



# Lunar Resources

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October 5, 2010

Workshop for the Lunar Applications of Mining and  
Mineral Beneficiation



# Outline

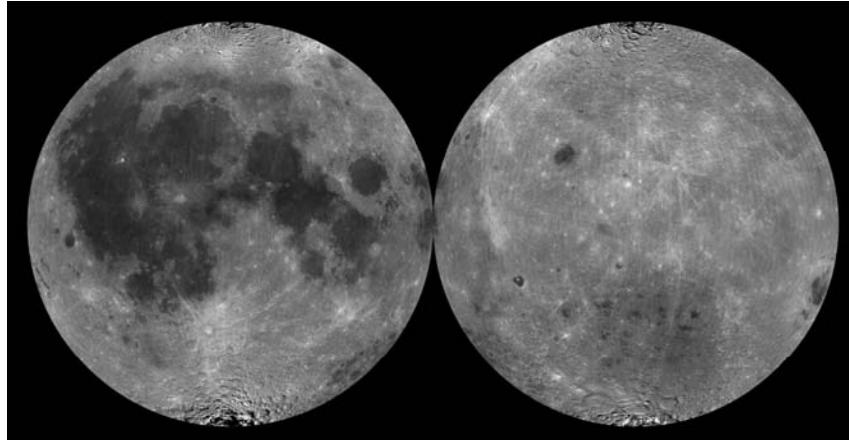
Regolith  
Conclusions

Water  
Rock Types

Sunlight  
Solar Wind

Introduction  
Locations

- Lunar resources
- Locations
  - Highlands
  - Mare
  - Poles / polar cold traps



- Sunlight
  - Solar power
- Solar wind
  - H,  $^3\text{He}$
- Water / ice
  - Source of the water
- Rock Types
  - Highlands
  - Mare
  - Recently identified concentrates
- Regolith
- Conclusions

# Location

Regolith  
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Procellarum  
KREEP  
Terrane

Eastern Basin  
Terrane

Feldspathic  
Highlands  
Terrane

SPA, outer  
SPA, inner

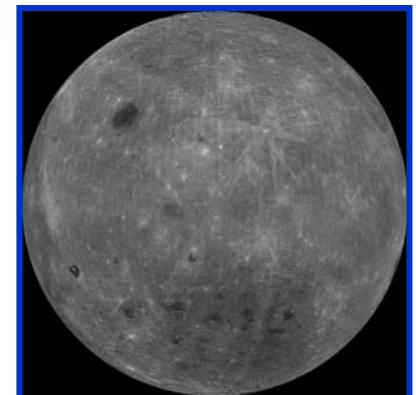
Near Side

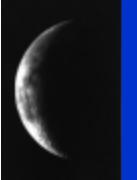
Far Side

Th, ppm

1 2 4 6 8 10 12

Gillis et al. (2000), Jolliff et al. (2000)





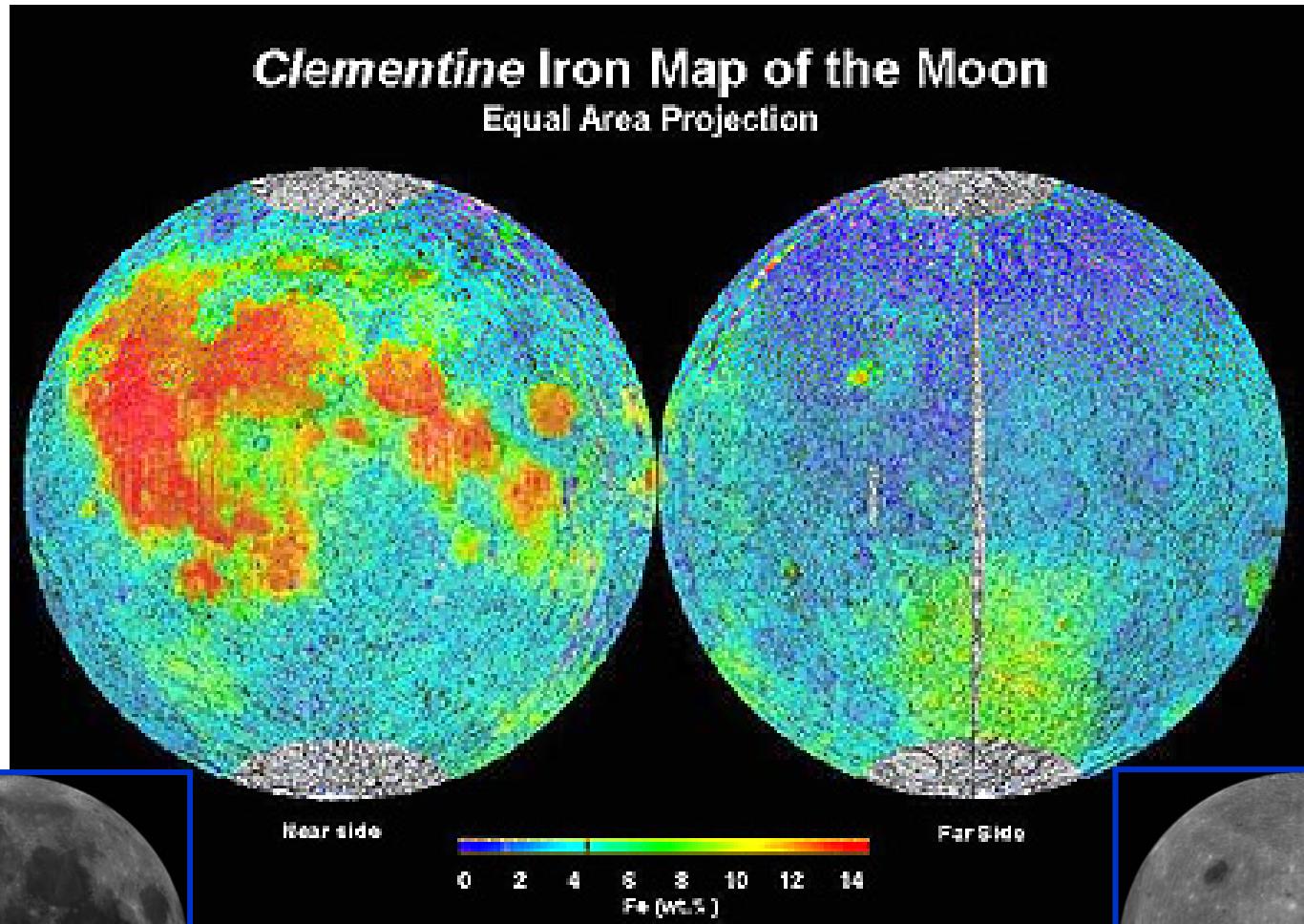
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# Location

## Common Rock Types

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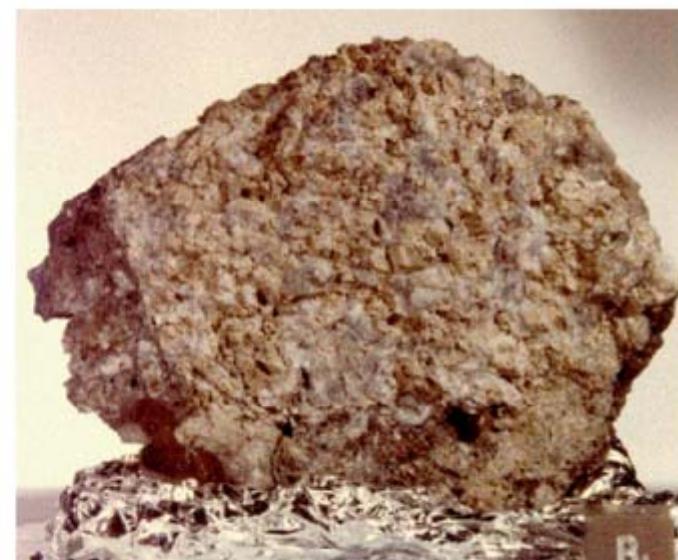
*anorthosite*



