AN INVESTIGATION INTO THE EFFECTS OF THE MAGNETIC ANOMALY ON REGIONAL SPACE WEATHERING AT MARE INGENII AND ITS INFLUENCE ON THE SPECTRA OF THE BASALTS AND LUNAR SWIRLS

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Introduction Mare Ingenii (Fig. 1a) is one of several isolated basalt ”ponds” in South Pole-Aitken (SPA) basin. Ingenii’s most striking features are its collection of lunar swirls, which spectrally dominate the southwestern portion of the mare. Lunar swirls are high albedo and optically immature curvilinear surface features that are found in discrete locations across the Moon’s surface [1, 2, 3]. Earth-based telescopic and Clementine orbital multispectral data show spectral characteristics suggesting the swirls are optically immature. In addition, each swirl is coincident with a region of remnant magnetism on a planetary body that does not, and may never have had, an active core dynamo with which to generate its own magnetic field. These characteristics led to two models to explain the lunar swirls:

(1) The swirls are only *apparently* fresh. The swirls’ optical characteristics reflects regions where crustal magnetic fields have been selectively preserving silicate surfaces over time from the effects of space weathering by solar wind ions [2]. Several lunar magnetic anomalies are antipodal to large impact basins formed between 3.8-3.9 Ga [4]. Magnetization of these antipodal regions could result from a plasma cloud generated by the basin forming impact interacting with a weak magnetic field present at the Moon at the time of basin formation [5]. The magnetized surface could be also due to impact-induced currents and seismic waves ringing the planet [6]. An unusually thick and/or strongly magnetized deposit of basin ejecta can be invoked to explain swirls, such as the Reiner Gamma Formation, that are not antipodal to a basin.

(2) The swirls are *actually* fresh. The swirls depict a relatively recent impact of disrupted meteoroid debris [7] or unconsolidated comet material [3, 8], which scoured the surface and exposed fresh material. The sinuous form of the swirls is the remnant manifestation of the coma’s turbulent flow of gas and dust across the lunar surface. The comet impact could create a magnetic anomaly from magnetization of near-surface materials heated above the Curie temperature through hyper-velocity gas collisions and micro-impacts.

Analysis, Results, & Interpretation Our primary objective was to characterize the *pristine* basalt unit(s) in Mare Ingenii. To achieve this we extracted compositional information from pixels that depict the rims and proximal ejecta of small, immature craters (0.5-5 km in diameter) that impacted onto the mare surface. These small craters act as windows through the regolith, exposing the underlying mare basalt [9, 10, 11].

Testing the Swirls’ “Freshness”: Impact craters of these sizes should be randomly distributed across the surface. However, if a magnetic field is continually shielding the swirls from solar wind ions, thereby retarding maturation, there should be a greater density of immature craters on swirl surfaces. The reason is that recent impacts onto the magnetically shielded swirl surfaces will be better protected from solar wind maturation, as opposed to contemporaneous impacts onto off-swirl locations. If Ingenii’s swirls are from a recent meteoroid swarm or comet impact, which exposed fresh material, then subsequent impacts would be randomly distributed across the mare. In this case, the on-swirl immature crater density should be approximately equal to the density of immature craters off-swirl. Our results show a clear propensity for immature impacts to be located on the high albedo swirls, supporting a model for continued shielding of the solar wind by the magnetic field.

	Total # craters	Approx. (area km^2)	Craters per 1000 km^2
Off-swirl	66	19,000	$\sim$ 3.5
On-swirl	151	11,000	$\sim$ 14

Space Weathering Effects on Spectra and Spectral Parameters: Spectral characteristics of space weathered soils can be divided into three types: (a) an overall decrease in visible (VIS) to near-infrared (NIR) reflectance, (b) reduction in the contrast of diagnostic mineralogical absorption bands, and (c) introduction of a strong ”red” spectral slope. The creation of nanophase iron ($npFe^0$) is the space weathering effect largely responsible for observed spectral changes. In the space environment $npFe^0$ is created by vapor deposition during micrometeoriod impact and solar wind sputtering, and reduction of Fe^{2+} in minerals and glasses by implanted solar wind protons (H^+) [e.g., 12, 13]. Particle sizes of $npFe^0$ deposited on soil grain surfaces by vapor deposition/sputtering range between 1 and 15 nm with a median of 3 nm [14], where the median represents an equilibrium state between creation/deposition and re-vaporization. $npFe^0$ particle sizes created by solar wind protons could have a wide range. Incident H^+ has the energy to direct reduce Fe^{2+} at mineral surfaces, in which case the resultant $npFe^0$ particle would be small - on the same order of sizes created by sputtering. $npFe^0$ particles in agglutinates are larger and have a wide range of sizes - up to several hundred nanometers [12, 14]. This range is caused by the random vaporization, mixing and merging of $npFe^0$ particles that resided at the target site of the micrometeorite impact.

