Headline Article

May 30, 2013

Magnesium-rich Basalts on Mercury

--- Crystallization modeling using the MELTS computer code with MESSENGER-derived compositions finds Mg-rich lavas on Mercury.

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

X-ray and gamma-ray spectrometers on NASA's MESSENGER spacecraft are making key measurements regarding the composition and properties of the surface of Mercury, allowing researchers to more clearly decipher the planet's formation and geologic history. The origin of the igneous rocks in the crust of Mercury is the focus of recent research by Karen Stockstill-Cahill and Tim McCoy (National Museum of Natural History, Smithsonian Institution), along with Larry Nittler and Shoshana Weider (Carnegie Institution of Washington) and Steven Hauck II (Case Western Reserve University). Using the well-known MELTS computer code Stockstill-Cahill and coauthors worked with MESSENGER-derived and rock-analog compositions to constrain petrologic models of the lavas that erupted on the surface of Mercury. Rock analogs included a partial melt of the Indarch meteorite and a range of Mg-rich terrestrial rocks. Their work shows the lavas on Mercury are most similar to terrestrial magnesian basalt (with lowered FeO content). The implications of the modeling are that Mg-rich lavas came from high-temperature sources in Mercury's mantle and erupted at high temperature with exceptionally low viscosity into thinly bedded and laterally extensive flows, concepts open to further evaluation by laboratory experiments and by geologic mapping of Mercury's surface using MESSENGER's imaging system and laser altimeter to document flow features and dimensions.

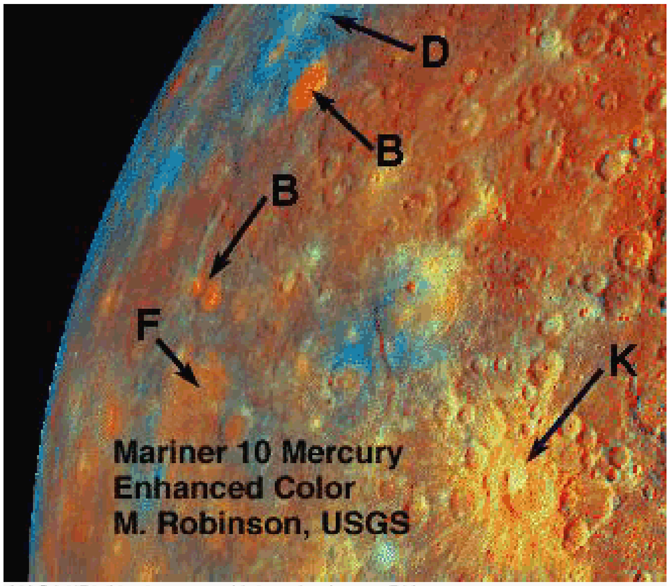
Reference:

- Stockstill-Cahill, K. R., T. J. McCoy, L. R. Nittler, S. Z. Weider, and S. A. Hauck II (2012) Magnesium-rich Crustal Compositions on Mercury: Implications for Magmatism from Petrologic Modeling, *Journal of Geophysical Research,* v. 117, E00L15, doi: 10.1029/2012JE004140. [**abstract**]

The Mercury We Knew Before MESSENGER

Mercury was our least explored terrestrial planet before NASA's current MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) orbiter mission launched on August 3, 2004. MESSENGER's three flybys in 2008–2009 and its orbital insertion on March 18, 2011 marked the first return of new data from Mercury since the three flybys of NASA's Mariner 10 spacecraft in 1974–1975.

Imaging 45% of the surface at an average resolution of about 1 kilometer, Mariner 10 revealed heavily cratered surfaces reminiscent of the **highlands** on the Moon and smoother regions interpreted as either volcanic plains (analogous to the **maria** on the Moon) or fluidized impact ejecta. Mark Robinson (then at USGS, Flagstaff and currently at Arizona State University) and Paul Lucey (University of Hawaii) recalibrated the Mariner 10 data more than 20 years after its colletion and identified distinct geologic terrains and volcanically emplaced material on the surface (see **PSRD** article: **Mercury Unveiled**).



NASA/JPL/Northwestern University. Image PIA 02440

False-color image from recalibrated Mariner 10 data

D = relatively dark and blue unit consistent with enhanced titanium content.
B = bright red unit that may represent primitive crustal material.
F = color unit that follows plains boundaries, interpretated as lava flow.

