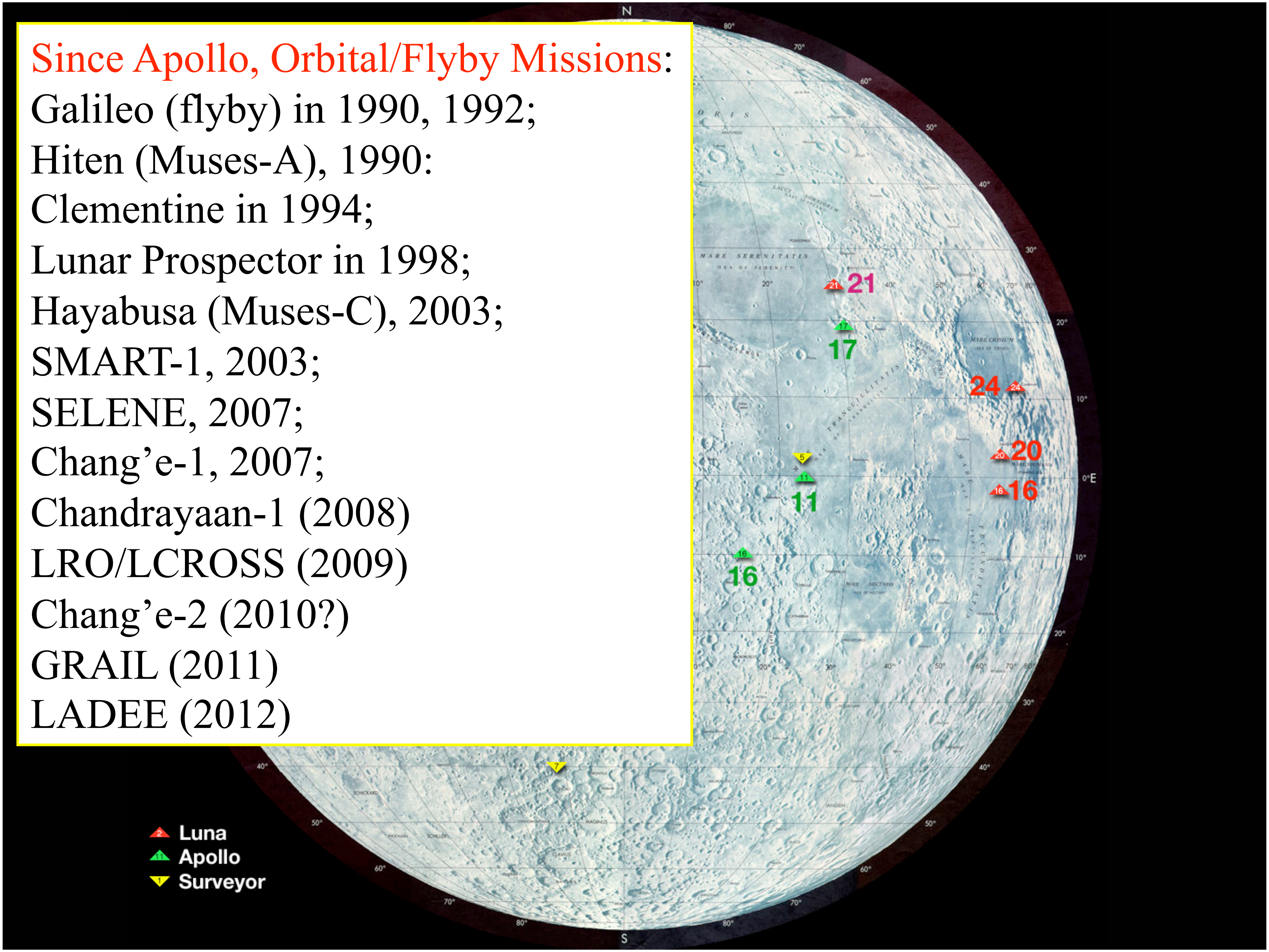

Of the Moon

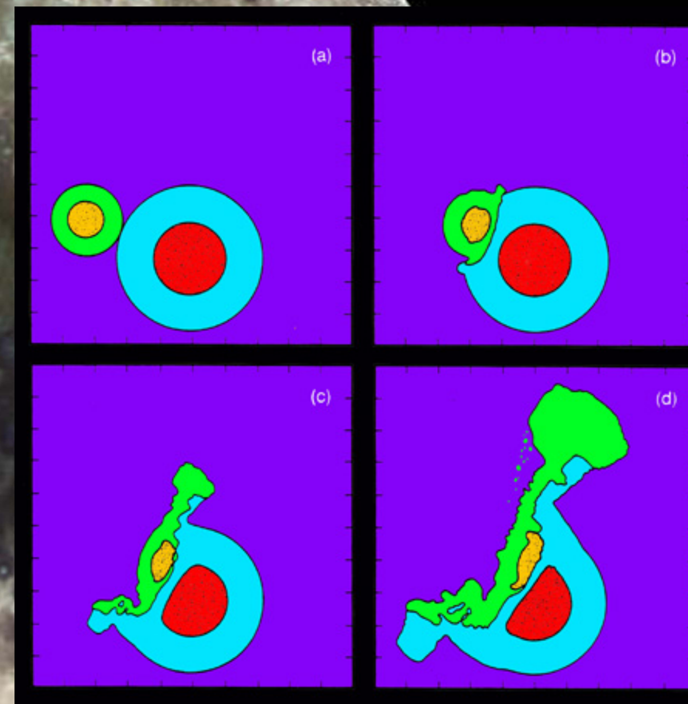
Since Apollo, Orbital/Flyby Missions:

Galileo (flyby) in 1990, 1992;
Hiten (Muses-A), 1990:
Clementine in 1994;
Lunar Prospector in 1998;
Hayabusa (Muses-C), 2003;
SMART-1, 2003;
SELENE, 2007;
Chang'e-1, 2007;
Chandrayaan-1 (2008)
LRO/LCROSS (2009)
Chang'e-2 (2010?)
GRAIL (2011)
LADEE (2012)



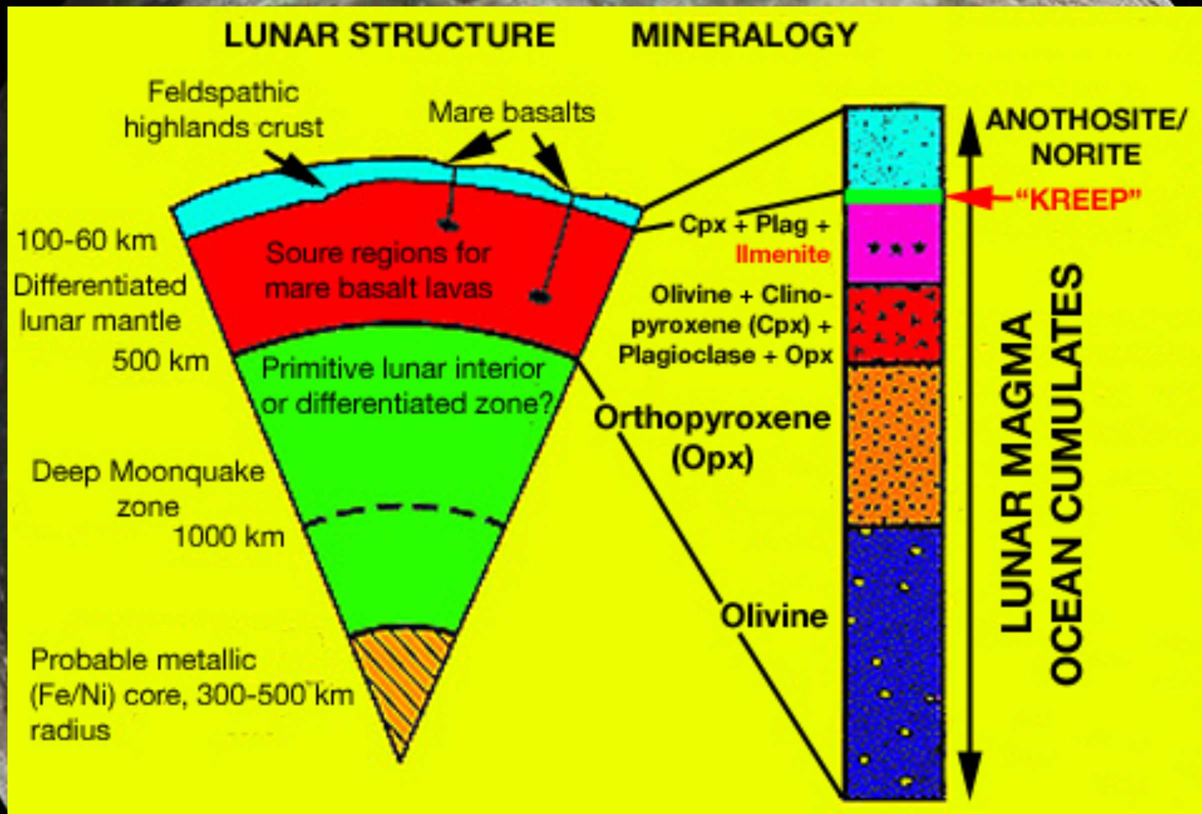

What do we know about the Moon?

What do We Know about the Moon?



Moon is depleted in volatile elements and “core” elements

What do We Know about the Moon?



Differentiated source for basalts:

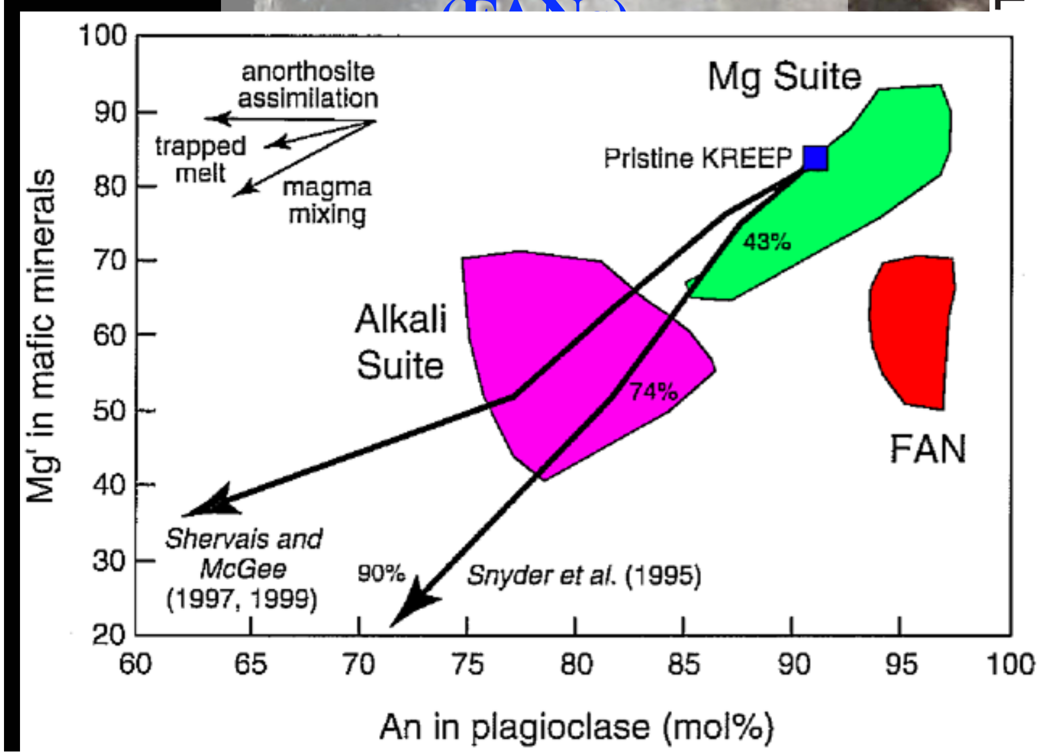
- •Olivine + Orthopyroxene (Opx) early
- •Plagioclase, Clinopyroxene (Cpx) and Ilmenite later
- •"KREEP" = last dregs
- •Density instability

