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Has erosion globally increased? Long-term erosion rates as a function of climate derived from the impact crater inventory

Stefan Hergarten[1] and Thomas Kenkmann[1]

[1]Institut für Geo- und Umweltnaturwissenschaften, Albert-Ludwigs-Universität Freiburg, Freiburg i. Br., Germany

Correspondence: S. Hergarten
(stefan.hergarten@geologie.uni-freiburg.de)

Abstract. Worldwide erosion rates seem to have increased strongly since the beginning of the Quaternary, but there is still discussion about the role of glaciation as a potential driver and even whether the increase is real at all or an artefact due to losses in the long-term sedimentary record. In this study we derive estimates of average erosion rates on the time scale of some tens of million years from the terrestrial impact crater inventory. This approach is completely independent from all other methods to infer erosion rates such as river loads, preserved sediments, cosmogenic nuclides and thermochronometry. Our approach yields average erosion rates as a function of present-day topography and climate. The results confirm that topography accounts for the main part of the huge variation of erosion on Earth, but also identifies a significant systematic dependence on climate in contrast to several previous studies. We found a fivefold increase in erosional efficacy from the cold regimes to the tropical zone and that temperate and arid climates are very similar in this context. Combining our results to a worldwide mean erosion rate we found that erosion rates on the time scale of some tens of million years are at least as high as present-day rates and suggest that glaciation has a rather regional effect with a limited impact at the continental scale.

1 Introduction

The origin of the apparently huge increase of worldwide erosion in the late Cenozoic era is one of the major puzzles in the younger geologic history of our planet (Molnar and England, 1990; Zhang et al., 2001; Molnar, 2004; Willenbring and von Blanckenburg, 2010; Herman et al., 2013; Wang et al., 2014; Marshall et al., 2015; Willenbring and Jerolmack, 2015). As high temperatures facilitate weathering of rocks, the cooling climate during the Cenozoic era should rather result in decreasing erosion rates, bringing Pleistocene glaciation as a major driver of erosion into discussion (Brocklehurst, 2013; Egholm, 2013; Herman and Champagnac, 2016; Pedersen and Egholm, 2013; Yanites and Ehlers, 2012; Koppes et al., 2015).

However, most of the knowledge about the apparent worldwide increase relies on estimates of long-term erosion rates from preserved sediments in the oceans (e.g., Wilkinson and McElroy, 2007). Based on Sadler's theory (Sadler, 1981) addressing the scale dependence of sedimentary records, the existence of a worldwide increase has already been questioned by Willenbring and von Blanckenburg (2010). In their study the theoretical arguments were supported by Beryllium isotope ratios revealing no systematic variation in the overall sediment delivery rates the last 12 Ma. On the other hand, a recent study on thermochronometric data not depending on the long-term sedimentary record has revealed a strong increase at least in some mountainous regions with high erosion rates during the last 10 Ma (Herman et al., 2013). However, potential systematic errors in thermochronometry have been discussed in the previous years (Valla et al., 2010; Willenbring and Jerolmack, 2015), and the a worldwide increase found by Herman et al. (2013) has recently been questioned by Schildgen et al. (2018).

Worldwide present-day erosion rates have also been addressed in several studies. However, all approaches suffer from the need to upscale point data, leading to a large variation in the estimates of the worldwide mean rate (see, e.g., the compilation by Willenbring et al., 2013). As an additional source of uncertainty, an increasing portion of the eroded sediments is trapped in artificial reservoirs today (Syvitski et al., 2005).

As topography, climate, and lithology are the main controls on erosion, there have been several approaches to quantify the contribution of these components. Concerning the variation over Earth's surface, topography has the strongest influence. The seminal study of Ahnert (1970) suggested a linear dependency of the erosion rate on mean relief (difference between maximum and minimum elevation) even without any correlation to precipitation. Later studies used either relief, slope or modal elevation and also obtained a linear or almost linear increase of the erosion rate with the respective geomorphic property (for a comparison see Summerfield and Hulton, 1994).

The relationship to climate was found to be less systematic. In a study on organic carbon fluxes, Ludwig and Probst (1996) also estimated sediment fluxes into the oceans and found a strong correlation with climate. According to their results, the wet tropic climate zone contributes about 44 % to the worldwide sediment supply, while the tundra and taiga zone contributes only 5 %, although both cover the same area on Earth in total. In contrast, the presumably most comprehensive compilation of millennial-scale erosion rates (Portenga and Bierman, 2011) involving cosmogenic nuclide data from almost 1600 drainage basins and outcrops yielded an unsystematic dependence on climate in contradiction to the widely accepted increase of erosion with temperature and precipitation.

