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EETA 79001, a shergottite meteorite, includes a pair of nonbrecciated basaltic lithologies joined along a planar igneous contact. These two lithologies, A and B, are examples of the type of basaltic contacts likely to occur on the surfaces of many planetary bodies. As such, EETA 79001 offers a unique opportunity to compare analysis techniques available in situ with those available remotely. For comparison to petrologic and geochemical studies, reflectance spectra of Lithologies A and B are obtained and analyzed with the Modified Gaussian Model (MGM). This modeling leads to the unambiguous identification of two pyroxene phases in each lithology. All spectral features, including an absorption near 1.2 μm, often attributed to plagioclase, are found to be due solely to the presence of two pyroxenes. This ambiguity between pyroxene and plagioclase absorptions suggest that caution be used in interpretation of remote spectra. Results from the MGM analysis of spectra of EETA 79001 are also used to provide estimates on the major element composition of the pyroxene phases in the two lithologies. In addition, based solely on spectral analyses, Lithology B is shown to have 11–17% more high-calcium pyroxene relative to low-calcium pyroxene than Lithology A. Each of the results derived independently with the MGM are shown to compare favorably (within 5–10%) to those obtained from more traditional geochemical and petrographic methods. The compositional inferences that were derived from modeling the spectra of EETA 79001 with the MGM are examples of the type of information available from remotely acquired spectral data. By providing a method for determining changes in relative composition and abundance of pyroxenes in neighboring units, the MGM offers an opportunity to add compositional information to geologic and morphologic data and thus greatly enhance the science return on studies of surfaces throughout the Solar System. © 1993 Academic Press, Inc.

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INTRODUCTION

Since its discovery in an Antarctic glacial moraine in 1979 (Cassidy and Rancitelli 1982) the Elephant Moraine A (EETA) 79001 meteorite has been the focus of much interest for two primary reasons. First, EETA 79001 is a basaltic achondrite which has been classified as a shergottite based on its composition, redox state, radiometric age, and oxygen isotope signature (cf. McSween 1985 and references therein). Not only can studies of EETA 79001 aid in our understanding the SNC (shergottites, nakhlites, and Chassigny) meteorite group as a whole, but they can also expand our knowledge of the SNC parent body. If the current presumption that the SNC meteorites are from Mars is in fact true (see reviews by Wood and Ashwal 1981, McSween 1985), EETA 79001 and the other SNCs are our only samples of Mars and thus serve an important role as ground truth for martian remote sensing studies.

Although EETA 79001 has obvious significance as an SNC meteorite, its second and unique contribution to the meteorite collection is that it is the first known meteorite to consist of two distinct nonbrecciated lithologies (McSween and Jarosewich 1983). The two lithologies in EETA 79001, Lithology A and Lithology B, are joined along a planar igneous contact, which is apparently pri-
In general, reflectance spectra should include combined signatures from each of the major mineral components present. The mineralogy of Lithologies A and B is described in the petrographic studies of the EETA 79001 (Steele and Smith 1982, McSween and Jarosewich 1983). The matrix of Lithology A is a fine-grained groundmass consisting mainly of pigeonite, augite, maskelynite and opaques (chromite, spinel, ilmenite, and pyrrhotite) in general abundances of approximately 77% pyroxene, 20% maskelynite, and 2% opaques. This matrix is similar in composition to Lithology B, but Lithology B is coarser grained and contains more augite, relative to pigeonite, than the A matrix. Lithology A also includes xenolithic megacrysts of olivine and orthopyroxene, which can be up to 5 mm in diameter. These megacrysts generally constitute <15% of Lithology A. However, at these abundances, the orthopyroxene megacrysts are too similar in composition to the pigeonite in the matrix to be resolved by current spectroscopic techniques. Similarly, the olivine megacrysts are at too low an abundance. Therefore, the spectrum of Lithology A should dominantly be a measurement of the mineral components of the matrix of Lithology A.

Based on this description of EETA 79001, the spectra of Lithologies A and B should contain absorption features from two different compositions of pyroxene, plagioclase, and opaques. As can be seen in Fig. 1, the spectra of Lithologies A and B are dominated by strong absorptions in both the 1- and 2-μm regions. This unique combination of absorption features is diagnostic of pyroxenes and is caused by electronic transition absorptions of Fe²⁺ located in asymmetric octahedral sites in the pyroxene structure (e.g., Burns 1970b, Adams 1974, Rossman 1980). In addition to these strong absorption features, the spectra of 79001 also contain broad absorption "shoulders" between 1.1 and 1.5 μm. Such absorption shoulders are often attributed to plagioclase (e.g., McCord et al. 1981). However, there are also pyroxene absorption bands in this region, which are particularly strong in clinopyroxene spectra (Burns 1970b, Rossman 1980, Sunshine and Pieters 1993b), making the interpretation of this absorption feature nonunique. In the case of 79001, petrographic studies show that the plagioclase in both samples has been converted by shock processes into maskelynite (Steele and Smith 1982, McSween and Jarosewich 1983). The shock destroys the crystal structure of the plagioclase, and without a well-developed crystal structure plagioclase cannot give rise to any absorption bands (Adams et al. 1979, King 1986). The absorption shoulders in the spectra of 79001 are therefore not attributable to plagioclase and are thought to be due to the presence of pyroxene. This conclusion is consistent with previously studied spectra of pyroxene mixtures which include similar absorption shoulders, yet are known to be free of plagioclase.
SPECTRA OF 79001: IMPLICATIONS FOR REMOTE SENSING