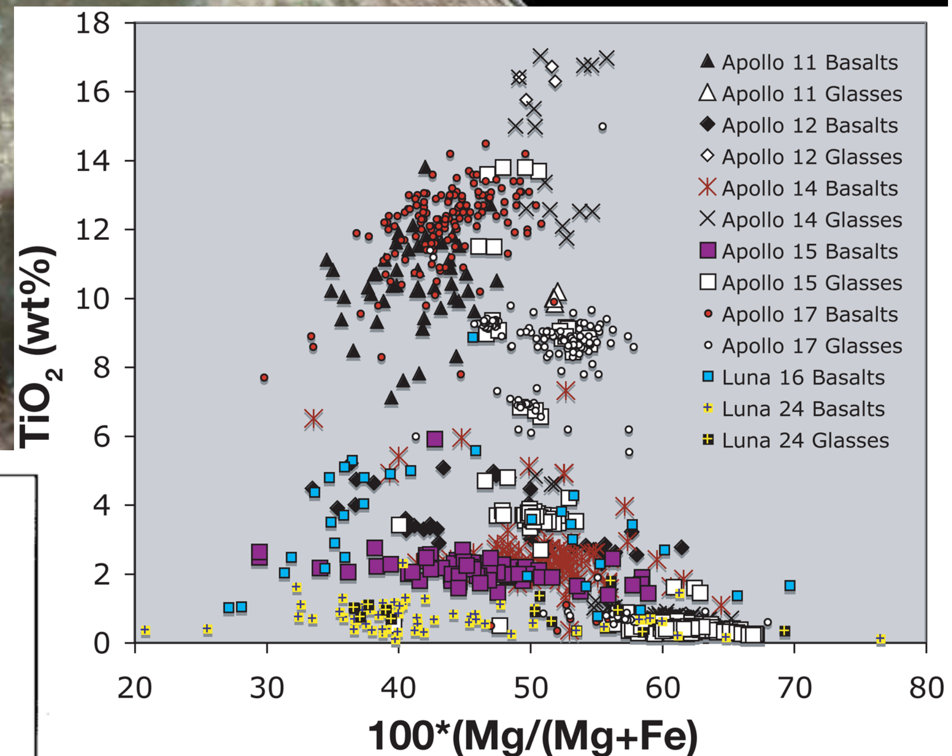
Lunar Rock Types

Samples

Highlands (intrusive)

Ferroan Anorthosites



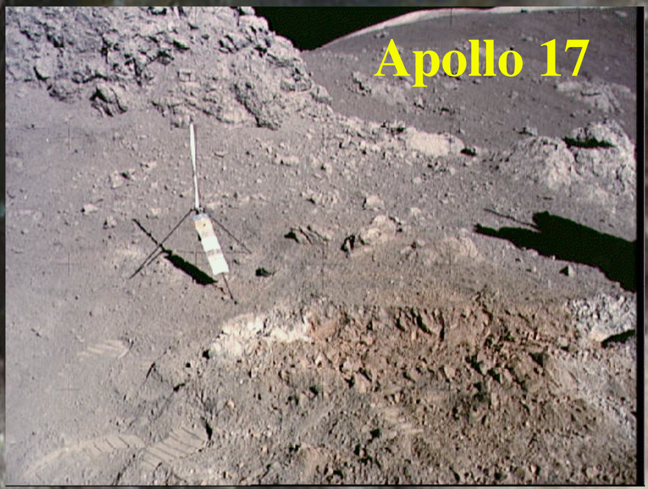


Very Low-Ti (VLT)
Low-Ti
High-Ti

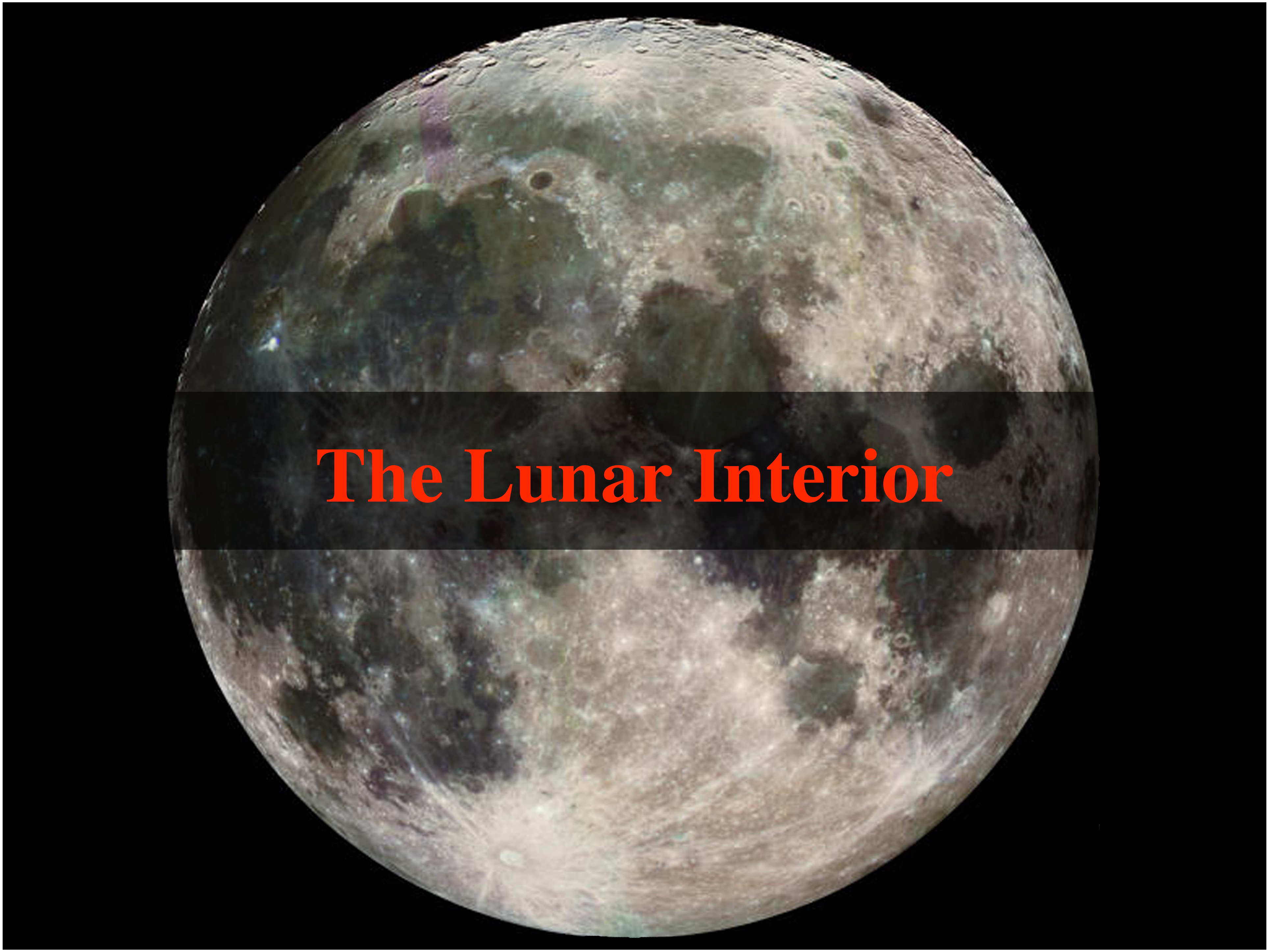
P’’

Lunar Rock Types

- Very little of the lunar surface was sampled.
- No direct sampling of the lunar mantle (no mantle xenoliths).
- Difficult to identify a primary melt (glasses are the best bet!)

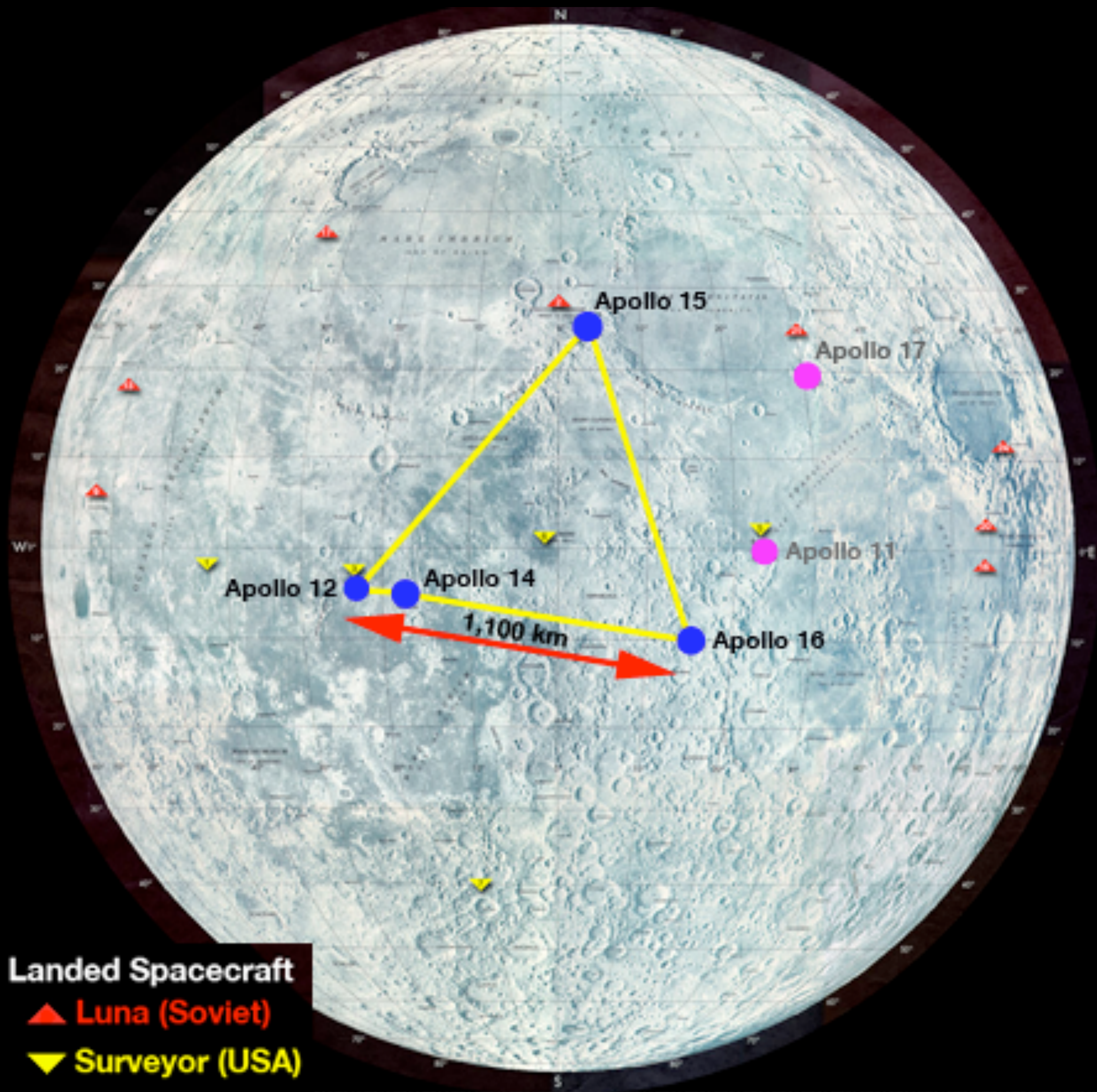


Volcanic glass beads from fire fountaining.
Distinct from crystalline mare basalts.
<u>Source Regions</u>: Mare basalts = 100-250 km;
Glasses = 360-520 km.


