A COMPREHENSIVE GEOLOGICAL CHARACTERIZATION OF THE INA VOLCANO SUMMIT PIT CRATER ON THE MOON: EXTRUSIONS OF WANING-STAGE LAVA LAKE MAGMATIC FOAMS PRODUCES ANOMALOUSLY YOUNG CRATER RETENTION AGE. L. Qiao[1, 2], J. W. Head[2], Z. Ling[1], L. Wilson[3], L. Xiao[4] and J. Dufek[5], [1]Inst. Space Sci., Shandong Univ., Weihai, 264209, China (LeQiao.GEO@Gmail.com), [2]Dep. Earth, Env. & Planet. Sci., Brown Univ., Providence, RI, 02912, USA, [3]Lancaster Env. Centre, Lancaster Univ., Lancaster LA1 4YQ, UK, [4] Planet. Sci. Inst., China Univ. Geosci., Wuhan 430074, China, [5]Sch. Earth & Atmos. Sci., GA Tech, Atlanta, GA, 30332, USA.

Introduction: Ina, a distinctive ~2×3 km D-shaped depression located atop a 22 km-diameter shield volcano in the nearside lunar maria (18.65°N, 5.30°E), is composed of unusual bulbous-shaped mounds surrounded by optically immature hummocky and blocky floor units (Fig. 1). The crisp appearance, optical immaturity and low number of superposed impact craters combine to strongly suggest a geologically recent formation for Ina, and to involve currently ongoing modification processes. The specific formation mechanism, however, has remained controversial, and includes interpretations of geologically very recent extrusive basaltic volcanic activity within the last ~33 Ma [1], an extremely young age for volcanism on the Moon.

In this contribution, following our preliminary analyses of Ina and its origin [2,3], we conduct a comprehensive characterization of the geological context of Ina and the nature of the suite of its associated terrains, using newly-obtained multi-source orbiter data sets. We then assess the nature and characteristics of magmatic-volcanic processes associated with similar terrestrial small shield volcano summit pit craters in Hawai'i. We combine these data and terrestrial perspectives with new theoretical and observational insights into the generation, ascent and eruption of magma on the Moon, particularly in relation to behavior in the final stages of dike emplacement and magma degassing. Finally, we address the formation mechanism of the ranges of characteristics associated with Ina and their post-emplacement geologic modifications, especially the observed anomalously young crater retention age.

Location, Context and Age: Superposition of Ina on an Ancient Small Shield Volcano. Ina is located in the middle of Lacus Felicitatis, a small Imbrian-aged mare on the lunar nearside. The mare basalts emplaced within central Lacus Felicitatis exhibit apparent compositional changes as a function of time, with underlying (relatively old) basalts more titanium-rich than the surface (most recently emplaced) basalts. Locally, Ina occurs as an ~2×3 summit pit crater atop a broad ~22 km diameter and ~320 m high dome, which is interpreted as a small shield volcano built up through accumulating low-effusion rate, cooling-limited flows during eruptions ~3.5 Ga ago (Fig. 2). Theories of the origin of Ina structure and its unusual features must account for the fact that Ina is the summit pit crater on an ancient ~3.5 Ga old shield volcano and associated mare deposits.

Similarity of Ina Shield Volcano Summit Pit Crater to Those in Hawai'i: The Ina interior is defined by an inward-facing wall and a relatively flat basal terrace-ledge with a steep inward-facing scarp up to ~12 m high, and the pit crater is externally bordered by a low raised "collar" structure. On the basis of our documentation and the similarities to Hawai'ian small shield volcano pit craters (Fig. 3), we interpret Ina's external narrow collar to be the remnant of lava lake filling and overflow, and the interior basal terrace and steep inward-facing scarp to be the chilled margin of a lava lake remaining after lava lake cooling and/or recession.

Theoretical Assessment of the Ascent and Eruption of Magma in Late Stage Summit Pit Craters on the Moon: On the basis of our latest theoretical treatment of lunar late-stage shield-building magmatic activity, documentation of magmatic-volcanic processes from Hawai'i and comprehensive geological characterization of Ina pit crater, we interpret the wide range of characteristics associated with Ina to be consistent with an origin during the waning stages of shield volcano summit pit crater eruption activities characterized by the extrusion and solidification of magmatic foams on a subsided lava lake crust, occurring ~3.5 Ga ago, contemporaneous with the underlying shield volcano and the major global phase of lunar mare volcanism.

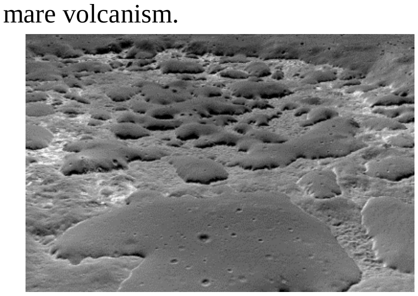

Fig. 1. Perspective view of the Ina interior (looking west), based on LROC NAC image and DTM, VEX.=~3.

Origin of the Ina Summit Pit Crater Floor Mounds: The bleb-like mounds (Fig. 1) are interpreted to be magmatic foam extruded through cracks in the solidified lava lake crust. Extrusion of the foam causes subsidence and flexure of the lava lake crust in the immediate vicinity of the foam, enhancing the meniscus-like borders of the mounds, the scarp-like contacts with the floor terrains, and the creation of moats at the margins.

