A REVIEW OF LUNAR METEORITE IMPACT-MELT CLAST COMPOSITIONS AND AGES. Barbara A. Cohen, Marshall Space Flight Center, Huntsville AL 35812 (Barbara.A.Cohen@nasa.gov).

Introduction: One of the important outstanding goals of lunar science is understanding the bombardment history of the Moon and calibrating the impact flux curve for extrapolation to the Earth and other terrestrial planets. Obtaining a sample from a carefully-characterized interior melt sheet or ring massif is a reliable way to tell a single crater's age. A different but complementary approach is to use extensive laboratory characterization (microscopic, geochemical, isotopic) of float samples to understand the integrated impact history of a region. Both approaches have their merits and limitations. In essence, the latter is the approach we have used to understand the impact history of the Feldspathic Highland Terrain (FHT) as told by lunar feldspathic meteorites.

Feldspathic lunar meteorites: The feldspathic lunar meteorites are regolith and fragmental breccias with high Al_2O_3 / low Th content relative to the KREEPy, mafic impact-melt rocks of the Apollo collection. The stochastic nature of lunar meteorite launch events implies that these meteorites are more representative of the feldspathic lunar highlands than the Apollo and Luna samples [e.g., 1-3]. More than 100 impact melt clasts from 12 feldspathic lunar meteorites (MAC 88105, QUE 93069, DaG 262, DaG 400, NWA 482, Dhofar 025, Dhofar 303, Dhofar 910, Dhofar 911, Kalahari 008) and two possible nearside lunar meteorites (Calcalong Creek and SaU 169) have been studied [4-10]. Impact-melt clasts within the meteorites in the meteorites have usually been identified without regard for their composition, using textural criteria with the petrographic and scanning-electron microscopes. The identified clasts are generally microporphyritic or quench-textured and fully crystalline, having textures similar to well-known rocks of impact origin that establish their origins as impact-melt samples.

Clast Compositions: Figure 1 shows that the majority of impact-melt clasts in the studied meteorites are similar in composition to the bulk feldspathic meteorite field rather than the typical mafic, KREEPy impact melts of the Apollo collection, which came from the Procellarum KREEP Terrain (PKT). The impacts in which they were produced either predate the PKT or were sited in the feldspathic highlands where KREEPy material is rare. By extension, breccias that do not contain KREEPy clasts either formed far from the PKT or were lithified and closed to new input prior to formation for the PKT. Impact-melt clasts within each meteorite tend to cluster around the bulk composition, indicating that they are locally derived. However, the textural variety and the range in Mg# (Fig. 1c) suggest that the clasts originated in more than one impact event. The range of clast com-

