Geological History of Asteroid 4 Vesta: The "Smallest Terrestrial Planet"

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The asteroid 4 Vesta is the only known differentiated asteroid with an intact internal structure, probably consisting of a metal core, an ultramafic mantle, and a basaltic crust. Considerable evidence suggests that the HED meteorites are impact ejecta from Vesta, and detailed studies of these meteorites in terrestrial laboratories, combined with ever more sophisticated remote sensing studies of the asteroid, have resulted in a good understanding of the geological evolution of this fascinating object. Extensive mineralogical, petrological, geochemical, isotopic, and chronological data suggest that heating, melting, and formation of a metal core, a mantle, and a basaltic crust took place in the first few million years of solar system history. It is likely that many more Vesta-like asteroids formed at the dawn of the solar system but were destroyed by impact, with the iron meteorites being remnants of their cores. Such differentiated objects may have played an important role in the accretion and formation of the terrestrial planets, and it is therefore highly desirable to explore by spacecraft this world that can be viewed as the smallest of the terrestrial planets.

1. INTRODUCTION

The world's collections contain meteorites from at least three sources: asteroids (tens of thousands), Earth's Moon (~26), and Mars (~26). Incredible progress has been made in recent years in the study of asteroidal meteorites, stimulated by the discoveries of thousands of new specimens in Antarctica and hot deserts. Among these many thousands of meteorites are many new types and rare individuals that represent asteroidal parent bodies heretofore unrepresented in our collections. Detailed studies of asteroidal meteorites have shown that, based on their mineralogical, chemical, and isotopic properties, an astonishing ~135 different asteroids are represented (*Meibom and Clark,* 1999). Although nearly all asteroids of which we have samples have been affected by postaccretionary heating to some degree (*Keil,* 2000), many (108 of the 135) were actually partially or completely melted and differentiated (*Meibom and Clark,* 1999).

One of the most fascinating asteroids is 4 Vesta. Remote sensing shows that it is a differentiated, nearly intact object with a basaltic crust (e.g., *McCord et al.,* 1970) and ultramafic mantle rocks (pyroxenite; olivine-bearing) exposed in a huge impact crater (e.g., *Binzel et al.,* 1997; *Gaffey,* 1997; *Thomas et al.,* 1997a). Modeling (e.g., *Righter and Drake,* 1997; *Dreibus et al.,* 1997) and density estimates (e.g., *Thomas et al.,* 1997b) further suggest that Vesta has a metal core and thus the asteroid is a differentiated object with crust, mantle, and core, analogous in its structure to the terrestrial planets, albeit much smaller in size. Vesta can therefore be thought of as the smallest of the terrestrial planets. Fortuitously, we are not restricted to remote sensing data for understanding the geological history of Vesta. The howardite-eucrite-diogenite meteorites (or HEDs; *Takeda et al.,* 1983), a large suite of differentiated basalts (eucrites), pyroxenites (diogenites), and breccia mixtures principally of these two rock types (howardites) (e.g., *Mason,* 1962; *Takeda et al.,* 1976; *Takeda,* 1979; *Mittlefehldt et al.,* 1998, and references therein) are, in all likelihood, impact-produced fragments of Vesta (e.g., *McCord et al.,* 1970; *Consolmagno and Drake,* 1977; *Drake,* 1979, 2001; *Binzel and Xu,* 1993; *Gaffey,* 1997). Their detailed study in terrestrial laboratories, combined with the remote sensing data and numerous modeling studies, have contributed to a reasonably good understanding of the complex history of this unique world.

Because much of the geological history of Vesta (i.e., heating, melting, fractionation, extrusion, and solidification of the basaltic crust) took place in the first 10 m.y. of solar system history (e.g., *Lugmair and Shukolyukov,* 1998; *Srinivasan et al.,* 1999; *Nyquist et al.,* 2001), it is of great interest for understanding the earliest differentiation of solar system bodies at the dawn of the solar system. The asteroid is also of interest because differentiated objects of this type are thought to have been the embryos that may have played an important role in the accretion and formation of the larger terrestrial planets (e.g., *Taylor and Norman,* 1990; *Carlson and Lugmair,* 2000).

In the present paper, I summarize the most important properties of Vesta, based on remote sensing data and the study of HEDs. I also use these data, supported by modeling studies, to outline Vesta's early geological history.

2. ORBIT, SIZE, SHAPE, MASS, AND DENSITY OF 4 VESTA

Asteroid 4 Vesta was discovered by H. W. Olbers in Bremen, Germany, on March 29, 1807 (*Pilcher,* 1979). It orbits the Sun at a mean heliocentric distance of a = 2.36 AU, has a proper eccentricity of e = 0.097, and a proper sine of inclination of sin i = 0.112 (*Williams,* 1989). Based on Hubble Space Telescope (HST) images, *Thomas et al.* (1997b) concluded that the asteroid is a triaxial ellipsoid of radii 289, 280, and 229 km, all ±5 km. This compares well with the earlier data of *McCarthy et al.* (1994) of 278 ± 12, 261 ± 9, and 232 ± 5 km (see also *Drummond et al.,* 1998). Its mean radius is 258 ± 12 km and its volume is ~7.19 ± 0.87 × 10^7 km^3 (*Thomas et al.,* 1997b). The mass of the asteroid has been estimated by *Schubart and Matson* (1979) to be 1.38 ± 0.12 × 10^{-10} $M_\odot$ or 2.75 ± 0.24 × 10^{20} kg, and by *Standish and Hellings* (1989) as 1.5 ± 0.3 × 10^{-10} $M_\odot$ or 2.99 ± 0.60 × 10^{20} kg [note that the recent mass estimate, based on perturbations of Vesta on 26 selected asteroids of 1.36 ± 0.05 × 10^{-10} $M_\odot$ by *Michalak* (2000), is very close to that of *Schubart and Matson* (1979)]. Using the *Thomas et al.* (1997b) volume and the *Schubart and Matson* (1979) mass yields a mean density of 3800 ± 600 kg/m^3, whereas the *Standish and Hellings* (1989) mass yields a density of 4100 ± 950 kg/m^3 [*Thomas et al.* (1997a) give 3500 ± 400 and 3900 ± 800 respectively].

