Derivation of the Moon's Mineralogy, Chemistry, & Maturity from Reflected Light and the Anomaly of the Lunar Swirls

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ESS 495 - NASA Space Grant Seminar: Rocks-n-Stars
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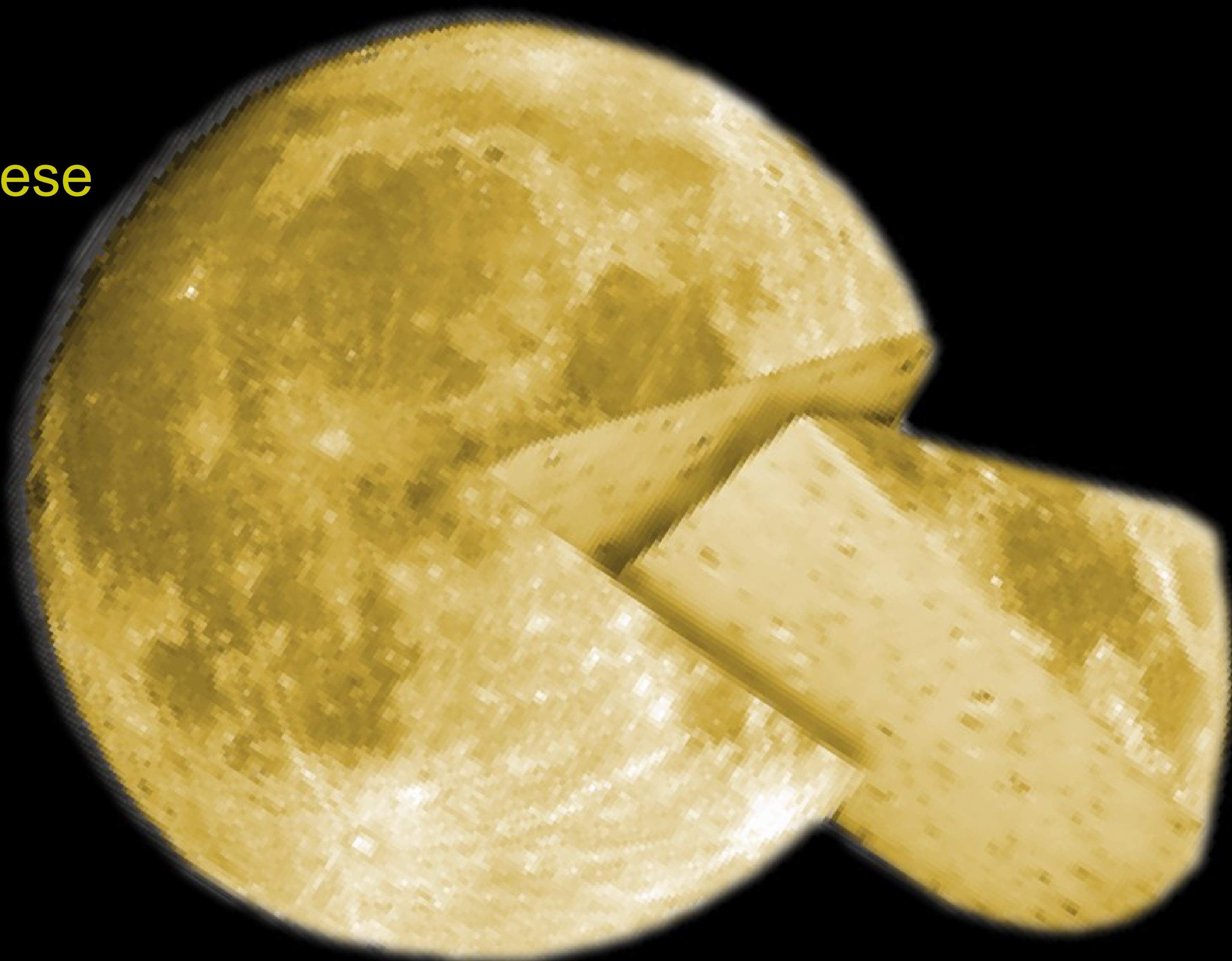
Presentation Outline
or Guide to Preferential Napping

- Know your Moon
- Introduction to lunar swirls
  - Characteristics & associated features
- Everything you ever wanted to know about reflectance spectroscopy, but were afraid that if you asked you'd fall asleep
- Space weathering or How to look mature to a spectroscopist
- Swirl formation hypotheses
- New data and research that tests these models
- Implications for space weathering as a solar system phenomenon

What is the Moon made of?

What is the Moon made of?

NOT cheese
(sorry)



What is the Moon made of?

<u>Maria</u>

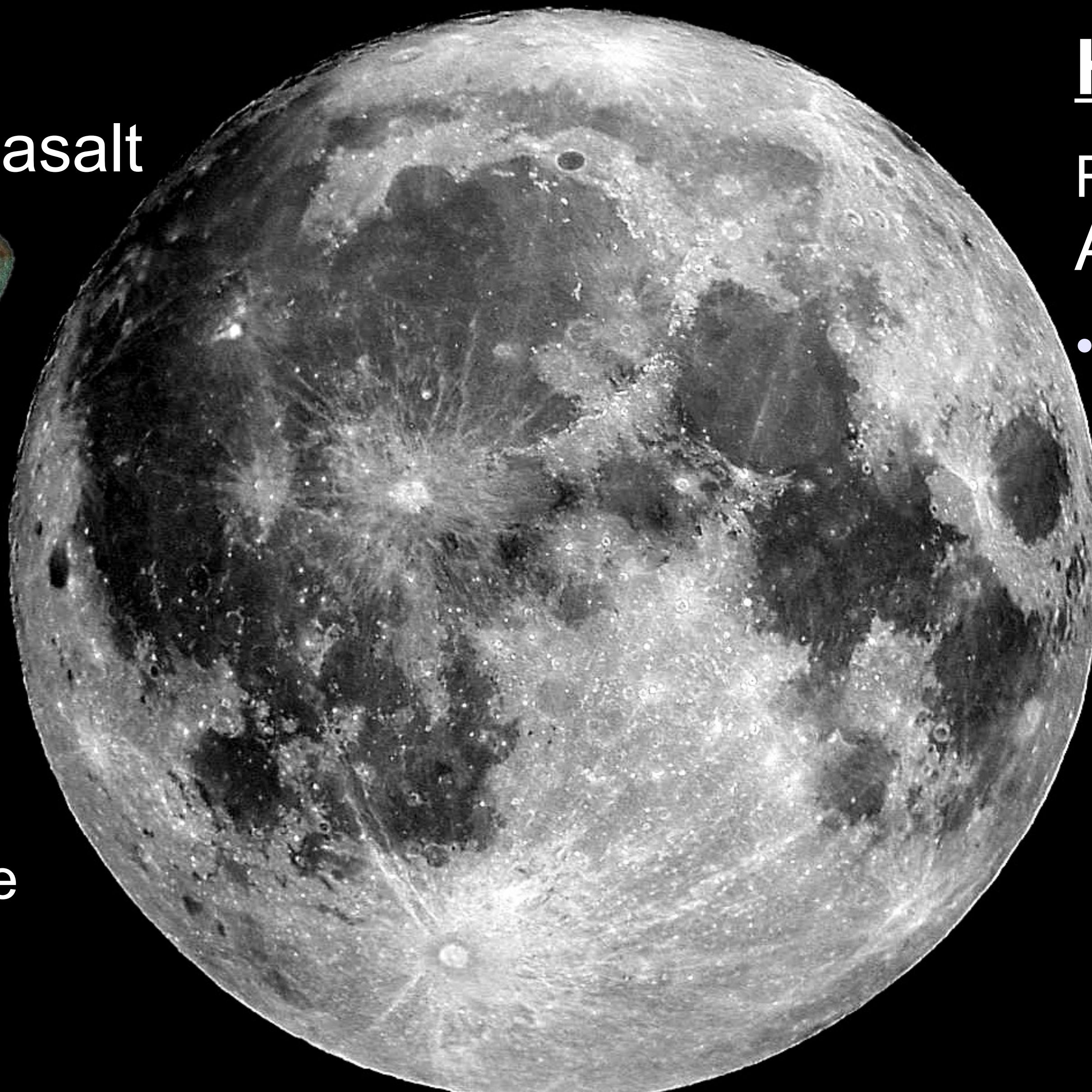
Rock type: Basalt

- pyroxene

- olivine

- plagioclase

- ilmenite



<u>Highlands</u>

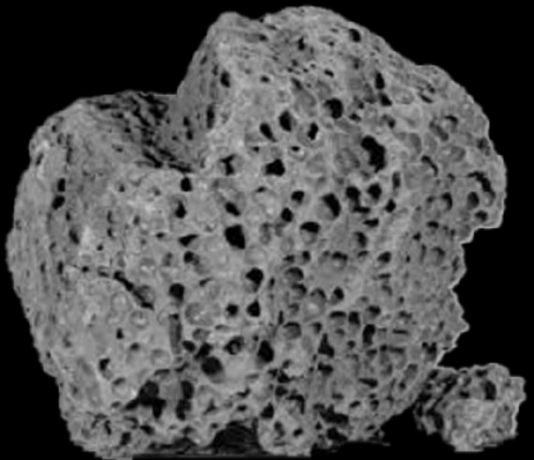
Rock type: Anorthosite

- plagioclase

How do we know?

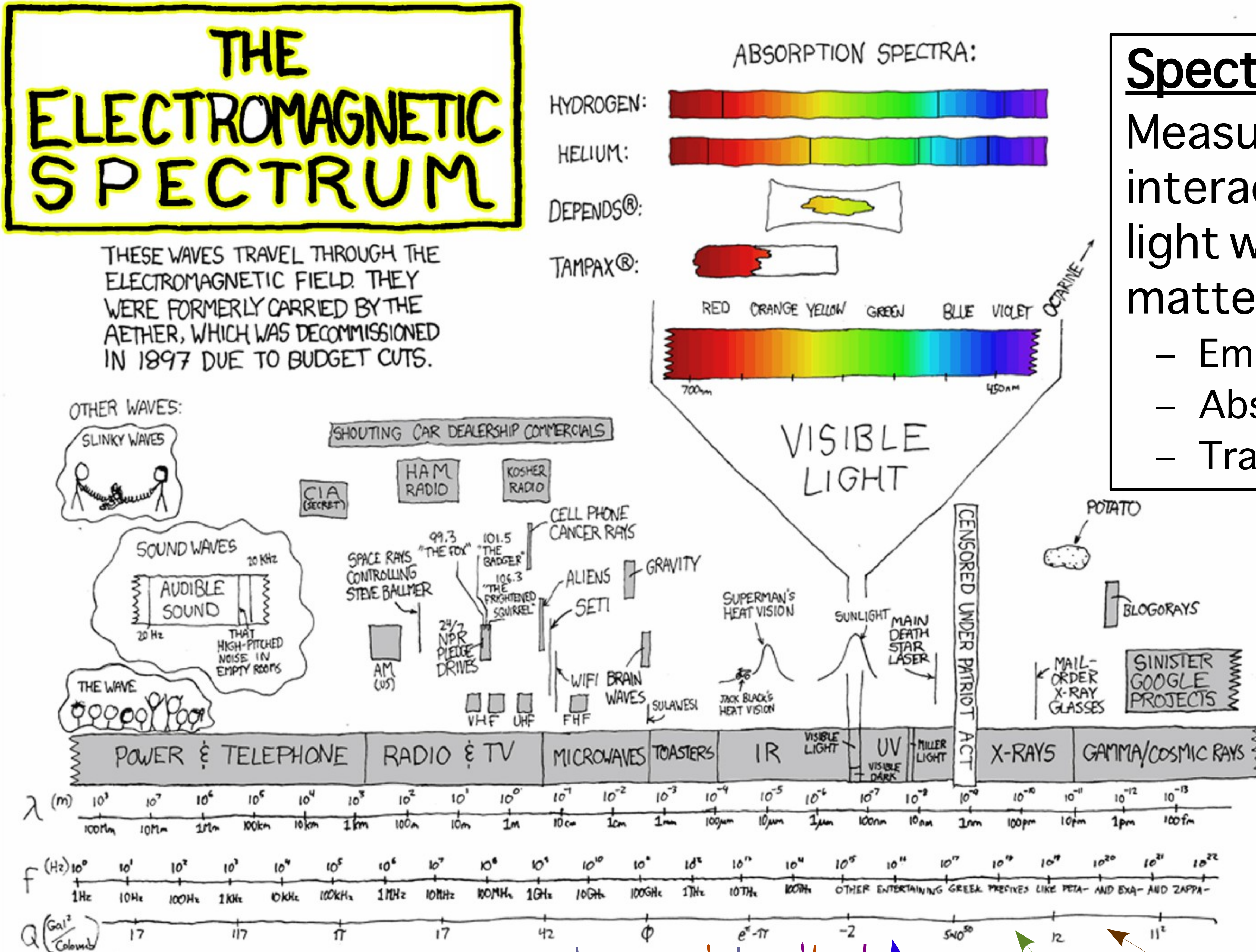
Laboratory analysis of returned samples ...

Apollo 15 highland sample 15415



Apollo 15 mare basalt sample 15556

… and remote analysis using ...



rotational transitions

vibrational transitions

electronic transitions

photo-electric effect

ionization

ejection of core electrons

Because there are specific effects on the matter that are a function of energy

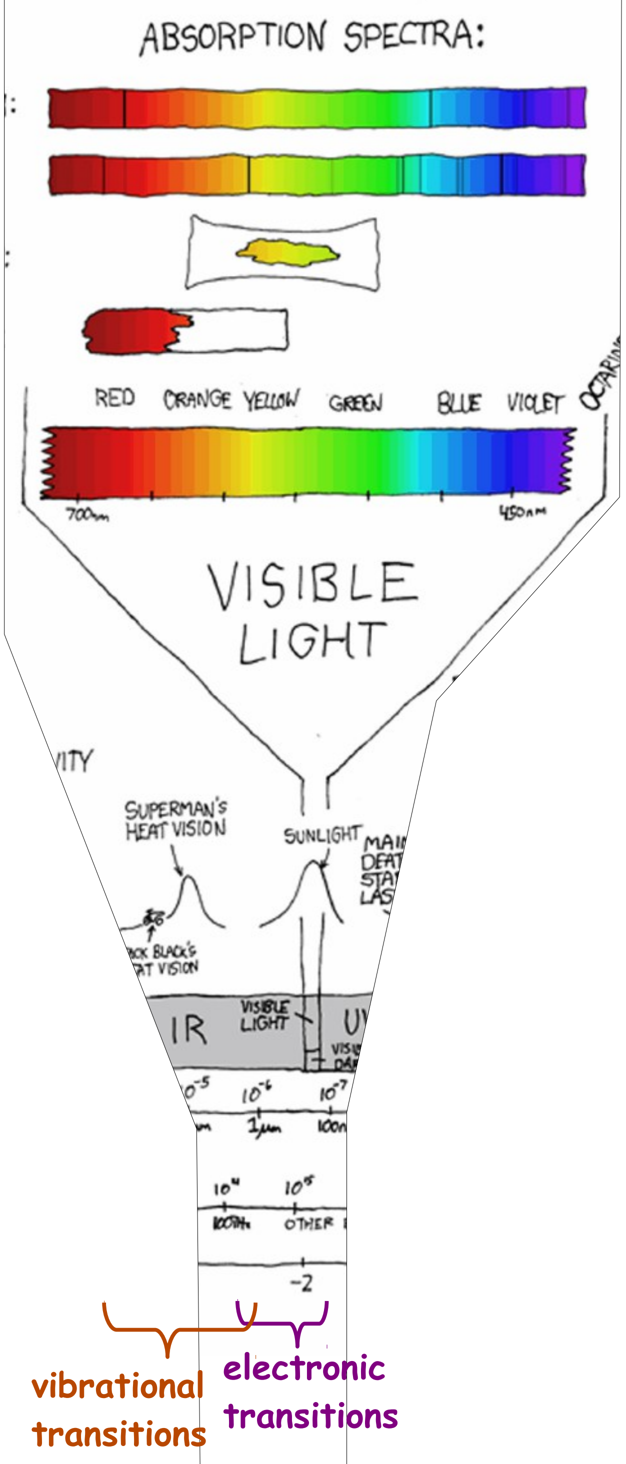
Spectroscopy

Measuring the interaction of light with matter

- Emission
- Absorption
- Transmission

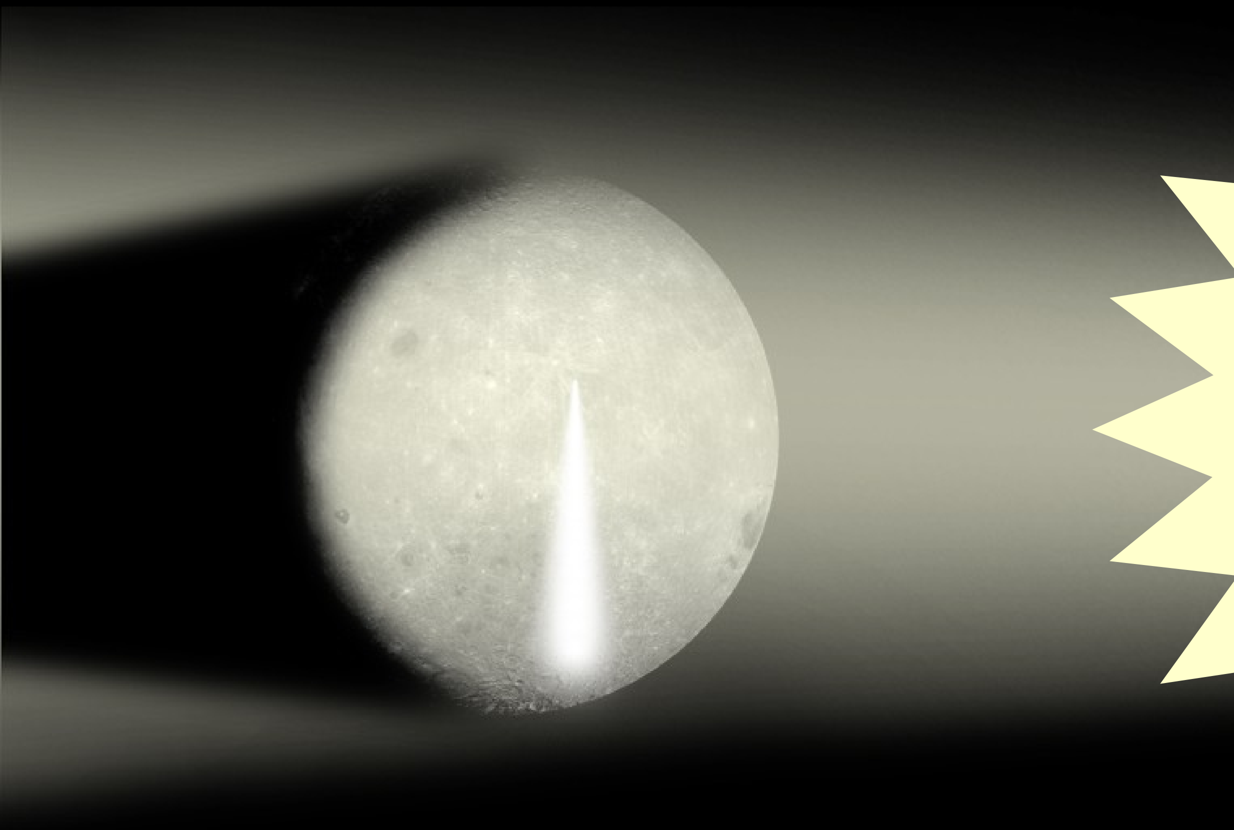
Spectroscopy in the UV, VIS, NIR

Measures the continuum of energies reflected and absorbed due to the interaction of light with matter.



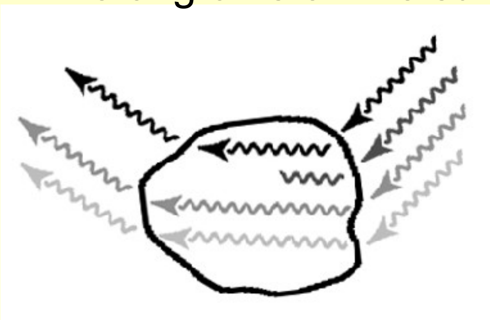
Reflectance Spectroscopy

Reflectance Spectroscopy



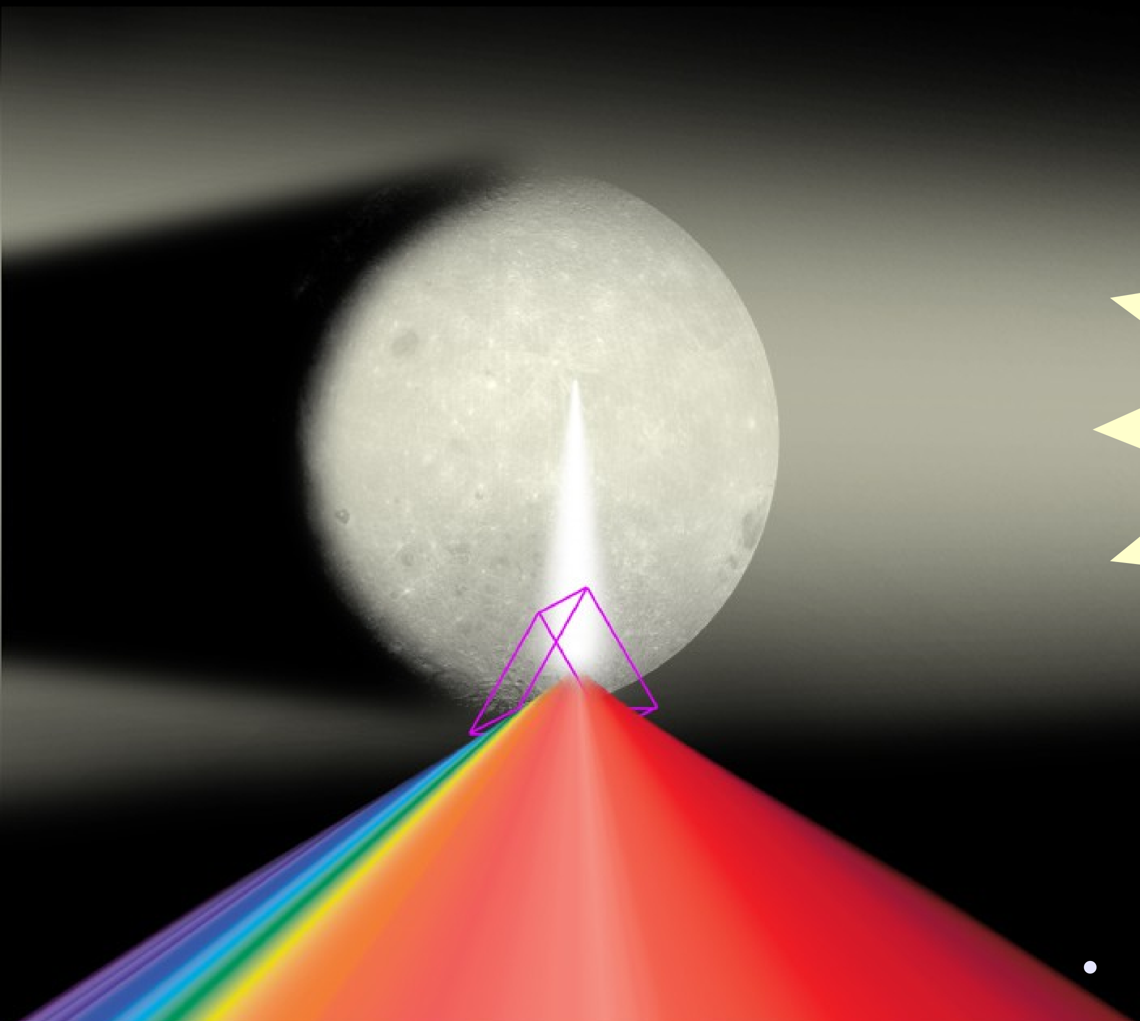
Light from the Sun (solar irradiance)

- interacts with the atoms in the mineral grains on the surface



- Some light is reflected
- Some absorbed

Reflectance Spectroscopy



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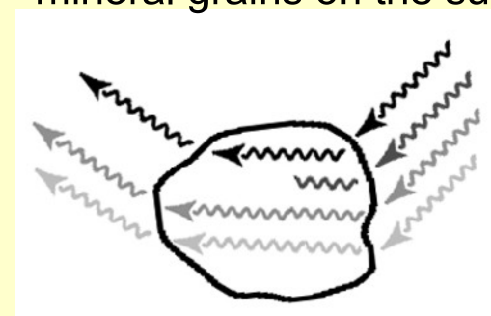
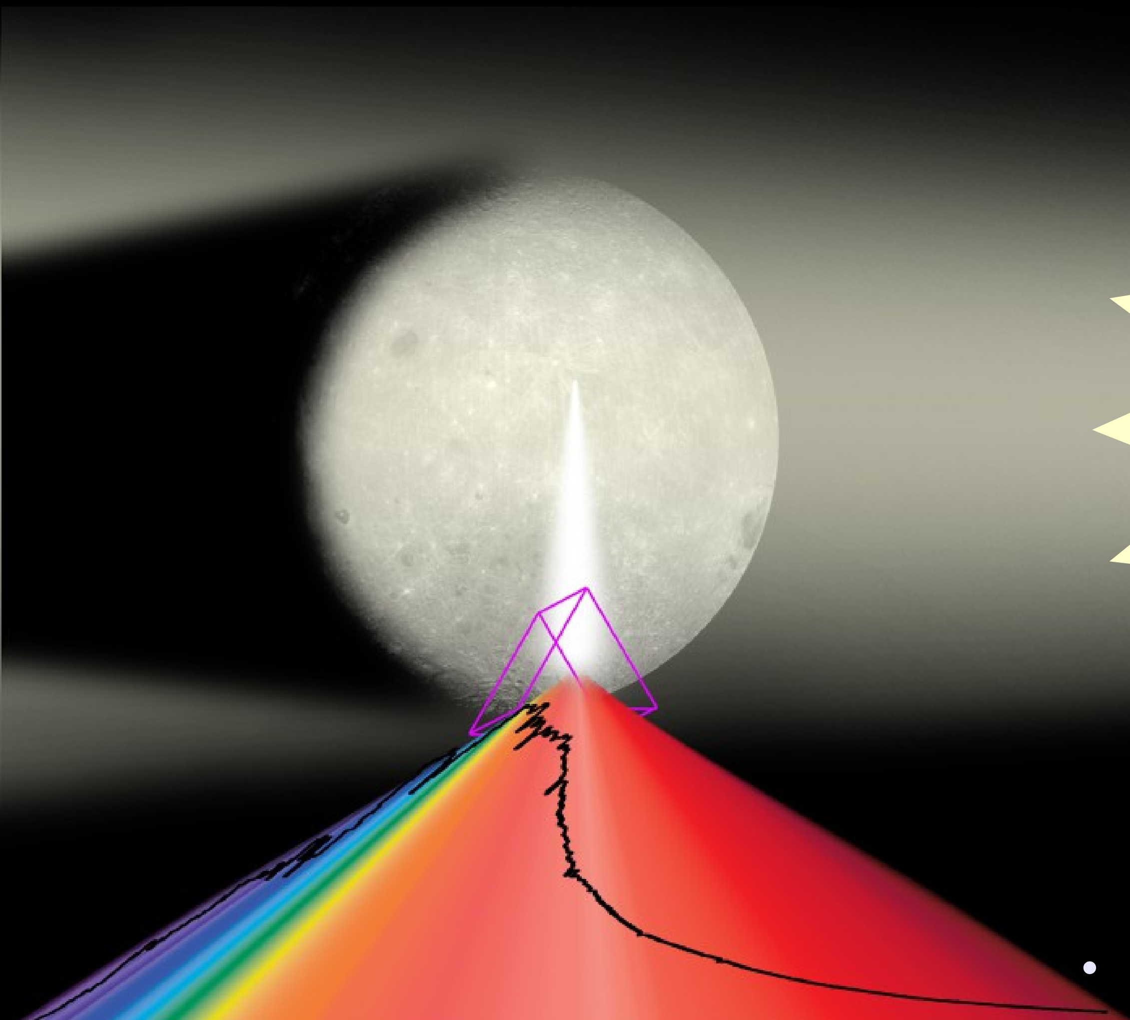


- Some light is reflected
- Some absorbed

- This reflected light goes into the instrument optics and is diffracted into its component wavelengths.

Reflectance Spectroscopy



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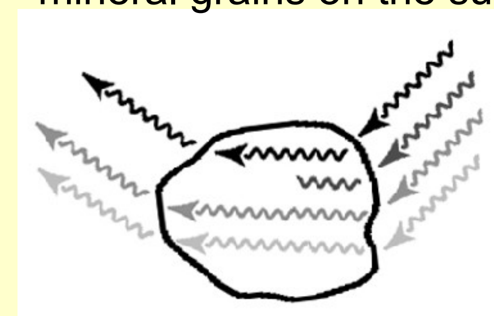
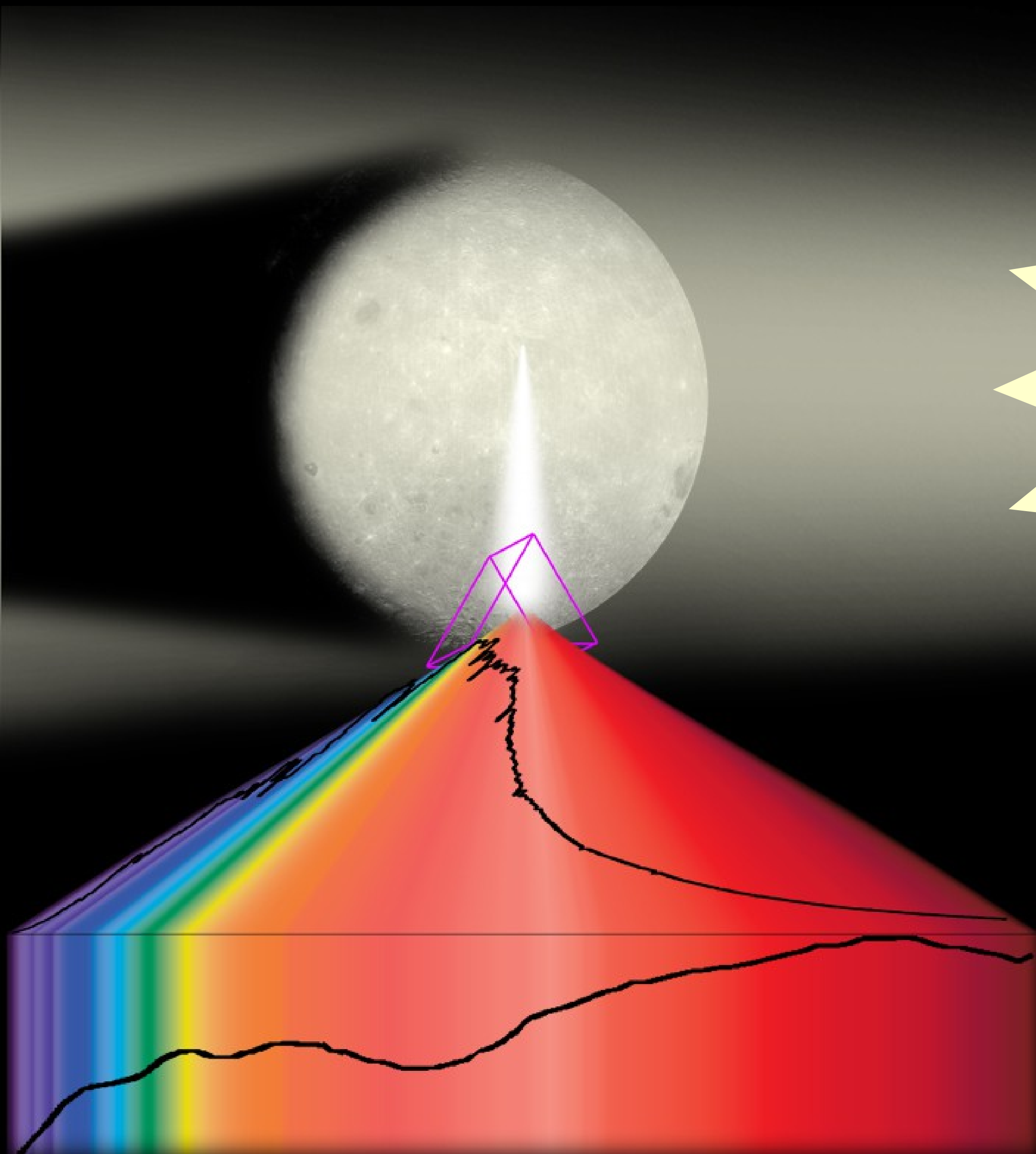


- Some light is reflected
- Some absorbed

- This reflected light goes into the instrument optics and is diffracted into its component wavelengths.
- The instrument detector measures the intensity of light at each wavelength.

Reflectance Spectroscopy



We want to observe the intensity of light at different wavelengths – the ***spectrum*** - that is reflected or absorbed by the surface material *independent* of the spectrum of the incident light.

