NASA PLANETARY MISSION CONCEPT STUDY: ASSESSING DWARF PLANET CERES' PAST AND PRESENT HABITABILITY POTENTIAL. J. C. Castillo-Rogez[1], M. T. Bland[2], D. L. Buczkowski[3], A. R. Hendrix[4], K. E. Miller[5], T. H. Prettyman[4], L.C. Quick[6], J. E. C. Scully[1], Y. Sekine[7], M. M. Sori[8,9], T. Titus[2], D. A. Williams[10], H. Yano[11], M. Zolensky[12], C. A. Raymond[1], J. Brophy[1], W. Frazier[1], G. Lantoine[1], B. G. Lee[1], M. S. Kelley[13], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA. [2]United States Geological Survey, Flagstaff, AZ. [3]John Hopkins University, Applied Physics Laboratory, Laurel, MD. [4]Planetary Science Institute. [5]Southwest Research Institute, San Antonio, TX. [6]NASA Goddard Space Flight Center, Greenbelt, MD. [7]Earth-Life Science Institute, Tokyo Institute of Technology, Tokyo, Japan. [8]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ. [9]Purdue University, West Lafayette, IN. [10]School of Earth and Space Exploration, Arizona State University, Phoenix, AZ. [11]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Kanagawa, Japan. [12]Astromaterials Research and Exploration Science, NASA Johnson Space Center, Houston, TX. [13]NASA Headquarters, Washington, DC. Email: Julie.C.Castillo@jpl.nasa.gov.

Introduction: The Dawn mission revolutionized our understanding of Ceres during the same decade that has also witnessed the rise of ocean worlds as a research and exploration focus. We will report progress on the Planetary Mission Concept Study (PMCS) on the future exploration of Ceres under the New Frontiers or Flagship program that was selected for NASA funding in October 2019. At the time this writing, the study was just kicked off, hence this abstract reports the study plan as presented in the proposal.

Background: Dwarf planet Ceres is the largest object in the main belt and the most water-rich object in the inner solar system after Earth. Ceres had sufficient water and silicates (i.e., radioisotopes) to host a deep ocean in its history, leading to a layered interior structure with a high degree of aqueous alteration [1]. Dawn revealed evidence for recent and possibly ongoing geologic activity on Ceres [2,3], the potential presence of liquid below an ice-rich crust [4], and high concentrations of organic matter (locally) and carbon (globally) in the shallow subsurface [5,6]. Recent expressions of brine-driven exposure of material onto Ceres' surface can be found at Occator Crater [3] and the ~4-km tall, geologically recent mountain Ahuna Mons [7]. Ceres could have been active throughout its history [8]. The hints of deep liquid and long-lived energy sources led to Ceres' being categorized as a "candidate ocean world" in the Roadmap for Ocean Worlds (ROW) [9]. The state of understanding of Ceres' habitability potential in the context of ROW is summarized in Figure 1.

PMCS Proposal: The overarching thrust of the mission concept proposed for study is to advance our understanding of Ceres within ROW. Specific goals are to (1) determine Ceres' evolutional path, placing it in context as a possible warm end-member in the family of ocean worlds; (2) assess Ceres' habitability and use Ceres as a test case for understanding the habitability through time of other ocean worlds; (3) determine Ceres' origin and implications for solar system dynamical evolution. While the latter goal does not directly relate to ROW, it addresses the place of Ceres in the early solar system and its potential connection to other large dwarf planets.

Future exploration of Ceres would reveal the degree to which liquid water and other environmental factors may have combined to make this dwarf planet a habitable world. Confirmation of the existence of liquid inside Ceres at present, and the assessment of its extent, is the next natural follow-on step to the ROW study [9].

Figure 1. Knowledge of Ceres' astrobiological potential framed in the context of ROW based on Dawn's results (fourth row) and projected increase in knowledge from the future mission conceptualized in the proposed study (last row). A future mission will considerably improve understanding of Ceres' habitability as well as its relationship to icy satellite Ocean Worlds. (Modified from [9]).

Another key question for any new Ceres mission is whether oxidants exist at the surface, which would facilitate the emergence of life, or at least promote habitability. A favorable redox discovery would deepen the case for Ceres meeting our current definition of habitability. Determining the origin(s) and fate of organics on Ceres is essential for assessing habitability. Future missions will aim to quantify the abundance, sources and sinks, and chemical forms of CHNOPS elements and provide detailed characterization of organic compounds beyond Dawn's observations. The projected increase in knowledge against various aspects of ROW are presented in Figure 1.

