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A global inventory of central pit craters on the Moon: Distribution, morphology, and geometry

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ABSTRACT

The origin of central pit craters on the Moon has long been an enigma, and a primary reason is that their geographic distribution and morphometric characteristics were unknown. We investigated a global inventory of lunar central pit craters using high-resolution image and topography data obtained from the Lunar Reconnaissance Orbiter. 56 certain and 35 probable central pit craters are found on both the lunar maria and highlands. The certain pit craters are ~9–57 km in diameter. The average diameter ratio between the central pits and their parent craters is ~0.12 and the average depth/diameter ratio for the central pits is ~0.072. With irregular-shaped rims, the central pits have conical profiles and some have flat floors. The central pits occur on both crater floors and central peaks. The floor pits are generally larger, deeper, and with more irregular shape compared with summit pits. Both the summit and floor pit craters have formed in every lunar stratigraphic epoch from Nectarian to Copernican. Target properties of background terrains affect the morphology and size of central pits, but they do not determine whether or not a central pit forms during a cratering event. The lunar central pits may have formed by deformation of central peaks caused by some mechanical processes during or soon after the cratering process of their parent craters.

1. Introduction

Impact craters with central pits have been found on Mercury (Xiao and Komatsu, 2013), the Moon (Allen, 1975; Schultz, 1976a, 1976b, 1988), Earth (Milton et al., 1972; Croft, 1981), Mars (e.g., Smith, 1976; Wood et al., 1978), Ganymede and Callisto (e.g., Passey and Shoemaker, 1982; Croft, 1983; Schenk, 1993; Bray et al., 2012). Various formation models have been proposed for the central pits on Mars and icy satellites, such as impacts into layered targets (Greeley et al., 1982), collapse of central peaks in weak ice (Passey and Shoemaker, 1982), explosive release of volatiles (Carr et al., 1977; Wood et al., 1978), and drainage of impact melt or impact related debris to subsurface fractures (e.g., Croft, 1981; Senft and Stewart, 2011; Elder et al., 2012). Most of these hypotheses require water ice or other volatile species involving in the cratering process. Although central pits in impact craters that have different sizes and locations on a same planet or those on different planetary bodies may not have a unique formation mechanism (e.g., Bray et al., 2012), the pits form during or soon after the cratering process of their parent craters, possibly by some impact-related mechanical processes and/or gravity-driven modification processes.

Central pit craters were not expected to occur on the Moon or Mercury due to the relatively low content of crustal volatiles compared with Mars and icy satellites (e.g., Barlow and Bradley, 1990; Elder et al., 2012). Recently, Xiao and Komatsu (2013) discovered central pit craters on Mercury and suggested that target volatiles were not required in forming the pits. Lunar central pit craters are another end member likely supporting the argument that volatiles are not required in forming central pits (Xiao and Komatsu, 2013). However, few studies mentioned the existence of this crater population on the Moon. Allen (1975) studied central peaks in 580 impact craters on the lunar nearside using the Lunar Orbiter IV imagery. That study found 37 central pit craters that were ~8–100 km in diameter, and 35 of the central pits were located on summits of central peaks. Allen (1975) interpreted that the pits might be explosive volcanoes postdating their parent impact craters. Schultz (1976b) found that central pits occurred in numerous lunar impact craters that are as small as 18 km in diameter, and Schultz (1988) suggested that some of the central pits may represent natural voids surrounded by central peak clusters. The formation mechanism of lunar central pit craters remains an enigma to date. A primary reason is that previous studies did not systematically study the distributional, morphological, or geometrical characteristics of the central pits (e.g., Allen, 1975; Schultz, 1988).

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Here, we report a global inventory of central pit craters on the Moon collected from the use of high-resolution image and topography data. The distributional, morphological and geometrical properties of the central pits are compared with those on other planetary bodies to investigate their possible formation mechanisms.

2. Methodology and research material

We searched for central pits on the Moon that form together with their parent craters and that have a similar morphology with those on other planetary bodies. The "certain" central pits are different in many morphological aspects from similar-sized impact craters and endogenic pits on the Moon (e.g., volcanic pits) which postdate their parent craters. For example, the certain central pits mostly do not have circular rims but usually have conical shapes or flat floors, which are different from typical impact craters (e.g., Melosh, 1989). Volcanic edifices, such as diffuse pyroclastic deposits that are associated with many endogenic pits on the Moon (e.g., Gaddis et al., 2003), are not visible around the certain central pits. In addition, volcanic pits seldom occur on central peaks of lunar complex craters, but most of the certain central pits on the Moon are located on top of or in the place of central peaks. On the other hand, some depressions on crater floors and/or central peaks on the Moon could not be easily distinguished from degraded volcanic pits and/or impact craters that postdate their parent craters. Some other depressions that occur on summits of central peaks could simply be natural voids surrounded by clusters of central peaks (Schultz, 1988). These uncertain depressions are classified as probable central pits in our inventory, possibly having origins different from those of the certain central pits. In this study, we have included the "probable" central pit craters in the database (see the Appendix) but only the certain central pit craters are evaluated for their origins.

