The Violent Early Solar System, as Told by Lunar Sample Geochronology

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- One of the legacies of the samples collected by the Apollo and Luna missions is the link forged between radiometric ages of rocks and relative ages according to stratigraphic relationships and impact crater size-frequency distributions. Our current understanding of the history of the inner solar system is based on the relative chronology of individual planets, tied to the absolute geochronology of the Moon via these important samples.

But wait

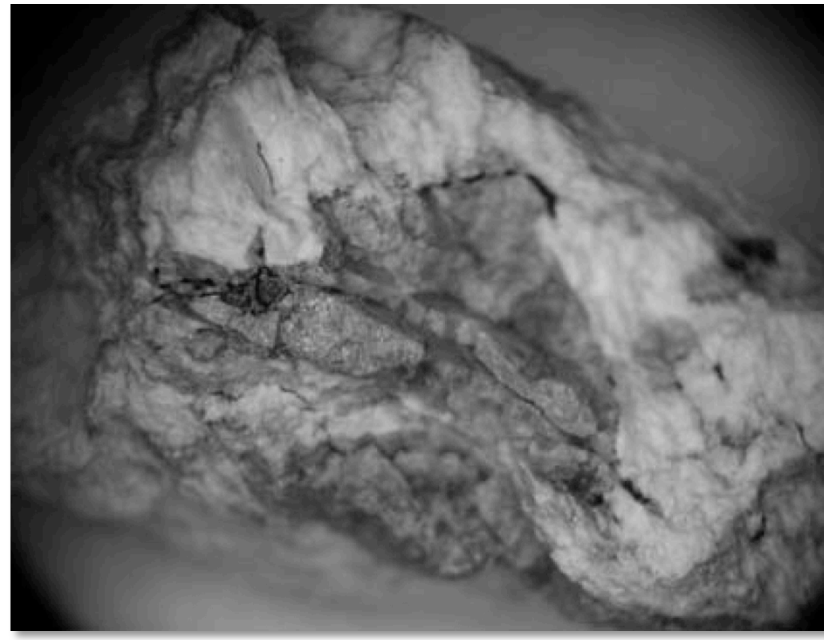
- Samples from these nearside locations reveal a preponderance of impact-disturbed or recrystallized ages between 3.75 and 3.95 billion years. Argon and lead loss (and correlated disturbances in the Rb-Sr system) have been attributed to metamorphism of the lunar crust by an enormous number of impacts in a brief pulse of time, called the Lunar Cataclysm or Late Heavy Bombardment. Subsequent high-precision geochronometric analyses of Apollo samples and lunar highlands meteorites show a wider range of ages, but very few older than 4 Ga. The paucity of ancient impact melt rocks has been interpreted to mean that either that most impact basins formed at this time, or that ejecta from the large, near-side, young basins dominates the Apollo samples.

The Lunar Cratering Record

- Sample ages have enabled us to infer that impact-melt breccias from Apollo 14 and 15 record the formation of the Imbrium Basin, those from the highland massifs at Apollo 17 record the age of Serenitatis, those from the KREEP-poor Apollo 16 site record the age of Nectaris, and materials from Luna 24 record the age of Crisium. Ejecta from smaller and younger craters Copernicus and Tycho were sampled at Apollo 12 and 17, respectively, and local craters such as Cone at Apollo 14, and North Ray and South Ray at Apollo 16 were also sampled and ages determined for those events. Much of what we understand about the lunar impact flux is based on these ages.

Pre-3.9 Ages are rare

- Pre-3.9 Ga ages of non-impact-melt samples
  - Apollo 16 and 17 granulitic breccias have peak metamorphic ages of 3.9 Ga OR 4.1 Ga (Hudgins et al. 2008)
  - A14 and A17 zircon overgrowths are 4.33 and 4.2 Ga (Grange et al. 2009, 2011)
  - Seven Apollo 16 regolith samples (feldspathic breccias and anorthosites) have plateau ages 3.9 Ga OR 4.2 Ga (Shuster et al. 2010)
  - Unique mafic-mineral rich sample of FAN 60025 has a multiple-isotopic age of 4360 ± 3 Ma (Borg et al. 2011)
- Are these recording ancient basin-forming impact events or lunar igneous activity?

