Investigating 16 Irregular Mare Patches with Visible/Near-Infrared Spectra From the Moon Mineralogy Mapper.
H. Vannier[1], B. Horgan[1] and J. Stopar[2], [1]Earth Atmospheric and Planetary Science, Purdue University (hvannier@purdue.edu), [2]Lunar and Planetary Institute, USRA

Introduction: Irregular mare patches (IMPs) are morphologically distinct features on the Moon distinguished by smooth, high relief mounds that overlie a topographically lower blocky/hummocky unit [e.g. 4,15,19]. Because of their association with volcanic rilles, vents, and mare regions, they are likely the product of lunar volcanism [4,9,18,19]. The small sizes of IMPs (<4 km), lack of surface weathering, and preservation of small-scale surface textures make them distinct from their surroundings [4,19], but most intriguing is the greatly reduced appearance of surface cratering within smooth mounds, implying ages of <100 Ma [4]. If IMPs are young, they may be examples of very recent volcanism, long after the expected cessation of lunar volcanism ~1.5 Gyrs ago, implying an extended decline of lunar volcanism rather than a rapid termination.

However, it is currently unknown whether the youthful appearance of IMPs is due to recent volcanism, recent physical modification, or other factors. Only a handful of the numerous known IMPs have undergone detailed morphological study, and none have included detailed compositional analysis. Mineralogy, and in particular the presence or lack of glass within and around IMPs, has the potential to help determine both the presence of past explosive volcanic activity and the relationship between IMPs and local volcanic units [1,2,7,8,9,11]. We investigated of a diverse suite of 16 IMPs using VNIR spectra (0.35-3 μm) from the Moon Mineralogy Mapper (M^3) to constrain their mineralogy and test the proposed formation mechanisms.

Methods: We extracted average spectra of 3-4 different regions of interest (ROI) at IMP locales, including: the IMP itself (smooth and rough patches for large IMPs and an average of both for small IMPs), nearby mare, and fresh mare craters. We compared M^3 band ratios after [11], Kaguya and Clementine spectral maps [13,14], and clinopyroxene (CPX), orthopyroxene (OPX), and glass band parameter maps [2] to identify any spectral diversity in or around each IMP. For each average ROI spectra, we removed the spectral continuum [11] by dividing by two line segments fit to endpoints at 0.7-1.0, 1.2-1.7, and 2.0-2.6 μm. We then computed the position, area, and asymmetry of the 1 and 2 μm absorption bands in the continuum-removed spectra to identify dominant iron-bearing minerals and glass [2,11]. These techniques have been employed effectively elsewhere on the Moon to establish the mineralogy of diverse volcanic settings and features [2,3,12].

Results: Both small and large IMP regions have 1 μm band centers that range from ~0.95-1.02 μm. The interiors of large IMPs exhibit 2 μm band centers between ~2.15-2.3 μm, and we do not observe clear compositional differences between rough and smooth textures. Small IMPs have 2 μm band centers from ~2.1-2.3 μm and show greater variability, though this is likely due to noise in the spectra. These results are consistent with CPX-dominated spectra in all IMPs, surrounding mare, and fresh craters, though fresh craters at Ina may show evidence of excavation of a subsurface layer with a different composition. In general, the low 1 μm band asymmetry (<10%) for all spectra indicates no significant contributions from glass or olivine. However, there may be a minor glass component supported by higher asymmetry within a halo region surrounding Hyginus. Furthermore, large IMPs (plusses and circles; Figure 1) tend to have higher band centers than their surrounding mare (diamonds; Figure 1), a subtle trend that could be consistent with small additions of olivine or glass. This trend is less consistent within smaller IMPs, possibly due to the small surface area available at M^3 resolution or due to noise in the data.

Discussion: Generally, our analyses show that both IMPs and their surroundings appear to be composed of similar material and are CPX-dominated, implying that IMPs are composed of mare material, possibly generated from a similar magmatic source as the surrounding mare. This does not support recent formation from a long-lived magma chamber, as might be expected beneath a caldera-shaped depression [20], since significant magmatic evolution over time would likely result in greater contrast between IMP and mare compositions.

The general absence of significant glass deposits within or around IMPs does not support their formation during a sustained pyroclastic eruption of juvenile materials (vs. fragmented country rock) [2,7]. The low thermal inertia of Ina's mounds is consistent with >10 cm of fine-grained materials [5,6], so while in disagreement with fine-grained glassy pyroclastics, mound material is likely different compositionally than typical regolith. It has also been proposed that IMP material composed of a rapidly cooled magmatic foam could be glass dominated [16], but we do not observe deposits with a significant quantity (>40-50%) of glass at any IMP locations.

