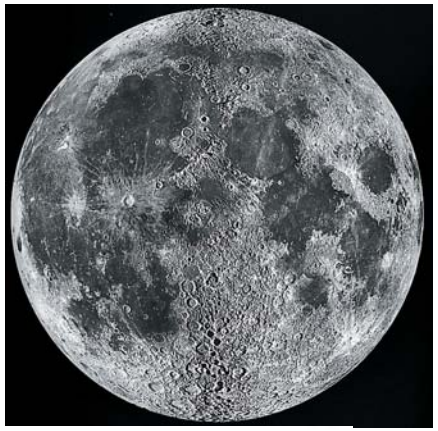
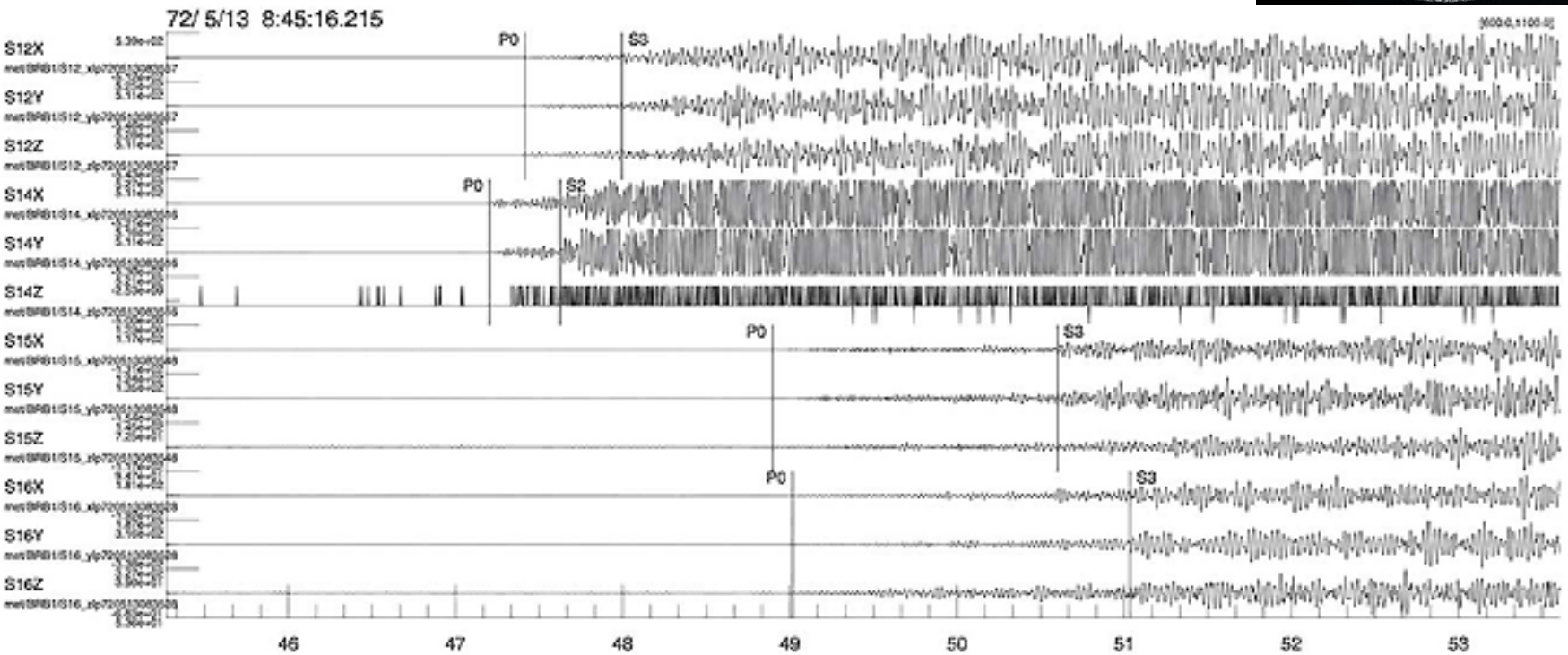
The Importance of Establishing a Global Lunar Seismic Network

Clive R. Neal[1] (neal.1@nd.edu) & the LuSeN Team





[From Lognonné et al. (2003) *EPSL* **211**, 27-44]

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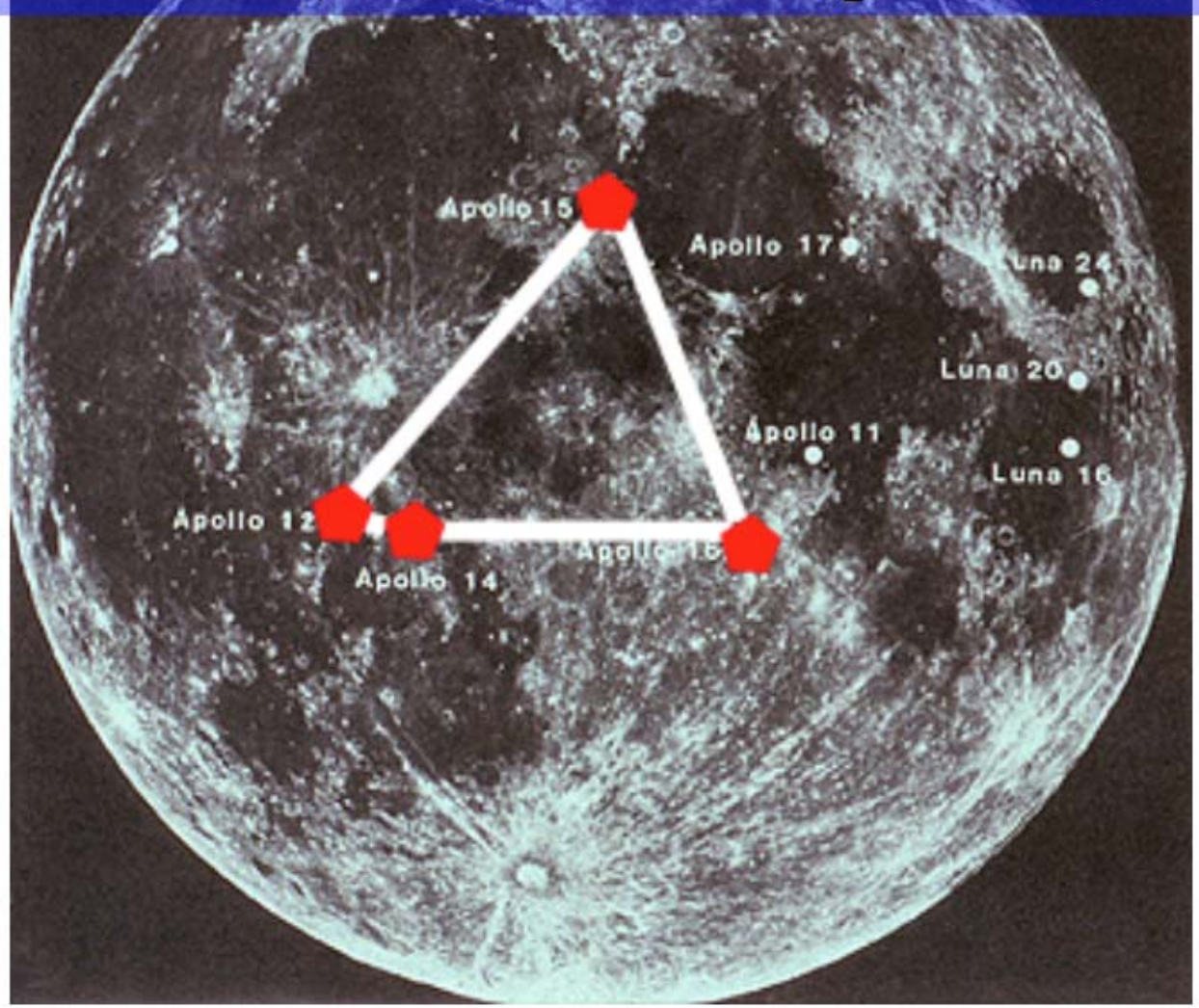
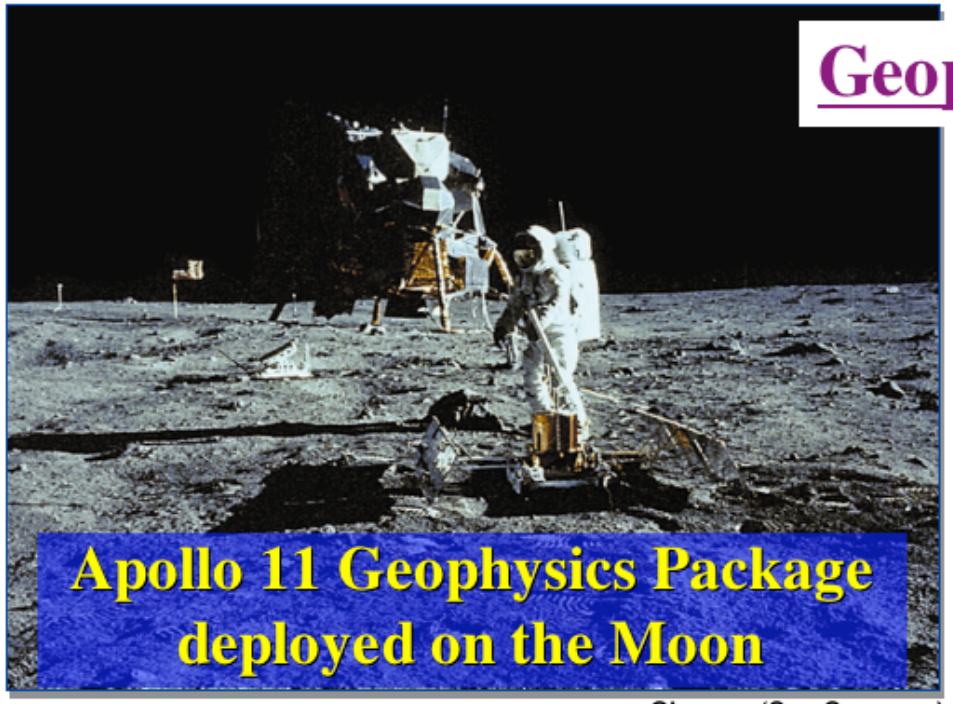
Science and exploration goals are <u>not</u> mutually exclusive nor are they in competition. They are intimately linked and feed off each other, thus enhancing the success of the overall mission goals.

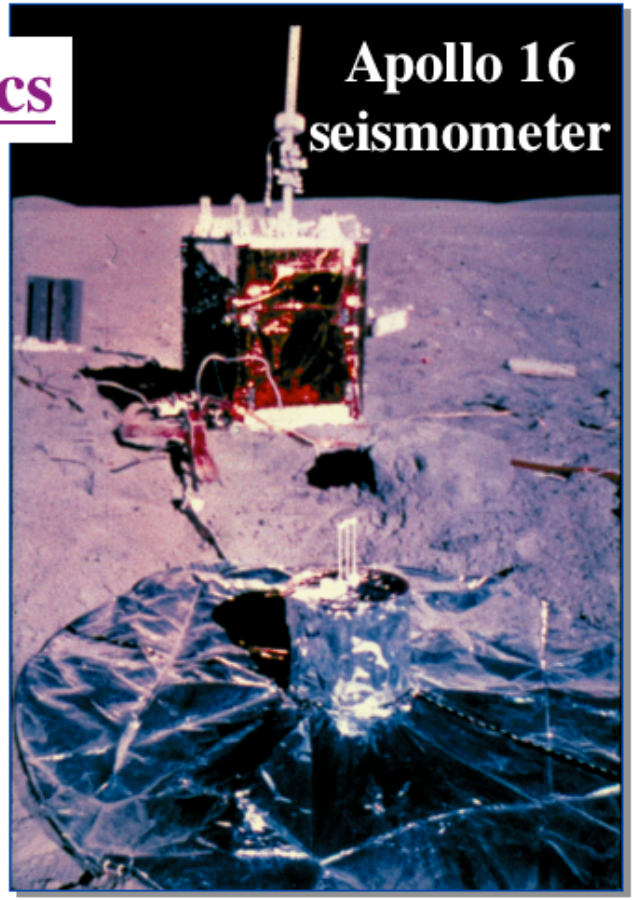
Apollo Seismic Stations

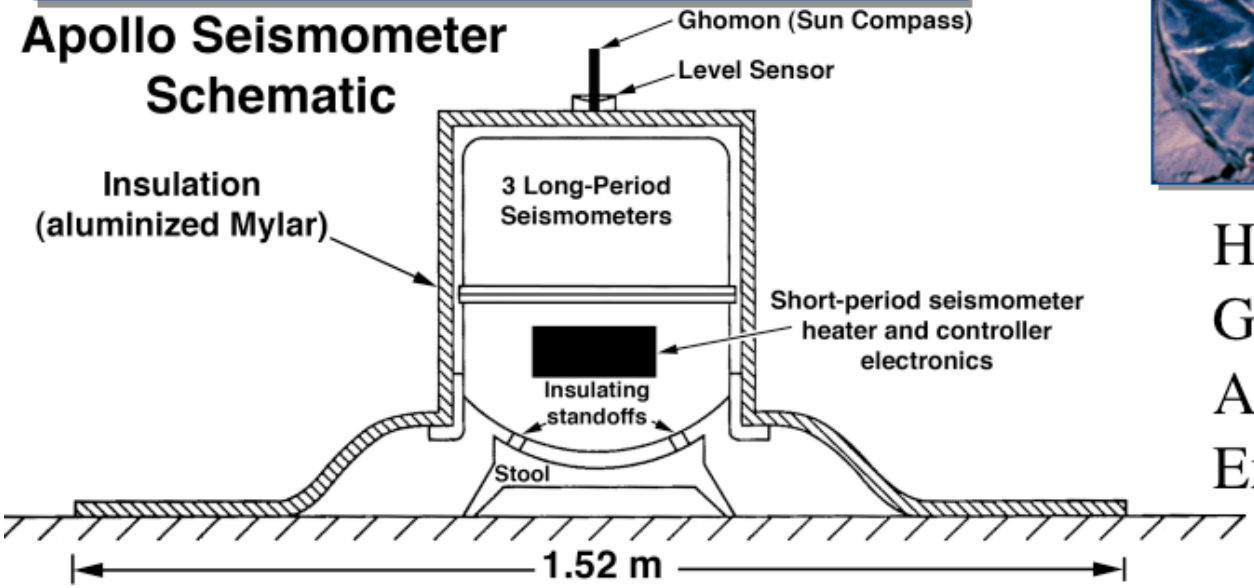
The *complete* Apollo seismic network operated from 14 December, 1972, until 30 September, 1977.



