Planetary seismology

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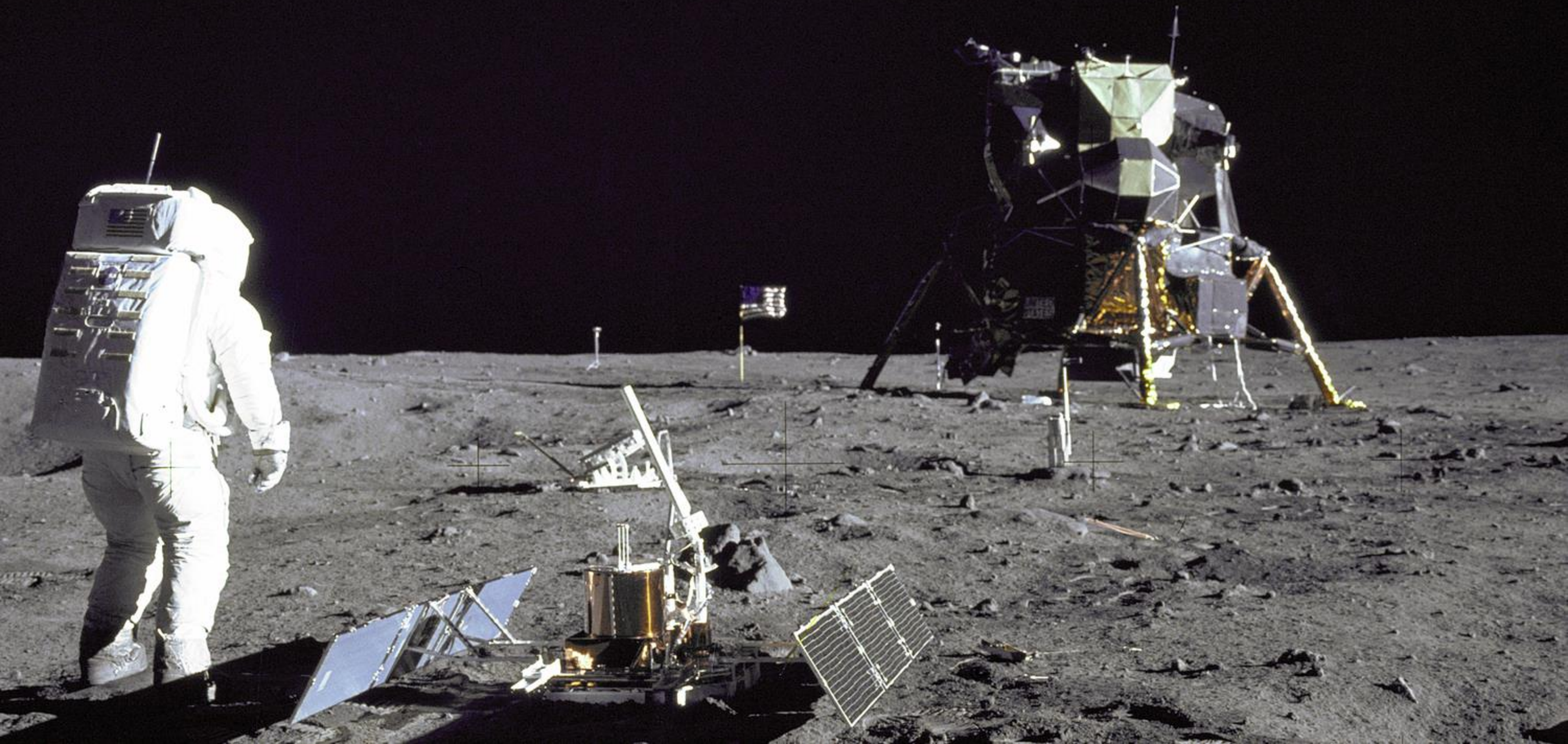
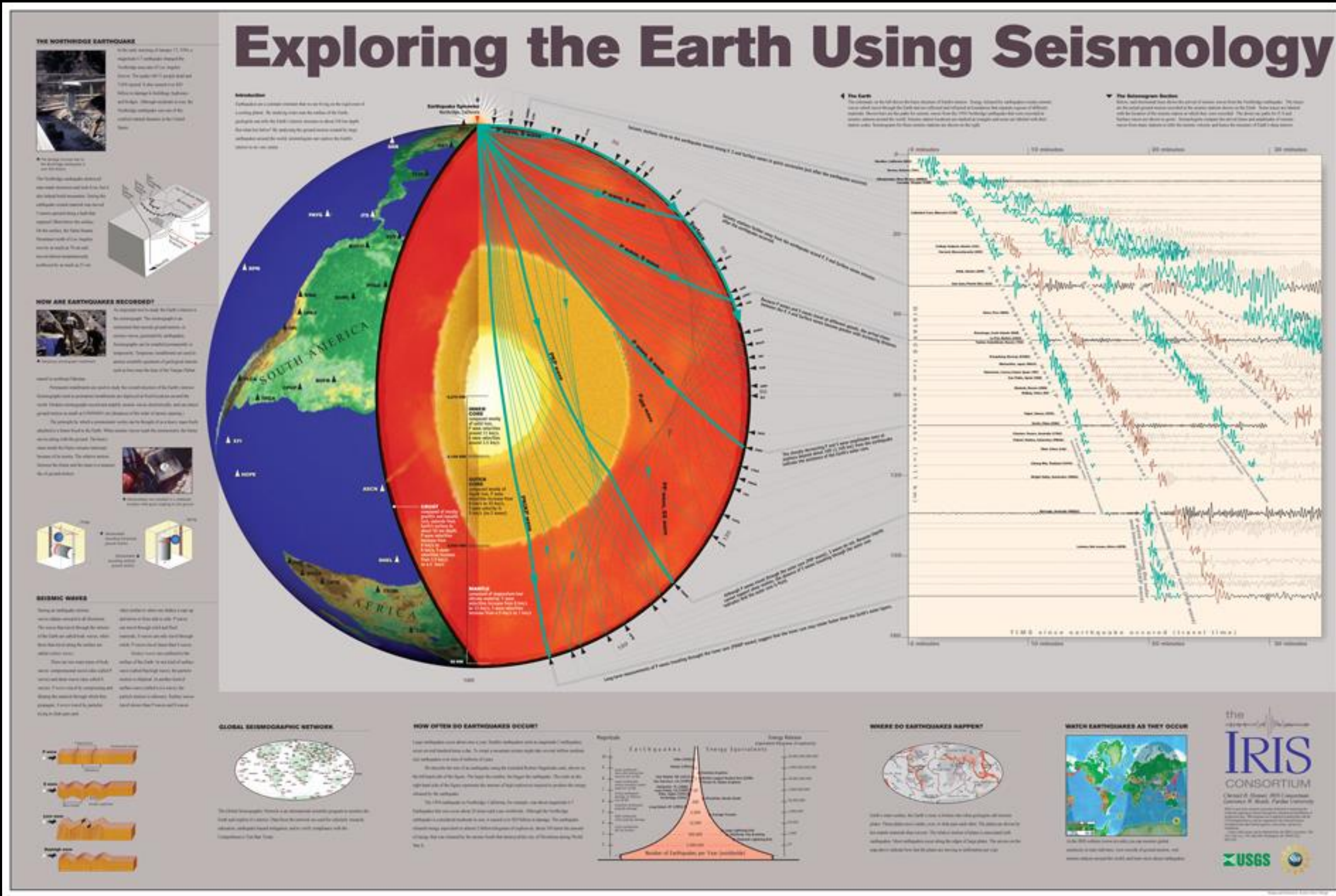