The Lunar Interior

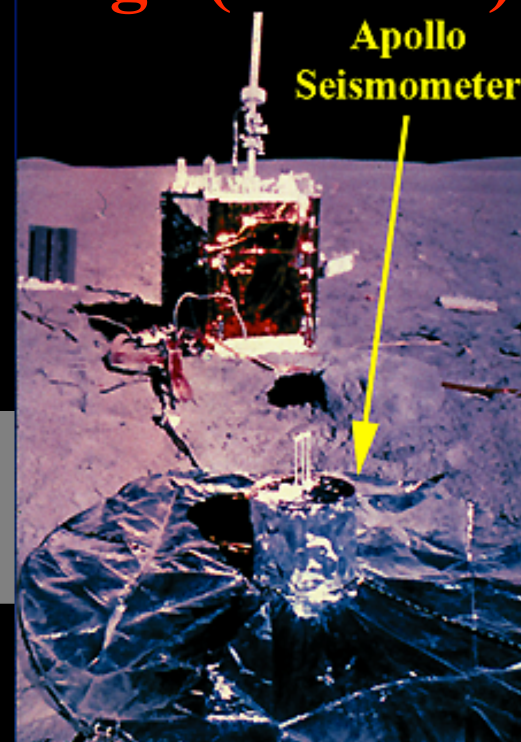
Apollo Seismic Stations

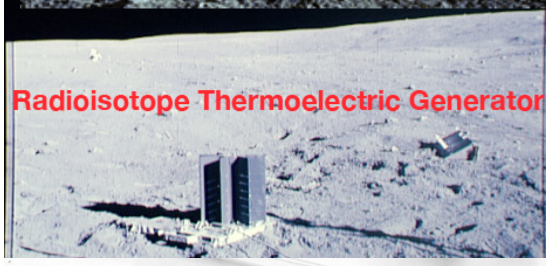
The *complete*
Apollo passive
seismic network
operated from
20 April, 1972, until
30 September, 1977

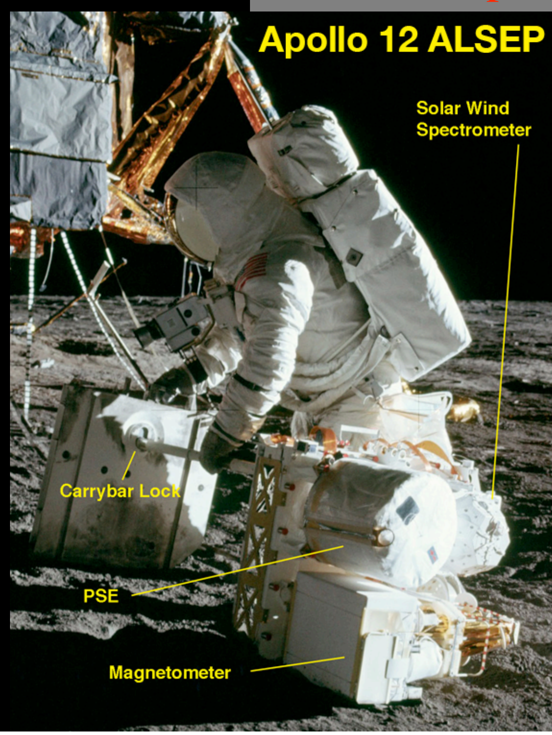


Apollo Lunar Surface Experiment Package (ALSEP)

Heat flow; Magnetometer; Gravity; Apollo Passive Seismic Experiment.

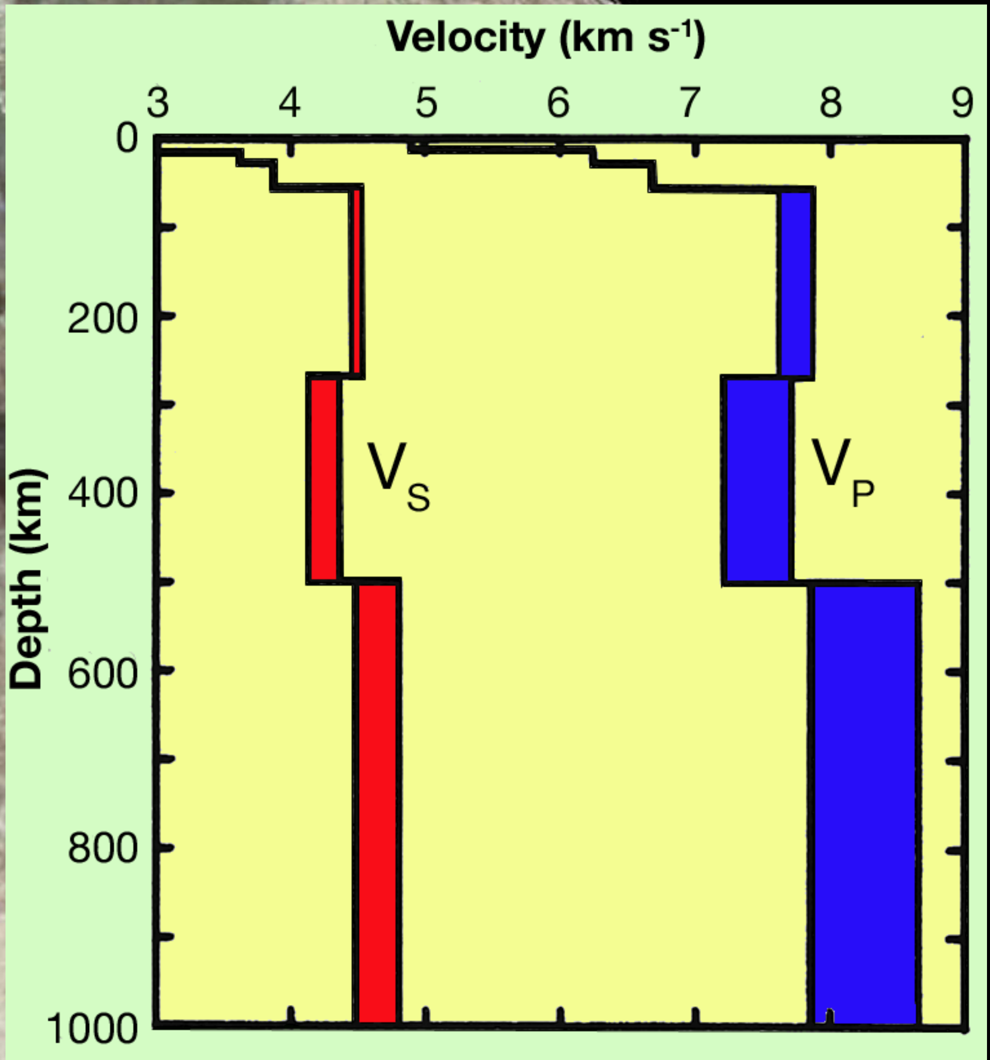






Lunar Interior: Seismic Data

- **There is a seismic discontinuity at ~500 km on the lunar nearside.**
- **There is probably a small (250-350 km radius) core.** (Righter, 2002, Icarus 158, 1-13; Hood et al., 1999, GRL 26, 2327).
- **The lower mantle may contain a significant quantity of Mg-rich olivine** (Nakamura et al., 1974, GRL 1, 137) **or a small quantity of garnet** (e.g., Hood and Jones, 1987, PLPSC 17, in JGR 92, E396).

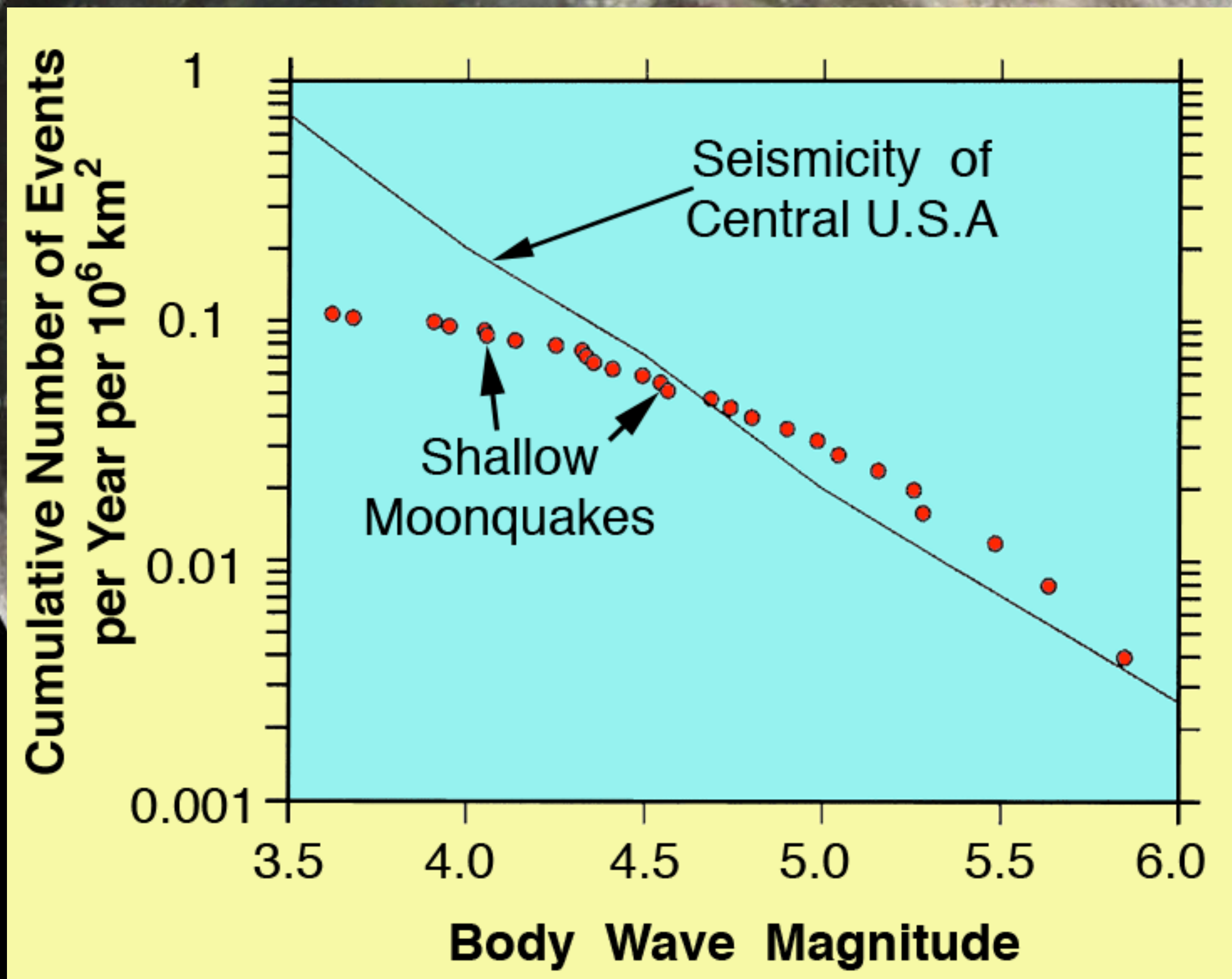


[From Nakamura, *JGR* 88, 677-686, 1983]

Lunar Interior: Seismic Data

The Moon is NOT seismically dead!

It is a "one-plate planet" with shallow seismicity is equal to that of an intraplate setting on Earth.

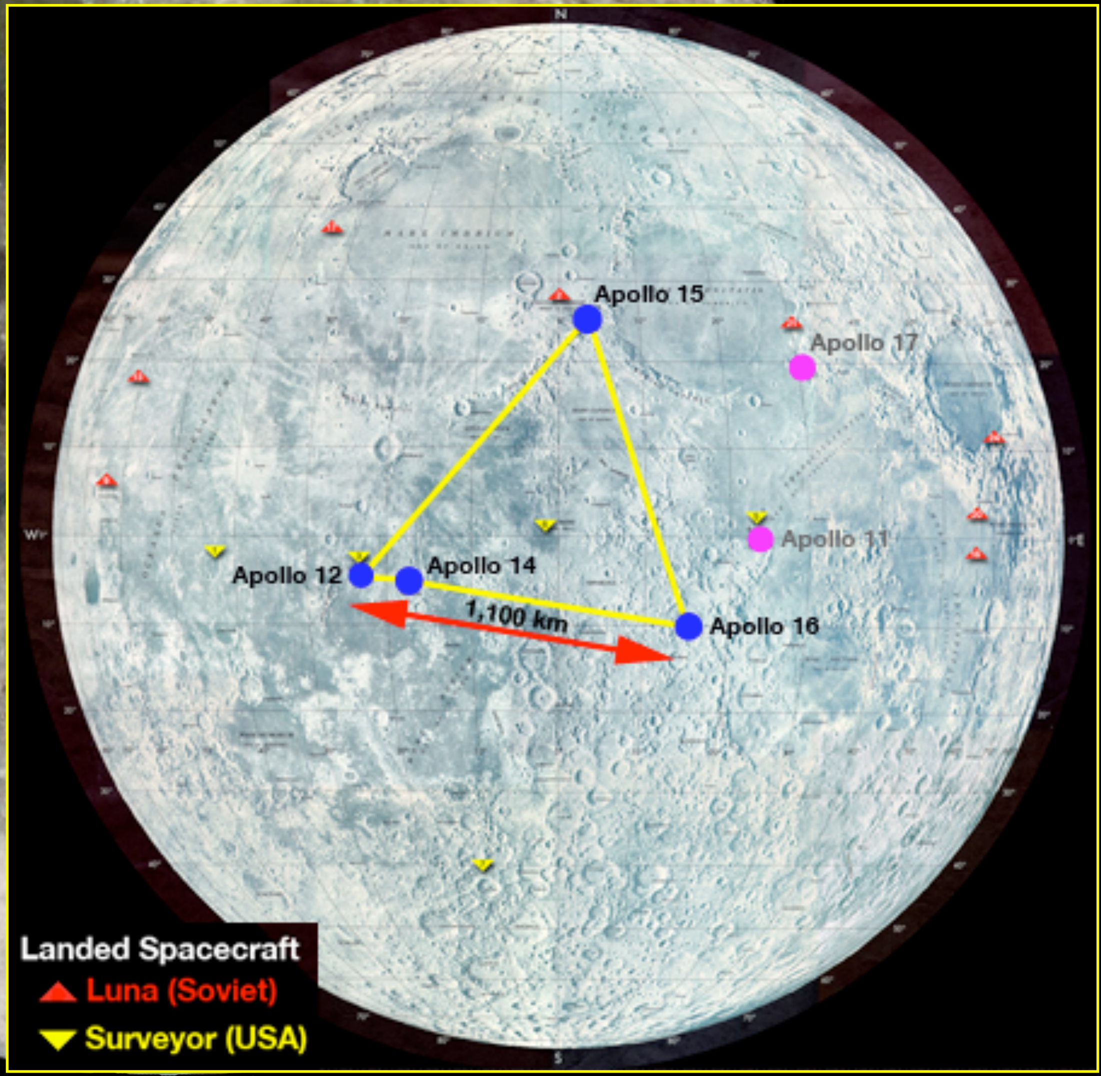


[Oberst & Nakamura (1992) 2nd *Conf. on Lunar Bases & Space Activities*]