Information on the Interior of the Moon





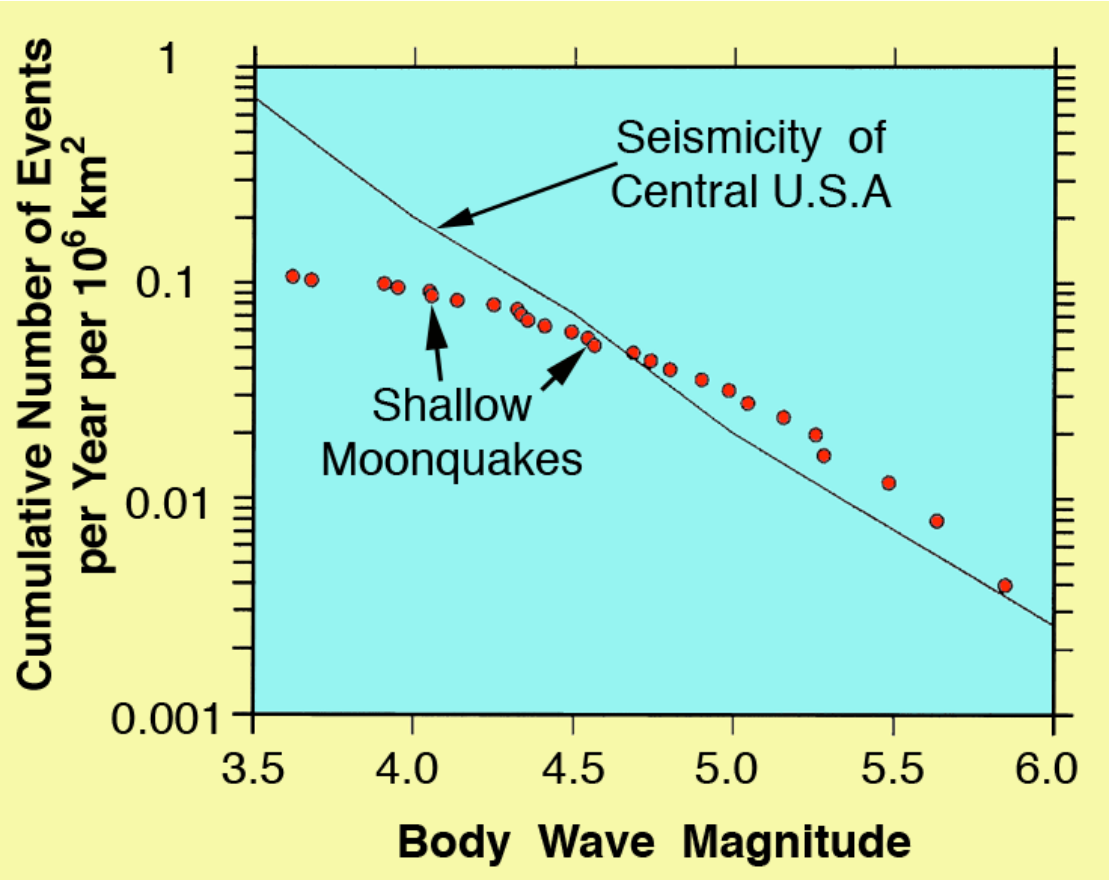


Heat flow.
Gravity.
Apollo Passive Seismic Experiment.

Seismology of the Moon

The Moon is NOT seismically dead!

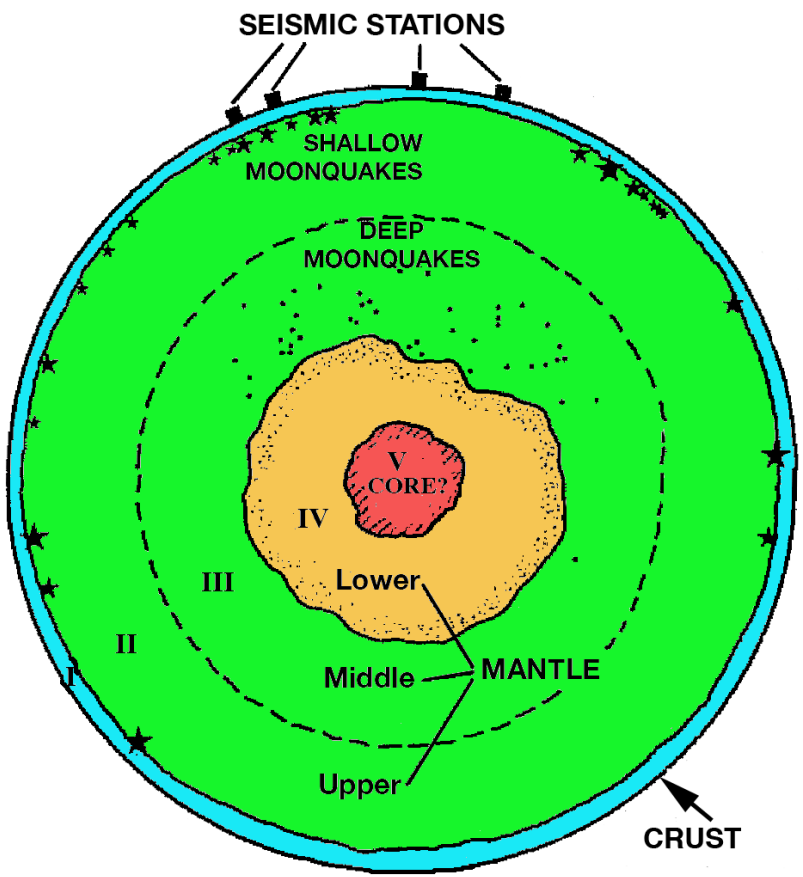
It is a "one-plate planet" with seismicity is equal to that of an intraplate setting on Earth.



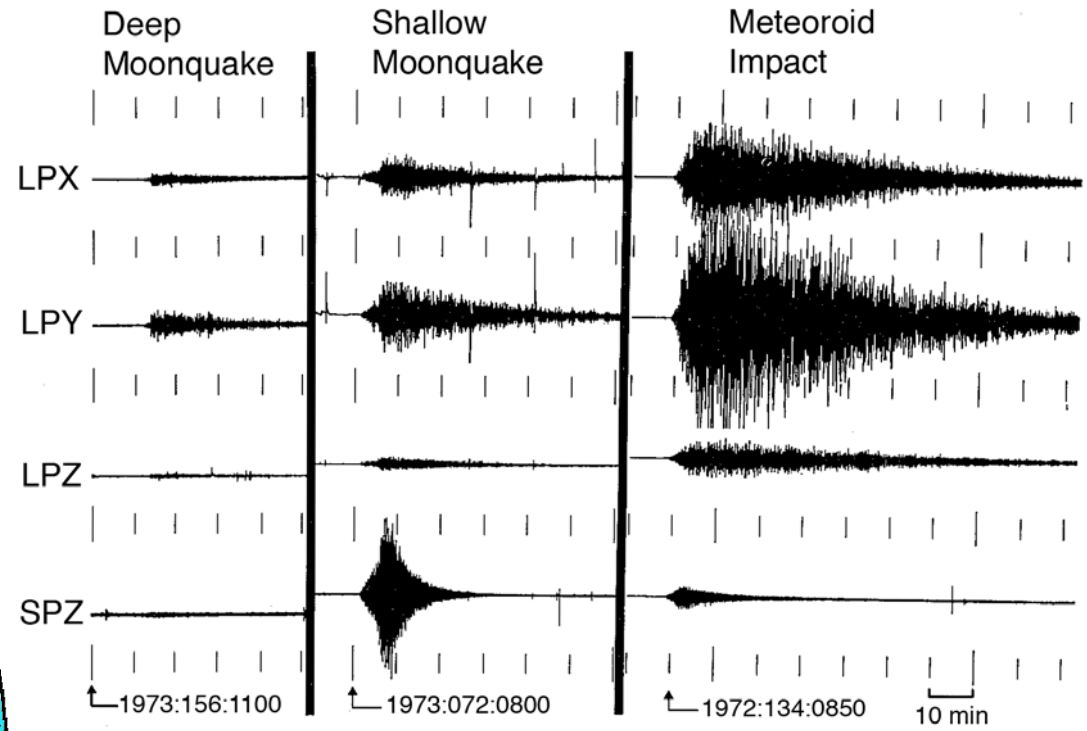
[Oberst & Nakamura (1992) **2nd** *Conference on Lunar Bases & Space Activities*]

Seismology of the Moon

Four types of events induce seismicity on the Moon.



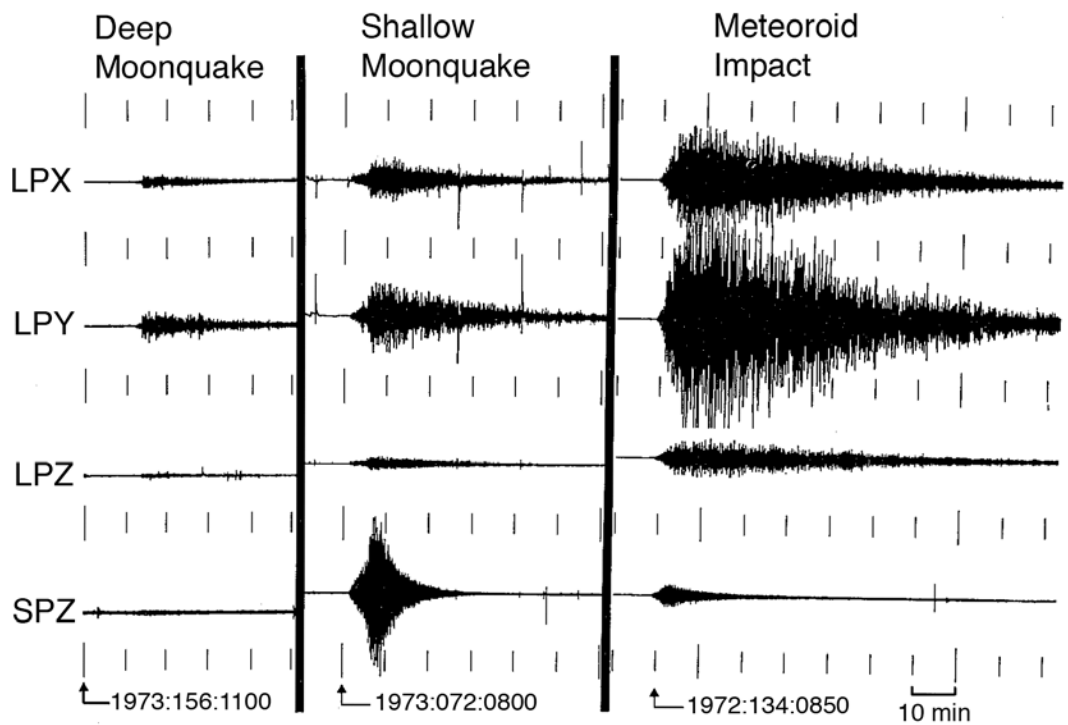
[Nakamura et al. (1982) *PLPSC* **13th**]



1) Deep Moonquakes - 850-1,000 km. > 7,000 recorded. Originate from "nests" - 318 nests defined from Apollo seismic data to date. Small magnitude (< 3). Associated with tidal forces.

Seismology of the Moon

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



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.

Lunar Seismology: A Lunar Base Context

Shallow Moonquakes and **Meteoroid Impacts** present significant risks to any proposed lunar outpost.
[see also Oberst & Nakamura, 1992, Lunar Base Workshop, LPI]

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.

Meteoroid Impact: > 1,700 impacts of mass > 0.1 kg recorded by Apollo seismometers.

Need for a Global Lunar Seismic Network

Meteoroid Impacts

[From Oberst & Nakamura (1991) *Icarus* **91**, 315-325]

Data used only after the network was complete.

A “small” event was only detected by one seismometer.