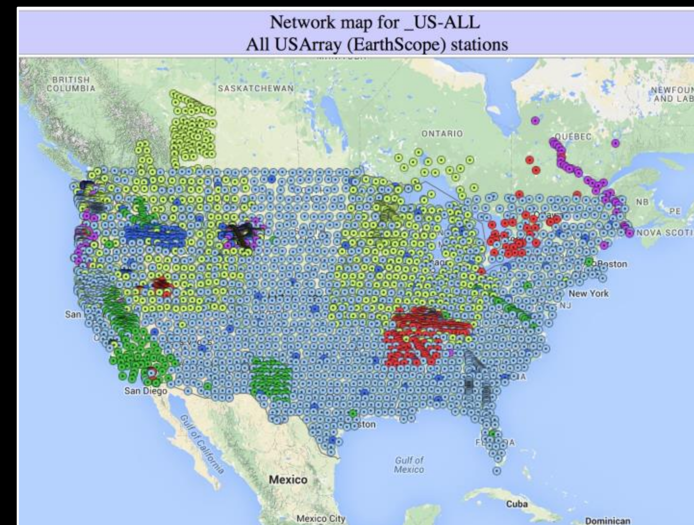
Seismology:

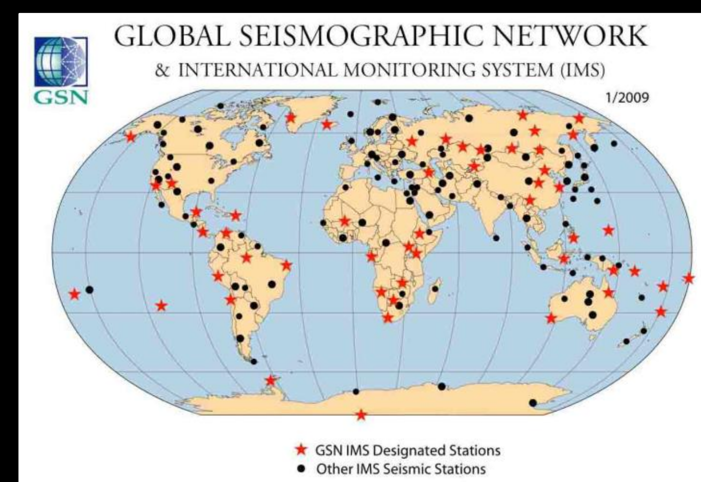
The scientific study of earthquakes and the propagation of elastic waves through the Earth or through other planet-like bodies.



Characteristics of a “good” seismic network:

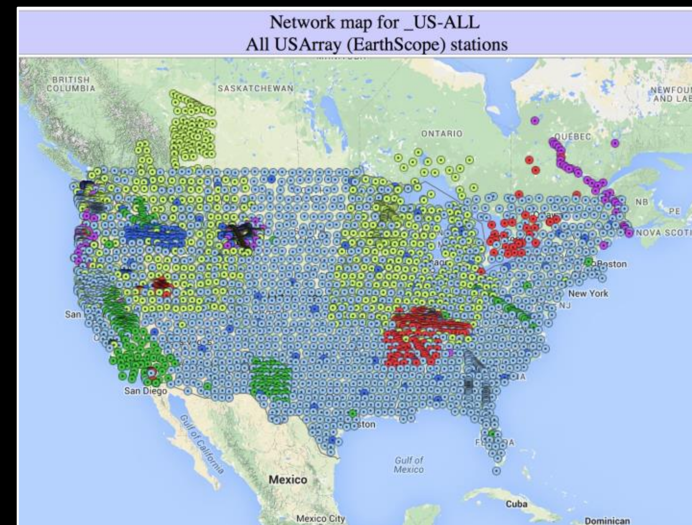
- long-lived observation & reliable communication
- stations have strong ground coupling
- widespread distribution