Limitations to understanding of the Lunar Interior

No direct sampling of the lunar mantle (i.e., no mantle xenoliths)

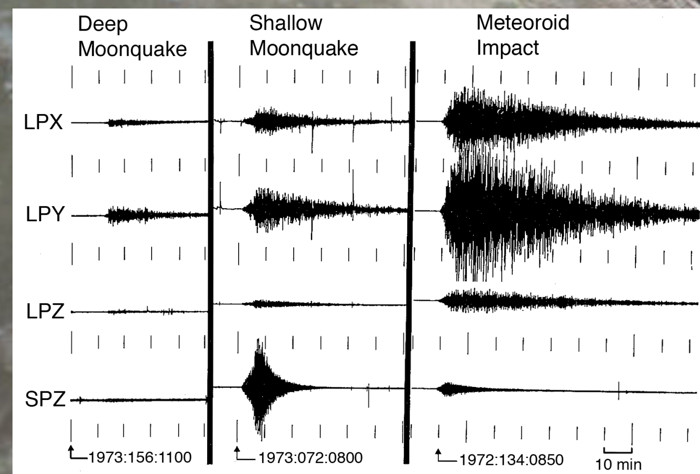
- Difficult to identify a primary melt (glasses are the best bet!)
- Only a small proportion of the lunar surface was sampled.

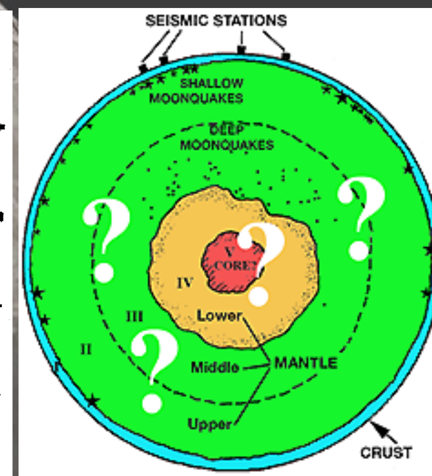


- Geophysical data only from limited sites on the near side
- Seismic network only of limited extent on the near side

Seismology of the Moon

Four types of events induce seismicity on the Moon.





1) Thermal Moonquakes - Associated with heating and expansion of the crust. Lowest magnitude of all Moonquakes.

2) Deep Moonquakes - 850-1,000 km. > 7,000 recorded. Originate from "nests" - >300 nests defined from Apollo seismic data to date. Small magnitude (< 3). Associated with tidal forces. Predominantly near side.

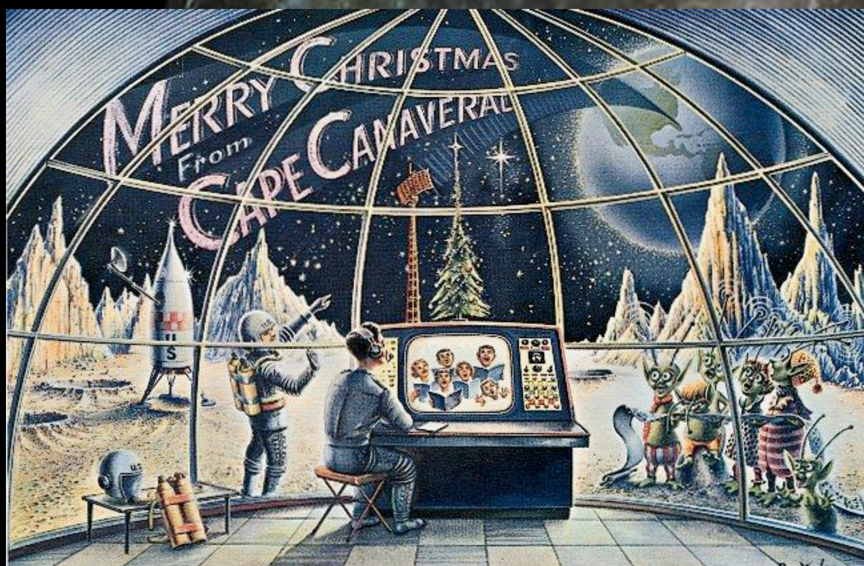
3) Meteoroid Impacts - > 1,700 events representing meteoroid masses between 0.1 and 100 kg were recorded 1969-1977. Smaller impacts were too numerous to count.

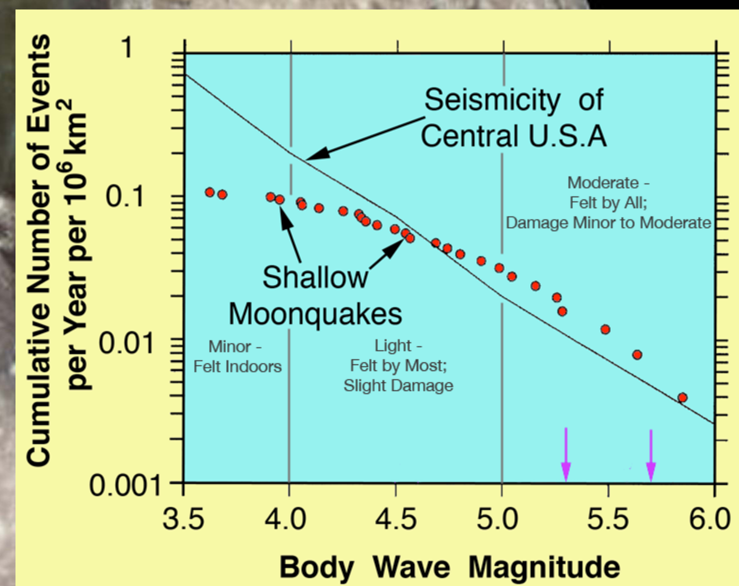
4) Shallow Moonquakes - some > 5 magnitude. Exact locations unknown. Indirect evidence suggests focal depths of 50-200 km. May be associated with boundaries between dissimilar surface features. Exact origin unknown.

Seismology & A Moon Base

Shallow Moonquakes present a potential significant risk to any proposed lunar outpost

[Oberst & Nakamura, 1992, Lunar Base Workshop, LPI; Oberst & Nakamura (1991) *Icarus* **91**, 315-325]





Shallow Moonquake seismicity similar to intra-plate seismicity on Earth.

28 Shallow Moonquakes recorded, 7 with magnitude > 5.

Seismology & A Moon Base

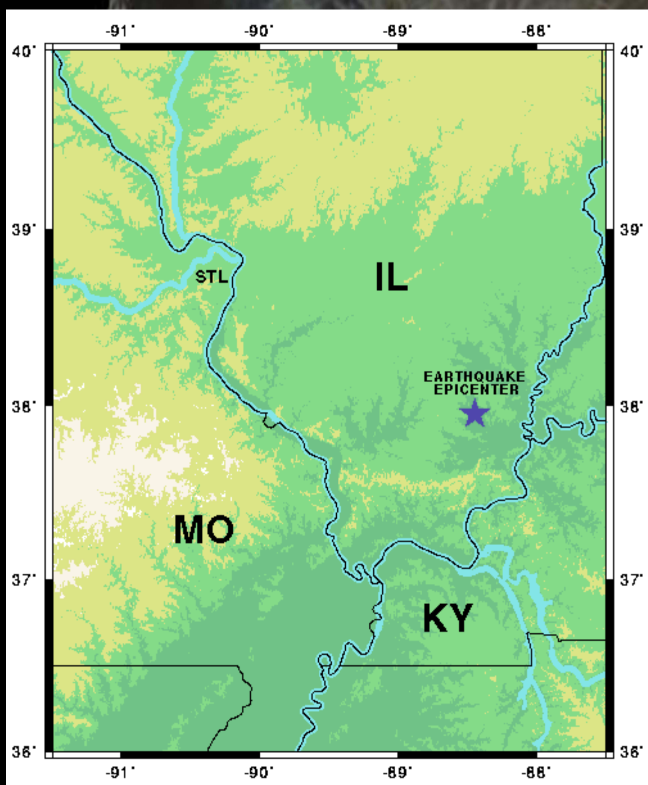
Examples of Earthquake Damage

Richmond, Utah: 30 Aug. 1962
Duration: 35 seconds.
Magnitude: 5.7

Seismology & A Moon Base

Examples of Earthquake Damage

South-Central Illinois: Nov. 9th, 1968.
Magnitude: 5.3.
Duration: <60 seconds.

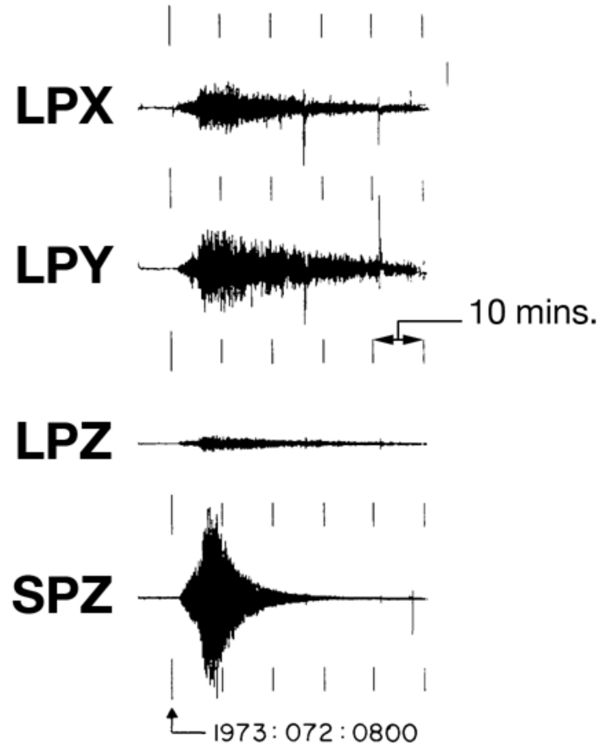


Seismology & A Moon Base

Shallow Moonquake

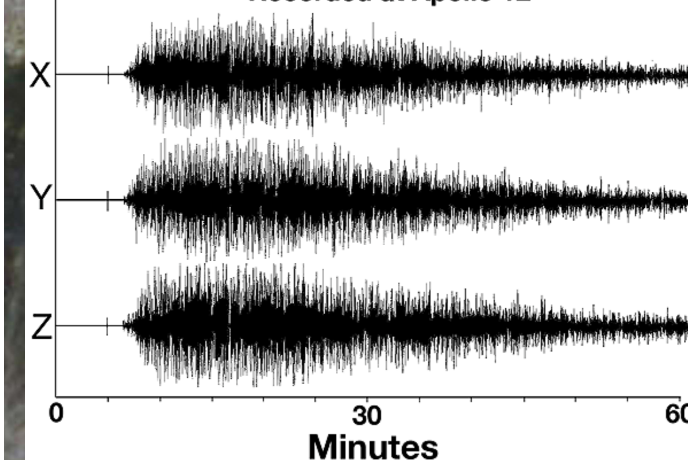
Apollo 16 Seismogram

From: Nakamura et al. (1974)
Proc. Lunar Sci. Conf. 5th, 2883-2890



LP = Long Period instrument;
SPZ = Short Period vertical component.