3. THE HED-VESTA-VESTOID CONNECTION

The proposal that the HED meteorites are impact ejecta from Vesta has important implications for understanding the geological history of the asteroid. Detailed studies of the HEDs in terrestrial laboratories with sophisticated analytical techniques have provided a wealth of ground truth data that supplement the "global field geology observations" made possible by ever-improving remote sensing techniques. The link between the HED meteorites and Vesta was originally based on the similarities in the compositions of the HEDs and the surface mineralogy of Vesta, as determined by spectroscopy. More recently, dynamical considerations that connect the so-called "vestoids" of the Vesta family to Vesta and to the 3:1 and ν_6 escape hatch resonances have added strong evidence in favor of this proposition (*Binzel and Xu,* 1993).

McCord et al. (1970) were the first to determine, through spectroscopy in the visible and near-infrared using ground-based telescopes, that the surface of Vesta exhibits absorption features typical for low-Ca pyroxene and that it is similar in composition to certain basaltic achondrites (i.e., eucrites) (Fig. 1). Since then, many Earth-based measurements in the visible and infrared (e.g., *Larson and Fink,* 1975; *McFadden et al.,* 1977; *Feierberg et al.,* 1980; *Gaffey,* 1983, 1997, and references therein; *Cochran and Vilas,* 1998) have confirmed the *McCord et al.* (1970) findings. For example, *Feierberg et al.* (1980) determined that the surface of Vesta consists of a mixture of pyroxene ($Fs_{50 \pm 5}$) and plagioclase, with a pyroxene/plagioclase ratio of 1.5–2.0, consistent with Vesta's surface being covered by a mixture of eucrites and howardites, suggesting that Vesta is an intact, differentiated object with a basaltic crust. Furthermore, *Cochran and Vilas* (1998) observed a spectral absorption feature centered at 5065 Å in spectra across the complete surface of Vesta that is indicative of the presence of relatively Ca-rich augite. Recent Earth-based (*Gaffey,* 1997) and HST images (*Binzel et al.,* 1997) of Vesta as it rotates have confirmed earlier observations of geological diversity across the asteroid (e.g., *Gaffey,* 1983) and revealed a heterogeneous surface, consistent with a composition similar to that of the HED meteorites. Specifically, *Gaffey* (1997) noted that Vesta appears to have an old, age-darkened surface akin to the howardites and polymict eucrites, with fresher rocks akin to diogenites and olivine-bearing material exposed in impact craters. *Binzel et al.* (1997) note that the eastern hemisphere of Vesta is dominated by what appear to be impact-excavated plutonic rocks made of Mg-rich and Ca-poor pyroxene, akin to diogenites, with some units containing a substantial amount of olivine. The western hemisphere, on the other hand, is dominated by Fe-rich and relatively Ca-rich pyroxene, consistent with eucrites.

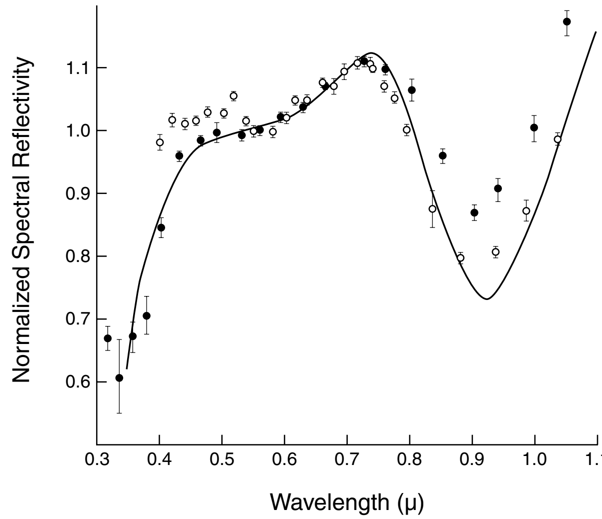

Fig. 1. Laboratory measurements of the spectral reflectivity of the Nuevo Laredo eucrite (solid line), compared to telescope data points from Vesta, suggesting that Vesta is covered by eucritelike material. Solid circles, data obtained at Cerro Tololo, Chile, December 1969; open circles, data obtained at Mount Wilson, California, October 1968. The standard deviation for each average value is shown as an error bar. Reprinted with permission from *McCord et al.* (1970). Copyright 1970, American Association for the Advancement of Science.

One argument against the origin of the HEDs from Vesta and the vestoids has been that space weathering will make basaltic asteroids look like S asteroids. Hence, the sharp, uniquely defined basaltic reflection spectra of Vesta and the vestoids must be due to recent (<10 Ma) impact resurfacing and covering of their surfaces by fresh basalt debris (*Wasson and Chapman,* 1996; *Wasson et al.,* 1996). These authors suggested that many S asteroids might be space-weathered basaltic chunks from the differentiation of the many iron meteorite parent bodies and that the parent body of the HEDs is hiding among the S asteroids. However, *Gaffey* (1983) concluded that the maturation of the Vesta surface (e.g., reddening of the IR curve) is ~100–1000× lower than that of the surface of the Moon, and *Hiroi et al.* (1994) suggested that the good matches between the reflectance spectra and brightness of Vesta and the HED meteorites indicate that Vesta's surface is free from heavy space weathering. In addition, *Yamada et al.* (1999) have recently shown that olivine may be the principal mineral altered by space-weathering processes. Since Vesta's surface is dominated by pyroxene rather than olivine as the mafic mineral, it is much less susceptible to space weathering than, for example, ordinary chondrites would be. Thus, Vesta's surface does not have to be "made fresh" in order for it to provide the exceptionally well-defined spectral matches to the HEDs