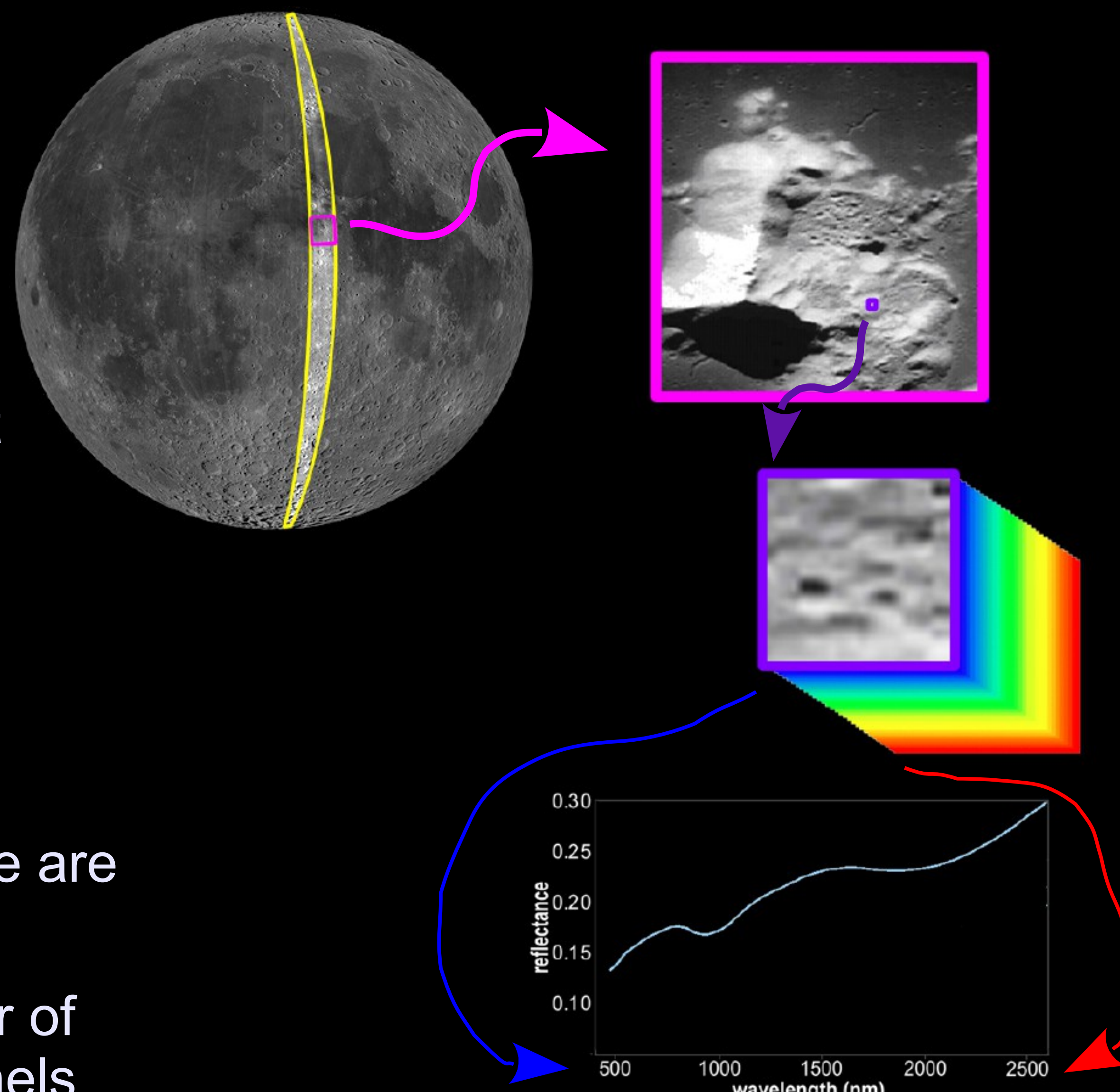
So all measurements are normalized to the solar spectrum

$$\text{Reflectance} = \frac{\text{Reflected radiance}}{\text{Incident light (irradiance)}}$$

Imaging Spectroscopy

- Point spectrometers
  - e.g., telescopic spectra
  - Lack inherent context
  - Requires accurate location information
- Imaging spectrometers
  - For every image there are actually **X** images

    where **X** = number of wavelength channels



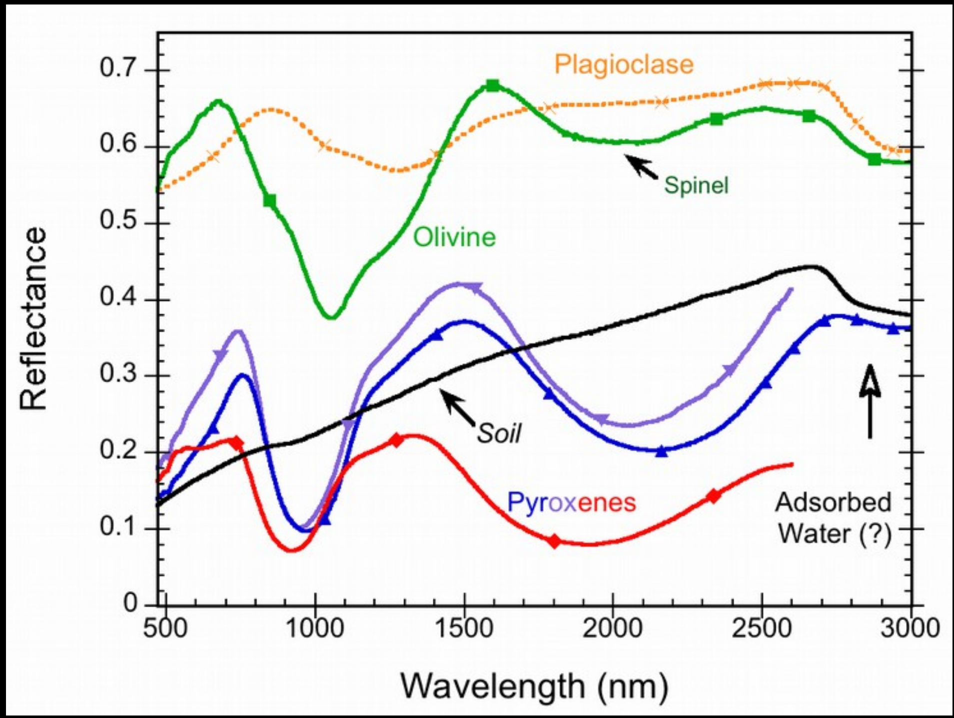
Lunar Imaging Spectrometers

- Moon Mineralogy Mapper (2008-2009)
  - 85 channels between 500-3000 nm
    - More spectra, more complexity
- Kaguya Multiband Imager (2007-2009)
  - 8 channels between 415-1550 nm
- Clementine (1994)
  - **UVVIS**: 5 channels between 415-1000 nm
  - **NIR**: 6 channels between 1100-2780 nm

- Those first 5 channels and 15 years of analysis were enough to do a lot of science.

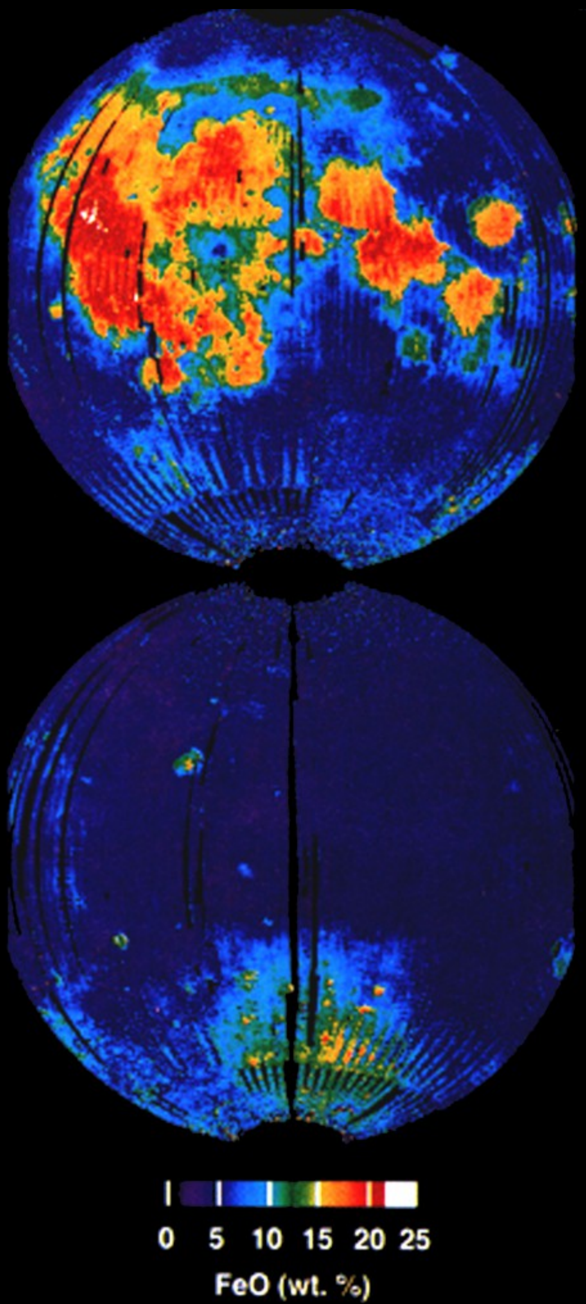
The Shape of the Continuum

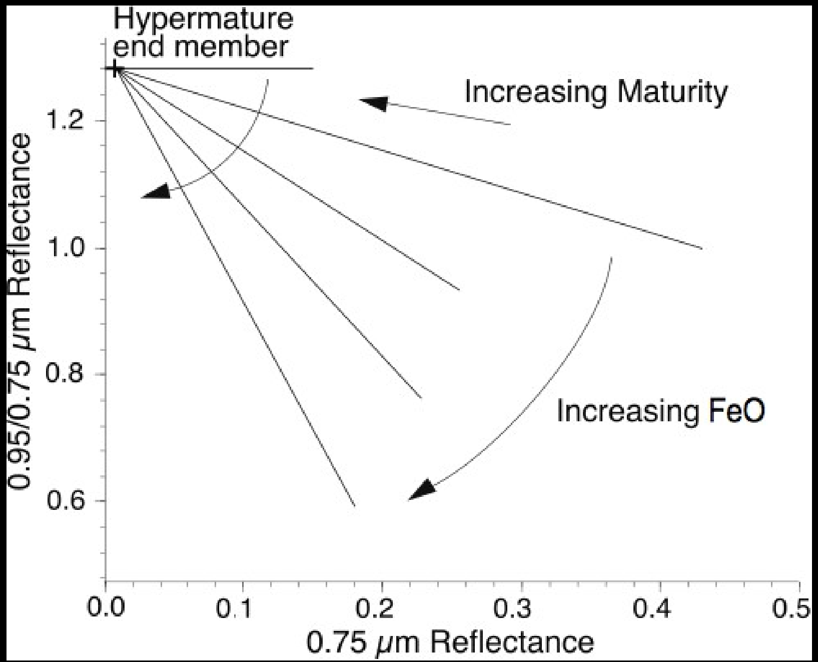
- Minerals are identified by albedo,
  - Intensity of reflected light
- Shape of the continuum,
  - Flatness, redness, concavity
- Absorption features
  - Depth, width, wavelength of maximum absorption

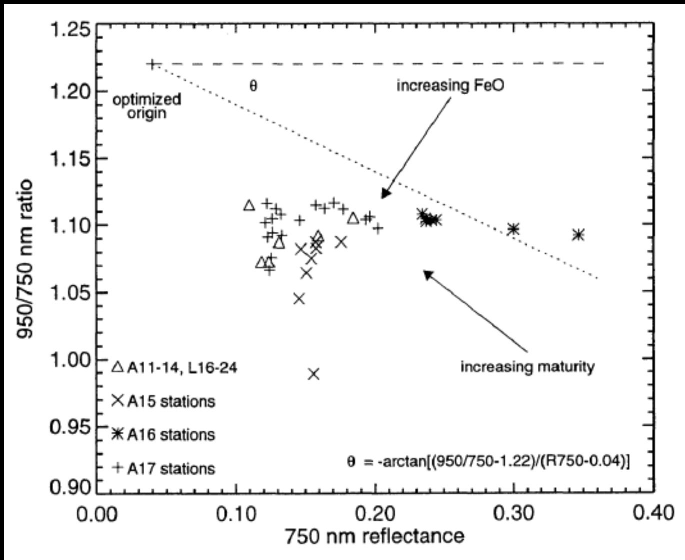


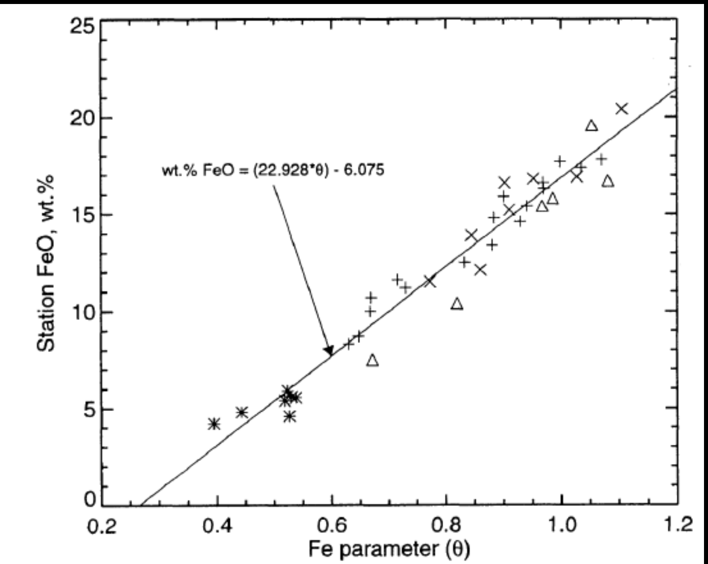
- A rock is an aggregate of minerals.
- The spectrum of a rock is a mixture of the constituent mineral spectra.

FeO Abundance from Clementine UVVIS Data

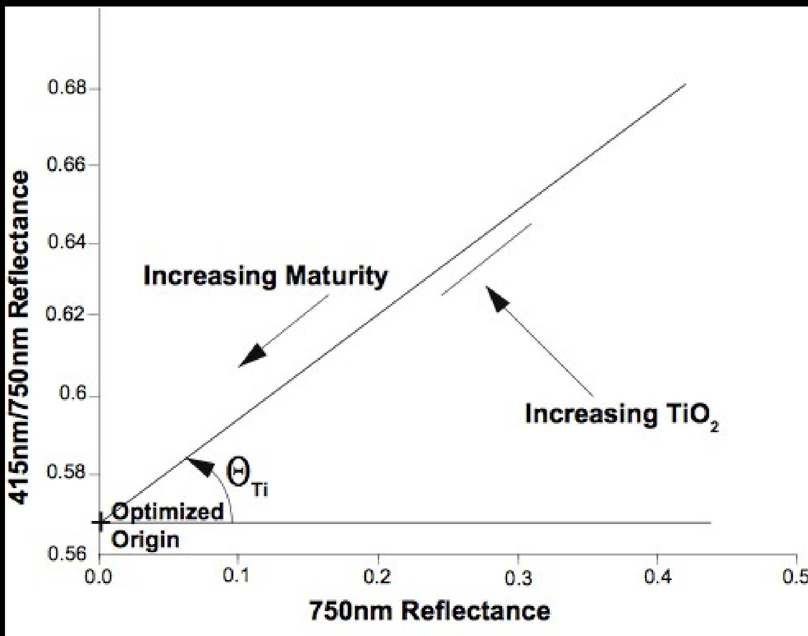


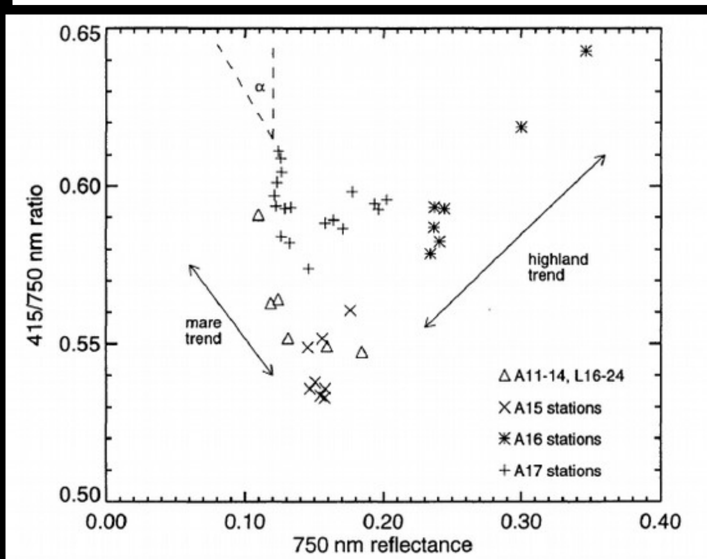


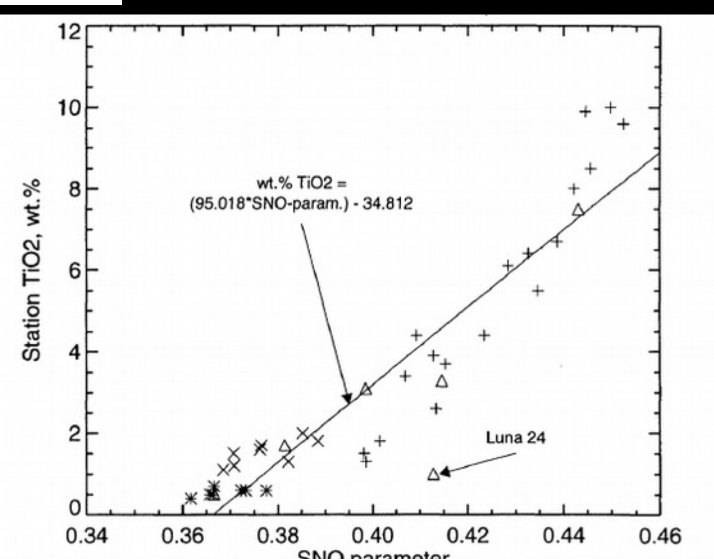


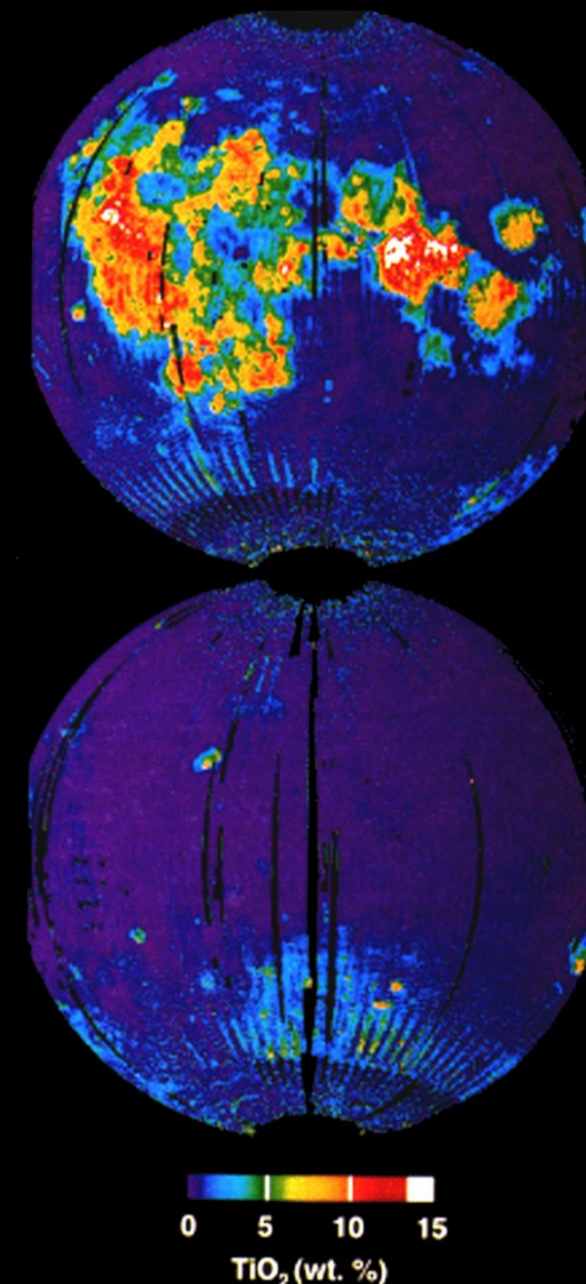


TiO_2 Abundance from Clementine UVVIS Data







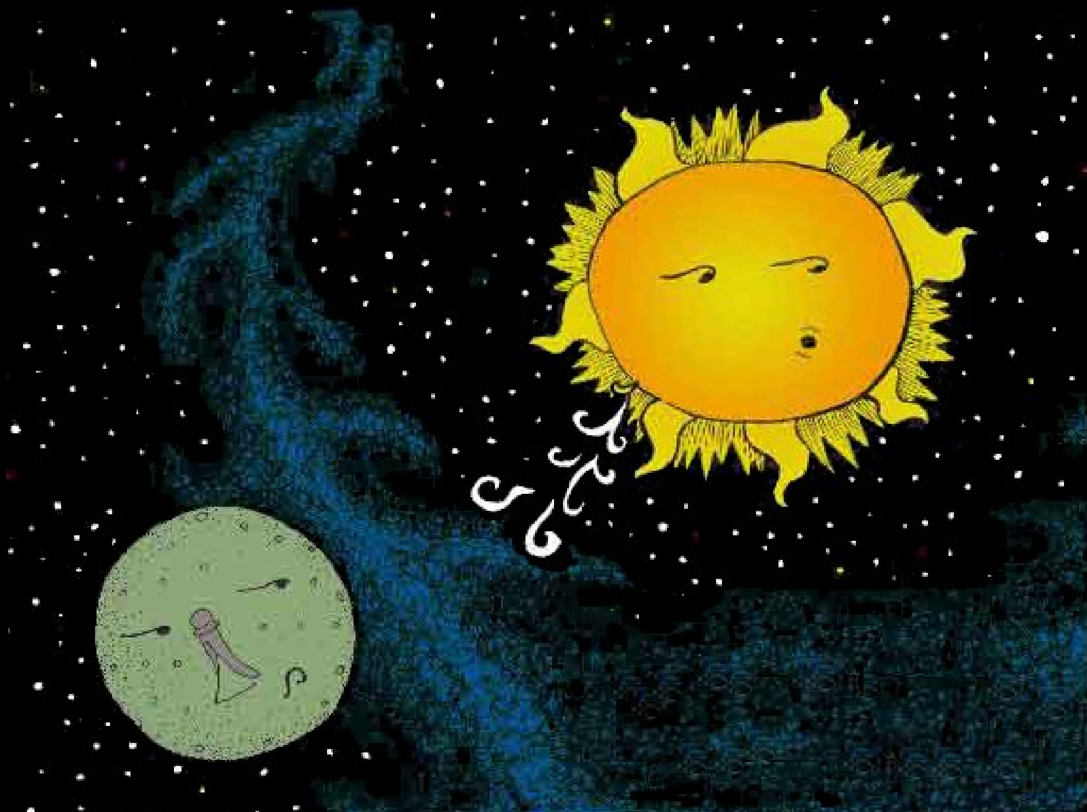


Space Weathering

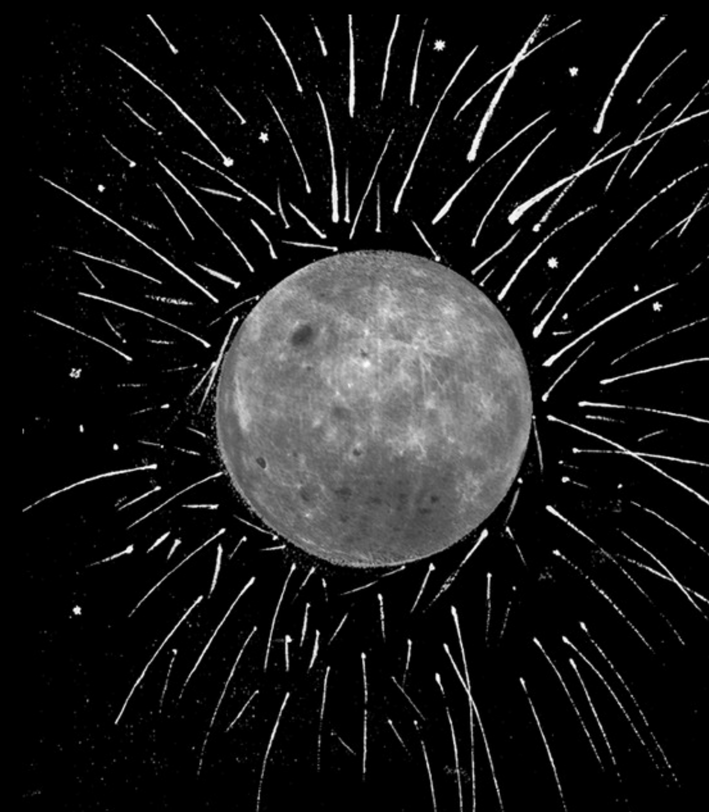
Describes a group of processes that alter the surface of planetary bodies that lack an atmosphere to protect their surface.

They effectively come down to:

solar wind

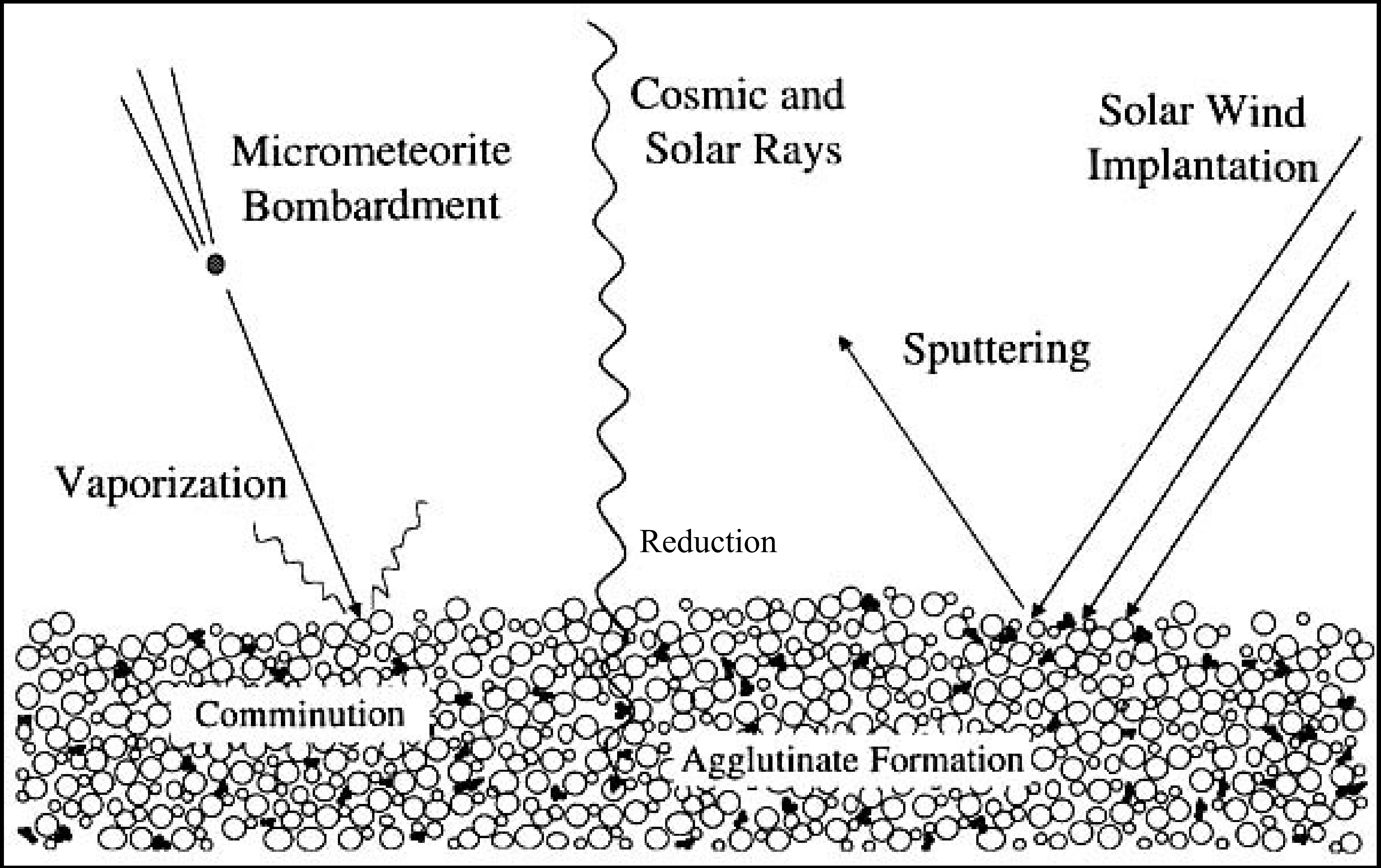


meteoritic bombardment



Also cosmic rays, but those are less significant.