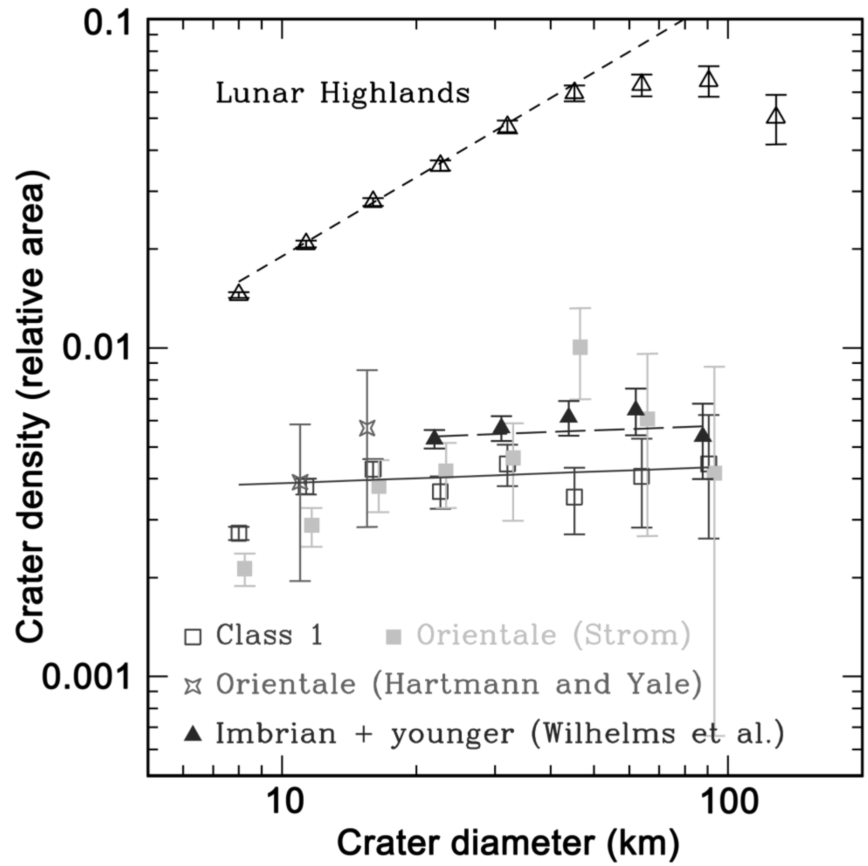


Ferroan anorthosite 60025 has a crystallization age of 4.36 Ga (Borg et al. 2011).

- The impact history of the Moon has significant implications because the lunar bombardment history mirrors that of the Earth. During the cataclysm, 80% of the lunar surface was resurfaced; on Earth, this would scale to ~23,000 large impacts in a brief time. Impact ages in ordinary chondrites, HED meteorites, and the Martian meteorite ALH 84001 suggest that this early bombardment event affected the entire inner solar system. If true, the late heavy bombardment may have directly affected the evolution of life on Earth and our understanding of "habitable" planets.

