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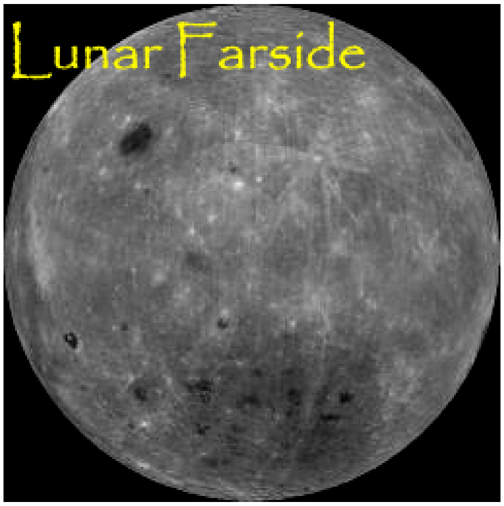
Hot Idea April 29, 2008



Clementine 750 nm image mosaic. DSPSE/USGS
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A Farside Geochemical Window into the Moon

--- Findings show geochemical enhancements in the Dewar region are caused by thorium-rich mare basalt fragments in the regolith.

Written by Linda M. V. Martel
Hawai'i Institute of Geophysics and Planetology

A low-albedo area on the lunar farside near Dewar crater has the geochemical characteristics of mare basalt despite the fact that no maria have ever been identified there. The area sits in the previously-mapped Feldspathic Highlands Terrane (FHT) that is characterized by very low thorium and iron oxide abundances. Yet further remote sensing studies show the featured area near Dewar has anomalously elevated thorium, samarium, iron oxide, and titanium oxide values compared to the FHT. Samuel Lawrence (formerly at the Hawaii Institute of Geophysics and Planetology and now at Arizona State University) and colleagues from Hawaii, Los Alamos National Lab, and USGS Flagstaff analyzed a suite of Lunar Prospector data, Clementine ultraviolet-visible (UVVIS) images, and Lunar Orbiter photographs to determine the composition and probable origin of the Dewar anomaly. The body of evidence points to excavated material from a farside buried mare basalt, or cryptomare, derived from a magma with enhanced thorium concentrations.

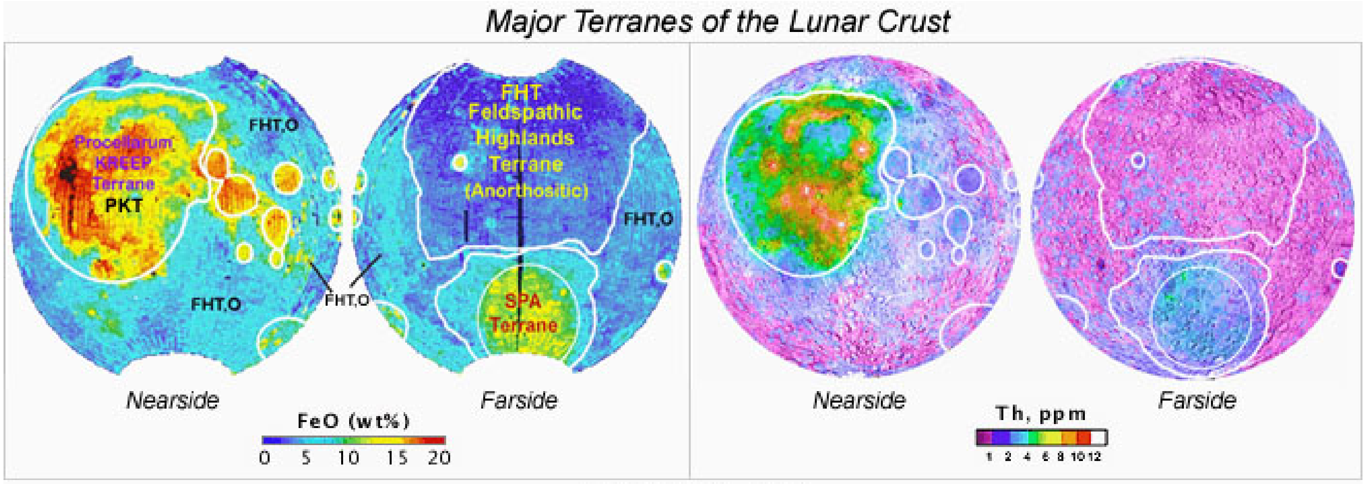
Reference:

- Lawrence, S. J., Hawke, B. R., Gillis-Davis, J. J., Taylor, G. J., Lawrence, D. J., Cahill, J. T., Hagerty, J. J., Lucey, P. G., Smith, G. A., and Keil, K. (2008) Composition and Origin of the Dewar Geochemical Anomaly, *Journal of Geophysical Research*, v. 113(E02001), doi: 10.1029/2007JE002904.

PSRDpresents: Lunar Farside Geochemical Feature --Short Slide Summary (with accompanying notes).

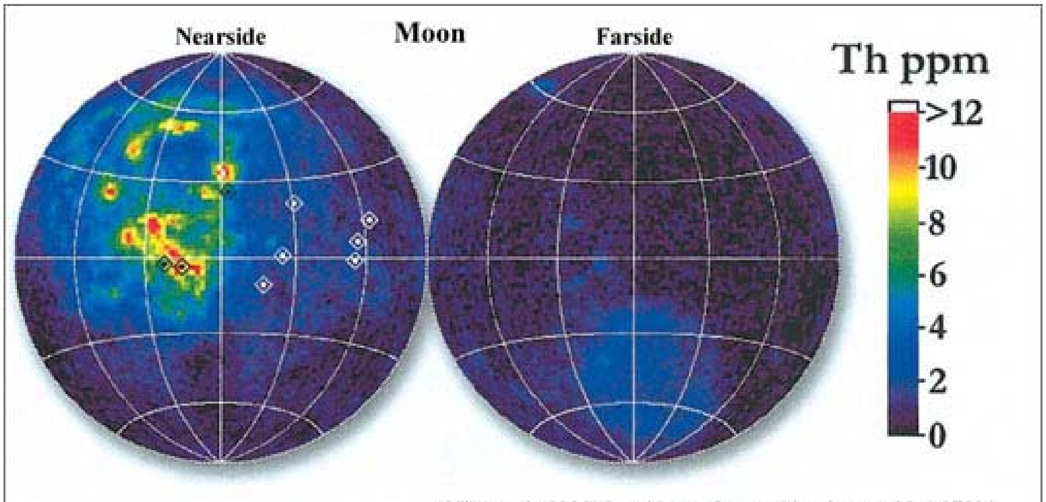
Focus on the Farside

As reported in **PSRD** articles A New Moon for the Twenty-First Century and Composition of the Moon's Crust, Lunar Prospector and Clementine global datasets integrated with lunar sample data have led to new insights about the composition of the lunar crust, hence of the whole Moon. Entirely new regions on the Moon have been mapped based on specific chemical characteristics, as shown below. The farside, in particular, is characterized by low iron oxide (4.2 wt% on average) and very low thorium (0.8 parts per million), which Brad Jolliff (Washington University in St. Louis) and colleagues termed the Feldspathic Highlands Terrane (FHT). Together with a related terrane that they call the outer Feldspathic Highlands Terrane (FHT,O), these distinctive geologic provinces dominate the farside and globally cover 65% of the lunar surface.



(From Jolliff et al., 2000.)
FeO (wt%) maps on the LEFT use a base image from Lucey et al. 1995. Th(ppm) maps on the RIGHT use Th concentrations from Lunar Prospector data, calibrated to landing site soils by Gillis et al., 2000.

