A global catalogue of Ceres impact craters $\geq 1$ km and preliminary analysis

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**ABSTRACT**

The orbital data products of Ceres, including global LAMO image mosaic and global HAMO DTM with a resolution of 35 m/pixel and 135 m/pixel respectively, are utilized in this research to create a global catalogue of impact craters with diameter $\geq 1$ km, and their morphometric parameters are calculated. Statistics shows: (1) There are 29,219 craters in the catalogue, and the craters have a various morphologies, e.g., polygonal crater, floor fractured crater, complex crater with central peak, etc.; (2) The identifiable smallest crater size is extended to 1 km and the crater numbers have been updated when compared with the crater catalogue ($D \geq 20$ km) released by the Dawn Science Team; (3) The $d/D$ ratios for fresh simple craters, obviously degraded simple crater and polygonal simple crater are $0.11 \pm 0.04, 0.05 \pm 0.04$ and $0.14 \pm 0.02$ respectively. (4) The $d/D$ ratios for non-polygonal complex crater and polygonal complex crater are $0.08 \pm 0.04$ and $0.09 \pm 0.03$. The global crater catalogue created in this work can be further applied to many other scientific researches, such as comparing $d/D$ with other bodies, inferring subsurface properties, determining surface age, and estimating average erosion rate.

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1. Introduction

The geologically primitive dwarf planet Ceres, with approximately 940 km diameter and a mass of one third of the total mass of the asteroid belt, is an intact protoplanet since its formation, which is key to understand the origin and evolution of the solar system (Russell et al., 2004; Russell and Raymond, 2011). The Dawn spacecraft, chiefly equipped with Framing Camera (FC), Visible and infrared spectrometer (VIR) and Gamma Ray and Neutron Detector (GRaND), has mapped Ceres with Framing Camera at different orbital heights during the early approach phase, the Survey orbit, the High Altitude Mapping Orbit (HAMO) and the Low Altitude Mapping Orbit (LAMO) after orbit insertion on March 6, 2015 (Russell et al., 2016).

FC images reveal the surface of Ceres is heavily cratered with a large variety of crater morphologies, e.g., bowl shaped craters, polygonal craters, floor-fractured craters (Hiesinger et al., 2016). Cratering is one of the most important processes that greatly shaped the surface of Ceres, and the morphology and distribution of the craters can provide insights into geological settings, subsurface properties, and even the evolution history of Ceres. Therefore, crater catalogue with morphometric properties have significant scientific application potentials for the research of Ceres, which is impossible to accomplish before the Dawn mission. Though studies on craters at a global scale for Ceres have been done by the Dawn Science Team (Hiesinger et al., 2016; Marchi et al., 2016), the spatial resolution of the base map for constructing their crater catalogues is about 135 m/pixel (Roatsch et al., 2016b).

In this research, the recently released global LAMO image mosaic and global HAMO DTM derived from FC images with a resolution of about 35 m/pixel (Roatsch et al., 2017) and 135 m/pixel respectively are utilized comprehensively to construct a global crater catalogue with diameter $\geq 1$ km, and crater morphometric parameters are further measured and calculated. Preliminary analyses of their spatial distribution characteristics and morphometric parameters are also included in this research. We hope this global crater catalogue for Ceres can contribute to the community and be used broadly in the future.