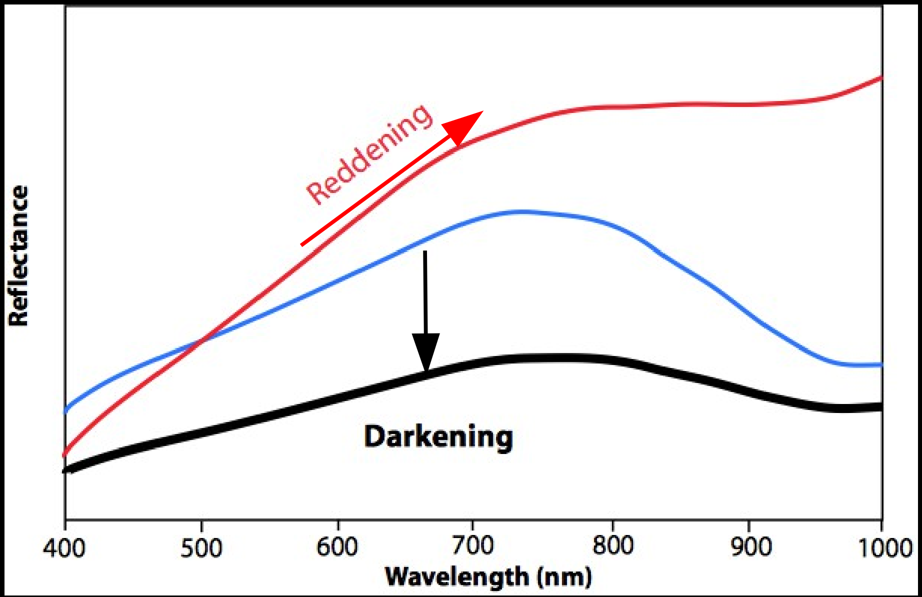
Space Weathering Processes

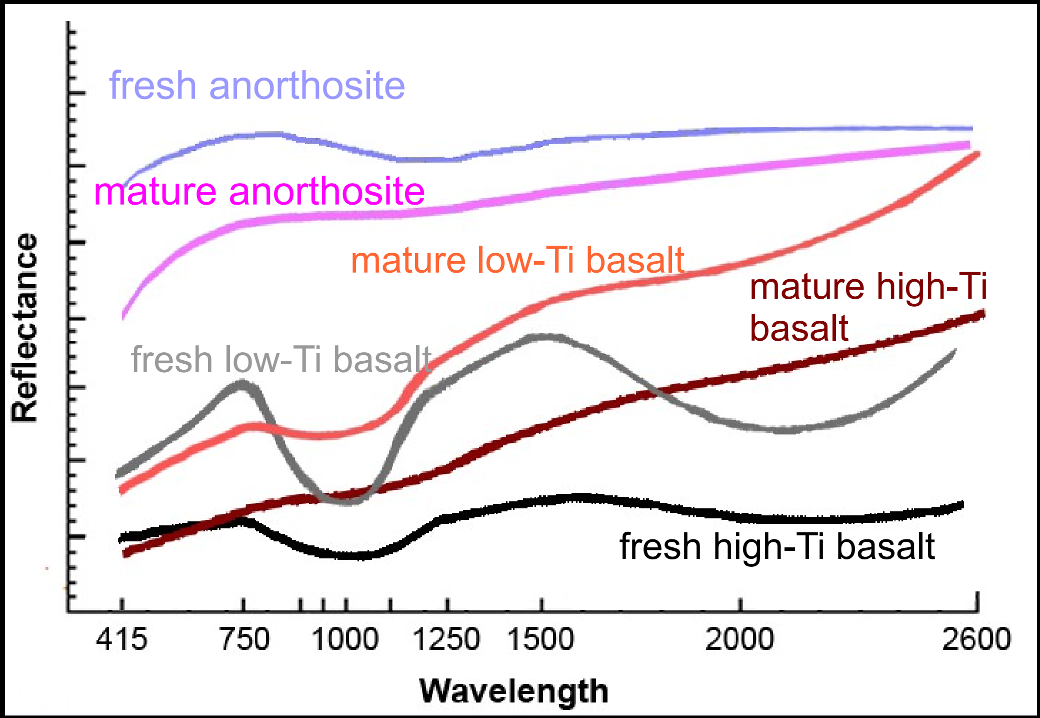


Spectral Characteristics of Space Weathered Soils

1. Decrease in visible (VIS) to near-infrared (NIR) reflectance
2. Reduction in contrast of diagnostic mineralogical absorption bands
3. Introduction of a strong "red" spectral slope

- Spectral effects of space weathering of lunar soil attributed to production of $npFe^0$ via reduction of Fe^{2+} in silicates





Creation & spectral properties of different npFe^0 particle sizes

npFe^0 formation method

- Vapor deposition
- Reduction
- Sputtering
- Micrometeorite Impact melt
- Agglutination

Particle size

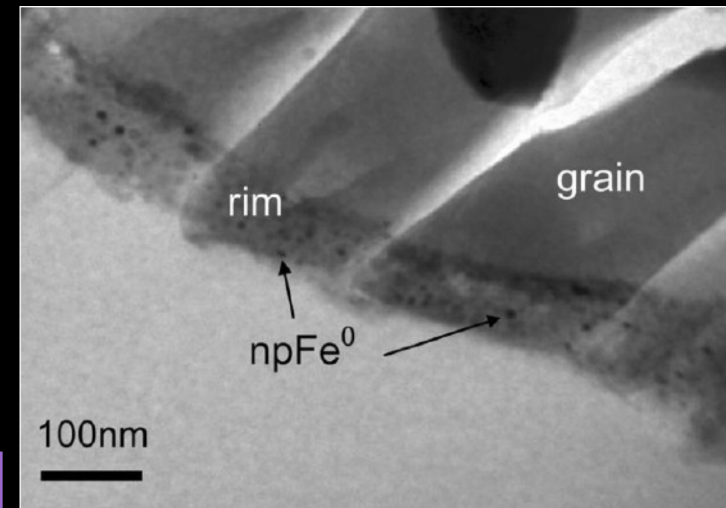
- Small (<10 nm)
- Larger (>40 nm)

Spectral effect
Hapke (2001), Keller & Clemett (2001)

- Attributed to reddening
- Attributed to darkening

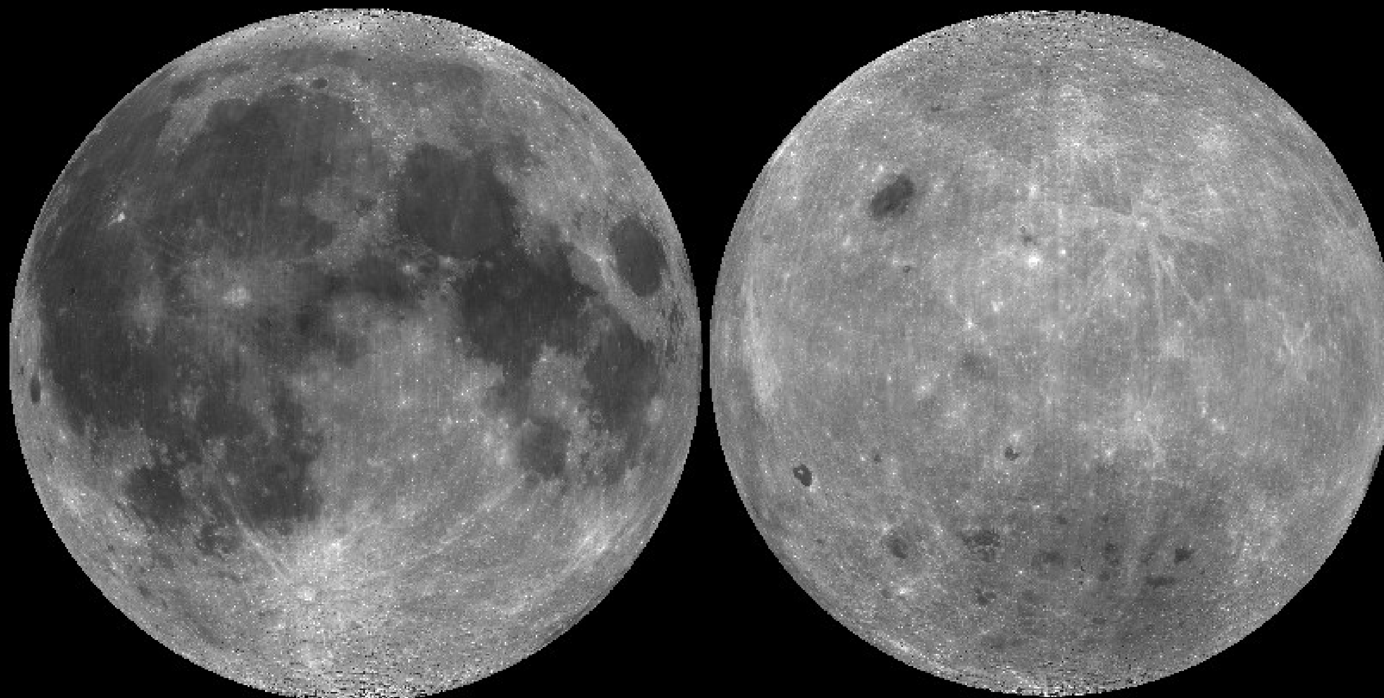
Spectral effect
Noble et al. (2007)

- npFe^0 < 10 nm: reddening in VIS w/ little effect in NIR
- npFe^0 > 40 nm: Darkening across VIS-NIR w/ little Δ continuum shape



"Normal" darkening & reddening of surfaces from mixed npFe^0 particle sizes (& mixed lithologies)

Optical Maturity

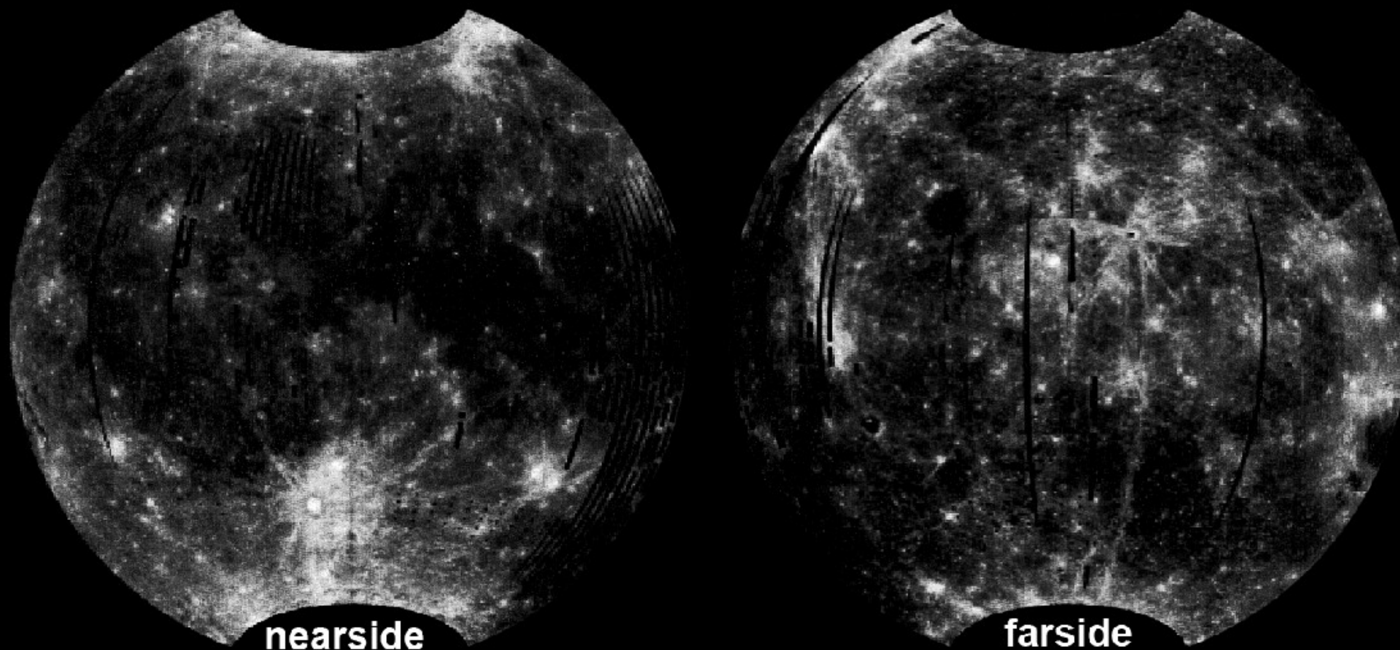


Maturation is the evolution or aging of the surface regolith, which increases with increased exposure to the space environment.

Maturity is a measure of this evolution by quantification of observable and measurable changes that occur in the regolith.

Optical maturity is a measure of maturity using spectral reflectance

Optical Maturity



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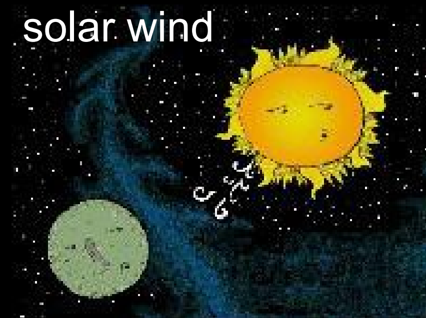
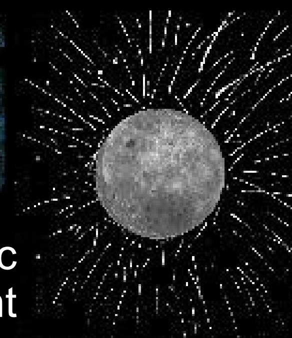
Components of the Measured Spectrum

+



Meteoritic bombardment



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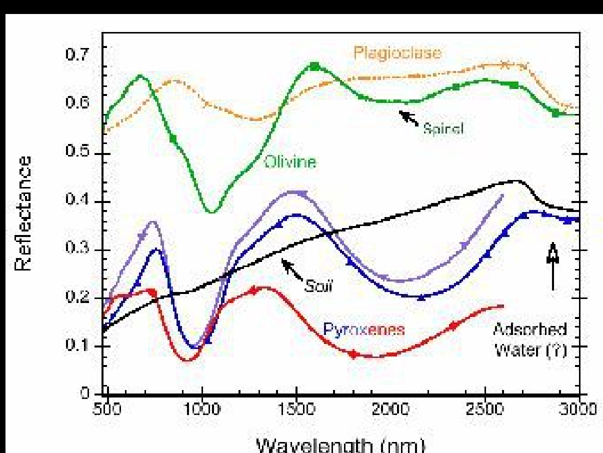
constituent minerals + space weathering = surface soils



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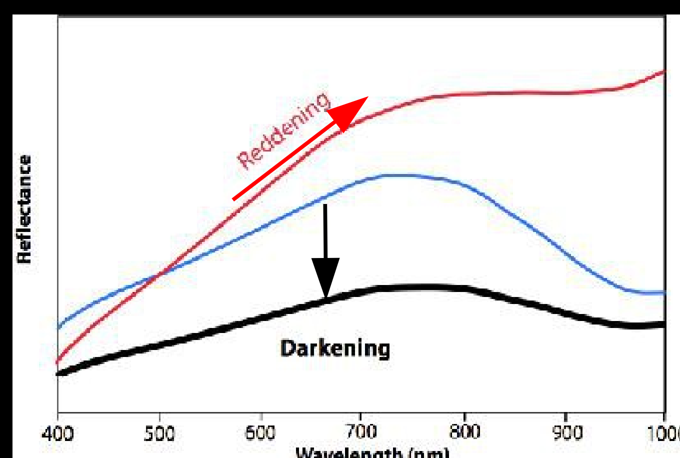

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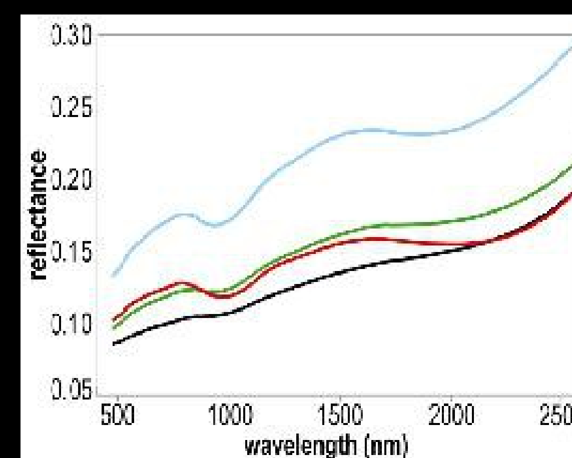
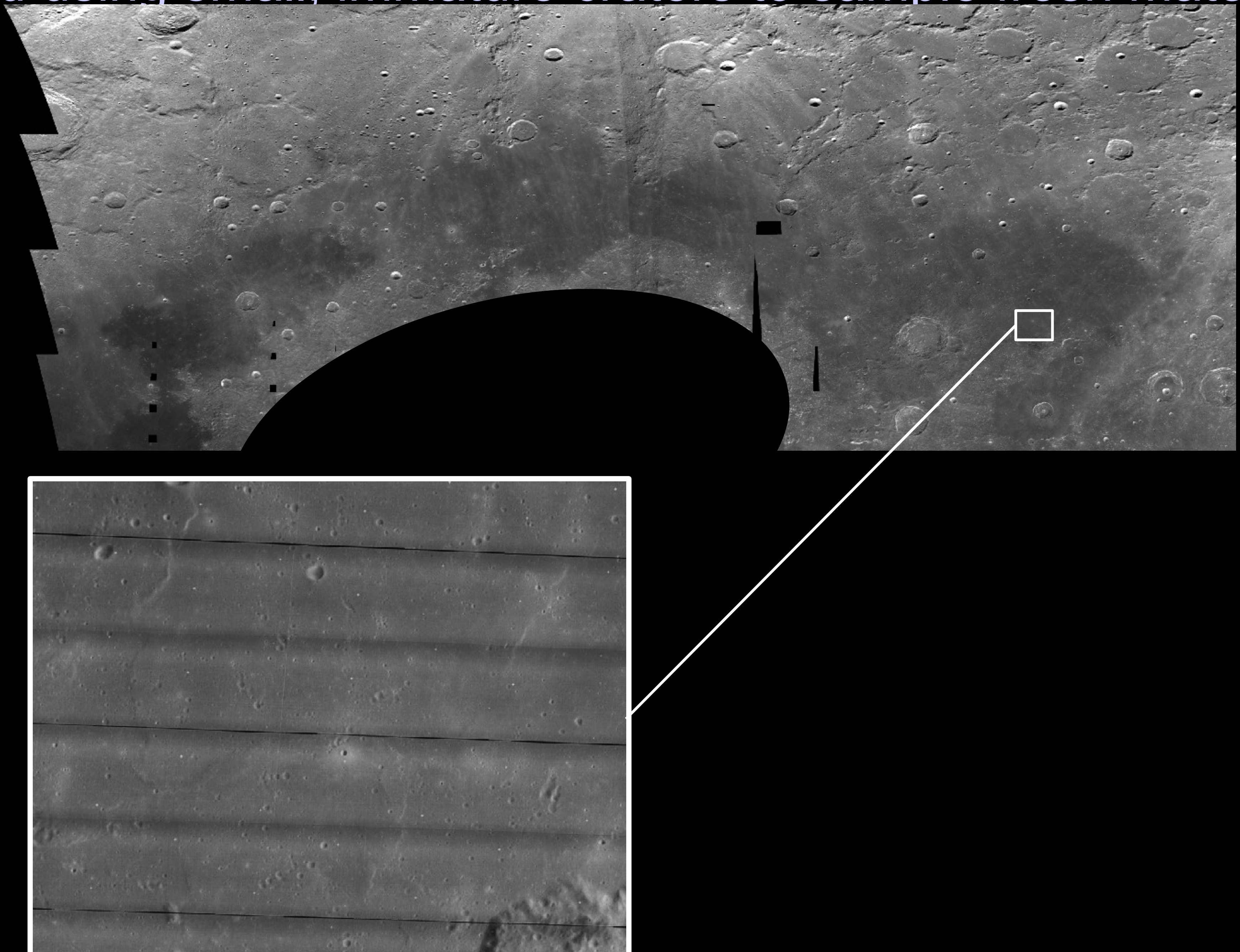


Mineral spectra + darkening, reddening, & band attenuation = measured spectra

Example maturing basalt at Mare Frigoris

(and using small, immature craters to sample fresh material)



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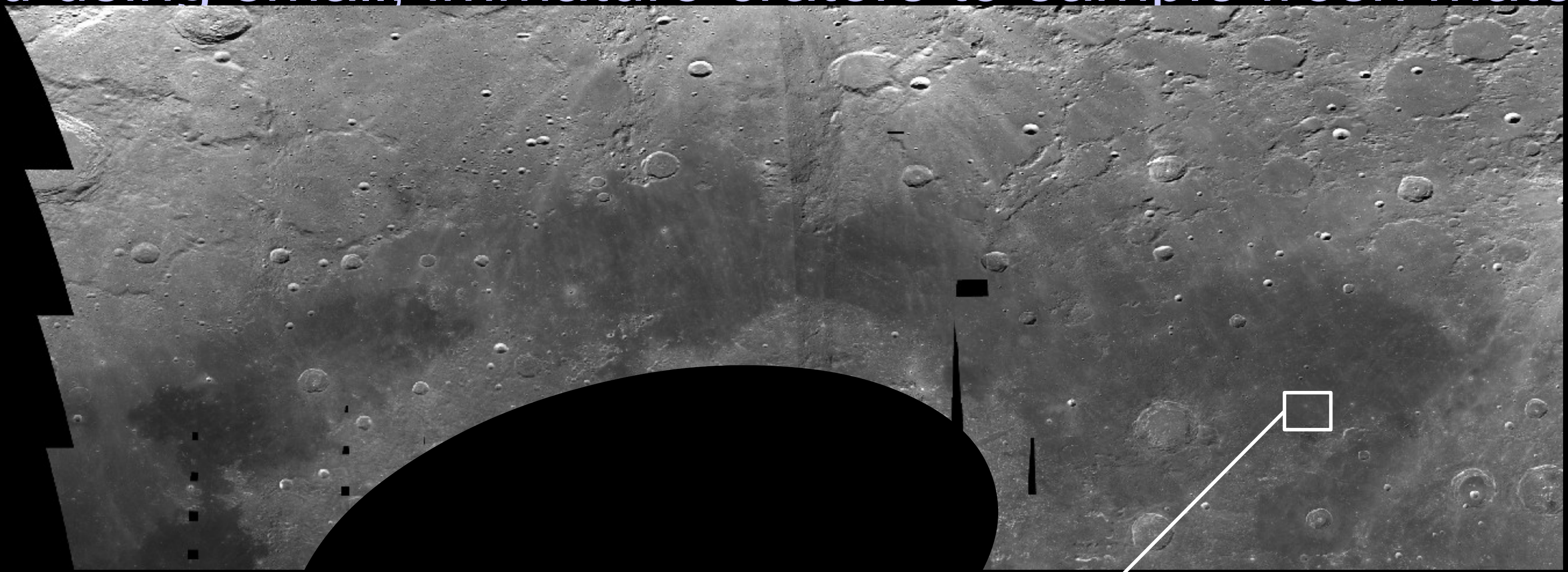

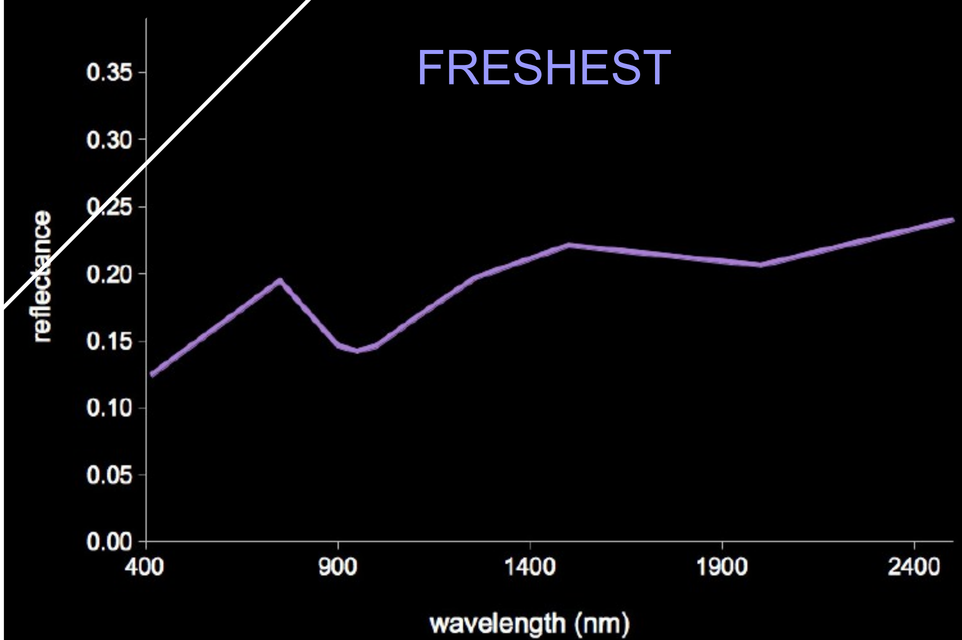

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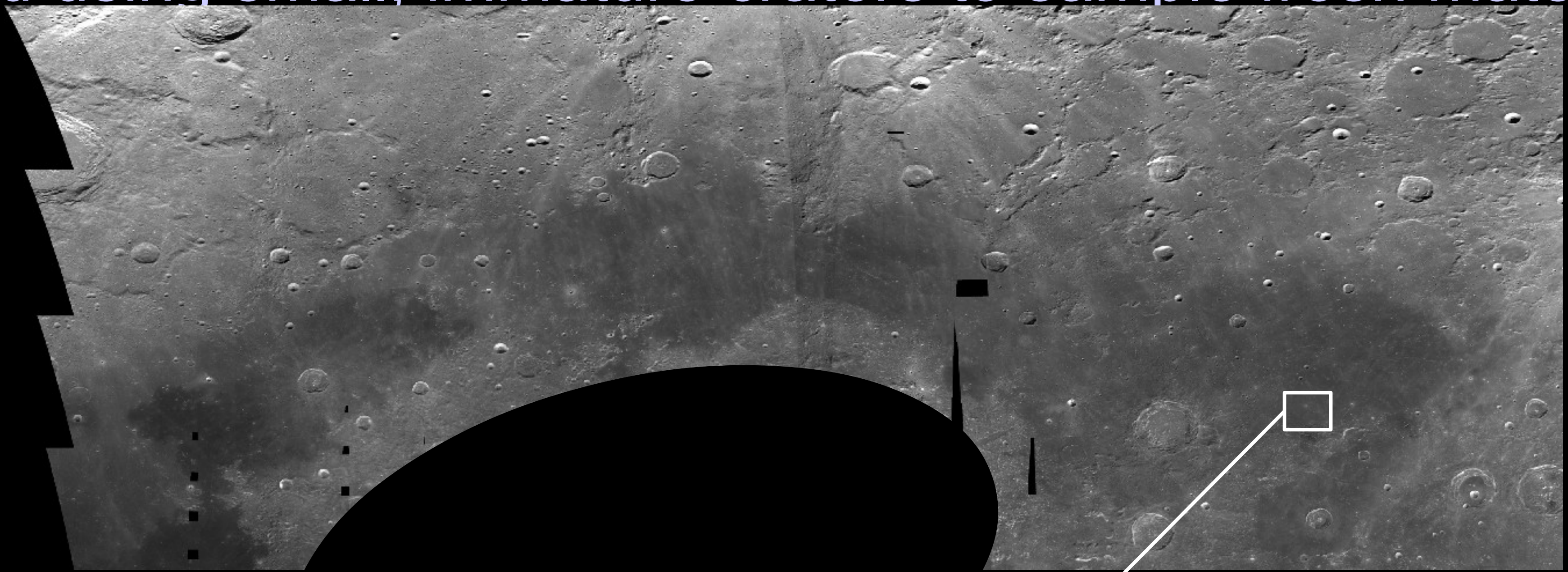

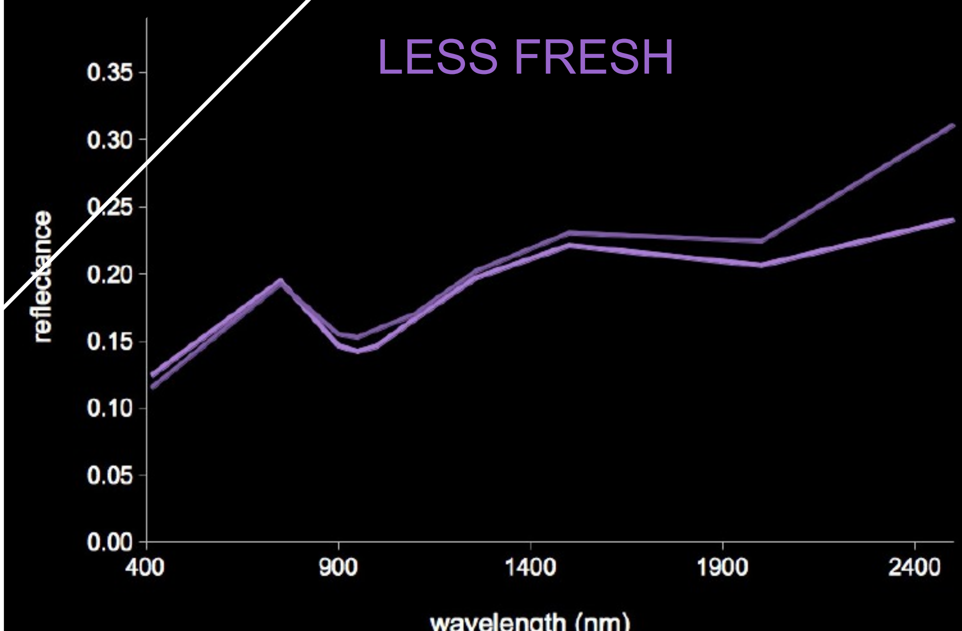

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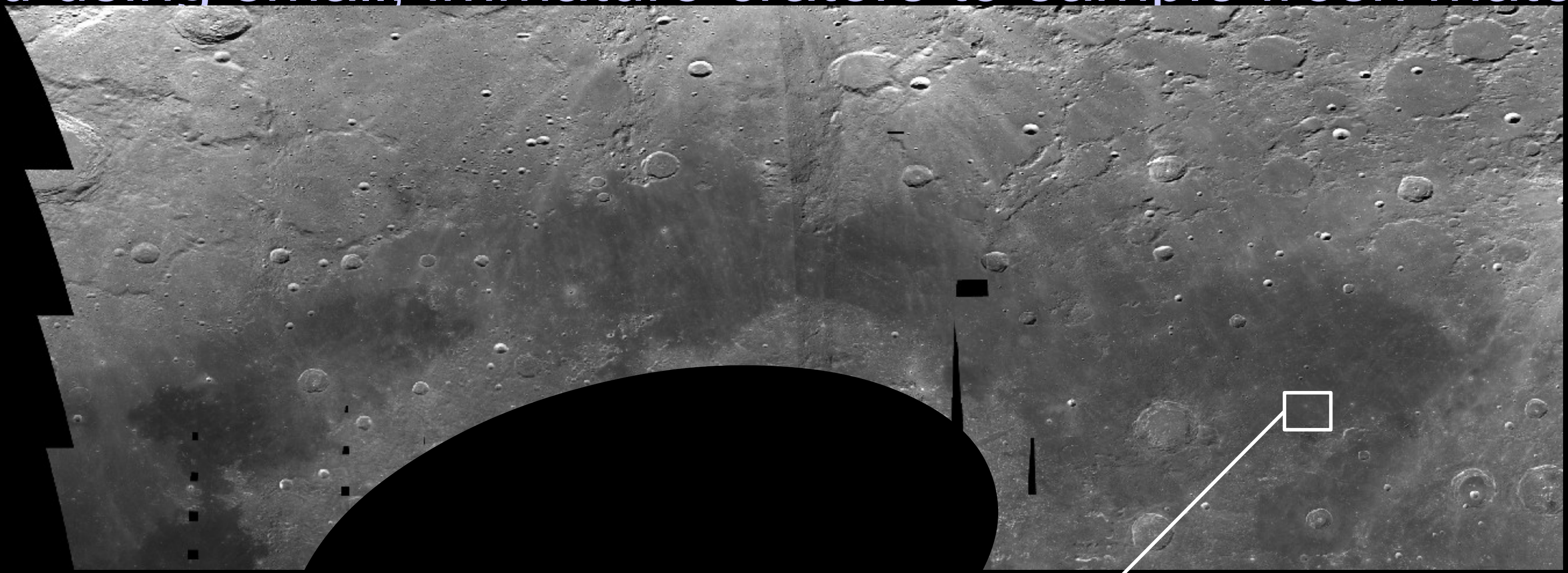

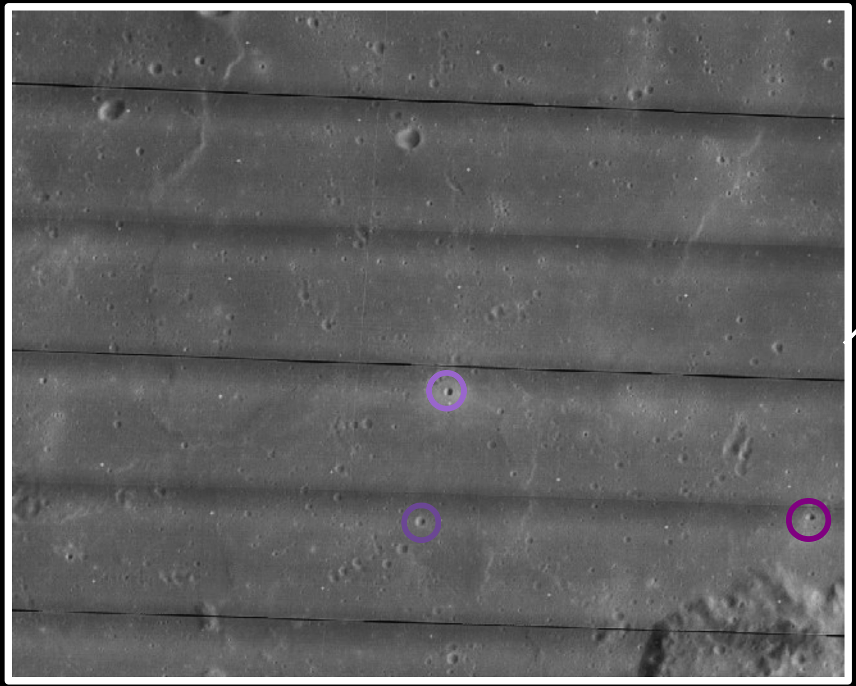

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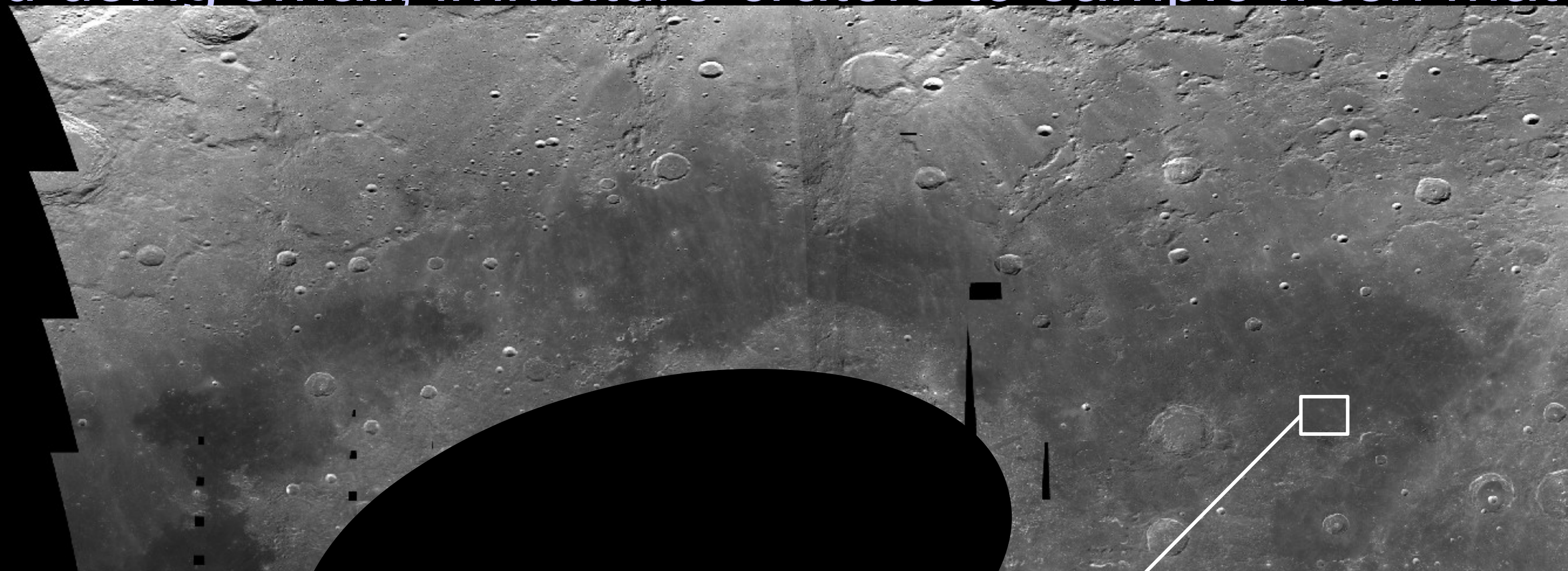

