DRILLING FOR WATER ON THE MOON.

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Introduction: Recent discoveries have bolstered the case for the presence of billions of tonnes of frozen water located at the lunar poles [1, 2]. However, extraction of such water is problematic because the high latitudes require a comparatively high delta v budget, direct line of sight communication with Earth is not possible for most potential locations, and game-changing amounts of water would require an industrial scale mining operation. It is as if the world's first petroleum had to come from Alberta tar sands rather than shallow wells drilled in Pennsylvania. Consequently, a low latitude, Nearside source of volatiles that could be extracted using comparatively simple drilling technology would be highly desirable.

Prospecting for Volatile Reservoirs: The technique used to find likely locations for the world's first oil and gas wells was very simple: look for surface oil and gas seeps, and drill there. To apply this analogy to the Moon, we should look for low latitude locations that harbor evidence of previous outgassing events. Such episodic events have long been suspected as possible explanations for the mysterious transient lunar phenomena (TLPs). Although purported observations of TLPs have been made for centuries, the status of these phenomena remains unsettled [3].

Meniscus hollows. Rather than directly looking for TLPs, it would probably be more productive to look for actual geological features that could have been caused by outgassing events. The most promising such features are the "meniscus hollows": irregularly shaped, low rimmed craters, so-called because they tend to contain hummocks that resemble mercury menisci when viewed in orbital photographs. At least 27 meniscus hollows have been identified on the Moon [4], in addition to several similar hollows on Mercury [5].

Of these, the most studied is the paradigmatic Ina "D-Caldera" (18.7°N, 5.3°E). Ina is D-shaped and roughly 3 km across. It is located atop a low, shield volcanic dome within the graben and horst region of Lacus Felicitatus, and lies within the Imbrium Basin ejecta blanket [6, 7]. Its interior is characterized by numerous, convex-upward mounds that range in height up to 30 m, and are interspersed by a blocky, apparently fresh terrain [4] exposed by the removal of a thick, >12 m regolith layer [7]. Although alternative theories have been suggested for the formation of Ina, including caldera collapse [8] and inflated lava flows [6], outgassing remains a likely explanation [3, 7, 9].

Observations. A peculiarity of Ina is its bluish tint first observed by Apollo 17 astronauts [8]. Reflectance observations by Clementine [7, 9] and the Moon Mineralogy Mapper (M^3) [10] quantitatively demonstrated higher reflectance at the blue end of the spectrum, and that the interior, blocky terrain has spectral properties typified by high titanium basalts exposed in very recent impact craters (Fig. 1).

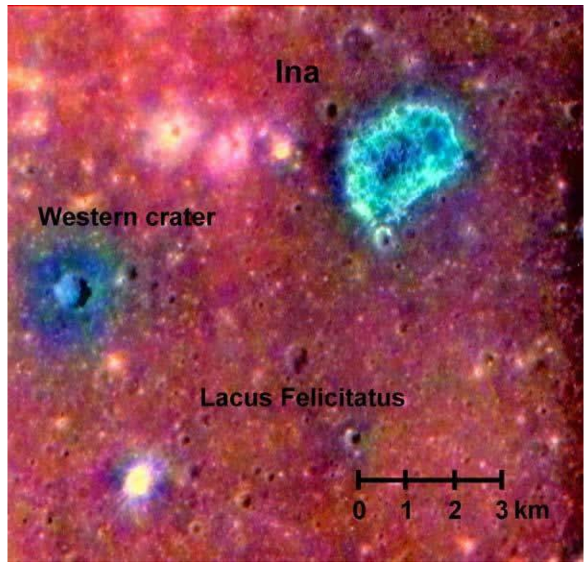

Figure 1: Clementine false color image superimposed on Apollo 15 photograph.

Thermodynamics of Caldera Formation: If expulsion of volatiles are responsible for the Ina caldera, the most likely chemical species would be a combination of H_2O and CO_2 [9]. In order to excavate 12 m of regolith, the pressure of the volatiles must exceed the overburden pressure (~0.4 MPa). Given that Ina is likely perched atop hot mantle plume, it is reasonable to assume a regolith temperature gradient of ~2 K m^{-1} [11]; thus, a temperature of ~274 K could be expected at the base of the regolith, and H_2O would condense to its liquid phase. Moreover, any CO_2 present would tend to dissolve in liquid water.

