Eos, Transactions, American Geophysical Union, Vol. 81, No. 31, August 1, 2000, Pages 349, 354 - 355

New Views of the Moon: Improved Understanding Through Data Integration

Understanding the Moon is crucial to future exploration of the solar system. The Moon preserves a record of the first billion years of the Earth-Moon system's history, including evidence of the Moon's origin as accumulated debris from a giant impact into early Earth. Lunar rocks provide evidence of early differentiation and extraction of a crust.

Lacking an atmospheric shield, the Moon's regolith retains a record of the activity of solar wind over the past 4 billion years. It also holds a complete record of impact cratering, and analysis of samples has allowed calibration of ages, and thus dating of other planetary surfaces. And because of its proximity to Earth, it's low gravity well, and stable surface, the Moon's resources will be useful both in establishing lunar habitations and as fuel for exploration beyond the Moon.

Lunar science has advanced tremendously in the 30 years since the Apollo and Luna missions. We know that the Moon is strongly differentiated, and recent tungsten isotope studies indicate that this differentiation occurred soon after solar system formation. The Moon probably accreted rapidly from debris that formed as a large planetesimal struck the early Earth. Ancient highland rocks provide evidence of early lunar differentiation, and basalts formed by later melting within the mantle reveal its cumulus nature. However, the timing, extent, and depth of differentiation, variations within the mantle, and lateral and vertical variations within the crust can only be surmised from the limited sample suites, gravity studies, and surface geophysics of the Apollo era.

Data from the recent Lunar Prospector and Clementine missions permit reassessment of the global characteristics of the Moon and a reexamination of the distribution of elemental components, rock and soil types, and resources, as well as remanent magnetism, gravity field, and global topography. New research provides some answers, but also leads to new questions.

These data need to be integrated with what has been learned from surface exploration, geophysical experiments, a sample base of known geologic context, and 30 years of sample analysis. Toward this end, a lunar science initiative is underway to integrate information now in hand with new global geochemical, spectroscopic, and geophysical data. This effort brings together a diverse group of scientists including geologists, geophysicists, petrologists, geochemists, and spectroscopists.

Through this initiative we seek to show, from experience with the Moon, how to explore the constitution and history of any rocky planet through the integration of remotely sensed and sample data.

Global Perspectives of the Moon

Global perspectives provide a view of the compositional complexity of the Moon's surface and, from the excavation of materials by impacts, knowledge of the distribution of materials at depth. The geochemistry of the Moon's crust, its gravity field, and its magnetic structure have now been investigated on a global scale. In most cases, the global data can be tied to rock and soil samples of known spatial and geologic context.

Lunar "hot spots" and compositional anomalies. The thorium gamma-ray map from Lunar Prospector reveals a concentration of radioactive elements in the crust of the Procellarum-Imbrium region of the lunar nearside. The inferred concentrations of heat-producing elements in this region would have had profound effects on its thermal and magmatic evolution. A map derived from an integration of Lunar Prospector neutron spectrometer and Clementine compositional data (Figure 1) also shows that these lunar "hot spots" are enriched in the rare earth elements Gd and Sm, and that the lower-than-expected neutron absorption of many lunar mare basalts corresponds to those with unusually high estimates of TiO_2 from Clementine data.

Using impact craters to probe crustal stratigraphy. Impact craters on the Moon—through uplifted central peaks and steep, rocky crater rims—provide views of fresh crustal

