

Anatomy of a Partially Differentiated Asteroid: A “NEAR”-Sighted View of Acapulcoites and Lodranites

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With the insertion of the NEAR spacecraft into orbit around the asteroid 433 Eros, a new stage of asteroid exploration has begun, with the return of spatially resolved mineralogical, geological, and chemical information from specific asteroids. In this paper, we outline the features of a partially differentiated asteroid using the acapulcoite and lodranite meteorites as a guide. Such a body would likely contain a variety of lithologies, including chondritic rocks largely unaltered by melting, residues of partial melts, and basaltic and Fe,Ni-FeS rocks crystallized from the partial melts. The presence or nature of the regolith remains largely unconstrained. Mineralogical and isotopic heterogeneities preserved in these rocks suggest spatial separation of these rock types by distances in excess of 200 m. Spacecraft-based remote sensing instrumentation should detect substantial spectral heterogeneity (most prominently manifested in the band area ratio) and chemical heterogeneity. Observation of these various lithologies *in situ* would provide important new constraints on the processes involved during the earliest differentiation of asteroids.

Key Words: asteroids; asteroids, Eros; asteroids, composition; meteorites; NEAR mission.

INTRODUCTION

The encounter of the Near-Earth Asteroid Rendezvous (NEAR) spacecraft with the asteroid 433 Eros represents a milestone in the study of asteroids and their relationship to mete-

orites. NEAR will obtain spatially resolved elemental, spectral, topographic and morphological information on the surface of Eros, as well as data on the mass, volume, magnetic field and possible satellites (Cheng *et al.* 1997). Data returned from NEAR should allow inferences to be made about the mineralogy, chemical composition, and internal structure of 433 Eros. The detailed study of Eros, followed by similar proposed missions to an array of other asteroids of different spectral types, will serve as an important ground truth in our ongoing efforts to understand the origin and geologic evolution of both individual asteroids and the asteroid belt as a whole during 4.56 billion years of Solar System evolution.

Eros is a particularly interesting target asteroid. It is an S-class asteroid thought to be composed of olivine, pyroxene, plagioclase and metal and sometimes linked to ordinary chondrites. Even among S-class asteroids, Eros is unusual. Ground-based (Murchie and Pieters 1996) and NEAR flyby (Veverka *et al.* 1999) spectral studies suggest significant hemispheric-scale heterogeneity, which may result from primary heterogeneity, “space weathering,” or differentiation. It is this last possibility—that Eros might have experienced some degree of igneous differentiation—that is particularly intriguing.

The study of meteorites has provided a wealth of information about the types of rocks and their chemical and spectral signatures that might be found on both differentiated and chondritic asteroids. Indeed, we even have samples of the upper regoliths of these bodies, in the form of regolith breccias, in our collections. From this information, meteoriticists and asteroid

spectroscopists have established ideas, at least to a first order, of what these asteroids might look like in detail. However, the portrait of a partially melted asteroid is still emerging, due in large part to the dramatic increase in the recovery of meteorites from partially differentiated asteroids in Antarctica. In this paper, we examine a specific group of meteorites—acapulcoites and lodranites—to infer the lithologies present, their spatial distribution, spectral signatures, and chemical compositions anticipated on a partially differentiated asteroid. Throughout this discussion, we consider the limitations in spatial resolution of the NEAR instruments in recognizing lithologic heterogeneity. This paper is designed as a broader framework for future missions and to provide a parent body context for these unusual rocks and should not be viewed as a prediction for NEAR at 433 Eros.

LITHOLOGIC DIVERSITY

The acapulcoites and lodranites sample a lithologically diverse asteroid, which includes rocks that are broadly chondritic in chemical composition and mineralogy, those that are residues of partial melting, and samples of partial melts which have been concentrated on the acapulcoite–lodranite parent body. We discuss each of these in turn, as well as implications for the presence and nature of a regolith.

Acapulcoites—Chondritic Rocks

The world's meteorite collections hold 11 acapulcoites. In many respects, these rocks are broadly chondritic. Their chemical, texture, and mineralogy are similar in many respects to chondrites. They are fine-grained, equigranular rocks (Fig. 1a)

