THE TERRESTRIAL IMPACT CRATER INVENTORY AND ITS IMPACT BEYOND IMPACT RESEARCH. S. Hergarten[1] and T. Kenkmann[1], [1]Institut für Geo- und Umweltnaturwissenschaften, Albert-Ludwigs-Universität Freiburg i. Br., Germany

More than 300,000 impact craters at least one kilometer wide have been found on Mars [1], while only 188 impact craters have been confirmed on Earth so far with only 128 of them exposed at the surface. A recently published study [2] addresses the question whether the sparse crater record on Earth can indeed arise from the rapidly changing face of our planet, or whether the inventory must be highly incomplete.

The basic idea is that each crater remains detectable at the surface until the total erosion exceeds a given depth $H(D)$ depending on the diameter D. Taking into account the distinction between simple and complex craters, the approximation

$$H(D) = \begin{cases} m_s\, D & \text{for } D \leq D_{sc} \\ m_c\, D + D_{sc}\,(m_s - m_c) & \phantom{\text{for }} D > D_{sc} \end{cases} \qquad (1)$$

with a transition at a diameter $D_{sc} = 3$ km was used. While the parameter m_s referring to simple craters is well constrained to $m_s \approx 0.3$ by available data, the respective parameter m_c for complex craters is exposed to a higher uncertainty. As a first estimate, $m_c = 0.07$ was used and later confirmed by considering it as an adjustable parameter. The finite age of the crust or, more precisely, a limited thickness of material to be eroded was taken into account by clipping the function $H(D)$ to a maximum erosion depth $H_{\max}$, i.e, by using

$$H_{\text{eff}}(D) = \min\{H(D), H_{\max}\} \qquad (2)$$

instead of $H(D)$.

In combination with the presumably best estimate of the terrestrial crater production rate available [3], this approach allows for the prediction of a crater inventory as a function of the diameter for a given erosion rate. As shown in Fig. 1, this inventory deviates systematically from the crater production function itself due to the increase of crater lifetime with diameter. An almost perfect agreement with the real inventory of the confirmed craters exposed at the surface [4] above 6 km diameter was found for an erosion rate of $r = 59$ m/Ma and a transition to the probably age-limited regime at a diameter of 90 km ($H_{\max} = 7$ km).

After verifying this finding by different statistical tests (χ^2 and Kolmogorov-Smirnov tests), this led to the conclusion that there is no evidence for any systematic incompleteness in the inventory of the craters at least 6 km wide exposed at the surface. A significant incompleteness was, however, found for smaller caters. The relative completeness of the inventory at smaller diameters was found to be proportional to D^b with $b \approx 1.5$. This incompleteness max be related to the transition from simple to complex crater morphology, but a quantitative explanation has not been found so far.

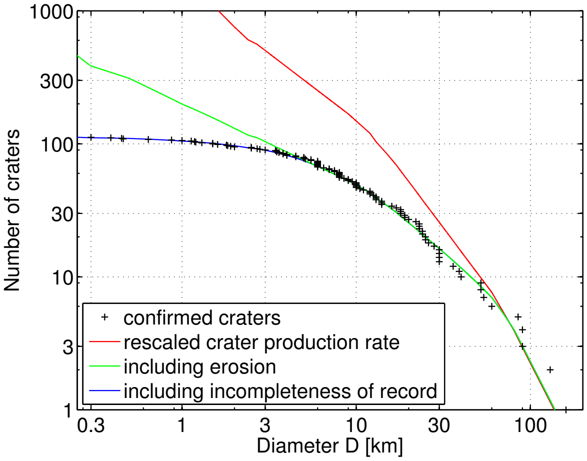

Figure 1: Cumulative crater-size distributions. Black markers: confirmed craters exposed at the surface [4]; red line: predicted number of craters obtained by rescaling the crater production function; green line: predicted number taking into account crustal age and erosion; blue line: predicted number also taking into account the incompleteness of the record at diameters $D < 6$ km.

The statistical completeness of the inventory at $D > 6$ km or the quantification of the incompleteness at smaller crater sizes makes the terrestrial impact crater inventory usable in a wider geological context, in particular with respect to long-term erosion rates where available information, e.g, from preserved sediments, is surprisingly uncertain. Our approach provides a simple relationship for estimating an erosion rate r in a given region of area A from the number of craters n found in this region,

$$r = \frac{AI}{n} \qquad (3)$$

with $I = 4.94 \times 10^{-5}\ \frac{\mathrm{m}}{\mathrm{Ma\,km^2}}$ if n refers to all craters with $D \geq 0.25$ km.

