LUNAR IRREGULAR MARE PATCH (IMP) SUB-TYPES: LINKING THEIR ORIGIN THROUGH HYBRID RELATIONSHIPS DISPLAYED AT CAUCHY 5 SMALL SHIELD VOLCANO.

L. Qiao[1, 2], J. W. Head[2], L. Wilson[3] and Z. Ling[1], [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.

Introduction: The distinctive Ina structure, composed of unusual bulbous-shaped mounds surrounded by optically immature hummocky and blocky floor units, intrigued lunar scientists for decades after its discovery in the 1970s [1]. Recent observations using high-resolution LROC NAC images have identified 70 small topographic anomalies with textures and structures resembling Ina, termed Irregular Mare Patches (IMPs) [2,3]. These IMPs range from 100 m to 5 km in maximum dimension, and occur on the lunar nearside in association with mare deposits.

The three largest IMPs, Ina, Sosigenes and Cauchy 5 (3–5 km in length), often have isolated smooth mounds surrounded by rough terrains, and are large enough to obtain impact crater CSFD-based model ages. [3] found all of these to be younger than 100 Ma (Sosigenes, 18 Ma; Ina, 33 Ma; Cauchy 5, 58 Ma), implying that small basaltic eruptions had occurred within the last 100 Ma, "significantly after the established cessation of lunar mare basaltic volcanism".

However, the vast majority of these IMPs are very small (average ~300 m in length) and could not be dated with CSFD techniques. These small IMPs share some of the morphologies with the larger ones, while also showing many differences. The smaller IMPs do not always contain isolated smooth deposits, but do have smooth deposits connected to the surrounding mare; these smooth mounded deposits consistently have lobate margins and steep boundary slopes, and are interpreted to superpose the uneven deposits [3].

In summary, the morphology and distribution of all the mapped IMPs can be subdivided into two categories: (1) a small number of larger features (3–5 km in dimension) related to pit craters and vent like structures (e.g., Ina and Sosigenes), and (2) a much larger number of "Mare-IMPs" dominantly smaller than ~300 m, and distributed in the lunar maria with typically no clear relation to a pit crater or vent. Whether the two IMP sub-types have similar origins is unknown due to the fact that 1) the morphologies of each subtype have some similarities, but also some differences, and 2) the smaller Mare-IMPs are too small to date confidently. In this analysis we assess: 1) the origin of IMPs, 2) the ages of IMPs, and 3) the relationships between the two types of IMPs in terms of their mode(s) of origin.

Hypotheses for the Origin of Lunar IMPs: Following the identification and documentation of the 70 IMPs and the dating of the three largest ones, interpretations different from that proposed by [3] emerged.

Pit craters environment. Examination of the ascent and eruption of magma in the waning-stages of eruptions [4] in small shield summit pit crater floors, such as Ina, showed that many IMP characteristics can be explained in this final-stage eruptive context. Specifically, the floor hummocky and blocky units are interpreted as the very vesicular and porous lava lake crust, and the convex mounds are magmatic foams extruded from fractures within the chilled lava lake crust; foam physical properties (aerogel-like) inhibit typical impact crater formation and regolith development, creating an artificially young crater retention age.

Reanalysis of the large IMPs Ina and Sosigenes [7,8], both associated with pit craters, showed that the morphologies of the mounds and rough floor were consistent with the lava lake and magmatic foam scenario. Furthermore, when the effects of impacts into magmatic foam were considered (much smaller crater diameters, etc.), the CSFD of the mounds was consistent with the ancient >3 Ga old age of the surrounding volcanic deposits within which the largest IMPs reside. Thus, the final-stage lava lake and magmatic foam formation mechanism [4] appears to account for the main features of the two major large IMPs without resorting to lunar volcanic activity in the last 100 Ma.

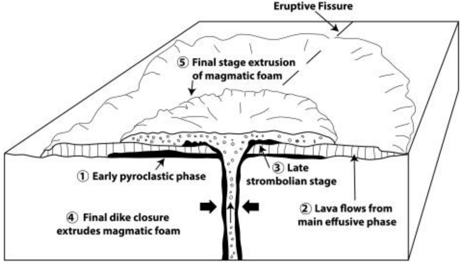

Fig. 1. Model for final-stage foam-rich mare basalt extrusions in unconfined fissure mare foam flows [4].

Near-Vent Mare Flow Environment. The mechanism described by [4] for the production and extrusion of very vesicular magmatic foams is also applicable to waning-stage dike closure associated with mare fissure eruptions (Fig. 1), providing a potential explanation for the many smaller IMPs. In this case, instead of being contained by a summit pit crater or vent and forming a lava lake, the final-stage, very vesicular, foamy magma exits the vent and flows out onto the flows from the earlier phases of the eruption, flowing away from the vent area as meters-thick foamy lava.

Relationship Between the Large and Small IMP Sub-Populations: Based on the observed characteristics and theoretical treatment of the closing stages of lunar eruptions in both pit crater and near-vent mare flow environments [4], we propose that the differences between the small and large IMP populations could be related to whether they are 1) contained in a pit crater or 2) simply spread out onto the maria to produce dispersed smaller collapse craters in the closing-stage void-rich foamy lava flows. We find that the relationships displayed at the Cauchy 5 small shield volcano summit and flanks may provide a hybrid example of the genetic link between the large pit crater and small mare IMPs.

