The Maturely, Immature Orientale Basin

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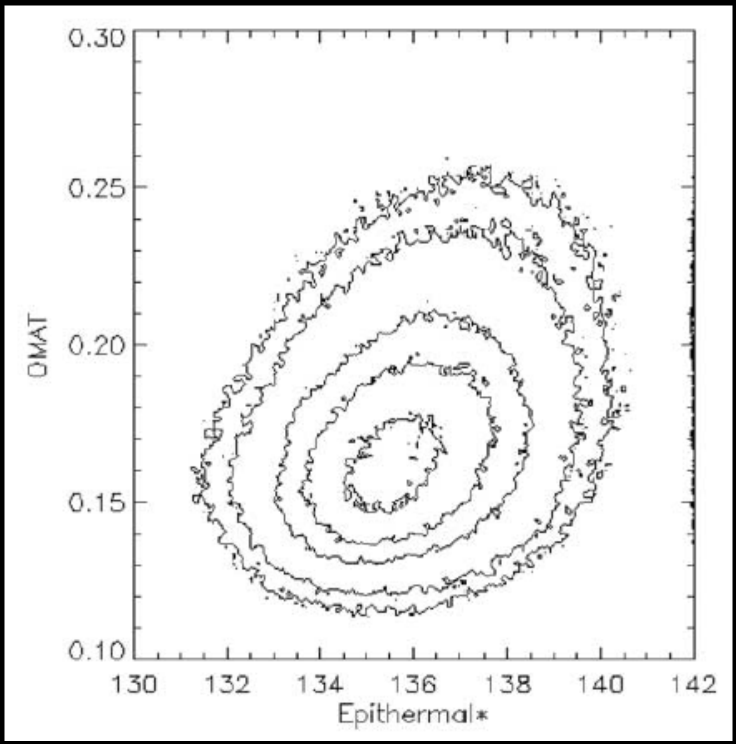
Epithermal neutron versus Optical Maturity (OMAT)

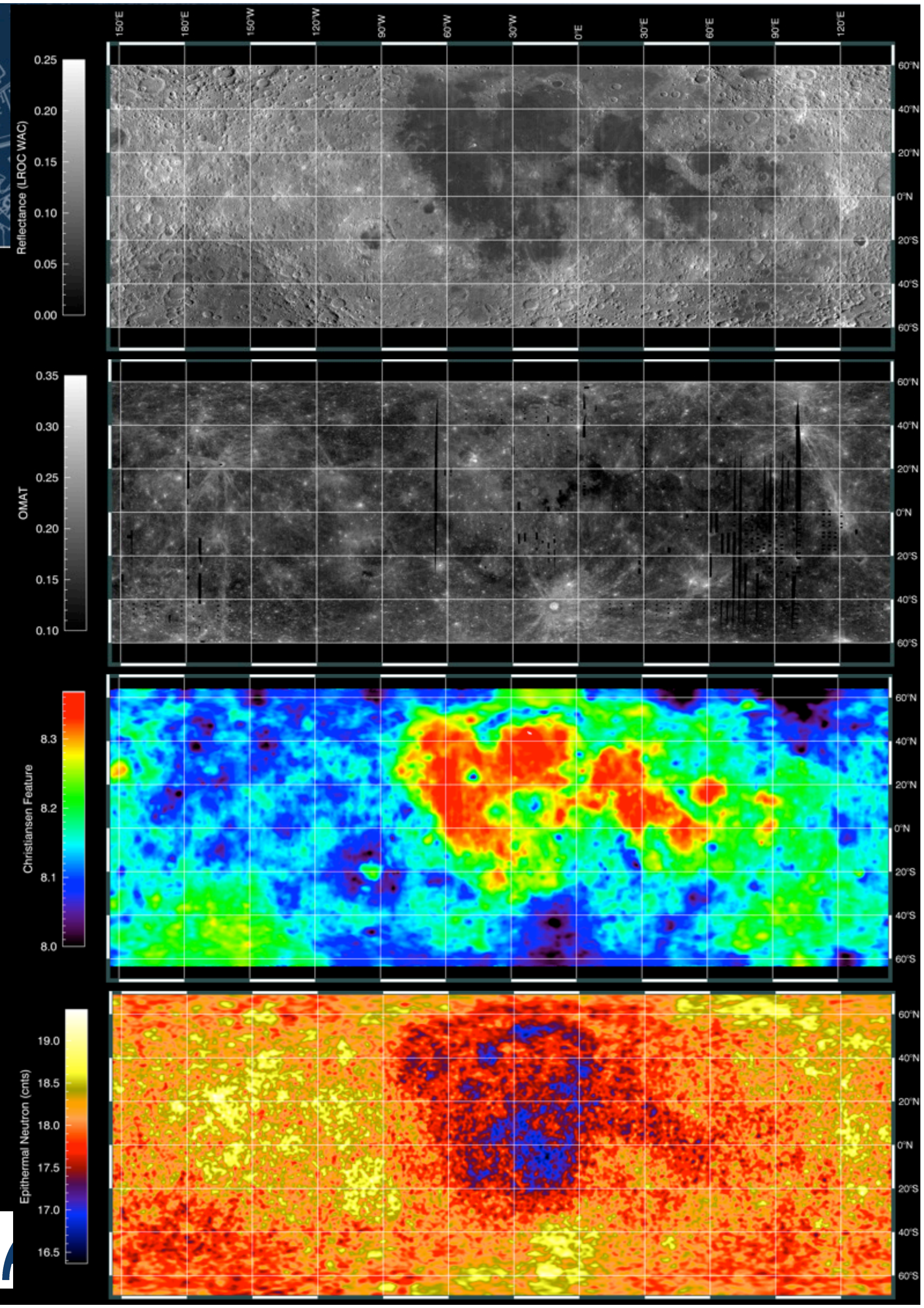


Lunar Prospector epithermal neutrons versus optical maturity (Johnson et al., 2002).

- *Johnson et al.* (2002) studied the relationship between LP epithermal neutrons and non-polar hydrogen/ optical maturity.
- Only a moderate correlation was found between OMAT and epithermal neutrons.
- Plot was completed for global maps – both mare and highlands.

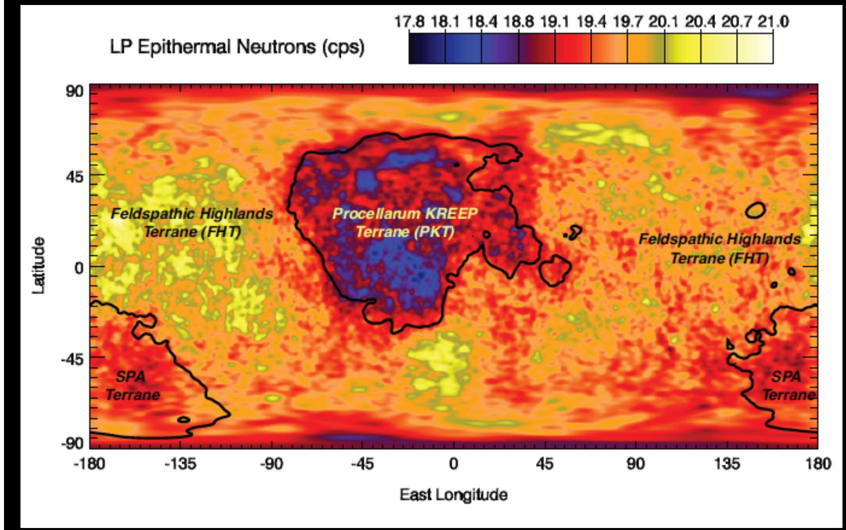
Measures of Regolith Maturity

- Albedo
- Optical Maturity parameter (*Lucey et al.*, 2000)
- Diviner Christiansen Feature (CF) data shows compositional variability across the Moon with some of the variability attributable to variations in Fe and Ti content (*Greenhagen et al.*, 2010; *Allen et al.*, 2012).
- In lunar highlands, unexpected evidence for variation of CF with soil maturity (*Greenhagen et al.*, 2010; *Allen et al.*, 2012).
- *Lawrence et al.*, (2015) decided to take another look at Lunar Prospector epithermal neutrons…

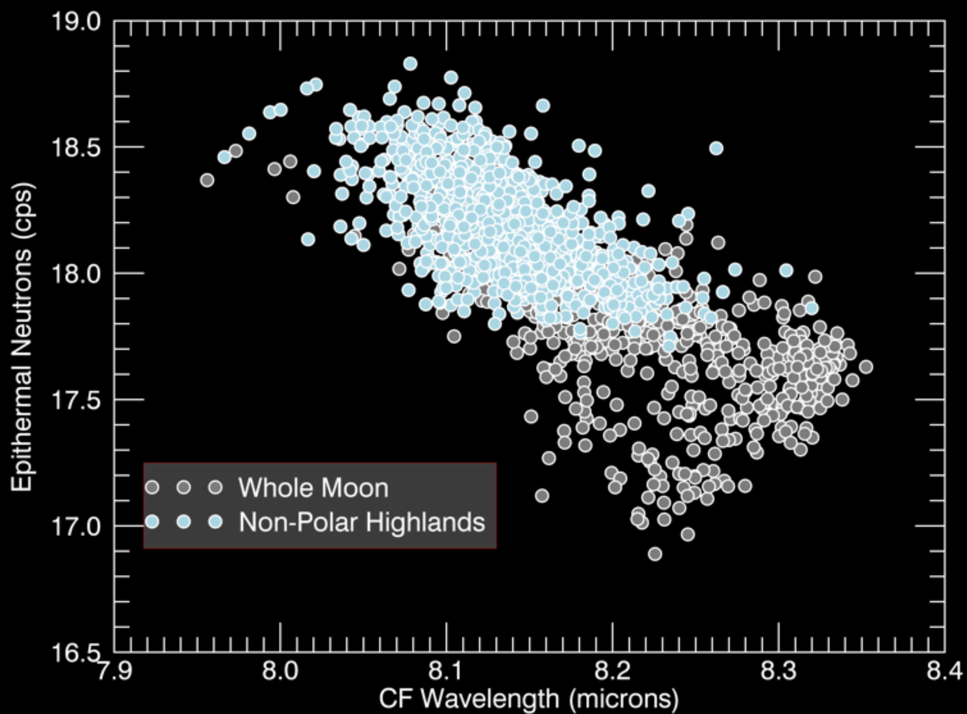


Lunar Prospector Epithermal Neutron Abundances and Maturity

- *Lawrence et al. (2015)* found epithermal neutron counts correlate with Clementine albedo, OMAT, and CF.
- Here we've also taken a look at LOLA Normal Albedo (*Lucey et al.*, 2014)



- *Whole Moon is ±65° latitude*
- *Highlands are determined by excluding high KREEP areas (>1 ppm Thorium) as it is more complicated to determine bulk Hydrogen*
- *Statistical equal area smoothing similar to handling of Lunar Prospector epithermal neutron data set*