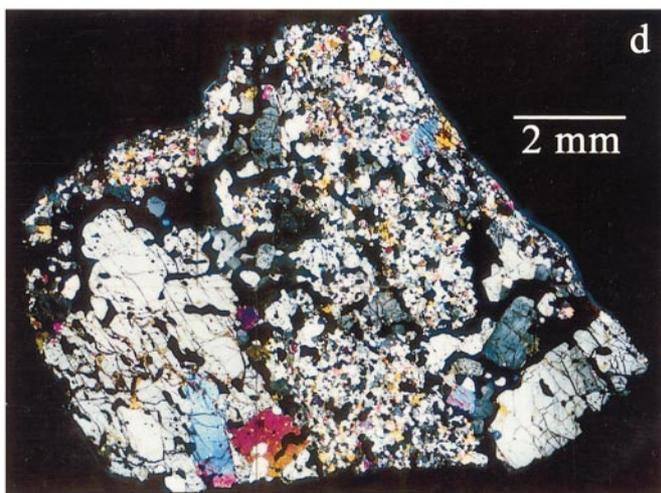
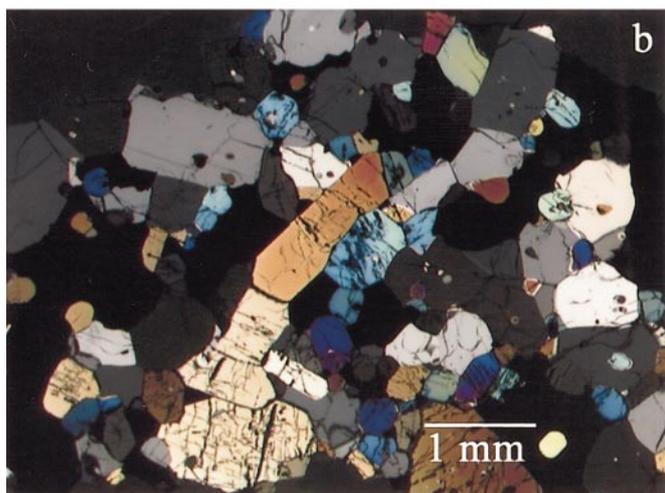
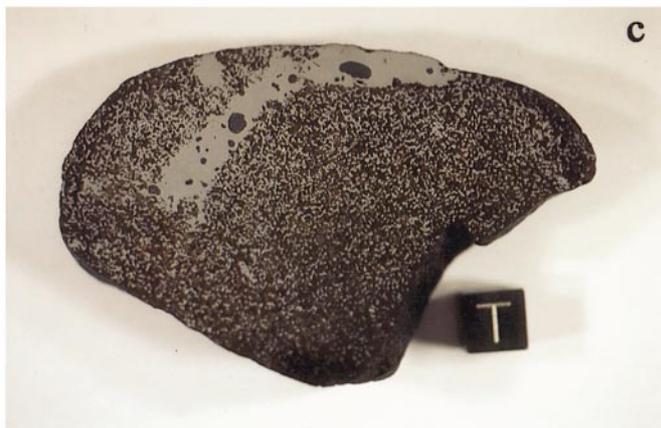
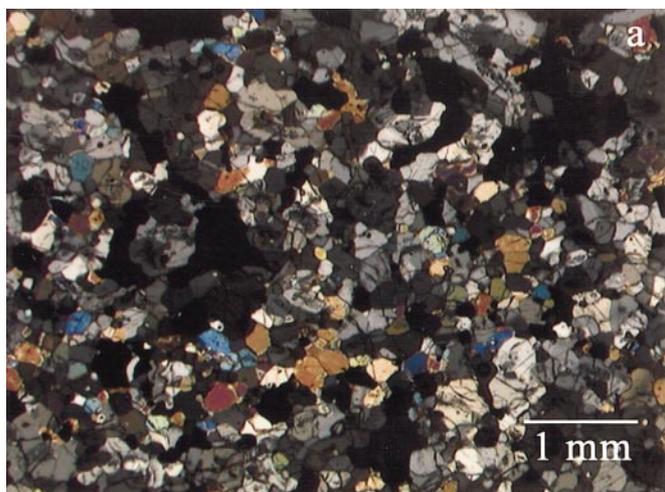


FIG. 1. Photos of acapulcoites and lodranites. (a) Acapulco is a fine-grained equigranular rock composed of pyroxene, olivine, plagioclase, metal, and sulfide—a broadly “chondritic” mineralogy. (b) Lodran, shown to the same scale as Acapulco, is a much coarser-grained rock. It is a residue of partial melting, containing pyroxene, olivine, and metal, with no plagioclase and only minor sulfide. (c) Graves Nunataks (GRA) 95209 contains a large vein of metal, rich in phosphorus and carbon. This vein is a trapped sample of the cotectic Fe,Ni–FeS partial melt formed around 950°C. Cube is 1 cm on a side. (d) Lewis Cliff (LEW) 86220 contains a coarse-grained lithology of plagioclase, pyroxene, metal, and sulfide, which samples the basaltic partial melts complementary to the residual lodranites.

with average grain sizes (150–230 μm ; McCoy *et al.* 1996) only slightly greater than equilibrated chondrites. Several members of the group (e.g., Monument Draw, Yamato 74063, and GRA 98028) contain rare relict chondrules (Yanai and Kojima 1991, McCoy *et al.* 1996), pointing to a chondritic precursor. All members of the group have mineralogies dominated by orthopyroxene, olivine, chromian diopside, sodic plagioclase, Fe,Ni metal, and troilite, a mineral assemblage similar to that of ordinary chondrites. Mafic silicate compositions (olivine, $\text{Fa}_{4.2-11.9}$; orthopyroxene, $\text{Fs}_{6.5-12.6}$) are intermediate between enstatite and H-group ordinary chondrites. The reduced nature of the acapulcoites is also reflected by their orthopyroxene/olivine ratio, which is higher in acapulcoites (~ 1.9 ; Hiroi and Takeda 1991) than in H-group ordinary chondrites (~ 0.8 ; McSween *et al.* 1991). These similarities have led several authors (e.g., Yanai and Kojima 1991) to suggest that acapulcoites are chondritic rocks intermediate between E and H chondrites.