2. Datasets and methodologies

2.1. Datasets

The datasets used in our research are global mosaic products from the Dawn mission, which is the first spacecraft to orbit separately two extraterrestrial bodies: Vesta and Ceres.
(Russell et al., 2016). After orbital insertion on March 6, 2015, the framing camera onboard Dawn had imaged Cerean surface through a clear filter and 7 narrow-band filters covering the wavelengths from the visible to the near-infrared, at different orbital heights under various viewing angles and illumination conditions (Sierks et al., 2011). Global image mosaics of different resolutions have been produced from these collected images, including global survey mosaic with a resolution of about 400 m/pixel (Roatsch et al., 2016a), global HAMO mosaic with a resolution of about 135 m/pixel (Roatsch et al., 2016b), global LAMO mosaic with a resolution of about 35 m/pixel (Roatsch et al., 2017). In addition, about 2350 clear filter images acquired from HAMO in six different cycles, each of which is optimized for stereo photogrammetry, are used to construct digital terrain models (DTMs). A global HAMO DTM, formatted as image where the DN values give the height in meters above a reference sphere of 470 km, is generated with a lateral spacing of about 135 m/pixel and a vertical accuracy of about 10 m. The DTM covers approximately 98% of Ceres surface, with only few permanently shadowed areas near the poles interpolated (Preusker et al., 2016). Hence, the global LAMO mosaic and global HAMO DTM, both of which provided in equidistant cylindrical projection, are the highest resolution cartographic products available at present, and are the two most important basemaps to map craters on Cerean surface and to calculate their morphometric parameters in this research. The inappropriate illumination geometry and the permanently shadowed areas of the mosaics (Schorghofer et al., 2016) have influence on crater identification on polar regions and will be discussed in Section 3.2.2.

2.2. Methodologies

2.2.1. Crater identification

The crater identification is the basis for further morphometric measurement and analysis. The crater identification procedure over the Cerean surface is performed manually with global LAMO mosaic as basemap in a geographic information system environment by using the CraterTools extension for ArcGIS, which helps to avoid errors of crater diameters and measurement area sizes related to map-projection induced distortions automatically (Kneissl et al., 2011). The craters are identified by their unique characteristics (e.g., presence of rim, circularity of the rim, etc.), and they are digitized by a three-point rim fitting method (Kneissl et al., 2011), so the resulted diameter is rim diameter in this research. The basemap for crater identification is shown in polar stereographic projection for single hemisphere areas poleward of 60° and the other areas is mapped in equidistant cylindrical projection.

2.2.2. Morphometric measurement

After the completion of crater extraction over Cerean surface, the morphometric parameters for each crater are measured based on the global HAMO DTM. Because of the limitation of the resolution (~135 m/pixel) of DTM, the smallest diameter of the crater that can be reliably resolved is ~1 km, or ~8 pixels across (Garvin and Frawley, 1998; Robbins and Hynek, 2012). Hence, the morphometric measurements are only applied onto those craters with diameter ≥ 1 km by following the algorithm shown in Fig. 1.

1. Crater selection The craters ≥ 1 km in diameter in previous identification are selected for morphometric measurements (Fig. 2a). Within this step, obvious secondary craters that align in chains or form clusters are excluded for further calculation to preclude possible contamination on crater morphometric analysis, especially those secondaries around Occator, Dantu and Yalode identified by Scully et al. (2016)_ENREF_43 and Schmedemann et al. (2017).

2. Profile creation Because there are many craters that cannot be perfectly fitted by a circle, so 8 profiles crossing the initial circle center of each crater are drawn starting from north with fixed interval angle 22.5° (Fig. 2b).

3. Profile update Taking into account the uncertainty of the initial diameter measurement in CraterTools, the local topographic inflection point (local maxima) along the profile is found within 10% diameter on both sides of the initial circle (Fig. 2c), and the profiles are updated by connecting the two local maxima points in each previous profile. During this process, if any of the local maxima is within other crater, the relief along this profile is affected and the profile is marked as invalid. And if none of the local maxima can be found along the profile, this profile is also marked as invalid.

4. Major axis localization Though the major axis within the updated 8 profiles can be determined, it may be not the real case, so it is named as ‘pseudo major axis’. The exact major axis crossing the crater center is searched and localized within the current ‘pseudo major maxis’ and its left and right neighbors by binary search method with the search threshold is set to 1°. The major axis localization procedure can make morphometric measurement more accurate and reliable, especially for fresh craters.

