WORKSHOP ON

EVOLUTION OF IGNEOUS ASTEROIDS: FOCUS ON VESTA AND THE HED METEORITES

Edited by

D. W. Mittlefehldt and J. J. Papike

Held at
Houston, Texas

October 16–18, 1996

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Description of Workshop

In 1970, McCord et al. first demonstrated that the reflectance spectra within a restricted wavelength region of the asteroid 4 Vesta showed remarkable similarity to that of the eucrite Nuevo Laredo. This led to the suggestion by Consolmagno and Drake in 1977 that Vesta was indeed the parent body of the eucrites and that therefore, through study of the eucrites and the related achondrites, the howardites, and diogenites (HED meteorites), we could begin to decipher the geologic history of Vesta. Unfortunately, at that time the observational techniques available to astronomers were insufficient to do more than affirm that the spectra of Vesta did indeed resemble that of eucrites for all regions of the spectrum examined. Details of the surface geology were beyond available astronomical capabilities. During this time, more and more HED meteorites were being returned from Antarctica, and HED meteorites were being studied using ever more sophisticated analytical techniques. In spite of the wealth of new data, the lack of geologic context hampered definitive interpretation of the genesis of eucrites.

Recently, the geology of the surface of Vesta has been coming to light. In 1983 Gaffey first began showing maps of the surface geology of Vesta constructed from numerous spectra obtained at different times as the asteroid rotated. By noting the details of spectral variation with rotation, he was able to develop two possible gross-scale geologic maps of Vesta showing the distributions of mafic and ultramafic materials. These maps were published in 1997. Finally, the capabilities of the Hubble Space Telescope were brought to bear on Vesta and images with a resolution of about 50 km were obtained using four different filters by Binzel and co-workers. Maps produced by this team published in 1997 began to reveal the geology of Vesta in sufficient detail that crude interpretations of the geologic history of the asteroid could be attempted.

Additionally, in 1993 Binzel and Xu published a study of small asteroids in the region near Vesta in orbital-element space. In this study, they showed that there are a number of asteroids a few kilometers in size with reflectance spectra like that of Vesta that form a trail in orbital-element space from near Vesta to near resonances that can more easily supply material to near-Earth space. Binzel and Xu thus concluded that these small asteroids were spalls of Vesta ejected by impact and that some of their brethren had been perturbed to Earth-approaching orbits. They suggested that these latter were the immediate parents of HED meteorites. This seemed to remove a long-standing dynamical objection to Vesta as the HED parent body, as discussed by Wasson and Wetherill in 1979.

Within the last few years, NASA has initiated the Discovery program of low-cost, rapid-timescale development, exploration missions. Vesta has been proposed as an object worthy of study by a Discovery mission, although a Vesta mission has not yet been selected.

With all the recent activity aimed at studying Vesta and the HED meteorites, and the possibility of a space mission to Vesta, we felt that time was ripe to convene a workshop bringing together astronomers, meteoriticists, and planetary geologists to focus on what could be learned about the geologic evolution of Vesta through integrating astronomical and HED meteorite studies. This, of course, assumes that the HED meteorites are from Vesta, and this issue was specifically addressed (but not resolved) in the workshop. Indeed, it seems likely that this issue can only be resolved by returning samples from Vesta for detailed study on Earth.

The workshop was held at the LPI on October 16–18, 1996, and was attended by some 70 scientists. Sessions included a set of talks on Earth- and space-based astronomical observations of Vesta plus the evidence pro and con for Vesta being the HED parent body, talks on the petrology and geochemistry of HED meteorites, talks on the formation and dynamics of ejecta from Vesta, talks on the thermal history of asteroids and HED meteorites, volcanic processes and differentiation history, and a short session devoted to possible missions to Vesta. By all accounts, the workshop was considered a great success, although this is the opinion of a biased set of observers.

Alas, just after the workshop the two of us jointly embarked on a major publication project and never did find time to do a synopsis of the workshop. Rather than risk a major faux paux by dredging up from two-year-old memories the talks and lively discussion that occurred in the workshop, we instead refer you to Part 1 of this volume, which contains the abstracts accepted for presentation at the meeting, and two other sources. Derek Sears, the Executive Editor of *Meteoritics & Planetary Science*, wrote a brief editorial published in the January 1997 issue that highlighted some of the salient points brought out during the workshop. He and the editorial board of *Meteoritics & Planetary Science* also kindly agreed to publish worthy full-length papers that resulted from of the workshop. A total of 13 papers were published in the November 1997 issue, and these cover a wide range of topics. Of particular interest is the fact that several of these papers present models for the origin of the basaltic eucrites, and they are mutually exclusive. Clearly, although we have learned much about the HED meteorites, the fundamental question of how their parent body differentiated remains unresolved.

Also included here is an abstract by E. Asphaug on cratering of asteroidal-sized bodies that we solicited for the workshop, but which was received too late to include in the printed abstract volume.

