Assessing The Recent Impact Flux In The Inner Solar System: 1 Ga to the present

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Key concepts:

Inner solar system evolution is intimately tied to the history of bombardment

The impact rate—and variations over time and space—are fundamentally important for understanding the histories of individual bodies and of the solar system as a whole

The lunar impact record—and its calibration, through returned samples, to an absolute time scale—forms the basis for all planetary geological timescales

Events during the period from ~1 Ga to the present are particularly important because of their influence on the geological and biological evolution of the inner solar system bodies.

Credit: Mesa Shumacher/Santa Fe Institute

Credit: NASA

We currently have an unprecedented opportunity to investigate impact events that may be correlated across bodies.

An integrated approach is required to gain a clearer understanding of the inner solar system and its evolution as a whole.

Our questions:

How did the impact flux vary over the past billion years, and how do we know?

Do similar impact ages assigned to some craters on the Moon, Mercury, Mars, and Earth mean they were formed at the same time, and if so, what do they tell us about the impactor population?

How did the population of impactors vary over the past billion years?

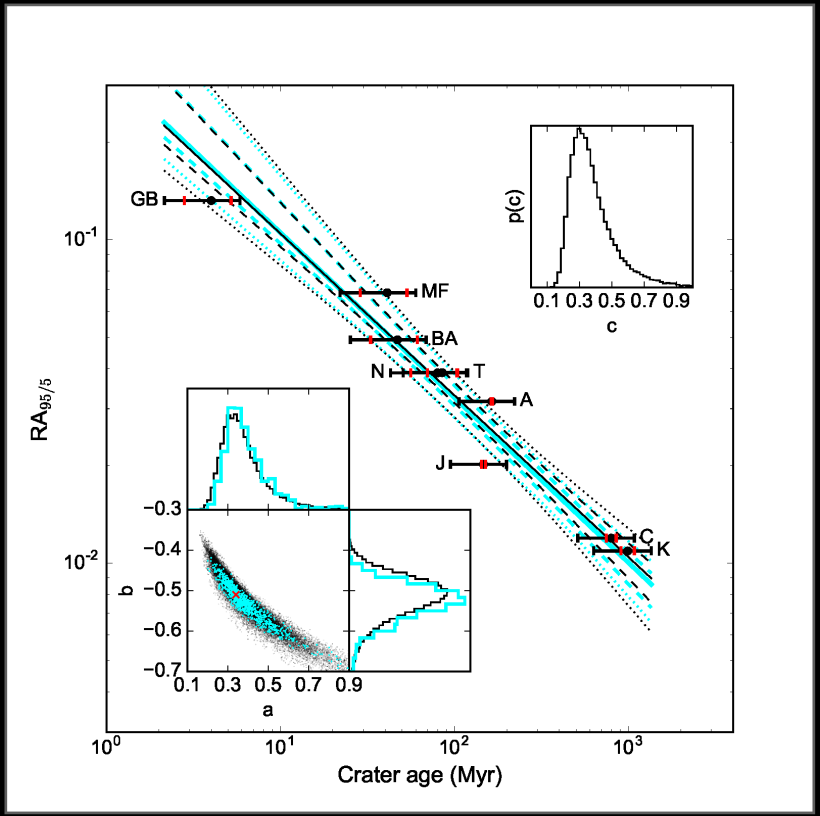
What can the modern impact flux tell us about the current populations of impactors?

