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Reflectance spectra of the Yamato 000593 nakhlite: Spectroscopic similarities to other nakhlites

Yuji Ueda[1], Masamichi Miyamoto[1], Takashi Mikouchi[1] and Takahiro Hiroi[2]

[1] *Department of Earth and Planetary Science, University of Tokyo, Hongo 7-chome, Bunkyo-ku, Tokyo 113–0033*
[2] *Department of Geological Sciences, Brown University, Providence, Rhode Island 02912, U.S.A.*

Abstract: Yamato (Y) 000593 is a newly found nakhlite and its component minerals are augite (~80 vol%), olivine (~10 vol%) and mesostasis (~10 vol%). We compare the reflectance spectrum of Y000593 with those of two other nakhlites, Nakhla and Lafayette. The reflectance spectrum of Y000593 is similar to that of Nakhla, and is also similar to Lafayette except for differences in slope from 0.6–0.8 μm in wavelength. Reflectance spectra of all these nakhlites show two strong absorption bands around 1 μm and 2 μm due to augite. Their band minimum wavelengths were calculated using the polynomial fitting and the modified Gaussian model (MGM). Almost all of their band centers and band parameters were similar to one another, which is consistent with the mineralogical and petrological study of nakhlites.

key words: Yamato 000593, nakhlite, reflectance spectrum, modified Gaussian model, deconvolution

1. Introduction

Yamato 000593 (Y000593) was brought back by the 41st Japanese Antarctic Research Expedition, and is the first nakhlite found among the Antarctic meteorite collections (*e.g.,* Kojima and Imae, 2001; Imae *et al.,* 2002a, b). Although only three nakhlites (Nakhla, Lafayette and Governador Valadares) were known until recently, fourth sample Northwest Africa 817 was found in 2001, and Y000593 is the fifth sample of this group. Y000593 is also thought to the paired with Y000794 and Y000802, judging from their petrographical studies and noble gas data (*e.g.,* Okazaki *et al.,* 2002; Imae *et al.,* 2002a, b; Kojima *et al.,* 2002).

Nakhlite belongs to olivine-bearing cumulate clinopyroxenite, and is widely believed to have originated from the planet Mars (*e.g.,* Wood and Ashwal, 1982; Treiman *et al.,* 1993; McSween, 1994). The most abundant mineral in Y000593 is augite (~80 vol%) which has large euhedral to subhedral elongated grains and almost uniform core compositions ($En_{39}Fs_{22}Wo_{39}$). Olivine (~10 vol%) is present as the second major mineral. Mesostasis (~10 vol%) consists of several minerals such as plagioclase, orthopyroxene, and iddingsite (*e.g.,* Mikouchi *et al.,* 2003). It was reported that Y000593 is compositionally similar to nakhlites, especially Nakhla (Imae *et al.,* 2002a, b; Mikouchi *et al.,* 2002).

The reflectance spectra of many SNC meteorites have been obtained and studied in many researchers: Nakhla (Gaffey, 1976; McFadden, 1988; Schade and Wasch, 1999), Shergotty (McFadden, 1988), Zagami (Schade and Wasch, 1999), EETA 77005 (McFadden, 1988), EETA 79001 (Sunshine *et al.,* 1993b), Chassigny (Gaffey, 1976; McFadden, 1988) and ALH 84001 (*e.g.,* Bishop *et al.,* 1994, 1998). Although the reflectance spectrum of Nakhla was measured several times, those of other nakhlites have not been studied as thoroughly. Moreover, analytical comparisons of reflectance spectra among nakhlites have not yet been performed.