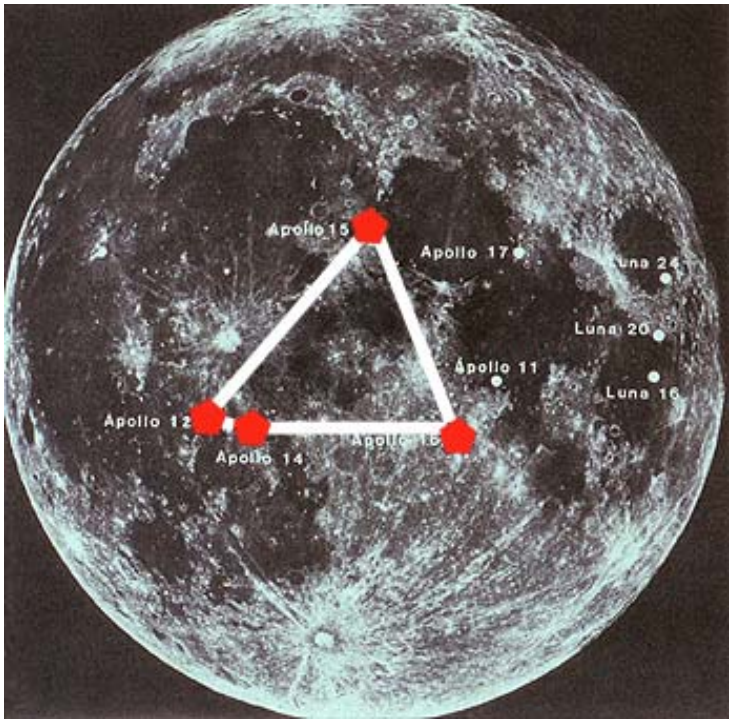
A “large” event was detected by all seismometers.

511 impacts = small = < 1 kg.

416 impacts = large = > 1 kg.

486 impacts detected by > 1 but < 4 seismometers.

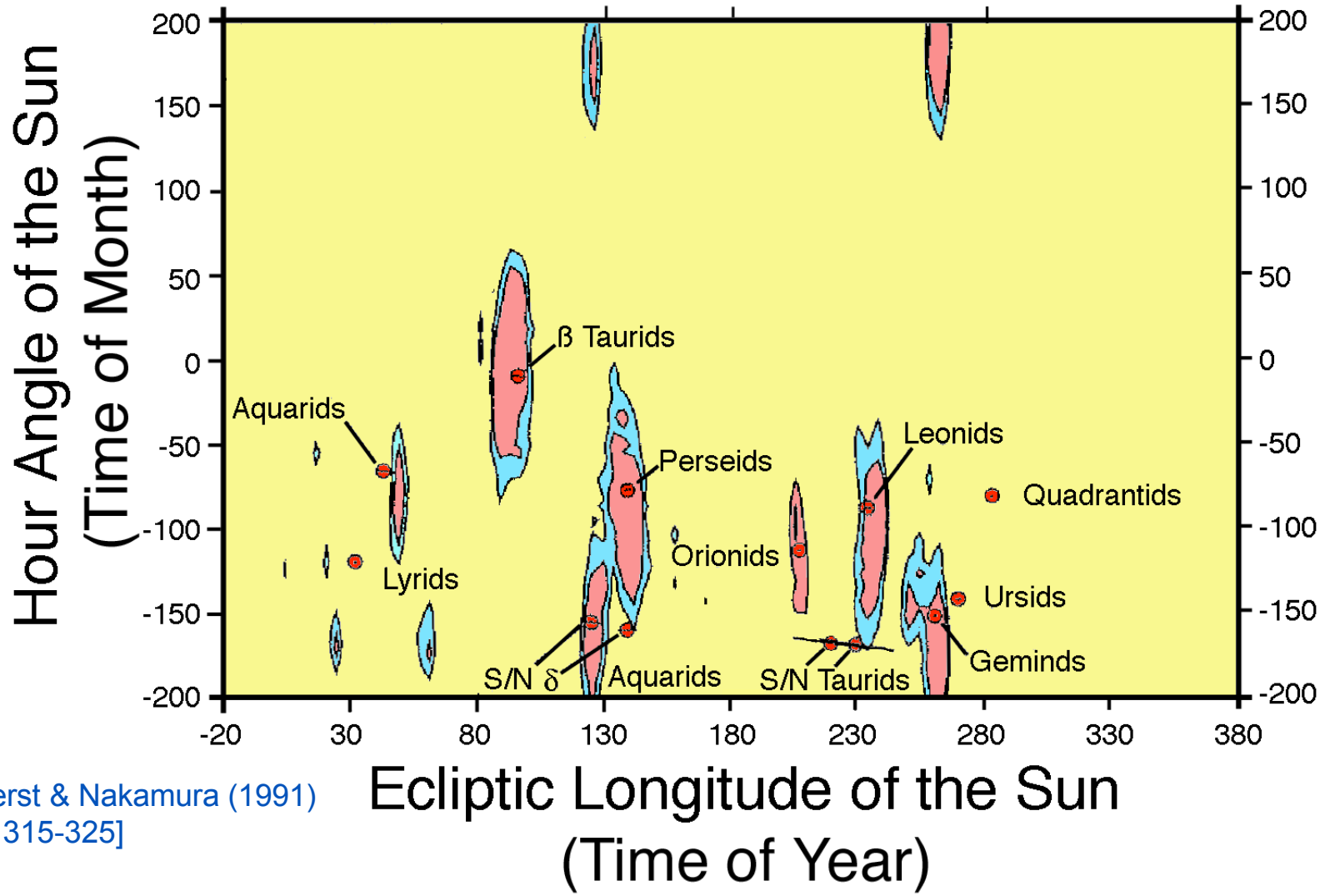
331 impacts detected before the network was complete.



Need for a Global Lunar Seismic Network

Meteoroid Impacts

Resolution of the small (< 1 kg) meteoroid impacts.

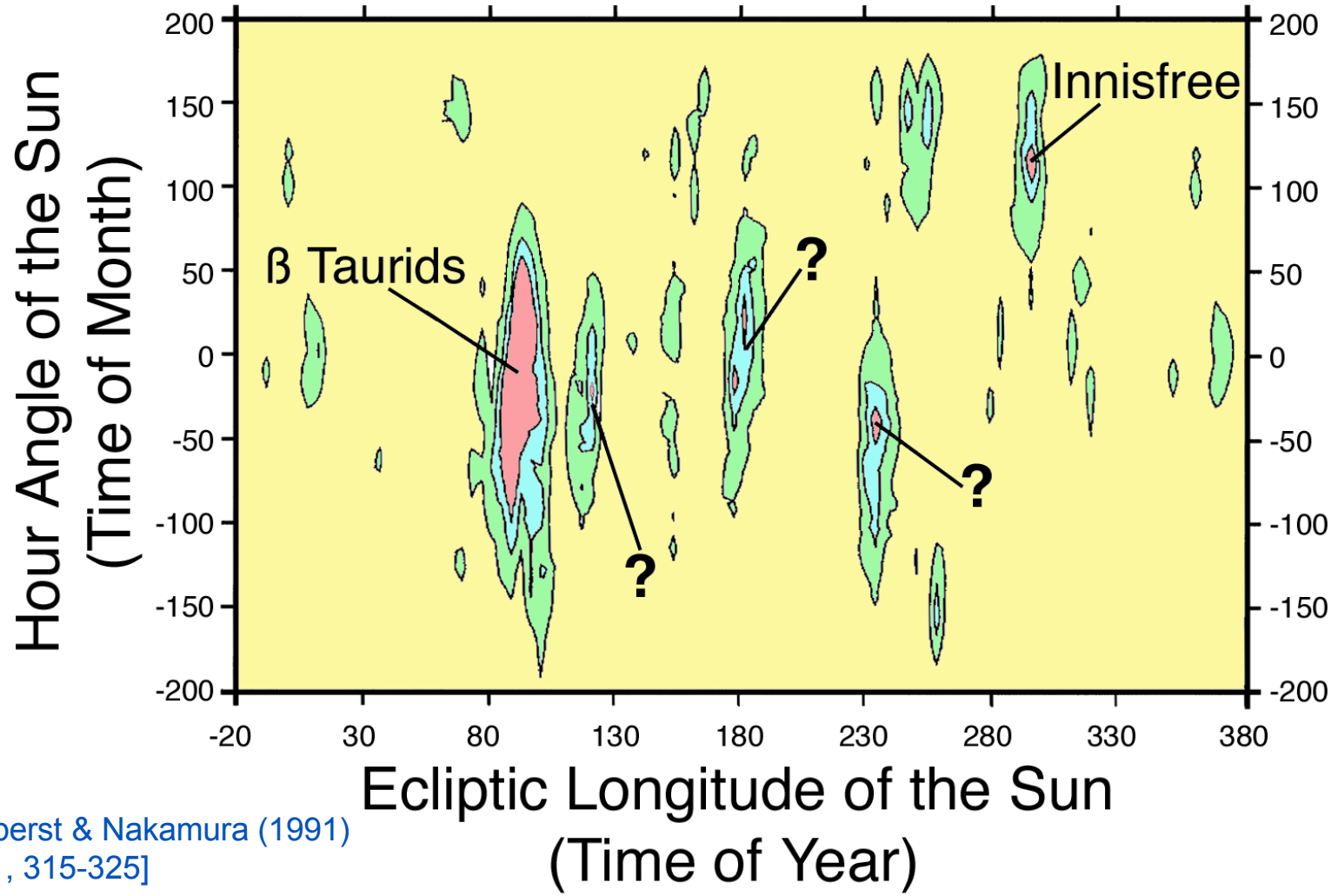


[From Oberst & Nakamura (1991) *Icarus* **91**, 315-325]

Need for a Global Lunar Seismic Network

Meteoroid Impacts

Resolution of the large (> 1 kg) meteoroid impacts.



[From Oberst & Nakamura (1991)
Icarus **91**, 315-325]

Need for a Global Lunar Seismic Network

Meteoroid Impacts

28% of Small (< 1 kg) impacts exhibit clustering.

Only 15% of large (> 1 kg) impacts exhibit clustering.

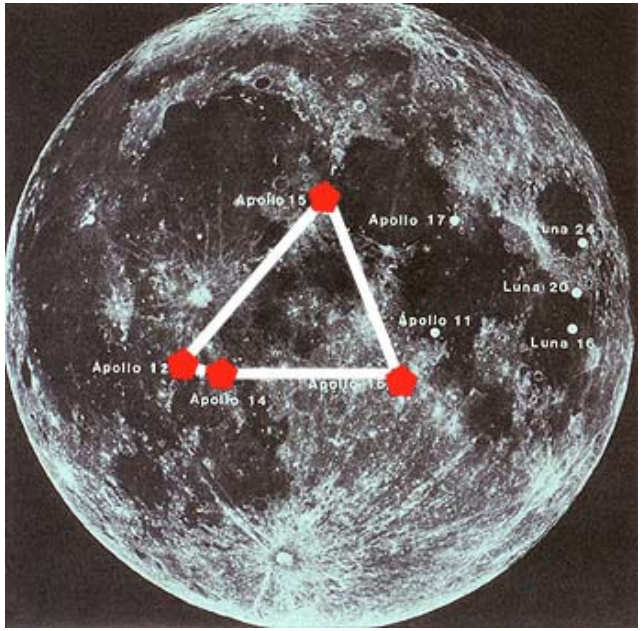
Meteor showers that have high latitude radiants (>50°; *Quadrantids*, *Lyrids*, and *Ursids*) were not detected - important for a polar lunar base. Apollo seismic network was only on the nearside around the equator.

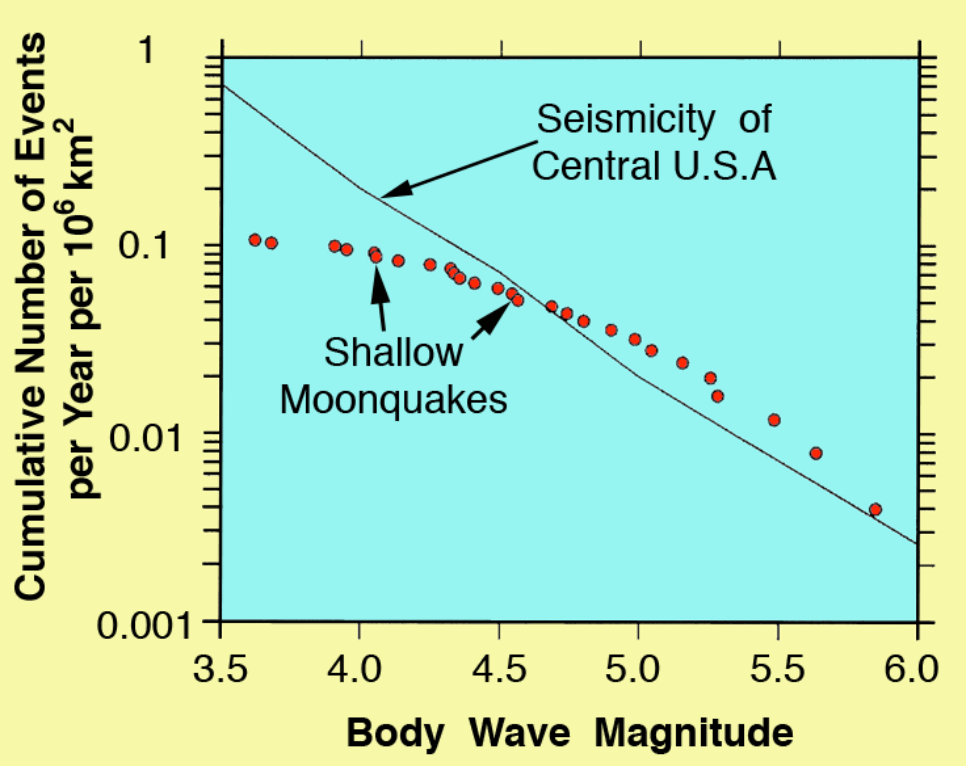
As the lunar rotational axis is ~ perpendicular to the ecliptic and seismometers were located near the equator, this results in poor control of heliocentric latitude, but good control over longitude, of the radiant of meteoroids.