FIG. 2. Wavelength position of 1 μm vs. 2 μm absorptions in pyroxene spectra. After Cloutis and Gaffey (1991) and Adams (1974), using data provided by E. Cloutis (personal communication, Adams 1968, Adams 1974, 1975, Nash and Connell 1974, Gaffey 1976, Hazen et al. 1978, Feierberg et al. 1980, Miyamoto et al. 1983). The trend from low-calcium pyroxenes (<11% Wo, solid symbols) to high-calcium pyroxenes (>11% Wo, open symbols) reflects the general increase in calcium content across the orthopyroxene–clinopyroxene solid solution series (see Fig. 3). Derived band centers from MGM modeling of spectra of Lithologies A and B are denoted by “A” and “B” for results from modeling with single absorption bands (Fig. 8) and “a” and “b” from modeling with two absorption bands (Fig. 9).

(Sunshine et al. 1990, Sunshine and Pieters 1993b). Although the plagioclase, in the form of maskelynite, does not add any absorption bands to the spectra of EETA 79001, it does nonetheless contribute to the overall albedo. Similarly, the opaques in these lithologies reduce the overall albedo, but do not add any major absorption bands to the spectra. Thus, the principal absorption features in the spectra of Lithologies A and B should be attributable to pyroxenes. This assumption will be substantiated in subsequent analyses of the EETA 79001 spectra.

The principal absorption features in the spectra of EETA 79001 are not merely diagnostic of the presence of pyroxene, but are also indicative of the composition of the pyroxenes. The wavelength positions of pyroxene absorptions are known to vary as a function of major element composition (e.g., Burns 1970b, Bell and Mao 1972, Adams 1974, Adams 1975, Hazen et al. 1978, Rossman 1980, Cloutis and Gaffey 1991). Pyroxene absorption features in both the 1- and 2-μm regions are correlated and follow a unique and well known compositional trend from orthopyroxene to clinopyroxene when the positions of 1-μm absorptions are plotted against those in the 2-μm region, as shown in Fig. 2 (Adams 1974). This increase in wavelength position reflects the general increase in calcium content across the orthopyroxene–clinopyroxene solid solution, as illustrated in Fig. 3 (derived from Cloutis and Gaffey 1991). These changes in the position of pyroxene absorptions are directly related to the size of the absorption sites which vary as different size ions substitute in the solid solution series. Coulombic potential energies (i.e., energy ~1/radius) dictate that larger ions, which result in larger absorption sites, will produce absorptions at lower energies and thus longer wavelengths (energy ~1/wavelength). Therefore, increasing the proportions of relatively large calcium ions will increase the size of the absorption sites and result in absorptions at longer wavelengths. A similar, but more complex, relationship exists between the position of pyroxene absorption bands and their iron content as shown in Fig. 4 (derived from Cloutis and Gaffey 1991). The correlation between band position and proportion of calcium and iron provide a means of estimating the composition of pyroxenes from their reflectance spectra.

However, it should be noted that these trends in pyroxene absorptions as a function of composition were derived from individual pyroxene samples and that in natural settings, as in EETA 79001, multiple pyroxene compositions often coexist as either well exsolved or compositionally zoned phases. In spectra, absorptions from multiple pyroxene components, whether exsolved or zoned, overlap and often manifest as single absorption features in both the 1- and 2-μm regions. Composite absorption features from multiple pyroxenes are broader than absorption bands from a single pyroxene and are located at wavelengths intermediate to those of the actual endmember pyroxene components (e.g., Adams 1974, Singer 1981, Cloutis and Gaffey 1991). As such, composite absorption features from multiple pyroxenes will plot in the middle of compositional trends such as Figs. 2, 3, and 4. In many circumstances, as the case with Lithologies A and B (see Fig. 1), it is difficult to visually detect the presence of multiple pyroxenes from their reflectance spectra. However, as summarized below, more quantitative analysis techniques can be used to resolve the signatures of multiple pyroxenes in spectra such as EETA 79001.

ANALYSES OF PYROXENE MIXTURES USING THE MODIFIED GAUSSIAN MODEL

Natural lithologies, including EETA 79001, usually include multiple mineralogic phases. Therefore, their spectra frequently contain complex absorption features that are composed of overlapping absorption bands from each of the various minerals in the sample. Often the presence of multiple minerals can be qualitatively inferred from subtle changes in the shape and position of absorption features. However, more sophisticated analysis approaches are required in order to unambiguously identify each mineral and determine its composition.
FIG. 3. Wavelength positions of pyroxene absorptions as a function of calcium content: (a) absorptions in the 1-\(\mu\)m region, (b) absorptions in the 2-\(\mu\)m region. Derived from Cloutis and Gaffey (1991), data as in Fig. 2. The range of values determined from MGM fits to the spectra of Lithologies A and B are denoted by "A" and "B" for models with single absorption bands (Fig. 8) and "a" and "b" for models with two absorption bands (Fig. 9).