Due to the limited number of craters on Earth, estimates with a reasonable error range can only be obtained either for large regions or for regions with low erosion rates. For the Baltic Shield, e.g., the 14 confirmed craters yield a very low estimate of $r = 4.1$ m/Ma with a 95 % confidence interval from 2.5 m/Ma to 7.6 m/Ma. As the other extreme, all orogens together (19 craters) according to the classification of the main geological provinces [5] yield $r = 100$ m/Ma with a 95 % confidence interval from 64 m/Ma to 166 m/Ma. Since the method refers to the lifetime of the craters depending on the erosion rate, the respective time scale also depends on the erosion rate and ranges from some tens of million years to more than 100 million years.

However, all estimates of this type suffer from two major limitations beyond the statistical errors due to the limited number of craters. First, impact craters are not only consumed by erosion, but may also be buried by sediments, and the estimated rate is rather a total rate of crater consumption than a real erosion rate. As local sediment accumulation rates in a crater may be much higher than regional erosion rates, the total rate of crater consumption r may be significantly larger than the mere erosion rate. This effect is clearly visible when the rates estimated from Eq. 3 for the six basic types of continental crust [5] are plotted against their mean relief. While the predominantly erosive crustal types shield, orogen, and igneous province show a strikingly linear relationship between the rate of crater consumption r and the mean relief, the three other types are characterized by much higher rates in relation to their relief, suggesting that deposition of sediments significantly contributes to the consumption of craters here.

Beyond this limitation to predominantly erosive regions, the approach in principle refers to the lifetimes of craters depending on the erosion rate. Thus, applying Eq. 3 to a region with a non-uniform rate of crater consumption yields the harmonic mean rate being always lower than the arithmetic mean, so that any spatial variation in erosion due to relief or climate within the considered region results in a systematic underestimation of the mean erosion rate.

The most interesting applications, however, consist in a worldwide mean erosion rate and in the relationship between climate and erosion rates. Although a wealth of data on local to regional scales is available, large-scale or even worldwide estimates are quite uncertain. This concerns both the present-day rates, mostly estimated from sediment fluxes to the oceans [6], as well as long-term rates estimated from preserved sediments [7]. When deriving a worldwide mean erosion rate from our approach, the variation in both relief and climate must be taken into account. Using the primary classes of the Köppen-Geiger classification of the recent climate [8], our results suggest that the erosion rates in the temperate zone and in the tropical are quite similar in the mean, and that these are about three times higher than in the coldest regions. The worldwide mean erosion rate itself on the 100 Ma scale seems to be significantly higher than previously estimated from preserved sediments [7] and much closer to present-day rates than assumed before.

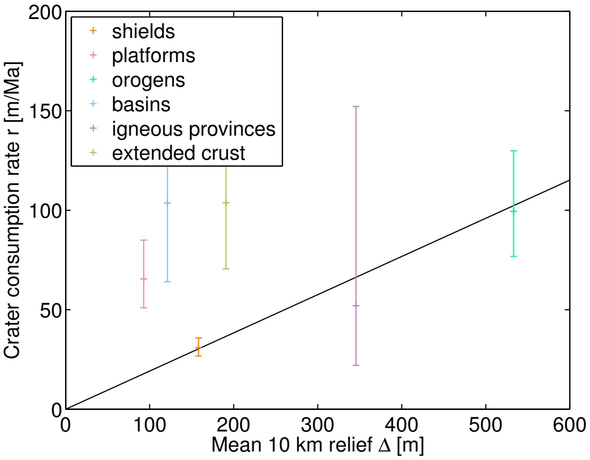

Figure 2: Crater consumption rates. Rates of crater consumption derived from Eq. 3 vs. mean relief for the basic types of continental crust [5]. The error bars represent 70 % confidence intervals corresponding to the standard deviation for a Gaussian distribution.

References: [1] Robbins, S. J. and Hynek, B. M. (2012) *J. Geophys. Res.: Planets*, *117*(E5). [2] Hergarten, S. and Kenkmann, T. (2015) *Earth. Planet. Sci. Lett.*, *425*, 187–192. [3] Bland, P. A. and Artemieva, N. A. (2006) *Meteorit. Planet. Sci.*, *41*, 607–631. [4] http://www.passc.net/earthimpactdatabase. [5] http://earthquake.usgs.gov/data/crust/type.html. [6] Willenbring, J. K., Codilean, A. T. et al. (2013) *Geology*, *41*, 343–346. [7] Wilkinson, B. H. and McElroy, B. J. (2007) *Geol. Soc. Am. Bull.*, *119*, 140–156. [8] Peel, M. C., Finlayson, B. L. et al. (2007) *Hydrol. Earth Syst. Sci.*, *11*, 1633–1644.