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

Sponsored by
Lunar and Planetary Institute

Lunar and Planetary Institute 3600 Bay Area Boulevard Houston TX 77058-1113
LPI Technical Report Number 96-02, Part 1
LPI/TR--96-02, Part 2
This report may be cited as


This report is distributed by

ORDER DEPARTMENT
Lunar and Planetary Institute
3600 Bay Area Boulevard
Houston TX 77058-1111.

Mail order requestors will be invoiced for the cost of shipping and handling.
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program</td>
<td>v</td>
</tr>
<tr>
<td>Description of Workshop</td>
<td>1</td>
</tr>
<tr>
<td>Solicited Abstract</td>
<td>3</td>
</tr>
<tr>
<td>List of Workshop Participants</td>
<td>5</td>
</tr>
</tbody>
</table>
Program

Wednesday, October 16, 1996
8:30 a.m.–12:00 noon

ASTRONOMY AND THE VESTA-HED CONNECTION
Chairs: C. R. Chapman and M. J. Gaffey

Does Vesta = HED Parent Body?

R. P. Binzel* (review talk)
Astronomical Evidence Linking Vesta to the HED Meteorites: A Review

J. T. Wasson* and C. R. Chapman (review talk)
Space Weathering of Basalt-covered Asteroids: Vesta an Unlikely Source of the HED Meteorites

Discussion

Astronomical Observations

M. J. Gaffey*
Asteroid Spectroscopy: Vesta, the Basaltic Achondrites, and Other Differentiated Asteroids

R. Jaumann*, A. Nathues, S. Mottola, and H. Hoffmann
Multispectral Lightcurves of Vesta

K. L. Reed*, M. J. Gaffey, and L. A. Lebofsky
Shape and Albedo Variations of Asteroid 4 Vesta

Geologic Mapping of Vesta with the Hubble Space Telescope

C. Dumas* and O. R. Hainaut
Mapping Vesta in the Visible and Near-Infrared: The 1994 and 1996 Oppositions as Viewed from the Ground

Discussion

Wednesday, October 16, 1996
1:30–5:30 p.m.

PETROLOGY AND GEOCHEMISTRY
Chair: G. J. Taylor

H. Takeda* (review talk)
Mineralogical Records of Early Planetary Processes of the HED Parent Body

*Denotes speaker
Cumulate Eucrite Controversy

P. H. Warren*, G. W. Kallemeyn, and K. Kaneda

*Cumulate Eucrites: Volatile-depleted Asuka 881394, Cr-loaded EET 87548, and Cumulate vs. Noncumulate Relationships

A. H. Treiman and D. W. Mittlefehldt*

*The Cumulate Eucrite Serra De Magé: New INAA Data, and the Composition of Its Parent Magma

W. Hsu and G. Crozaz*

*Noncumulate vs. Cumulate Eucrites: Heterogeneity of 4 Vesta

Discussion

Relationship Between Basaltic Eucrites and Diogenites?


*The Origin of Eucrites: An Experimental Perspective

J. J. Papike*, L. E. Bowman, M. N. Spilde, G. W. Fowler, and C. K. Shearer

*Diogenites: Cumulates from Asteroid 4 Vesta—Insights from Orthopyroxene and Spinel Chemistry

C. K. Shearer*, G. Fowler, and J. J. Papike

Petrogenetic Models for the Origin of Diogenites and Their Relationship to Basaltic Magmatism on the HED Parent Body

P. H. Warren*

*HED Petrogenesis: Are Orthopyroxenitic Magmas Plausible?

Discussion

Wednesday, October 16, 1996
5:30–7:30 p.m.

