# Characterising the lunar crust-mantle transition zone with visible-near infrared spectroscopy from $M^3$ data

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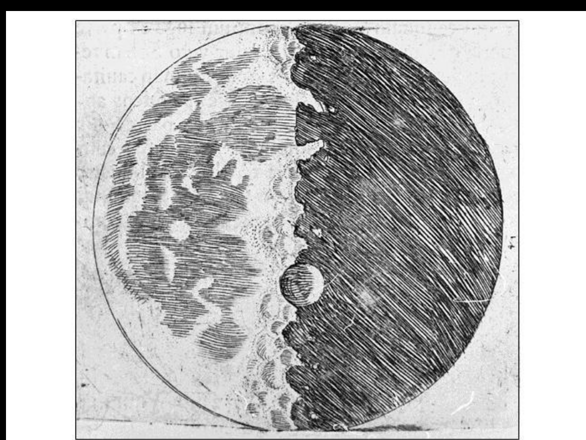
# Outline

- Short introduction to lunar exploration
- Current scientific questions related to lunar science
- Research project

# What we knew from the Moon before the space era

## Mountains = *terrae* / Seas = *mare*

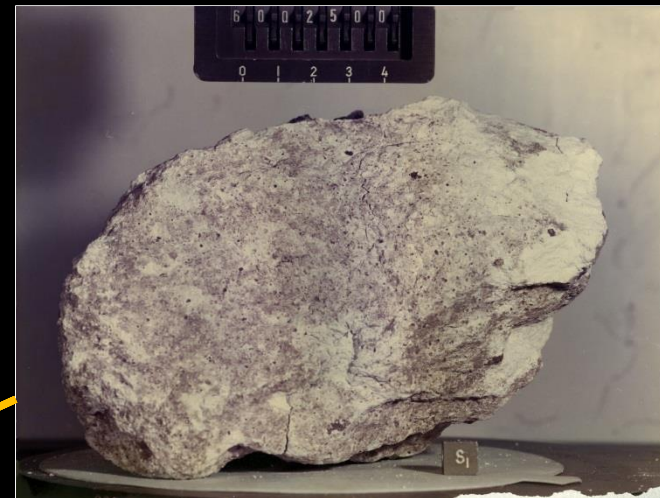


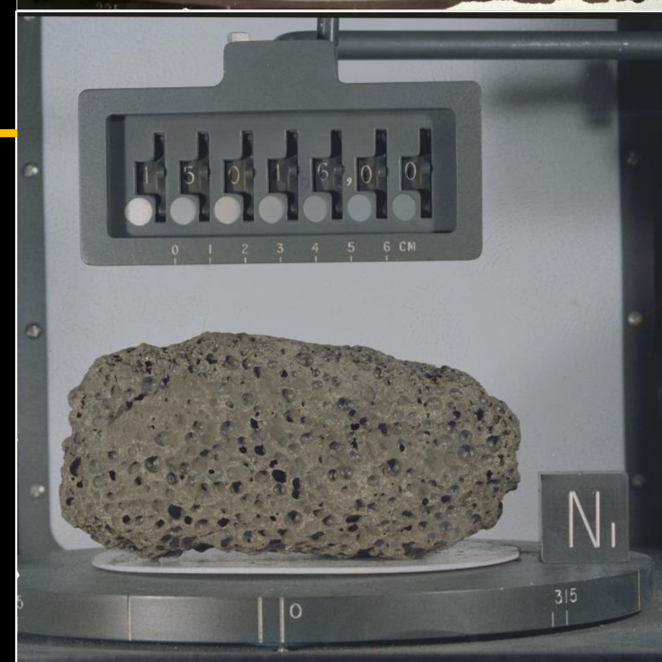
Galileo Galilei's sketch of our Moon

Claude Mellan's sketch of our Moon, 1634-1635

Apollo 15 photograph AS15-82-11145.

# Apollo legacy





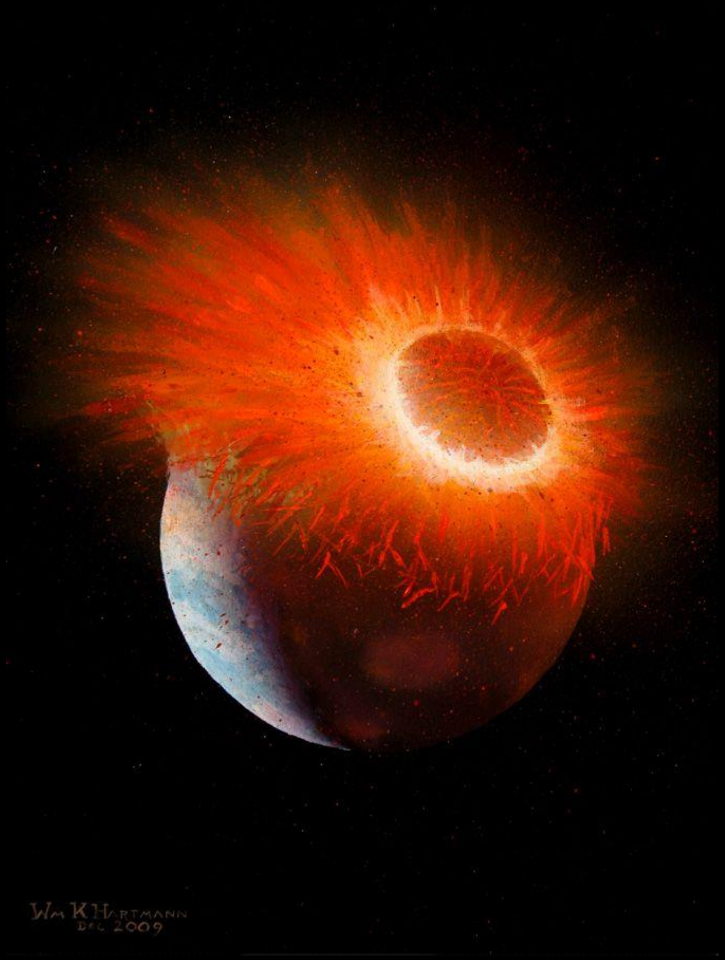
- Samples analysis results:
  - crust = anorthosite
    (plagioclase + some pyroxene)
  - mare = basalt
    (pyroxene + plagioclase, olivine)

- Moon formation in dry conditions (samples contain very little water)

# Moon formation

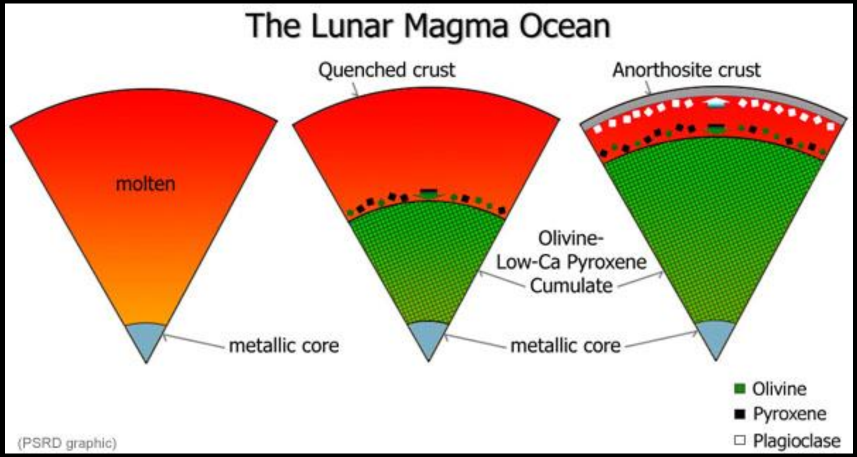
- Earth-Moon system formation

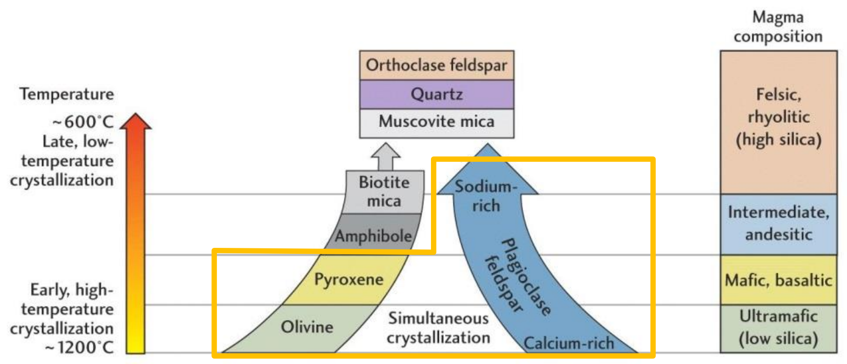
- 4 theories:
  - Capture
  - Fission
  - Accretion
  - Impact (current preferred hypothesis)



# Moon formation

- Cristallisation of a molten body: magma ocean concept
- Earth and Moon mantle = olivine-rich

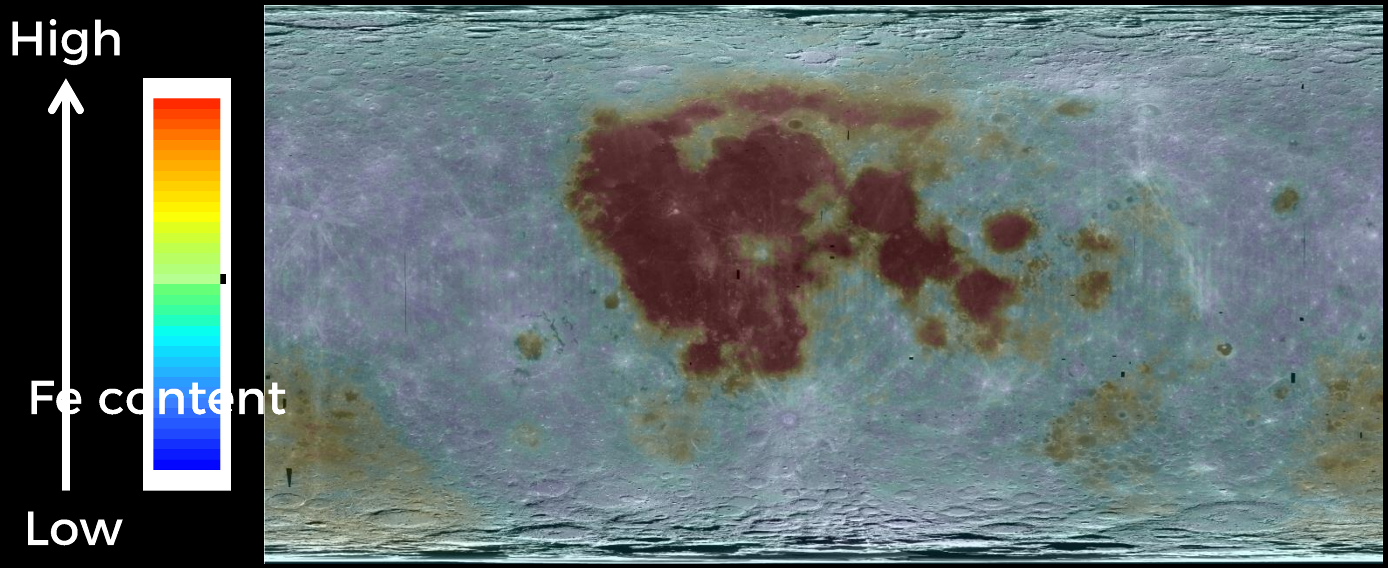



Bowen's fractional cristallisation series

# Lunar space missions 1990s

- Clementine:
  - Crustal thickness maps (0-120 km)
  - Water ice at the poles?
- Lunar Prospector:
  - Global compositional maps
  - Water at the poles



