The In Situ Exploration of a Relict Ocean World: An Assessment of Potential Landing and Sampling Sites for a Future Mission to the Surface of Ceres

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Abstract

The Dawn orbiter’s exploration of Ceres, the most water-rich body in the inner solar system after Earth, revealed the dwarf planet to be a relict ocean world of great interest to the astrobiology and ocean worlds communities. Evidence for an early global subsurface ocean is preserved in Ceres’ surface minerals. While most of the subsurface ocean froze billions of years ago, its liquid (preserved in a deep brine reservoir) and solid remnants are responsible for spectacular surface features such as the faculae in the Occator crater, Ahuna Mons, and Haulani crater. Therefore, the next step in Ceres exploration is an in situ mission to the surface, with these three features being among the most scientifically compelling targets. Here we demonstrate the process of identifying potential landing/sampling sites. Using the highest resolution data obtained by Dawn (up to ∼5 m/pixel in Occator and up to ∼35 m/pixel elsewhere), we identify safe and scientifically compelling potential landing/sampling sites in these three regions. For future landing/sample return, higher spatial resolution data (a few decimeters per pixel to ∼1 m/pixel) than are currently available are needed to identify hazards on the scale of a ∼1–5 m lander. Such data could be obtained in an orbital reconnaissance phase prior to landing/sampling. Orbital reconnaissance, in combination with terrain relative navigation/hazard avoidance, and the ability to land within a ≤100 m diameter circle (>800,000 of which fit within Occator), makes it highly likely that safe and scientifically compelling landing/sampling sites could be reached by a future in situ mission.

Unified Astronomy Thesaurus concepts: Ceres (219); Landers (901); Asteroid belt (70); Dwarf planets (419); Orbiters (1183)

1. Introduction

1.1. Current Understanding of Ceres

Ceres is the most water-rich body in the inner solar system, after Earth, and the largest object in the asteroid belt (diameter of 940 km and semimajor axis of ∼2.8 au). The astrobiological relevance of the dwarf planet has been recognized as the result of observations taken by the Dawn mission (Castillo-Rogez et al. 2020). Dawn orbited Ceres from 2015 to 2018 (Russell et al. 2016), during which time it observed the surface and near-subsurface with its Framing Camera (FC; Sierks et al. 2011; Buczkowski et al. 2016), Visual and InfraRed mapping spectrometer (VIR; De Sanctis et al. 2011, 2015), and Gamma Ray and Neutron Detector (GRaND; Prettyman et al. 2011, 2017). Moreover, the radio science investigation allowed for the global structure of the deeper subsurface to be inferred (Konopliv et al. 2011; Park et al. 2016, 2020).

The current state of understanding is that Ceres accreted early (>3 Myr and <5 Myr after calcium–aluminum inclusions (CAIs)) and underwent partial differentiation into a volatile-rich crust and rocky interior (Castillo-Rogez & Bland 2021 and references therein). The crust is ∼40 km thick on average and is composed of rock, salts, clathrate hydrates, and no more than 40 vol.% water ice (Ermakov et al. 2017; Fu et al. 2017). The rest of the interior (called the mantle) is composed of aqueously altered rock (Ermakov et al. 2017; Fu et al. 2017). Water ice is visible on the surface in impact craters such as Juling and Oxo (Combe et al. 2016; Raponi et al. 2018). Ceres lacks a permanent atmosphere and has a low average temperature (an equatorial average of ∼155 K below the skin depth; Hayne & Aharonson 2015). Water ice exposed on Ceres’ surface rapidly sublimates on a geologic timescale (Landis et al. 2017). As a result, the visible water-ice deposits were likely excavated in the geologically recent past by processes such as the formation of their host impact craters and/or mass wasting (Combe et al. 2016). Vapor production has been reported around Ceres (Küppers et al. 2014; Villarreal et al. 2017). Modeling by Landis et al. (2017) found that newly exposed surface ice, under appropriate conditions, is a likely source for the water vapor. Water-vapor haze was proposed to occur in the Occator crater (Nathues et al. 2015) but has not been confirmed by subsequent studies.

The VIR spectrum of Ceres’ average surface is best fit by a mixture of ammonia-bearing phyllosilicates, magnesium serpentine, carbonates, and an undefined dark component (De Sanctis et al. 2015). The dark component is likely rich in carbon (Prettyman et al. 2017; Marchi et al. 2019). Areas rich in organic matter were found in association with the Ernutet crater, and it is debated whether they are endogenic or exogenic in origin (De Sanctis et al. 2017; Pieters et al. 2018; Bowling et al. 2020). Phyllosilicates are ubiquitous across Ceres’ surface and are evidence for pervasive aqueous alteration in Ceres’ history (Ammannito et al. 2016). The minerals preserved on the surface provide evidence for an ancient subsurface ocean, most of which would have frozen relatively early in the dwarf planet’s history (Castillo-Rogez et al. 2018). While the majority of the ancient subsurface ocean froze, limited amounts...
of interior liquid were retained until the present, possibly because of slow heat leakage due to abundant hydrates in the crust (Castillo-Rogez et al. 2019). The aforementioned authors predict that, in the worst case, ∼1%–2% of the ancient oceanic liquid remains today in Ceres’ subsurface at the crust/mantle boundary, which is ∼40 km deep on average (Ermakov et al. 2017). The ancient oceanic liquid forms a deep brine reservoir that may take the form of pore fluids (Fu et al. 2017; Castillo-Rogez et al. 2019) and also form larger regions, such as in the subsurface below the topographically high region Hanami Planum (Raymond et al. 2020). On the basis of geophysical and geological observations, the deep brine reservoir at the base of the crust is likely the source of some of the most spectacular features on Ceres’ surface: the faculae in the Occator crater (e.g., Raymond et al. 2020; Scully et al. 2020 and references therein; Quick et al. 2019; see Section 3.1) and Ahuna Mons (Ruesch et al. 2016, 2019a; Figure 1; see Section 3.3). Furthermore, the Haulani crater exposed shallow crustal material, which has been only slightly altered by space weathering and infall contamination (Castillo-Rogez et al. 2021; see Section 3.2).

1.2. Ceres as a Target of Future Exploration

Ceres is a target of interest for future missions because Dawn’s orbital exploration revealed it to be a complex relict ocean world with astrobiological relevance that, as a nontidally heated body (unlike most ocean worlds), is a key piece in the puzzle of our understanding of ocean world evolution (Castillo-Rogez et al. 2020). In the past, there is evidence of water, organic material, energy sources, and redox gradients at Ceres, and these ingredients could potentially be present today (Castillo-Rogez et al. 2020). In accordance with these discoveries, the NASA Roadmap to Ocean Worlds study classified Ceres as a candidate ocean world (Hendrix et al. 2019). Moreover, the results from the last phase of the Dawn mission confirm the presence of liquid within Ceres, at least on a regional scale (e.g., De Sanctis et al. 2020). 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...” (National Academies of Sciences, Engineering, and Medicine 2017, p.8). In addition to its scientific richness, Ceres is located at ∼2.8 au in a mild radiation environment. Thus, it is by far the most accessible of the confirmed/candidate ocean worlds.

As a result, there is great community interest in sending an in situ mission to Ceres. A Ceres mission-concept study was funded by the NASA ROSES C.30 Planetary Mission Concepts Studies (PMCS) entitled “Assessing Dwarf Planet Ceres’ Past and Present Habitability Potential” (Castillo-Rogez et al. 2021). The aims of this study were to assess implementation strategies for exploring Ceres’ past and current habitability and determine Ceres’ origin, all of which require detailed compositional measurements that could only be obtained via a landed mission and/or sample return. The regions of greatest interest to the PMCS study were the Occator crater, Ahuna Mons, the Haulani crater, and the Ernutet crater (Figure 1). A consideration of these regions by the Ceres PMCS team resulted in the Occator crater becoming the primary target of the study, owing to the significant science value associated with investigating the recently exposed brines that formed the faculae (see Section 3.1). The study investigated two separate mission concepts targeting Occator, each of which is intended to fall within a New Frontiers cost cap: (1) a hopping lander would study the northeastern dark ejecta (Homowo Regio) and the faculae in the eastern crater floor (Vinalia Faculae), or (2) a sample would be returned from the Vinalia Faculae to Earth after an in situ search for deep brines by a lander (Castillo-Rogez et al. 2021). Ahuna Mons was included in the PMCS investigation because this isolated mountain is interpreted to be formed from a rising slurry of brine and solid particles deriving from the deep brine reservoir (Ruesch et al. 2016, 2019a; see Section 3.3). Haulani crater was also considered by the PMCS team because the materials excavated by the Haulani impact likely represent materials that accreted into the crust as the ancient subsurface ocean froze. In contrast, the materials mobilized in solution at Occator likely included a contribution from the impactor (Bowling et al. 2019; Castillo-Rogez et al. 2021; see Section 3.2).