2 Deriving erosion rates from the impact crater inventory

In planetary geology, the inventory of impact craters provides the most valuable data for unraveling the geological history (e.g., Neukum et al., 2001; Stöffler and Ryder, 2001) The terrestrial inventory, however, has not been exploited systematically beyond the research on impact processes themselves, probably due to its small extent compared to other planets and to its uncertain completeness. Taking into account the age distribution of the Earth's crust, it was recently found that the inventory of the craters at least 85 km wide may already be complete (Johnson and Bowling, 2014). A subsequent study (Hergarten and Kenkmann, 2015) also considering the consumption of craters by erosion even revealed no evidence for any incompleteness in the crater record above 6 km diameter exposed at the ice-free part of Earth's land surface and also quantified the incompleteness in the diameter range from 0.25 km to 6 km.

Using the presumably best estimate of the terrestrial crater production rate available (Bland and Artemieva, 2006) it was found that the expected number n of craters with a diameter of at least 0.25 km (taking into account the incompleteness) in a given region of area A at an erosion rate r is

$$n = \frac{AI}{r} \tag{1}$$

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with a constant $I = 4.94 \times 10^{-5}\ \frac{\mathrm{m}}{\mathrm{Ma\,km^2}}$. Equation 1 can be used to estimate the long-term mean erosion rate from the number of impact craters. As this method directly yields some spatially averaged erosion rate, it avoids any sampling bias occurring in other methods based on point-like measurements. In turn, an inevitable statistical uncertainty arises from the low number of impact craters exposed at Earth's surface. At the time of the original study, the Earth Impact Database (http://www.passc.net/EarthImpactDatabase/) comprised 188 terrestrial craters in total with only 112 of them exposed at the surface and wider than 0.25 km. While two more craters have been added to the database until now, the number of relevant craters is still 112, so that the value of I given above is still valid. Due to this low total number, the approach is most suitable for large regions. Application to the entire ice-free surface of Earth yields a worldwide mean erosion rate of $r = 59$ m/Ma (Hergarten and Kenkmann, 2015).

Although this method is not susceptible to sampling errors, spatial heterogeneity introduces a bias since the approach is based on lifetimes of craters instead of erosion rates, reflected in the occurrence of r in the denominator of Eq. 1. In other words, it is measured how long it takes to erode a given amount of material and not how much material is eroded in a given time span. As a consequence, applying Eq. 1 to a region with a non-uniform erosion rate yields the harmonic mean rate being always lower than the arithmetic mean, resulting in an underestimation of the mean rate. In turn, craters are not only consumed by erosion, but may also be buried by sediments. As local sediment accumulation rates in a crater may be much higher than regional erosion rates, the total rate of crater consumption may be significantly larger than the mere erosion rate. Thus, sediment deposition in parts of the considered domain leads to an overestimation of the erosion rate. So the estimate $r = 59$ m/Ma contains two sources of systematic errors in opposite directions.

3 The influence of topography on erosion

Topography contributes the largest part to the spatial variation in erosion. Ahnert (1970) suggested a linear dependency of the erosion rate on the mean relief. In contrast to the local slope often used in the context of erosion at small scales (Summerfield and Hulton, 1994; Montgomery and Brandon, 2002; Whipple et al., 2013; Willenbring et al., 2013), the relief is more robust against the resolution of the considered digital elevation model (DEM). In this study we measure relief over squares of 10 km edge length using the worldwide ETOPO1 DEM with a mesh width of one arc minute and also verified that our results basically persist for squares of 5 km and 20 km edge length as originally used by Ahnert (1970). In contrast to the widely used definition of relief based on circles, the relief taken over squares can be computed efficiently for all points of a large domain.

In order to verify the relationship between relief and erosion rate on large scales, we first subdivide the ice-free land surface into the six basic types of continental crust (shield, platform, orogen, basin, igneous province, extended crust) defined in the world map of the main geological provinces provided by the USGS (http://earthquake.usgs.gov/data/crust/type.html). Figure 1 relates the mean apparent erosion rates (rates of crater consumption) estimated from Eq. 1 for each of the types of crust to their average 10 km relief. The three crustal types shield, orogen, and igneous province expected to be predominantly erosive regimes differ strongly in their mean relief, but show a strikingly linear relationship between the rate of crater consumption r

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and the mean relief Δ,

$$r = s\Delta. \tag{2}$$

The three other types, platform, basin, and extended crust, are characterized by much higher rates in relation to their mean relief, suggesting that deposition of sediments significantly contributes to the consumption of craters here. We therefore consider only the three predominantly erosive crustal types in our analysis and assume a linear relationship between relief and long-term erosion rate.

4 The influence of climate on erosion

Beside topography climate is the second major influence on erosion. In the following we consider the primary classes tropical (A), arid (B), temperate (C), cold (D), and polar tundra (ET) of the Köppen-Geiger classification of the recent climate (Peel et al., 2007) shown in Fig. 2. The class polar frost (EF) was omitted as it primarily consists of ice-covered areas. Each of these classes is then subdivided into the six main types of crust where only the three predominantly erosive types are used for estimating erosion rates. This yields a subdivision of the predominantly erosive provinces into 89 subdomains (13–22 per climate zone) with sizes from about $1600\,\mathrm{km}^2$ to about 11 million km^2 (for details see supplementary material).