Apollo 14 Saturn IVB Booster Impact
Recorded at Apollo 12



Dainty et al. (1974)
The Moon 9, 11-29.

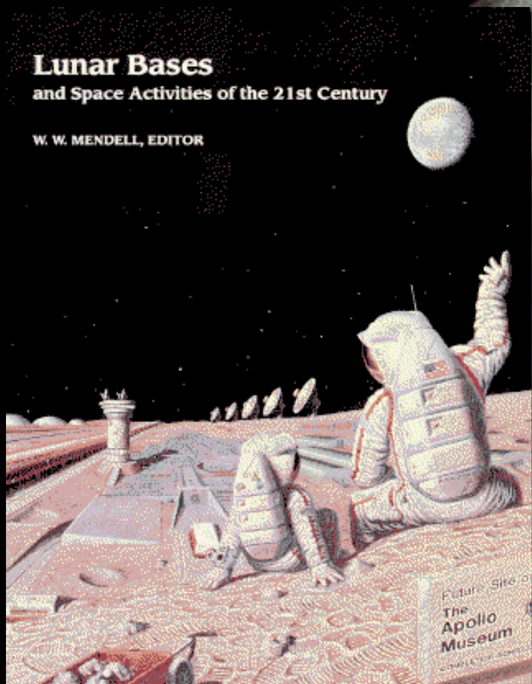
Initial build-up phase;
Long duration of energy tail off.
Highest energy release over a period of 10 minutes or longer.

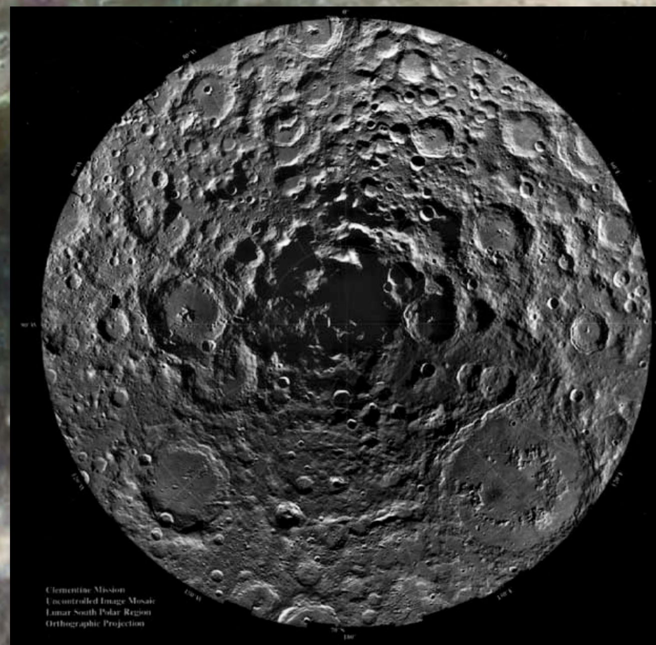
Lack of chemical alteration allows the Moon to "vibrate" for much longer than the Earth (high Seismic "Q").

Moon seismic Q is approximately an order of magnitude higher than that of Earth.

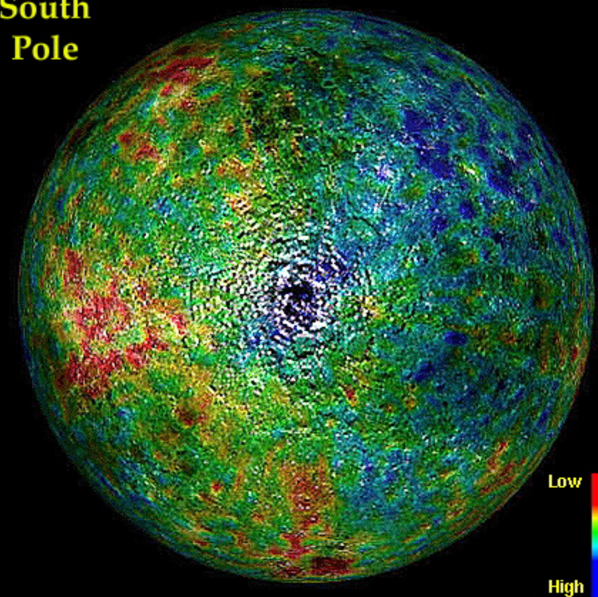
Ground shakes for a long time!

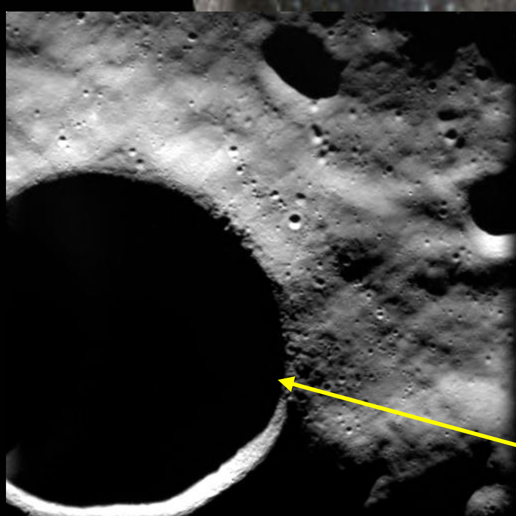
Seismology & A Moon Base- South Pole

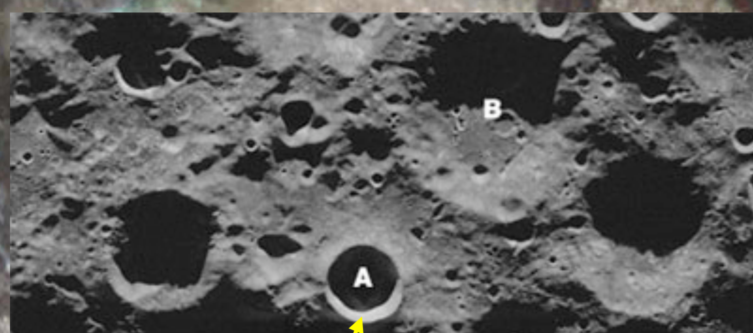




South Pole







Shackleton Crater

Rim of Shackleton Crater permanent sun and close to H-deposits.

Seismology & A Moon Base- South Pole

Using terrestrial formulations, ground motion for a magnitude 5.7 quake is estimated at 3-20 cm with ground acceleration of 0.6-0.8 ms^{-2}.

But are these estimates applicable to the Moon?

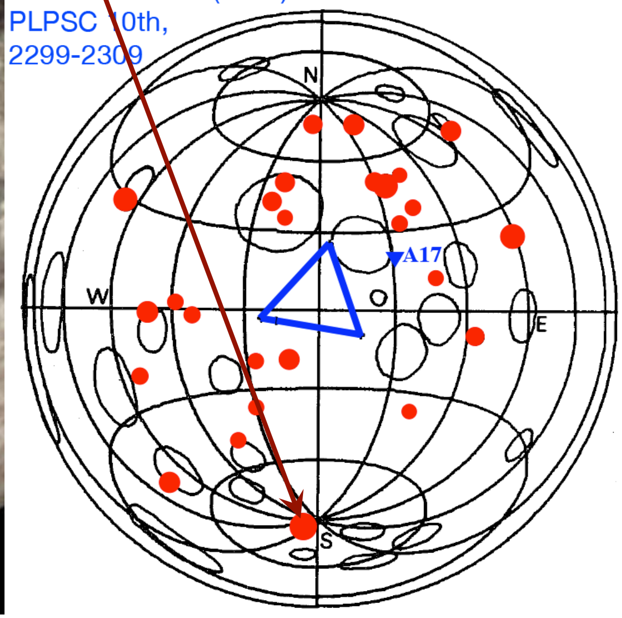
Shallow Moonquakes: more energy at higher frequencies than equivalent earthquakes.

Although regolith will scatter surface waves, seismic waves are much less attenuated on the Moon relative to Earth (effects felt much further than an earthquake of comparable magnitude).

Possible locations of Shallow Moonquakes: Impact craters.

Seismic risk if lunar outpost is on the rim of Shackleton?

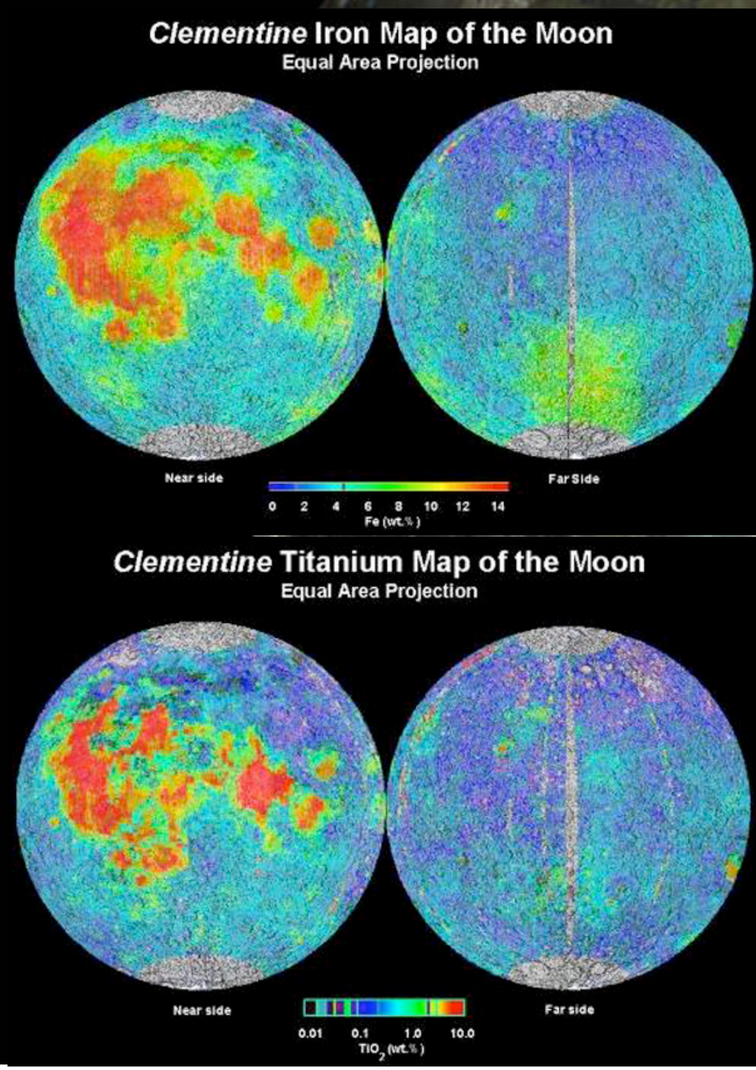
Nakamura et al. (1979)
PLPSC 10th,
2299-2309