POSTER SESSION
Great Room

A. Ruzicka, G. A. Snyder, and L. A. Taylor

The Composition of the Eucrite Parent Body: Implications for the Origin of the Moon and for Planetary Accretion

M. E. Zolensky, M. K. Weisberg, P. C. Buchanan, and D. W. Mittlefehldt

Carbonaceous Chondrite Clasts in HED Achondrites

L. Ksanfomality and W. K. Hartmann

Practical Evaluation of Regolith Maturation Processes

L. E. Bowman, M. N. Spilde, and J. J. Papike

Automated SEM Modal Analysis Applied to the Diogenites

P. C. Thomas, R. P. Binzel, M. J. Gaffey, B. H. Zellner, A. D. Storrs, and E. Wells

Vesta: Spin Pole, Size, and Shape from HST Images
P. H. Warren, G. W. Kallemeyn, and T. Arai

*Compositional-Petrologic Investigation of Quench-textured Eucrites: Microporphyritic ALH 91001 and Vesicular PCA 91007*

T. D. Swindle, R. Lipps, and I. Scott

*Is There Another Link in the Chain? Looking for Streams of HED Meteorites*

M. M. Grady, I. P. Wright, and C. T. Pillinger

*The Content and Isotopic Composition of C in HED Basaltic Achondrites*

C. S. Schwandt and G. A. McKay

*REE Partition Coefficients from Synthetic Diogenite-like Enstatite and the Implications of Petrogenetic Modeling*

L. Bussolino, R. Somma, C. Casacci, V. Zappalà, A. Cellino, and M. Di Martino

*A Space Mission to Vesta: General Considerations*

**Thursday, October 17, 1996**

8:30 a.m.–12:00 noon

**DYNAMICS, SURFACE PROCESSES, AND MISCELLANEOUS TOPICS**

Chair: J. F. Bell

**Asteroid Break-Up and Families**

E. Asphaug* (review talk)

*Large Ejecta Fragments from Vesta and Other Asteroids*

F. Marzari, A. Cellino, D. R. Davis, P. Farinella*, V. Zappalà, and V. Vanzani

*The Vesta Asteroid Family: Origin and Evolution*

F. Migliorini*, V. Zappalà, A. Morbidelli, and A. Cellino

*A Dynamical Study of Vesta-Family Fragments*

D. R. Davis*, P. Farinella, F. Marzari, and E. Ryan

*Disrupting and Destroying Families from Differentiated Parent Bodies*

K. C. Welten*, L. Lindner, K. van der Borg, Th. Loeken, P. Scherer, and L. Schultz

*Cosmic-Ray Exposure Ages of Diogenites and the Collisional History of the HED Parent Body or Bodies*

Discussion


*Early Energetic Particle Irradiation of the HED Parent Body Regolith*

M. Humayun* and R. N. Clayton

*Isotopic Constraints on the Origin of Eucrites*

G. I. Consolmagno

*Cosmogonic Implications of the HED-Vesta Connection*

Discussion
Thursday, October 17, 1996
1:30–5:30 p.m.

PLANETARY HEATING AND DIFFERENTIATION
Chair: J. J. Papike

Thermal History of Vesta and HEDs

A. Ghosh* and H. Y. McSween Jr.
_The Thermal History of Asteroid 4 Vesta, Based on Radionuclide and Collisional Heating_

A. Yamaguchi*, G. J. Taylor, and K. Keil
_Significance of the Most Metamorphosed Eucrites_

L. E. Nyquist* and D. D. Bogard
_Pyroxene Homogenization and the Isotopic Systematics of Eucrites_

D. W. G. Sears*, S. J. K. Symes, and P. H. Benoit
_Metamorphism of Eucrites and Eucrite-related Meteorites and Implications for Parent Body Sources_

M. Zema*, M. C. Domeneghetti, G. Molin, and V. Tazzoli
_Cooling Rates of Diogenites: A Study of Fe²⁺/Mg Ordering in Orthopyroxene by X-Ray Single-Crystal Diffraction_

Discussion
L. Wilson* and K. Keil (review talk)
_The Nature of Volcanic Eruptions on 4 Vesta_

