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Crater depth-to-diameter distribution and surface properties of (4) vesta

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ABSTRACT

Orbiting asteroid (4) Vesta from July 2011 to August 2012, the Framing Camera on board the Dawn spacecraft has acquired several tens of thousand images of the asteroid surface, revealing a complex landscape. The topography is dominated by craters of all sizes and shapes, from fresh, simple, bowl-shaped craters to giant basins, as seen in the southern hemisphere. Craters of different ages or states of degradation can be seen all over the surface; some have very sharp rims and simple morphology, whereas others are highly eroded and have sometimes been filled by landslides and ejecta from nearby craters. The general depth/Diameter (d/D) distribution on Vesta is similar to what has been observed on other small rocky objects in the Solar System with a distribution peaking at 0.168 ± 0.01 in the range 0.05–0.35. However, the global map of d/D reveals important geographic variations across the surface, unlike any other asteroid. The northern most regions of Vesta show d/D values comparable to other asteroid surfaces, with a mean d/D of 0.15 ± 0.01, and a steep cumulative distribution. Craters in the regions affected by the giant southern impacts are deeper (mean $d/D = 0.19 \pm 0.01$) and show less erosion. It can be interpreted as the southern surface being younger than the rest of the asteroid, or made of a material which either allows the formation of deeper features or prevents their erosion. This picture is consistent with the idea of a southern Vestan hemisphere resurfaced relatively recently by the giant impact that created the Rheasilvia basin. The analysis of depth-to-Diameter variations over the whole surface also brings some insight into the transition regions between different cratering regimes: about 20 km for the strength-to-gravity dominated regime, and 38 km for the beginning of the simple-to-complex transition.

1. Introduction

(4) Vesta is the eleventh asteroid to have been visited by a spacecraft, and also the largest one. From July 2011 to August 2012, NASA's Dawn mission (Rayman et al., 2006) orbited the asteroid, and the Framing Camera (Sierks et al., 2011) on board has mapped the surface down to a resolution of 20–70 m per pixel. One of the most prominent morphological features is craters seen everywhere on the surface, ranging from small fresh impacts to the giant basins Rheasilvia and Veneneia close to the South pole. Craters provide very valuable information on the surface properties and evolution. Their statistical distribution is usually used as a tool to date the surface, derive its chronology, and constrain the dynamical evolution of the asteroid belt, and more generally that of the Solar System. For Vesta, such studies have been presented by Marchi et al. (2012b) and Schmedemann et al. (2012a,b). Leaving aside the age determination, the current paper focuses on the interpretation of morphological characteristics of the craters, more precisely the general distribution of depth-to-Diameter ratio of craters across the surface (abbreviated as d/D

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in the rest of the paper). A crater is formed when a projectile collides with the surface, and its physical characteristics are determined first by the impactor properties (size and velocity) and the local structure of the surface (material, strength, and porosity). Later on, the original morphology of the crater will be affected by aging processes. On airless bodies, sharp terrains become rounded and craters are eroded or totally erased by overlapping craters or deposits of ejecta from subsequent impacts. In the case of Vesta, the large southern impacts (Schenk et al., 2012) erased a quantity of pre-existing craters, and the region presents strong evidence for mass wasting events which also contributed to the resurfacing (Jaumann et al., 2012). It has been suggested for Eros (Richardson et al., 2005) and Itokawa (Hirata et al., 2009) that seismic shaking induced by other impacts can destabilise the rim of a given crater and trigger avalanches which fill in the crater bowl. On Vesta the vibrations created by the giant impacts probably contributed to the smoothing and erasing of small features far beyond the extent of the ejecta blanket of the basins.

Our purpose in this paper is to provide a review of the general d/D properties of craters across the surface, regardless of their ages, so that we can compare the results with the overall distribution across other Solar System bodies. We use crater morphology as a tool to investigate local physical properties of the surface; for instance, to see whether there is a correlation between the depth-to-diameter ratio (d/D) and geological units of the surface. For small craters in the strength regime, we expect the variation of depth with respect to diameter to follow a near-linear law (Grieve, 2007) with a constant slope for a given terrain. The ratio depends on properties of both impactor and local surface. However, following the cratering history of Vesta proposed by Marchi et al. (2012b), we find a density of craters compatible with isotropic bombardment and resurfacing caused by the giant impacts, and it is very unlikely that one region of Vesta encountered a significantly different group of impactors than the rest of the surface. Therefore, the variation of d/D for fresh craters reflects mainly the variation of surface properties, and can help us to better identify or constrain different geological units.