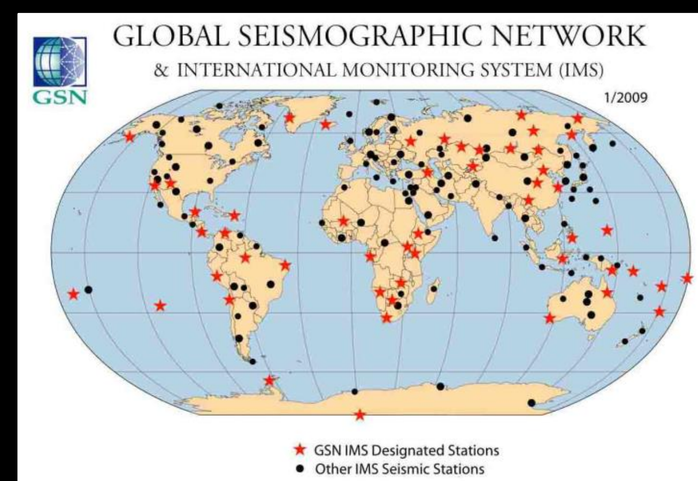




Characteristics of a "good" seismic network:

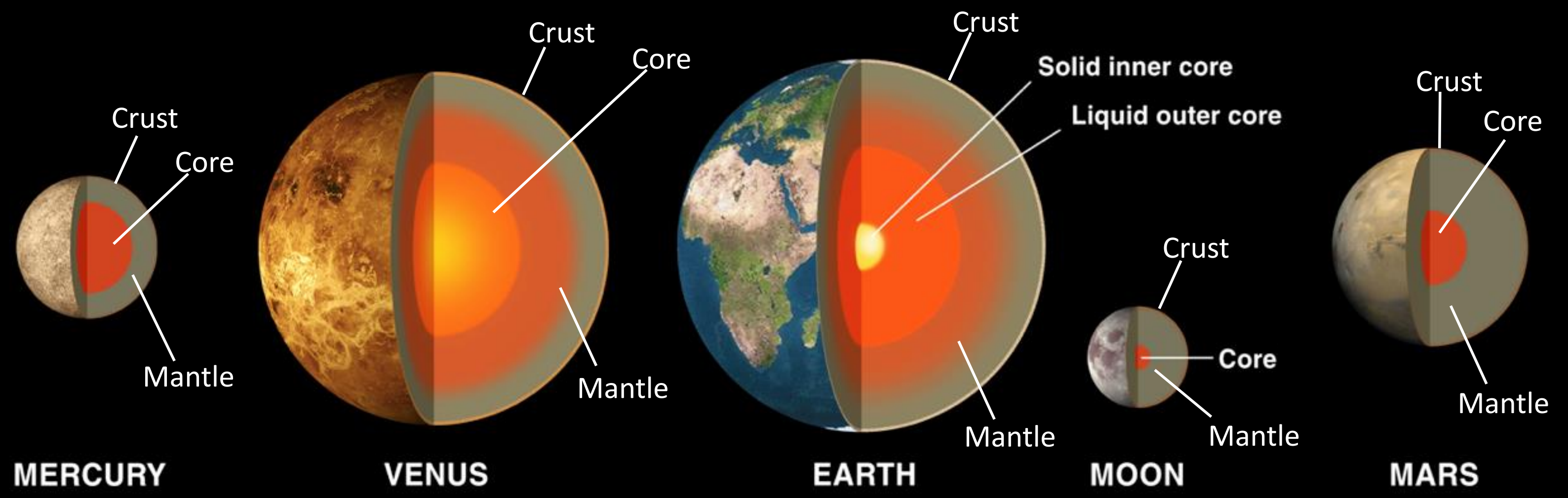
- long-lived observation & reliable communication (continuous power)
- stations have strong ground coupling (complicated installation)
- widespread distribution (many stations)





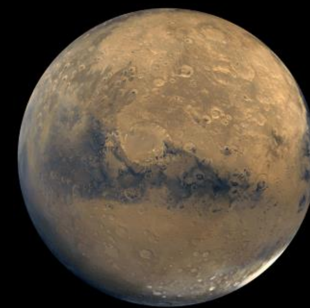
Why planetary seismology?