Logistics, administrative, and publications support for the workshop were provided by the Publications and Program Services Department of the Lunar and Planetary Institute. We thank the LPI and the many individuals on the staff who helped make the workshop such a great success.

—*David W. Mittlefehldt, Lockheed Martin Houston, Texas*
James J. Papike, University of New Mexico, Albuquerque, New Mexico

References

Binzel R. P. and Xu S (1993) Chips off of asteroid 4 Vesta: Evidence for the parent body of basaltic achondrite meteorites. *Science, 260,* 186–191.

Binzel R. P., Gaffey M. J., Thomas P. C., Zellner B. H., Storrs A. D., and Wells E. N. (1997) Geologic mapping of Vesta from 1994 Hubble Space Telescope images. *Icarus, 128,* 95–103.

Consolmagno G. J. and Drake M. J. (1977) Composition and evolution of the eucrite parent body: Evidence from rare earth elements. *Geochim. Cosmochim. Acta, 41,* 1271–1282.

Gaffey M. J. (1983) The asteroid (4) Vesta: Rotational spectral variations, surface material heterogeneity, and implications for the origins of basaltic achondrites (abstract). In *Lunar and Planetary Science XIV,* 231–232.

Gaffey M. J. (1997) Surface lithologic heterogeneity of asteroid 4 Vesta. *Icarus, 127,* 130–157.

McCord T. B., Adams J. B., and Johnson T. V. (1970) Asteroid Vesta: Spectral reflectivity and compositional implications. *Science, 168,* 1445–1447.

Sears D. W. G. (1997) "The evolution of igneous asteroids: Focus on Vesta and the HED meteorites," Houston, Texas, 1996 October 16–18. *Meteoritics & Planet. Sci., 32,* 3.

Wasson J. T. and Wetherill G. W. (1979) Dynamical, chemical and isotopic evidence regarding the formation locations of asteroids and meteorites. In *Asteroids* (T. Gehrels, ed.), pp. 926–974. Univ. of Arizona, Tucson.

Solicited Abstract

LARGE EJECTA FRAGMENTS FROM VESTA AND OTHER ASTEROIDS. E. Asphaug, Mail Stop 245-3, NASA Ames Research Center, Moffett Field CA 94035 (asphaug@cosmic.arc.nasa.gov).

The asteroid 4 Vesta, with its unique basaltic crust, is a primary mystery of solar system evolution [1] and a key to our understanding of the origin of asteroid families and the accretion of planets. A localized olivine feature [2] suggests excavation of subcrustal material in a crater or impact basin comparable in size to the asteroidal radius ($R_{Vesta} \approx 280$ km [3]). Furthermore, small asteroids associated with Vesta (by spectral and orbital similarity [4]) comprise likely ejecta from this impact [5]. To escape, and to reach the Kirkwood gap, these ~4–7-km bodies had to be ejected at speeds considerably greater than $v_{esc} \approx 350$ m/s.

This evidence that large fragments were ejected at high speed from Vesta has not, however, been fully reconciled with our understanding of impact physics. The main problem is that large impact accelerations tend to create small fragments, not approximately kilometer-sized asteroids. Simply analytical spallation models [4,6], for instance, predict that an impactor capable of ejecting these multikilometer "chips off Vesta" would be almost the size of Vesta! Such an impact would lead to the catastrophic disruption of both bodies, in contradiction to the evident preservation of much of Vesta's primordial crust. A more direct analysis, based on comparison with cratering on Mars, shows that Vesta could survive an impact capable of ejecting kilometer-scale fragments at sufficient speed. Specifically, the same impactor that ejected ~1-km blocks from the surface of Mars at ~1 km/s during the formation of the ~220-km crater Lyot [7] could have impacted Vesta without destroying it. This result is obtained by (1) applying gravity scaling [8] to an ≈150-km transient crater (probably an upper limit for Lyot) to derive the impactor radius and speed (17 km at 8 km/s), and (2) applying the same scaling rule (in reverse) to Vesta to give the diameter of the transient crater (270 km) the same impactor would have formed there, under lower gravity. Since the craters on both bodies form in basalt, similar fragment size/velocity distributions would form. Furthermore, any material-related scaling errors cancel, making this argument particularly robust. In short, if kilometer-sized blocks are ejected at 1 km/s on Mars, the same will happen on Vesta, provided Vesta can survive such an impact without catastrophically disrupting.

To what extent, then, does Vesta survive the formation of a crater whose diameter is equal to the planet radius? This is best addressed using a hydrocode such as SALE 2D [9,10] to predict global surface velocities subsequent to the impact just described. Earlier efforts [11] showed that Vesta survives impacts by 50-km-diameter, 5-km/s objects without large-scale disassembly or global overturning of the crust. The numerical resolution of such models was, however, not adequate to directly demonstrate the creation of large fast spalls during such impacts. With the application of new grid methods on modern workstations, the desired result has now been obtained: kilometer-sized fragments from Vesta at kilometers per second velocity.

