POTENTIAL LANDING SITES FOR A FUTURE CERES LANDER. J. E. C. Scully(1), S. R. Baker(1/2), J. C. Castillo-Rogez(1), D. L. Buczkowski(3), D. A. Williams(4) and M. M. Sori(5/6). (1)Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA (jennifer.e.scully@jpl.nasa.gov), (2)University of Chicago, Chicago, IL, USA, (3)Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, (4)School of Earth and Space Exploration, Arizona State University, Tempe, Arizona, USA, (5) Lunar and Planetary Laboratory, Tucson, AZ, USA, (6) Purdue University, West Lafayette, IN, USA.

Introduction – Ceres as a target of future exploration: Ceres is a target of interest for future missions because Dawn's orbital exploration of Ceres revealed it to be a complex relict ocean world: it is hypothesized that Ceres once had a subsurface ocean, the bulk of which froze relatively early, forming salts, clathrates and water ice [1]. Thermal modeling predicts that ~1-2% of this oceanic liquid remains in Ceres' subsurface at the crust/mantle boundary (~40 km deep on average [2]), likely in pore spaces [3]. This is consistent with viscosity estimates of Ceres' interior, which derive from analyses of Ceres' topography as observed by Dawn [4].

The 2017 Committee on Astrobiology and Planetary Science (CAPS) report outlined the scientific richness of dwarf planets like Ceres, concluding that: "…there is much that is not understood and much that could be learned about the structure, origin, and evolution of the solar system by further investigation of dwarf planets… Logical follow-on missions… include a Ceres lander…" In addition to its scientific richness (e.g. the brine effusion/cryovolcanic activity at Occator crater and Ahuna Mons [e.g. 5-6]), Ceres is located at ~2.8 AU in a mild radiation environment. Thus, it is by far the most accessible of the candidate ocean worlds described in 'The NASA Roadmap to Ocean Worlds' [7].

A Ceres mission concept study has been funded by NASA ROSES' C.30 Planetary Mission Concepts Studies (PMCS) [8], and a Ceres sample return mission is under consideration by ESA for its Voyage 2050 program [9], demonstrating the interest in Ceres as a possible target for future exploration. Future exploration of Ceres from orbit, in situ, and/or via sample return would require a detailed understanding of the surface. Here we use the Dawn data to identify potential landing sites for a future Ceres lander. While any future mission would likely collect more detailed reconnaissance data before landing on Ceres, our analysis demonstrates the general process that a future mission would undertake to identify a landing site, and illustrates that safe and scientifically interesting landing sites likely exist.

Methods: For each potential landing site, we obtained the highest spatial resolution Dawn image, composition and topographic data. We georeferenced the datasets to one another using the software ArcGIS, and analyzed the safety and scientific interest of three potential landing regions: Occator crater, Haulani crater and Ahuna Mons (Figure 1).

Results – potential landing sites in Occator crater: The bright deposits in Occator crater (called faculae) are hypothesized to be formed by brines that originated from the remnant ocean fluid: the central Cerealia Facula likely originates from the remnant ocean fluid and an impact-induced melt chamber, while the adjacent Vinalia Faculae likely originate from the remnant ocean fluid alone [e.g. 3,5]. The facula materials that could be identified by Dawn's Visible and InfraRed spectrometer (VIR), including sodium carbonate and ammonium chloride [10-11], indicate a source of alkaline nature and mild temperature. However, VIR could not identify all materials predicted to be present [1]. The activities a lander could perform at Occator include measuring the full mineralogical and elemental compositions of the faculae, which would help to constrain the stages of evolution of the remnant ocean fluid and impact-induced melt chamber. The sites of greatest geologic and compositional interest in Occator are the faculae and the ultra-dark material in the northeast of the crater.

The data we used to assess potential landing sites in Occator crater are (i) ~10 m/pixel and ~35 m/pixel greyscale Framing Camera (FC) mosaics, made by the German Aerospace Center (DLR); (ii) The shape model, derived from ~35 m/pixel greyscale FC data, using the stereophotogrammetry technique, made by DLR and referenced to Ceres' best fit ellipsoid by Anton Ermakov; (iii) Slope data derived from the shape model; (iv) The geologic map of Occator crater [5], made using the ~10 m/pixel greyscale FC mosaic as the base data and (v) The classified abundances of minerals of interest in Occator crater (e.g. sodium carbonate and ammonium phyllosilicate), derived from VIR data [11].

We find that much of the crater floor appears safe to land, i.e. slopes <10°. However, precision landing would be needed to avoid lander-scale hazards such as boulders, pits and fractures. Not all of these lander-scale hazards are resolved in the Dawn data, but are expected from our understanding of the geology of the region.