- At the dawn of the age of planetary exploration, seismology was considered a key technique for understanding a planet and its interior.
- Terrestrial planets all share a common structural framework (crust, mantle, core), which is developed very shortly after formation and which determines subsequent evolution.
- Much of Earth's early structural evidence has been destroyed by plate tectonics and mantle convection
- "Ancient" planets retain more information about their formation and evolution



Early planetary seismology:



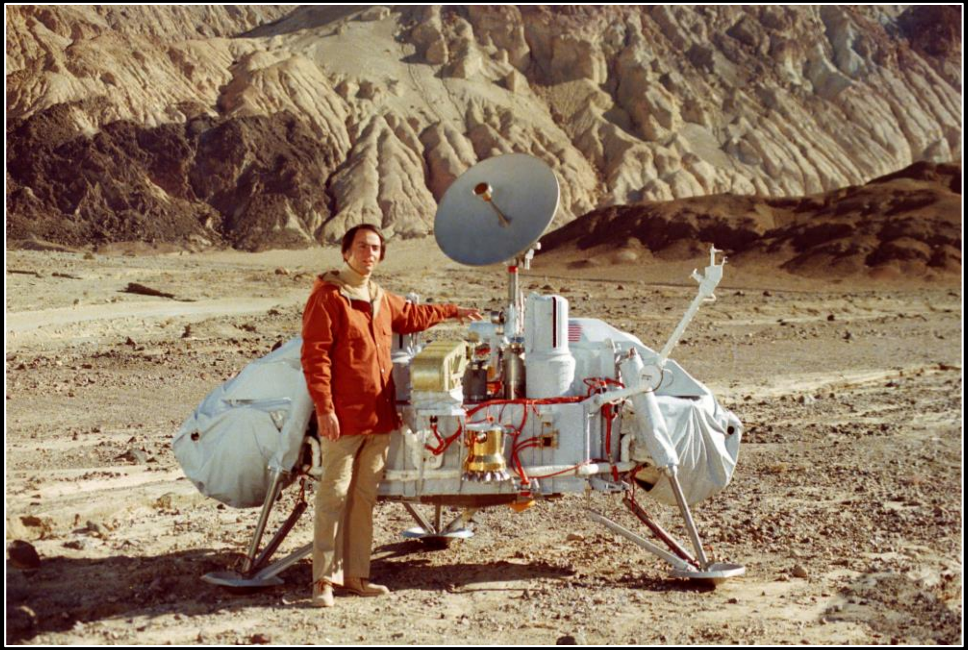


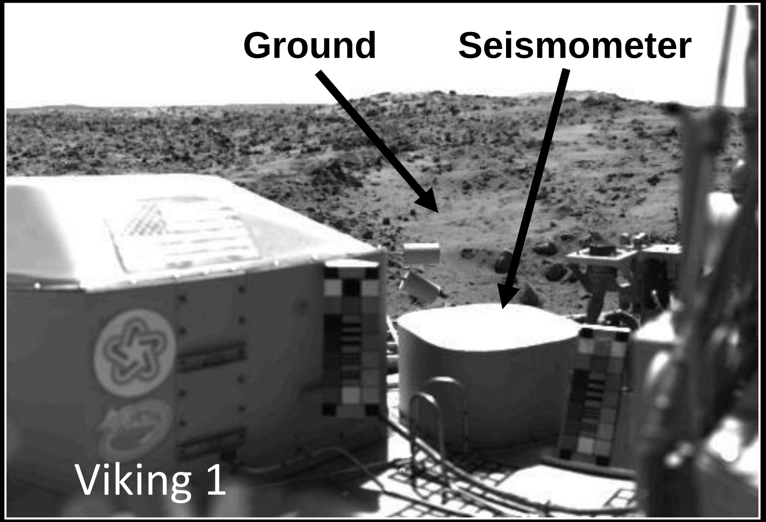

- Seismology has been recognized/studied on Earth throughout antiquity
  - Earliest known “seismoscope” invented in China 132 A.D.
- The first instruments sent to the surface of another planet were seismometers.
  - Rangers 3–5; 1962
- The highest scientific priorities of the Apollo program were sample return and seismology.
  - Apollo 11, 12, 14, 15, 16; 1969–1977
- The first landers sent to Mars carried seismometers.
  - Vikings 1, 2; 1976–80
- Several of the Soviet Venera missions also had seismometers
  - Venera 13 & 14, 1982

