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The quantitative relationship between small impact crater morphology and regolith depth

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ABSTRACT

Small impact craters (~10–300 m) that encounter a strength transition in the target (like a regolith over bedrock) have unique morphologies. Previous studies have used these morphologies as indicators of regolith depth. This paper reports on several new analyses that expand our understanding of the quantitative relationship between small crater morphology and target layering. I describe three practical situations where the application of the updated method is ambiguous because the specific relationship between the target layering and the crater morphology has never been analyzed. In order to resolve the ambiguity, I report on new analyses of computer models and lunar data that demonstrate how the dimensions of the crater shape relate to layer depth. I also analyze the boundary conditions under which the crater-layering relationship will enable determination of layering depth. Finally, in light of the greater understanding of the crater-layering relationship, I discuss the possible application of this method to Mars.

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1. Introduction

Planetary surfaces reveal the history of a body in terms of duration and strength of the active surface processes. For example, the surface of the Moon has been pummeled by impacts over eons. These impacts have broken up the surface into a weak layer called the regolith (Melosh, 2011, Ch. 7). The Moon's regolith layer can indicate the size, and to some extent the duration, of the impacts that have gardened the surface. Mars's surface is also altered by craters, but additional processes have played a large part in defining the surface; water, volcanism, and aeolian processes all show pronounced effects on the surface of Mars. Nevertheless, the surface of Mars also consists of a broken up, regolith-like layer, though on Mars it is not a purely impact-generated regolith as on the Moon. For example, a deeper "regolith" in one region of Mars might indicate an area that tends to collects blowing dust.

Researchers have developed several approaches to allow determination of the depth of a regolith layer from remote imagery. One approach is to examine small craters and determine whether boulders (former consolidated substrate) were ejected from the craters. The excavation depth of the crater then gives an upper limit for the regolith depth (Shoemaker and Morris, 1969; Wilcox et al., 2005). Another approach is to use Earth-based radar data and a quantitative radar scattering model to estimate nearside lunar regolith depth (Shkuratov and Bondarenko, 2001; Campbell and Campbell, 2006; Fa and Wieczorek, 2012). A third technique, the one examined in this paper, uses the unique morphology of small craters formed in a layered target to determine regolith depth (Oberbeck and Quaide, 1967; Quaide and Oberbeck, 1968; Bart et al., 2011).

This paper performs several new analyses that expand our understanding of the relationship between small crater morphology and target layering. Section 2 begins by describing the original experimental work that led to the ability to determine regolith depths from small crater morphologies (Quaide and Oberbeck, 1968). Also described are two different ways the small-crater-morphology-method has been implemented: the original studies by Quaide and Oberbeck (1968) vs. the recent studies by Bart et al. (2011). The more recent implementation raises new questions regarding the nature of the relationship between small crater morphology and regolith depth. This paper examines those questions and reports on analyses performed to further clarify this relationship.

Section 3 describes three practical situations where the application of the updated method is ambiguous because the specific relationship between the target layering and the crater morphology has never been analyzed. In order to resolve the ambiguity, Section 4 reports on a series of new analyses that demonstrate how the dimensions of the crater shape relate to layer depth. These analyses are then also applied to real lunar data in Section 5. This

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new understanding results in a more accurate assessment of planetary regolith depths.

Another aspect of the crater-layering relationship that has not been previously considered is the boundary conditions under which the relationship will enable determination of layering depth; Section 6 explores this issue. Finally, in light of the greater understanding of the crater-layering relationship, Section 7 discusses the possible application of this method to Mars.

2. Background

To develop their technique, Oberbeck and Quaide (1967) conducted a series of experimental impacts into targets of uniform composition as well as into layered targets having a weak surface layer (a "regolith") atop a cohesive substrate. Their experiments showed that although impacts that form in a coherent, uniform substrate produce round, bowl-shaped craters, impacts that form in a substrate covered with fragmental material produce different crater morphologies: the craters progress from bowl shape, to central mound, to flat floor, to concentric as regolith depth decreases with respect to the crater size. Table 1 describes this progression in terms of D_A/t, where D_A is crater diameter and t is regolith thickness. Typical values of D_A/t at which this morphology change occurs are given in Table 1. These transition values are approximate; the actual transition values can vary by $\pm\sim1$, depending on other cratering processes such as impact angle or target properties such as substrate strength (Quaide and Oberbeck, 1968).

