NEW M-CUBE INSIGHTS ON THE CHARACTER OF THE MYSTERIOUS REINER GAMMA SWIRLS.
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Introduction: Lunar swirls are some of the loveliest yet enigmatic terrains on the lunar surface. They consist of distinct wispy bright and dark markings associated with no discernable topographic features [1, 2]. Nevertheless, all appear coupled to prominent local magnetic anomalies which potentially shield the surface from energetic particles [3] and result in unusual soils. Lunar swirls are of high interest for science and exploration, and Reiner Gamma has been selected as an early landing site for a Commercial Lunar Payload Services (CLPS) lander [4].

Initial assessment of Reiner Gamma with Moon Mineralogy Mapper (M^3) [2] highlighted many classic properties of swirls and noted the low abundance of OH within the bright regions. Reiner Gamma was measured three times by M^3 (OP1a, OP1b, OP2c1 at phase angles ~24°, 60°, 4° respectively). These data were obtained in the low-resolution 'Global Mode' at ~140 m/pixel [5]. Although limited to a single orbit, OP1a data exhibit the best quality (good illumination with minor detector thermal issues).

M^3 OP1a Analyses. M^3 data products across the main Reiner Gamma feature are presented in **Fig. 1**. FOV is ~40 km. The 750 nm and 2200 nm images are calibrated L2 reflectance images at those wavelengths. Since 2200 nm is close to the center of a basaltic pyroxene absorption band, most moderately immature craters appear faint while freshest craters may be darker than surroundings (eg. arrows). This relation of pyroxene absorption bands is also seen in the 1000 nm Band Depth image where the freshest craters exhibit the strongest absorption (brightest). The 1000 nm Continuum used to measure the 1000 nm band depth is measured across the pyroxene 1000 nm absorption defined by tangent points near the wavelengths 750 nm and 1600 nm and is similar to a 1600/750 nm ratio. The OH 2800 nm band depth image is difficult to measure because M^3 data only extend to 3000 nm, but the image nevertheless exhibits coherency indicating the bright swirl areas are the least hydrated (dark). M^3 supplemental image #3 is total radiance (reflected + thermal) of the scene measured at 2976 nm which can be sensitive to the overall topography and illumination during measurement.

Shown in **Fig 2.** are spectra illustrating distinct gradations of spectral properties across a typical Reiner Gamma bright swirl and prominent dark lane (including site C in Fig. 1). Spectra of normal mare regolith and craters of the region are also shown for comparison. Both mare regolith and craters are from the same unit

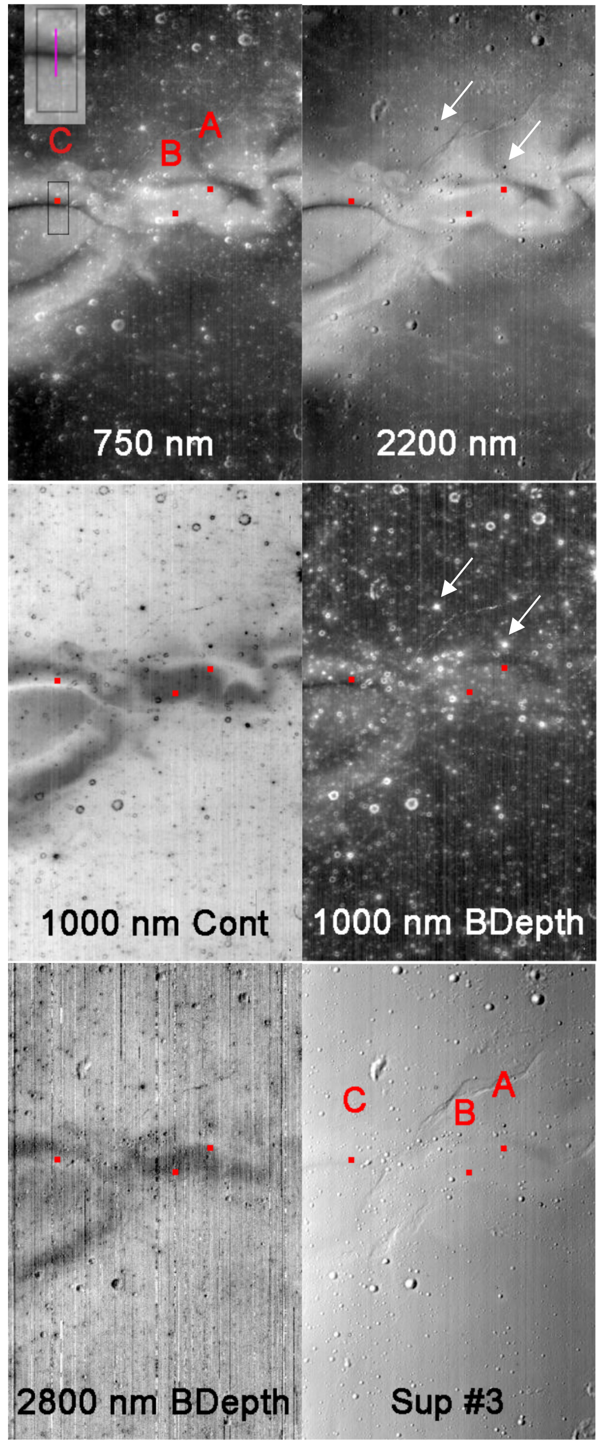

*Fig. 1. M^3 OP1a data products across Reiner Gamma. Three example landing targets (**A, B, C**) are indicated on each image. Insert box: Traverse3 (Fig. 2) crosses the dark lane near C including a small fresh crater to the north in bright swirl terrain.*

located a few km to the south but away from the effects of the magnetic anomaly. The images of Fig 1 illustrate that the properties seen in Fig 2 are representative of the overall relations of bright swirls and dark lanes to normal mare soils of the region.

