Curie: Constraining Solar System Bombardment Using In Situ Radiometric Dating

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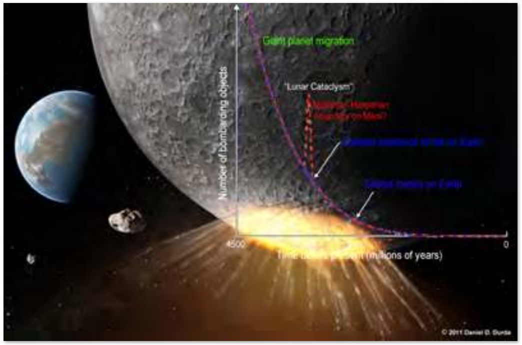


The story of a cataclysmic bombardment, written in the rocks of the Moon, has far-reaching consequences.

The leading, but contentious, model for lunar impact history includes a pronounced increase in impact events at around 3.9 Ga. This late heavy bombardment would have scarred Mars and the terrestrial planets, influenced the course of biologic evolution on the early Earth, and rearranged the very architecture of our Solar System.

But what if it's not true? In the last decade, new observations and sample analyses have reinterpreted basin ages and "pulled the pin" on the cataclysm – we may only have the age of one large basin (Imbrium).

The **Curie** mission would constrain the onset of the cataclysm by **determining the age of a major pre-Imbrium lunar basin** (Nectaris or Crisium), **characterize new lunar lithologies** far from the Apollo and Luna landing sites, including the basalts in the basin-filling maria and olivine-rich lithologies in the basin margins, and provide a unique vantage point to **assess volatiles** in the lunar regolith from dawn to dusk.

A Lunar Cataclysm?

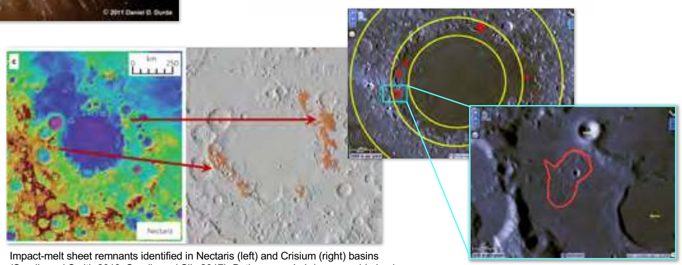
Until recently there has been a broad consensus among lunar geologists about the relationships of samples collected by the Apollo missions to the Imbrium (Apollo 14), Serenitatis (Apollo 17), Nectaris (Apollo 16), and Crisium (Luna 20) basins (Stöffler et al., 2006). **Today, most of these relationships have been questioned and are under active debate.**

- **Imbrium**. The best available age for Imbrium is 3.92 ± 0.01 Ga from KREEP-rich breccias and melt rocks collected at the Apollo 12 and 14 sites (Liu et al., 2012; Merle et al., 2017; Nemchin et al., 2009; Snape et al., 2016).
- ~~Serenitatis.~~ LRO images of A17 boulder tracks verified that they originated in outcrops within the North Massif walls, which had been interpreted as Serenitatis ejecta (Hurwitz and Kring, 2016; Schmitt et al., 2017). However, U-Pb dating of Ca-phosphates in these boulders appears to support an Imbrium origin for these rocks (Thiessen et al., 2017) and the overlying Sculptured Hills deposits may be more closely related to Imbrium rather than Serenitatis (Fassett et al., 2012; Spudis et al., 2011).
- ~~Nectaris.~~ The aluminous Descartes breccias range in age from 3.9 to 4.1 Ga, leading to a proposed old age for Nectaris (Fernandes et al., 2013; James, 1981). However, the youngest population of clasts in the Descartes breccias is coeval with KREEP-rich, crystalline melt rocks related to Imbrium ejecta, supporting geological observations that favor emplacement of the Descartes Fm as Imbrium ejecta (Norman et al., 2010).
- ~~Crisium~~. Luna 20 and Apollo 17 fragments interpreted to be Crisium impact melt have radiometric ages ranging from ~3.84 Ga to 3.895 Ga (Cadogan and Turner 1977, Stettler and Albarede 1978, Swindle et al. 1991, Schmitt et al. 2017), but crater density ages for Crisium ejecta vary from 3.99 Ga to 3.94 Ga (Neukum 1983, van der Bogert et al. 2018).