SALE 2D has been modified so that the near-surface layers are far more highly resolved than the interior. We can also model impactors such as ice, rock, or metal hitting a layered target such as basalt over iron, or regolith over basalt. These boundaries are important in near-surface ejection processes and in large-scale disruption leading to asteroid families and to stripped cores. Figure 1 shows an initial target Vesta, a 275-km-radius sphere with iron core, dense rock mantle, lower density upper mantle, and basalt crust. The bump is the impactor, a 5-km/s, 20-km-radius rocky asteroid in one simulation, and an 8-km/s, 24-km-radius ice comet in

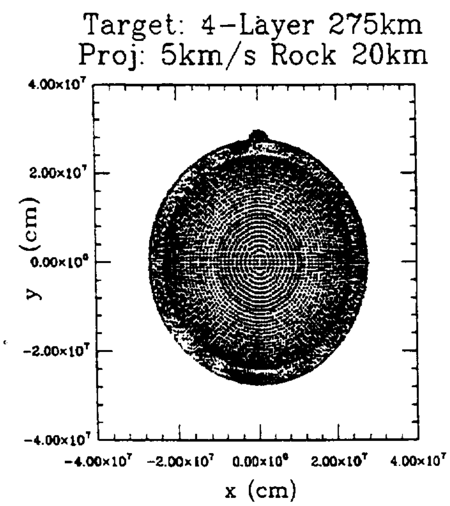
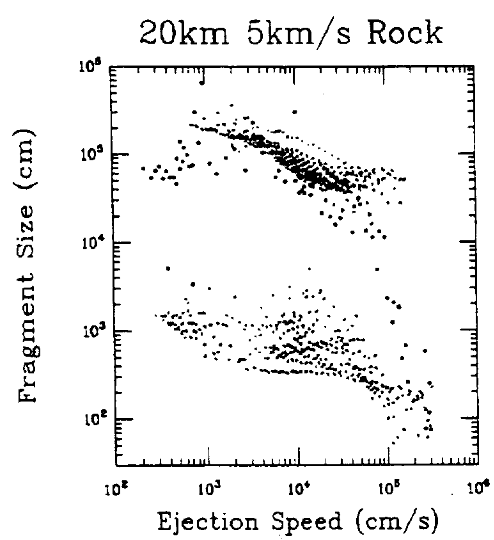


Fig. 1.



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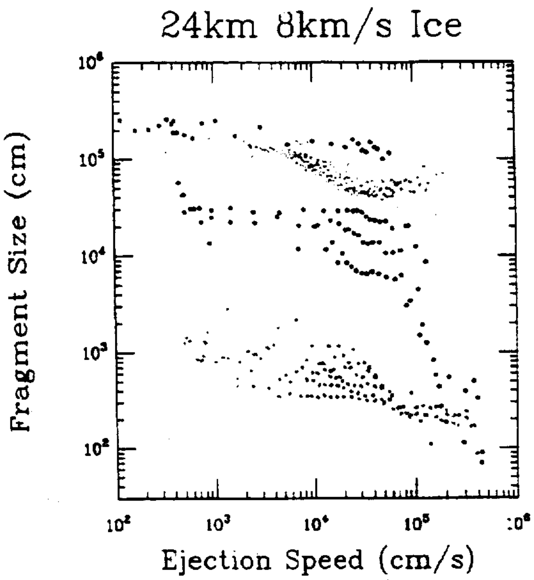

Fig. 3.

another. Figure 2 shows the prompt ejecta from the asteroid impact: The blackest dots represent basalt from the near-surface, and one of these regions contains 1-km fragments at 1 km/s. The faster comet impact achieves a more favorable result (Fig. 3), with somewhat larger fragments traveling at several hundred meters per second. Each dot represents a subvolume of the target containing hundreds to thousands of fragments. Future work will involve higher numerical resolution, a thorough exploration of the effect of surface layers and pre-fracture, and three-dimensional models using HST-derived asteroid shapes. Such efforts will lead to a better understanding of spallation, such as that which brought martian meteorites to Earth, and of the catastrophic disruption of asteroids and the formation of families.

Acknowledgments: This work was supported by NASA grant NAGW 3904.

References: [1] Davis et al. (1989) in *Asteroids II*, Univ. of Arizona, Tucson. [2] Gaffey (1983) *LPS XIV*, 231–232. [3] Lebofsky et al. (1991) *BAAS, 22*, 1112. [4] Binzel and Xu (1993) *Science, 260*, 186–191. [5] Drake (1979) in *Asteroids*, Univ. of Arizona, Tucson. [6] Melosh (1984) *Icarus, 59*, 234–260. [7] Vickery (1987) *GRL, 14*, 726–729. [8] Housen et al. (1983) *JGR, 88*, 2485–2499. [9] Asphaug and Melosh (1993) *Icarus, 101*, 144–164. [10] Asphaug et al. (1996) *Icarus, 120*, 158–184. [11] Asphaug (1994) *Meteorites, 29*, 440–441.

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