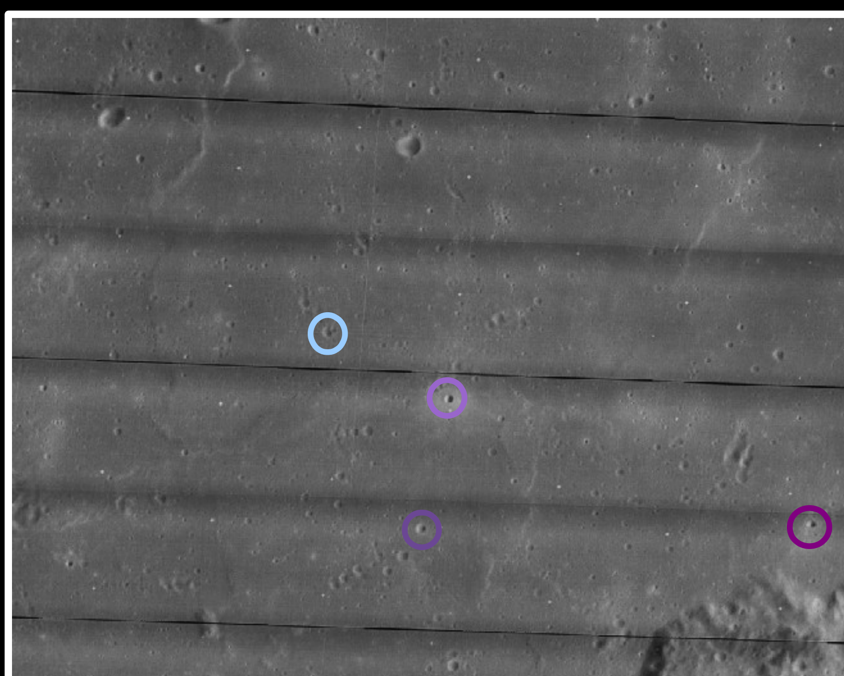

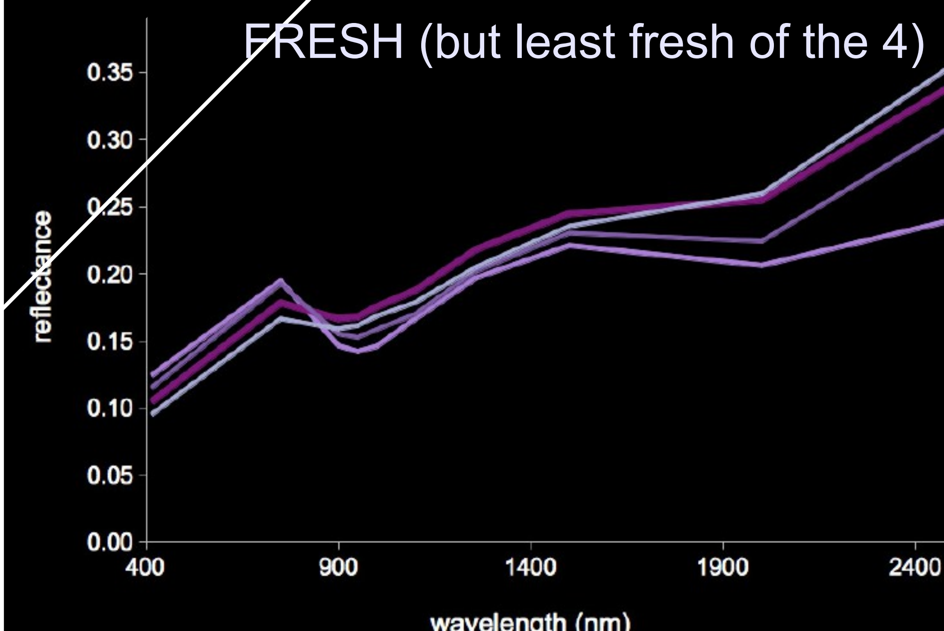

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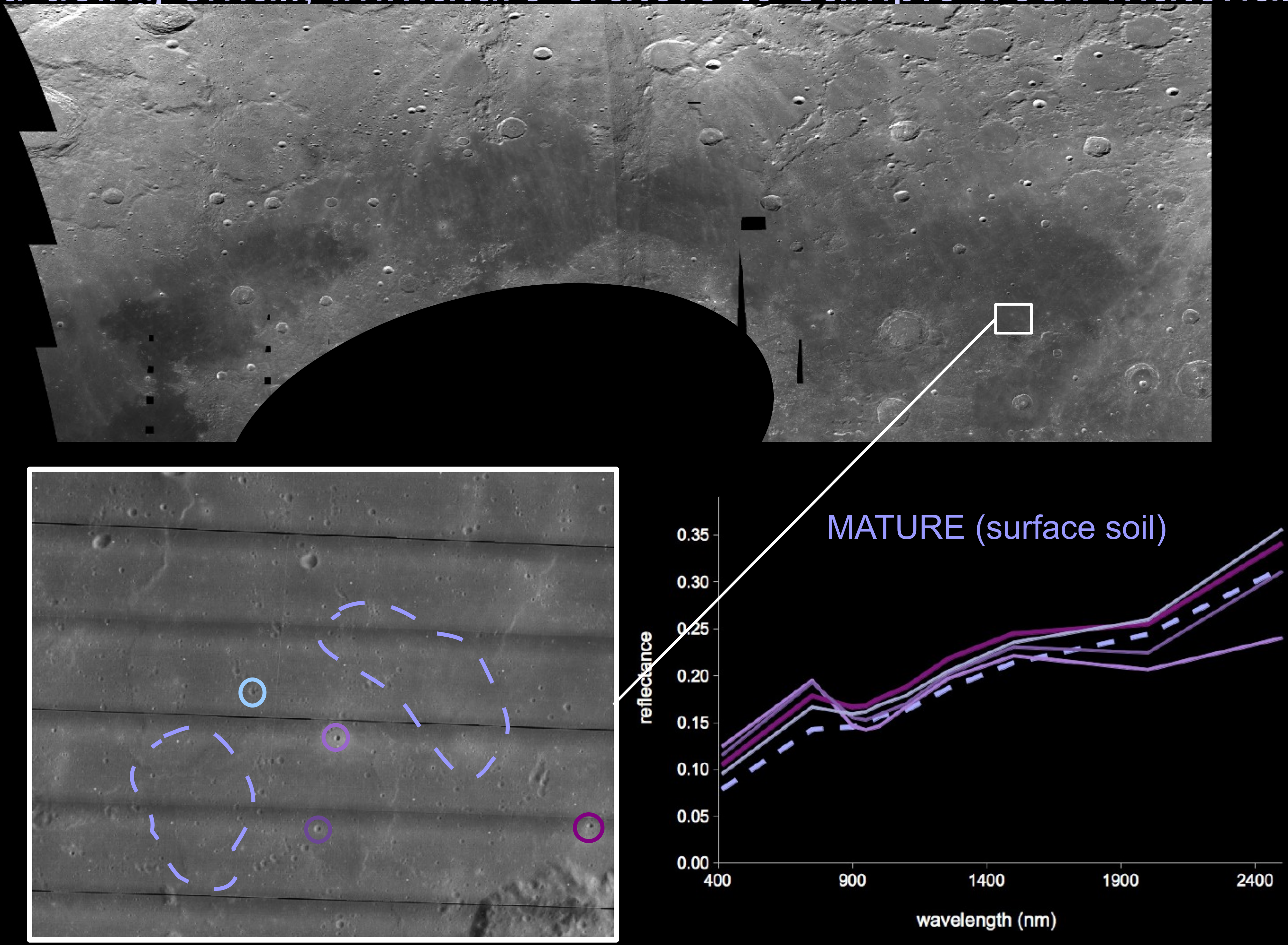


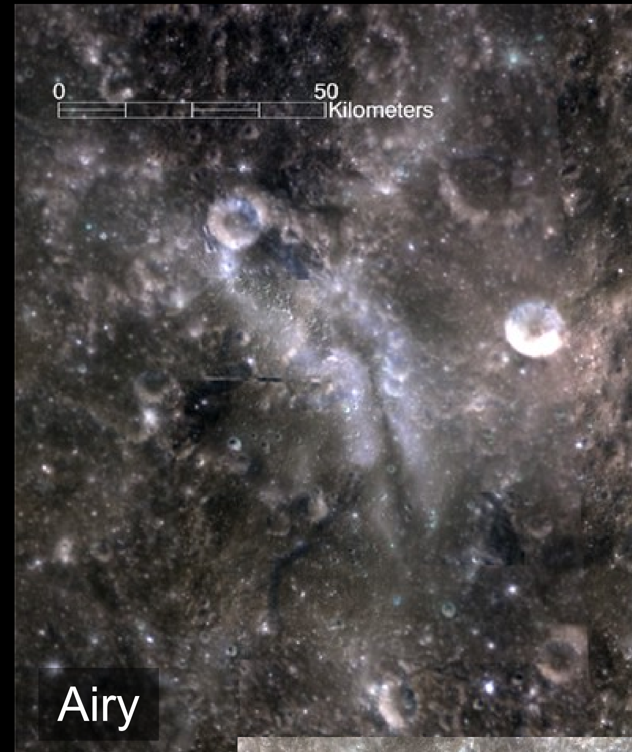
This all works very well …

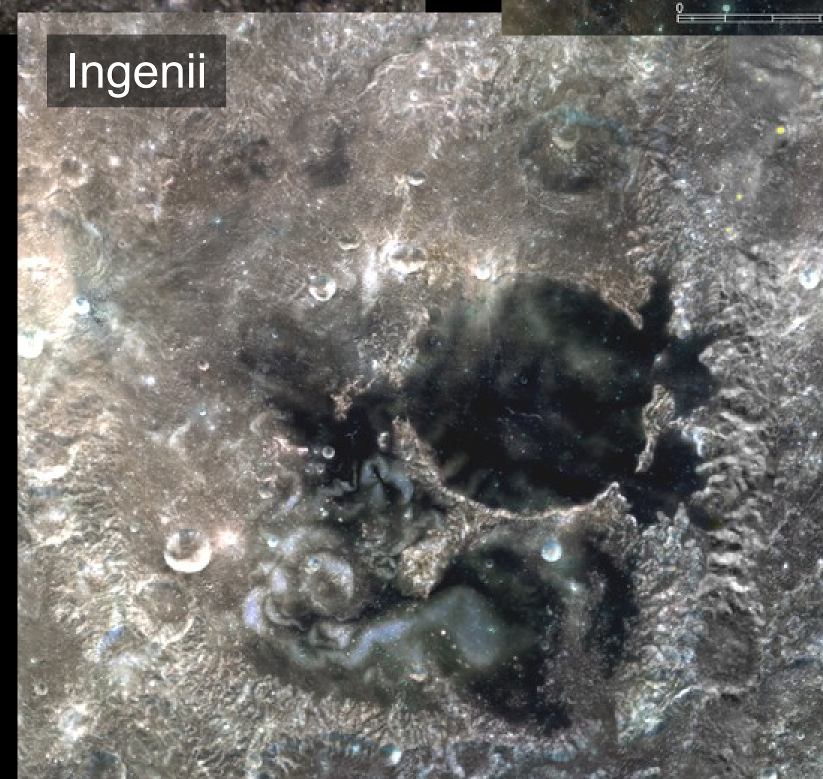
… until you investigate the lunar swirls

What's a lunar squirrel?

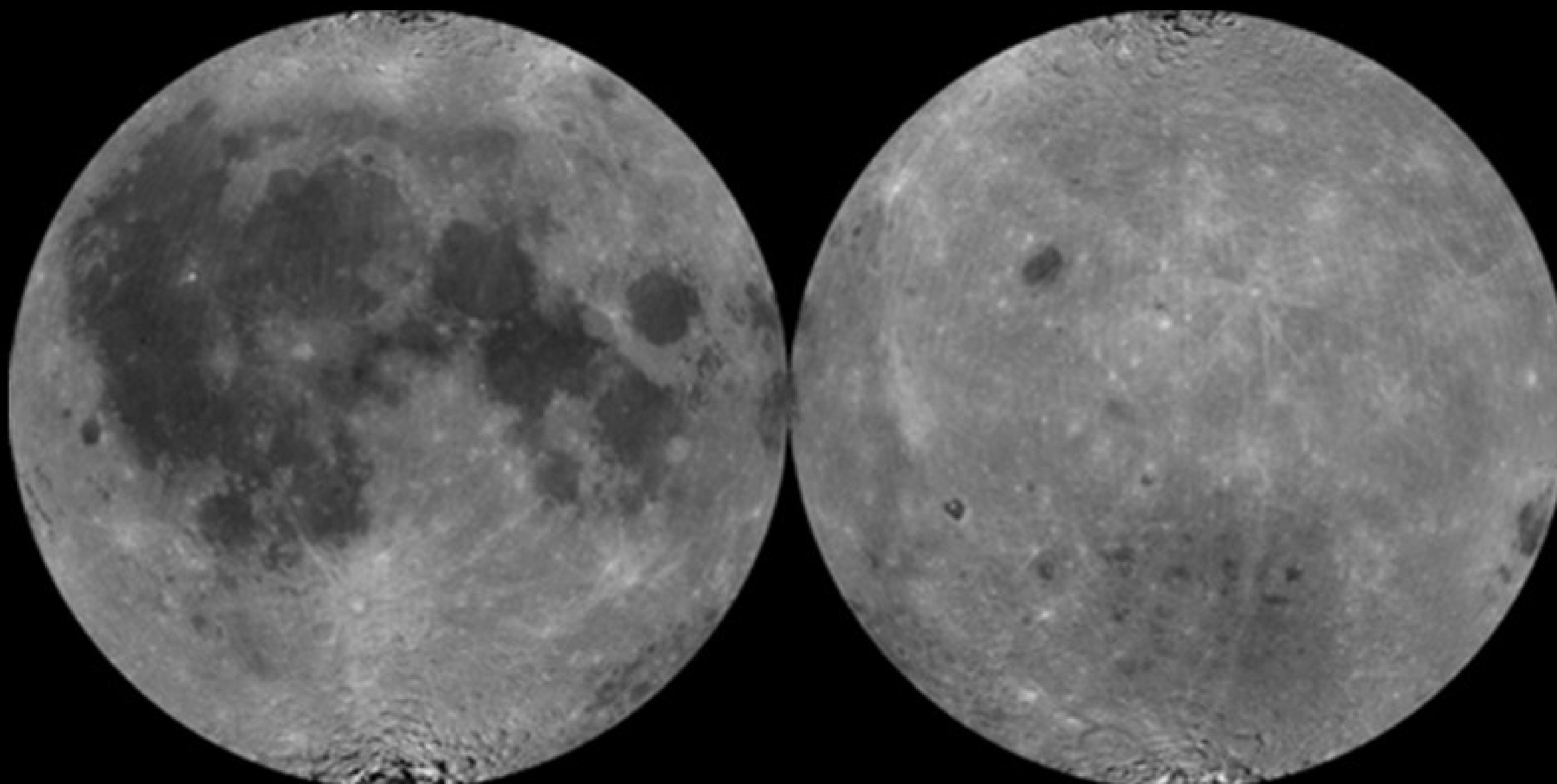
What are Lunar Swirls?

- Sinuous shape & interweaving dark lanes
- Associated with magnetic anomalies
- Impart no topography
  - i.e., they drape the existing topography
- High albedo
- Optically immature





The lunar swirls are associated with magnetic anomalies



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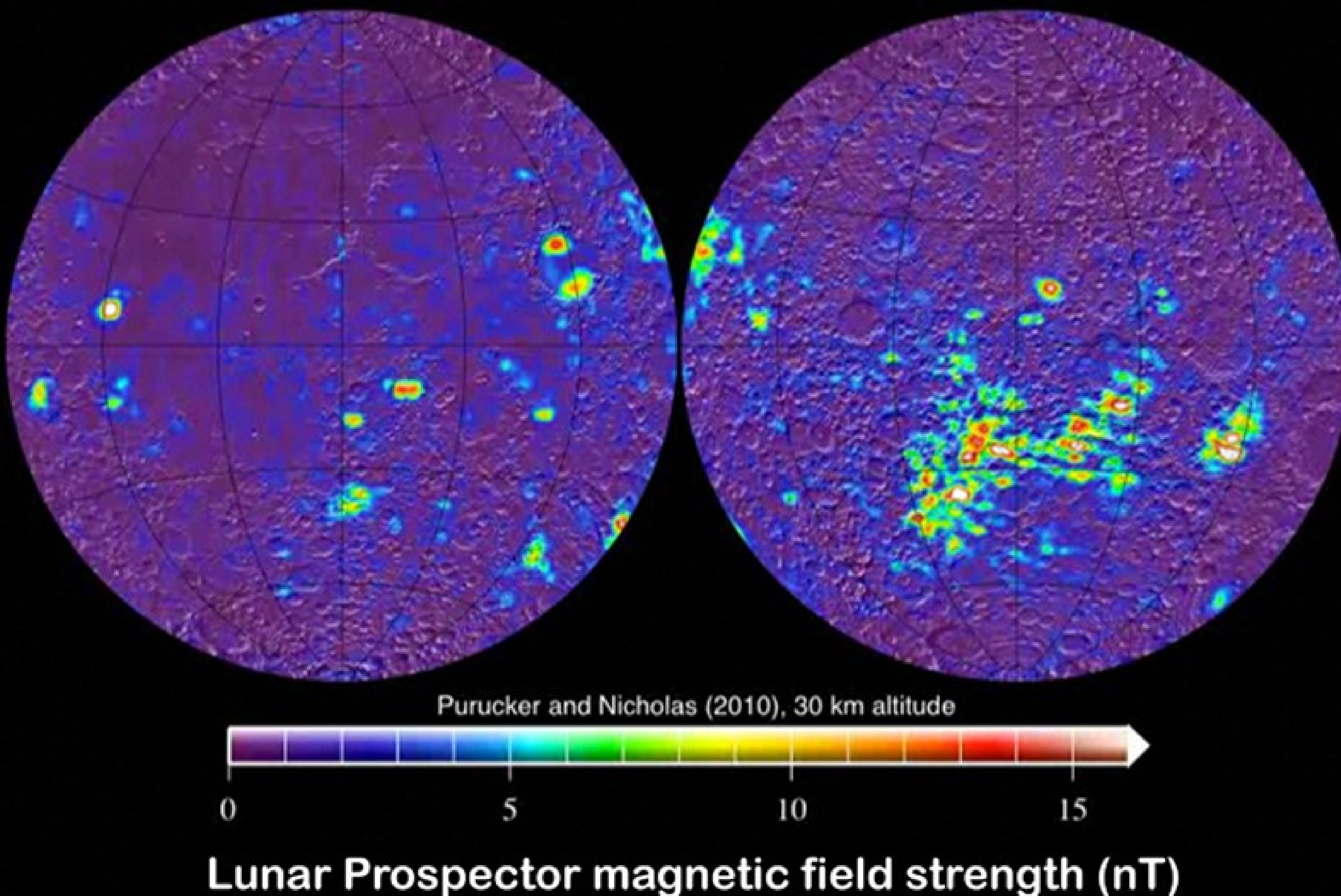
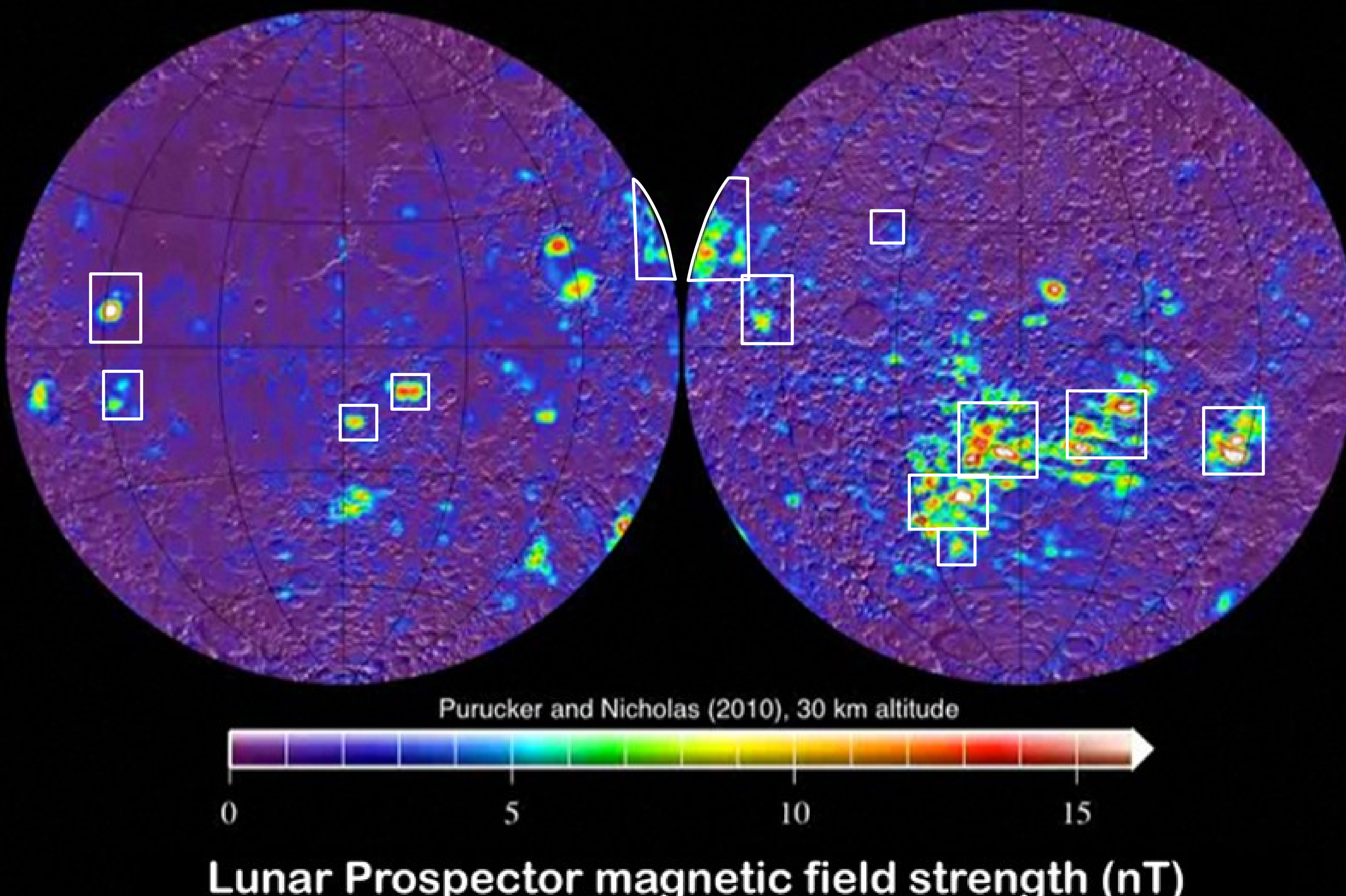


The lunar swirls are associated with magnetic anomalies

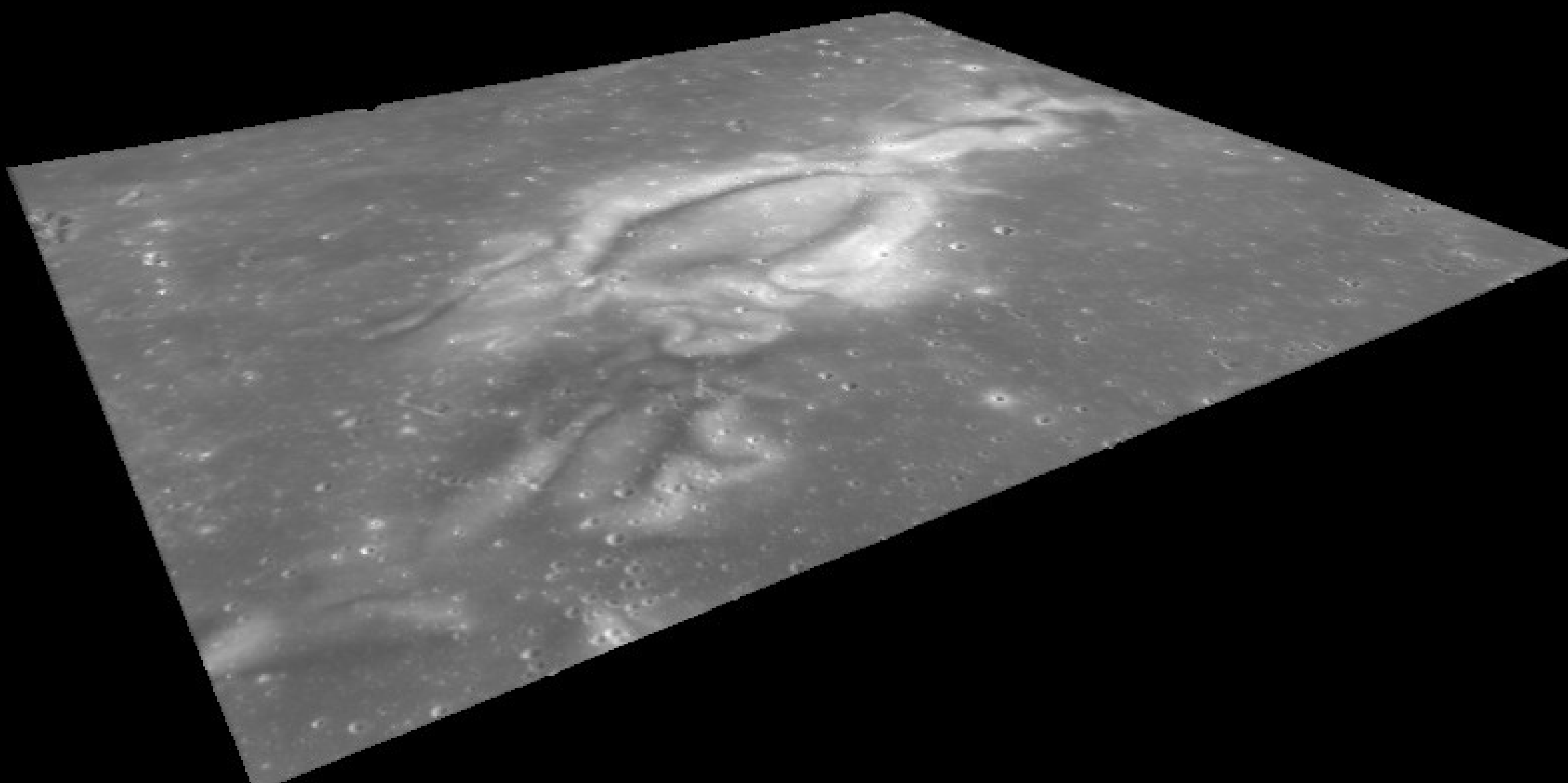
- But not every anomaly has an (identified) swirl



Swirls impart no topographic expression

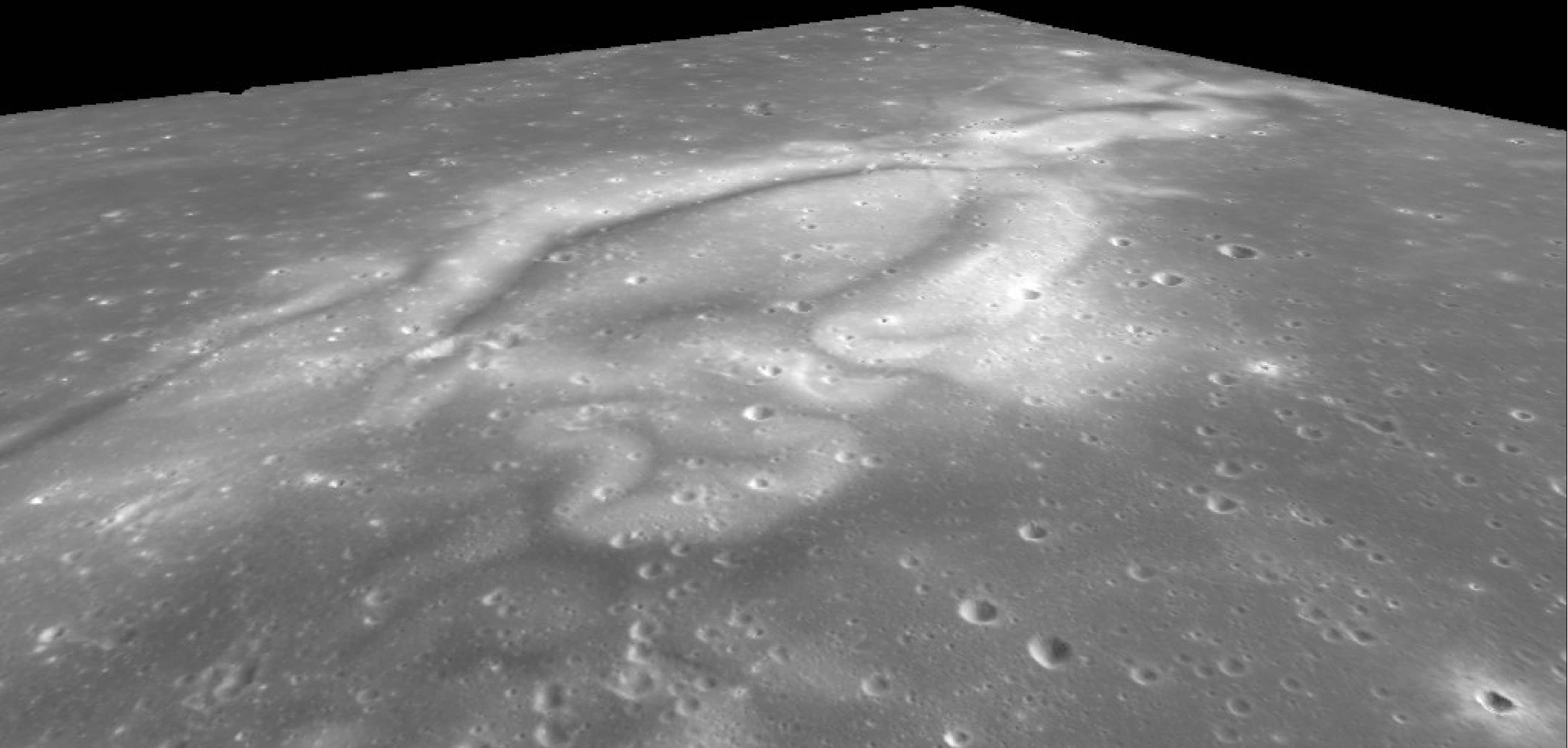
Mare Ingenii

Reiner Gamma



Kaguya Terrain Camera DTM

Reiner Gamma



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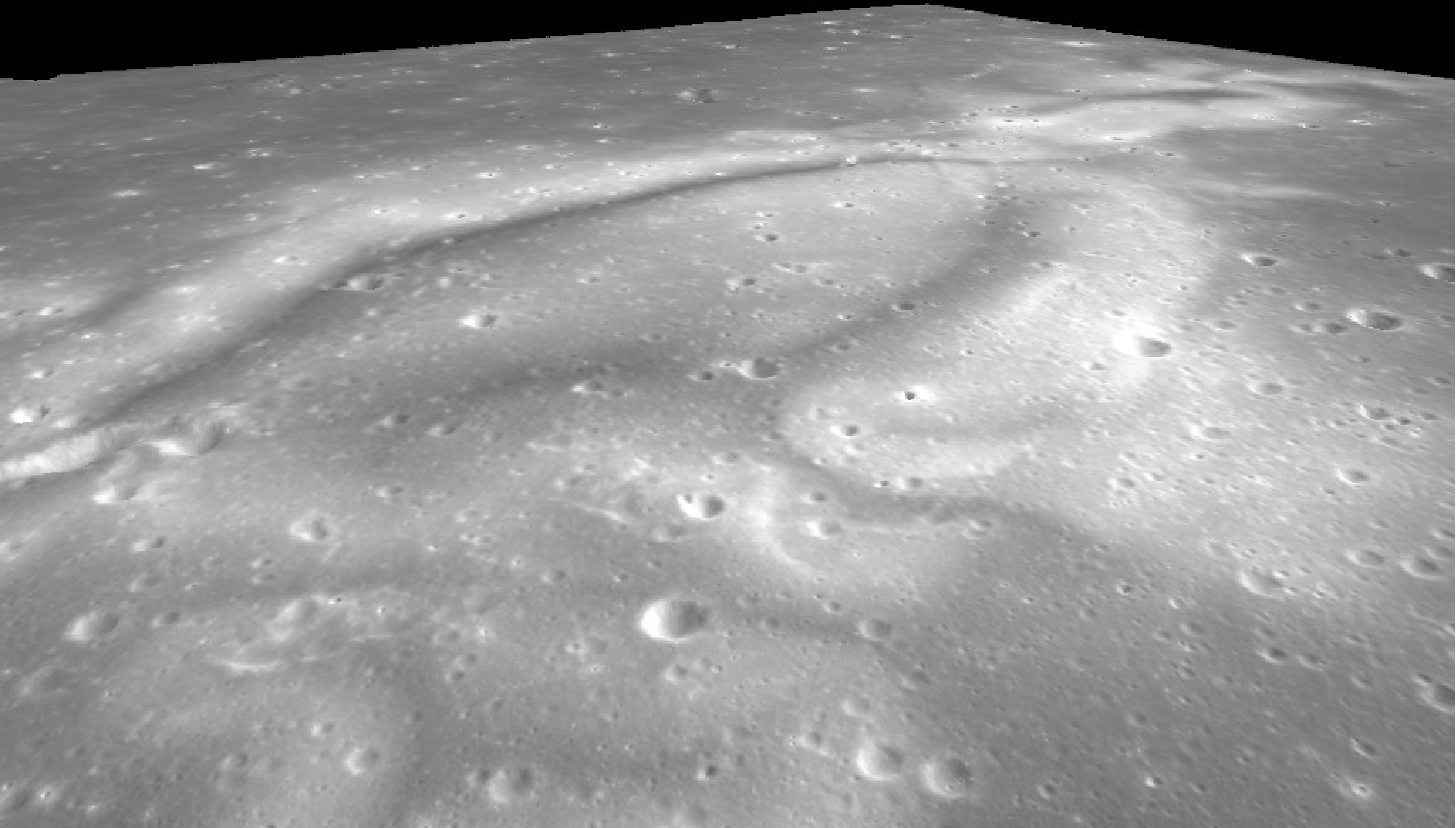