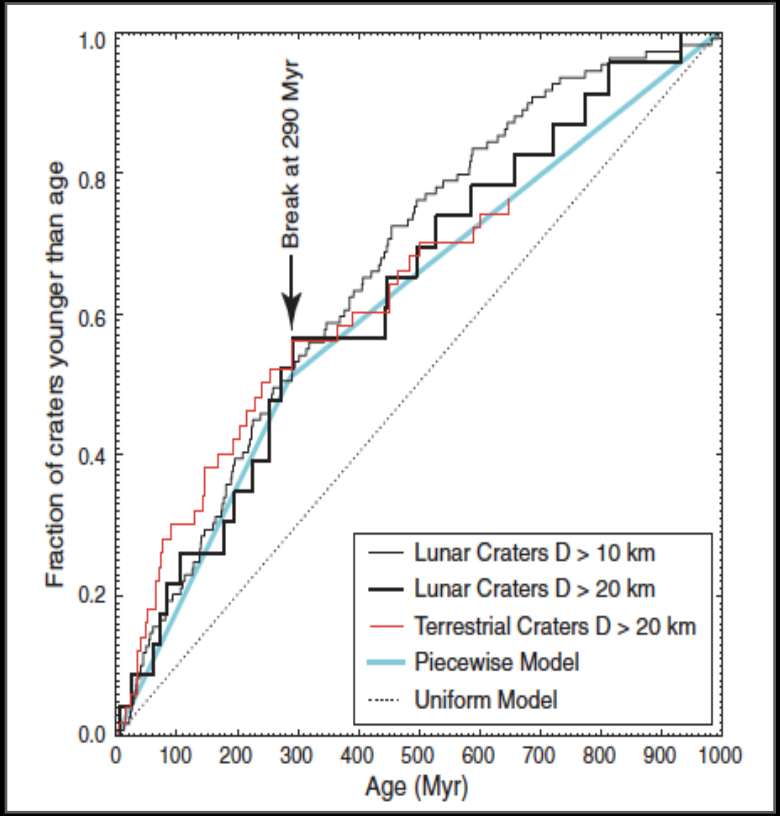
A Solar System View

Modern approaches to planetary science consider the solar system ***as a system:*** events preserved on one body likely signal important events in other parts of the system

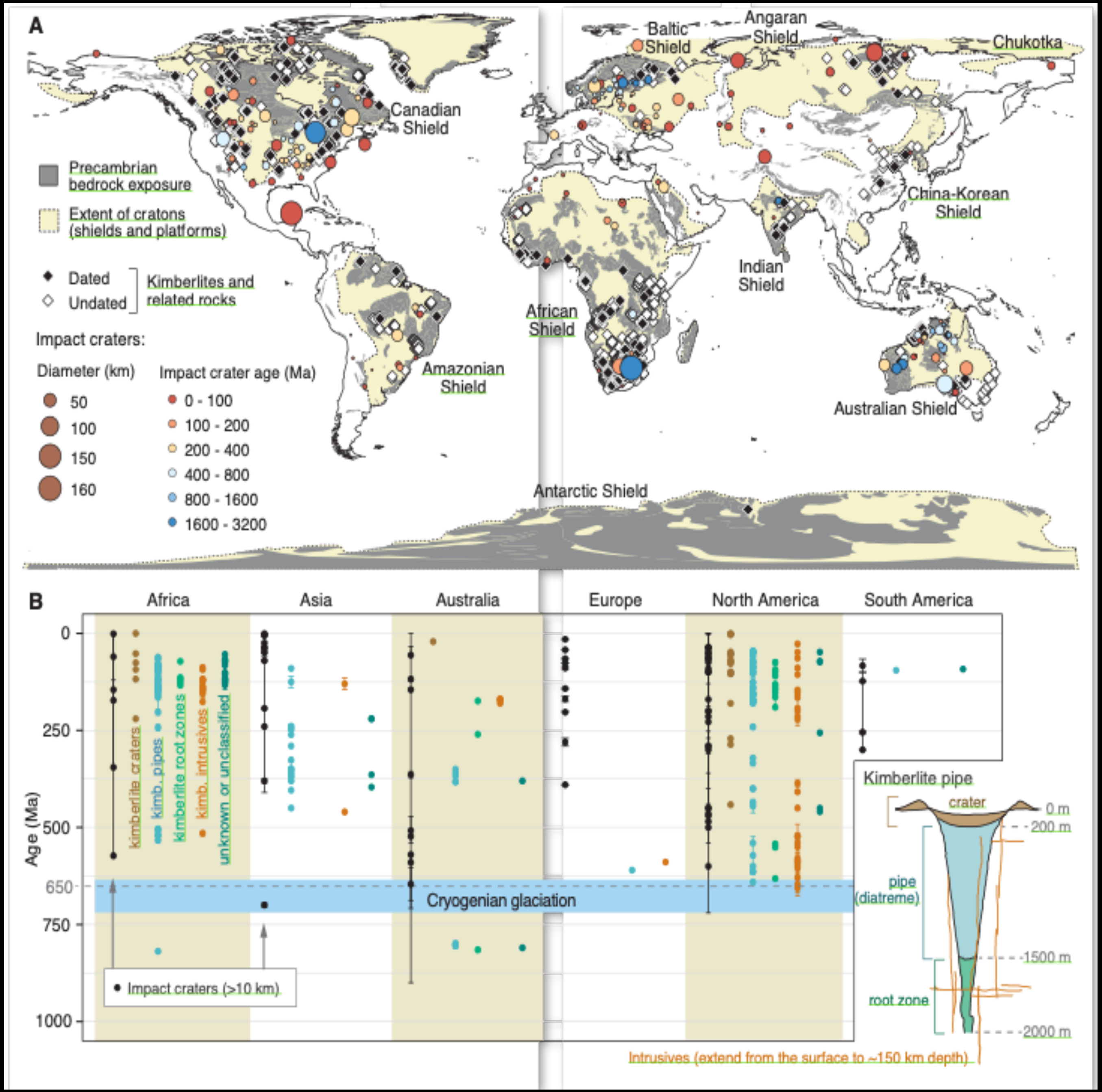
Case Study #1: Age spectrum of large craters <650 Ma on both the Moon and Earth reveal evidence for a non-uniform cratering rate on both bodies, with a step-wise factor of 2-3 increase at ~290 Ma

