**ATYPICAL REGOLITH PROCESSES HOLD THE KEY TO ENIGMATIC LUNAR SWIRLS.** C. M. Pieters[1], D. P. Moriarty III[1], I. Garrick- Bethell[2]; [1]Brown University, Providence, RI 02912, [2]Univ. of California, Santa Cruz. [Carle_Pieters@brown.edu]

**Introduction and Summary:** The lunar swirls are some of the most enigmatic, yet beautiful, features on the lunar surface [e.g., 1,2,3,4,5]. They are unusual albedo features typically of a sinuous and local nature and exhibit distinct anomalous forward scattering properties. They have no detectible topography of their own, and are almost always associated with local magnetic anomalies. Several investigators suggest lunar swirls represent a regolith that has been shielded from normal space weathering effects by magnetic standoff of the solar wind. Although solar wind shielding of the surface has indeed been observed at lunar magnetic anomalies [6], we show that a simple reduced space weathering model for swirls cannot be correct.

The origin, and consequent character, of the swirls is closely tied to when and how the magnetic anomalies formed. If they are relatively young, the comet model [e.g;, 1,7] may prove to be a viable hypothesis for their origin. If the anomalies are endogenic, they must have formed during the period when the lunar dynamo was active [8,9] and are hence ancient. For such older anomalies, swirl properties must be sustained as the regolith evolves over billions of years. To accommodate the observed character of swirls we are developing an integrated model involving local collapse of any regolith 'fairy castle' along with minor redistribution of lunar dust by local electric fields.

**Observations**. New analytical tools [10.11] are applied to $M^3$ data for swirls. These tools are well suited for evaluating spatial relation of near-infrared spectral parameters linked to composition and maturity of the surface, especially when the data may have insufficient quality for detailed analysis. We use the Ingenii region on the lunar farside as an example here because it includes swirls across the mare as well as more feldspathic regions. Shown in Fig. 1 is a $M^3$ mosaic of the region obtained during OP2C1 (i.e., low phase angle, but when the detector was relatively warm). Since the lunar continuum is curved we use a two line approximation, one across the 1 µm and one across the 2 µm region where most mafic mineral absorptions occur. We derive a band depth for features relative to the continuum and average band center for both the 1 and 2 µm regions [10]. (It should be noted that the commonly used 950/750 nm ratio for Clementine images does not separate continuum from band strength and consequently is a combination of two properties.)

Other than albedo, the property that best delineates the swirls is a continuum slope scaled to eliminate albedo effects. In contrast, the swirls almost disappear in a continuum-removed band depth image which highlights immature mafic-rich areas at craters (small bright areas) as well as regional soil variations (mare soils on the right are more mafic). Highly feldspathic areas appear almost black (almost no mafic band). On the other hand, the average band center image for this region captures regional compositional variations of pyroxene in the soil and is almost insensitive to maturity variations (ignoring unrelible values for very weak bands). This image also nicely delineates regions with Hi-Ca pyroxene (maria) from the more noritic areas. In some cases, swirls are seen to cross from one to the other (e.g., below center). Example spectra from representative areas in the blue box are presented below.

Taken together, the swirls do not fit along any trend describing soil evolution for either the maria or the more feldspathic regions as soils normally evolve in the space environment. Nor do they represent a mixture of local components. They are a special environment and require a special soil evolution model.

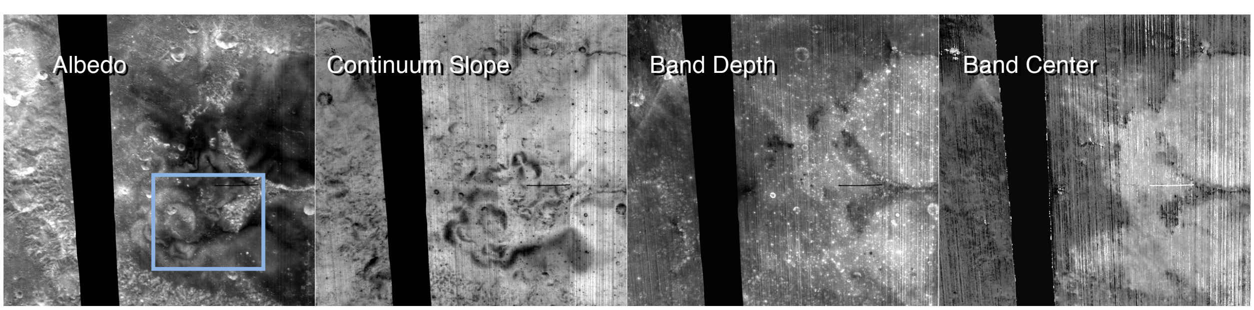


Fig. 1. $M^3$ mosaic of western Ingenii. Left to right: 1489nm brightness (SUP image), scaled 1µm continuum, 1µm band depth, 2 µm band center. All values are low to high = dark to bright. Swirls are apparent in the albedo and continuum measurements, but not in the mafic band strength nor in band center (pyroxene composition) variations.

Locations for representative areas that illustrate some of these properties are shown in Fig. 2 and their M3 spectra in Fig. 3. Band center variations are best seen comparing the crater spectra for the maria (MCr2) and the more feldspathic mottled terrain (HCr1), which indicate the presence of high-Ca and low-Ca pyroxene respectively. Areas that are relatively bright and exhibit regional weak mafic absorptions are interpreted to be feldspathic. Some contain no detectible mafic absorption (FM). Undisturbed soils for the feldspathic terrain (H1) are darker than fresh craters or sloped topography. Such albedo relations are not always the case for maria where any brightness contrast is wavelength dependent. The properties of absorption bands for swirls in the feldspathic terrain (SH2) are similar to general soils (H1), but exhibit a slightly flatter continuum. Swirls across the maria are typically brighter than undisturbed soils, but the dark lanes appear to be both darker and often with a steeper continuum. Although there may be a slightly enhanced band strength for some bright swirls compared to soils, it is difficult to confirm because this region also contains numerous small craters (see band depth image).