Several attempts to find out surface materials on Mars and to link them with SNC meteorites from their reflectance spectra have been performed. Earth based telescopic surveys detected pyroxene and ferric minerals on the surface of Mars (*e.g.,* Adams and McCord, 1969; McCord and Westpal, 1971; McCord *et al.,* 1982). Using Imaging Spectrometer for Mars (ISM) onboard the Phobos-2 spacecraft (Bibring *et al.,* 1989), a high resolution surface mapping of Mars has shown significant fraction of high- and low-Ca pyroxene (*e.g.,* Mustard and Sunshine, 1995; Murchie *et al.,* 2000). Therefore, combining the experimental analyses of SNC meteorites with the remote sensing analyses of Mars may be a key to understanding the surface mineralogy and geology of Mars.

In this study, as a part of the consortium study of the Yamato nakhlites (Kojima *et al.,* 2002), we report a spectroscopic study of Y000593 and compare it with that of Nakhla and Lafayette.

2. Samples and instruments

Y000593 was supplied by National Institute of Polar Research, and Nakhla was by University Museum, University of Tokyo. Both samples were hand-grounded with a corundum mortar and pestle. After grinding, they were sieved to $<100\,\mu$m size particles. The bidirectional reflectance spectra were measured by a UV-Visible-NIR spectrometer equipped at Earth and Planet. Sci., University of Tokyo. Illumination was a deuterium lamp in the spectral range of 0.2–0.3 μm and a tungsten lamp in the range of 0.3–2.5 μm. A photomultiplier was used as a detector in the range of 0.2–0.82 μm and a PbS cell in the range of 0.82–2.5 μm. In our previous report (Ueda *et al.,* 2002b), all spectra were measured at incidence and emergence angles of 30°. In this report, we re-measured all spectra at an incidence angle of 30° and an emergence angle of 0° for an easier comparison with previous researchers' data. Spectra were scanned at a constant rate of 2 nm/s and were obtained at every 5 nm. Halon was used as the reflectance standard. The spectrometer chamber was purged with dry air throughout spectral measurements for preventing atmospheric water being absorbed on samples.

In addition to our measurements, reflectance spectra of two nakhlites, Nakhla (LM-LAM-022) and Lafayette (LM-LAM-023) were taken from RELAB database (Pieters, 1983) and were also analyzed in this report. Both samples were $<100\,\mu$m size particles, and were measured at an incident angle of 30° and an emergence angle of 0°.

3. The modified Gaussian model

To analyze the reflectance spectra of nakhlites, the modified Gaussian model (MGM) (Sunshine *et al.,* 1990; Sunshine and Pieters, 1993a) was used in this study. The MGM is one of the most powerful tools for deconvolving a reflectance spectrum of mixtures of minerals such as pyroxene and olivine. This method has been used for understanding composition of the surface material of Mars (Sunshine *et al.,* 1993b; Mustard and Sunshine, 1995), lunar (Hiroi *et al.,* 2000) and asteroids (*e.g.,* Hiroi *et al.,* 1995; Binzel *et al.,* 2001; Hiroi and Sasaki, 2001; Ueda *et al.,* 2002a). The natural logarithm of a reflectance spectrum is deconvolved into absorption bands and a background continuum, where each absorption band is expressed as a Gaussian in wavelength, and the continuum as a linear function of wavenumber.

The original MGM formula is expressed as:

$$\ln R(\lambda) \cong f(\lambda) = C(\lambda) + \sum_i s_i \cdot \exp\left[-\frac{1}{2} \{(\lambda - \mu_i)/\sigma_i\}^2 \right], \quad (1)$$

where $R(\lambda)$ is the measured reflectance and band parameters s, μ and σ denote the band strength, center and width, respectively. The background continuum component $C(\lambda)$ is expressed as:

$$C(\lambda) = c_0 + c_1/\lambda, \quad (2)$$

where c_0 and c_1 are constants.