While acapulcoites share a number of features in common with known chondrites, there are important differences. Most importantly, acapulcoites have experienced more extensive heating than chondrites, leading to destruction of the chondrule-matrix texture typical of chondrites and creating micrometer- to centimeter-sized veins of metal and troilite which appear to have migrated only locally (McCoy *et al.* 1996). As we discuss in a later section, melt migration was limited and the bulk major element composition of these rocks remains essentially unchanged from their chondritic precursors. Peak temperatures for these rocks probably reached 950–1050°C (McCoy *et al.* 1996).

Prior to melting, the chondritic precursor to acapulcoites and lodranites differed from known chondrites in a variety of properties, including their oxygen isotopic composition, mafic silicate composition (intermediate between E and H chondrites), and the relative abundances of olivine and pyroxene (higher px/ol ratio than observed in H chondrites). This difference in relative mineral abundances is, potentially, measurable from orbit.

Lodranites—Residues from Partial Melting

The 12 rocks classified as lodranites are a diverse group both chemically and mineralogically, although they share the common feature of being residues from partial melting. Lodranites are coarser-grained than acapulcoites, with average grain sizes of ~ 500 – $600 \mu\text{m}$ (McCoy *et al.* 1997a) (Fig. 1b). They have equigranular textures with abundant 120° triple junctions indicative of extensive heating. All traces of chondritic texture have been erased. Like acapulcoites, they exhibit a broad range of mineral compositions ($\text{Fa}_{3.1-13.3}$, $\text{Fs}_{3.7-13.8}$) intermediate between E and H chondrites. They vary dramatically in pyroxene/olivine ratio, from ~ 1.9 to ~ 0.4 (Hiroi and Takeda 1991). They also vary dramatically in abundances of feldspar (0–11.4 vol%), troilite (FeS) (0.2–5.3 vol%), and Fe,Ni metal (0.5–20 vol%) (McCoy *et al.* 1997a and references therein). Thus, these rocks, as a group, are silicate-dominated, with either olivine or orthopyroxene as the major phase, with lesser feldspar, metal, and troilite. The similarities in mineralogy and

mineral compositions, as well as the occurrence of members intermediate in texture between classic acapulcoites and lodranites (e.g., EET 84302) support a common parent body for these groups. The differences between lodranites can be largely traced to partial melting and migration of Fe,Ni–FeS melts (beginning at $\sim 950^\circ\text{C}$) and basaltic partial melts (beginning at $\sim 1050^\circ\text{C}$). Peak temperatures for those depleted in both troilite and plagioclase must have reached $\sim 1250^\circ\text{C}$ (McCoy *et al.* 1997a).

Partial Melts within Acapulcoites and Lodranites

Acapulcoites and lodranites contain within them rare examples of the trapped partial melts which have accumulated into larger volumes and been trapped during cooling and crystallization. Centimeter-scale veins predominantly composed of metal with lesser amounts of sulfides, phosphides, phosphates, and graphite occur in the acapulcoite Monument Draw and the lodranite GRA 95209 (Fig. 1c) (McCoy *et al.* 1996, McCoy and Carlson 1998). In Acapulco and Monument Draw, we also find veins composed almost entirely of phosphates (McCoy *et al.* 1996). These metal–sulfide–phosphate veins form relatively early in the process of partial melting. They are found in rocks which experienced little, if any, silicate partial melting and, thus, the silicate matrix acted as a solid which could be fractured and migrating Fe,Ni–FeS cotectic melts (formed at $\sim 950^\circ\text{C}$ and rich in phosphorus) formed veins.

A more complex melt is found in the unusual meteorite Lewis Cliff (LEW) 86220. In this rock, a coarse-grained region composed of Fe,Ni metal, troilite, plagioclase, augite, and orthopyroxene occurs within a finer-grained region which is similar in mineralogy and texture to an acapulcoite (Fig. 1d). McCoy *et al.* (1997b) interpreted this assemblage as a basaltic Fe,Ni–FeS melt which had migrated out of the lodranite source region and was trapped in a cooler acapulcoite source. A similar conclusion was reached based on trace element signatures in the minerals of this melt lithology (Floss 2000). Thus, this coarse-grained region, which is only ~ 1 cm in diameter, is our best sample of the basaltic materials formed during partial melting. The commingling of melts complementary to lodranites and an acapulcoite host further strengthen the interpretation of a common parent asteroid.

