WHAT TO EXPECT IN LUNAR PITS. R. V. Wagner and M. S. Robinson. School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-3603 (rvwagner@asu.edu).

Introduction: Lunar pits are an unusual negative relief landform characterized by near-vertical walls and inward-sloping rims, hypothesized to be formed by collapse into a pre-existing tectonically- or volcanically-derived subsurface void space [**1**,**2**]. There are currently 17 known pits in the lunar maria, along with almost 300 pits in impact melt ponds, and three pits in the lunar highlands unassociated with any impact craters [**1**,**2**,**3**,**4**,**5**]. This work focuses on mare pits, as they expose cross-sections through the lunar maria, rather than simply through a likely-uniform impact melt unit.

We used oblique Narrow Angle Camera images from the Lunar Reconnaissance Orbiter Camera with pixel scales ranging from 0.5 to 2 m [**6**] to investigate the interiors of mare pits. Where multiple viewing angles were available with similar lighting, we produced stereo models of the walls to get 3D models of the pit walls and floors, and depths of layer exposures [**5**].

Morphology: Mare pits show a sequence of morphologies, from extremely crisp features, steep funnels, and vertical or overhung walls, to rounded edges, wide shallow funnels, and significant infilling (**Fig. 1A-D**).

The pits with the best exposures of vertical walls lie in the middle of the morphology range (e.g. **Figs. 1B,F**), with vertical to slightly-overhung walls and funnels that smoothly increase in slope from flat surroundings to around the angle of repose near the pit rim (e.g. **Fig. 2**). Crisper pits tend to have significantly overhung walls and smaller openings, making observation difficult, and more-worn pits have less remaining vertical exposure.

Overhangs. Our pit interior 3D models show floor extending 10 m under the east rim of the Mare Tranquillitatis pit (MTP), and 15 m under the southwest rim of the Mare Ingenii pit (MIP). In both cases, the floor slopes downward under the overhang, indicating that debris may not have fully filled in the original void space. The Marius Hills pit (MHP) and Lacus Mortis pit (LMP), by contrast, do not have significant overhangs on the modelled walls and have flat or upward-sloping floors at the wall, suggesting a more complete infilling. At MHP, the rim shows no evidence of extensive mass wasting to produce that infill, suggesting that either the original void space was very small or that the as-yet-unimaged west wall might have a significant opening.

Void origin. The nature of the void spaces into which lunar pits collapsed is still an open question. Lava tubes are a frequent suggestion, and potential detections of an intact lava tube near the Marius Hills pit have been reported [**7,8**], but these identifications are inconclusive. Only two mare pits are in close enough proximity to each other to be plausibly related [**3**], so we cannot use linearly-aligned pits as evidence of lava tubes as we can on Earth and Mars. Alternate mechanisms, such as stoping of tectonically-formed voids [**9**], could produce these morphologies without a large cave system.

Layer Exposure: Layers of apparently coherent rock do not appear in pits until near the bottom of the funnel, usually as thin exposures sticking out of angle-of-repose regolith slopes (**Fig. 2**, far left edge). It is unlikely that most exposed layers can be reached with an untethered rover, due to the need to traverse unstable steep slopes. The main exception is LMP, where one wall is covered by a ~23° debris slope from rim to floor, which may be traversable and would provide access to exposed bedrock on the north and south walls (**Fig. 1H**).

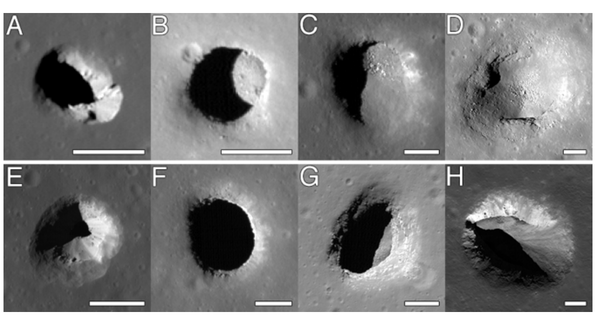

Figure 1: *A-D)* Examples of mare pits exhibiting a range of degradation states, from nearly pristine (*A*) to highly degraded (*D*). *E-H*) Other pits mentioned in this abstract. *A)* Schlüter. *B)* Marius Hills. *C)* Central Fecunditatis. *D)* Insularum. *E)* Southwest Fecunditatis. *F)* Tranquillitatis. *G)* Ingenii. *H)* Lacus Mortis. Scale bars are 50 m, all panels have similar incidence angles.