Terrestrial analogues. The morphologically most similar features on Earth to lunar meniscus hollows are maars. On Earth, all known such craters are caused by phreatomagmatic explosions: rising magma encounters groundwater that flashes into steam, creating a violent explosion. Most terrestrial maars tend to be about roughly the same size as Ina, with steep sides surrounded by a tephra rim [12].

Energetics of the Ina caldera. Inspection of the Clementine spectral data (Fig. 1) reveals that Ina's tephra halo extends to about ~0.5 km beyond the rim. This ejection distance places constraints on the energy of the eruption that formed Ina. The velocity *u* necessary to launch an object on a ballistic trajectory downrange a distance *d* is

$$u = \left(\frac{d\,g}{\sin 2\theta}\right)^{1/2}, \qquad (1)$$

where g is the gravitational acceleration and θ is the launch angle. Assuming that the farthest edge of the halo is from material ejected at a 45° launch angle implies an overall exit velocity of ~28.3 m s^{-1}. Such velocities suggest a relatively low energy process comparted to terrestrial maars, the eruptions of which are known to throw large rocks many kilometers from the site of the crater [12]. Although a phreatomagmatic origin for the Ina caldera cannot be ruled out, an alternative mechanism is suggested.

Possible lunar cryovolcanism. Ordinary, non-carbonated water probably would not have enough energy to cause the observed excavation. However, if the water were saturated with CO_2, dramatically higher energies could be expected. The unit kinetic energy of a water jet can be estimated as

$$\frac{1}{2}u^2 \approx \lambda \frac{P_0}{\rho_0}\left(\ln\frac{P_0}{P_{out}} - 1 + \frac{P_{out}}{P_0}\right), \qquad (2)$$

where *u* is the exit velocity, λ is the Ostwald solubility coefficient (defined as the volume of gas able to dissolve into a unit volume of pure liquid), ρ_0 is the density of water, P_0 is the starting pressure, and P_{out} is the ending pressure [13].

The Ostwald solubility coefficient for CO_2 dissolved at 274 K and 0.1 MPa is approximately ~1.8; assuming $P_0 \approx 0.1$ MPa, an exit velocity of 106 m s^{-1} is obtained. In order to account for regolith entrainment, a first order estimate of the ratio *f* of entrained regolith to liquid water is

$$f = \frac{u_0^2}{u_1^2} - 1, \qquad (3)$$

where u_0 is the velocity with no entrainment calculated according to eq. (2), and u_1 is the observed ballistic velocity according to eq. (1) [13]. Thus, a slurry consisting of 1 m^3 CO_2-water and 6.5 m^3 of regolith could be accelerated to 28.3 m s^{-1}.

Reservoir Conceptual Model: A lunar volatile reservoir would share the essential features of terrestrial hydrocarbon reservoirs: (1) a source rock; (2) a porous reservoir rock; and (3) a cap rock.

Source rock. Assuming a 35 km thick crust and total fractured zone extending down 85 km [14], there would be a 50 km-thick "source rock" able to donate water. The dome-shaped plateau upon which Ina is perched could gather water from an area of ~700 km^2. Thus, reasonable juvenile water concentrations [15, 16] would result in an original, total water content within the underlying fractured portion of the upper mantle of order 10^{11} to 10^{13} tonnes.

Reservoir rock. The megaregolith underlying the Ina caldera would make an excellent reservoir rock, as it is both permeable and porous. Although conventional hydrocarbon reservoir rocks typically consist of sandstone, fractured basalts are often used as natural gas storage facilities.

Regolith cap rock. The permeability of regolith (1-6 10^{-12} m^2) [17], is much higher than the highly fractured rock expected to underlie Ina (>>10^{-10} m^2) [18]. Moreover, once the pressure of gases attempting to diffuse through the regolith exceeded 100 Pa, any H2O molecules would freeze, forming an impermeable barrier to further diffusion. The shape of the volcanic dome would form a classic structural trap.

Conclusion: A plausible causal explanation for the formation of the Ina caldera and similar features has historically been the outgassing of volatiles, particularly the combination of H_2O and CO_2. The temperatures and pressures required for this to be effective demand that the water be in its liquid phase. The energetics of carbonated water would be sufficient to excavate the Ina caldera. Moreover, the Ina caldera is located in one of the most easily accessible locations on the Moon. It could be the case that abundant water resources from the Moon may be obtained from shallow water wells drilled in the right location.

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