Dynamical difficulties to get impact debris off Vesta and into the far-away 3:1 jovian and ν_6 secular resonances have also been cited as evidence against an origin of the HEDs from Vesta, as this would require implausibly high launch velocities (e.g., *Wasson and Wetherill,* 1979; *Wetherill,* 1987). However, the discovery by *Binzel and Xu* (1993) of main-belt asteroids <10 km in diameter with surface compositions similar to that of Vesta (basalt) that constitute a small Vesta family located between Vesta and the major dynamical resonances are powerful evidence in favor of the HED-Vesta link. Specifically, these authors found 12 of the Vesta family members and 8 other small main-belt asteroids, collectively referred to as vestoids, to have spectra like typical basaltic achondrites, and 14 of these are similar to Vesta and have the spectral characteristics of the eucrites (i.e., a strong absorption band near 9000 Å). The remaining six are interpreted as diogenitic in composition and were designated as J asteroids (mnemonic for the Johnstown diogenite). Currently, more than 40 vestoids <10 km in diameter with Vesta-like spectral characteristics are known that fall inside 2.5 AU, the Kirkwood gap defined by the 3:1 jovian resonance (*Binzel et al.,* 1999). Note that *Binzel and Xu* (1993) also suggested that the then-known three near-Earth V-type asteroids with diameters of 1–4 km (*Cruikshank et al.,* 1991) were also derived from Vesta, a view that is not shared by *Cruikshank et al.* (1991) but is advocated by *Migliorini et al.* (1997) for the newly discovered ones (now totaling seven) as well. Recently, *Vilas et al.* (2000) confirmed the *Binzel and Xu* (1993) results and found that of the 13 asteroids dynamically linked to Vesta that they studied, 9 show deep 9000 Å absorption bands, suggesting a pyroxene composition consistent with rocks of the HED clan. In addition, six of these asteroids also show an absorption feature centered at 5065 Å, consistent with the occurrence of a high-Ca pyroxene, as previously shown for Vesta (*Cochran and Vilas,* 1998). This supports the notion that the vestoids are indeed impact ejecta from Vesta, but the fact that not all objects show this feature suggests that the vestoids are derived from different layers of the parent body [or from a different parent body altogether (*Vilas et al.,* 2000)]. *Burbine et al.* (2001) also concluded, based on new measurements of 20 vestoids, that they hail from Vesta and that there is a clear connection to the HEDs. It should be noted that dynamical modeling studies show that the Vesta family asteroids can, in fact, be launched off Vesta by large impacts (e.g., *Zappalà et al.,* 1995; *Marzari et al.,* 1996; *Asphaug,* 1997).

The recent Hubble Space Telescope discovery near the south pole of Vesta of a large impact crater ~460 km in diameter and ~13 km deep with a central uplift and bounding rim, as well as of several smaller depressions ~160 km and ~150 km in diameter (*Thomas et al.,* 1997a) (Plate 7), is further evidence in favor of the origin of the vestoids and HEDs from Vesta. The dimensions of the huge crater are consistent with excavation deep into the high-Ca pyroxene-rich crust or olivine-rich upper mantle, or both. The volume of this cratering event of ~1 vol% of Vesta (~10^6 km^3) is more than sufficient to account for the volume of the vestoids, which amount to only a few percent of this volume.

Cosmic-ray-exposure ages (CREAs) are also consistent with the HED-Vesta-vestoids connection. *Eugster and Michel* (1995), for example, found two major peaks at 21 ± 4 and 38 ± 8 Ma and three minor peaks at 6 ± 1, 12 ± 2, and 73 ± 3 Ma in the CREAs of the HEDs. This suggests that the immediate parent bodies of the HEDs (the vestoids) should contain all three meteorite types. *Welton et al.* (1997) determined the CREAs of diogenites and found that 10 ages cluster at 21–25 and 4 at 35–42 Ma (while all 20 studied range from 6 to 50 Ma). The two peaks coincide with the two major peaks for the HEDs. Since the surface compositions of some of the vestoids are dominated by only one type of HED meteorite (*Binzel and Xu,* 1993; *Xu et al.,* 1995) but all HED CREAs peak in two major peaks, *Welton et al.* (1997) favor Vesta rather than the vestoids as the source for the HEDs, although the recent work of *Burbine et al.* (2001) has shown a great diversity of objects among the vestoids.

Could the HED meteorites have originated from a main-belt asteroid other than Vesta and the vestoids? The only other large main-belt asteroid with a basaltic surface that has no known dynamical link to Vesta, the vestoids, any family, or any nearby large asteroid is 1459 Magnya (*Lazzaro et al.,* 2000). These authors argue that Magnya is not a fragment of Vesta, as it would require an ejection velocity of ~5 km/s. Rather, they suggest that this 30-km-diameter object is a fragment of a large, differentiated asteroid that was disrupted long ago and must have had a remarkably thick (at least 30 km) basaltic crust. Since the delivery efficiency of fragments to Earth from Magnya at 3.15 AU is much less than that from Vesta and the vestoids, *Lazzaro et al.* (2000) do not consider Magnya as a likely alternative source to Vesta for the HED meteorites.

Are all eucrites from the same parent body? They presumably are, except for a recently recovered, fascinating, highly metamorphosed rock originally classified as a noncumulate eucrite, Northwest Africa 011, with FeO/MnO ratios of pyroxenes considerably higher (~65) than those of normal ordinary eucrites (≤40), has been described by *Yamaguchi* (2001). More recent work, including O-isotopic measurements, suggests that this is a new type of basaltic achondrite that originated on a different parent body from the HEDs, but one that was probably similar in size and history to Vesta (*Yamaguchi et al.,* 2001b, 2002).

