

IRREGULAR MARE PATCHES ON THE MOON: SITES OF REGOLITH DRAINAGE INTO SUBSURFACE VOIDS? *M. A Kreslavsky*¹ and *J. W Head*², ¹Earth & Planetary Sciences, Univ. of California – Santa Cruz, Santa Cruz, CA, 95064, USA, mkreslav@ucsc.edu, ²Earth, Environmental & Planetary Sciences, Brown Univ., Providence, RI 02912, USA.

Introduction: *Irregular mare patches* (IMPs) (Fig. 1, 2a) are rare features of debated origin [e.g., 1, 2 and references therein]. The largest IMPs are several km in size, while the smallest identifiable ones are tens of meters. In [3] the term “meniscus hollows” is used for these features, which appropriately describes their morphology: they consist of two subunits: bright hummocky lower subunits (“hollows”) and dark smooth convex-upward slopes surrounding them and forming the upper subunits (“menisci”). The boundary between the subunits is sharp and “crisp”; it is associated with a very sharp slope break between the rough, but generally horizontal lower subunit and the rather steep slope of the upper subunit. In some of the largest IMPs in addition to hollow surroundings, the upper subunit also forms islands, elevated mounds (class 1 IMP according to [2] in contrast to class 2 without inner mounds), such as in the most well-known IMP example of Ina [e.g., 4, 5] (Fig. 2a). The transition between the upper subunit and its surroundings is gradational. Reflectance spectra suggest that the higher albedo of the lower subunit is caused by surface immaturity [6]. Small superposed craters are hard to identify in the hummocky lower subunit; the upper subunits of the largest IMPs have sparser population of superposed small impact craters than surrounding mare, suggesting a young crater retention age [1]. Totally 91 IMPs and their clusters are catalogued in [1, 2].

The *formation mechanism of IMPs* is debated. It has been suggested [1] that IMPs are young volcanic features with the hollows being collapse depressions often observed in terrestrial inflated lava flows. This mechanism has some difficulties: (1) It is inconsistent with the observed gradational boundary between the upper subunit and IMP surroundings. (2) The morphology of small craters superposed on the upper subunit is identical to the morphology of craters of the same size in the surrounding maria, as documented in [7], which suggests a thick regolith layer, and thus an ancient age for the upper subunit. It has been suggested [8] that IMPs formed recently, when regolith was blown away by release of gas from the subsurface. This mechanism explains the IMP morphology and apparent young crater retention age of the upper subunit (due to partial obliteration of small craters by infill with ejected regolith). This mechanism also has difficulties: (1) Accumulation of significant amount of gas under pressure in the shallow subsurface and its sudden release seem unlikely. (2) This mechanism predicts a halo of immature regolith, which is not observed. In [5, 9] it has been suggested that the inner mounds of class 1 IMPs are old volcanic extrusions of highly vesicular lavas, while the immaturity of the lower subunit is due to

recent drainage of regolith into the shallow subsurface voids. Here we hypothesize that all IMPs, both large and small, can be formed by drainage of regolith into shallow subsurface voids alone.

Formation Scenario: From observations it is known [e.g., 10, 11 and references therein] that large subsurface voids exist in the lunar maria. Theoretical considerations [e.g., 12] outline several environments, in which magma degassing can occur and formation of large voids and/or vesicular volcanic rocks with high macroporosity is likely. Void roofs were likely fractured soon after lava emplacement due to temperature variations, seismicity and small impacts. Some roofs collapsed early, however despite fractures, some of them were mechanically stable like vaults, and survived for billions of years being protected from impacts by an accumulating regolith cover. Occasionally, seismicity or relatively larger impacts may break mechanical stability of a vault-like roof and cause collapse; collapsing a single void cell would likely cause loss of mechanical stability of adjacent void cell roofs, triggering collapse over some area.

We hypothesize that the IMPs form as a consequence of such collapse events. The IMP's lower subunit is a place where the pre-existing regolith layer drained down into voluminous spaces between blocks of collapsed material. Removal of the regolith layer is responsible for the lower subunit being lower than the IMP surroundings. Ongoing drainage of newly produced fines is responsible for the immature optical signature of the lower subunits; unresolved cracks, blocks, etc. are responsible for the hummocky appearance of the subunit in the high-resolution images. The convex menisci of the upper subunit are created by topographic diffusion [13, 14] due to regolith gardening induced by micrometeoritic bombardment. In the context of this scenario, the mounds in class 1 IMPs are the remnants of the old regolith layer.