From the experimental data they found the following relationship between D_F/D_A and D_A/t:

$$D_F/D_A = k - (D_A/t)^{-1} 2 \cot\alpha, \tag{1}$$

where D_F is the diameter of the inner mound, flat floor, or concentric feature, α is the angle of repose of the material, and k is a constant. They showed experimentally that the constant k depends weakly on material properties and that a value of $k = 0.86$ is the best match to the properties of the lunar surface. However, they did not use this equation to estimate actual regolith depths. Rather, they estimated regolith depth by observing a population of craters and noting the diameter at which the craters transitioned from one morphology to the next. Thus, D_F was never measured for planetary craters.

In contrast, Bart et al. (2011) realized that regolith thickness (t) on solid planetary bodies can be calculated from two observable measurements:

1. the apparent, rim-to-rim, final crater diameter, D_A,
2. the diameter of the "inner feature", D_F,

Table 1
Morphology progression with increasing D_A/t (crater diameter/layer thickness) for craters less than about 300 m diameter (data in this table are from Quaide and Oberbeck, 1968). The transition values have a precision of $\pm\sim1$.

D_A/t	Morphology	Physical description
<4	Bowl-shaped crater	Crater formed completely within the regolith
4–7.5	Bowl-shaped crater with a central mound	Crater still completely within the regolith; bottom of crater is close to the regolith/bedrock interface
7.5–10	Bowl-shaped crater with a flat floor	Crater still completely within the regolith; flat floor is at the regolith/bedrock interface
>10	Crater within a crater (concentric)	Upper part of crater is within the regolith; inner crater is formed in the bedrock

and Eq. (1), solved for t:

$$t = (k - D_F/D_A) D_A \tan(\alpha)/2. \tag{2}$$

Thus, to measure lunar regolith depth, Bart et al. (2011) made those two measurements on each crater and used Eq. (2) to directly calculate the regolith depth at that crater's specific location. Because Bart et al. (2011) was the first to implement the small-crater-morphology method in this way, new questions have arisen regarding the quantitative relationship between small crater morphology and regolith depth: how does the regolith depth relate to the specific morphology of the crater? And what are the conditions under which this crater-layering relationship holds? The rest of the paper examines those questions and reports on analyses performed to further clarify this relationship.

3. Inner feature measurement

Use of Eq. (2) is straightforward when the locations of D_F and D_A are apparent, as they frequently are in small craters and as they appear in poorly resolved images. However, modern instruments are returning images of lunar craters at extremely high resolution (as good as 0.5 m/pixel with Lunar Reconnaissance Orbiter (LRO) Lunar Reconnaissance Orbiter Camera (LROC)). Better-resolved craters reveal more details of the interior of the crater, making it more difficult to determine where to measure D_F.

Consider first the case of a central mound (Fig. 1, central mound). Having a central mound implies that there should be a slope change between the wall of the crater and the slope of the central mound. If there is a sharp change in slope between the two, the measurement would be made at that point. But many central mound craters have crater walls that smoothly transition into the mound, at times even leaving a somewhat flat floor in

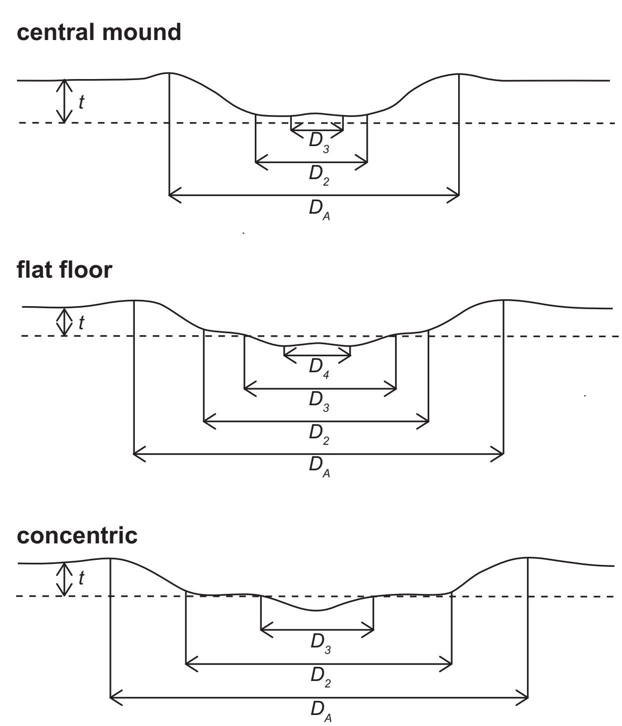

Fig. 1. Schematic diagram of numerically modeled profiles of craters formed in layered targets (profiles from Senft and Stewart (2007, Fig. 12b–d)). The solid curvy line is the crater's profile at the surface, the dashed line indicates the location of the regolith–bedrock interface prior to the impact, and t indicates the thickness of the regolith. Note that the central mound crater is fully formed within the regolith. This figure illustrates the various dimensions measured and recorded in Table 2.

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