

**CONCEPTUAL LUNAR MISSIONS TO THE INA LUNAR IRREGULAR MARE PATCH: DISTINGUISHING BETWEEN ANCIENT AND MODERN VOLCANISM MODELS.** L. Qiao<sup>1</sup>, J. W. Head<sup>2</sup>, L. Wilson<sup>3</sup> and Z. Ling<sup>1</sup>, <sup>1</sup>Inst. Space Sci., Shandong Univ., Weihai, Shandong, 264209, China (LeQiao.GEO@Gmail.com), <sup>2</sup>Dep. Earth, Env. & Planet. Sci., Brown Univ., Providence, RI, 02912, USA, <sup>3</sup>Lancaster Env. Centre, Lancaster Univ., Lancaster LA1 4YQ, UK.

**Introduction:** The Ina Irregular Mare Patch (IMP), a distinctive ~2×3 km D-shaped depression located atop a 22 km-diameter shield volcano in the nearside lunar maria, is composed of unusual bulbous-shaped mounds surrounded by optically immature hummocky and blocky floor units. Its peculiar shape and interior structures intrigued lunar scientists for decades. Previous investigations have documented substantial geological characteristics of Ina in various aspects, and called on various models to interpret its formation mechanism and age, including sublimation [1], small lava intrusions within a volcanic dome summit caldera [2], episodic outgassing of volatiles within the past 10 Ma [3], lava flow inflation [4], small basaltic eruptions within the past 100 Ma [5], pyroclastic eruption [6], ancient (>3 Ga) lava lake processes and magmatic foam extrusion [7,8]. We find that the range of hypotheses for the origin of Ina can be broadly subdivided into two categories:

(1) Formation age: (a) Geologically extremely young, as indicated by the CSFD ages of ~33 Ma, optical immaturity, and sharp contacts; (b) Geologically ancient, coincident with the ~3.5 Ga age of the surrounding shield volcano, with other factors explained by unusual substrate characteristics; (c) Hybrid, geologically old, but rejuvenated by recent activity (outgassing).

(2) Setting and mode of emplacement: (a) Formation in the summit pit crater of an ancient shield volcano; (b) Formation in the summit pit crater of an ancient shield volcano, but due to magmatic activity ~3.4 billion years later; (c) Formation by flow inflation processes in a summit pit crater; (d) Formation by late stage volatile exsolution processes in the waning stages of an ancient shield volcano summit vent; (e) Formation by recent deep gas release processes in an ancient shield volcano summit pit crater.

**Significance of this Controversy: The Thermal Evolution of the Moon.** While Ina/IMPs are now generally considered to be volcanic in origin, the specific formation mechanism is still highly controversial. One of the most contentious issues concerning Ina's origin is its emplacement age, especially between the geologically very recent (<0.1 Ga) small basaltic eruption model (Young Model [5]) and the ancient (>3 Ga) magmatic foam extrusion hypothesis (Old Model [7, 8]). The Old Model generally complies with the conventional models of lunar geological and thermal evolutions, which suggest the Moon progressively lost its primordial and internally generated heat effectively by conduction, leading

to volcanism having waned in middle lunar history and ceased sometime in the last ~1 Ga [9]. The Young Model, however, raises a line of questions that conflicts with the above lunar evolution model, and indeed requires the overall evolution history to be very different in various aspects including lunar interior thermal status, abundance of lunar heat-producing elements, and stress status of the lunar lithosphere.

**Critical Unresolved Issues About the Two End-Member (Young and Old) Models.** Questions raised about the young volcanism interpretation includes (1) the unlikely longevity (3.4 Ga) of the magma source, (2) the similar composition of Ina with the adjacent mare deposits, (3) the range of morphological peculiarities of the Ina mounds (e.g., bulbous-like shapes and marginal moats), and (4) the Diviner-derived thickness (>10–15 cm) of regolith in the Ina interior. Difficulties and critical unresolved issues also characterize the ancient, shield-contemporaneous summit lava lake magmatic foam eruption interpretation: (1) incomplete understanding of cratering mechanism into highly porous targets and the effects on crater sizes, (2) the seemingly typical characteristics of impact craters on Ina mounds, (3) the unusually high reflectance and optical immaturity of Ina floor terrains, and (4) steep scarps between Ina mounds and floor terrains. We thus conclude that in order to resolve the differences between these two hypotheses for the origin of Ina, new data, experiments, and missions are required.