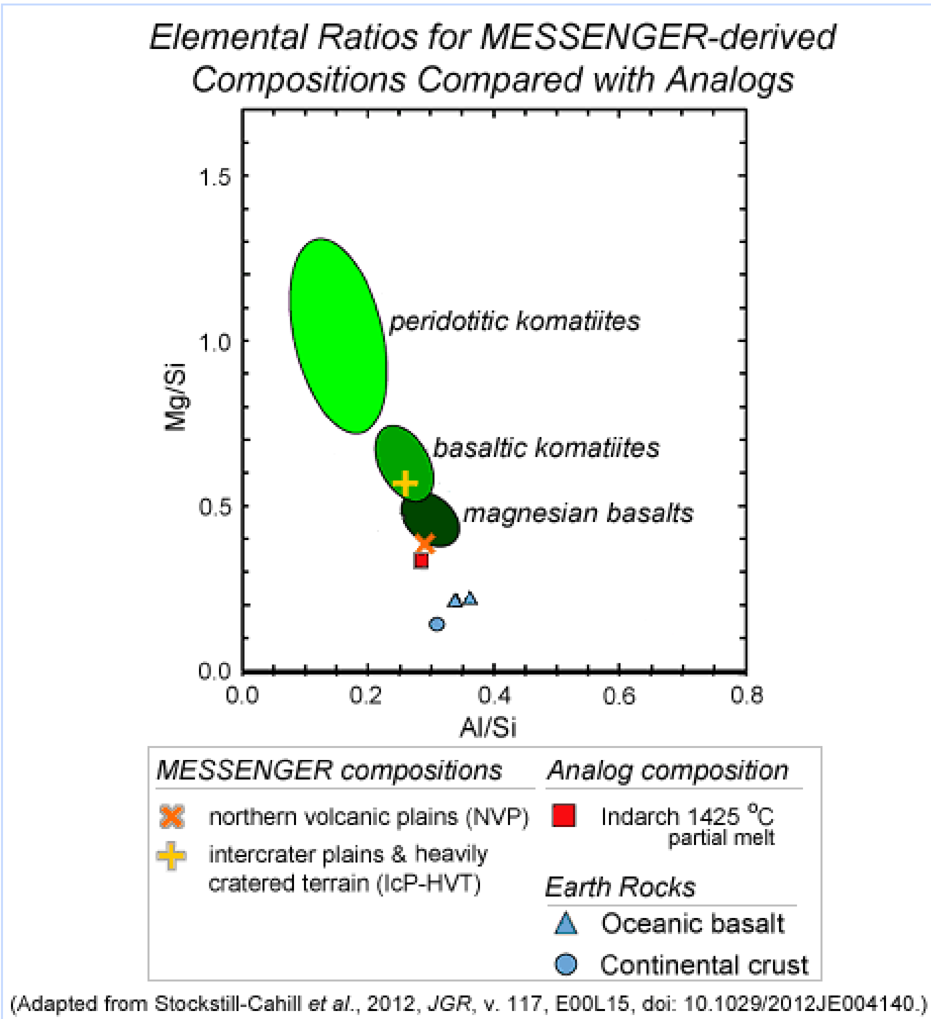
K = crater Kuiper shows color consistent with fresh material excavated from a subsurface unit that may have an unusual composition. (Caption from NASA Planetary Photojournal, click on image for higher resolution options.)

In addition to its imaging system, Mariner 10's instruments collected data on the planet's magnetic field, huge metallic core that comprises about 70 to 80 wt% of the planet, and its extreme surface temperatures (-183^{o}C to 187^{o}C, which we now know extends to a whopping 427^{o}C at local noon). Rounding out what we knew about Mercury before MESSENGER, reflectance spectra from Mariner 10 and ground-based telescopes indicated low FeO (~ 3–6 wt%) in surface silicates. A 2001 conference explored the state-of-the-art of Mercury's geological investigations and concluded with previews of NASA's MESSENGER mission and the European Space Agency/Japanese Space Agency's BepiColombo mission projected for 2015 (see **PSRD** article:**New Data, New Ideas, and Lively Debate about Mercury**).