The full width at half maximum (FWHM) is calculated by

$$\mathrm{FWHM} = 2\sqrt{2\ln 2} \cdot \sigma \cong 2.35482\sigma, \quad (3)$$

which will be simply called the bandwidth. Each parameters in eq. (1) is optimized to minimize the square deviation ε between the measured and calculated spectra,

$$\varepsilon = \sum_{j=1}^{N} (\ln(R(\lambda_j)) - f(\lambda_j))^2, \quad (4)$$

where λ_j denotes the wavelength of the j-th data point, and N the total number of the data points. The root mean square deviation (RMSD) is described as

$$\mathrm{RMSD} = \sqrt{\varepsilon/N}, \quad (5)$$

in order to evaluate the quality of the deconvolution.

In addition to the MGM analysis, we applied the N-th order polynomial fitting to spectral curves for calculating band minimum wavelengths of pyroxene.

4. Result and discussion

The reflectance spectrum of low-Ca pyroxene has two major absorption bands around 0.9 μm (band I) and 1.9 μm (band II) in visible to NIR wavelengths (*e.g.,* Adams, 1974; Cloutis and Gaffey, 1991). Due to the crystallographic distortion derived from calcium occupying the M2 site, each band of high-Ca pyroxenes shifts to

a longer wavelength than that of low-Ca pyroxenes (Burns, 1993). Band centers of low-Ca pyroxenes also shift to longer wavelengths with increasing the Fe content (*e.g.,* Cloutis and Gaffey, 1991; Burns, 1993). Although the reflectance spectra of high-Ca pyroxenes are much more complicated, the general trend is the same as those of low-Ca pyroxenes. While reflectance spectra of pyroxenes have a characteristic absorption band around 2μm (band II) as mentioned above, olivine does not have any absorption feature there, and has three intricate absorption bands overlapped around 1μm (*e.g.,* Sunshine *et al.,* 1990; Sunshine and Pieters, 1998).

In the previous report (Ueda *et al.,* 2002b), we measured the reflectance spectra of Y000593 and Nakhla at incident and emergence angles of 30° degrees. Shown in Fig. 1 is a comparison of reflectance spectra at these two different phase angles. Reflectance at a specular geometry is usually higher than reflectance at other geometries (Hapke, 1993). Although the reflectance spectra of Nakhla fall in this trend, those of Y000593 show the opposite effect, that is, reflectance spectrum at a specular geometry (dashed line) is slightly lower than at the other geometry (solid line). This is probably because of differences in measurement conditions such as packing density or particle direction.

Reflectance spectra of Y000593 and Nakhla that we measured at an incident angle of 30° degree and an emergence angle of 0° degree and those of Nakhla (LM-LAM-022) and Lafayette (LM-LAM-023) measured at RELAB (Pieters, 1983) are plotted in

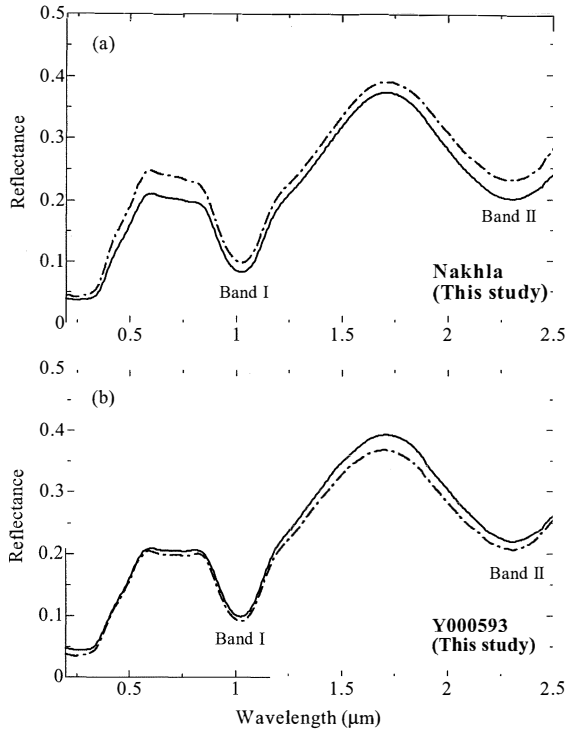

Fig. 1. Reflectance spectra of (a) Nakhla and (b) Y000593 at different emergence angles. Solid line was measured at incident and emergence angles of 30° degrees. Dashed line was measured at an incident angle of 30° degree and an emergence angle of 0° degrre.