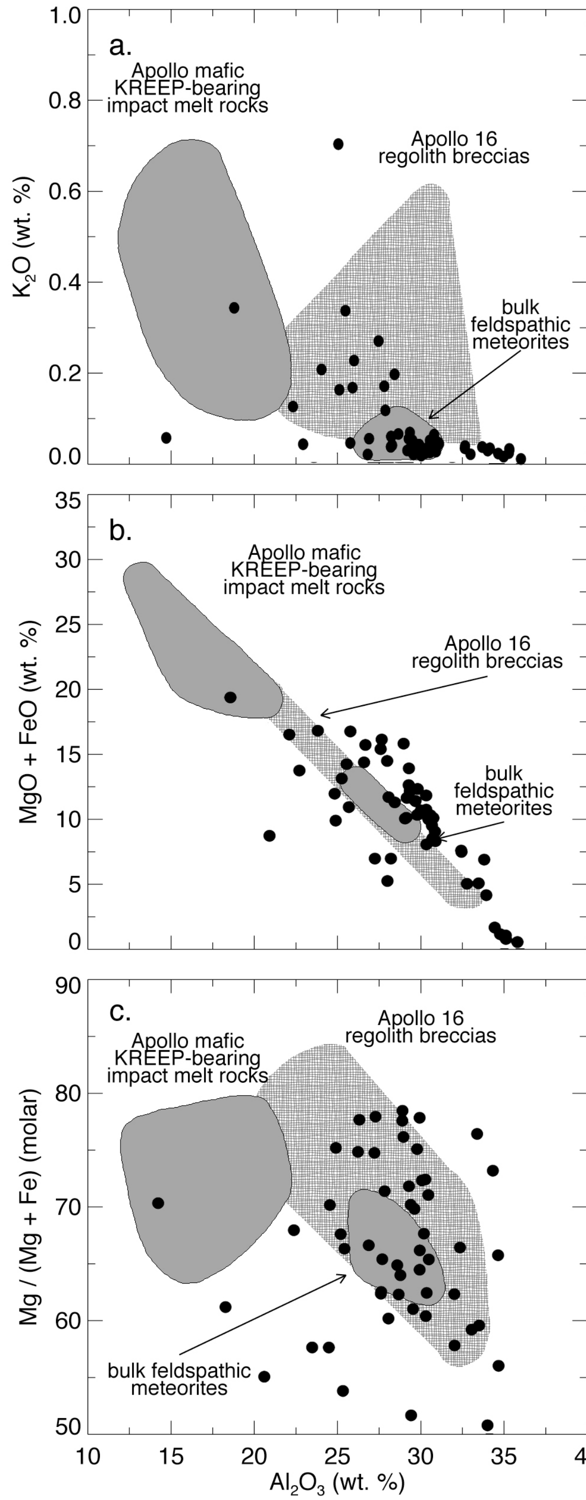

Fig. 1: Impact-melt clast compositions in lunar meteorites [4-10].

positions within each meteorite is similar to the compositional range displayed by Apollo 16 regolith breccias, which is the result of mixing of feldspathic lithologies with the more mafic lithologies of the PKT. Though trace elements on dated impact-melt clasts have not yet been obtained, Fig. 1 implies that the mafic component in the meteorite breccias is not the same as in the A16 breccias, and is more likely to be gabbroic or basaltic.

Clast Ages: Figure 2 shows that impact-melt clast ages range from ~4.0 Ga to younger than 2.0 Ga, with a statistical peak around 3.5 Ga. It appears that impact-melt rocks created in post-basin bombardment dominate the very surface of the lunar regolith and are readily incorporated into regolith breccias until the breccia lithification event. No samples are >1.1 σ older than 4.0 Ga, the older limit of the predominant age range among Apollo impact melt rocks. This older age limit is consistent with a resurfacing event in the FHT at that time, such as a global lunar cataclysm. Alternatively, older impact melt rocks may have been gardened back into the regolith column, becoming volumetrically rare. Either way, the impact rate after 4.0 Ga is probably low enough that the impact-melt clasts now at the surface effectively sample the impact flux since 4.0 Ga.

Conclusions: Impact-melt clasts in lunar meteorites show that surface breccias provide a relatively representative sample of the upper lunar surface in the area where they formed. The impact-melt ages within them therefore record of the impact history of that region between the time of the last major resurfacing (or gardening) event and the time of breccia closure, perhaps with a statistically small number of older samples entrained in the upper regolith. Because the samples come from the uppermost surface, we can correlate composition of the clasts with lunar terrains from remote sensing data [11-12] to conclude that the age distribution of clasts in the feldspathic meteorites reflects the impact history of the FHT from ~4 Ga to the closure age of the meteorites.