One such method, the Modified Gaussian Model (MGM), was developed by Sunshine et al. (1990) to deconvolve spectra which include overlapping absorptions into their constituent absorption bands. The MGM is built around an accurate mathematical description of the shape of isolated absorption bands. These modified Gaussian distributions resulted from a refinement of the Gaussian approach used previously by many authors (Burns 1970a, Smith and Strens 1976, Farr et al. 1980, Clark 1981, McCord et al. 1981, Singer 1981, Clark and Roush 1984, Gaffey 1986, Huguenin and Jones 1986, Roush and Singer 1986) and were derived, as discussed in previous work (Sunshine et al. 1990, Sunshine and Pieters 1993b), by more closely adhering to the physical processes that give rise to electronic transition absorptions.

Under the MGM, a spectrum is modeled as a sum of absorption bands, each represented by a modified Gaussian distribution, superimposed onto a baseline, or continuum. Each absorption is described by three model parameters: a band center, a band width, and a band strength. Until the physical causes of continua are better understood, for simplicity and consistency they are mod-

FIG. 4. Wavelength positions of pyroxene absorptions as a function of iron content: (a) absorptions in the 1-\(\mu\)m region, (b) absorptions in the 2-\(\mu\)m region. Derived from Cloutis and Gaffey (1991), data as in Fig. 2. The range of values determined from MGM fits to the spectra of Lithologies A and B are denoted by "A" and "B" for models with single absorption bands (Fig. 8) and "a" and "b" for models with two absorption bands (Fig. 9).
eled as a straight lines in energy and characterized by two additional model parameters, a slope and an offset. However, it should be noted that unlike other approaches (e.g., Clark and Roush 1984, Cloutis and Gaffey 1991), under the MGM continua are neither predetermined nor constrained to be tangent to spectra. Thus, like the absorption bands, the parameters that describe the continua are free to move based on the data until the residual errors are minimized. Because modeling is carried out in natural log reflectance and energy, these residual errors are measured as the difference between the log of the actual spectrum and the log of the modeled spectrum. The errors resulting from MGM analyses are therefore much larger then they would be if the difference between the spectra were measured in reflectance. In order to maintain maximum clarity, all figures are displayed in log reflectance and, for convenience, as a function of wavelength. Further details of the mathematics of the MGM are described by Sunshine et al. (1990, Appendix) and Sunshine and Pieters (1993b).

The MGM has been shown to accurately resolve individual absorption bands in laboratory spectra. To date, the MGM has been used to quantify variations in absorption bands as a function of composition in the spectra of olivines (Sunshine and Pieters 1990, 1993a), actinolites (Mustard 1992), and pyroxene mixtures (Sunshine and Pieters 1993b). The results from the MGM analysis of pyroxene mixture spectra are of obvious significance to the study of spectra from EETA 79001, and are therefore summarized here.

Sunshine and Pieters (1993b) analyzed a series of spectra collected from mass fraction mixtures created using different proportions of two pyroxenes samples, a calcium-poor (orthopyroxene) and a calcium-rich (clinopyroxene) phase. All spectra contain relatively broad composite absorption features in both the 1- and 2-μm regions, like those in the spectra from EETA 79001. Using the MGM, it was possible to demonstrate that each of the composite absorption features is actually composed of absorption bands from the two endmember pyroxene components. MGM model fits to spectra of two different proportions of pyroxene endmembers are shown, as examples, in Fig. 5. Although the composite absorption features appear to shift toward longer wavelengths with increasing proportion of the calcium-rich phase, the position of the endmember absorption bands that makeup these absorption features were shown to be invariant (e.g., compare absorptions denoted with arrows in Figs. 5a and 5b).

While band centers remain fixed, the relative strength of the pyroxene absorptions were shown to change systematically in proportion to the amount of the different endmembers. As the relative strength of the absorption bands fluctuate, they convolve in such a way that the composite absorption features appear to shift. Additional results from MGM modeling of spectra of a variety of different particle sizes (<45, 45–75, 75–125, and 125–250 μm) showed that the center, width, and relative strength of the absorptions are all largely independent of particle size. Analyses as a function of modal abundance and particle size were combined to yield particle-size-independent relationships between modal abundance and relative band strengths for both the 1- and the 2-μm regions. These correlations, shown in Fig. 6, provide a method for estimating modal abundances from spectra using the band strengths derived with the MGM.

The analyses of spectra of laboratory mass fraction mixtures were also applied to spectra of natural pyroxene samples exhibiting exsolved and zoned characteristics. Using the MGM, the spectral signatures from both pyroxene components in the spectra of exsolved pyroxenes were successfully resolved. The relative band strengths of absorption from each of the two pyroxene components derived with the MGM were used, in conjunction with the relationship shown in Fig. 6, to accurately estimate the modal abundance of the two pyroxene phases to within 5–10%.