While existing samples of the separated partial melts are at scales of less than 10 cm, there is some reason to believe that they may have formed larger masses. Modeling of dike propagation on the acapulcoite-lodranite parent body (McCoy *et al.* 1997b) suggests that these veins might have high length/width ratios on the order of 100–1000. Thus, centimeter-wide veins might have lengths approaching several meters and meter-wide veins would have lengths approaching 1 km. Finally, while veins may have trapped some of the migrating material in subsurface conduits, much of it may have reached the surface where, on larger bodies, it might have formed surficial lava flows. We have not sampled such materials as meteorites to date, but the expectation is that migrating partial melts could easily form bodies exceeding 1 m in dimension.

A Regolith on the Acapulcoite–Lodranite Parent Body?

While meteorites provide an excellent record of the geologic processes that occur on asteroids, it is not clear that they are representative of the regolith that exists today on asteroids and that is measurable with spectral reflectance or X-ray/gamma-ray spectrometry. The existence of regolith, particularly one which is globally homogenized and highly altered by the range of processes collectively termed “space weathering,” could substantially obscure the subsurface geology and make many of the arguments for lithologic diversity presented here irrelevant. None of the acapulcoites and lodranites in our collections are breccias, let alone regolith breccias that have been exposed to the space environment at the surface of the asteroid. This may simply be a feature of the small number of acapulcoites and lodranites, since gas-rich regolith breccias comprise only $\sim 3\%$ of the more abundant ordinary chondrites (Britt and Pieters 1991).

It is interesting to speculate, however, about the nature of such a regolith. Chemically and mineralogically, the regolith of such a parent body would be expected to contain components derived from both acapulcoites and lodranites and, possibly, fragments of basaltic material that migrated to the surface of the asteroid. If the material was comminuted to micrometer-sized fragments, it would be extremely difficult to establish their parentage (acapulcoites vs lodranites). However, even the lunar soils contained larger rock fragments that could be confidently attributed to a parent lithology.

We suggest that regolith on the acapulcoite-lodranite parent body may be loose rubble owing to the metal-rich nature of acapulcoites and lodranites. The world’s iron meteorite collection contains no true breccias (Buchwald 1975)—rocks formed by consolidation of fragments of other rocks—possibly because of the difficulty in cementing metal-rich fragments by subsequent impact. While metal–silicate mixtures are known from a number of meteorite groups (e.g., IAB irons, pallasites, mesosiderites), all of these were formed when at least one component was molten and all formed very early in the history of the Solar System. If metal-rich fragments cannot be easily consolidated into brecciated rocks, regolith breccias may not even exist on the surface of the acapulcoite–lodranite parent body.

SPATIAL SCALE

While the lithologic heterogeneity on the acapulcoite–lodranite parent body is impressive, its detection on the surface of the asteroid requires that the various units be separated by distances in excess of the spatial resolution of the spacecraft instruments. In the case of NEAR, spatial resolution ranges from a few meters for the multispectral imager through 1–2 km for the near-infrared spectrometer and X-ray spectrometer to nearly 10 km for the gamma-ray spectrometer. Ideal spatial heterogeneity for these various lithologies would be on the order of 1–2 km.

Recovered acapulcoites and lodranites tend to be small in mass (less than 1 kg, typically a few tens of grams) and, thus, small in dimensions (less than 10 cm in diameter). It is rare

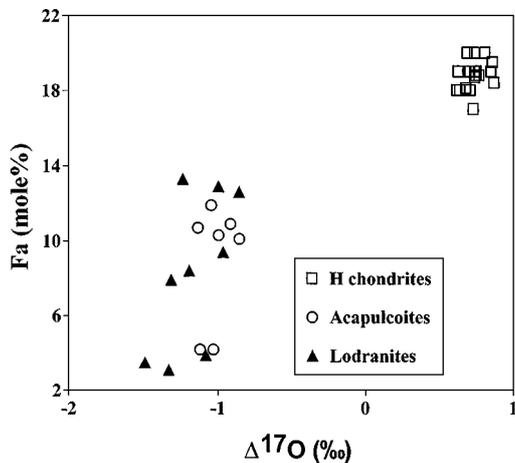


FIG. 2. Average fayalite (Fa) concentration in olivine versus $\Delta^{17}\text{O}$ in the whole-rock for H chondrites, acapulcoites, and lodranites. Data are taken from Graham *et al.* (1985) and references therein, Clayton *et al.* (1991), and McCoy *et al.* (1996, 1997a) and references therein. The δ notation indicates deviation in isotopic ratios from a known standard ($\delta^i\text{O} = (((^i\text{O}/^{16}\text{O})_{\text{sam}}/(^i\text{O}/^{16}\text{O})_{\text{std}}) - 1) \times 1000$). The Δ notation indicates perpendicular offset from the line defined by all terrestrial materials (the terrestrial mass fractionation line) ($\Delta^{17}\text{O} = \delta^{17}\text{O} - 0.52 \delta^{18}\text{O}$). The preservation of mineralogical and isotopic heterogeneity in acapulcoites and lodranites suggests separation by distances in excess of 200 m. This scale of heterogeneity should be resolvable by spacecraft-based remote sensing instrumentation.