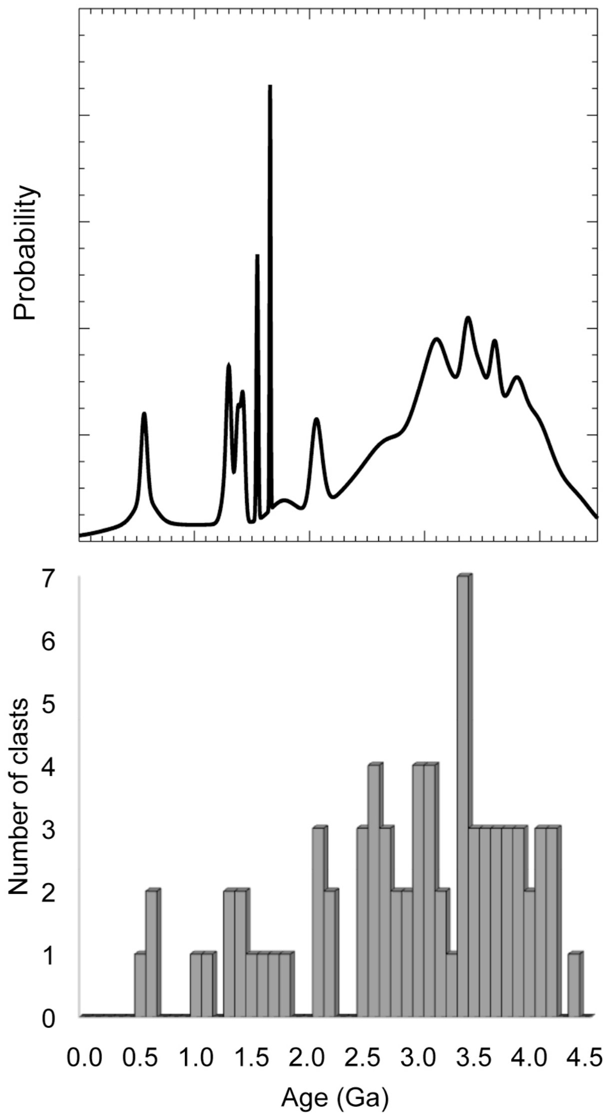

Fig. 2: Impact-melt clast ages in lunar meteorites [4-10].

References: [1] Taylor, G. J. (1991) Impact melts in the MAC88105 lunar meteorite: Inferences for the lunar magma ocean hypothesis and the diversity of basaltic impact melts. GCA 55(11): 3031-3036. [2] Warren and Kallemeyn (1991) The MacAlpine Hills lunar meteorite and implications of the lunar meteorites collectively for the composition and origin of the Moon. GCA 55:3123–3138.3. [3] Korotev (2005) Lunar geochemistry as told by lunar meteorites. Chemie der Erde 65: 297–346. [4] Cohen, B. A., T. D. Swindle, et al. (2000) Support for the lunar cataclysm hypothesis from lunar meteorite impact melt ages. Science 290(5497): 1754-1756. [5] Fernandes et al. (2000) Laser argon-40-argon-39 age studies of Dar al Gani 262 meteorite. MAPS 35(6): 1355-1364. [6] Cohen et al. (2002). ^{40}Ar-^{39}Ar ages from impact melt clasts in lunar meteorites Dhofar 025 and Dhofar 026. LPSC 33, #1252. [7] Daubar et al. (2002) Northwest Africa 482: A crystalline impact-melt breccia from the lunar highlands. MAPS 37(12): 1797-1813. [8] Fernandes et al. (2004). Ar-Ar studies of Dhofar clast-rich feldspathic highland meteorites: 025, 026, 280, 303. LPSC 35, #1514. [9] Cohen et al. (2005) Geochemistry and ^{40}Ar-^{39}Ar geochronology of impact-melt clasts in lunar meteorites Dar al Gani 262 and Calcalong Creek. LPSC 36, #1481. [10] Cohen (2008) Lunar Meteorite Impact Melt Clasts and Lessons Learned for Lunar Surface Sampling. LPSC 39, #2532. [11] Zellner et al. (2002) Impact glasses from the Apollo 14 landing site and implications for regional geology. JGR E107: 12-1. [12] Gnos et al. (2004) Pinpointing the source of a lunar meteorite: Implications for the evolution of the Moon. Science 305: 657–659.