In addition to the PMCS investigation, the Ceres Lander for Astrobiological Exploration and Geology (CLaEG) was submitted to the first round of the 2019 Discovery Program (House et al. 2019). Moreover, several studies have advocated for sample return from Ceres (e.g., Burbine & Greenwood 2020). A Ceres sample-return mission is also under consideration by ESA for its Voyage 2050 program: Genesis of Asteroids and Evolution of the Solar System (GAUSS; Shi et al. 2021). The GAUSS orbiter would survey Ceres to assess potential landing sites, before the deployment of a lander to the surface to collect samples. The samples would be returned to Earth in a capsule under cryogenic conditions, which would preserve volatiles and organics. The Calathus mission concept, designed at the Alpbach Summer School 2018 (sponsored by ESA and the Austrian Research Promotion Agency), also proposed to investigate the Occator crater via orbital, lander, and sample-return phases (Gassot et al. 2021).

The preceding discussion demonstrates the great community interest in Ceres as a possible target for future exploration. Future exploration of Ceres by an in situ lander and/or via sample return requires a detailed understanding of the surface in order to identify scientifically compelling sites accessible with a small lander (∼1–5 m). Here we identify potential landing/sampling sites for a future Ceres mission based on the best data returned by the Dawn spacecraft until its final transmission in October of 2018. For this investigation, we assess potential landing/sampling sites within three potential landing/sampling regions: the Occator crater, the Haulani crater, and Ahuna Mons. We did not analyze the Ernutet crater as a potential landing/sampling region because there is significant debate about whether the Ernutet organics originate from Ceres or were exogenically emplaced (De Sanctis et al. 2017; Pieters et al. 2018; Bowling et al. 2020).

A landing/sampling region encompasses an entire geologic landform (e.g., a crater or a mons). A landing/sampling site is a smaller specific location, within a region, in which a spacecraft would touch down. The purpose of analyzing these three potential landing/sampling regions is to identify areas in which potential landing/sampling sites could be located. For Ceres, it is possible to land within a circle that is ≤100 m in diameter, as long as sufficiently high spatial resolution data are available for ingesting into the descent and landing procedure (a landing ellipse/circle will be ∼6× the spatial resolution of the data; Castillo-Rogez et al. 2021). The implementation strategy described in the Ceres mission-concept study, using Terrain Relative Navigation (TRN) and hazard avoidance, included landing circles as small as ∼20 m in diameter that would be defined after data were acquired during an orbital phase (Castillo-Rogez et al. 2021). In this study, we define landing/sampling sites as 100 m diameter circles. Our analysis demonstrates the general process that a future mission would undertake to identify a landing/sampling site and illustrates that safe and scientifically compelling landing/sampling sites are likely to exist, based on the highest spatial resolution Dawn data.

1.3. Precedents for the Definition of a Safe Landing/Sampling Site

The state of the art for landing on planetary bodies is primarily based on experience gained from Martian landers. The greatest concerns for landing safety are slopes and hazards (e.g., boulders) that are of a similar scale to the lander (i.e., ∼1–5 m). For example, the InSight landing site was required to have slopes of <15° at the 1–5 m length scale and a rock abundance of <10% (Golombek et al. 2016). Following the community standard 5:1 rule of thumb, images of ∼20 cm/pixel to ∼1 m/pixel are needed to characterize ∼1 m to ∼5 m scale hazards. For example, HiRISE images (High Resolution Imaging Science Experiment; McEwen et al. 2007) of ∼30 cm/pixel are used to definitively identify rocks >1.5 m in diameter, and HiRISE data form the keynote of the landing site selection process for contemporary Martian rovers and landers (e.g., Golombek et al. 2008, 2012, 2016). However, prior to the existence of HiRISE, the analysis of ∼1.5 to ∼6 m/pixel MOC images (Mars Orbiter Camera Malin & Edgett 2001) was one of the main data sets that enabled the selection of safe landing sites for the Spirit and Opportunity rovers (Golombek et al. 2003).
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The landing site constraints for the Europa Lander mission concept are consistent with the experience gained from landing on Mars: slopes within the landing area must be $<25^\circ$ and vertical relief at the lander scale can be no more than 0.5 m (Hand et al. 2017). The lack of an atmosphere at Europa enables landing in a circle of $\sim$100 m in diameter. Martian landing ellipses are much larger than those on Europa and Ceres because parachuting through the atmosphere results in greater uncertainties in the landing site placement: e.g., the MSL (Mars Science Laboratory) landing ellipse was 25 km $\times$ 20 km (Golombek et al. 2012).

We use the aforementioned experiences as a basis for the approach used in this study. Slopes and hazards on the scale of a $\sim$1–5 m lander would need to be characterized for safe landing/sampling on Ceres, which requires images of a few decimeters per pixel to $\sim$1 m/pixel (based on the 5:1 rule of thumb). Moreover, we define the safe slopes for an in situ spacecraft to be $\leq$10°, which is in keeping with the aforementioned precedents. Slopes $\leq$10° enable safe landing/sampling by removing the hazards formed by steeper slopes, such as the solar panels striking the surface and the spacecraft being unable to stay in place due to a lack of friction.

2. Methods

2.1. Data Sets

For each potential landing/sampling region, we obtained the highest spatial resolution Dawn image and topographic data, from the Framing Camera, and compositional data, from VIR:

1. We used the grayscale Framing Camera mosaics to understand the two-dimensional properties of the regions and to identify the presence of hazards and locations that are particularly scientifically compelling.
2. Geologic maps were also used to identify the presence of hazards and locations that are particularly scientifically compelling.
3. We used the shape models and slope maps to understand the three-dimensional properties of the regions and to identify topographic hazards (e.g., slopes $>10^\circ$ and areas of rapidly changing topography).
4. Mineral abundances were used as an additional input to the identification of locations that are particularly scientifically compelling.
5. We also assessed the material properties of the potential landing/sampling regions, which were based on the aforementioned Dawn data sets and terrestrial analog measurements. We synthesized knowledge about their compositions, based on Dawn data, with assumptions made about the nature of each of these materials, based on geomorphic analyses and modeling.

These data sets are described in detail below.

1. We used grayscale Framing Camera Low Altitude Mapping Orbit (LAMO) mosaics for the analysis of Occator, Haulani, and Ahuna Mons. These LAMO mosaics have a spatial resolution of $\sim$35 m/pixel and were made by the German Aerospace Center (DLR; Roatsch et al. 2017). The images used to create these mosaics were obtained during the LAMO phase of the mission, during which the highest spatial resolution global data set ($\sim$35 m/pixel) was acquired.

(a) For Occator, we also used the grayscale Framing Camera XM2 mosaic of the crater, which has a spatial resolution of $\sim$5 m/pixel and was made by DLR (Roatsch et al. 2018). The images used to create this mosaic were obtained during Dawn’s second extended mission (XM2), during which very high-resolution images were acquired along a swath of the surface that targeted the Occator crater. In addition, we also used data obtained during the High Altitude Mapping Orbit (HAMO) phase of the mission: enhanced color RGB composite and photometrically corrected Framing Camera HAMO mosaics of Occator ($\sim$135 m/pixel), both made by DLR. In the enhanced color mosaic, $R$ is the 0.96 $\mu$m filter, $G$ is the 0.75 $\mu$m filter, and $B$ is the 0.44 $\mu$m filter, such that the colors are an enhanced version of what the human eye would see.

(b) For Haulani, we also used an enhanced color RGB composite Framing Camera HAMO mosaic of the crater ($\sim$135 m/pixel), which was presented in Tosi et al. (2019).

2. We also utilize two shape models, which derive from the same LAMO grayscale Framing Camera data set. The SPG shape model was made by DLR using the stereophotogrammetry technique (Preusker et al. 2016). The SPC shape model was made by JPL using the stereophotoinometry technique (Park et al. 2016). In addition, our analysis used slope maps, which were made from the shape models by Anton Ermakov (Jet Propulsion Laboratory, California Institute of Technology/University of California, Berkeley). Shape models were also made using the SPG and SPC techniques when the Dawn mission orbited Vesta, using the same techniques that were used to create the Cerean shape models. When compared, the Vestan SPG and SPC shape models had systematic differences on the order of a few hundreds of meters (Ermakov et al. 2014). Thus, it is also probable that there are similar systematic differences between the Cerean SPG and SPC shape models. These differences have a minor impact on our work because we do not compare the topography/slopes between landing/sampling regions, and we do not use the shape models to identify specific future landing/sampling sites. We use them to demonstrate the general process that a future mission would undertake and to illustrate that safe and scientifically compelling sites are likely to exist. A future mission would create its own shape models from which to identify landing/sampling sites.

(a) For Occator, we used the SPG shape model (Preusker et al. 2016; Jaumann et al. 2017), which was referenced to Ceres’ best-fit ellipsoid by Anton Ermakov. This shape model has a horizontal resolution of $\sim$32 m/pixel and an intrinsic height accuracy of $\sim$1.5 m (Jaumann et al. 2017).

(b) For Haulani and Ahuna Mons, we used sections of the SPC shape model (Park et al. 2016), which was referenced to Ceres’ best-fit ellipsoid by Anton Ermakov. The version of the global shape model used in our analysis has a horizontal resolution of $\sim$100 m/pixel and an absolute radial error of $\lesssim$20 m.