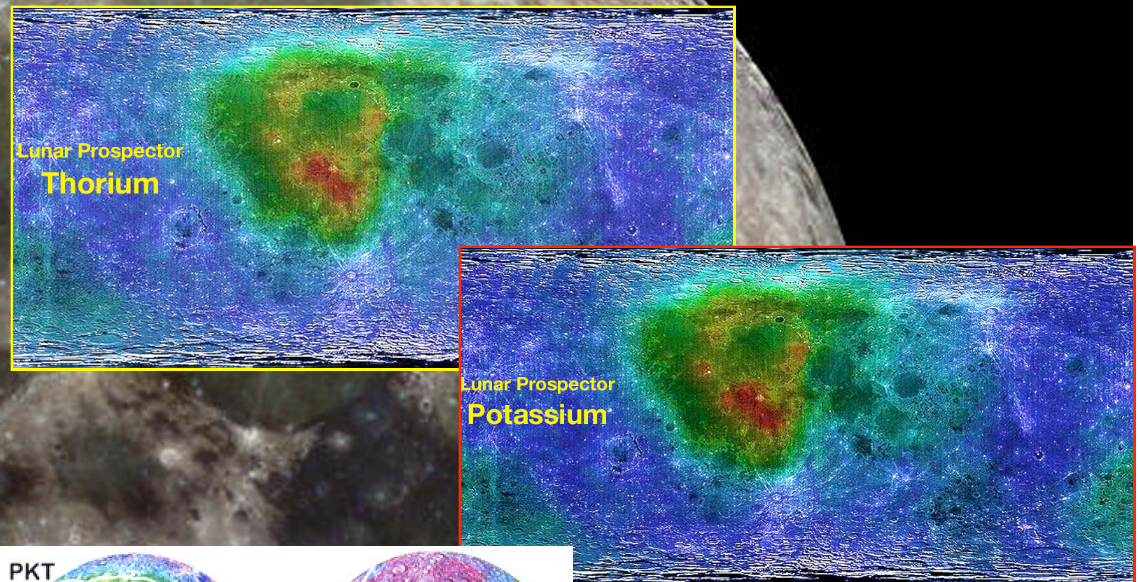


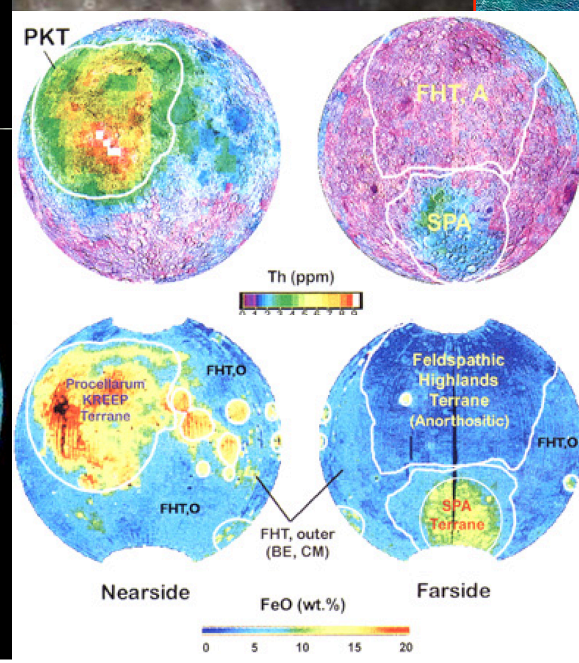

The Lunar Surface

Lunar Surface Composition

Global Element Maps





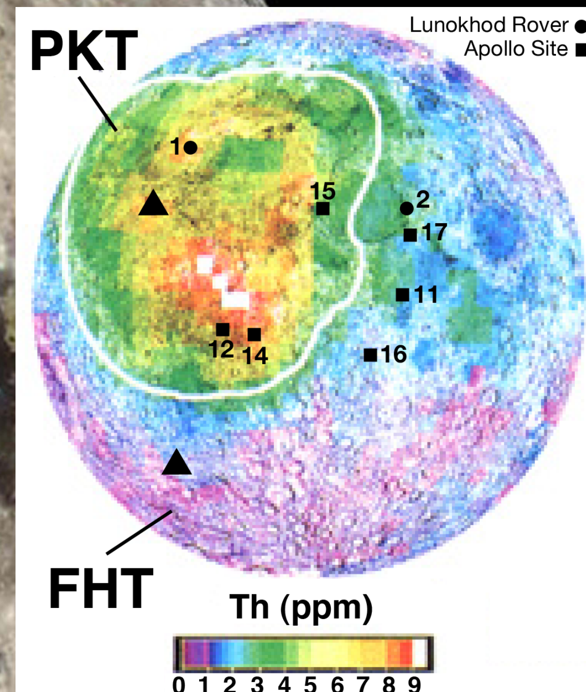


[B. Jolliff et al. (2000) *JGR* **105**, E2]

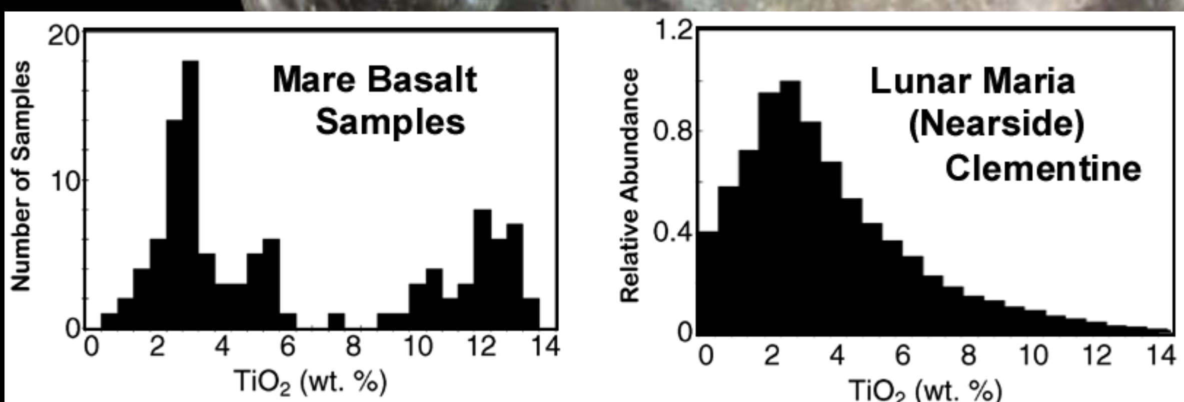
Terrane Boundaries.

Apollo landing sites were not ideal for exploring the Moon.

- Apollo sites close to terrane boundaries;
- Samples contain PKT signature;
- Apollo sample collection is not representative of the lunar compositional diversity (Clementine/LP and more recent missions) – sample return needed.

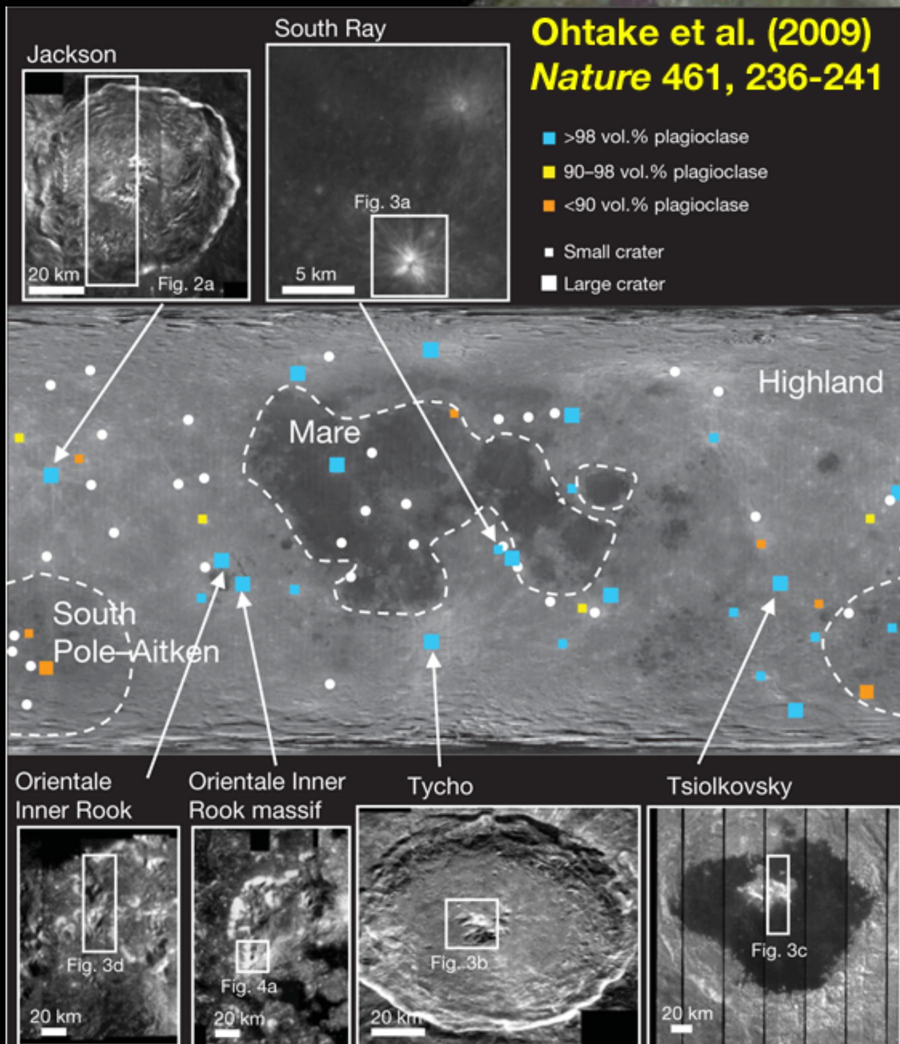


Jolliff et al. (2000) JGR 105, 4197



Giguere et al. (2000) MaPS 35, 193

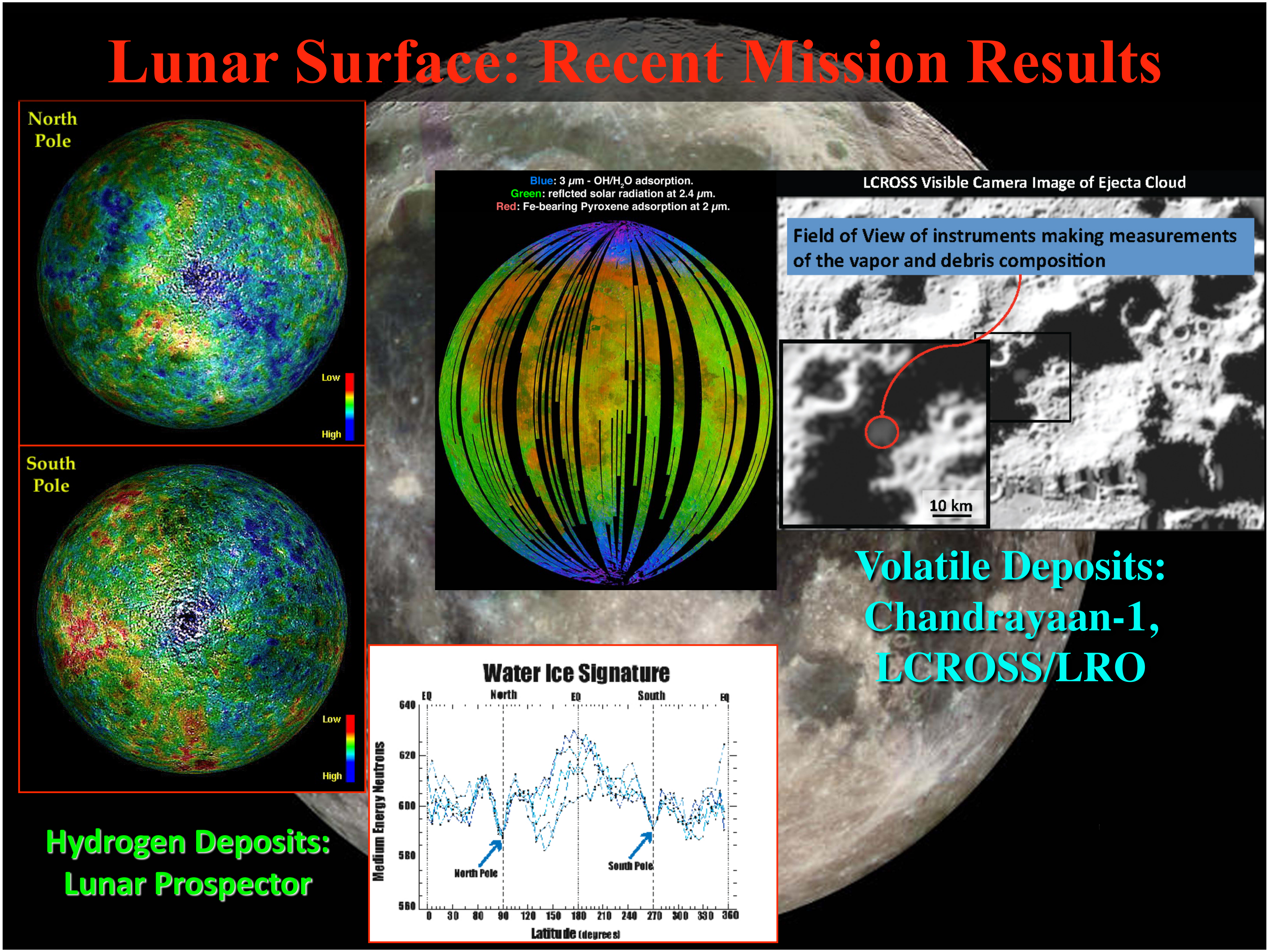
Lunar Surface: Recent Mission Results



New Rock Types not represented in the sample collection.