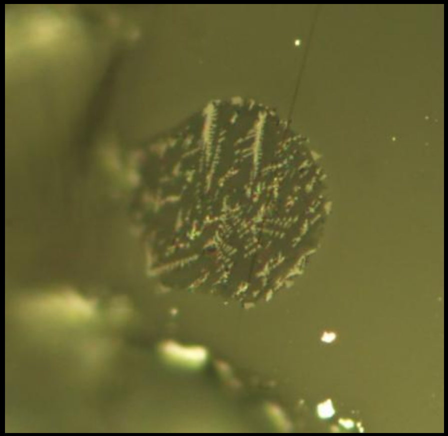

Lunar Prospector Iron abundance map overlaid on Clementine global UVVIS map

# Lunar space missions 2000s-2010s

- SMART-1 (ESA)
- Kaguya (JAXA)
- Chang'e 1, 2, 3 (CNSA)
- Chandrayaan-1 (ISRO)
- LRO (NASA)
- LCROSS (NASA)
- GRAIL mission (NASA)
- LADEE (NASA)

- + water discovered in Apollo sample, in the form of melt inclusions

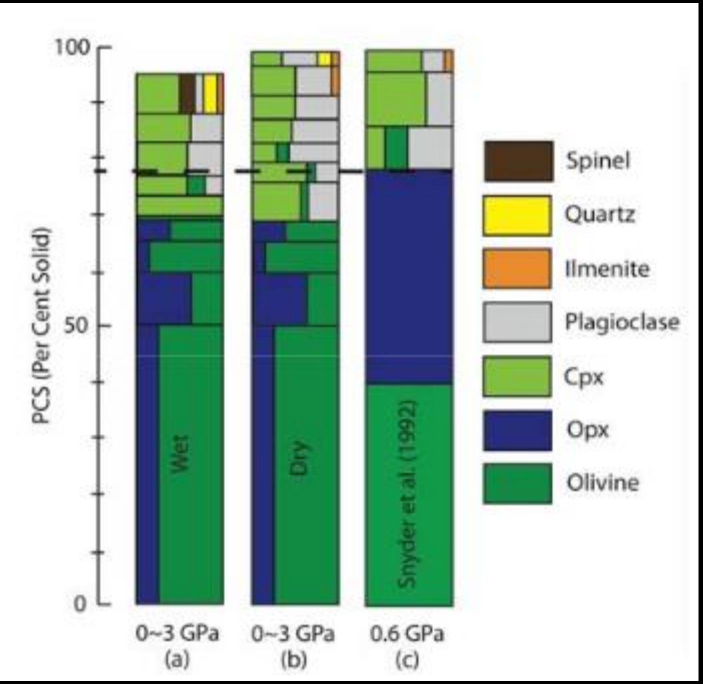
- High resolution images, spectroscopic data, gravimetric data...



Saal lab/Brown University

# New questions to be addressed by lunar scientists

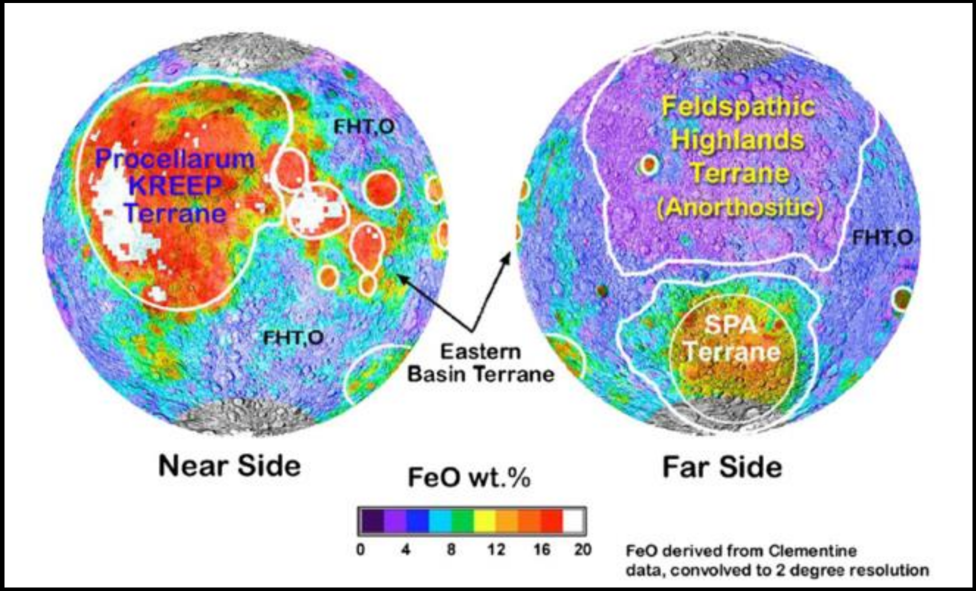
- What is the effect of water during LMO cristallisation?
- How does water influence the thermal evolution of the Moon?
- What is the evolution of the crustal composition with depth? And laterally, are there differences?
- Terrestrial planets' mini-me




Lin *et al.*, LPSC 2016

# Lateral variations

- 3 main terrains on the Moon
- 17% Moon is covered in volcanic material (mare). Intrusions in depth elsewhere?



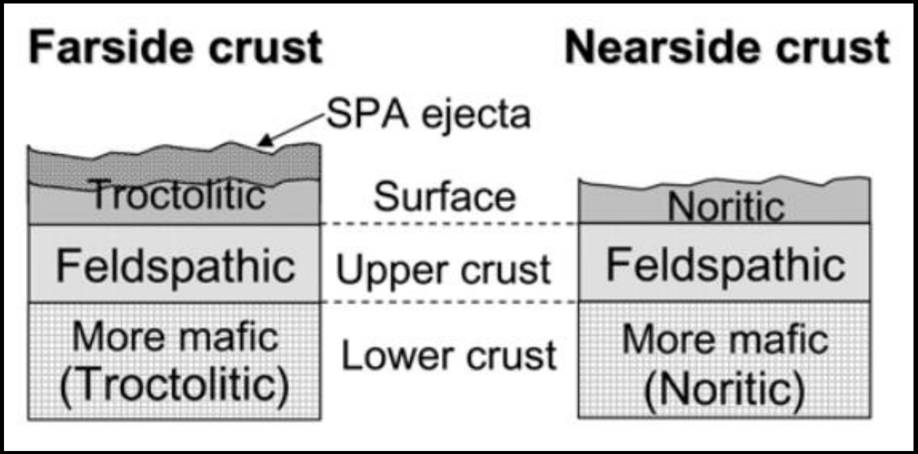

Jolliff *et al.* (2000)

# Research questions

- Establish a **stratification** of the lunar crust

- Characterize the **lateral variations** of composition (if existing)

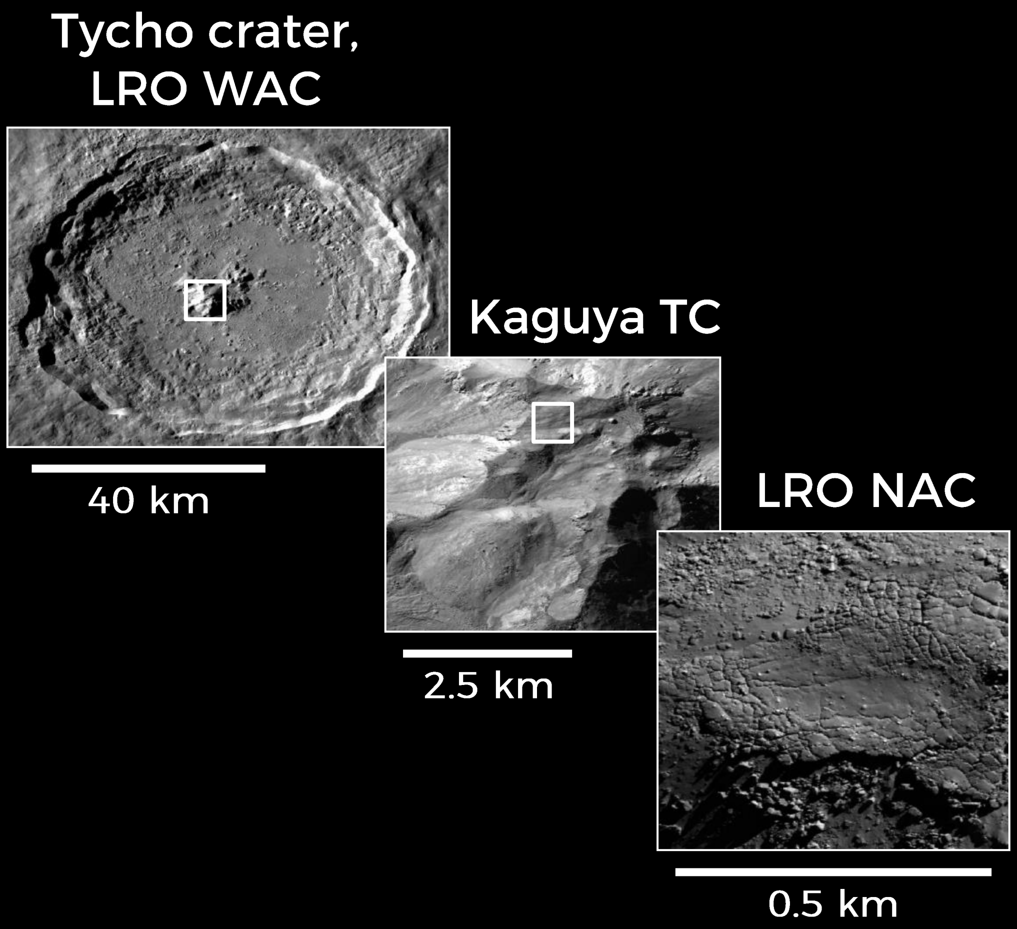
- Characterize the **crust-mantle transition zone** (composition, depth)




Arai *et al.* (2008), from Hawke *et al.* (2003) and Lucey (2004)