Need for a Global Lunar Seismic Network

Shallow Moonquakes

The Apollo Seismic network was of limited extent.





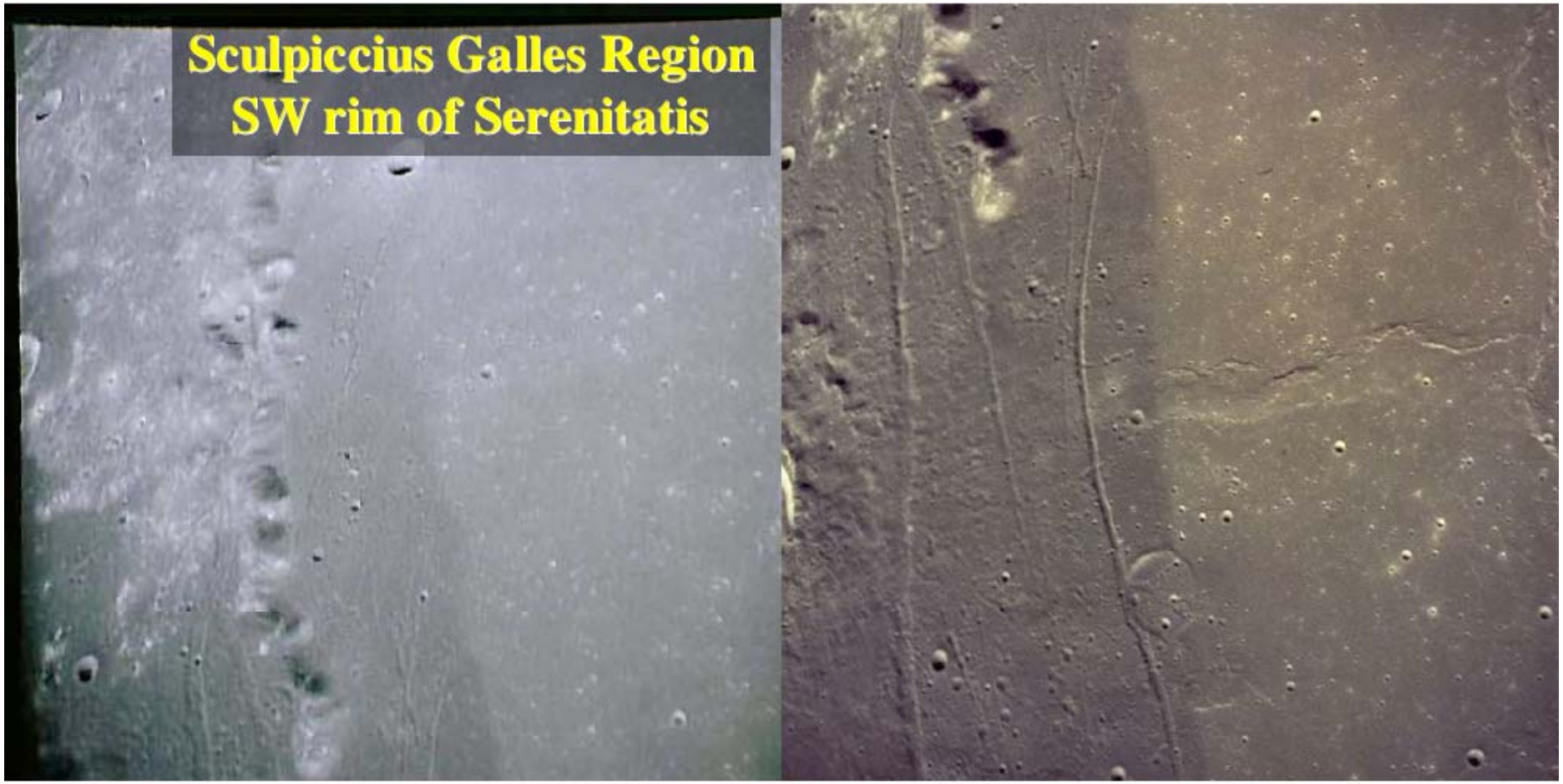
Did not yield locations of the largest Moonquakes.

Twenty-eight **Shallow Moonquakes** recorded, seven with magnitude > 5.

Need for a Global Lunar Seismic Network

Shallow Moonquakes

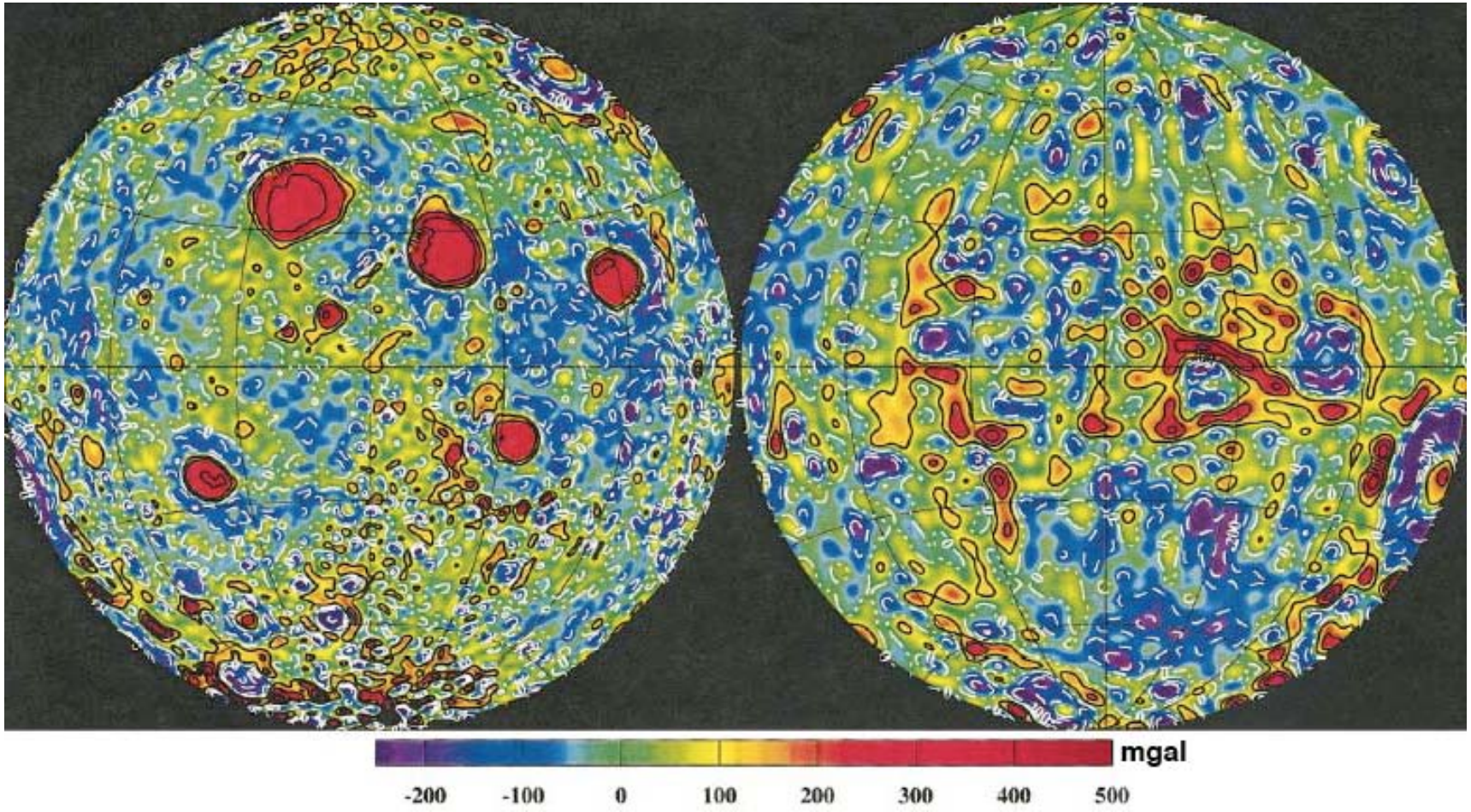
Possible locations: Tensional faults, rifts.



Need for a Global Lunar Seismic Network

Shallow Moonquakes

Possible locations: Boundaries of gravity anomalies.



[From Konopoliv et al. (2001) *Icarus* **150**, 1-18]

Need for a Global Lunar Seismic Network

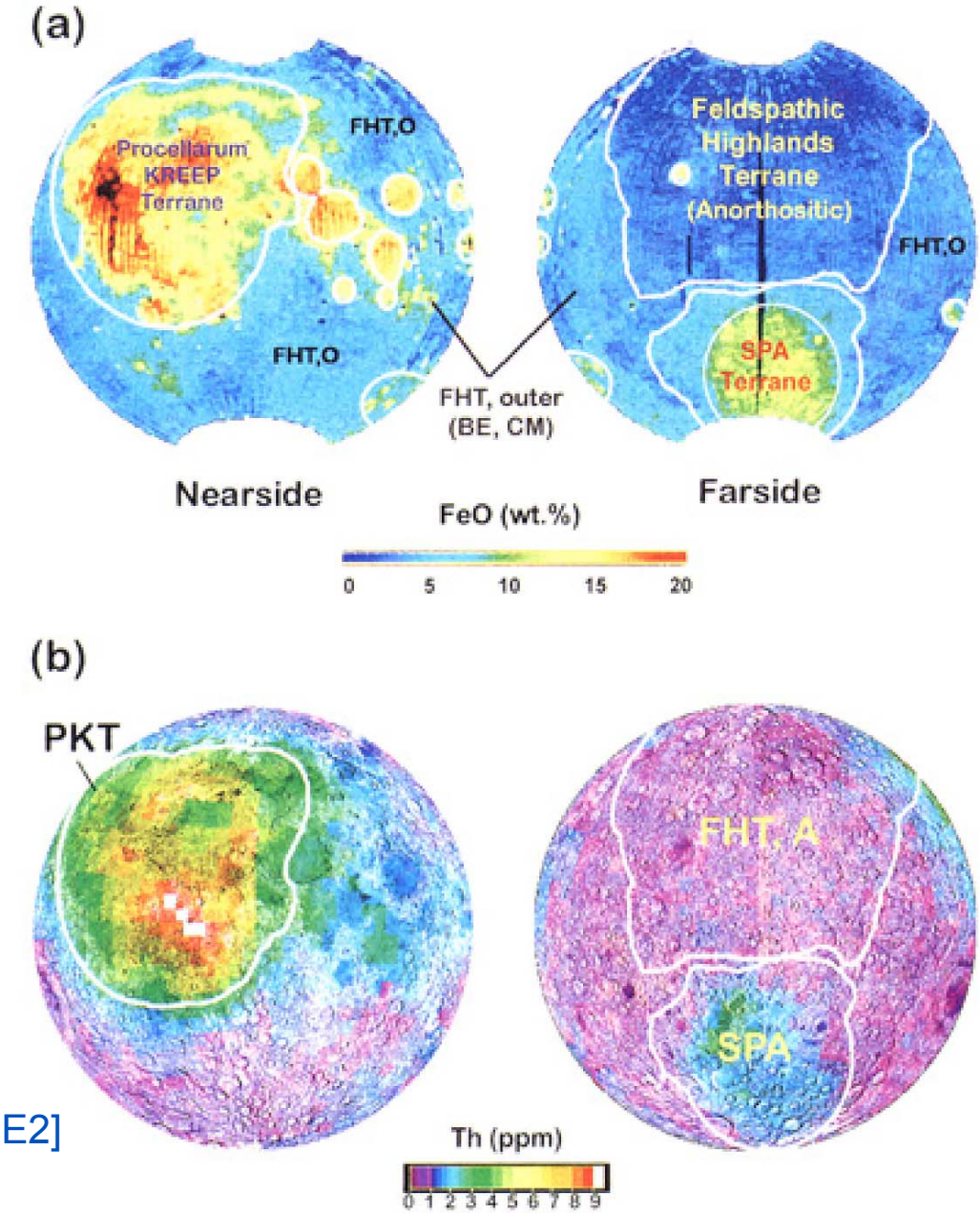
Shallow Moonquakes - Possible locations: Impact craters.

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

Need for a Global Lunar Seismic Network

Shallow Moonquakes

Possible locations:
Terrane Boundaries.



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

Need for a Global Lunar Seismic Network

Where should the proposed lunar outpost be situated?

Need to consider:

Location(s) and origin(s) of Shallow Moonquakes are unknown.

Need a better understanding of meteoroid impact locations.

Need a better understanding of general lunar tectonic activity.

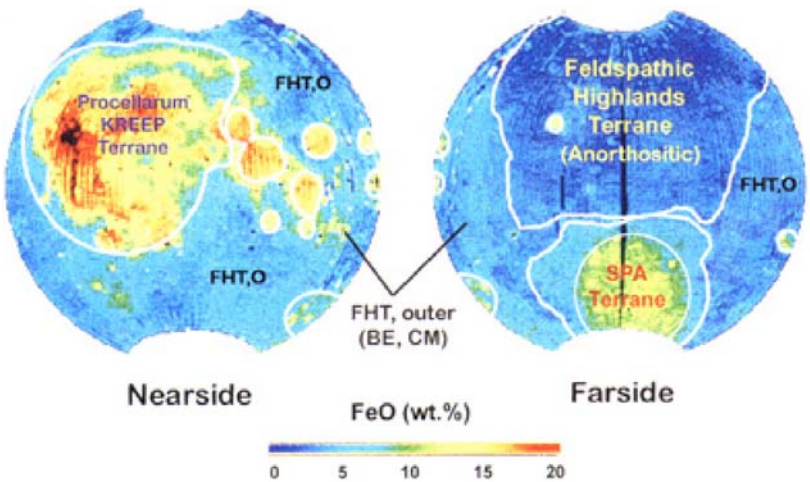
Need for a Global Lunar Seismic Network

Conclusion:

There are ***practical, logistical, and engineering*** needs for a global **Lu**nar **Se**ismic **N**etwork in support of building and maintaining a long-term lunar outpost.