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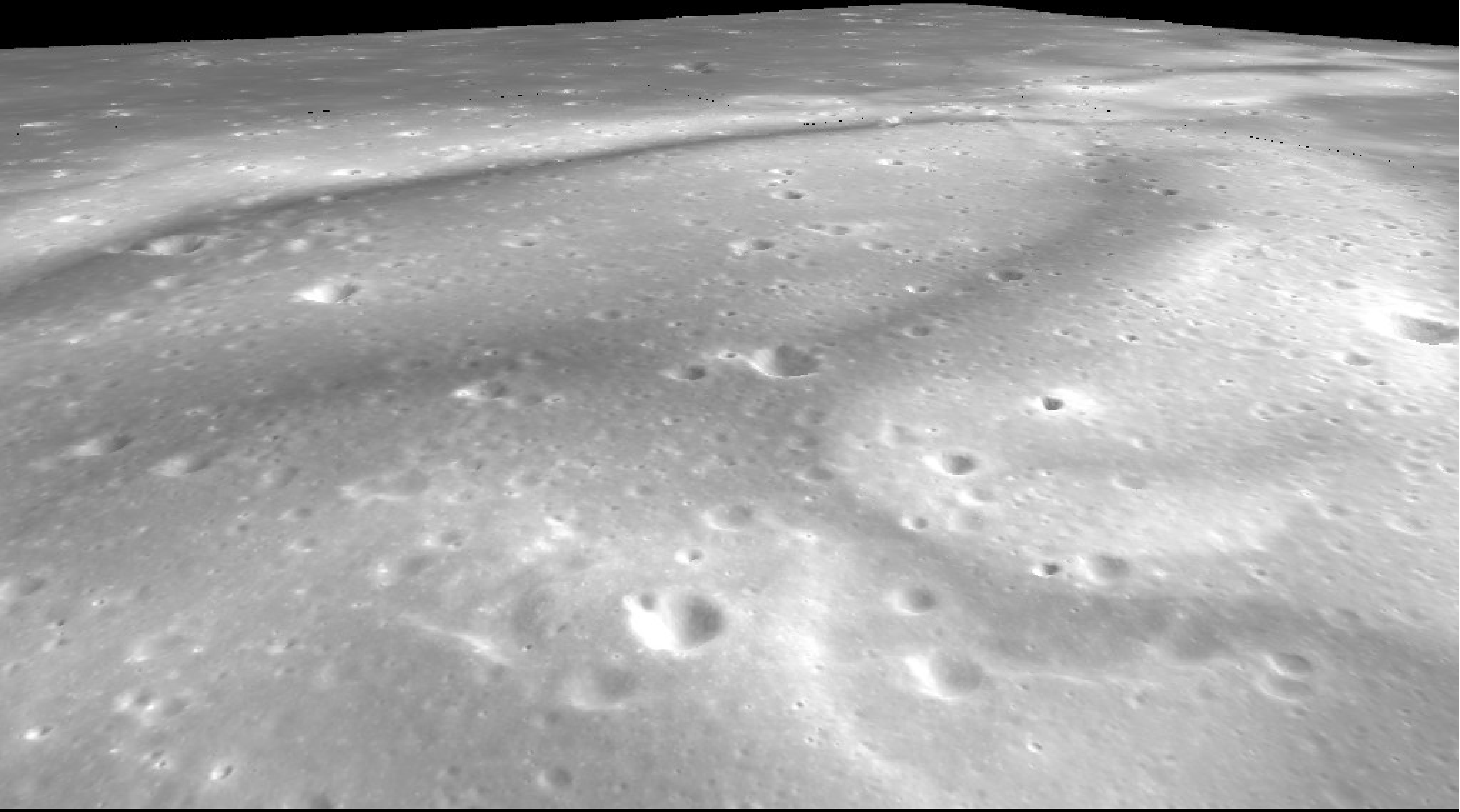


Kaguya Terrain Camera DTM

Reiner Gamma

Kaguya Terrain Camera DTM

Lunar swirls are high albedo

- Lunar swirls are considered an albedo anomaly

Lunar swirls are high albedo

- Lunar swirls are considered an albedo anomaly

Why?

Lunar swirls are high albedo

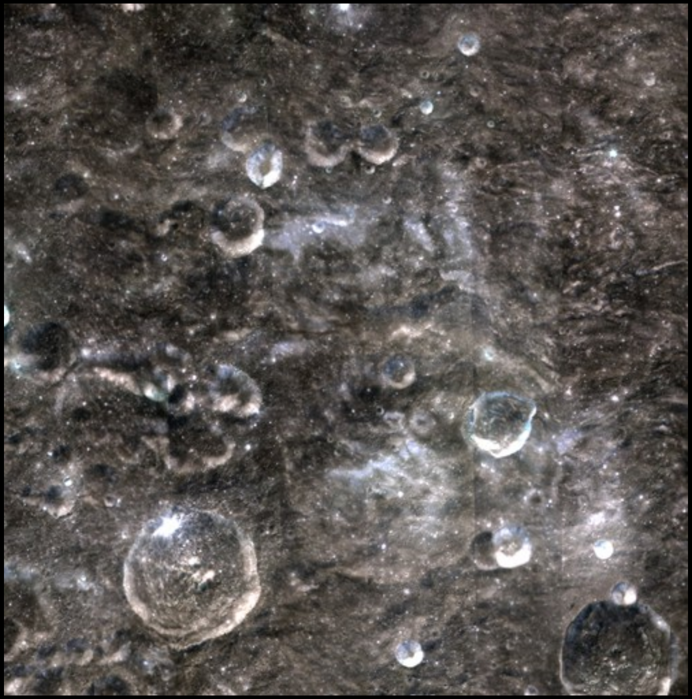
- Lunar swirls are considered an albedo anomaly

Why?

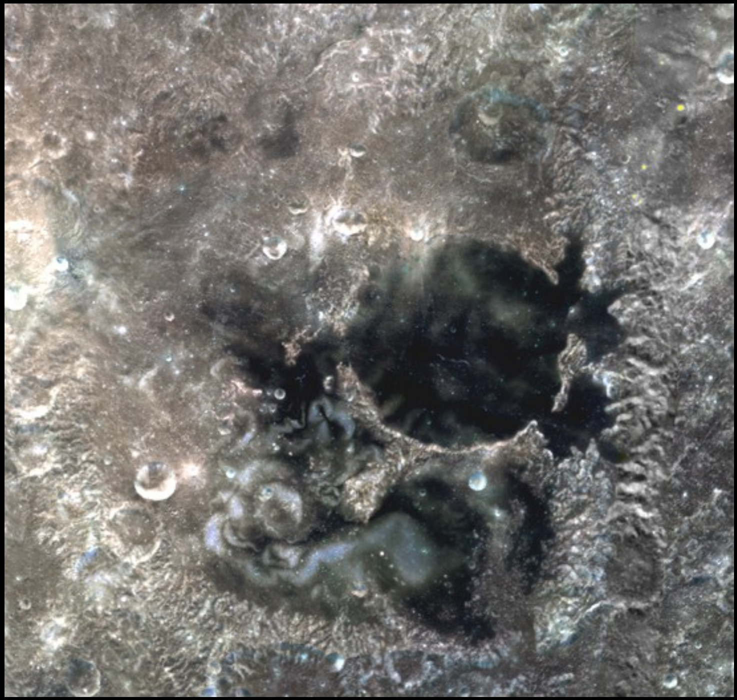
- Because they are as bright as the brightest lunar features – fresh highland ejecta rays.
  - They remain bright while everything else around them gets darker with time

Lunar swirls are optically immature

Reiner Gamma



Gerasimovich



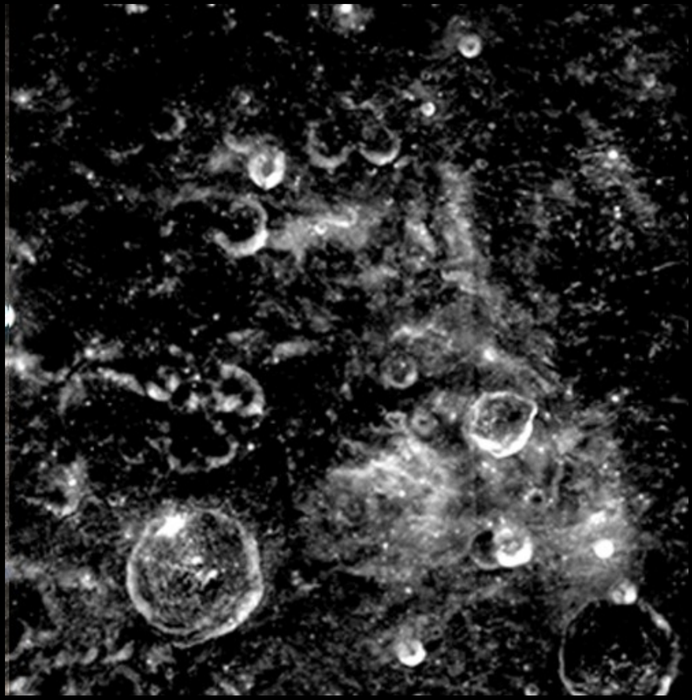
Mare Ingenii

Clementine “true color”

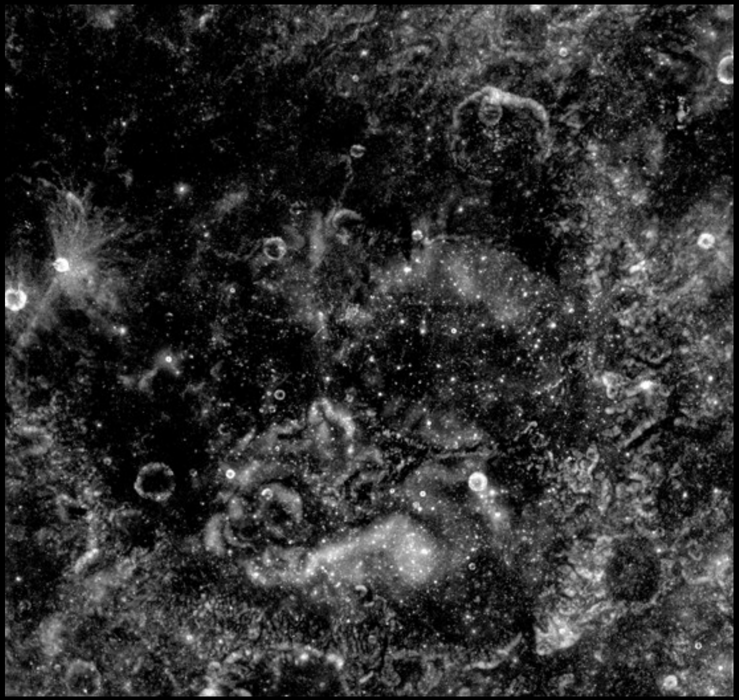
That is, they appear ***fresh***, or recently made.

Lunar swirls are optically immature

Reiner Gamma



Gerasimovich



Mare Ingenii

Clementine optical maturity

That is, they appear ***fresh***, or recently made.

Hypotheses for Swirl Formation

(1)

Basin impact antipode-generated magnetic field & solar wind shielding

(Lon Hood & colleagues, 1980-present)

- Formation & recording of magnetic field generated antipodal to major basin-forming impact.
- Deflection of solar wind ion bombardment by magnetic field ***preserves fresh silicate materials albedo over time***.

(2)

Cometary impact

(Schultz & Srnka, 1980; Pinet et al., 2000)

- Magnetic field generated by complexities if a comet impact shock from coma, hyper-velocity gas collisions and interparticle collisions.
- ***Recent comet impact event scoured top-most surface regolith***, and exposed fresh material

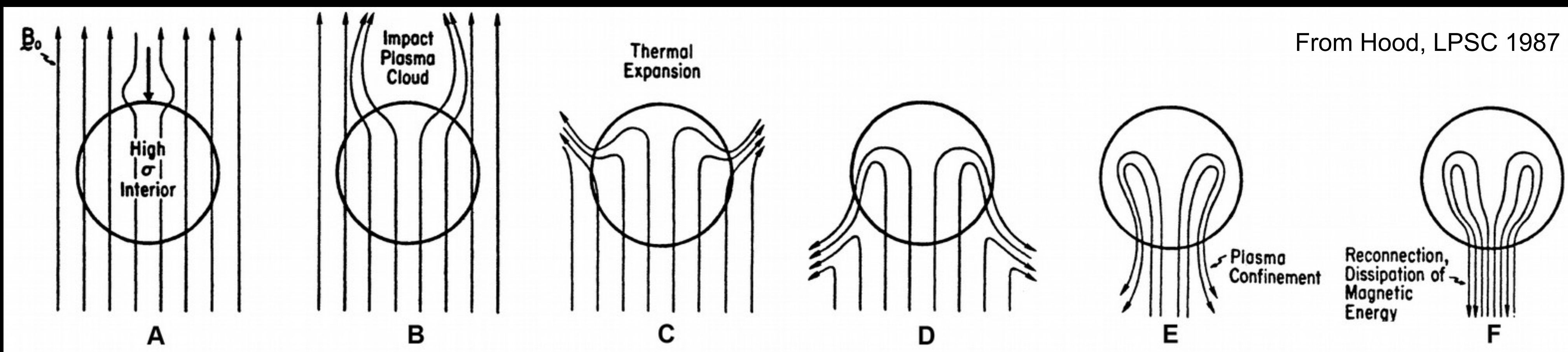
(3)

Charged dust levitation

(Ian Garrick-Bethel et al., 2009)

- Solar wind interaction with crustal magnetic anomalies creates weak electric elds that attracts or repels electrically charged ne dust
- **Finest fraction of soil enriched in bright, feldspathic component**

Hypothesis (1): Formation of “magcons” at basin antipodes



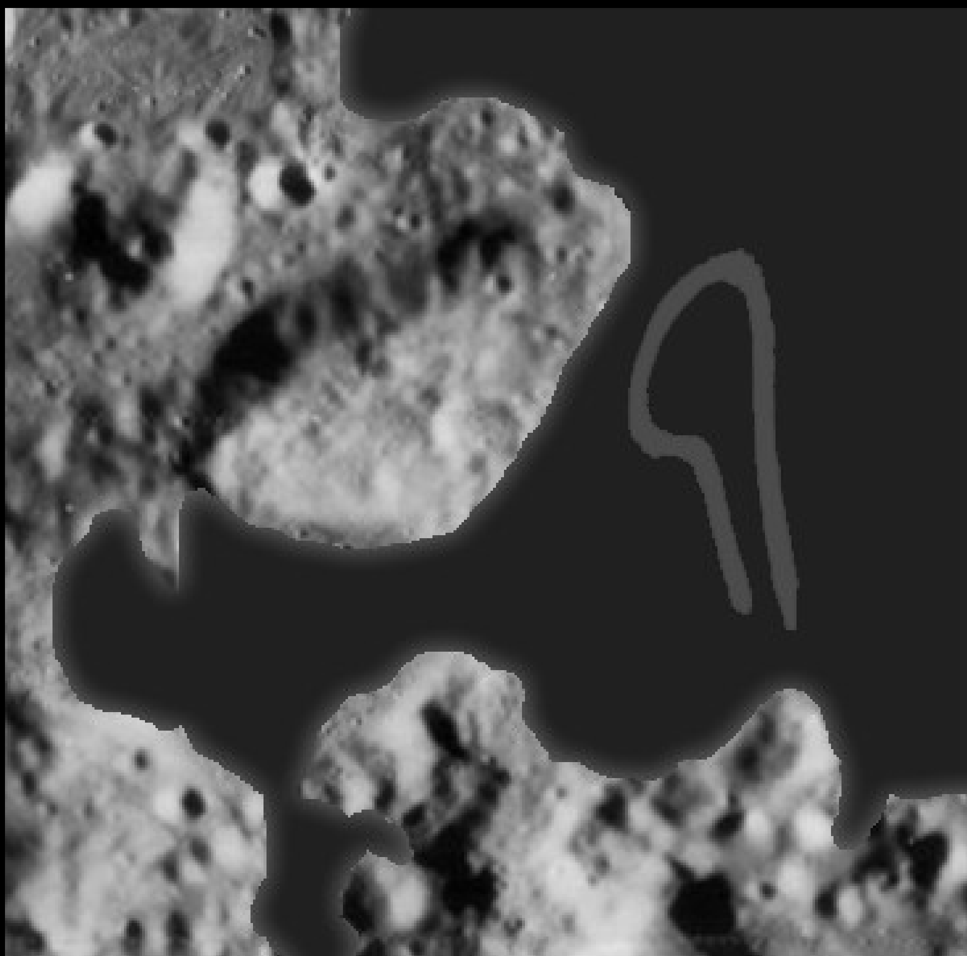
- Presence of weak ambient magnetic field diffused into highly conducting lunar interior.
  - internal (core) or external (solar wind)
- Modeled field lines are spatially uniform and oriented along impact axis of symmetry.

- Impact.
- Partial vaporization and subsequent ionization of ejecta.
- Formation of thermally expanding vapor and plasma cloud.

- Highly conducting gas expands around Moon
- Field lines tied to the highly conducting lunar interior, but forced away from impact point external to surface
- Field strength increased by compression at antipode.

- Compressed field magnetic reconnects and dissipates with dissipating plasma cloud.

Hypothesis (1): Swirl formation by solar wind shielding

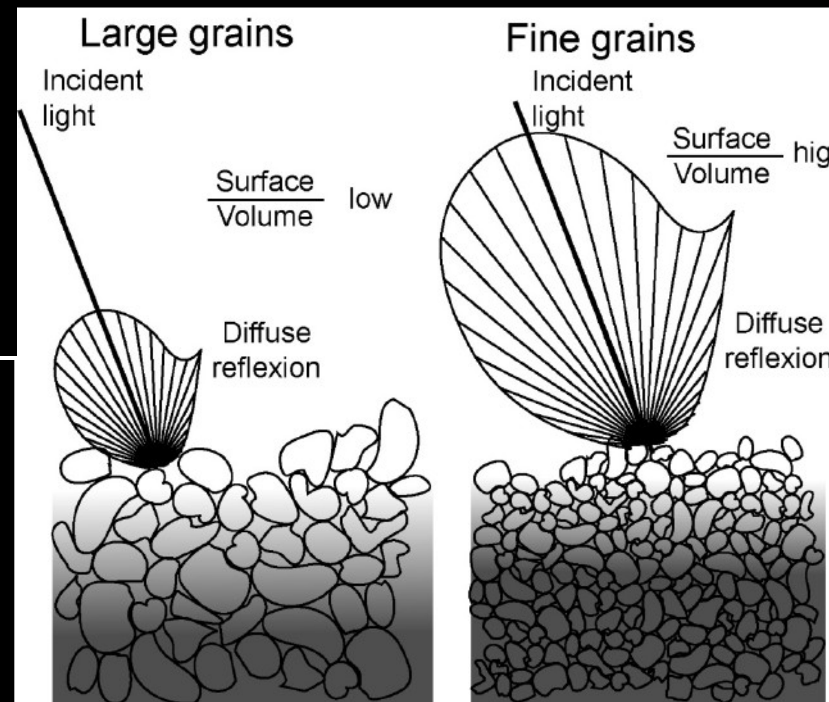


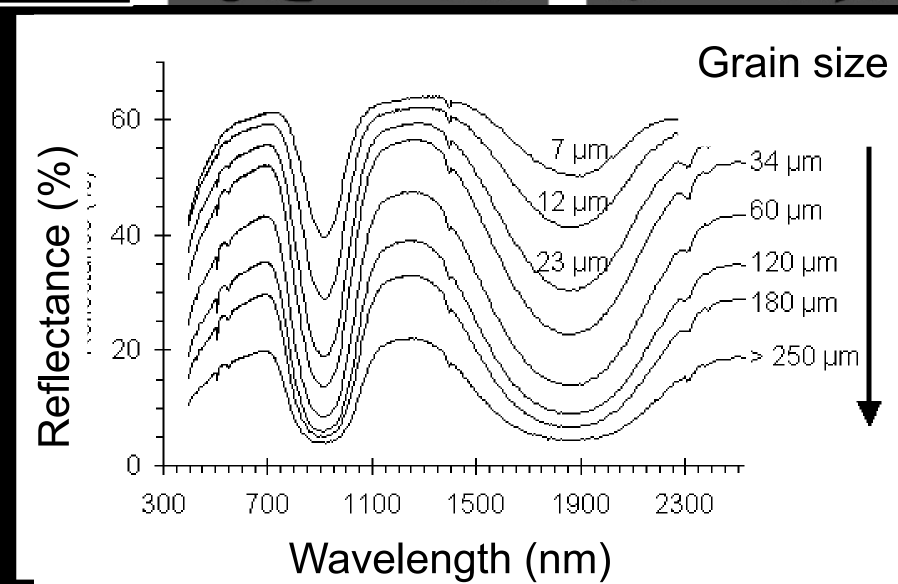
- Magcon created prior to or contemporaneous with regional mare basalt volcanism.
- Subsequent flows cover magnetized ejecta material, yet record it thereby transmitting it through surface.

Hypothesis (2):Comet Impact

- Scouring of surface by recent comet impact
  - Left very fine particle sizes on surface
  - Based on the observation (Schultz & Srnka, 1980) that the high-albedo swirls are photometric anomalies – diffuse reflectors
- Optically immature swirl surface is ***actually*** immature
- **Explanation of associated magnetic anomaly:** Hypervelocity impacts of micro-particles and super-heated gas within impacting coma & nucleus magnetize surface material.

Finer grain size
⇒ more scattering, less absorption



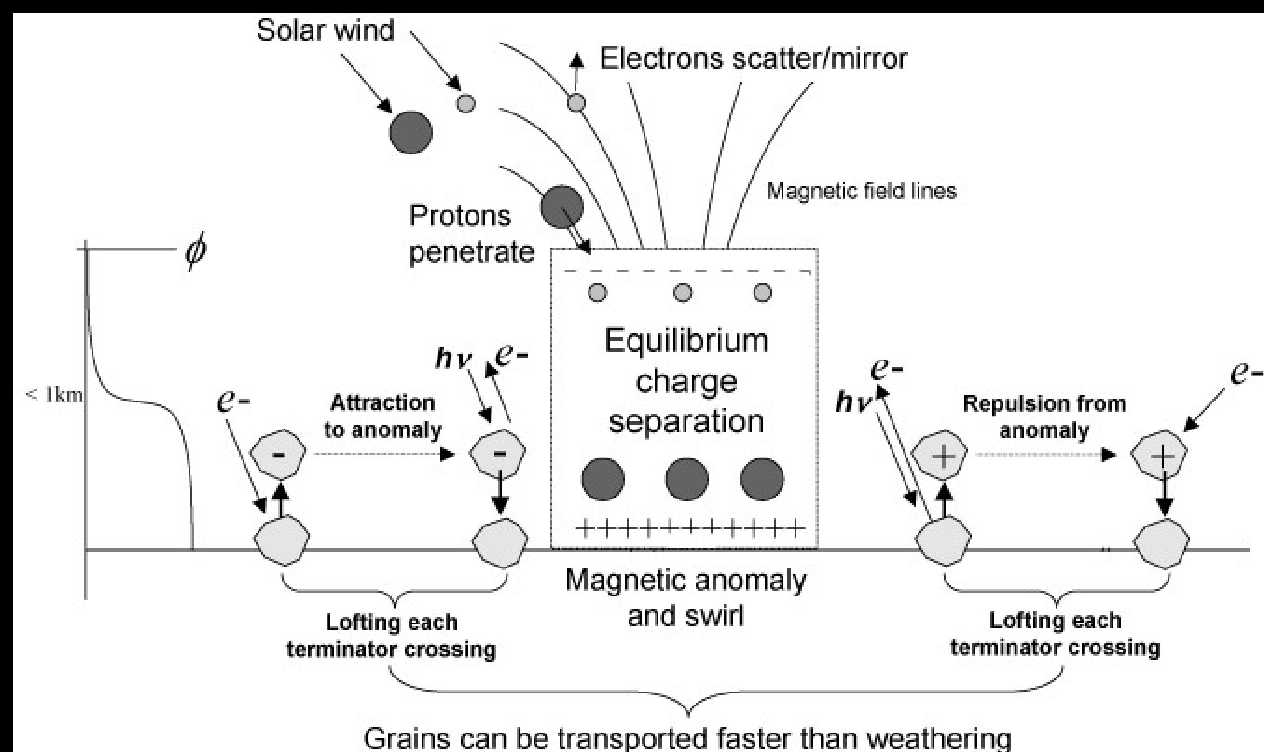


Hypothesis (3): Dust Transport

Garrick-Bethel et al., 2011

Solar wind interacts with crustal magnetic anomalies → Creates weak electric elds → Dust lofted above surface during terminator crossings → Electric f elds attract/repel electrically-charged ne dust

- Finest fraction of the lunar soil enriched in feldspathic (bright) material
- Lofted dust preferentially accumulates in swirl regions thereby increasing the swirls’ re ectance



Testing the models

These models were tested by extracting spectral data from pixels that depict the rims and proximal ejecta of small (0.5-5 km in diameter), immature craters on the swirls, off the swirls, and outside the swirl area.

- **If magnetic field is shielding the swirls from solar wind ions**

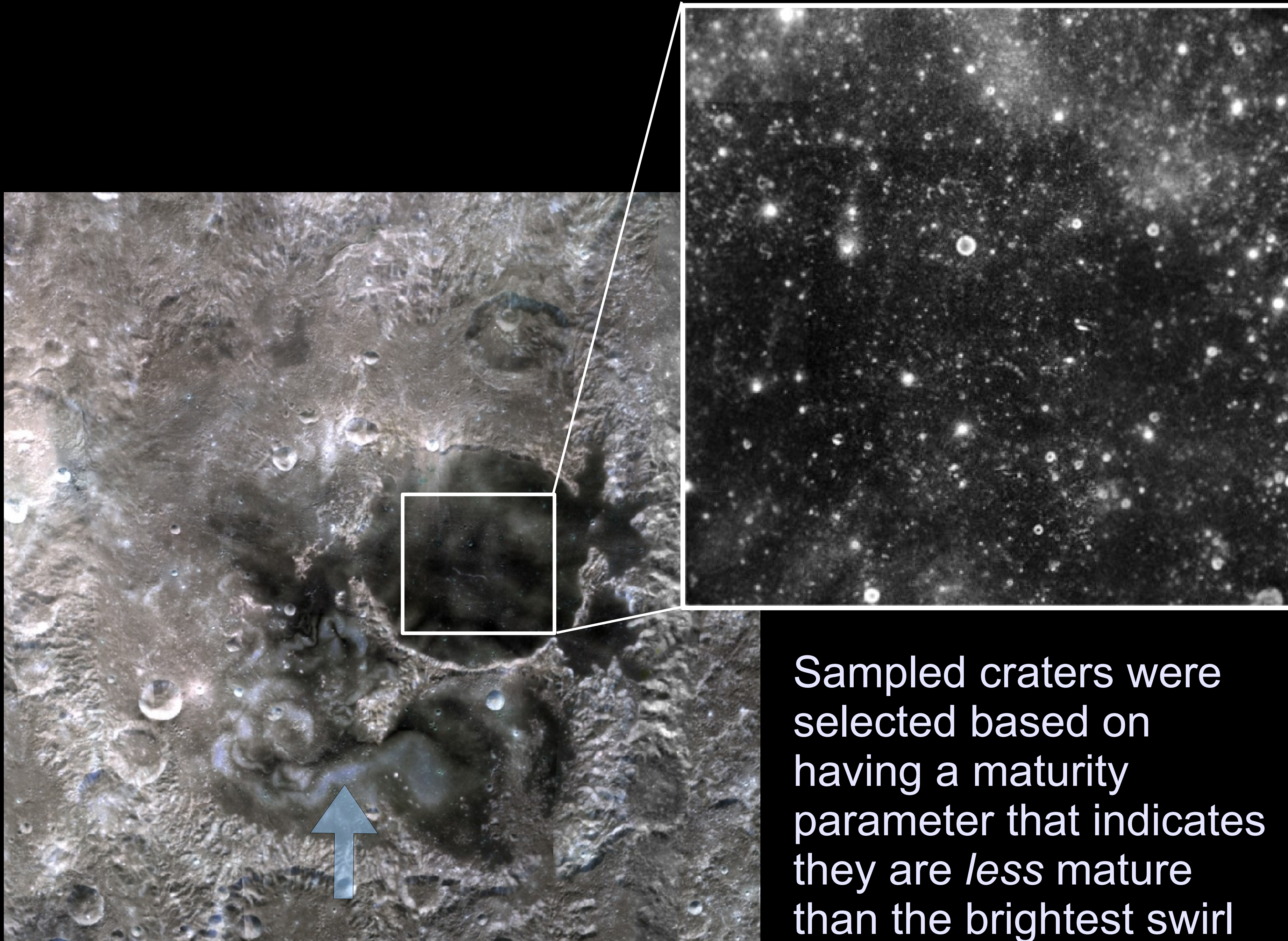
  there should be a greater density of immature craters on swirl surfaces.

  - Recent impacts on-swirl appear to mature slowly due to magnetic shielding from solar wind charged particles
  - Recent impacts off-swirl not shielded, so mature (at least)

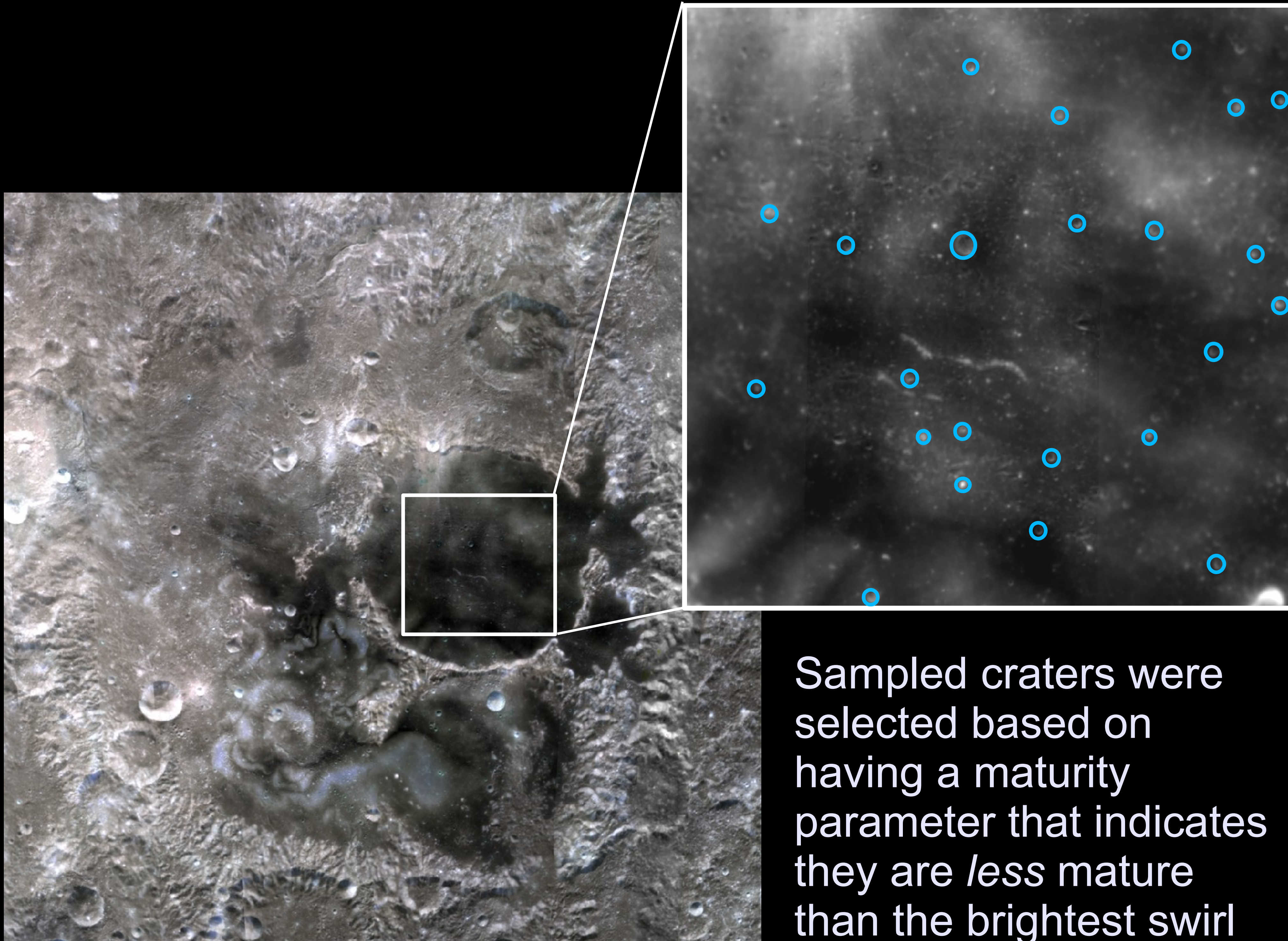
- **If a recent, one-time comet impact exposed fresh material**,

  then small, immature impacts should be randomly and evenly distributed across the mare.