*basalt*



*norite*





# Location

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## Common Components

Anorthite



Ilmenite



Olivine



Pyroxene

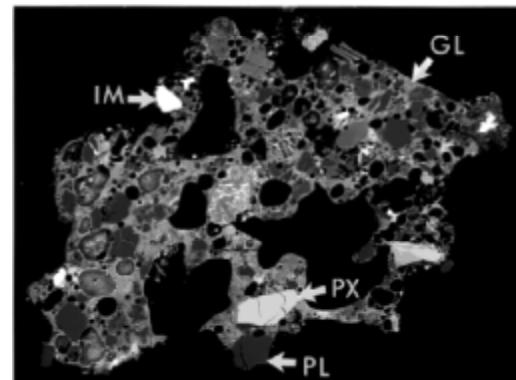


CPX

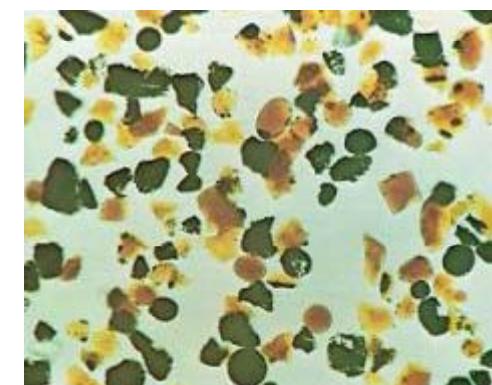
OPX

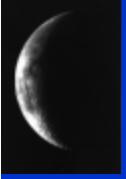


Agglutinate



Volcanic Glass Beads





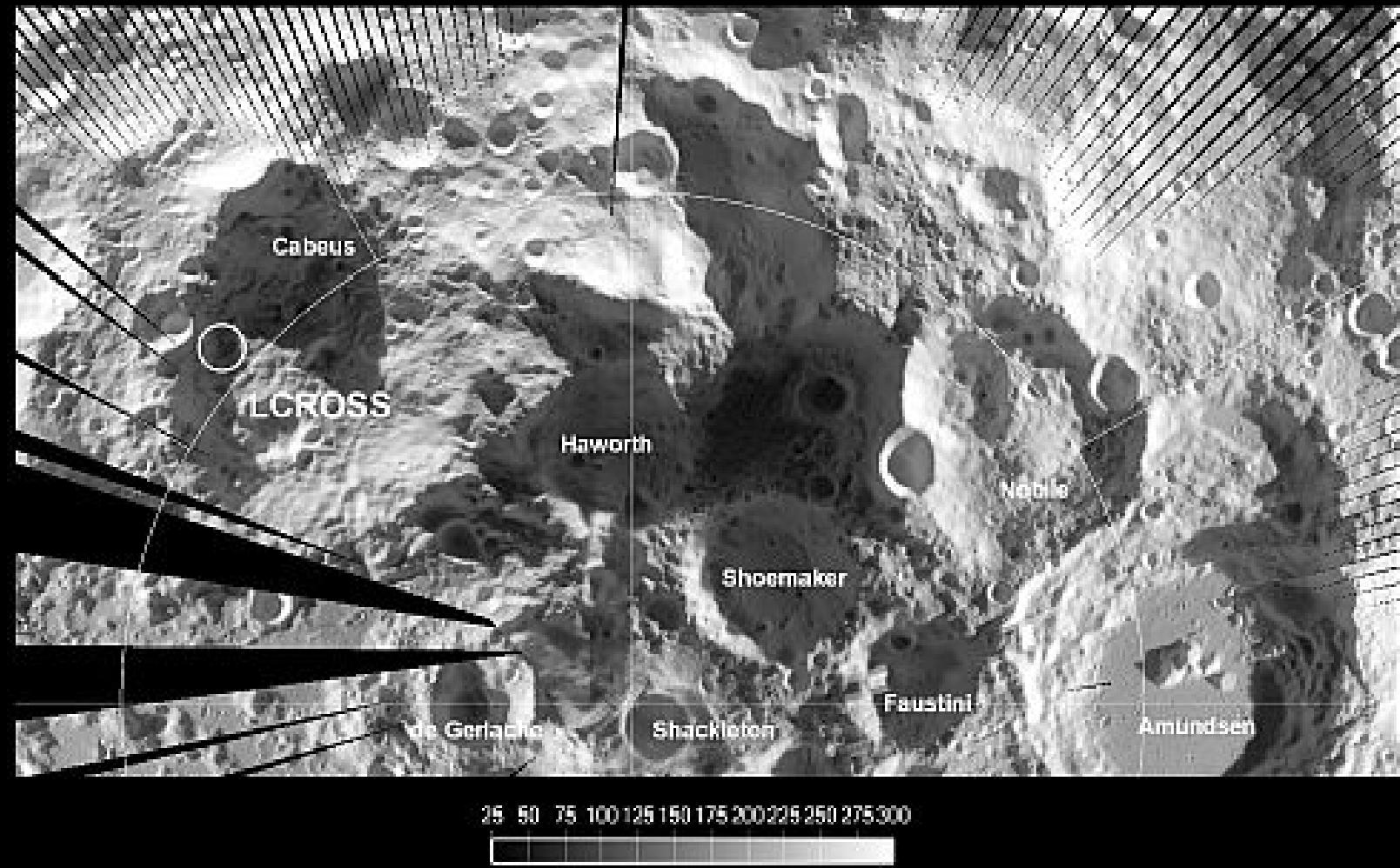
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Diviner Channel 8 Brightness Temperature Map (K)

# Location

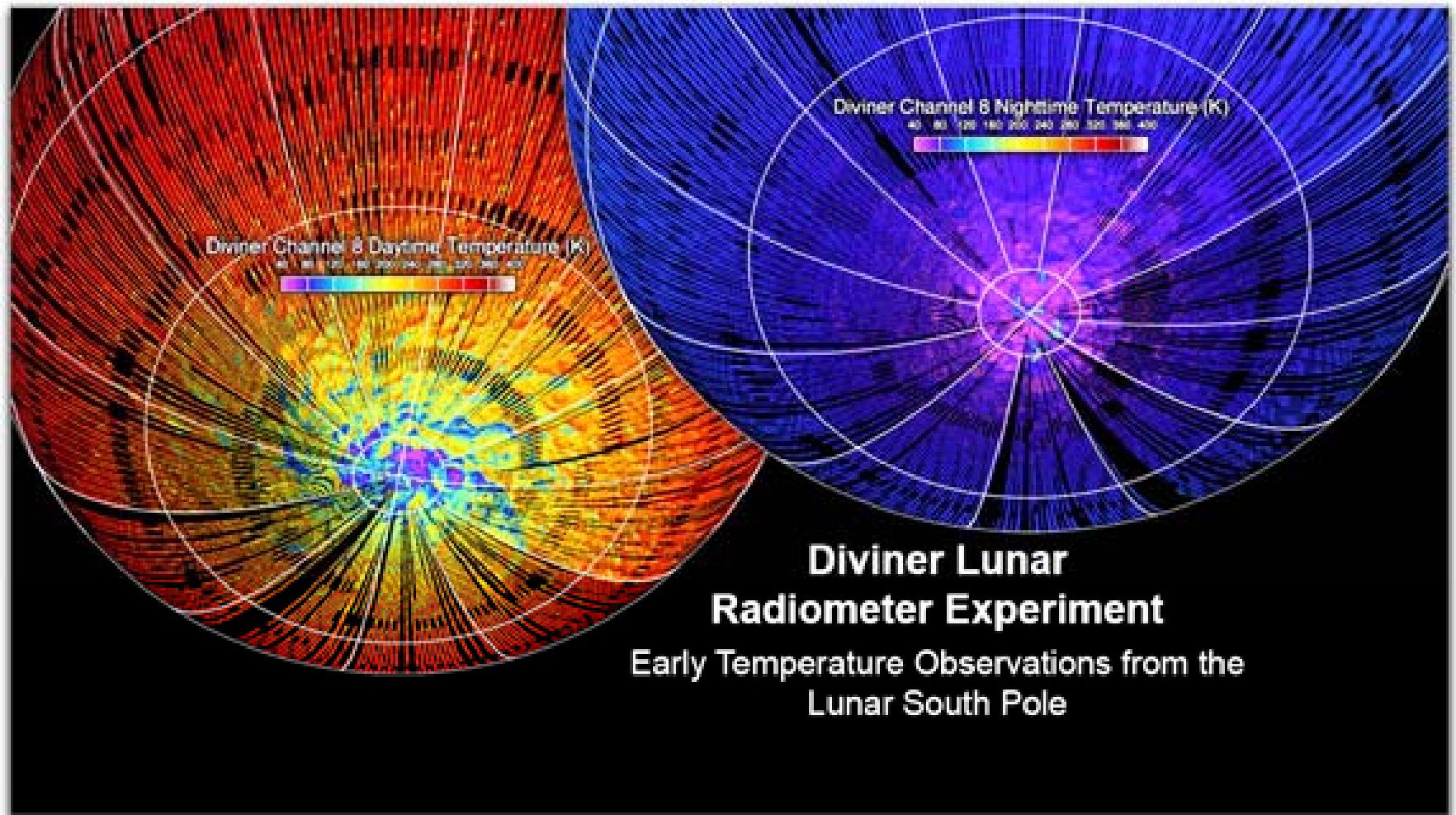
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Diviner measures T of the top 1mm of the surface