that we find multiple lithologies in direct contact, although the basaltic Fe,Ni–FeS melts within the acapulcoite host of LEW 86220 provides such an exception. Do we have any evidence that a significant distance separated these meteorites? Figure 2 plots the fayalite concentration of olivine versus the $\Delta^{17}\text{O}$ (the perpendicular offset from the terrestrial mass fractionation line on a plot of $\delta^{17}\text{O}$ vs $\delta^{18}\text{O}$) for H chondrites, acapulcoites, and lodranites. Two features become obvious. First, acapulcoites and lodranites exhibit almost complete overlap on this plot, providing further evidence of their origin from a common parent body. Second, acapulcoites and lodranites exhibit much greater ranges than H chondrites. In particular, $\Delta^{17}\text{O}$ varies by 0.64‰ in the acapulcoites and lodranites, compared to 0.25‰ in the H chondrites. McCoy *et al.* (1997a) have argued that the range of olivine and oxygen isotopic compositions observed in acapulcoites and lodranites is a preserved nebular feature not erased during the extensive thermal processing experienced by these rocks. Heterogeneity in olivine and oxygen isotopic compositions is also observed in ureilites (Clayton and Mayeda 1988). For the ureilites, Scott *et al.* (1993) have argued that the preservation of oxygen isotopic heterogeneities can be used to infer spatial separation of these rocks. Using measured oxygen diffusion rates, diffusion distances of about 200 m for basaltic melt and about 3 mm for olivine would occur at 1200°C in 10 Myr (Jaoul *et al.* 1980, Wendlandt 1991). These are plausible thermal conditions for melting of the acapulcoite–lodranite parent body and, certainly, abundant evidence exists to suggest that basaltic melts were present and migrating on this body. Thus, we would infer

spatial separation in excess of 200 m for the group of acapulcoites and lodranites. Given the migration of basaltic melt on the acapulcoite–lodranite parent body, which would probably increase the effective diffusion distance, it seems reasonable to infer spatial scales approaching 0.5 km or greater. This implies that the spatial resolution of remote sensing instruments, such as those carried by NEAR, could allow detection of lithologic heterogeneity on a partially differentiated asteroid. At the least, we should be able to detect multiple lithologies clearly with the spatial resolution of an instrument like the NEAR multi-spectral imager, even if they are not easily resolved with the coarser-resolution near-infrared spectrometer or X-ray/gamma-ray spectrometer.

SPECTRAL HETEROGENEITY

We have documented significant mineralogical and compositional variability within acapulcoites and lodranites. We expect that these differences will manifest themselves in the spectral features of these meteorites. Olivine and pyroxene abundances, compositions, and particle size control the depth and position of the 1- and 2- μm features. The differences should be observed in both the spectra and the derived spectral parameters. The most notable of these parameters is the band area ratio (ratio of the areas of the 2- and 1- μm features) that Cloutis *et al.* (1986) have found is directly related to the pyroxene/olivine abundance ratio and is relatively insensitive ($<10\%$) to mafic mineral chemistry. In the case of the acapulcoites and lodranites, the higher pyroxene/olivine ratio compared to ordinary chondrites should produce a higher band area ratio.

Spectra for the lodranites Yamato 74357 and Yamato 791491 and the acapulcoite ALH A77081 (Hiroi and Takeda 1991, Hiroi *et al.* 1993a) are plotted in Fig. 3a. Their mineralogy varies from relatively olivine-rich (83% olivine, 9% pyroxene, 8% metal and troilite in Yamato 74357) to intermediate (42% olivine, 28% pyroxene, 30% metal and troilite in Yamato 791491) to pyroxene-rich (16% olivine, 62% pyroxene, 10% metal and troilite in acapulcoite ALH A77081) (Hiroi *et al.* 1993a). Spectral features reflect these differences in mineralogy, with the olivine-rich lodranite Yamato 74357 exhibiting a weak 2- μm absorption feature, while Yamato 791491 and ALH A77081 exhibit stronger 2- μm features.

While these spectra exhibit some features consistent with their mineralogies, all of these spectra were measured on the surfaces of unprocessed chips. Chip spectra have suppressed spectral features compared to those of powders (Hiroi *et al.* 1993b, Burbine 2000) and chips are clearly not representative of the finely comminuted material likely to occur on asteroidal surface. Further, these spectra exhibit signs of terrestrial weathering in the form of very strong UV features and the absorption bands at 0.50 and 0.65 μm (Hiroi *et al.* 1993a).