5. Morphometric measurement The diameter of the crater measured by CraterTools is adopted in this research, the depth of the crater is defined as the average elevation difference between the rim and the floor of each profile, and the depth-to-diameter ratio (abbreviated as d/D) is defined as the ratio of the average depth to the diameter. In the morphometric measurement procedure, in order to avoid any influence of map projection and terrain relief, the coordinates of each crater are converted to local coordinate system (the origin is the crater center, x direction is local east, y direction is local north, and z direction is perpendicular to the
2.2.3. Uncertainties

The accuracy of the crater diameter is related to the positioning accuracy of crater rim of ‘Circle by points’ approach in ArcGIS during crater identification. We estimate the maximum diameter error $\Delta D$ is 2 pixels (1 pixel error per rim) in the global LAMO image product, that’s $\Delta D_{\text{max}} = 70$ m. The accuracy of depth measurement is mainly derived from the elevation difference of each profile which depends on the vertical accuracy of global HAMO DTM, and its maximum value can be estimated as $\Delta d_{\text{max}} = 20$ m. The $d/D$ uncertainty is estimated as $\Delta d/D = d/D \times (\Delta d/d + \Delta D/D)$.

3. Results

3.1. Crater morphology

The surface of Ceres is peppered with craters of various morphologies, such as simple bowl-shaped crater (Fig. 3a), polygonal craters (Fig. 3b), complex crater with central peak (Fig. 3c), complex crater with terraces and central pit (Fig. 3d), complex crater with concentric terraces (Fig. 3e), degraded crater caused by viscous relaxation (Fig. 3f), craters with flow-like features (Fig. 3g), floor-fractured craters (Fig. 3h), and craters with bright spots on the floor or along the rim (Fig. 3i).

Craters on Cerean surface are not necessarily circular, and there are many irregular craters. Of interest among above craters of
various morphologies is the polygonal crater. Otto et al. (2016) discovered 258 polygonal craters with diameter greater than 5 km, which distributes widely across the surface of Ceres. The formation of polygonal craters are thought to be related with the preexisting subsurface fractures (Melosh, 1989), and their widespread distribution indicates the crust of Ceres is extensively fractured, which in turn suggests that the subsurface must be both brittle enough to fracture and mechanically strong enough to retain fractures for long time (Buczkowski et al., 2016; Russell et al., 2016).

3.2. Crater distribution

3.2.1. Global distribution and density

Fig. 4a shows the global distribution of all the identified craters with diameter $\geq$ 1 km in this research. There are 29,219 craters with diameter $\geq$ 1 km in the completed catalogue, regardless of deformation and degradation. These craters forms high crater density regions, e.g., areas around Tibong crater (Fig. 4b), showing the varying degree of cratering on Ceres. The regions with low crater density are also very obvious from Fig. 4b, for example,
Fig. 4. Crater distribution and spatial density on the surface of Ceres. All maps are shown in equidistant cylindrical projection.
areas around Occator, Abellio, Ikpati, Gaua and Danu crater in the northern hemisphere, and areas around Urvara, Sekhet, Yalode, Mondamin, Sintana and Kupalo crater in the southern hemisphere. Maps of spatial density of craters with diameter \( \geq 20 \text{ km} \) (Fig. 4c) or \( \geq 50 \text{ km} \) (Fig. 4d) show large craters are mainly distributed in the northern hemisphere, which is in good agreement with the work done by Hiesinger et al. (2016) and Marchi et al. (2016) derived from HAMO mosaic.

3.2.2. Longitudinal and latitudinal variations

The crater distribution by longitude (Fig. 5a) shows an overall 'W' trend, and the highest crater density is found at three intervals: 160–180°W, 0–30°W and 160–180°E, while the lowest is located within two intervals: 100–130°W and 110–140°E. These two low crater density intervals may be related with large craters, which can obliterate the existing craters, causing the crater density changed significantly. For example, Occator (19.86°N, 238.85°E, \( \sim 92 \text{ km} \)) on the Hanami Planum, Danu (24.21°N, 137.43°E, \( \sim 125 \text{ km} \)) on the Vendimia Planitia, and Urvara (45.66°S, 248.71°E, \( \sim 163 \text{ km} \)) and Yalode (42.23°S, 290.64°E, \( \sim 271 \text{ km} \)) in the southern hemisphere.