As shown in A, the erosion rates per mean relief s can be estimated for each of the climatic classes using a maximum-likelihood approach according to

$$s = \frac{I}{n}\sum_{i=1}^{k}\frac{A_i}{\Delta_i}. \tag{3}$$

Here, k is the number of subdomains within each climate zone, A_i and Δ_i are the size and the mean relief of each subdomain, and n is the total number of craters in the climate zone. As variations in lithology should not be significant at the large scales considered here, s can be seen as a measure for the erosional efficacy of the respective climatic regime.

In contrast to previous studies (Ahnert, 1970; Riebe et al., 2001a, b; von Blanckenburg, 2006; Portenga and Bierman, 2011), our erosion rates per relief s (Fig. 3a) show a clear systematic dependence on climate, at least for those classes primarily defined by temperature (A, C, D, ET). While the two cold Köppen-Geiger classes D and ET are very similar ($s = 0.13\,\mathrm{Ma}^{-1}$), the mean erosion rate per relief in the tropical zone ($s = 0.62\,\mathrm{Ma}^{-1}$) is almost 5 times higher. With $s = 0.30\,\mathrm{Ma}^{-1}$, the temperate class is close to the (geometric) mean of the two extremes. This clear trend goes along with the increase in both temperature and precipitation from polar to tropical regions.

The result for the arid zone, $s = 0.30\,\mathrm{Ma}^{-1}$, suggests that that the erosional efficacy of the arid climate is as high as that of temperate climate. This may be surprising as the arid zone is defined by low precipitation in relation to the temperature and covers a wide range of temperatures. However, the major part of the worldwide arid range is characterized by high temperatures (Köppen-Geiger classes BWh and BSh), so that the mean rate of chemical weathering should indeed be high here. But as water is the main agent for mechanical erosion and sediment transport, the result that the high temperatures are able to compensate the low precipitation compared to the temperate climate is still surprising.

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In this context, the time scale of the considered mean values must be taken into account, too. Based on the estimated lifetimes of the considered impact craters, a time scale of 10–100 Ma was estimated (Hergarten and Kenkmann, 2015). Mean temperatures have varied over this time span, accompanied by changes in overall precipitation, so that the climate classes primarily defined by temperature have shifted with the coldest and warmest classes extending or shrinking. Furthermore, continents have also moved on this time scale. Thus, each of our estimates is a mean value over a range in climate which is wider than the respective Köppen-Geiger class, so that the systematic increase in erosional efficacy from polar to tropical climate may be even larger than the fivefold increased revealed in this study. However, this simple argument does not necessarily hold for the arid class that might temporarily have been much smaller than today. In this sense, our results do not refute the importance of water for erosion, but may tentatively suggest that the present-day arid zone may have been wetter than today in the past.

The clear relationship between mean erosion rate per relief and climate (Fig. 3a) is slightly blurred after computing absolute erosion rates using the mean relief (Fig. 3b). The mean relief of the predominantly erosive provinces is highest in the temperate zone, $\Delta > 500\,\mathrm{m}$, while it is lower than 300 m in both the tropical and the arid zone and on an intermediate level ($\Delta \approx 400\,\mathrm{m}$) in the two cold regimes. As a consequence, the variation in the absolute erosion rates shown in Fig. 3b is smaller than the variation in s, and the temperate zone is characterized by a high mean erosion rate almost catching up with the tropical zone.

Figure 3c shows the extrapolation of the results for the entire ice-free surface including the types of crust excluded not taken into account so far (platform, basin, and extended crust). For the extrapolation we assumed that the relationship between relief and erosion found for the predominantly erosive provinces holds there, too. This procedure is appropriate if the not predominantly erosive provinces consist of erosive parts and parts dominated by sediment deposition with a very small (strictly speaking, zero) relief. Otherwise, the erosion rates given in Fig. 3c may be slightly biased towards high values. Depending on the climate class, the mean erosion rates decrease by 13 % to 32 % due to the lower relief of the extrapolated provinces. However, the results are qualitatively similar to those obtained for the predominantly erosive provinces.

The area-weighted mean over the five climatic zones (Fig. 3c) yields a worldwide mean erosion rate of $r = 78$ m/Ma (107 m/Ma for the predominantly erosive provinces) with 95 % confidence limits of 52 m/Ma and 116 m/Ma (see B). Our result is almost 40 % higher than the mean Pleistocene (2.58–0.01 Ma b.p.) erosion rates of $r = 56$ m/Ma obtained from preserved sediments (Wilkinson and McElroy, 2007). The latter value is even close to our lower 95 % confidence limit, and all known values for earlier periods of Earth's history are even lower. This result already suggests that erosion rates in the past might be much higher than those obtained from preserved sediments. We will return to this point after considering the time scale addressed by our approach more thoroughly (Sect. 6).

