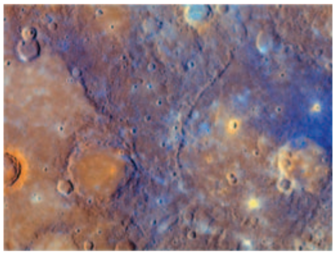
THE SURFACE COMPOSITION OF MERCURY AS SEEN FROM MESSENGER



False color Mercury Dual Imaging System (MDIS) image, illustrating the relationship between the relatively young smooth plains on the left and the older, dark blue material on the right. Image credit: NASA/Johns Hopkins University Applied Physics Laboratory / Carnegie Institution of Washington

Little was known about Mercury, the smallest and innermost planet of the Solar System, prior to NASA's MErcury Surface, Space Environment, GEochemistry, and Ranging (MESSENGER) mission (Solomon et al. 2001). Mercury has a dark and heavily cratered surface, similar in appearance to the Moon, and 45% of its surface was imaged during three Mariner 10 flybys in the 1970s. Mercury does not have an atmosphere, but does maintain a tenuous exosphere containing several species, including H, He, O, Na, K, and Ca. The planet's unusually high density indicates that its interior structure consists of a thin crust and mantle overlying a large core, the outer part of which is molten and gives rise to Mercury's weak magnetic field. It is also possible that there is a solid troilite (FeS) layer at the top of the core (Smith et al. 2012). Earth-based observations identified radar-bright deposits in permanently shadowed craters at both poles, and it has recently been shown that these contain a substantial amount of water ice (Lawrence et al. 2013; Neumann et al. 2013; Paige et al. 2013). The MESSENGER mission was designed to answer several key scientific questions and to increase our understanding of Mercury's geological history and evolution. Remote sensing of the surface's chemical composition has a bearing on a number of these questions. We focus on several of these topics in this article, including models for Mercury's original formation, whether or not Mercury experienced an early magma ocean, and how its mantle and volcanism have evolved with time.

The suite of geochemical instruments in MESSENGER's scientific payload includes the X-Ray Spectrometer (XRS) and Gamma-Ray Spectrometer (GRS), which are used to characterize the surface abundance of several elements via X-ray fluorescence (e.g. Nittler et al. 2011) and gamma-ray spectroscopy (e.g. Peplowski et al. 2011). Together, the XRS and GRS on MESSENGER provide abundant information for several elements, including O, Na, Mg, Al, Si, K, Ca, Ti, Cr, Mn, Fe, Th, and U, with spatial resolutions that range from hundreds to thousands of kilometers.

Orbital results from XRS (Nittler et al. 2011; Weider et al. 2012) have revealed that Mercury's surface is Mg rich but Al and Ca poor, compared to typical materials from the terrestrial and lunar crusts (Fig. 1). The surface's ultramafic composition, in terms of these elements, is similar to terrestrial komatiites (extremely Mg-rich rocks produced by high degrees of partial melting, most of which are Archean in age). A surprising result was the detection of S at an abundance of up to about 4 wt%, a level that is ten times higher than on the other terrestrial planets. The XRS data have also confirmed that Mercury's surface contains a low total amount of Fe (less than 4 wt%), even though the planet as a whole must contain a large amount to account for its high density. The abundances of Al, S, Ca, and Fe as derived from GRS data (Peplowski et al. 2012a; Evans et al. 2012) are generally in agreement with the XRS results. Together, the high S and low Fe abundances indicate that Mercury must have accreted under highly reducing conditions and that its surface mineralogy (probably dominated by Mg-rich silicates such as enstatite and forsterite, plagioclase feldspar, and sulfides) is unlike those of the other terrestrial planets.

