CHARACTERIZING VOLCANIC AND IMPACT MATERIALS IN LUNAR CRATERS. G. Robbins[1], G. W. Patterson[1], D. Dyar[2], L. Ostrach[3]. [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA; [2]Mount Holyoke College, South Hadley, MA, USA; [3]United States Geological Survey, Flagstaff, AZ, USA.

Introduction: The interiors of lunar craters can contain fill deposits that originate from melt formed in the initial impact and/or during later volcanic activity [1]. Type distinguishment allows us to better understand the evolution and origins of the moon. Endmember cases of these processes are straightforward to classify. However, overlapping morphological characteristics and weathering processes complicate this classifaction. Here we use Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Cameras (NAC) and Wide Angle Camera (WAC) image data to examine eight craters with diameters >30 km that include both types of fill and that vary in age, location, and morphological characteristics. The goal of our research is to determine whether any single or combination of characteristics can aid in the classification of non-endmember fill types.

Background: The volume of crater fill generated during impact events and the morphology of the resulting melt flows are directly related to the preexisting topography and diameter of the crater created [2]. Seismic shaking may also impact the final appearance of an impact melt flow as it solidifies [3]. Generally speaking, all craters include impact melt deposits. Many craters later accumulate volcanic melt fill that superposes the impact melt. Estimates suggest that volcanic activity ceased approx. 1-2 Ga [4], while major (but rare) impact events have occurred as recently as 0.5 Ga [1]. Both types of crater are subject to erosion from micrometeorite bombardments [5] and accumulation of regolith. Common features and prominent craters with those features can be seen in Table 1.

Methods: We used nested data during the mapping process by labeling features of note at a set scale, then zooming in and repeating until the features measured approximately <5 km in either the vertical or horizontal direction. We compiled larger mosaics at 100 m/pixel from LROC with incidence angles at 70° ∓ 10°, as well as image pairs that provided 0.5 meter-scale panchromatic images over a 5 km swatch. We decided on the crater diameter minimum of >30 km because smaller craters lack distinct features intrinsic to fill types [6] and thus were not viable for broader characterization.

Characteristics Due to Origin: Volcanically-filled craters have the same chemical composition (basaltic and heavy in iron) at a global scale. The only major features along the crater floor are linear (i.e. scarps and wrinkle ridges) and often exceed 5 km in length. These formed as extensional stress accumulated during cooling [6]. Volcanically-filled craters exhibit no major elevation changes along fill, save for any uncovered central peaks, unfilled superposed craters, and embayed craters. Embayed craters are unique to volcanically-filled craters and therefore are material-defining, not every volcanically-filled crater has them.

All of the impact melt-filled craters exhibited a "ponded" appearance. Observation of image pairs reveal rough crater floors. Meter-sized boulders and blocks left over from crater formation rest in topographic lows. Cooling fractures surround mounds on the crater floor. All of these features are at the meter scale. Around crater rims are terraces and melt pools, where melt accumulated and then flowed downward, solidifying mid-movement. All of these features are obscured by future flows or impacts. The crater floor is a mix of impactor and preexisting material, however central peaks can exhibit more ancient compositions. Compared to mare, however, impact melt is substantially lower in iron.

Characteristics Due to Age: When examining craters of varying ages, we noticed that certain features commonly associated with one fill type are rather due to the age of the crater. Rim terraces, for example, are not indicative of a crater fill. While lower elevation terraces may be obscured by volcanic fill, the erosion of these terraces occurs over millions of years, gradually wearing down the terraces into slopes leading to the crater floor. Younger volcanically-filled craters (Tsiolkovsky, see Fig 1) still have intact terraces and a distinct crater rim, while the older impact melt-filled craters (Eratosthenes, see Fig 2) exhibit eroded slopes leading into the crater floor. An older crater is less likely to have intact rims, and volcanic craters are typically older, but the presence or absence of terraced rims alone cannot determine the fill type. Older craters also lack the rough terrain of younger impact craters. Thus, while small-scale features are indicative of an impact melt-filled crater, they are not universal, and in fact are only temporary.

High iron, low albedo crater floors, while considered the standard definition for volcanically-filled craters, cannot be considered a defining feature because space weathering and regolith accumulation can also change a crater's appearance and composition. As micrometeorites bombard the lunar surface, crater floors slowly fill with debris, homogenizing to appear consistently iron-rich. While the lower albedo of Eratosthenes may in part be due to its location in the Imbrium Basin, the lack of small-scale features and heavy regolith accumulation suggests age may also contribute to its darker color. Copernicus (<1 Ga) is significantly lighter than the multiple mare basins it borders, further supporting this connection.