Old crater counts, revisited

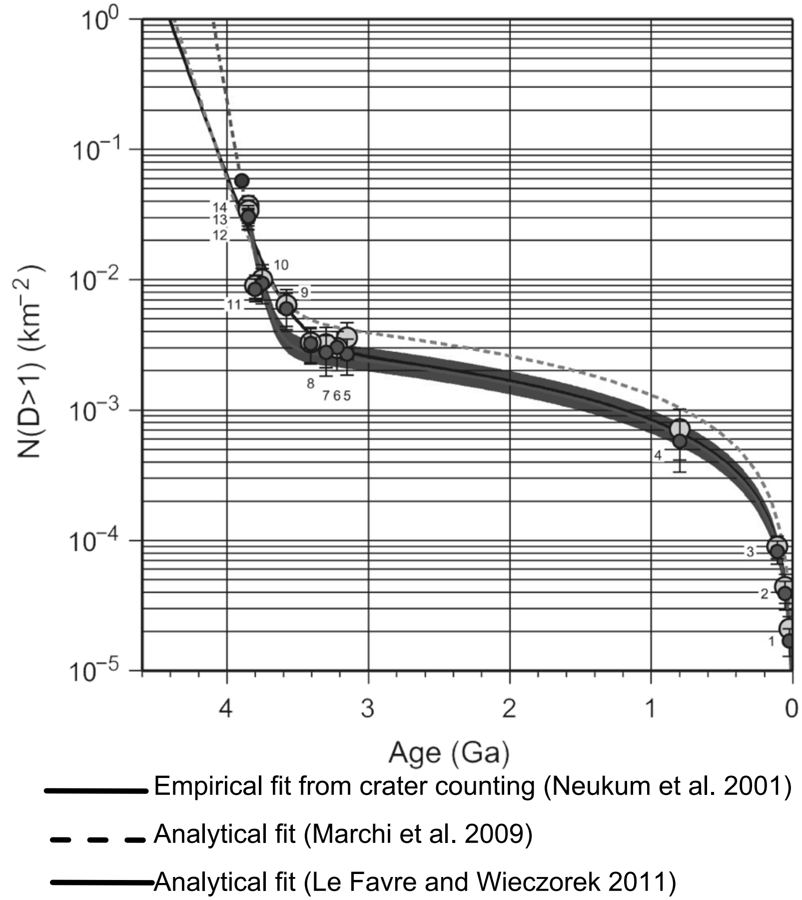
- Lunar highlands have SFD similar to main belt asteroids, while “morphologically fresh” Class 1 craters have SFD similar to NEAs (Strom et al. 2005)
- Cuk et al. (2010) argue that Class 1 craters have the same density on the whole moon as on basin ejecta blankets – therefore must be remnants of the LHB
- How can crater counts from different units be combined? Does crater morphology correlate with age? How are secondaries accounted for?



Size-frequency distributions of different crater classes (Cuk et al. 2010)

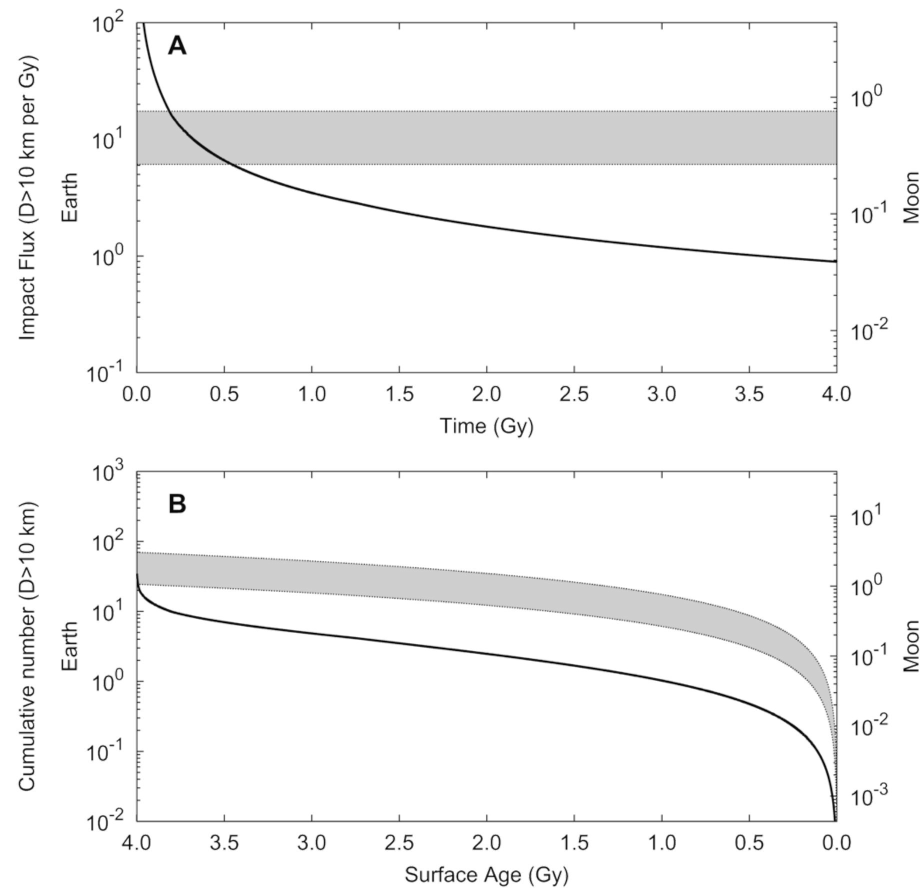
Lunar crater chronology calibration curves