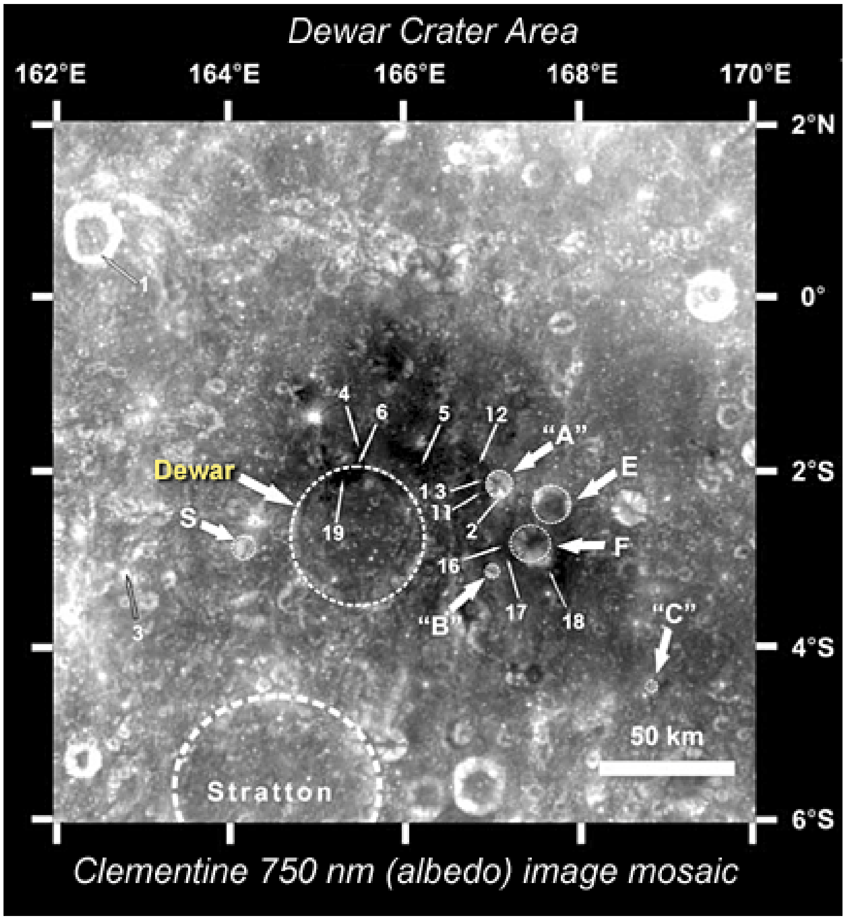
The maps above show the three major terranes on the Moon as defined by Brad Jolliff and colleagues (Washington University in St. Louis). The Feldspathic Highlands Terrane (**FHT**) includes its somewhat different outer portion (**FHT,O**); this terrane has low FeO and Th. The Procellarum KREEP Terrane (**PKT**) is characterized by high FeO and Th. The South Pole Aitken Terrane (**SPA Terrane**) has relatively moderate FeO and Th.



(Gillis, et al., 2004, Geochim. et Cosmochim. Acta, v. 68, p.3793.)

The asymmetry in the concentration of thorium (Th) on the lunar surface is again shown in the maps, above, derived from recalibrated Lunar Prospector gamma-ray spectrometer data, which shows lower Th values for the Feldspathic Highlands Terrane than previous studies. (Diamonds on the nearside map show the locations of the six Apollo and three Luna landing sites.)

A global survey of small-area features with either anomalously high or low thorium abundances made by David Lawrence (Los Alamos National Lab) and colleagues found that most occurred on the nearside. However, one notable, anomalously high-thorium area that coincides with a dark, low-albedo surface is in the farside highlands located east-northeast of Dewar crater, a 50-kilometer impact structure of Imbrian age (3.85 to 3.2 billion years old). The thorium values here could be as high as 6-7 ppm compared to <1.1 ppm in the surrounding highlands of the FHT. This so-called Dewar anomaly also correlates with enhancements in iron oxide and titanium oxide, and is particularly important to study if we want to better understanding the distribution of thorium outside the thorium-dominated Procellarum KREEP Terrane (PKT). Thorium is important because it is easily measured from orbit and correlates with a host of other geochemically diagnostic elements such as the rare earths. Because of the unique characteristics of the Dewar anomalous area, Sam Lawrence and colleagues set out to determine its chemical and rock compositions and explain how it formed.



