Commentary: A Sharper Picture of the Moon's Bombardment History from Gravity Data

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Key Points:

- Evans et al. (2018) use gravity data to identify buried craters within large basins
- They re-interpret the relative ages of lunar basins using these observations
- The relative ages correlate quite well with the degree of basin relaxation

Abstract

Some large impact basins on the Moon are covered with younger basalts, making it hard to determine their age by crater counting. Evans et al. (2018) use GRAIL gravity data to identify buried craters larger than 90 km, and construct a relative chronology for the impact basins. This relative chronology is broadly consistent with the degree to which the basins have relaxed: older basins tend to be more relaxed. Pre-Nectarian basins are likely saturated, so the roughly constant measured crater density does not require a brief formation interval. Some of the results of Evans et al. (2018) are at odds with other determinations e.g. they suggest Imbrium could be older than Crisium, and Serenitatis as young as Imbrium.

Plain Language Summary

To tell the age of an impact basin on the Moon, you count the number of craters. But some basins are flooded by later lavas, making crater counting difficult. Evans et al. (2018) identify buried craters by looking for small changes in the Moon's gravity. This allows them to decide how old each impact basin is. The older basins are also generally shallower. This is because the older basins formed when the Moon was hotter, and the lunar rocks were able to flow and partly fill the basin in.

1. Introduction

The collisional growth of the terrestrial planets was mostly complete by about 100 Myr after solar system formation (Agnor et al. 1999). However, leftover material continued to strike the planets, a process that continues to the present day, albeit at a much-reduced rate. The scars left by these late collisions are visible across the inner solar system as large impact basins, such as Caloris on Mercury and Hellas on Mars. Quantifying this flux of material is important for at least two reasons. First, if the flux evolution is known, then an absolute chronology can be established – the number of craters observed on a surface can be converted directly to an age. Second, the flux evolution can provide clues to the dynamical evolution of the solar system. In particular, a "spike" in the impact rate (e.g. Tera et al. 1974) might be an indication of a sudden change in solar system architecture, as has been suggested by the so-called Nice Model (Gomes et al. 2005).

Because plate tectonics and erosion have destroyed almost all evidence of ancient impacts on Earth, the Moon has two attributes making it the best place with which to develop an absolute chronology. It has old, heavily cratered surfaces recording ancient impact fluxes; and, crucially, we have Apollo-era samples of known provenance which can be radiometrically dated in the laboratory.

Unfortunately, neither of these attributes is free of complications. It turns out to be very hard to unambiguously identify the provenance of a particular sample: ejecta from large impacts travel long distances. As a result, whether the preponderance of ages around 3.9 Ga found in Apollo samples is an indication that multiple, large impacts happened around that time, or whether the majority of samples represent ejecta from a single impact, is currently unclear (e.g. Stoffler et al. 2006, Bottke & Norman 2017). And although the Moon does indeed have ancient terranes, in many cases these areas have been covered by later lavas, making it hard to establish the age of the underlying surface. Overcoming this second problem is the focus of the work by Evans et al. (2018).

2. Evans et al. (2018)

Lunar stratigraphy, established by crater counting and superposition relationships, recognizes five periods, of which the three oldest are pre-Nectarian, Nectarian, and Imbrian. Apollo-era mapping established the relative stratigraphic relationships of all the major lunar basins (Wilhelms 1987), although as noted above the absolute ages of almost all the basins except Imbrium and (perhaps) Orientale is uncertain (Bottke & Norman 2017).

Large, ancient impact basins are particularly good stratigraphic markers because they result in instantaneous formation of a new surface. This surface then accumulates craters; if at some point the basin is flooded with mare basalts, most or all of the accumulated craters are buried (Figure 1). What Evans et al. (2018) demonstrate, however, is that these buried craters can still be detected using the remarkable high-resolution gravity maps produced by the GRAIL spacecraft (Zuber et al. 2013). This is because of the density contrast between the mare basalts and the underlying crust: buried basins produce a thicker basalt column, and show up as a positive circular gravity anomaly, denoted by Evans et al. as quasi-circular mass anomalies (QCMAs).