Conclusions: While we initially started this research with the goal of creating a list of defining features, it quickly became apparent that features vary with both composition and age. There are defining features, however they are not universal. Many traits are interconnected, and it is the specific combination of traits that defines a crater with one fill or another. Moving forward, studies of craters with varying ages and sizes may provide more insight. When examining the craters listed in Table 1, the boundary for homogenization appears to be sometime during the Eratosthenian epoch, and focusing on Eratosthenian craters may yield a more specific date. Another option would be to examine the rate of erosion on other bodies and apply this thinking beyond the moon.

References: [1] Jaumann et al. (2012) *Planetary and Space Science*, 15-41. [2] Lev et al. (2021) *Science Direct.*, 1145-1178. [3] Kreslavsky and Head (2012) *Journal of Geophysical Research: Planets*, E12. [4] Hiesinger et al. (2003) *Journal of Geophysical Research: Planets*, E7. [5] Lucey et al. (2006) *Reviews in Mineralogy and Geochemistry*, 83-219. [6] Carter et al. (2012) *Journal of Geophysical Research: Planets*, E12. [7] Pieters and Tompkins (1999) *Journal of Geophysical Research: Planets*, E9 21935-49. [8] Hiesinger et al. (2003) *Journal of Geophysical Research: Planets*, E7. [9] Ding and Xu (2019) LPSC L, Abstract #2132. [10] Thaker et. al (2020) *Planetary and Space Science*, 104856.

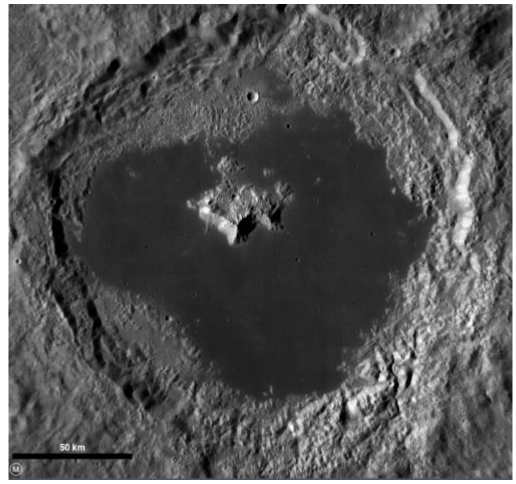

Fig. 1. Tsiolkovsky -20.383°N, 129.808°E. Taken with LROC WAC.

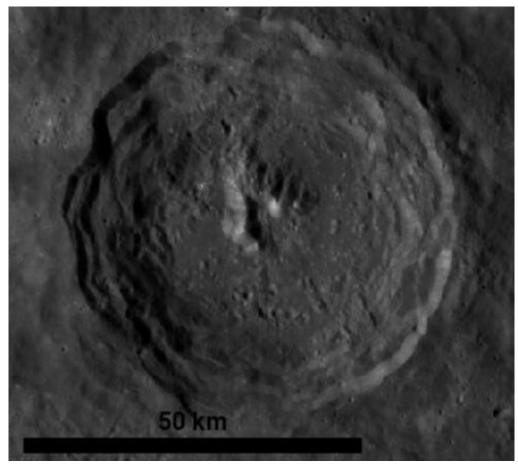

Fig. 2. Eratosthenes 14.703°N, 348.797°E. Taken with LROC WAC.

Table 1. Common features in impact craters and well-known craters that exhibit these traits.

	VOLCANIC MELT			IMPACT MELT		
	JOLIOT	JULES VERNE	TSIOLKOVSKIY	OHM	COPERNICUS	ERATOSTHENES
AGE	>3.7Ga	>3.4Ga	3.5-3.2Ga	<1.1Ga	<1Ga	1.1-3.1Ga
RELATIVE AGE	Imbrian [8]	Imbrian [9]	Late Imbrian [7]	Copernican [10]	Copernican	Eratosthenian [9]
LOW ALBEDO	✓	✓	✓	X	X	✓
EMBAYED CRATERS	✓	✓	X	X	X	X
EVIDENCE OF FLOW	X	✓	X	✓	✓	✓
“PONDED” APPEARANCE	X	X	X	✓	✓	✓
HIGH IRON CONTENT	✓	✓	✓	X	X	✓
SMALL SCALE FEATURES	X	X	X	✓	✓	X
REGOLITH ACCUMULATION	✓	✓	✓	X	X	✓