# Datasets (1)

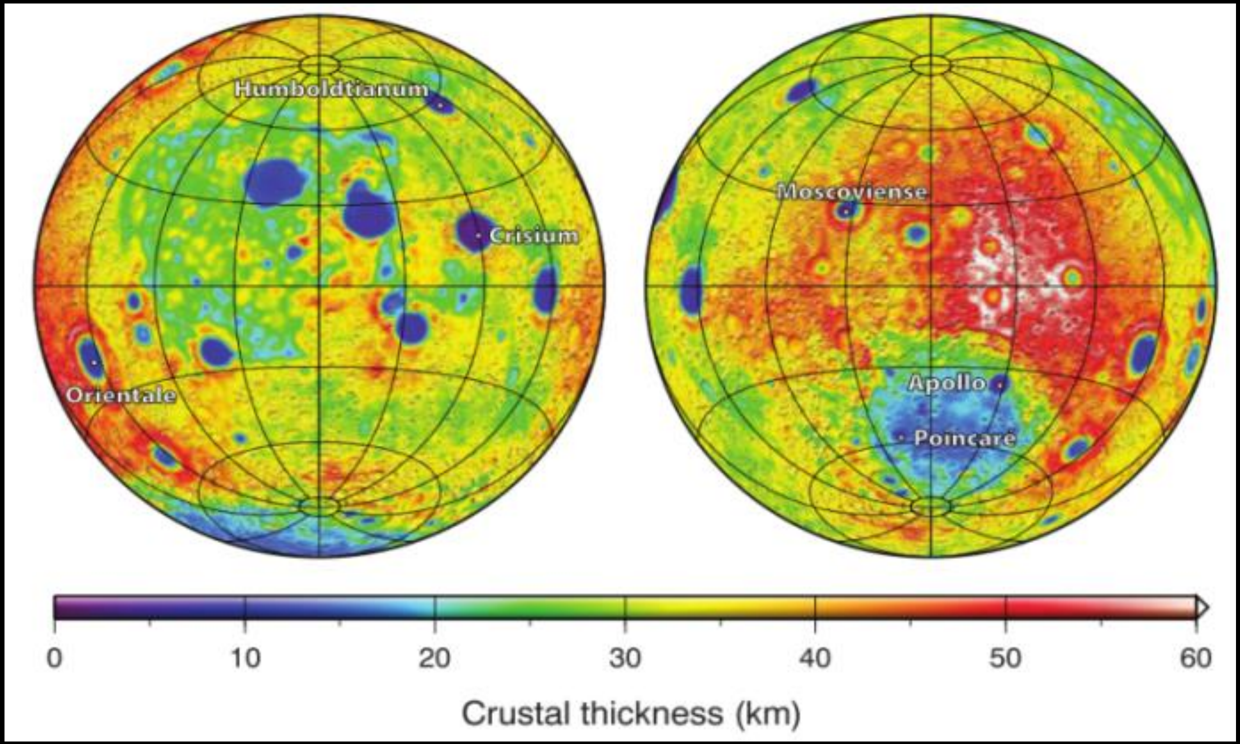
- Lunar Reconnaissance Orbiter Cameras (LROC) and Kaguya Terrain Camera (TC): high resolution images



# Datasets (2)

4 GRAIL crustal thickness models from Wieczorek *et al.* (2013)

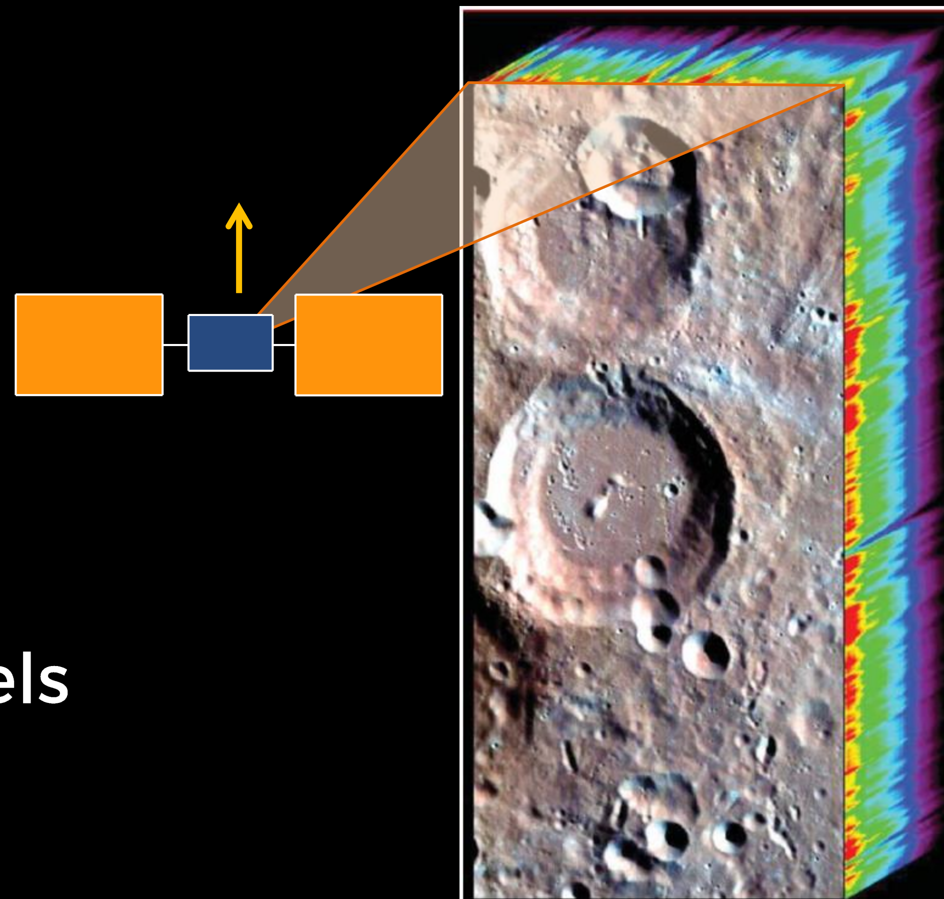
| Model | Average thickness (km) | Minimum thickness (km) | Apollo 12/14 thickness (km) | φ (%) | $\rho_m$ (kg m$^{-3}$) | λ |
|---|---|---|---|---|---|---|
| 1 | 34 | 0.6 | 29.9 | 12 | 3220 | 80 |
| 2 | 35 | 0.2 | 30.8 | 7 | 3360 | 80 |
| 3 | 43 | 1.0 | 38.1 | 12 | 3150 | 70 |
| 4 | 43 | 0.5 | 38.0 | 7 | 3300 | 70 |




Wieczorek *et al.* (2013)

# Datasets (3)

- Moon Mineralogy Mapper (M³) data (2008-2009):
  - hyperspectral imager onboard Chandrayaan-1
  - 85 spectral channels
  - 430 – 3000 nm
  - spatial resolution: 140 or 280 m/pixel



Green *et al.*, 2011

# Surface composition
# VNIR spectroscopy

| Application Field | 13000 $cm^{-1}$ | 4000 $cm^{-1}$ | 400 $cm^{-1}$ | 100 $cm^{-1}$ | |
|---|---|---|---|---|---|
| Spectroscopy | VIS | NIR (13000 - 4000 $cm^{-1}$) | MIR (11000 - 400 $cm^{-1}$) | FIR (400 - 100 $cm^{-1}$) | |
| Astronomy | VIS | NIR (0.7/1.0 - 5μm) | MIR (5 - 25/40μm) | FIR (25/40 - 200/300μm) | |
| Remote Sensing | VIS | NIR (0.7 - 1.0) | SWIR (1.0 - 2.5μm) | TIR ([illegible] - 5 μm MWIR) ([illegible] - 14μm LWIR) | |
| | 0.7μm | 1.0μm | 2.5μm | 14μm | |

Hecker *et al.*, 2010

**$M^3$: 430 – 3000 nm**

# Surface composition VNIR spectroscopy

Band I (~1000 nm):

Iron oxide contained in the minerals (olivine, pyroxene, glass) (Burns *et al.*, 1972)

Band II (~2000 nm):

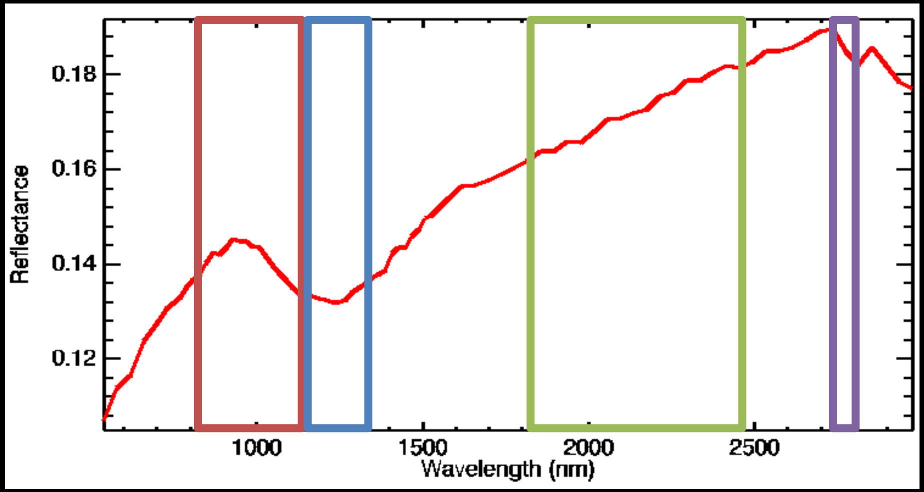
Electron transitions in the minerals (pyroxene, spinel, glass) (Burns *et al.*, 1972)

Band 1250 nm:

Plagioclase (Adams and Goullaud, 1978)

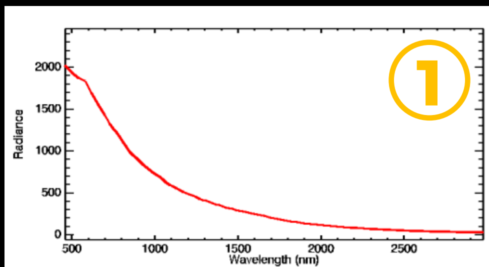
Band 2800 nm:

Water molecules and hydroxyl ion (Clark *et al.*, 2010)

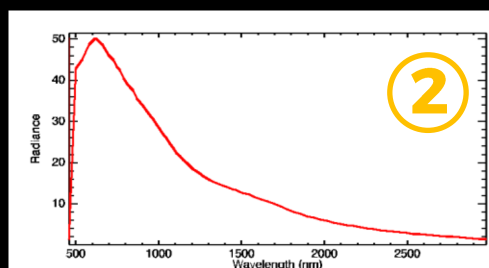



Surface reflectance spectrum (plagioclase spectrum)