In contrast to the two discrete pyroxene components detected in the spectra of exsolved samples, the spectra of highly lunar zoned pyroxenes were shown to include only single components. The spectral signatures of highly zoned samples apparently represent average pyroxene compositions. This inference was confirmed by examining the widths of the derived absorption bands. As shown in Fig. 7, the absorptions in zoned pyroxenes (indicated with diamonds) are wider than those of typical pyroxenes including those derived for the mass fraction mixtures (boxes) and exsolved samples (pluses).

These MGM analyses of pyroxene mixtures, combined with the results of studies of pyroxene spectra as a function of major element chemistry (e.g., Adams 1974, Cloutis and Gaffey 1991), provide the background necessary to examine the spectra from EETA 79001 in more detail. The MGM provides a method for quantifying the exact shape, strength, and position of the absorption features in the spectra from EETA 79001. The results from the MGM can then be used to infer the major element chemistry and relative abundance of the pyroxenes in Lithologies A and B directly from their spectra.

MGM ANALYSES OF LITHOLOGIES A AND B

It is known from the petrographic studies of EETA 79001 (Steele and Smith 1982, McSween and Jarosewich 1983) that the matrix of Lithologies A and B each contain two different pyroxene phases. However, to begin the MGM analysis of their spectra, the primary absorption features, near 1 and 2 μm, are each initially modeled with a single major absorption band. This approach, to start
FIG. 5. Representative MGM deconvolutions of spectra from the suite pyroxene mass fraction mixtures: (a) 45- to 75-μm particles of 75% clinopyroxene and 25% orthopyroxene, (b) 45- to 75-μm particles of 25% clinopyroxene and 75% orthopyroxene. From top to bottom in each figure: The residual error between the log of the modeled spectrum and the log of the actual spectrum (offset 10% for clarity), the individual modified Gaussian distributions representing absorption bands, the continuum or baseline onto which these distributions are added (dashed line), and the modeled spectrum superimposed onto the actual spectrum. Large arrows indicate absorption bands from the orthopyroxene (low-calcium) component and small arrows indicate absorption bands from the clinopyroxene (high-calcium) component. The RMS residual errors in the models are 0.77 and 0.57% for Figs. 5a and 5b, respectively. Comparisons of Figs. 5a and 5b reveal that while the overall absorptions features appear to shift, the constituent absorption bands (denoted by the arrows) remain fixed. It is only the relative strengths that vary with proportion of the different endmembers. From Sunshine and Pieters (1993b).

with the minimum number of absorptions, is chosen to determine if it is possible to detect two distinct pyroxene phases and to more accurately mimic analyses of remotely acquired spectra for which information from in situ studies would be unavailable.

Preliminary results from modeling the spectra from EETA 79001 using single absorption bands in both the 1- and 2-μm regions were presented by McFadden and Pratt (1989). These models are shown in Fig. 8 and the parameters that describe these fits are listed in Table I. In addition

FIG. 6. Relative band strengths of primary orthopyroxene (low-calcium) to clinopyroxene (high-calcium) absorptions as a function modal abundance from the suite of mass fraction mixture spectra: (a) absorption in the 1-μm region, (b) absorptions in the 2-μm region. The curves are best fits to the data from all particle sizes. From Sunshine and Pieters (1993b). The values derived from modeling spectra of Lithologies A and B are as indicated. As discussed in the text, although not valid for determining absolute modal abundances, these data suggest an increase in the relative proportion of high-calcium pyroxene of 11–17% between Lithologies B and A.
FIG. 7. Band widths of primary pyroxene absorptions including the range of values derived for the <45-μm size mass fraction suite (indicated by boxes), the exsolved mantle sample (pluses), and the zoned lunar pyroxene (diamonds). From Sunshine and Pieters (1993b). The results from modeling the spectra of Lithologies A and B are denoted by "A" and "B" for models with single absorption bands (Fig. 8) and "a" and "b" for models with two absorption bands (Fig. 9). Note that the results from modeling with two absorption bands are similar to those obtained for the mass fraction suite and the exsolved sample, while the results using single absorptions are anomalous and more similar to those obtained for zoned lunar pyroxenes.

to the two principal pyroxene absorptions (Bands IV and VI), there are several weaker absorptions (Bands I–III, V) which have been attributed to a variety of processes, including electronic transitions of Fe$^{+2}$ in the M1 site (Band V), electronic transitions of other elements, spin-forbidden absorptions, and/or charge transfer absorptions (Burns 1970b, Adams 1974, 1975, Marfunin 1979, Rossman 1980, Straub et al. 1991). In general, these models appear to reasonably fit the spectra of Lithologies A and B, suggesting that each lithology may be composed of a single pyroxene component. The derived band centers of the primary absorptions from this modeling are presented in relation to other pyroxenes on Figs. 2, 3, and 4, as indicated by "A" and "B" for Lithologies A and B, respectively. Under this model, the major absorptions in Lithology B are at longer wavelengths (0.96 and 2.13 μm) than those in Lithology A (0.94 and 2.04 μm). Based on the relative position of these absorptions and the general increase in wavelength of absorptions in calcium-poor (orthopyroxene) samples compared to those in calcium-rich (clinopyroxene) samples (see Figs. 2 and 3), one could argue that Lithology B is more enriched in high-calcium pyroxene than Lithology A.