MESSENGER Data and MELTS

During its first two years of orbital operations, MESSENGER acquired over 150,000 images and extensive other data sets. The impressive **payload of seven scientific instruments** on MESSENGER includes two spectrometers collecting vital data researchers need to determine the chemical composition of the surface materials. The X-ray spectrometer (XRS) is being used to map the elements in the top millimeter of Mercury's crust—specifically, magnesium, aluminum, silicon, sulfur, calcium, titanium, and iron. These data indicate Mercury's surface, normalized to the Si abundance, has relatively high abundances of Mg and S, is low in Al and Ca, and very low in Fe, Ti, Cl, Cr, and Mn compared to typical materials in the crust of Earth and the Moon. The **Gamma-ray** spectrometer (GRS) is being used to map the abundance and distribution of hydrogen, magnesium, silicon, oxygen, iron, titanium, sodium, calcium, potassium, thorium, and uranium in the top tens of centimeters of the surface.

Stockstill-Cahill and colleagues used MESSENGER data from the northern volcanic plains (NVP) and the older surrounding intercrater plains and heavily cratered terrain (IcP-HCT), which are the two most common terrains measured by the spectrometers. Taking published elemental ratios derived previously from the average XRS data for Mg/Si, Al/Si, Ca/Si, S/Si, Ti/Si, and Fe/Si by Larry Nittler (Carnegie Institution of Washington) and colleagues, Stockstill-Cahill and colleagues derived elemental and oxide abundances. Abundances for Cr and Mn were also gathered from XRS data and set equal to the upper limit of both at 0.5 wt% before their oxides were calculated. Abundances for K were calculated from GRS data and found to be relatively low; Na abundance was initially set equal to that of K. These procedures gave the team two starting compositions for the Mercury surface materials. They then chose rock analogs to compare with these MESSENGER-derived compositions. The analogs included three terrestrial basalts that differ in MgO wt%: magnesian basalt (8.5–12 wt% MgO), basaltic komatiites (12–20 wt% MgO), and peridotitic komatiites (>20 wt% MgO). The forth analog was a 1425 °C partial melt of the Indarch (EH4) meteorite [**Data link** from the Meteoritical Bulletin]. Cosmochemists have done melting experiments on this enstatite chondrite to learn more about magma compositions in highly reduced systems (see **PSRD** article: **Difficult Experiments on Weird Rocks**). Enstatite chondrites, perhaps with high densities, have been proposed previously as good candidate materials from which Mercury formed. Work by Shoshana Weider (Carnegie Institution of Washington) and coauthors showed that high-degree partial melts of Indarch (though with less iron) are a generally good match for the composition and mineralogy determined by MESSENGER's XRS for much of Mercury's surface.