The relatively low Al and Ca concentrations and the high Mg content of Mercury's surface indicate that it is unlike the Moon's anorthosite-dominated crust, believed to have formed as a flotation crust in a cooling magma ocean. However, we cannot say for certain whether or not a magma ocean played a role in the formation of Mercury's crust. Brown and Elkins-Tanton (2009) showed that when the total Fe content of a planet's silicate portion is low, as seems to be the case for Mercury, the density contrasts in a magma ocean might be insufficient to permit plagioclase flotation. Without a flotation crust, Fe-rich cumulates forming later than their Mg-rich counterparts could have crystallized closer to the surface. The resulting unstable configuration of the cumulate pile might have promoted mantle overturn, partial melting, and the formation of a secondary crust through lava flows, which may have helped form the surface we now observe. The exact geochemical consequences of a magma ocean on the surface composition of Mercury depend on the planet's starting composition, but no models have yet been reported that are based on the geochemical results from MESSENGER. However, Charlier et al. (2013) suggest that variations in lava composition across Mercury's surface may have arisen from different magma sources within a crystallizing, layered magma ocean.

Before MESSENGER, several hypotheses for the formation of Mercury primarily focused on explaining the planet's high density and therefore high metal-to-silicate ratio. In some of the proposed models, much of Mercury's silicate crust and mantle were removed by a high-temperature event early in its history, for example a giant impact (Benz et al. 1988) or evaporation within a hot (2500–3500 K) solar nebula (Cameron 1985). The ratio of the moderately volatile element K to the refractory element Th for Mercury (Peplowski et al. 2011; 2012b) is similar to that of Mars and higher than for the Moon. Taken together, the high abundances of K, S (Nittler et al. 2011; Weider et al. 2012), and Na (about 3 wt%; Evans et al. 2012) indicate that Mercury is not depleted in volatile elements relative to the other terrestrial planets. Such a characteristic is seemingly inconsistent with formation models that require extreme heating early in the planet's history, but the question is still being investigated (e.g. Stewart et al. 2013). Other formation scenarios invoke accretion of high-temperature equilibrium condensates (Lewis 1973), mixtures of refractory-enriched and Earth-like compositions (Morgan and Anders 1980), or chondritic precursors (e.g. Krot et al. 2001). The XRS and GRS results seem to be most compatible with accretion from highly reduced chondritic material with a high metal-to-silicate ratio and a substantial volatile inventory. Such precursors may have been similar to the metal-

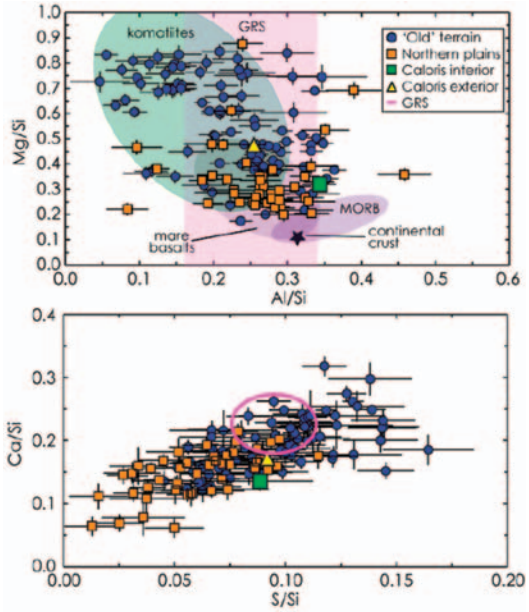


Figure 1 Elemental weight ratios from individual XRS measurements of regions about 100 km in diameter on Mercury's surface (modified from Weider et al. 2012), illustrating the differences in composition between the northern smooth plains and the surrounding older terrain. Compositions for smooth plains interior and exterior to the Caloris basin are also shown. The 1σ errors for the GRS results (from Evans et al. 2012) are shown as a pink band (there is no Mg estimate from GRS) in the top diagram and as a pink ellipse in the bottom one. Compositional fields of terrestrial and lunar rocks are indicated for comparison.