Immature ⟷ Mature

Lunar Prospector Derived Hydrogen Budget and Regolith Maturation

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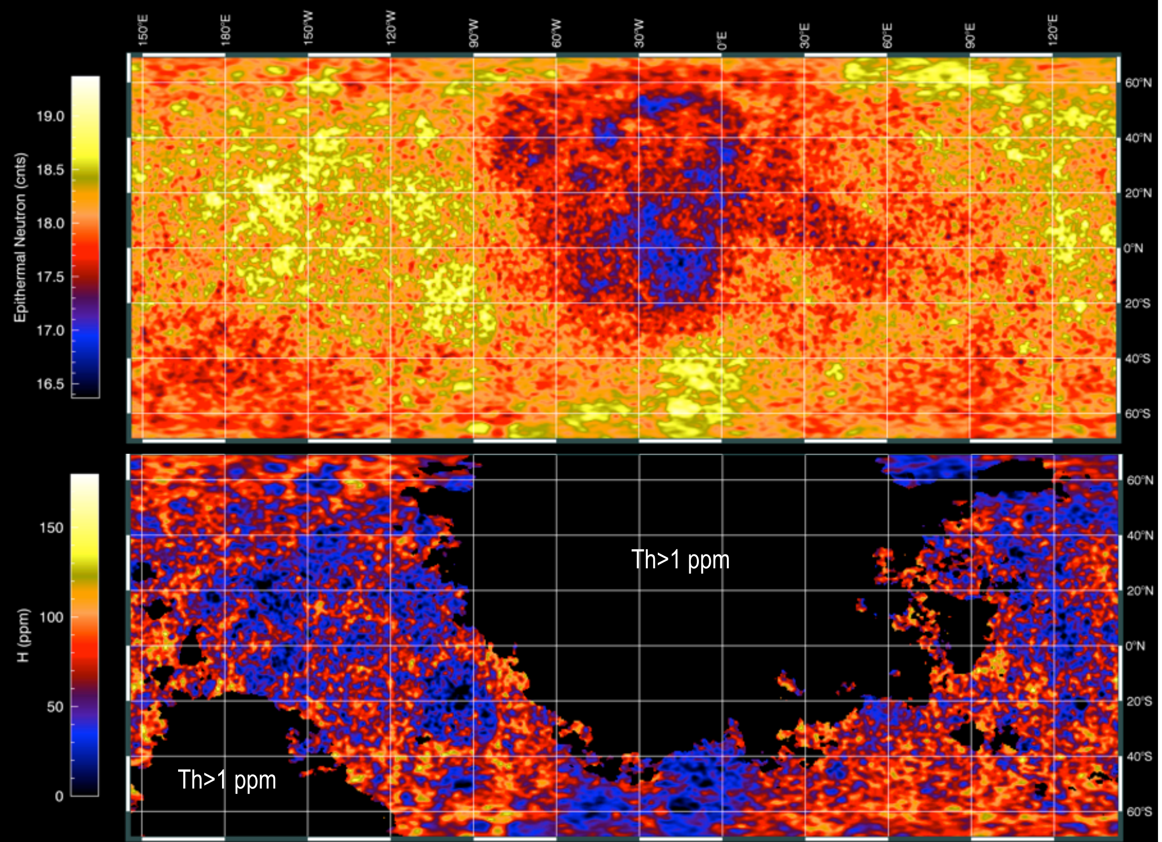
- *Lawrence et al., (2015)* derived H-abundances from neutron data
- Where epithermal counts are low, hydrogen is high
- Where epithermal neutron counts are high, hydrogen is low
- *Lawrence et al. (2015)* key interpretation suggests bulk of the *non-polar* Hydrogen budget is result of regolith maturation by space weathering hydrogen implantation
- Specific to non-polar contexts:
  - Younger, immature > low H-abundances
  - Older, mature > higher H-abundances



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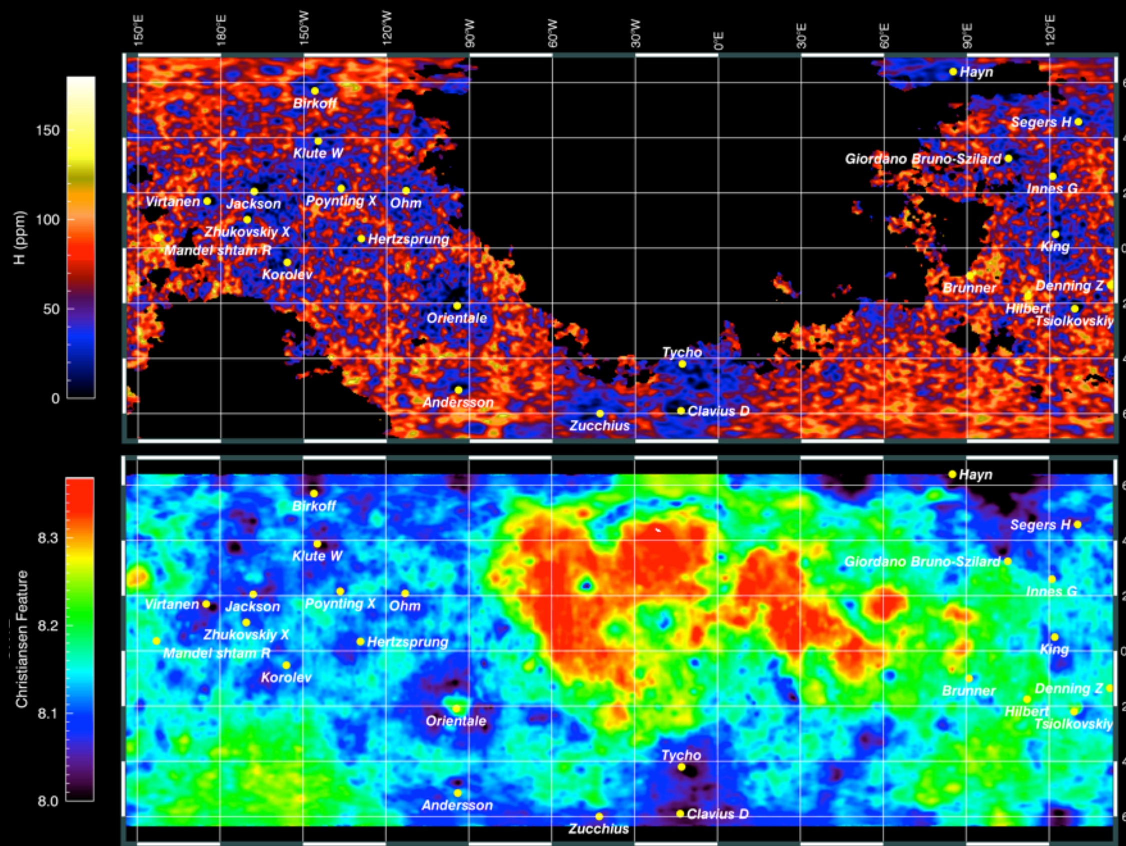
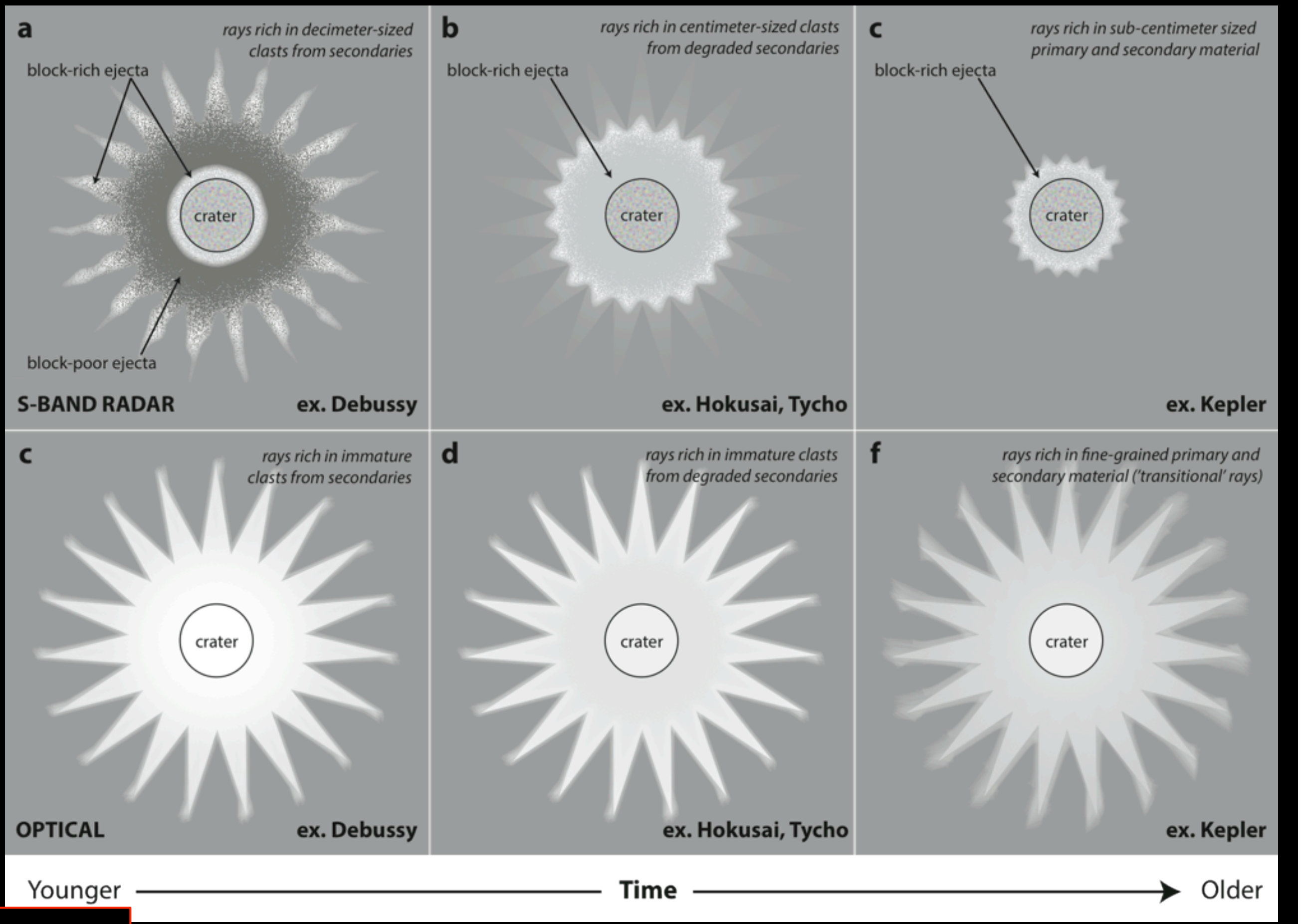
Regional Non-Polar Spatial Similarities with Bulk Hydrogen

- Volatile Hydrogen enrichments of great interest, but…
- Both enriched and depleted areas are important in the context of space weathering => relative age
- Tycho: H-depleted is consistent with immature OMAT and albedo values suggesting relatively young age
- Orientale: *also* H-depleted and one of the older features on the Moon
- OMAT: Orientale is relatively mature, albeit not the most mature on the lunar surface
- Orientale at least <3.8 Ga



Maturity: S-band Radar and Hydrogen

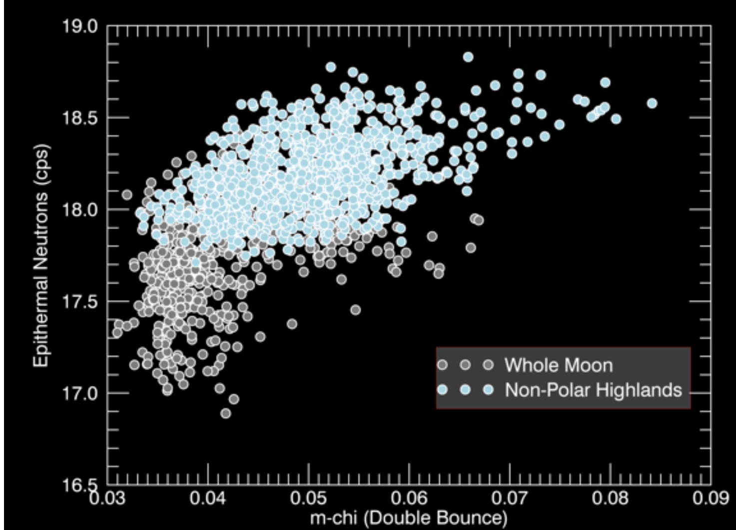
- Radar often used as proxy for maturity (e.g., *Neish et al.*, 2014)
- S-band CPR gives us a measure of scattering at the surface and within the top ~1.25 m

