Do Lunar Polar Volatiles Record the Geophysical Evolution of the Moon?

M.A. Siegler[1], J.T. Keane[2], M. Laneuville[3], Y. Chen[4], R.C. Economos[5] [1]Planetary Science Institute, [2]University of Arizona, [3]Earth Life Sciences Institute, Tokyo Institute of Technology [4]JPL/California Institute of Technology [5]Southern Methodist University msiegler@psi.edu

Introduction: The origin of lunar polar volatiles has been a long-standing mystery. As these volatile deposits are confined to permanently shadowed regions, their abundance and spatial distribution are highly sensitive to subtle changes in the lunar spin axis and illumination conditions at the poles. Therefore, polar volatiles may serve as a record of many parallel geophysical processes that alter the Moon's spin, including orbital and obliquity evolution due to external tidal torques [1], true polar wander due to mantle convection [2-4] and impact basin formation [5]. Polar volatiles are also intrinsically sensitive to volatile influx from impacts and degassing [6]. In this sense, a better understanding of the lunar volatile record may provide a way link these processes, and tie together disparate parts of the Moon's geologic history.

True Polar Wander Hypotheses: As presented in [2-4] the lunar polar hydrogen deposits have been found to lie preferentially on a path consistent true polar wander (TPW) induced by the thermal evolution of the Procellarum KREEP Terrain (PKT). The past north pole is found to have migrated towards the lunar farside (and similarly the past south pole migrated to the lunar nearside) in response to a low density mantle thermal anomaly below the PKT. This motion is counteracted by uplift of the PKT, which depends on the thickness and rigidity of the crust as a function of time. Therefore the separate geophysical variables of thermal evolution and crustal evolution can be tuned to alter the timing of this event dramatically.

Assuming the PKT-TPW hypothesis to be true, his leads us to advocate two plausible origins of the lunar volatiles:

1) They are a remnant of a large period of water deposition prior to TPW (likely >3 Gya), or
2) They are records of episodic deposition of water as TPW was occurring (possibly <3Gyr).

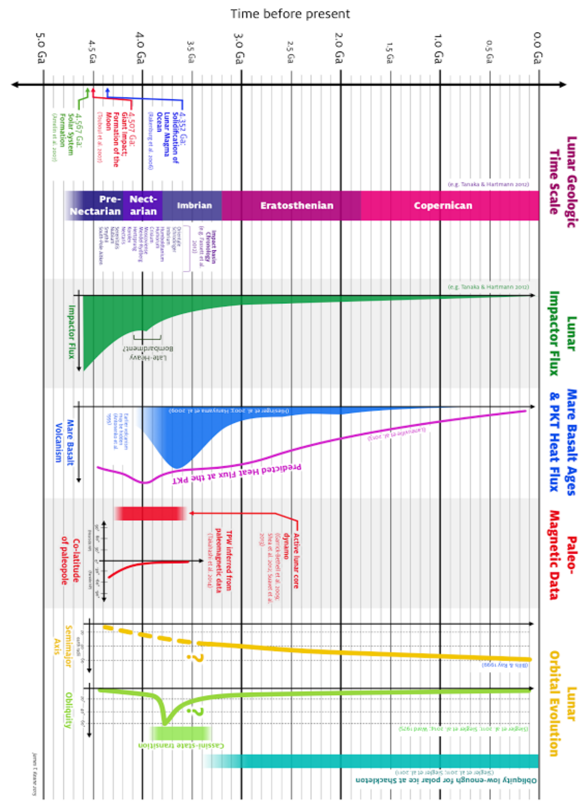

Figure 1: Unified timeline of geophysical processes on the Moon including impacts, mare volcanism, paleomagnetism, volatiles and orbital evolution (graphic by J.T. Keane).

Each of these hypotheses has different ramifications for the timing of the geophysical evolution of the crust and interior of the Moon relative to other aspects of lunar evolution, possibly allowing for a linked geophysical timeline of the Moon.

Existing Geophysical Timelines:

The past two decades have brought a plethora of new geophysical information about the Moon, each with their own information about the timing and evolution of specific processes on the Moon. High resolution imaging from LRO and Kaguya have enabled dramatically improved measurements of relative surface ages of surfaces, past impact flux [e.g. 7], mare thicknesses and tectonic processes [8,9]. High precision gravity measurements from GRAIL have provided greater constraints on crustal thickness [10] and global scale tectonics [11]. New analytical techniques have allowed for detailed studies of lunar returned samples and the lifetime of the lunar core dynamo [12], and water content of the mantle and erupted materials [13,14]. Thermal evolution models have also advanced dramatically, aiding in further constraints on these processes [15-17].