G. J. Taylor*, R. C. Friedman, and A. Yamaguchi
_Eucrites, Terrestrial Basalts, and Volcanic Processes on Vesta_

Discussion
K. Righter and M. J. Drake*
_Core Formation in Vesta_

H. E. Newsom*
_Core Formation in the Howardite-Eucrite-Diogenite Parent Body (Vesta)_

A. Ruzicka*, G. A. Snyder, and L. A. Taylor
_Asteroid 4 Vesta as the HED Parent Body: Implications for a Metallic Core and Magma Ocean Crystallization_

Discussion
Friday, October 18, 1996
8:30 a.m.–12:00 noon

MISSION TO VESTA
Chair: D. W. Mittlefehldt


MASTER: An Orbiter for the Detailed Study of Vesta

J. F. Bell*
Vesta: The Big Questions

R. Z. Akhmetshin*, T. M. Eneev, and G. B. Efimov
On the Sample Return from Vesta by Low-Thrust Spacecraft

Discussion

Workshop Wrap-Up Discussion
Some Possible Topics

Should we send a spacecraft to Vesta?
What do we need to learn about Vesta?
What do we need to learn about HEDs?
What measurements should be made at Vesta?
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 considere1 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


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 \( R_{\text{crust}} = 280 \text{ km} \) [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 \( \sim 4-7 \text{-km} \) bodies had to be ejected at speeds considerably greater than \( v_{\text{esc}} = 350 \text{ m/s} \).

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 \( \sim 1 \text{-km} \) blocks from the surface of Mars at \( \sim 1 \text{ km/s} \) during the formation of the \( \sim 220 \text{-km} \) crater Lyot [7] could have impacted Vesta without destroying it. This result is obtained by (1) applying gravity scaling [8] to an \( \sim 150 \text{-km} \) 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
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.

List of Workshop Participants

Glen Akridge  
Department of Chemistry and Biochemistry  
University of Arkansas  
Fayetteville AR 72701  
Phone: 501-575-3170  
Fax: 501-575-7778  
E-mail: dakridge@comp.uark.edu

Tomoko Arai  
University of Tokyo  
7-3-1 Hongo  
Tokyo 113  
JAPAN  
Phone: 310-825-2015  
Fax: 310-206-3051  
E-mail: tomoko@min.s.u-tokyo.ac.jp

Erik Asphaug  
Mail Stop 245-3  
NASA Ames Research Center  
Moffett Field CA 94035  
Phone: 415-602-0786  
Fax: 415-604-6779  
E-mail: asphaug@cosmic.arc.nasa.gov

Jeffrey F. Bell  
Institute of Geophysics and Planetology  
University of Hawai‘i  
2525 Correa Road  
Honolulu HI 96822  
Phone: 808-956-3136  
Fax: 808-956-6322  
E-mail: bell@pgd.hawaii.edu

Richard P. Binzel  
Mail Stop 54-410  
Department of Earth, Atmosphere and Planetary Sciences  
Massachusetts Institute of Technology  
77 Massachusetts Avenue  
Cambridge MA 02139  
Phone: 617-253-6486  
Fax: 617-253-2886  
E-mail: rpb@mit.edu

Donald Bogard  
Mail Code SN2  
NASA Johnson Space Center  
Houston TX 77058  
Phone: 281-483-5146  
Fax: 281-483-2911  
E-mail: donald.d.bogard1@jsc.nasa.gov

Claudio Casacci  
Alenia Space  
P.O. Box 70110  
146 Torino  
ITALY  
Phone: 39-11-7180385  
Fax: 39-11-7180244

Clark R. Chapman  
Southwest Research Institute  
1050 Walnut, Suite 429  
Boulder CO 80302  
Phone: 303-546-9670  
Fax: 303-546-9687  
E-mail: cchapman@boulder.swri.edu

Guy Consolmagno  
University of Arizona  
Vatican Observatory Research Group  
Steward Observatory  
Tucson AZ 85721  
Phone: 520-621-7855  
Fax: 520-621-1532  
E-mail: gjc@as.arizona.edu