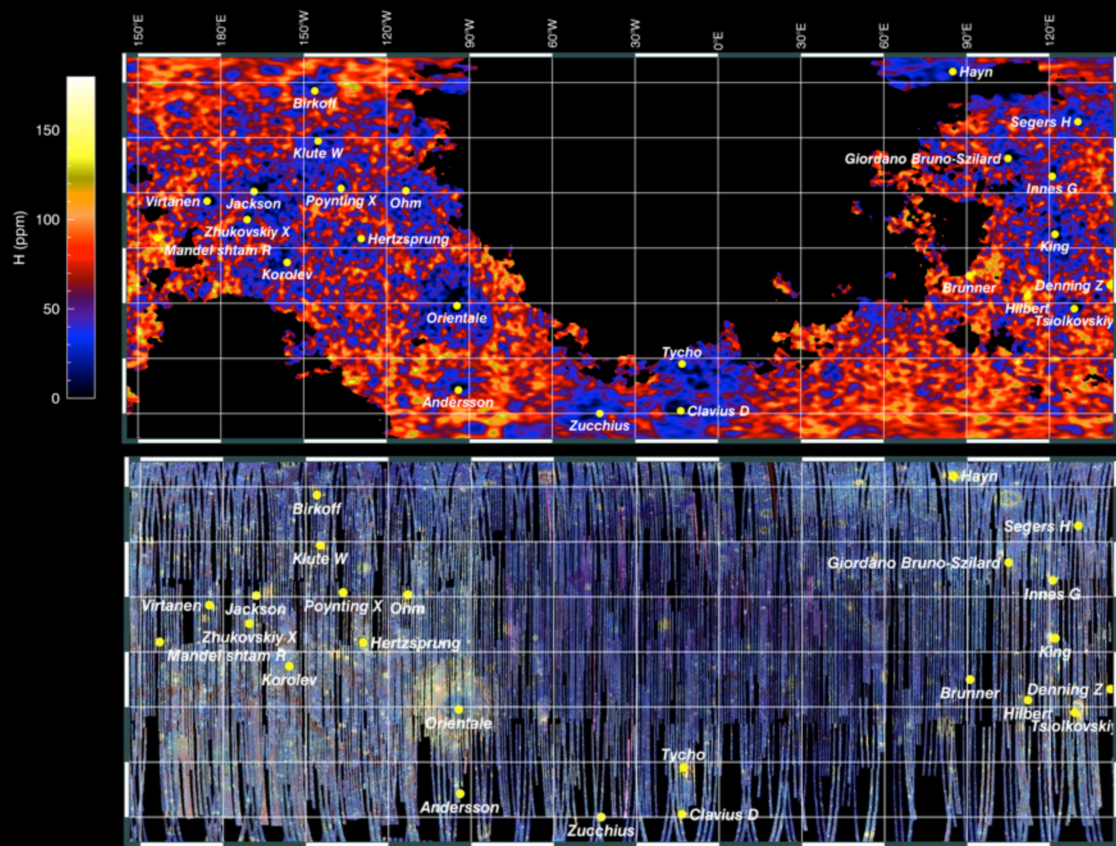


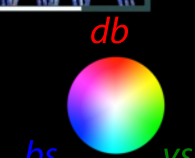
Neish et al., (2014)

Maturity: S-band Radar and Hydrogen

- *Campbell, Ghent, and others have noted the prominence of Orientale in radar…*
- *Cahill et al.* (2014) reported on Mini-RF global coverage and full view of Orientale…
- *Raney et al.* (2012) demonstrated that *m-chi* differentiates these by differentiating double bounce and volumetric scattering







- *R* - double bounce backscatter (*e.g., dihedral structures, ice*)
- *G* - depolarized (*e.g., volume scattering*)
- *B* - single bounce backscatter (*e.g., Bragg scattering*)

Bulk Hydrogen Relative to Geologic Age

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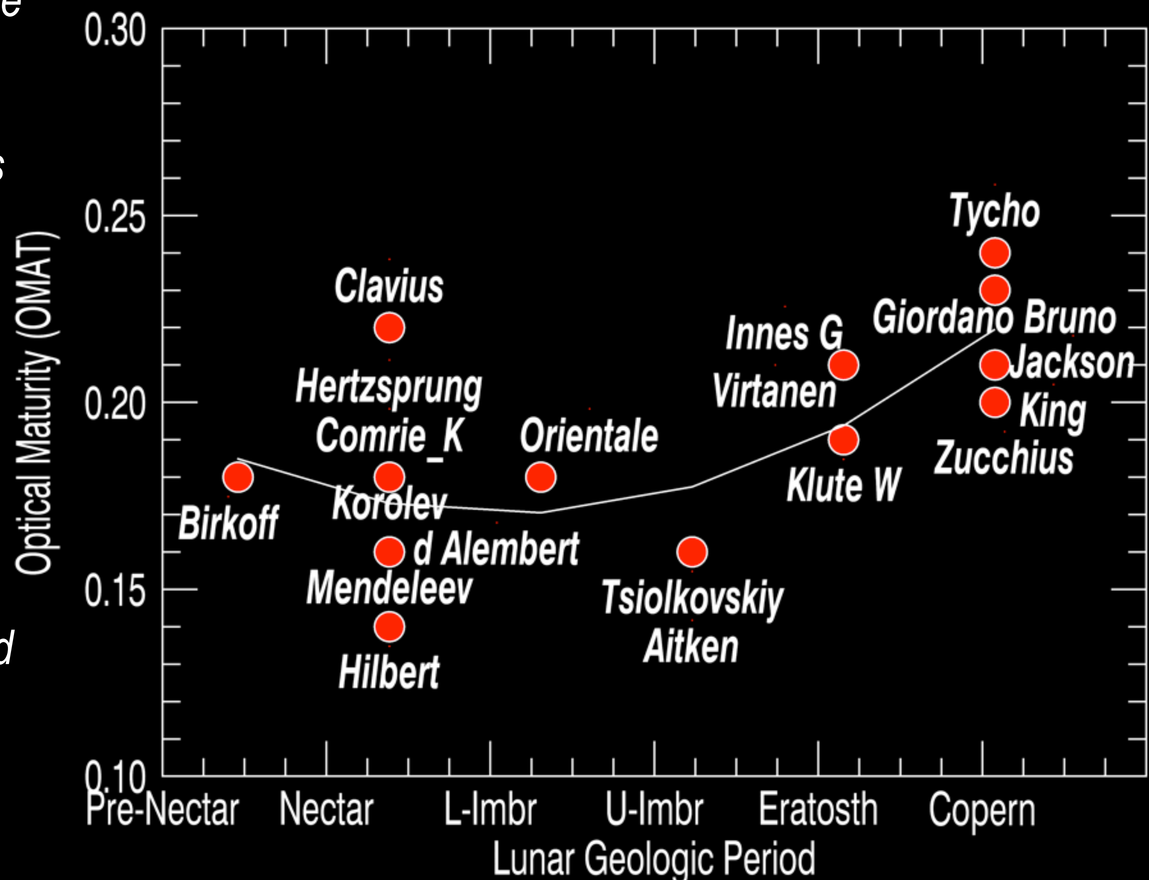
- *Our initial theory is that in most cases Hydrogen will accumulate with increasing surface age…*
- *Preliminary results suggest this holds true in a variety of cases*
- *H-depleted anomalies with notable Eratosthenian and Copernican craters all have mean H-abundances <30 ppm*
- *Of the H-enriched non-polar areas selected (only 4 sites and tend to be very localized) all have >130 ppm*
- *Differences between background H and depleted H areas more pronounced*



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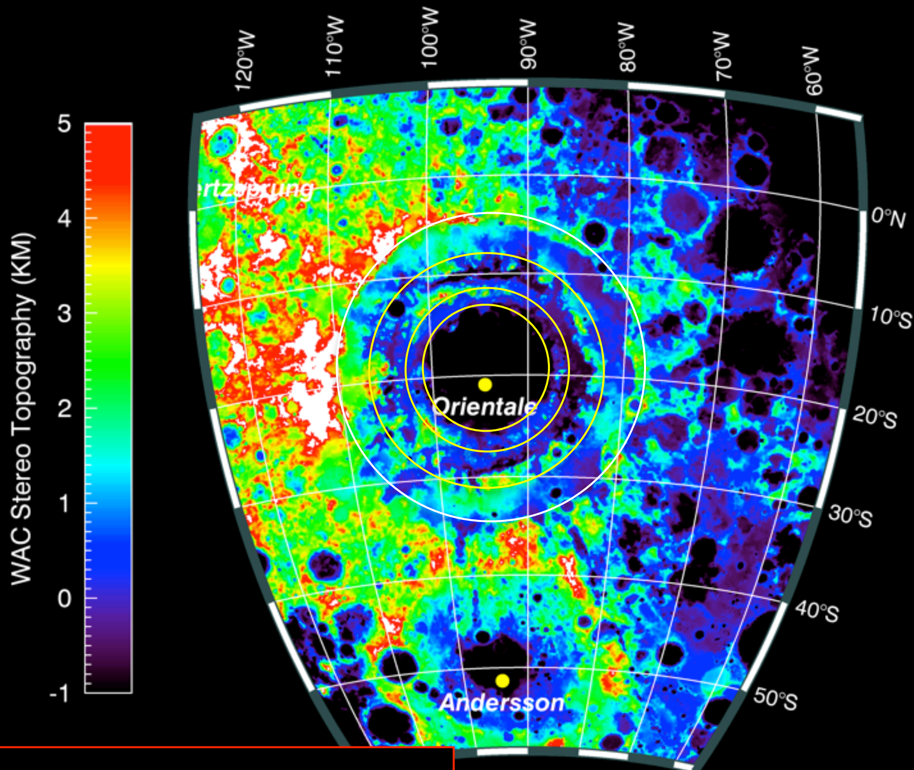
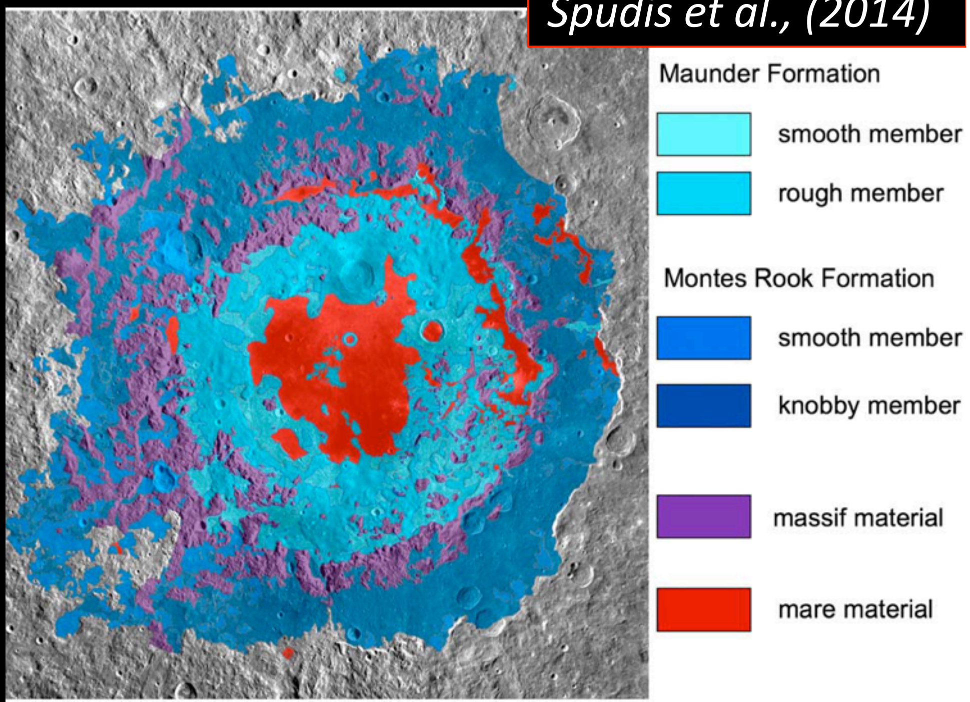
Orientale

- A recent re-examination of Orientale with the LROC WAC and M3, Spudis et al., (2014)
- Primarily stayed within Cordillera Ring
- Moore et al. (1974) lumped Maunder and Montes Rook Fms together and largely impact melt.



