

INA PIT CRATER ON THE MOON: EXTRUSION OF WANING-STAGE LAVA LAKE MAGMATIC FOAM RESULTS IN EXTREMELY YOUNG CRATER RETENTION AGES. L. Qiao^{1,2}, J. W. Head², L. Wilson³, L. Xiao¹, M. Kreslavsky⁴ and J. Dufek⁵, ¹Planet. Sci. Inst., China Univ. Geosci., Wuhan 430074, China, ²Dep. Earth, Env. & Planet. Sci., Brown Univ., Providence, RI, 02906, USA, ³Lancaster Env. Centre, Lancaster Univ., Lancaster LA1 4YQ, UK, ⁴Earth & Planet. Sci., UC Santa Cruz, Santa Cruz, CA 95064, USA, ⁵Sch. Earth & Atmos. Sci., GA Tech, Atlanta, GA, 30332, USA. Contact: LeQiao.GEO@Gmail.com, James_Head@Brown.edu.

Introduction: Ina is an unusual lunar feature in Lacus Felicitatis (18.65°N, 5.30°E), ~170 km southeast of the Imbrium impact basin, first discovered in Apollo 15 data [1]. Located in the midst of mare deposits interpreted to be ancient basalts, the ~2×3 km D-shaped shallow depression consists of dozens of mounds with cross-section resembling a convex meniscus shape, surrounded by a relatively optically fresh hummocky and blocky floor (Fig. 1). The Ina interior is defined by an inward-facing wall (5–10°) and a relatively flat basal terrace/ledge with a steep (10–30°) inward-facing scarp up to ~12 m high. The floor is generally flat, slopes gently (<2°) toward the interior, and mainly lies about 40–60 m below the rim. About 50% of the interior terrain is made up of the unusual bleb-like mounds with the remainder composed of two floor units: 1) a hummocky unit (44%), composed of relatively optically immature terrain with ridged and pitted textures, and 2) an optically immature blocky unit (6%) with a rougher texture, and 1–5 m exposed blocks. The meniscus-like mounds rise up to ~20 m above the floor, and have marginal slopes typically in the range of ~10–30°. Moat-like features, 1–3 m wide and several meters deep and sometimes containing blocks, are often observed around the edges of mounds, and at the foot of the scarp bounding the Ina interior (Fig. 1).

The usually crisp appearance and lightly cratered surface of Ina appear to indicate a geologically recent origin. Recent analysis interpreted it to be formed by extrusive basaltic volcanic activity during the last ~33 Myr of lunar history [2], an extremely unusual young age for volcanism on the Moon, which, if true, challenges the current lunar thermal evolutionary history and models. Alternative formation hypotheses have also been suggested, including lava flow inflation [3], pyroclastic deposits [4], and out-gassing, causing removal of surface regolith [5]. But no single hypothesis yet successfully explains the regional setting of Ina and the nature and origin of the suite of unusual units within it.

Here, we utilize previous studies, new Lunar Reconnaissance Orbiter (LRO) data and mapping, terrestrial analogs and the latest assessment of the generation, ascent and eruption of magma on the Moon [6, 7] to reassess the origin of Ina and its enigmatic characteristics [8]. An accompanying analysis of another major Ina-like feature, Sosigenes, is also presented at this conference (abstract #1129, [9]).

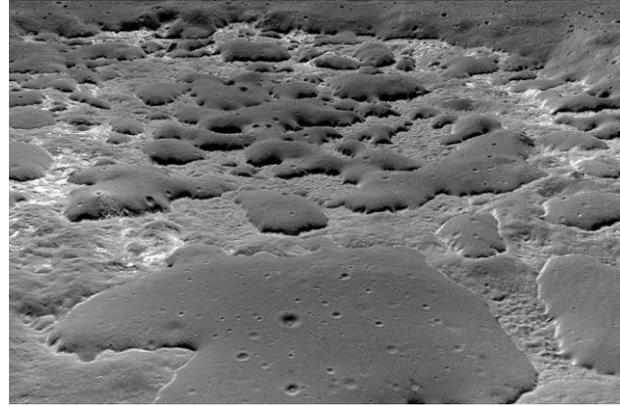


Fig. 1. Perspective view of the Ina interior, based on LROC NAC frame M119815703 overlaid on LROC NAC DTM, VEX.=~3.