Unresolved Science Questions

What are the structural and thickness variations in the lunar crust (nearside vs. farside)?



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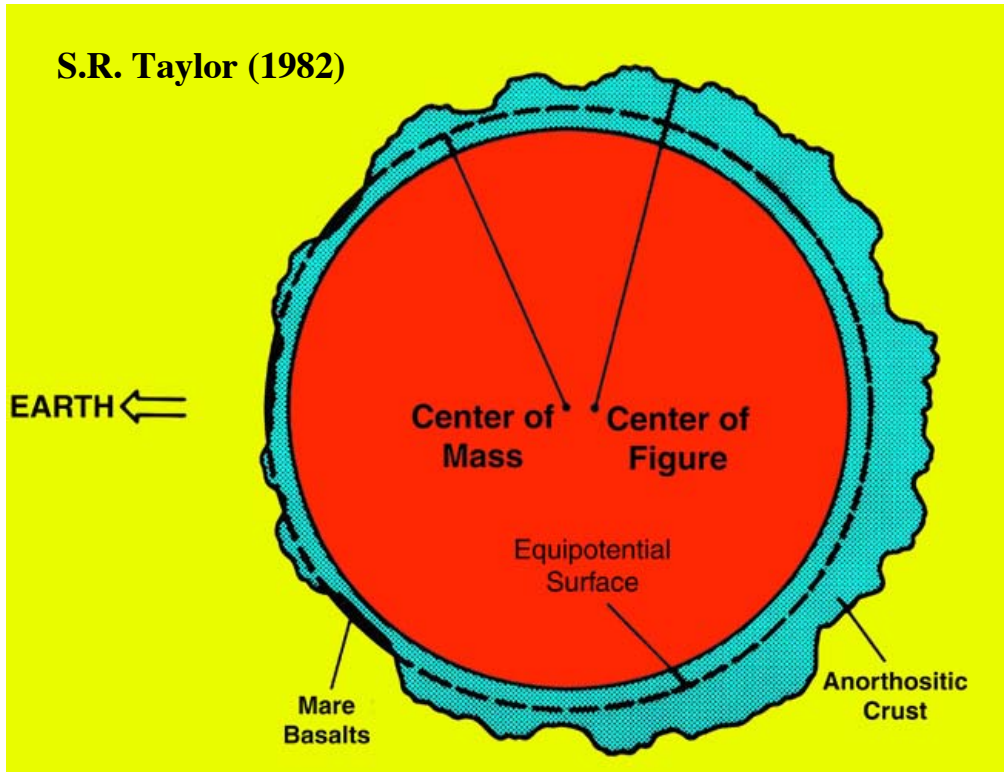
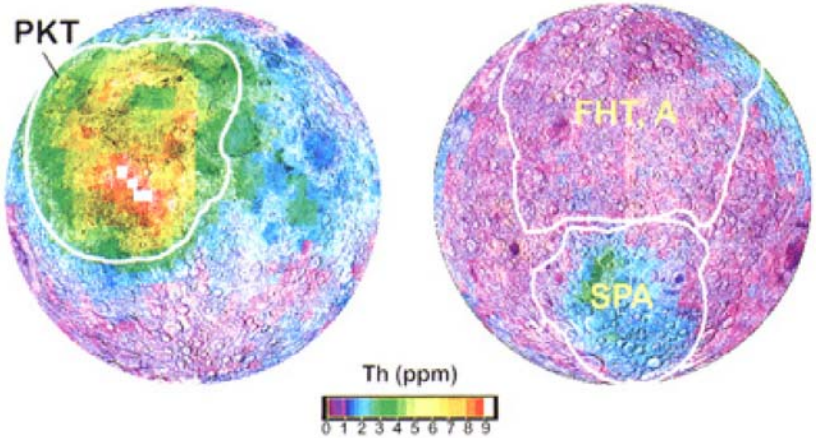


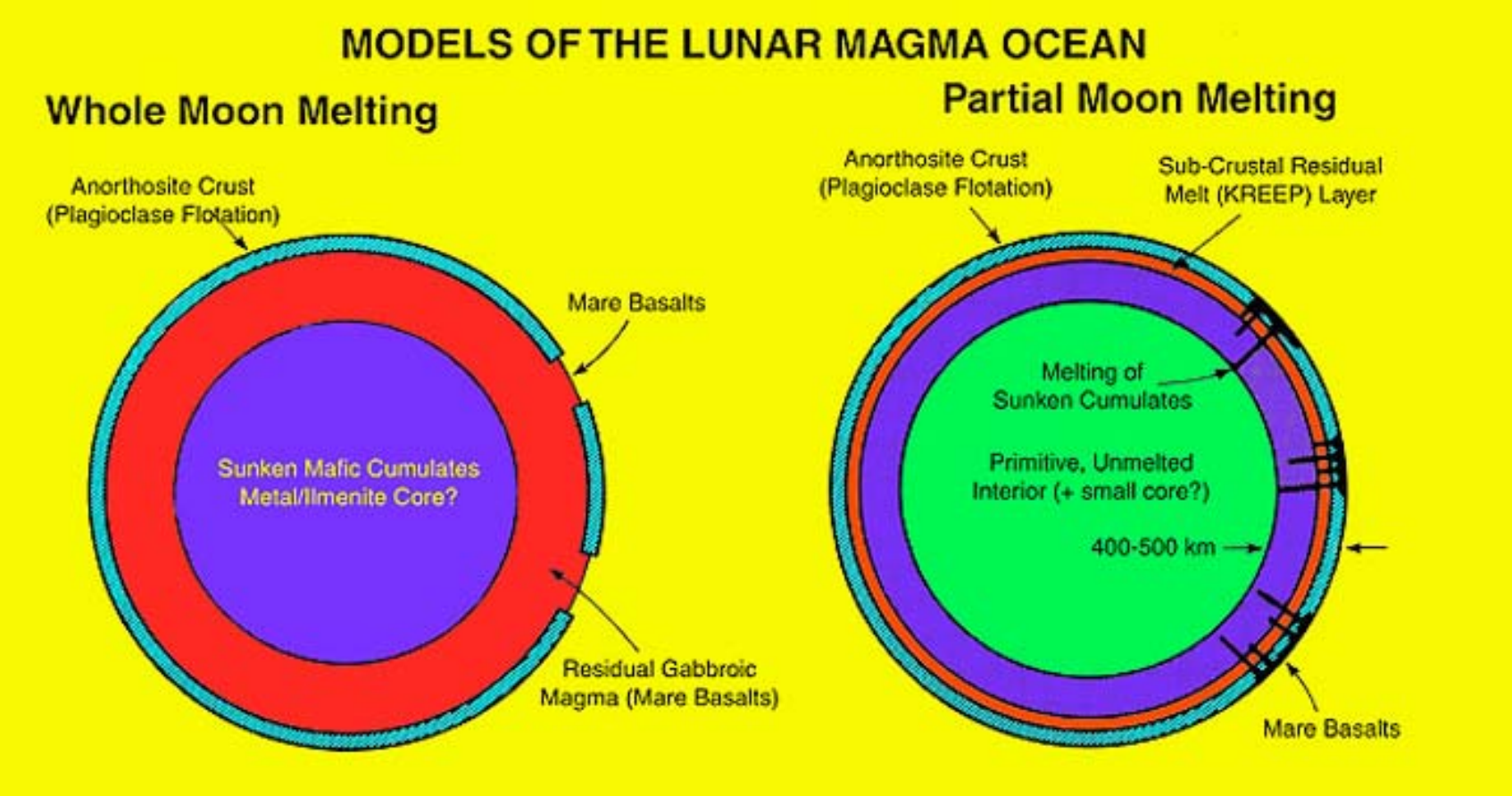


Are crustal structure changes gradational or are distinct domains present?

Do such boundaries extend into the lunar mantle?

Unresolved Science Questions

- If there was a magma ocean, how deep was it? Is there a Moon-wide ~500 km discontinuity?
- What is the nature of the deep lunar interior?
- Is the upper lunar mantle really pyroxenitic?

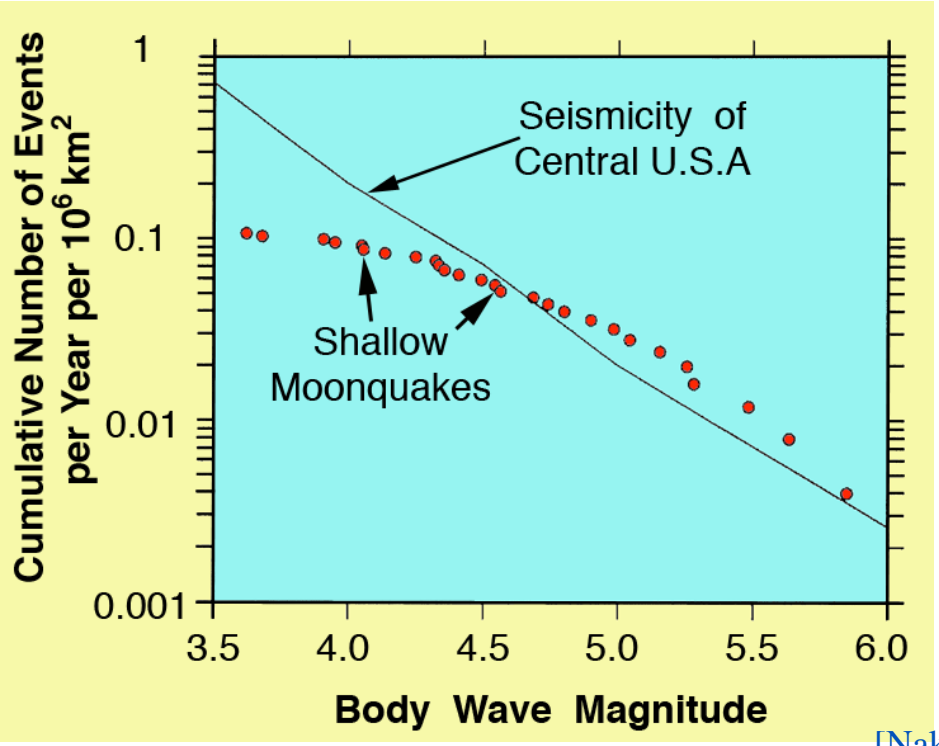


Unresolved Science Questions

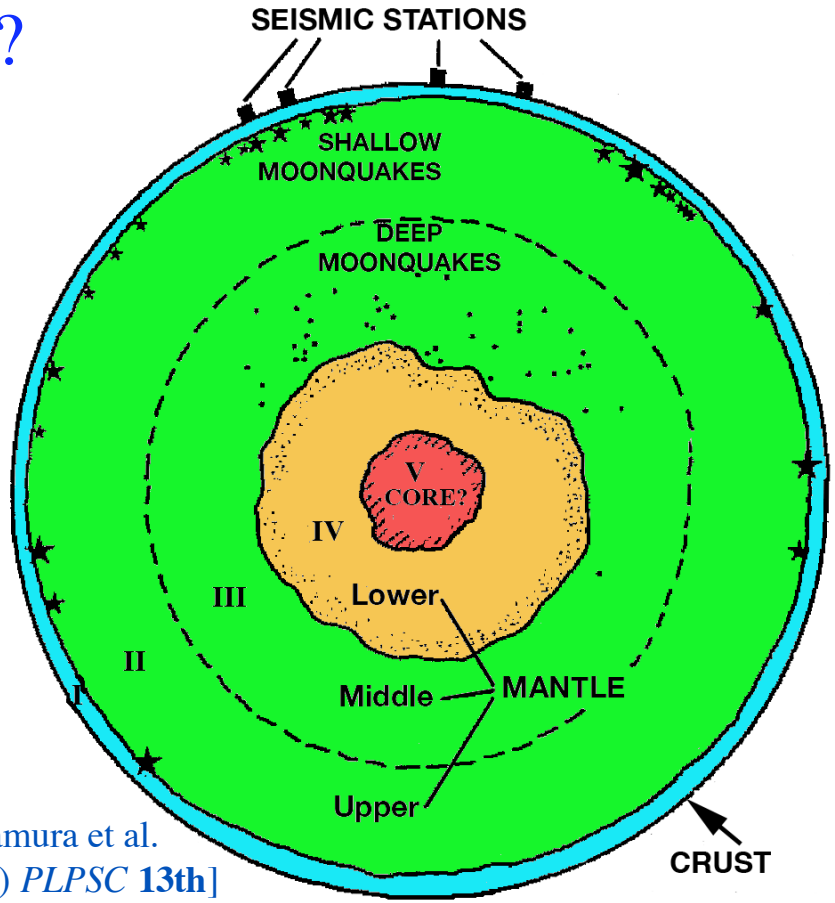
Geophysical data only from limited sites on the nearside because seismic network only of limited extent.

Are there seismic "nests" on the lunar farside?