Scholten et al., (2012)



Spudis et al., (2014)

Orientale Thermal Observations of Surface Maturity

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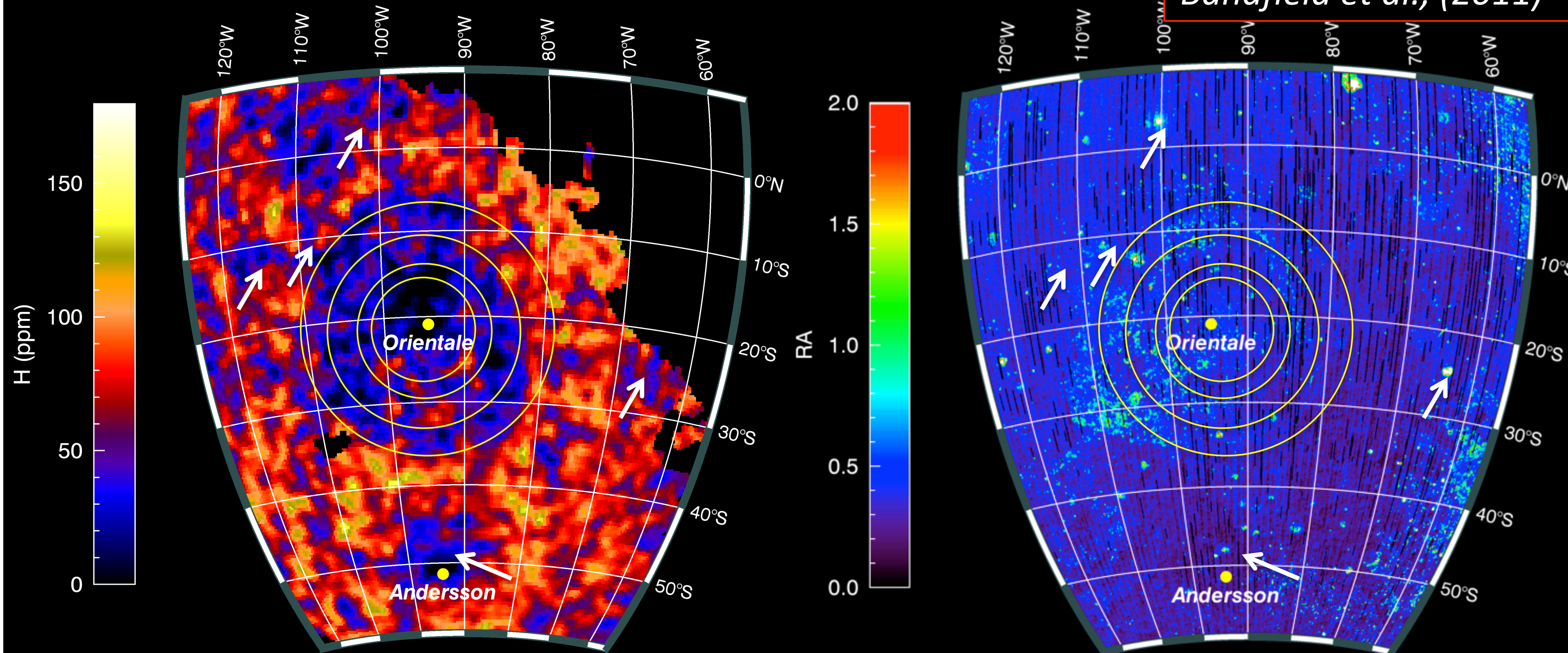
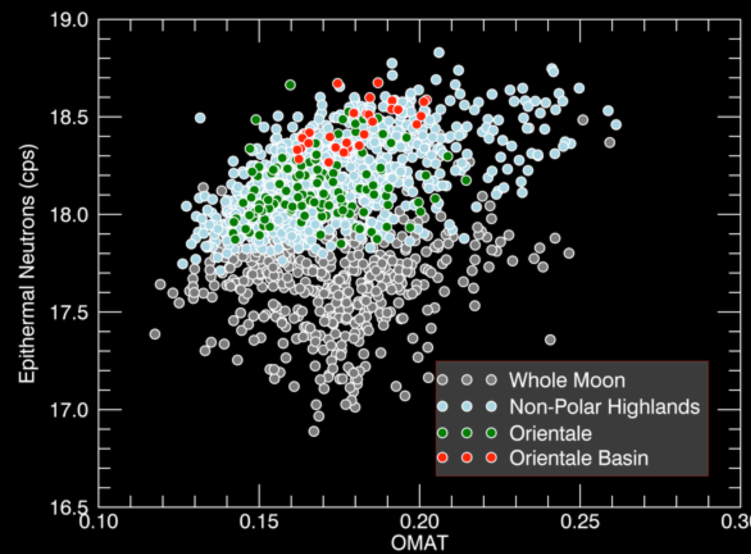
- Very low concentrations of surface meter sized boulders in rock abundance maps.
- Suggests relatively mature surface regolith
- Contrasts with Bulk H maps suggesting near subsurface sample

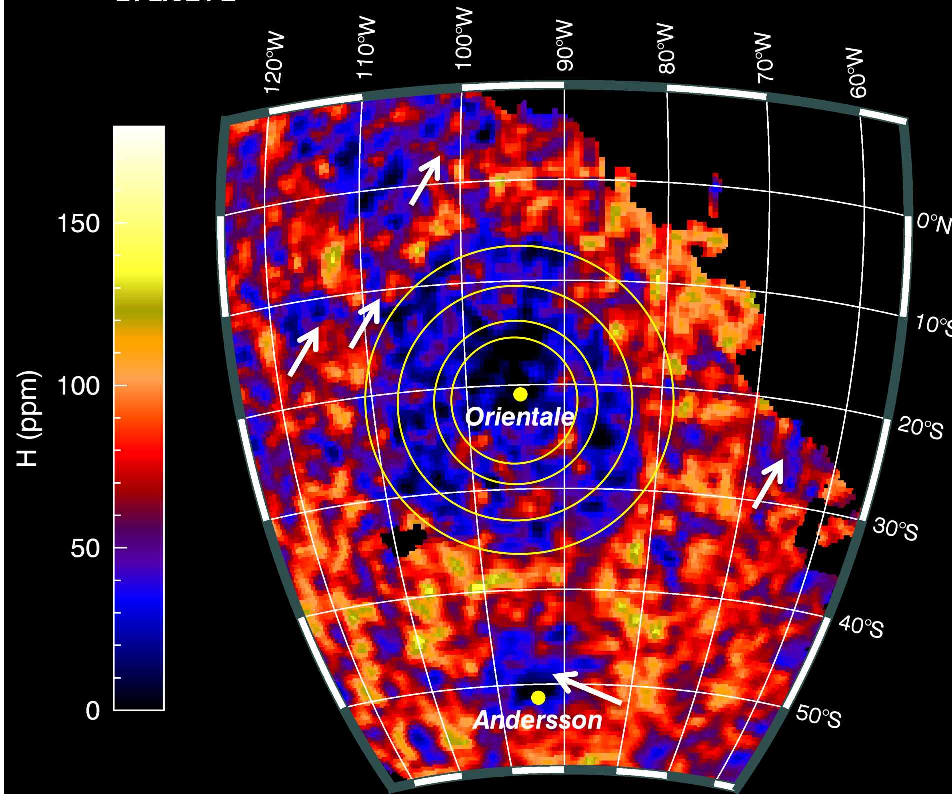
Bandfield et al., (2011)

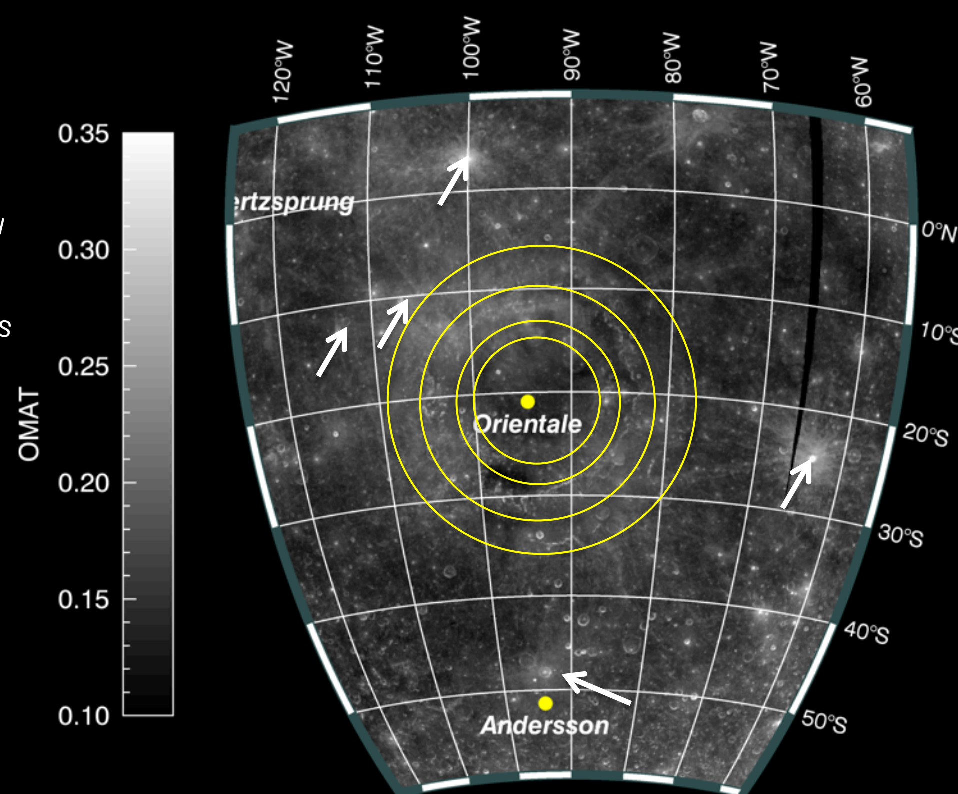


Orientale Optical Observations of Surface Maturity

- Orientale highlands region and basin proper has relatively mature OMAT values (mean = 0.17)
- Mean Hydrogen for Orientale proper is 42.7 ppm
- Most immature signatures are due to Copernican craters