# Surface composition VNIR spectroscopy

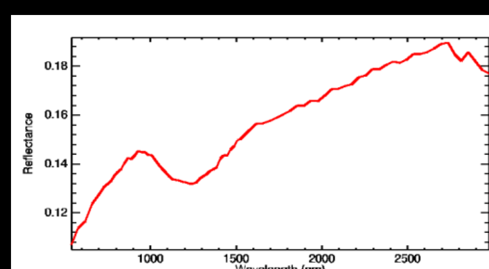



Solar radiance spectrum

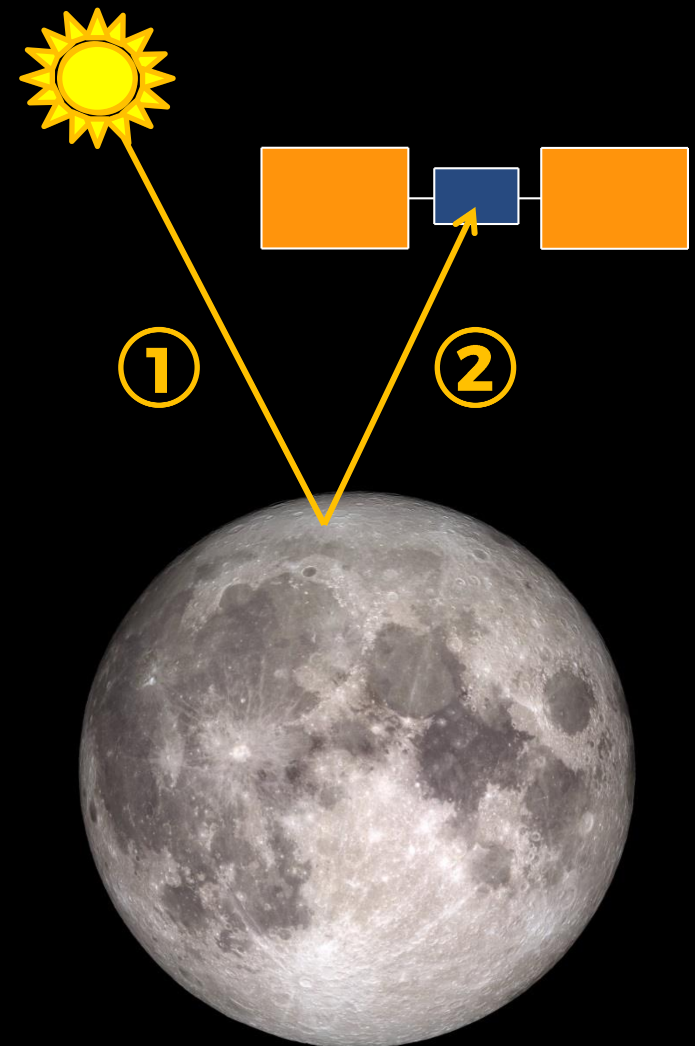



Surface radiance spectrum

② divided by ① = surface reflectance spectrum

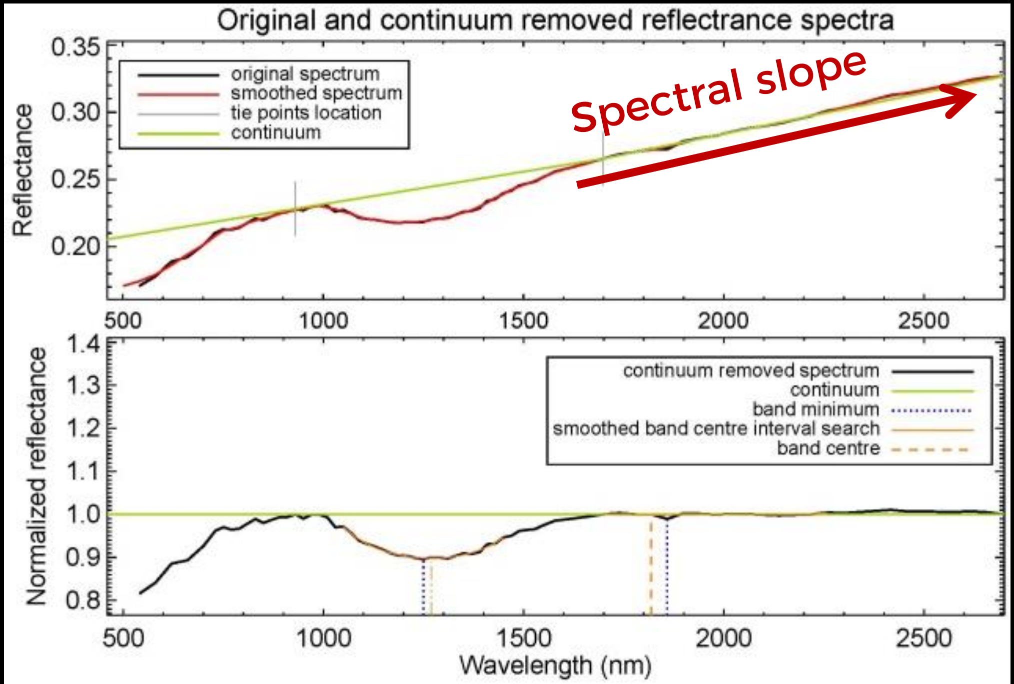



Surface reflectance spectrum



# Surface composition VNIR spectroscopy

- Spectral slope caused by space weathering: nanophase metallic iron is created (darkens the soil and weakens the 2000 nm absorption band)




$M^3$ plagioclase spectra

# Link between spectroscopy and stratification of the crust?

Spectroscopic data gives mineralogical informations

→

Plagioclase = crustal material
Pyroxene and olivine = mantle material?

↓

Crustal thickness models

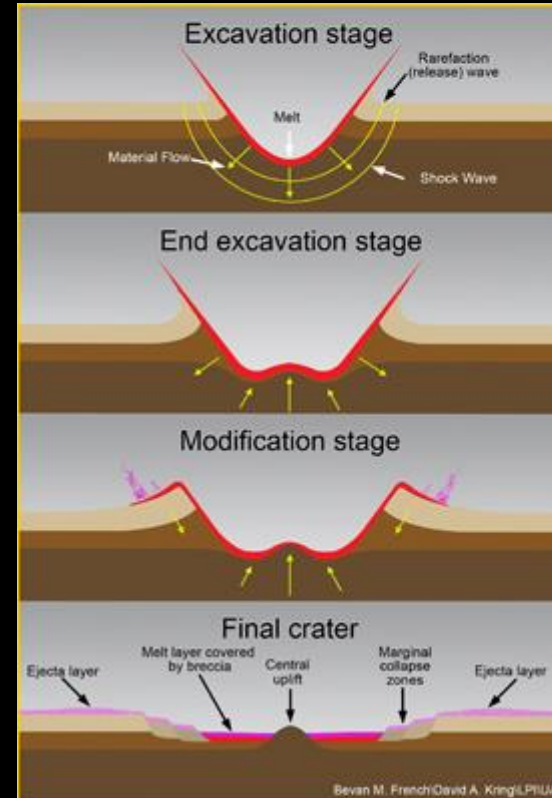
←

**Does all this match?**

# Methods
# Craterisation process

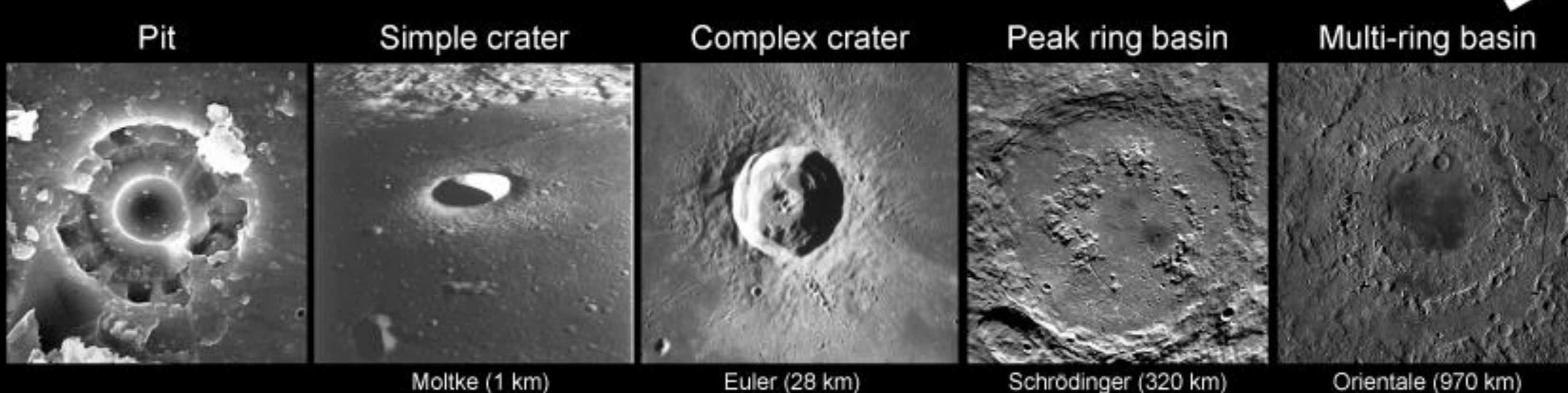
How can we see the crust-mantle transition zone with surface data??

**CRATERS**



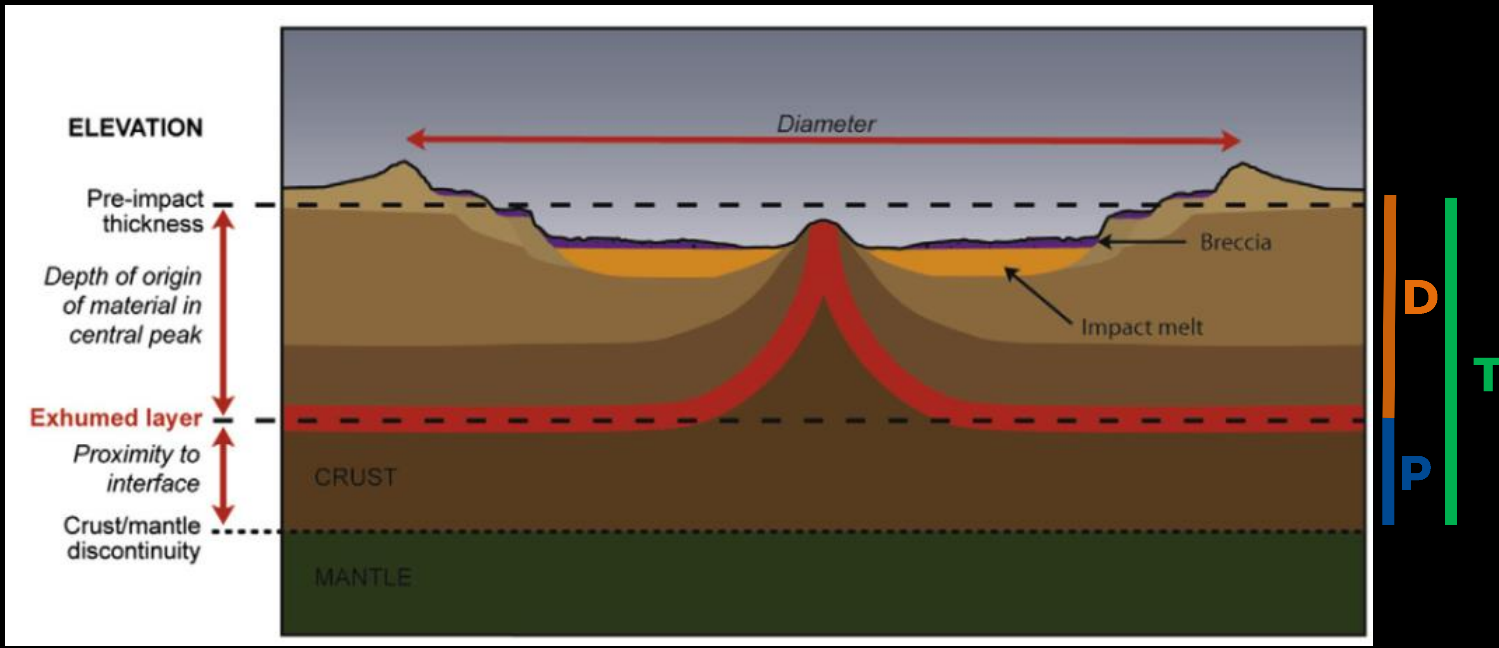

Bevan M. French\ David A. Kring\LPI\UA.