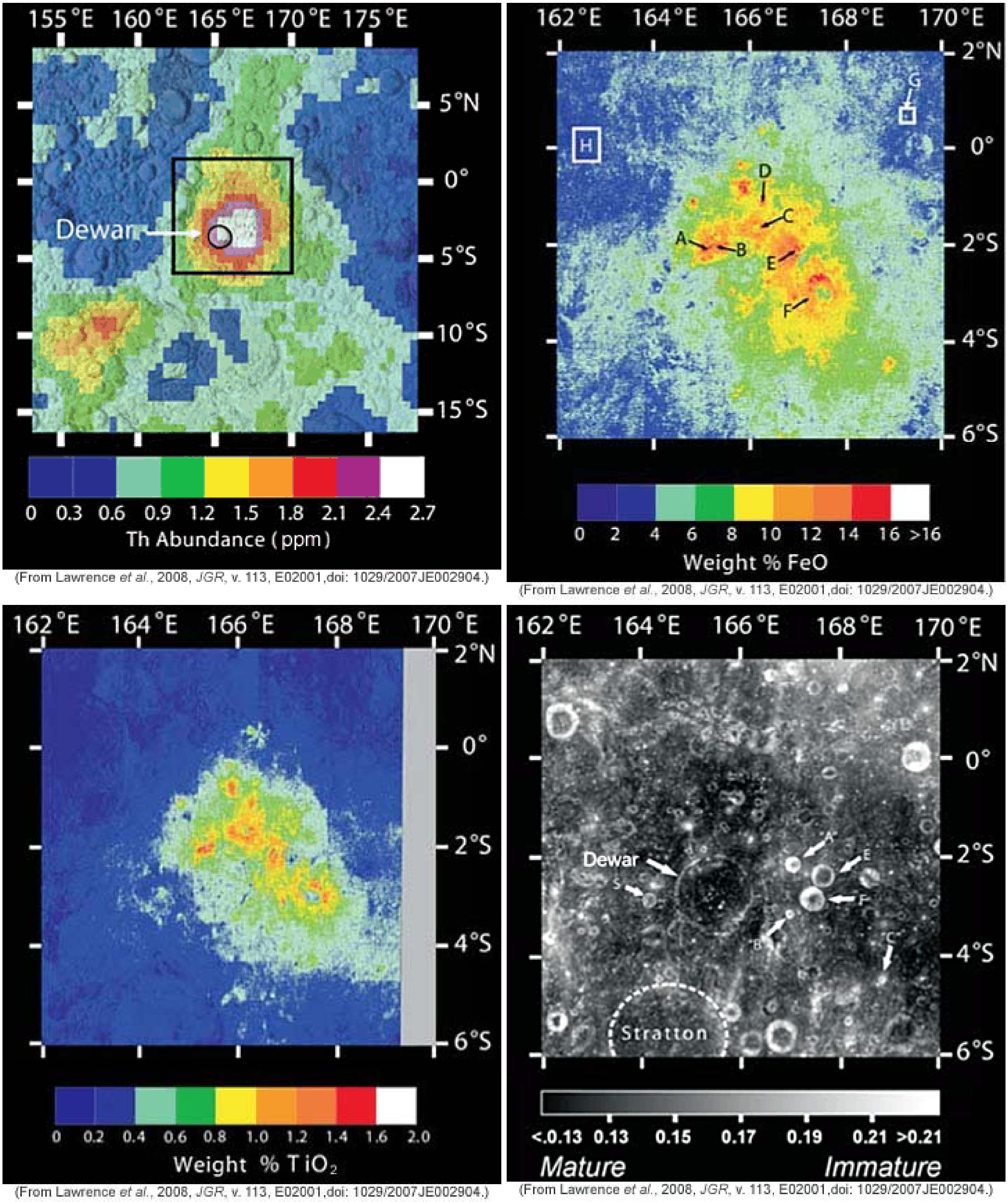
(From Lawrence *et al.*, 2008, *JGR*, v. 113, E02001,doi: 1029/2007JE002904.)

Dewar crater is centered at 2.7°S, 165.5°E. Names and letters identify craters. Numbers indicate locations where Clementine UVVIS spectra were collected for this study.

Data Galore

Four maps compiled and analyzed by the research team to study the Dewar region are described and shown below. In addition, Sam Lawrence and his colleagues made extensive use of the vast database of lunar rock compositions developed by cosmochemists.