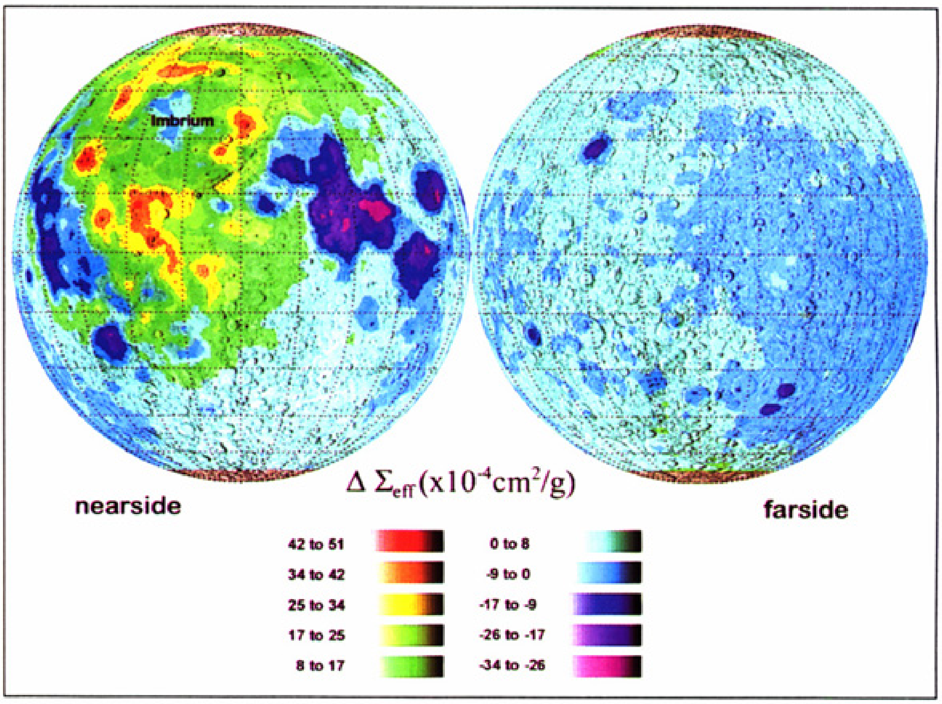

Fig. 1. Image of the Moon highlighting areas of rare earth element enrichment [Elphic et al., 1998]. "Delta sigma effective" values represent fast/thermal neutron flux observed by the Lunar Prospector neutron spectrometer minus flux calculated from thermal neutron absorption expected from Fe and Ti derived from Clementine data. Positive values mark areas where strong thermal neutron absorbers (the rare earth elements Gd and Sm) are abundant; negative values mark high-titanium mare basalts where thermal neutron absorption is less than expected. Location of the Imbrium basin is shown for reference. Neutron spectrometer data are from the low-altitude phase of the Lunar Prospector mission.

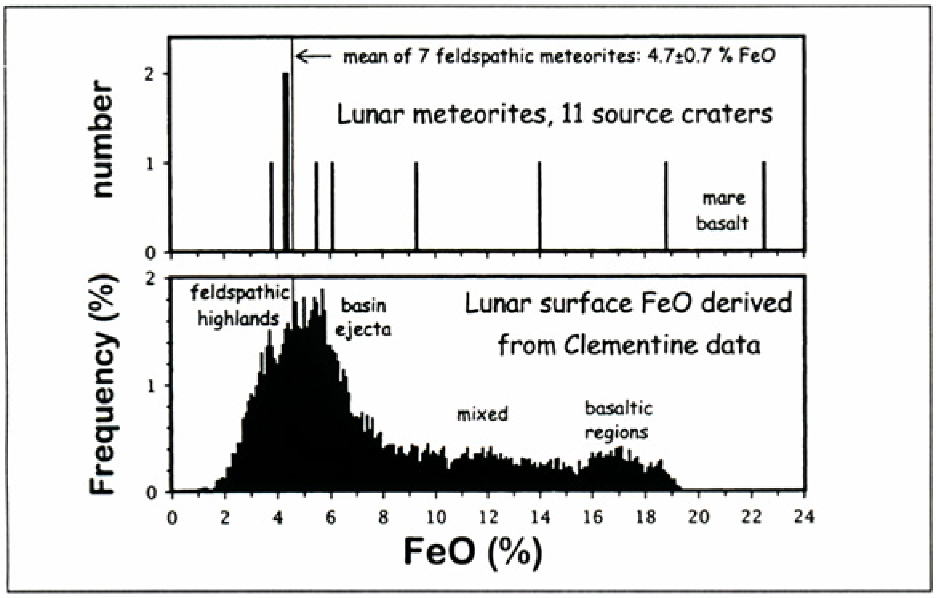

Fig. 2. Global FeO concentrations from Clementine data compared to FeO concentrations of lunar meteorites. The mean FeO concentration of 7 feldspathic meteorites is close to that of average feldspathic highlands on the lunar farside (~4.5%). FeO concentrations of basaltic meteorites extend to higher values than remotely sensed data because the latter reflect soils that are mixed and averaged over large areas.

rocks. Clementine multispectral data are being used to survey lunar rock types and to investigate upper-level crustal stratigraphy using rock exposures in impact craters [*Tompkins and Pieters*, 1999]. Compositional maps of ejecta from large impacts reveal how the composition of the crust varies laterally and at intermediate-to-deep levels. In many cases, deeply exhumed ejecta are more mafic than the local surface. In some locations, central peaks and mountains in basin rims expose highly anorthositic rocks through the well-mixed, impact-generated "megaregolith" that constitutes the upper few kilometers of the crust. The Imbrium impact, which formed one of the last of the great nearside basins, excavated Th-rich mafic material, distributing it extensively, possibly even to the basin's antipode.