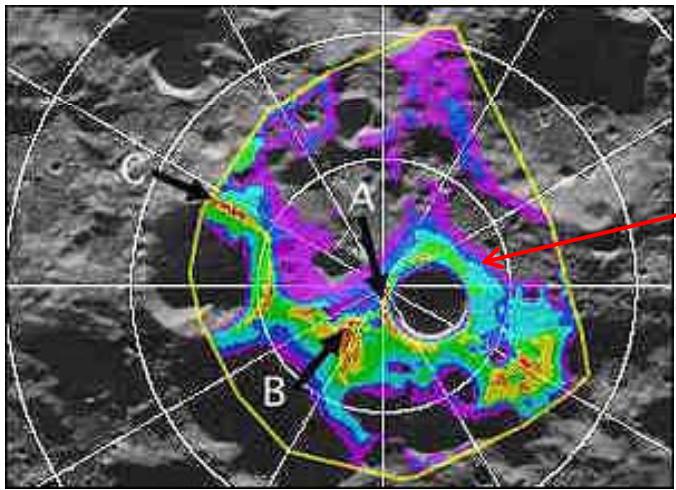
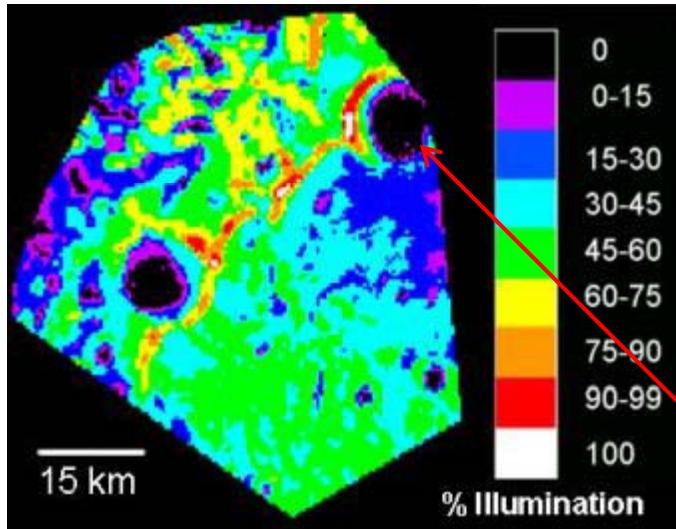
# Sunlight

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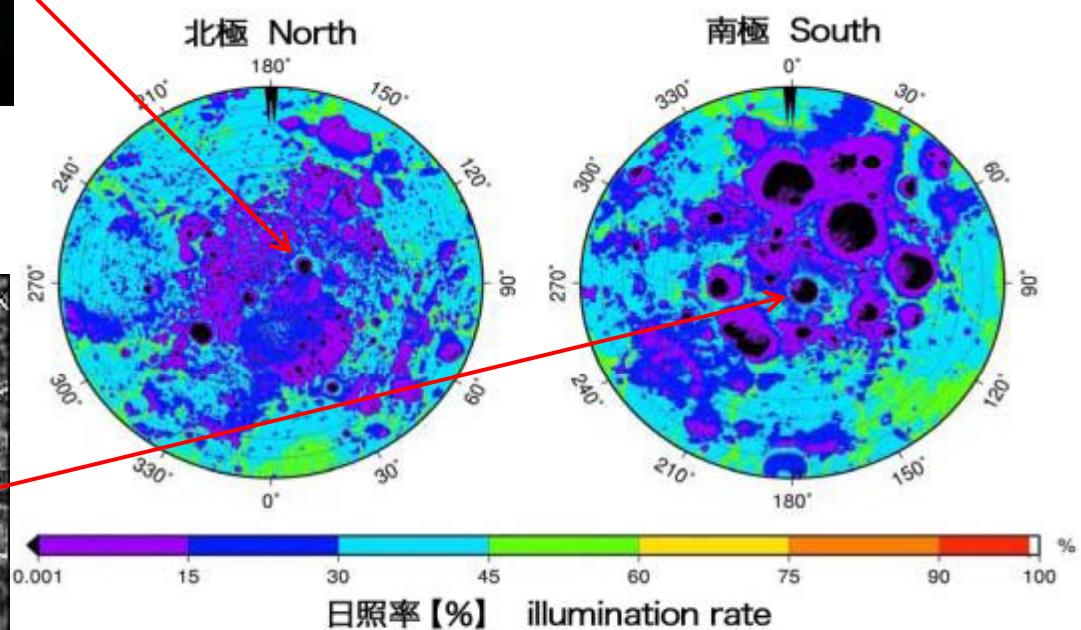
Sunlight  
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Regions of permanent sunlight and shadow at the poles

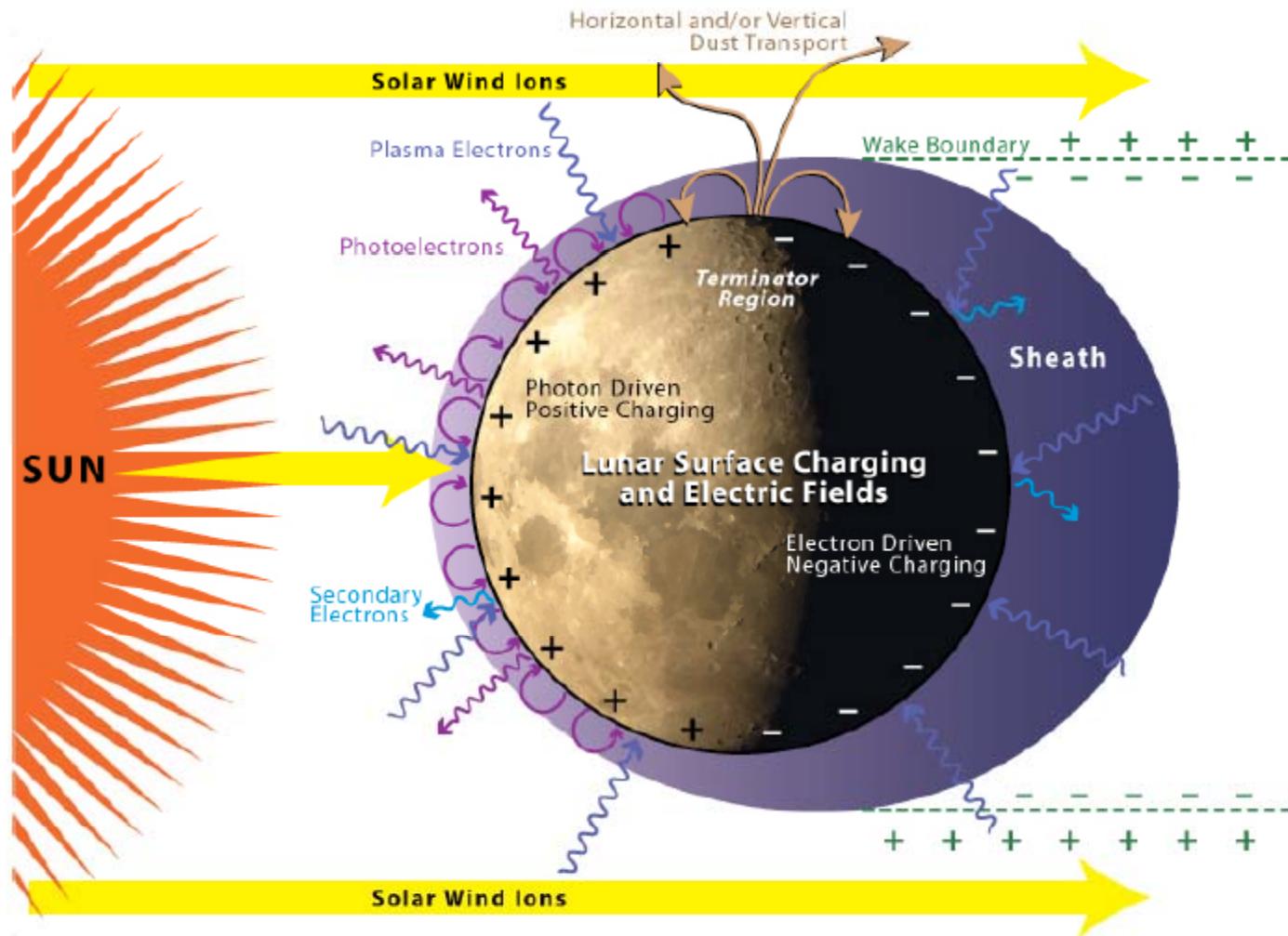
Temperatures in craters  $\sim 40\text{K}$





# Solar Wind

Introduction  
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Sunlight  
Solar Wind  
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Regolith  
Conclusions



Stubbs, 2007



# Solar Wind

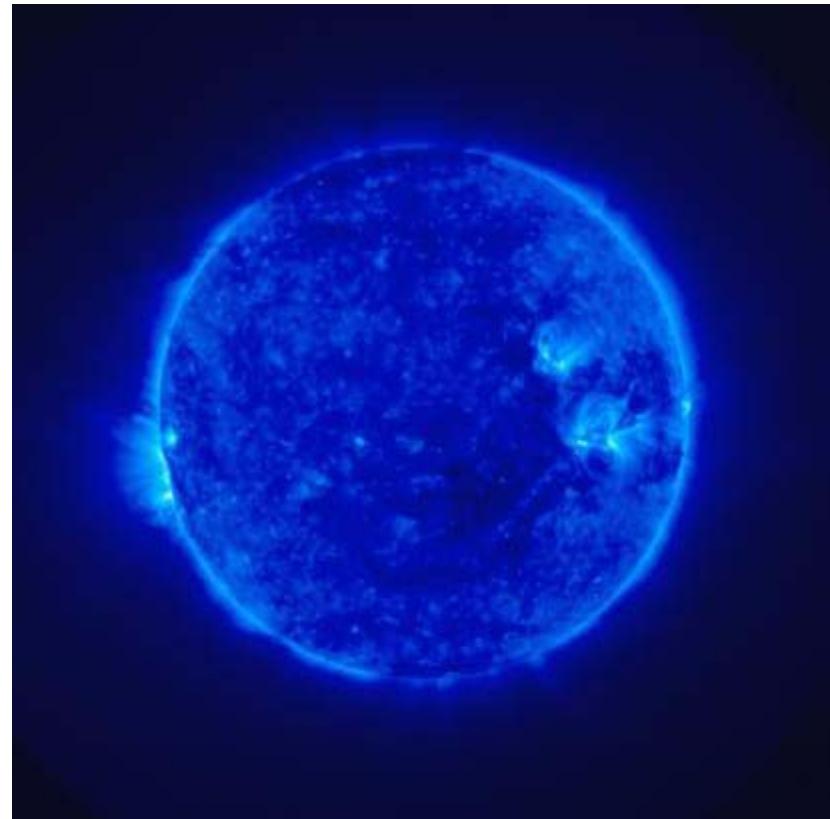
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- Hydrogen
  - Implanted on surface
  - Reducing environment
  - Source of OH/H<sub>2</sub>O on the surface(?)
- Helium-3
  - Source of electricity
  - Estimates vary based on exposure to solar wind particles
  - Greatest concentration likely found in the mineral ilmenite



