NEAR-SHOEMAKER AT EROS: THE FIRST DETAILED EXPLORATION OF AN ASTEROID

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On 14 February 2000, a small robotic probe entered orbit around the asteroid 433 Eros to undertake a groundbreaking mission aimed largely at clarifying the relationships between asteroids in space and meteorite samples collected on Earth. The Near Earth Asteroid Rendezvous (NEAR) mission (Cheng et al. 1997) was the first in NASA's line of "faster, better, cheaper" Discovery planetary missions. Launched on 17 February 1996, the NEAR spacecraft (later renamed NEAR-Shoemaker[2] in honor of pioneering astrogeologist Eugene Shoemaker) collected images and spectra during a ~1200 km flyby of asteroid 253 Mathilde in 1997 (Veverka et al. 1999). The Eros orbit insertion on Valentine's Day 2000, appropriate for a mission to a body named for the Greek god of love, began a successful year of data collection by a suite of scientific instruments, culminating in a controlled descent and gentle landing on the asteroid's surface on 12 February 2001. The mission ended two weeks later, just over 5 years after launch.

As an S-class asteroid, Eros is typical of the most abundant asteroids of the inner main belt, which are postulated to be progenitors of the ordinary chondrites (OCs). However, as a Mars-crossing Amor asteroid (perihelion distance of 1.133 AU), Eros was reachable by a relatively low-cost spacecraft. The geological, mineralogical, and geochemical data obtained by NEAR from Eros support the relationship between S-class asteroids and OC meteorites (McCoy et al. 2002) and laid the groundwork for the recent successes of Hayabusa and Dawn in their investigations of 25143 Itokawa and 4 Vesta (Tsuchiyma 2014 this issue; McSween et al. 2014 this issue).

GEOLOGY

Eros is a potato-shaped body, roughly 35 km long by 10 km across, marked by impact features large and small and a huge number of boulders (Fig. 1). Its inferred bulk density of ~2.7 g/cm^3 (Veverka et al. 2000) is too high for it to be a rubble pile and suggests rather that the asteroid is a coherent body, but with significant porosity due to large-scale fracturing from impacts. The NEAR magnetometer detected no hint of a magnetic field, consistent with Eros being a primitive, undifferentiated object. NEAR returned more than 160,000 images of Eros acquired at a variety of resolutions and under different lighting conditions. These images revealed abundant features, including grooves and ridges, depressions, crater chains, and rectilinear craters, and showed the asteroid to be covered by a thick layer of fragmental debris (regolith). Particularly interesting was the discovery of deposits known as "ponds" (Robinson et al. 2001). These are smooth deposits that have infilled many craters and depressions (Fig. 1c). They are possibly due to preferential movement of extremely fine regolith material via electrostatic levitation and thus might represent a physical fractionation of material by size across the surface. Based on the final images returned by the spacecraft during its controlled descent, it is believed that NEAR's landing site was in fact in one of these dusty ponds. More recently, Hayabusa discovered similar ponds on Itokawa (Yano et al. 2006), suggesting that they are a common asteroidal feature.

MINERALOGY

Reflectance spectroscopy is a widely used tool for inferring mineralogical information from rocky planets, including asteroids. Particularly useful are near-infrared spectral absorption features (bands) at wavelengths around 1 and 2 microns arising from the common Fe-bearing silicate minerals olivine and pyroxene. Data from the Near-Infrared Spectrometer onboard NEAR both confirmed ground-based measurements indicating the presence of the 1- and 2-micron bands and

