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Meteorite–Asteroid Spectral Comparison: The Effects of Comminution, Melting, and Recrystallization

BETH E. CLARK AND FRASER P. FANALE

Planetary Geosciences Division, Hawaii Institute of Geophysics, University of Hawaii, 2525 Correa Road, Honolulu, Hawaii 96822

AND

JOHN W. SALISBURY

Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland 21218

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Laboratory results from a simulation of the possible effects of spectral alteration on reflectance of the optical surface of ordinary chondrite parent bodies is presented. Diffuse reflectance spectra from 0.3 to 2.6 μm were obtained for three chondritic meteorites. To simulate possible regolith processes the samples were comminuted to finer grain sizes, and the effect of comminution on their reflectance spectra was measured. Following comminution, the samples were melted, recrystallized, recomminuted, and remeasured. These laboratory alterations produced a decrease in absorption band depths at 0.95 μm, and melting and recrystallization produced a significant drop in albedo. A reddening of the continuum, as previously reported for CM meteorites upon comminution and for lunar samples upon vitrification, also occurred for OC meteorites to a minor extent. Thus, although it was found that spectral characteristics could each be significantly changed by these procedures, no set of procedures was able to simultaneously affect all relevant parameters in such a way as to improve the match between ordinary chondritic meteorites and S-class asteroids. These results are consistent with what is known of the physical aspects of asteroid regolith evolution and also with the existence of several currently satisfactory spectral matches between meteorites and asteroid spectral classes. © 1992 Academic Press, Inc.

INTRODUCTION

Studies of mineralogical properties of the asteroids are of fundamental importance for our understanding of the formation and early evolution of the Solar System. In this vein the connections between meteorite types and their possible parent-body asteroids continue to be an area of active research. Many satisfactory spectral matches have been found between meteorite classes and spectral classes of asteroids. However, there are very few known asteroidal analogs to the ordinary chondrites (OCs) (Gaffey 1985, McFadden 1983a, McFadden *et al.* 1985), and it is unclear whether there are meteoritical analogs to the S-class asteroids in our meteorite collection (Gaffey *et al.* 1989, Bell *et al.* 1989). The failure to find meteoritical matches for all asteroid classes could reflect poor statistical sampling of the asteroids. Alternatively, it is possible that our method of spectral comparison overlooks unknown regolith processes that may be occurring on asteroids which would alter the reflectance spectra of their optical surfaces (Wetherill and Chapman 1988). The most likely regolith processes are comminution and vitrification, which are known to affect spectra of lunar materials (Housen *et al.* 1979, Matson *et al.* 1977, Pieters 1984) and can be simulated in the laboratory. The spectral effects of these two processes is the subject of this paper.

We begin by asking the questions: Based on spectral characteristics, if there is a qualitative match between the inferred mineralogies of a meteorite and an asteroid, could there be some extraneous reason for a poor match in albedo, continuum slope, or band depth? Is there any possible process that could alter these characteristics without altering band center position? In fact, these are the very characteristics altered by vitrification in lunar regolith samples. In order to determine the extent to which these factors could be altered by possible asteroidal regolith processes operating on ordinary chondritic material, comminution and vitrification were simulated in the laboratory by pulverizing, melting, quenching, and then repulverizing meteorite samples. The results of this experiment are presented here together with some discussion of the implications for asteroid–meteorite spectral linkage.

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PREVIOUS WORK

The method used so far for meteorite–asteroid comparisons is to pulverize meteorite samples to grain sizes thought to approximate asteroid surface textures (Dollfus and Zellner 1979, Dollfus *et al.* 1989), to obtain their reflectance spectra in the laboratory, and then to compare the meteorite spectra with asteroid spectra obtained telescopically (Gaffey 1976, McFadden and Gaffey 1978, McCord and Gaffey 1974). Polarization data (Chapman *et al.* 1975; Dollfus *et al.* 1989) indicate that asteroid surfaces are fine grained (between 30 and 300 μm). Also, in the case of the Moon, mean particle sizes in the repeatedly comminuted fine fractions of lunar soils peak between 45 and 100 μm, which may set a good lower limit for less-worked materials (Housen *et al.* 1979) such as those which supposedly exist on asteroidal surfaces. Photometric modeling of telescopic spectra supports this interpretation of grain sizes (Hapke, 1981) and leads to the expectation that pulverization occurs to some extent on atmosphereless planetary surfaces. Thus, the conventional laboratory method is based on the assumption that pulverization is the main regolith-forming process in effect on asteroid surfaces, and that reflectance spectra of exposed optical surfaces of asteroids are not affected by solar-wind implantation, glass or agglutinate formation, or other effects, to a greater extent than the deeper material which may supply meteorites. This presents a weakness in the procedure as it is only the topmost few micrometers of an asteroid's surface (its optical surface) that we must consider to be representative of its entire composition. (See McKay *et al.* 1989 for a review of shortcomings in our knowledge of the properties of asteroid surfaces.) If there is some alteration process affecting this optical surface, then the surface is not necessarily representative of the asteroid's interior composition (King *et al.* 1984). If accepted connections between meteorites and asteroids are valid, such a "weathering" process, if it exists, must affect mineralogically distinct asteroid types to different degrees, or in various ways.