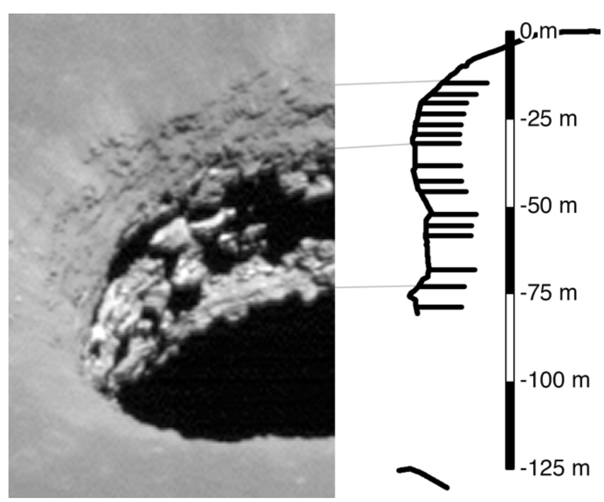

Figure 2: Mare Tranquillitatis pit (see **Fig. 1F**) east wall, image (*left*) and cross-section of 3D model (*right*).

Layer thickness. We observed horizontal morphologic features, interpreted as outcrops, with a spacing of ~3.7±1.3 m at the two pits with completed models (MTP and MIP) [**5**]. These findings are in line with previous work that reported layer thicknesses exposed in impact crater walls of 2-14 m [**10**] and 15±5 m [**11**]. It should be noted that from Earth analog studies, these morphologic layers may include multiple flow units, and are an upper limit on how thick individual flows can be [**12**].

Inter-layer disruptions. MTP has a >8 m deep recess on the west, north, and possibly east walls at 40 m depth, suggesting a strength discontinuity- possibly evidence of a buried layer of unconsolidated material, the most likely candidates for which would be a layer of pyroclastic material, a paleoregolith that developed between mare flows, or ejecta from a nearby impact crater.

Potential *in-situ* observations: *In-situ* observations of mare pit walls could constrain the timing, volume, and flow rate of the individual eruptions that formed the lunar maria, without any of the impact process alterations that would complicate crater wall layer sequences from [**10**] or [**11**]. A good instrument suite would constrain all of those factors, as well as allow correlation between flow units in the wall and samples or orbital observations from elsewhere on the Moon.

Instrumentation. A minimal sensor suite to discriminate flow thicknesses and mineralogies from the rim or floor would include a high-resolution monochrome camera and a visible/NIR spectrometer with a narrow field of view and high spectral resolution to determine the mineralogy of individual layers, and in particular to discriminate the orthopyroxene/clinopyroxene ratios.

Surficial coatings of fine-grained material may be a concern with spectral observations, especially for the upper layers. In MTP, the albedo of the wall changes abruptly at ~40 m depth, where there is an overhang which may shield the lower (brighter) wall from infalling debris (**Fig. 2**). This albedo boundary is not obvious at the other large pit with an overhung wall (MIP), but that may be due to illumination angle effects, as the only wall seen so far below the MIP overhang is facing downward, away from the Sun, whereas MTP has vertical walls both above and below the overhang.