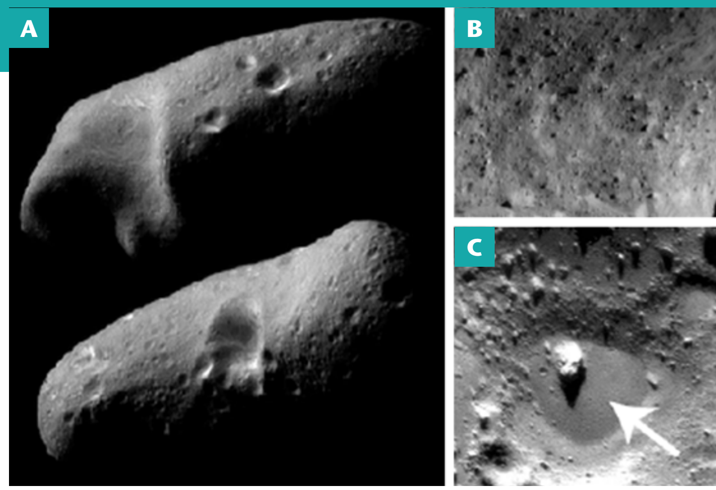

Figure 1 Images of Eros taken by the NEAR spacecraft (NASA/JHU/APL). (**A**) Global view of two sides of Eros, revealing its battered surface. (**B**) View (~1 km across) showing numerous boulders. (**C**) Smooth "ponded" deposit about 100 m across (arrow).

revealed a remarkable degree of mineralogical uniformity across the surface (McFadden et al. 2001; Bell et al. 2002). The nature of these spectral features (e.g. band centers, band area ratios) depends on the relative amounts of olivine and pyroxene as well as on the composition of the minerals, and analysis of the Eros data indicates a silicate composition similar to (but not unique to) that of OC meteorites. However, as commonly seen in ground-based observations of S-asteroids, the near-infrared reflectance spectrum of Eros is considerably redder, that is, it has a more steeply increasing slope at longer wavelengths, compared to laboratory measurements of OCs. This discrepancy is generally attributed to "space weathering," the alteration of the optical properties of the surface materials due to bombardment by radiation and micrometeoroids.

CHEMICAL COMPOSITION

NEAR carried two instruments designed to directly determine the chemical composition of Eros: the X-ray Spectrometer (XRS) and the Gamma Ray Spectrometer (GRS). XRS detected fluorescent X-rays emitted from surface atoms of Mg, Al, Si, S, Ca, Cr ,and Fe (<100 µm depth) under solar X-ray bombardment, and GRS detected gamma ray emission from the top tens of centimeters due to natural radioactive decay (^{40}K) or to interactions with galactic cosmic rays (O, Mg, Si, Fe). XRS acquired its best data during several solar flares, periods of enhanced solar X-ray emission, when it was sampling regions across the asteroid. GRS did not obtain interpretable signals during orbit. However, following NEAR's controlled descent, GRS was fortuitously in an ideal orientation to carry out surface measurements, and the mission was extended a week to obtain high signal-to-noise gamma ray data at the landing site.

For most of the elements measured by either XRS or GRS (in particular Mg/Si, Al/Si, and Ca/Si ratios and K abundance), Eros's surface was found to have a composition most consistent with that of OC meteorites (H, L, and LL chondrites; Fig. 2), compared to other types of asteroidal meteorites (Trombka et al. 2000; Evans et al. 2001; Nittler et al. 2001). The Fe/Si ratio was also found to be consistent with OCs. However the values measured by the two instruments did not agree with each other, with the XRS measurements indicating high (H chondrite–like) iron contents and the GRS showing lower (L- or LL-like) ones (Fig. 2b). This difference is not fully understood. It may reflect a systematic uncertainty in one or both of the measurement techniques, not taken into account in the analysis methodology (Okada 2004). Alternatively, it may indicate a local difference in Fe/Si at the NEAR landing site, where the GRS measurement was made, compared to the larger-scale XRS measurements. The latter possibility could be explained by a physical separation of Fe metal grains from finer-grained silicate material during

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2 Abbreviated to NEAR throughout the text