Sites A, B, C: Three areas in Fig. 1 are used as examples worthy of detailed study. All sites occur in relatively smooth un-cratered terrain. Areas A & B are in bright swirl areas and are notably dry. A is a bright area with a prominent dark lane a few km to the north. If the unusual small ~parallel very bright zones (best observed in the 2200 nm image) are linked to the local character of swirl magnetic signatures, area B could be particularly key to understanding the origin of swirls. Area C is near a dark lane and in a hydration transition zone.

Special Regolith at Swirls: The regolith across swirls is quite different from other lunar regolith sampled and studied to date. Reiner Gamma is located across an extensive area of basaltic terrain of Oceanus Procellarum. The bright swirl features are not consistent with ray deposits from distal highland craters nor with classic basaltic immature regolith. Instead, regoliths of bright swirl features appear to be a yet-to-be-determined

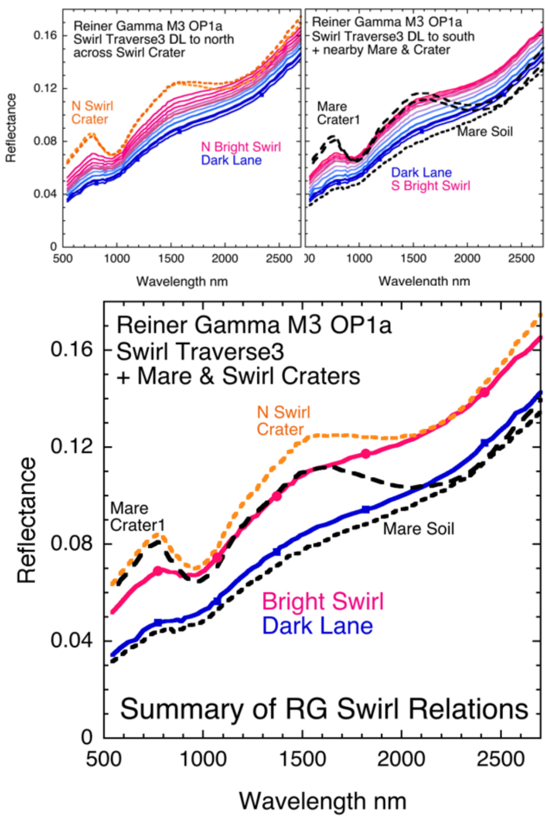

***Fig. 2**. Distinct regolith optical properties at Reiner Gamma compared to nearby mare and crater. The two small panels document a ~4 km N - S traverse across the swirl, dark lane, and area C of Fig. 1. The same 3 pixels from the dark lane appear in each. The main panel summarizes systematic relations between different regolith of the region.*

unique result of the unusual local magnetic environment and its effect on normal lunar regolith evolution.

Swirl bright areas and dark lanes both exhibit a similar absolute red slope in reflectance (increase in reflectance with increase of wavelength). [Note: this is different from a relative slope measured as a ratio, which is affected by albedo.] The general red slope is thought to be linked to development of npFe^0 on grain surfaces during space weathering [6]. Nevertheless, the bright swirl areas appear to lack a wavelength-independent darkening component common to well-developed normal mare regolith. The apparently more transparent particles of swirl bright regions also account for a slightly enhanced 1000 nm band depth of **Fig. 1.**

We hypothesize the common dark component missing from bright swirls is micron-size Fe^0 particles [7], as distinct from npFe^0 (<10-20 nm). These larger Fe^0 particles are normally abundant within agglutinate grains [8], but appear to either be prevented from forming during regolith development or grains bearing micron-size Fe^0 are systematically removed from the regolith by the local magnetic environment over time.

Swirl Assessment in the Near Future:

Phase I Orbiter: Lunar Trailblazer [9] has identified several swirls as key targets to be measured with higher spatial and spectral resolution instruments (HVM3 and LTM). These new data will provide significantly improved characterization of OH/H_2O abundance and spatial distribution across the swirl surface along with measurements of the swirl's brightness temperature.

Phase I Lander: A CLPS lander is planned for a site within Reiner Gamma in December 2023 [4]. In situ spectral and polarimetric observations at the landing site could provide an initial assessment of local swirl regolith including physical, compositional and photometric properties as well as the site's *in situ* OH/H_2O variation, if any. Linking optical and thermal observations of the regolith at multiple times of the lunar day with measurements of the magnetic and particles environment could constrain hypotheses for lunar swirl formation.

Phase II: Next Generation rover/orbiters [e.g.10]: Extended assessment across the geologic and magnetic environment of swirls would constrain the magnetic history and origin of swirls in the context of lunar evolution while also assessing a possible safe base for humans.

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