Physical and Chemical Properties of LHB Impactors

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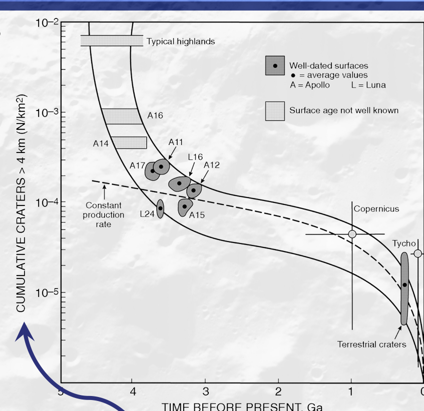
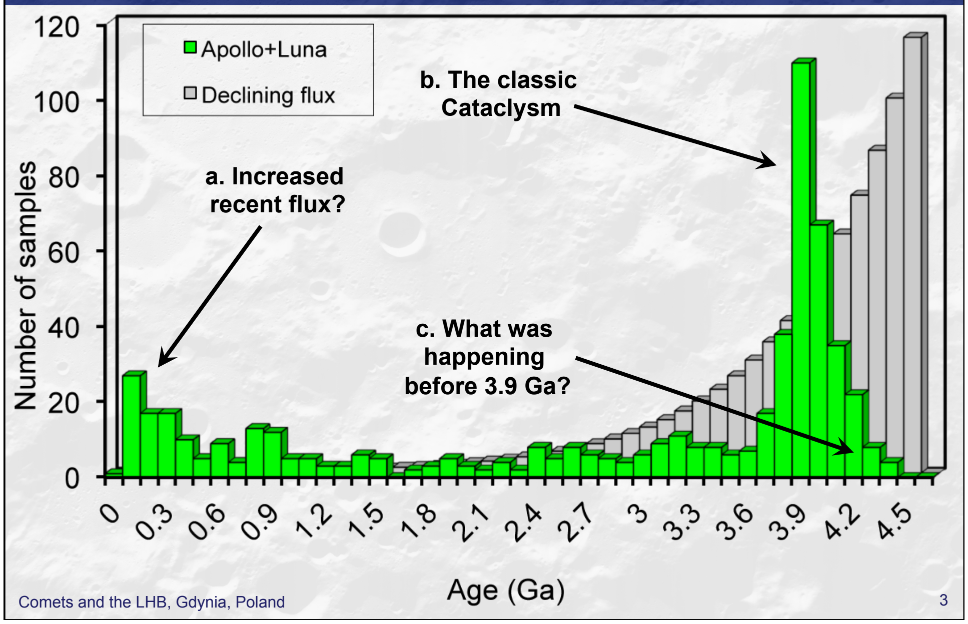
The absolute lunar timescale

- One of the legacies of the Apollo samples is the link forged between radiometric ages of rocks and relative ages according to stratigraphic relationships and impact crater size-frequency distributions
  - Ejecta from Copernicus at Apollo 12
  - Imbrium Basin impact-melt breccias from Apollo 14 and 15
  - KREEP-poor IMBs from Apollo 16 record the age of Nectaris and/or Imbrium
  - Highland massifs at Apollo 17 give age of Serenitatis, and younger samples from Tycho
  - Materials from Luna 24 record the age of Crisium basin



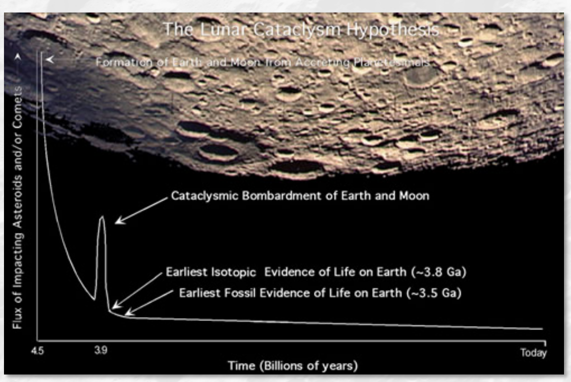
This axis depends on both elapsed time and rate of impacts/time = flux