Mars: Viking

Viking 1: landed 20 July 1976
- Uncaging mechanism failed to unlock the seismometer

Viking 2: landed 3 September 1976
- Recorded data until batteries failed 11 April 1980





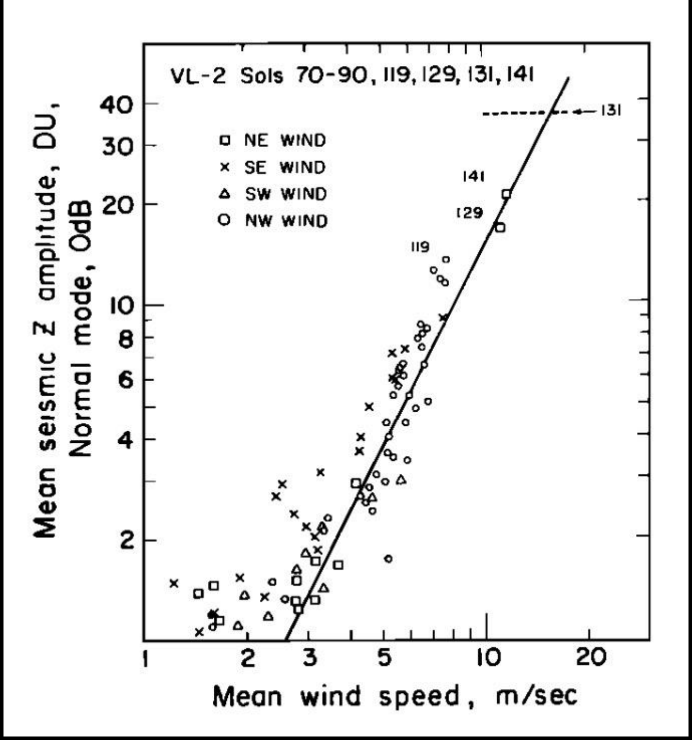
problem: poor ground coupling!

