GEOCHEMICAL ADVANCES IN MERCURY SCIENCE FACILITATED BY A LANDED MISSION.

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Introduction: The data from the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft have revealed several surprising characteristics about the surface of Mercury, leading to its classification as a geochemical endmember among the terrestrial planets. Some of these features include elevated abundances of up to 3 wt% S, C enrichment as high as 4 wt% over the local mean in low reflectance materials (LRM), Na up to 5 wt% at high northern latitudes, and Fe abundances typically lower than 2 wt% [e.g., 1–4]. The S and Fe concentrations have been used to infer that Mercury's igneous history evolved under highly reduced oxygen fugacity conditions between 2.6 and 7.3 $\log_{10}$ units below the iron-wüstite buffer [e.g., 5], which is more reducing than any other terrestrial planet in the solar system [e.g., 6]. This highly reduced nature has important consequences for the differentiation and thermal/magmatic evolution of Mercury. While the immense amount of data collected by MESSENGER revealed Mercury as a geochemical endmember, this new knowledge gained raised additional questions that necessitate continued exploration of the planet. Fortunately, BepiColombo launched in October of 2018, and this joint ESA/JAXA dual-orbiter spacecraft is the most ambitious effort yet attempted to explore Mercury [e.g., 7]. Looking beyond BepiColombo, there are major aspects of Mercury's geochemical character and evolution for which significant knowledge gaps can be dramatically improved with data acquired from the planet's surface via *in situ* landed science.

Landed Science: Following the general strategy of exploration of other planets, the continued exploration of Mercury should be conceived as a multi-mission, multi-generational effort, following a sequence comprising flyby, orbiter, lander/rover, and, ultimately, sample return. A Mercury lander could greatly advance our understanding of the planet's geochemical makeup, its interior structure, geological evolution, the present-day processes at work there, and the planet's polar volatile inventory [8]. In particular, geochemical knowledge could be advanced by various *in situ* compositional and petrological measurements. Although a wide variety of potential landing sites and science goals exist, we focus on a mission to understand the nature and origin of Mercury's crust, the mineralogy of the planet's varied surface materials, and the composition of the planet as a whole. Currently, a Mercury Lander mission concept is being studied to inform the next Decadal Survey [9].

Geochemistry Goal for Landed Science. The main geochemistry goal for the current Mercury Lander study is to investigate the highly chemically reduced, unexpectedly volatile-rich mineralogy and geochemistry of Mercury's oldest terrain type (i.e., the LRM). This information will help us to better understand the earliest evolution of Mercury. To date, all surface mineralogical information for Mercury is the result of modeling efforts from MESSENGER elemental measurements [e.g., 10, 11] as direct measurements of Mercury's surface mineralogy have not yet been made. The geochemical data obtained from MESSENGER, combined with experimental and modeling efforts, have led to the proposal of a primary graphite flotation crust on Mercury [Fig 1; e.g., 12]. Present-day remnants of this proposed exotic graphite flotation crust, identified by MESSENGER within the LRM [13], would represent the earliest solid crustal materials on Mercury, providing a window into the planet's earliest differentiation. Any volcanic eruptions through this crust would likely result in the stripping of oxygen from the melts and the reduction of materials currently present on the surface [14]. Due to this smelting process, Mercury's surface mineralogy is hypothesized to be unlike that of any other terrestrial body in our solar system, making Mercury a unique environment for planetary differentiation and evolution.