Geologic Setting of Ina: New LRO altimetry and image data show unequivocally that Ina is not only located within the lunar maria, but also at the summit of a small round shield volcano, ~22 km in diameter and ~300 m high (Fig. 2), at the upper end of the diameter size range for >200 small shield volcanoes on the Moon [10]. The diameter of Ina also lies on the summit pit diameter/dome base diameter trend line for small shields [10]. We used LROC image data to count impact craters superposed on the flanks of the shield volcano below the Ina summit pit and obtained a model age of ~3.54 Ga for the shield (Fig. 3). Summit pit craters are common at small terrestrial shield volcanoes in Hawai'i, Iceland and elsewhere. How will summit crater context and terrestrial analogs assist in understanding the properties and origin of Ina interior?

Terrestrial Analogs: The 1959 eruption at Pu'u Pua'i on Kīlauea that flooded the Kīlauea Iki pit crater (~0.9×1.6 km) [11] provides a very well-documented example of cyclic pit crater flooding, lava lake formation and drainage. During the eruption, the extruded lava flooded the Kīlauea Iki crater floor several times, inflating the lava lake and surface crust by 100s of meters, accompanied by the formation of a rigid and platy thermal boundary layer. During lava lake inflation and deflation, the magma continuously degassed and bubbles and foams accumulated below the lava crust. In summary, the results of the final stage of lava lake activities are: 1) a steep-sided solidified lava ledge or terrace around the lake margins, 2) highly porous surface deposits, and 3) shal-

low surface layers with abundant vesicles, with porosity up to 40–60% [12, 13].

On the basis of these observations, we interpret the interior of Ina to be related to characteristic features associated with a lava lake at the summit of a lunar shield volcano formed ~3.5 Byr ago. The basal terrace and steep inward-facing scarp at the base of the interior walls of Ina are analogous to the chilled margin of a lava lake remaining after subsidence of its crusted surface, and the topographically low hummocky/blocky terrain is analogous to the subsided macro- and micro-vesicular lava crust.

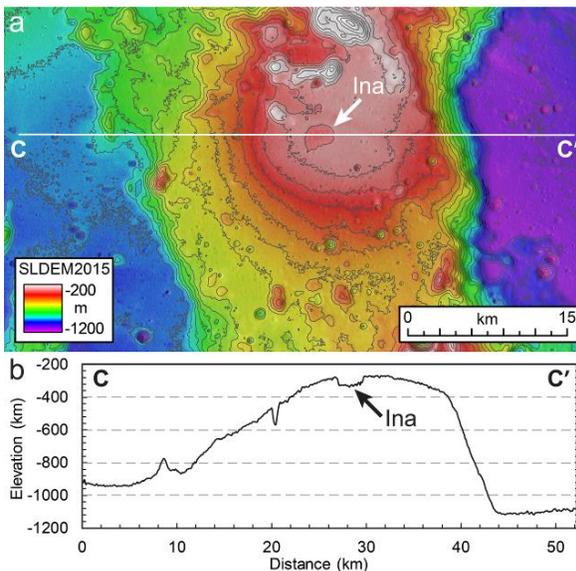


Fig. 2. Topography of middle Lacus Felicitatis, showing the geologic context of Ina pit crater.