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



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

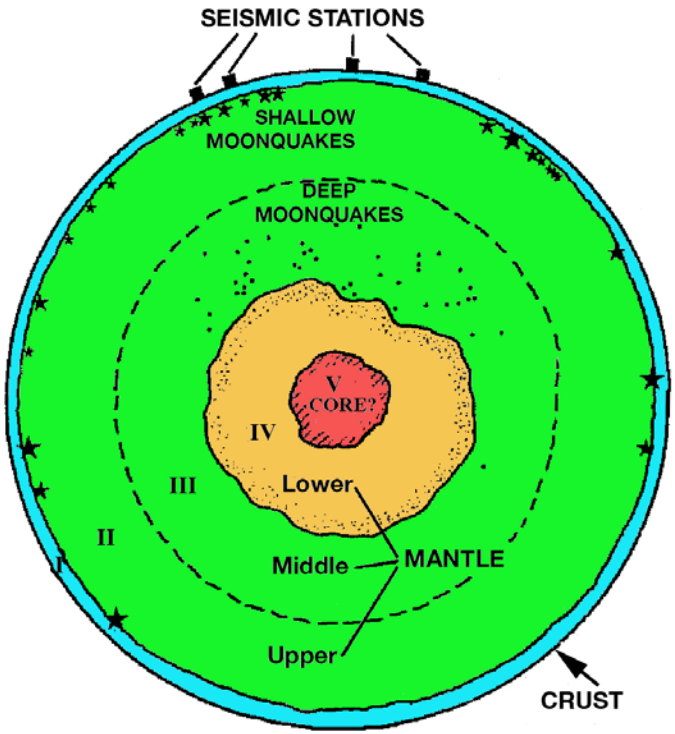


[Nakamura et al. (1982) *PLPSC* **13th**]

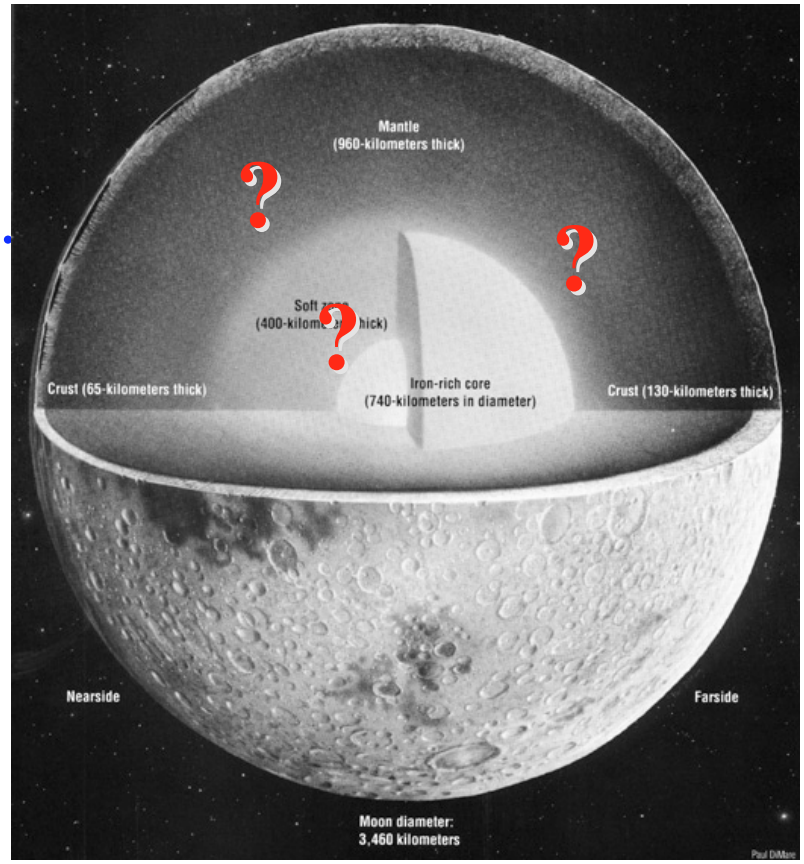
Unresolved Science Questions

Moon has a small core ~250 - 350 km*. MAY be Fe, FeS, but MAY be ilmenite ($FeTiO_3$).

*[Righter (2002) *Icarus* **158**, 1-13; Hood et al. (1999) *GRL* **26**, 2327].



"Plastic" zones present?

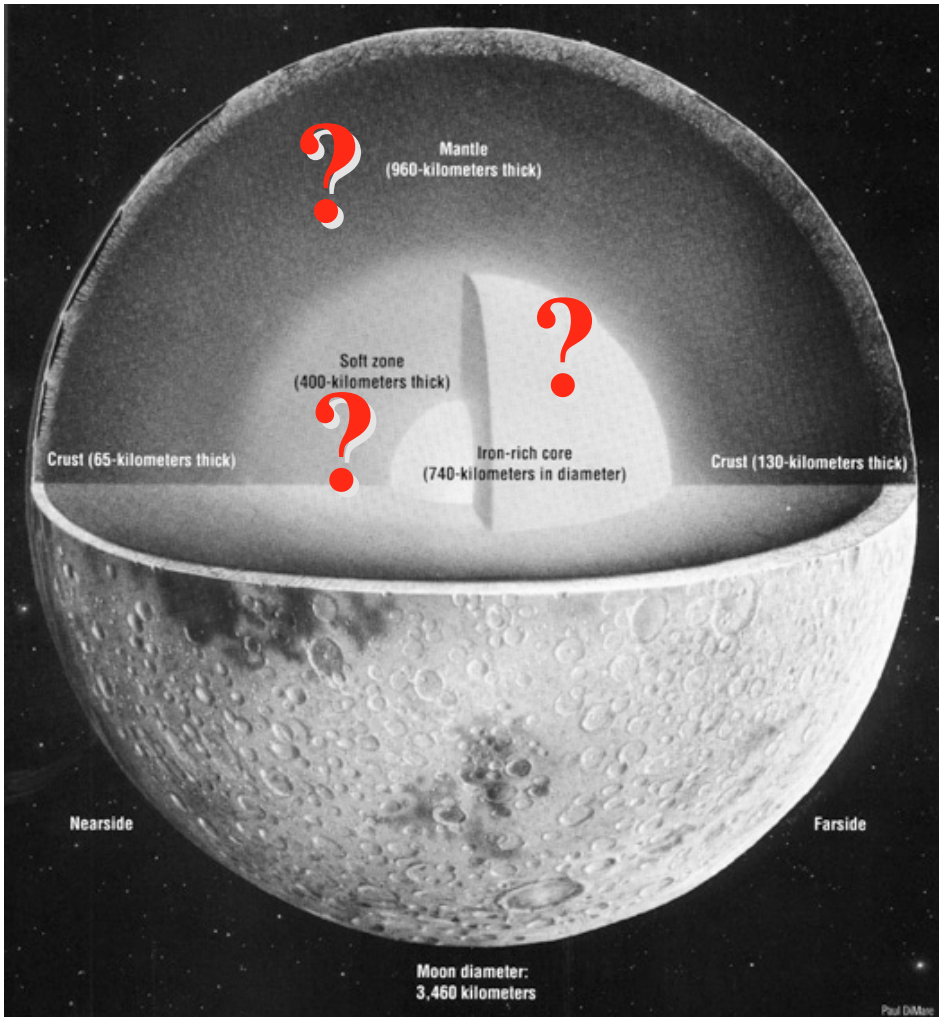


Current models suggest that the core would be solid if Fe metal, but could still be liquid if it was FeS.

Need for a Global Lunar Seismic Network

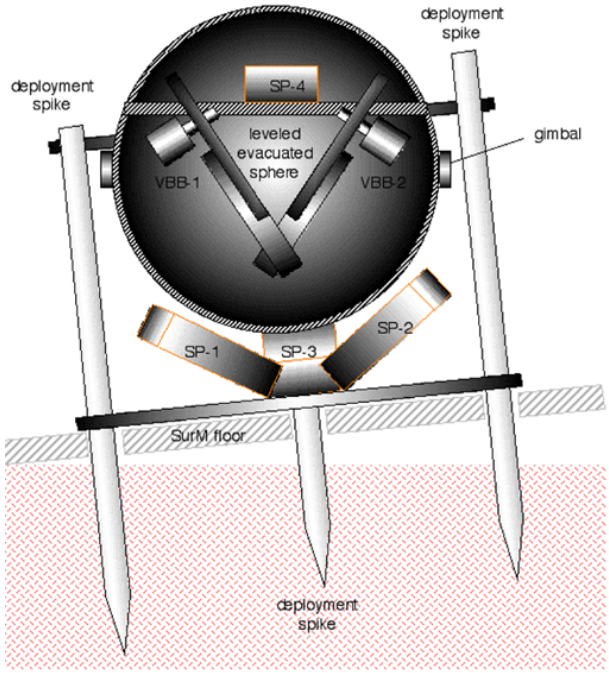
Conclusion:

There are ***scientific*** needs for a global **Lu**nar **Se**ismic **N**etwork to better understand the origin and evolution of the Moon.



The LuSeN Mission Concept

- A minimum of 8 (preferably 10) seismometers deployed around the Moon.
- Mission life = 5 years (minimum).
- Communication satellite required.



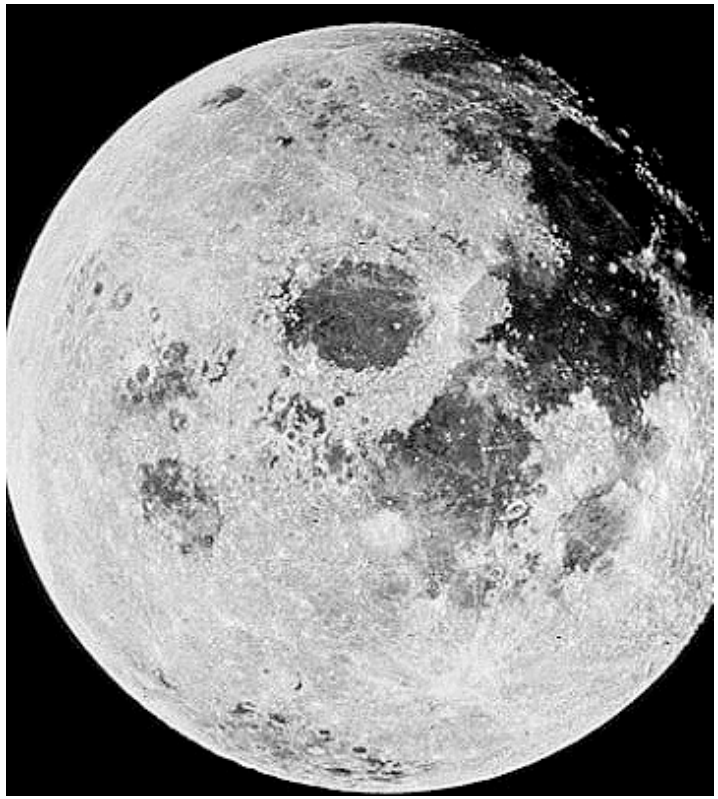
Technology Developments:

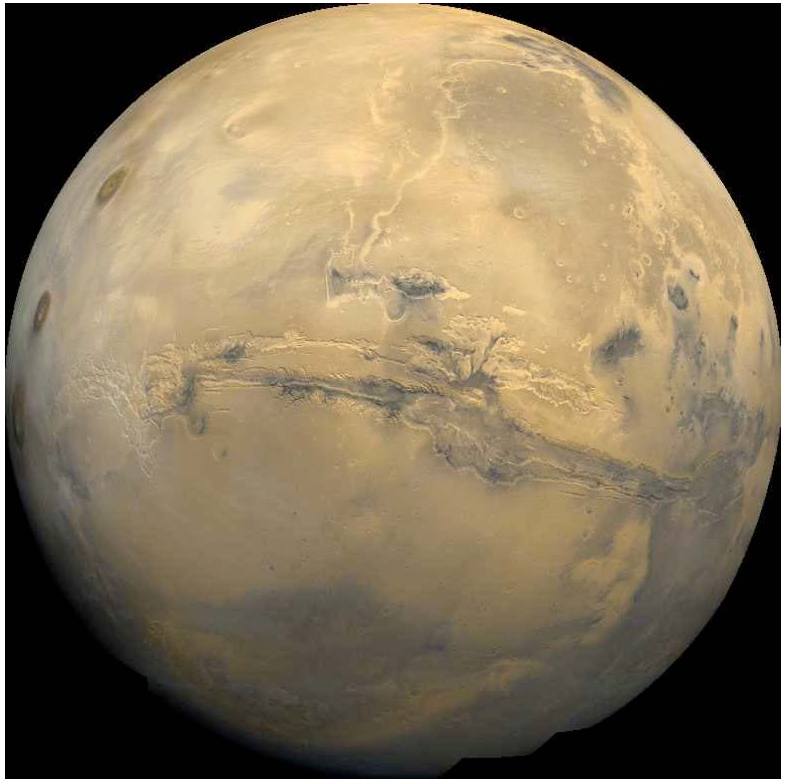
- Power Supply - mini-RTG needed.
- Deployment - hard vs. soft landing of each package.
- Robust, yet sensitive seismometer package that can survive a hard landing, yet be able to detect the smallest of Moonquakes. Netlander?

The Need for Global Seismic Networks

The ability to deploy long-lived global seismic networks on other planetary bodies will yield invaluable data on planetary interiors and tectonic activity that can be used to plan future exploration.

The Moon is an ideal test-bed for this technology.





The “Lunar-L”

An e-mail list server to facilitate communication within the lunar community. Currently 267 subscribers worldwide.

LUNAR-L@LISTSERV.ND.EDU

E-mail Clive R. Neal at neal.1@nd.edu to subscribe.