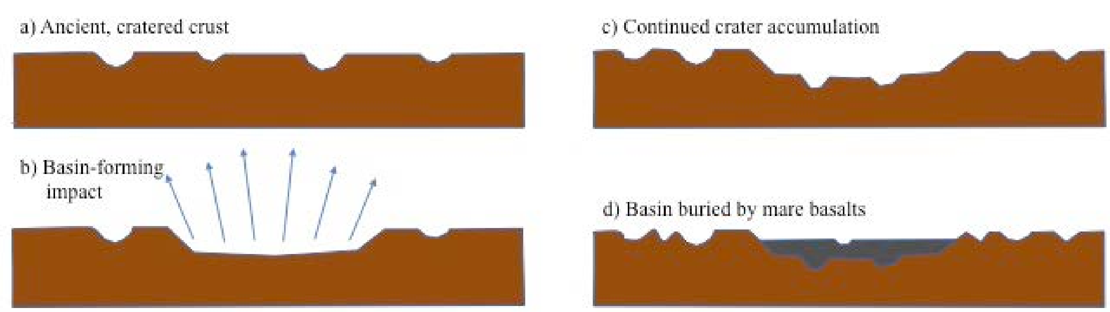

Figure 1. Cartoon of relevant processes. A basin forms and accumulates craters which are then buried by mare basalts. The gravity signals associated with these buried craters gives rise to QCMAs, which can be used to determine the age of the basin floor.

Evans et al. surveyed various regions for QCMAs of different sizes. They found that smaller QCMAs were relatively less abundant than larger QCMAs, which makes sense, because the gravity anomalies associated with smaller QCMAs are more likely to be obscured by other effects. By comparing the populations of QCMAs with regular craters, Evans et al. concluded that the record of QCMAs 90 km or larger in diameter was effectively complete. Thus, a basin’s true age can be inferred by summing the total number of visible craters plus QCMAs greater in diameter than 90 km. This metric is reported as N(90), the number of such basins per million square kilometers.

Although by focusing only on large craters the statistical uncertainty is increased, this approach largely avoids systematic undercounting due to burial. While it may not avoid this problem completely - both Crisium and Serenitatis still exhibit an apparent deficit of QCMAs in their central, basalt-filled regions - including QCMAs as well as visible craters can in some cases make a significant difference to apparent age. For instance, the Serenitatis basin has an N(90) of 1 ± 1 using visible craters, but 5 ± 2 including QCMAs. Because of these differences, Evans et al. argue that some aspects of lunar chronology need to be re-assessed.

One interesting outcome of Evans et al. is that, within error, all the pre-Nectarian basins have the same N(90) value (~13). They suggest that this result may simply reflect equilibrium: roughly speaking, addition of one extra 90~km diameter crater results in the destruction of one such crater. This is reasonable: real planetary surfaces at equilibrum typically exhibit crater densities 5-10% of the geometric saturation value (Melosh 1989). For 90~km diameter craters this translates to 7-14 craters per million km^2, similar to what is measured.

Figure 2 summarizes the main results of Evans et al. It plots the N(90) value including QCMAs for different basins and terrains, with colours denoting relative stratigraphic position. The vertical axis is the extent to which different basins have undergone viscous relaxation, thus removing their initial topography. This latter quantity is also derived from GRAIL data (Conrad et al. 2018), and is useful because older basins will have formed in crust that was warmer, and thus more likely to undergo relaxation. This figure thus shows three independent indications of basin age: N(90), stratigraphic position, and relaxation fraction.