Yet, as shown on Figs. 2, 3, and 4, the positions of the absorption bands derived from modeling the EETA 79001 spectra with single absorptions in the 1- and 2-μm regions plot in the middle of the population of pyroxenes for both Lithology A and Lithology B. Furthermore, as can be seen in Fig. 7, these absorptions, denoted with "A" and "B," are wider than those of typical pyroxenes and are of similar width to those obtained by Sunshine and Pieters (1993b) for the spectra of highly zoned lunar pyroxenes. Recall that in the case of these zoned lunar pyroxenes, single pyroxene components with anomalously wide absorptions were interpreted as representations of the average pyroxene compositions. Therefore, while one can model both of the spectra from EETA 79001 with single absorption bands in both the 1- and 2-μm region, one would infer, based on the widths of the derived absorption bands and their intermediate compositions, that these absorption bands represent an average of the pyroxene phases in Lithologies A and B.

Upon closer examination of residual error between these modeled spectra and the actual spectra (Fig. 8), it

FIG. 8. MGM fits to Lithologies A and B using single absorption bands in the 1- and 2-μm regions. The rms error of these models are 1.09 and 0.66% for Lithologies A and B, respectively. Curves are as in Fig. 5. Note the systematic pattern of the residual errors and, as discussed in the text, that the peaks of the residual errors are offset from the derived absorption bands. Model parameters for these fits are given in Table I.
### TABLE I
Derived Model Parameters from MGM Fits to Lithologies A and B Using Single Absorption Bands for Both the 1-µm and 2-µm Regions

<table>
<thead>
<tr>
<th>Lithology A</th>
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<th>Lithology B</th>
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<th></th>
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<tr>
<td></td>
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<tr>
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<tr>
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<td>0.16</td>
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<tr>
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<td></td>
<td>0.96</td>
<td>0.26</td>
<td>-1.01</td>
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<tr>
<td>Band V</td>
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<td>Continuum</td>
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<td></td>
<td>RMS Error</td>
<td>0.66%</td>
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*Note.* The values for the continua are the offset and slope of a straight line in energy and natural log reflectance. Each absorption band is described by a center (µm), a full width at half maximum (µm), and a strength (natural log reflectance). The RMS error between the log of the modeled spectrum and the log of the actual spectrum provides a measure of the quality of the fit.

It is apparent that there are systematic errors in the fits to both spectra in the 1- and 2-µm regions. The maximum errors in these models occur at 0.97 and 2.14 µm and at 0.98 and 2.15 µm in the spectrum of Lithologies A and B, respectively. In each case, these maxima are offset from the center of the modeled absorption bands (at 0.94 and 2.04 µm and at 0.96 and 2.13 µm for Lithologies A and B, respectively). Although the magnitudes of these residual errors are not exceptionally large, as discussed by Sunshine and Pieters (1993b) the systematic pattern of offsets between the residual errors and the modeled band centers is diagnostic of presence of additional absorption bands.

This analysis of the residual errors suggests that the addition of two more absorption bands to the MGM models of both spectra, one in the 1-µm region and one in the 2-µm region, is warranted (i.e., at 1.0 ± 0.5 µm and at 2.0 ± 0.5 µm, see Sunshine and Pieters 1993b for discussion of constraints on values of model parameters). The model fits resulting from using two absorptions in both the 1- and 2-µm regions are shown in Fig. 9 and the model parameters that describe these fits are given in Table II. The derived band centers from this modeling are also presented on Figs. 2, 3, and 4, as indicated by "a" and "b" for Lithologies A and B, respectively. In contrast to the models with single absorption bands (Fig. 8 and Table A).

**FIG. 9.** MGM fits to Lithologies A and B using two absorption bands in the 1- and 2-µm regions. The rms error of these models are 0.53 and 0.51% for Lithologies A and B, respectively. Curves are as in Fig. 5. Large arrows indicate absorptions from a low-calcium component. Small arrows indicate absorptions from a high-calcium phase. Model parameters for these fits are given in Table II.
### TABLE II
Derived Model Parameters from MGM Fits to Lithologies A and B Using Two Absorption Bands for Both the 1-μm and 2-μm Regions

<table>
<thead>
<tr>
<th></th>
<th>Lithology A</th>
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<th>Lithology B</th>
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<tr>
<td></td>
<td>Center</td>
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<tr>
<td>Band A</td>
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<td>Band G</td>
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</tr>
<tr>
<td>Band H</td>
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<td>RMS Error</td>
<td></td>
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**Note.** Parameters are as in Table 1.

...I), the use of two sets of absorption bands in the 1- and 2-μm regions results in very small residual errors which are free of any systematic misfits. Thus, arguing solely on the quality of the fits, in terms of both the magnitude and the uniformity of the errors, one can conclude that the two major absorption features near 1 and 2 μm in the spectra of Lithologies A and B are each composed of two pyroxene absorption bands.