Finally, it has been suggested that the HED meteorites and certain other meteorite groups, because of their mineralogical and, particularly, O-isotopic similarities, come from one and the same parent body, although there are conflicting statements in the literature. For example, *Mittlefehldt* (1980), *Clayton and Mayeda* (1996), and *Mittlefehldt et al.* (1998) suggested that the HEDs, mesosiderites, main-group pallasites, and IIIAB irons may have originated on the same parent body, although they do not propose that this is Vesta [note that *Mittlefehldt* (1990) and *Rubin and Mittlefehldt* (1993) argued that mesosiderites and HEDs come from different parent bodies]. Since Vesta has a nearly intact basaltic crust that formed in the first few million years of solar system history (e.g., *Shukolyukov and Lugmair,* 1993a,b; *Lugmair and Shukolyukov,* 1998; *Srinivasan et al.,*1999; *Nyquist et al.,* 2001), the asteroid clearly did not go through a catastrophic breakup and reassembly episode since formation of the crust (*Gaffey,* 1983). Such a breakup would be required to excavate the extremely slowly cooled mesosiderites, main-group pallasites, and IIIAB irons from great depths. For that reason, *Cruikshank et al.* (1991) suggested that this parent body could not have been Vesta, although the identical O-isotopic compositions of mesosiderites, main-group pallasites, IIIAB irons, and HEDs are consistent with formation on the same body. Instead, they suggested that the HEDs come from the three near-Earth V-type asteroids they discovered, and that these are fragments of some other, totally disrupted, differentiated asteroid. In view of the recent evidence that the HED meteorites originated on Vesta and the vestoids, it is evident that the mesosiderites, main-group pallasites, and IIIAB irons, in spite of their similar O-isotopic compositions to those of the HEDs, did not form on Vesta but must have originated on a different parent body(ies), a view now shared by D. Mittlefehldt (personal communication, 2001). However, they clearly formed from a related O-isotopic reservoir.

4. MINERALOGY, PETROLOGY, CHEMISTRY, AND PETROGENESIS OF THE HED METEORITES

The identical O-isotopic compositions of the HEDs, their similarities in mineralogy and composition [e.g., the Fe/Mn ratios of pyroxenes (*Papike,* 1998)], the occurrence of polymict breccias among them [e.g., howardites that contain fragments of eucrites and diogenites, polymict eucrites that contain fragments of diogenitic material, and polymict diogenites that contain fragments of eucrites (e.g., *Delaney et al.,* 1984)] and the existence of rocks intermediate between diogenites and cumulate eucrites (*Takeda and Mori,* 1985) are strong evidence that all these meteorites come from the same parent body.

The classification of the HED meteorites and their most important mineralogical characteristics are summarized in Table 1 and their textures are shown in Plate 8. Rocks are listed arranged in order of decreasing depth of origin on the parent body as proposed in the layered crust model of *Takeda* (1979, 1997).

Diogenites are coarse-grained, usually brecciated, cumulates (Plate 8a) from a fractionally crystallizing magma and consist on average of (in vol%) 92.2 orthopyroxene, 4.2 olivine, 1.2 clinopyroxene, 0.9 chromite, 0.4 plagioclase, 0.1 metallic Fe,Ni, 0.6 troilite, and 0.4 silica phase (average of 21 diogenites) (*Bowman et al.,* 1997). Diogenites are thought to be the most deep-seated known lithology from the HED parent body and, in the layered crust model of *Takeda* (1997), for example, are thought to be overlain successively by the cumulate eucrites, ordinary eucrites, unequilibrated eucrites, and howardites. One would therefore expect that cooling rates of the diogenites should be the slowest of all HEDs, but this is not the case. Cooling rates estimated from Fe^{2+}-Mg ordering in orthopyroxene (*Zema et al.,* 1997) are ~50°C/ka for Johnstown and ~800°C/ka for Roda, at closure temperatures between 311° ± 29°C and 408° ± 10°C respectively. These rates are much faster than those for the cumulate and noncumulate eucrites, which are thought to have overlain the diogenites (see below). *Zema et al.* (1997) suggested that their diogenite cooling rates are not the result of cooling deep within Vesta, but are due to cooling at different (and shallower) burial depths in the ejected fragments. Note that H. Takeda (personal communication, 2001) pointed out that "Fe^{2+}-Mg ordering in the orthopyroxene structure is easily modified or reset by subsequent minor events and it cannot be used as an estimate of the cooling rate of the original rocks."

Cumulate eucrites are coarse-grained and mostly unbrecciated gabbros (Plate 8b). To estimate the depth of origin (and thus the thickness of the basaltic crust) of Vesta, *Miyamoto and Takeda* (1994) computed the cooling rate of the cumulate eucrite Moore County. Their estimate is based on the Ca compositional gradients and the widths of augite lamellae in pyroxene, and assumes a parent body 250 km in radius. They found that Moore County originally cooled at 0.16°C/ka, which corresponds to a burial depth of about 8 km, assuming a rocklike thermal diffusivity. After this, a sudden increase in temperature is recorded, probably as the result of excavation due to an impact, from which Moore County cooled down at 350°C/ka. This corresponds to a burial depth of ~100 m assuming rocklike or ~10 m assuming regolithlike thermal diffusivity. The original burial depth of 8 km suggests that the basaltic crust of Vesta was at least that thick, and this is in agreement with the largest eucritic vestoid being ≤10 km in diameter (*Binzel and Xu,* 1993).

Noncumulate (basaltic) eucrites formed originally as quickly cooled and hence unequilibrated surface lava flows (Plate 8d) (i.e., the unequilibrated eucrites; also referred to as unmetamorphosed or least-metamorphosed eucrites) at cooling rates, based on their textures, of ~0.001°–100°C/h (*Walker et al.,* 1978). Their pyroxenes (pigeonite; mg# ~70–20) are compositionally zoned and have exsolution lamellae on the TEM scale. However, most unequilibrated euc-

TABLE 1. Classification and principal properties of HED meteorites (modified after *Takeda*, 1997).

Diogenites: Orthopyroxenites (usually brecciated), with ~84–~100 vol% orthopyroxene [(Mg,Fe)SiO_3] with mg# ~85–67*.

Eucrites: Pyroxene-plagioclase basalts.