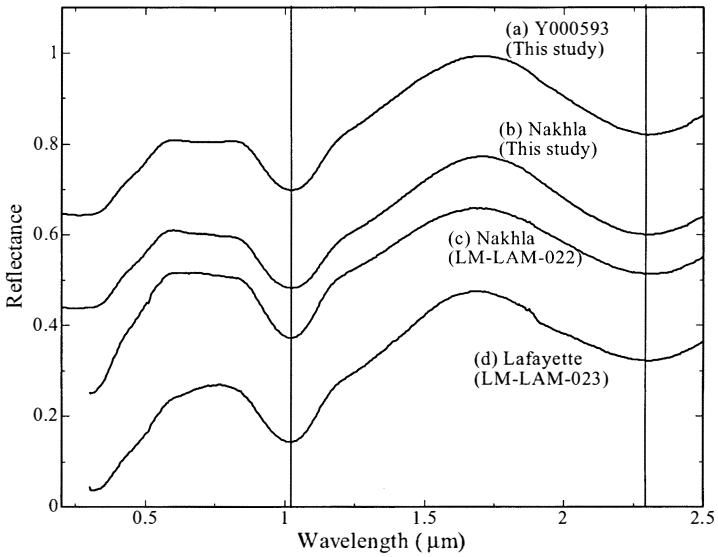

Fig. 2. The reflectance spectra of (a) Y000593 (This study), (b) Nakhla (This study), (c) Nakhla (LM-LAM-022) and (d) Lafayette (LM-LAM-023). All spectra were measured at incident and emergence angles of 30° and 0° degree, respectively. Reflectance spectra of (a) and (b) were measured at Earth and Planet. Sci., University of Tokyo, and those of (c) and (d) are both obtained by L.A. McFadden using RELAB facility at Brown University.

Fig. 2. The major mineral in nakhlite is euhedral to subhedral augite (*e.g.,* McSween, 1994), that shows absorption bands around 1.02 μm (band I) and 2.3 μm (band II). Judging from its slightly broad absorption band around 1.2 μm, absorption bands due to olivine may exist. It is, however, difficult to detect the presence of olivine from Fig. 2. Since the amounts of other minerals such as plagioclase, low-Ca pyroxene and iddingsite in mesostasis are small, their features cannot be found clearly from the reflectance spectra of nakhlites.

All spectra in Fig. 2 have several similarities to one another: absorption band minima around 1 μm and 2.3 μm, a maximum peak around 1.7 μm and almost the same albedo. Although Y000593 and Nakhla have characteristic band slope around 0.6–0.8 μm, Lafayette differs a little from other two spectra. Its spectrum has a slightly clear convex curve around 0.75 μm, which is not similar to the bluish band slopes of Y000593 and Nakhla at these wavelengths. Lafayette is a unique nakhlite, and has a different zoning profile in augite (*e.g.,* Harvey and McSween, 1992). The reflectance difference between Lafayette and other nakhlites is probably considered as due to this compositional difference and/or maybe minor modal variations.

Band center is an essential and important property for remote sensing analysis, because it is related to the species and composition of minerals. Figure 3 shows the band II *vs.* band I center positions of pyroxene (Hazen *et al.,* 1978; Cloutis and Gaffey, 1991, Sunshine *et al.,* 1993b), where a solid line is the first order polynomial fitting of all data points. For comparing with the previous studies, band centers of reflectance spectra of all nakhlites are calculated using 4th to 7th order polynomial fitting to the