Exploring the depths of the Moon. A region of the Moon that was under-appreciated until the advent of global perspective is the farside South Pole-Aitken basin. This ~2500-km diameter basin was formed by an impact of such magnitude that it might have penetrated through the thicker farside lunar crust and into the mantle. The basin is geophysically anomalous compared to smaller and later impact basins [*Wieczorek and Phillips*, 1999], suggesting either that the impact was oblique or that thermally induced relaxation erased what was once a more anomalous mass concentration. Although the floor of the basin is known to be mafic, not enough is known about its composition to determine if it represents lower crust, upper mantle, or a mixture. The paucity of basalt flows within the basin also remains a mystery.

Meteorites from the Moon. In the past 2 decades, 19 rocks that originated on the Moon have been found on Earth. While the Apollo and Luna samples came from a small area on the lunar nearside, the lunar meteorites represent as many as 11 source craters from random locations on the surface. The lunar meteorites appear to be fairly representative of the entire Moon (Figure 2). In fact, the feldspathic lunar meteorites appear to represent feldspathic highlands better than does regolith from the one nominally highlands mission, Apollo 16. Thus, the lunar meteorites extend sample coverage of the Moon and provide important new information that, when coupled with remotely sensed data, enables more accurate assessments of surface distribution of rock types and bulk crustal composition.

Early Lunar History and Lunar Interior

The early physical and chemical differentiation of the Moon, although perhaps well understood in the general sense of crust-mantle separation, is not well understood in detail. On the basis of dynamical modeling and new isotopic data, both accretion and differentiation must have taken place rapidly following the creation of a debris ring around the growing Earth [*Drake and Halliday*, 1998]. The formation of a magma ocean following hot accretion and the extraction of a highly aluminous crust represent a planetary-scale differentiation event. However, the depth and extent of melting of the magma ocean, the possible existence of undifferentiated mantle, and the mechanism of core formation remain subjects of debate.

A lunar core. High-resolution gravity data and careful analysis of the magnetic field following the Lunar Prospector mission indicate

Recent Advances in Lunar Science

➢ **Global maps of the Moon**

- Rock and soil composition at hundred meter to kilometer scales
  - ➤ Major mineralogy
  - ➤ FeO, TiO_2, soil maturity
- Elemental composition at tens of kilometer scales
  - ➤ H, Fe, Ti, Th, K, REE (Sm, Gd)
  - ➤ Hydrogen mapped at poles
- Geophysics
  - ➤ Gravity (*Clementine, Lunar Prospector*)
  - ➤ Magnetic fields (*Lunar Prospector*)
  - ➤ Topography (*Clementine*)
- Accurate global coordinate system

➢ **Regolith-forming processes**

- Differential grain size breakdown effects caused by micrometeorite impacts have been quantified
  - ➤ 10-40 μm fraction dominates optical properties
- Solar wind and cosmic rays cause grain surface alteration and accretion
- Buildup of microscopic Fe metal modifies reflectance spectra

➢ **Lunar crust**

- Heat-producing elements concentrated in Procellarum-Imbrium region of lunar nearside
- Farside South Pole - Aitken Basin (2500 km) possibly penetrated crust, exposing mafic lower crust or upper mantle
- Nearly pure anorthosite blocks exposed in impact basin rings

➢ **Lunar volcanism and intrusive activity**

- Basaltic samples provide evidence of mantle overturn
- Magnesian plutonic suite related to interaction with magmatic residua of early differentiation
- Volcanic glasses formed by deep (> 400 km) melting
- Globally, basalts show full range of TiO_2 (distribution *not* biomodal)
- Volcanism extended to relatively recent time (~1.3 Ga)