- New lunar crater production functions derived from impact modeling differ significantly from those based on measurements (Marchi et al. 2009, Le Fevre and Wieczorek 2011)
  - reconcile measured lunar SFD with near-Earth asteroid population by assuming craters < few km form in a porous megaregolith, suggested by Ivanov et al. (2007)
  - quantify spatial cratering asymmetries that may bias crater density ages – worse for smaller bodies than larger
  - Estimate both Orientale and Caloris basins to be 3.73 Ga



Dynamical evolution of the source

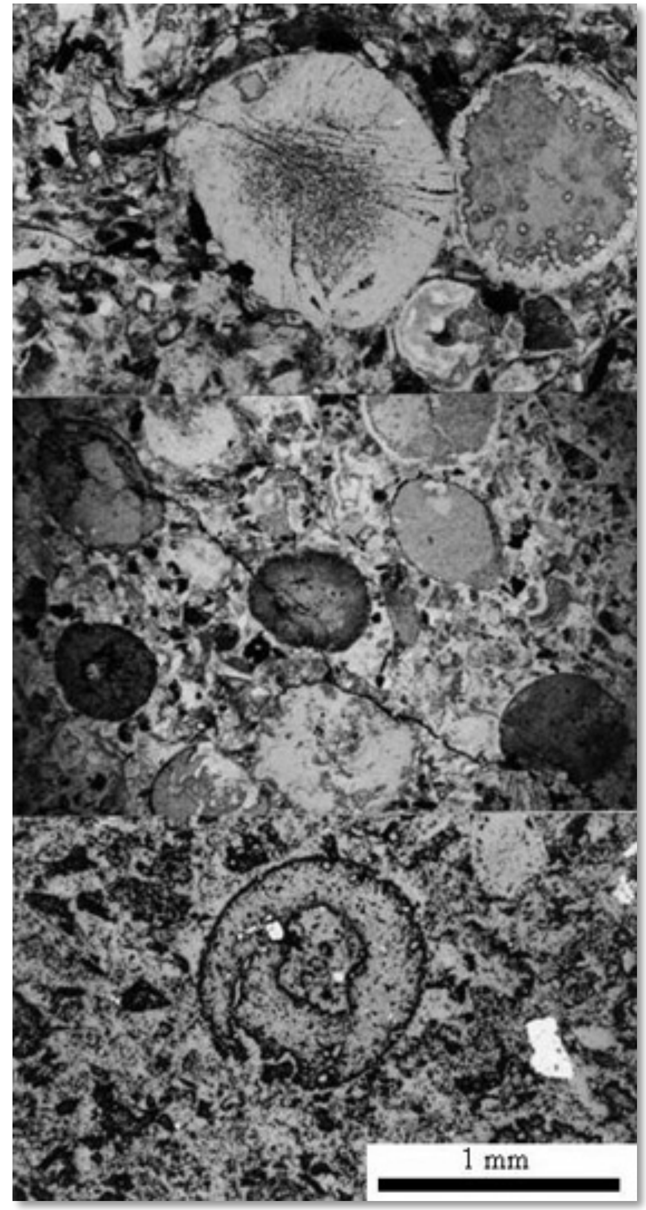
- Dynamical modeling of larger main belt asteroids shows that these are subject to loss; predicted rate of impacts declines by a factor of 3 over the last 3 Gyr (Minton and Malhotra 2010)
- "E-belt" source of main-belt asteroids predicts production of large lunar basins, long tailoff at Earth, and later siderophile veneer (Bottke et al. 2010, 2011)