A record of bombardment



The classic Cataclysm

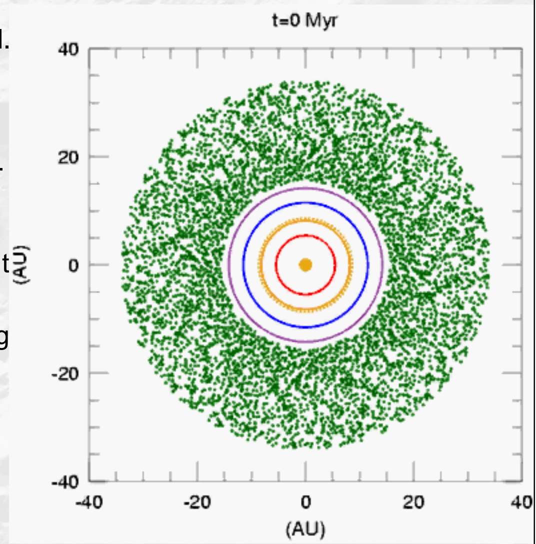
- Many Apollo 14, 16, 17 rocks crystallized at 4.5 Ga but experienced Pb loss at 3.9 Ga Tera et al (1974)
- Subsequent Rb-Sr and Ar-Ar ages on impact-melt rocks corroborate the large number of ~3.9 reset or disturbance ages



- Elements of the classic cataclysm:
  - Widespread lunar metamorphism by impact
  - Created at least three large basins in <0.2 Gyr (Serenitatis, Imbrium, Orientale)
  - Resurfaced much of the lunar nearside
- An important time in Earth-Moon system

The classic Cataclysm

- Nice Model (Tsiganis et al., Morbidelli et al. and Gomes et al. 2005): Planet/planetesimal interaction causes Uranus and Neptune to migrate outward (destabilizing icy planetesimals - Trojan asteroids) and Jupiter to move inward, sweeping resonances through asteroid belt (late heavy bombardment)
- Consistent with secular sampling of asteroid belt (Strom et al. 2005); modeling of main belt asteroids predicts production of large lunar basins, long tailoff at Earth, and siderophile veneer (Minton and Malhotra 2010; Bottke et al. 2011)



Searching for signs of the LHB impactors

- On the Earth:
  - Atmosphere
  - Hydrosphere
  - Oldest Rocks
  - Spherule beds

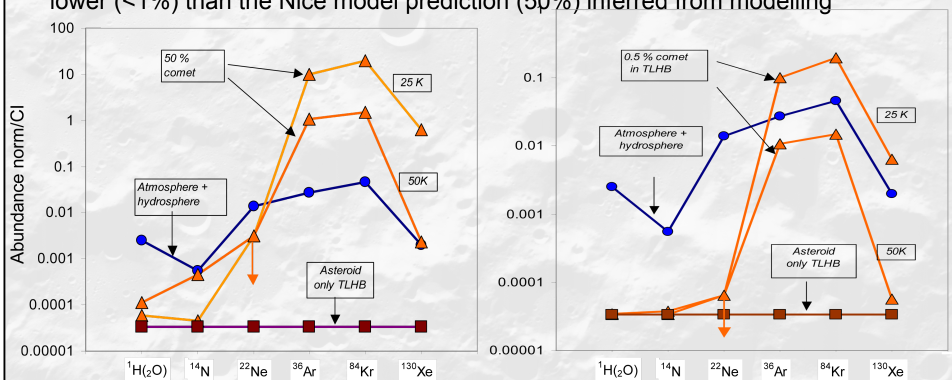

Barberton spherules – oldest terrestrial impact evidence

- On the Moon
  - Chemical signatures of the impactors in impact-melt rocks
  - Pieces of the physical impactors