Numerical Modeling illustrates the shaping of the upper subunit by topographic diffusion [14]. We took a part of Ina (Fig. 2a) and mapped its subunits. Then we solved the diffusion equation $\frac{\partial h}{\partial t} = K \nabla^2 h$, where t is time, h is elevation, K is topographic diffusivity, and ∇^2 is the two-dimensional Laplacian. We applied the boundary condition $h = 0$ everywhere in the lower subunit, which models the instant drainage of material into the subsurface, and the initial condition $h = h_0 = 10$ m within the upper subunit at $t = 0$. (Specific h_0 value only affects

the vertical scale of the result). **Fig. 2b** shows the solution at $Kt = 220 \text{ m}^2$. For $K = 5.5 \text{ m}^2\text{Ma}^{-1}$ [14] this corresponds to $t = 40 \text{ Ma}$. It is likely that some lower effective diffusivity should be used for such small features as Ina mounds [15], which would give higher t values. Fig. 2b demonstrates that diffusion realistically reproduces the shapes of Ina mounds. For much greater Kt values the mounds would become lower. This points that IMPs are 10s to 100s Ma old.

Thus, within our scenario the IMPs are geologically young features made of old material (old lavas and old regolith). They are currently active, meaning that there is ongoing drainage of fines transported downhill from the upper subunit and newly created in the lower subunit. The void space needs to be at least tens of meters thick to loosely accommodate all sank regolith and provide space for ongoing drainage.

In the frame of this scenario, the *young apparent crater retention age* of large IMPs is an *observational artefact*. The basic assumption of surface dating by crater counting is that the counting area is chosen independently of craters. This assumption is violated for craters counted on IMPs. The IMPs can only exist in the stochastically formed gaps between large ($> \sim 100 \text{ m}$) craters, because such craters would destroy the subsurface void and make IMP formation impossible. Moreover, even within these gaps, the upper subunit must be devoid of relatively larger craters, because they would initiate collapse and therefore would belong to the lower subunit. This absence of larger craters would mimic steep cumulative size-frequency distributions of a young age. In addition, small craters within the upper subunit in proximity to its steep edges would be rapidly erased by anomalously intensive regolith transport. This would further reduce the apparent crater density.

Discussion: The outlined scenario of IMP formation naturally explains a number of IMP characteristic features, for example, the following:

- The IMPs occur in several distinct geological settings that correspond to settings in which formation of voluminous shallow voids is likely (as discussed in [2,16]).
- There are wide variations in albedo of the lower subunit (see, e.g., Fig. 1b). Places of active drainage of fines are the brightest, while in darker places the voids are filled or their openings are clogged, and accumulation and maturation of new regolith occurs.
- The absence of a distinctive contact between the upper subunit and surroundings is natural because both are made of the same regolith and diffusion does not produce any slope breaks.
- The diffusion model predicts that among small mounds, the larger mounds are systematically taller (e.g., mounds marked by **arrows in Fig. 2b**). This is indeed observed in Ina (cf. Fig. 1a) and other class 1 IMPs.
- Narrow moats at some sharp contacts between the

subunits [5] may form because the lower subunit at the contact must be active (otherwise the contact would not be sharp), while further away from the contact the lower subunit may be inactive, accumulating regolith, which result in an active moat between the slope of the upper subunit and inactive surface of the lower subunit.

- It is natural to expect that the cracks at the contacts between the subunits may get clogged at some place. In this case the diffusion model predicts formation of a concave “ramp” connecting the lower subunit with the convex slope of the upper subunit. Such “ramps” indeed are often found in IMPs (several examples are marked with **arrows in Fig. 2a**).

- The largest impact craters in the lower subunit of Ina are systematically larger than the largest craters in its upper subunit [5]. This is natural, because a larger impact into the upper subunit would cause void collapse and transform the area into the lower subunit.

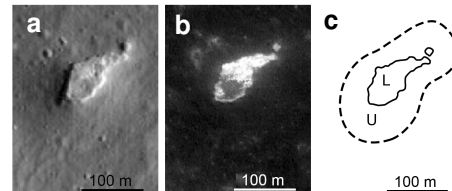


Fig. 1. A small IMPs from IMP cluster Carrel-1 [1]. (a) Low-sun image, illumination from the left. (b) Contrasted high-sun image. (c) Sketch map. L, lower subunit; U, upper subunit; solid line, sharp contact between them; dashed line, gradational contact with surroundings.

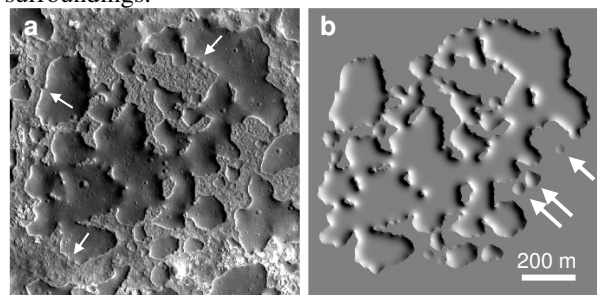


Fig. 2. A part of Ina. (a) Low-sun image, illumination from the left. Arrows point at “ramps” (see Discussion). (b) Model illuminated from the left. Arrows point at mounds of different size (see Discussion).

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