5 The spatial distribution of erosion on Earth

Figure 4 shows a world map of the estimated erosion rates using the 10 km relief on a $0.1^\circ \times 0.1^\circ$ lattice and the values s of the respective climate zones. The dominance of topography over climate is immediately visible. While the mean relief amounts to 260 m, the maximum relief is 5887 m, which is more than 20 times larger than the mean relief. In contrast, the erosional efficacy s differs only by about a factor of 5 between the warmest and the coldest climate classes. However, very high erosion rates above 1000 m/Ma occur over considerable areas only in combination of tropical climate and high relief. The largest domain with estimated erosion rates above 1000 m/Ma is found in New Guinea.

Figure 5 compares the estimated erosion rates with the present-day erosion erosion rates published by (Wilkinson and McElroy, 2007) based on the study of Ludwig and Probst (1996). As this study focused on organic carbon, specific bioclimatic zones were defined instead of the Köppen-Geiger climate classes used in our study. Therefore a direct comparison based on climate zones is not possible, so that a comparison by latitude remains as the most convenient approach.

In general our estimates show a much more homogeneous distribution on Earth than the estimates of the recent erosion rates. The quite inhomogeneous distribution of the latter is reflected in a strong asymmetry between the two hemispheres, a strong decrease towards the polar regions and a pronounced peak at 20°N. However, the smaller variation of our results is not surprising since the climatic zones may have moved in the past as discussed in Sect. 4.

As shown in Fig. 6, the contribution of the area with an erosion rate greater than r can be approximated well by an exponential distribution $C(r) = 0.25\exp(-\frac{r}{200\,\mathrm{m/Ma}})$ at high erosion rates above 250 m/Ma. This means that the area on Earth with an erosion rate greater than r decreases by about 40 % if r increases by 100 m/Ma. Qualitatively the same behavior was found for soil losses at the plot scale, but with a decay constant about 5 times smaller (Wilkinson and McElroy, 2007). Even more striking, there is a significant deviation from the exponential decay at erosion rates below 250 m/Ma. The exponential part covers only 8 % of the total ice-free land surface. This steeper decrease in the cumulative distribution at smaller erosion rates indicates that smaller areas with small erosion rates contribute much more to the total area than the exponential tail. However, when considering the contribution to the worldwide erosion, a different behavior is observed. Here, the contribution of the large area with small erosion rates is not so high. Using our estimate of the worldwide mean erosion rate of 78 m/Ma the data reveal that only about 25 % of the total land surface have an erosion rate above the mean, but these 25 % contribute about 75 % to total erosion. This 75 to 25 relation describes a more uneven distribution than Willenbring et al. (2014) obtained (about 70 to 30), but it is less inhomogeneous than the 80 to 20 relation often referred to as Pareto's principle in many contexts.

At this point the question may arise whether the spatial distribution of the impact craters on Earth might cause a systematic error. As the lifetime of a crater is inversely proportional to the erosion rates, the majority of craters is found in regions with rather low erosion rates, which is confirmed by the erosion rates at the 77 craters used in the analysis shown in Fig. 6. In order to avoid a bias by the local topography of the craters, we used the mean erosion rate of the respective province instead of the estimate at the location of the crater itself. For the temperate zone, the median erosion rates of the existing craters is 61 m/Ma. Repeating the analysis of Fig. 5 for this climate zone we found that 60 % of the area have a higher erosion rate, which means that 50 % of the craters are in these 40 % of the area with the lower erosion rate, and 50 % in these 60 % of the area with a higher erosion. This distribution seems to be not very asymmetric, but the 60 % of the area with a higher erosion contribute more than 92 % to the total erosion. As a consequence, half of the craters in the temperate zone are located in a part of the climate zone contributing less than 8 % to the total erosion.

In view of this result, the estimate of the worldwide erosion rate strongly relies on the assumed and to some extent verified linear relationship between relief and erosion rate. However, to our knowledge all studies in this context either found linear

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or slightly convex relations between morphometric parameters and erosion rates. It we assumed a convex dependency of the erosion rate on the relief, the estimated erosion rates at large relief and thus the worldwide mean erosion rate would even increase. This result would even strengthen our finding that the worldwide erosion rates on the million year scale were higher than suggested by the sedimentary record in the oceans.

6 The time scale of the terrestrial crater inventory

According to Fig. 7, the estimated lifetimes of the considered craters are in the range from 1 Ma to 1000 Ma. As available information about the age of individual craters is often vague or only provides an upper or a lower limit, we use half of the estimated lifetime as an estimate of the age. Figure 8 gives the cumulative distribution of these ages. This distribution can also be interpreted as a sensitivity with regard to the time before present as it states how many of the existing craters would be affected by a change in erosion rate at a given time. It is immediately recognized that these sensitivity functions roughly decrease exponentially with time for all considered climatic zones as well as worldwide.