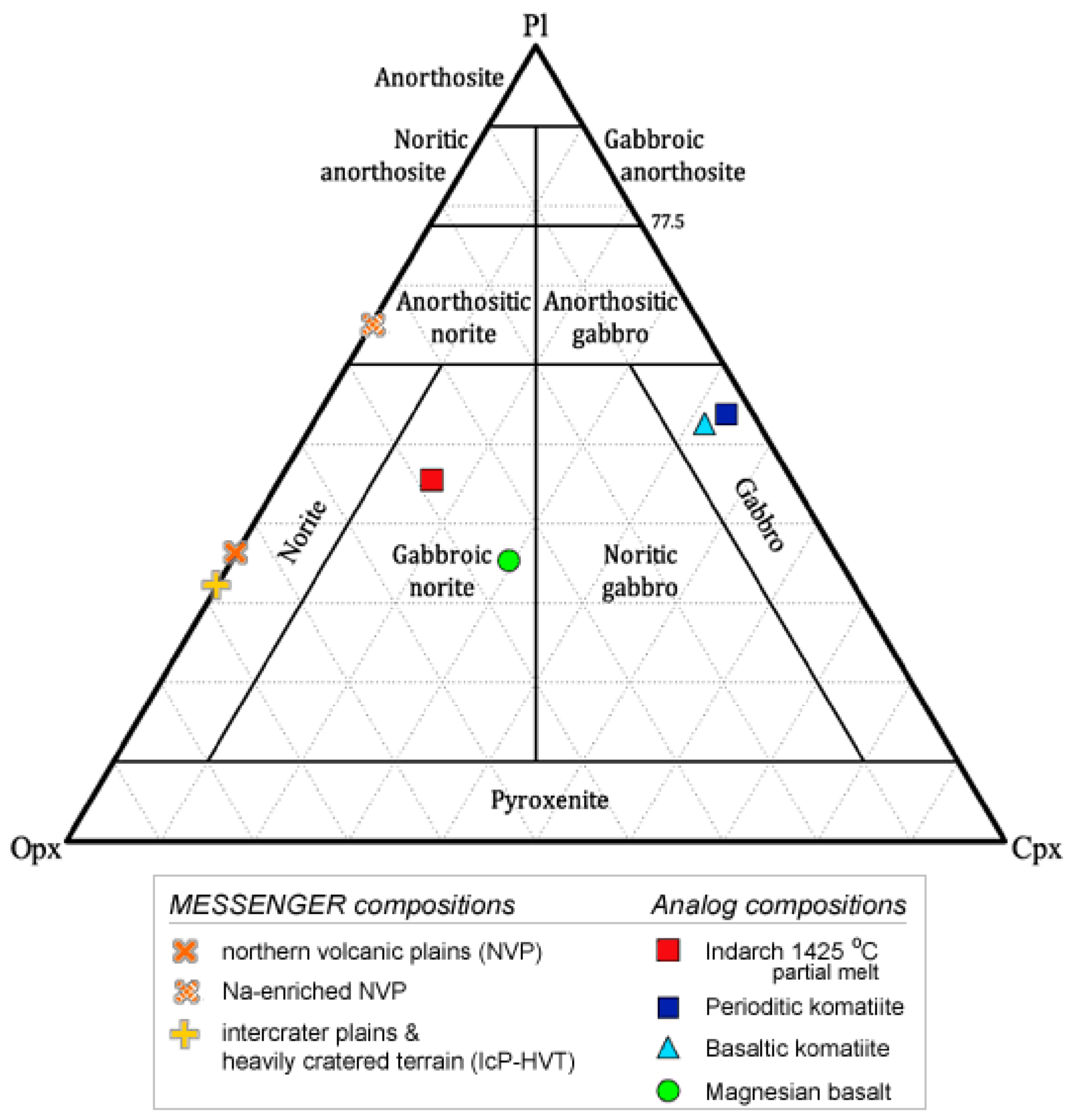
Elemental ratios Mg/Si vs. Al/Si are plotted for Mercury compositions derived from MESSENGER XRS data (orange and yellow symbols). These are compared with Mg-rich terrestrial rocks (green fields), Earth crustal rocks (blue symbols) and the partial melt of the Indarch meteorite (red square). Even the Mg-rich terrestrial rocks contain more FeO than does the surface of Mercury, so Stockstill-Cahill and coauthors lowered the FeO content of the terrestrial rocks and renormalized to 100.

Prior to the modeling, the team made specific modifications to the FeO contents of the terrestrial analogs (to account for the low FeO on Mercury's surface) and removed the S content of the other three compositions (slightly decreasing the Mg/Si and Ca/Si ratios as well) because MELTS modeling is not well calibrated for sulfur-rich compositions. More details and rationales for these modifications are found in their paper.

Using MELTS, the team simulated the cooling and equilibrium and fractional crystallization of the six magma compositions along a specified oxygen buffer. Stockstill-Cahill and colleagues used the **iron-wustite buffer** to simulate the reducing conditions that likely existed during the formation of Mercury. Modeling began 20 °C above the **liquidus** temperature through 20 °C steps to a final temperature ~400 to 500 °C below the liquidus temperature to approximate the **solidus**.

Modeled Mineral Compositions and Abundances

Running MELTS allowed Stockstill-Cahill and colleagues to track the mineralogy and mineral compositions produced by crystallization of melts of the MESSENGER-derived Mercury surface compositions, the Indarch 1425 °C partial melt, and the Mg-adjusted terrestrial rock analogs. The modeled Mercury compositions, plotted as crosses in the figure below, are dominated by high-magnesian orthopyroxene and plagioclase, which classifies them as norites. The lack of clinopyroxene reflects the low Ca abundance measured for Mercury surface material, though the authors note that recent reports of GRS measurements suggest a somwehat higher global average Ca/Si than was used in their modeling, so high-Ca clinopyroxene somewhere on Mercury's surface is not ruled out.