- Th abundance map using Lunar Prospector gamma-ray spectrometer data and the methods developed by David Lawrence and others, 2003.
- FeO abundance map using Clementine UVVIS data and the methods developed by Jeff Gillis-Davis and others, 2004.
- TiO_2 abundance map created using the technique of Jeff Gillis-Davis and others (2003) with Clementine UVVIS data
- Optical maturity map using Clementine UVVIS data and the algorithms of Paul Lucey and others, 2000.



(From Lawrence *et al.*, 2008, *JGR*, v. 113, E02001,doi: 1029/2007JE002904.)

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Maps of the farside Dewar region. **TOP LEFT:** Th abundance map. Measured Th values are shown on the map key, but they could be as high as 6-7 ppm when adjusted for instrument response and mathematical smoothing techniques. Box outlines the area shown in the other maps. **TOP RIGHT:** FeO abundance map. Letters show where researchers collected average FeO and TiO_2 values. **BOTTOM LEFT:** TiO_2 abundance map. Gray vertical stripe is an area where data are missing. **BOTTOM RIGHT:** Optical maturity image. Dark tones indicate mature surfaces and bright tones indicate immature surfaces. A mature surface has been exposed to space weathering for a longer time than an immature surface.

The highest Th and FeO abundances in the Dewar geochemical anomaly are correlated with the highest values of TiO_2, and are in the darkest portions of this low-albedo area. The researchers found that the range of FeO and TiO_2 values in the darkest portions overlap the range of FeO and TiO_2 values determined for mare basalt deposits on the nearside. Thorium values in the Dewar anomaly greatly resemble those of an Apollo sample of thorium-rich mare basalt. There is also an enhancement in samarium (not shown) detected in the Lunar Prospector neutron spectrometer data in the Dewar anomaly area.

Sam Lawrence and colleagues used an algorithm they developed in order to predict the modal mineralogies for the Clementine spectra extracted from the darkest areas of the Dewar anomaly. Without exception, they found the calculated mineralogies had mafic assemblages dominated by high-calcium clinopyroxene. This is a diagnostic characteristic of mare basalts.

The research team compiled the summary table below to show the compositional data for the Dewar region and selected lunar samples. (Please refer to their publication for references for data shown.)

	Dewar anomaly (low-albedo areas)	Background Highlands	Mafic-Impact Melt Breccias (MIBs)	Apollo 15 Yellow Impact Glass 15010,3189	Th-Rich Mare Basalt 12032,266-18	Representative Mare Basalts (avg. of four lunar samples)
FeO, wt%	14.5-16.2	< 6.0	6.4-10.6	18.9	19.5	18.5
TiO_2, wt%	0.8-2.0	< 0.4	0.7-1.8	4.2	4.2	5.2
Th, ppm	6-7	< 1.1	2.9-16.1	8	7	0.7
% of pyroxene that is high-Ca pyroxene	73-93	-	11-37	-	64	77-86