In order to obtain a robust estimate of the decay constant τ we use the time where the area below the curve from 0 to τ amounts to a fraction $1-\exp(-1) \approx 63\,\%$ of the total area. This results in a minimum value of $\tau = 13$ Ma for the temperate zone and a maximum value of $\tau = 70$ Ma for the cold climate zone. So it is not possible to define a distinct time window of sensitivity for our method, but find that the sensitivity exponentially decreases with time before present. As the worldwide mean erosion is dominated by the temperate zone and the tropical zone showing the smallest decay constant, we suggest $\tau = 13$ Ma as a conservative estimate. So our approach covers a time span characterized by a cooling climate, but without any fundmental changes in the location of the continents on Earth and in the spatial distribution of the orogens.

7 Has erosion globally increased?

Taking into account an exponentially decreasing sensitivity with $\tau = 13$ Ma, Fig. 9 compares our result on the worldwide long-term mean erosion rate with previous results. The green area represents our result of $r = 78$ m/Ma with the 70 % confidence intervals. The decreasing opacity visualizes the exponentially decreasing sensitivity with $\tau = 13$ Ma.

Except for the average Pleistocene (2.58–0.01 Ma b.p.) erosion rate, our result is significantly higher than the estimates derived from preserved sediments for all epochs. All these estimates are even much below our lower 95 % confidence limit of 52 m/Ma. This result supports the hypothesis of Willenbring and von Blanckenburg (2010) that the erosion rates obtained from preserved sediments are much too low.

As a reference value for the worldwide present-day erosion rate we use the values compiled by Willenbring et al. (2013). The studies starting from 1950 show a high variablity from 35 m/Ma to 218 m/Ma. The mean value of these 31 studies is 76 m/Ma, and the standard deviation is 37 m/Ma, i.e., 50 % of the mean value. The standard deviation reduces if we consider only those 16 studies not older than 1975. We then obtain a mean value of 63 m/Ma with a standard deviation of 15 m/Ma. As these values do not change much if we reduce the data set further, we take $r = 63 \pm 15$ m/Ma as a reference value for the present-day erosion

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rate. As it is recognized in Fig. 9, the uncertainties in our long-term estimate and in the present-day erosion rate are similar, and the recent erosion rate is slightly below the lower bound of our 70 % confidence interval. This means that we could reject the hypothesis of equal erosion rates at about 15 % error level, but clearly not at 5 % error level following the widely used practice in statistics. So our long-term estimate is even higher than the present-day erosion rates, but the uncertainty in the data does not allow the conclusion that the long-term erosion rates were indeed higher than the present-day rates, although this would be consistent with the retention of sediments in artificial reservoirs and with the widely accepted trend of decreasing erosion in a cooling climate.

8 Conclusions

Our study yields long-term mean erosion rates as a function of topography expressed in terms of the 10 km relief and climate represented by the primary Köppen-Geiger classes. While the huge variation of topography on Earth makes the biggest contribution to the worldwide variablity of erosion rates, our results reveal a significant systematic dependence on climate in contrast to the results of several previous studies. We found an fivefold increase in erosional efficacy defined by the erosion rate per relief from the cold regimes to the tropical zone. Furthermore we found the temperate and arid climates to be very similar concerning their erosional efficacy. In this context it has to be taken into account that our study relates long-term erosion rates on the time scale of some tens of million years to present-day topography and climate. As the climatic zones have shifted on this time scale, the difference in recent erosional efficacy may be even higher than predicted by our method. Furthermore the erosional efficacy of the arid climate being similar to the temperate climate does not refute the importance of water for erosion, but may be related to less dry conditions in the arid zone in the geological history.

Concerning the worldwide erosion rates we obtained a mean value on the time scale of some tens of million years of 78 m/Ma which is much higher than previous estimates derived from preserved sediments. This result supports the hypothesis of Willenbring and von Blanckenburg (2010) that the apparent increase in worldwide erosion may be an artefact of the sedimentary record and that the observed increase in some mountainous regions (Herman et al., 2013) probably related to the Pleistocene glaciation could be a regional effect with a limited worldwide relevance. Our estimate is even about 25 % higher than the mean value of the results published since 1975. This result is qualitatively consistent with the widely accepted decrease of erosion with decreasing temperature and could also be related to the retention of sediments in artificial reservoirs. However, both our long-term erosion rates and the present-day rates have uncertainties in the order of magnitude of the difference. Therefore we can conclude that the erosion rates have clearly been higher than they seem from preserved sediments and that there is no evidence for any change in worldwide erosion rates on the scale of some tens of million years.

Data availability. Data for reproducing the results and generating additional figures are available at http://hergarten.at/supplement.zip (preliminary location during the review process).