With a robot capable of traversing the wall (e.g. [**13**,**14**,**15**]), spectral analysis could be supplemented with contact elemental abundance instruments (such as APXS or Mössbauer spectrometers), as well as microscopic imagers to determine crystal size and thus cooling rate. Contact would also allow a surface preparation tool, like the Rock Abrasion Tool on the Mars Exploration Rovers, to remove any problematic dust coatings.

Collection of samples from a pit wall would allow precise age dating of individual flows and more detailed analysis of how the source magma or magmas evolved over time, and might include exotic materials such as ancient solar wind particles emplaced between flows.

Conclusion: Between pits and crater wall exposures it is now certain that significant portions of lunar mare were emplaced as relatively thin flows. Lunar mare pits expose up to ~100 meters of mare flow units, and could provide a detailed look into the history of the flows that formed the maria, with >30 m exposures in at least six different maria allowing for comparative studies. The biggest outstanding question about pits themselves is the source of the original void space into which mare pits collapsed. Current orbital evidence is insufficient to distinguish between collapsed lava tubes, magma chambers, or tectonically-formed voids.

References: [**1**] Haruyama et al. (2009), *GRL*, doi:10.1029/2009GL040635. [**2**] Wagner and Robinson (2014), *Icarus*, 237C, 52–60. doi: 10.1016/j.icarus. 2014.04.002 [**3**] Wagner et al. (2017), *48th LPSC*, #1201. [**4**] Yokota et al. (2018), *49th LPSC*, #1907. [**5**] Wagner and Robinson (2019), *50th LPSC*, #2138. [**6**] Robinson et al. (2010), *Space Sci. Rev*. doi: 10.1007/s11214-010-9634-2. [**7**] Chappaz et al. (2017), *Geophys. Res. Lett.* doi: 10.1002/2016GL071588 [**8**] Kaku et al. (2017) *Geophys. Res. Lett.* doi: 10.1002/2017GL074998 [**9**] Okubo and Martel (1998), *J. Volc. And Geotherm. Res.*, 86, 1-18. [**10**] Robinson et al. (2012), *Planet. and Space Sci.*, 69, 18-27. doi: 10.1016/j.pss.2012.05.008. [**11**] Enns and Robinson (2013), *44th LPSC*, #2751. [**12**] Wagner et al. (2018), *49th LPSC*, #1538. [**13**] Nesnas et al. (2019), *2019 IEEE Aerospace Conference*, doi: 10.1109/AERO.2019.8741788. [**14**] Parness et al. (2017), *IEEE ICRA*. doi: 10.1109/ICRA.2017.7989643 [**15**] Kalita et al. (2018), *IEEE PLANS*. doi: 10.1109/ PLANS.2018.8373521

Appendix A: New mare pit: Since last year [**5**], we located one new mare pit, at 35.104°N, 17.402°E in Mare Serenitatis (**Fig. 3**). The pit is ~25×17 m across (excluding the funnel), and >22 m deep from the top of the funnel (the floor has not yet been imaged). The pit is located a few hundred meters from a ~150 m deep elliptical depression that may be a volcanic vent.

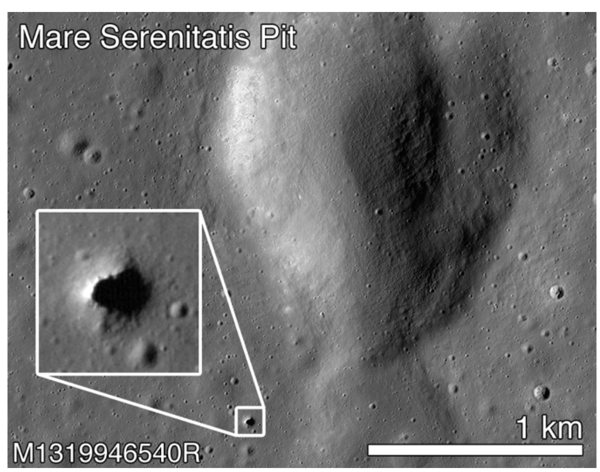

Figure 3: Newly-discovered pit in Mare Serenitatis.