Crater size




LPI (Priyanka Sharma)

# Methods
# Proximity calculation




Flahaut *et al.* (2012)

**P = T – D**

- **T** = pre-impact thickness
- **D** = melting depth (Cintala and Grieve, 1998)

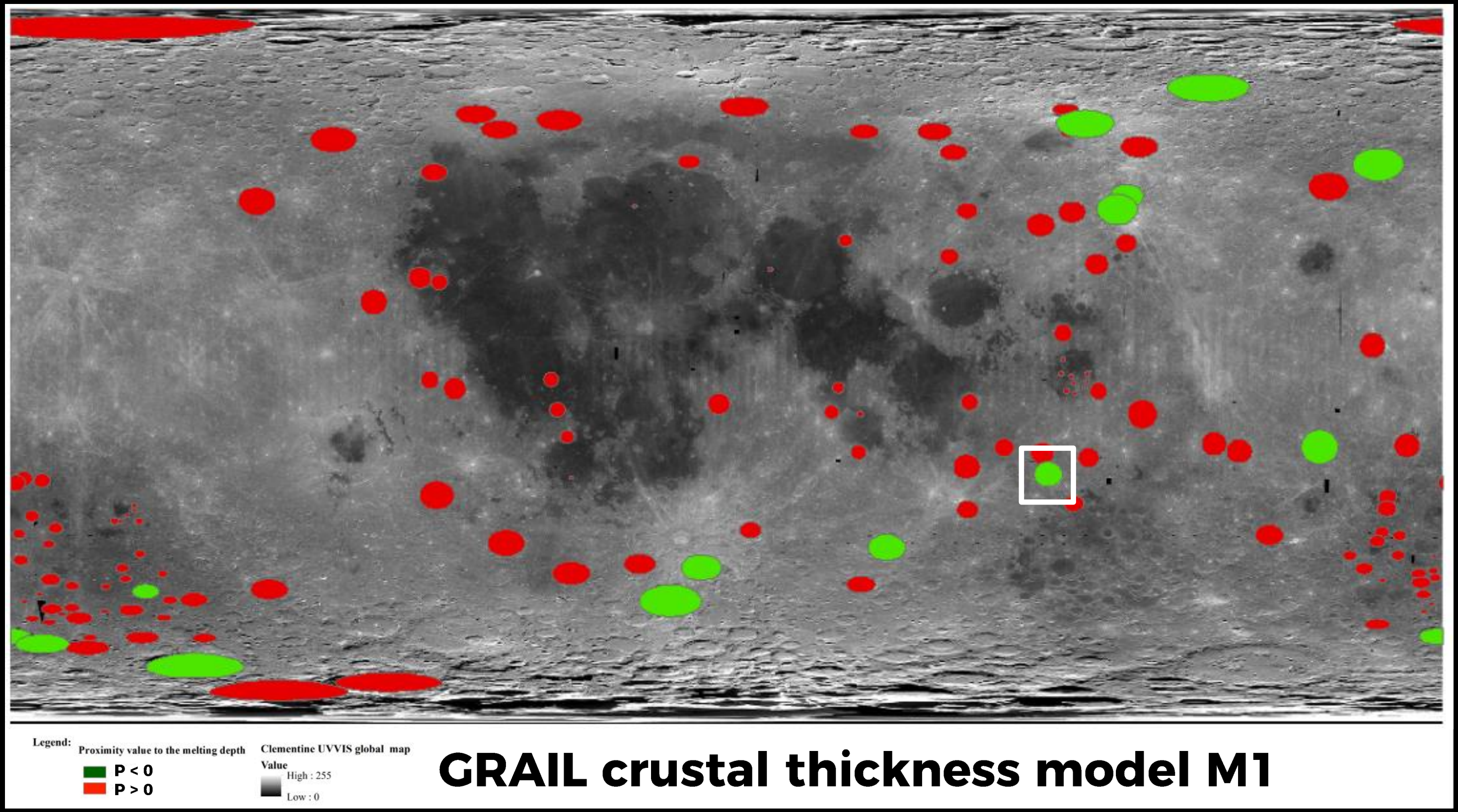
**Proximity > 0**: only the crust is sampled

**Proximity < 0**: the mantle might be sampled

# Methods
# Crater selection

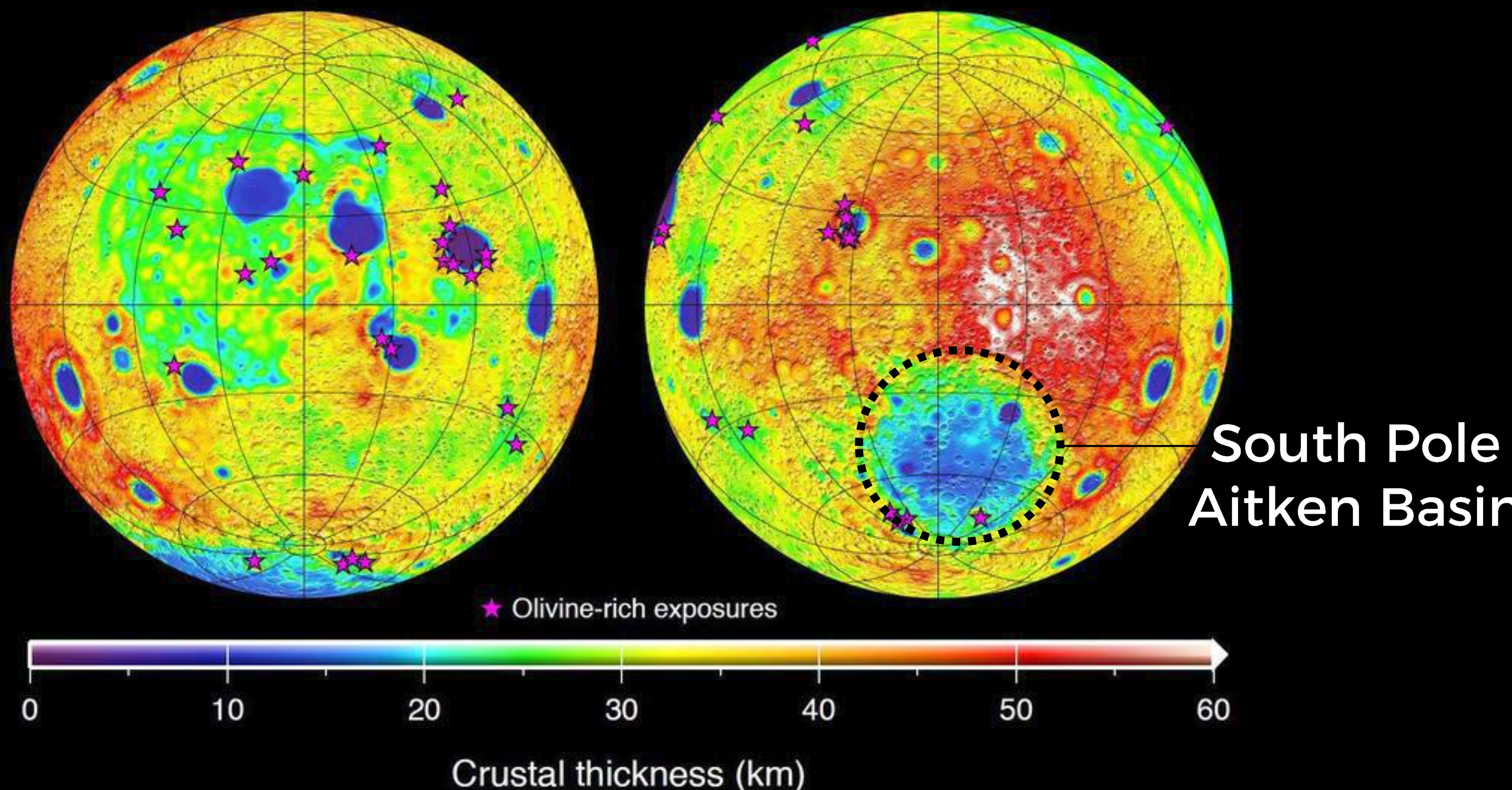
- Selection of craters:
  - Central peak / peak ring **preserved**
  - −10 km < **proximity value** < +10 km
  - **$M^3$ coverage** of the crater central peak / peak ring

~140 craters, 10 of which are studied as a test pool




P > 0
P < 0

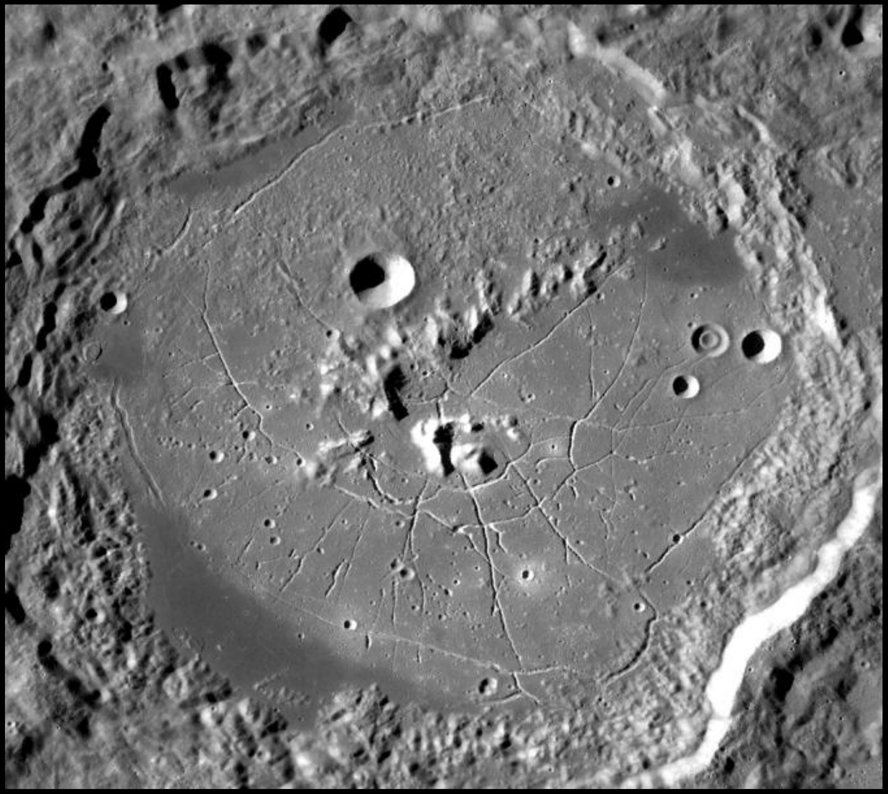
# South Pole Aitken Basin: excavating the lunar mantle?