One exception so far to the general trend is Hyginus where we observe potential glass mixing in the region immediately surrounding Hyginus' crater, a volcanic collapse feature containing IMP texture [20], and we observe possible glass additions within larger IMPs. The region immediately surrounding Hyginus shows an increase in 1 µm asymmetry toward higher values and spectra of the halo region displays absorption between 1.15 and 1.2 microns, both associated with glass absorption. This implies some explosive pyroclastic volcanism may have occurred during formation of Hyginus, but no sustained eruptive column, as this should consist of a glass rich deposit and strong glass signature [2]. Radar data suggests a thin pyroclastic mantling [5,10,20], also consistent with past explosive volcanism. In most large IMPs, a subtle increase in IMP 1 and 2 µm band centers compared to nearby mare may suggest a systematic trend of minor glass (e.g. thin and degraded pyroclastic deposits) or olivine mixing, but a more detailed evaluation of error is needed.

Our results from the 16 IMPs in this study are most consistent with IMPs having formed from recent process or are composed of materials poorly suited for crater preservation. Both mounds and other interior deposits are CPX-dominated and glass-poor. Recent episodic outgassing has been invoked to explain the spectral immaturity, well preserved fine-scale features, and number of small craters within IMPs, as the outgassing would remove older surface layers and expose younger material [17]. This mechanism is consistent with the similarity observed between IMPs and the surrounding mare, and if accompanied by minor (gas-rich) explosive eruptions, could include a minor amount of juvenile glass. It has also been proposed that IMPs are ancient deposits composed of highly porous magma foam, where regolith drainage or collapse into subsurface void space and ineffective crater preservation are responsible for IMPs' youthful appearance [15,16,19]. Our observations suggest that such a deposit would need to be largely crystalline rather than glassy.

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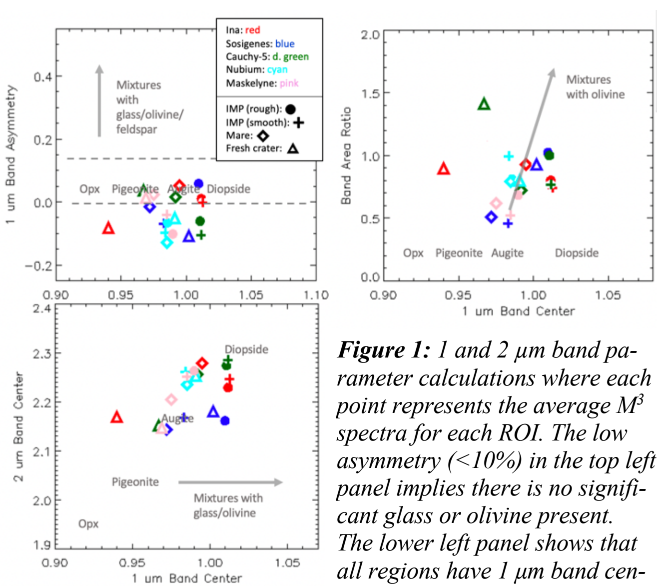

Figure 1: 1 and 2 µm band parameter calculations where each point represents the average M^3 spectra for each ROI. The low asymmetry (<10%) in the top left panel implies there is no significant glass or olivine present. The lower left panel shows that all regions have 1 µm band centers ranging from ~0.95-1.02 µm and 2 µm band centers from ~2.15-2.28 µm that are consistent with clinopyroxene (CPX). The relatively low band area ratio (top right) implies there is no significant contribution from olivine.

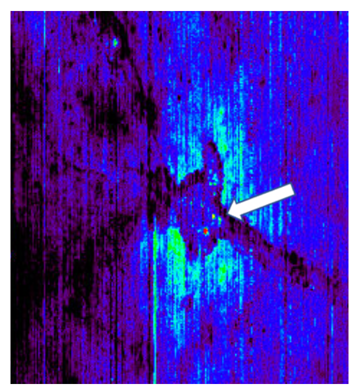

Figure 2: The glass band parameter map (top left) highlights in bright green absorption from 1.15-1.2 µm, associated with glass, and shows evidence of glassy halo. Arrow points to location of IMP texture within Hyginus. Continuum removed spectra (bottom left) for the Hyginus ROIs and associated band parameter calculations (directly below).