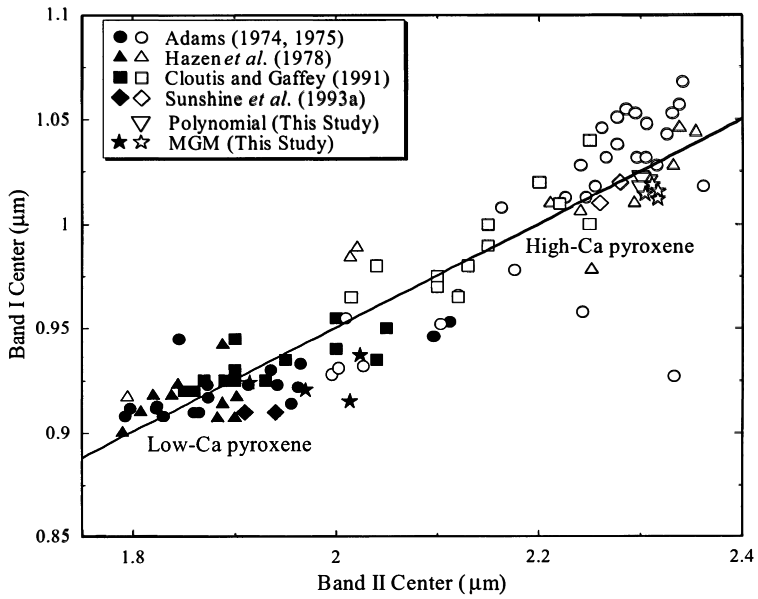

Fig. 3. The band II vs. band I center wavelength plot of pyroxene. Band centers are from Adams (1974, 1975), Hazen et al. (1978), Cloutis and Gaffey (1991) and Sunshine et al. (1993b). All data except for Hazen et al. (1978) were digitalized from the plot of Sunshine et al. (1993b). Solid line is the first order polynomial of least square minimization. Symbols for orthopyroxenes are the closed and those for clinopyroxenes opened marked, same as previous researchers.

Table 1. Minimum wavelengths of the band I and II of pyroxene in nakhlites calculated by 4th to 7th order polynomial fitting to the spectral curve around 1.0 μm and 2.3 μm in wavelength.

	Y0000593	Nakhla	Nakhla*	Lafayette**
Band I (μm)	1.022	1.023	1.021	1.018
Band II (μm)	2.301	2.300	2.308	2.300

(*) LM-LAM-022 and (**) LM-LAM-023 are taken from RELAB database (Pieters, 1983).

spectral curve around 1.0 μm and 2.3 μm in wavelength (Table 1). The band positions of nakhlites we calculated plotted in the high-Ca pyroxene zone, consistent with previous studies.

Mineralogical studies reported that the Fe contents at the rim of augite in Y000593 and Nakhla is similar to each other, but that the Fe content of Lafayette is lower than those of Y000593 and Nakhla (Mikouchi *et al.,* 2002). In general, the more the Fe content is in pyroxene, the longer the band I and band II centers become (*e.g.,* Hazen *et al.,* 1978; Cloutis and Gaffey, 1991; Burns, 1993). As shown in Table 1, the minimum wavelength of band I of Lafayette that was calculated by polynomial fitting is slightly shorter than other ones. However, that of band II of Lafayette does not differ

from those of Y000593 and Nakhla. No significant band parameter change due to the compositional difference among three nakhlites could be seen there.

In order to investigate the mineral assemblage in detail, we analyzed the reflectance spectra of four nakhlite data by using the MGM scheme (Sunshine *et al.,* 1990; Sunshine and Pieters, 1993a). Figure 4 shows the deconvolution of reflectance spectra of nakhlites. The band parameters attributable to augite and low-Ca pyroxene are listed in Table 2. The band I and II parameters of augite in nakhlites are coincident with each other. This result is consistent with mineralogical and compositional similarities of these meteorites (*e.g.,* Treiman *et al.,* 1993; Mikouchi *et al.,* 2002; Treiman and Goodrich, 2002). Absorption bands around 0.8 μm to 1.2 μm may derive from olivine (*e.g.,* Sunshine *et al.,* 1998), although they are small and cannot be distinguished from bands of other minerals.