Statistically, impact events on the Moon result in ~20 times more events on Earth





Mazrouei et al. 2019



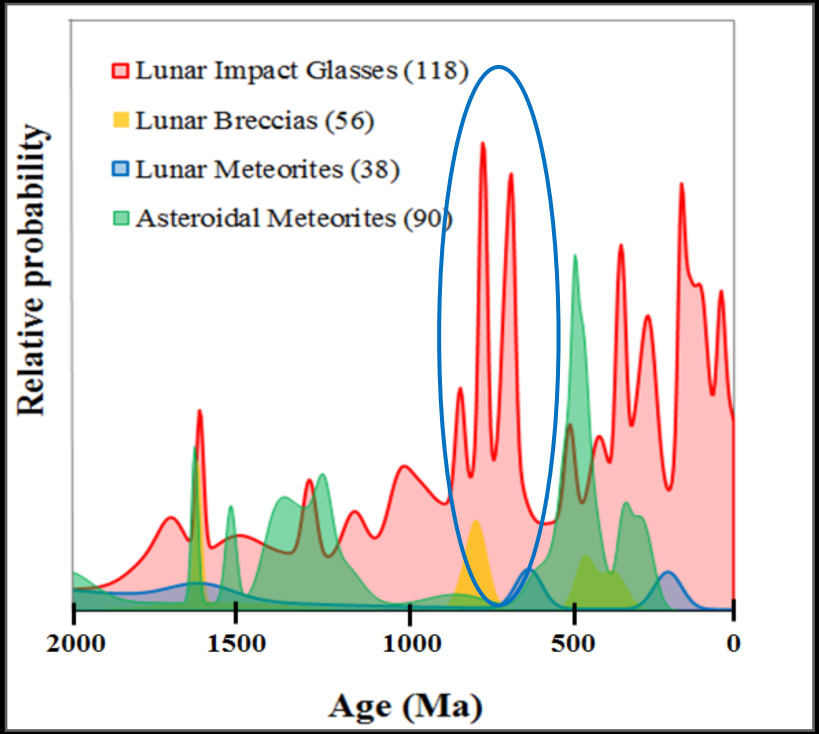
Global melting of Snowball Earths (660-710 Ma, 645-655 Ma) may have been influenced by water vapor lofted into the terrestrial atmosphere during coincident periods of enhanced impact flux.

This melting and associated erosion may be responsible for the observed lack of large terrestrial craters and spatially associated kimberlite diatremes on cratonic terrains, expressed as a sharp cutoff in the number of both features at 650 Ma relative to later times.