Since all regional lithologies have low-Ti abundances, the Ti abundance of the high-Ti mare surface regolith is expected to be reduced to some extent by impact garden-

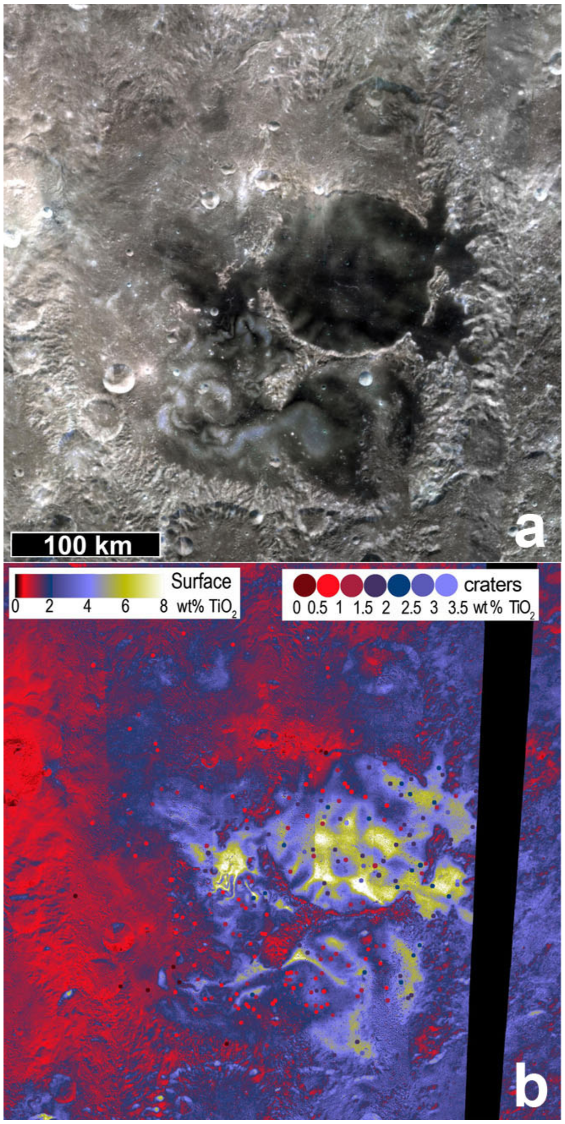

Figure 1: (a) Clementine "true color" (R=900 nm, G=750 nm, B=415 nm) image of Mare Ingenii. (b) TiO_2 abundance [15] map for the surface regolith and the underlying pristine basalt as revealed by small, fresh impacts (circles). The contradiction of a significantly higher surface Ti abundance than any analyzed crater suggests the TiO_2 algorithm is portraying an unusual surface phenomenon.

ing. Any small crater into the high-Ti surface should reveal higher-Ti in its ejecta. The TiO_2 abundance surface map (Fig. 1b) shows that the darkest (low albedo) regions on Mare Ingenii have values up to 8 wt% TiO_2, while the southwest swirl swarm has some of the lowest surface Ti abundances of the mare. There is clearly no lithology in reasonable proximity to have contaminated the surface with high-Ti regolith, so the high-Ti influence must be the underlying basalt unit itself. The higher TiO_2 abundances revealed in immature crater ejecta are well correlated with the dark and optically mature portions of mare surface, or dark lanes. However, the highest TiO_2 abundance of the sampled craters is only 3.5 wt% TiO_2. The TiO_2 algorithm describes a significantly higher TiO_2 abundance for the surface at the dark lanes than it does for impacts into it.

There is no petrological explanation for the cause of the parameter anomaly, but spectroscopically it suggests a process that causes the TiO_2 algorithm[15] to return an *apparently* high Ti abundance. Ilmenite is the dominant carrier of Ti, and has a very flat, low-albedo spectrum. The presence of ilmenite in a rock or soil has the effect of darkening and flattening the overall spectrum the degree to which is proportional to its increasing abundance. It is this spectral darkening and flattening that the TiO_2 algorithm is portraying. We interpret the algorithm to be revealing the dominance of one maturity effect over another: we are looking for a product of space weathering that mimics a high-Ti abundance, that is, darkens and flattens the spectrum more than the spectral reddening effects of space weathering. [16] showed that the spectral effects of larger $npFe^0$ particles (>40 nm) darken and flatten the entire VIS-NIR spectrum with little changing of the continuum slope. This effect mimics the spectral effect of ilmenite, and would therefore cause the TiO_2 algorithm to erroneously depict high Ti abundances.

Larger $npFe^0$ particles are found in agglutinates, which are considered to be formed by micrometeorite impacts - a process *not* influenced by a magnetic field. However, the magnetic shielding at the swirls causes deflection and focusing of the protons into the dark lanes [2]. The deflected proton loses sufficient energy to spontaneously reduce surface Fe^{2+}. The H+ sits inert on the surface until a micrometeorite hits, providing the energy for greater amounts of Fe^{2+} reduction into one particle.

This model explains a process responsible for the dominance of larger $npFe^0$ particles to be created at the dark lanes relative to $npFe^0$ particle sizes created on lunar surfaces *not* influenced by a magnetic field. Furthermore, the resultant $npFe^0$ particle size sorting cannot be efficient through magnetic shielding because sputtering/vapor deposition, which creates <10 nm particle sizes, would not be affected by a magnetic field. Our model explains the spectral effects of a magnetic field affecting the dominance of $npFe^0$ particle size ranges based on their different spectral effects. Our model indicates the importance of solar wind implanted protons in creating $npFe^0$.

References

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