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Response to Comment on "Earth and Moon impact flux increased at the end of the Paleozoic"

Sara Mazrouei[1]*, Rebecca R. Ghent[1,2], William F. Bottke[3], Alex H. Parker[3], Thomas M. Gernon[4]

[1]Department of Earth Sciences, University of Toronto, Toronto, ON, Canada. [2]Planetary Science Institute, Tucson, AZ, USA. [3]Southwest Research Institute, Boulder, CO, USA. [4]School of Ocean and Earth Science, University of Southampton, Southampton SO14 3ZH, UK.

*Corresponding author. Email: sara.mazrouei.seidani@mail.utoronto.ca

Hergarten *et al.* interpret our results in terms of erosion and uncertain calibration, rather than requiring an increase in impact flux. Geologic constraints indicate low long-term erosion rates on stable cratons where most craters with diameters of ≥20 kilometers occur. We statistically test their proposed recalibration of the lunar crater ages and find that it is disfavored relative to our original calibration.

Hergarten *et al.* (*1*) present an alternative interpretation of the impact record on Earth and the Moon. Their argument requires that Earth's cratons have been deeply eroded over the past 650 million years (Ma), removing many craters with diameters $D \geq 20$ km. The existing crater inventory has been taken to imply substantial global erosion rates of ~59 m Ma^{-1} (*2*), more than 20 times cratonic rates (*3*).

Thermochronological data (*3*) provide consistent constraints on long-term cratonic erosion rates. Global mean erosion rates (*2*, *4*) cannot be applied to cratonic regions because such estimates include the high erosion rates prevalent in tectonically active regions today. Long-term integrated estimates do not preclude short-lived pulses of exhumation (*3*). Therefore, the application of present-day erosion rates over 100-million-year time scales is tentative and uncertain (*2*).

The global mean erosion rate (*2*) would imply 30 to 40 km of erosion on the cratons over the past 650 Ma. Such losses are inconsistent with geologic constraints (*5*), including the widespread cratonic occurrence of shallow (≤2 km) crustal features such as kimberlite pipes (*6*). Moreover, 85% of $D \geq 20$ km terrestrial craters are located on stable cratons (*6*), which have remained largely intact since the Proterozoic (*3*, *7*).

If the 20- to 30-km terrestrial craters have erosion lifetimes of 35 to 47 Ma (*2*) and erode at an exponential rate, the fraction of craters surviving longer than 290 Ma should only be 0.02 to 0.2% of the initial population. Instead, nearly one-third (5 of 16) have ages between 290 and 650 Ma (*3*).

We now address the alternative calibration of our lunar crater dating method (*1*). We argue that a goodness of fit based on R^2 and residual root mean square (RMS) scatter is not sufficient for model selection given the available information.

Our Bayesian model selection framework (*6*) can self-consistently accommodate uncertainty in the functional form proposed for the relationship between age and rock abundance, $\text{RA}_{95/5}$. There are parameter sets for a power-law relationship that provide crater age distributions consistent with an impact rate uniform in time, as there are for Hergarten *et al.*'s proposed exponential relationship. The issue is whether these parameter sets are likely given the ages of "index" craters, defined as $D \geq 20$ km craters whose ages were derived by independent means. Our analysis indicated that they are not (*6*), instead favoring parameter sets that include a change in the impact rate.

Using the same method (*6*), we performed a likelihood ratio test on the power-law and exponential models (Fig. 1). The relative likelihood of the exponential model to the power-law model is 0.004, disfavoring the former.

We can additionally include the choice of the power-law versus exponential models as part of the approximate Bayesian computation rejection (ABCr) analysis used to determine the Bayes factor for the broken impact rate versus the uniform impact rate (*6*). At the step of selecting parameters for the age-$\text{RA}_{95/5}$ from the posterior probability density function (PDF), we modified our method to select which model we are using for this trial, and choose each model with a probability proportional to the relative likelihood of each model as determined by the likelihood ratio test (that is, 99.6% of the cases selected to be the power-law distribution, and 0.4% of the cases selected to be the exponential distribution). If the evidence presented by the craters themselves outweighed the strong evidence against the exponential model, this treatment would allow that evidence to speak for itself.

Taking lunar craters alone, we still find a Bayes factor of 6:1 in favor of the broken impact rate over the uniform rate. Marginalizing over both the model of the age-$\text{RA}_{95/5}$ relationship and its parameters, we find evidence against a uniform impact rate. Including terrestrial craters has the same effect as before (*6*), producing a Bayes factor of 100:1 in favor of the broken impact rate over the uniform rate.

Finally, we examine whether a constant impact flux for large impactors is consistent with lunar data. Given that our age-$RA_{95/5}$ relationship has been questioned (*1*), here we only use the index crater Copernicus, whose age of 800 Ma was directly derived from Apollo 12 samples (*6*, *8*). We find that 20 lunar craters with $D \geq 20$ km have higher $RA_{95/5}$ values than Copernicus. Accordingly, within reasonable error, all should be < 800 Ma. The terrestrial production rate of $D \geq 20$ km craters over the past ~100 Ma is ~2.5 to ~3.0 × 10^{-15} km^{-2} $year^{-1}$ [(*9*), used by (*1*, *2*); see also (*6*)]. When translated to the Moon (*6*) and kept constant for 800 Ma, it would yield 50 to 60 lunar craters—2.5 to 3 times the number observed. This high number of craters is also inconsistent with (i) the relative ages of large lunar craters as derived from optical maturity observations (*6*, *10*), and (ii) superposed crater counts on large lunar craters [i.e., many $D > 50$ km craters once considered Copernican-era are instead much older (*11*)].