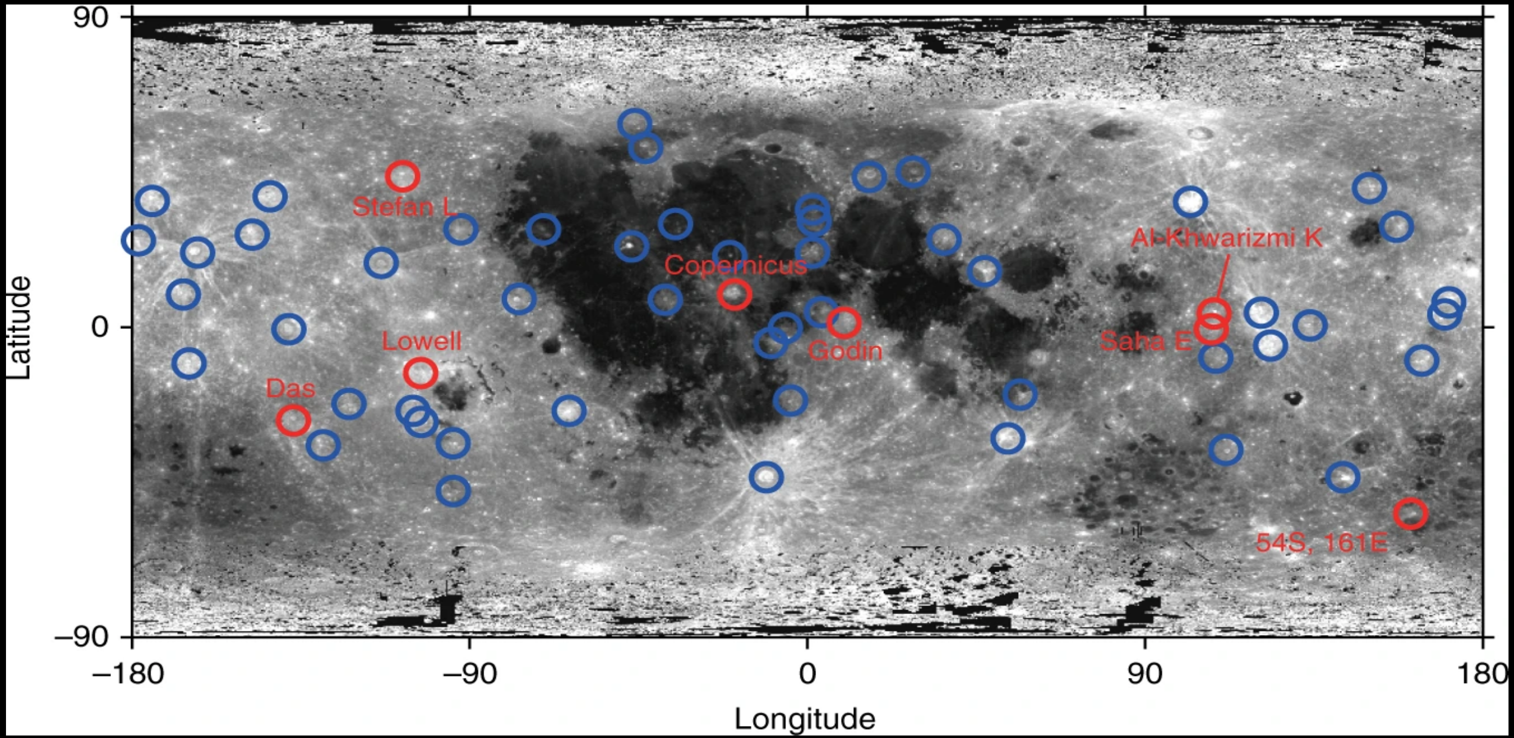
Case Study #2: Analyses of impact melts, particularly lunar impact glasses, show evidence of stochastic impact events – asteroid showers? – in the inner solar system:

e.g., during melting of Snowball Earths (645-710 Myr ago) and at 800 Myr ago; coincident ages of impact melts in H- and L-chondrites; samples of Chelyabinsk; identification of Copernican-aged craters on the Moon by the Kaguya mission.

Formation of the Flora family of asteroids may be responsible.



Modified from Zellner & Delano (2015)



59 craters w/ ages <800 Myr; red circles are craters ~800 Myr (Terada et al. 2020)

Case Study #3: Ages of fossil chondrite meteorites found in lower Ordovician (480 Ma) sediments provide evidence for an enhanced impact flux that may be dynamically linked to the break-up of the L-chondrite asteroid parent body and possibly others.