(From Stockstill-Cahill *et al.*, 2012, *JGR*, v. 117, E00L15, doi: 10.1029/2012JE004140.)

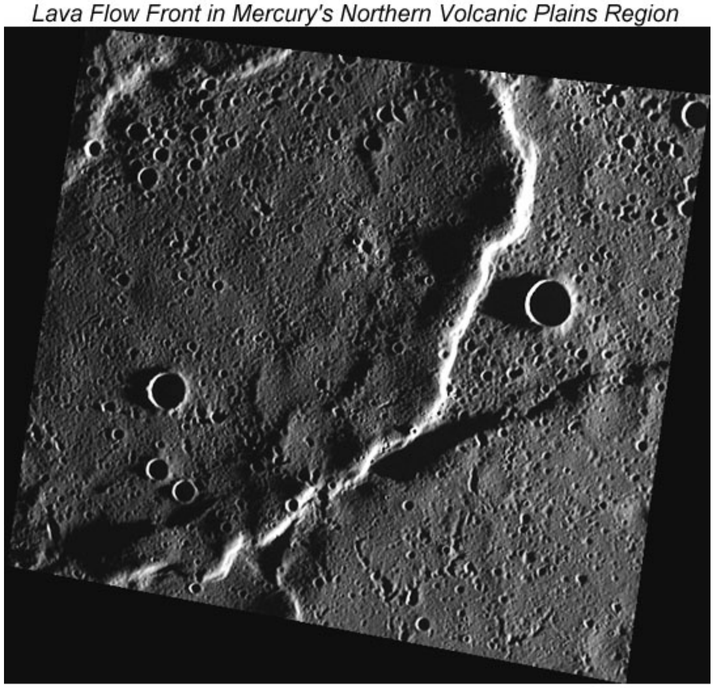
Standard rock classification diagram showing the compositions of Mercury lavas compared with analogs predicted from MELTS modeling. Pl = plagioclase, Opx = orthopyroxene, Cpx = clinopyroxene. The MESSENGER-derived Mercury compositions plot as norites.

Laboratory experiments using rock powders of MESSENGER XRS-derived compositions for regions outside the Northern Volcanic Plains by Bernard Charlier and colleagues (at the Massachusetts Institute of Technology) identified the lavas as basaltic komatiites, which is different from the norite composition inferred by Stockstill-Cahill and her coauthors. Norites consist of roughly equal amounts of **plagioclase** and low-Ca **pyroxene**, whereas komatiites are composed of a lot of olivine and high-Ca pyroxene. Charlier's experiments do support the high lava temperatures indicated by the MELTS calculations.

Inferred Eruption Sytle on Mercury

Stockstill-Cahill and team collected liquidus temperatures (1381 to 1680 °C) calculated by MELTS and they derived the **viscosities** (0.02 to 14.2 Pa·s) of the predicted lavas. For comparison, the most fluid lavas erupting in Hawaii have viscosities of about 100 Pa·s. Liquid hand soap has a viscosity of about 10 Pa·s. (Pa·s stands for Pascal seconds, the unit of measurement for viscosity, a measure of a liquid's resistance to flowing.) The high liquidus temperatures and low viscosities (relative to typical values of lavas on Earth) lead Stockstill-Cahill and colleagues to predict that the Mg-rich lavas originated from high temperature (>1500 °C) source regions in the mantle and if not cooled before reaching the surface would have erupted very fluid, low-viscosity lava flows. The Northern Volcanic Plains and the older surrounding intercrater plains and heavily cratered terrain may have been constructed by thin, laterally extensive flows. Recent studies by Paul Byrne (Carnegie Institution of Washington) and colleagues document lava flow features on Mercury. Geologic mapping of Mercury shows that these thin lavas were quite voluminous. The planet's northern plains, for example, cover an area equal to 60% of the continental United States and pooled inside ancient craters, some up to a mile deep.