There is little consensus on what samples represent impact melt from basins other than Imbrium, reopening the pre-Imbrian impact history to debate. **Samples thrown from basins don't come tagged with their origin – need to visit the intact impact-melt sheet of a pre-imbrian basin!**

References can be found in abstract #1029

Sampling in situ impact melt



Impact-melt sheet remnants identified in Nectaris (left) and Crisium (right) basins (Spudis and Smith 2013, Spudis and Sliz 2017). Both are pre-Imbrian, nearside basins outside of the Procellarum KREEP terrain. See Runyon poster #1536 tonight and hope you didn't miss van der Bogert's talk #1028 this morning!

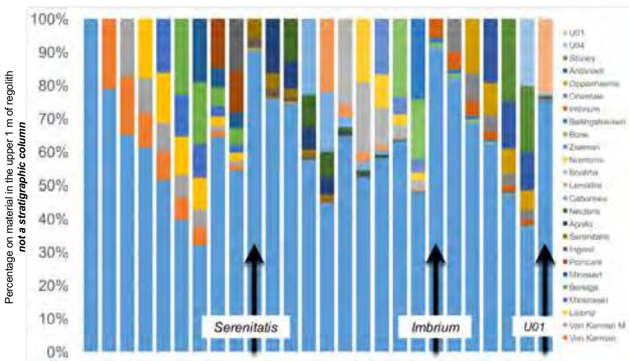
Much of the present debate about the ages of the nearside basins arises because of the difficulty in understanding the relationship of distal samples to their parent basin

That doesn't mean that we don't understand regolith samples! Remember that *none* of the lunar returned samples were from in-place bedrock.

- Apollo 11 landed on Mare Tranquilitatis, sampled predominantly basalts
- Apollo 14 landed on the Fra Mauro Fm, sampled predominantly Imbrium ejecta from Fra Mauro

Landing on a basin melt sheet is a **fundamentally different strategy** for identifying impact-melt samples from that basin. Regolith formed on the impact-melt substrate, diluting but not destroying native impact-melt rocks. We can recover impact-melt rocks and distinguish them from basalts and KREEPy rocks using a scoop-sieve-triage strategy. See Curran et al. poster #2732 tonight!

2 - 4 mm rock fragments sieved from an Apollo 11 soil sample - most fragments are dark basalts, along with pieces of white, feldspar-rich rock and impact breccias

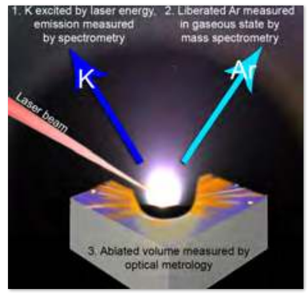


Modeled proportion of material from different craters in the upper 1 m at the Bhabha site in the interior of the South Pole-Aitken basin. The substrate (SPA impact melt) is gardened and diluted but not destroyed, even after generations of bombardment.

Dating impact melt in situ

K-Ar geochronology for in situ applications demonstrated by multiple laboratories (Cohen et al. 2014, Cho et al. 2016, Devismes et al. 2017) See Cho & Cohen poster #1129 Thursday for more detail!

- K measured using laser-induced breakdown spectroscopy
- Laser-liberated Ar measured using mass spectrometry
- K and Ar related by volume of the ablated pit using optical metrology
- Multiple spots on a single sample build a whole-rock isochron
- Precision ±100 Myr achievable for an 8-point isochron on a 4 Ga sample



The K-Ar dating approach has been validated by Curiosity measurements that date both detrital minerals and authigenic phases (Farley et al. 2014, Vasconcelos et al. 2015, Martin et al. 2017)

- Uses TRL 9 instruments (system-level TRL 4) that do multiple duties – all their proven science plus a novel geochronology measurement and volatiles measurements
- Conops fits with real mission flight ops, low risk, known cost

Payload Element	Objective	Heritage
Sample collection & triage	•Scoop & sieve regolith •Present rocks to LIBS and MI for triage •Introduce individual rocks to analysis chamber	Phoenix, SAM (MSL), Apollo, MoonRise
LIBS	•Characterize and prioritize samples •Determine K for geochronology •Measure surficial and implanted volatiles	ChemCam (MSL), SuperCam (Mars 2020)
Mass Spectrometer	•Determine Ar for geochronology •Measure volatile compounds in regolith	NMS (LADEE, MAVEN, MSL, etc.)
Cameras	•Mast camera - workspace documentation, triage samples •Microimager – metrology of LIBS pits for geochronology	MI/Pancam (MER) MAHLI/Mastcam (MSL)