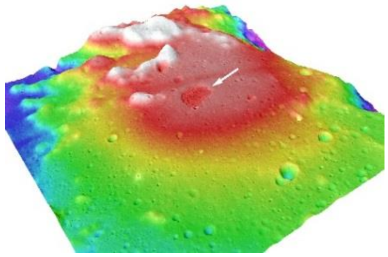

Fig. 2. Perspective view (looking NE) of the Ina shield volcano, which Ina pit crater (pointed by white arrow) sit on, based on Kaguya TC image mosaic overlaid on SLDEM2015 topography. VEX.=~5.

Fig. 3. 1959 eruption of Kīlauea Volcano, third phase of activity in Kīlauea Iki Crater. Note the chilled margin and inner scarp with tilted lava plates (right) and the chilled and blistered lava crust. USGS photo.

Origin of the Ina Summit Pit Crater Floor Units: We interpret the Ina floor terrains (Fig. 1) as solidified lava lake crust, and each of their complex topographic and morphologic characteristics correspond to the various processes operating during lava lake formation, evolution and solidification processes: 1) the three-stage annular, inwardly lower floor topography is interpreted to be formed through lava lake inflation, drainage and ultimate solidification; 2) the hummocky textures are analogous to lava lake inflation, lava lake crust flexure, bending, fracturing and ridge formation; 3) abundant pits due to regolith infiltration/sifting into porous macro-vesicular lava lake crust and void space below; 4) fractures are interpreted to be modified cracks in the lava lake surface formed by flexure, cooling and shrinkage during lava lake deflation and deformation; 5) polygonal patterns are analogous to highly deformed and cracked lava lake crust; 6) ridged textures are interpreted to be locally deformed lava lake surface crust; 7) floor blocky units are analogous to blocks of solidified lava lake crust exposed by impact and subsurface drainage of regolith fines.

Effects of Unusual Summit Pit Crater Floor Substrate on the Subsequent Impact Cratering: On the Ina floor terrains, due to the highly vesicular nature of the substrate, impact cratering will be dominated by permanent crushing and compaction of the targets, disruption of vesicle walls, excavation of the blocky portions of the crust substrate, and a negligible amount of lateral ejecta beyond the crater rim. The resultant craters are predicted to be poorly developed, filled with crushed rubble, abnormally-shaped, difficult to identify and to degrade rapidly, and to show a deficit of larger craters due to the decreased diameter-depth relationship. On the Ina floor mounds, subsequent impact cratering will operate in a style dominated by permanent compressing, crushing, shattering and penetrating the foam vesicles (the aerogel effect), rapid decay of impact-induced shock waves, leading to a significant reduction of cratering efficiency. Under these circumstances, the mound craters tend to be much smaller in diameter and deeper, non-blocky, poorly preserved and easily degraded, compared to a similar impact into typical solid basalt or regolith.

Effect of the High-porosity Substrate Characteristics of Ina Floor on Its Crater Retention Age: The Ina floor has a comparable, or slightly lower areal density of superposed impact craters than the Ina mounds, and both Ina interior units yield crater retention ages less than 100 Ma, significantly younger than the ~3.5 Ga old age estimated for the adjacent and underlying shield volcano flanks. The apparent discrepancy in impact crater populations and the resultant crater retention ages can be understood in the context of the role of unique substrate characteristics (chilled lava lake crust floor and solidified magmatic foam extrusions) in the formation and retention of superposed impact craters. Accounting for the effects of the reduced size of craters (~1/3–1/5 diameter scaling [4]) formed in the highly porous magmatic foam mounds results in a shift of the crater SFD model ages from <100 Ma to ~3.5 Ga (Fig. 4), contemporaneous with the underlying ancient shield volcano and the major global phase of lunar mare volcanism. We conclude that extremely young mare basalt eruptions to account for the Ina summit pit crater floor formation are not required.

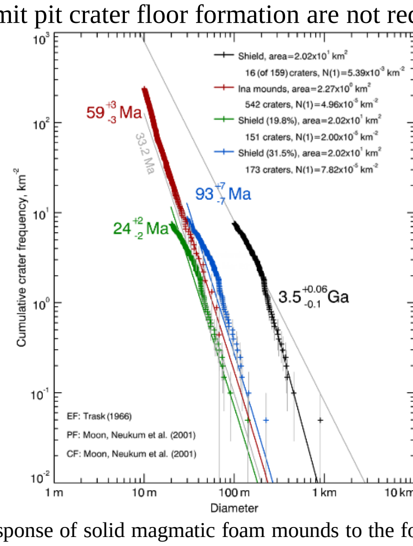

Fig. 4. Response of solid magmatic foam mounds to the formation and retention of superposed impact craters, and the estimated crater retention ages. The cumulative SFD of craters on the shield flank and Ina mounds are plotted as black and red crosses, respectively. All the counted shield craters are re-sized with a diameter scaling of 19.8% and 31.5%, and cumulatively plotted as green and blue crosses, separately.

References: [1] Braden et al. (2014) *NGEO* 7, 787-791. [2] Qiao et al. (2017) *Geology* 45, 455-458. [3] Wilson & Head (2017) *JVGR* 335, 113-127. [4] Poelchau et al. (2013) *MAPS*, 48, 8-22.