Cumulate eucrites of the Binda and Moore County types: Coarse-grained gabbros, often not brecciated. Orthopyroxene inverted from low-Ca clinopyroxene (mg# ~67–58); orthopyroxene inverted from pigeonite (mg# ~57–45); thick high-Ca pyroxene exsolution lamellae.

Noncumulate (basaltic) eucrites

Ordinary ("equilibrated; metamorphosed") eucrites: Monomict-brecciated or unbrecciated basalts, with homogeneous host pigeonite (a low-Ca clinopyroxene; mg# ~42–30) and fine high-Ca pyroxene exsolution lamellae. Includes the main-group eucrites (Juvinas type) and the Stannern and Nuevo Laredo types.

Unequilibrated ("unmetamorphosed; least metamorphosed") eucrites (Pasamonte type): Surface lavas that experienced minor metamorphism. Pigeonites (mg# ~70–20) with compositional zoning and TEM scale exsolution.

Polymict eucrites: Polymict breccias of various types of eucrites with <10 vol% orthopyroxene.

Howardites: Polymict breccias of eucritic and diogenitic materials with >10 vol% orthopyroxene.

*mg# = Mg × 100/(Mg + Fe) atomic %.

rites subsequently experienced extensive thermal metamorphism to form the metamorphosed eucrites (e.g., *Takeda and Graham,* 1991; *Yamaguchi et al.,* 1996, 1997).

The metamorphosed (equilibrated), noncumulate eucrites (Plate 8c) are collectively referred to as the ordinary eucrites and include the main-group eucrites (Juvinas type) and the Stannern and Nuevo Laredo types. They are monomict-brecciated or unbrecciated, metamorphosed basalts, with homogeneous host pigeonite and fine high-Ca pyroxene exsolution lamellae. The widths of their exsolved pyroxene lamellae allows estimation of the cooling rates of the rocks and hence their burial depths. *Miyamoto et al.* (2001), for example, calculated a subsolidus cooling rate of 20°C/ka down to 550°C for the highly metamorphosed nonbrecciated eucrite Ibitira. Depending upon assumptions for thermal diffusivity of the overlaying material, this corresponds to a burial depth of ~550 m in solid rock, ~30 m in regolith with 50% porosity, and ~90 m in a compacted regolith.

Polymict eucrites are polymict breccias consisting mostly of eucritic material with <10 vol% orthopyroxene (diogenitic component) (Plate 8e). These rocks were originally recognized in the collections from Antarctica (e.g., *Delaney et al.,* 1984).

Howardites are polymict regolith breccias consisting mostly of eucritic and diogenitic components, with >10 vol% orthopyroxene. They also contain some olivine, suggesting yet another source rock, as well as carbonaceous chondrite xenoliths. Their matrixes are fine-grained, and into these are embedded rock and mineral clasts, including a variety of impact-melt rocks and breccias (e.g., *Fredriksson and Keil,* 1963; *Metzler et al.,* 1995; *Pun et al.,* 1998) (Plate 8f). The clastic matrix contains solar-wind-implanted gases, indicating that its constituents were once exposed at the very top surface of the parent body (e.g., *Suess et al.,* 1964).

A number of models have been proposed to explain the petrogenesis of the HED meteorites (i.e., the origin of the eucrites and diogenites). *Mason* (1968) was the first to discuss their origin by fractional crystallization, and a recent summary of this and other models of eucrite petrogenesis is given by *Takeda* (1997). *Stolper* (1977), for example, carried out melting experiments on basaltic eucrites and concluded that they formed by crystallization of primary partial melts. These melts are thought to have formed by low degrees [~4–15 vol% (*Consolmagno and Drake,* 1977)] of partial melting in the temperature interval of ~1150°–1190°C, possibly from a chondritic (CM) source material (*Jurewicz et al.,* 1993). Cumulate eucrites formed from a fractionally crystallizing melt of mafic composition, and *Stolper* (1977) pointed out that these rocks are too Fe-rich to have crystallized from the melts from which the basaltic eucrites crystallized. However, *Treiman* (1997) suggested that they could have formed as mixtures of cumulus minerals and trapped melt. *Stolper* (1977) further suggested that the diogenites crystallized from melts of essentially orthopyroxene composition, and *Warren* (1997) proposed that they formed as early cumulates from a large magma system, probably a global magma ocean. On the other hand, *Shearer et al.* (1997) suggested that diogenites are cumulates from ~10–20% fractional crystallization of specific basaltic melts.

While the *Stolper* (1977) model of eucrite petrogenesis requires low degrees of partial melting, a variety of models have been proposed that visualize the origin of these rocks as the products of fractional crystallization of residual melts that formed by higher degrees of partial melting, such as from a magma ocean on the HED parent body (*Ikeda and Takeda,* 1985; *Taylor et al.,* 1993; *Ruzicka et al.,* 1997; *Warren,* 1997; *Takeda,* 1997). The magma ocean concept has also been championed by *Righter and Drake* (1997) and *Drake* (2001) who, based on the abundances of moderately siderophile elements (Ni, Co, Mo, W, P) in the HED mantle, visualize melting of the entire HED parent body, including formation of a metal core.