  - The ratio of immature craters to on-swirl area should be ~ equal to immature craters to off-swirl area.

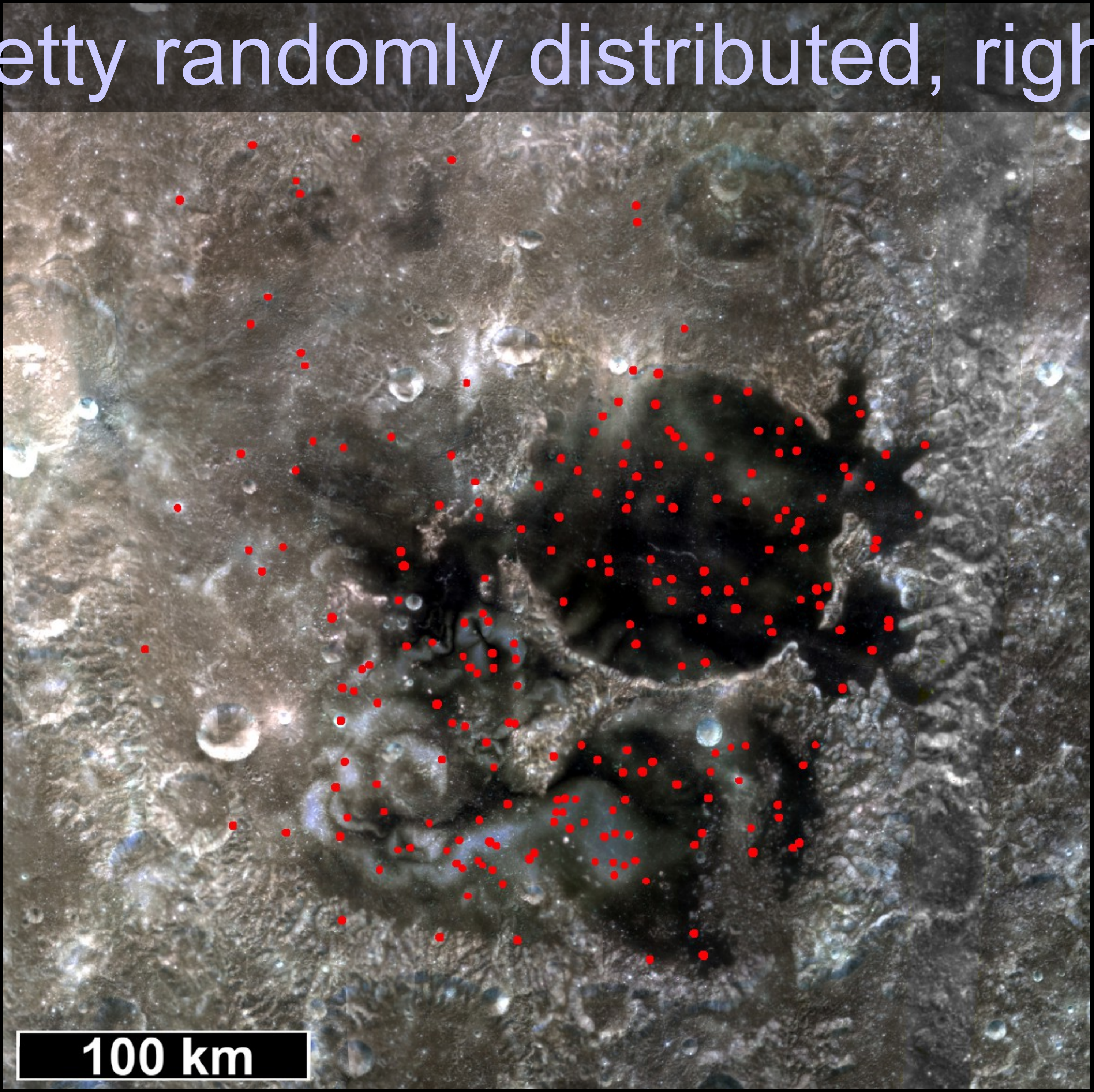


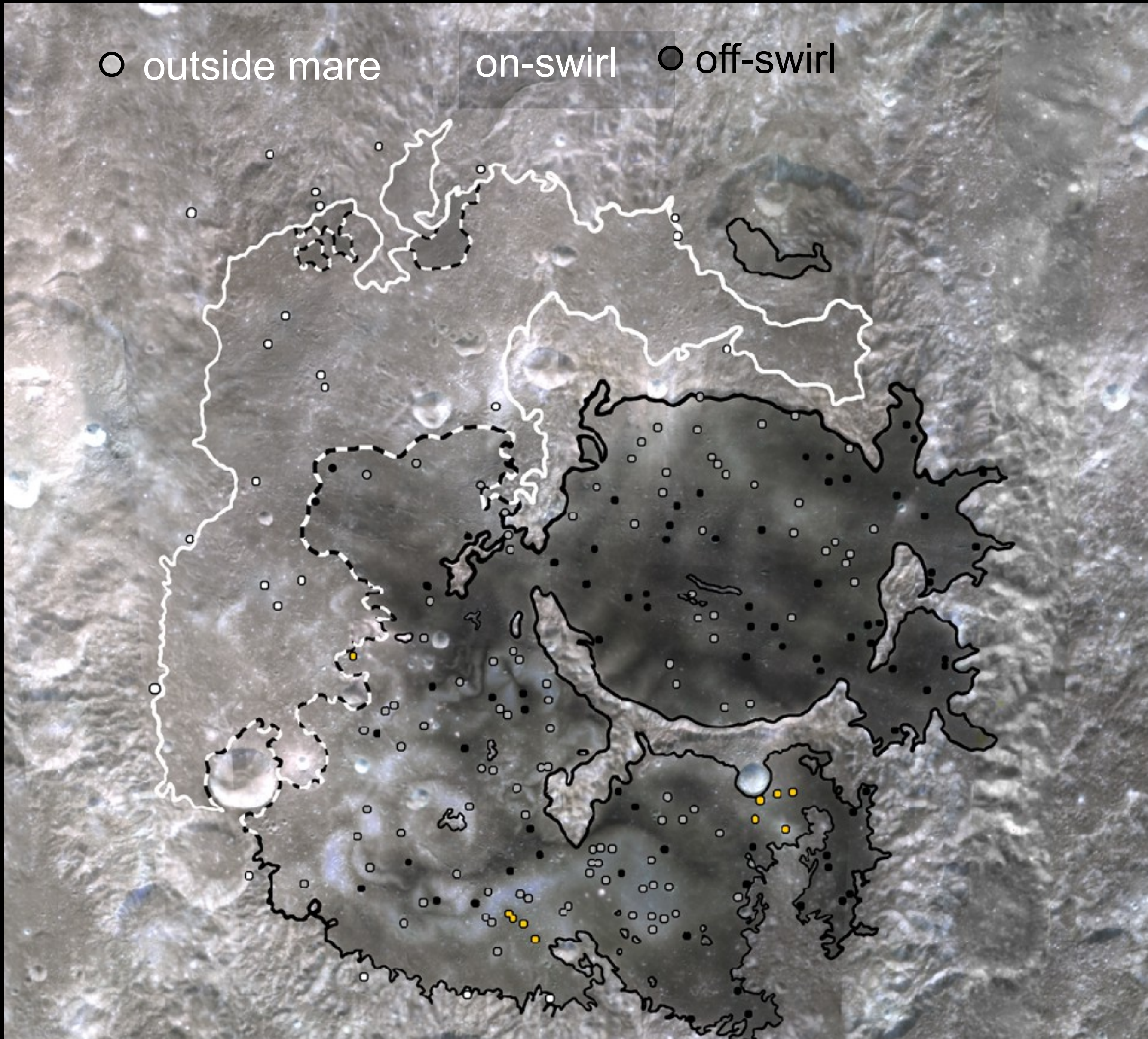
Sampled craters were selected based on having a maturity parameter that indicates they are *less* mature than the brightest swirl surface



Sampled craters were selected based on having a maturity parameter that indicates they are *less* mature than the brightest swirl surface

Pretty randomly distributed, right?

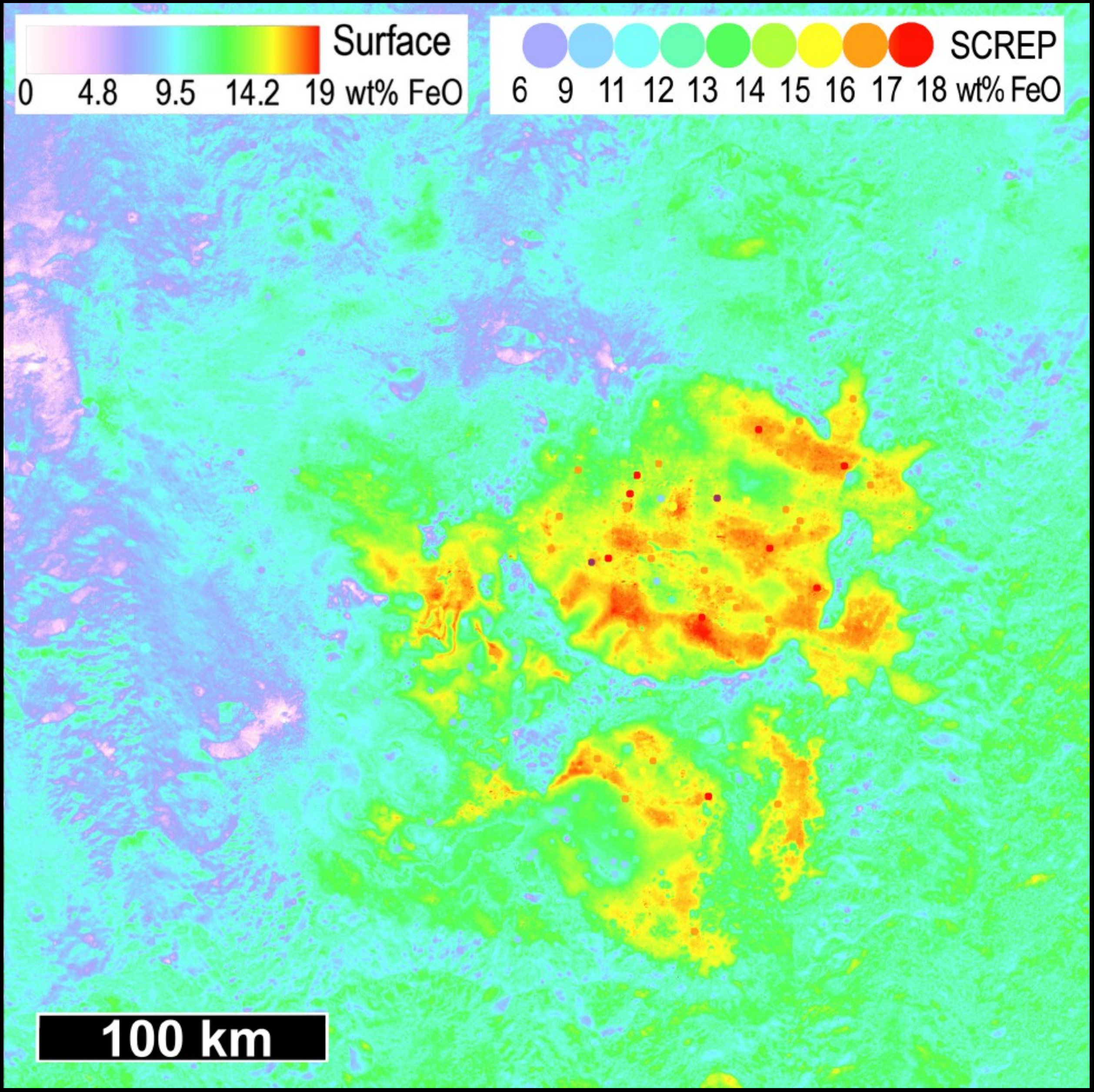




- Density of immature craters on-swirl is 4 times the number of immature craters off-swirl.
- This is not because there is a higher cratering rate on-swirl, but rather the craters on the swirls are maturing at a slower rate compared to the surrounding region.

Area (km^2)		Count of sampled craters					Crater density (craters/1000	
swirls	total	on-swirl	off-swirl	ambig.	outside	total	on-swirl	off-swirl
8420	33,400	107	83	10	30	220	12.4	3.7

If the swirls are fresh, do swirl surfaces have the same composition as fresh craters?



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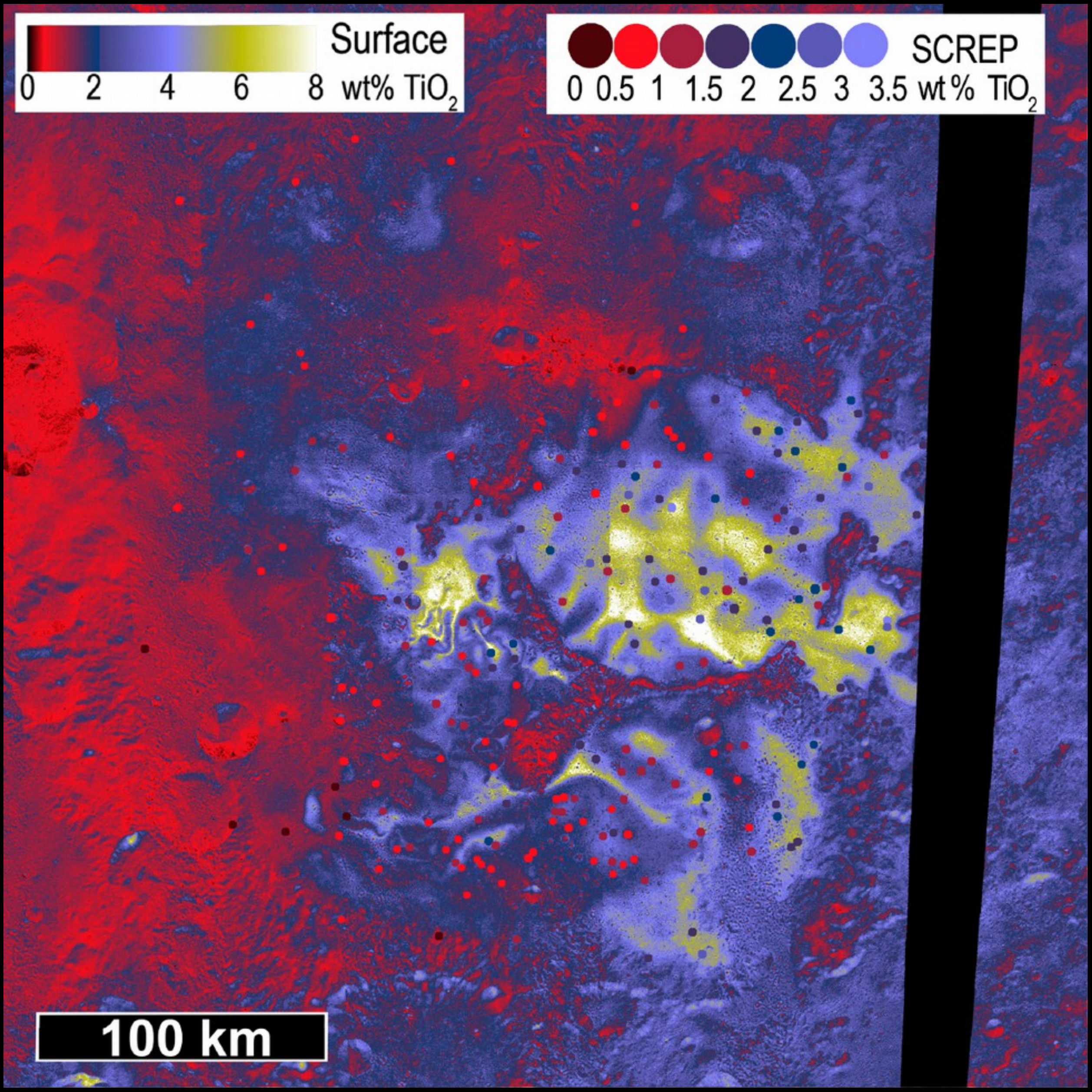
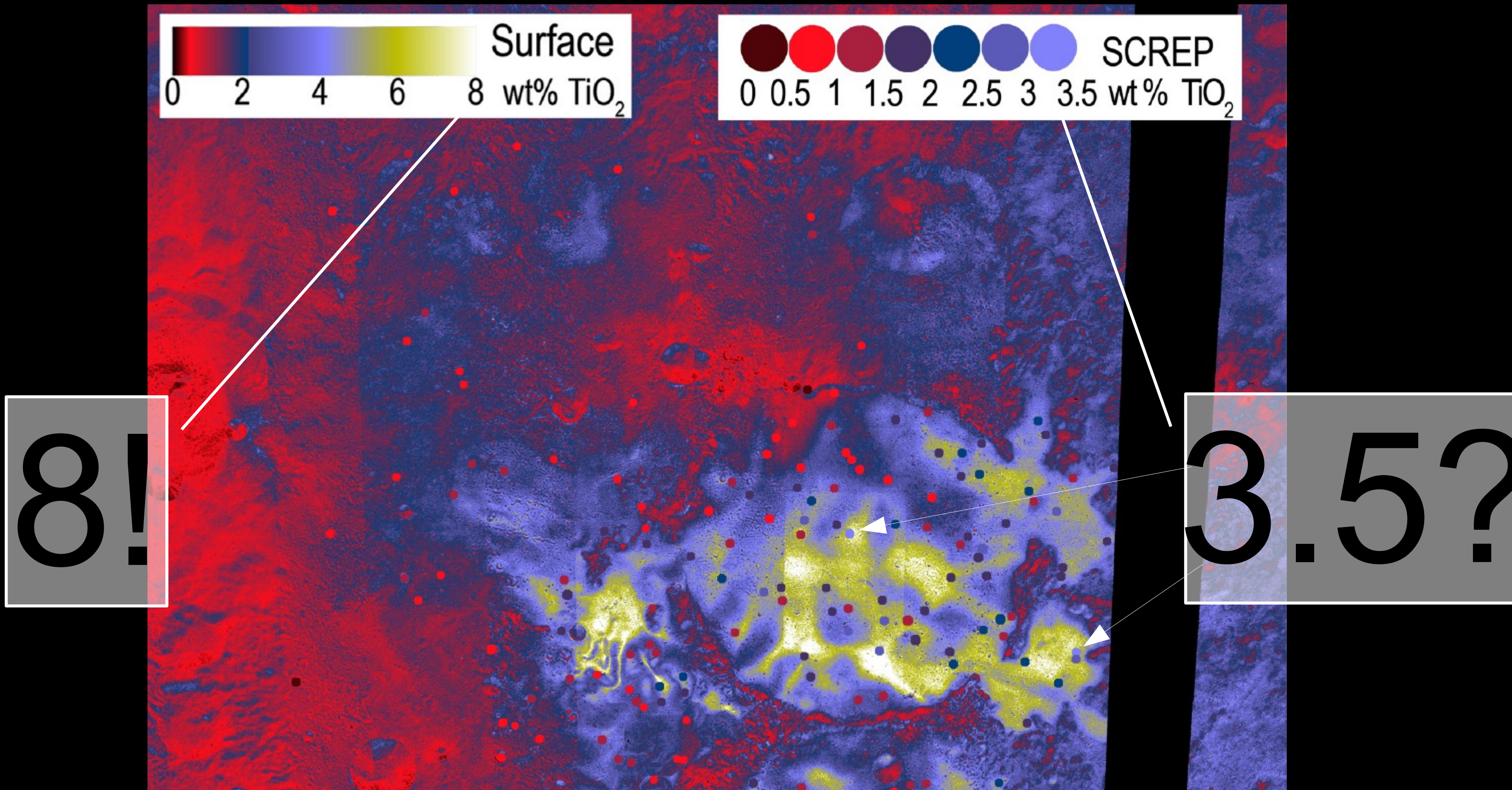
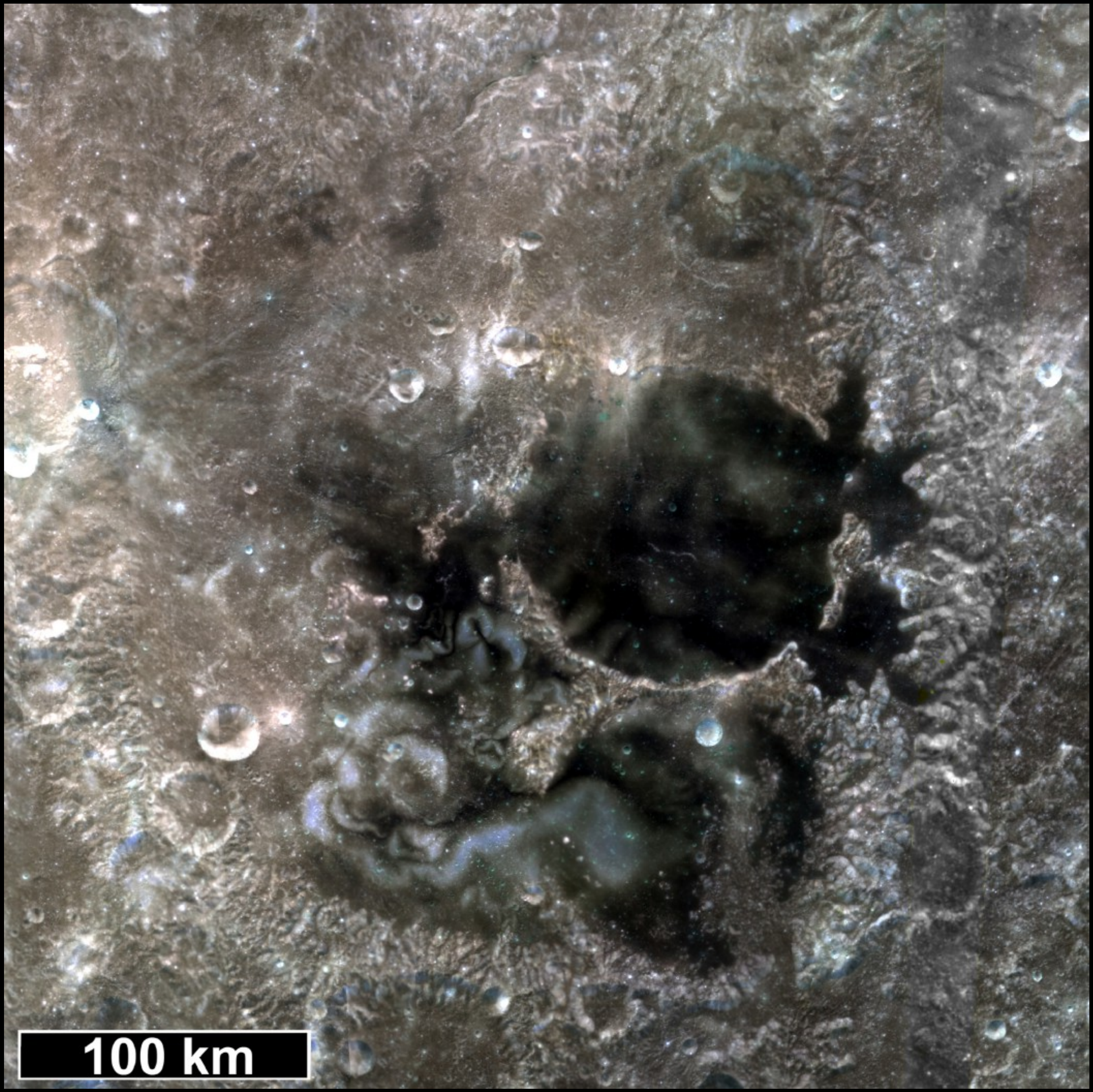


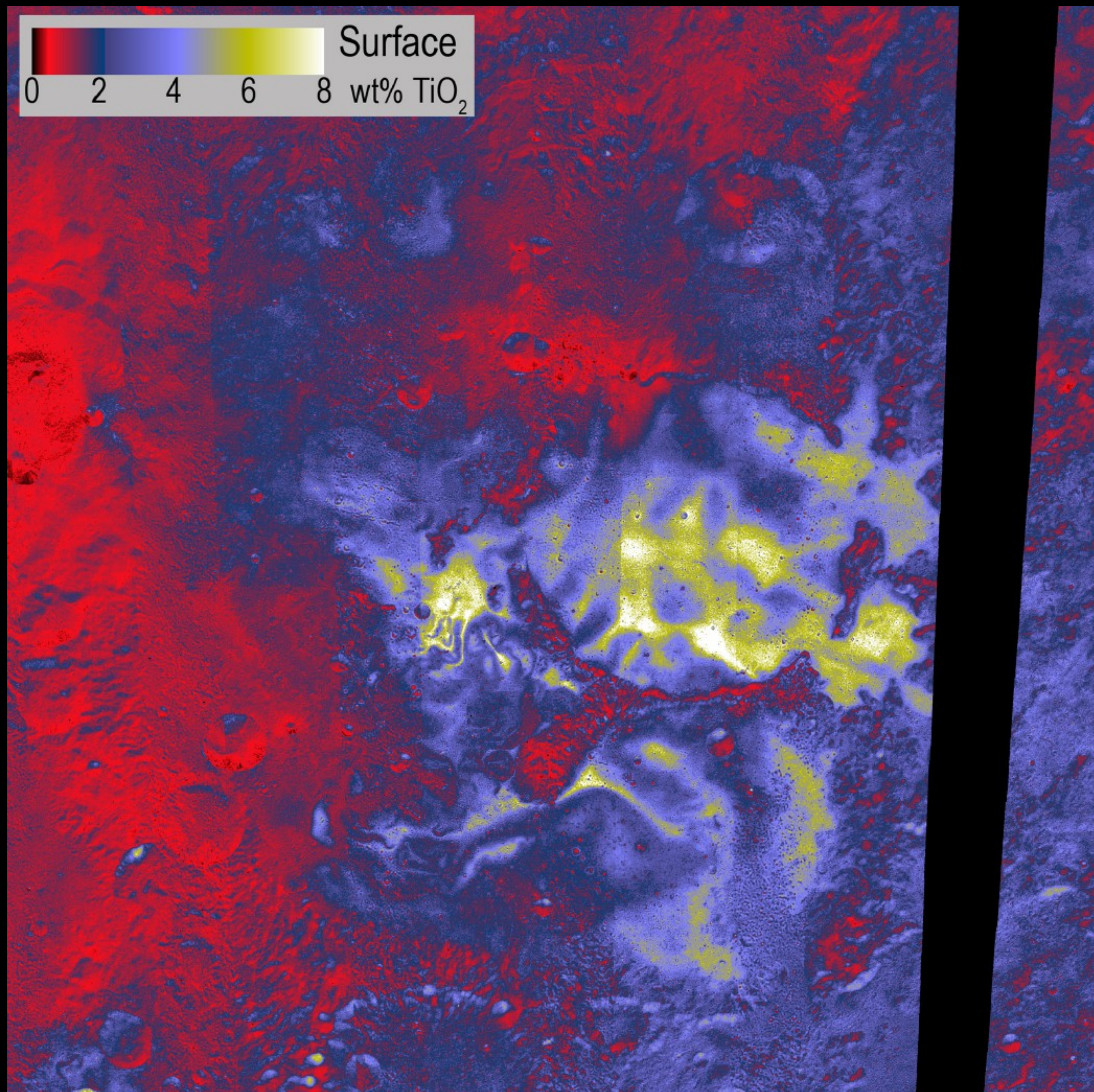


- Immature impacts into high-Ti regolith should reveal Ti abundance ≥ Ti abundance of regolith.
- No nearby high-Ti units from which high-Ti ejecta deposits could derive.
- TiO_2 algorithm is inaccurately calculating Ti abundance in this location.
- Must be detecting a surface phenomenon that *mimics* what the algorithm calculates as high-Ti.

“High-Ti” surfaces correlate with dark lanes

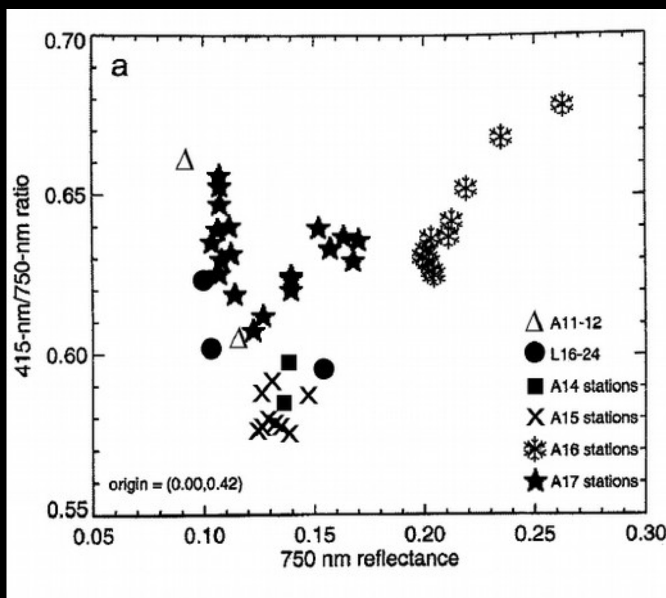


“High-Ti” surfaces correlate with dark lanes

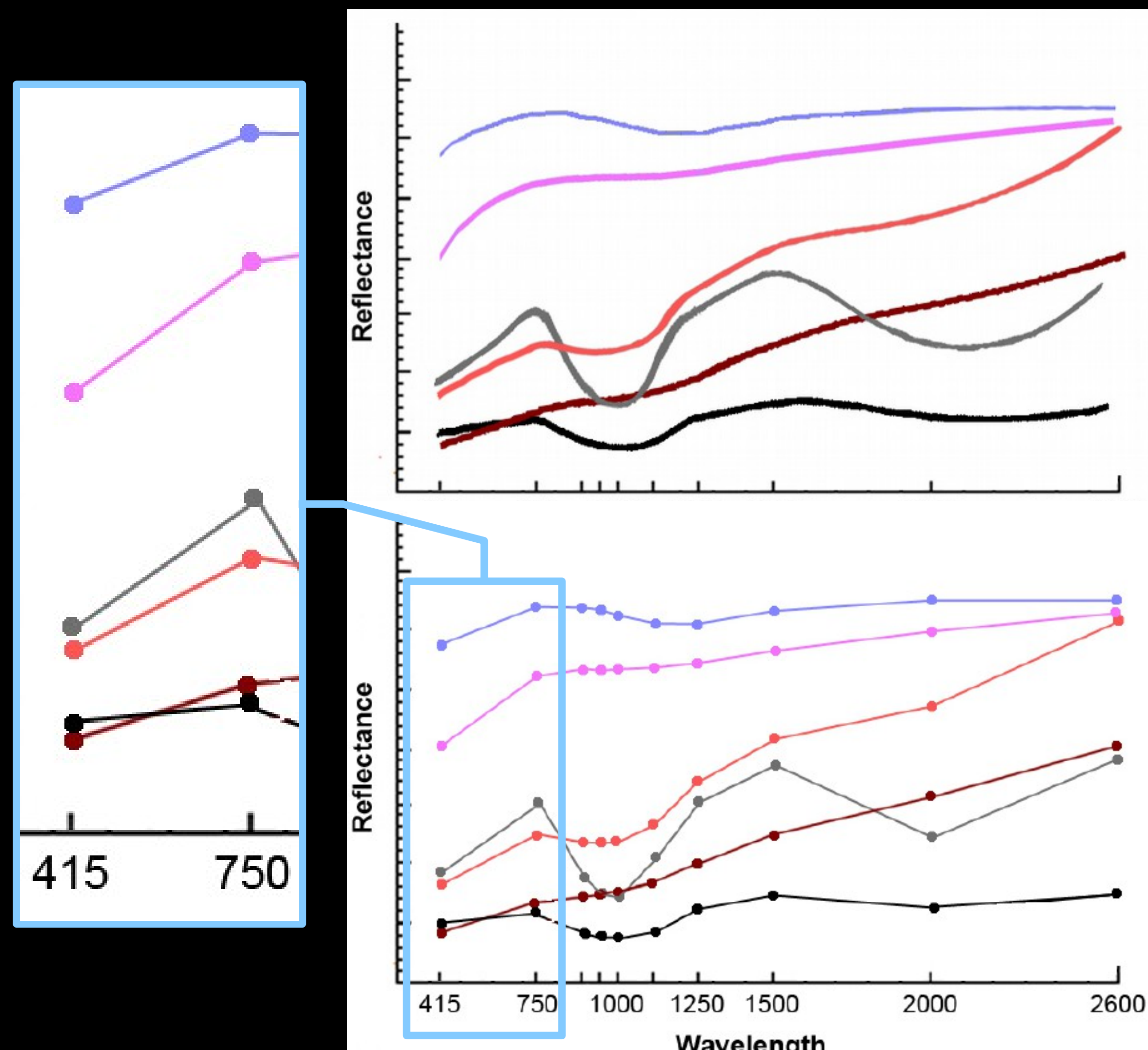


What *is* Clementine actually measuring?