The central pits observed in lunar impact craters are classified as summit pits and floor pits based on whether the floors of the pits lie below (floor pit) or above (summit pit) the lowest elevations of the crater floors. We measure topographic profiles and depths for the central pits using a combination of gridded elevation data obtained from Lunar Orbiter Laser Altimeter (LOLA; Smith et al., 2010) and the Global Lunar DTM 100-m topographic data (GLD 100; Scholten et al., 2012). The gridded LOLA elevation data are produced from resampled and interpolated altimetry data that have a horizontal resolution of 1024 pix/degree (i.e., ~30 m/pixel) and a vertical resolution of ~±0.1 m (Smith et al., 2010). Due to the non-uniform coverage of LOLA footprints on the lunar surface, the actual horizontal resolution of the gridded LOLA data varies at different locations. Therefore, we refer to the GLD 100 data to verify the topographic measurements performed on LOLA data. The GLD 100 data are constructed from WAC stereo images and they cover ~98% of the lunar surface from ~79°S to 79°N latitudes. The resolution of GLD 100 is close to 300 m, and the accuracy of the elevations is about 10–20 m (Scholten et al., 2012). When the topography of a central pit is resolved in both the GLD 100 and LOLA gridded data, results derived from the two topographic dataset should be consistent with each other.

Most central pits in lunar craters have complex surrounding massifs. The depth of a central pit varies with measuring profiles that have different azimuths. Here we measure elevations along the rim of each pit, and the average value of the rim elevations is then compared with the lowest elevation in the pit floor to derive a depth value, together with the estimated maximum and minimum depth values. We do not attempt to estimate the volumes for the central pits in order to avoid large uncertainties caused by their irregular shapes. Errors in measuring the depths of the central pits can be ignored because the depth values are usually at least an order of magnitude larger that the vertical resolution of the topographic data used.

The locations, stratigraphic ages, and morphological classes of the central pit craters are collected. The stratigraphic ages are referred from the global database of lunar impact craters (Losiak et al., 2009). Based on the preservation states of crater structures (e.g., sharpness of crater rims, number of superposed craters, preservation states of secondary craters, etc.), Arthur et al. (1964) classified impact craters on the lunar nearside to morphological Class 1–6 populations: Class 1 craters are the freshest and Class 6 are the most degraded. We applied the same criteria to assign morphological classes for central pit craters on the lunar farside. Image data obtained from the Lunar Reconnaissance Orbiter Camera (LROC) are used to search for lunar central pits craters. LROC consists of a Wide Angle Camera (WAC) that provides global imaging at a resolution of 100 m/pixel and two Narrow Angle Cameras (NACs) that provide up to 0.5 m/pixel panchromatic images (Robinson et al., 2010).

Since most of the observed central pits in lunar craters have irregular-shaped rims, their dimensions cannot be accurately measured in diameters. Instead, we measure the areas (A_p) for the pits and the equivalent diameters (D_p) are calculated from A_p using the following equation:

$$D_p = 2(A_p/\pi)^{0.5} \quad (1)$$

The perimeters of the pits (P_p) are also measured to quantitatively show the morphologic circularity for the pits. We employ the degree of irregularity to represent the shape of the pits, which is manifested as Γ (Kargel, 1989; Barlow, 1994; Boyce et al., 2010). The definition of Γ is in Eq. (2). $\Gamma = 1$ means the pit is symmetrically circular in shape and larger Γ means the pit is more irregular in shape.

$$\Gamma = P_p/(4\pi A_p)^{0.5} \quad (2)$$

The systematic errors in the measurements of the areas and perimeters of the pits are inferred from adding/deducting one pixel dimension of the base images (100 m/pixel as the maximum) to the equivalent radius of the pits ($D_p/2$), which corresponds to a measurement error of A_p and P_p of less than 10% (see the Appendix). The error of Γ is transferred from that of A_p and P_p, which is usually less than 5%. The table in the Appendix lists all the information collected for both the certain and probable central pit craters on the Moon.

3. Results

3.1. Morphology of lunar central pit craters

On the Moon, central pits in impact craters occur on both summits of central peaks and crater floors (Fig. 1). Both summit pits and floor pits are also identified on Mars (Barlow, 2010) and Ganymede (Bray et al., 2012), but only floor pits have so far been identified on Callisto (Schenk, 1993). The summit pits on the Moon have a planar morphology similar to that of the peak pits on Mercury (Xiao and Komatsu, 2013), as they all have elliptical or irregular-shaped rims and some summit pits exhibit a cone-shaped morphology because their vertical profiles are in V-shape (e.g., Fig. 1A). However, the depths of the peak pits on Mercury are not well constrained (Xiao and Komatsu, 2013), thus whether or not the pits have extended to crater floors (i.e., qualified as summit pits) is unknown.

The observed floor pits on the Moon are located at centers of crater floors. Although some of the floor pits appear to occur on central peaks, their topographic profiles show that the pits have extended into crater floors (e.g., Fig. 1B). Surrounding uplifted mas-