LuSeN Team

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Catherine L. Johnson: IGPP, SCRIPPS, UC San Diego
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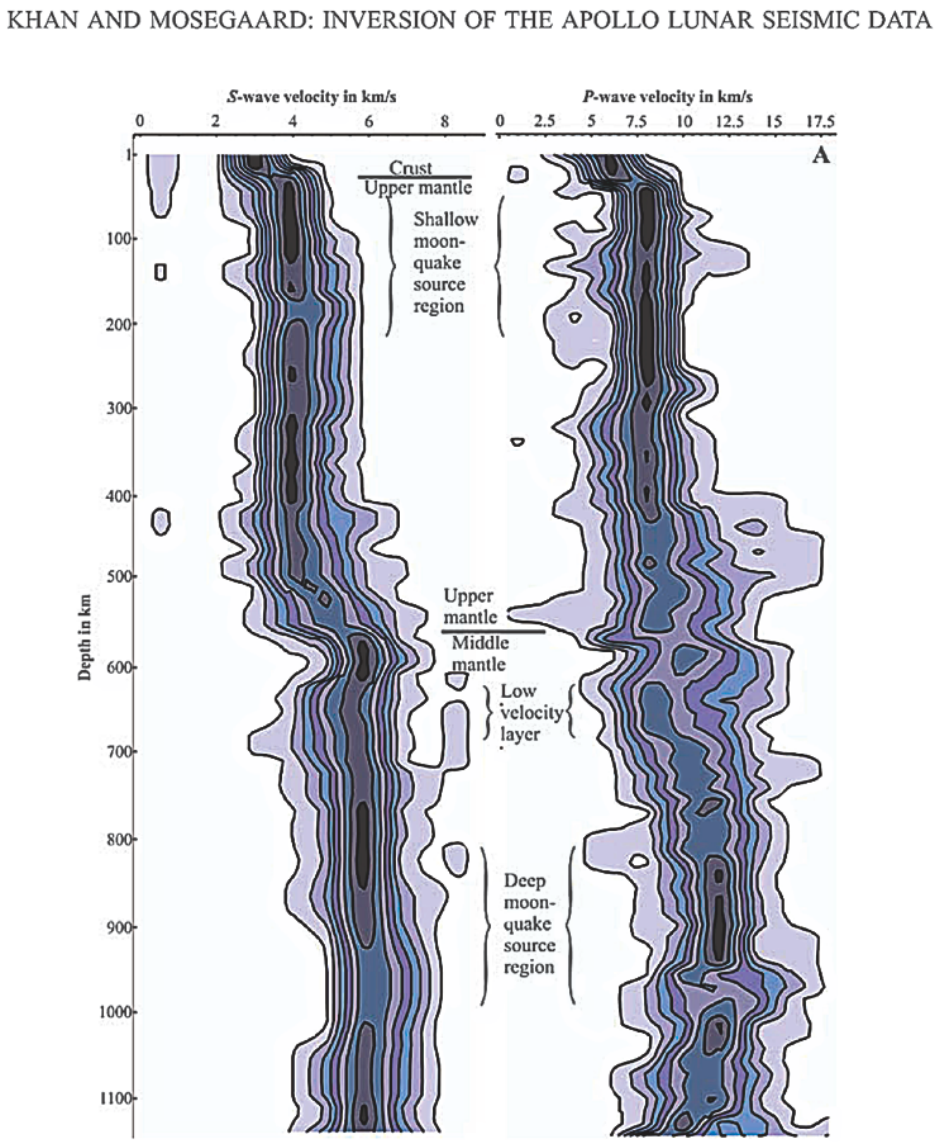
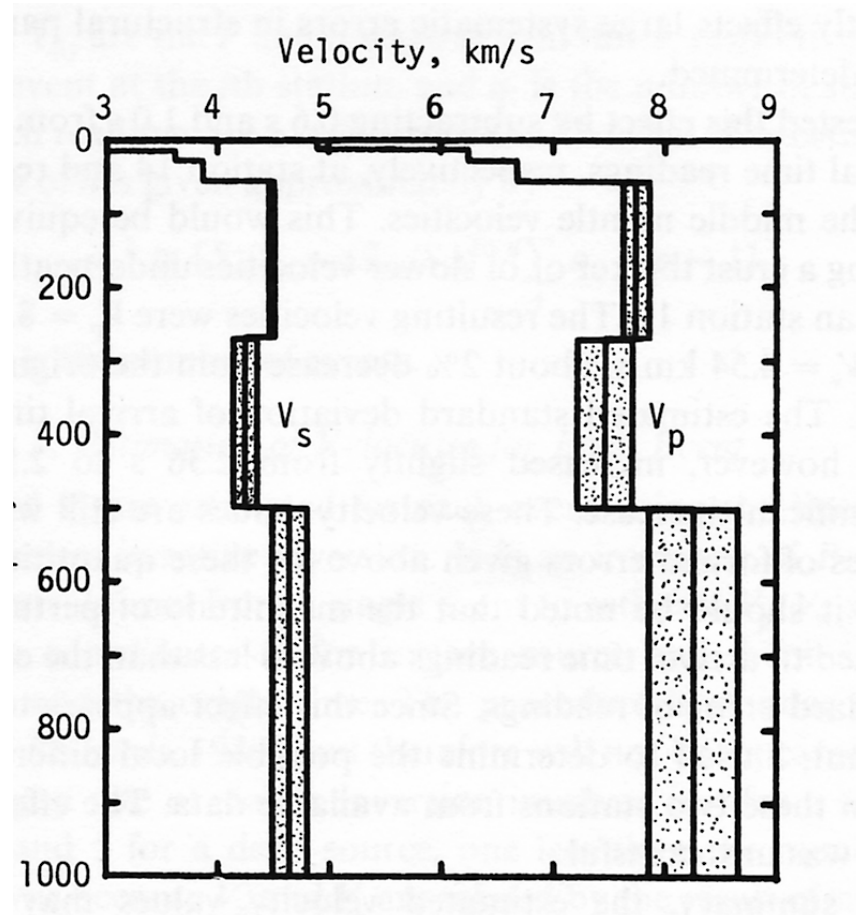
Jack Schmitt: University of Wisconsin
Chip Shearer: University of New Mexico
Mark Wieczorek: IPGP, Paris

The Lunar Interior



[Kahn & Mosegaard, *JGR* **107**, 10.1029/2001JE001658]



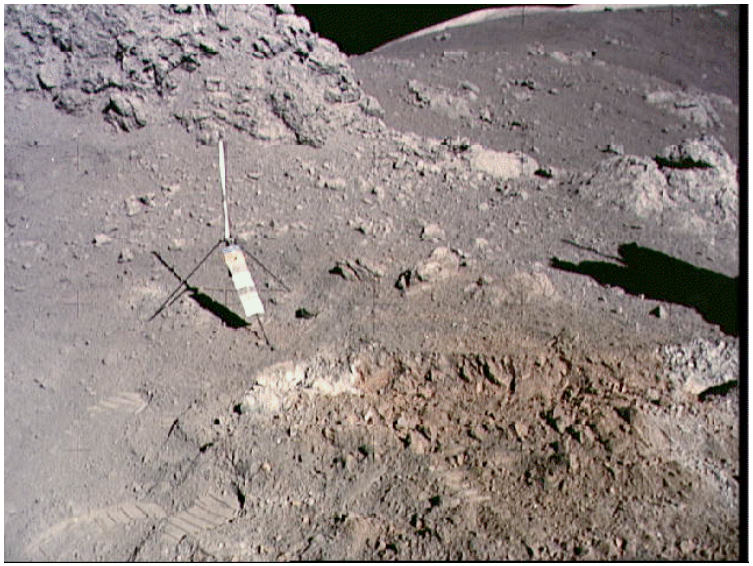
[From Nakamura, *JGR* **88**, 677-686, 1983]

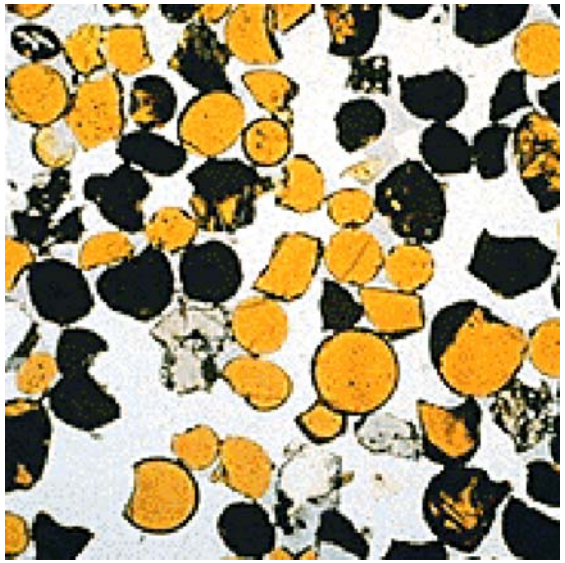
Understanding the Lunar Interior

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!)





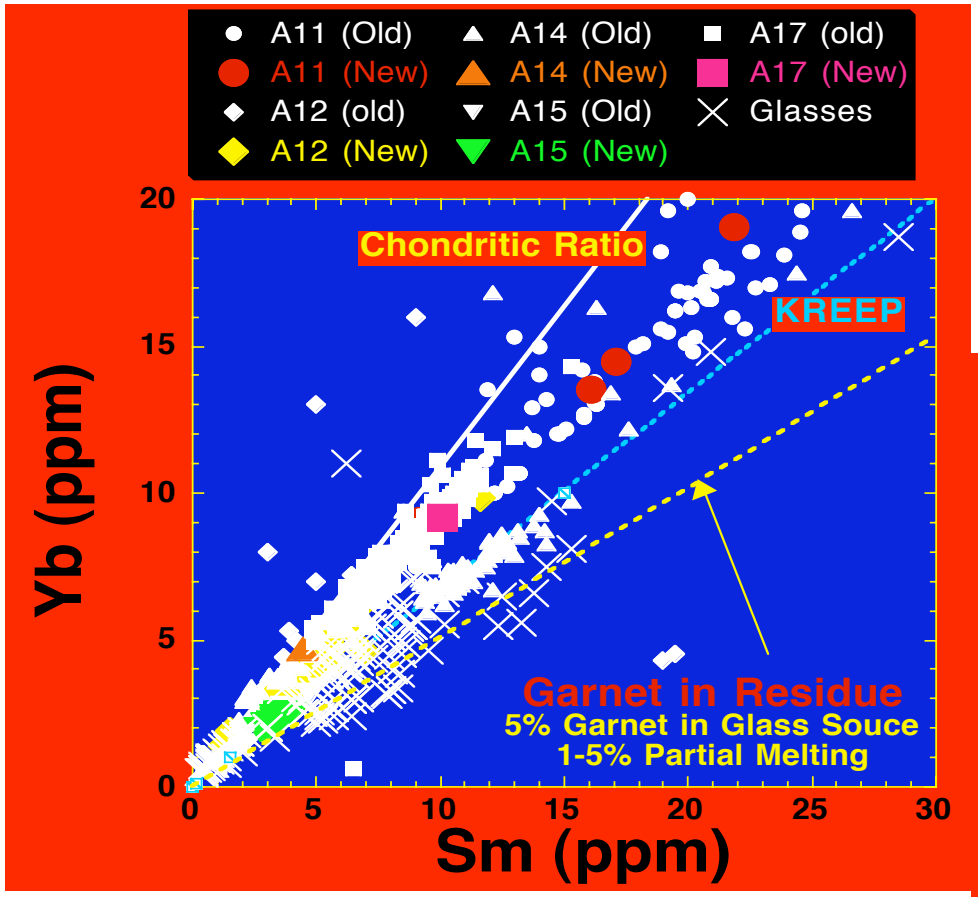
Volcanic glass beads from fire fountaining.

Distinct from crystalline mare basalts.

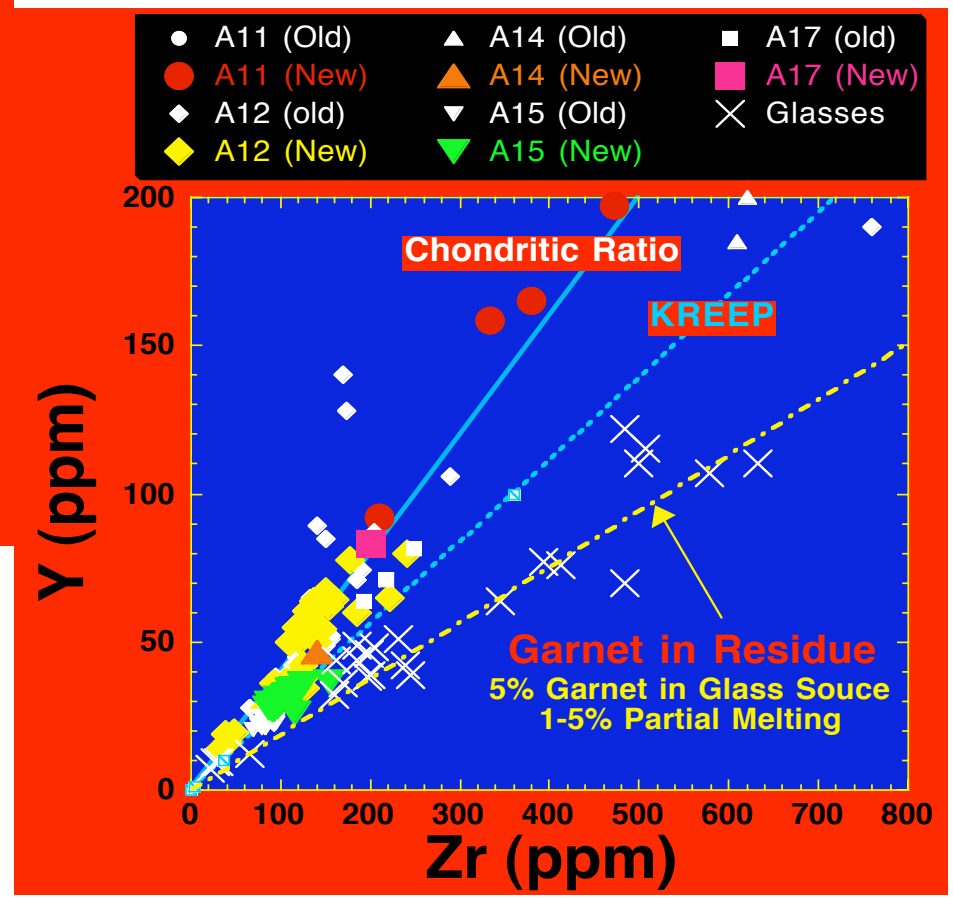
<u>Experimental Petrology</u>: Mare basalts = 100-250 km

Glasses = 360-520 km.