The crater distribution by latitude (Fig. 5b) shows an overall parabolic concave downward 'Y' trend. The crater numbers decreased drastically towards both polar regions, which may be caused by their smaller covering areas and illumination defects mainly due by grazing illumination and self-shadowing (Schorghofer et al., 2016).

The red squares in Fig. 5a and b show the possible crater distribution if all 29,219 craters are distributed evenly on the surface of Ceres, which can be used together with the actual crater distribution as an indication for the heterogeneous crater distribution across the surface. Figs. 4b and 5b jointly show that the equator and the north polar regions have about the same spatial density of craters when taking into account for the different surface area. They also show the spatial density of craters in the mid-latitude of southern hemisphere and that in the high-latitude of northern hemisphere is close to or above the average distribution, while that of the south polar regions and the mid-latitude of the northern hemisphere is significantly below. The low density of south polar regions is partially due to the bad illumination condition and self-shadowing that part of the south pole was in the dark when images collected at LAMO cycles that make the crater identification in this research difficult. The low spatial density of the mid-latitude of the northern hemisphere may be caused by large craters such as Occator and Danu (Fig. 4b) that erase or cover the previously existing craters.

3.3. Crater morphometry

3.3.1. Crater diameter

The number of craters decreases with the increasing of crater diameter, which is consistent with other planetary bodies, indicating small impacts are more prevalent. There are 14,014 and 15,108 craters with diameter \( \geq 1 \text{ km} \) on the northern and southern hemisphere, respectively (Table 1), indicating the cratering process happened on both hemispheres at almost the same frequency. Small sized craters with diameters of 1.0–3.0 km are dominant, accounting for 85.44\% of the total number of craters in the catalogue. Compared with the catalogue released by Hiesinger et al. (2016) (numbers in brackets in Table 1), the numbers of craters with diameter greater than 20 km and 100 km in this catalogue are 578 and 21 respectively, indicating the refinement of this work when using global LAMO mosaic with higher resolution. Fig. 6 shows craters (20 \( \leq \) D \( \leq \) 50 km) that are catalogued in this study but not catalogued by Hiesinger et al. (2016). Fig. 6e is an obvious degraded crater with diameter about 40 km, which cannot be easily identified from HAMO mosaic (135 m/pixel). And the rest are craters with diameters a bit greater than 20 km, which may be identified and catalogued as craters with diameters marginally below 20 km when using HAMO mosaic. It’s likely that those craters were not missed by Hiesinger et al. (2016), but simply they have a slightly lower diameter than that in this work.

<table>
<thead>
<tr>
<th>Diameter (km)</th>
<th>1.0–1.5</th>
<th>1.5–3.0</th>
<th>3.0–5.0</th>
<th>5–10</th>
<th>10–20</th>
<th>20–50</th>
<th>50–100</th>
<th>100–300</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern hemisphere</td>
<td>6468</td>
<td>5040</td>
<td>1226</td>
<td>653</td>
<td>334</td>
<td>310(278)</td>
<td>68(60)</td>
<td>7(7)</td>
<td>14,106</td>
</tr>
<tr>
<td>Southern hemisphere</td>
<td>8262</td>
<td>5193</td>
<td>873</td>
<td>380</td>
<td>212</td>
<td>142(137)</td>
<td>37(37)</td>
<td>14(12)</td>
<td>15,113</td>
</tr>
<tr>
<td>Total</td>
<td>14,730</td>
<td>10,233</td>
<td>2099</td>
<td>1033</td>
<td>546</td>
<td>452(415)</td>
<td>105(97)</td>
<td>21(19)</td>
<td>29,219</td>
</tr>
<tr>
<td>Percentage</td>
<td>50.41%</td>
<td>35.02%</td>
<td>7.18%</td>
<td>3.54%</td>
<td>1.87%</td>
<td>1.55%</td>
<td>0.36%</td>
<td>0.07%</td>
<td></td>
</tr>
</tbody>
</table>

* The number in the brackets are crater numbers catalogued by Hiesinger et al. (2016) with diameter \( \geq 20 \text{ km} \).
Fig. 6. Craters \((20 \leq D \leq 50 \text{ km})\) that are identified in this study but not catalogued by Hiesinger et al. (2016), shown in equidistant cylindrical projection. (a)-(c), and (g)-(i) are shown in polar stereographic projection, (d)-(f) are shown in equidistant cylindrical projection.
3.3.2. Crater depth
Because the estimated maximum uncertainty on calculated crater depth is 20 m, only the craters with depth greater than 20 m are included in this analysis. Statistics show among these 11,401 craters, 34.63% of the crater depth is shallower than 50 m, and there are only 13 craters deeper than 4 km.