NASA/JPL-Caltech/ IPGP

★ Olivine exposure (Yamamoto *et al.*, 2010)

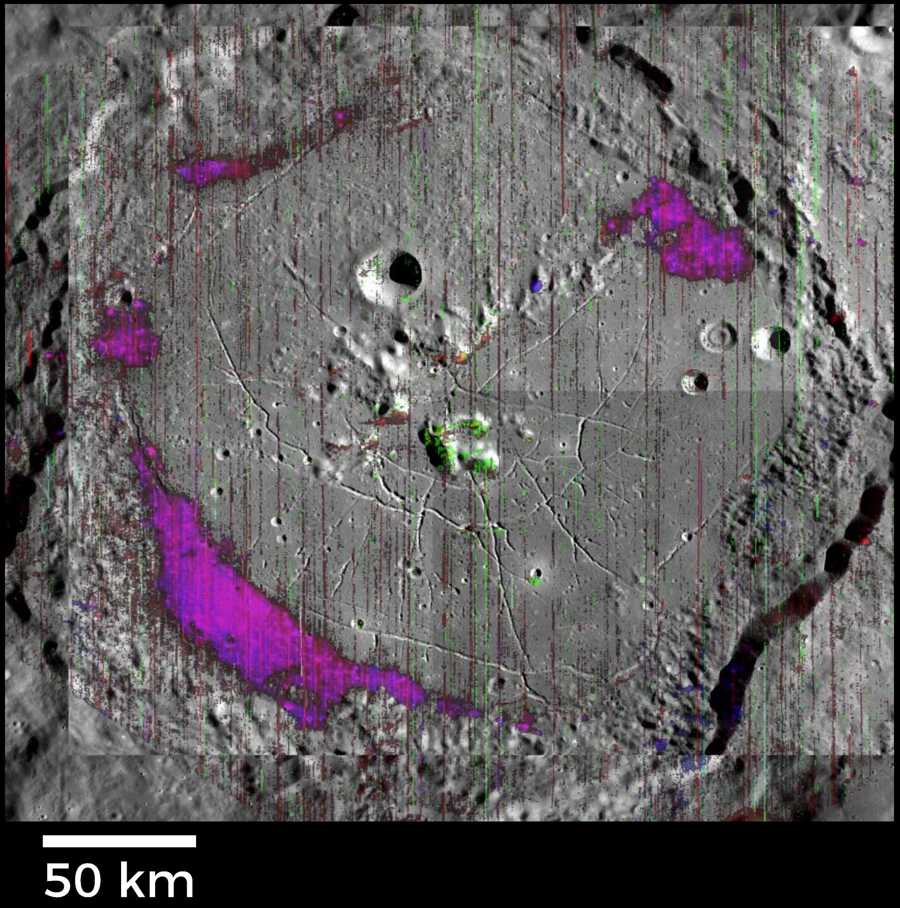
# Focus on Humboldt crater



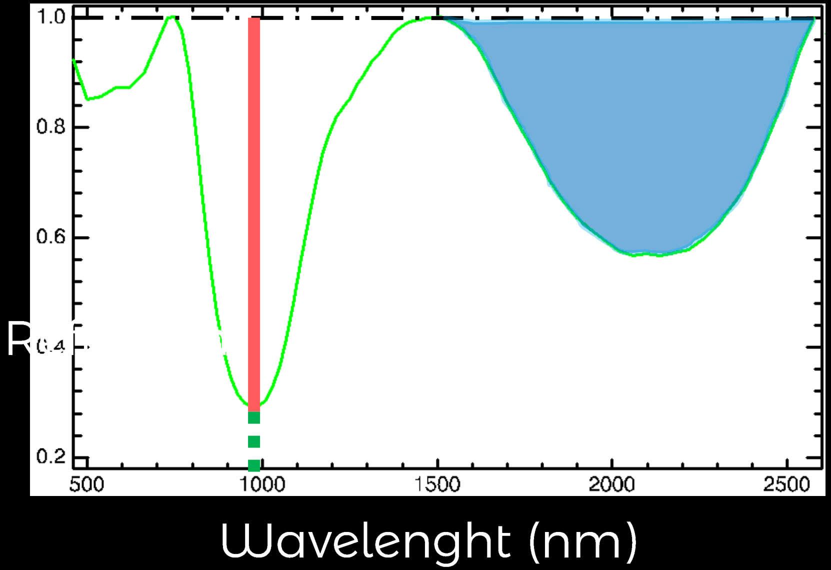
100 km LROC WAC

- Floor-fractured crater (Jozwiak *et al.*, 2012)
- Pure cristalline plagioclase occurrences on the central uplift (Donaldson-Hanna *et al.*, 2014)

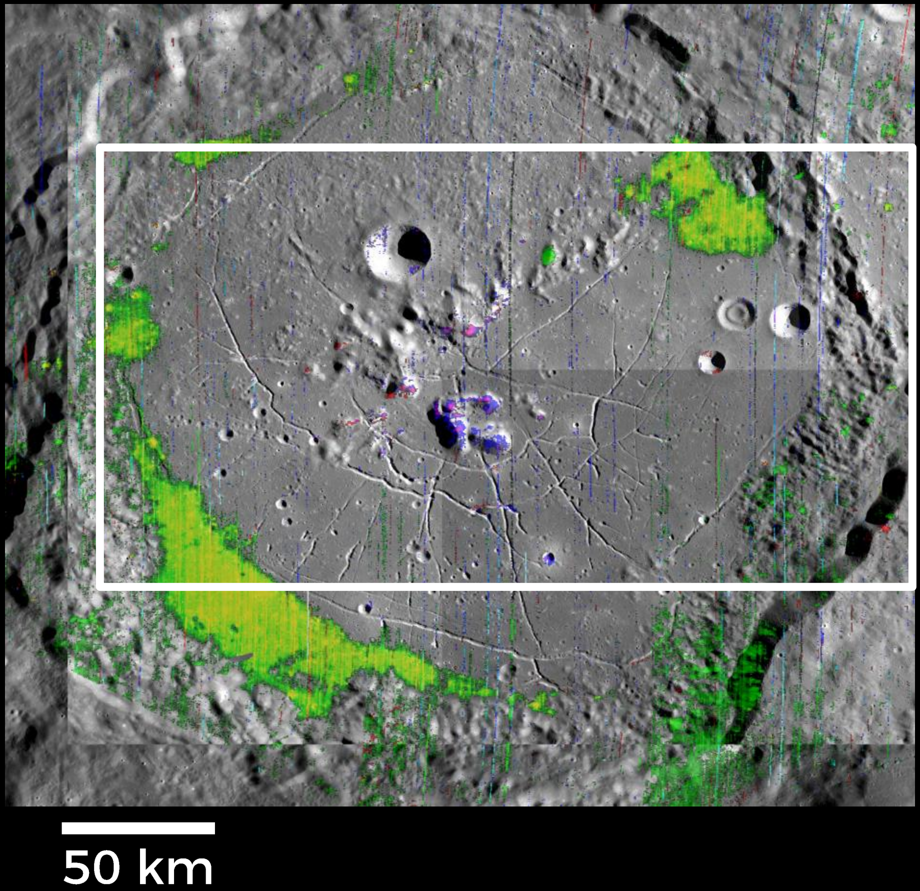
# Spectroscopic results



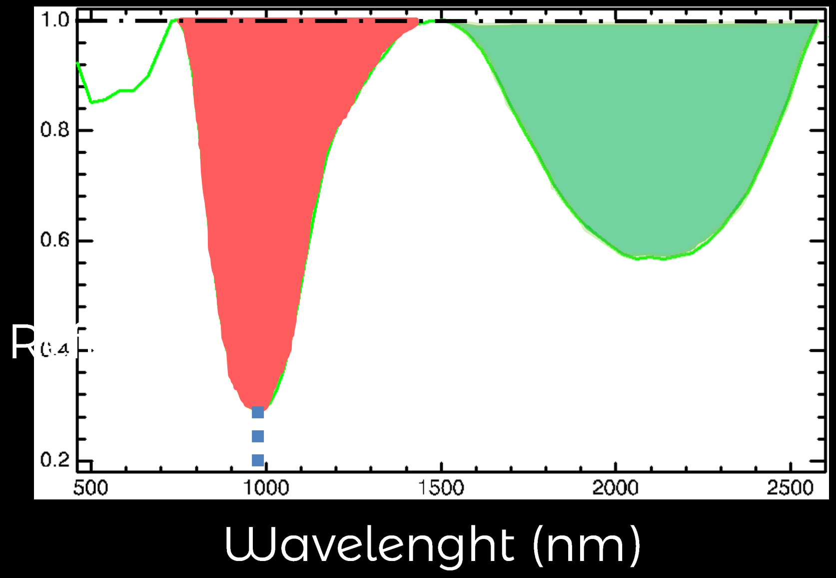

R/G = Plagioclase
R = Olivine
R+B = Glass
R+B = CPX
B = Spinel



# Spectroscopic results




Plagioclase
R = Olivine
R+G = CPX



# Spectroscopic results

Plagioclase
R = Olivine
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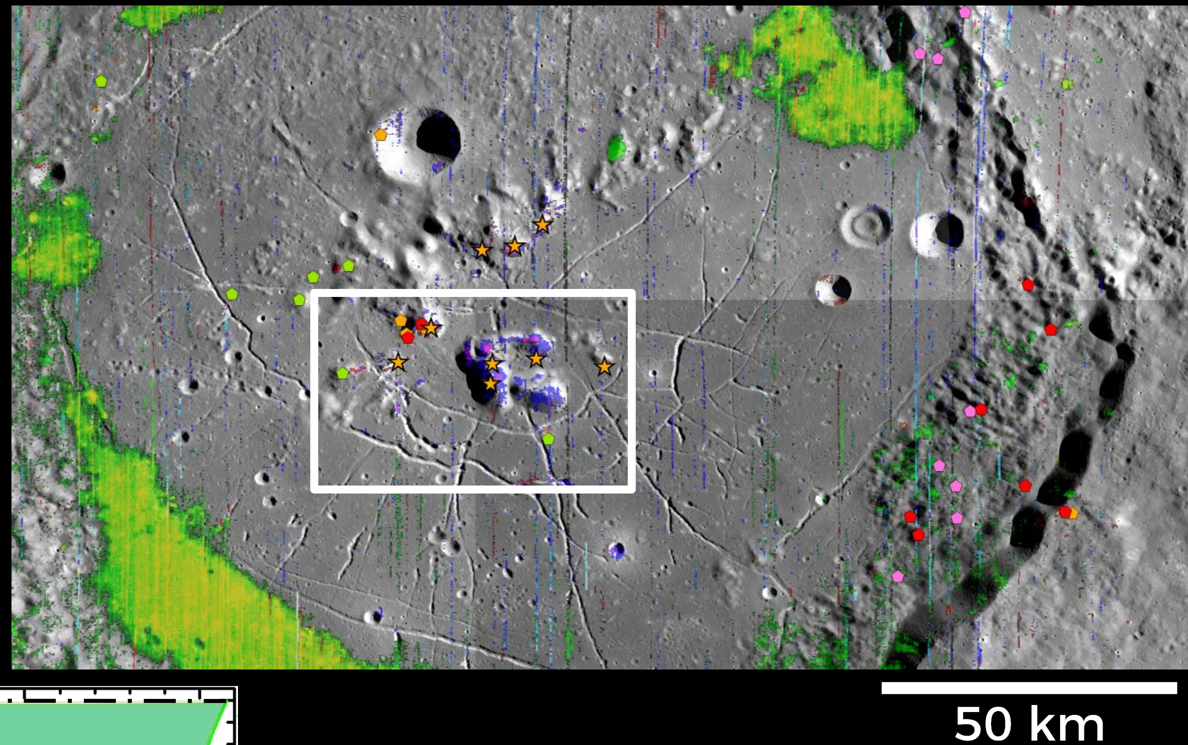
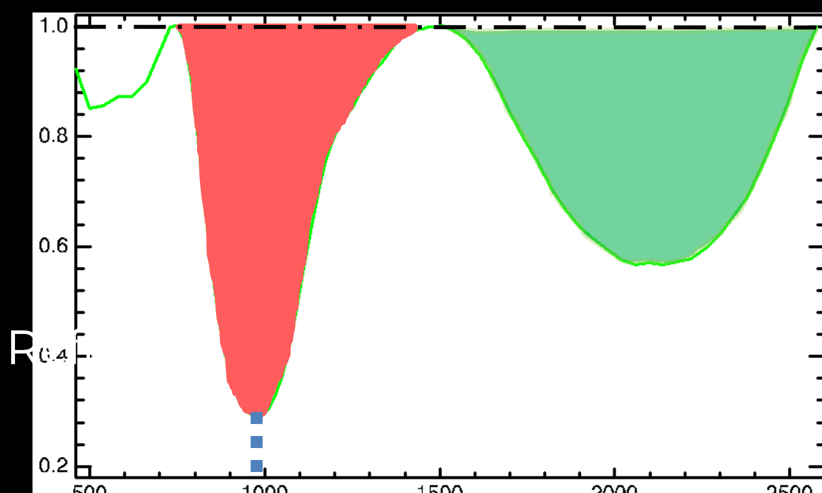