Bench Crater, Apollo 12 – first extraterrestrial meteorite

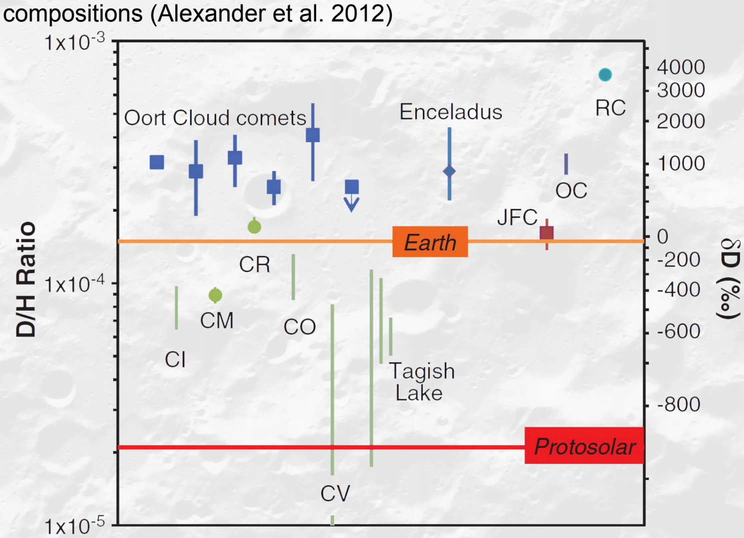
On the Earth (1): Atmosphere

- The terrestrial atmosphere and hydrosphere is enriched in noble gases relative to the abundance of volatiles in the mantle
- Consistent with the mass delivered to Earth during the LHB from Nice model (Gomez et al., 2005) - Kuiper-belt (cometary) objects (KBOs) + chondritic (asteroidal) impactors
- Fraction of KBOs necessary to account for the atmospheric composition is much lower (<1%) than the Nice model prediction (50%) inferred from modelling



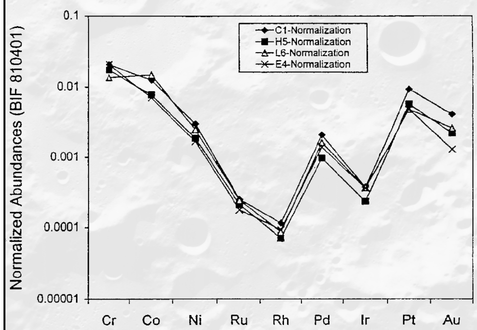
On the Earth (2): Hydrosphere

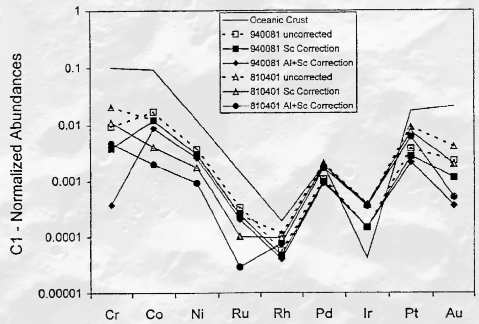
- Asteroidal sources can most simply explain Earth's bulk hydrogen and nitrogen isotopic compositions (Alexander et al. 2012)



One the Earth (3): Isua Gneiss

- Metasedimentary rocks from the Isua greenstone belt in Greenland (2.8 Ga)
- Average iridium abundance of ~150 ppt (7x earth and 15x Moon) - qualitative agreement with a cometary LHB but not asteroids (Jørgensen et al Icarus 2009)
- However, abundance of other siderophile elements does not match known meteorites and does track well with oceanic crust (Koeberl)