Spinel-rich lithologies: Chandrayaan-1

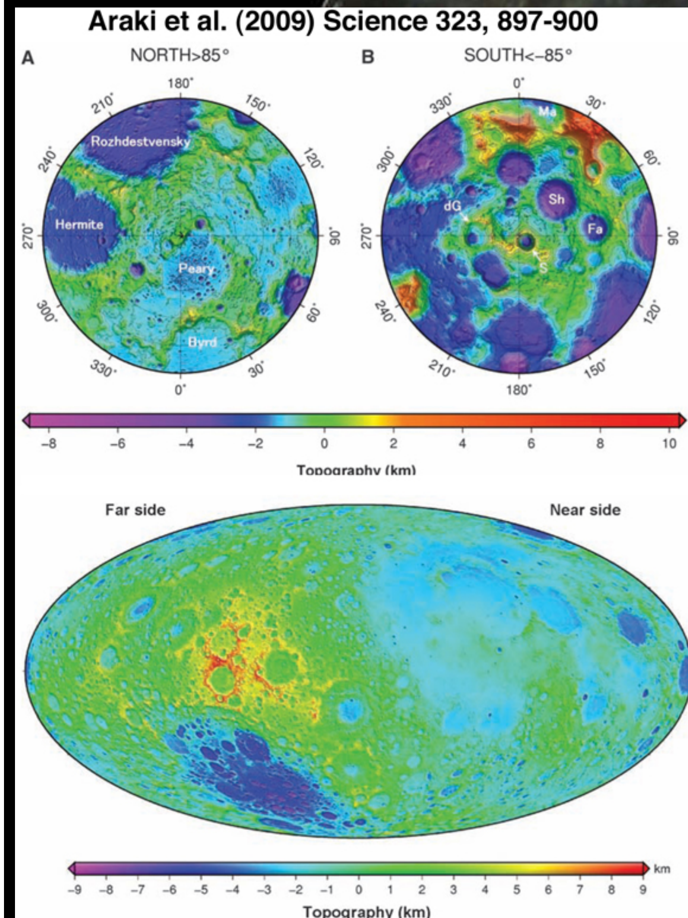
Pure Anorthosite: Kaguya (SELENE)


Lunar Surface: Recent Mission Results
North Pole
Low
High
South Pole
Low
High
Hydrogen Deposits: Lunar Prospector
Blue: 3 μm - OH/H2O adsorption.
Green: reflcted solar radiation at 2.4 μm.
Red: Fe-bearing Pyroxene adsorption at 2 μm.
LCROSS Visible Camera Image of Ejecta Cloud
Field of View of instruments making measurements of the vapor and debris composition
10 km
Volatile Deposits: Chandrayaan-1, LCROSS/LRO
Water Ice Signature
EQ
North
EQ
South
EQ
640
620
600
580
560
Medium Energy Neutrons
North Pole
South Pole
0 30 60 90 120 150 180 210 240 270 300 330 360
Latitude (degrees)

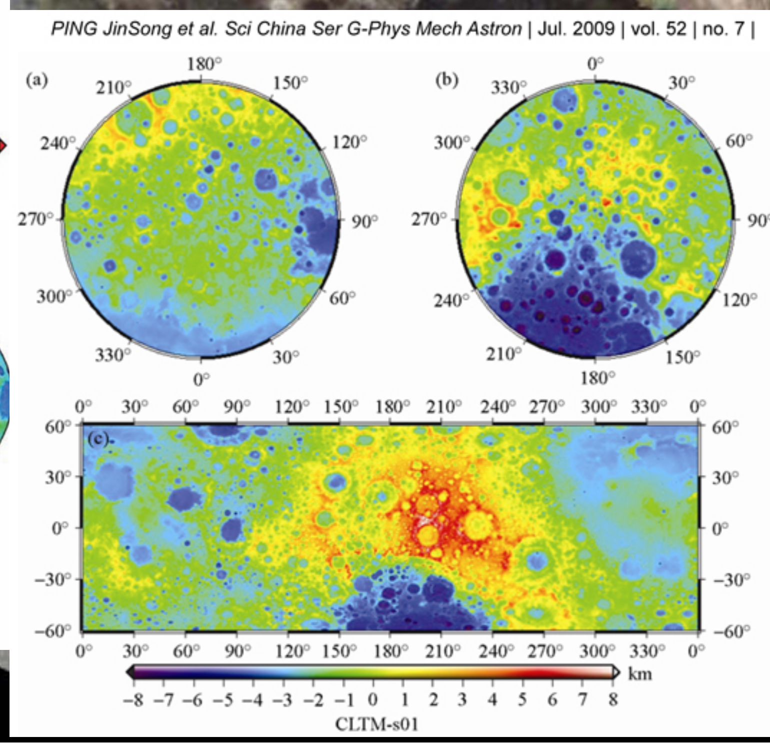
Lunar Surface: Recent Mission Results

Lunar Topography

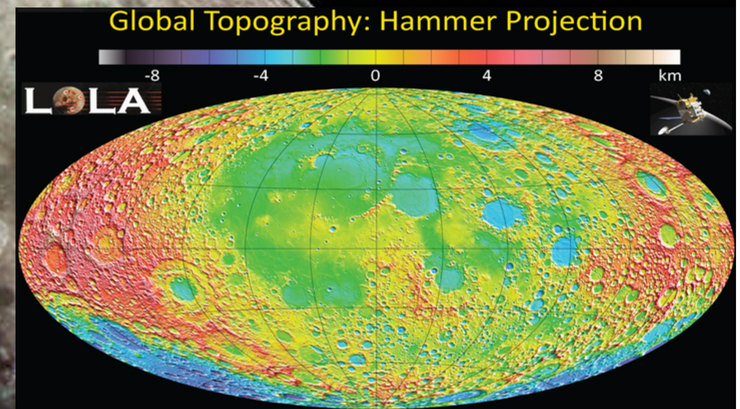
Kaguya (SELENE)



Chang'e-1



LRO (LOLA)



Why Should We Go Back to the Moon?

Public/Political Perception:

“We’ve been there and done that. Why go back?”

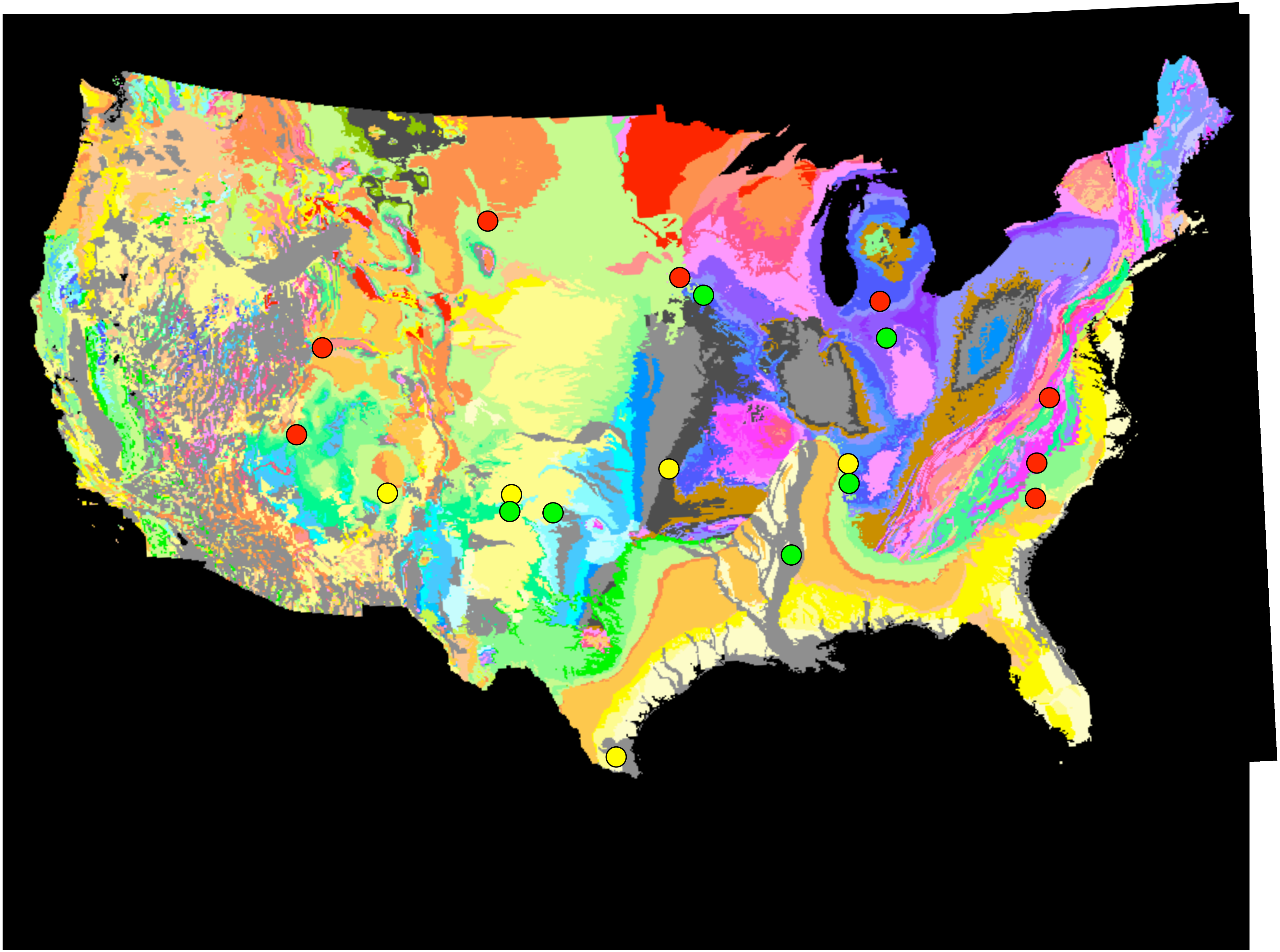
Reality:

Less than 5% of the lunar surface has been explored in detail. Orbital missions for which we have data have a footprint of, at best, 100 m^2.

We have NOT "been there-done that"!!

The Moon has a surface area of 3.793×10^7 km^2.

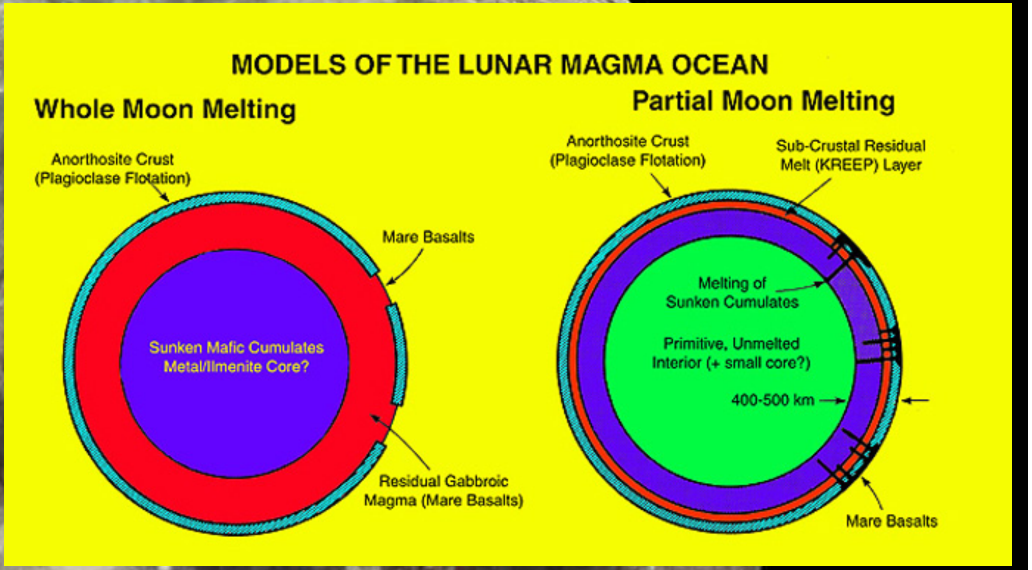
The closest continent is Africa (3.007×10^7 km^2) or Asia (4.458×10^7 km^2).

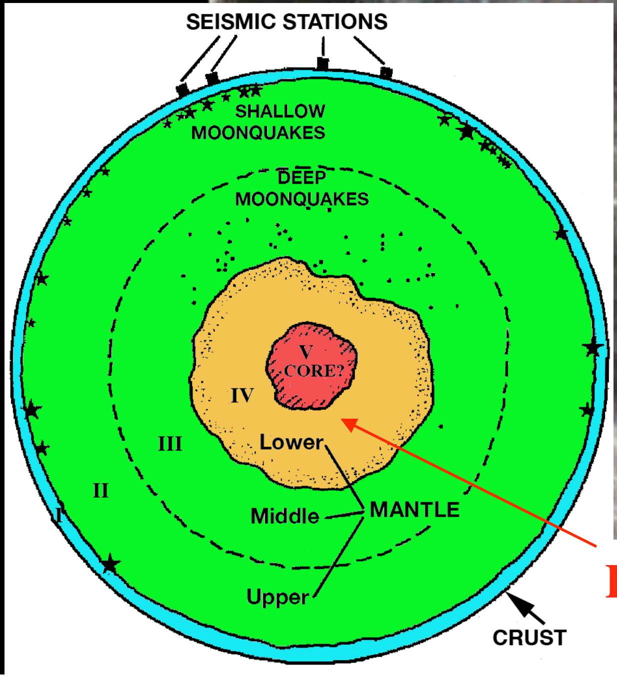


Why go back?
Unresolved Questions: Lunar Interior

If there was a magma ocean, how deep was it?