3. Geologic maps, derived from the grayscale Framing Camera LAMO and XM2 mosaics, were also used in this analysis.
For Occator, we used a geologic map of the crater interior by Scully et al. (2020), which was based on the grayscale Framing Camera XM2 mosaic, and a geologic map of the crater interior and ejecta by Scully et al. (2019a), which was based on the grayscale Framing Camera LAMO mosaic. The XM2-based geologic model allowed us to investigate the detailed distribution of the faculae, while the LAMO-based geologic map defined the extent of the Homowo Regio dark ejecta.

For Haulani, we used a geologic map of the crater by Krohn et al. (2018), which was based on the grayscale Framing Camera LAMO mosaic. The distribution of the pitted terrain, smooth terrain, and fractures as defined by Krohn et al. (2018) was particularly important for our analysis.

For Ahuna Mons, we used the definition of geologic units by Ruesch et al. (2016), which is based on the grayscale Framing Camera LAMO mosaic: the summit unit, the talus unit on the flanks, and the surrounding smooth and cratered units.

The final data sets are classified abundances of minerals of interest, derived from VIR data taken during the HAMO and LAMO mission phases. The spatial resolution of the VIR LAMO data is \(\sim 100\) m/pixel and that of the VIR HAMO data is \(\sim 400\) m/pixel. The spectral resolution of VIR is 1.8 nm/band in the visible and 9.8 nm/band in the infrared.

(a) For Occator, we used maps of mineral abundance derived from VIR LAMO and HAMO spectra by Raponi et al. (2019), which classified the abundance of magnesium carbonate, sodium carbonate, aluminum phyllosilicate, ammoniated phyllosilicate, magnesium phyllosilicate, ammonium chloride, and dark material in Occator. We also used a grain size map of Occator derived from VIR data (Raponi et al. 2019).

(b) For Haulani, we used maps of mineral abundance derived primarily from VIR HAMO spectra, with a small contribution from LAMO spectra, by Tosi et al. (2019), which classified the abundance of sodium carbonate, ammoniated phyllosilicate, and magnesium phyllosilicate in Haulani.

(c) For Ahuna Mons, we used the results of a spectral unmixing model that was applied to VIR HAMO spectra by Zambon et al. (2017). The results of the model indicate that the northern flank is richer in sodium carbonate, magnesium–calcium carbonate, and ammoniated species than the other flanks and the surrounding materials. The specific location of the northern flank is defined in Section 3.3.

2.2. Technique

To enable us to align the data sets with one another and to analyze them in one comprehensive display, we chose to use ESRI ArcGIS software. ArcMap allows for multiple data sets to be georeferenced to one another and for the accurate measurement of distance, area, etc. We created one ArcMap project for each potential landing/sampling region and added the data sets that were already georeferenced: (i) the grayscale Framing Camera LAMO and XM2 mosaics, (ii) all of the shape models, (iii) all of the slope maps, and the (iv) Scully et al. (2020, 2019a) geologic maps. We did not have access to the georeferenced versions of the remaining data sets, which meant that they would not automatically align correctly with the georeferenced data sets in ArcMap. Thus, we used the Georeferencing toolbar in ArcMap to manually align the non-georeferenced data sets to the georeferenced data sets. We began by using the Rotate, Shift, and Scale tools to align the data sets, which was sometimes the only necessary step, for example, in the cases where the data sets had the same map projection. In instances where it was necessary to further warp the data sets for them to align, we used the Control Points tools. Once all of the data sets were aligned to one another, we analyzed the properties of each potential landing/sampling region in a consistent order: (1) grayscale Framing Camera mosaics, (2) geologic maps, (3) shape models and slope maps, (4) mineral abundances, and (5) material properties.

3. Results

3.1. Potential Landing/Sampling Sites in the Occator Crater

Occator is the largest young impact crater on Ceres: it is 92 km in diameter and \(\sim 22\) million years old (Mest et al. 2018; Neesemann et al. 2019). It contains bright salt deposits (faculae) in its floor, which are the solid residues of brines exposed to Ceres’ surficial vacuum (De Sanctis et al. 2016). Occator’s faculae are hypothesized to be formed by brine effusion: brines sourced in the subsurface were emplaced on the surface ballistically and via short-lived flows (Scully et al. 2020 and references therein; Ruesch et al. 2019b; Quick et al. 2019). Occator’s initial impact-derived subsurface melt chamber would have consisted of brines formed when impact-melted water ice mixed with salts, both derived from the crust (Bowling et al. 2019; Figure 2). However, the faculae are unlikely to be sourced from this melt chamber alone: absolute ages estimated from crater counts (Nathues et al. 2020 and references therein) indicate that the faculae were emplaced many millions of years after the melt chamber would have solidified (Hesse & Castillo-Rogez 2019). The melt chamber and deep brine reservoir likely underwent thermal merging, which would have refreshed the melt chamber and enabled the central faculae (called Cerealia Facula and Pasola Facula) to be emplaced geologically recently (Hesse & Castillo-Rogez 2019), in keeping with the absolute ages (Nathues et al. 2020 and references therein). The recent discovery of hydrated sodium chloride at Cerealia Facula indicates that brine emplacement may be ongoing, making it possible that liquid is still present in the subsurface below the Occator crater today (De Sanctis et al. 2020). In addition, impact-induced fracturing enabled deep brines to reach the surface and form additional faculae deposits in the crater floor (called Vinalia Faculae), unconnected to the melt chamber (Raymond et al. 2020; Scully et al. 2020; Figure 2). Fracturing could also be aided by excess pressures from partial crystallization of the melt chamber (Quick et al. 2019). Thus, because the Vinalia Faculae–forming brines originate directly from the deep brine layer (e.g., Raymond et al. 2020; Scully et al. 2020), they inform on Ceres’ current habitability potential (Castillo-Rogez et al. 2020). Homowo Regio is also a compelling location for a lander and/or sample-return mission. The very dark blue color of these fine-grained ejecta materials (Raponi et al. 2019) has been interpreted as a highly porous structure resulting from the sublimation of fine rock grains originally mixed with a high fraction of water ice.
Figure 2. Schematic subsurface structure below a vertically exaggerated cross section of the Occator crater. The impact-induced subsurface melt chamber is located underneath the center of the Occator crater. The deep brine reservoir is laterally extensive at a depth of $\sim 40$ km and thermally merges with the base of the melt chamber (Bowling et al. 2019; Hesse & Castillo-Rogez 2019). The melt chamber is located directly below Cerealia Facula and Pasola Facula, which are the central bright regions. Vinalia Faculae are located in the eastern crater floor and are sourced from the deep brine reservoir via the prevalent fractures below Occator (Scully et al. 2020; Raymond et al. 2020). The colors match the geologic map of the interior of the Occator crater by Scully et al. (2020). Image adapted from Scully et al. (2020), in which all of the labeled features are fully discussed.

Figure 3. Extents of the faculae and Homowo Regio. The extents of the Cerealia Facula and Vinalia Faculae are illustrated by (a) the grayscale Framing Camera XM2 mosaic and by (b) the Scully et al. (2020) geologic map. The extent of Homowo Regio is illustrated by (c) the enhanced color RGB composite and photometrically corrected Framing Camera HAMO mosaics and by (d) the Scully et al. (2019a) geologic map. In (b) and (d), each color corresponds to a specific geologic unit, which are discussed in detail in Scully et al. (2020, 2019a).
Homowo Regio might sample the shallow subsurface (S. Marchi 2021, personal communication) and thus represent material accreted from the early freezing of Ceres’ subsurface ocean, which would explain the higher abundance in material accreted from the early freezing of Ceres.

The geologic map of the Occator crater (Scully et al. 2020), and the grayscale Framing Camera LAMO and XM2 mosaics on which they are based, allows us to define the extent of the faculae (Figures 3(a) and (b)). The extent of Homowo Regio is clearly illustrated by the enhanced color RGB composite and photometrically corrected Framing Camera HAMO mosaics, and corresponds to a unit of dark crater material (i.e., ejecta) mapped by Scully et al. (2019a; Figures 3(c) and (d)). We also identify a variety of hazards based on the Framing Camera data and geologic maps: fractures, pits, and boulders are present at all scales (Figure 4). The largest fractures are up to tens of kilometers long, up to hundreds of meters wide, and up to hundreds of meters deep (Buczkowski et al. 2019; Schenk et al. 2020). The progression from the LAMO (∼35 m/pixel) to XM2 (∼5 m/pixel) images resolved smaller scale fractures than were previously clearly visible (Figures 4(a) and (b)), indicating that there are likely smaller fractures in existence than can be resolved in the ∼5 m/pixel XM2 data. There is no widespread, well-developed pitted terrain in the Occator crater (Sizemore et al. 2017), but there are isolated, irregularly shaped pits that are interpreted as endogenic features formed by the release of volatiles during the post-impact cooling of the crater (Schenk et al. 2020; Figure 4(c)). Boulders are also found throughout the crater and concentrate in the ejecta and interior of some small, fresh craters (Figure 4(d)) and at the base of Occator’s steeply sloping crater walls (Scully et al. 2020). Kilometer- and tens-of-meter-scale pits and boulders are clearly visible in the XM2 data and, similar to the fractures, are likely present at all scales, with the smaller examples being currently unresolved in the Dawn data. Fractures, pits, and boulders on the scale of a ∼1–5 m lander, or larger, would all be hazards for an in situ mission. However, the highest spatial resolution ∼5 m/pixel XM2 Dawn data cannot adequately characterize hazards on the scale of a ∼1–5 m lander, which requires images of a few decimeters per pixel to ∼1 m/pixel (based on the 5:1 rule of thumb; see Section 1.3).