Extrusion of Magmatic Foam in the Waning Stage of Lunar Shield Volcanic Eruptions: Despite the fact that volcanic eruptions on the Moon take place under very different conditions from those on Earth, an important similarity between lunar and terrestrial shield-building eruptions is the presence of magmatic volatiles (e.g., water) exsolved in the final stages of approach of magma to the surface. In the final phase of the eruption, as the magma rise speed at depth approaches zero, the exsolved water vapor accumulates under the cooling and highly disrupted lava lake crust. The combination of the near-zero magma rise rate, likely high bubble number density from abundant nucleation sites, and water contents typical of many lunar magmas (several hundred ppm [14]) results in gas bubble sizes that are so small (~20 μm radius) that surface tension forces allow them to remain stable against the internal gas pressures and thus to form a magmatic foam that can have a vesicularity up to ~95% and vertical extent of several hundred meters [15]. The final stage of evolution occurs when dike overpressure decreases to zero and the elastic response of the

crust attempts to close the dike, squeezing the magmatic foam toward the surface and forming the meniscus-like mounds. The final product of the shield-building eruption is the superposition and solidification of magmatic foam mounds on a lava lake crust characterized by abundant micro- and macro-vesicularity, and overlying a residual magmatic foam substrate. We suggest that these processes operated when the Ina pit crater floor formed ~3.5 Byr ago.

Age of Ina Mounds: The unusually high porosity of the magmatic foam mounds (up to ~95%) has significant effects on the subsequent impact cratering processes, dominantly in a manner of permanent crushing and compaction of the target material, smaller crater diameter, and much smaller amounts of ejected materials. Experimental impacts show that cratering efficiency (excavated mass/projectile mass) on highly porous targets can be readily reduced by a factor of two compared with cratering on low-porosity materials [16, 17]. Assuming a porosity of 75% for the extruded magmatic foam of the Ina mounds, the predicted factor-of-two decrease in cratering efficiency results in an ~30% smaller crater diameter. The reduced diameter of craters formed in magmatic foam results in a shift of the estimation of the model crater retention age from <100 Ma to ~3.5 Ga (Fig. 3), contemporaneous with the underlying shield volcano, making an anomalously young formation age for Ina unnecessary.

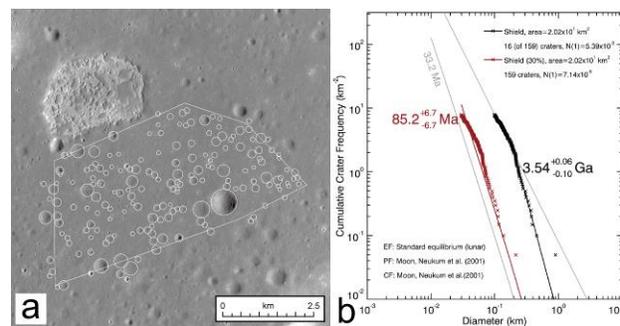


Fig. 3. Impact crater population analysis of the Ina shield volcano (black 'x's), and the effect of reduced crater diameter (~30%), caused by the high porosity of the magmatic foam, on the crater retention age (red 'x's').

References: [1] Whitaker (1972) *NASA SP-289*, 25-84-25-85. [2] Braden et al. (2014) *NGEO* 7, 787-791. [3] Garry et al. (2012) *JGR* 117, E00H31. [4] Carter et al. (2013) *LPSC XLIV*, #2146. [5] Schultz et al. (2006) *Nature* 444, 184-186. [6] Wilson & Head (2017) *Icarus* 283, 146-175. [7] Head & Wilson (2017) *Icarus* 283, 176-223. [8] Qiao et al. (2017) *Geology*, in press, doi:10.1130/G38594.1. [9] Qiao et al. (2017) *LPSC XLVIII*, #1129. [10] Head & Gifford (1980) *Moon & Planets* 22, 235-258. [11] Eaton et al. (1987) *USGS SP-1350*, 1307-1335. [12] Richter & Moore (1966) *USGS PP-537-B*. [13] Mangan & Helz (1986) *USGS OPR* 86-424. [14] Hauri et al. (2015) *EPSL*, 409, 252-264. [15] Wilson & Head (2016), *7th Moscow S³*, 7MS3-MN-08. [16] Schultz et al. (2002) *LPSC XXXIII*, #1875. [17] Poelchau et al. (2013) *MAPS*, 48, 8-22.