The characteristics most often measured for diagnostic meteorite–asteroid comparison include albedo, in the case of meteorites (both values taken at 0.56 mm) (Lebofsky and Spencer 1989, Gaffey 1976). Also measured are continuum slope, vibrational and electronic absorption band depths, areas, and center positions. For comparisons between telescopic and laboratory data, small (~10%) differences in albedo are considered less important than variations in continuum slope and band depths (Clark and Roush 1984, McFadden 1983b, Gaffey and McCord 1978, Gaffey 1984).

Asteroidal Regolith Processes

Models for glass and agglutinate formation in asteroidal regoliths generally conclude that these processes are largely inhibited by (a) low relative impact velocities in the main belt and (b) large percentages of material lost due to collisions between small bodies (Matson *et al.* 1977, Horz and Schaal 1981, McKay *et al.* 1989). Such models are consistent with the low levels of agglutinates found in meteorite regolith breccias (McKay *et al.* 1989, Bell and Keil 1988) and with interpretations of telescopic observations (Gaffey and McCord 1978). Before concluding that glass and agglutinate formation processes do not occur on asteroidal optical surfaces, however, it is important to understand the contribution of vitrified material to spectral reflectance curves. Clearly, the spectral properties of a glass will depend on its chemical composition (Cloutis *et al.* 1990b). For impact-produced glasses, the minerals from which it forms are of primary importance. On the moon ilmenite is an abundant opaque phase and, when included in glass, it tends to reduce the albedo of the lunar regolith. In the formation of agglutinates, meanwhile, iron is reduced to metallic iron, and this results in a reddening of the slope of its spectrum. Agglutinate formation is a result of micrometeorite bombardment, and the agglutinitic fraction of the regolith increases with time (Adams and McCord 1971, Matson *et al.* 1977, Horz and Schaal 1981). This creates a measure of the exposure age or "maturity" of a lunar soil in the space environment (Matson *et al.* 1977, Nash and Conel 1973). Formation conditions are also important, however, and variations in temperature and rates of fusion can affect reflectance characteristics. Darker glasses are produced, for example, if the heating times are increased (Cloutis *et al.* 1990b). This is probably the result of the increasing concentration of refractory elements or of a change in the oxidation states of the transition series metals. The spectral differences between glass and agglutinate formation products are as yet undetermined. It may be that the vitrification processes for these two products are sufficiently different in terms of energy and oxidation state environments that the metal components of target lithology will behave differently (McKay *et al.* 1989).

In addition, shock effects are known to affect spectra, partly as the result of enhanced dispersal of the metallic phase (Gaffey 1976, Britt and Pieters 1989). Submicrometer grains of NiFe metal and troilite will appear in optically important areas, such as grain boundaries, due to shock-induced dispersion, and this will change the reflectance of the material considerably (Britt and Pieters 1989). Also, Salisbury *et al.* (1975) note an overall increase in reflectance and band strength with increasing petrologic type among ordinary chondrites due to the corresponding reduction in the percentage of opaque material present.

Bell and Keil (1988) studied the spectra obtained from cut sections of ordinary chondrites which were high in solar-wind-implanted gases. This high gas content implies that the OC breccias were at the surfaces of their parent

