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Hot Idea
posted December 10, 2004

Composition of the Moon's Crust

--- New empirical calibrations of Lunar Prospector and Clementine data yield improved global maps of Th, K, and FeO. The movie of the Moon, shown to the right, consists of compositional data for Th, K, FeO, and the Clementine 750 nm albedo image played in that order. (Courtesy of J.J. Gillis.)

Lunar nearside Th concentrations
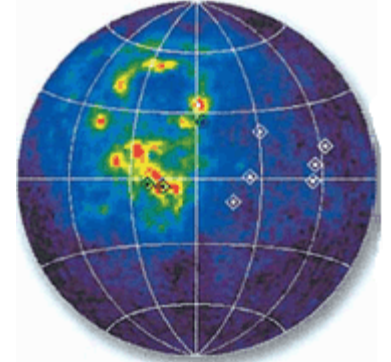
(Gillis, et al., 2004, Geochim. et Cosmochim. Acta, v. 68, p.3793.)

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In 1997, PSRD first reported on the trailblazing efforts to map the abundance and distribution of titanium and iron on the entire lunar surface based on Clementine orbital remote sensing data [see **PSRD** article: Moonbeams and Elements]. Researchers calibrated the remote sensing data with the best ground-truth standards available: lunar soil and rock samples. Since the initial mapping, planetary scientists have been striving to improve the calibration of the remote sensing data to correct for over or under estimates of the global concentrations of primary elements. This work is important because it prevents us from getting erroneous ideas about the Moon's composition and origin. New calibrations to Lunar Prospector and Clementine data by Jeff Gillis (previously at Washington University in St. Louis and now at the University of Hawai'i), Brad Jolliff, and Randy Korotev (both at Washington University in St. Louis) have resulted in updated global maps for thorium (Th), potassium (K), and iron oxide (FeO) that are more consistent with the compositions of lunar samples and lunar meteorites, and allow a better understanding of the Moon's formation and evolution.

Reference:

Gillis, J. J., Jolliff, B. L., and Korotev, R. L. (2004) Lunar surface geochemistry: Global concentrations of Th, K, and FeO as derived from Lunar Prospector and Clementine data. *Geochimica et Cosmochimica Acta,* v. 68, p. 3791-3805.

Why refinements in the Calibrations Were Needed

Deriving the abundance of various elements on the surface of the Moon from orbital remote sensing data is a complicated task. It involves understanding instrument performance and resolution (how much surface area is in one pixel of data) as well as the geology and how to relate the energy reflected by the surface to actual elemental abundance values. Calibrating the remote sensing data to ground truth is a critical step: the derived elemental abundances must make sense at every point on the surface where we are certain of the soil compositions, such as at the Apollo landing sites on the nearside. Ground truth for the farside highlands comes indirectly in the form of feldspar-rich lunar meteorites. Only when we have derived accurate measures of the global abundance and distribution of elements do we gain a realistic understanding of the crustal and bulk Moon compositions.

The difficulty has been that the elemental concentrations derived from Lunar Prospector gamma-ray