A review of lunar meteorite impact-melt clast compositions and ages

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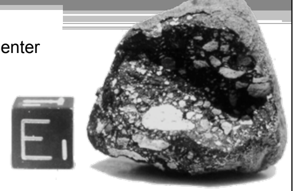
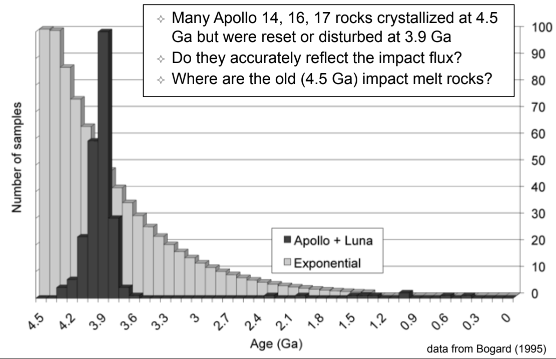
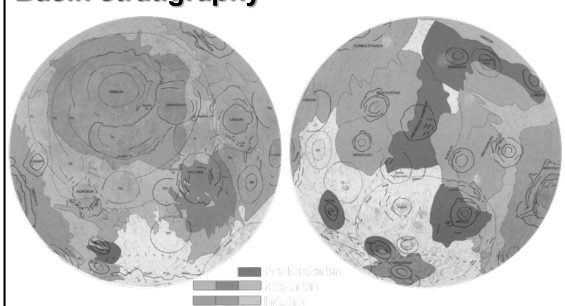


Lunar impact record



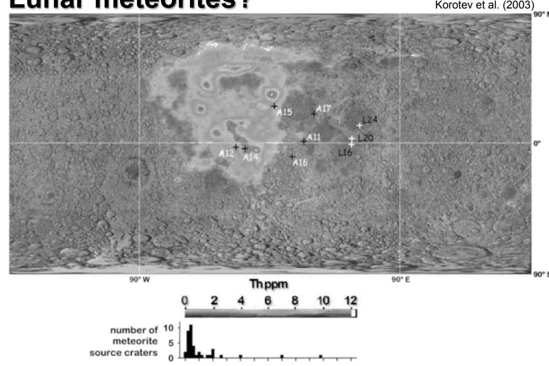
data from Bogard (1995)

Basin stratigraphy



Lunar meteorites?

Korotev et al. (2003)



Lunar meteorites

- ~50 lunar meteorites (more stones) recovered from Antarctica, African and Arabian deserts, and Australia
- >100 impact melt clasts studied so far in 10 lunar feldspathic breccias
- Feldspathic (An 95-98), high Al, low Ti
- Similar major-element chemistries as each other, but different from Apollo mafic, KREEPy impact melt rocks
- ^{40}Ar-^{39}Ar ages on microsamples (50-200 μg each)
- Small samples push the envelope of sample analysis capabilities – ages have fewer heating steps & larger uncertainties

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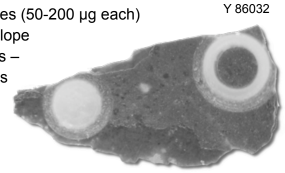
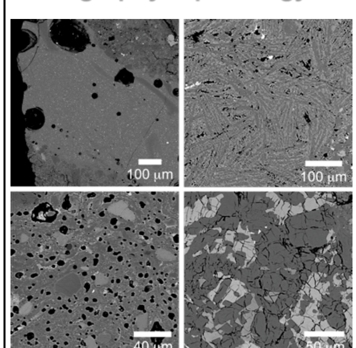


5 mm

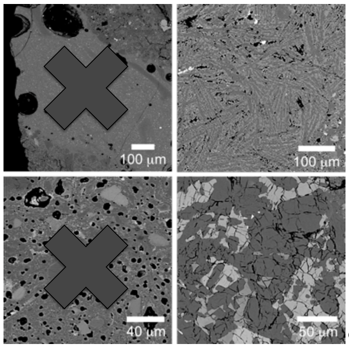
Petrography & petrology



- Crystalline impact melt clasts identified in thin sections
- Distinctive poikilitic textures, quench lathes
- Clasts identified before compositional data acquired – prevents bias in K_2O content