The measure of TiO_2 from Clementine data is actually limited to 2 bands: 415 and 750 nm.

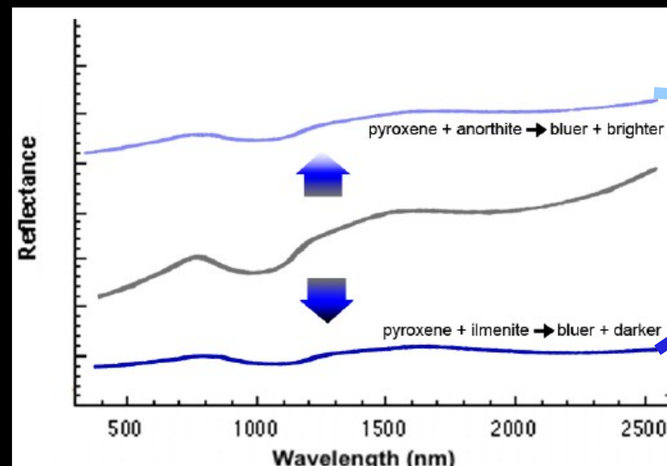


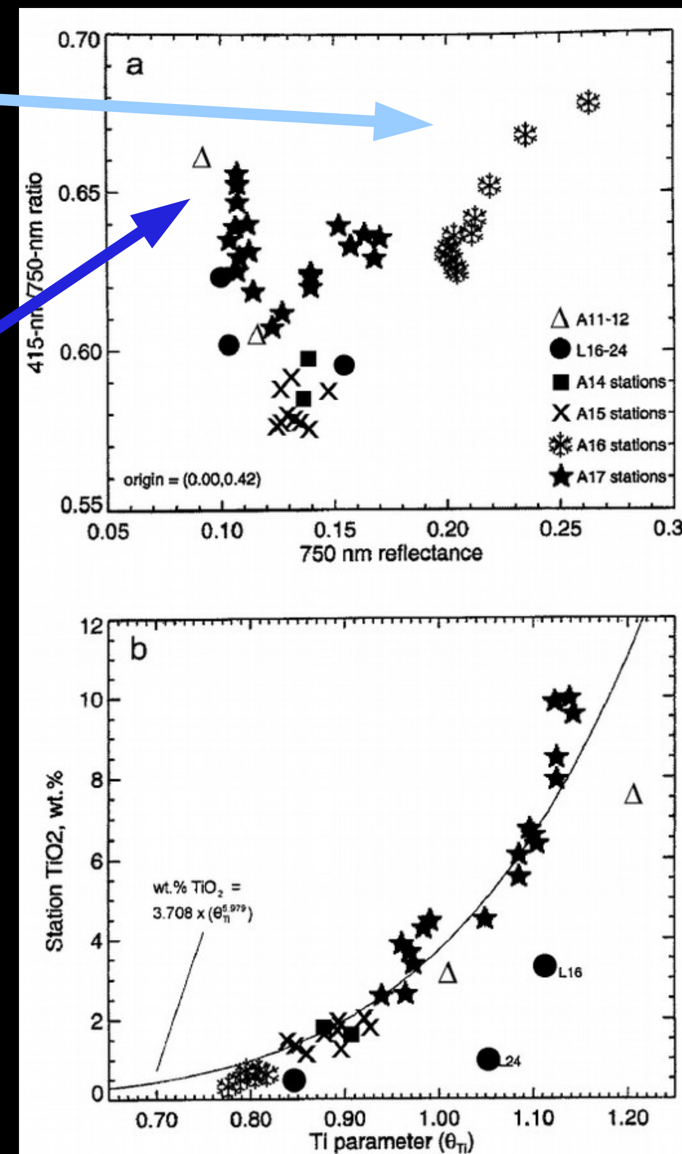
- The algorithm *assumes* “normal” space weathering is affecting the pristine spectrum
- Accuracy depends on a measure of reddening to accompany a darkening



What does the Clementine Ti algorithm assume to measure?

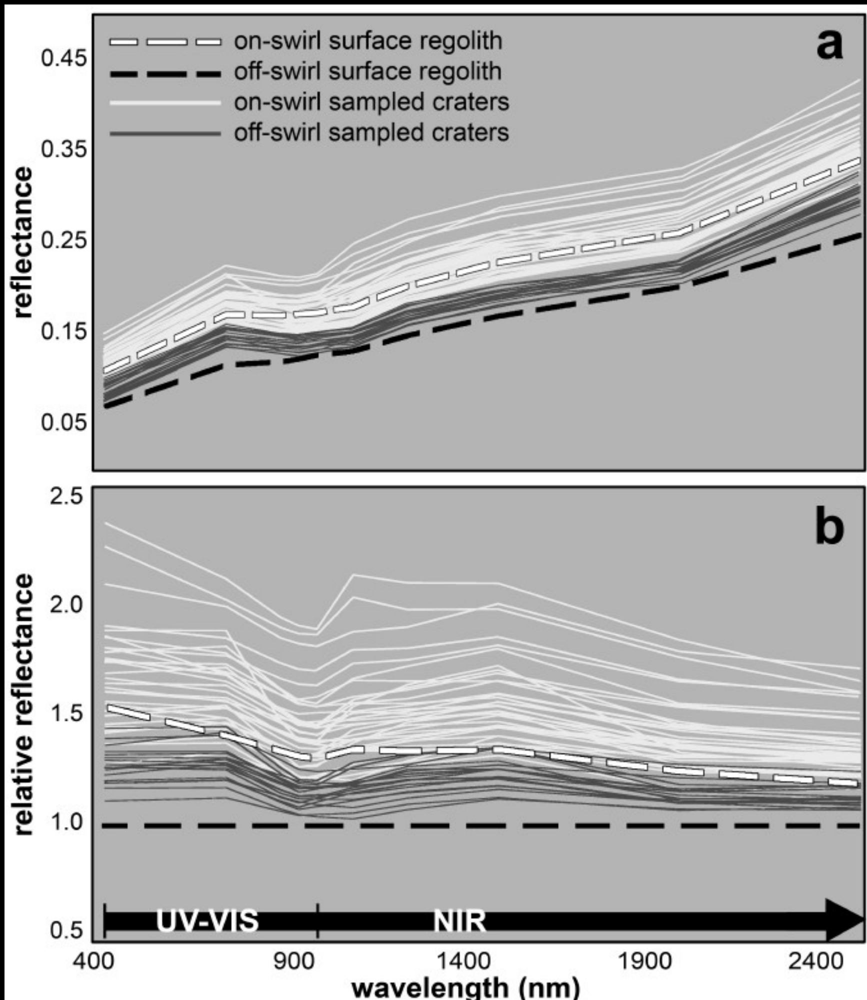
- Effectively measuring the degree of slope in the UV/VIS (before mafic absorption influence) compared with overall albedo.
- Measuring the "darkness" associated with the "flatness" in a spectrum.

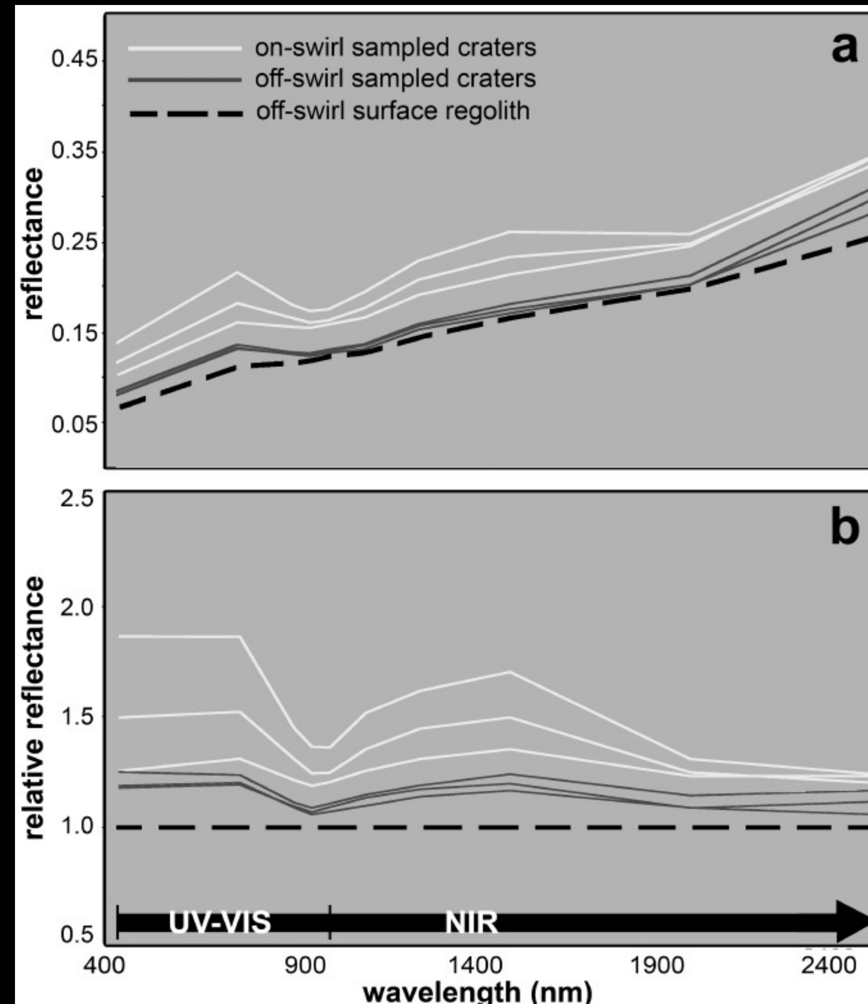




- What is it based on?
  - Spectrum of ilmenite in basalts (the primary Ti-bearing phase).
  - As UV/VIS ⇑ & albedo ⇓: ilmenite ⇑, so TiO_2 ⇑
  - Data from the near side, in magnetically neutral regions
    - **i.e., from "normal" space weathering places.**

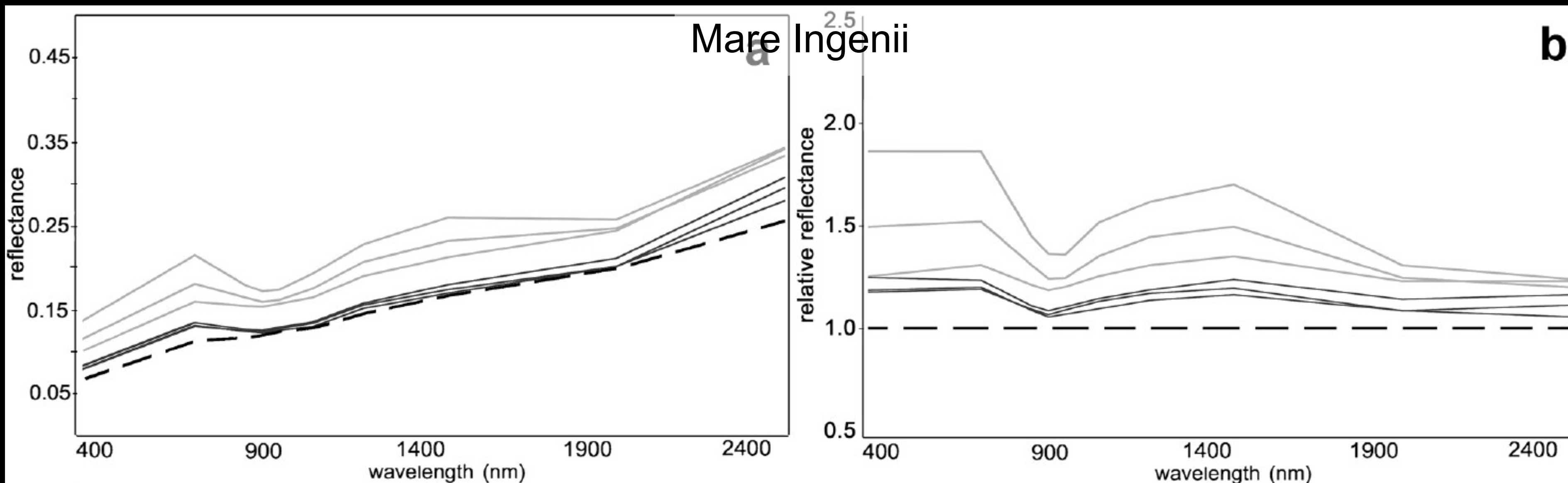
Why the dark lanes look like high TiO_2

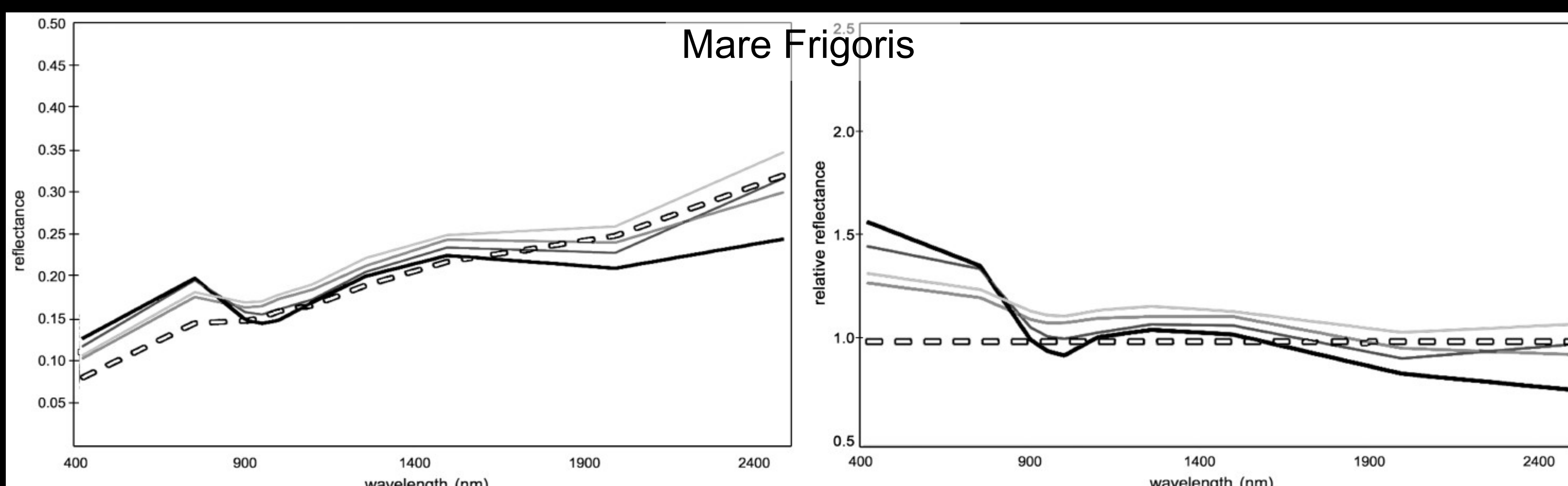




- Spectra from maturing surfaces in the dark lanes exhibit only darkening (no reddening)
  - Also maturation appear to happen very quickly

Spectral maturation at lunar swirl vs. not lunar swirls





Explanation for TiO_2 anomaly

"Normal" darkening & reddening of maturing spectra result from mixed $npFe^0$ particle sizes (& mixed lithologies).

- $npFe^0$ < 10 nm diam: spectral reddening in VIS with little effect in IR
  - Smaller $npFe^0$ attributed to proton implantation and vapor deposition, and sputtering
- $npFe^0$ > 40 nm diam: lowers albedo across VIS-NIR with little change in continuum shape (little reddening)
  - Larger $npFe^0$ particles made by merging smaller grains in micro-impact melts with agglutinate formation
- ***Larger $npFe^0$ (>40 nm) will mimic spectral effect of increased ilmenite abundance.***
- ***Apparent*** **high Ti surface abundance at dark lanes**

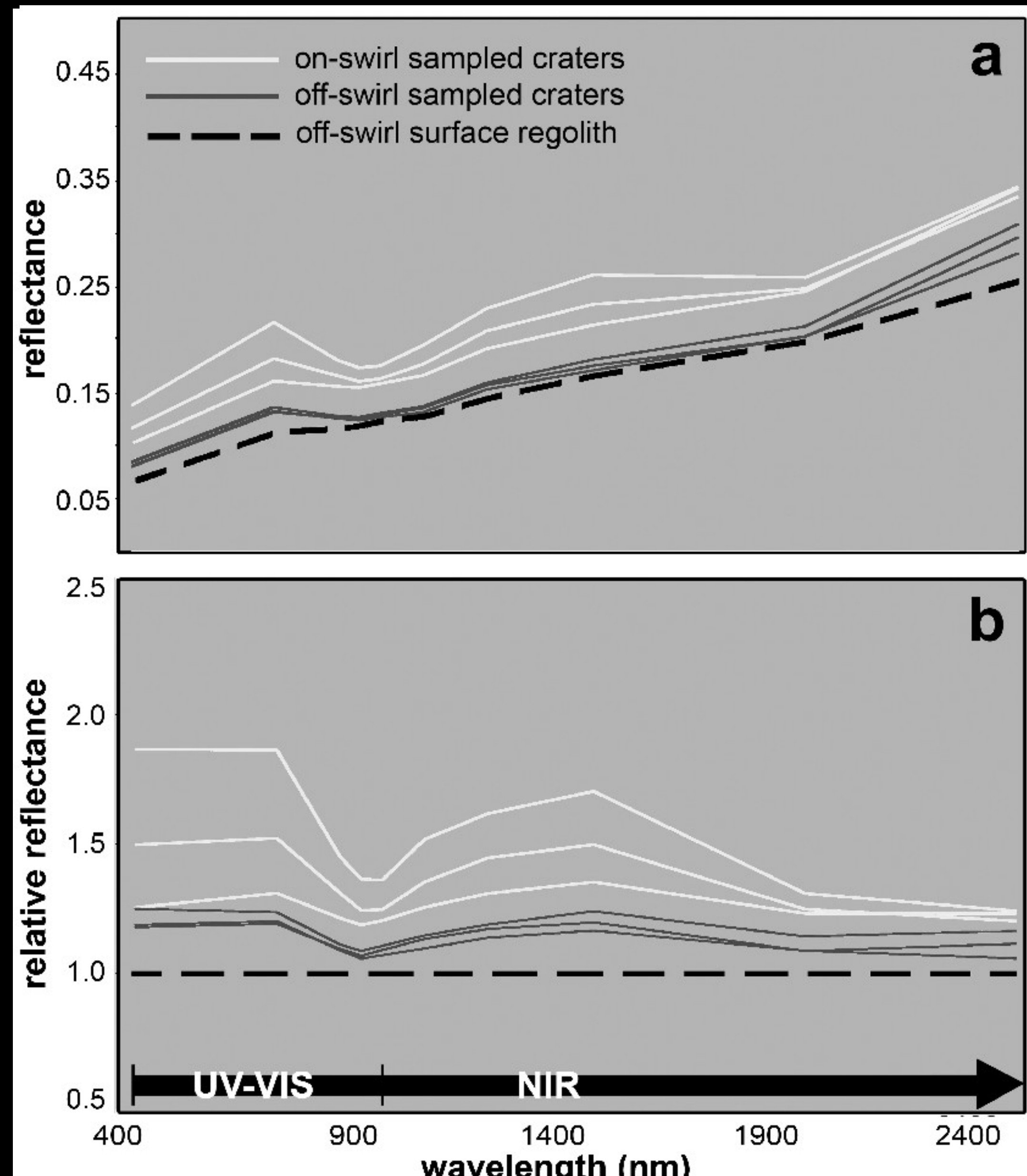
  suggests that proportion of larger $npFe^0$ sizes greater than at normal (not magnetically influenced) weathered surfaces

Spectra from fresh craters on- and off-swirl

Spectra of immature craters and surface regolith for on-swirl and off-swirl regions in Mare Ingenii.

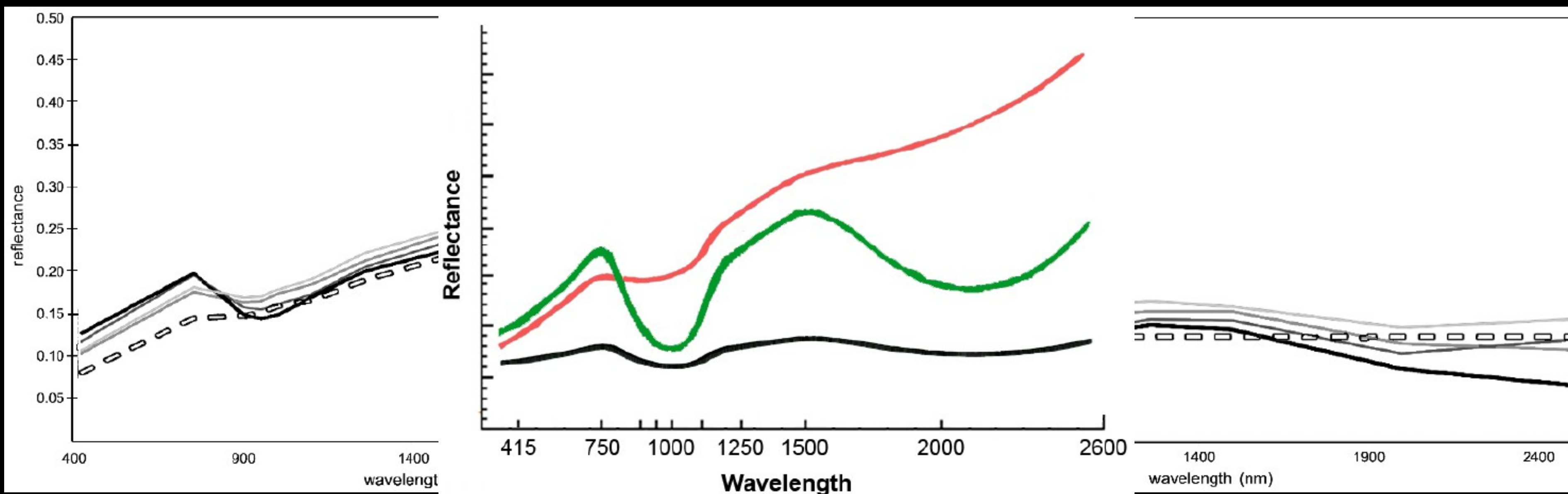
- On-swirl spectra look like truly fresh material
- Off-swirl spectra look old

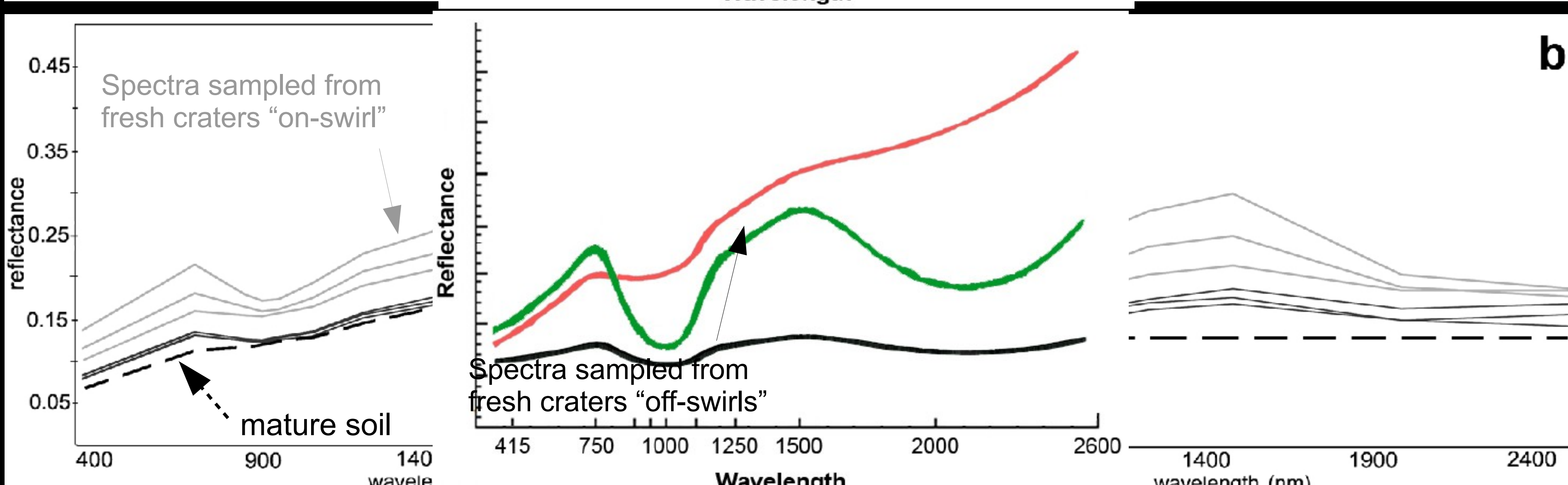
Spectra of immature craters and on-swirl surface regolith normalized to off-swirl mature surface soil.



Although both on- and off-swirls span the range of sampled OMAT values, spectral albedos and characteristics clearly split based on the sampled crater's occurrence on- (or off-) swirl.

Maturation on-swirl and off-swirl vs. typical maturation trends

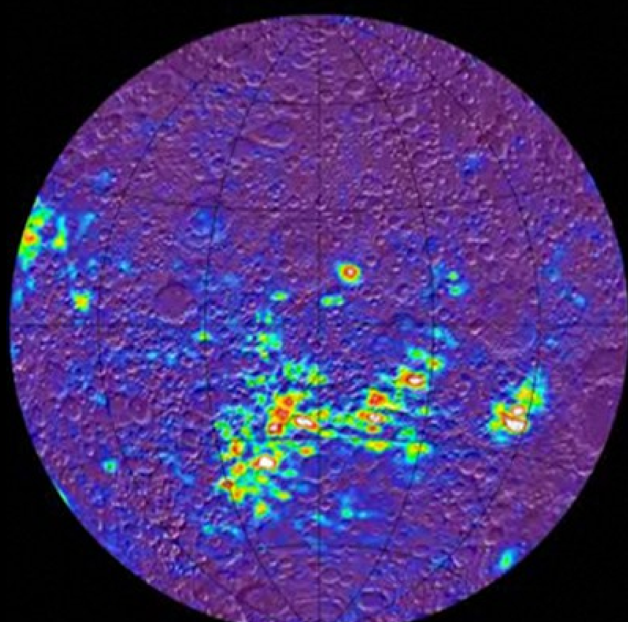


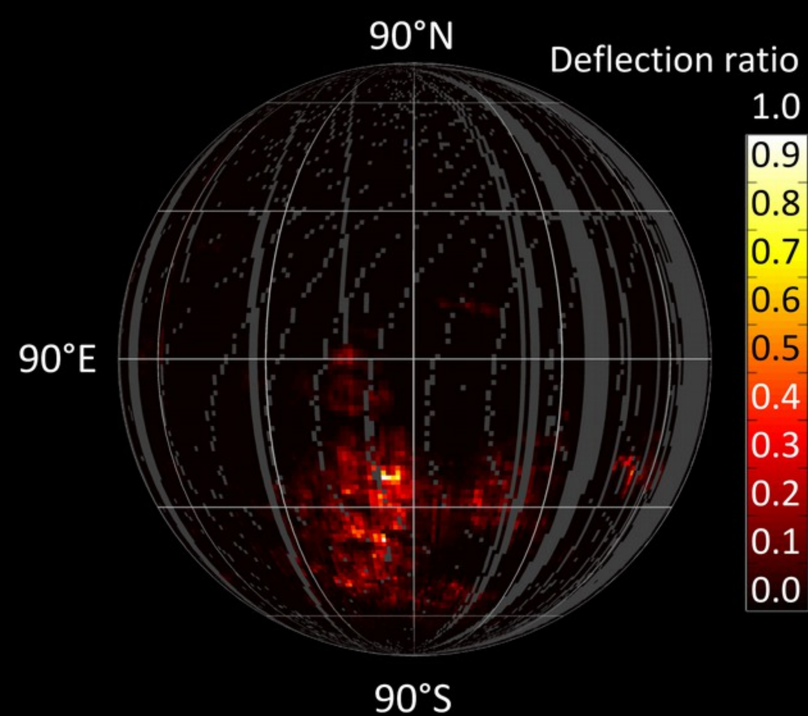


Recent measurements & research results all point to solar wind deflection model

Sub-keV Atom Reflecting Analyzer (SARA)

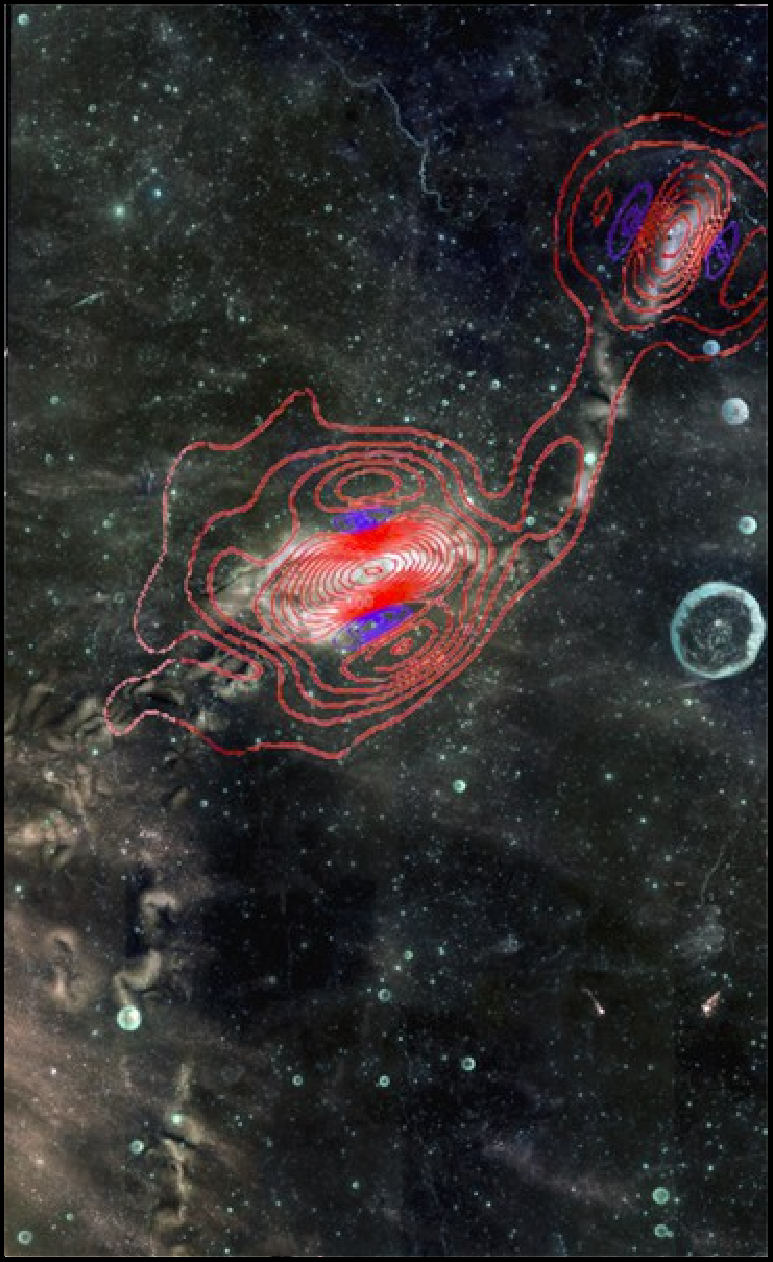
- SARA measures the solar wind flux at the lunar surface.
- SARA showed that a strong magnetic anomaly reflects solar wind protons, and that below the magnetic anomaly the solar wind flux is decreased by half.
- (right) Map of the ratio between outflowing proton flux and inflowing proton flux for the lunar farside.
  - Note similarity to magnetic field map (left)





Improved magnetic field maps

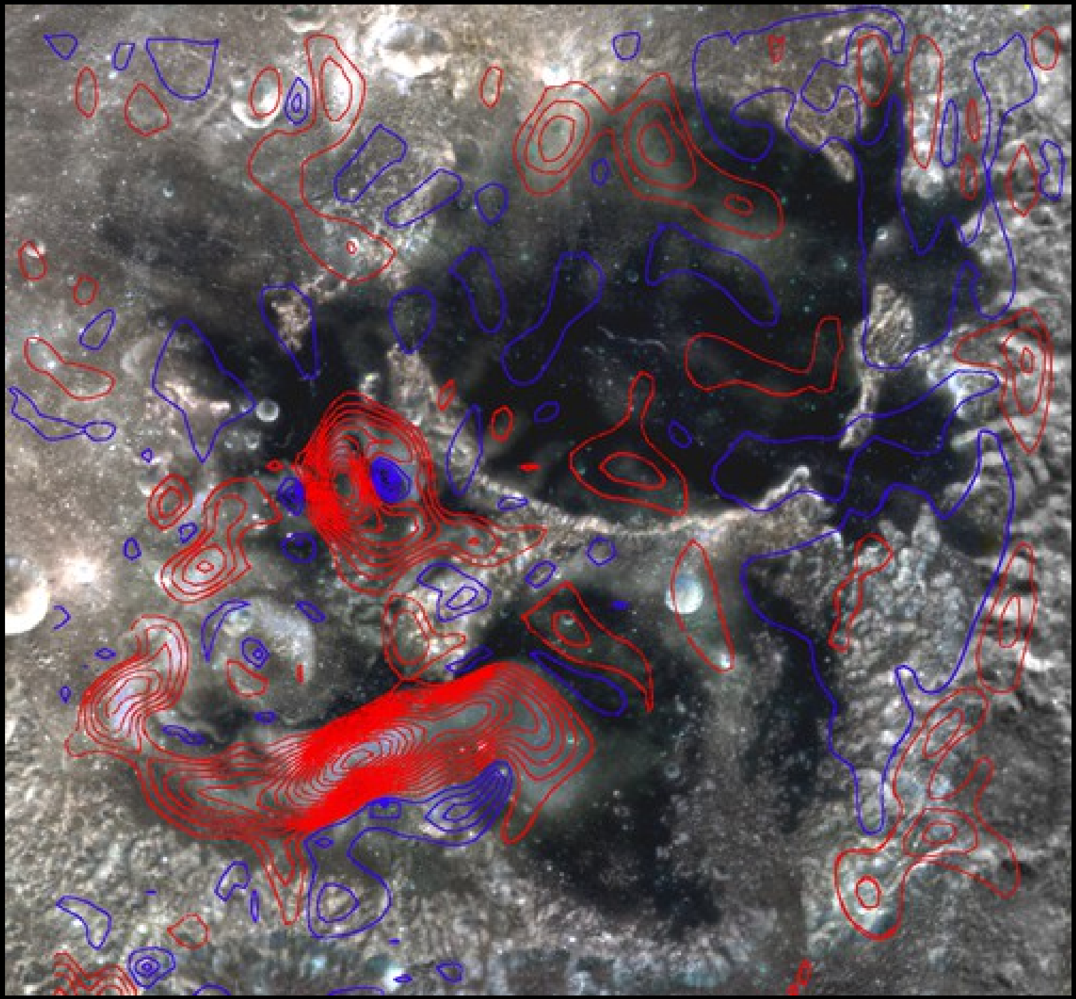
- New and improved magnetic field maps at lunar swirls show that the horizontal component of magnetic field (Bh) follows the sinuous shape of the swirls.