3.3.3. Crater depth-to-diameter ratio
Statistics on depth-to-diameter ratio (abbreviated as d/D) are also computed only on these 11,401 craters deeper than 20 m. The d/D value of all the craters is in the range of 0.004–0.24, with mean d/D of 0.06 ± 0.04. 79.58% of the d/D are less than 0.10, and only 0.19% is larger than 0.2.

The simple-to-complex crater transition on Ceres occurs at diameters of about 7.5–12 km (Hiesinger et al., 2016), here we choose 10 km as intermediate delimiter to classify these 11,401 craters on Ceres and discuss their d/D separately. This division leads to 10,387 craters are classified as simple crater and the rest 1014 are complex craters.

The 10,387 simple craters include 1377 fresh simple craters, 8996 obviously degraded simple craters and 14 polygonal simple craters, the mean d/D for above different type simple craters are: 0.11 ± 0.04, 0.05 ± 0.04 and 0.14 ± 0.02 respectively.

The 1014 complex craters are composed of 766 non-polygonal complex craters and 248 polygonal complex craters, and the average d/D values for them are 0.08 ± 0.04 and 0.09 ± 0.03.

4. Discussions
4.1. Comparison of d/D with other bodies
The crater d/D is widely used to describe crater shape, and it has been measured on many other bodies (Table 3). For example, the ratio of fresh lunar craters less than 15 km is about 0.2 (Pike, 1974), which is also found on other terrestrial planets like Mars (Pike, 1980) and Mercury (Barnouin et al., 2012; Pike, 1988). Daubar et al. (2014) even further reported the average d/D of new meter- to decameter-scale Martian craters formed in the last ~20 years is 0.23. However, the d/D is ~0.11 for the fresh secondary craters on the Moon (Pike and Wilhelms, 1978) or ~0.08 on Mars (McEwen et al., 2005).

The general distribution of d/D of fresh simple craters on Ceres (0.11 ± 0.04) is slightly below that had been measured on many other rocky or icy bodies except the rocky Itokawa and Steins and icy Ariel (Table 3). The depth and diameter plot for fresh craters on Gaspra indicates the d/D is close to 0.125 (Carr et al., 1994). Sullivan et al. (1996) concluded the ratio for fresh craters on Ida is about 0.154 by photoclinometry method. Thomas et al. (1999) reported the ratio for intermediate sized craters on Mathilde (diameters about 1–5 km) ranges from 0.12 to 0.25 by shadow measurements. Robinson et al. (2002) found the ratio on Eros is about 0.13 ± 0.03, and the freshest craters approach lunar values of 0.2. Shingareva et al. (2008) derived d/D on Phobos to range from 0.15 to 0.24 by measuring 6 craters from 1.8 to 8.6 km in diameter. The average ratio for 38 identified craters on Itokawa is 0.08 ± 0.03 (Hirata et al., 2009). The typical d/D derived from shadows on Lutetia is 0.12 (Vincent et al., 2012). The derived d/D for craters from 0.15 to 2.1 km on Steins varies from 0.04 to 0.25, with the mean value of 0.10 (Besse et al., 2012). The d/D from the global statistics on Vesta is 0.168 ± 0.01 (Vincent et al., 2014). The simple to complex transition is similar on the three icy Galilean satellites (Europa, Ganymede, Callisto) and the d/D for the unmodified and unrelaxed fresh craters is on the order of ~0.2 (Schenk, 2002; Schenk et al., 2004). The d/D derived by photoclinometry method for the 4 icy satellites of Uranus and Saturn (Miranda, Dione, Ariel and Rhea) are 0.13 ± 0.01, 0.11 ± 0.02, 0.09 ± 0.02, 0.12 ± 0.02 respectively (Schenk, 1989).