5. GEOLOGICAL HISTORY OF 4 VESTA

5.1. Accretion, Melting, Differentiation, Core Formation, and Heat Source

One of the most fascinating developments in the chronology of the HEDs is the recognition that accretion, melting, and fractionation of their parent body, Vesta, and extrusion to, and crystallization on, its surface of eucritic basalts, occurred in the first few million years of solar system history (e.g., *Srinivasan et al.,* 1999; *Nyquist et al.,* 2001; *Carlson and Lugmair,* 2000, and references therein). This knowledge stems from much progress that has been made in recent years in the determination of precise absolute U-Pb ages of meteorites based on the still-extant radionuclide ^{235}U, and the measurement of the decay products of now-extinct radionuclides (e.g., ^{53}Mn with a half-life of 3.7 m.y. decaying into ^{53}Cr) that allow an astonishingly precise timescale for these processes to be established. For example, the oldest-recorded Pb-Pb age of calcium-aluminum-rich inclusions (CAIs; high-temperature condensates and, hence, thought to be the most ancient solar system materials) from the Allende CV3 chondrite is 4566 ± 8 Ma (*Chen and Wasserburg,* 1981) and 4566 ± 2 Ma (*Allègre et al.,* 1995), and the Pb model age for the differentiated angrite Angra dos Reis is 4557.8 ± 0.5 Ma (see references in *Carlson and Lugmair,* 2000). Taking into account the somewhat uncertain radial heterogeneity in ^{53}Mn in the formation regions, these ages can be used to translate the ^{53}Mn-^{53}Cr formation intervals of eucrites into an absolute age for the differentiation of Vesta. Based on measurements of the basaltic eucrite Chervony Kut, for example, an age of 4563.6 ± 0.9 Ma is derived, only a few million years younger than the formation of CAIs (*Lugmair and Shukolyukov,* 1998). Furthermore, the great antiquity of the eucrites and hence the evidence for melting and differentiation of Vesta on a timescale of a few million years is further supported by the detection of the decay products of other extinct radionuclides such as ^{26}Mg from the decay of ^{26}Al (half-life 0.73 m.y.) (*Srinivasan et al.,* 1999; *Nyquist et al.,* 2001) and ^{60}Ni from the decay of ^{60}Fe (half-life 1.5 m.y.) (see references in *Carlson and Lugmair,* 2000). Finally, it should be noted that the "most pristine," unmetamorphosed surface lava flow (i.e., unequilibrated eucrite), which is represented by clasts in the polymict eucrite Y 75011, also yields very old ages, albeit with larger error bars. These clasts are coarse-grained, mesostasis-rich basalts with subophitic texture and extensive Mg-Fe zoning in their pyroxenes. The Rb-Sr ages of the largest clast are 4.60 ± 0.05 and 4.50 ± 0.05 Ga, depending upon the assumed value of the ^{87}Rb decay constant, and the internal Sm-Nd isochron age for clasts and matrix is 4.55 ± 0.14 Ga (*Nyquist et al.,* 1986).

Cumulate eucrites, which crystallized and cooled at depth, have younger ages of <4480 Ma, due to thermal processing at depth over a longer time span than the quickly-cooled basaltic eucrites (see references in *Carlson and Lugmair,* 2000). Modeling of the thermal history of Vesta by *Ghosh and McSween* (1998) suggests that heating by ^{26}Al would keep the mantle hot for ~100 m.y., consistent with the younger ages of cumulate eucrites. Also, many eucrites (and howardites) experienced extensive impact processing and reheating that resulted in resetting of some chronometers (e.g., *Nyquist et al.,* 1997) and, for example, partial or complete resetting of ^{39}Ar-^{40}Ar ages in the relatively narrow time interval of 3.4–4.1 G.y. ago (the "cataclysmic" early bombardment) (e.g., *Bogard,* 1995). However, a few rare metamorphosed noncumulate eucrites such as Ibitira and EET 90020 have relatively old ^{39}Ar-^{40}Ar ages of 4.485 and 4.49 Ga respectively, and thus escaped the widespread cataclysmic impact resetting (*Bogard and Garrison,* 1995; *Yamaguchi et al.,* 2001a).

There is convincing geochemical evidence that Vesta experienced a high degree of (or possibly complete) melting that resulted in the formation of a metal core. For example, the depletion in moderately siderophile incompatible elements (e.g., Ni, Co, Mo, W, P) relative to nonsiderophile incompatible elements in HED meteorites suggests metal segregation and hence core formation (e.g., *Hewins and Newsom,* 1988, and references therein; *Righter and Drake,* 1997). However, estimates of the amount of metal in Vesta vary widely between 0 and 50 wt% (see references in *Ruzicka et al.,* 1997). For example, *Ruzicka et al.* (1997) estimated the mass of the core by mass balance from the density of Vesta and the density of the silicate fraction to be between ~0 and 25 wt%, with the best estimate being ~5 wt%. They also suggested that the core is <130 km in radius, the olivine-rich mantle is ~65–220 km thick, the lower crustal diogenite unit is ~12–43 km thick, and the upper crustal eucrite unit is ~23–42 km thick. *Dreibus et al.* (1997) estimated the mass of the core from their calculated composition of the bulk silicate portion of Vesta (assuming CI abundances for Fe and Ni) to be 21.7 wt%. They also calculated the density of the mantle to be 3400 kg/m^3 and, with a core density of 7900 kg/m^3, calculated the bulk density of Vesta to be 3800 kg/m^3, in good agreement with the astronomically determined values (see above). With a radius of 263 km and a core mass of 21.7 wt%, they calculated a core radius of 123 km.

The time of formation of the core was estimated by *Lee and Halliday* (1997). This estimate is based on the measurement in two eucrites (ALHA 78132, Juvinas) of excess ^{182}W from the decay of short-lived ^{182}Hf (half-life 9 m.y.). Since Hf fractionates into silicates and W into metal, the W-isotopic composition is a function of the timing of the Hf/W fractionation and hence the silicate-metal segregation (i.e., core formation). They concluded that accretion, differentiation, and core formation on Vesta took place in the first 5–15 m.y. of solar system history (note that these two meteorites may not be the best samples for this work, as they are extensively brecciated and metamorphosed; H. Takeda, personal communication, 2001).

What was the heat source for the melting of Vesta and the parent bodies of the many other differentiated asteroids of which we have samples in our collections? In recent years, discussions have largely focused on electrical conduction heating by the T-Tauri solar wind from the pre-main-sequence Sun (e.g., *Sonett et al.,* 1970) and the decay of now extinct ^{26}Al, as first proposed by *Urey* (1955). The discovery of excess ^{26}Mg from the decay of ^{26}Al in CAIs from ordinary, carbonaceous, and enstatite chondrites; in chondrules from carbonaceous and ordinary chondrites (see references in *MacPherson et al.,* 1995; *Huss et al.,* 2001); and in plagioclase from the equilibrated noncumulate eucrite Piplia Kalan (*Srinivasan et al.,* 1999) and the crystalline eucrite A 881394 (*Nyquist et al.,* 2001) suggests that ^{26}Al was widespread in the early solar system and most likely was the heat source for heating and melting of Vesta. It should be noted that the discovery of excess ^{26}Mg in these eucrites also suggests that they formed only 4–5 m.y. after CAIs, lending support to the notion that Vesta melted, fractionated, and differentiated, and that basalts extruded and crystallized, within the first few million years of solar system history. Thermal models based on ^{26}Al decay are broadly consistent with this constraint, producing Vesta's core and crust within 7 m.y. of CAI formation (*Ghosh and McSween,* 1998).