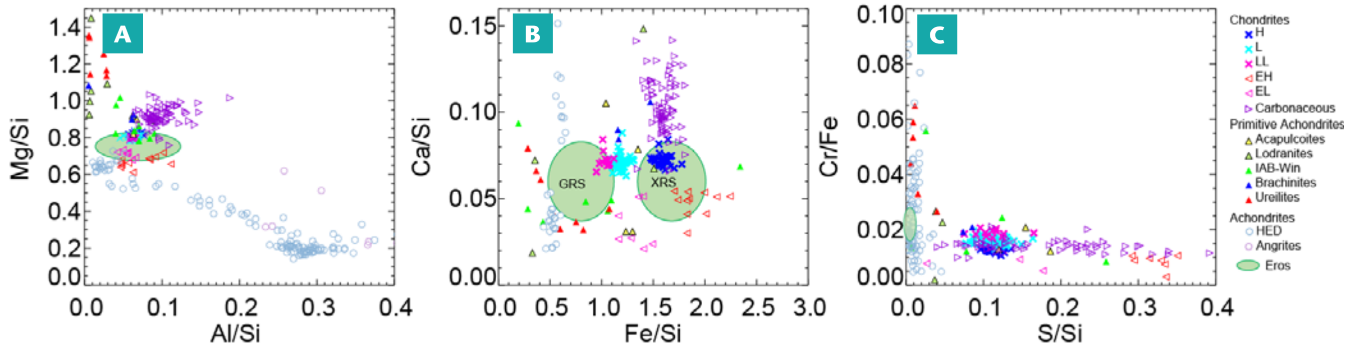

FIGURE 2 Element weight ratios on Eros (green ellipses) compared to laboratory data for meteorites (Nittler et al. 2004). (**A**) Mg/Si versus Al/Si, both determined by XRS. (**B**) Ca/Si (XRS) versus Fe/Si (XRS and GRS). (**C**) Cr/Fe versus S/Si, both determined by XRS. Except for a strong S depletion, Eros's surface is most consistent with the composition of ordinary chondrite (H, L, LL) meteorites. The OC-like Cr/Fe ratio argues for a space weathering explanation for the low S/Si ratio. XRS data are from Trombka et al. (2000), Nittler et al. (2001), Foley et al. (2006), and Lim and Nittler (2009); GRS data are from Evans et al. (2001).

the formation of the pond deposit on which NEAR most likely landed. In any case, the range of measured Fe/Si ratios is consistent with undifferentiated, chondrite-like compositions.

A major surprise of NEAR geochemical measurements was the discovery that the surface of Eros is highly depleted in sulfur; the XRS-derived S/Si ratio is an order of magnitude lower than that of OCs (Fig. 2c). Two possible explanations were originally suggested to explain this strongly nonchondritic composition (Trombka et al. 2000). First, the space weathering processes invoked to explain the red slope of Eros's near-infrared reflectance spectrum (micrometeoroid and/or ion bombardment) could in principle also preferentially remove surface S, relative to less volatile species. If so, the observed S depletion would be essentially a surface regolith effect, and the bulk of Eros could have OC-like S/Si ratios. Alternatively, Trombka et al. (2000) pointed out that the first melt to form when chondritic material is heated is rich in S, so the observed S depletion could instead reflect a limited amount of partial melting and melt separation in a mainly undifferentiated body. In this case, Eros might represent a type of "primitive achondrite" akin to some known meteorite groups (McCoy et al. 2000), rather than being directly related to OCs. Subsequently, Foley et al. (2006) noted that Cr is also likely strongly affected by limited degrees of partial melting, and through a reanalysis of two XRS solar flare spectra, they determined that Eros has a chondritic Cr/Fe ratio (Fig. 2c). This result strongly suggests that Eros has not undergone partial melting, but rather is an OC-like body whose surface S has been lowered through interactions with the space environment. The feasibility of S loss through space weathering as well as the general importance of FeS in asteroidal space weathering have subsequently been demonstrated experimentally (Loeffler et al. 2008; Keller et al. 2013). Note that X-ray fluorescence observations of Itokawa by the Hayabusa spacecraft did not find evidence for a large sulfur depletion on this S-class asteroid, as seen on Eros (Arai et al. 2008), though errors are large due to low solar activity during the orbital phases of the Hayabusa mission. However, the analysis of returned Itokawa samples has shown clear evidence for space weathering, in many cases clearly involving S mobilization (Noguchi et al. 2011).

NEAR was a milestone in the exploration of the Solar System and in advancing understanding of the relationships between asteroids and meteorites. The mineralogical and geochemical data returned by NEAR strongly indicate that Eros is a space-weathered, undifferentiated body with affinities to OC meteorites. However, ambiguities inherent in all remotely sensed data accentuate the additional need for sample return, as spectacularly demonstrated by the combined robotic-exploration / sample-return Hayabusa mission (Tsuchiyama 2014).