Cohen et al. (2000, 2006)

Petrography & petrology



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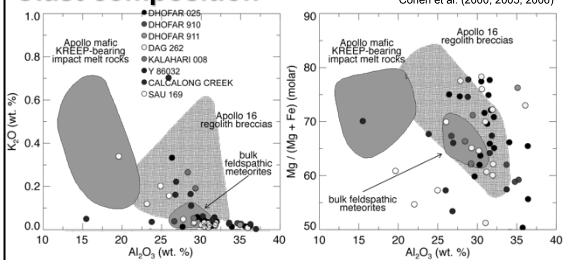
Clast composition

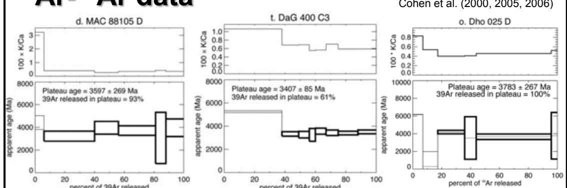
Cohen et al. (2000, 2005, 2006)



- Meteorite clasts are more feldspathic than previously dated impact melt rocks
- Magnitude of the KREEP component may inversely correlate with age / distance from Imbrium

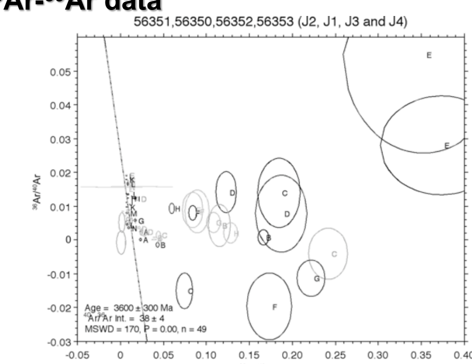
^{40}Ar-^{39}Ar data

Cohen et al. (2000, 2005, 2006)

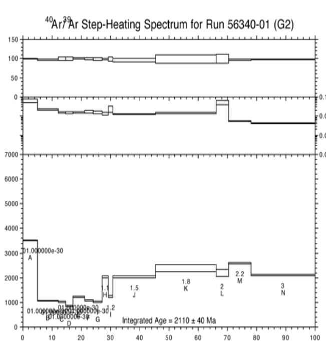


- Combination of temperature and time is effective at resetting the K-Ar clock: daughter ^{40}Ar released when rocks remelted
- Shock alone does not allow diffusion
- Multiple heating steps with apparent ages within 1σ constitute plateau (alternatively, isochrons)
- ^{40}Ar-^{39}Ar plateau/isochron ages reflect crater formation time

^{40}Ar-^{39}Ar data



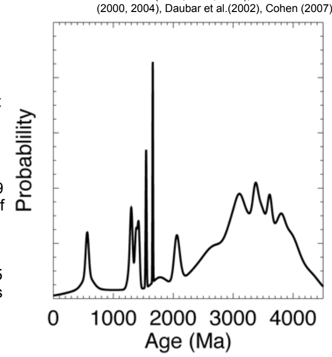
^{40}Ar-^{39}Ar data



Clast ages

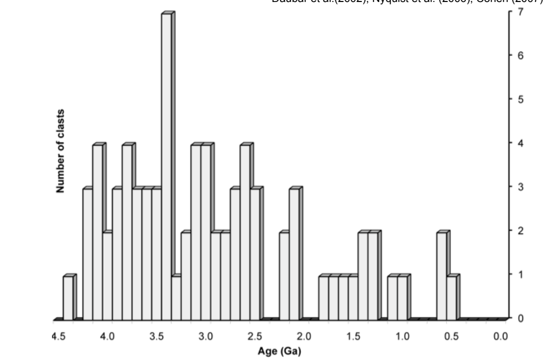
Cohen et al. (2000, 2002, 2005), Fernandes et al. (2000, 2004), Daubar et al.(2002), Cohen (2007)