5.2. Volcanism and Metamorphism on 4 Vesta

As noted above, accretion, partial to perhaps total melting, fractionation, and differentiation of Vesta and extrusion and crystallization of basaltic partial melts all took place in the first few million years of solar system history. Thus, unlike on Earth, tectonically controlled magmatism, which requires long times of melting and fractionation to develop, did not occur on Vesta. Instead, the basaltic crust formed in a few million years.

Although the world's collections of meteorites contain samples from some 108 differentiated asteroidal parent bodies (*Meibom and Clark,* 1999), the only abundant basalts are the eucrites. Clearly, many other differentiated asteroids must have produced basaltic partial melts, so the question is, where are the basalts that should have crystallized from these partial melts? *Wilson and Keil* (1991) proposed that if early basaltic partial melts contained a few hundred parts per million of volatiles, these melts would have been ejected from parent bodies ≤100 km in radius as small pyroclastic droplets by explosive volcanism as these melts migrated to the asteroidal surfaces and encountered the vacuum of space. The small pyroclasts, whose sizes have been estimated on the basis of pyroclastic droplet sizes in the lunar regolith to range between ~30 and 4000 μm, would be accelerated into space and lost by spiraling into the Sun (*Wilson and Keil,* 1996a). As is indicated in Fig. 2, basaltic partial melts on the much bigger Vesta (~258 km in radius) would have had to contain ~3.8% of volatiles to be ejected with velocities that would exceed the escape velocity of ~390 m/s. Such high magma volatile contents are rare among basaltic magmas on Earth and are particularly unlikely to have formed on the "dry" Vesta (e.g., *Mittlefehldt,* 1987; *Grady et al.,* 1997), and thus basaltic melts were retained on Vesta and formed its basaltic crust.

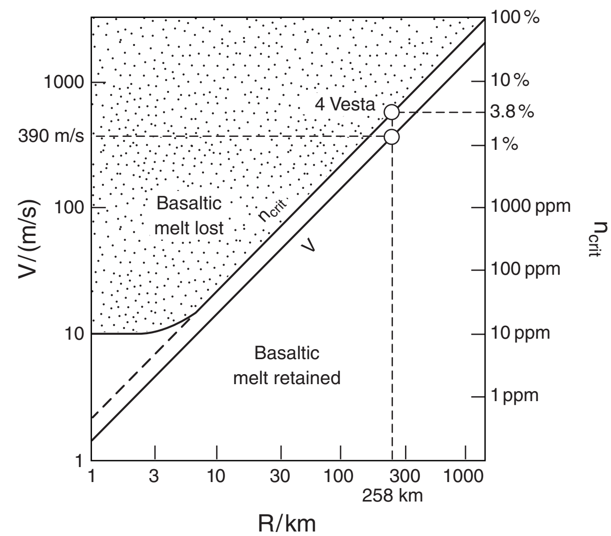

Fig. 2. Values of the escape speed, V, for asteroids of radii, R, assuming a density of 3500 kg/m³. Also shown as a function of R are the critical values of magma gas content, n_{crit}, at which the eruption velocity, U, equals the escape speed, V. For the approximate radius of 258 km for Vesta, an unrealistically high magma gas content n_{crit} of >3.8 wt% would be required to overcome the escape velocity of ~390 m/s to eject into space basaltic pyroclast/gas mixtures. Thus, Vesta is sufficiently large to retain basalts on its surface. Modified from *Wilson and Keil* (1991). Reprinted from *Earth and Planetary Science Letters,* copyright 1991, with permission of Elsevier Science Publishers.

Cooling rates of cumulate eucrites (*Miyamoto and Takeda,* 1994) and the sizes of the largest vestoids of eucritic composition (*Binzel and Xu,* 1993) suggest that the basaltic crust of Vesta is at least 10 km thick. What were the physical processes that formed this crust? *Wilson and Keil* (1996b), for example, used basic principles of volcanic fluid dynamics to model the nature of the basaltic intrusions and extrusions on a body with the physical properties of Vesta and compared these modeling studies to relevant properties of the HEDs. They concluded that dikes carrying basaltic magma upward from zones of partial melting in the mantle of Vesta may have had vertical extents of 1–30 km and widths of ~10 mm to 4 m. Typical surface lava flows might have had lengths of a few kilometers to several tens of kilometers, widths of a few hundred meters to several kilometers, and thicknesses of 5–20 m. These modeled thicknesses are in excellent agreement with those calculated for unequilibrated eucrites based on comparisons of plagioclase crystal sizes in eucrites and in experimental charges of eucrite composition of known cooling rates (*Walker et al.,* 1978). Eruptions from dikes that reached the surface are estimated to have lasted 8–60 h and, per meter of horizontal surface fissure outcrop, may have had effusion rates of ~0.05 to >3 $m^3 s^{-1}$, similar to those of current basaltic eruptions on Earth. The erupted lava volumes for individual eruptions may have ranged from negligibly small to up to

3 km^3. Assuming that a 20-km-thick crust formed on Vesta in ~1 m.y., then the time interval between successive lava flow emplacements is estimated to be ~1000 yr. Intrusions with vertical extents of <10 km and widths of ~1 m could have formed at very shallow depth in the forming basaltic crust as cooling dikes stalled before they erupted completely to the surface. Furthermore, intrusions with lateral extents of ~1–30 km, thicknesses of 10 mm to 3 m, and volumes of 10^4 m to 3 km^3 could have formed at the base of the crust because magmas in these locations would have been neutrally buoyant as the density structure of Vesta evolved.