Similar studies have been carried out for asteroid (21) Lutetia (Vincent et al., 2012) and have found a very good correlation between regions of constant d/D and geological units. We expect this effect to be even more clearly visible on Vesta where part of the body might have experienced stronger resurfacing than other asteroids, due to the presence of the large south polar basins. However, other authors have investigated the d/D of small craters on Mercury and did not find any correlation between d/D and terrain (Andre and Watters, 2008).

2. Materials and methods

2.1. Crater selection

Vesta's surface is covered with craters of various sizes and shapes. A preliminary list of 1872 craters larger than 4 km has been catalogued in Marchi et al. (2012b), based on survey data, and shows a different distribution across the surface. The northern hemisphere is heavily cratered, with regions close to geometric saturation, whereas the southern hemisphere, especially within the Rheasilvia basin, shows comparatively few craters. The study of the collisional history of Vesta and the geomorphology of the southern hemisphere (Schenk et al., 2012) led to the idea that the body experienced two very large impacts. These impacts, which created Rheasilvia and Venneneia basins, erased many craters in the southern hemisphere, and covered part of the northern hemisphere with ejecta. This is clearly seen from the point of view of crater morphologies, where southern craters are fresh and well preserved, while the northern population is more mixed, with craters showing different levels of degradation: from fresh ones with sharp distinct features to degraded impact features partially destroyed or filled-in by subsequent impacts. However, craters must not be too degraded in order to be measurable, and this introduces a bias towards more sharply defined and recent craters that we will need to keep in mind when interpreting the results.

We used, in total, 1025 craters all across the surface, focusing on variations of d/D and morphology across regions. We took into account all craters for which we could reliably measure both depth and diameter. This excludes craters with a diameter smaller than 1.5 km, and most of the craters at high northern latitudes. We checked that the variation of crater density is compatible with other studies (Marchi et al., 2012b), so that we are not over- or under-sampling a region. We combined all the data in maps of d/D binned to equal areas equivalent to resolutions of 15×15 degree and 10×10 degree per grid cell at the equator. The highest resolution is defined by the absolute requirement to have at least one crater per cell. However, because it might not be statistically significant, we also produced a 15×15 degree map which has lower spatial resolution but better statistics (at least three craters per cell). We will see in Section 3.4 that the two maps are totally consistent. To remove the aliased noise inherently created by the binning process, the maps have been filtered with a two dimensional Gaussian.

2.2. Measurements

The Framing Camera has taken more than 31 000 images of Vesta, about 16 000 of which used a clear filter. This led to a map with a spatial resolution of 20 m/pixel at the South pole (latitudes below -60°) and about 70 m/pixel elsewhere. The images have been combined with a stereo-photoclinometry (SPC) software to reconstruct the topography for about 75% of Vesta's surface. The formal RMS vector position uncertainty is about 26 m but it is latitude-dependent. It varies from 20 m at the South pole to 65 m at the North pole (Gaskell, 2012).

In this study we use the latest model available, combining 17 409 images acquired between 17-July-2011 and 26-August-2012, and presented as a 1/64 degree gridded map with 70 m/px resolution. The map is divided into 30×30 degree maplets. We initially measured the crater diameters on a conformal map-projected images by fitting an ellipse to five points manually selected on the rim. The measurements take into account the latitude-dependent change in image scale induced by the projection. While very accurate, this technique is time-consuming when one has to measure more than a thousand craters. We found out that for most craters, there was no real benefit with respect to the simpler measure along a meridian and we used the direct measure for all craters apart from a few with distinct noncircular shape.

Once a crater is selected, and its diameter is known, we automatically extract and analyse the topographic profile from the full shape model. For each crater, our algorithm extracts four profiles (0° to 180°/45° to 225°/90° to 270°/135° to 315°) slightly larger than the measured diameter to take into account the error bar of the previous measure. Each profile is then automatically analysed to measure the depth. A profile normally goes from rim to rim but we check first for the presence of local maxima close to the edges. This gives us a way to measure again the diameter of the crater and compare with the value obtained from the map. The whole analysis is repeated manually in case of discrepancy. After extracting a topographic profile, we subtract the general slope of the terrain so that the two maxima are at the same height, and the depth is measured as the difference in altitude between the rim and the floor in the corrected profile. This adjustment is important