Earth and Planetary Science Letters 293 (2010) 388–395

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Confident thickness estimates for planetary surface deposits from concealed crater populations

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ARTICLE INFO

Article history:
Received 2 December 2009
Received in revised form 1 March 2010
Accepted 5 March 2010
Available online 1 April 2010

Editor: T. Spohn

Keywords:
crater size-frequency distribution
lava flow
volcanic
lunar
Moon
mare
terrestrial bodies

ABSTRACT

An improved technique is presented to determine more accurately deposit thicknesses of any surface units using crater size-frequency distributions (CSFDs). This new approach enables thickness estimates of deposits that completely cover their underlying unit, i.e., where no flooded craters are observed. Here, the crater populations of the unit of interest and its underlying unit (or a representative surface area) are measured and their cratering model ages determined. The CSFD of the younger unit is then treated as if it had the same age as the older unit and the expected cumulative numbers of craters for each bin size are calculated. The crater deficiency for each bin size is then determined by subtracting the expected cumulative crater number from the observed cumulative crater number per bin. The probability is calculated such that the crater deficiency corresponds to the age of the older, underlying unit. The crater bin size where we are 95% confident that these craters are there but just covered by the younger unit is chosen to derive the deposit thickness value using known crater diameter-rim height relationships. We demonstrate the use of the method at two sites of different scales and settings on Mars: Pickering crater and Lunae Planum, and compare our estimates with those obtained by other methods. For the Lunae Planum area a significantly higher minimum thickness of >840 m is predicted.

1. Introduction

Thickness determinations of geological/geomorphological units on planetary surfaces are essential for estimating volumes and rates of deposition. In the past, thickness measurements were mainly restricted to volcanic units since their emplacement occurred on short time-scales, often covering larger areas (e.g., Eggleton, 1963; Marshall, 1963; Baldwin, 1970; De Hon, 1974, 1975, 1979; Head and Wilson, 1992). Early thickness studies focussed on the basalt fills of Lunar Maria. The most commonly used method to determine minimum thicknesses utilises partially or nearly completely flooded craters (see references above). From known crater diameter-to-rim-height relations, unit thicknesses can be calculated. An advancement of this method is the exploitation of crater populations where the crater size-frequency distributions exhibit a characteristic deflection in slope which is used to find thickness values (Neukum and Horn, 1976; Hiesinger et al., 2002). However, both methods ultimately rely on the visible presence of flooded craters. Another way to determine deposit thicknesses is the penetration or excavation method where ejecta blankets and central peaks of craters are analysed spectrally to discover whether the impact penetrated the upper layer exposing material of the underlying unit (Budney and Lucey, 1998; Thomson et al., 2009). Although geophysical techniques, such as seismic, gravity or radar measurements, can also be applied, they are commonly restricted to global features or units due to resolution limitations (Phillips et al., 2001).

The new technique introduced in this paper to estimate deposit thicknesses uses characteristic features of crater size-frequency distributions and is applicable to any cratered surface unit regardless of the presence of visible flooded craters.

2. New approach

The new approach requires the crater size-frequency distributions (CSFD) of two surface units – the unit of interest and its underlying unit – from which the thickness is calculated. In comparison to the method described by Hiesinger et al. (2002), where CSFDs are also measured, our method has three further characteristics: firstly, a thickness estimate can be made in the absence of the characteristic deflection in the CSFD; secondly, a lower limit on the thickness of a surface unit can be reliably calculated; and thirdly, a confidence level (2σ) is provided to better constrain and validate the estimate.

The idea behind the method is based on the observation that younger planetary surface units can cover older units in such a way that even the early and very large impact craters (even $D>100$ km) are completely buried, regardless of their stage of degradation. Bearing that in mind, a solution was sought to interpret the CSFDs of the unit of interest together with that of its underlying unit or, if not

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doi:10.1016/j.epsl.2010.03.012

available, a reference location which is representative of the underlying topography.

The following scenario is chosen to demonstrate the new method. A planetary surface unit continuously records from its time of formation the impact history which is reflected in its CSFD. However, at a later time a resurfacing event, such as a lava flow, can bury low-relief parts of the unit (Fig. 1a) or cover it entirely (Fig. 1b). The new top surface (i.e. the surface of the lava flow) begins to accumulate new impact events, and hence, records a different crater population (Fig. 1). The difference is best shown when the CSFDs of both units are plotted: each CSFD follows a different isochron depending on the time of accumulation.

In order to estimate the thickness of the younger unit from CSFD data, the following steps are made:

– determine the cratering model age of the older, unmodified surface unit,
– calculate the expected number of craters for each cumulative size bin in the area of the younger unit as if it had the *same* age as the older portion, i.e. the expected crater population on the underlying surface,
– determine the crater deficiency in each cumulative bin – the shortfall in the observation compared to expectation – and calculate the probability that such a deficiency could nevertheless correspond to the age of the underlying surface,
– find the diameter bin where we may be 95% confident that craters have been obliterated by the resurfacing, and
– derive the flow thickness from the known rim-height of craters of this diameter.