It can be noticed that the d/D of the fresh simple craters (0.11 ± 0.04) on Ceres is somewhat similar to that of secondary craters on the Moon and Mars, and more akin to the icy bodies. As to the d/D of complex craters on Ceres, Hiesinger et al. (2016) found a best fit for the ratio is 0.13, but the ratio 0.08 ± 0.03 in this work also is more akin to that on icy bodies which decreases to slightly below 0.1 for complex craters (Schenk, 2002). The possible reasons for the slight difference of average d/D ratios between Ceres in this study and the other bodies can be classified into 4 categories: (1) The errors and uncertainties introduced by depth measuring methods used in previous studies. Shadow technique tends to overestimate the crater depth while photoclinometry underestimates the depth, especially for the smaller craters, and stereo-photogrammetry is the most accurate technique, but requires multi-imaging of the surface (Marchi et al., 2015). The elevation for measuring crater depth used in this study is based on stereo-photogrammetric processing (Preusker et al., 2016), while most of the others are not, so the ratios here should be more reliable. (2) The lack of enough crater samples for deriving average d/D accurately. For example, the d/D on Phobos and Lutetia is derived from 6 and 125 craters respectively (Shingareva et al., 2008; Vincent et al., 2012). If high resolution images that cover the entire surface of these bodies can be collected, more craters should be identified and measured for a better d/D evaluation, which may decrease the average ratio. (3) The correction of topographic effect in this research. Topographic effect is not considered and corrected when measuring crater depth in many previous studies, which can lower the d/D ratio greatly, especially for the craters on the irregular bodies. For example, the elongated asteroid Eros (Veverka et al., 1999). (4) The influence of subsurface ice on Ceres’ crater morphologies. Bland et al. (2016) concluded Ceres’ shallow subsurface is no more than 30–40% ice by volume, with a mixture of rock, salts and/or clathrates accounting for the other 60–70%. The slightly shallower d/D on Ceres than the other rocky bodies indicates the crust’s mechanical property that controls the final crater morphology is affected by the ice content.

4.2. Implications for subsurface
The transition diameter between simple and complex craters occurs is dependent on the gravity of the planetary body (Melosh, 1989). If the crust of Ceres is mainly made of rock, then the transition diameter could be ~50 km and if it’s an ice–rock mixed body, the transition should be ~10.3 km (Hiesinger et al., 2016). Fig. 7a shows the crater depth increases quasi-linearly with the diameter gradually, however, when the diameter reaches about 10 km, the depth does not increase as significant as before, which is inconsistent with a pure rocky outer shell. This phenomena, together with morphologies of crater with viscous relaxation (Fig. 3f) and crater with flow-like feature (Fig. 3g), suggests that the outer shell is mixed with materials that has a rheology weaker than that of pure rock. Both pre-Dawn mission (Küppers et al., 2014) and present orbital observations support the widespread of water ice on the subsurface of Ceres, especially the high latitude polar regions (Prytyma et al., 2017), so the outer shell is an ice–rock mixture that allows for limited viscous relaxation. This inference have been verified by the gravity field and shape model deduced from gravity and topography data acquired by the Dawn spacecraft (Park et al., 2016). The plot of d/D versus diameter scatter (Fig. 7b) demonstrates a tendency of increase first and then decrease, and the ratio value reaches maximum of 0.24 around 6 km in diameter, corresponding to 1.4 km in depth, which may be attributed to differences in regional terrain and subsurface properties, e.g., the variations of water ice and rock in Ceres’ outer layer.
Polygonal craters have been discovered on a variety of planetary bodies, for example, Mars (Ohman et al., 2006), Mercury (Weihs et al., 2015), Venus (Aittola et al., 2007), and Dione (Beddingfield et al., 2016). Among the 276 polygonal craters identified on Cerean surface in this research, 90% of them are greater than 10 km with depth greater than 20 m. The average d/D value for the polygonal craters is somewhat higher than their corresponding counterparts as shown in Table 2, for example, polygonal simple crater (0.14 ± 0.02) versus fresh simple crater (0.11 ± 0.04), polygonal complex crater (0.09 ± 0.03) versus non-polygonal complex crater (0.08 ± 0.04), indicating (hidden) fractures of subsurface or surface not only favor the formation of irregular polygonal craters, but also may alter the physical properties (such as the increase of porosity) of the target strata, resulting in excavating a bit deeper during the cratering process (Wünnemann et al., 2006).