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Appendix A: Maximum-likelihood estimate of the erosion rate per relief

We consider a domain consisting of k subdomains (here, k is between 13 and 22) of areas A_i and mean relief Δ_i. According to Eqs. 1 and 2, the expected number of craters in each subdomain is

$$\lambda_i = \frac{A_i I}{s \Delta_i} \tag{A1}$$

where we used the symbol λ_i instead of n_i in order to distinguish it from the actual number. The probability $p_i(n_i)$ that the actual number n_i of craters occurs, is given by the Poisson distribution,

$$p_i(n_i) = \frac{\lambda_i^{n_i} e^{-\lambda_i}}{n_i!}. \tag{A2}$$

Then the joint probability to find the actual combination $n_1, \ldots, n_k$ is

$$p(n_1, \ldots, n_k) = \prod_{i=1}^{k} p_i(n_i). \tag{A3}$$

This probability depends on the parameter s via Eqs. A1 and A2. The maximum likelihood-method determines the most likely value of s in such a way that the probability to obtain the actual combination $n_1, \ldots, n_k$ becomes maximal. For convenience, the function

$$\begin{aligned} L(s) &= \log p(n_1, \ldots, n_k) && \text{(A4)} \\ &= \sum_{i=1}^{k} \log p_i(n_i) && \text{(A5)} \\ &= \sum_{i=1}^{k} \left(n_i \log \lambda_i - \lambda_i - \log(n_i!) \right). && \text{(A6)} \end{aligned}$$

is maximized instead of p itself, so that

$$\begin{aligned} L'(s) &= \sum_{i=1}^{k} \left(\frac{n_i}{\lambda_i} - 1 \right) \frac{d\lambda_i}{ds} && \text{(A7)} \\ &= -\frac{1}{s^2} \sum_{i=1}^{k} \left(n_i s - \frac{A_i I}{\Delta_i} \right). && \text{(A8)} \end{aligned}$$

The condition $L'(s) = 0$ immediately leads to Eq. 3.

Appendix B: Confidence intervals for the estimated erosion rates

Equation 3 used for determining the erosion rates per relief s of the climatic zones only involves the total number of craters n in the considered zone as a random variable. As this variable follows a Poissonian distribution, confidence limits are readily obtained from the respective cumulative distribution. This also holds for the erosion mean absolute rates within each climatic zone according to Eq. 2. Only the worldwide mean erosion being the area-weighted mean of the individual rates,

$$r = \frac{\sum_i A_i r_i}{\sum_i A_i}, \tag{B1}$$

involves multiple random variables, so that confidence interval cannot be directly computed from a single statistical distribution. However, as shown in Fig. 3, the 70 % confidence intervals (corresponding to the standard deviation for a Gaussian distribution) are almost symmetric on a logarithmic scale. We therefore use half of the widths of these intervals as estimates of the individual errors $\delta \log_{10} r_i$ and compute $\delta \log_{10} r$ by Gaussian error propagation:

$$(\delta \log_{10} r)^2 = \sum_i \left(\frac{\partial \log_{10} r}{\partial \log_{10} r_i} \delta \log_{10} r_i \right)^2 \tag{B2}$$

$$= \sum_i \left(\frac{r_i}{r} \frac{\partial r}{\partial r_i} \delta \log_{10} r_i \right)^2 \tag{B3}$$

$$= \frac{\sum_i (A_i r_i \delta \log_{10} r_i)^2}{(\sum_i A_i r_i)^2}. \tag{B4}$$

Following the analogy of the 95 % confidence interval to twice the standard deviation for a Gaussian distribution, we define the 95 % confidence interval for the worldwide mean erosion rate by $2\delta \log_{10} r$. As the individual 95 % confidence intervals are more asymmetric and smaller than two times the 70 % confidence intervals on the logarithmic scale, this is a rather conservative estimate in the sense that the error towards lower erosion rate is overestimated.

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Competing interests. The authors declare that they have no competing interests.

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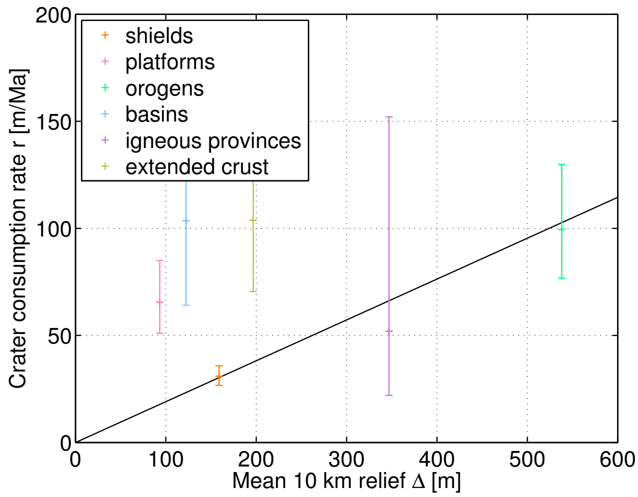

Figure 1. Rates of crater consumption derived from Eq. 1 vs. mean relief for the basic types of continental crust (http://earthquake.usgs.gov/data/crust/type.html). The error bars represent 70 % confidence intervals corresponding to the standard deviation for a Gaussian distribution.