➢ **Lunar meteorites**

- 18 specimens from regions not previously sampled

➢ **Tenuous lunar exosphere related to regolith-forming processes**

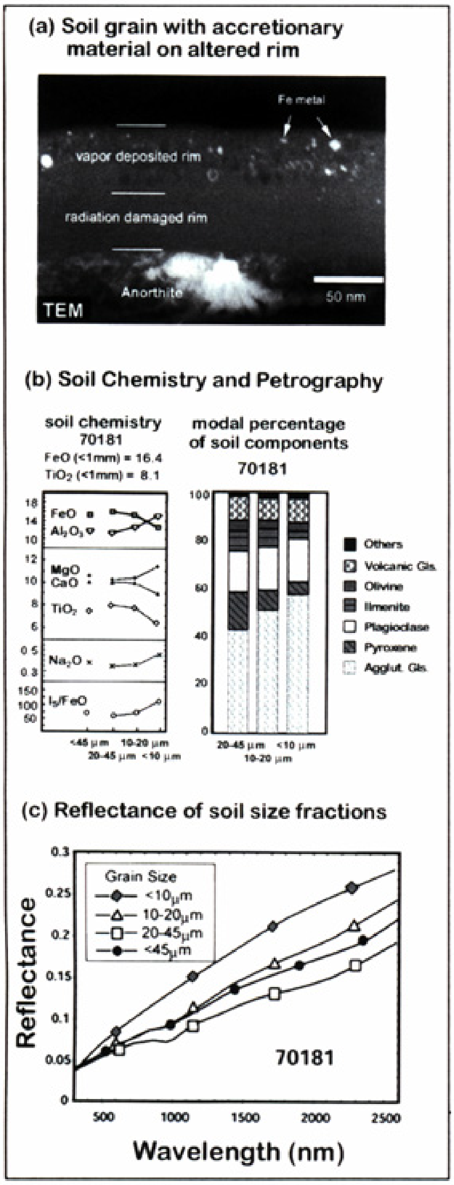

Fig. 3. Characteristics of fine materials in lunar soils. (a) TEM micrograph of an alteration zone and accretionary rim on an anorthite grain. There is little Fe in the alteration zone, but nanophase Fe grains are abundant in the accretionary zone. (b) Chemistry and mode of the finest grain-size fractions of an Apollo 17 soil showing variations as a function of decreasing grain size. (c) Reflectance spectra for the same grain-size fractions as (b); filled circles are for < 45 µm fines, which coat all coarser soil grains.

an iron-rich core with a radius of 300–450 km [*Hood et al.*, 1999], consistent with analyses of data from Earth-based, laser-ranging retroreflectors [*Williams et al.*, 1999]. Together these different sources of information reveal possible dynamo activity in the Moon's past, and provide critical constraints on internal heat sources and on the possibility that shortly after its formation, the Moon was entirely molten.

Lunar crustal asymmetry. The crust of the Moon appears to be substantially thinner on the nearside than on the farside, the center of mass and center of figure are offset, and basaltic volcanism was more abundant on the nearside. This asymmetry dates back to the early differentiation of the Moon and the production of its crust. The lunar magma ocean apparently did not solidify uniformly and concentrically. Factors associated with heat transfer in the molten parts of the early Moon and insulation associated with early protocrust and thick deposits of impact debris likely influenced the asymmetry. Several lines of investigation are leading to the possibility that sustained hotspot-like volcanism and related intrusive activity, fueled by concentrations of Th, U, and K-rich residua left after solidification of the magma ocean, would have resulted from the asymmetry. In light of new information about the global distribution of heat-producing elements, this topic is worth investigating.

Mantle melting. Extensive basaltic volcanism provides a record of melting in the lunar mantle. If during the solidification of the magma ocean the olivine and pyroxene cumulates expelled most of their trapped residual melt, they would lack the needed heat source for later remelting. Mantle overturn, driven by density contrasts between deep, magnesian olivine cumulates and shallow, Fe- and Ti-rich cumulates, may provide part of the solution. However, a strong concentration of magma-ocean residua in some regions must have contributed to the extended thermal history recorded by basalt flows that range in age from > 4 Ga to ~1.3 Ga. The dynamics of this highly localized thermal and mass transfer within the early mantle are thus integrally related to early differentiation and global asymmetry.

Lunar volcanism. Data from Clementine and Lunar Prospector, coupled with recent analyses of lunar samples, are providing new constraints on lunar volcanism. Although Apollo samples indicated that the distribution of basalt according to TiO_2 content was strongly bimodal, TiO_2 contents derived from remotely sensed data indicate a unimodal distribution that is skewed about a mean of low TiO_2 concentration [*Giguere et al.*, 2000]. Detailed crater chronologic studies suggest the existence of young (~1.3 Ga) basalts in some regions. Current efforts are aimed at characterizing pyroclastic deposits over the full range of chemical composition, and include distinguishing glass-poor from glass-rich deposits.