Having successfully modeled the spectra of 79001, it is now possible to evaluate whether or not the assumption made at the onset of this study, that the absorption features in the spectra of Lithologies A and B result solely from the presence of pyroxenes, is valid. The results derived from modeling the spectra of EETA 79001 with the MGM are in full agreement with previous results of modeling spectra which are known to be mixtures of only pyroxenes (Sunshine and Pieters 1993b). In addition, the presence of absorptions from other phases should drive the band centers of the coupled pyroxene absorptions off their unique 1-to-2-μm trend (Fig. 2) (Adams 1975). In particular, absorptions from megacrysts of olivine and/or maskelynite (if it has glass bands), would result in band centers that lie above the pyroxene trend. Examination of Fig. 2 reveals that this is not the case. The absorption features in the spectra of 79001 can therefore confidently be attributed to pyroxenes and, as discussed below, the positions, relative strengths, and widths of these absorptions can be used to make several inferences about the composition of the pyroxene phases in Lithologies A and B.

### COMPARISON OF SPECTRAL ANALYSES TO MINERALOGY

The major absorption bands derived with the MGM in the spectra of Lithologies A and B can be attributed to two distinct pyroxene phases. As can be seen in Fig. 9 and Table II, the 1- and 2-μm regions in each spectrum consist of two sets of absorption bands, one located at shorter wavelengths (denoted with large arrows; Bands D and G), and a second set of absorption bands at longer wavelengths (denoted with small arrows; Bands E and H). Based on the relative position of these absorption bands and the general increase in wavelength of absorptions in calcium-rich (clinopyroxene) relative to calcium-poor (orthopyroxene) spectra (Figs. 2 and 3), the short-wavelength absorptions (Bands D and G) are interpreted to result from a relatively low-calcium phase, while the long-wavelength absorptions (Bands E and H) are due to a relatively high-calcium pyroxene component. Although derived independently using spectroscopy, this conclusion is consistent with the results of the petrologic studies of EETA 79001 which show that the matrix of Lithology A and Lithology B each contain two pyroxene phases, an augite, and a pigeonite (Steele and Smith 1982, Munsen and Jarosewich 1983).

Comparisons among the absorption bands derived with the MGM for each of the spectra from EETA 79001 can also be used to determine differences in relative composition between the two lithologies. For example, the position of the four major pyroxene absorptions (Bands D, E, G, and H) all occur at longer wavelengths in the spectrum of Lithology B than they do in the spectrum of Lithology A. This increase in the wavelength of all absorptions, including absorptions from both the high- and low-calcium pyroxenes phases, most likely suggests an enrichment in iron in Lithology B relative to the matrix of Lithology A (e.g., Adams 1974, Cloutis and Gaffey 1991). This increase in iron in Lithology B relative to Lithology A is in accord with the Munsen and Jarosewich (1983) conclusion, based on their normative calculations (diop-
FIG. 10. Pyroxene quadrilaterals showing the chemistry of Lithologies A and B derived from microprobe analyses. From McSween and Jarosewich (1983). Regions outlined denote ranges derived from MGM modeling of spectra (see Figs. 3 and 4).

side: Wo51En28, hypersthene: En56 for Lithology A and diopside: Wo49En19, hypersthene: En38 for Lithology B), that Lithology B is more evolved than Lithology A.

The position of the absorption bands derived with the MGM can be used, along with the relationships derived from previous studies of pyroxene spectra, to more specifically estimate the iron and calcium contents of each of the individual pyroxene phases. However, it should be noted that these trends in pyroxene spectra as a function of composition (Figs. 3 and 4) were determined from empirical studies of pyroxene spectra (Adams 1974, Cloutis and Gaffey 1991) and are thus likely to be different in absolute numbers than those that could be obtained with more quantitative approaches like the MGM. Nonetheless, as indicated on Figs. 3 and 4, these relationships and the band centers derived with the MGM can be used to establish bounds on the likely compositions of the pyroxenes. The range in major element compositions determined from the band centers are summarized in the pyroxene quadrilateral presented in Fig. 10.

With the exception of a systematic overestimation of the calcium content of calcium-rich phases (by \(\approx 10\)%), the compositions derived for Lithologies A and B from these spectroscopic techniques are in good agreement with those obtained from microprobe analyses of individual pyroxenes (McSween and Jarosewich 1983). It is likely that the remaining discrepancies will be improved when the laboratory data presented in Figs. 3 and 4 (derived from Cloutis and Gaffey 1991) are reanalyzed using the same technique as is used in this study. In particular, a large source of error can be attributed to the fact the MGM-derived band centers are effectively continuum removed, while the work of Cloutis and Gaffey (1991) uses band minimum. The trends predicted from this difference in techniques are consistent with the offsets present in Fig. 10. An updated study, using the MGM to more accurately determine pyroxene band centers across a wide range of compositions is currently underway. Nonetheless, even with our existing data bases, there is an agreement of 5–10% between compositions derived by spectroscopic and geochemical techniques.