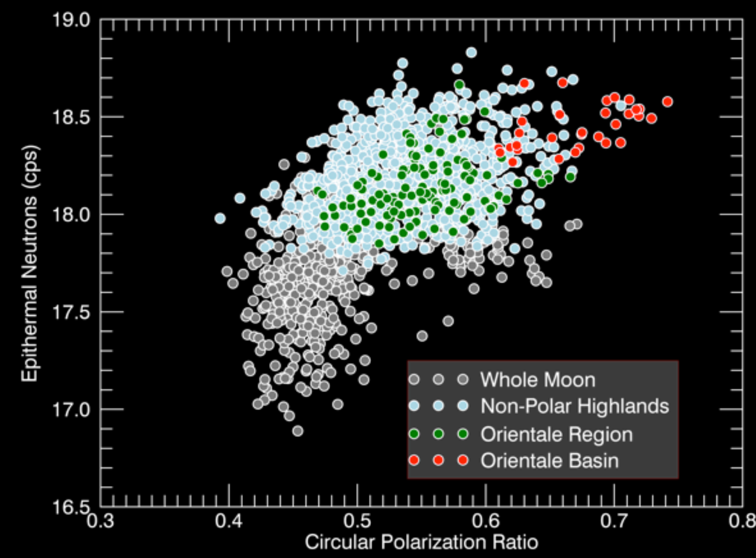


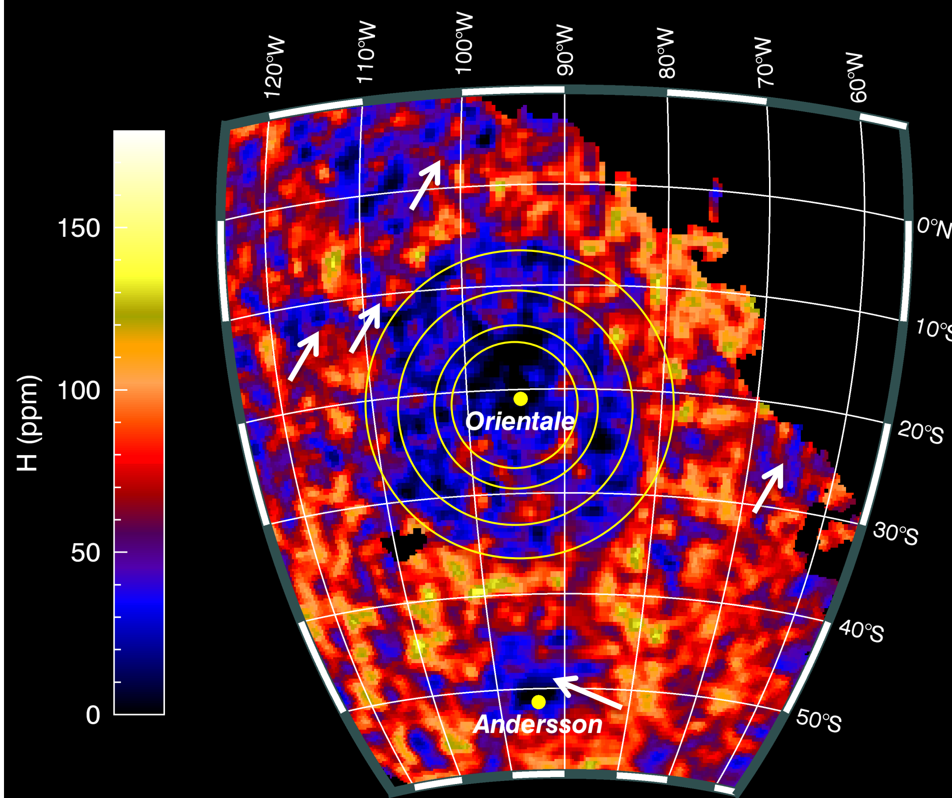


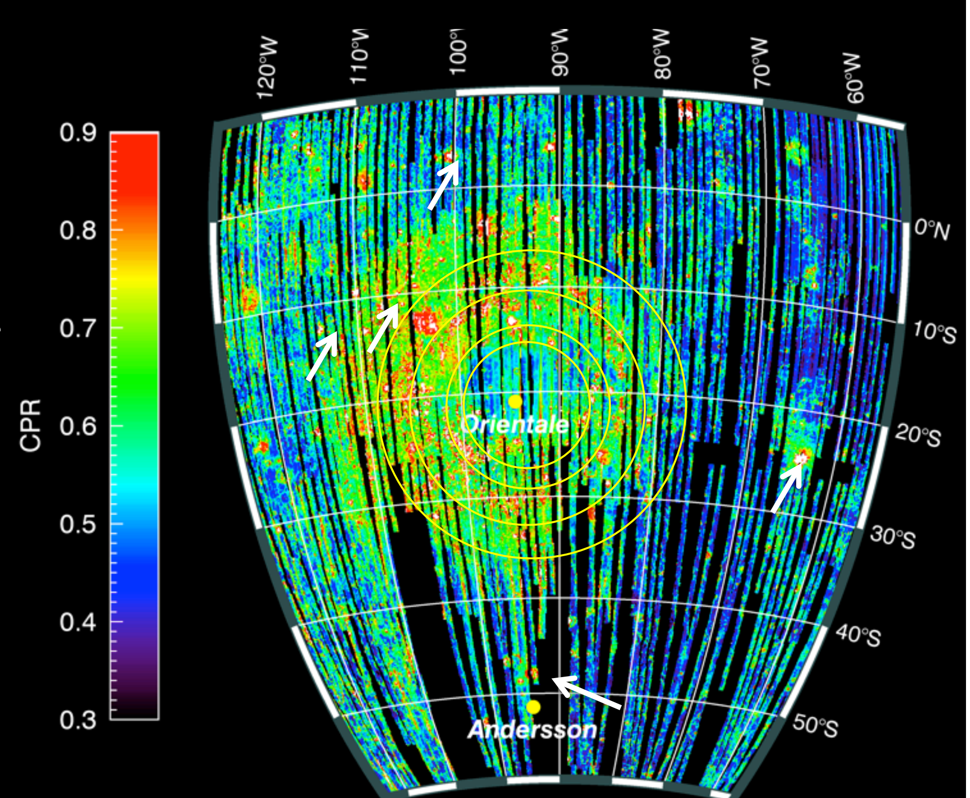


Orientale Mini-RF S-Band Radar Observations: Sampling Depth Effect

- High CPR suggest predominance of rocky subsurface materials
- Orientale Highlands Region <1 ppm Th
- Orientale Basin <1 ppm Th and >0.6 CPR
- Orientale proper Mean Hydrogen is 42.7 ppm; CPR is 0.67
- H spatial footprint is consistent with CPR

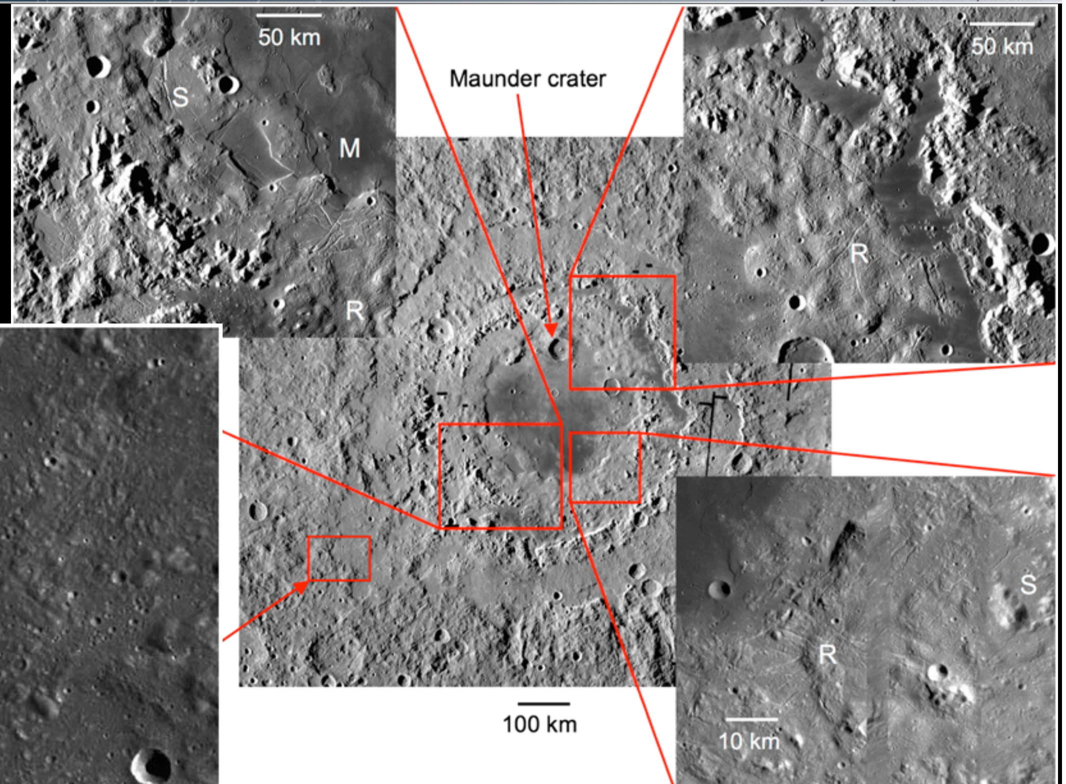


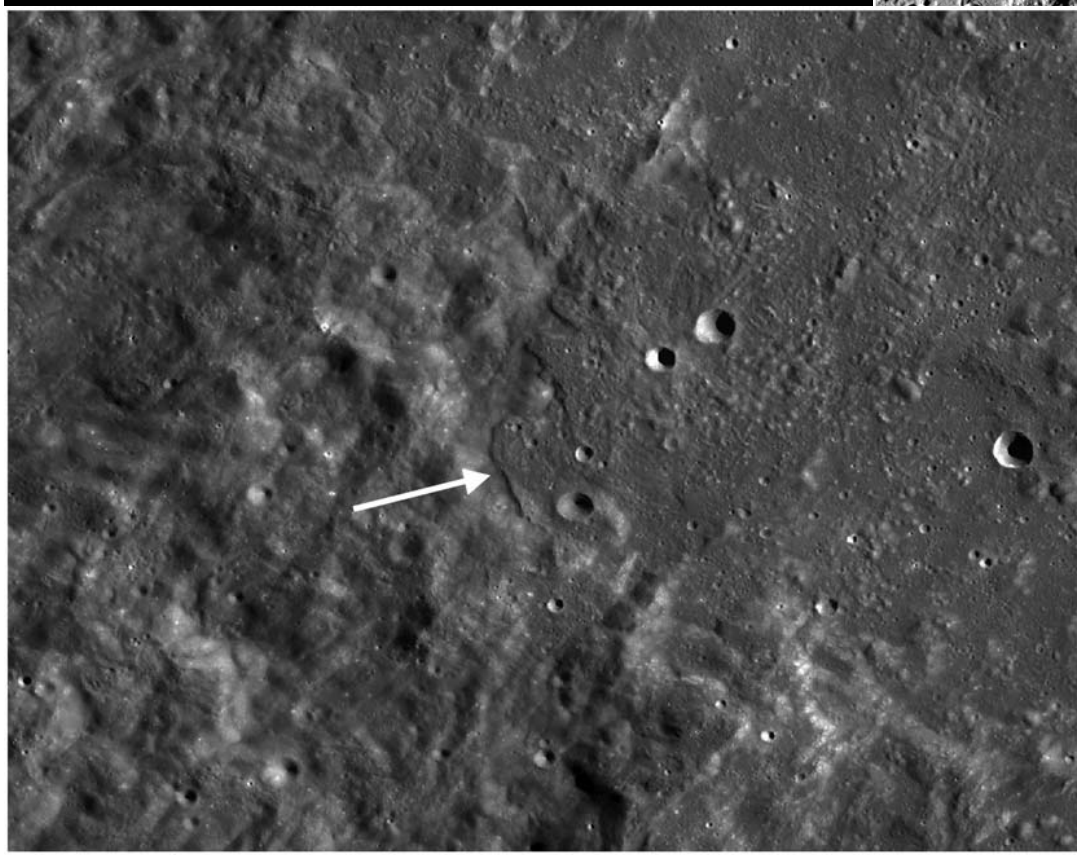




Orientale Hydrogen Depletion and Elevated CPR… Impact Melt Glass?