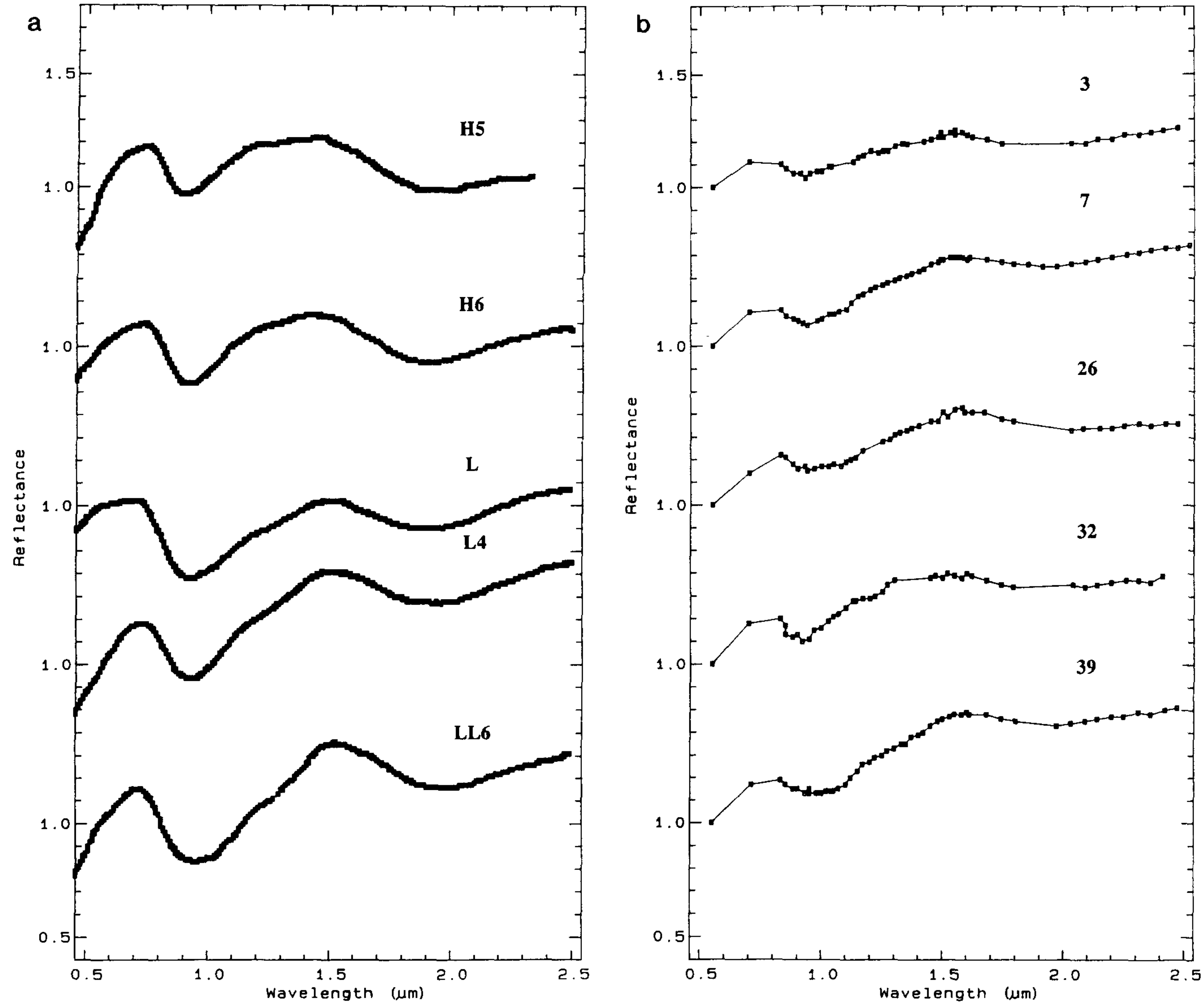

FIG. 1. A comparison of: (a) ordinary chondrite meteorite spectra (from Gaffey 1976) and (b) archetypical S-class asteroid spectra (from J. F. Bell *et al.*, unpublished data). Both data sets have been normalized to 1 at 0.56 μm.

bodies for some length of time and may represent the very regolith which we attempt to simulate. The results of Bell and Keil show no evidence for surface alteration processes which may indicate that (1) there is no such process or (2) it is not detectable in the OC breccias.

Spectral Matching

Although several satisfactory asteroid–meteorite matches have been made (Gaffey *et al.* 1989) an example of a spectral mismatch is the hypothesized link between the ordinary chondrites and the S-class asteroids (see Fig. 1). Wetherill and Chapman (1988) have presented a full discussion of this problem, but a brief overview of the relevant points are needed here. The most abundant single class of asteroids observed in the inner main asteroid belt are S-class, and over 80% of meteorites in the current collection are ordinary chondrites (Sears and Dodd 1988). In fact, 81% of all observed falls are OCs, while 89% of all Antarctic finds are OCs. At first glance they are indeed spectrally similar, and a genetic link is suggested. Both the OCs and Ss appear to reflect varying proportions of olivine, pyroxene, and Ni–Fe metal (Gaffey 1976, Gaffey *et al.* 1989, Bell *et al.* 1989, Cloutis *et al.* 1990a), and both types have a roughly similar range of albedos (reflectance at 0.56 mm) (see Table I). Additionally, modeling by Wisdom (1983, 1985) and Wetherill (1985) has quantitatively

TABLE I

A Table of Typical Values for Continuum Slope (as Measured from 0.7 to 1.5 μm), Band Center Depths (as Defined by Clark and Roush 1984), and Albedo for Both the S-Class Asteroids (from Bell *et al.*, Unpublished Data) and the Ordinary Chondrite Meteorites (from Gaffey 1976)

	SLOPE	BAND DEPTH	ALBEDO	TYPE
S- ASTEROIDS				
3 Juno	0.141	0.089	0.22	
7 Iris	0.661	0.116	0.25	
12 Victoria	0.458	0.093	0.16	
15 Eunomia	0.329	0.103	0.19	
26 Prosepina	0.238	0.081	0.16	
32 Pomona	0.291	0.103	0.25	
37 Fides	0.401	0.131	0.17	
39 Laetitia	0.403	0.087	0.29	
68 Leto	0.307	0.119	0.20	
80 Sappho	0.469	0.133	0.15	
average:	0.370	0.105	0.20	
OC- METEORITES				
Vavilovka	0.047	0.336	0.27	LL
Dhurmsala	0.262	0.314	0.29	LL6
Soko Banja	0.073	0.257	0.29	LL4
Elenovka	0.012	0.331	0.31	L
Bjurbole	0.287	0.239	0.24	L4
Borkut	0.213	0.168	0.16	L5
Mocs	0.084	0.392	0.33	L6
Zjoutnevyi	0.013	0.261	0.36	H
Nanjemoy	0.055	0.242	0.32	H6
Bur Gheluai	0.055	0.184	0.15	H5
average:	0.110	0.272	0.27	

shown that ordinary chondritic meteorite fluxes and orbital parameters can be supplied by asteroidal sources near the 3 : 1 Kirkwood gap in the asteroid belt, which is just where the S-class asteroids are found. Most workers, however, agree that the specific problems with this spectral comparison far outweigh the statistically comfortable connection.