These problems are particularly apparent in the derived spectral parameters. Figure 3b plots band area ratios versus band I (1 μm feature) center wavelengths for acapulcoites (Acapulco,

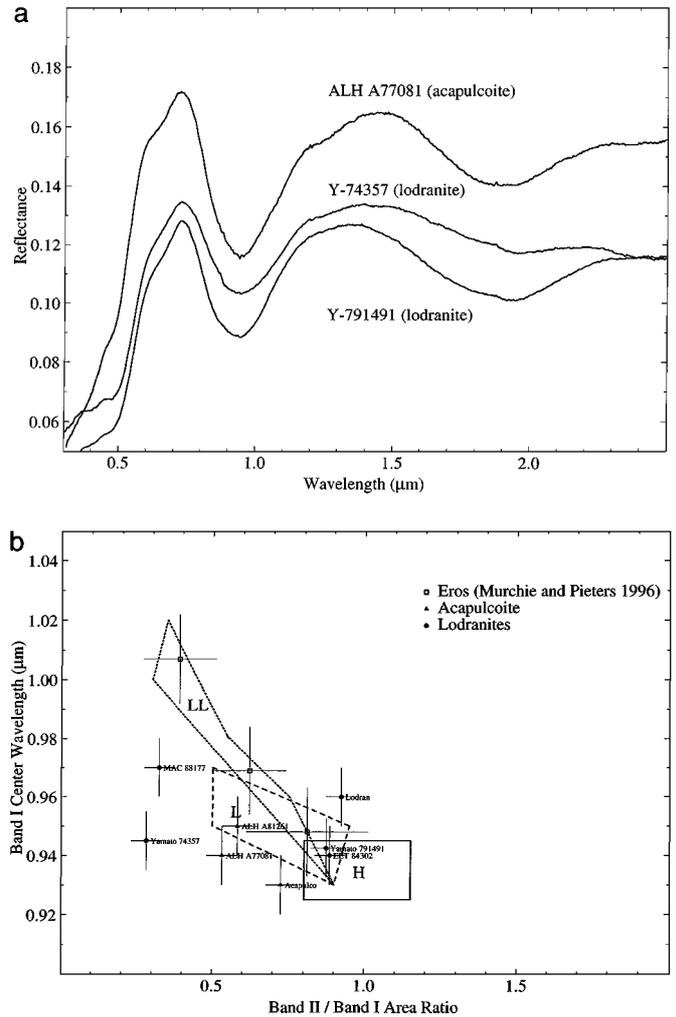


FIG. 3. (a) Reflectance versus wavelength for the acapulcoite ALH A77081 and lodranites Yamato 74357 and Yamato 791491. All spectra are measurements of chips. Acapulcoite and lodranite data from Hiroi and Takeda (1991) and Hiroi *et al.* (1993a). Dramatic differences in the strength of the 2- μm absorption feature reflect highly variable pyroxene/olivine ratios. (b) Band II/Band I area ratio versus Band I center wavelength for acapulcoites, lodranites, ordinary chondrites, and Eros. The acapulcoite and lodranite parameters are taken from spectra in Hiroi *et al.* (1993a) and Hiroi (pers. commun.). The estimated ordinary chondrite fields are taken from Gaffey and Gilbert (1998). Eros parameters are taken from Murchie and Pieters (1996) and are for a pyroxene-rich hemisphere, an olivine-rich hemisphere, and an average composition.

ALH A77081, ALH A81261) and lodranites (Lodran, MAC 88177, EET 84302, Yamato 74357, Yamato 791491) (T. Hiroi pers. commun.), ordinary chondrites (H, L, and LL) (Gaffey and Gilbert 1998), and 433 Eros (Murchie and Pieters 1996). Primitive achondrites, which have pyroxene/olivine ratios ranging from ~ 1.9 to ~ 0.4 , should have band area ratios ranging from ~ 1.5 to ~ 0.5 , respectively (Cloutis *et al.* 1986). In fact, measured spectra for acapulcoites and lodranites yield band area ratios ranging from ~ 0.3 to ~ 0.9 . Also note that while spectral differences exist between individual acapulcoites and lodranites, no systematic difference is seen between these two groups.