![Diagram](image1.png)

**Fig. 7.** Craters (D ≥ 1 km and depth > 20 m) on the surface of Ceres, regardless of deformation and degradation: (a) depths versus diameters; (b) depth-to-diameter ratios versus diameters, which shows that simple craters (D ≤ 10 km) cover all the range of d/D.

<table>
<thead>
<tr>
<th>Crater type</th>
<th>Numbers in the catalogue</th>
<th>Average d/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>All craters</td>
<td>11,401</td>
<td>0.06 ± 0.04</td>
</tr>
<tr>
<td>All simple craters (D ≤ 10 km)</td>
<td>10,387</td>
<td>0.06 ± 0.04</td>
</tr>
<tr>
<td>All complex crater (D &gt; 10 km)</td>
<td>1014</td>
<td>0.08 ± 0.03</td>
</tr>
<tr>
<td>Fresh simple crater</td>
<td>1377</td>
<td>0.11 ± 0.04</td>
</tr>
<tr>
<td>Degraded simple crater</td>
<td>8996</td>
<td>0.05 ± 0.04</td>
</tr>
<tr>
<td>Polygonal simple crater</td>
<td>14</td>
<td>0.14 ± 0.02</td>
</tr>
<tr>
<td>Non-polygonal complex crater</td>
<td>766</td>
<td>0.08 ± 0.04</td>
</tr>
<tr>
<td>Polygonal complex crater</td>
<td>248</td>
<td>0.09 ± 0.03</td>
</tr>
</tbody>
</table>

Table 2: Statistics of d/D of different crater types (D ≥ 1 km and depth > 20 m).

4.3. Determining macroscopic surface age

According to the theories of crater size-frequency distribution (Neukum et al., 1975), the cratering processes on the surface of planetary body are randomly and the erosion rate of craters is much smaller than the forming rate before saturation reached. Therefore, the older the geological unit is, the denser the craters are. In principle, the ages of areas with higher crater density may be older, while the lower crater density regions are relatively younger.

The crater degrades gradually with time due to erosion, such as rim collapse, infill, seismic shaking, etc., resulting in shallower depth, which can be reflected by the decrease of d/D value. Though the d/D ratio is also influenced by other factors, e.g., impact happens on loose eject blanket around large crater always favor the formation of deep crater, the global distribution and variation of d/D can be used as a first order estimation of the geological age of Cerean surface. Both global crater density shown in Fig. 4b and global variations of d/D shown in Fig. 8 exhibit apparent dichotomy over the Cerean surface; however, there seems to be an anticorrelation between the two maps. The crater density is lower but the average d/D is higher in the northern hemisphere, and the crater density is higher while the d/D is relative lower in the southern hemisphere.

In addition, the cumulative distribution function (CDF) of d/D also illustrates that a slightly larger number of shallow craters remained in the southern than that in the northern hemisphere (Fig. 9). For example, 66.6% of the craters in the southern hemisphere have d/D value less than 0.06 (mean value for all the craters), while 57.3% of that in the northern hemisphere. Though we cannot completely exclude the influence of massive deposits of ejecta from forming deep new crater but shallowing or obliterating existing craters, especially those regions around Haulani, Dantu and Occator crater in the north, the general trend of both crater density and CDF of d/D support the macroscopic interpretation that geological age of the southern hemisphere may be older.