Interpretation of S-class spectra based on band area ratios have led to estimates of olivine/pyroxene ratios that are too high to match the contents found in OC meteorites (Feierberg *et al.* 1982, Gaffey 1986). Band depths (calculated as outlined by Clark and Roush 1984) are a measure of the strength of the absorption, and thus an indicator of relative abundance of the absorbing medium, and tend to be deeper for the OC meteorites than for the S-class asteroids. This fact has led to some estimates of high metal/silicate ratios for S asteroids relative to those found in OC meteorites (Gaffey and Ostro 1987). In addition, the slope of the S-class continuum (see Table 1) is characteristically more red than that of the OCs (Gaffey and McCord 1979). Continuum reddening can result from (a) increased metal components, (b) comminution effects (Johnson and Fanale 1973), (c) temperature decreases (Roush 1984), (d) high specular return from flat metal surfaces (Britt and Pieters 1988), or from (e) glass and agglutinate contents (Adams and McCord 1971). As mentioned above, direct comparisons between meteorite reflectance and asteroidal albedo are inexact at best (Lebofsky and Spencer 1989, Britt 1991). It should also be noted that the errors introduced by size and flux uncertainties into asteroid albedo calculations can be significant (Tedesco *et al.* 1989). The meteorites measured for Table I were ground to a fine grain size (~60 μm), and although this fact enhances the match between asteroid and meteorite albedos, it serves to intensify the differences in their band depths. Considering the uncertainties inherent in the standard comparison procedure, it is conceivable, therefore, that phenomena peculiar to the surface of asteroids are affecting the diagnostic value of reflectance spectroscopy in asteroid–meteorite spectral comparisons.

PROCEDURE AND RESULTS

This paper is an attempt to further constrain the effects of comminution and vitrification as optical surface alteration processes by studying their effects on the three spectral parameters of continuum slope, absorption band depth, and albedo of ordinary chondrites. Several different meteorites were selected on the basis of availability to be used for this study: Ozona, an *H*6 find; Lacriolla, an *L*6 fall; and Nuevo Mercurio, an *H*5 fall, all ordinary chondrites. These meteorites also sufficiently represent the range of possible reflectance values found among ordinary chondrites (see Tables I and II). Samples were ground to various grain sizes with an ordinary ceramic mortar and pestle. Different grain sizes were obtained not by separation but by repeated grinding of the same sample, and the sizes noted are to be considered the upper limit of grain sizes in the sample as the distribution allowed through the sieving process favors larger numbers of the finer fraction. In order to cover the range of grain sizes expected to be present on asteroidal surfaces, three size fractions were prepared: 350, 150, and 50 μm. Bidirectional reflectance spectra were obtained at the NASA-supported Reflectance Experiment Laboratory (RELAB) facility at Brown University (see Fig. 3). Observational geometry in the lab is set up to simulate likely telescopic observational geometry: an incidence angle of 30° and an emission angle of 0°. Spectra were taken at a resolution of 1.5% (see Fig. 2), using halon as a reference material, with a spot size of 0.5 cm. Samples are prepared for reflectance measurements in the following manner: The dish is partially filled and then tapped lightly to induce settling. This process is repeated until the sample cup is filled. The surface is then made level by passing the edge of a stainless steel spatula straight across the top. All samples are carefully prepared in exactly the same manner (Mustard and Pieters 1989). It should be noted, however, that significant changes in reflectance of samples are observed when sample preparation varies from a packed to a sifted surface. This effect has been especially noted in the thermal infrared and may also be important in the

TABLE II
Values for Continuum Slope, Band Depth, and Albedo (Actual Reflectance at 0.56 μm) for the Unaltered and Altered Meteorites Presented in Figs. 2 and 3

	SLOPE	BAND DEPTH	ALBEDO		SLOPE	BAND DEPTH	ALBEDO
OC-METEORITES							
Nuevo Mercurio H5				Nuevo Mercurio Altered			
50 microns	0.007	0.289	0.27	50 microns	0.151	0.058	0.14
150 microns	-0.022	0.325	0.26	350 microns	0.049	0.124	0.08
350 microns	-0.022	0.390	0.30				
La Criolla L6				La Criolla Altered			
50 microns	0.044	0.185	0.18	50 microns	0.188	0.090	0.13
150 microns	0.100	0.285	0.19	350 microns	0.078	0.127	0.07
350 microns	0.083	0.275	0.16				
Ozona H6				Ozona Altered			
50 microns	-0.096	0.114	0.13	50 microns	0.042	0.071	0.10
150 microns	-0.094	0.166	0.10	350 microns	-0.046	0.079	0.07
350 microns	-0.070	0.156	0.10				

wavelength region considered here (Salisbury and Wald 1992).

Small (< 2 g) subsamples of the 350-μm grain size were melted in a nitrogen controlled-atmosphere fusion furnace (for design specifications see Jezek *et al.* 1980) at 1700°C for approximately 10 sec with subsequent rapid cooling under a flow of nitrogen gas at a temperature of 0°C. During melting the meteorite powder was observed to reach the vapor pressure of silicate chemistry. The attempt to quench the fused sample to a glass by exposure to cold nitrogen gas resulted in a microcrystalline texture due to the olivine normative chemistry of ordinary chondrite material. Thus, true vitrification as observed for feldspathic minerals on the Moon was not possible for ordinary chondrite meteorites. The conditions specified above were imposed in an effort to simulate, as closely as possible, the nonoxidizing environment and low temperatures of an asteroidal space environment. Following melting and recrystallization the samples were reground to grain sizes of 350 and 50 μm (see Table II).