spectrometer data and Clementine five-band UVVIS (ultraviolet-visible) spectral reflectance data have not quite matched the ground truth. For example, the graph below compares Th and K values from previous calibrations of Lunar Prospector gamma-ray data to the Apollo sample and lunar meteorite data.
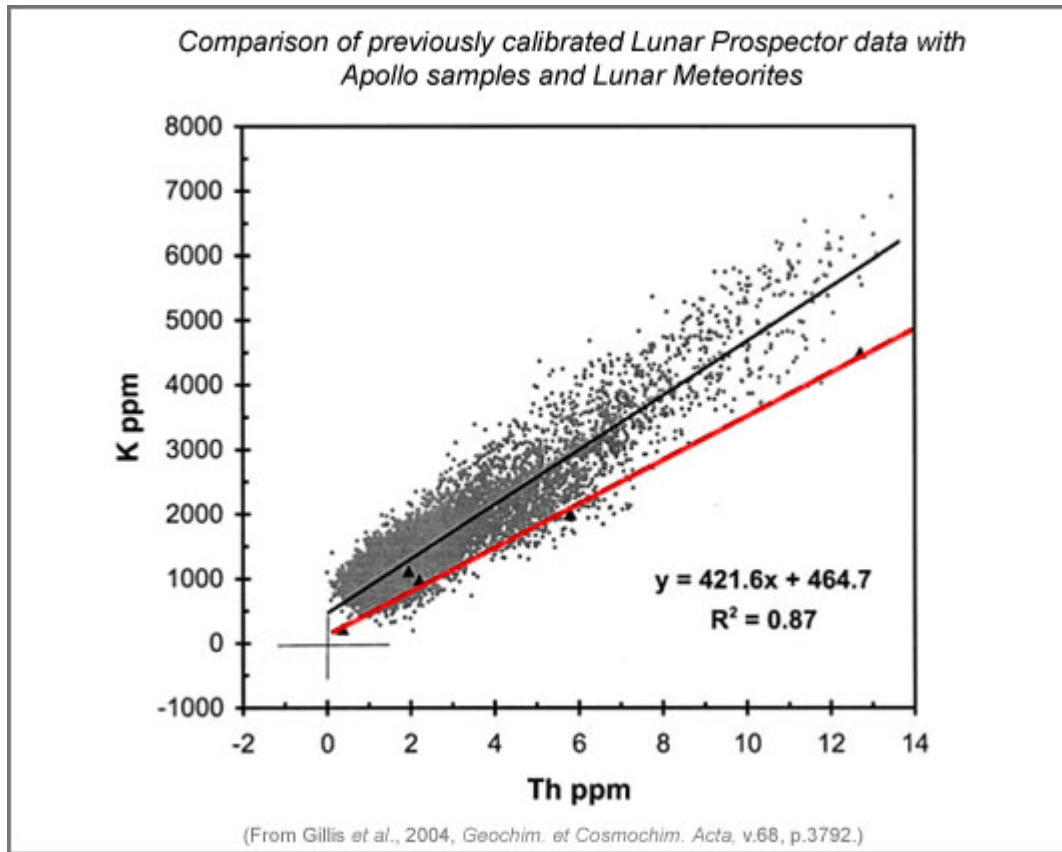
The data points on this graph (where the 0,0 origin is marked with a cross) are concentrations of K and Th obtained from the Lunar Prospector gamma-ray spectrometer data by previous (as of 2002) theoretical-based calibration techniques (by David Lawrence and Tom Prettyman, both at Los Alamos National Laboratory, and others). The black line is a best-fit linear regression to these data points. Small black triangles denote ground truth data points (Apollo samples and lunar meteorites) and the red line is a linear least squares fit to these data. The lines do not match. The black line and most of the data points lie above the red line indicating a systematic overestimation of both Th and K.

The talented scientists mapping the composition of the Moon's crust are improving the quality, and their understanding, of the remote sensing data and they are continually upgrading the calibration techniques. After correcting the uncertainties and systematic errors they are successfully minimizing discrepancies between the derived data and lunar sample data.

Jeff Gillis and colleagues focused their recent recalibration work on Th, K, and FeO because these elements are important for determining geologic processes, as well as understanding the crustal and bulk compositions of the Moon. For example, high-Th concentration can be used to infer high concentrations of other incompatible trace elements and is a useful marker for KREEP materials--late crystallizing igneous rocks that relate to the lunar magma ocean and theories of crustal formation. Also, Th and K (and by correlation uranium) are naturally radioactive elements, so a better understanding of their distribution at the surface allows the researchers to extrapolate their concentrations to depth, thereby allowing them to work out the thermal evolution of the Moon's crust and mantle. Global FeO abundance (iron is expressed as an oxide because it is chemically bonded to oxygen inside minerals) is used to estimate Al_2O_3 abundance, and to determine rock types and regolith mixing caused by impacts. Calibration methods previously used to derive FeO concentrations from Clementine UVVIS spectral reflectance data showed a slight but systematic underestimation of FeO values in locations with low-titanium mare soils.

The new calibrations and techniques by Gillis and his coauthors, summarized in the next section, have corrected the estimates that were too high for Th and K and too low for FeO compared to the ground truth.