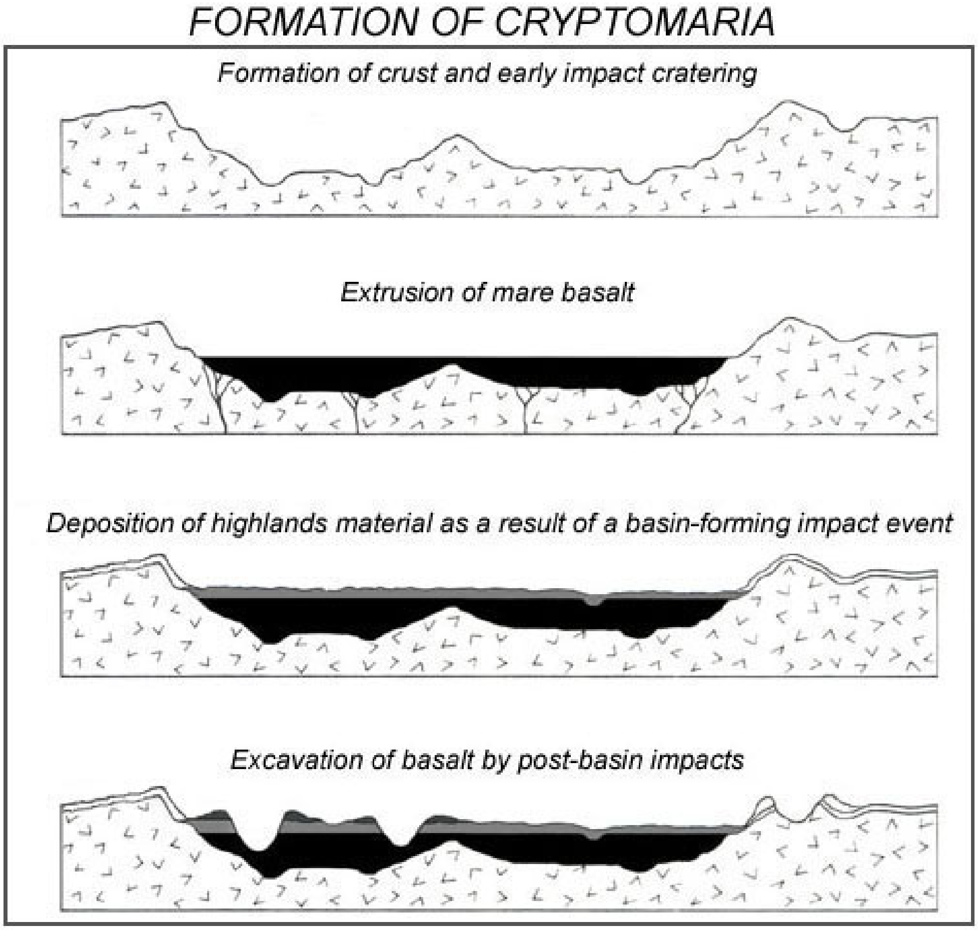
Making Sense of the Data

Spectral data for the Dewar anomaly are similar to those of nearside mare basalts. The spectral modeling by Sam Lawrence and colleagues also show these low-albedo materials contain mafic assemblages dominated by high-Ca pyroxene. In addition, some craters in the Dewar region display partial or complete dark haloes with high concentrations of iron oxide. Taken together, these results are consistent with the presence of large quantities of mare basalts in the areas where the Dewar remote sensing data were collected. Nevertheless, the team evaluated other origins for the anomaly and the pros and cons of three possibilities are summarized in the table below.

Possible Origin	**Arguments In Favor**	**Arguments Against**
Mafic Impact-Melt Breccias (MIBs)	High Th, relatively high FeO, TiO_2	FeO and high-Ca clinopyroxene abundances for the darkest materials in Dewar region are too high.
Surface Deposits of Mare Basalt or Pyroclastics	FeO and TiO_2 values in the darkest portions of the Dewar anomaly are similar to values for mare basalts on the lunar nearside. Both Dewar anomaly and pyroclastic materials have low albedo.	No level surfaces, no visible basalt ponds. No visible lava flows. Albedo of the Dewar anomaly is generally higher than albedo of nearside pyroclastic mantling deposits. There are no clearly defined source vents in the Dewar region for pyroclastic deposits, but they could be obscured.
Excavated Material from Cryptomare (buried mare basalt lava)	Mafic geochemistry dominated by high-Ca clinopyroxene. Presence of dark-haloed impact craters in the area.	No arguments against.

Sam Lawrence and colleagues suggest the geochemical enhancements in the Dewar region are caused by thorium-rich mare basalt fragments in the regolith despite several known facts: (1) maria are extremely rare on the farside covering only 1% of the surface as compared with 16% coverage on the nearside, (2) no maria are seen in the Dewar region, (3) examples of thorium-rich mare basalts are rare in the Apollo, Luna, and lunar meteorite collections.

The enhanced thorium values associated with the Dewar cryptomare deposit are unlike most of the other known mare units on the central farside of the Moon, which exhibit low thorium abundances. A possible geologic history of the Dewar area might be illustrated in the diagram below.



(PSRD graphic; after drawing by Jeffrey Bell and B. Ray Hawke, Univ. of Hawaii.)