**Update**. It has long been known that lunar swirls exhibit unusual photometric properties – forward scattering rather than the normally strongly backscattering [e.g. 1, 12]. This is often interpreted to indicate an unusual regolith. There are several additional recent clues. a) Lunar soils measured in their natural environment are systematically darker than 'ground truth' samples in the laboratory [13]. b) Similarly, systematic brightening observed around landing sites is interpreted [14] to be destruction of the normal 'fairy castle' structure of lunar soils [15]. c) The lunar plasma environment is complex and the surface encounters strong diurnal cycles of electric field [e.g. 16,17]. d) The LADEE LDEX experiment has recently detected sub-micron lunar dust from orbit [18] suggesting some dust mobility on the Moon.

**Swirl Regolith Hypothesis under study:** The brighter soil at swirls is due to a lack of 'fairy castle' structure with a small component of mobile dust, both of which are controlled by the local magnetic field and the diurnal plasma environment. The wispy form reflects the scale and character of the local magnetic field.

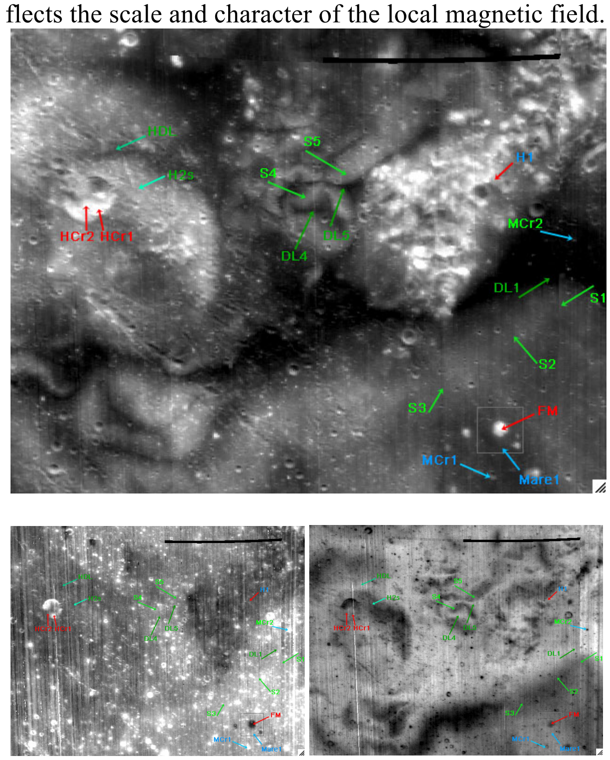


Fig. 2. Subsection of M3 mosaic for the Ingenii region. Top) 1489 reflectance image from SUP data. Bottom). Estimated 1 μm Band Depth (left) and Normalized Continuum Slope across 1 μm (right).

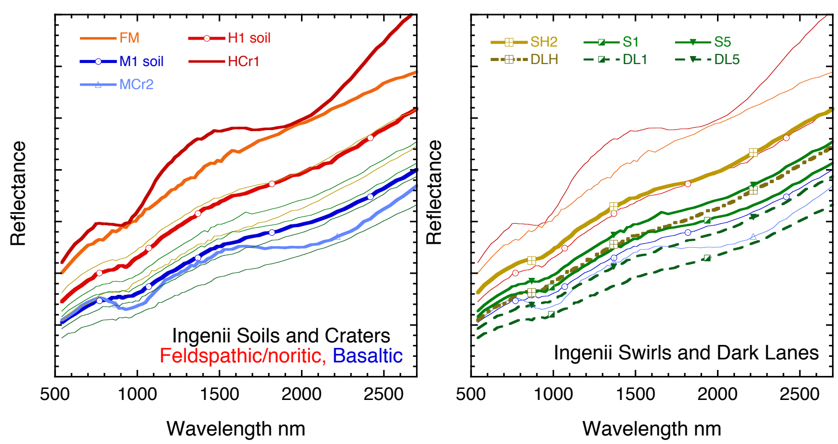


Fig. 3. M3 reflectance spectra (3x3 pixels) of areas in Ingenii. Both figures are the same, but the left highlights normal local craters and soil and the right highlights swirls (solid) and nearby dark lanes (dashed).

Acknowledgements: This research is supported through NASA SSERVI.

**References.** 1] Schultz and Srnka, 1980, Nature. 2] Hood and Schubert, 1980, Science. 3] Blewett et al. 2011, JGR 4] Garrick-Bethell et al., 2011, Icarus. 5] Kramer et al., 2011, JGR. 6] Wieser et al., 2010 GRL 7] Bruck et al. 2013 LPS44-2569. 8] Shea et al. 2012 Science. 9] Suavet et al., 2013, PNAS. 10] Moriarty et al. 2013 JGR. 11] Moriarty and Pieters 2014 LPS45. 12] Shkuratov et al., 2010 Icarus 208, 20. 13] Pieters et al., 2013, Icarus. 14] Clegg et al., 2014, Icarus 15] Hapke & Van Horne 1963, JGR. 16] Halekas et al. 2011, PSS 59. 17] Farrell et al. 2007, GRL. 18] Horanyi et al., 2014 LPS45.