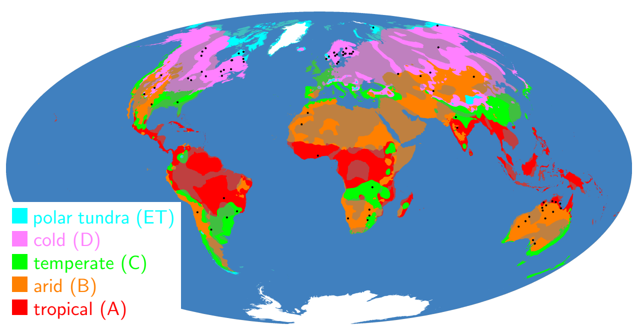

Figure 2. The primary Köppen-Geiger climate classes (Peel et al., 2007) considered in this study. Solid colors correspond to the predominantly erosive provinces (shield, orogen, igneous), while the respective pale colors mark those regions not considered in order to avoid a bias by sediment deposition. The black dots show the craters with diameters $D \geq 0.25$ km located in the predominantly erosive provinces being the basis of our analysis.

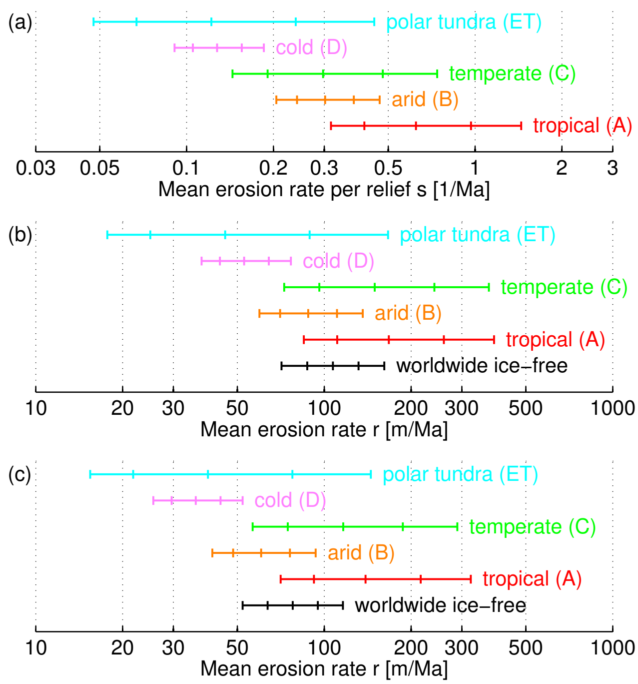

Figure 3. Erosion rates by climatic zones. (a) Mean erosion rates per relief for the primary classes of the Köppen-Geiger scheme. (b) Respective absolute mean erosion rates for the predominantly erosive provinces. (c) Absolute mean erosion rates extrapolated to the entire ice-free surface including the classes platform, basin, and extended crust. Error bars represent the 70 % confidence intervals (corresponding to the standard deviation for a Gaussian distribution) and the 95 % confidence intervals (see B).

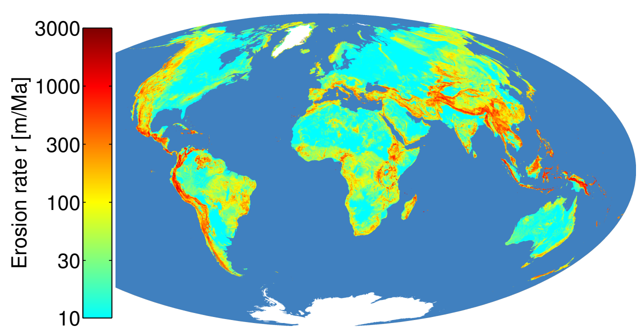

Figure 4. World map of the erosion rates obtained in this study.

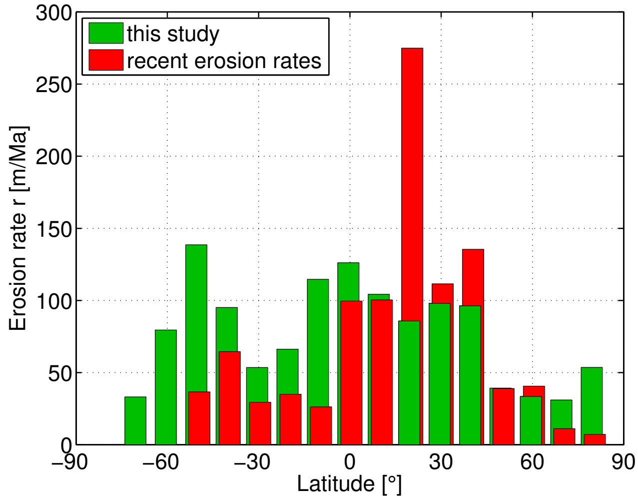

Figure 5. Mean erosion rates as a function of latitude in 10° intervals. Present-day erosion rates are taken from Wilkinson and McElroy (2007).