**Literature**

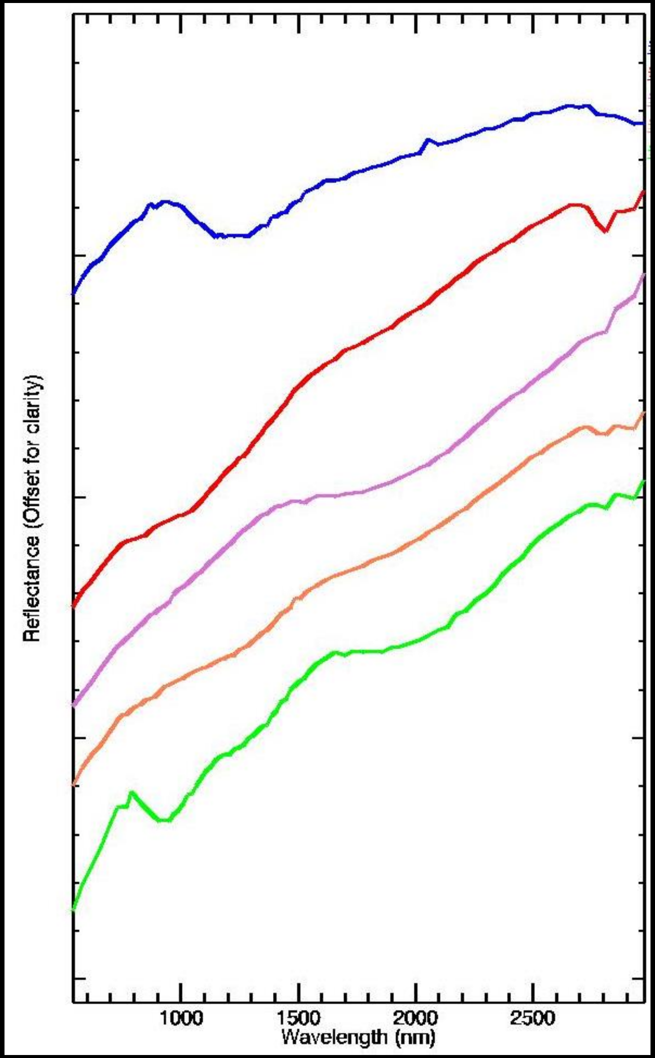
★ PAN detection (Donaldson-Hanna *et al.*, 2014)

**This study**

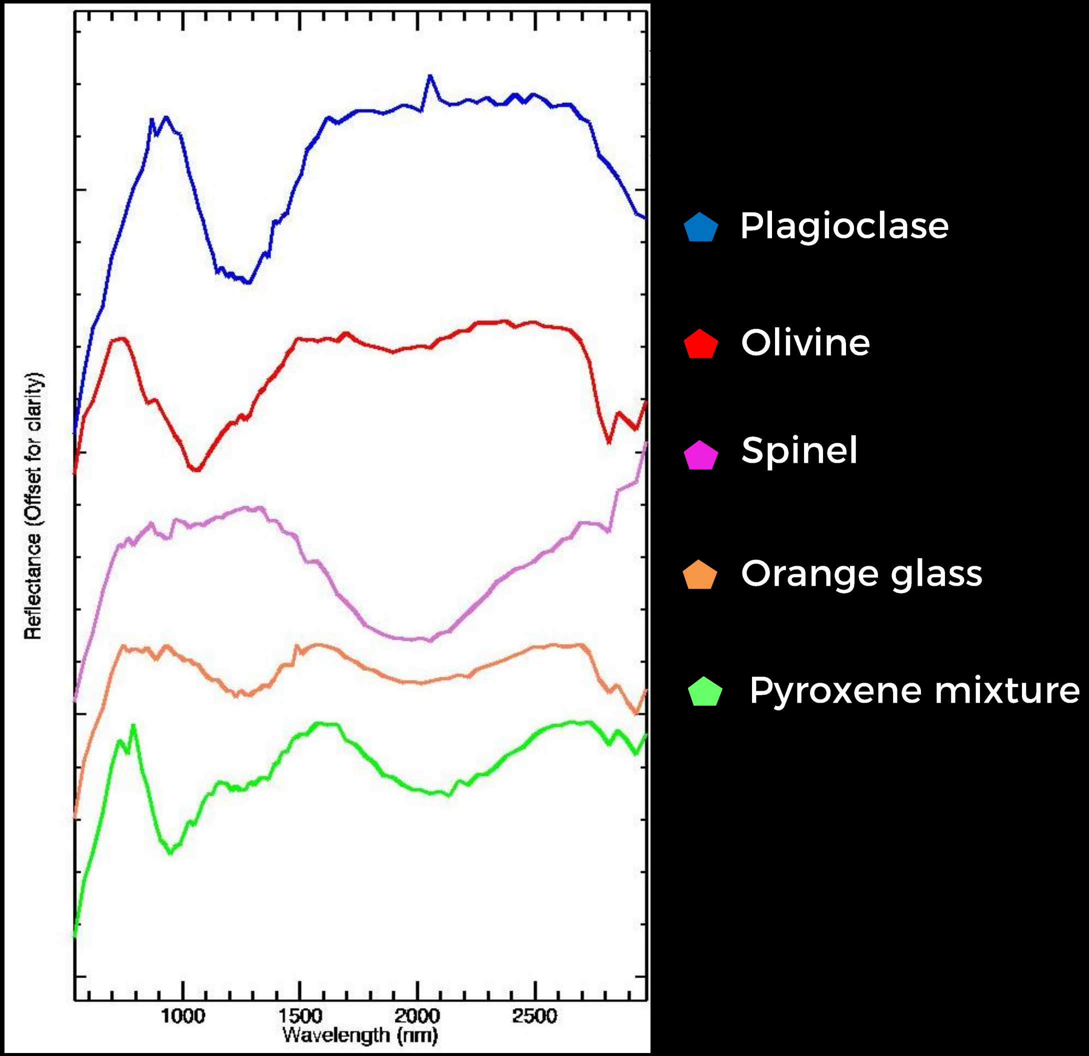
- Olivine
- Spinel
- Orange glass
- Pyroxene mixture