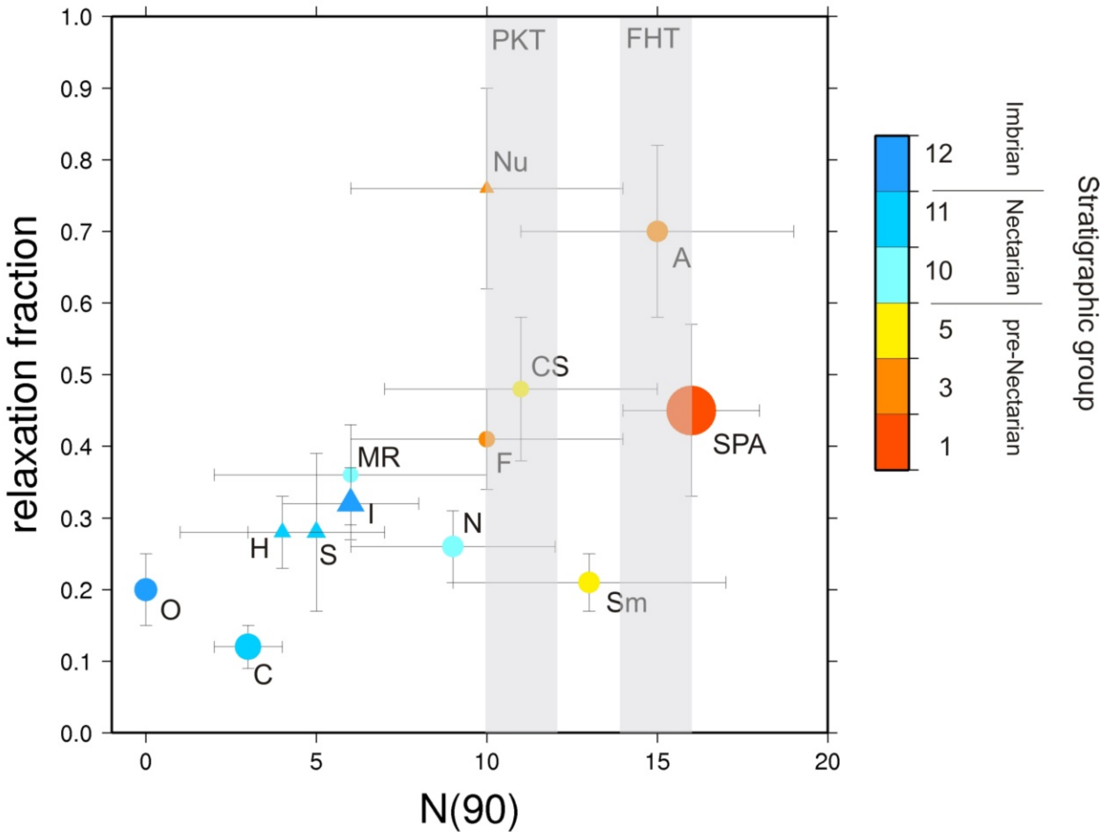

Figure 2. Crater density (N(90) from Evans et al. 2018) plotted against basin relaxation fraction (from Conrad et al. 2018). Colours denote stratigraphic position, from Evans et al.; symbol size is proportional to basin diameter. Only basins with diameters exceeding 650 km are plotted. Triangles represent basins within the PKT; circles represent basins outside this region. Vertical shaded regions are crater densities for PKT and Feldspathic Highland Terrain regions. Labels are as follows: O-Orientale; C-Crisium; H-Humorum; S-Serenitatis; I-Imbrium; MR-Mendel-Rydberg; N-Nectaris; F-Fecunditatis; Nu-Nubium; CS-Coulomb-Sarton; Sm-Smythii; A-Asperitatis; SPA-South Pole-Aitken.

It is immediately apparent that there is a strong correlation between these three factors – as one would expect. However, the correlation is not perfect, and several outliers are of interest.