New Ground-Truth Calibrations

- Lunar Prospector gamma-ray spectrometer K and Th Data

Gillis, Jolliff, and Korotev used a mathematical regression technique (or empirical technique) to fit a straight line to the standards (Apollo samples and lunar meteorites) that takes into account the uncertainties in each data point. This allowed them to relate Lunar Prospector elemental concentrations to sample elemental concentrations (see the graph below). Apollo soil compositions span much of the range of Th and K observed over the Moon's surface, but Apollo 15 and 17 data were specifically excluded because both sites were located at a mare and highlands boundary and the soil compositions vary too much across the site at the resolution of the Lunar Prospector pixel (a 2° area or 60 km/pixel). Feldspar-rich lunar meteorites were included in their calibrations to serve as proxies for the low-Th highlands rocks and as anchors at the low-concentration ends of the Th and K correlations.
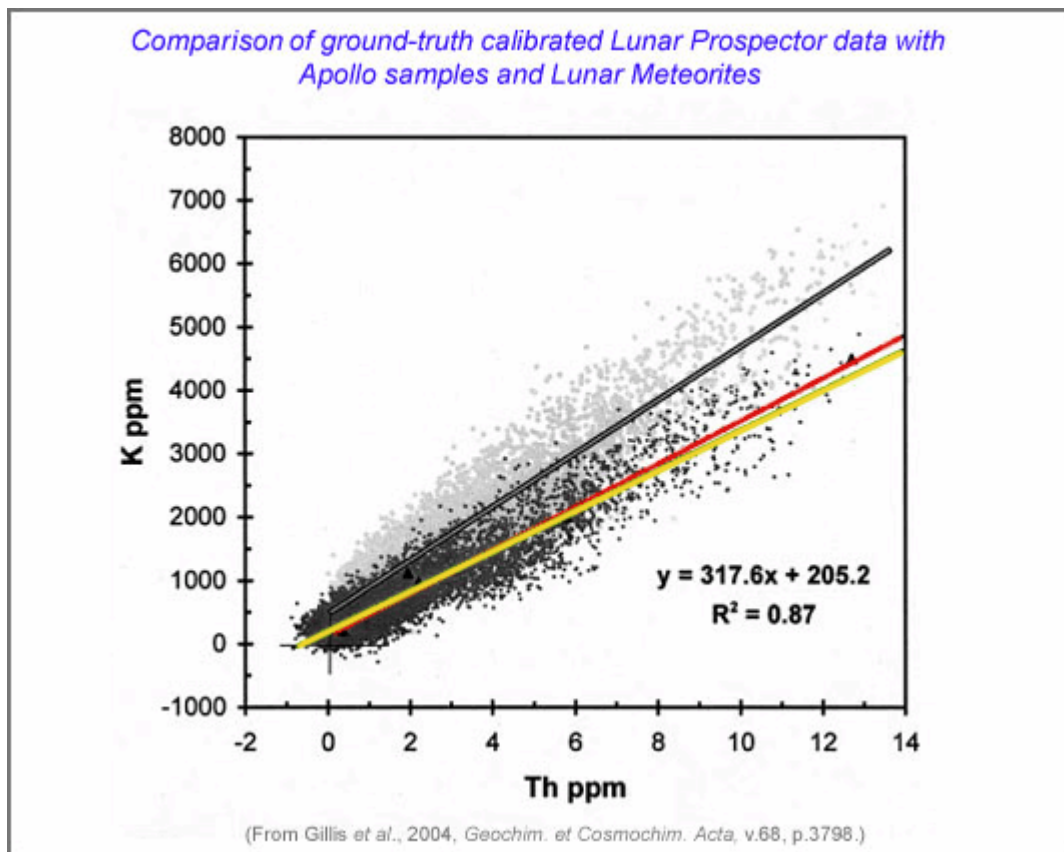
This graph is similar to the one above except that now the black points are the new, ground-truth calibrated Lunar Prospector gamma-ray data calculated by Gillis and colleagues. The gold line is the best-fit line to these data points. As in the graph above, the red line is the best fit line to ground truth from Apollo samples and lunar meteorites. These two lines match more closely than in previous calibration studies (indicated by the light gray points and their black best-fit line). A few of the new data points have negative values. These are geochemically impossible, but Gillis and coauthors suggest they are warranted on the basis of remaining uncertainties in the detection and calibration of the gamma-ray data. They suggest that all negative values should be treated as near-zero concentrations.