# Water



Regolith  
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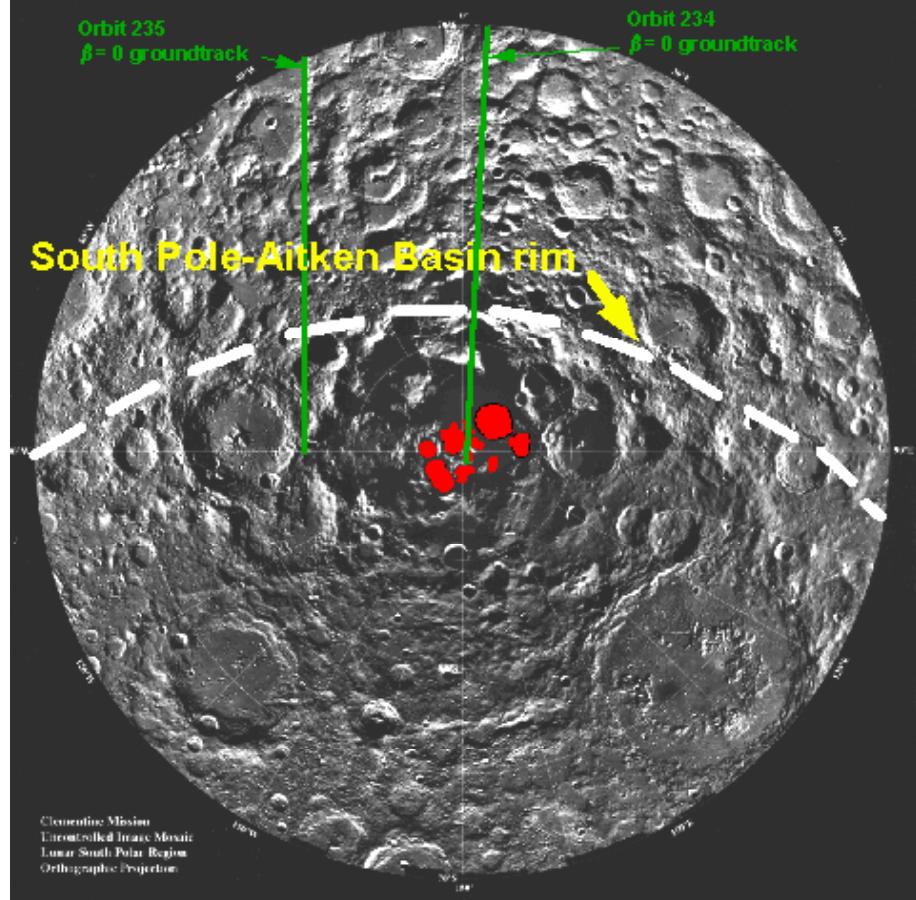
Introduction  
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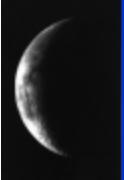
Magnitude and polarization  
of radar signals indicated  
volatile ices (Bistatic Radar  
Experiment)

First detection of possible  
water ice (or surface  
roughness – doubt caused  
by similar results for other  
areas by the Arecibo  
Telescope)



Clementine Map of the South Polar Region  
of the Moon





# Water

## Lunar Prospector Epithermal Neutrons (Poles)

Regolith Conclusions

Water Rock Types

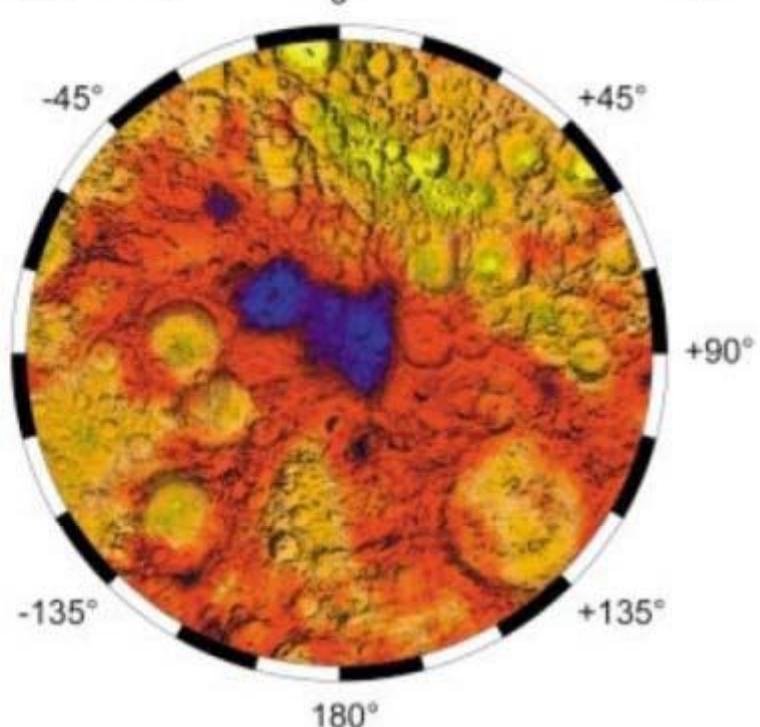
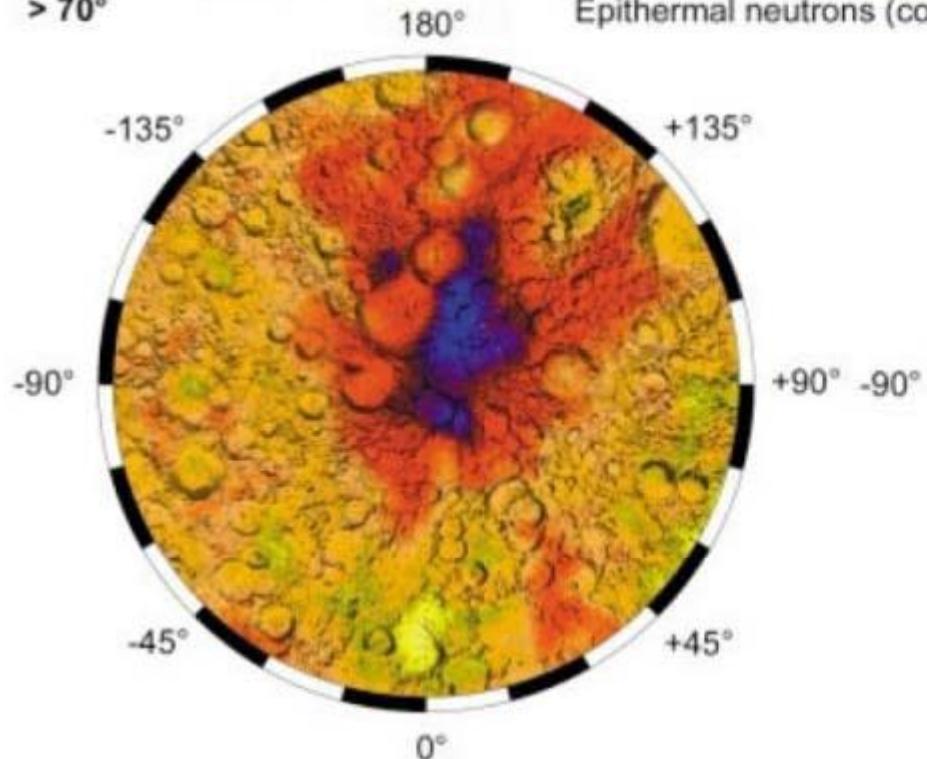
Sunlight Solar Wind

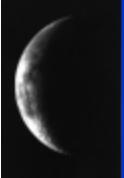
Introduction Locations



NORTH  
 $> 70^\circ$

SOUTH  
 $< -70^\circ$





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[Water](#)  
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Chandrayaan-1