The relative strengths of the absorption bands derived with the MGM can also be used to estimate the abundance of different pyroxene phases. As can be seen on Fig. 9 and in Table II, the high-calcium absorptions (small arrows; Bands E and H) in the spectrum of Lithology B are stronger than the low-calcium absorptions (large arrows; Bands D and G) relative to those in the spectrum of Lithology A. Based on the correlation of modal abundance and relative band strength (Fig. 6), this result suggests that there is relatively more high-calcium pyroxene in Lithology B than in Lithology A. This is consistent with petrographic studies which show Lithology B to contain more augite relative to pigeonite than the matrix of Lithology A.

A more quantitative estimate of modal abundances can be made using the correlation between relative band strengths in the 1- and 2-\(\mu\)m regions and modal abundance shown in Fig. 6. However, as pointed out by Sunshine and Pieters (1993b), although relative modal abundances can be estimated, until a more complete evaluation of a full range of pyroxene compositions is undertaken, it is not possible to use these relationships to determine absolute model abundances for mixtures of pyroxenes that differ widely in composition from those used in the mass fraction mixture study. Although the band centers derived for the spectra from EETA 79001 indicate that the pyroxenes have a greater iron content than those used in the mass fraction mixtures, the relative modal abundances between Lithology A and Lithology B derived with the MGM approach should, nonetheless, be accurate. The results of the MGM analysis of Lithology A (Fig. 9 and Table 2) yield a relative strength of absorptions in the 1-\(\mu\)m region (strength of Band D, small arrow, divided by strength of Band E, larger arrow) of 1.4, while data from the 2-\(\mu\)m region of Lithology A yield a relative strength of 1.6 (Bands G, small arrow, relative to Band H, large arrow). Similar results from Lithology B yield a
relative strength of 1.0 and 0.9 from the 1- and 2-µm regions, respectively. Based on these data, as indicated by the lines marked "a" and "b" on Fig. 6, one would predict a relative increase in the proportion of high-calcium pyroxene of approximately 11-17% between Lithology B and the matrix of Lithology A. This relative change is in excellent agreement, within 5%, with the abundances derived with mode counts by McSween and Jarosewich (1983) of 25.6% high-calcium pyroxene for Lithology A and 38.4% for Lithology B, which yield a relative change of 13.2% between the two lithologies. Given the complexities in determining modal abundance both spectrally and petrographically, the relative abundances derived with the MGM are remarkably consistent with the microprobe analyses.

Finally, MGM modeling of the spectra from EETA 79001 also yields data on the width of the absorption bands. By comparing the band widths derived from the spectra of Lithologies A and B to those obtained by Sunshine and Pieters (1993b) for the very rapidly cooled pyroxenes in lunar basalts, one can place some constraints on the formational history of EETA 79001. As indicated on Fig. 7, unlike the large band widths determined for the spectra of EETA 79001 by modeling each lithology with single absorptions in the 1- and 2-µm regions ("A" and "B"), the band widths derived for the spectra of each lithology using two distinct pyroxene components ("a" and "b") are typical of most pyroxenes and not as wide as those determined for the highly zoned pyroxenes in lunar basalts. From the MGM analysis of the spectra from EETA 79001 one can therefore infer not only that Lithologies A and B cooled slowly enough to allow for two pyroxene components to be resolved, but also, based on the width of the absorption bands, that none of these pyroxene components are highly zoned. Although mineralogic studies indicate that the pyroxenes in EETA 79001 do in fact exhibit some zonation (McSween and Jarosewich 1983), they do not have as extreme a zonation pattern as those found in lunar basalts. While these results do not provide strong limits on the cooling history, they do imply that the lithologies of EETA 79001 did not cool at as rapid rates as lunar basalts. This inference is consistent with the contrast between the high effusion rates involved in lunar mare emplacement and the conclusion, based on the cumulative textures, grain sizes, and zonation patterns in Lithologies A and B, that EETA 79001 was emplaced in a shallow chamber or at the surface, but under such conditions that allowed for gravity settling to occur within the magma (McSween and Jarosewich 1983, McSween 1985).

IMPLICATIONS FOR ANALYSIS OF REMOTELY ACQUIRED DATA

Remotely acquired data can, in principle, be analyzed in a manner similar to the analyses of the spectra from EETA 79001 presented here. Chemical information on pyroxene phases could be derived from MGM analyses of high spectral resolution data. In addition, one could compare the results to the 1-µm vs 2-µm trend of pyroxene absorptions (Fig. 2) in order to infer the presence of other mafic phases, for example, olivine, iron-bearing glass, and/or ferric minerals (e.g., Adams 1975, Singer and McSween 1993). The work presented here, and that in previous analyses (Sunshine and Pieters 1993b), has also revealed that the broad absorption which occurs in the 1.1-1.5-µm region can completely be attributed to pyroxenes. This ambiguity between pyroxene and plagioclase absorptions near 1.2 µm suggests that caution be used in future interpretations and that existing identifications of plagioclase in remote spectra (e.g., McCord et al. 1981) be reexamined.