Ghislaine Crozaz  
Washington University  
Box 1169  
One Brookings Drive  
St. Louis MO 63130  
Phone: 314-935-6257  
Fax: 314-935-4083  
E-mail: gcw@howdy.wustl.edu

Donald R. Davis  
Planetary Science Institute  
620 North 6th Avenue  
Tucson AZ 85705  
Phone: 520-622-6300  
Fax: 520-622-8060  
E-mail: drd@psi.edu

Chiara Domeneghetti  
Universita di Pavia  
CNR-CSCC  
Via Abbiategrasso, 209  
Pavia I-27100  
ITALY  
Phone: 39-382-505871  
Fax: 39-382-505887  
E-mail: demeneghetti@crystal.unipv.it
John Jones  
Mail Code SN2  
NASA Johnson Space Center  
Houston TX 77058  
Phone: 281-483-5319  
Fax: 281-483-1573  
E-mail: john.h.jonesl@jsc.nasa.gov  

Klaus Keil  
Department of Geology and Geophysics  
Planetary Geosciences Division  
University of Hawai‘i at Manoa  
Honolulu HI 96822  
Phone: 808-956-8761  
Fax: 808-956-3188  
E-mail: keil@kahana.pgd.hawaii.edu  

David J. Lindstrom  
Mail Code SN2  
Planetary Science Branch  
NASA Johnson Space Center  
Houston TX 77058  
Phone: 281-483-5012  
Fax: 281-483-1573  
E-mail: david.j.lindstroml@jsc.nasa.gov  

Marilyn M. Lindstrom  
Mail Code SN2  
NASA Johnson Space Center  
Houston TX 77058  
Phone: 281-483-5135  
Fax: 281-483-5347  
E-mail: marilyn.m.lindstroml@jsc.nasa.gov  

Gary Lofgren  
Mail Code SN4  
NASA Johnson Space Center  
Houston TX 77058  
Phone: 281-483-5276  
Fax: 281-483-5276  
E-mail: gary.e.lofgrenl@jsc.nasa.gov  

Francesco Marzari  
Department of Physics  
University of Padova  
Via Marzolo 8  
I-35131 Padova  
ITALY  
Phone: 39-49-827-7190  
Fax: 39-49-827-7102  
E-mail: marzari@pd.infn.it  

Lucy Ann McFadden  
Department of Astronomy  
University of Maryland  
College Park MD 20782  
Phone: 301-405-2081  
Fax: 301-314-9067  
E-mail: mcfadden@astro.umd.edu  

David S. McKay  
Mail Code SN1  
NASA Johnson Space Center  
Houston TX 77058  
Phone: 281-483-5048  
Fax: 281-244-8892  
E-mail: david.s.mckayl@jsc.nasa.gov  

Gordon A. McKay  
Mail Code SN2  
Planetary Science Branch  
NASA Johnson Space Center  
Houston TX 77058  
Phone: 281-483-5041  
Fax: 281-483-1573  
E-mail: gordon.a.mckayl@jsc.nasa.gov  

Fabio Migliorini  
Armagh Observatory  
College Hill  
Armagh  
Northern Ireland BT61 9DG  
United Kingdom  
Phone: 44-1861-522928  
Fax: 44-1861-527174  
E-mail: pat@star.arm.ac.uk  

David Mittlefehldt  
Mail Code C23  
Lockheed Martin Engineering  
2400 NASA Road 1  
Houston TX 77058  
Phone: 281-483-5043  
Fax: 281-483-5347  
E-mail: david.w.mittlefehldtl@jsc.nasa.gov  

Horton Newsom  
Institute of Meteoritics  
University of New Mexico  
Northrop Hall, Room 306D  
Albuquerque NM 87131  
Phone: 505-277-0375  
Fax: 505-277-3577  
E-mail: newsom@unm.edu
Laurence E. Nyquist  
Mail Code SN2  
NASA Johnson Space Center  
Houston TX 77058  
Phone: 281-483-5038  
Fax: 281-483-1573  
E-mail: laurence.e.nyquist1@nasa.gov