Importance of Elemental and Mineralogical Measurements. Direct *in situ* elemental and mineralogical measurements on Mercury's surface are essential to address the new science questions that have arisen since MESSENGER. One crucial measurement is of

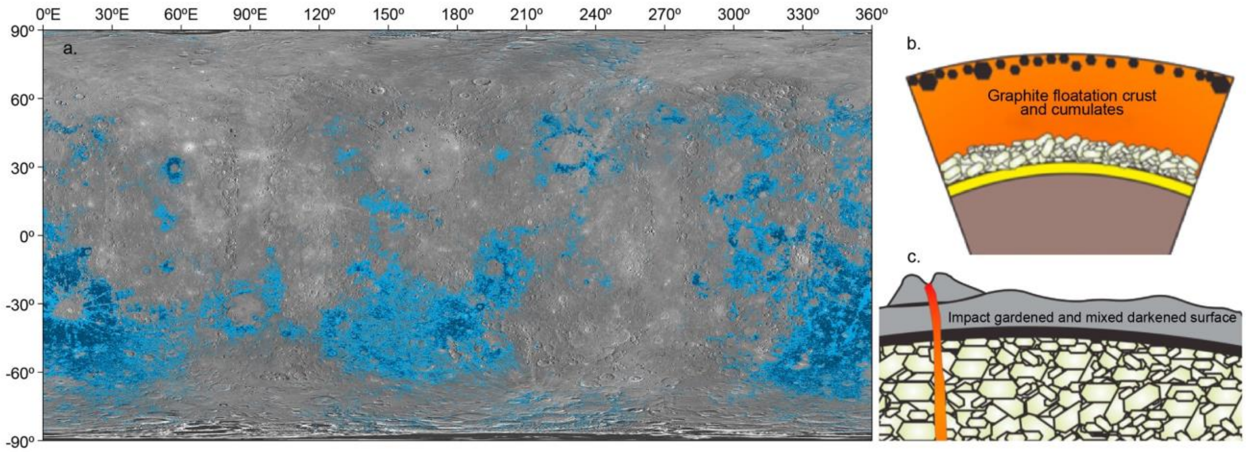

Figure 1. a) Mercury's globally distributed LRM [1] shown in blue, which likely includes carbon-bearing deposits. b) Schematic of a thin, primary graphite flotation crust forms in an early magma ocean [12]. c) Impacts mix the volcanic secondary crust and graphite primary crust [12].

the major and minor elemental compositions of the LRM at a spatial scale and sensitivity far superior to orbital measurements by MESSENGER or BepiColombo. In particular, quantifying the LRM's carbon content, volatile element abundances (e.g., Na, K, S), and minor elements that are not well resolved from orbit (e.g., Cl, Cr, and Mn) will enable testing of current hypotheses and provide key new constraints to advance petrologic modeling and laboratory experimental studies. The most critical data to be obtained from Mercury landed science from a geochemical standpoint are the mineralogical hosts of the measured elements. Unfortunately, since diagnostic phases are relatively low in abundance and mixed with silicate materials that dominate the emission spectrum, measurements from geochemical instruments onboard BepiColombo are insufficient to meet the goals of this lander study [7]. Understanding the mineralogy of Mercury's exotic surface materials opens a new window into the thermochemical evolution of the planet. Characterizing Mercury's mineralogy is necessary to interpret the petrologic history, oxidation states, and the early processes the planet experienced. Understanding the mineralogical host(s) of Mercury's surprisingly high surface S content will provide key insights into the planet's differentiation and evolutionary history, and help to constrain the phase(s) removed to form Mercury's hollows, which are closely associated spatially with the LRM [e.g., 14].

Potential Instrumentation. To investigate the highly chemically reduced, yet unexpectedly volatile-rich mineralogy and chemistry of Mercury's oldest terrain type, the current Mercury Lander study is considering a suite of geochemical instruments. Potential instruments include: Gamma-ray Spectrometer, Raman, X-ray Diffractometer, Mössbauer, Alpha Particle X-ray Spectrometer, and Laser Induced Breakdown Spectrometer.

Conclusion: Mercury holds crucial clues to understanding the original distribution of elements in the earliest stages of the solar system and how planets form and evolve in close proximity to their host stars. Contextual *in situ* elemental and mineralogical measurements acquired from the surface of Mercury will revolutionize our view of the planet, enable the next step in determining its formation, and advance our understanding of planetary evolution under highly reducing conditions. Evaluating heterogeneity of the landing site by acquiring compositional and mineralogical measurements from multiple locations within the landing ellipse would provide key information about the geologic evolution of the planet.

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