Debris from these impacts may have initiated the mid-Ordovician ice age

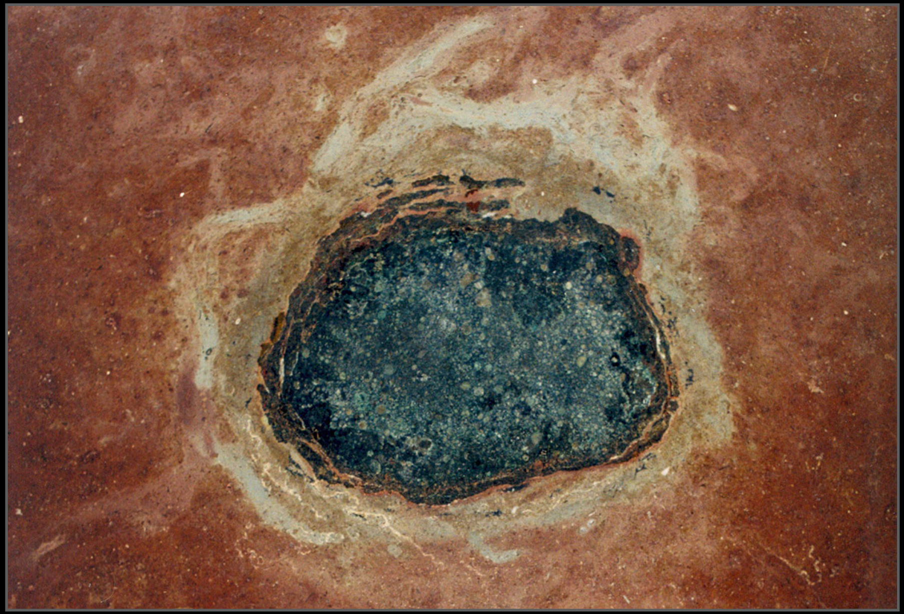
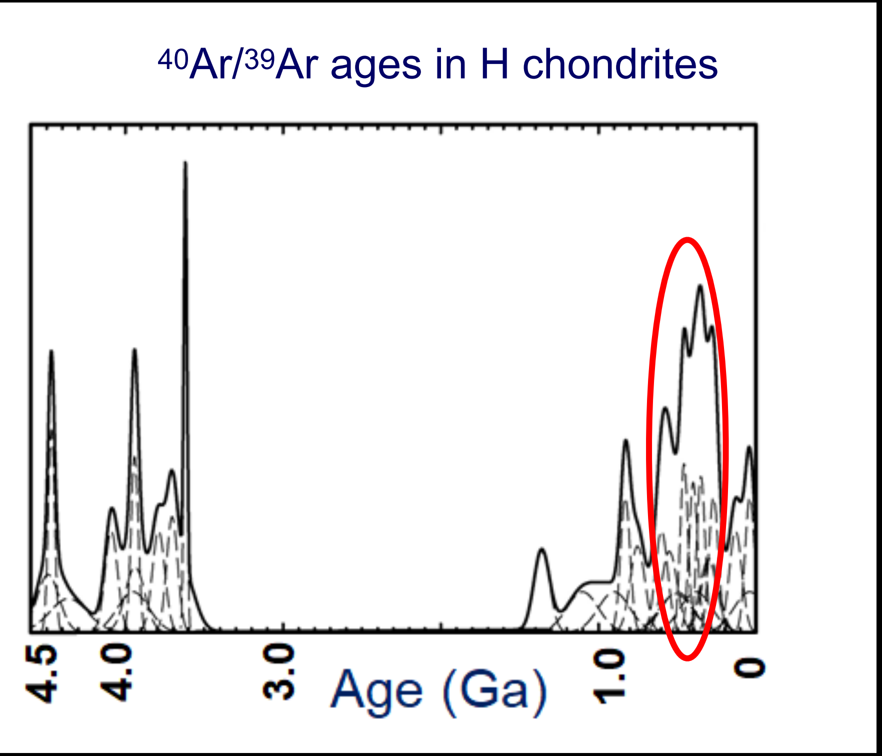