James J. Papike  
Institute of Meteoritics  
University of New Mexico  
Northrop Hall 313  
Albuquerque NM 87131-1126  
Phone: 505-277-3577  
E-mail: jpapike@unm.edu

Michael Rampino  
Department of Applied Science  
New York University  
26 Stuyvesant St.  
New York NY 10003  
Phone: 212-998-3743  
Fax: 212-995-3820  
E-mail: rampino@is3.nyu.edu

Kevin L. Reed  
GDE Systems, Inc.  
MZ 6500-E  
16250 Technology Drive  
San Diego CA 92127  
Phone: 619-592-1089  
Fax: 619-592-5407  
E-mail: kevin.reed@gdesystems.com

Kevin Righter  
Lunar and Planetary Laboratory  
Space Science Building #92  
University of Arizona  
Tucson AZ 85721-0092  
Phone: 520-621-2816  
Fax: 520-621-4933  
E-mail: righter@lpi.arizona.edu

Alex Ruzicka  
Department of Geological Sciences  
Planetary Geosciences Institute  
University of Tennessee  
Knoxville TN 37996-1410  
Phone: 423-974-6023  
Fax: 423-974-6022  
E-mail: aruzicka@utkux.utcc.utk.edu

Graham Ryder  
Lunar and Planetary Institute  
3600 Bay Area Boulevard  
Houston TX 77058  
Phone: 281-486-2141  
Fax: 281-486-2162  
E-mail: zryder@lpi.jsc.nasa.gov

Hans Josef Schober  
Institut für Astronomie  
University of Graz  
Universitätsplatz 5  
A-8010 Graz  
AUSTRIA  
Phone: 43-316-384-091  
Fax: 43-316-380-9820  
E-mail: hans.schober@kfunigrat.ac.at

Craig S. Schwandt  
GDE Systems, Inc.  
Mail Code C23  
Lockheed Martin Engineering  
2400 NASA Road 1  
Houston TX 77058  
Phone: 281-483-1368  
Fax: 281-483-1573  
E-mail: craig.s.schwandt@nasa.gov

Derek W. G. Sears  
Cosmochemistry Group  
Department of Chemistry and Biochemistry  
University of Arkansas  
Fayetteville AR 72701  
Phone: 501-575-5204  
Fax: 501-575-7778  
E-mail: cosmo@uafsysb.uark.edu

Charles K. Shearer  
Department of Earth and Planetary Sciences  
Institute of Meteoritics  
University of New Mexico  
Albuquerque NM 87131  
Phone: 505-277-9159  
Fax: 505-277-3577  
E-mail: cshearer@unm.edu

Alexander Shukolyukov  
 Scripps Institution of Oceanography  
Mail Code 0212  
University of California, San Diego  
La Jolla CA 92037-0212  
Phone: 619-534-4886  
Fax: 619-534-0784  
E-mail: ashukolyukov@ucsd.edu
Mike Spilde  
Institute of Meteoritics  
University of New Mexico  
Northrop Hall, Room 313  
Albuquerque NM 87131-1126  
Phone: 505-277-1644  
Fax: 505-277-3577  
E-mail: mspilde@triton.unm.edu

Paul Spudis  
Lunar and Planetary Institute  
3600 Bay Area Boulevard  
Houston TX 77058  
Phone: 281-486-2193  
Fax: 281-486-2162  
E-mail: spudis@lpi.jsc.nasa.gov

Timothy D. Swindle  
Lunar and Planetary Laboratory  
University of Arizona  
P.O. Box 210092  
Tucson AZ 85721-0092  
Phone: 520-621-4128  
Fax: 520-621-4933  
E-mail: tswindle@u.arizona.edu