Compositional studies of volcanic glasses and mare basalts, and related phase equilibria suggest that the melts that produced the glasses are originated deeper (e.g., > 380 km) than melts that produced the basalts. Variations in trace element compositions are being used to explore the possibility that the glasses derived from garnet-bearing or undifferentiated regions of the mantle. Samples from future returns must be studied to understand whether and how chemical compositions, depths of origin, and volcanism rates varied as a function of time on the Moon.

Also, future sample returns are needed to better understand the role and source of volatiles in the lunar mantle, the relationship between magma composition and eruption dynamics, and the mechanism for transporting magmas represented by the volcanic glasses from great depths without fractionation. Establishing seismic stations on the surface of the Moon is key to understanding the structure of the deep lunar interior, especially with regard to the depth and character of volcanic source regions.

Impact history of the Moon. The history of impact cratering on the Moon is a key to the chronology of all bodies in the inner solar system, including Earth. Early, accretional bombardment events were rapid and geocentric, while subsequent impacts were protracted and heliocentric, and recent work supports an abrupt decline in the late basin-forming episode. Impacts during accretion may have influenced global asymmetry. The timing of later mare and post-mare impacts is unclear, although recent advances in obtaining relative ages on rayed craters using optical maturity parameters derived from Clementine data may be useful. The data suggest a reasonably constant flux over the last 2 billion years, while new Ar-isotopic ages from glass beads in lunar soil suggest that the flux declined until about 500 m.y.a. and then increased. Lunar impact chronology is expected to benefit from continued study and integration of sample and remotely sensed information.

Microscopic to Macroscopic Views of Lunar Soils

Lunar soils provide a record of inner solar system processes that fall under the term "space weathering." Knowledge of these processes, including alteration effects of micro-meteorite bombardment, cosmic and solar irradiation, and ion implantation, help characterize not only the space environment, but also the formation of soils on the Moon and other airless bodies. This information is needed to obtain accurate compositional information from remotely sensed data. Future resource processing schemes on the Moon will depend on understanding the entrainment of hydrogen and other materials in lunar soils.

At the nanometer scale, Fe-metal blebs occur in accreted material and as amorphous alteration rims on over 90% of grains in "mature" soils, and appear to account for the alteration of optical and magnetic properties (Figure 3). Detailed analyses of different lunar soil size fractions reveal significant changes in composition and modal mineralogy that occur with diminishing grain size, and that correlate with changes in the magnetic properties related to the nonometer-scale Fe.

Reflectance spectra of these samples show that grains < 45µm, which coat all coarser grains, dominate the macroscopic optical properties. Characterizing such effects in soils of different composition, mineralogy, and exposure histories is essential to understanding how reflectance spectra relate to soil chemistry and mineralogy, and ultimately to the rocks from which the soils derive.

Lunar Resources

The Moon offers significant resources for future exploration and exploitation. The current state of technology takes lunar resource utilization beyond scientific curiosity and into the realm of practical application. As human interests and activities extend beyond low-Earth orbit, the Moon will be a logical place to establish permanent human presence, possibly because of commercial and resource development pressures, or to provide a stepping-stone for exploration of Mars and beyond. Lunar bases will be test beds for exploration technologies, facilitating scientific endeavors such as testing human endurance and exposure to the space environment under low gravity conditions, and developing materials and technologies that use near-vacuum pressures or nearly continuous solar energy sources. A lunar base could host astronomical, solar, and Earth observatories with a level of stability and clarity not achievable on Earth. Recent global remote sensing provides important information for the siting and support of future lunar bases.

Key to any human exploration activities will be the extraction and use of H and O for fuel and life support. Solar wind-implanted volatiles are well known from the study of Apollo soils, but results of the neutron spectrometer mapping from Lunar Prospector are illuminating the global distribution of H concentrations. From the combination of sample studies, photogeological investigation of local rock formations and soil thicknesses, and remote sensing of soil geochemistry and maturity, locations that will make the best hosts for H extraction can be identified. If polar ice deposits exist in permanently shaded regions, they would represent an alternative source of water. However, the concentration, depth, local distribution, and physical form of such deposits will determine whether they are worth mining. Other potentially favorable deposits may exist in the form of ilmenite-rich, pyroclastic soils, which are also rich in ^3He, a potential fuel for nuclear fusion energy.

Remaining Questions and Future Exploration

Recent global data sets and their integration with existing information has led to a renewed focus on key questions of lunar science, as well as to a new set of questions. Some pertain to a more complete understanding of the early catastrophic impact history and thermal evolution of the Earth-Moon system. Others focus on the siting and development of resources for future human habitation, and the use of the Moon that will occur as human presence projects beyond Earth and low-Earth orbit.