recorded only wind events

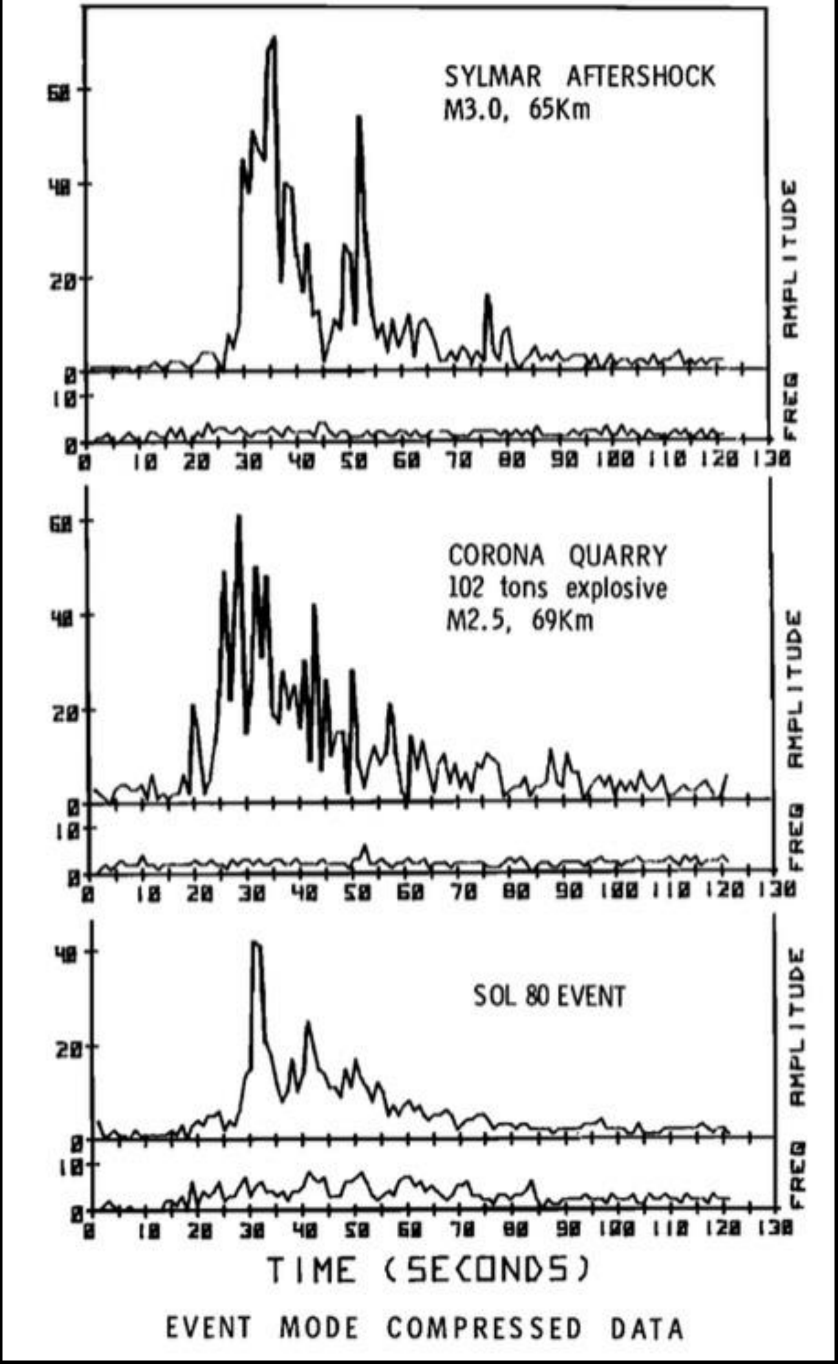
Mars: Viking

Viking 2 collected in total, about 2100 hours of seismic data (89 days) spread over the 560 sols of lander operation

All but one of the observed seismic events were found to correlate with wind gusts (reason: temporary malfunction prevented recording of wind data at time of event)