The slope map derived from the SPG shape model shows that the highest slopes are located on the crater walls, on the massifs surrounding the central pit, and on the faces of terraces (Figure 5). There are generally lower slopes in parts of the ejecta blanket and within the central crater floor, which roughly correspond to the bright material (i.e., faculae), lobate material, and crater floor material geologic units. In the current SPG slope map, there are large areas of the crater interior and exterior that have slopes ≤10°, and thus would be safe for touching down. Many of these areas intersect the faculae and Homowo Regio (Figures 5(a) and (b)). While there are limited areas with slopes ≤10° within Cerealia Facula, almost the entire Vinalia Faculae have slopes ≤10°. This is because Cerealia Facula is predominantly located in a region of intense
topography: Cerealia Facula coats the majority of the central pit (~1 km deep) and is cut by prominent fractures surrounding the central pit (Buczkowski et al. 2019; Schenk et al. 2019; Scully et al. 2019b and references therein; Figure 5(d)). At the base of the central pit, there is a central dome, called Cerealia Tholus (up to ~700 m high), that is entirely coated by and/or made of the Cerealia Facula bright material (Schenk et al. 2019; Scully et al. 2019b and references therein). The aforementioned slopes are derived from the SPG shape model, which has a horizontal resolution of ~32 m/pixel and an intrinsic height accuracy of ~1.5 m. Therefore, they are not necessarily representative of the slopes on the scale of a ~1–5 m lander, which would need to be considered for the safe and successful operation of an in situ mission.

The Raponi et al. (2019) maps of mineral abundance show that sodium carbonate is concentrated within the faculae, with an abundance of up to ~70%, and is less than ~10% in the majority of the rest of the crater interior and ejecta (Figure 6(a)). A form of aluminum phyllosilicate and magnesium carbonate are also present within the faculae. Both minerals also have relatively high abundances in parts of the crater wall/floor and, in the case of magnesium carbonate, in Homowo Regio (Figures 6(b) and (c)). However, the highest abundances of the aluminum phyllosilicate and magnesium carbonate in the faculae are not as high as the sodium carbonate: only ~15% and ~7%, respectively. Raponi et al. (2019) also find up to ~7% ammonium chloride in the center of Cerealia Tholus and lower abundances in parts of Vinalia Faculae. Ammonium chloride is present in negligible abundance in the rest of the crater. The magnesium and ammoniated phyllosilicates are strongly concentrated in Homowo Regio and in parts of the crater walls, with the highest abundances in these areas of ~18% and ~9%, respectively (Figures 6(d) and (e)). Although the albedo of Homowo Regio is the lowest on Ceres

Figure 5. Slopes within and surrounding the Occator crater, derived from the SPG shape model. In panels (a) and (b), locations with slopes >10° are shaded in orange, and locations with slopes ≤10° are not shaded, i.e., the underlying grayscale Framing Camera XM2 mosaic can be seen clearly. (a) Slopes ≤10° would be safe for landing, and many occur within the faculae and Homowo Regio. (b) Almost the entire Vinalia Faculae have slopes ≤10°. There are limited areas with slopes ≤10° in Cerealia Facula. (c) and (d) The SPG shape model of the Occator crater. The depression of the central pit and peak of Cerealia Tholus are clearly visible in (d).
(0.03), the abundance of dark material in that area (∼75%) is less than the average Cerean regolith in the Occator region (up to ∼92%; Figure 6(f)). Raponi et al. (2019) hypothesize that this is due to Homowo Regio being composed of an unusual low-albedo material that is intrinsically darker than the average dark material found across Ceres. The faculae and Homowo Regio also appear to have smaller grain sizes (as low as ∼30 μm) in comparison to the rest of the crater floor and ejecta (up to ∼130 μm). Overall, the nature of the materials found in the faculae and Homowo Regio, and the information they may give us about Ceres’ current habitability potential and the environmental conditions in Ceres’ ancient subsurface ocean (Castillo-Rogez et al. 2021), makes these locations the most scientifically compelling in Occator (Figure 7).

We assessed the material properties of four types of material in the Occator crater: average floor material, Cerealia Facula material, Vinalia Faculae material, and Homowo Regio material (Table 1). Raponi et al. (2019) found the composition of the average floor material to be broadly similar in nature to the average Cerean crust, within which magnesium serpentine, ammoniated smectite clays/phyllosilicates, and calcium/magnesium carbonates have been identified (De Sanctis et al. 2015). The main difference to the average Cerean crust is that Occator’s average floor material is significantly depleted in ammonium phyllosilicates, and slightly depleted in magnesium phyllosilicates, hypothesized to be due to impact-induced release of OH− and NH₄⁺ during the Occator-forming impact (Raponi et al. 2019). We approximate that the load-bearing capacity (or strength against shear) of the average floor material is most comparable to that of magnesium serpentine, for which Buczowski et al. (2019; and references therein) derived a shear modulus of ∼13 GPa. All of the load-bearing capacities inferred in this work are significantly greater than that required by an in situ mission: based on a lander mass of ∼1660 kg and leg radii of ∼0.1 m (Castillo-Rogez et al. 2021), each leg only exerts ∼15 kPa. The 100–130 μm grain size of the average floor material (Raponi et al. 2019) is consistent with a grain size categorization of “very fine sand”, which corresponds to an angle of internal friction of 27°–41° (clayey fine sand; Geotechdata.info 2013). The grain size of 100–130 μm is the largest of the four Occator materials evaluated, suggesting that the floor material is the most compactable, because as grain size increases, compactability also increases (Barik et al. 2011). We estimate that the average floor material has a porosity of >20%. This estimate is based on a comparison to the inferred porosity of the Homowo Regio material (at least 20% (Prettyman et al. 2017; discussed in the following paragraphs)), the fact that porosity of soil generally increases as grain size increases, and the additional pore space increase from the heavy fracturing in Occator’s floor. The average floor material is likely to be more cohesive than the Cerealia Facula material, Vinalia Faculae material, and Homowo Regio material because the emplacement mechanisms of these three materials (as discussed in the

*Figure 6. Maps of mineral abundance for the interior and ejecta of Occator crater. These maps are from Raponi et al. (2019) and were created from VIR LAMO and HAMO spectra. The following are illustrated: (a) sodium carbonate, with highest abundances of ∼70%; (b) aluminum phyllosilicate, with highest abundances of ∼15%; (c) magnesium carbonate, with highest abundances of ∼7%; (d) magnesium phyllosilicate, with highest abundances of ∼18%; (e) ammonium phyllosilicate, with highest abundances of ∼9%, and (f) dark material, with a range of abundances from ∼75% to ∼92%.*
following paragraphs) likely resulted in more diffuse, less cohesive deposits than the average floor material.