# Spectroscopic results

**Original spectra**

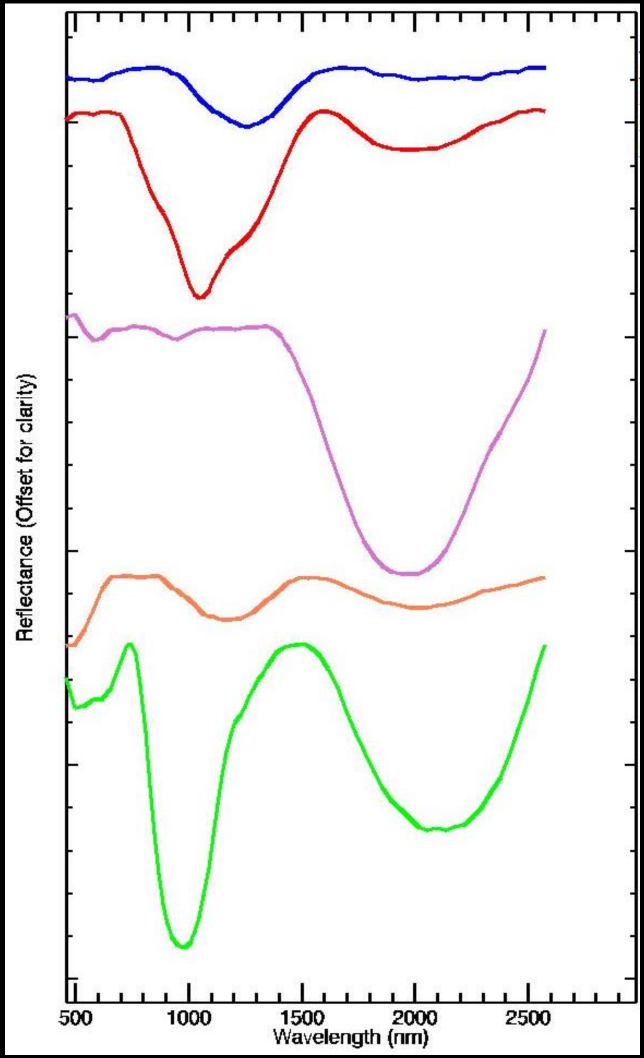



**Continuum removed data**

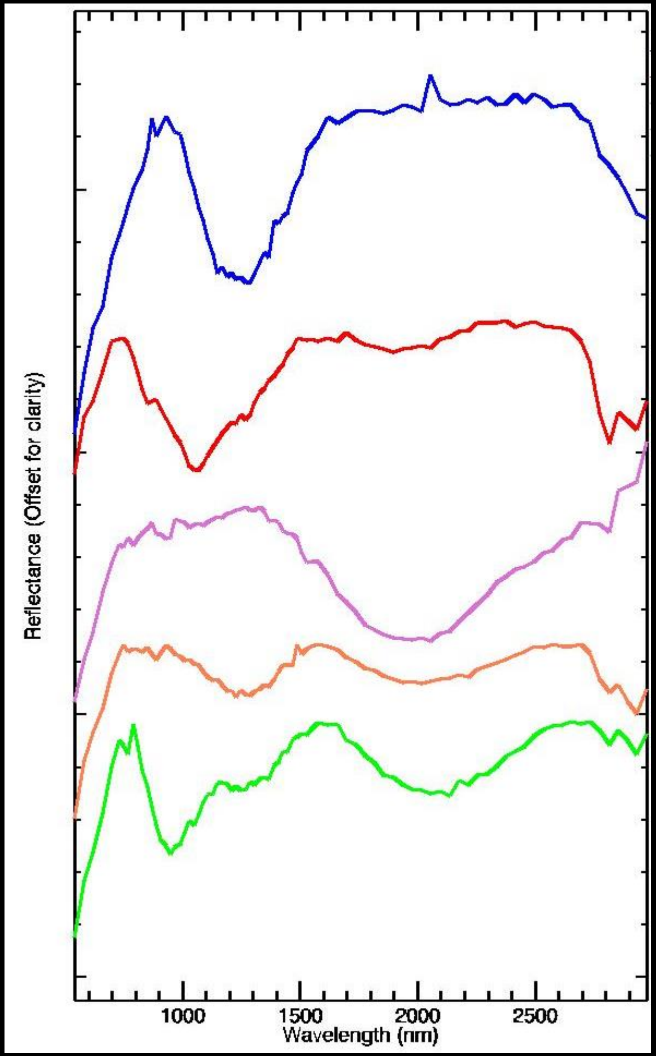


# Spectroscopic results

**Laboratory reflectance data**




**Continuum removed data**




- Plagioclase
- Olivine
- Spinel
- Orange glass
- Pyroxene mixture

# Spectroscopic results

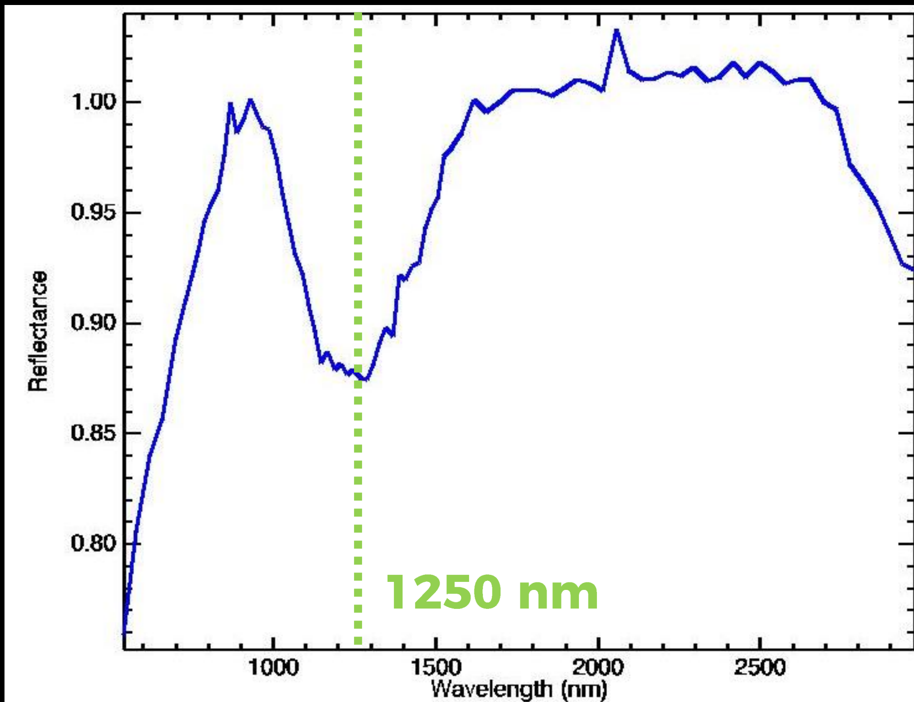



**Table 2.** Spectral Classes of Exposures Examined Across the Orientale Basin[a]

| Spectral Class | Absorptions Present | Dominant Absorption | Estimated Plagioclase Content (vol %)[b] |
|---|---|---|---|
| A | ~1250 nm (plagioclase) | ~1250 nm (plagioclase) | 99–100 |
| B | ~1250 nm (plagioclase) and ~1000 nm (pyroxene) | ~1250 nm (plagioclase), and ~1000 nm (pyroxene) absorptions are similar in strength | 96–98 |
| C | ~1250 nm (plagioclase) and ~1000 nm (pyroxene) | ~1000 nm (pyroxene) | ≤95 |

[a]The three spectral classes, defined by which mineral absorption is the most prominent in an $M^3$ spectrum over the 1000–1500 nm region.
[b]Estimated plagioclase contents for each class based on the results of the nonlinear mixing analyses using lunar highland plagioclase and low-calcium pyroxene spectral end-members (Figure 7).

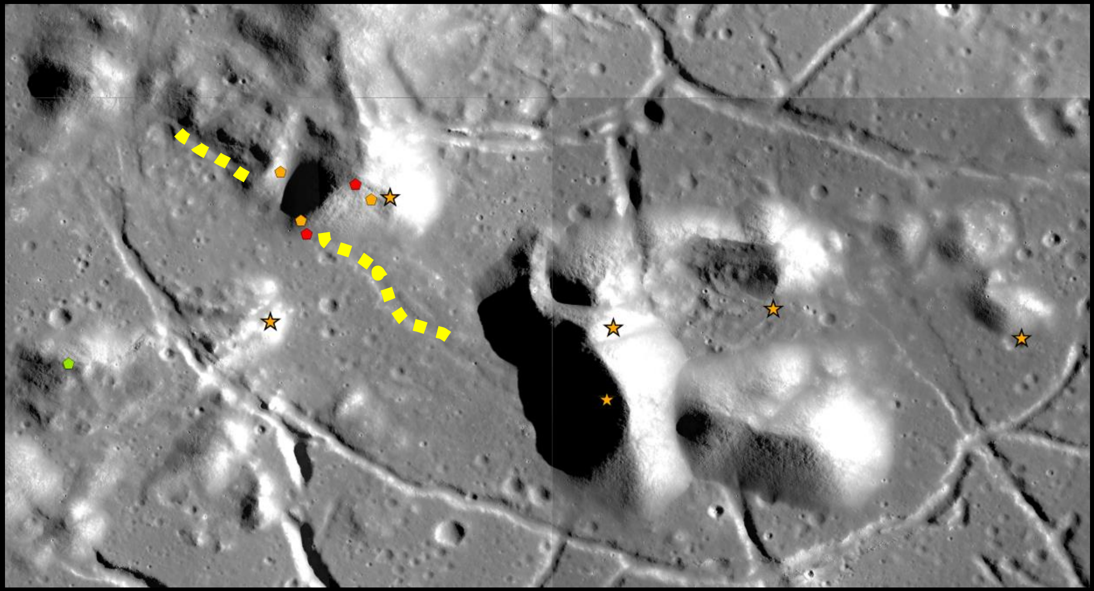
Cheek *et al.*, 2013

Deep absorption band at 1250 nm, no absorption band at 1000 and 2000 nm

→ pure plagioclase

# Spectroscopic results

- Olivine and glass detections in the central uplift
- Associated with a fracture: volcanic origin of these minerals?



50 km

Fracture

**Literature**

★ PAN detection (Donaldson-Hanna *et al.*, 2014)

**This study**

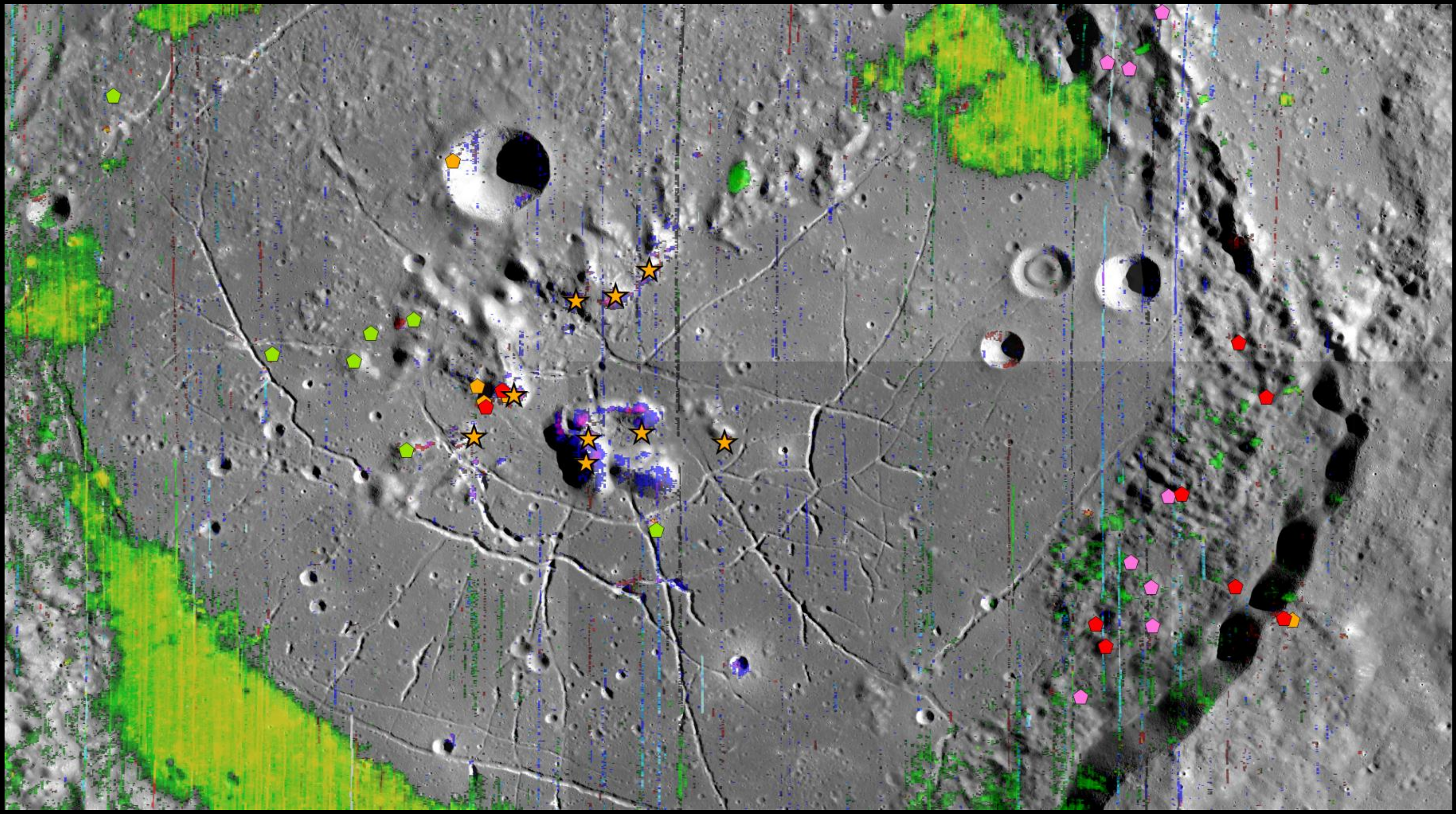
Olivine

Spinel

Orange glass

Pyroxene mixture

# Spectroscopic results



50 km

**Literature**

★ PAN detection (Donaldson-Hanna *et al.*, 2014)

★ Olivine detection (Yamamoto *et al.*, 2010)

**This study**

Olivine

Spinel

Orange glass

Pyroxene mixture

# Discussion and conclusions

- Donaldson-Hanna *et al.*, 2014: the locations where only pure anorthosite is identified are concentrated in regions where the crust is thicker (30-63 km)
- This study: Humboldt central uplift = crustal signature

| Proximity values (km) | GRAIL M1 | GRAIL M2 | GRAIL M3 | GRAIL M4 |
|---|---|---|---|---|
| | -1.2 | -0.4 | 7.4 | 7.3 |

**Better crustal thickness estimates for Humboldt region?**

- Check with craters close to Humboldt crater to see if this thicker crust is a local or regional trend

# Thank you for your attention!

Any questions?