For comparison purposes, spectra of various OC meteorites and of typical S-class asteroids were measured for continuum slope, for band depth at the band center near 0.95 μm, and for albedo (in the case of asteroids, or reflectance in the case of meteorites). These measurements are listed in Table I. The meteorite data were taken from spectra of the finer grain size (~60 μm) presented by Gaffey (1976). It should be noted that the grain size distribution of Gaffey's meteorite samples was cut off at 60 μm, resulting in a lack of finer grains which tend to coat large grains and dominate the spectra of the optical surface. This lack of fines may produce a reduction in reflectance and continuum slope.

The results from the vitrified samples of this study are presented in Table II. Grain sizes for the finest meteorite powders presented here are less than or equal to 50 μm, slightly smaller than the grain size for Gaffey's ordinary chondrites. The asteroid measurements were taken from unpublished data provided by J. F. Bell *et al.* (in preparation). For a complete description of the calculations of band depth and continuum slope see Clark and Roush (1984). The values for band depth listed in Tables I and II are calculated by fitting a straight-line continuum between the maxima near 0.7 and 1.5 μm. The slope of the continuum is calculated simply as the rise in reflectance divided by the change in wavelength. The band depth to the relative minimum near 0.95 μm is, then,

$$D = (R_c - R_b)/R_c \qquad (1)$$

where R_c is the reflectance of the continuum at the band center, R_b is the reflectance of the sample at the band minimum, and D is the band depth.

The normalized reflectance spectra of the unaltered meteorite powders are shown in Fig. 2. All samples show the 0.95-μm olivine/pyroxene band, although their reflectances and spectral contrasts vary (see Table II). These samples have continuum slopes, reflectances, and spectral shapes typical of ordinary chondrites (see Table I). After melting, recrystallization, and regrinding (see Fig. 3), the reflectance at 0.56 μm has dropped drastically (from 0.27 to 0.14 in the case of Nuevo Mercurio), and the absorption band depth at 0.95 μm has decreased by as much as 23%. The slope of the continuum, however, increases from the 50-μm-size sample of the unaltered meteorites to the 50-μm size of the fused samples. For La Criolla this increase is most dramatic—from 0.044 for the unaltered powder to 0.188 for the vitrified powder (see Table II). This amounts to an increase of 77% in the continuum slope value.

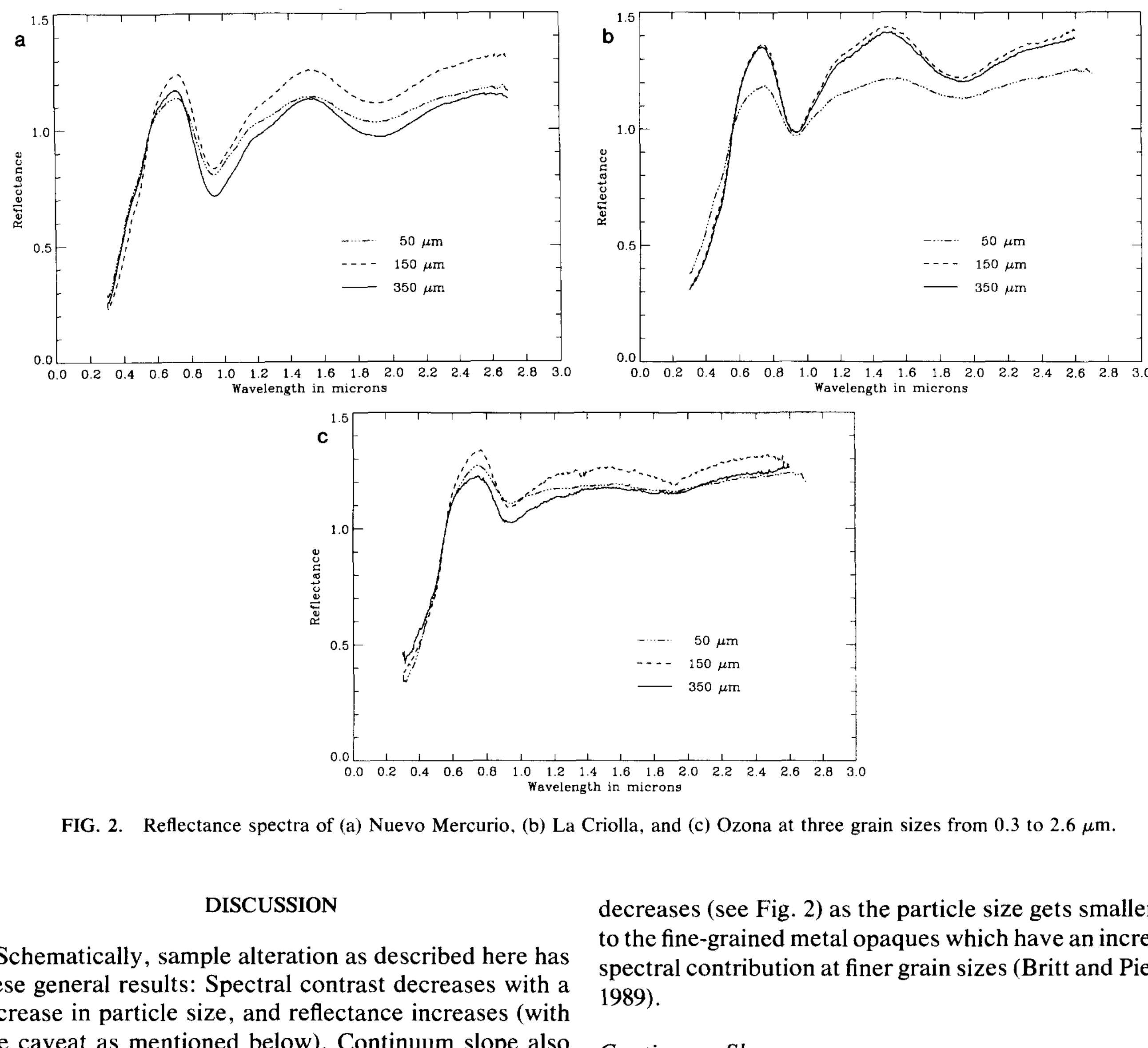

FIG. 2. Reflectance spectra of (a) Nuevo Mercurio, (b) La Criolla, and (c) Ozona at three grain sizes from 0.3 to 2.6 μm.