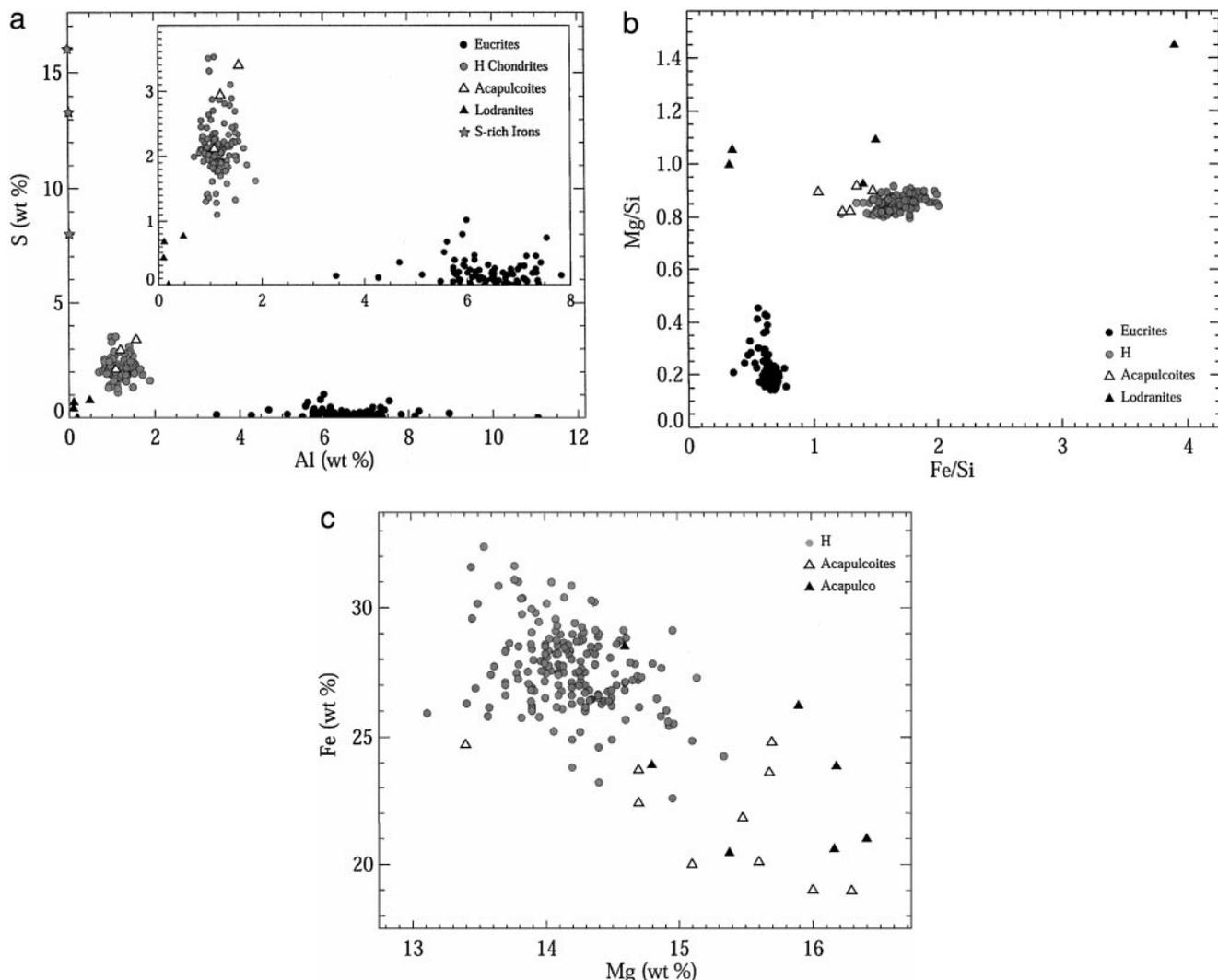


FIG. 4. (a) Aluminum and sulfur abundances measured in bulk samples of five classes of meteorites. (Inset) An expanded view of most of the data. Acapulcoites are similar to chondrites, while the other classes are clearly distinguished due to the effects of partial melting and melt migration. A similar range in S and Al abundances would be expected at the surface of a partially melted asteroid. Data are taken from a large database of literature meteorite analyses compiled at NASA/Goddard Space Flight Center (Nittler *et al.* 2000). Major sources of the plotted data include Jarosewich (1990), Kallemeyn *et al.* (1989), Mittlefehldt *et al.* (1998) and references therein, Urey and Craig (1953), and Yanai and Kojima (1995). (b) Mg/Si and Fe/Si ratios measured in four classes of meteorites; these ratios are easily measured by remote-sensing X-ray/gamma-ray spectrometry and distinguish meteorites which have undergone melt separation (eucrites, lodranites) from those that have not (chondrites, acapulcoites). (c) Iron and magnesium concentrations measured in H chondrites, acapulcoites, and seven samples of the Acapulco meteorite. The range of Fe and Mg abundances reported for Acapulco span the range observed in the entire class of acapulcoites, illustrating the difficulty of determining “bulk” abundances for heterogeneous samples.

Suggestive evidence of significant spectral heterogeneity within the acapulcoites and lodranites can be found in the existing spectra. However, a more complete set of acapulcoite and lodranites spectra is clearly desirable. We are currently undertaking spectral measurements of a variety of acapulcoites and lodranites, in both chip and powdered form and acid-washed to remove weathering, to address some of these questions. This new data set should allow us to determine the range of expected heterogeneity on an acapulcoite–lodranite parent body, as well as how the spectral parameters will differ from other meteorite groups.