Pyroclastic rocks that formed by explosive eruptions of volatile-bearing magmas are abundant on Earth and Moon (e.g., *Wilson and Head,* 1981, 1983). Unless magmas on Vesta were totally free of volatiles, which is not likely (e.g., *Grady et al.,* 1997), pyroclastic material should therefore occur in HEDs. However, no such pyroclasts were found during detailed microscopic studies of numerous polished thin sections of howardites (A. Yamaguchi, personal communication, 1995). Modeling studies by *Wilson and Keil* (1997) indicate that the physics of pyroclastic eruptions on the relatively small Vesta are sufficiently different from those of Earth and Moon to explain the lack of products of pyroclastic eruptions in HEDs. Specifically, lava fountains on Vesta would have been extremely optically dense, and hence pyroclastic melt/gas mixtures would tend not to cool in flight but land as liquid and form lava lakes that would feed lava flows indistinguishable from those that formed by extrusion. For example, for a typical magma discharge rate from a fissure of 0.3 m^3/s/m and a released gas content of 300 ppm, the gas-droplet eruption speed would be 33.9 m/s; the maximum droplet range would be 4.4 km; and the thickness of the outer layer within which pyroclastic droplets would cool before landing would be 40 m. This corresponds to a fractional area of only 0.9% within which pyroclasts would cool, and an area of 99.1% within which pyroclasts would land as hot, molten droplets, thus readily explaining the lack of pyroclastic materials within HEDs.

Although most eucrites originally formed as quickly cooled surface lava flows (the unequilibrated eucrites), most were subsequently metamorphosed (the equilibrated eucrites) at >800°C for periods of about 1 m.y. (e.g., *Yamaguchi et al.,* 1997). As most eucrites have experienced this metamorphism, it has been suggested that Vesta experienced global crustal metamorphism (e.g., *Yamaguchi et al.,* 1996). Eucrite metamorphism was recognized early and led *Takeda and Graham* (1991) to establish a metamorphic scale for eucrites, based on compositional and textural relationships of their pyroxenes [it is important to remember that this scale concerns the nature of the pyroxenes of eucrites and thus is different from the petrologic type scale of chondritic meteorites of *Van Schmus and Wood* (1967)].

Various heat sources and physical settings have been proposed for the origin of the global metamorphism. *Takeda and Graham* (1991), for example, suggested that impact heating during cratering events was an important process for thermal metamorphism, but *Keil et al.* (1997) argued that on relatively small asteroids impact into cold rock is not an efficient heat source for global thermal events. *Takeda et al.* (1997) later proposed that, after formation of an early scarflike crust that experienced more heating from the magma beneath it, additional heating may have been supplied by impacts into the hot crust. *Sears et al.* (1997) also suggested that metamorphism was triggered by impacts, but they are alone in proposing that metamorphism took place relatively late in the history of Vesta, at ~3.9 Ga at the end of the cataclysmic bombardment and at the time the Ar-Ar ages were reset. They further argued that the different degrees of metamorphism of eucrites resulted from burial under regolith ejecta blankets of highly variable thicknesses (from nonexistent to 2 km), rather than from different initial burial depths.

Clearly impacts have played a role in reheating eucrites, but this process alone cannot be responsible for the global thermal metamorphism experienced by most noncumulate eucrites. *Metzler et al.* (1995), for example, argued that the textures of HEDs reflect complex postigneous histories dominated by multistage thermal and impact metamorphism. Specifically, they recognized six evolutionary phases: (I) crystallization of primary magmas and formation of unequilibrated, noncumulate eucrites; (II) slow subsolidus cooling or reheating during which pyroxene equilibrated; (III) and (V) periods of impact brecciation during which rocks were brecciated *in situ* or, in the case of the polymict HED breccias, mixed with various other rock types; (IV) and (VI) breccias suffered annealing and recrystallization due to thermal metamorphism. They noted that thermal events that caused recrystallization and equilibration of HED lithologies were active prior to, during, and after the formation of impact breccias, indicating that thermal input by impact might be responsible for some thermal overprinting.

However, the relatively old ^{39}Ar-^{40}Ar ages of 4.485 and 4.49 Ga of the highly-metamorphosed noncumulate eucrites Ibitira and EET 90020 respectively indicate that these rocks escaped the widespread cataclysmic impact resetting in the time interval of 3.4–4.1 G.y. ago (*Bogard and Garrison,* 1995; *Yamaguchi et al.,* 2001a), suggesting that impact alone cannot have been the heat source for eucrite metamorphism and that an internal heat source is responsible for global metamorphism of noncumulate eucrites. Note, however, that *Takeda et al.* (1997) argue that impacts into a hot crust could be responsible for global metamorphism. *Warren* (1997), for example, argued that the thermal metamorphism resulted from baking of earlier eucrite lava flows by superjacent flow units. *Yamaguchi et al.* (1996, 1997), on the other hand, modeled the development of the eucritic crust of Vesta by serial volcanism. They argued that the eruption of lava flows and subsequent burial of earlier by later lava flows in the growing basaltic crust of Vesta in the first few million years of Vesta's history resulted in metamorphism of deeply buried flows from heat from within the asteroid as a result of a steep thermal gradient in the growing crust of Vesta.

6. WHAT NEXT?

Among all the asteroids, it appears Vesta is the only one that has preserved nearly intact its original differentiated internal structure with a metal core, an ultramafic mantle, and a basaltic crust. In its structure and composition, it can be viewed as the smallest terrestrial planet, and its further exploration, particularly by spacecraft such as the now approved Dawn Discovery Mission (*Farquhar et al.,* 2002), is highly desirable and anticipated. This mission will add much to our understanding of the accretion, heating, melting, fractionation, and differentiation of small asteroid-sized objects that may have played an important role in the accretion and formation of the terrestrial planets.

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