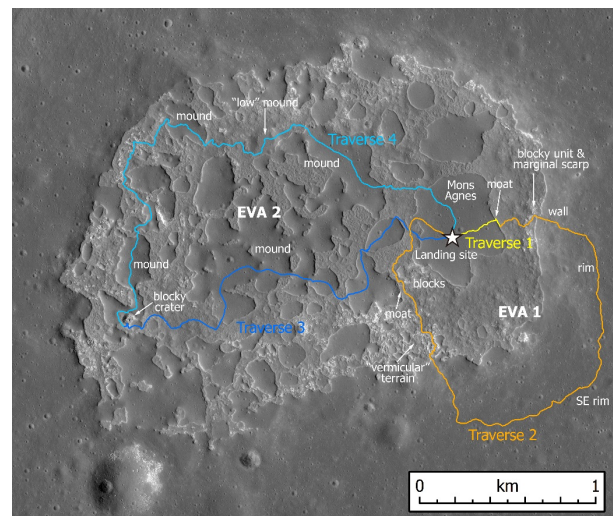
**Key Measurements to Distinguish between the End-member Models.** We identify the key measurements that would help distinguish between the two models: (1) Radiometric ages of the Ina mounds and floor materials, (2) Characteristics of the regolith material on the mounds and on the floor, (3) 3-D structure of the mounds and floor material (porosity), (4) Regolith thickness; any change with depth on mound and floor material, (5) Nature of ejecta from craters into mound and floor material, (6) Level of vesicularity of surface rocks, (7) Volatile content of magma petrogenesis, (8) Comparison of rocks, soils (and ages) inside Ina and on the shield rim, and (9) Paleomagnetism measurements.

**Missions Capable of Addressing these Objectives.** We define a range of conceptual lunar missions to the Ina feature, including (1) Robotic Lander Mission, (2) Robotic Sample Return Mission, (3) Robotic Rover Mission, and (4) Human Landing and Exploration Mission. We present an assessment of the mission styles and modes, optimal landing sites, and where appropriate,

conceptual traverses. Here we present a human landing and exploration design reference mission for an Apollo J-Mission-scale expedition to the Ina summit pit crater and vicinity (Fig. 1), designed specifically to resolve the issue of the two (old and young) origins for the Ina crater interior, but more importantly to provide the data to establish a refined or new model that can help explain these enigmatic features in Ina.

In this “Design Reference Mission” (Fig. 1), we propose landing on the floor of Ina on the largest of the mounds (Mons Agnes) and deploying ALSEP-like geophysical monitoring stations, and undertaking extensive coring and analysis of the regolith and substrate of the mounds, sampling laterally within walking distance with meters-scale cores and extensive geologic observations and sampling, guided by Astronaut visual observations and in-situ GPR data. Following the first EVA (yellow path in Fig. 1), the crew would traverse due east, down the flanks of the mound, across the moat, stopping to examine the characteristics and morphology of the moat structure, before proceeding across the more mature floor regolith deposits. Samples and observations here from traverse geophysics and GPR data will help measure the substrate density and search for evidence of macro-vesicularity predicted by the Old Model. The second traverse (gold path in Fig. 1) continues to the bright and optically immature blocky unit and outcrops at the eastern margin of the Ina floor (labelled in Fig. 1), where stratigraphy may also be exposed in the marginal scarp. Following analysis of the floor margin contact, the traverse would continue up the wall of the pit crater to the rim to continue traverse geophysics and sampling to compare the ancient rim of the shield volcano with the potentially >3 Ga younger floor (Fig. 1). The traverse would then extend along the southeast rim of the pit crater, obtaining perspective views and measurements of the Ina interior, and then descend down to the pit crater floor at the “vermicular” terrain, before heading to the western margin of the largest Ina mound and moat, and ascending the mound back to the landing site (Fig. 1). Total traverse distance of the first EVA would be about 3.2 km, a modest distance compared with Apollo J-Mission traverses. The second EVA (blue path in Fig. 1) would traverse from the landing site in a west-southwest direction, crossing multiple mounds for comparison with the major mound, its moat margins and the intervening floor subunits, and would have as a target, an unusual blocky impact crater on the southwest Ina floor (labelled in Fig. 1). Here, exploration and analysis of the unusual nature of impact craters and the stratigraphic relationships between mounds and floor units will significantly assist in the determination of the origin of the Ina floor

deposits and the specific processes operating to form them. A fourth traverse (cyan path in Fig. 1) explores the northern and northwestern part of the Ina floor, providing additional characterization of the Ina floor units and their three-dimensional structure. The astronauts would traverse down onto a peculiar “low” mound feature (labelled in Fig. 1) in the northern floor. This “low” mound is ~100×80 m in size, the largest one among six “low” mounds identified in Ina interior floor with smooth surface textures and lower elevations than the surrounding terrains. These extensive geologic field investigations and sampling of Ina’s materials will provide fundamental insights into its characteristics and formation mechanisms. Together, these four traverses cover a total distance of about 11.6 km (Fig. 1), well within the range for the successful Apollo J-missions. Clearly, human exploration and associated mobility provide significantly more scientific results than can be obtained by a robotic mission alone.



**Fig. 1.** Traverse map of human landing and exploration “Design Reference Mission” to the Ina Irregular Mare Patch and vicinity, showing the suggested landing site, astronaut traverse paths, and scientific investigations sites.

**References:** [1] Whitaker (1972) *NASA SP-289*, 25-84–25-85. [2] Strain & El-Baz (1980), *LPSC XI*, 2437–2446. [3] Schultz et al. (2006) *Nature* 444, 184-186. [4] Garry et al. (2012) *JGR* 117, E00H31. [5] Braden et al. (2014) *NGEO* 7, 787-791. [6] Carter et al. (2013) *LPSC XLIV*, #2146. [7] Qiao et al. (2017) *Geology* 45, 455-458. [8] Wilson & Head (2017) *JVGR* 335, 113-127. [9] Head & Wilson (2017) *Icarus* 283, 176-22.