Though spatial density of craters larger than 20 km (Fig. 4c) demonstrates there are more large craters in the northern than the southern hemisphere, however, Marchi et al. (2016) inferred the northern hemisphere has reached a level of crater spatial density compatible with saturation in the range 20–70 km. The inference on macroscopic surface age comprehensively from both crater spatial density (D ≥ 1 km) and cumulative distribution function (CDF)
of \(d/D\) with the exclusion of possible contamination from secondary craters in this work is in good agreement with the latest geologic mapping work done by Williams et al. (2017), who found Kerwan, Urvara and Yalode impact basins on the southern hemisphere are the oldest terrains, which defines much of Cerean geological time scale, and the faculae-containing Occator crater and bright rayed craters such as Haulani on the northern hemisphere are the youngest.

4.4. Estimation of erosion rate around Kerwan

The variations of depth for craters of similar age and size still can bring some constraints on the erosion rate of the surface (Vincent et al., 2014). As the oldest and largest confirmed impact crater on Ceres, Kerwan crater and its surroundings is selected as the region of interest in this research for erosion rate estimation.

The revised absolute model age for the smooth region associated with Kerwan crater from lunar-derived model and asteroid-derived model is \(>1.3\) Ga and \(>280\) Ma respectively (Hiesinger et al., 2016; Williams et al., 2017). And a general depth difference between deep and eroded craters of similar size (e.g., \(\sim10\) km) is \(\sim500\) m which is found in the vertical dispersion shown in Fig. 10. Hence an estimation of average erosion rate of \(>0.38\) m/Ma or \(>1.8\) m/Ma for this region can be deduced, depending on which chronology model is applied. Though the average erosion rate on Ceres are much faster than that \((2 \times 10^{-4}\) m/Ma) on the Moon (Craddock and Howard, 2000), it’s still comparable to that found on other bodies from the main asteroid belt. For example, average erosion rate on Vesta is \(0.35\) m/Ma (Vincent et al., 2014), and on Gaspra is \(0.1–1.0\) m/Ma (Carr et al., 1994). And the slight discrepancy of aver-
age erosion rate between Ceres and other asteroids may be related with the viscous relaxation on Ceres (Bland et al., 2017).

5. Conclusions

A global crater catalogue with diameter \( \geq 1 \) km across the entire Ceres surface has been created in this work, which consists of 29,219 entries. The crater morphology and distribution are analyzed, and their morphometric parameters are calculated, which shows that: (1) Craters forms high crater density regions, such as areas around Tibong crater. The crater distribution by longitude and latitude shows an overall ‘W’ trend and parabolic concave downward ‘\( \Uparrow \)’ trend respectively. (2) The identifiable smallest crater size is extended to 1 km and the crater numbers have updated when compared with the crater catalogue \( (D \geq 20 \text{ km}) \) released by the Dawn Science Team. (3) The \( D/D \) ratios for fresh simple craters, obvious degraded simple crater and polygonal simple crater are \( 0.11 \pm 0.04 \), \( 0.05 \pm 0.04 \) and \( 0.14 \pm 0.02 \) respectively. (4) The \( D/D \) ratios for non-polygonal complex crater and polygonal complex crater are \( 0.08 \pm 0.04 \) and \( 0.09 \pm 0.03 \) respectively.

The created catalogue has a variety of potential scientific applications, for example, comparing \( D/D \) with other bodies, the implications for subsurface properties, determining macroscopic surface age, and estimation of average erosion rate are preliminarily discussed in this research. The general distribution of \( D/D \) of fresh simple craters on Ceres \( (0.11 \pm 0.04) \) is slightly below that had been measured on many other rocky or icy bodies except the rocky Itoika and Steins and icy Ariel. The crater depth increases obviously with the diameter until 10 km, consistent with the simple-to-complex transition diameter prediction if the outer shell is a mixture of rock and ice. The general distribution of both crater density and cumulative distribution function (CDF) of \( D/D \) support the interpretation that the macroscopic geological age of the southern hemisphere may be older. The average erosion rate of the smooth region around Kerwan crater is \( >0.38 \text{ m/Myr} \) or \( >1.8 \text{ m/Myr} \), depending on the chronology model used for geological age determination. We hope the created crater catalogue, which is available upon request, can contribute to the community and be used broadly in the future in different applications.

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