Hiroshi Takeda  
Chiba Institute of Technology  
Research Institute  
2-17-1 Tsudanuma  
Narashino City  
Chiba 275  
JAPAN  
Phone: 81-474-78-0587  
Fax: 81-474-78-0587  
E-mail: takeda@cc.it-chiba.ac.jp

Ivan Thorsos  
Institute of Meteoritics  
University of New Mexico  
Northrop Hall, Room 332  
Albuquerque NM 87131-1126  
Phone: 505-277-1644  
Fax: 505-277-1126

Allan Treiman  
Lunar and Planetary Institute  
3600 Bay Area Boulevard  
Houston TX 77058  
Phone: 281-486-2117  
Fax: 281-486-2162  
E-mail: treiman@lpi.jsc.nasa.gov

Heinrich Wänke  
Max-Planck-Institut für Chemie  
Abteilung Kosmochemie  
Saarstrasse 23  
Mainz  
D-55122  
GERMANY  
Phone: 49-6131-305-231  
Fax: 49-6131-371290  
E-mail: waenke@mpch-mainz.mpg.de

Paul H. Warren  
Institute of Geophysics  
University of California  
Los Angeles CA 90095-1567  
Phone: 310-825-3202  
Fax: 310-206-3051  
E-mail: pwarren@ucla.edu

Jeffrey Taylor  
Planetary Geosciences Division  
University of Hawai‘i  
2525 Correa Road  
Honolulu HI 96822  
Phone: 808-956-3899  
Fax: 808-956-6322  
E-mail: gtaylor@pgd.hawaii.edu

John T. Wasson  
Institute of Geophysics  
University of California-Los Angeles  
Los Angeles CA 90095-1567  
Phone: 310-825-1986  
Fax: 310-206-3051  
E-mail: wasson@igpp.ucla.edu

Peter Thomas  
Cornell University  
422 Space Sciences Building  
Ithaca NY 14853  
Phone: 607-255-5908  
Fax: 607-255-9002  
E-mail: thomas@cospif.tn.cornell.edu

Kees C. Welten  
Space Sciences Laboratory  
University of California  
Berkeley CA 94720-7450  
Phone: 510-495-2445  
Fax: 510-486-5496  
E-mail: kcwelten@ulinky.berkeley.edu
George W. Wetherill  
Department of Terrestrial Magnetism  
Carnegie Institution  
5241 Broad Branch Road NW  
Washington DC 20015  
Phone: 202-686-4370 x4375  
Fax: 202-364-8726  
E-mail: wetherill@eros.ciw.edu

Lionel Wilson  
Institute of Environmental and Biological Sciences  
Environmental Science Division  
Lancaster University  
Lancaster LA1 4YQ  
United Kingdom  
Phone: 44-1524-593975  
Fax: 44-1524-593985  
E-mail: l.wilson@lancaster.ac.uk

Akira Yamaguchi  
National Institute for Research in Inorganic Materials  
1-1 Namiki  
Tsukuba 305, Ibaraki 305-0044  
JAPAN  
Phone: 81-298-51-3354 x2629  
Fax: 81-298-51-2768  
E-mail: yamaguchi@nirim.go.jp

Vincenzo Zappalà  
Astronomical Observatory  
10025 Pino Torinese  
Torino  
ITALY  
Phone: 39-11-4919035  
Fax: 39-11-4919030  
E-mail: zappala@to.astro.it

Michele Zema  
Dipartimento di Scienze della Terra  
Università di Pavia  
Via Abbiatierrasso, 209  
Pavie  
I-27100  
ITALY  
Phone: 39-382-505887  
E-mail: zema@crystal.unipv.it

Anna Zezulová  
Jihlavská Street No. 22/613  
Prague 4-140 00  
CZECH REPUBLIC  
Phone: 42-2692-9569

Michael E. Zolensky  
Mail Code SN2  
NASA Johnson Space Center  
Houston TX 77058  
Phone: 281-483-5128  
E-mail: michael.e.zolensky@jsc.nasa.gov