- Impact ages in lunar meteorites should reflect flux on lunar far side
- Few/no reliable ancient (>4.0 Ga) ages (depends on acceptance of uncertainties)
- Impact age cutoff at 3.9 Ga implies some sort of global resurfacing event to the depth of meteorite assembly
- Impact age tailoff to 2.5 Ga - meteorite breccias sample all impacts, not just nearest basins

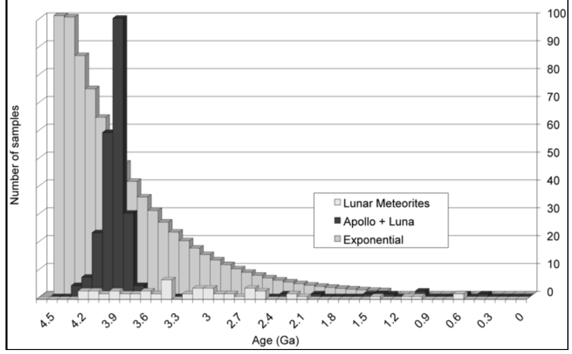


Clast ages

Cohen et al. (2000, 2002, 2005), Fernandes et al. (2000, 2004), Daubar et al.(2002), Nyquist et al. (2006), Cohen (2007)

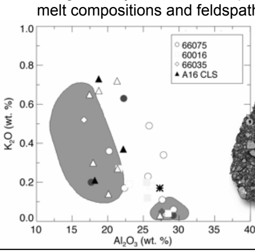


Sure could use more data….



Apollo 16 breccias

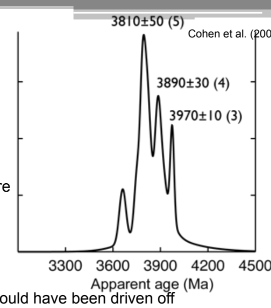
- Feldspathic fragmental breccias containing abundant impact-melt clasts
- Ancient exposure indicators (high $^{40}Ar/^{36}Ar$, excess fission Xe), lack mature regolith components
- Melt clasts are microporphyritic
- Range in major-element composition between mafic nearside impact-melt compositions and feldspathic highlands



A16 breccia ages

Cohen et al. (2007)

- All impact-melt products in three A16 breccias are ~3900 ± 200 Ma
- Are all pieces part of the same impact-melt sheet? Unlikely.
  - Range in chemistry and texture
  - Resolvable age differences
- Were all breccia components reset by, e.g., lithification event? Unlikely.
  - Surface-correlated volatiles would have been driven off
  - No evidence of clast remelting; shock itself is insufficient to reset Ar ages
- Do clasts represent multiple impacts at 3.9 Ga? Most plausible.



Complications

- Understand sample bias on lunar surface
  - Sampling many different impact products – what are the differences between lunar meteorite breccias, Apollo breccias/soils, and hand-sample impact melt rocks from basin massifs?
  - What do sample ages tell us?
- Understand sample bias in the inner planets
  - Statistical sampling of impact products from other planets
- How does composition play a role in grouping or separating?
  - Does all basin ejecta have one common composition?
  - Does the melt sheet itself have a common composition?
- Fingerprinting the impactors
  - PGE analysis
  - Potential fractionation processes
- 3-D regolith modeling
  - Fate of old impact melt sheets, volumetric importance
- Pin down one large, old basin age (South Pole-Aitken Basin)

Conclusions

- Resolvable differences in texture, chemistry and age show that impact-melt clasts in lunar meteorites can be related to individual (though not known) impact events
- Lunar meteorite clasts record multiple different impact events into lunar feldspathic terrain (far side?) between 4.0 and 3.5 Ga
- Lunar meteorites do not contain very much evidence for impacts prior to 4.0 Ga
- A statistical database of impact-melt clasts from feldspathic lunar meteorites is useful in building a regional impact history of the lunar feldspathic terrain and complements Apollo samples
- Regolith breccias contain impact-melt products that uniquely record the bombardment history of the inner Solar System