WHAT REALLY HAPPENED TO EARTH'S OLDER CRATERS? W. F. Bottke[1], S. Mazrouei[2], R. R. Ghent[1,2], A. H. Parker[1], T. M. Gernon[4]. [1]Southwest Research Institute and NASA's SSERVI-ISET Team, Boulder, CO (bottke@boulder.swri.edu) [2]Dept. Earth Sciences, University of Toronto, Toronto, ON, Canada. [3]Planetary Science Institute, Tucson, AZ. [4]Ocean and Earth Science, University of Southampton, Southampton, UK.

Introduction. Most assume the Earth's crater record is heavily biased, with erosion/tectonics preferentially destroying older craters. This matches expectations, but is it actually true? To test this idea, we compared Earth's crater record, where nearly all $D \geq 20$ km craters formed < 650 Myr ago (Ma) [1], to the Moon's, where we applied a new method to date all $D \geq 10$ km lunar craters younger than 1 Ga [2].

Our lunar crater ages were computed using LRO-Diviner temperature data [2]. Large lunar rocks have high thermal inertia and remain warm through the night relative to the regolith. Analysis shows young craters with numerous meter-sized fragments are easy to pick out from older craters with eroded fragments. Moreover, an inverse relationship between rock abundance and crater age exists, as measured from craters with known ages (e.g., Tycho, Copernicus). Using this rock abundance-age function, we computed ages for 111 rocky craters with $D \geq 10$ km that formed between 80°N and 80°S over the last 1 Gyr (**Fig. 1**).

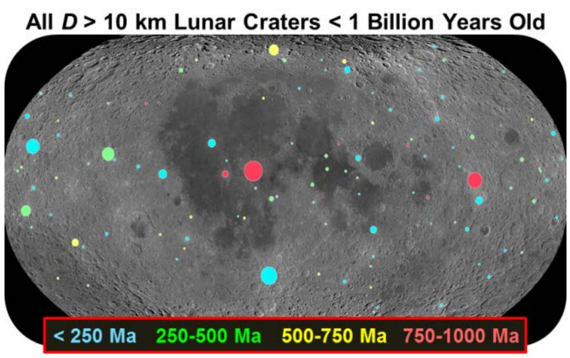

Fig. 1. Geographic distribution of 111 *rocky* craters with diameter $D \geq 10$ km between 80ºN and 80ºS on the Moon, scaled by size and color coded according to age.

Earth/Moon Results. The age distribution of lunar and terrestrial craters is shown in **Fig. 2 (see also Figs. 1 & 3)**. Our analysis yielded several surprising results.

1. The production rate of $D \geq 10$ km lunar craters increased by a factor of 2.2 [-0.9, +4.4; 95% confidence limits] over the past 250 Myr compared to the previous 750 Myr. Interestingly, this increase matches the ages and abundances of lunar impact spherules [3].

2. Both age and size distributions of $D \geq 20$ km lunar and terrestrial craters < 650 Ma have similar shapes (ages shown in **Fig. 2**). This implies that crater erasure is limited on stable terrestrial terrains; in an average sense, for a given region, the Earth either keeps or loses all of its $D \geq 20$ craters at the same rate, independent of size. It also implies the observed deficit of large terrestrial craters between 250-650 Ma in **Fig. 2** is ***not preservation bias*** but rather reflects a distinctly lower impact flux. If erosion had dominated, the age distribution of terrestrial craters would be strongly skewed toward younger ages, which is not observed.

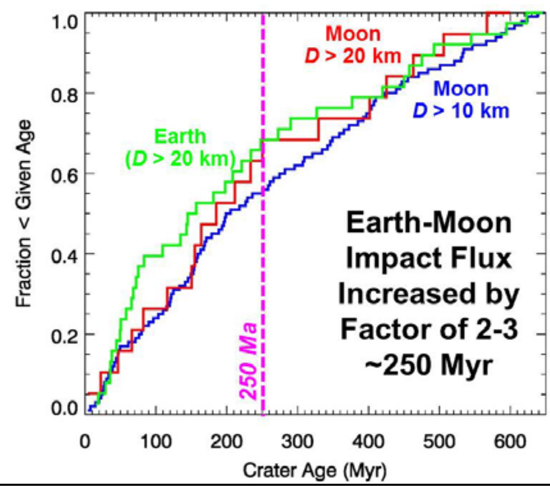

Fig. 2. Age-frequency distributions of lunar and terrestrial craters. Impact flux increases by a factor of 2-3 near 250 Ma. The similarity between curves suggests that increase in terrestrial impacts is not a preservation bias.

3. Our work challenges studies that have used rayed lunar craters to compute impact flux rates. We find 11 farside rocky craters with $D \geq 20$ km formed in the last 1 Gyr, compared to 28 to 32 farside rayed craters assumed to be this age [4]. Our results, however, are fairly consistent with optical maturity studies [5].

4. Scaling from the Moon, we predict 355 ± 86 $D \geq$ 20 km craters formed on Earth over the last 650 Myr. Only 38 ± 6 are known, so the ratio, 10.7 ± 3.1%, is a measure of the Earth's surface that is well searched and stable to large crater formation over 650 Ma.

5. Our results suggest the NEO population was considerably lower ~250-1000 Ma. Consequently, Chicxulub-type impacts also occurred less frequently in this interval, with implications for our biosphere.

Eroded Craters Younger Than 650 Ma? Here we provide additional evidence that large craters on cratons did not experience deep erosion over 650 Ma.

1. U-Pb thermochronology (temperature-sensitive radiometric dating) constrains the thermal structure and erosion history of the continents [6]. Analysis indicates extremely low cratonic erosion rates of -2.5 to 2.5 m/Myr, equating to <1.6 km vertical erosion over the last 650 Myr. These values are insufficient to eradicate $D \geq 20$ km craters, given that crater depths are equal to ~10% of their original diameter [11].