Figure 1 summarizes some of the primary geophysical processes on the Moon as a function of time. Each of these parallel processes (impact flux, mare production, magnetic field, orbital evolution) have independent, poorly constrained timelines, all of which may impact polar volatiles.

Using lunar polar volatiles to unify lunar geophysics: Using volatiles as a link, we can constrain relative timing of geophysical processes.

In general, an early TPW scenario (>3.5 Gya) will require an early crust to be moderately rigid. If TPW occurred early, the presence of a long lived lunar dynamo (to as recently as 3.5 Gya [12]) and protective magnetic field could be credited for enabling and preserving ancient volatile deposits. The lack of the protective magnetic field since this time could be a reason modern deposits have not overprinted this ancient ice. However, if the magnetic field is a cause of the presence of ice, it must have persisted after the high obliquity Cassini State Transition [1], which occurred when the Moon was at roughly half its present semimajor axis. Therefore the growth of the lunar semimajor axis needs to be very fast.

If instead volatiles are found to track later stage TPW (<3.5 Ga), which can happen if the early crust is less rigid, it may be that the polar deposits record more recent lunar geophysical activity (in the past 3 Gyr). We would expect a gradient of "old" to "young" ice as we move from the paleopole location to the present day pole. If the ice is the result of comets, this could provide a potential progression of the highly unknown comet flux versus time. Intriguingly, the water could also be a result of outgassing from the Moon itself [6]. It may be that lunar polar ice tracks the later stage mare production and outgassing record. Given estimates of 100 ppm water content for lunar mare basalts [14], a moderate 5000 km^2, 50 m thick mare eruption will release roughly the same amount of water as would be retained from a 1km comet (assuming ~10% retention of impacted mass). Figure 2 illustrates the cumulative water outgassed from visible mare flows (adapted from [8]) assuming 100ppm water is released. It is not unreasonable that a large fraction of the detected water could come from the mare themselves. Such ideas may be testable with geochemical analysis of polar materials returned by future missions. Such analysis could potentially differentiate the endogenic (such as mare outgassing) vs exogenic (comet, solar wind, etc.) contributions to the lunar volatile reservoirs as a function of time.

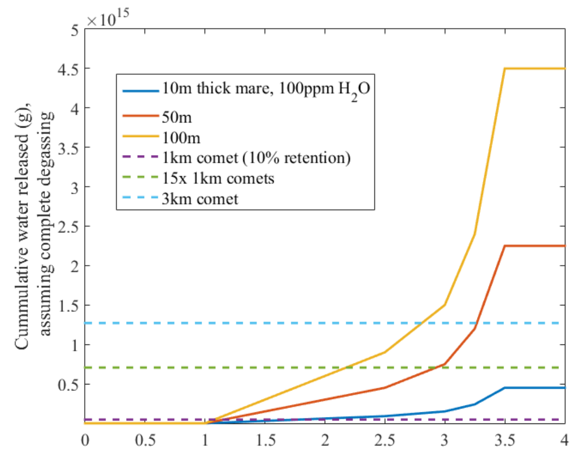

Figure 2: After Hiesinger et al. (2003), cumulative volume of mare water production vs time assuming 100ppm water released from mare.

In this presentation, we summarize how individual processes constrain the lunar geophysical history, and how they may relate to polar volatiles. We will synthesis new constrains on timing of these geophysical processes given assumptions on ice deposition. We will propose plausible measurements testable by LRO, GRAIL, and possible future data that could differentiate different models of geophysical evolution.

References:[1] Siegler et al. 2011, JGR [2]Siegler et al., 2015, *LPSC* [3] Keane et al., 2015, *AGU* [4] Siegler et al., 2016, *Nature*, in revision[5] Keane e & Matsuyama 2014, GRL. [6] Arnold et al. 1979, JGR [7] Fassett et al. 2012 JGR [8] Heisinger et al, 2003, *JGR* [9] Haruyama et al, 2009 [10]Wieczorek et al. 2013, Science [11] Andrews-Hanna, 2014, *Nature* [12]Shea et al. 2012 *Science* [13]McCubbin, et al. 2010 *PNAS* [14] Chen et al. 2015, EPSL [15] Zhong, et al. 2000, EPSL [16] Zhang, et al. 2013 JGR [17]Laneuville et al, 2014, JGR.