LANDING ON MERCURY: A GEOCHEMICAL PERSPECTIVE. K. E. Vander Kaaden[1], C. M. Ernst[2], N. L. Chabot[2], R. L. Klima[2], S. J. Indyk[3], P. N. Peplowski[2], E. B. Rampe[4], S. Besse[5], D. T. Blewett[2], P. K. Byrne[6], B. W. Denevi[2], S. Goossens[7,8], S. A. Hauck, II[9], N. R. Izenberg[2], C. L. Johnson[10,11], L. M. Jozwiak[2], H. Korth[2], R. L. McNutt, Jr.[2], S. L. Murchie[2], J. M. Raines[12], M. S. Thompson[13], R. J. Vervack, Jr.[2], S. Z. Weider[14]. [1]Jacobs, NASA Johnson Space Center, Houston, TX. [2]The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland. [3]Honeybee Robotics, Altadena, CA. [4]NASA Johnson Space Center, Houston, TX. [5]ESA/ESAC Camino Bajo del Castillo s/n, Ur. Villafranca del Castillo, Madrid, Spain. [6]North Carolina State University, Raleigh, NC. [7]University of Maryland Baltimore County, Baltimore MD. [8]NASA Goddard Space Flight Center, Greenbelt, MD. [9]Case Western Reserve University, Cleveland, OH. [10]University of British Columbia, Vancouver, British Columbia, Canada. [11]Planetary Science Institute, Tucson, AZ. [12]University of Michigan, Ann Arbor, MI. [13]Purdue University, West Lafayette, IN. [14]Arctic Slope Technical Services, Beltsville, MD. (Email: Kathleen.E.VanderKaaden@nasa.gov)

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, as much as 4 wt% C enrichment in low-reflectance materials (LRM) over the local mean, 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 raised additional questions that necessitate continued exploration of the planet. Indeed, the joint ESA–JAXA dual-orbiter BepiColombo mission, launched in October 2018, is the most ambitious effort yet attempted to explore Mercury [e.g., 7]. Direct *in situ* elemental and mineralogical measurements on Mercury's surface, however, are essential for addressing the new science questions that have arisen since MESSENGER.

Geochemistry Perspective of Landed Science: A mission concept study for conducting landed science on Mercury was undertaken ahead of the 2023–2032 Planetary Science and Astrobiology Decadal Survey by the National Academies of Sciences, Engineering, and Medicine [8]. The geochemistry goal for this Mercury Lander study was to investigate the highly chemically reduced, unexpectedly volatile-rich mineralogy and chemistry of Mercury's surface. This information would help us to better understand the earliest evolution of Mercury. To date, all surface mineralogical information for Mercury is the result of experimental and modeling efforts from MESSENGER elemental measurements [e.g., 9] 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 hypothesis of a primary graphite flotation crust on Mercury [Fig 1; e.g., 10]. The LRM is believed to be remnants of this exotic graphite flotation crust [10, 11], and, hence, represents the earliest solid crustal materials on Mercury, providing a window into the planet's earliest differentiation. Volcanic eruptions through this crust would likely have resulted in the stripping of oxygen from the melts and the emplacement of reduced materials on the surface [12]. Due to this smelting process, Mercury's surface mineralogy is hypothesized to be unlike that of any other terrestrial body, making Mercury a unique environment for planetary differentiation and evolution.

Significance of Elemental and Mineralogical Measurements. Direct *in situ* elemental and mineralogical measurements of Mercury's surface are essential to address the geochemistry-related science questions that have arisen since MESSENGER, including:

- What is the composition of the LRM, and what does this material tell us about the primary processes taking place on the planet?
- Is the LRM the planet's primary crust? If so, how does it compare with the primary crusts of other rocky bodies?
- What role does C play in controlling the development of space weathering features on Mercury, and on airless surfaces generally?
- What do the volatile abundances of Mercury tell us about volatile distribution across the inner solar system?
- How can orbital data from MESSENGER and BepiColombo be refined with new ground-truth data?