Information on the Interior of the Moon



Geochemical evidence for garnet in the lunar interior.

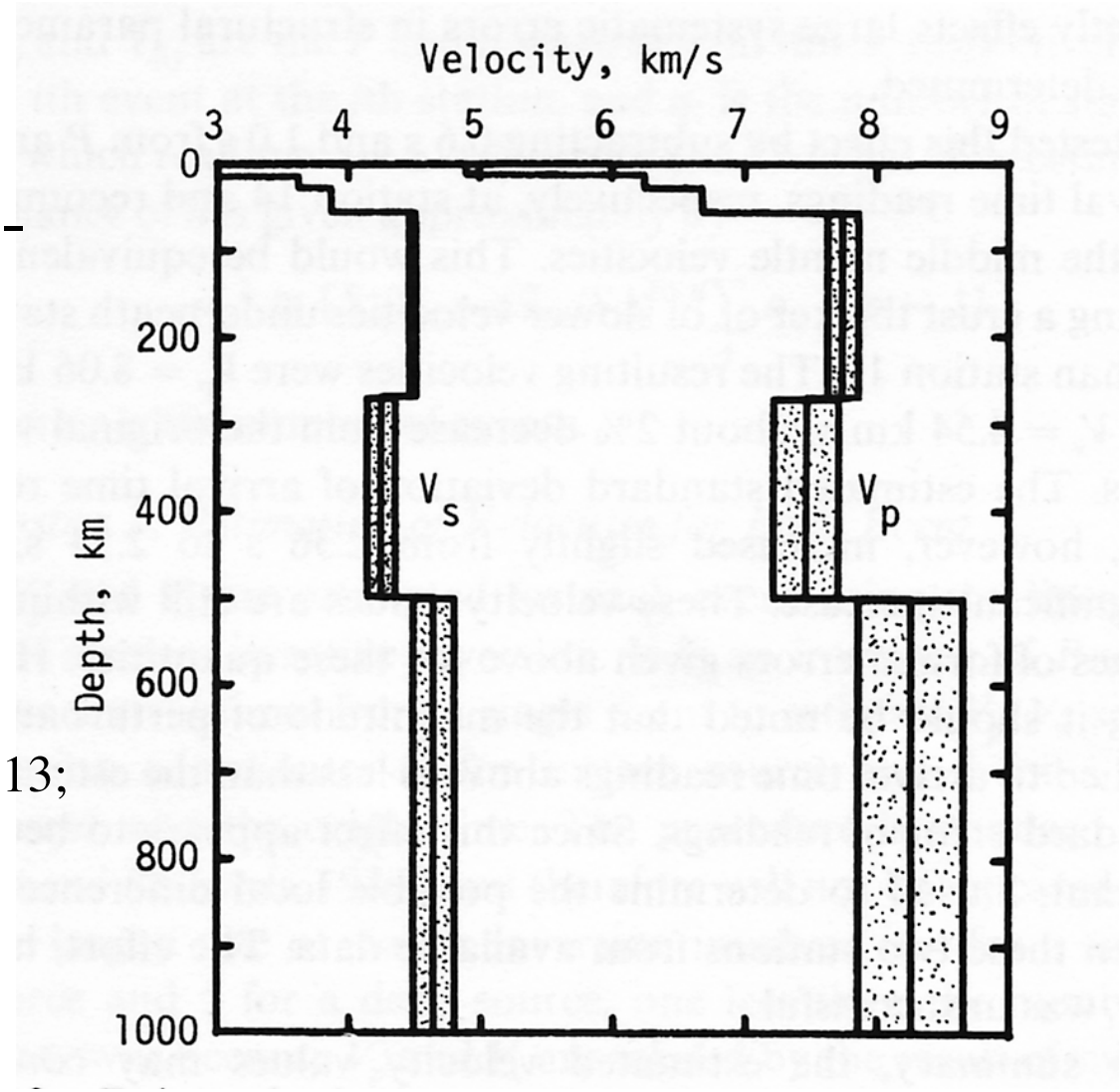


"Garnetophile" elements are depleted in *some* glasses.

What Do We "Know" About the Lunar Interior?

- There is a seismic discontinuity at ~500-600 km on the lunar nearside.
- There is probably a small (250-350 km diameter) core.

(Righter, 2002, Icarus 158, 1-13; Hood et al., 1999, GRL 26, 2327).



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

The LuSeN Mission Concept

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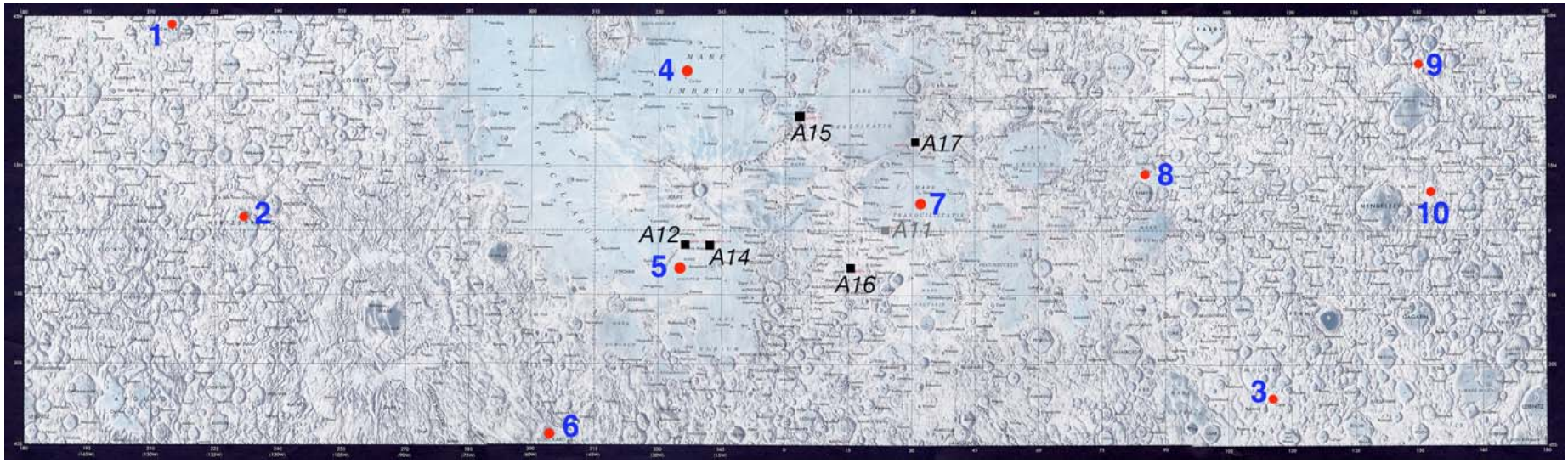


1. Fowler Crater.
2. Hertzsprung Crater.
3. Between Bjerknes & Clark craters.
4. Mare Imbrium.
5. Mare Cognitum.
6. Schickard Crater.
7. Mare Tranquilitatis.
8. Mare Marginis.
9. Kurchatov.
10. Between St. John & Mills craters.

Science Goals and Objectives

Mission Goal: Investigate, in detail, the deep interior of the Moon

– **Objective 1**: Determine the thickness of the crust and its lateral variation.

- What is the mean crustal thickness?
- Establish the nature of the near side – far side dichotomy.
- Measure the thickness beneath a mascon basin.

– **Objective 2**: Determine the size, and structure of the core.

- What is the core's radius and flattening?
- What is its density?
- Is it solid or liquid (or both)?

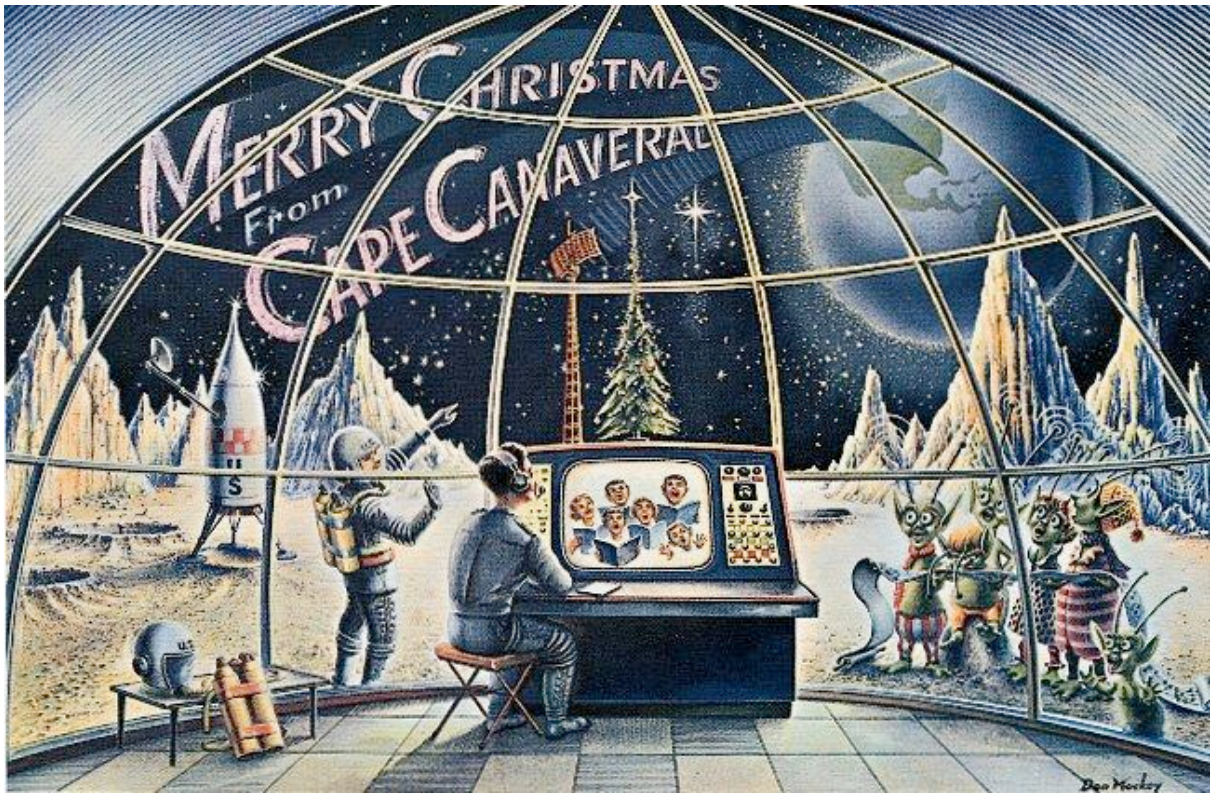
Science Goals and Objectives

- **Objective 3**: Investigate the structure and composition of the mantle.
  - What discontinuities exist in the mantle?
  - Nature of discontinuities: distinct vs. gradational?
  - Is garnet present in the lower mantle?
  - What is the nature of the seismogenic layer at 800 km?
  - Do plastic zones exist?
- **Objective 4**: Map far side seismicity of the Moon.
  - What is the 3-dimensional distribution of seismic activity on the far side?
  - Are there correlations with surface geology?
  - Is there a component that is correlated with tides?

Science Goals and Objectives

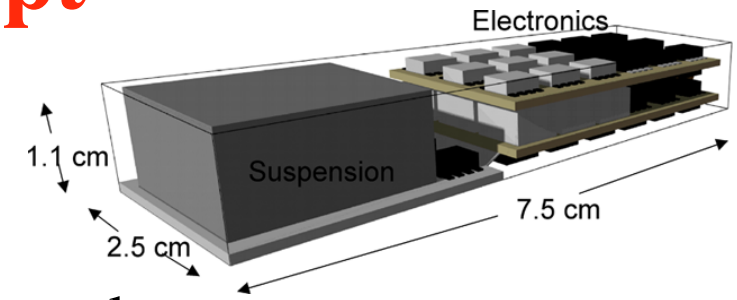
– **Objective 5**: Get statistical data on the locations & magnitudes of shallow moonquakes & meteoroid impacts.

- Where is the safest place for a Moon base?



The LuSeN Mission Concept

Technology Developments:



Power Supply - mini-RTG/RPS needed.

Deployment - hard vs. soft landing of each package.

Robust, yet sensitive seismometer package that can survive a hard landing, yet be able to detect the smallest of Moonquakes. Netlander?

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