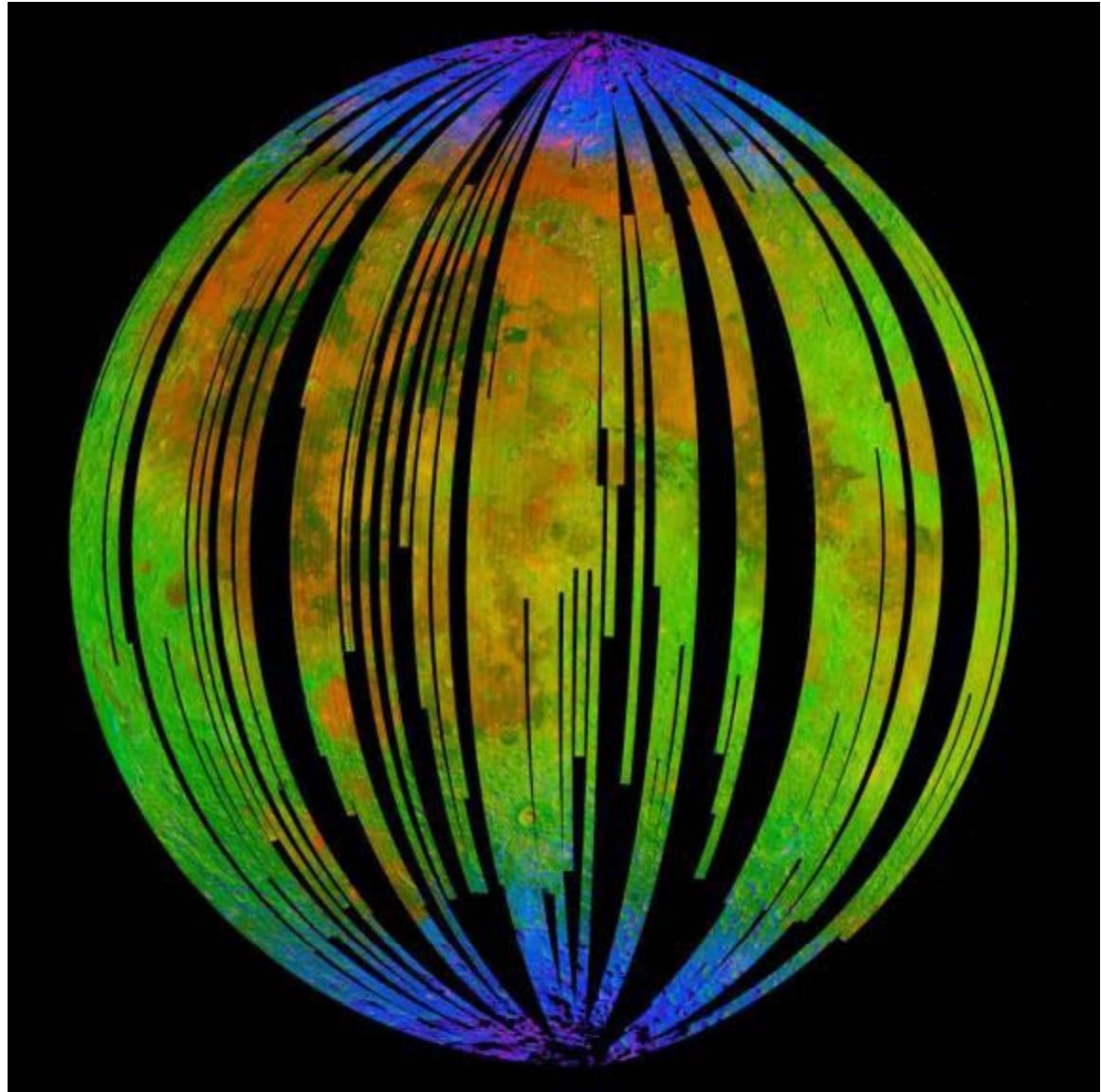
Reflected near  
infrared radiation

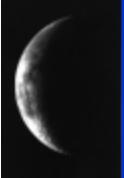
Purple/blue =  
water/hydroxyl  
signature

Red = pyroxene

Cover of Science Magazine,  
10-23-09

# Water





# Water

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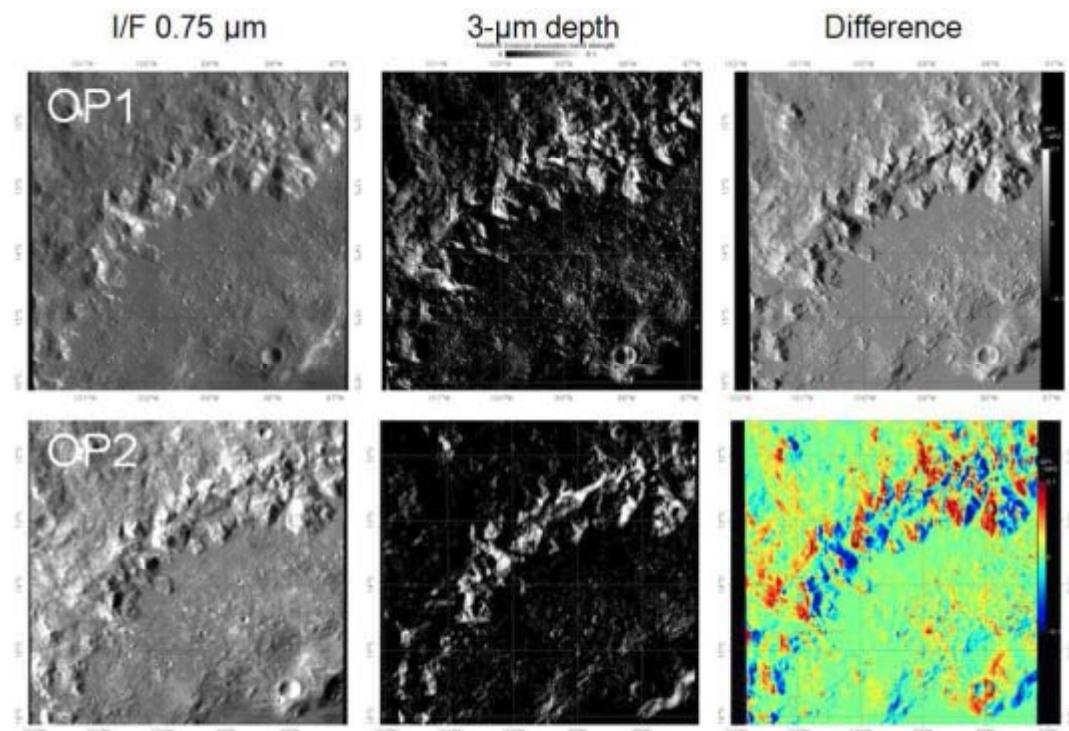
Introduction  
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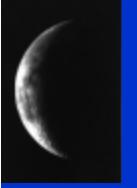
## Water Formation on the Lunar Surface ( $M^3$ )

- Hypothesized that water forms by the bombardment of the lunar surface by solar wind hydrogen
- The hydrogen bonds with oxygen from lunar surface minerals
- If the  $\text{OH}^-$  remains bound to the surface, it has a chance of bonding with another H
- Subject to photodissociation

$\text{H}_2\text{O}$  band  $3\mu\text{m}$ ,  
 $\text{OH}$  band  $2.85\mu\text{m}$

$3\mu\text{m}$  band depth for Orientale  
(lunar **8AM** and **4PM**)  
- A surface effect?





# Water

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## Lunar CRater Observation and Sensing Satellite

Visible and Infrared  
Spectrometers, Cameras,  
and a Photometer

Impacted Cabeus Crater  
(south pole)

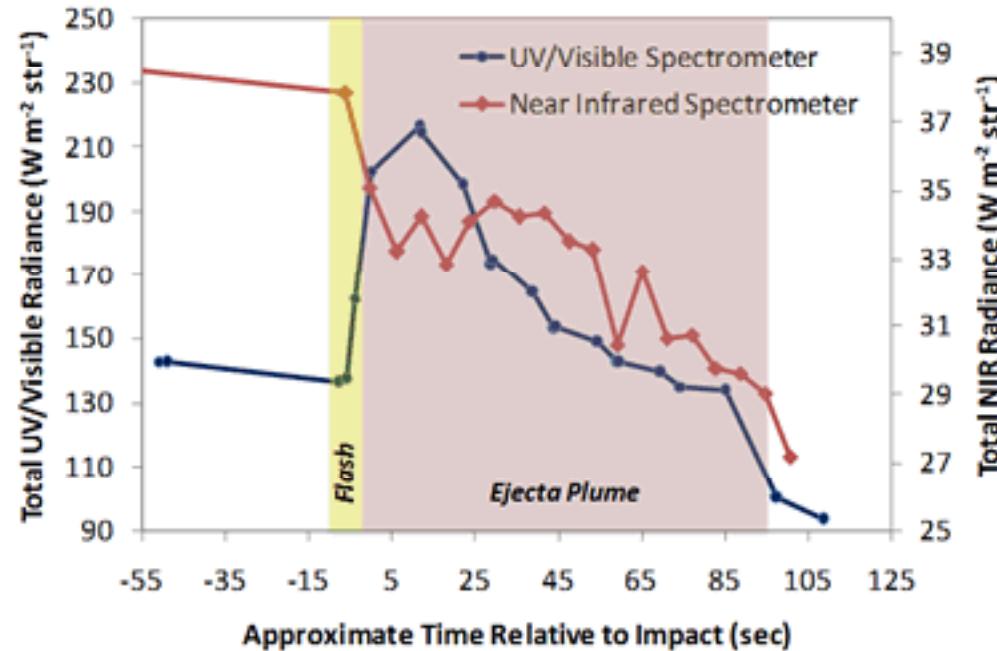
Confirmed the presence  
of water (~25 gallons  
within the plume)!



