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# The number of impact craters on Earth: Any room for further discoveries?

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ABSTRACT

Only 128 impact craters exposed at Earth's surface have been found so far, while new craters are discovered occasionally. Taking into account the permanent consumption of craters by erosion we present the first estimate on the number of impact craters that should be present at Earth's surface. Our study yields no evidence for any systematic incompleteness in the available inventory of the craters larger than about 6 km in diameter exposed at the surface. In contrast, more than 90 craters in the diameter range from 1 km to 6 km should still be waiting to be discovered, and even more than 250 between 0.25 km and 1 km diameter. The transition from a probably complete inventory above 6 km to a strongly incomplete record at smaller sizes may be related to the difference between simple and complex craters. Beyond these results on the terrestrial crater record, our findings tentatively suggest that erosion rates on the 10 to 100 million year scale may be closer to present-day erosion rates than previously assumed.


## 1. Introduction

More than 300,000 impact craters at least one kilometer wide have been found on Mars (Robbins and Hynek, 2012), while the surface of Moon's highlands is even saturated with craters. In contrast, only 188 impact craters have been confirmed on Earth so far. Only 128 of them are exposed at the surface, covering less than 0.1% of the land surface. The permanently changing face of our planet is the obvious reason for this sparse crater record. New craters are found occasionally, but there is little knowledge on the number of craters still waiting to be discovered.

In a recent paper (Johnson and Bowling, 2014), the distribution of the crustal ages was used to derive a theoretical number of impact craters larger than 85 km in diameter. It predicts a number of 8 craters with a (Poissonian) standard deviation of ±3. As 6–7 craters have already been detected in this size range, this result suggests that the vast majority of these large craters on Earth has already been discovered. According to previous studies (Grieve and Robertson, 1979), 85 km is a reasonable minimum diameter to assume the crater record not being strongly diminished by erosion. If, though, some of these big craters had been eroded or destroyed by other processes such as tectonic garbling (Grieve, 1991), this would even strengthen the argument that the majority of the existing large craters have already been discovered.

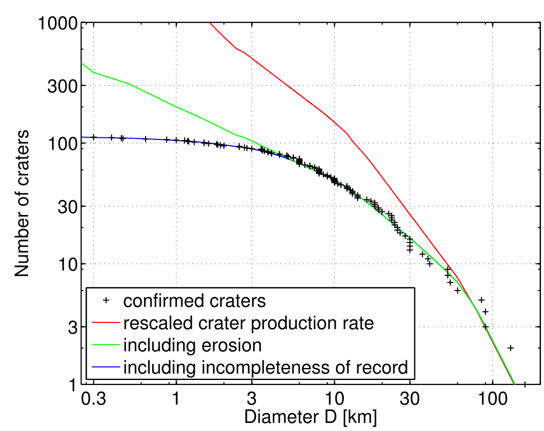


**Fig. 1.** Cumulative crater-size distributions. Black markers: confirmed craters exposed at the surface (http://www.passc.net/EarthImpactDatabase/); red line: predicted number of craters obtained by rescaling the crater production function; green line: predicted number taking into account crustal age and erosion; blue line: predicted number also taking into account the incompleteness of the record at diameters $D < 6$ km. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

This result can, however, not directly be transferred to smaller craters. The red line in Fig. 1 provides a conservative estimate of the expected number of craters exposed at the surface in absence of erosion based on the findings of Johnson and Bowling (2014) in combination with the presumably best estimate

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of the terrestrial crater production rate available (Bland, 2005; Bland and Artemieva, 2006). The latter constructs a complete size–frequency distribution of impactors for the Earth's surface by transforming the well-known lunar crater production rate (Neukum et al., 2001), correcting it for atmospheric disruption (Bland and Artemieva, 2003) and constraining it further, e.g., by fireball data (Nemtchinov et al., 1997), acoustic data (ReVelle, 1997), and telescopic observations of near-Earth objects. The rate defined as a number per surface area and time was converted to an absolute number assuming that the inventory of craters at least 85 km wide is indeed already complete. Only 5 out of the 7 craters considered by Johnson and Bowling (2014) are exposed at the surface, while the Chicxulub and Chesapeake Bay impact structures are buried by sediments. As the sixth largest crater is significantly smaller (60 km), we assumed a number of 5 craters larger than 72.5 km in diameter (the mean of the 5th and 6th largest craters' diameters) for a conservative estimate. The resulting expected crater population (red line in Fig. 1) would suggest a significant deficit in the real crater inventory at diameters below about 40 km. While 300 craters larger than 5 km in diameter should be detectable at the surface, only 78 have been found so far.