Both the Cerealia Facula material and Vinalia Faculae material are composed of sodium carbonate, aluminum phyllosilicate, magnesium carbonate, and ammonium chloride, with lower abundances in Vinalia Faculae than in Cerealia Facula (Raponi et al. 2019). Buczkowski et al. (2019) thus estimate that the load-bearing capacity of the faculae materials is between that of particulate clays (∼1 GPa) and solid carbonate (∼2 GPa). The load-bearing capacity of the faculae materials (∼1–2 GPa) is therefore approximately an order of magnitude less than that of the average floor material (∼13 GPa). The grain size of the faculae materials was determined to be 10–60 μm by Raponi et al. (2019), which fits within the category of silt-sized grains. Such grain sizes correspond to an angle of internal friction of 22°–32° (Geotechdata.info 2013) if they are organic bearing, or 30°–35° if they are inorganic (Carter & Bentley 1991; Obrzud & Truty 2018). The faculae material’s small grain size could mean they undergo less compaction than the coarser-grained average floor material. A greater proportion of ballistic emplacement is thought to have occurred at Vinalia Faculae in comparison to Cerealia Facula, where short-lived flow emplacement may have been more prominent (Scully et al. 2020 and references therein; Ruesch et al. 2019b; Quick et al. 2019). The porosity of the Cerealia Facula material might be comparable to that of the terrestrial analog travertine (calcite deposits formed by chemical precipitation out of solution), which is 15%–17% (Yetkin et al. 2017). However, Ceres’ much lower gravity could result in porosities >15%–17%. The higher amount of ballistic emplacement in the Vinalia Faculae material likely corresponds to higher porosities (≫15%–17%) and less cohesion than at Cerealia Facula. Moreover, in ballistic emplacement processes, grain size decreases with distance from the source (e.g., Southworth et al. 2015; Quick & Hedman 2020), so the porosity of the Vinalia Faculae material is probably higher close to the deposit centers and lower at the margins of the deposits. On account of the increasingly diffuse deposition of Vinalia Faculae material away from the source, the material properties would grade toward those of the average floor material with distance from the centers of the Vinalia Faculae deposits. Rognini et al. (2020) find that the thermal inertia of the faculae is compatible with low (1–17 TIU) or high values (up to 140 TIU). Rognini et al. (2020) do not favor either set of values but note that the lower values are compatible with finer grain sizes while the higher values are
| Location                      | Load-bearing Grain Thermal Location Capacity Size Compactability Porosity Cohesion Thermal Inertia | Occator crater                                                                 |
|-------------------------------|-------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Occator average floor material | ~13 GPa (approximated as magnesium serpentine; Buczkowski et al. 2019)                         | 100–130 μm (Raponi et al. 2019) Most compactable of Occator materials (based on grain size) | >20% (based on grain size and fractures) Most cohesive of Occator materials (based on emplacement mechanisms) | Not calculated |
| Occator Cerealia Facula material | ~1–2 GPa (approximated between particulate clays and solid carbonate; Buczkowski et al. 2019) | 10–60 μm (Raponi et al. 2019) Less than Occator average floor material (based on grain size) | >15–17% (based on terrestrial analog and Ceres’ gravity) Less cohesive than Occator average floor material (based on emplacement mechanisms) | 1–17 TIU probable, up to 140 TIU also possible (Rognini et al. 2020) |
| Occator Vinalia Faculae material | ~1–2 GPa (approximated between particulate clays and solid carbonate; Buczkowski et al. 2019) | 10–60 μm (Raponi et al. 2019) Less than Occator average floor material (based on grain size) | >15–17% (based on more ballistic emplacement) Less cohesive than Cerealia Facula material (based on more ballistic emplacement) | 1–17 TIU probable, up to 140 TIU also possible (Rognini et al. 2020) |
| Occator Homowo Regio material | ~1 GPa (approximated by particulate clays; Buczkowski et al. 2019)                            | 30–60 μm (Raponi et al. 2019) High porosity and internal cohesion suggest highly compressible (Schröder et al. 2021); less than Occator average floor material and similar to Occator faculae materials (based on grain size) | At least ~20% (Prettyman et al. 2017); likely >50% (foam like; Schröder et al. 2021) Less cohesive than Occator average floor material (based on emplacement mechanisms) | Not calculated |

| Haulani crater                                           |                                                                                                         |                                      |
|----------------------------------------------------------|---------------------------------------------------------------------------------------------------------|-------------------------------------|
| Haulani interior material (apart from SE wall)            | ~13 GPa (approximated as magnesium serpentine; Buczkowski et al. 2019)                               | 93–135 μm (Tosi et al. 2019) Comparable to Occator average floor material (based on grain size) | <20% (less fractured than Occator average floor material) Central ridge more cohesive than mass-wasting deposits and pitted terrain (based on emplacement mechanisms) | Central ridge 160 TIU, floor 80 TIU (Tosi et al. 2018); central ridge 110–130 TIU (Rognini et al. 2020) Not calculated |
| Haulani SE wall material                                  | ~13 GPa (approximated as magnesium serpentine; Buczkowski et al. 2019)                               | 28 μm (Tosi et al. 2019) Less than Haulani interior material (apart from SE wall; based on grain size) | <20% (less fractured than Occator average floor material) Central ridge more cohesive than mass-wasting deposits and pitted terrain (based on emplacement mechanisms) | Not calculated |

| Ahuna Mons                                                |                                                                                                         |                                      |
|----------------------------------------------------------|---------------------------------------------------------------------------------------------------------|-------------------------------------|
| Ahuna Mons flank material                                | ~1–2 GPa (approximated between particulate clays and solid carbonate; Buczkowski et al. 2019)         | 72–122 μm (Zambon et al. 2017) Comparable to Occator average floor material and Haulani interior material (apart from SW wall; based on grain size) | Greater than Ahuna Mons surrounding material (based on emplacement mechanisms and grain size) Comparable to Occator faculae materials (based on emplacement mechanisms) | Not calculated, but northern flank inherently cooler (Zambon et al. 2017) |
| Ahuna Mons surrounding material                          | ~13 GPa (approximated as magnesium serpentine; Buczkowski et al. 2019)                               | 57 μm (Zambon et al. 2017) Less than Ahuna Mons flank material (based on grain size) | Less than Ahuna Mons flank material (based on emplacement mechanisms and grain size) Less than Ahuna Mons flank material (based on emplacement mechanisms) | Likely similar to Ceres’ average: 1–15 TIU or ~50–60 TIU (Rognini et al. 2020) |
compatible with coarser grain sizes. Thus, the 10–60 μm grain size estimate of the faculae (Raponi et al. 2019) would indicate that the lower thermal inertia values are correct.

The Homowo Regio material is made of anomalously dark, fine-grained ejecta materials (Buczkowski et al. 2019; Raponi et al. 2019; Scully et al. 2019a). It is comparable in composition to the average Cerean crust, but with greater abundances of magnesium serpentine, ammoniated smectite clays, and magnesium carbonates (Raponi et al. 2019). Schröder et al. (2021) simulated the material in Homowo Regio as a mixture of ice with a small fraction of rock particles of the same composition as Ceres’ average surface. The high ice fraction is justified by the Homowo Regio material originating in the upper crust. Schröder et al. (2021) demonstrated that following sublimation, the hyperporous residual material reproduces the observed dark blue color. Hence, Homowo Regio might have a foam-like texture, which Schröder et al. (2021) assessed to be of higher tensile strength and lower compressive strength, although they do not quantify these properties. The load-bearing capacity of the Homowo Regio material is likely ~1 GPa (particulate clays; Buczkowski et al. 2019), and the grain size was determined to be 30–60 μm (Raponi et al. 2019). Given their composition and grain size, the angle of internal friction for the Homowo Regio materials is determined to be 18°–28° (clay; Geotechdata.info 2013). The porosity of the Homowo Regio material has been inferred to be at least 20% (Prettyman et al. 2017), and it is likely even >50% because of the foam-like texture inferred by Schröder et al. (2021). The high porosity and internal cohesion suggest the material is highly compressible (Schröder et al. 2021). Based on the grain size (30–60 μm), compactability should be less than the average floor material and similar to the faculae materials. The results of Schröder et al. (2021) indicate that the Homowo Regio material is likely more cohesive than entirely dry ejecta, but less cohesive than the average floor material.

In summary, for an in situ mission at Occator crater, we find that there are multiple hazards (fractures, pits, and boulders) at all scales, which likely occur at smaller sizes than can be resolved in the highest resolution Dawn data (~5 m/pixel). Precision landing would be needed to avoid these hazards. While there are large areas of the crater interior and ejecta with slopes ≤10°, higher spatial resolution slope data will be needed to confirm if this is also the case on the scale of a ~1–5 m lander. The locations that are particularly scientifically compelling are the Vinalia Faculae and Homowo Regio, because of their connection to the current deep brine reservoir and ancient subsurface ocean, respectively, along with high abundances of a variety of materials, including salts. The Cerealia Faculae are also scientifically compelling, but they are sourced from crustal material and impactor material in addition to the deep brine reservoir via fractures and possible thermal merging. Moreover, there are only limited areas with slopes ≤10° within Cerealia Facula. The design of an in situ mission would need to take into account the faculae material’s estimated load-bearing capacity of ~1–2 GPa, the porosity of >15%–17%, and less compactability and cohesion than the average Occator floor material. Based on the aforementioned considerations, we identify 10 example potential landing/sampling sites in both Vinalia Faculae and Homowo Regio, which occur in locations with slopes of ≤10° and are free of hazards in the XM2 Framing Camera data (Figures 8 and 9). Our current inability to resolve slopes and hazards on the scale of a ~1–5 m lander (which requires images of a few decimeters per pixel to ~1 m/pixel) means that the acquisition and analysis of higher spatial resolution data would be needed to definitively identify potential landing/sampling sites for a real in situ mission. However, our analysis indicates that safe and
3.2. Potential Landing/Sampling Sites in the Haulani Crater

Haulani is a young impact crater that has a model age of formation of approximately 2 million years ago (Sizemore et al. 2017) and, with a diameter of 34 km, is roughly one-third the size of Occator. Because the energy involved in forming the smaller Haulani crater was less than at Occator, the materials excavated by the Haulani impact, rather than being mobilized in a solution like at Occator, are likely more directly representative of the materials that accreted into Ceres’ crust as the ancient subsurface ocean froze. Moreover, the geologically young age of the crater means that the exposed material has not been significantly altered by space weathering and contamination by infalls. Consequently, investigating the detailed composition of the material excavated by the Haulani impact could constrain the environmental conditions in Ceres’ ancient subsurface ocean (Castillo-Rogez et al. 2021).