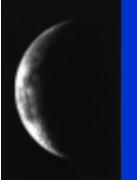
# Water

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- NIR detected dust, vapor, and ice,  $\text{SO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{CH}_3\text{OH}$ ,  $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{H}_2\text{CO}$ ,  $\text{C}_2\text{H}_2$
- UV detected OH, obtained grain size measurements due to reddening or bluing of spectra, also  $\text{NH}+\text{NH}_2$ , CN, CH, HCO,  $\text{H}_2\text{S}$ , CS, CO
- Data reduction is “a work in progress”



UV spectra also shows  
“prompt dissociation of  $\text{H}_2\text{O}$ ”



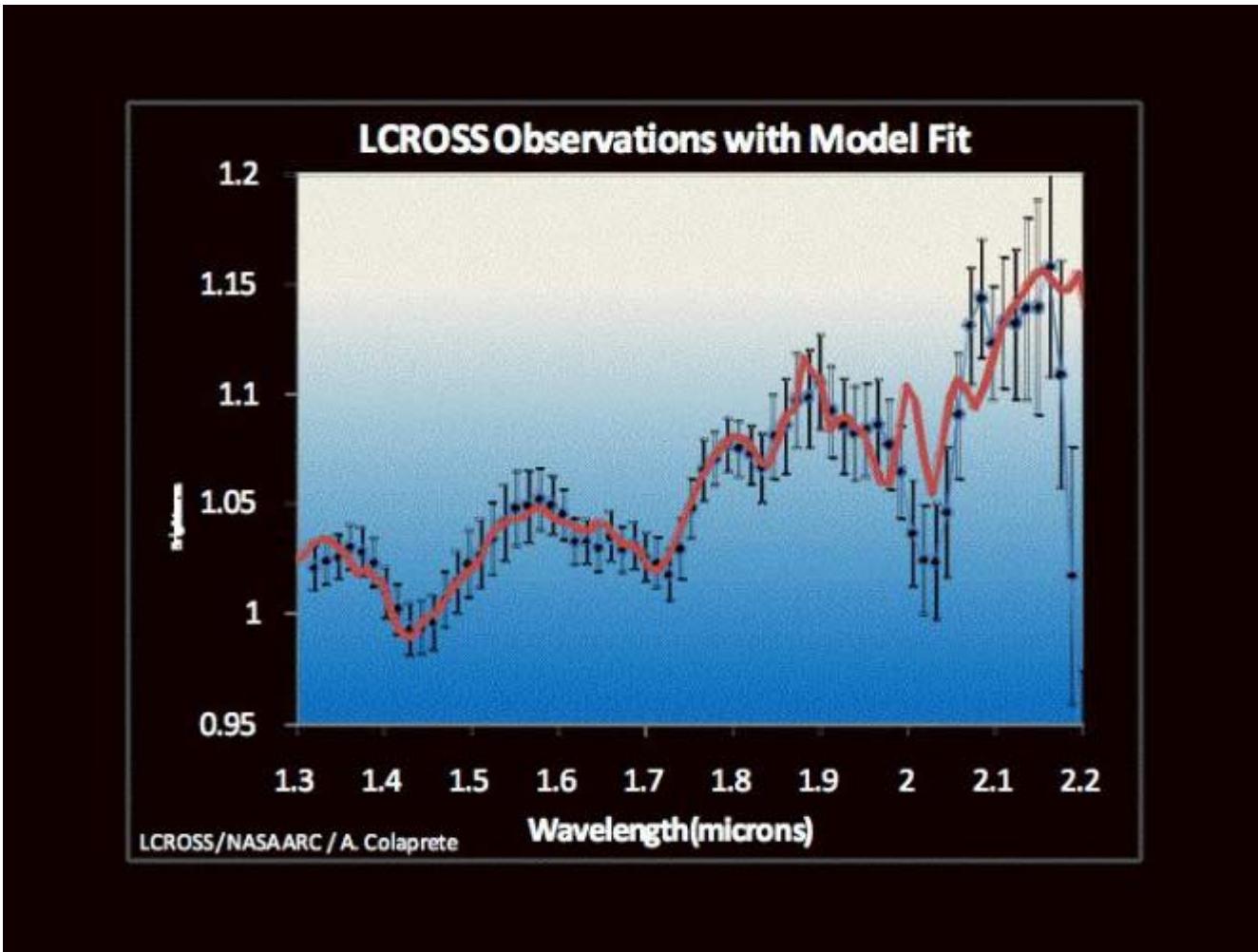
# Water

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Model fit includes water and other compounds (hydrocarbons and mercury)

Estimated mercury content based on LCROSS H<sub>2</sub>O results:  
~6 gallons in plume (after Reed, 1999)



# Water

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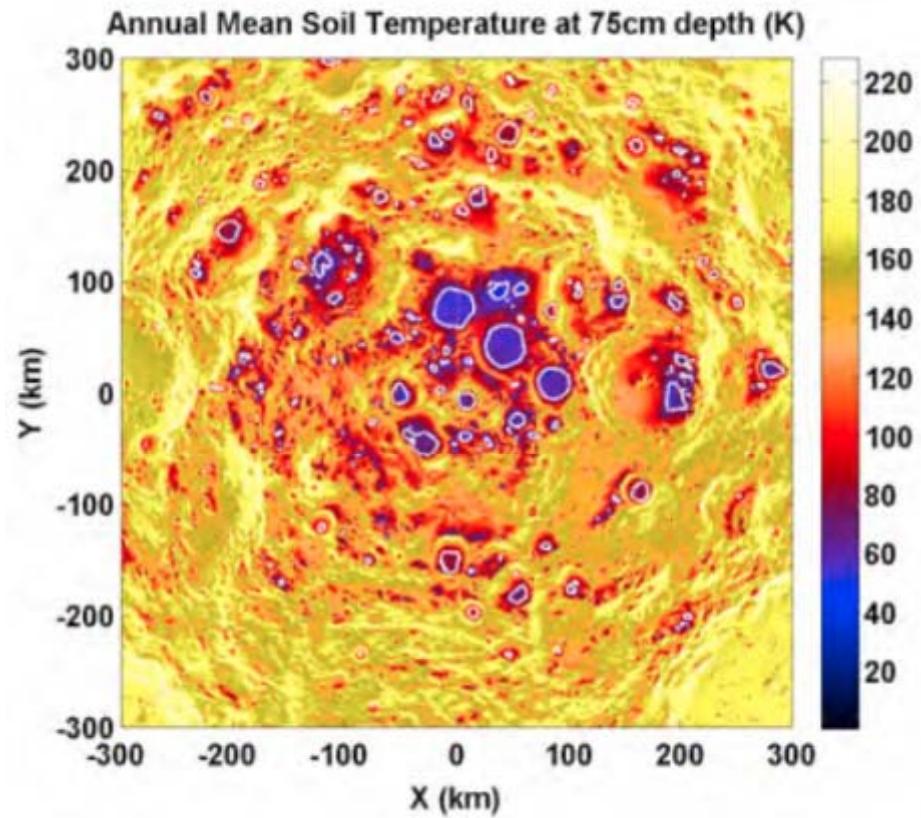
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- Annual temperature is ~60-70K at 75cm depth, indicates residence time of water is >1Ga in permanently shadowed regions
- Diffusion by regolith gardening would make permafrost disappear in regions except PSRs
- The obliquity of the Moon's orbit had to be less than 4 degrees for volatile emplacement
- Different methods of water collection proposed, none definitive
  - Hydrothermal
  - Random Walk
  - Cometary Source

Modeled from Diviner data by Elphic et al.