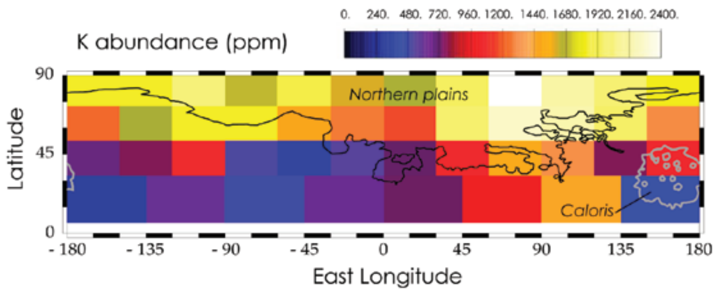


FIGURE 2 Map of K abundance on the surface of Mercury, showing the outlines of the northern smooth plains (black) and the Caloris basin (grey). IMAGE FROM PEPLOWSKI ET AL. (2012B)

rich CB chondrites or enstatite chondrites; partial melts from an example of the latter (McCoy et al. 1999) contain about the same abundance of S as the surface of Mercury. Another intriguing possibility is that Mercury was built from solids enriched in C-rich chondritic interplanetary dust particles (Ebel and Alexander 2011).

As the MESSENGER orbital mission has progressed, more-detailed and higher-spatial-resolution geochemical information has been acquired so that heterogeneities related to previously mapped units can be explored. On the basis of Mariner 10 images and images acquired by MESSENGER on its three flybys (2008–2009) of Mercury prior to orbital insertion in 2011, various units were defined according to their morphologies and color differences. One such unit is the volcanic smooth plains that fill low-lying areas and have few impact craters (Denevi et al. 2009). The smooth plains associated with the Caloris impact basin (Murchie et al. 2008) and the northern plains (Head et al. 2011) are deposits with the largest areal extent (see FIG. 2 for locations). Relatively high-spatial-resolution XRS analyses (about 100 km in diameter) have revealed that the northern smooth plains are compositionally distinct (lower in Mg, S, and Ca; higher in Al) from the older, more heavily cratered terrain that surrounds them (FIG.1; Weider et al. 2012). Although there is only a limited amount of data for the Caloris plains, the results suggest that the plains interior to the basin are consistent with the composition of the northern plains, whereas the plains exterior to the basin are more like the older terrain. The lower Mg content of the smooth plains, together with the chemical trends between the two regions (FIG. 1), suggests that this material was derived from a source that was more evolved and had a cooler magmatic temperature than that which produced the older terrain, rather than from remelting of a previously depleted source.

Surface heterogeneities in the abundance of K (Peplowski et al. 2012b) and Na (Evans et al. 2013) have also been identified with the GRS data. An area that approximately, but not precisely, corresponds to the northern plains (FIG. 2) has a K abundance (about 2000 ppm) that is significantly higher than that of the surrounding, older terrain (about 500 ppm). Likewise, the Na abundance at far northern latitudes (~4 wt%) is higher than at more equatorial regions (about 2.5 wt%). Rather than being primarily controlled by the underlying lithology, it has been proposed (Peplowski et al. 2012b; Evans et al. 2013) that the distributions of K and Na may be driven, at least partly, by a surface heating process that mobilizes these volatiles from equatorial and hot-pole regions (these are longitudinal areas subjected to solar radiation for longer periods than the mean surface, due to Mercury's 3:2 spin-orbit resonance, where surface temperatures can reach about 550 K) and redistributes them to the exosphere (which has variable Na content over both geologic poles) and/or polar regions. The smooth plains inside the Caloris impact basin (which lies on one of the hot-poles) have Mg, Al, S, and Ca abundances that are similar to those of the northern plains, but a lower K content, thus providing evidence for this process.

MESSENGER is currently in its extended mission and continues to unravel Mercury's many mysteries. We continue to analyze the surface geochemistry and aim to produce near-global maps for many rock-forming elements. The MESSENGER website provides more information about the mission: http://messenger.jhuapl.edu/. ▪

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