- *Moore et al. (1974) lumped Maunder and Montes Rook Fms together and largely impact melt.*





- *Spudis et al. (2014) suggests while this doesn't explain the entire diversity of morphological features in Orientale, it is at least supported by the presence of flow lobes in SW corner*

Hydrogen and Lunar Surface Materials

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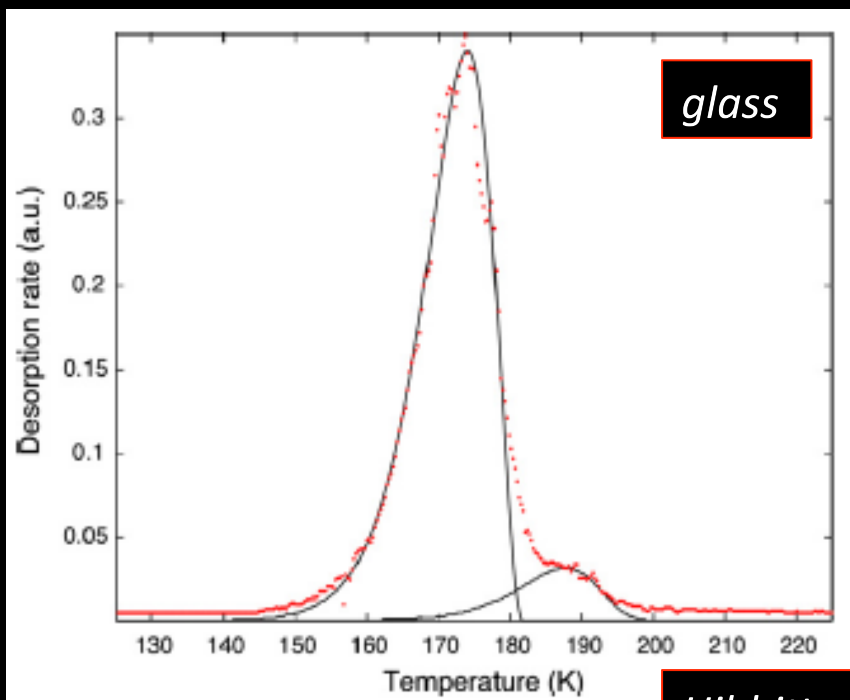
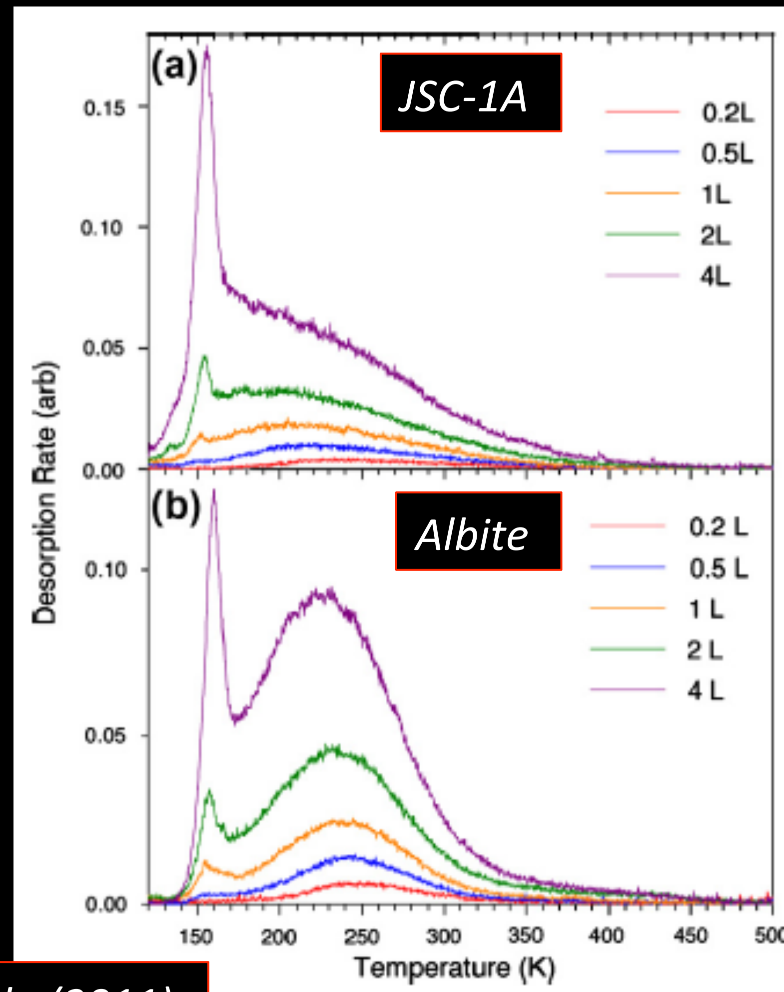
- JSC-1A and Albite chemisorb H_2O easily and up to high temperatures
- Fe-rich lunar glass does not do so easily and is hydrophobic





Hibbitts et al., (2011)

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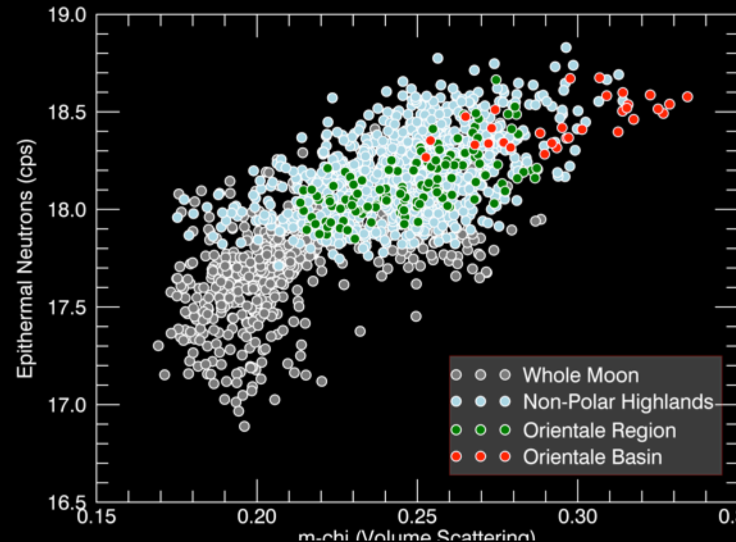
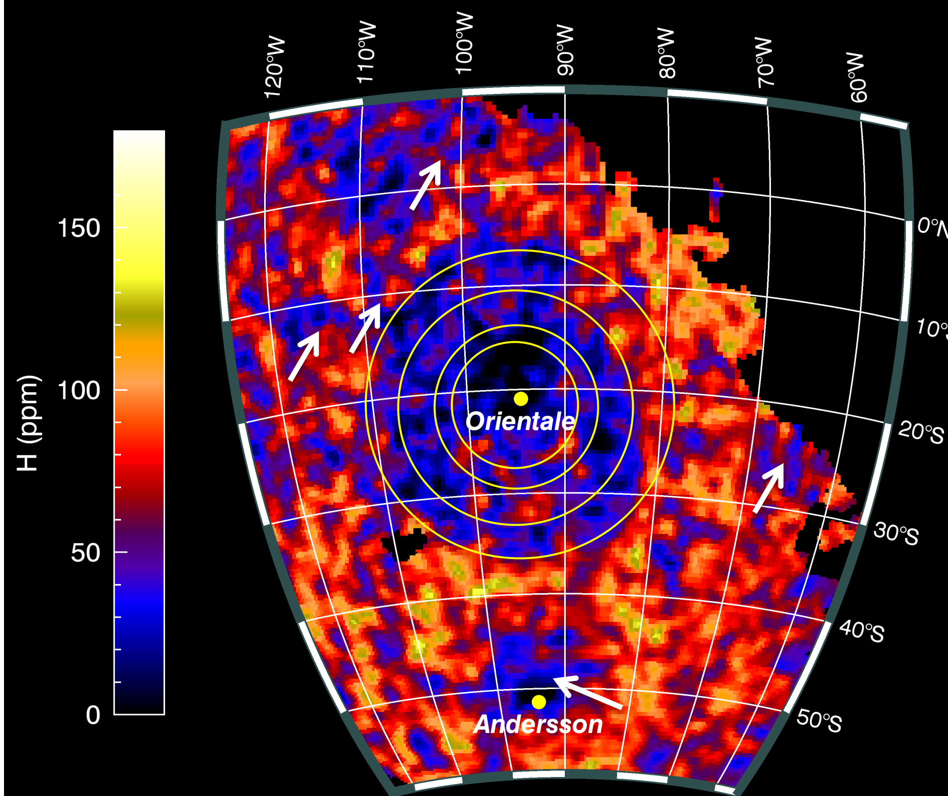
Summary

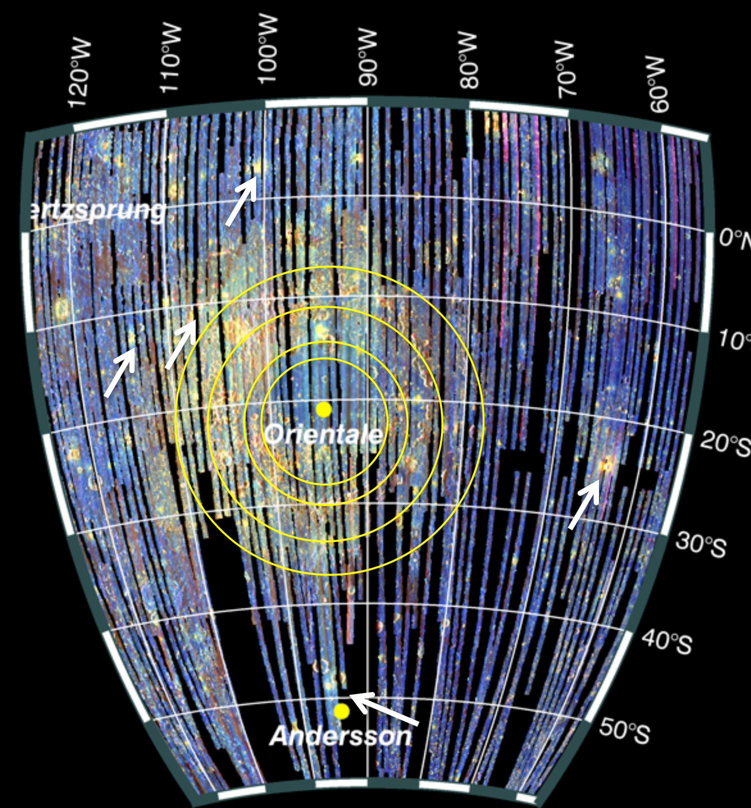
- LP epithermal neutron counts trend with other measures of maturity: (+*LOLA normal albedo and Mini-RF scattering parameters)*
- *Lawrence et al.,* (2015)'s insight that hydrogen implantation may predominantly be responsible for observed ***non-polar*** Hydrogen Budget has expanded our view of regolith maturation → another independent measure of relative age
- Important to recognize each parameters is measuring different aspects of space weathering (H implantation, impact melting and reduction of FeO to npFe, and roughness)
- Orientale is 'supposed' to be old (~3.8 Ga) and mature (OMAT, albedo, morphology)
- But is hydrogen depleted (<45 ppm) and radar bright (~0.7 CPR) → Immature.
- Differences are apparent during examination of each parameters maps
  - Sampling depths
    - Clementine, LOLA, Diviner (RA and CF) shallower sampling depths
    - Lunar Prospector and Mini-RF overlap somewhat in regolith sampling cross section sampling the upper ~10 cm (LP) to 10 cm to 1.5 m (Mini-RF)
  - Composition (glass vs. minerals)