What is the nature of the deep lunar interior?





Plastic/liquid zones?

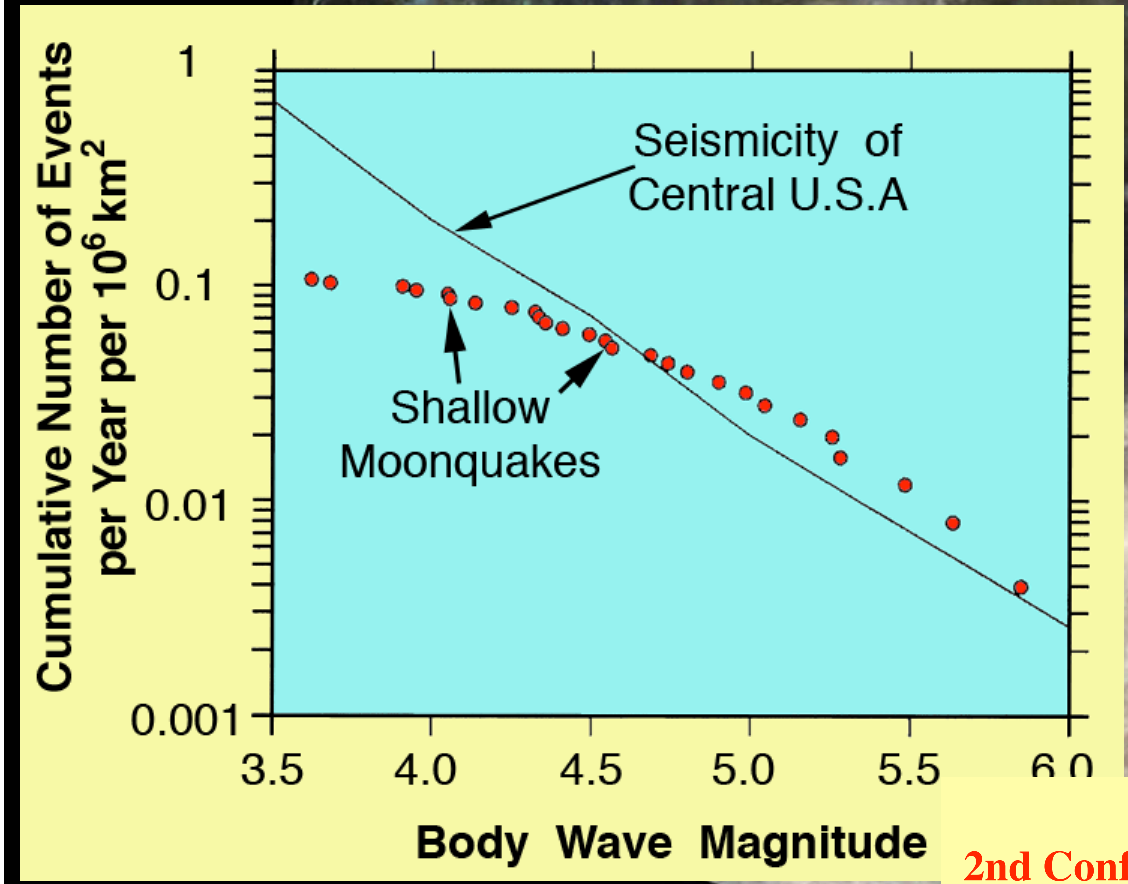
Deep Moonquakes: why so few from the far side?

MAY have a small core ~250 km. MAY be Fe, FeS, but MAY be ilmenite ($FeTiO_3$).

Current models suggest that the core would be solid if Fe metal, but could still be liquid if it was FeS.

Why go back?
Unresolved Questions: Seismology

What are the locations and origins of shallow Moonquakes, the largest lunar seismic events?



How does the lunar regolith affect transmission of seismic energy?

What is the effect of seismic shaking in a low gravity environment?

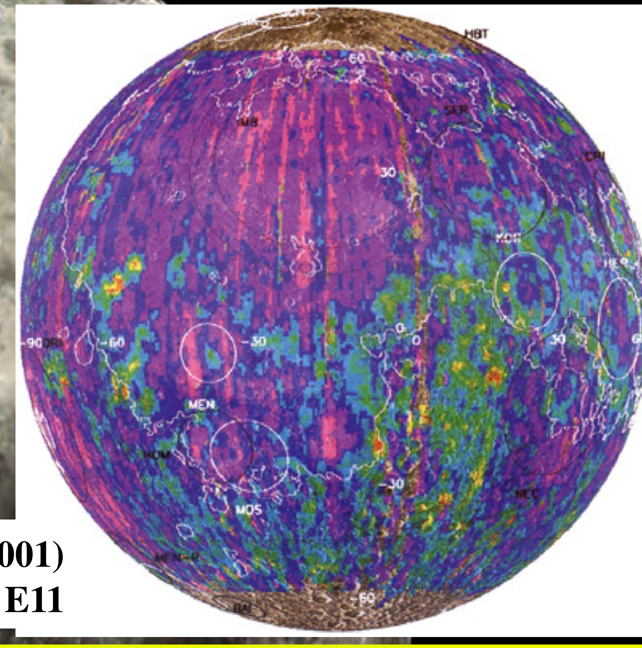
Oberst & Nakamura (1992)
2nd Conference on Lunar Bases & Space Activities

Why go back?

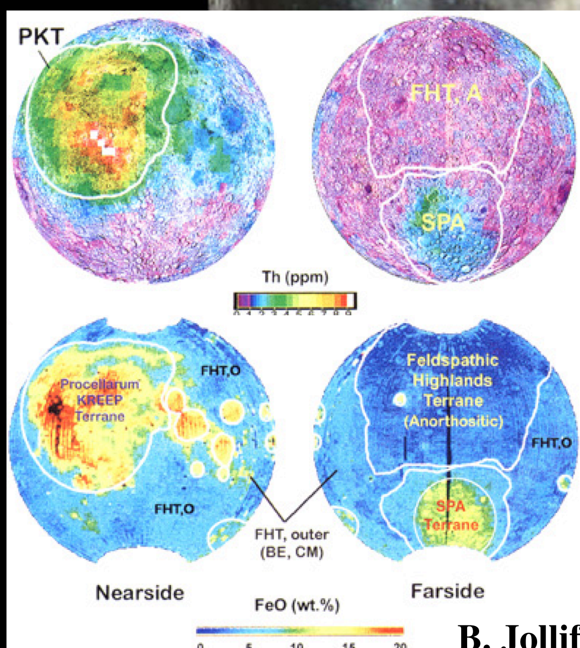
Unresolved Questions: Lunar Surface

Origin of the magnetic anomalies in the lunar crust?

Are crustal structure changes gradational or are distinct domains present? Do these extend into the lunar mantle?



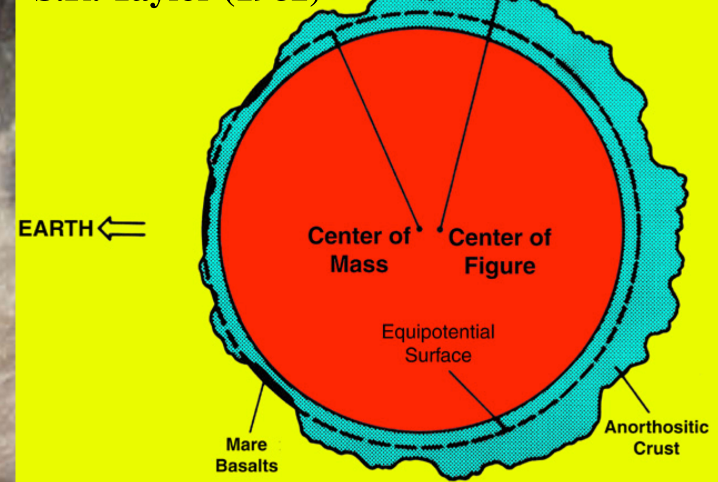
J. Halekas et al. (2001) JGR 106, E11

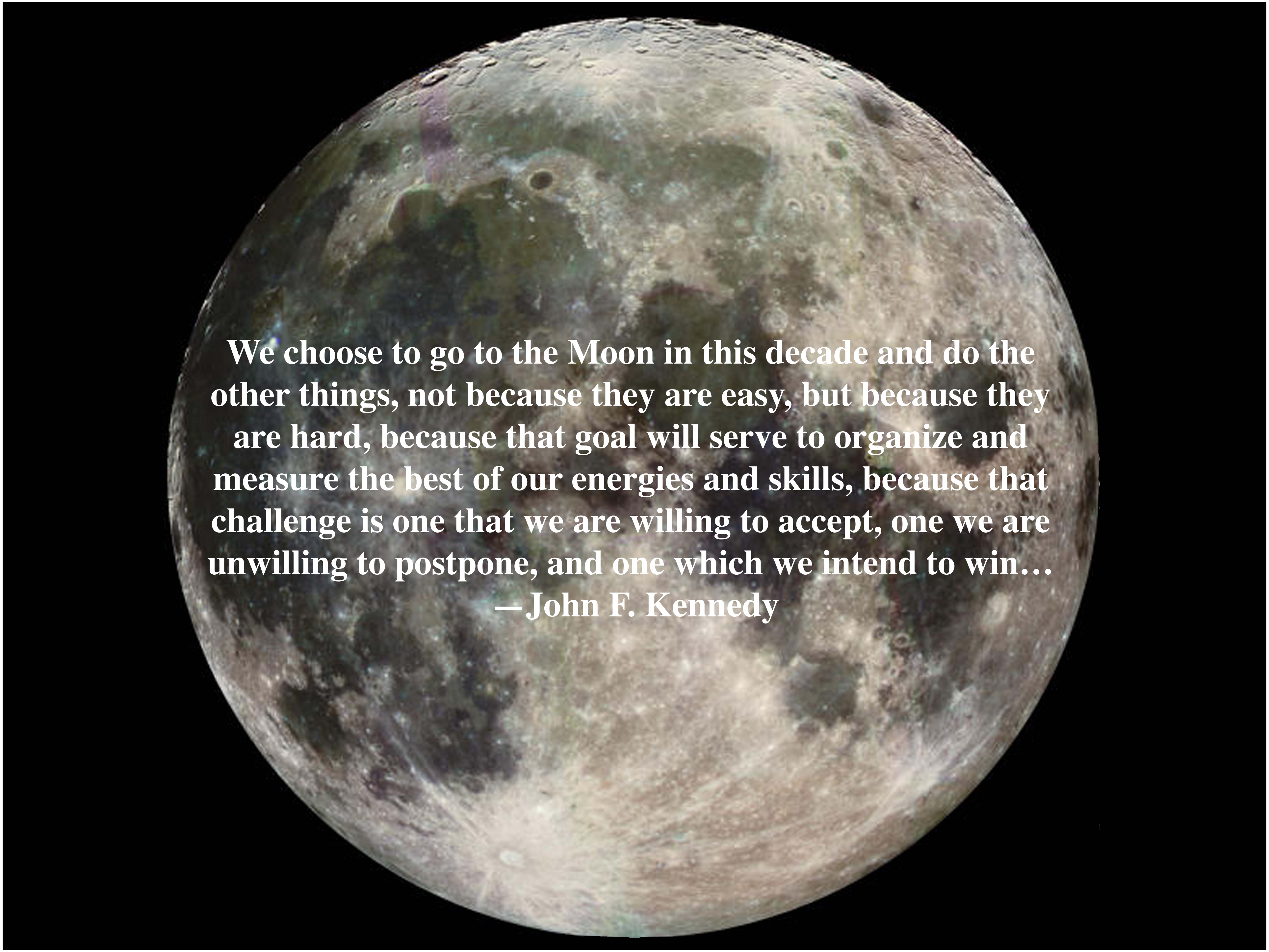


B. Jolliff et al. (2000) JGR 105, E2

What are the structural and thickness variations in the lunar crust (near side vs. far side)?

S.R. Taylor (1982)




We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win…
—John F. Kennedy