The cratering model age of the older unit can be obtained by plotting the cumulative number of craters per unit area against the crater diameter, fitting the known production function of the planetary body (e.g., Neukum and Wise, 1976; Neukum, 1983; Neukum and Ivanov, 1994; Ivanov, 2001; Marchi et al., 2009; Schmedemann et al., 2009) obtaining the equivalent cumulative crater frequency at a standard diameter (1 km), and using this value to find the surface age from the chronology function (e.g., Hartmann and Neukum, 2001; Neukum et al., 2001a,b; Marchi et al., 2009). We have made use of the software tool Craterstats for this purpose (Michael and Neukum, in press).

We take the exposed older unit to be the model for the underlying surface of the younger unit. Having the age of the older unit, we can predict the expected crater population of the underlying surface of the younger unit according to its area and the known crater production function. First the cumulative crater frequency at the standard diameter of 1 km, $N(1)$, is found from the chronology function. The production function, when plotted to pass through this point, gives the expected cumulative crater frequencies for all other diameters, $N(D)$. We can thus construct a table of the expected and observed populations for each diameter bin. Using the probability mass function for a Poisson distribution,

$$p = \frac{\lambda^k e^{-\lambda}}{k!}$$

where k is the observed number of craters in each cumulative bin and λ is the expected number, we can obtain the likelihood that the deficiency in the observation is a statistical effect of the random cratering process. We take a confidence value of 95% (2σ) to be the indicator that the population has been diminished by resurfacing. As a rule of thumb, if we expect a bin to hold a cumulative number of three craters but we see none, then we can be 95% certain that this is not a statistical effect and that craters of this size are really covered.

Moving up the table towards lower bin diameters, we find the point where all further bin counts have a likelihood of less than 5%: this diameter corresponds to the largest craters which we know to be covered by the resurfacing process. The known relation between the Martian crater diameter (D) and rim height (h) above the surrounding terrain used in this study is (Garvin et al., 2002):

$$h = 0.07D^{0.52} (D < 7\text{km})$$

$$h = 0.05D^{0.60} (7\text{km} < D < 110\text{km})$$

allows us to derive a value for the thickness of the covering layer.

Surface units at two locations on Mars which differ in age, spatial extent, thickness, and deposition volume were studied to validate this approach: Pickering crater (southern Daedalia Planum) and Lunae Planum.

3. Method

Crater size-frequency distributions on units Ht1 and Ht2 within Pickering crater (Scott and Tanaka, 1986) were measured using a CTX mosaic (Malin et al., 2007, Table 1). All craters equal to or larger than 100 m in diameter were counted. For the Lunae Planum surface unit Hr and the reference site immediately to the east consisting of Noachian plains units (Scott and Tanaka, 1986), the global MOLA-DTM (Mars Orbiter Laser Altimeter-Digital Terrain Model) and the global Viking mosaic MDIM2.1 (Mars Digital Image Model) datasets constitute the basis for counts of craters with diameters $D \geq 10$ km

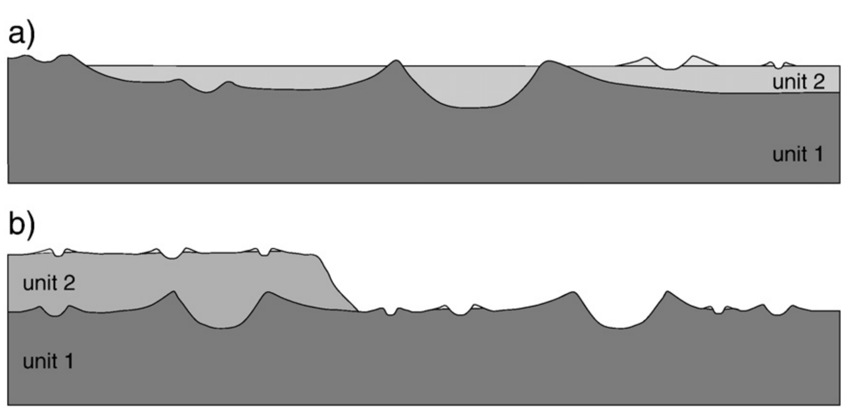

Fig. 1. Illustration of impact records on planetary surface units. a) Unit 1 is partly buried by the younger unit 2. Both surface units recorded different CSFD since their formations. Note that the large impact crater of unit 1 will be included in the CSFD of the area covered by unit 2 (redrawn from Hiesinger et al., 2002). b) A portion of unit 1 is fully buried by unit 2. As a result, the CSFD of unit 2 is also preserved in the unmodified part of unit 1.