The results of the new empirical calibrations by Gillis and team yield lower concentrations of Th and K than reported previously. The global surface mean Th concentration decreases from 2.4 to 1.6 parts per million. The global surface mean K concentration decreases from 1480 to 700 parts per million.

- Clementine spectral reflectance FeO Data

The method for deriving FeO content on the lunar surface from the intensity of light reflected at two wavelengths (Clementine UVVIS spectral reflectance data) was invented by Paul Lucey (University of Hawai'i) and incorporated the contemporary understanding of space weathering. In this technique, the spectral parameter angle Θ (theta) increases as FeO increases (see **PSRD** article: Moonbeams and Elements for diagrams and details). Gillis and coauthors observed the FeO concentrations calculated for the Apollo 15 site using the Lucey method were too low when compared to the samples, which are low-titanium and high-FeO mare soils. Fortunately, Clementine had better resolution (~125 meters/pixel) than Lunar Prospector, so the Apollo 15 data were included. The other high-FeO site, Apollo 17, has high-titanium, high-FeO mare soils. Gillis and colleagues concluded that the mineral ilmenite affects the spectral reflectance at the two wavelengths used in the Lucey method to calculate FeO. As a result, they made a small adjustment in the FeO method to account for the effects of TiO_2 in the mineral ilmenite on the UVVIS spectra of basalts. They called it the TiO_2-sensitive FeO derivation, which changes the slope and offset values in the FeO algorithm of Lucey's original method. The recalibrated FeO concentration matches the low-titanium and high-iron mare basalts better than any previous derivation. The new calibrations also produce FeO concentrations for the northern farside highlands that are consistent with the feldspar-rich lunar meteorite compositions. The surface mean FeO concentration reported by Gillis and coauthors for the maria is 16 wt%, and 5.7 wt% for non-mare areas.