Orientale m-chi Observations

- *Here, S-band CPR and M-chi measures may tell important things about maturity and relative age*
- *Here is an initial attempt to integrate maturity measures from different wavelengths in the context of Orientale Basin*

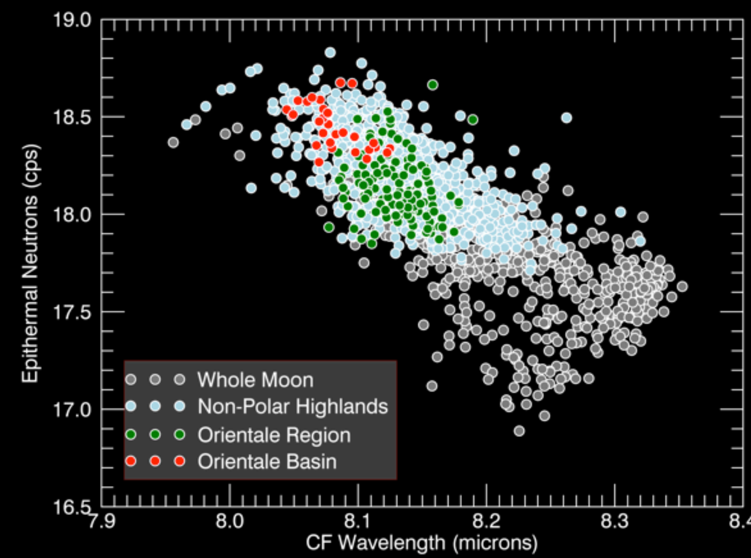


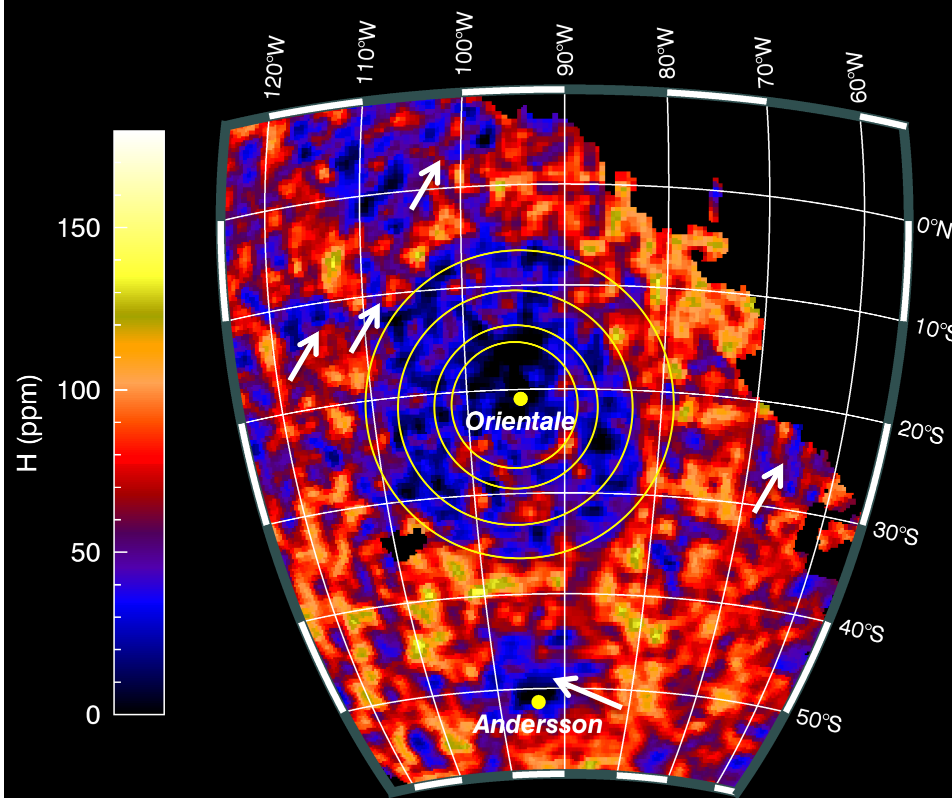


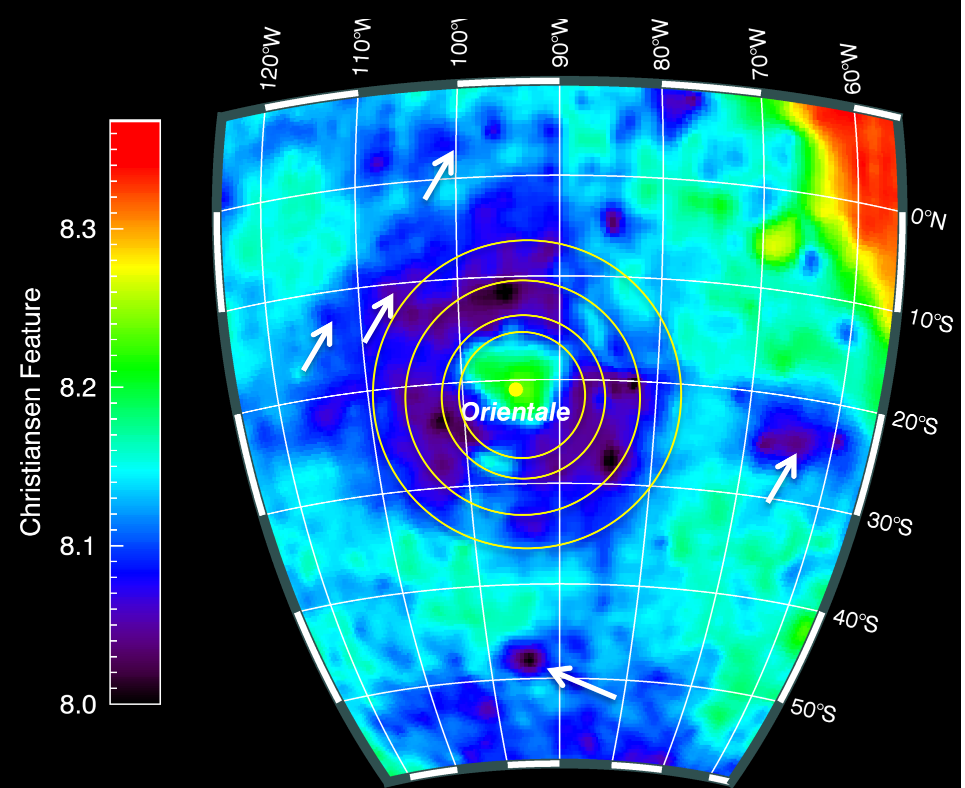


Orientale Thermal Observations of Surface Maturity

- Very low concentrations of meter sized boulders in rock abundance maps.
- Also suggests relatively mature regolith







RADAR PARAMETERS

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Raney et al. (*in revision*)

S_1 first Stokes parameter (*total power*)

m degree of polarization $m = (S_2^2 + S_3^2 + S_4^2)^{1/2} / S_1$

m_C degree of circularity $\sin 2\chi = -S_4/mS_1$

m-chi Parameters

Single Bounce Backscatter $= [S_1 m\,(1 - \sin 2\chi)/2]^{1/2}$

- Detection of Bragg Scatterers (smooth surfaces)

Double Bounce Backscatter $= [S_1 m\,(1 + \sin 2\chi)/2]^{1/2}$

- Detection dihedral structure scattering (rocky surfaces)
- Detection of coherent opposition effect backscattering (ice)

Volume Scattering $= [S_1\,(1 - m)]^{1/2}$

- Measure of depolarized return

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Mini-RF

Combining the Pieces

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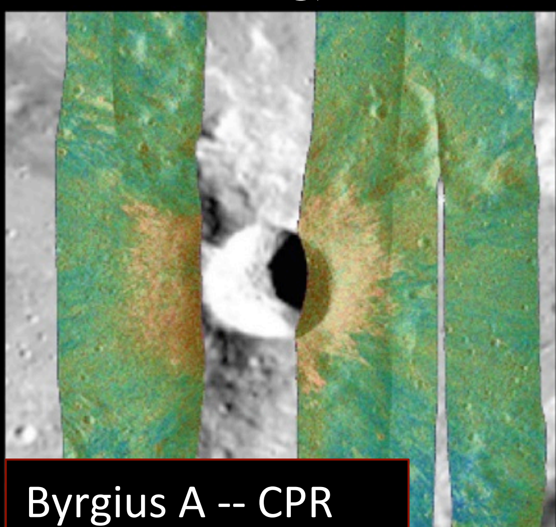
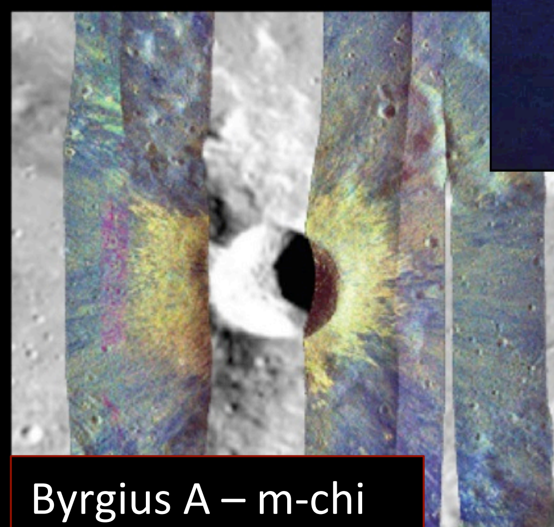
m-chi Decomposition

- *R* - double bounce backscatter (*e.g., dihedral structures, ice*)
- *G* - randomly polarized (*e.g., volume scattering*)
- *B* - single bounce backscatter (*e.g., Bragg scattering*)