Image credit: Birger Schmitz

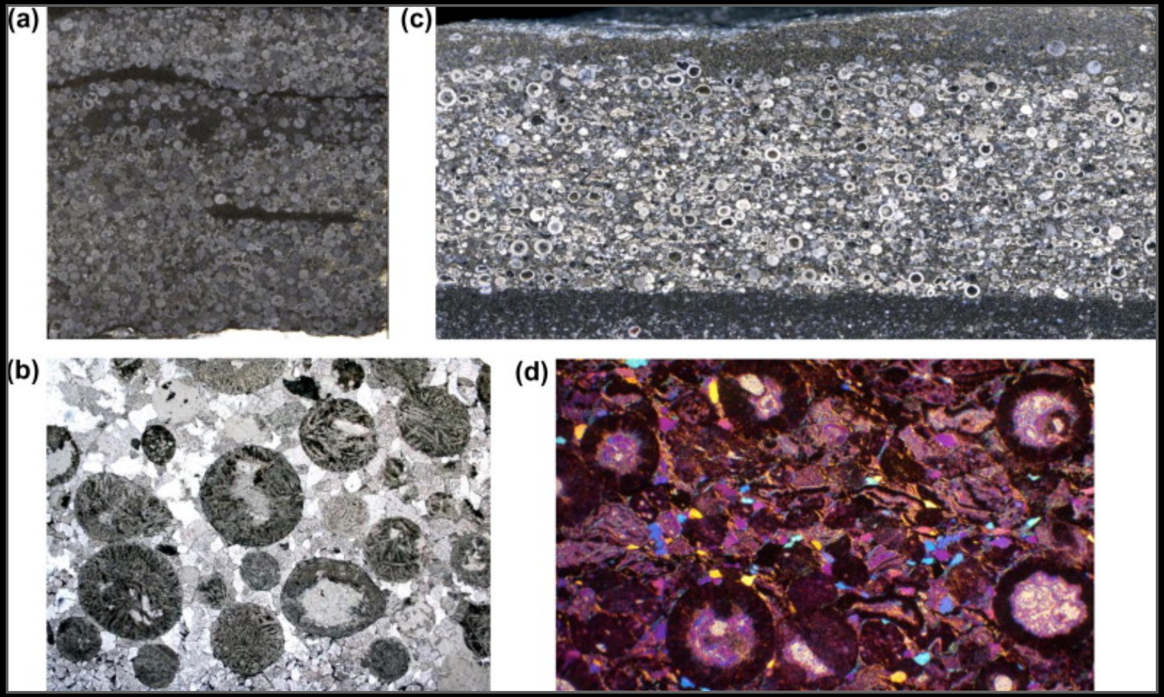


Modified from Swindle et al. (2009)

Ar isotope and U,Th-He ages of H chondrites show a range of impact melt ages <1Ga

Multiple samples with ages ~800 and ~500 Myr have been observed

Case Study #4: In addition to the record of terrestrial craters, there are ~ 20 impact spherule layers or tektite strewn fields younger than 2.0 Ga that are not associated with known craters