New Global Maps of Th, K, and FeO

Gillis, Jolliff, and Korotev produced empirical ground-truth calibrations of the Lunar Prospector gamma-ray spectrometer data for Th and K abundances and a TiO_2-sensitive, modified algorithm of the Clementine UVVIS spectral reflectance data for FeO abundance. Their recalibrated global maps are shown below.
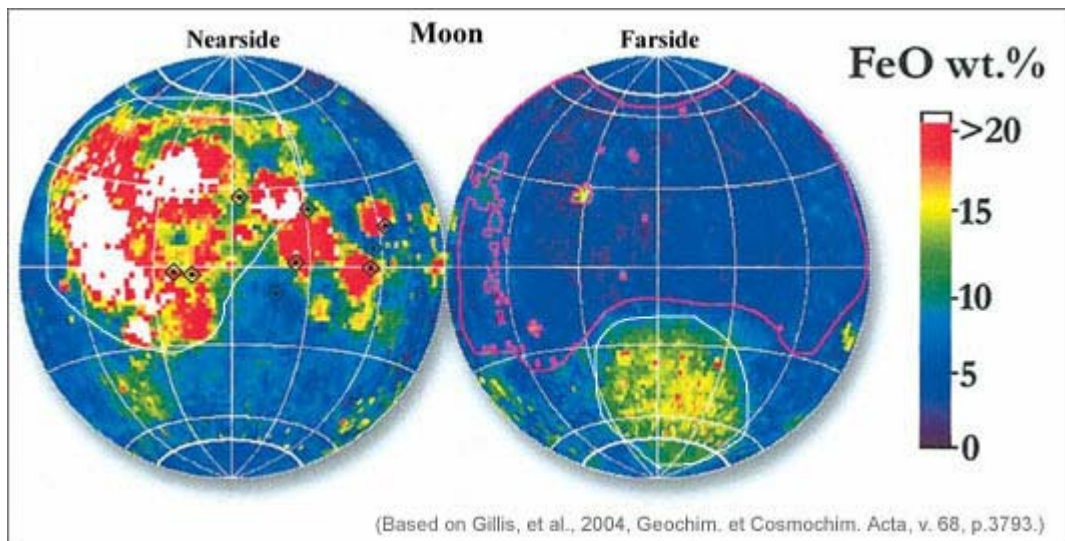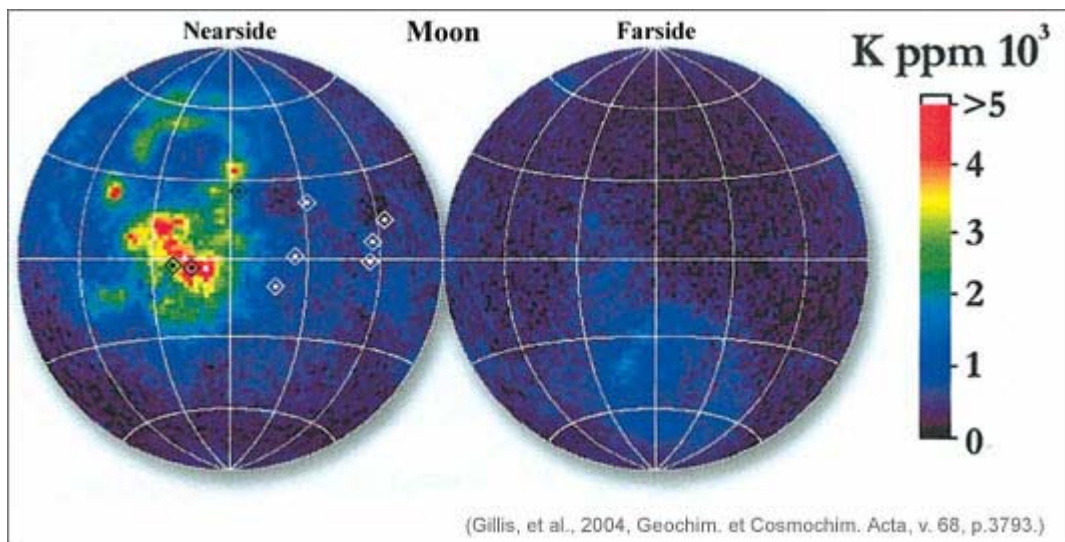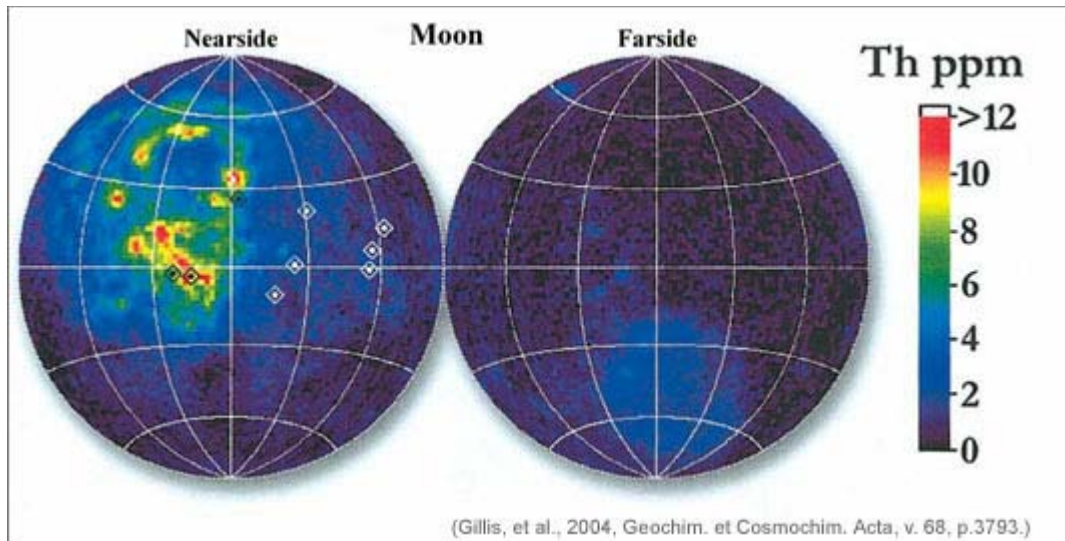
Diamonds on the three Nearside maps show the locations of the six Apollo and three Luna landing sites. The pink outline on the Farside FeO map defines the region of the northern feldspathic highlands (including the Feldspathic Highlands Terrane) from which Gillis and colleagues took data for comparison to feldspar-rich lunar meteorites. The white, circular outline on the Farside FeO map shows the South Pole-Aitken Terrane. The white outline on the Nearside FeO map indicates the Procellarum KREEP Terrane.