## 2. A model for the terrestrial crater inventory

Our approach to predict the consumption of craters by erosion was originally developed as part of an inverse approach to estimate erosion rates from the crater inventory (Hergarten et al., 2014). The basic idea is that the crater inventory in a given region reflects a dynamic statistical equilibrium between the production of new craters and their consumption by erosion. It is assumed that each crater remains detectable until the total erosion after the impact exceeds a characteristic depth $H(D)$ depending on its diameter $D$, so that the lifetime $\tau(D)$ of a crater at a given erosion rate $r$ is

$$\tau(D) = \frac{H(D)}{r}. \tag{1}$$

We assume a continuous, piecewise linear relationship

$$H(D) = \begin{cases} m_s\, D & \text{for } D \le D_{sc} \\ m_c\, D + D_{sc}\,(m_s - m_c) & \text{for } D > D_{sc} \end{cases} \tag{2}$$

between $H$ and $D$. The two regimes refer to the distinction between simple, bowl-shaped craters and complex craters with a rather shallow crater floor and an uplifted central region. For simplicity we assume a sharp transition from simple to complex craters at a diameter of $D_{sc} = 3$ km, while the diameter of transition varies between about 2 km and 4 km depending in the target rock in reality (Grieve, 1987). The first part of Eq. (2) originates from the almost linear relationship $d_t = 0.28D^{1.02}$ suggested by Grieve and Pilkington (1996) for the true crater depth $d_t$ of simple craters defined by the bottom of the allochthonous crater fill breccia. Borehole data from Meteor Crater (USA) (Shoemaker, 1960), Lonar (India) (Fredriksson et al., 1973), Brent (Canada) (Robertson and Grieve, 1977), and experimental results (Kenkmann et al., 2011) suggest that simple craters remain visible by means of shock effects in the rock down to a depth by about 7% larger than $d_t$. This finding leads us to the first part of Eq. (2) with $m_s = 0.3$. For complex crater structures we approximated $m_c = 0.07$ based on data of deeply eroded or drilled impact structures such as Upheaval Dome, Siljan, and Puchezh-Katunki. The estimated depths agree well to the structural uplift that was shown to provide a useful estimate of the depth of the geophysically constrained fracture zone (Pilkington and Grieve, 1992).

Combining Eqs. (1) and (2) yields the expected number of detectable craters per area, $N_d(D)$, with a diameter greater than or equal to $D$:

$$N_d(D) = \int_D^\infty -\dot{N}'(u)\,\tau(u)\,du \tag{3}$$

$$= \frac{1}{r}\int_D^\infty -\dot{N}'(u)\,H(u)\,du. \tag{4}$$

Here, $\dot{N}(D)$ denotes the crater production rate, i.e., the number of craters with a diameter greater than or equal to $D$ per unit area and time, and its negative derivative, $-\dot{N}'(D)$, is the corresponding frequency density.

The finite age of the crust or, more precisely, a limited thickness of material to be eroded can be taken into account by clipping the function $H(D)$ for the crater depth (Eq. (2)) to the maximum erosion depth $H_{\max}$, so that $H(D)$ has to be replaced by

$$H_{\text{eff}}(D) = \min\{H(D), H_{\max}\}. \tag{5}$$

After this modification, Eq. (4) can be written in the form

$$N_d(D) = \frac{1}{r}\int_D^\infty -\dot{N}'(u)\,H_{\text{eff}}(u)\,du \tag{6}$$

$$= \frac{1}{r}\int_D^{D_{ea}} -\dot{N}'(u)\,H(u)\,du + \frac{1}{r}\int_{D_{ea}}^\infty -\dot{N}'(u)\,H_{\max}\,du \tag{7}$$

$$= \frac{1}{r}\int_D^{D_{ea}} -\dot{N}'(u)\,H(u)\,du + \frac{H_{\max}}{r}\,\dot{N}(D_{ea}). \tag{8}$$

Here, $D_{ea}$ is the crater diameter where the depth according to Eq. (2) is the maximum erosion depth $H_{\max}$, i.e., $H(D_{ea}) = H_{\max}$. Equation (8) separates the predicted number of craters into two regimes. The first term describes the craters with diameters smaller than $D_{ea}$ where the number of craters is limited by erosion, while the second term refers to the larger craters whose number is limited by the age of the crust. The factor $\frac{H_{\max}}{r}$ corresponds to the age of the crust. The integral occurring in Eq. (8) can be evaluated semi-analytically by interpolating the tabulated crater production rate (Bland, 2005) by a piecewise power-law function.

Both the values of the erosion rate $r$ and the diameter $D_{ea}$ defining the transition from the erosion-dominated regime to the age-dominated regime are crucial parameters for the prediction, but cannot be constrained sufficiently by independent information. We therefore consider $r$ and $D_{ea}$ as adjustable parameters and determine their values by applying the maximum likelihood method directly to the sizes of the confirmed craters. This method was found to be superior to the widely used methods based on either binning or rank ordering (fitting to cumulative distributions) for simple power-law distributions (Clauset et al., 2009), and the arguments given there also hold for the distribution used here. The application of the method to the crater size distribution used here is described in Appendix A.

However, the range where Eq. (8) shall be applicable, i.e., where we assume the terrestrial crater record to be complete, must be defined a priori. Similarly to the alternative methods (binning and rank ordering), the direct application of the maximum likelihood method does not allow for the comparison of fits of different size ranges.

We therefore use a multi-step procedure for finding out down to which minimum diameter $D_c$ the terrestrial crater record is probably complete and for quantifying the incompleteness at smaller diameters. It starts from an initial guess that the inventory of the craters wider than $D_c = 10$ km in diameter is complete and test this hypothesis. In a second step we improve the estimate