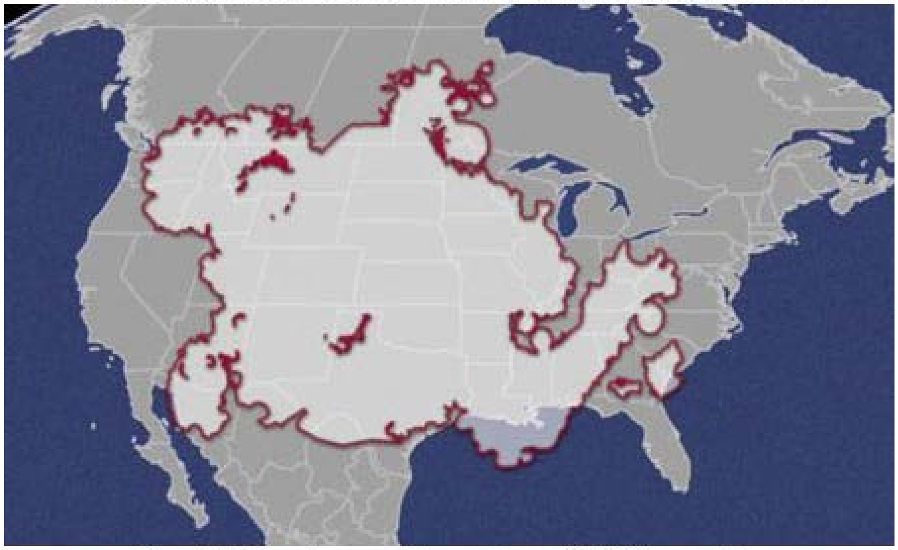
Lava Flow Front in Mercury's Northern Volcanic Plains Region



(MESSENGER WAC image. NASA/Johns Hopkins Univ. Applied Physics Laboratory/Carnegie Institution of Washington)

Highly fluid Mg-rich basalt comprise the Northern Volcanic Plains region of Mercury. This image of a lava flow front (bright sinuous line) was acquired by the Wide Angle Camera onboard NASA's MESSENGER spacecraft. Click for high-resolution version.

Mercury's Northern Volcanic Plains
in Comparison to the Continental United States



(From http://news.brown.edu/pressreleases/2011/09/mercury)

The vast plains around Mercury's north pole (outlined in red) composed of countless lava flows cover an area nearly 60% of the continental United States. Click to read the source News Release from Brown University.

Additional Resources

Links open in a new window.

- **PSRDpresents:** Magnesium-rich Basalts on Mercury --**Short Slide Summary** (with accompanying notes).

- Byrne, P. K., Klimczak, C., Williams, D. A., Hurwitz, D. M., Solomon, S. C., Head, J. W., Preusker, F., and Oberst, J. (2013) An Assemblage of Lava Flow Features on Mercury, *Journal of Geophysical Research,* in press, doi: 10.1002/jgre.20052. [**abstract**]
- Charlier, B., Grove, T. L., and Zuber, M. T. (2013) Phase Equilibria of Ultramafic Compositions on Mercury and the Origin of the Compositional Dichotomy, *Earth and Planetary Science Letters,* v. 363, p. 50-6-, doi: 10.1016/j.epsl.2012.12.021. [**abstract**]
- **MELTS website**
- Stockstill-Cahill, K. R., T. J. McCoy, L. R. Nittler, S. Z. Weider, and S. A. Hauck II (2012) Magnesium-rich Crustal Compositions on Mercury: Implications for Magmatism from Petrologic Modeling, *Journal of Geophysical Research,* v. 117, E00L15, doi: 10.1029/2012JE004140. [**abstract**]
- Taylor, G. J. (1997) Mercury Unveiled. *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/Jan97/MercuryUnveiled.html**.
- Taylor, G. J. (1999) Difficult Experiments on Weird Rocks. *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/Dec99/indarch.html**.
- Taylor, G. J. (2001) New Data, New Ideas, and Lively Debate about Mercury. *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/Oct01/MercuryMtg.html**.
- Weider, S. Z., Nittler, L. R., Starr, R. D., McCoy, T. J., Stockstill-Cahill, K. R., Byrne, P. K., Denevi, B. W., Head, J. W., and Solomon, S. C. (2012) Chemical Heterogeneity on Mercury's Surface Revealed by the MESSENGER X-Ray Spectrometer, *Journal of Geophysical Research,* v. 117, E00L05, doi: 10.1029/2012JE004153. [**abstract**]