These maps agree with the compositional data of soil samples in the lunar collection (i.e., KREEP-rich materials; Fe-poor and Th-poor and feldspar-rich materials; Fe-rich mare volcanics). But the new calibrations for Th, K, and FeO do show some differences from previous work in the three crustal terranes, defined previously by Jolliff and colleagues: the Procellarum KREEP Terrane, Feldspathic Highlands Terrane, and the South Pole-Aitken Terrane (see outlines on the FeO maps above). In particular, the Procellarum KREEP Terrane, which is the Th-rich nearside highlands, shows higher Th values in the new map than in previous maps--Jolliff used an earlier calibration by David Lawrence than the one discussed herein. Conversely, the new calibration map shows lower Th values for the Feldspathic Highlands Terrane than previous studies. The biggest differences between the revised FeO data and previous calibrations occur in the SPA Terrane and the Procellarum KREEP Terrane, where the TiO_2-sensitive algorithm reports higher FeO values. Gillis suggests these differences in FeO reflect an abundance of low-Ti, high-FeO mare materials that previously were reported as lower FeO due to their low TiO_2 contents.

Gillis and colleagues' ground-truth-calibrated abundances of Th, K, and FeO provide researchers a better look at the Moon's crust, which bears on all studies of the Moon's origin, crustal formation, and bulk composition. Future missions will enhance our knowledge of the chemical composition of the lunar surface. For instance, the SMART-1 (European Space Agency) and SELENE (ISAS, NASDA - Japan) missions carry instruments to directly measure magnesium and aluminum, two other important elements in the cosmochemist's tool box.

Additional Resources

Gillis, J. J., Jolliff, B. L., and Korotev, R. L. (2004) Lunar surface geochemistry: Global concentrations of Th, K, and FeO as derived from Lunar Prospector and Clementine data. *Geochimica et Cosmochimica Acta,* v. 68, p. 3791-3805.

Jolliff, B.L., Gillis J.J., Haskin L.A., Korotev R.L., and Wieczorek M.A. (2000) Major lunar crustal terranes: Surface expressions and crust-mantle origins. *Journal of Geophys. Res.,* v. 105, p. 4197-4216.

Korotev, R.L., Jolliff B.L., Zeigler R.A., Gillis, J.J., and Haskin, L.A. (2003) Feldspathic lunar meteorites and their implications for compositional remote sensing of the lunar surface and the composition of the lunar crust. *Geochimica et Cosmochimica Acta,* v. 67, p. 4895-4923.

Lawrence D.J., Feldman W.C., Barraclough B.L., Binder A.B., Elphic R.C., Maurice S., Miller M.C., and Prettyman T.H. (2000) Thorium abundances on the lunar surface. *Journal of Geophys. Res.,* v. 105, p. 20307-20331.

Prettyman, T.H., Feldman, W.C., Lawrence, D.J., McKinney, G.W., Binder, A.G., Elphic, R.C., Gasnault O.M., Maurice S., and Moore, K.R. (2002) Library least squares analysis of Lunar Prospector gamma ray spectra. *Lunar Planet. Sci. 33,*, abstract 2012.

SELENE The ISAS, NASDA - Japan mission scheduled for launch in 2005.

SMART-1 The European Space Agency's current mission to the Moon. It achieved lunar orbit on November 15, 2004. Science observations will begin in January, 2005 to study surface mineralogy and water ice.

Taylor, G.J. (1997) Moonbeams and Elements. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/Oct97/MoonFeO.html

Taylor, G.J. (2000) A New Moon for the Twenty-First Century. *Planetary Science Research Discoveries.*

http://www.psrd.hawaii.edu/Aug00/newMoon.html

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