REFERENCES

Arai T, Okada T, Yamamoto Y, Ogawa K, Shirai K, Kato M (2008) Sulfur abundance of asteroid 25143 Itokawa observed by X-ray fluorescence spectrometer onboard Hayabusa. Earth, Planets and Space 60: 21-31

Bell JF and 20 coauthors (2002) Near-IR reflectance spectroscopy of 433 Eros from the NIS instrument on the NEAR mission. I. Low phase angle observations. Icarus 155: 119-144

Cheng AF and 6 coauthors AG (1997) Near Earth Asteroid Rendezvous: Mission overview. Space Science Reviews 82: 3-29

Evans LG and 9 coauthors (2001) Elemental composition from gamma-ray spectroscopy of the NEAR-Shoemaker landing site on 433 Eros. Meteoritics & Planetary Science 36: 1639-1660

Foley CN and 6 coauthors (2006) Minor element evidence that asteroid 433 Eros is a space-weathered ordinary chondrite parent body. Icarus 184: 338-343

Keller LP and 6 coauthors (2013) Asteroidal space weathering: The major role of FeS. 44th Lunar and Planetary Science Conference, Abstract 2404

Lim LF, Nittler LR (2009) Elemental composition of 433 Eros: New calibration of the NEAR-Shoemaker XRS data. Icarus 200: 129-146

Loeffler MJ, Dukes CA, Chang WY, McFadden LA, Baragiola RA (2008) Laboratory simulations of sulfur depletion at Eros. Icarus 195: 622-629

McCoy TJ, Nittler LR, Burbine TH, Trombka JI, Clark PE, Murphy ME (2000) Anatomy of a partially differentiated asteroid: A "NEAR"-sighted view of acapulcoites and lodranites. Icarus 148: 29-36

McCoy TJ, Robinson MS, Nittler LR, Burbine TH (2002) The Near Earth Asteroid Rendezvous mission to asteroid 433 Eros: A milestone in the study of asteroids and their relationship to meteorites. Chemie der Erde 62: 89-121

McFadden LA and 7 coauthors (2001) Mineralogical interpretation of reflectance spectra of Eros from NEAR near-infrared spectrometer low phase flyby. Meteoritics & Planetary Science 36: 1711-1726

McSween HY, De Sanctis MC, Prettyman TH, Dawn Science Team (2014) Unique, antique Vesta. Elements 10: 39-44

Nittler LR and 14 coauthors (2001) X-ray fluorescence measurements of the surface elemental composition of asteroid 433 Eros. Meteoritics & Planetary Science 36: 1673-1695

Nittler LR, McCoy TJ, Clark PE, Murphy ME, Trombka JI, Jarosewich E (2004) Bulk element compositions of meteorites: a guide for interpreting remote-sensing geochemical measurements of planets and asteroids. Antarctic Meteorite Research 17: 233-253

Noguchi T and 17 coauthors (2011) Incipient space weathering observed on the surface of Itokawa dust particles. Science 333: 1121-1125

Okada T (2004) Particle size effect in X-ray fluorescence at a large phase angle: Importance on elemental analysis of asteroid Eros 433). 35th Lunar and Planetary Science Conference, Abstract 1927

Robinson MS, Thomas PC, Veverka J, Murchie S, Carcich B (2001) The nature of ponded deposits on Eros. Nature 413: 396-400

Trombka JI and 23 coauthors (2000) The elemental composition of asteroid 433 Eros: Results of the NEAR-Shoemaker X-ray spectrometer. Science 289: 2101-2105

Tsuchiyama A (2014) Asteroid Itokawa: A source of ordinary chondrites and a laboratory for surface processes. Elements 10: 45-50

Veverka J and 13 coauthors (1999) NEAR encounter with asteroid 253 Mathilde: Overview. Icarus 140: 3-16

Veverka J and 32 coauthors (2000) NEAR at Eros: Imaging and spectral results. Science 289: 2088-2097

Yano H and 19 coauthors (2006) Touchdown of the Hayabusa spacecraft at the Muses Sea on Itokawa. Science 312: 1350-1353