DISCUSSION

Schematically, sample alteration as described here has these general results: Spectral contrast decreases with a decrease in particle size, and reflectance increases (with one caveat as mentioned below). Continuum slope also increases with comminution (Johnson and Fanale 1973, Adams and McCord 1971). After melting, recrystallization, and repulverization, reflectance drops dramatically and spectral contrast goes down. After repeated comminution of the melted samples the increase in reflectance is accompanied by an increase in continuum slope and a drop in spectral contrast.

Reflectance

In general, reflectance increases with decreasing particle size (Adams and Filice 1967), but in the case of multimineral agglomerations such as the OCs we see the effects of two competing processes; increased reflectance due to increased volume scattering and decreased reflectance due to dispersion of opaques. Thus, overall reflectance decreases (see Fig. 2) as the particle size gets smaller due to the fine-grained metal opaques which have an increased spectral contribution at finer grain sizes (Britt and Pieters, 1989).

Continuum Slope

Other studies, conducted on different types of meteorites and lunar regolith powders, have also shown these general trends. Johnson and Fanale (1973) found increasing redness of the continuum due to decrease in the grain size of carbonaceous chondrites, all CMs (see Fig. 5). As the continuum slope increases in these samples, the ~0.95-μm olivine/pyroxene band grows more pronounced, increasing the spectral contrast (Johnson and Fanale 1973). An increase in reflectance and continuum slope with decreasing particle size is typical of iron-rich materials. This is due to the fact that only at finer particle sizes can significant volume scattering take place in the highly absorbing grains of iron-rich minerals. Thus a moderate decrease in particle size and an increase in volume scattering will result in an increase in reflectance and, with various iron absorptions typically decreasing toward