Cauchy 5 Small Shield Volcano: Linking the Two IMP Sub-Types: The Cauchy 5 small shield volcano (Fig. 2), located in Mare Tranquillitatis (7.169°N, 37.592°E), is a circular mound ~5–6 km in base diameter, and ~40 m high, and is typical of many small shield volcanoes on the Moon [9]. It displays an elongate summit pit crater, ~0.75×2.5 km and ~75 m deep, oriented in a WNW direction (Fig. 2). The shield flanks slope away (2°–6° slopes) from the summit pit crater to the base, where it joins the regional flat maria. A major large IMP, consisting of extensive mound-like deposits on the pit floor and rim, and rough and optically immature floor and rim/wall material, has been identified at the Cauchy 5 summit pit crater floor [3, Fig. 2], which can thus be readily interpreted through the closing-stage eruption model established for Ina and Sosigenes IMPs [4,7,8].

In addition, Cauchy 5 also shows many differences. (1) The elongate, tongue-depressor shape of the vent is perturbed to the west and north by an extension of the pit crater, although at a level 30–40 m shallower than the deepest part in the southeast, suggesting there may have been two topographic levels in the lava lake. The ~750×850 m, 30–35 m deep topographic extension/opening in the northern part of the pit crater suggests that this feature might have been an exit breach for waning-stage summit pit crater lava lake activity. (2) Mound and rough terrains typical of the interior of Ina, Sosigenes and Cauchy 5 depressions also occur in an ~750×800 m area on the NW rim, and in an ~1.3×1.4 km area within a rim depression to the north. These distinctive occurrences, and the two topographic levels of the pit floor, strongly suggest that the waning-stage lava lake and magmatic foams that occupied the pit crater interior raised and lowered in the pit interior, and also spilled out over the pit crater rim, particularly to the north and west. (3) Many small mare-like IMPs occur in two broad regions on the summit and flanks of the Cauchy 5 shield volcano: 1) an ~1×4 km broad belt on the northern flank (Fig. 2), and 2) a concentric zone adjacent to the southeastern edge and extending up to ~0.5–2 km from the pit crater rim (Fig. 2). These small mare-IMP-like features are very similar to the many documented in the small IMP catalog [3].

On the basis of geological characterization above, we interpret the history of the shield volcano and the two different styles of IMPs at Cauchy 5 as follows: 1) The Cauchy 5 small shield was constructed over a linear WNW-trending dike to produce low effusion rate, cooling limited flows erupting from the evolving summit pit crater, in a manner similar to the larger Ina shield volcano [4,6,7]; 2) As the shield-building eruptions began to wane and magma ascent rates decreased [4], magmatic volatiles were concentrated in the dike to produce very vesicular, foamy magmas; 3) As the dike began to close, foamy magma was extruded into the pit crater, forming and contributing to the lava lake, and inducing a strombolian phase and building up foams beneath the lava lake crust [4]; 4) In contrast to the situation in Ina and Sosigenes [7,8], as the Cauchy 5 dike closed, foamy magma filled the summit pit crater and overflowed the rim one or more times to produce foamy lava flows extending to the north flanks and southeast rim (Fig. 2). These meters-thick foam-rich rim and flank flows formed many small mare-type IMPs; 6) In the post-foam overflow stage, the magma degassed, and the lava lake level decreased; flexing of the lava lake surface led to fracturing and extrusion of the underlying magmatic foam, and to resurfacing of the pit crater floor by the extruded foam. All of these activities took place in the waning stages of the formation of the shield volcano and summit pit crater more than 3 Ga ago.

The Cauchy 5 small shield volcano IMP features (large pit-crater type IMP in the summit and small mare-like IMPa on the rim and flanks) thus provide a hybrid example which links the small and large IMP types. We interpret the mare-type small IMPs on the Cauchy 5 rim and flanks to be very analogous to the mare-type magmatic foam extrusions inferred to occur in the closing-stages of mare fissure eruptions where the waning stage foams are not contained within a pit crater (Fig. 1), as they are at Ina and Sosigenes.

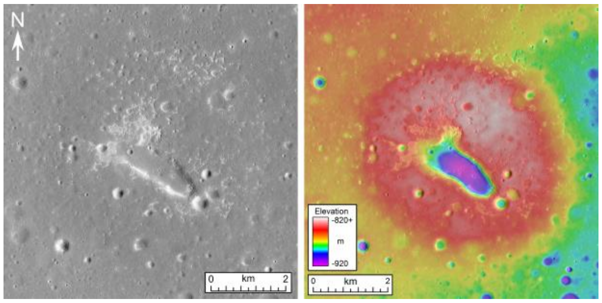

Fig. 2. Image and topography of Cauchy 5 small shield volcano.

References: [1] Whitaker (1972) *NASA SP-289*, 25-84. [2] Stooke (2012) *LPSC XLIII*, #1011. [3] Braden et al. (2014) *NGEO* 7, 787. [4] Wilson & Head (2017) *JVGR* 335, 113. [5] Wilson & Head (2017) *Icarus* 283, 146. [6] Head & Wilson (2017) *Icarus* 283, 176. [7] Qiao et al. (2017) *Geology* 45, 455. [8] Qiao et al. (2017) *MAPS*, doi:10.1111/maps.13003. [9] Head & Gifford (1980) *Moon & Planets* 22, 235.