Results – potential landing sites in Haulani crater: Haulani is a young impact crater (~3 Ma [12]) that is approximately one-third the diameter of Occator. Thus, it could not form an extensive impact-induced melt chamber like at Occator, and the bright and dark material it excavates is representative of the materials that were accumulated into Ceres' crust as the ancient subsurface ocean froze. Consequently, measuring the full mineralogical and elemental compositions of the bright and dark material at Haulani would help to constrain the composition and evolution of Ceres' ancient subsurface ocean. Sites of greatest geologic and compositional interest include areas on the crater floor and near the wall that display a variety of salt compounds such as hydrated sodium carbonate [13].

The data used are: (i) The ~35 m/pixel greyscale FC mosaic; (ii) The shape model, derived from ~35 m/pixel greyscale FC data; (iii) Slope data derived from the shape model; (iv) The geologic map of Haulani crater [14], made using the ~35 m/pixel greyscale FC mosaic as the base data and (v) The classified abundances of minerals of interest in Haulani crater [13]. Credits/attributions for these data are in the Occator crater section.

As with Occator, we find that much of Haulani's crater floor appears safe to land, i.e. slopes <10°, apart from the crater walls and central ridge. Hazards include more abundant pitted terrain than in Occator, along with fractures and boulders. Potential landing sites are located in the crater floor, where mixed bright and dark material is present.

Results – potential landing sites at Ahuna Mons: Ahuna Mons is a 4 km high isolated mountain interpreted to be a geologically recent cryovolcanic dome [6], formed by a slurry of brines and solid particles originating in the remnant ocean fluid at the base of the crust [15]. Therefore, analysis of the bright materials on the flanks of Ahuna Mons would provide insights into the composition and evolution of the remnant ocean fluid.

The data used are: (i) The ~35 m/pixel greyscale FC mosaic; (ii) The shape model, with 100 m grid spacing, made using the using the stereophotoclinometry technique by JPL; (iii) Slope data derived from the shape model and (iv) The locations and abundances of carbonates and ammoniated species [16]. Credits/attributions for these data are in the Occator crater section.

While there are no safe landing sites on the flanks, we find that sufficiently high and smooth regions are located to the north of the Mons, from which the northern flanks, which contain the highest abundances of the minerals of interest, could be viewed.

Initial conclusions and future work: We show that scientifically interesting landing sites in Occator crater, Haulani crater and at Ahuna Mons could be plausibly reached by a lander in the near future. We also continue to investigate other potential landing regions, such as the organic-rich Ernutet crater. The planetary protection requirements of landing in these sites, especially at Cerealia Facula, are currently under consideration.

Higher spatial resolution camera data than is currently available (~10s of cm) would likely be needed to minimize the risks associated with landing. The ability to land in a circle on the order of 10 m in diameter on Ceres, largely due to the lack of an atmosphere, would enable the precision landing necessary to avoid hazards such as pitted terrain, fractures and boulders.

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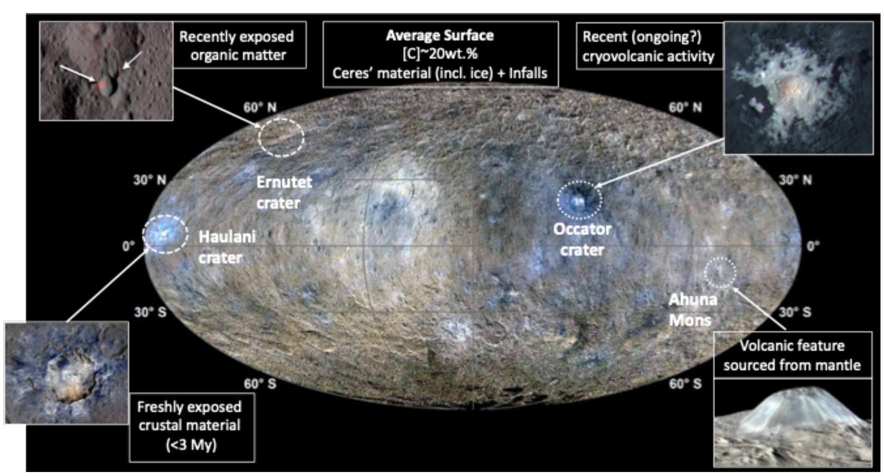

Figure 1. The locations of potential landing regions on Ceres' surface, and the associated potential scientific investigations. This figure is adapted from the Ceres PMCS proposal. The base mosaic is an enhanced color mosaic of the surface, made from FC data and with a Mollweide projection.