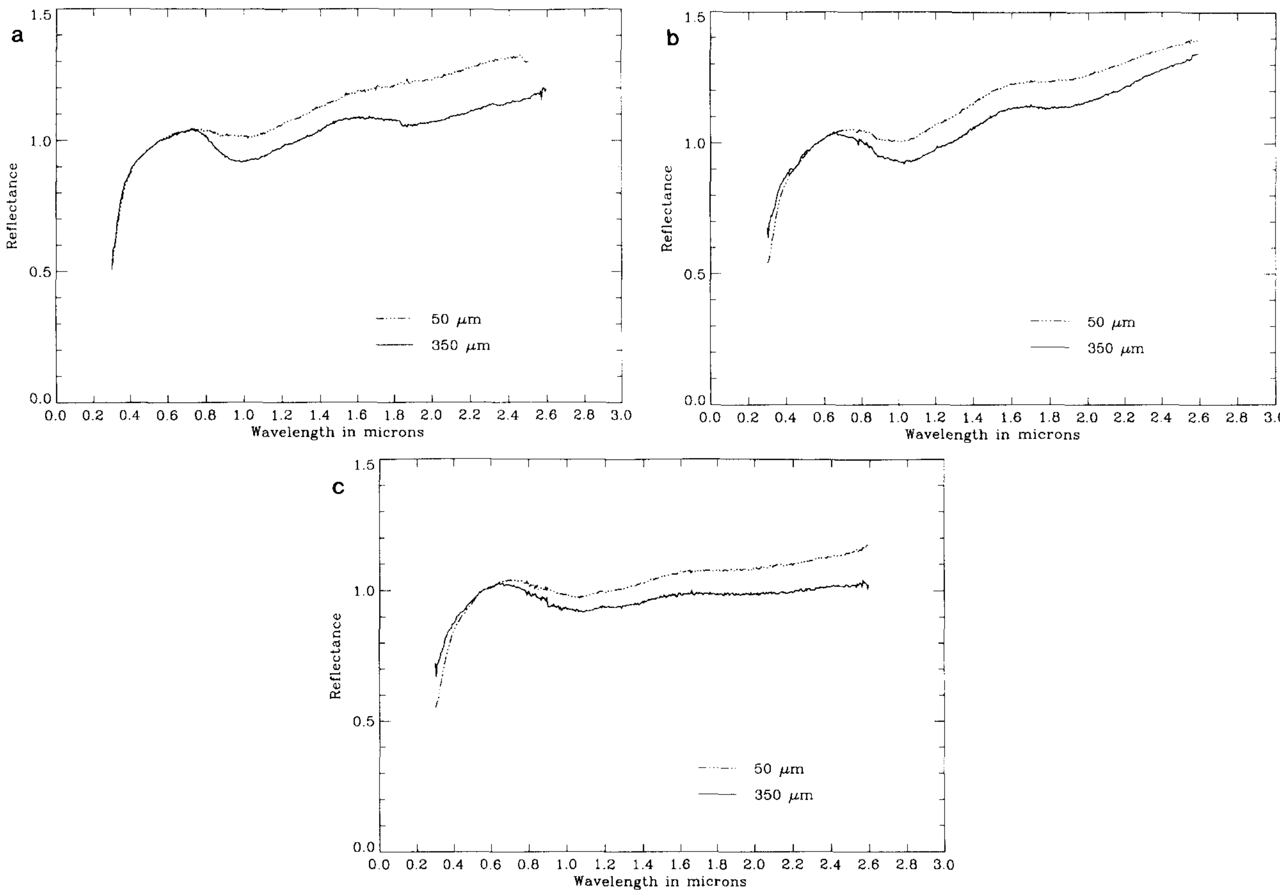

FIG. 3. Spectra of meteorite samples after melting, recrystallization, and regrinding. (a) Nuevo Mercurio, (b) La Criolla, and (c) Ozona.

longer wavelengths, a redder slope (J. Salisbury, personal communication).

Matson *et al.* (1977) found reddening of the continuum due to maturation, or increased impact glass production, of a lunar regolith. In this case the reddening was associated with a drop in albedo and spectral contrast and was linked with the presence of ilmenite, a spectrally red component. Cloutis *et al.* (1990b) found reddening of the continuum slope after vitrification of laboratory-concocted mixtures of pyroxene, plagioclase, and ilmenite. This was accompanied by a drop in albedo and spectral contrast.

It has been suggested that contamination of meteorite samples by terrestrial water could decrease the continuum slope by introducing an apparent downward trend of the continuum going into the water band at 2.9 μm. The magnitude of this effect has not been investigated here, although most workers argue that it is negligible (J. F. Bell, personal communication) due to the fact that the water band and its overtones are sharp absorption band features and have little effect on the reflectance of the continuum. On close examination of water-rich samples of montmorillonite, however, the strength of the water bands imparts a negative slope on the continuum in the 1.3–2.9 μm region, but the absorption bands in the 0.8 to 1.3 μm region do not affect the continuum. This negative effect on continuum slope thus appears to be possible for very water-rich samples, although even for the extreme case of montmorillonite the resulting change in reflectance is not more than 10%. The extent to which meteorites have been hydrated by terrestrial water is not investigated here. Therefore, since the continuum slopes for meteorites in this study were measured between 0.7 and 1.5 μm, they will have to be considered to be a minimum, keeping in mind that changes greater than 10% are highly unlikely due to the fact that ordinary chondrites are far less absorbent than montmorillonite clay.

Spectral Contrast

In general, spectral contrast will be a function of the absorption coefficient of the material and the surface roughness scale. Thus, at a particular wavelength, there will be an optimum particle size that maximizes the band depth (Clark and Roush 1984). For silicate bands,

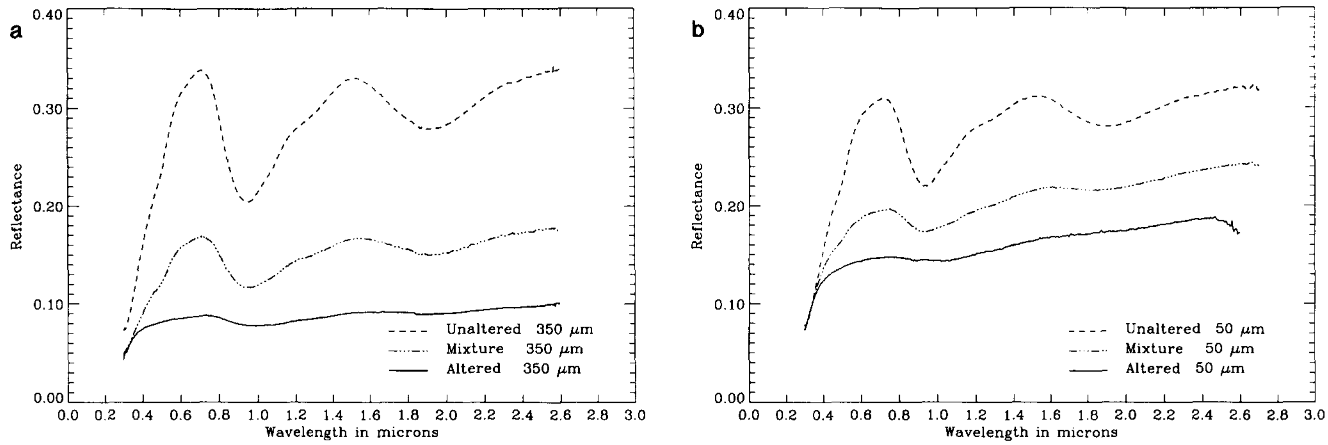

FIG. 4. Spectra of Nuevo Mercurio (a) at a grain size of <350 μm and (b) at a grain size of 50 μm. Shown are the curves for the unaltered meteorite, the altered meteorite, and a 50/50 mixture of the two.

like the olivine/pyroxene band at 0.95 μm, the optimum grain size is several hundred micrometers. Below that size a decrease in particle size will reduce spectral contrast.