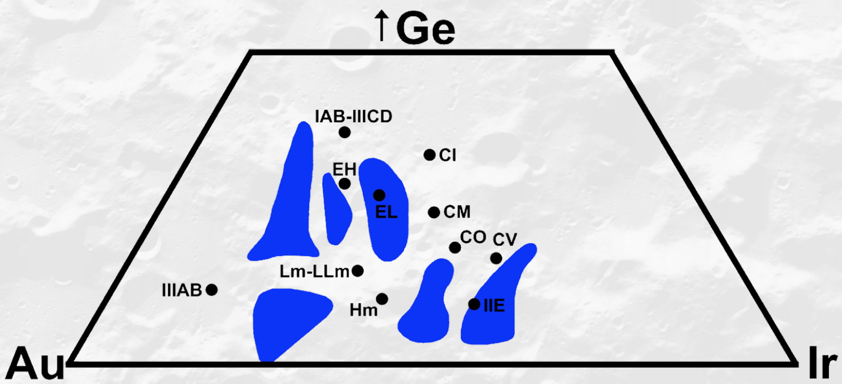


On the Earth (4): Barberton spherules

- Barberton (3.22 Ga) – carbonaceous chondrite
- ComparableresultscomefromthechromiumcontentandisotopicsignaturesofmaterialfoundinArchean-eraimpactspherulebedsfoundonEarth.TheoldestknownArcheanspherulebedslooklike theywereproducedbymetamorphosedcarbona-ceouschondrites,withtheclosestmatchbeingtoCVchondrites(orinsomecases,CKorCR chondrites)[5,61].TheyoungerArcheanandearly-Proterozoicspherulebedslookliketheywereproducedbyenstatiteandordinarychondrite-likeprojectiles[62].

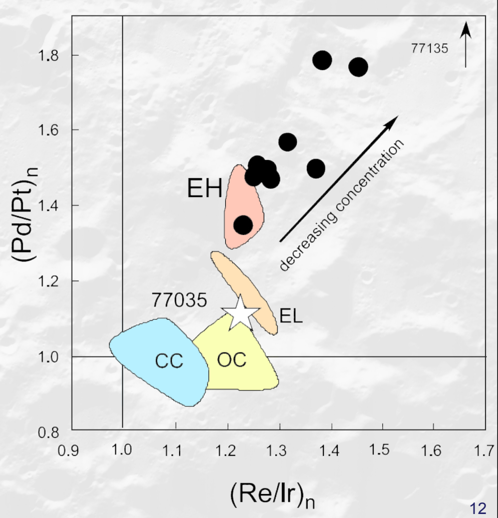
On the Moon (1): HSEs in impact melts

- Mature lunar regoliths exposed to space for tens to hundreds of millions of years have ~2 wt % added siderophile-rich material, with average chondritic composition
- HSE analyses of individual lunar basin impact melts imply projectile compositions similar to both chondritic and differentiated bodies that are interpreted to be asteroids rather than comets or Kuiper belt objects (Kring and Cohen 2001)



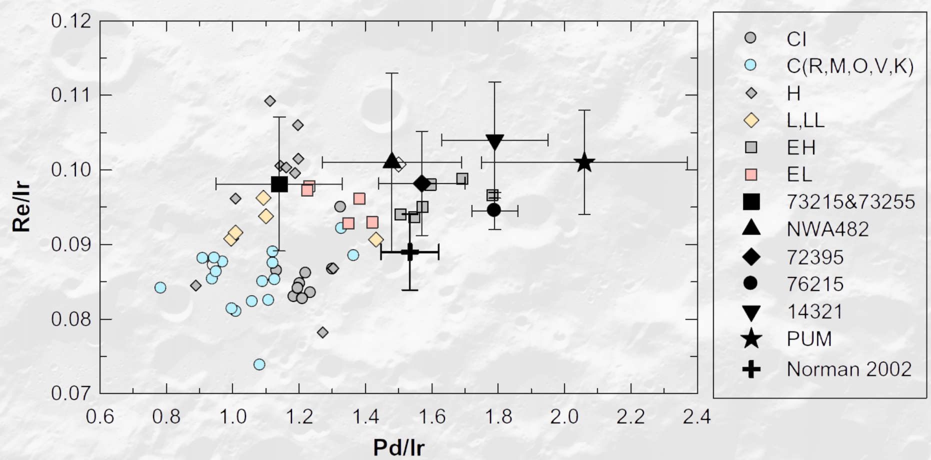
On the Moon (1): HSEs in impact melts

- The clear identification of specific types of meteoritic impactors (Norman et al. 2002) shows that the pre-Serenitatis lunar crust was not heavily contaminated with meteoritic siderophiles prior to the formation of these breccias
- more consistent with basin formation during a late heavy bombardment than during a declining accretionary tail