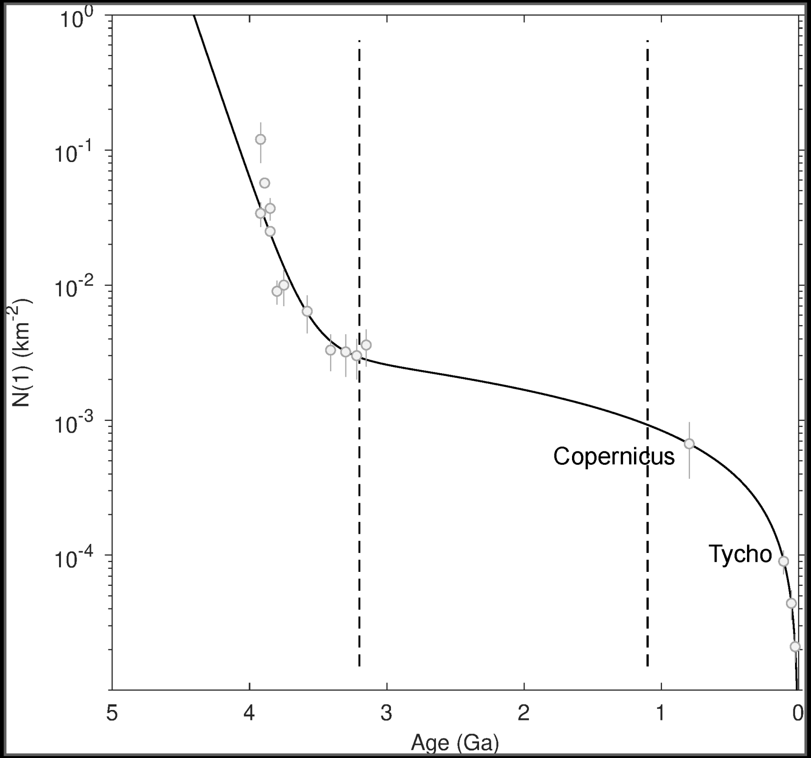


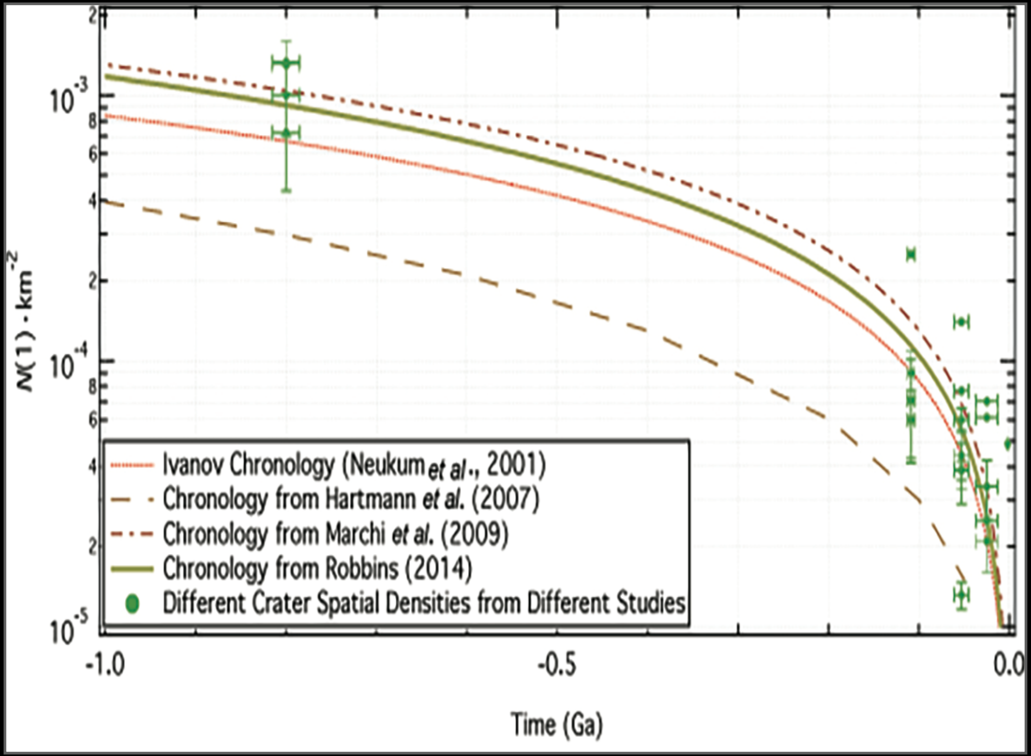
Reimold and Koeberl, 2014

Interpretations that tie these events together within each proposed timeframe are limited by small data sets, lack of well-characterized terrestrial geologic evidence, and/or large uncertainties in derived or estimated sample or crater ages.

More data are needed.

Canonical empirical chronology functions are anchored by the ages of a small number of returned lunar samples, all either >3 Gyr or <800 Myr in age; no samples exist with ages between 800 Myr and ~3.2 Gyr.





This large gap in the sample record represents a major source of uncertainty for defining the overall lunar chronology function, and the lack of data makes it challenging to accurately assign ages to lunar features <1 Gyr.

Additional complications include:

(1) systematic uncertainties in the absolute time scale calibration that can lead to age uncertainties that are both large and difficult to quantify

(2) crater counts that inherently average the terrains on which the counts are performed

(3) unrecognized secondary craters that can inflate crater counts and distort SFD curves
(4) counts on crater floors that yield systematically younger ages than ejecta counts

The latter two effects lead to a large spread in crater spatial densities calculated by different researchers. These uncertainties allow for different proposed chronology functions, all of which satisfy the available constraints.

These have important implications for recent events, and current data are insufficient to discriminate among them.

Addressing these questions requires a multidisciplinary approach that treats the entire system rather than individual bodies alone

Recommendations

1. New samples from well-documented and thoughtfully chosen lunar landing sites (e.g., P60, which has multiple flow units with AMAs as young as ~1 Ga); should represent a variety of compositions, ages, and source regions.
2. Continued support and development of Earth-based sample analysis laboratories; studies of multiple kinds of planetary samples, including meteorites
3. New approaches to the statistical treatment of impact cratering
4. New dynamical simulations of events affecting the Earth-Moon system
5. Further refinement of *in situ* sample dating techniques (e.g., Potassium-Argon Laser Experiment, KArLE [Cohen et al.]; Chemistry and Dating Experiment, CDEX [Anderson et al.]); missions to return those samples
6. New observations and analysis of craters on the Moon and other bodies, including Earth
7. Continued Earth-based investigations of micrometeorites and young craters and observations of lunar impact flashes + new work to quantify the small end of the impactor distribution represented by near-Earth objects
8. Creation of a diverse workforce that draws on multiple types of expertise and experience, specialties, and resources