the significance of this measured difference.

Significantly absent from the spectrum of Y-791197 is a signature of orthopyroxene, the dominant pyroxene of the front-side lunar highlands. In one area of the ALHA81005 slab, an orthopyroxene signature was measured (PIETERS *et al.*, 1983). Orthopyroxene absorptions are located near 0.90 and 1.8 μm. Although moderate-to-high Ca pyroxenes have been measured in highland craters with ground-based reflectance spectroscopy, they are in the minority (25% of the ~70 craters studied PIETERS, 1983b, 1985). Most highland craters consist of low-Ca orthopyroxenes. The average pyroxene composition for both lunar meteorites appears to be higher in calcium

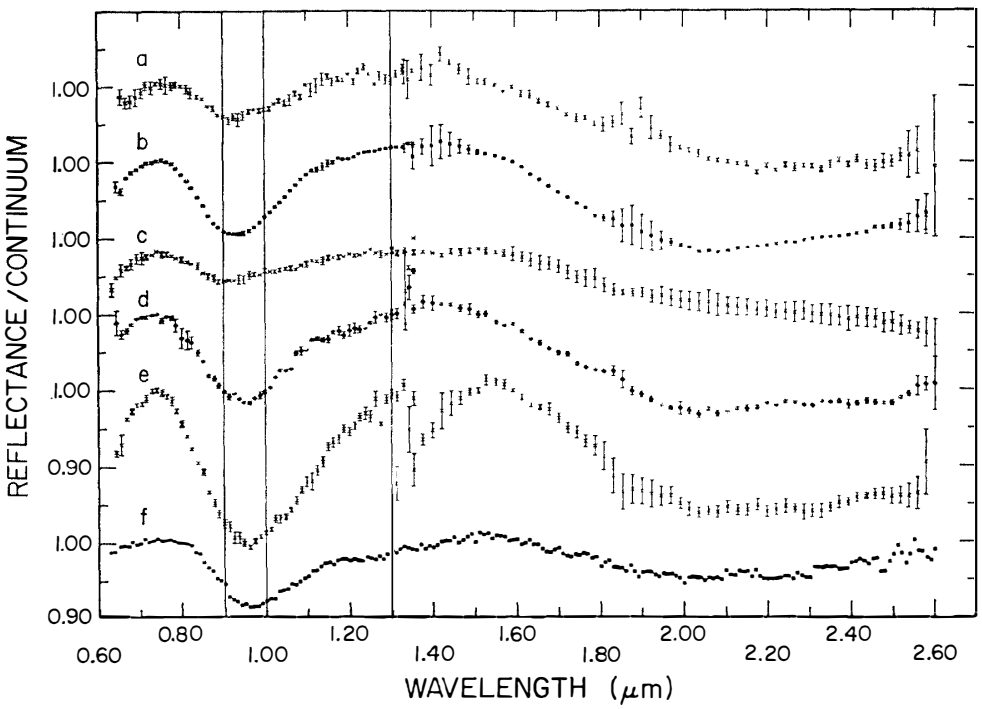

Fig. 8. Spectra of highland craters (a) North Massif, (b) Aratus, (c) Descartes 2, (d) Fra Mauro 6, (e) Eimmart A, (f) Y-791197,90 powder. Continuum is removed from all spectra and each spectrum is offset by 10% from the one below it. Telescopic spectra are discussed in more detail in PIETERS (1985).

than the majority of the highland craters on the nearside measured by reflectance spectroscopy.

The similarity of the feldspar and pyroxene composition for the two meteorites, and the fact that the mineral assemblage is observed infrequently for nearside highland craters (<25%) suggests that the two meteorites *could be* related, and they may not have come from the nearside. Currently, only one crater, Eimmart A, near the eastern limb (Fig. 8) (close to Mare Crisium) exhibits an average, moderately-rich calcium pyroxene and plagioclase assemblage with a significant olivine component (Pieters, 1985).

Acknowledgments

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