We used the Krohn et al. (2018) geologic map of Haulani, and the grayscale Framing Camera LAMO mosaic on which the geologic map is based, to analyze the two-dimensional properties of the crater (Figure 10). The sheer crater walls give way to terraces and then to crater floor material with a variety of textures, from smooth to hummocky. Within the center of the crater, there is a prominent central ridge of high-standing material, which is ~10 km long and up to ~4 km wide. Lobe-shaped mass-wasting deposits flow off the central ridge, and also from the crater walls, into the crater floor (Krohn et al. 2018). Pitted terrain is prevalent within Haulani’s floor, much more so than in Occator, and forms widespread deposits of unevenly shaped pits with partially or fully coalescing edges (Sizemore et al. 2017; Figures 10 and 11(a)).
Sizemore et al. (2017) conclude that the Cerean pitted terrain formed via a similar mechanism to Vestan (Denevi et al. 2012) and Martian pitted terrain (Boyce et al. 2012; Tornabene et al. 2012): via degassing of impact-heated volatile-bearing material. Larger pits tend to occur in the centers of the pitted terrain clusters, with pits decreasing in diameter toward the edges. The largest pit in Haulani is \( \sim 370 \) m in diameter, and pits are observed down to the spatial resolution limit of the \( \sim 35 \) m/pixel Framing Camera LAMO data. We infer that pits likely exist at smaller scales than can be resolved by the current Dawn data, by viewing HiRISE data of the Martian crater Zunil (Figure 12). This inference is based on similarities between Martian and Cerean pitted terrains (Boyce et al. 2012; Tornabene et al. 2012; Sizemore et al. 2017). The HiRISE data provide a one to two order-of-magnitude higher spatial resolution view of the pitted terrain than the Dawn data and demonstrate that as the pitted terrain is viewed at increasingly smaller scales, smaller pits become visible. Thus, it is highly likely that pits exist at smaller scales than can be resolved in the \( \sim 35 \) m/pixel data, such as pits on the scale of a \( \sim 1–5 \) m lander or larger, which would all be hazards for an in situ mission. Fractures are also present within the crater and would pose an additional hazard. When observed in the \( \sim 35 \) m/pixel Framing Camera images, fractures are not as prevalent in Haulani as in Occator, but they do exist, particularly in the northwest (Figures 10 (a) and (b)). The longest fracture in Haulani is \( \sim 5 \) km long, the widest is \( \sim 200 \) m wide and, based on a comparison with Occator, fracture depths are likely a few 10–100 s of meters. Similar to the pitted terrain, fractures are also likely present on a lander scale (\( \sim 1–5 \) m or larger), which cannot be resolved in the current \( \sim 35 \) m/pixel data. While pitted terrain and fractures would create hazards, there are also many areas of the Haulani crater that appear to be accessible to an in situ mission. For example, there is widespread smooth terrain within the crater floor (Figure 10), which does not have any resolvable texture in the highest spatial resolution data that are currently available: \( \sim 35 \) m/pixel Framing Camera LAMO data.

Analyzing/sampling the full suite of materials excavated by the crater-forming impact would be particularly scientifically compelling to an in situ mission at Haulani. Therefore, we identified locations within the crater that contain intermixed materials, which are of greater scientific interest than locations with only one type of material. We defined intermixed...

Figure 10. Geomorphologic features of the Haulani crater. (a) Grayscale Framing Camera LAMO mosaic of Haulani, in which the crater walls, terraces, central ridge, and lobe-shaped mass-wasting deposits are labeled. The locations of Figures 11(a) and (b) are also shown. (b) Krohn et al. (2018) geologic map of Haulani crater, over lain onto the grayscale Framing Camera LAMO mosaic. Each color corresponds to a specific geologic unit, which are discussed in detail in Krohn et al. (2018). The geologic features pertinent to our analysis are labeled: smooth terrains, hummocky material, pitted terrain, and fractures. The smooth terrain would be a preferable location for an in situ mission.

Figure 11. The main hazards within the Haulani crater are pitted terrain and fractures. (a) Pitted terrain is prevalent on the floor of the Haulani crater. The example shown here is to the north of the central ridge, the northwestern tip of which is seen at the bottom of the image. The full extent of the pitted terrain in Haulani is shown as the lilac geologic unit in Figure 10(b). (b) There are prominent fractures in Haulani’s northwestern floor. These fractures are shown as blue linear features in Figure 10(b). The locations of Figures 11(a) and (b) are shown in Figure 10(a).
materials based on the appearance of Haulani in the enhanced color RGB composite Framing Camera HAMO mosaic. We divide the materials in Haulani into four groups based on their color in this mosaic: (i) navy, (ii) brown, (iii) white, and (iv) a mixture of navy, brown, and white (i.e., the intermixed materials; Figures 13(a) and (b)). The colors in the enhanced color mosaic are a good proxy for the variation of material in the crater because the colors indicate differences in composition, grain size, etc. The intermixed materials are located in several parts of the crater floor (Figure 13(b)). We discount the areas of the intermixed materials that also include pitted terrain or fractures because these features would be hazardous to an in situ mission (Figure 13(c)). In contrast, areas of the intermixed materials that intersect with the smooth material make promising landing/sampling sites (Figure 13(d)). As with the smooth material, the identification of the intermixed material is based on the highest spatial resolution data that are currently available. A future mission would need to confirm that the material is mixed on a scale that could be reached/sampled by a ∼1–5 m lander.

Using the same slope threshold as for Occator (≤10°), we find that much of the crater floor (excluding the central ridge) appears to be safe for landing/sampling (Figure 14(a)). In general, the areas of intermixed materials that intersect with the
smooth material occur in regions with slopes of $\leq 10^{5}$ (Figure 14(b)). In addition to the central ridge, the crater walls and terraced parts of the floor adjacent to the walls have slopes of $>10^{5}$ and would not be safe for an in situ mission. The slopes are derived from the SPC shape model, which has a horizontal resolution of $\sim 100$ m/pixel and an absolute radial error of $\leq 20$ m. Thus, similar to Occator, when the slopes on the scale of a $\sim 1$–5 m lander are taken into consideration, there could be parts of the crater floor with apparent slopes of $\leq 10^{5}$ that actually have slopes of $>10^{5}$ at the scale of a lander.

Using abundance maps of minerals of interest, we identify that the highest abundances of sodium carbonate, ammoniated phyllosilicate, and magnesium phyllosilicate are located in the crater-wall region: on the walls themselves, just outside the crater rim, and in the crater interior adjacent to the walls (Figure 15(a); Tosi et al., 2019). Consequently, the areas with the highest abundances of the interest tend to occur within areas that have slopes of $>10^{5}$ (Figure 15(b)). Therefore, it is unlikely that an in situ mission would touch down in one of these areas. However, there are regions of high abundance of sodium carbonate that extend into the more shalllowly sloping crater floor ($<10^{5}$; Figure 15(b)). Moreover, Tosi et al. (2019) note that ammoniated phyllosilicate and magnesium phyllosilicate are present in lower abundances throughout the crater floor. Therefore, an in situ mission could analyze/sample an area of high abundance of sodium carbonate in the crater floor, which would also likely contain lower abundances of ammoniated phyllosilicate and magnesium phyllosilicate, while also being positioned to view the crater-wall region, which contains higher abundances of all the minerals. Such a ground-based remote-sensing investigation of the crater wall would be able to resolve mineral abundances with greater spatial resolution than possible from orbit and would also be able to resolve minerals with abundances too small to be seen from orbit.
Based on the aforementioned composition, we approximate that the load-bearing capacity of the material in Haulani is comparable to the average floor material in Occator, ~13 GPa (Buczkowski et al. 2019 and references therein; Table 1). The grain size in almost all of Haulani is 93–135 μm, with the material in the southeastern wall having an anomalously small grain size of 28 μm (Tosi et al. 2019). The compactability of the majority of the Haulani material (grain size of 93–135 μm) is likely comparable to the average floor material in the Occator crater (grain size of 100–130 μm), both of which will be more compactable than the finer-grained material of Haulani’s southeastern wall, Occator’s faculae material, and Occator’s Homowo Regio material. Haulani’s floor is less fractured than Occator, which would contribute to less porosity than Occator’s average floor material (which has an estimated porosity of >20%; see previous section). We thus estimate that the porosity of the interior of Haulani is <20%. Haulani’s central ridge is likely to be more cohesive than the mass-wasting deposits and pitted terrain, both of which were emplaced via processes that involved the movement of loose

Figure 14. Slopes of ≤10° overlaid onto the Haulani crater. (a) Locations with slopes >10° are shaded in black, and locations with slopes ≤10° are not shaded. (b) Many of the areas where the intermixed materials intersect with the smooth materials (shaded in pale green) display slopes of ≤10°. This figure builds on data presented in Figure 13.

Figure 15. Areas of highest abundances of minerals of interest and slopes >10° in Haulani crater. (a) The highest abundances of sodium carbonate (shaded purple), magnesium phyllosilicate (shaded orange), and ammoniated phyllosilicate (shaded pink) in the Haulani crater are in, and adjacent to, the crater-wall region. (b) The areas with the highest abundances of the minerals of interest tend to occur within areas that have slopes of >10°.
material. Tosi et al. (2018) also use VIR data to infer that Haulani’s central ridge has a thermal inertia of 160 TIU, while the crater floor has a value of 80 TIU, which is closer to, but still higher than, Ceres’ average. The higher thermal inertia of the central ridge is postulated to be due to a coarser grain size and/or higher thermal conductivity of the impact-excavated material. Similar behavior has not been observed in other young Cerean craters (Tosi et al. 2018). Rognini et al. (2020) agree that the central ridge in Haulani displays a higher thermal inertia than Ceres’ average, likely due to the higher compactness of the central ridge material: 110–130 TIU for the central ridge versus 1–15 TIU (corresponding to dust/very fine-grained regolith) or ∼50–60 TIU (coarser-grained regolith) for average Ceres.