COMPOSITIONAL HETEROGENEITY

The NEAR spacecraft includes X-ray and gamma-ray spectrometers (XGRS) to measure the surface elemental composition of 433 Eros on a scale of 2–3 km for X-rays to ~25% of the asteroid for gamma-rays. The elemental composition of an asteroid should reflect both initial variations in the precursor nebular materials from which it formed and variations due to subsequent geological processing (e.g., thermal differentiation, impact mixing). To examine the expected range of compositions for a partially melted asteroid, we consider bulk compositions

measured in five groups of meteorites. H-type ordinary chondrites represent the unprocessed starting material from which asteroids accumulated. Acapulcoites are representative of chondritic rocks that have undergone some thermal processing but not significant melt-migration. Partial melts are represented by the best-known class of meteoritic basalts, the eucrites, while lodranites are residues of partial melting. Finally, sulfur-rich iron meteorites represent the compositions of Fe,Ni-FeS partial melts. Bulk compositions are taken from a large database of published meteoritic measurements (Nittler *et al.* 2000).

Aluminum and sulfur, plotted in Fig. 4a for our five meteorite classes, are particularly diagnostic of igneous processing. As discussed above, acapulcoites have roughly chondritic compositions, hence their overlap on this plot with the field of H chondrites. The other groups are clearly distinguished from each other and from the chondrites and acapulcoites. As partial melting and melt migration occurs, the incompatible element Al strongly partitions into the silicate melts (eucrites), S partitions into Fe,Ni-FeS melts (S-rich irons), while the lodranite residues are clearly depleted in the two elements. Thus, an asteroid that has undergone partial melting might be expected to exhibit a large range of Al and S abundances, depending on what type of rock dominates in a given location. Both elements are in principle observable by the NEAR X-ray spectrometer, but their relatively low concentrations in undifferentiated meteorites might make detection limits a problem. A spatially heterogeneous detection of Al and/or S on Eros would likely indicate partial melting and melt migration has occurred to some extent on the asteroid.

Determining elemental abundance ratios from remote-sensing XGRS data is easier than obtaining absolute abundances because measuring elemental ratios eliminates many uncertain geometrical factors affecting the production of x-rays and gamma-rays from a planetary surface. Figure 4b shows Fe/Si plotted against Mg/Si for four of our meteorite classes (the S-rich iron meteorites do not contain significant Mg or Si). Iron, magnesium, and silicon are much more abundant in common rock types than Al and S and the NEAR XGRS should be able to determine these ratios with little difficulty. As in Fig. 4a, the different rock types are distinguished on this plot, but the variations are not as extensive as in the case of Al and S. Again the acapulcoites are broadly similar to the H chondrites. The slight differences in bulk composition between these two classes probably reflect nebular variations. The eucrites are depleted in Mg and Fe and enriched in Si, relative to their chondritic precursors. The lodranites show a much larger range in Fe/Si than the other plotted meteorite classes; this reflects the large variations in both silicate compositions and amount of metal in these meteorites, as discussed earlier.

As exemplified by Figs. 4a and 4b, an important diagnostic characteristic for a partially melted asteroid should be extensive heterogeneity in surface elemental composition, with some regions appearing chondritic and other regions reflecting the effects of igneous differentiation. This differs strongly from expectations for other types of asteroids. A completely unmelted

asteroid should have a homogenous chondritic bulk composition. A completely differentiated asteroid might be expected to have a surface dominated by basaltic material similar to the eucrites. Regions with chondritic composition would certainly not be expected on such a body, and assuming core formation has occurred, nor would large regions of Fe,Ni metal. Of course, this discussion ignores the possible effects of impact mixing and regolith formation (see above), but it is clear that the effects of partial melting could be inferred from remote-sensing compositional measurements.

We note that laboratory measurements of bulk meteorite compositions should be considered with care. Compositional variations between different members of a given class can arise due to intrinsic heterogeneity in the class, analytical errors, and terrestrial weathering. Moreover, many bulk analyses of meteorites use relatively small (<1 g) samples, leading to the possibility of unrepresentative samples. Potential difficulties are illustrated by Fig. 4c, which shows iron and magnesium concentrations in H chondrites, acapulcoites and seven reported analyses of the Acapulco meteorite. The apparent ranges in the H chondrites are certainly larger than the intrinsic ranges in this class, due to the inclusion in the data set of many weathered meteorite finds, especially Antarctic meteorites. More interestingly, the reported abundances of Fe and Mg in different samples of Acapulco span the ranges reported for the entire class of acapulcoites. Since Acapulco was an observed fall, it has experienced little weathering, and the observed range probably reflects both sampling error of this heterogeneous rock and analytical error. In any case, Figs. 4a and 4b clearly show that the compositional ranges expected for a partially melted asteroid far exceed variations reported for any class of meteorites.

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