# Rock Types

## Common Rock Types

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*anorthosite*



*basalt*



*norite*





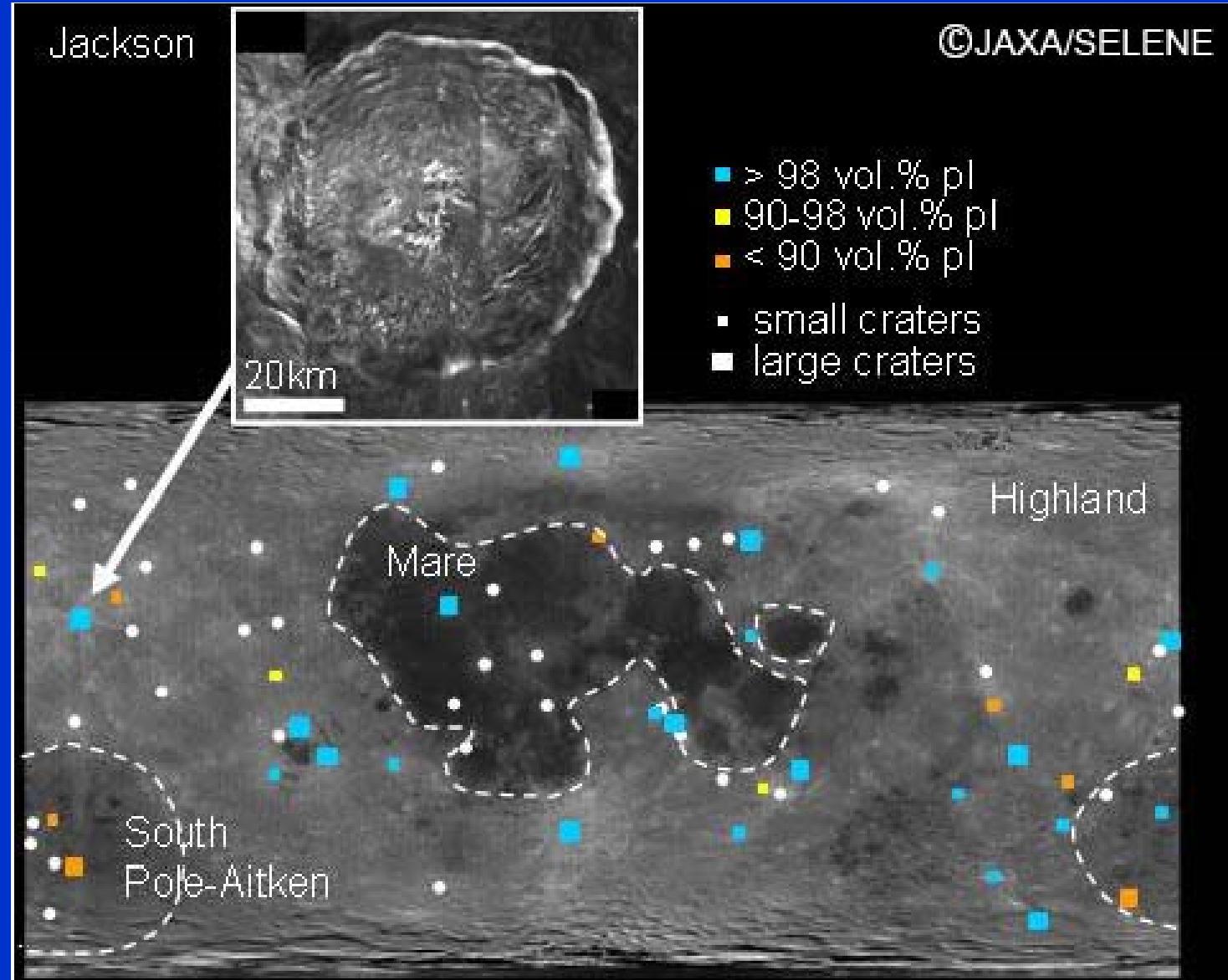
# Rock Types

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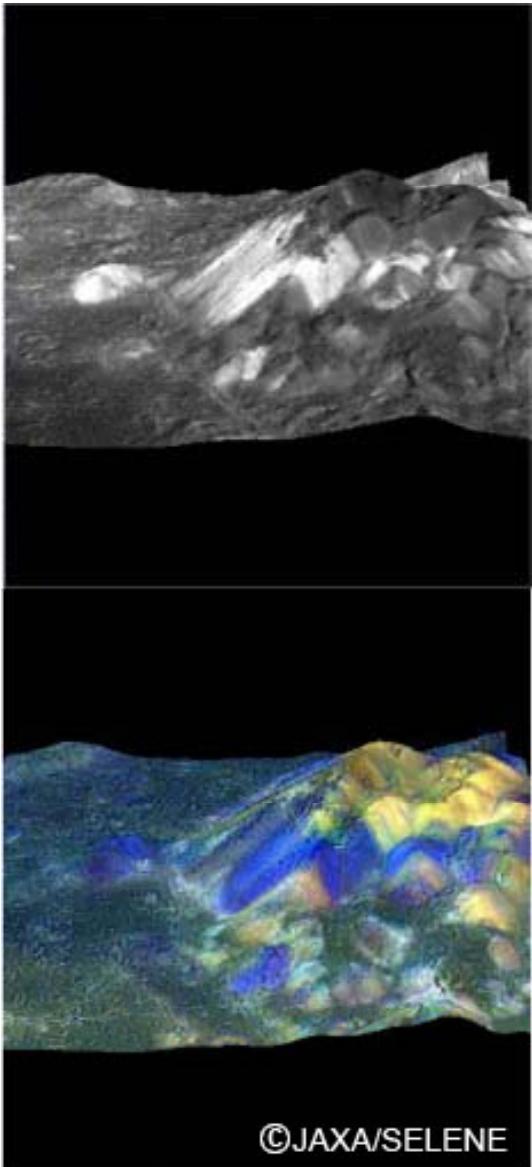
# Rock Types

## Jackson Crater

“Single-band (750 nm) image and a color image showing rock types (the strengths of absorption bands characteristic of individual minerals are indicated in red: pyroxene, green: olivine, and blue: plagioclase)”

[http://www.jaxa.jp/press/2009/09/20090910\\_kaguya\\_e.html](http://www.jaxa.jp/press/2009/09/20090910_kaguya_e.html)

Areas of olivine-rich rocks have also been found (Mare Frigoris, Imbrium, and near Mare Humorum)





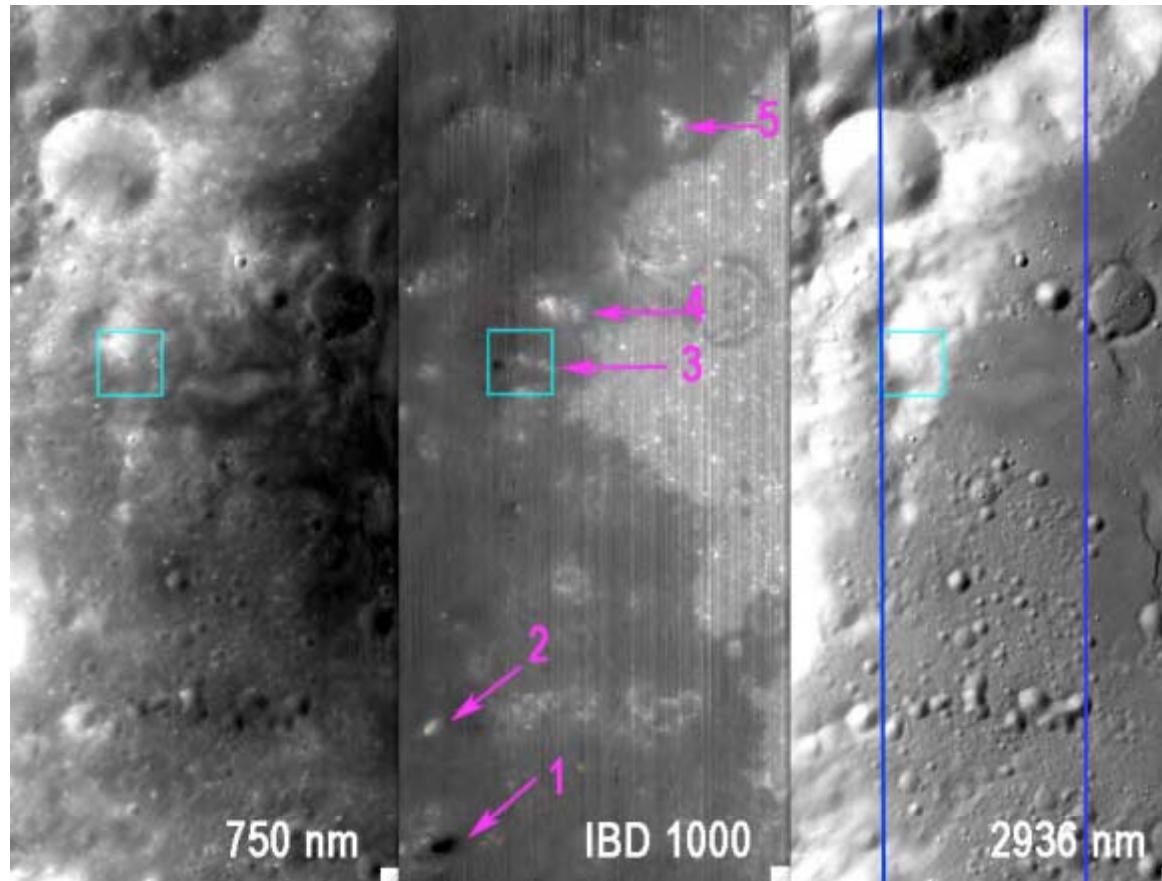
# Rock Types

Regolith  
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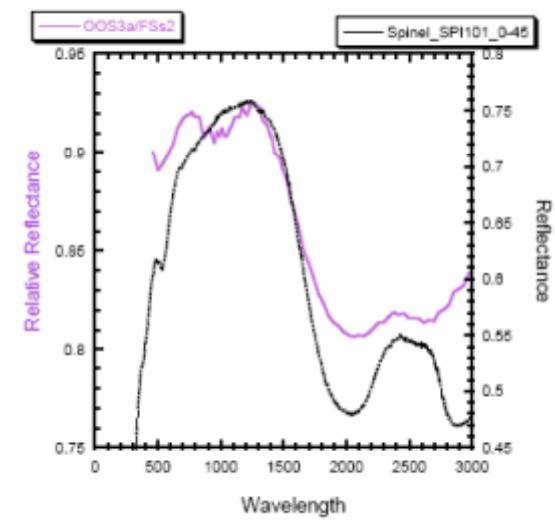
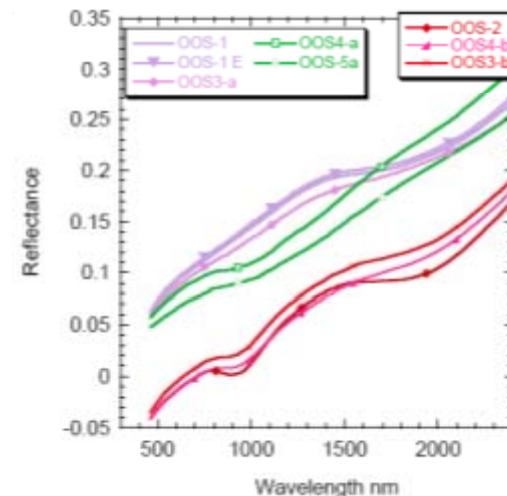
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Five areas in the rim of Mare Moscovиense are rich in olivine (green), pyroxene (red, offset), and spinel (purple)