Small absorption bands around 0.9 μm and 2.0 μm are probably due to low-Ca pyroxene (Table 2), although they are also small and their absorption strength are weak. Schade and Wasch (1999) reported that in their result of the MGM deconvolution for Nakhla, the bandwidths of augite are slightly larger than those of pure augite from Sunshine and Pieters (1993a). They concluded that this is because of the strong zoning in augite, which results in the overlapping of absorption bands and, in consequence, makes the bandwidth larger. In our results (Fig. 5), the band I and band II parameters

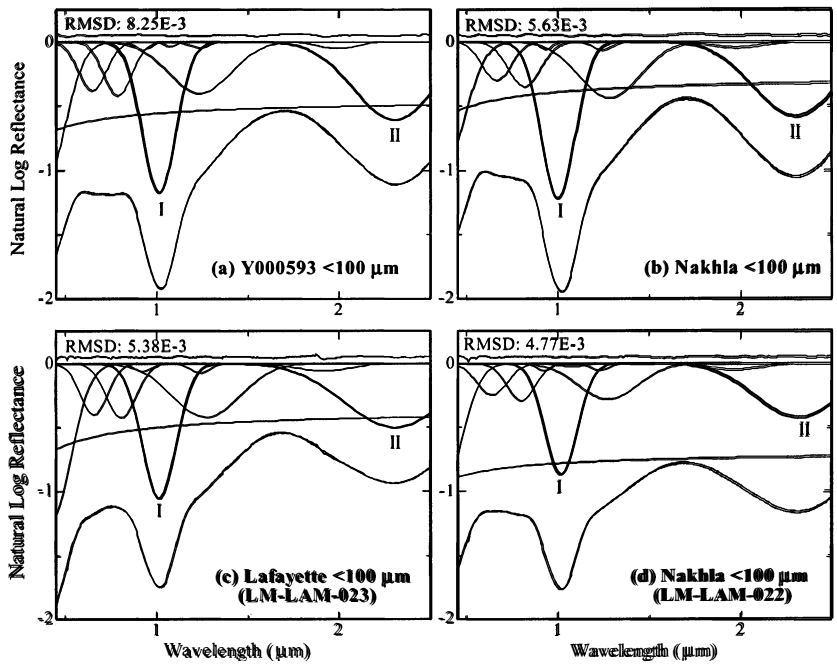

Fig. 4. The MGM results of (a) Y000593, (b) Nakhla, (c) Lafayette (LM-LAM-023) and (d) Nakhla (LM-LAM-022). Background continuum is shown in a solid curve. The root mean square deviation (RMSD) of each fit is (a) 8.25E-3, (b) 5.63E-3, (c) 5.38E-3 and (d) 4.77E-3, respectively. Residual error spectrum is shown at the top, offset by 0.05 for clarity. Numbers below the modified Gaussians indicate the band I and band II of augite.

Table 2. Band parameters attributable to (a) augite and (b) low-Ca pyroxene in nakhlites calculated using the MGM deconvolution.

(a) Augite

	Band I			Band II		
	Center (μm)	FWHM (μm)	Strength	Center (μm)	FWHM (μm)	Strength
Y000593	1.013	0.221	−1.171	2.317	0.538	−0.611
Nakhla	1.019	0.225	−1.302	2.311	0.547	−0.656
Nakhla*	1.016	0.208	−0.869	2.317	0.551	−0.427
Lafayette**	1.015	0.222	−1.058	2.304	0.648	−0.504

(b) Low-Ca pyroxene

	Band I			Band II		
	Center (μm)	FWHM (μm)	Strength	Center (μm)	FWHM (μm)	Strength
Y000593	0.915	0.121	−0.060	2.013	0.271	−0.056
Nakhla	0.937	0.091	−0.075	2.024	0.274	−0.055
Nakhla*	0.921	0.092	−0.062	1.969	0.348	−0.051
Lafayette**	0.924	0.110	−0.064	1.914	0.347	−0.061

(*) LM-LAM-022 and (**) LM-LAM-023 are taken from RELAB database (Pieters, 1983).