Impact rates of D > 10 km asteroids on the Earth and Moon from model of Minton and Malhotra (2010) compared with the Neukum Production Function (shaded regions).

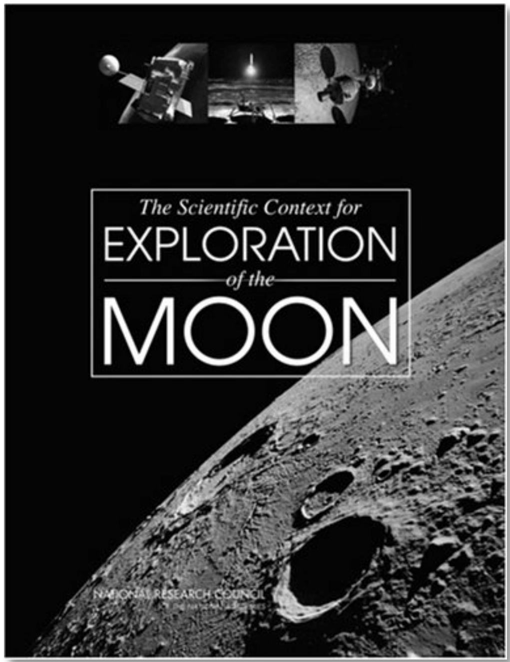
Terrestrial record

- Terrestrial spherule beds continue to be discovered: 3.47-3.23 Ga (7) 2.63-2.49 Ga (4) 2.1-1.6 Ga (2) (Glikson 2010)
- Isua metasedimentary rocks are enriched (150 ppt) in iridium compared to present-day ocean crust (20 ppt) – argues to be evidence of cometary input rather than asteroidal (Jørgensen et al. 2009)
- New (U, Th)-He technique for terrestrial impact-generated zircons (van Soest et al. 2010, Wartho et al. 2011)



Impact spherules of altered glass in 3.24 Ga impact ejecta in the Barberton , South Africa (Glikson 2010)

High-priority lunar science goals



1a. Test the cataclysm hypothesis by determining the spacing in time of the creation of the lunar basins.

1b. Anchor the early Earth-Moon impact flux curve by determining the age of the oldest lunar basin (South Pole-Aitken Basin).

1c. Establish a precise absolute chronology.

4a. Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions.

3a. Determine the lateral extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation.

2a. Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales.

2b. Characterize the chemical/physical stratification in the mantle, particularly the nature of the putative 500-km discontinuity and the composition of the lower mantle.

8a. Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity.

2c. Determine the size, composition, and state (solid/liquid) of the core of the Moon.

3b. Inventory the variety, age, distribution, and origin of lunar rock types.

8b. Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy.

Conclusions

- Selenochronology is getting more complicated: new results question meaning of sample ages, crater counts, crater production functions, and the solar system itself
- But there is hope!
  - Improved geological mapping of lunar geologic units and boundaries using multiple remotes-sensing datasets
  - High-resolution image-based crater counting of discrete geologic units and relating them to location
  - Improved understanding of the regolith thickness and its global variation (GRAIL)
  - Tying the sampling of impact-melt rocks to the lunar impact flux
  - Using improved techniques (magnetic fields, diffusion studies, isotopic analysis) on existing samples
  - New sample return from benchmark craters, particularly SPA, which appears in 2013 Decadal Survey