REFERENCES

1. S. Hergarten, G. Wulf, T. Kenkmann, Comment on "Earth and Moon impact flux increased at the end of the Paleozoic". *Science* **365**, eaaw7471 (2019).
2. S. Hergarten, T. Kenkmann, The number of impact craters on Earth: Any room for further discoveries? *Earth Planet. Sci. Lett.* **425**, 187–192 (2015). doi:10.1016/j.epsl.2015.06.009
3. T. J. Blackburn, S. A. Bowring, J. T. Perron, K. H. Mahan, F. O. Dudas, K. R. Barnhart, An exhumation history of continents over billion-year time scales. *Science* **335**, 73–76 (2012). doi:10.1126/science.1213496 Medline
4. M. A. Summerfield, N. J. Hulton, Natural controls of fluvial denudation rates in major world drainage basins. *J. Geophys. Res. Solid Earth* **99**, 13871–13883 (1994). doi:10.1029/94JB00715
5. C. B. Keller, J. M. Husson, R. N. Mitchell, W. F. Bottke, T. M. Gernon, P. Boehnke, E. A. Bell, N. L. Swanson-Hysell, S. E. Peters, Neoproterozoic glacial origin of the Great Unconformity. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 1136–1145 (2019). doi:10.1073/pnas.1804350116 Medline
6. S. Mazrouei, R. R. Ghent, W. F. Bottke, A. H. Parker, T. M. Gernon, Earth and Moon impact flux increased at the end of the Paleozoic. *Science* **363**, 253–257 (2019). doi:10.1126/science.aar4058 Medline
7. R. M. Flowers, S. A. Bowring, P. W. Reiners, Low long-term erosion rates and extreme continental stability documented by ancient (U-Th)/He dates. *Geology* **34**, 925 (2006). doi:10.1130/G22670A.1
8. D. Stöffler, G. Ryder, Stratigraphy and isotope ages of lunar geologic units: Chronological standard for the inner solar system. *Space Sci. Rev.* **96**, 9–54 (2001). doi:10.1023/A:1011937020193
9. D. W. Hughes, A new approach to the calculation of the cratering rate of the Earth over the last 125 ± 20 Myr. *Mon. Not. R. Astron. Soc.* **317**, 429–437 (2000). doi:10.1046/j.1365-8711.2000.03568.x
10. J. A. Grier, A. S. McEwen, P. G. Lucey, M. Milazzo, R. G. Strom, Optical maturity of ejecta from large rayed lunar craters. *J. Geophys. Res. Planets* **106**, 32847–32862 (2001). doi:10.1029/1999JE001160
11. M. R. Kirchoff, C. R. Chapman, S. Marchi, K. M. Curtis, B. Enke, W. F. Bottke, Ages of large lunar impact craters and implications for bombardment during the Moon's middle age. *Icarus* **225**, 325–341 (2013). doi:10.1016/j.icarus.2013.03.018

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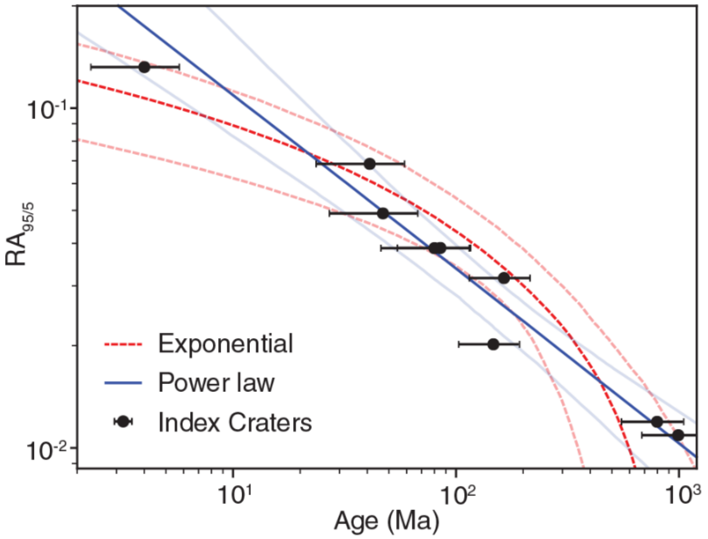

Fig. 1. Comparison of power-law and exponential age-$RA_{95/5}$ relationships for lunar craters. Posterior PDFs for model parameters are derived using the same approach as Mazrouei *et al*. (*6*). The median (dark lines) and 95% range (light lines) are illustrated. If the exponential model is adopted (dashed red lines), the uncertainty inflation term *c* prefers a higher value than if the power-law model is adopted (solid blue lines), with a mean uncertainty scaling factor *c* ~ 0.5 versus the mean of *c* ~ 0.3 found for the power-law model.

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