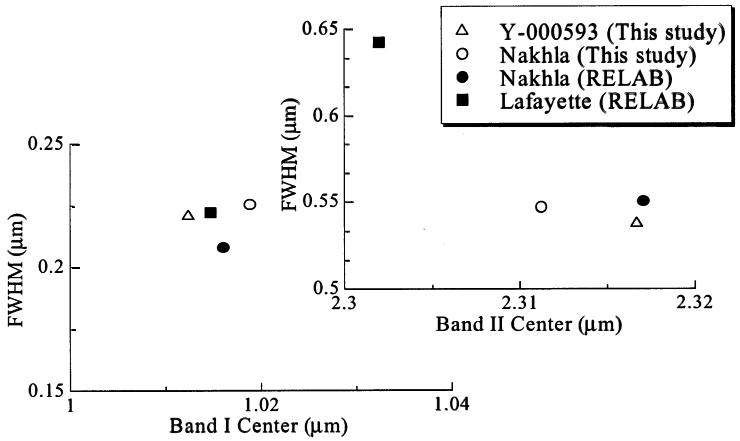

Fig. 5. The band I and band II center vs. FWHM plots of nakhlites calculated by the MGM (See Table 2).

of Y000593 and two Nakhla are similar to each other and also similar to those of clinopyroxenes in Sunshine and Pieters (1993a). The bandwidth of Lafayette is larger and its band center is shorter than those of Y000593 and Nakhla. This is because of the abnormal discontinuity in the spectrum around 1.9 μm. Since we use two absorption bands around 1.9 μm and 2.3 μm that arise separately from augite and low-Ca pyroxene, the band II of augite is well isolate.

Our derived band II center does not match in the quadrilateral diagram both by

Hazen *et al.* (1978) and Cloutis and Gaffey (1991). In the diagram by Cloutis and Gaffey (1991), the band II around 2.3 μm is located near the composition of diopside. This is probably due difference in the amount of minor elements in augite, such as aluminum (Cloutis *et al.,* 1990; Cloutis and Gaffey, 1991; Hayashi *et al.,* 2001). All nakhlites in our study contain 0.4–0.9 wt% of Al_2O_3 (*e.g.,* Harvey and McSween, 1992; Mikouchi *et al.,* 2002) whereas many high-Ca pyroxenes in the previous studies (*e.g.,* Adams, 1974, 1975; Hazen *et al.,* 1978; Cloutis and Gaffey, 1991) contain large amount of Al_2O_3. Sunshine *et al.* (1993b) estimated Ca contents of pyroxene from their band II positions using the data of Cloutis and Gaffey (1991). In their study, high-Ca pyroxenes having the band II centers around 2.3 μm have Ca contents of 33–49 mol%. The wide range of their Ca contents inferred from their band II centers may be due to variation of their Al contents, which apparently cause the band II center shift.

5. Conclusion

(1) The reflectance spectrum of Y000593 is similar to that of Nakhla, and is also similar to that of Lafayette except for the slope from 0.6 μm to 0.8 μm in wavelength. This result is consistent with the mineralogical and petrographical analyses of Y000593 (*e.g.,* Imae *et al.,* 2002a, b; Mikouchi *et al.,* 2002, 2003).

(2) Small absorption bands of low-Ca pyroxene in nakhlites could be roughly deconvolved using the MGM deconvolution.

(3) Our result does not match with the pyroxene quadrilateral diagram (Hazen *et al.,* 1978; Cloutis and Gaffey, 1991). Sunshine *et al.* (1993b) estimated a wide range of absorption band II center of high-Ca pyroxene. This is possibly due to the presence of Al_2O_3 in augite (Cloutis *et al.,* 1990, 1991; Hayashi *et al.,* 2001).

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