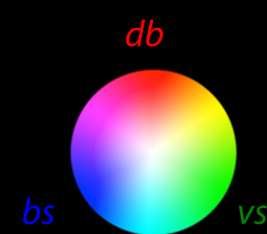
Byrgius A -- CPR



Byrgius A – m-chi

m/chi CL-pol Decomposition of San Francisco

Original source: AirSAR C-Band quad-pol data, courtesy of JPL



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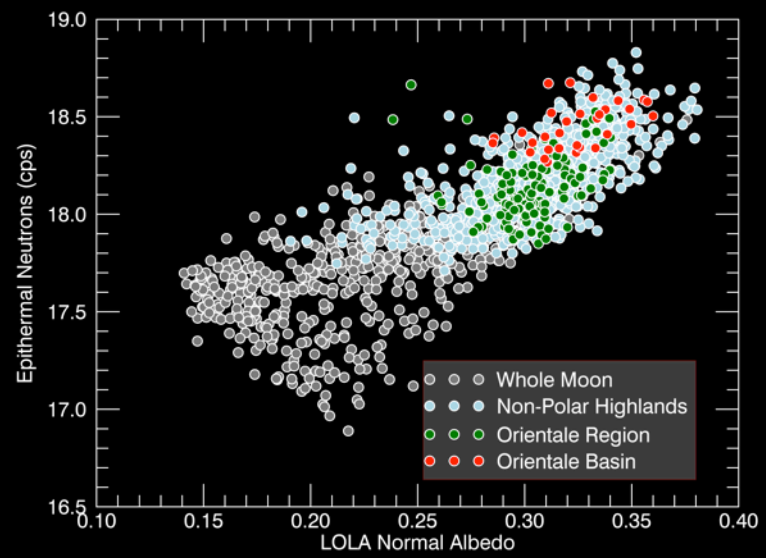
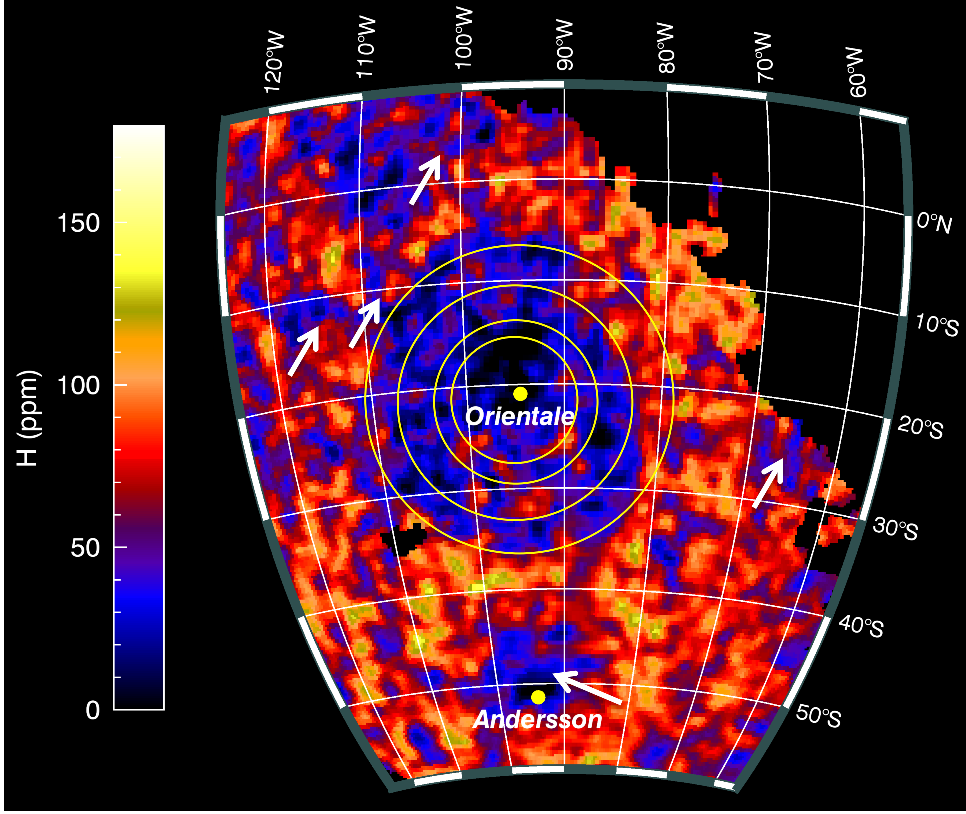
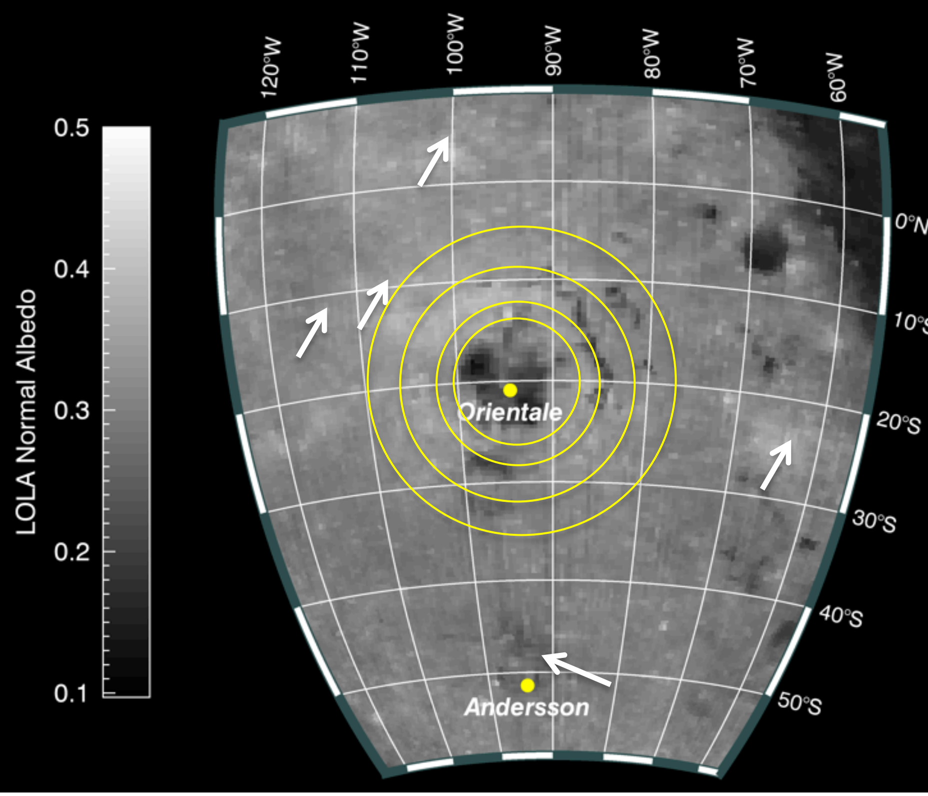
Mini-RF

Orientale Normal Reflectance Observations

- Mean albedo measurements for Orientale (0.32)
- May be indicative of highly anorthositic region

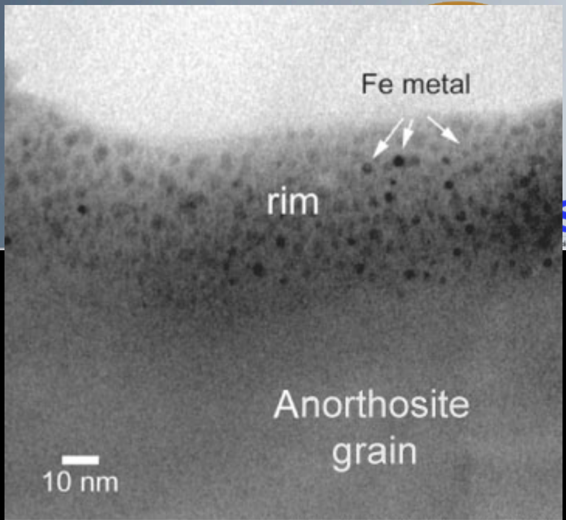




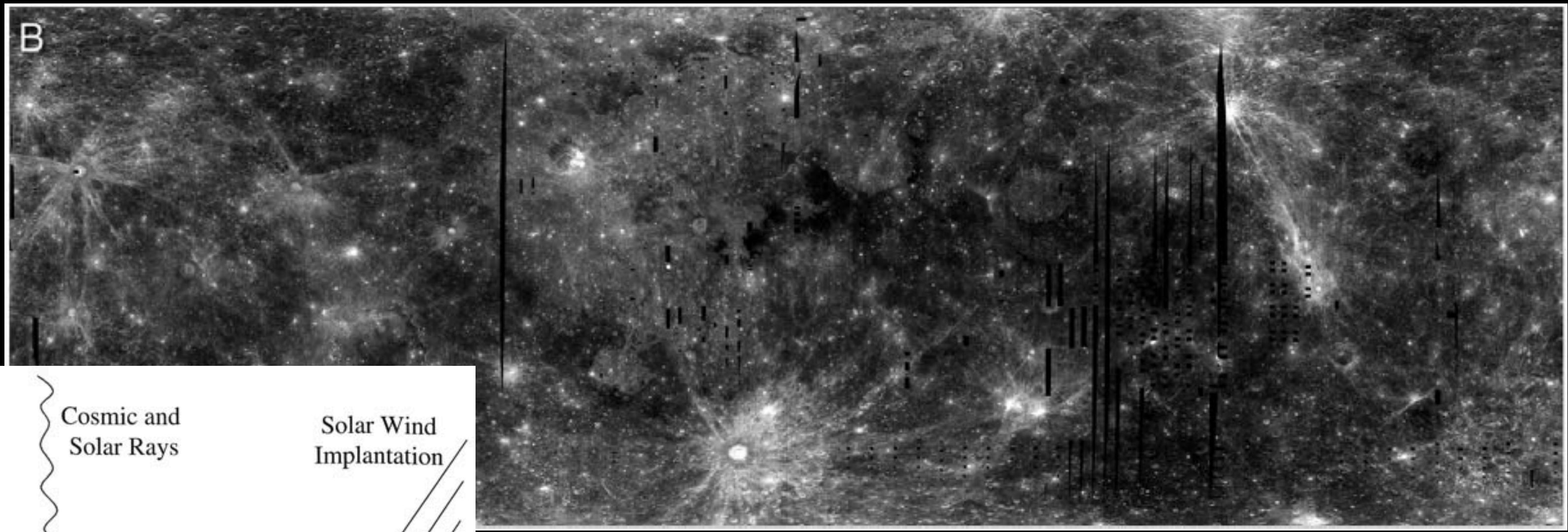


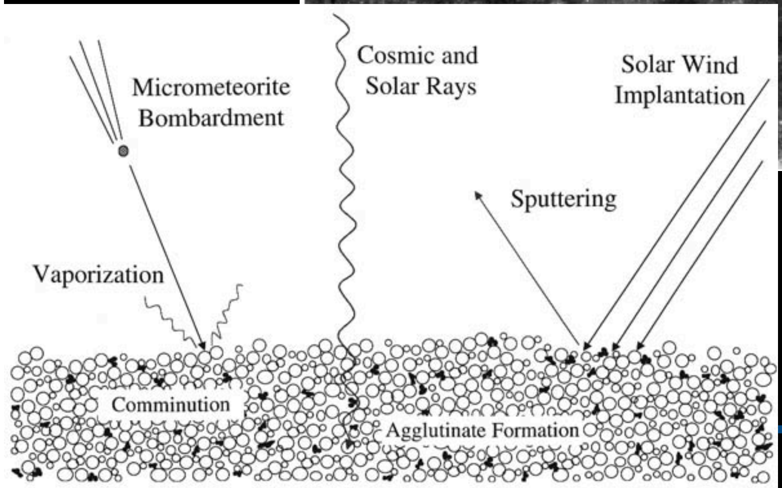
Lunar Surface Maturity as Viewed by Clementine

- *Lucey et al.* (2000) algorithm gave us a view of what we now consider the 'traditional OMAT Map' giving a quantitative way to evaluate levels of maturity on the surface of the Moon



(From Keller *et al.*, 1999; Pieters *et al.*, 2000.)





- *This view for the regolith, as complicated as it is, may be a little simplistic.*
- *Generally, assume regolith is homogeneous… perhaps not as much as we thought*