In summary, we find that there are areas on the floor of Haulani that would be safe for an in situ investigation (i.e., slopes ≤10° and a smooth surface with no hazards such as pitted terrain and fractures) and would be particularly scientifically compelling (i.e., the intermixed material). The design of an in situ mission would need to take into account material with an estimated load-bearing capacity of ∼13 GPa, estimated porosity of <20%, and higher compaction and cohesion than the Occator faculae material. The safe and particularly scientifically compelling areas occur in the middle of the crater floor to the north, northwest, southwest, and southeast of the central ridge (shaded in pale green in Figure 16(a)). The northwestern and southwestern areas are more promising because they contain higher abundances of one of the minerals of interest, sodium carbonate. Higher abundances of the minerals of interest would facilitate an in situ investigation more than lower abundances. The Tosi et al. (2019) data also indicate that lower abundances of ammoniated phyllosilicate and magnesium phyllosilicate would also be present for in situ analysis/sampling of the crater floor. Thus, we place the 10 example landing/sampling sites in these northwestern and southwestern areas, with an emphasis on where the intermixed material, smooth material, and high abundances of sodium carbonate intersect (Figures 16(b)–(e)). While these observations would need to be confirmed with images of a few decimeters per pixel to ∼1 m/pixel (based on the 5:1 rule of thumb (see Section 1.3) for resolving slopes and hazards on the scale of a ∼1–5 m lander), our Dawn data-based analysis indicates that safe and scientifically compelling landing/sampling sites are likely to exist in the Haulani crater.

3.3. Potential Landing/Sampling Sites at Ahuna Mons

The 4 km tall Ahuna Mons is one of the best candidate cryovolcanic features in the solar system. The prominent and isolated construct abruptly appears out of the otherwise unremarkable surrounding terrain. It is interpreted to be a geologically recent viscous cryovolcanic dome, similar to extrusive volcanic domes formed on Earth and the Moon (Ruesch et al. 2016). Gravity data point to its origin from a rising slurry of brine and solid particles deriving from the deep brine reservoir (Ruesch et al. 2019a; Figure 17(a)). Thus, Ahuna Mons is of interest as a potential landing/sampling region because of the hypothesized connection to the deep brine reservoir. Analysis of the materials on the Mons’ flanks could provide insights into the composition and evolution of the remnant ocean fluid found in the deep brine reservoir. There may also be older, viscously relaxed cryovolcanic structures elsewhere on Ceres, but their identification is not definitive (Sori et al. 2017), and their connection to the deep brine reservoir has not been established.

The base of Ahuna Mons is ∼20 km by ∼14 km, and the summit area is ∼10 km by ∼5 km. Analysis of the grayscale Framing Camera LAMO mosaic shows that the northern, western and eastern flanks of Ahuna Mons appear smooth at ∼35 m/pixel resolution. These flanks are covered by bright and dark streaks of talus emplaced via mass wasting, and
occasional boulders that are \( \sim 100 \) m across (Figures 17(a) and (b)). The surrounding terrain has a gently hummocky texture and is moderately cratered: nearby craters range in size from \( \sim 17 \) km (adjacent to Ahuna Mons to the northwest) to the limit of spatial resolution of the mosaic. The southern flank of the mons has a similar texture to the surrounding terrain. The summit of Ahuna Mons is also similar in morphology to the surrounding terrain: it has an uneven texture dominated by fractures and impact craters. The summit fractures form an irregular pattern and are a maximum of \( 1 \)–\( 2 \) km in length and a few hundreds of meters wide. Ruesch et al. (2016) interpret that the uneven, fractured summit material is a brittle dome carapace, formed when the outer layer of the ductile core cooled and underwent multiple phases of fracturing and/or small-scale extrusions during a multi-stage formation process. Ruesch et al. (2016) divided the Ahuna Mons area into four geologic units: the summit unit, the talus unit on the flanks and, surrounding the mons, the cratered and smooth units (Figure 17(c)). The cratered unit is to the south of the mons and the smooth unit is to the north, east and west. The talus deposits on the flanks of Ahuna Mons do not appear to have significantly mixed with one another or the surrounding material, and we thus interpret them to be freshly exposed in comparison to the other materials in the area. This is consistent with Ruesch et al. (2016), who hypothesize that the talus material is formed as the brittle dome carapace is fractured in multiple events, and over time cascades down the flanks via mass wasting. Thus, on account of their freshness, the talus deposits are particularly scientifically compelling. The summit area is less compelling because it does not contain freshly exposed materials. Moreover, the highly fractured surface would be challenging for the operation of an in situ spacecraft.

The pattern of slopes within the region are dominated by the flanks of the mons and the walls of nearby impact craters. The flanks generally display slopes of \( \sim 30^\circ - 40^\circ \), with small parts of the southern flanks displaying slightly gentler slopes of \( \sim 15^\circ - 20^\circ \) (Figure 18(a)). There are limited areas within the summit and the surrounding smooth/cratered units that have slopes of \( \leq 10^\circ \) (Figure 18(b)). However, these data are not necessarily representative of the slopes on the scale of a \( \sim 1\)–\( 5 \) m lander, because the horizontal resolution of the SPC shape model, from which these slopes are derived, is \( \sim 100 \) m/pixel, and there is an absolute radial error of \( \leq 20 \) m. When the slopes on the scale of a \( \sim 1\)–\( 5 \) m lander are considered, we expect that the pervasive fracturing in the summit area would rule out all or almost all of that area from being a potential landing/sampling site. More favorably, it is likely that some of the surrounding areas would have slopes of \( \leq 10^\circ \) on the scale.
of a ~1–5 m lander, particularly in the smooth unit to the north, east and west of the mons.

Zambon et al. (2017) find that the northern flank of Ahuna Mons is the most compositionally interesting: spectral unmixing indicates that it is richer in sodium carbonate, magnesium–calcium carbonate, and ammoniated species than the other flanks and the surrounding materials, which contain these carbonates/ammoniated species in lower abundances. Perhaps the higher abundances on the northern flanks are due to more recent mass wasting in this location. The approximate locations of the regions of interest used by Zambon et al. (2017) to define the northern flank are shown by the white circles in Figure 17(c). The flanks have a coarser grain size than the surrounding materials, which is interpreted to be due to the flank material being fresher than the surroundings (Zambon et al. 2017). By compositional analogy, we approximate that the load-bearing capacity of Ahuna Mons’ flank material is comparable to that of Occator’s faculae material, ~1–2 GPa, and that the load-bearing capacity of the material surrounding Ahuna Mons is closer to that of the average floor material in Occator, ~13 GPa (Buczkowski et al. 2019 and references therein; Table 1). The flanks have a grain size ranging from 72 to 122 μm, while the surrounding material is finer grained (57 μm; Zambon et al. 2017). Thus, the compactability of the flank material is likely greater than the surrounding material and broadly similar to that of Occator’s average floor material and to the majority of the Haulani material. Zambon et al. (2017) also find that the northern flank displays lower surface temperatures than the surroundings under the same illumination conditions, possibly due to variations in compaction. The VIR instrument could not directly measure thermal inertia, but when observed under the same illumination conditions, the surface temperature can yield similar insights as thermal inertia (Tosi et al. 2014). Because the flank material was emplaced via mass wasting, it is likely less cohesive and has a greater porosity than the surrounding material. The larger grain size of the flank material in comparison to the surrounding material also likely contributed to the greater porosity of the flank material. The Ahuna Mons flank material likely has cohesion comparable to Occator’s faculae material because they are diffuse deposits that were emplaced via processes that involved the movement of loose material.