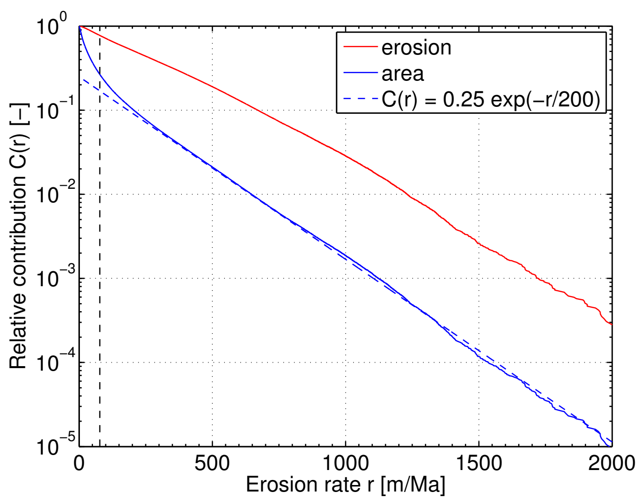

Figure 6. Cumulative distribution of the erosion rates and their contribution to the total erosion. The blue curve shows the contribution of the part of the land surface with an erosion rate greater than r to the total area, and the red curve its contribution to the total erosion.

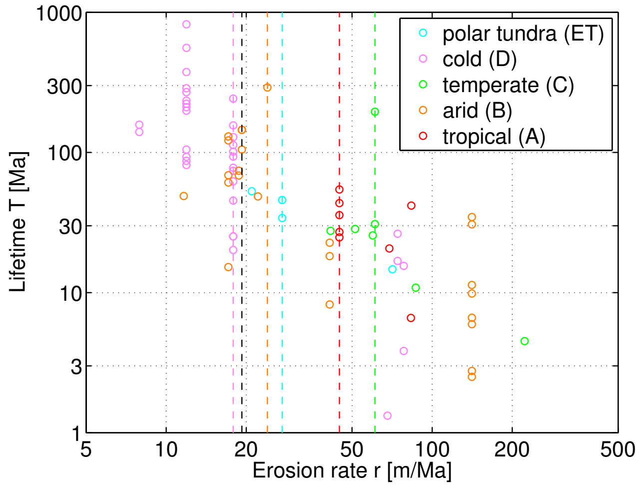

Figure 7. Erosion rates and estimated lifetimes of the considered craters. In order to avoid an influence of the local topography of the craters, the mean erosion rate of the respective province was used instead of the local value. Lifetimes were estimated from the size of the craters and the erosion rates as described by Hergarten and Kenkmann (2015). The dashed lines show the median erosion rate for the craters in the respective climate zone.

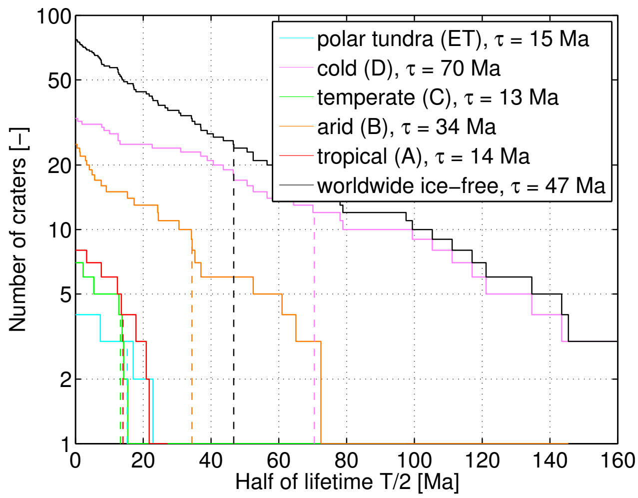

Figure 8. Cumulative size distribution of the considered craters as a function of half of their estimated lifetime, equivalent to the sensitivity of the number of craters to changes in the erosion rate at a given time. The values of τ given in the legend are the decay constants of the exponential decrease.

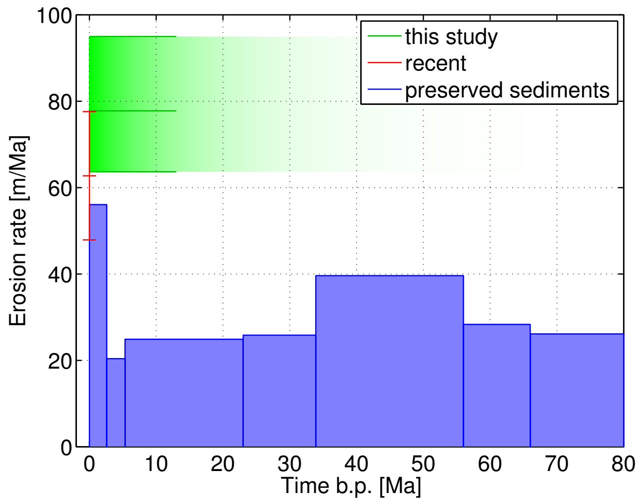

Figure 9. Comparison of our long-term erosion rate with estimates obtained from preserved sediments (Wilkinson and McElroy, 2007) and recent erosion rates compiled by (Willenbring et al., 2013). The green area represents our result for the mean erosion rate of $r = 77$ m/Ma with the 70 % confidence intervals. The decreasing opacity visualizes the exponentially decreasing sensitivity with $\tau = 13$ Ma.