2. Impact craters and kimberlites are frequently found in common regions on stable cratonic surfaces (**Fig. 3**). This means kimberlites are a proxy indicating the depth of erosion for surfaces of different ages.

Kimberlites are formed during explosive volcanism from deep mantle sources, generating carrot-shaped pipes 1-2 km deep [8, 9] (**Fig. 3b; see inset**). These features commonly preserve volcanic facies (e.g. crater, diatreme) that are depth-diagnostic [10].

Deep erosion of cratonic surfaces (> 2 km) should have removed most kimberlite diatremes, leaving behind deep-seated intrusive rocks, but diatremes are relatively common throughout the Phanerozoic era (**Fig. 3b**). Their spatio-temporal distribution suggests at best only modest erosion (< 1 km) on most cratons since 650 Ma [10], thereby favoring the survival of large $D \geq 20$ km impact craters.

Where Are Craters Older Than 650 Ma? There is a sharp cut-off of nearly all terrestrial craters at ~650 Ma [1]. Given the low cratonic erosion rates for < 650 Ma, our work predicts that similar conditions further back in time would have allowed most Precambrian craters to survive. So, where are all the old craters?

Intriguingly, the paucity of Precambrian craters is coincident with major episodes of globally-extensive Cryogenian glaciation (i.e., Snowball Earth) (**Fig. 3b**). Pervasive subglacial erosion at ~650–720 Ma is thought to have removed kilometers of material from all continents, enough to erase most existing diatremes and impact craters [11]. The main exceptions are the Chicxulub-sized or larger impact craters Sudbury (1.85 Ga) and Vredefort (2.023 Ga). Both craters were apparently deep enough to survive, but each experienced multiple kilometers of erosion [12].

Conclusions. The geologic records of the other terrestrial planets (e.g., Venus) may need to be reinterpreted in light of our suggested changes to the bombardment rate. We predict the change in the lunar/terrestrial impact flux is linked to the breakup of one or more large asteroids in the inner main belt (e.g., [13]). Those located near resonances may produce long-lived surges in the impact flux as fragments are driven to escape routes by non-gravitational forces.

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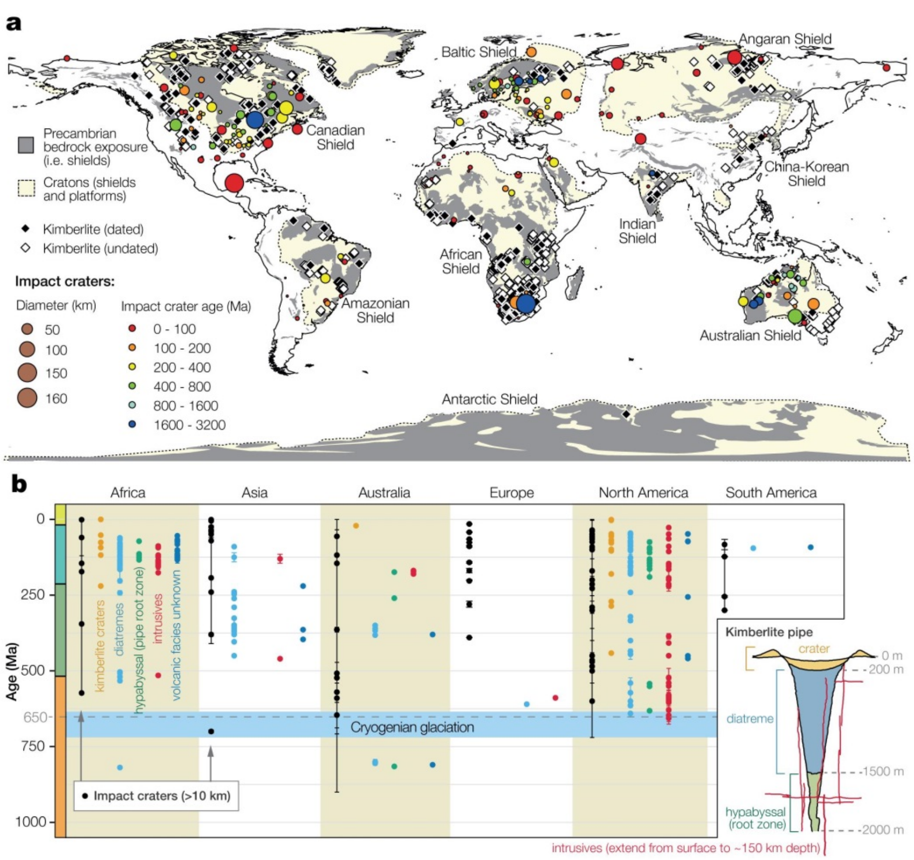

Fig. 3. Impact craters and kimberlites in space and time.

(a) Locations of impact craters scaled by size and colored by age. Kimberlite pipes are also shown, discriminating those with well-defined radiometric ages [14]. Grey regions correspond to major exposures of Precambrian basement rocks [15] forming stable cratons (where 83% of $D \geq 20$ km craters occur).

(b) Chronology of large impacts ($D \geq 10$ km) and kimberlites for each continent, excluding Antarctica [1, 14]. Colored symbols signify key kimberlite facies (see labels/inset at lower right). Preserved kimberlite craters indicate a low degree of erosion, probably not exceeding 200 m. These are typically underlain by diatremes that extend to 1–1.5 km beneath the surface. Note an abrupt cut-off in impact crater and kimberlite frequency at ~650 Ma, coincident with Cryogenian glaciation (i.e., Snowball Earth) [e.g., 11].