Very new results using new technique and combining Lunar Prospector and Kaguya magnetometer data (Shibuya, Lunar Swirls Workshop, 2011)

Improved magnetic field maps

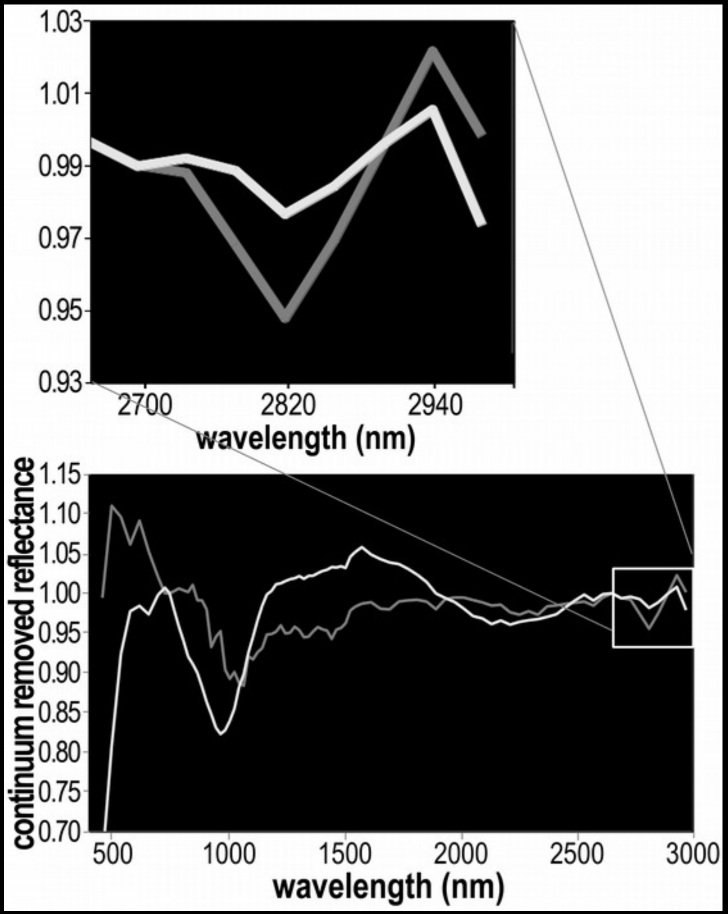
- New and improved magnetic field maps at lunar swirls show that the horizontal component of magnetic field (Bh) follows the sinuous shape of the swirls.
- Dark lanes between swirls may indicate where magnetic poles appear on the surface.
- This also supports the hypothesis that the swirls formed by magnetic shielding of solar wind particles.



Very new results using new technique and combining Lunar Prospector and Kaguya magnetometer data (Shibuya, Lunar Swirls Workshop, 2011)

Measuring the OH abundance from new Moon Mineralogy Mapper data

The absorption feature at 2.82 µm is diagnostic of the presence of hydroxyl (OH), and the depth of the band is a function of OH abundance.



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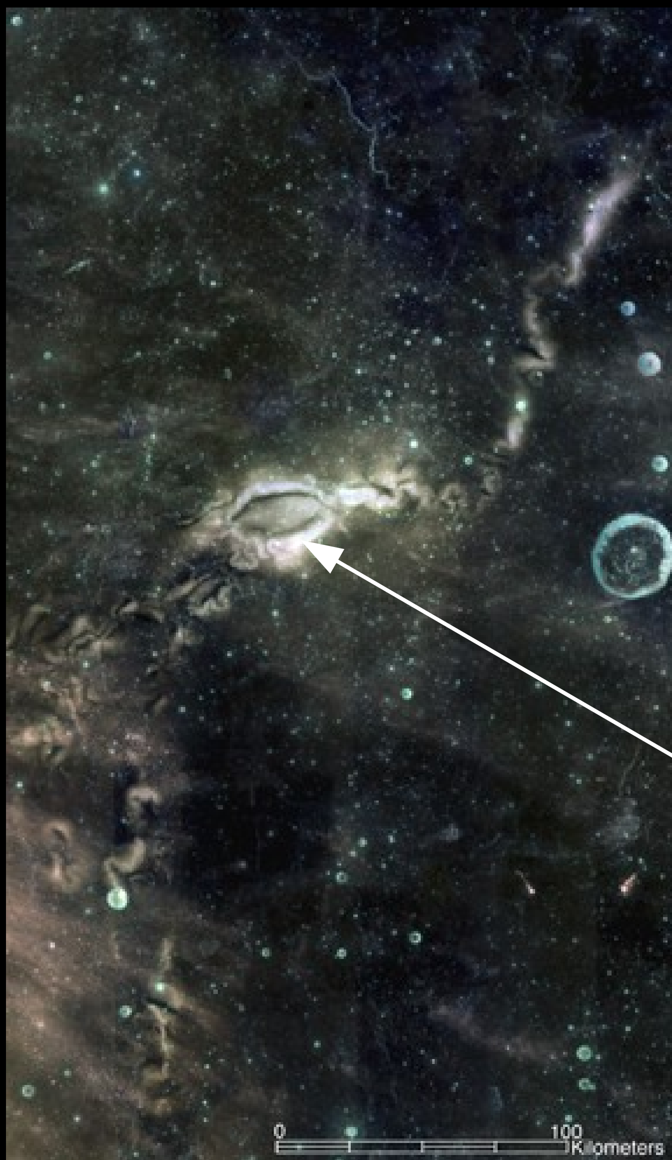

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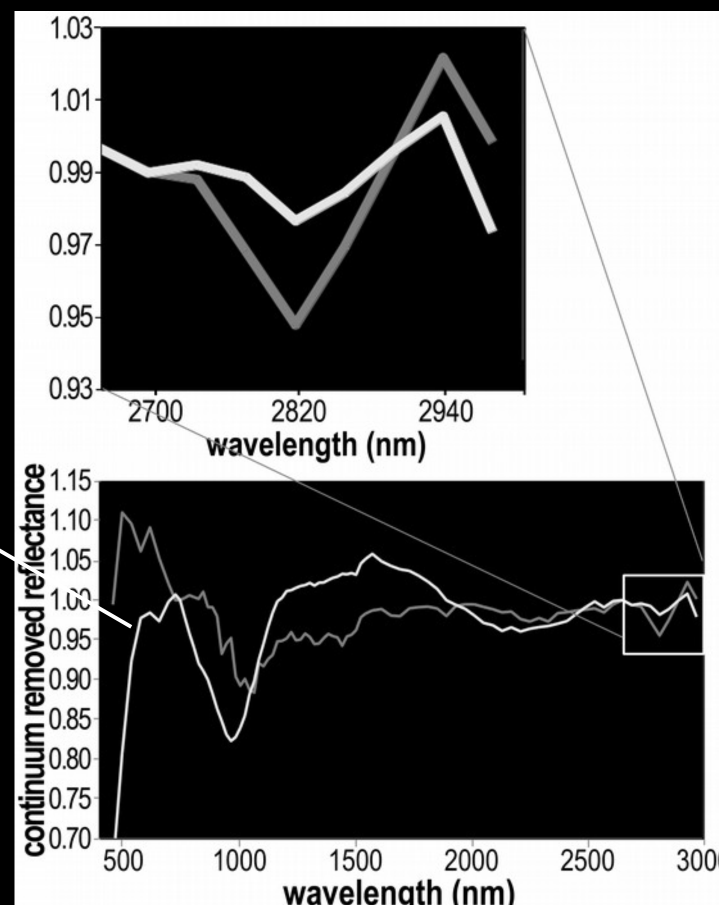

- The white spectrum is taken from a swirl

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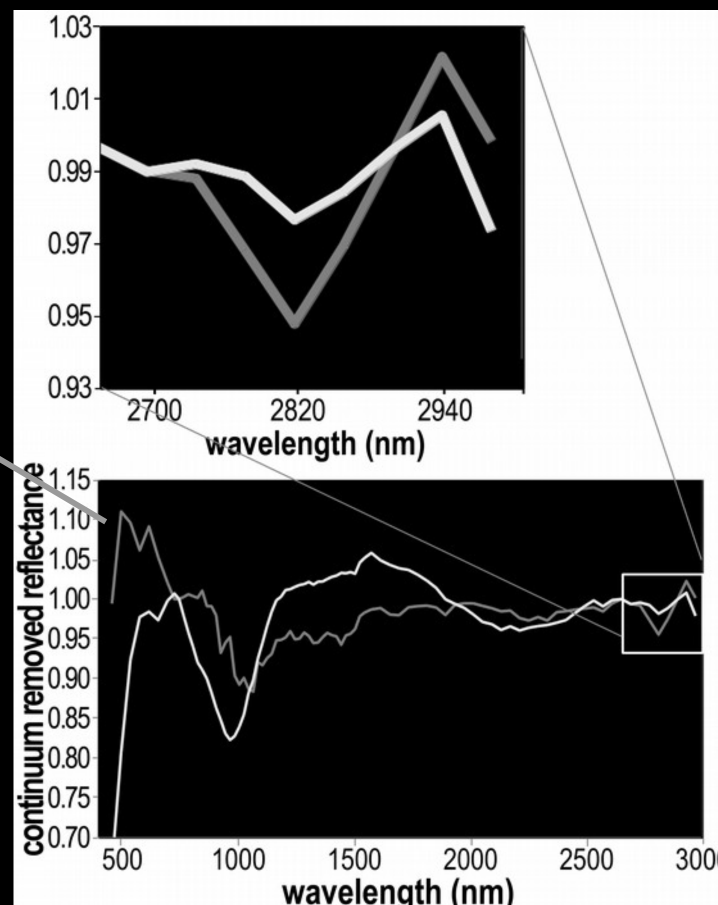
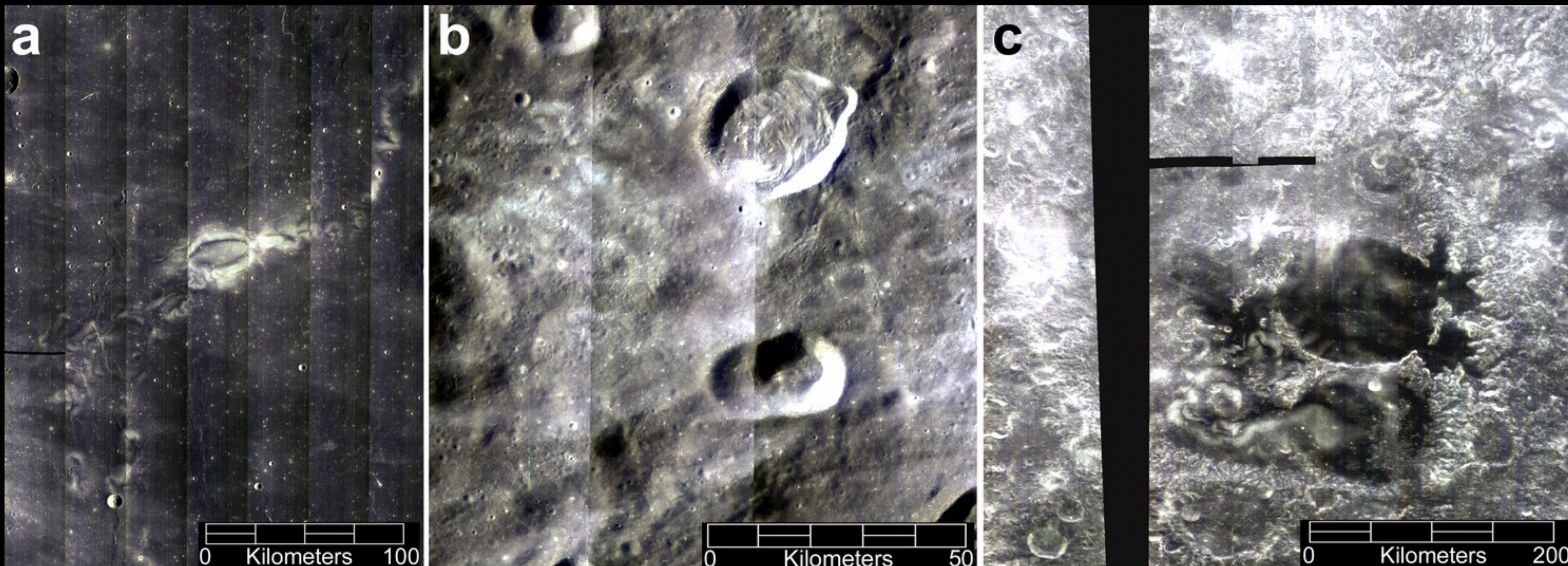


- The white spectrum is taken from a swirl
- The gray spectrum is taken from a dark lane

Further evidence for deflection of solar wind ions by magnetic anomaly



Reiner Gamma Gerasimovich Mare Ingenii

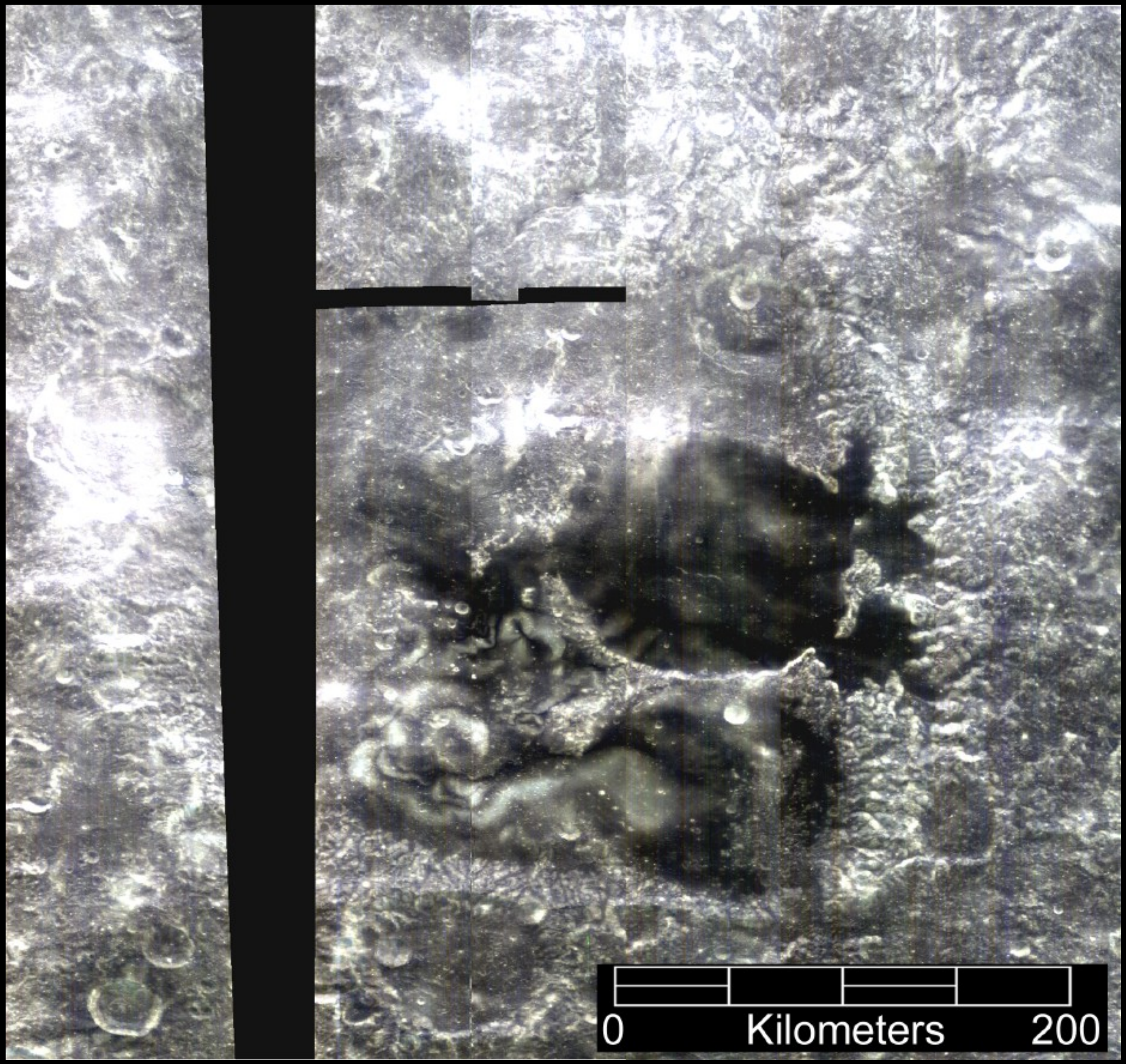
- True color mosaics of 3 swirl regions on different terrain types:
  - Reiner Gamma – on the mare
  - Gerasimovich – on the highlands]
  - Ingenii – crossing both mare and highlands

Further evidence for deflection of solar wind ions by magnetic anomaly

Reiner Gamma Gerasimovich Mare Ingenii

- These are OH parameter maps, which depict the variations in depth of the 2.82 µm band between on- and off-swirl locations for 3 swirl regions
- This suggests the swirls are depleted in OH relative to their surroundings.

It can be diff cult to distinguish swirls from strong ref ections off sun-facing slopes



But the method used to generate the OH parameter map corrects for such high angle reflections.

- The plethora of dark, swirly streaks in this OH parameter map are swirls that are otherwise difficult to distinguish from the high-albedo highlands

Summary of Observations

- Density of immature craters on-swirl is 4 times the number of immature craters off-swirl.
  - Despite having the spectral characteristics of immaturity, the lunar swirls do not reflect a recent event – they only *appear* to be recently created.
- Swirl surface spectra resemble fresh material in fresh impact craters with high albedos and strong absorption bands.
  - Something is keeping the swirls from maturing at a normal rate.
- Maturation in the dark lanes manifests only as spectral darkening (skips reddening) and occurs quickly.
  - Something is accelerating weathering in the dark lanes.
- OH is prevented from forming on the swirl surfaces.

Conclusions

- Density of immature craters on-swirl is 4 times the number of immature craters off-swirl.
  - Despite having the spectral characteristics of immaturity, the lunar swirls do not reflect a recent event that exposed or deposited fresh surface material as from a comet impact.
- On-swirl spectra look like fresh material with high albedos and strong absorption bands
  - Cannot be levitated fine-grained dust because fine-grained feldspathic dust would attenuate the absorption bands.
- The magnetic, spectral, topographic, and subatomic particle data support the hypothesis that the magnetic field is protecting the surface from maturation by solar wind ion bombardment.

Hypothesis: Comet Impact

- ✔ Explains why swirl surfaces are same as fresh spectra.
- Explains why dark lanes darken so quickly (why surface appears high-Ti to spectrometer).
- Explains association with magnetic anomaly.
- Explains lack of surface topography
- Explains why there is a higher density of fresh impact craters on swirls.
- Explains why swirls are deficient in OH compared to surroundings)

Hypothesis: Electrostatic Dust Levitation

Explains why swirl surfaces are same as fresh spectra.

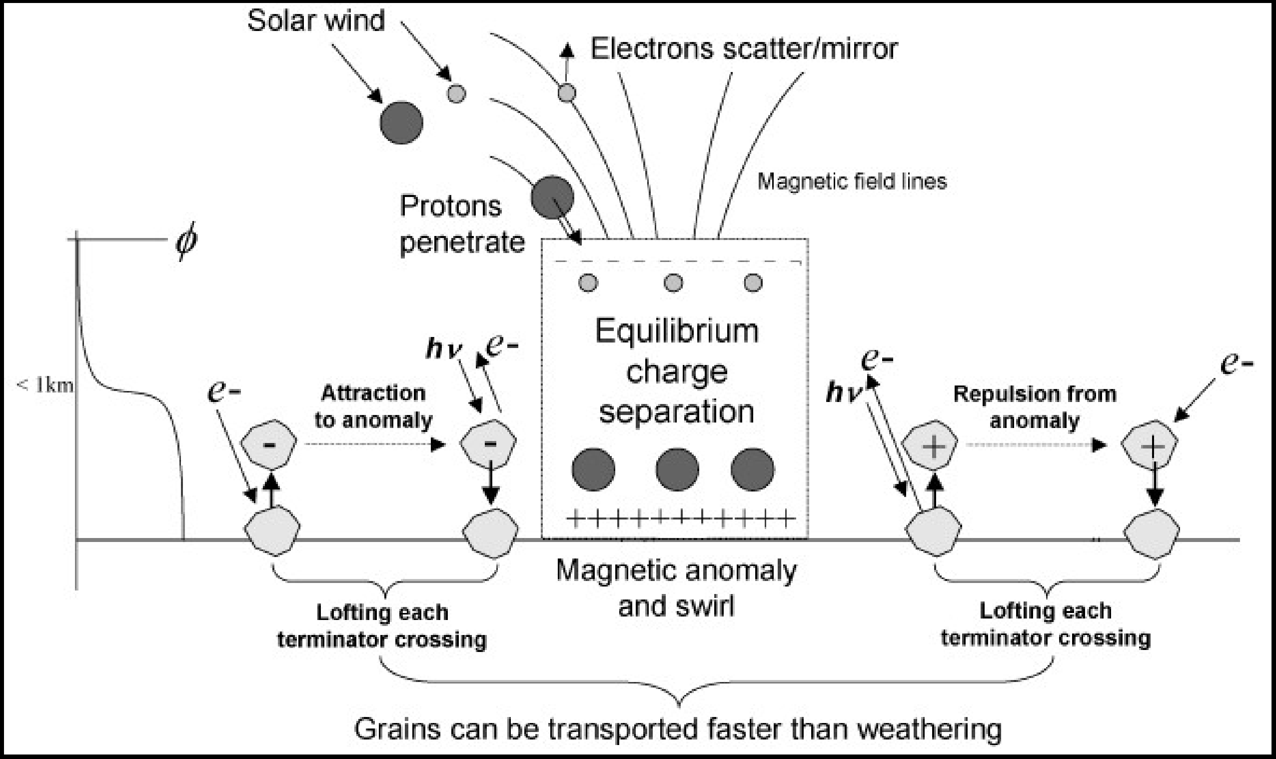
Explains why dark lanes darken so quickly (why surface appears high-Ti to spectrometer).

✔ Explains association with magnetic anomaly.

Explains lack of surface topography

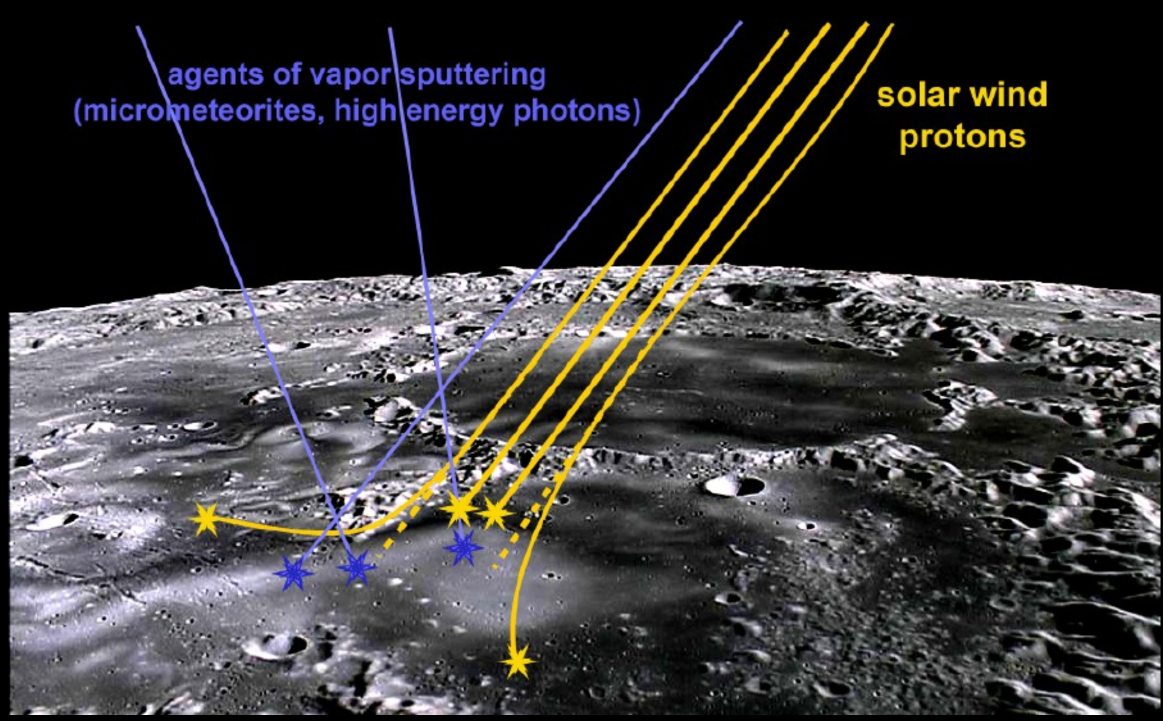
Explains why there is a higher density of fresh impact craters on swirls.

Explains why swirls are deficient in OH compared to surroundings)



Hypothesis: Magnetic Shielding from Solar Wind Ions

- ✔ Explains why swirl surfaces are same as fresh spectra.
- ✔ Explains why dark lanes darken so quickly (why surface appears high-Ti to spectrometer).
- ✔ Explains association with magnetic anomaly.
- ✔ Explains lack of surface topography
- ✔ Explains why there is a higher density of fresh impact craters on swirls.
- ✔ Explains why swirls are deficient in OH compared to surroundings)



On-swirl Space Weathering & Maturation

- On-swirl maturation is retarded because

  a) the flux of space weathering agents that create $npFe^0$ is reduced

  b) the creation of larger $npFe^0$ by agglutination is restricted by the decreased available $npFe^0$

- On-swirl spectral characteristics due to $npFe^0$ particles sizes created by space weathering agents *not* influenced by a magnetic field
  - e.g., heavier ions and impact vaporization by micrometeorites

Off-swirl Space Weathering & Maturation

- Weathering in the off-swirl regions darkens across VIS-NIR with little change in continuum shape
  - suggests the production of larger (>40 nm) $npFe^0$ is proportionally larger in these locations
- Model to explain off-swirl spectral maturation:
  - Deflected protons re-directed to off-swirl regions.
  - Increased nanophase iron production and
  - Over saturation of H in the off-swirl soils.
  - Greater proportion of >40 nm $npFe^0$ is created by micrometeorite impacts bcause there is
    - More small $npFe^0$ from increased proton flux, and
    - The over abundance of H allows a greater amount of Fe^{2+} to be reduced and create larger $npFe^0$ in one event and in one location.

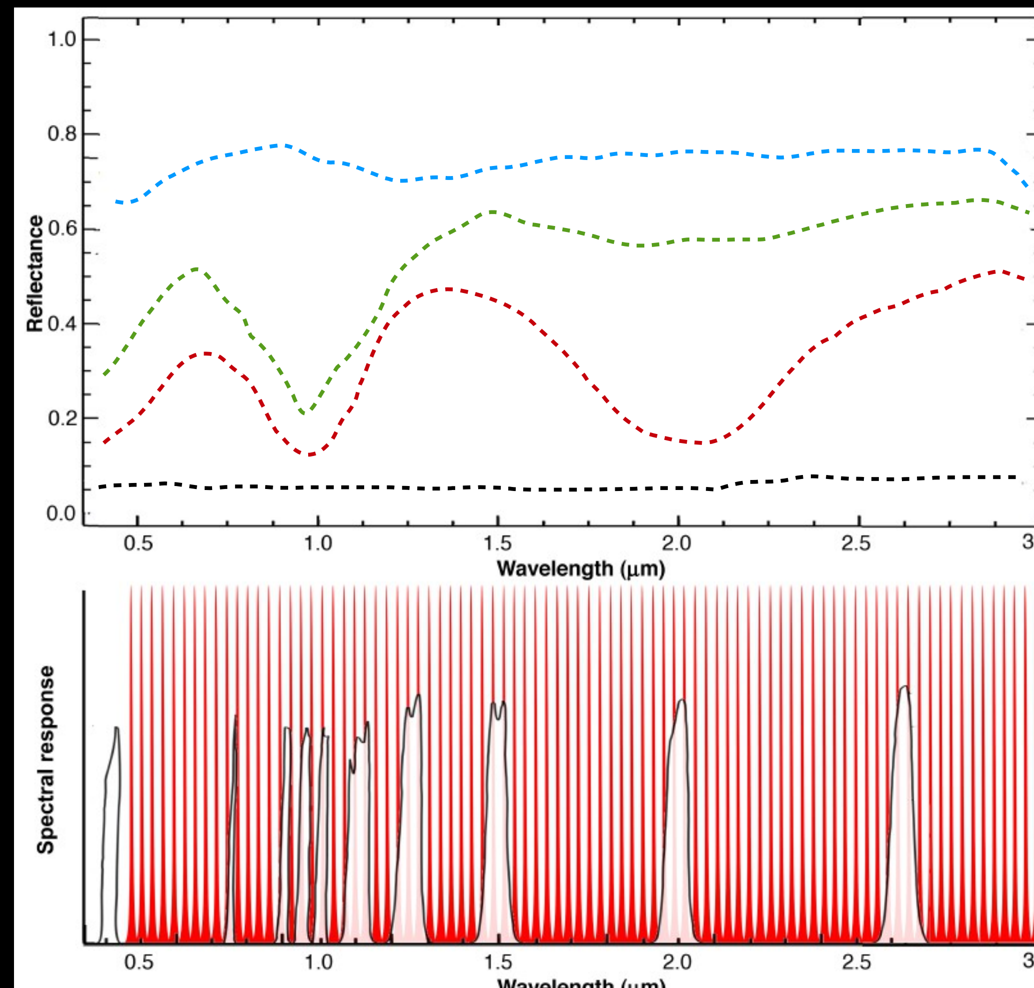
Final Word

The lunar swirls is of interest to a wide range of scientific fields and instrument observations demonstrates that the study of lunar swirls is more than just a study of a lunar phenomenon. The swirls provide a laboratory to study the solar wind, space weathering, and complex electromagnetic interactions in the solar system.

On September 7, 2011 the lunar swirls was the topic of a virtual workshop hosted by NASA's Lunar Science Institute.

The workshop can be viewed in its entirety at:

`http://lunarscience.nasa.gov/events/lunar-swirls-workshop-without-walls`



1.0
0.8
0.6
0.4
0.2
0.0
Reflectance
0.5
1.0
1.5
2.0
2.5
3.0
Wavelength (μm)
Spectral response
0.5
1.0
1.5
2.0
2.5
3.0
Wavelength (μm)

Optical Maturity

- The optical maturity parameter (OMAT) is an estimate of the exposure age of the surface
  - Based on spectral reddening and darkening