In summary, the most scientifically compelling area of the Ahuna Mons region are the flanks because of their apparent freshness. The northern flank is the most compelling because it is the richest in the minerals of interest. The high slopes of the flanks (~30°–40°) mean that an in situ mission could not touch down on the flanks. The summit area is also too highly fractured to be a plausible landing/sampling site for an in situ mission. However, the northern flanks could be observed from adjacent areas of smooth material that have slopes of ≤10°. There are two such areas, which are ~4–5 km in size: one directly north of Ahuna Mons and the other to the northwest (Figure 19(a)). We identify 10 example potential landing/sampling sites in these two areas (Figures 19(b) and (c)). The centers of these areas are only ~3–4 km from the base of the mons and would therefore provide an excellent vantage point for in situ remote sensing of the northern flanks. Measurements taken from a distance of only ~3–4 km would be greatly superior to orbital measurements because it would be possible to identify minerals with much lower abundances and be possible to resolve minerals with much higher spatial resolution. The ability to collect imaging and infrared spectroscopy data at the centimeter/meter per pixel scale in multiple locations on and surrounding Ahuna Mons would enable an investigation of the number of emplacement events that formed Ahuna Mons. This would be done by observing the superposition relations of the minerals of interest, and would also provide greater insights into the composition of subsurface brines on Ceres, by examining in detail the residual surface deposits. An example of an in situ remote-sensing instrument under development is the Mineralogy Mapper (MINMAP; Blaney et al. 2014). The design of an in situ mission would need to take into account that the material surrounding Ahuna Mons has an estimated load-bearing capacity of ~13 GPa, a compactability and porosity lower than the Ahuna Mons flank material, and a greater cohesion than the Ahuna Mons flank material. The areas to the north and northwest of Ahuna Mons appear generally smooth in the Dawn data, and safe landing/sampling sites would likely still exist in these scientifically
compelling areas when slopes and hazards on the scale of a \(\sim 1\text{–}5\) m lander, which requires images of a few decimeters per pixel to \(\sim1\text{ m/pixel}\), based on the 5:1 rule of thumb; see Section 1.3) were considered.

4. Discussion and Conclusions

We show that scientifically compelling landing/sampling sites are present in the Occator crater, the Haulani crater, and in the vicinity of Ahuna Mons and that they could be plausibly reached safely by an in situ mission to Ceres. By analyzing the highest resolution data obtained by the Dawn mission (up to \(\sim 5 \text{ m/pixel} \) in Occator and up to \(\sim 35 \text{ m/pixel} \) elsewhere), we demonstrate the general process that a future mission to the dwarf planet would undertake to identify a landing/sampling site. While hazards are present (slopes \(> 10^6\), fractures, pitted terrain, and boulders), our analysis illustrates that safe sites likely exist in locations that are particularly scientifically compelling. However, the Dawn data do not allow for the identification of slopes and hazards on the scale of a \(\sim 1\text{–}5\) m lander, which would need to be considered to increase the probability of success of a future in situ mission. Identifying slopes and hazards on the scale of a \(\sim 1\text{–}5\) m lander would require data of a few decimeters per pixel to \(\sim1\text{ m/pixel}\), based on the 5:1 rule of thumb (see Section 1.3). Therefore, we recommend that an orbital reconnaissance phase capable of acquiring data of a few decimeters per pixel to \(\sim1\text{ m/pixel}\) be included in any future mission. An orbital reconnaissance phase would resolve potential hazards on a \(\sim 1\text{–}5\) m lander scale and thus significantly lessen the risk of touching down on the surface of Ceres. A reconnaissance phase would be preferable, and less risky, than proceeding straight to the surface using TRN (e.g., Johnson et al. 2007) and hazard avoidance, because TRN can only navigate a spacecraft to a safe landing/sampling site if one has already been identified to exist within the landing/sampling region. Without the reconnaissance phase, it could not be guaranteed that a safe site exists within a region, at least for a rigid-legged lander like the one presented in the Ceres mission-concept study (Castillo-Rogez et al. 2021). Resiliency against potential hazards may also be increased by alternative lander configurations—for example, an approach similar to that used by the Europa Lander mission concept (Hand et al. 2017). The combination of an orbital reconnaissance phase and TRN/hazard avoidance would be the most robust way to land on, and possibly also collect a sample from, a specific site, without the need for a mobile platform. The ability to land precisely (within a circle that is \(\leq 100 \text{ m in diameter} \)) on Ceres’ surface is an enabling factor for future in situ exploration because there are numerous \(100 \text{ m diameter potential landing/sampling sites present within each landing/sampling region} \). For example, there are over \(800,000 \) potential landing/sampling sites (circular areas with a diameter of \(100 \text{ m} \)) present within the Occator crater alone. Thus, it is highly probable that at least one would be a safe and scientifically compelling site in which to continue our exploration of this relict ocean world from its surface.

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Data Availability

The Dawn mission data upon which this study is based are all archived and available on the PDS Small Bodies Node site: https://pds-smallbodies.astro.umd.edu/data_sb/missions/dawn/index.shtml.

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References

Ammannito, E., Sanctis, M. C., Ciarniello, M., et al. 2016, Sci, 353, aaf4279
Barik, K., Canbolat, M. Y., Yanik, R., & Islam, K. R. 2011, The Journal of Animal & Plant Sciences, 21, 186
Burbine, T. H., & Greenwood, R. C. 2020, SSRv, 216, 59
Buczkowski, D. L., Scully, J. E. C., Quick, L., et al. 2019, Icar, 320, 49
De Sanctis, M. C., Ammannito, E., Raponi, A., et al. 2015, Natur, 528, 241
Denevi, B. W., Blewett, D. T., Buczkowski, D. L., et al. 2012, Sci, 338, 246
Park, R. S., Konopliv, A. S., Bills, B. G., et al. 2016, Natur, 537, 515
Prettyman, T. H., Feldman, W. C., & McSween, H. Y. 2011, SSRv, 163, 1820
McEwen, A., Eliason, E. M., Bergstrom, J. W., et al. 2007, JGRE, 112, E05S02
Rognini, E., Capria, M. T., Tosi, F., et al. 2020, JGRE, 125, e05733
Roatsch, Th., Kersten, E., Matz, K.-D., et al. 2018, M&PSS, 4, 741
Schofield, S. G., Burton, A. J., Turrini, M., et al. 2021, ExA, 22pp, 2021 June Scully et al.

House, C. H., Ehlmann, B. L., Getty, S., Mazarico, E., & Williams, R. M. E. 2019, AGUFM, 2019, P14A-08
Jaumann, R., Presuker, F., Krohn, K., et al. 2017, LPSC, 48, 1440
Johnson, A. J., Ansar, A., Matthies, L., et al. 2007, in AIAA Conf. and Exhibit, 2007-2854, A General Approach to Terrain Relative Navigation for Planetary Landing (Reston, VA: AIAA)
Kopp, M., O’Rourke, L., Bockele-Morvan, D., et al. 2014, Natur, 505, 525
Landis, M. E., Byrne, S., Schörghofer, N., et al. 2017, JGRE, 122, 1964
Malin, M. C., & Edgett, K. S. 2001, JGRE, 106, 23429
Marchi, S., Raponi, A., Prettyman, T. H., et al. 2019, NatAs, 3, 140
McEwen, A., ElIason, E. M., Bergstrom, J. W., et al. 2007, JGRE, 112, E05S02
Mest, S. C., Crown, D. A., Yingst, R. A., et al. 2018, LPSC, 49, 2730
Nathues, A., Hoffmann, M., Schaefer, M., et al. 2015, Natur, 528, 237
Nathues, A., Schmedemann, N., Thangjam, G., et al. 2020, NatAs, 4, 794
National Academies of Sciences, Engineering, and Medicine 2017, Report Series: Committee on Astrobiology and Planetary Science: Getting Ready for the Next Planetary Science Decadal Survey (Washington, DC: The National Academies Press)
Neesemann, A., van Gasselt, S., Schmedemann, N., et al. 2019, Icar, 320, 620
Obrzud, R. F., & Truty, A. 2018, The Hardening Soil Model—A Practical Guidebook. Z_Soil.PC 100701 report, revised 21.10.2018, http://www.zsoil.com/zsoil_manual_2018/Rep-HS-model.pdf
Park, R. S., Konopliv, A. S., Bills, B. G., et al. 2016, Natur, 537, 515
Pieters, C. M., Nathues, A., Thangjam, G., et al. 2018, M&PSS, 53, 1983
Prettyman, T. H., Feldman, W. C., & McSween, H. Y. 2011, SSRv, 163, 174
Prettyman, T. H., Yamashita, N., Toplis, M. J., et al. 2017, Sci, 355, 55
Preusker, F., Scholten, F., Matz, K.-D., et al. 2016, LPSC, 47, 1954
Quick, L. C., Buczkowski, D. L., Ruesch, O., et al. 2019, Icar, 320, 119
Quick, L. C., & Hedman, M. M. 2020, Icar, 343, 113667
Scully, J. E. C., Bowling, T., Bu, C., et al. 2019b, Icar, 320, 213
Scully, J. E. C., Schenk, P. M., Castillo-Rogez, J. C., et al. 2020, NatAs, 4, 741
Roatsch, Th., Kersten, E., Matz, K.-D., et al. 2017, P&SS, 140, 74
Roatsch, T., Kersten, E., Matz, K. D., Jaumann, R., & Raymond, C. A. 2018, AGUFM, P35D-3869
Rognini, E., Capria, M. T., Tosi, F., et al. 2020, JGRE, 125, e05713
RUESCH, O. 2014, Geosciences, 4, 741
RUESCH, O., Zuber, M. T., Smith, D. E., et al. 2014, Icar, 240, 146
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
SCHMEDEN, N., & Malin, M. C., & Edgett, K. S. 2001, JGRE, 106, 23429
Ruesch, O., Platz., T., Schenk., P., et al. 2016, Sci, 353, aaf4286
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org
Scribner, S. S., & Ferhan, M. C. 2017, Indian Journal of Engineering, 14, 227, http://www.discoveryjournals.org