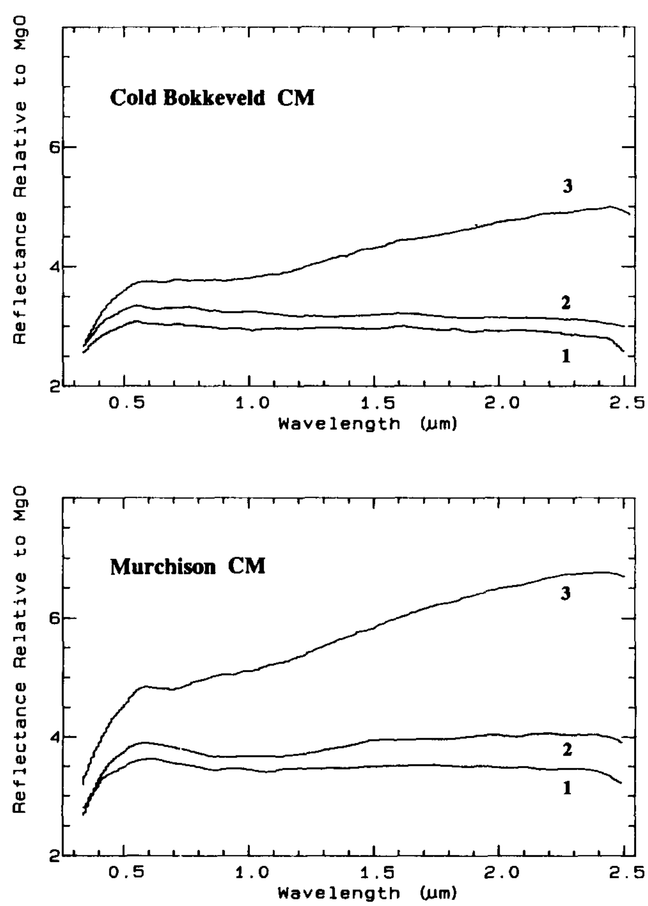

FIG. 5. Data from Johnson and Fanale (1973) showing the result of comminution on CM chondrites. Note the increase in slope toward longer wavelengths with finer grain sizes.

In the process of melting and recrystallization the spectral contrast of the mafic mineral bands has been highly reduced, as seen in the pure glass samples shown in Fig. 3. A mixture of fused and unfused samples (50% : 50%) at a grain size of 350 μm is presented in Fig. 4a. These spectra are left unnormalized to better portray the actual change in reflectance characteristics. The result of a drop in reflectance and in spectral contrast was anticipated, but this experiment was designed to test what happens upon repeated alteration of samples. In order to simulate a possible regolith environment where target materials on an asteroid's surface are presumably bombarded repeatedly in the course of their exposure time (Housen and Wilkening 1982), the altered samples were repulverized. Thus, after further comminution to a grain size of 50 μm,the samples were remeasured (see Fig. 4b). The results are presented in Table II; for all samples the reflectance and the continuum slope increased, but the spectral contrast decreased.

A comparison between Tables I and II shows the extent to which melting, recrystallization, and comminution have an effect on the spectra of ordinary chondrites. Based on the three spectral characteristics measured, none of the three meteorites in this study can be spectrally altered to have S asteroid characteristics. It thus appears that this experiment has failed to find a path by which the spectra of ordinary chondrites can be made to match those of the S-class asteroids.

CONCLUSION

In conclusion, the characteristics of the spectra of altered ordinary chondrites presented in this work do more closely resemble the S-class asteroids in that the mafic mineral bands are less intense. However, the albedo is decreased to values below those of the S-class and cannot be restored by further comminution. Most significantly, the slope of the continuum remains too low to be S-like. This may be the result of the fact that reddening associated with melting and vitrification may depend on the intrinsic redness of the dispersed opaques in the glass (as on the Moon). The opaque phases in glasses found in lunar soils, for example, are ilmenite-rich and are almost invariably characterized by an increase in reflectance toward longer wavelengths (e.g., Matson *et al.* 1977, Lucey *et al.* 1986). The opaque metal phases found in ordinary chondrites, however, are spectrally flat and contribute neither to the slope of the continuum nor to the spectral contrast, perhaps due to thin mineral coatings of iron oxides and/or iron sulfides that tend to mask their redness (Gaffey 1986). These anomalous coatings have been suggested to explain the absence of spectral redness, but their existence has not yet been proven (Britt and Pieters 1988). Having been completely melted and recrystallized, however, the metallic particles of the altered chondrite powders in this study might be expected to have different optical properties if indeed a mineral coating were present before alteration.

The results of this study indicate that either (1) the processes we chose to simulate regolith effects were inappropriate simulators of processes that actually occur on asteroid surfaces or (2) the effects of melting, recrystallization, and comminution (Table 2) on meteorite samples are insufficient to explain any mismatch between meteorites and the optical surfaces of asteroids. In the first case it is possible that the assumptions made about the space environment during melt-forming impacts were incomplete, and if so there may be alternative methods for simulation. For example, we were unable to simulate shock effects. However, studies of shocked chondrites have failed to suggest any spectral relationship to S-class asteroids although a relationship to some C-class asteroids has been suggested (Britt and Pieters, 1989). In the second case, this conclusion is supported by studies of OC regolith breccias such as that of Bell and Keil (1988) which indicate no evidence for appreciable vitrified melt contents nor for other space-weathering effects. Thus, if melt formation is not affecting the optical surfaces of asteroids, we have increased confidence in the conventional method of meteorite–asteroid comparison. This conclusion is consistent with the successful matches that have been made between meteorite and asteroidal spectral classes.

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