One apparent outlier is Imbrium. This basin has N(90) and relaxation fraction values consistent with other Nectarian basins – but stratigraphically it is at the base of the Imbrian. Since Imbrium is the basin over which there is least disagreement about its age (3.92-3.94 Ga; Bottke & Norman 2017), this discrepancy is disconcerting. Evans et al. pay most attention to the possibility that Imbrium is older than Crisium, supported by both N(90) and relaxation fraction, but opposite to the conventional stratigraphy and the surface crater densities at smaller diameters (Fassett et al. 2012). A similar issue arises at Serenitatis, which looks similar in Figure 2 to Imbrium, but has much higher surface crater densities at smaller diameters (Fassett et al. 2012) and is stratigraphically older. This kind of mismatch between different constraints suggests that some as yet unaccounted-for factor is operating, which will require further work to resolve.

Two other outliers are apparent. Nubium is more relaxed than one would expect. This is likely due to its location in the Procellarum Kreep Terrane (PKT), which has high concentrations of radiogenic elements and thus will have experienced higher heat flows (Jolliff et al. 2000). These high heat flows would have promoted unusual degrees of relaxation (Mohit and Phillips 2006). Smythii is less relaxed than one would expect. The explanation here is less obvious, but might simply be that the true N(90) is towards the lower end of the estimated range.

Although South Pole-Aitken looks anomalous, this is probably a result of its greater size compared to all other basins: the timescale for a basin to relax by crustal flow goes as the square of the diameter (Melosh 1989). The relaxation timescale will be further lengthened by the apparently thin crust beneath SPA (Mohit and Phillips 2006). Thus, it is not surprising that SPA is less relaxed than Asperitatis.

The other major result of the Evans et al. study is that there is a clean break between pre-Nectarian and younger basins, roughly at N(90)=10. This epoch also defines the age of the PKT as a whole, and is also associated with a steep drop in relaxation fraction (Figure 2). It thus appears that N(90)=10 represents an important time-marker in lunar evolution. Evans et al. use the oldest radiometrically-dated mare basalt units within the PKT to argue that the PKT basement must be older than ~4.3 Ga. This timescale is consistent with the onset of unrelaxed basins at 4.21-4.45 Ga inferred by Conrad et al. (2018).

Conveniently, this time-marker divides the basins plotted in Figure 2 almost exactly in half. As a result, roughly half the observed basins, including SPA, must be older than ~4.3 Ga (pre-Nectarian). Despite the uncertainties in absolute age, it is clear that the pre-Nectarian time interval was shorter than post-Nectarian, and thus that the early impact flux was (on average) higher. The roughly constant N(90) values of pre-Nectarian basins could be the result of a brief spike in basin formation. However, Evans et al. argue that this constancy is in fact the result of saturation (see above) and does not indicate a brief formation period. Furthermore, the observed wide variation in relaxation fraction within the pre-Nectarian basins suggests either significant spatial variations in heat flux, or a more extended period of early, high impact flux. The latter possibility is consistent with, but not required by, dynamical models (e.g. Morbidelli et al. 2018). Evans et al. also point out that a later episode of high impact flux (perhaps starting with Nectaris) cannot be ruled out with the present data.

3 Conclusions

By including buried craters, Evans et al. have sharpened our picture of lunar history. As the discussion of Imbrium and Serenitatis above shows, not all of this picture yet makes sense, but their approach has certainly moved the debate forwards, and the general correlation between QCMA density and relaxation fraction (Figure 2) is encouraging. Further mining of the GRAIL data may move the completeness threshold to smaller diameters, which will help reduce the current large uncertainties.

Evans et al. were unable to establish a really tight absolute chronology, not because of inadequacies in the GRAIL data or their approach, but because of uncertainties in which radiometric dates to use. This problem has bedeviled all such attempts since the Apollo era (Stoffler et al. 2006; Bottke & Norman 2017). However, several countries are planning lunar sample return missions in the immediate future and these, at last, may put some of the most vexing issues of lunar chronology to rest.

Acknowledgments, Samples, and Data

No data were generated in this work. Funding from NASA-LDAP (NNH14ZDA001N) is acknowledged. Caleb Fassett is thanked for helpful comments.

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