In order to address these science goals we will (1) formulate science objectives and quantify testable hypotheses; (2) work with the Jet Propulsion Laboratory to define the most affordable architecture(s) that can address these objectives; (3) identify two to three descope options that will lead to a portfolio of concepts for the future planetary science decadal survey committee to assess; (4) identify technologies that require investment in the next decade in order to support this concept and that may be relevant to other missions; and (5) deliver this information in the form of a report to NASA's Planetary Science Division as well as briefings to the community, one of which will be held at the 2020 LPSC.

Achieving the above goals involve observing from orbit and/or sampling multiple sites on Ceres (Fig. 2): regolith (average surface), organic-rich material (Ernutet Crater and regolith), expressions of the deep interior (Ahuna Mons and Occator facuale), salt-rich crust (e.g., Haulani Crater), and recent evaporites (Occator faculae). Some of the science investigations are site-specific. Thus, science return scales with the capability of the mission to analyze materials from as many sites as possible. We have already determined that the deployment of multiple small platforms is not cost effective and that these small platforms of incapable of carrying most of the payload options being considered. Instead, the envisioned concept will include a mobile surface platform with an orbiter and/or the capability to return samples acquired from one or more sites

The best approach to mobility in Ceres' gravity conditions is with a platform capable of hopping from one site to another. The key challenge for a mobile platform will be to guarantee multiple landings. Although this will increase mission risk, this risk may be countered by leveraging existing and emerging autonomous techniques. We note that site access may be an issue for scientifically rich sites in extreme terrains, for example in the region of Occator faculae, both for technical reasons and planetary protection restrictions. This issue will be assessed in further detail during the study.

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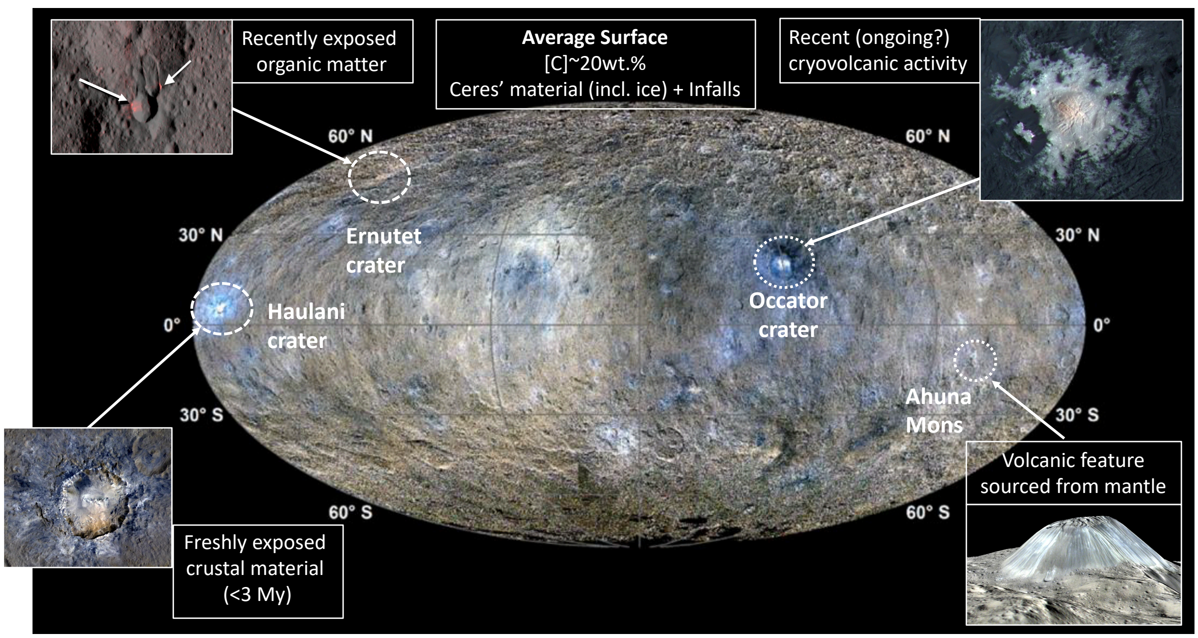

Figure 2. Ceres has multiple sites of high scientific value for future in situ exploration or sample return, as well as site-scale investigation from orbit. Targeted sites are separated by 100s of km, requiring a mobile platform to achieve all the science objectives outlined in this proposed study, or the capability to return samples from multiple sites.