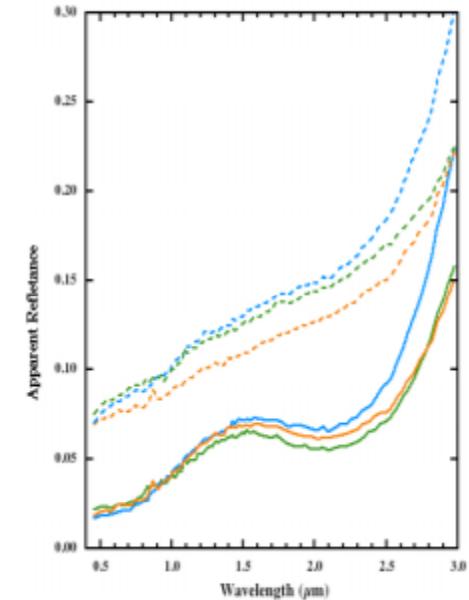
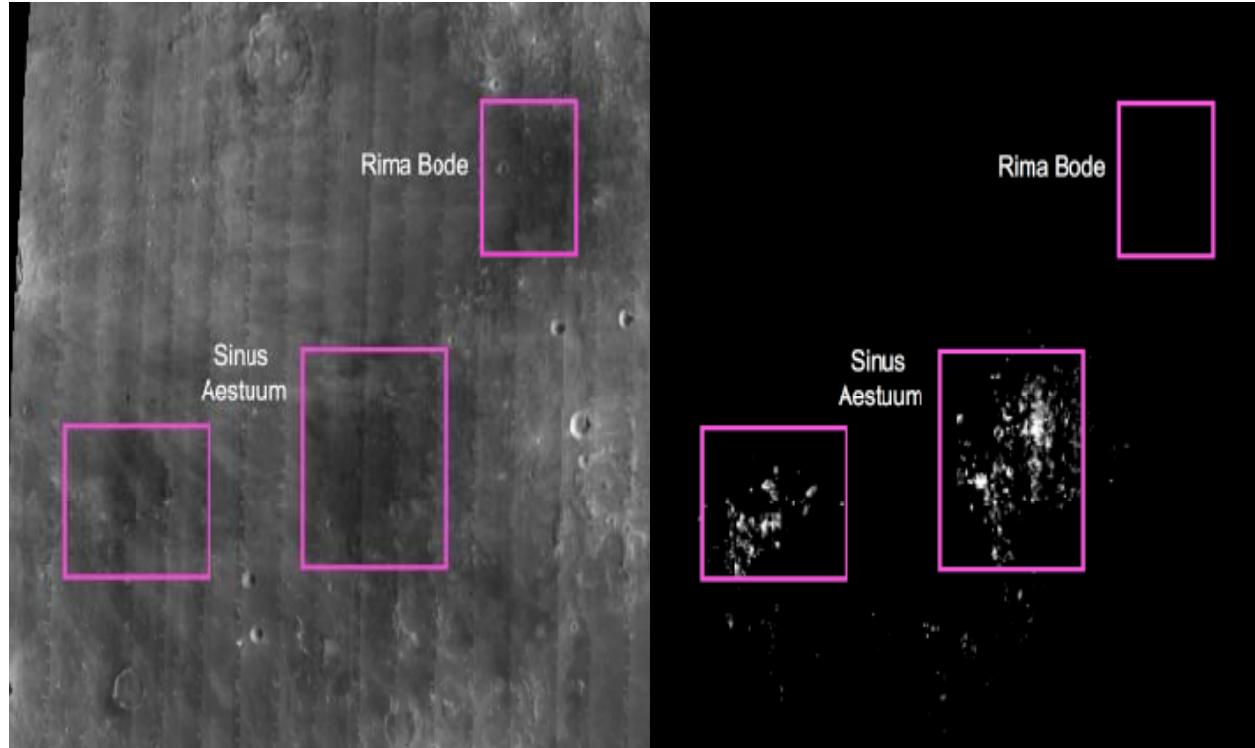
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Chromite deposits, hypothesized to be pyroclastics from a buried vent  
Rima Bode also has a dark mantle deposit, but does not have the chromite  
signature (solid bands, dashed bands are typical regolith)



# Regolith

Regolith  
Conclusions

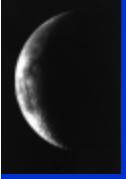
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- “Regolith” is the term for the layer or mantle of fragmental or unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms the surface (Lucey et al., 2006)
- Everything that separates the solid Moon from space
- The CELMS (Chang'e lunar microwave sounder) instrument was used to determine the maximum depth of regolith thickness by changes in temperature (max 20m). Other estimates are between 5 and 12m.





# Regolith

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- Regolith is what we measure with remote sensing satellites
  - X-ray fluorescence, optical and infrared spectra, and gamma ray techniques penetrate no more than 20 $\mu\text{m}$ , 1m, and 10-20cm, respectively. (Radar can penetrate ~30m.)
- All lunar materials were returned from the upper 3 meters of the surface
- ALL of our geochemical information was obtained from the lunar regolith!





# Regolith

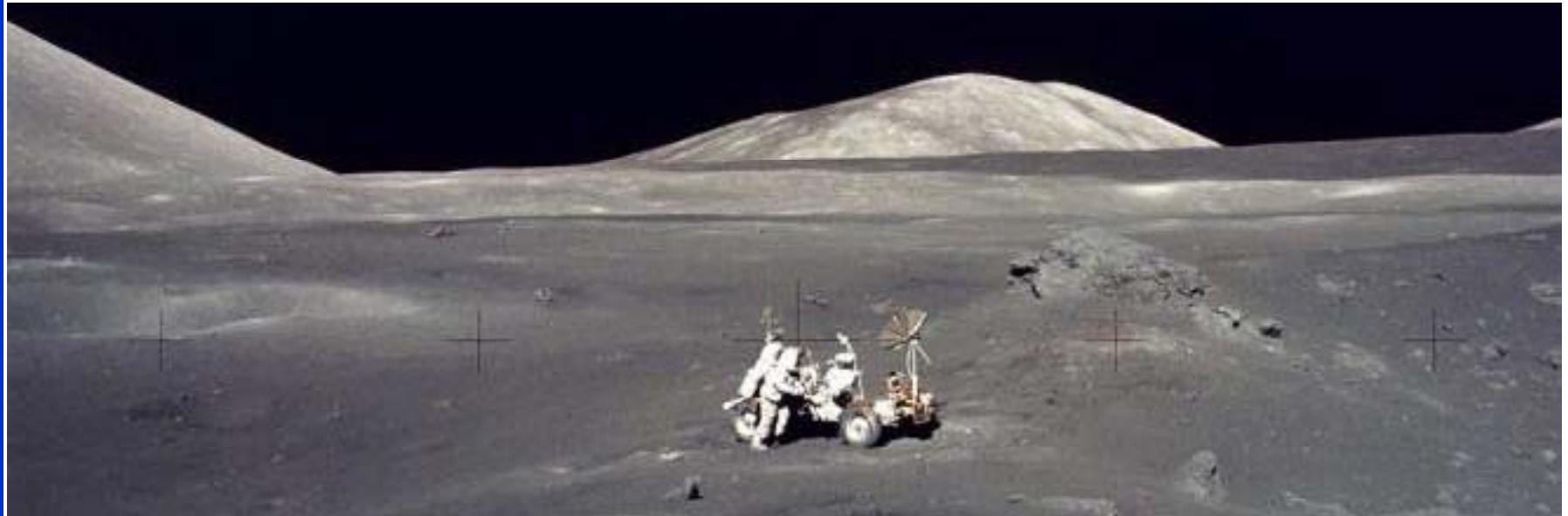
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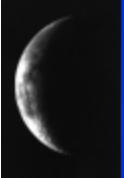
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- Can be sintered using microwaves to create roads
- Can provide radiation shielding
- Can be used as a growing medium for plants
- Habitat construction





# Conclusions

- We need to know where we are going to know what technologies we can use
- We also need to develop the technologies now so they can one day be applied to the Moon
- Multiple simulants must be developed to reflect the variability of the lunar surface
- Remote sensing continues to discover new variables in the lunar surface
  - Water/ice deposits
  - Rock types/concentrates