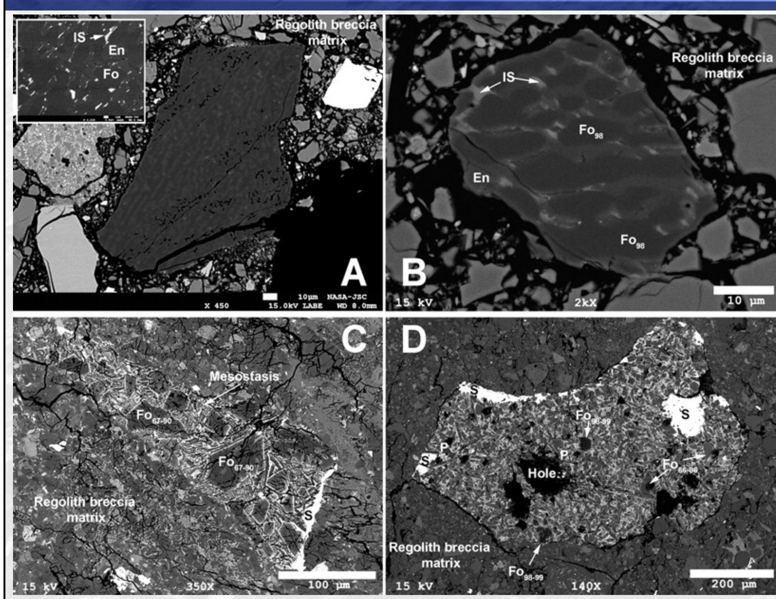


On the Moon (1): HSEs in impact melts

- Re, Os, Ir, Ru, Pt, and Pd in Apollo 17, Apollo 14, and lunar meteorite NWA482 (Puchtel et al 2008)

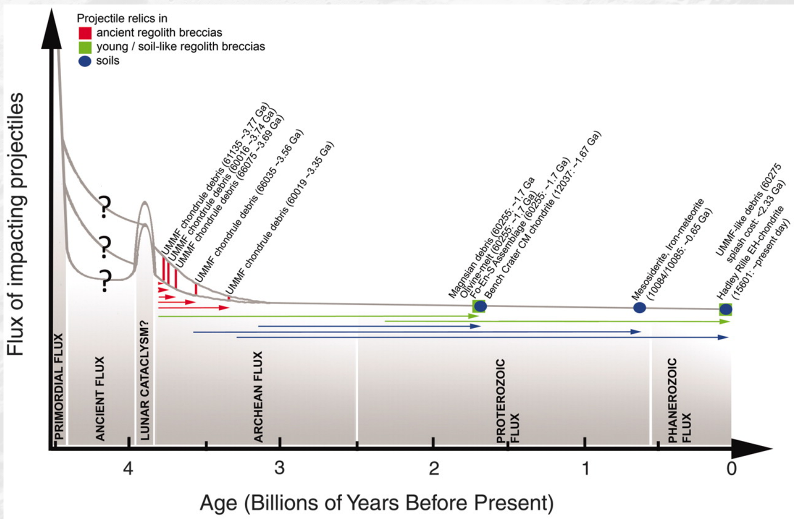


On the Moon (2): Projectile recovery



Backscattered electron images of representative projectile fragments found in ancient and younger lunar regolith breccias (Joy et al. 2012)

On the Moon (2): Projectile recovery



Ages and types of projectile debris on the Moon (Joy et al (2012)

Summary & Conclusions

- On balance, most evidence points away from cometary / carbonaceous chondrite sources
- Best fits seem to be enstatite chondrites
- E-chondrites are also best fit to bulk Earth
- Carbonaceous chondrites better fit to hydrosphere/later veneer?
- Remnants are the Hungaria family
- 4.0 Ga cataclysm may have contributed to siderophile element heterogeneity on the Earth, but would not have made a significant contribution to the volatile budget of the Earth or oxidation of the terrestrial mantle