The four panels in this diagram show cutaway, side views into the Moon to describe the basic formation of a cryptomare. Cryptomaria formed when low -lying areas in the heavily -cratered ancient highlands (TOP panel) were flooded by mare basalt lava flows (black deposit, SECOND panel). An impact event (here labeled basin-forming, but could also include the smaller Dewar crater impact event) deposited ejecta on top of the surface (THIRD panel). During deposition, some of the mare basalt was mixed with ejecta from the crater, forming a deposit consisting of broken and mixed highland rocks with fragments of mare basalt (grey deposit). Eventually, smaller craters punctured through the ejecta, (BOTTOM panel) depositing debris from the underlying mare basalts around them, creating dark -haloed craters and revealing the existence of the buried mare basalt. The bottom panel shows two dark -haloed craters on the left side of the panel. The small crater on the right side does not have a dark halo.

According to the formation model favored by Sam Lawrence and coauthors, the geochemical enhancements in the Dewar region are caused by the presence of variable amounts of thorium-rich mare basalt fragments in the regolith. This suggests that the portion of the lunar farside interior where the Dewar basalts came from was not thorium poor.

Thorium is Important

The source of the thorium enrichment is actually not well understood. As reviewed in **PSRD** article: Composition of the Moon's Crust, high thorium concentrations 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 lunar crustal formation. Also, thorium and potassium (and by correlation uranium) are naturally radioactive elements (hence release heat), so a better understanding of their distribution at the surface allows researchers to extrapolate their concentrations to depth, thereby allowing them to work out the thermal evolution of the Moon's crust and mantle. As pointed out by the team, there are at least two different models with multiple variations that could explain the origin of thorium-rich mare basalt on the Moon. One model involves melting of a Th-rich source region in the mantle, while the second model involves the assimilation of KREEP-rich (i.e., Th-rich) crustal materials as the magma rises from depth through the crust to the surface. In either case it is not clear how this patch of Th-rich mantle or lower crust formed on the farside, a hemisphere away from the Th-rich Procellarum KREEP Terrane. Though we don't yet have a definitive answer to the question of how the thorium enrichment occurred, lunar scientists are discovering tantalizing details about the Moon's surface and what lies underneath and out of sight, and in the case of Sam Lawrence's work at Dewar crater, way out of sight on the fascinating farside. This could be an interesting site for a sample return mission either by robotic lander or astronauts that could collect multiple samples for laboratory chemical analysis.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:** Lunar Farside Geochemical Feature --Short Slide Summary (with accompanying notes).

- Apollo Image Archive, hosted at Arizona State Univeristy.
- Gillis, J. J., Jolliff, B. L., and Elphic R. C. (2003) A Revised Algorithm for Calculating TiO2 from Clementine UVVIS Data: A Synthesis of Rock, Soil, and Remotely Sensed TiO2 Concentrations, *Journal of Geophysical Research*, v. 108(E2), 5009, doi: 10.1029/2001JE001515.
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- 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 Geophysical Research*, v. 105, p. 4197-4216.
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- Lawrence, S. J., Hawke, B. R., Gillis-Davis, J. J., Taylor, G. J., Lawrence, D. J., Cahill, J. T., Hagerty, J. J., Lucey, P. G., Smith, G. A., and Keil, K. (2008) Composition and Origin of the Dewar Geochemical Anomaly, *Journal of Geophysical Research*, v. 113(E02001), doi: 10.1029/2007JE002904.
- Lucey, P. G., Blewett, D. T., Taylor, G. J., and Hawke, B. R. (2000) Imaging of Lunar Surface Maturity, *Journal of Geophysical Research*, v. 105, p. 20,377-20,386.
- Lunar Mission: Clementine, with information about spacecraft sensors, including the Ultraviolet/Visible Camera.
- Lunar Mission: Lunar Orbiter photography.
- Lunar Mission: Lunar Prospector.
- Taylor, G. J., (2000) A New Moon for the Twenty-First Century. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/Aug00/newMoon.html
- Taylor, G. J., (2004) Composition of the Moon's Crust. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/Dec04/LunarCrust.html
- Taylor, G. J. (2005) Gamma Rays, Meteorites, Lunar Samples, and the Composition of the Moon. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/Nov05/MoonComposition.html
- Taylor, G. J. (2008) Chips Off an Old Lava Flow. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/Dec07/cryptomareSample.html