Possible future missions include sample investigations of sites such as the South Pole-Aitken basin, Th-enriched basalts in Oceanus Procellarum, unusually young basalts (1-2 Ga), and the unique volcanic area of the Aristarchus Plateau. Important geophysical information will come from distributed seismic networks and heat-flow experiments. Further understanding of the nature, extent, and distribution of the most enriched H deposits will remain a high priority.

In the meantime, we are reminded that the ever-important economic and political reality of our world may dictate scientific opportunities. Thus, we should be prepared to couple research endeavors with human exploration and commercial development programs.

Acknowledgments

This article is part of a Lunar Science Initiative, New Views of the Moon Enabled by Combined Remotely Sensed and Lunar Sample Data Sets, begun by the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM). The Lunar Science Initiative has received support from NASA's Cosmochemistry Program; the Lunar and Planetary Institute, Houston, TX; and the U.S. Geological Survey, Flagstaff, AZ

Lunar Science: Key Questions

- What elemental and molecular species make up the tenuous lunar atmosphere and how has it changed with time?
- What was the initial thermal state of the Moon?
- What was the cause of global scale asymmetry?
  - convection and density inversion dynamics?
  - Procellarum and early giant impact effects?
  - asymmetric crystallization of the lunar magma ocean?
  - tidal effects?
- What was the depth of differentiation during the lunar magma-ocean stage?
- What are the characteristics of the lunar core (size, composition), and did the Moon ever support a dynamo-driven magnetic field?
- Was there a significant late veneer of accretion (post-core formation/early differentiation)?
- Is there an undifferentiated lower mantle (limited or no involvement in magma-ocean melting); if so, what was its role in lunar magmatism?
  - Did the volcanic glasses come from a deep, garnet-bearing region beneath the cumulate mantle?
  - What volatiles are (were) present in the deep lunar interior and what was their role in magmatic processes and eruptive styles?
- What were the sources and magnitude of heating to drive secondary magmatism?
  - How was heat transferred from Th, U, K-rich crustal reservoirs to the mantle?
  - What was the role of large-scale crustal insulation?
  - How are the different suites of plutonic rocks related to specific or localized geologic terranes and to the global geochemical asymmetry?
- What and where are the most concentrated, extensive, and readily extractable deposits of H and ^3He?
  - What is the mineralogical or physical form, thickness, and concentration of H or H_2O ice deposits in permanently shadowed craters at the poles?
  - Is H at the poles an economically viable resource?
  - Where are the best sites for such facilities located? (H, ^3He, protection from radiation, communications, transportation)

Authors

B. L. Jolliff, L. R. Gaddis, G. Ryder, C. R. Neal, C. K. Shearer, R. C. Elphic, J. R. Johnson, L. P. Keller, R. L. Korotev, D. J. Lawrence, P. G. Lucey, J. J. Papike, C. M. Pieters, P. D. Spudis, and L. A. Taylor

For more information, contact Bradley L. Jolliff, Campus Box 1169, Washington University, One Brookings Dr., St. Louis, Mo. 63130 USA; E-mail: blj@levee.wustl.edu

References

Drake, M., and A. Halliday, *Origin of the Earth and Moon Conference*, Monterey, Lunar and Planetary Inst., Houston, Tex., 1998.

Elphic, R., et al., Lunar Fe and Ti abundances: Comparison of Lunar Prospector and Clementine Data, *Science, 281*, 1493–1496, 1998.

Giguere, T., et al., The titanium contents of lunar mare basalts, *Meteoritics and Planetary Science, 35*, 193–200, 2000.

Hood L. L., et al., Initial measurements of the lunar induced magnetic dipole moment using Lunar Prospector magnetometer data, *Geophys. Res. Lett., 26*, 2327–2330, 1999.

Tompkins, S., and C. M. Pieters, Mineralogy of the lunar crust: Results from Clementine, *Meteorit. Planet. Sci., 34*, 25–41, 1999.

Wieczorek, M. A., and R. J. Phillips, Lunar multiring basins and the cratering process, *Icarus, 139*, 246–259, 1999.

Williams, J. G., et al., A view of the lunar interior through lunar laser range analysis, In *Workshop on New Views of the Moon II*, Flagstaff, LPI Contrib. No. 980, Houston, Tex., 1999.