It should also be noted that this MGM analysis of EETA 79001 used data with very high signal-to-noise ratios. This high-quality data made it possible to determine, based on the magnitude and shape of the residual errors, that using a single set of absorptions to model the spectra of Lithologies A and B was inadequate, and that two distinct pyroxene phases were required for each lithology in order to accurately model their spectra. In data with lower signal-to-noise ratios, using a similar mathematical analysis of the residual errors to test whether or not two distinct pyroxene phases are present would be more difficult.

However, modeling surfaces which consist of two pyroxene phases with single absorptions, even in data with low signal-to-noise ratios, will result in absorption bandcenters that lie in the middle of the range of possible values for pyroxenes, as was the case for the models of the spectra from EETA 79001 (see Figs. 2 and 3). These intermediate band position imply intermediate compositions (Figs. 2, 3, and 4). Since such mid-range compositions are mineralogically unlikely, they probably represent average compositions. Intermediate compositions have in fact been predicted by several researchers using remote data, for example, by Singer and McSween (1993) using telescopic data of Mars and by Mustard et al. (1993) for data from the ISM imaging spectrometer. As was shown for EETA 79001, models using single absorption bands on samples which actually include two discrete pyroxene phases also result in anomalously wide absorption bands. One might conclude, based on the width of such absorptions that the pyroxenes cooled as rapidly as those in lunar basalts. Under such a model, both the anomalously wide absorption bands and the inferred intermediate compositions would therefore be interpreted as compositional averages of highly zoned minerals. Alternatively, for remotely acquired data one could argue, based on the geologic context, that it is more plausible that the anomalous band widths and intermediate compositions are merely signals of the presence of a second pyroxene
phase. Thus, although current remote data may have lower signal-to-noise ratios than the laboratory data used in this study, one can, with appropriate assumptions, model remotely acquired spectra with two pyroxene components and, as was done in this study, use the MGM to determine the major element composition and relative abundances of these phases.

Deriving such chemical information from spectroscopy would add a powerful dimension to many geological studies. When combined with morphology and geologic setting, information on major element composition could greatly aid in determining the emplacement history and petrogenesis of a region. One could, for example, remotely collect data on neighboring geologic units and use the compositional results obtained from analyzing their spectra to help determine how the units are related. The compositional information derived from spectra using the MGM can be used to place bounds on major element composition and to estimate changes in relative abundance. Spectroscopic studies are therefore particularly well suited for monitoring continuous changes in composition which occur in many natural environments including gradational volcanic contacts, like in EETA 79001, and/or differentiation sequences.

SUMMARY

Analysis of the spectra from EETA 79001 using the MGM (Sunshine et al. 1990) has led to the unambiguous identification of the presence of two distinct pyroxene components in Lithologies A and B. All absorption features, including the absorption shoulders between 1.1 and 1.5 μm, often attributed to plagioclase, were found to be fully consistent with pyroxenes. MGM analyses of the spectra of Lithologies A and B also provided many compositional inferences about the pyroxenes in these two adjoining lithologies.

The following conclusions were determined directly from the spectral analyses of EETA 79001: (1) Lithologies A and B each include a relatively high-calcium pyroxene phase and a relatively low-calcium pyroxene phase. (2) The pyroxenes in Lithology B are more iron-rich than those in the matrix of Lithology A. (3) Ranges in pyroxene compositions derived with the MGM for the matrix of Lithology A are, for low-calcium phase, 0–14% Ca/Ca + Mg + Fe and 10–54% Fe/Fe + Mg + Ca, and high-calcium phase, 33–59% Ca/Ca + Mg + Fe and 5–42% Fe/Fe + Mg + Ca; and for Lithology B, low-calcium phase, 0–17% Ca/Ca + Mg + Fe and 23–58% Fe/Fe + Mg + Ca, and high-calcium phase, 35–53% Ca/Ca + Mg + Fe and 2–33% Fe/Fe + Mg + Ca. (4) There is 11–17% increase in the relative abundance of high-to-low-calcium pyroxenes in Lithology B compared to the matrix of Lithology A. (5) The pyroxenes in both lithologies do not exhibit the spectral properties of extreme compositional zonation and therefore did not cool at extremely rapid rates. Each of these inferences about the major element compositions, modal abundances, and cooling histories of the pyroxenes in EETA 79001 derived from the MGM analyses was obtained independently of the petrologic and geochemical studies; yet, the results gathered by these very different methods are in excellent agreement.

Although modeling the spectra of EETA 79001 with the MGM has not contributed additional constraints on the origin of SNC meteorites, the major element chemistries derived from this modeling are certainly consistent with a martian origin. More importantly, because of the unique character of EETA 79001, the presence of two basaltic lithologies joined along an igneous contact, and the likelihood that many surfaces include such contacts, the results of the spectral analyses of EETA 79001 presented here have broad implications for the use of remote sensing on basaltic terrains throughout the Solar System. By way of example, the analyses of the spectra of EETA 79001 have thus shown that spectroscopy can provide an important bridge between laboratory samples and the wealth of data available remotely.

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