Geochemical Instrumentation. To investigate the highly chemically reduced, yet unexpectedly volatile-rich mineralogy and geochemistry of Mercury's oldest

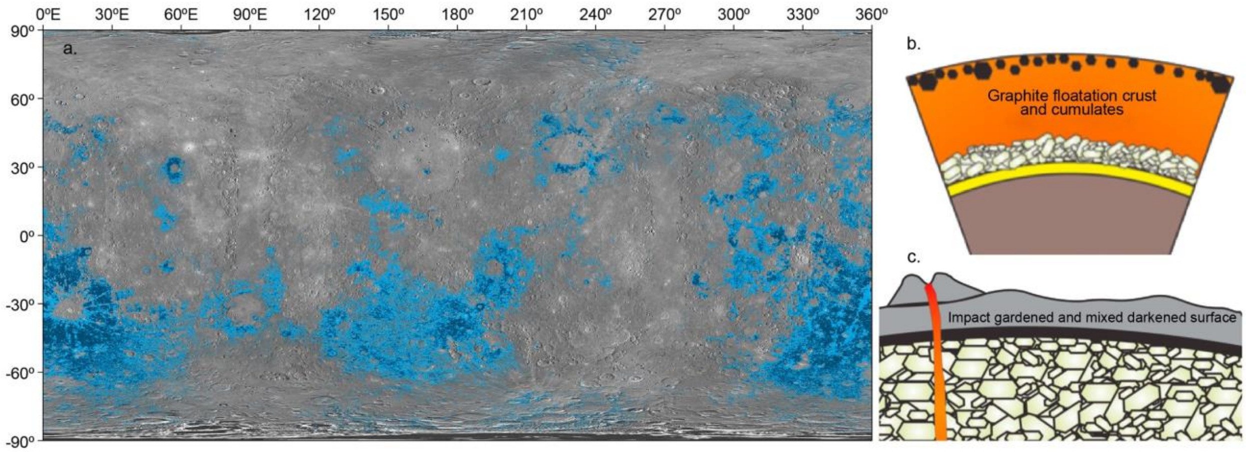

Figure 1. a) Mercury's globally distributed LRM [1] shown in blue, which likely includes carbon-bearing deposits. b) Schematic of a thin, primary graphite flotation crust forms in an early magma ocean [10]. c) Impacts mix the volcanic secondary crust and graphite primary crust [10].

terrain type, we selected a gamma-ray spectrometer (GRS) and an X-ray diffractometer/X-ray fluorescence spectrometer (XRD/XRF) as the geochemical instruments for this study. We also included two PlanetVac sampling systems in this payload, one on each of the two lander legs, to deliver surface samples to the XRD/XRF. The GRS would measure gamma-ray emissions from major and minor elements (O, Mg, Si, Al, Ca, Fe, C, Na, S, Ti, and Mn) and naturally radioactive elements (K, Th, and U). These gamma-ray emissions would be used to characterize the elemental composition of Mercury's surface, in a ~meter-cubed volume beneath the lander, following procedures developed for the analysis of GRS data from the Near Earth Asteroid Rendezvous [e.g., 13] and MESSENGER [e.g., 14] missions. The CheMin-V instrument, designed for the Venera-D mission, was adopted for this study, drawing heritage from the CheMin instrument on the Mars Science Laboratory Curiosity rover [e.g., 15]. The XRD data would be used to identify and quantify the Mg-rich silicates, oxides, sulfides, and metals predicted to be on the surface of Mercury [e.g., 9], as well as other minerals on the surface, to a detection limit of ~1 wt%. Minor and trace element abudances, derived from XRF measurements, would characterize elemental substitutions within minerals. We emphasize that our proof-of-concept study simply demonstrated that a scientifically compelling landed mission to Mercury is technically feasible and affordable in the next decade; our notional payload was neither prescriptive nor exhaustive. Were such a mission actually proposed, it should of course take advantage of the best state-of-the-art *in situ* geochemistry options available at that time.

*Science Operations***:** This mission was designed to touch down at dusk and operate for ~88 days through periods with and without direct-to-Earth (DTE) communication. The GRS would have a 36-hour cool-down period upon landing, after which it would operate continuously. The cool down would enable the highest-sensitivity elemental measurements for the mission and minimize instrument degradation during landed operations. The XRD/XRF instrument would only operate during periods of DTE communication. During the initial three weeks of operations, four distinct PlanetVac samples would be analyzed by the XRD/XRF, including one sample from each of the two PlanetVac samplers. Images would be acquired before and after PlanetVac operations. After DTE communication is restored for the final 24 days of the mission at least four additional XRD/XRF analyses would be conducted; the selection of which PlanetVac(s) to use for these later samples would be informed by analysis results of the four initial samples.

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