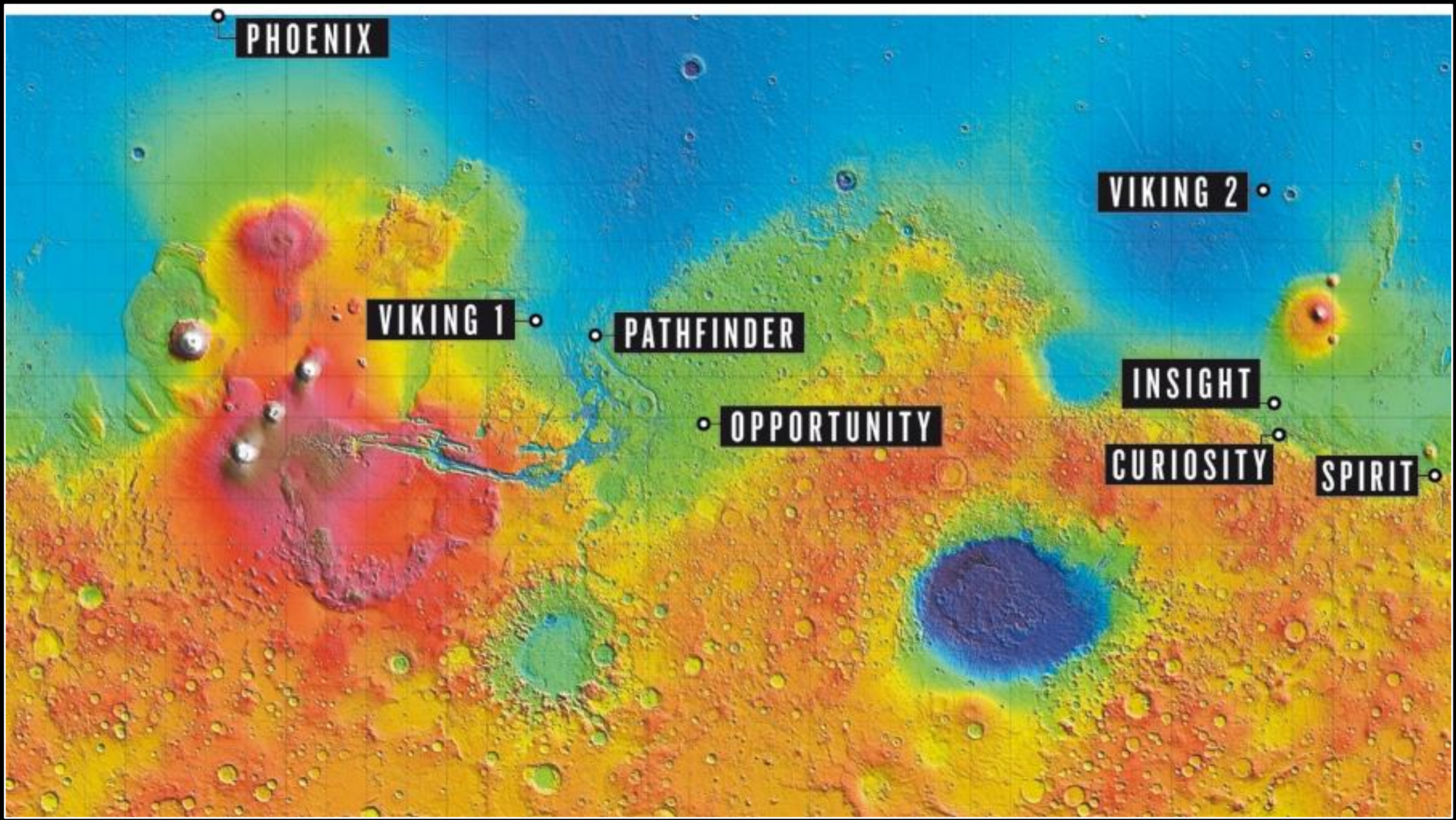
Anderson et al., 1977



Mars: Viking

sol 80 event:

- magnitude 3, distance 110 km
- Arrivals in the signal suggest a crustal thickness of 15 km at the Utopia Planitia landing site



Venus: Venera

Venera 13: landed 1 March 1982

- 127 minutes transmission from surface.

Venera 14: landed 5 March 1982

- Survived for 57 minutes on surface.

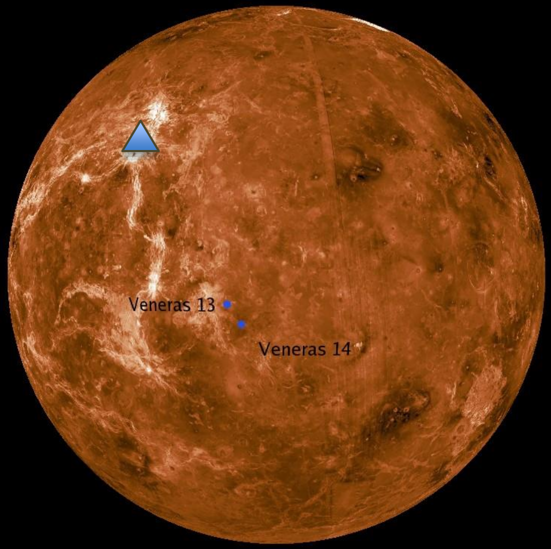
problem: not long-lived!

(inhospitable surface conditions: high temperature, high pressure, corrosive atmosphere)

Venus: Venera

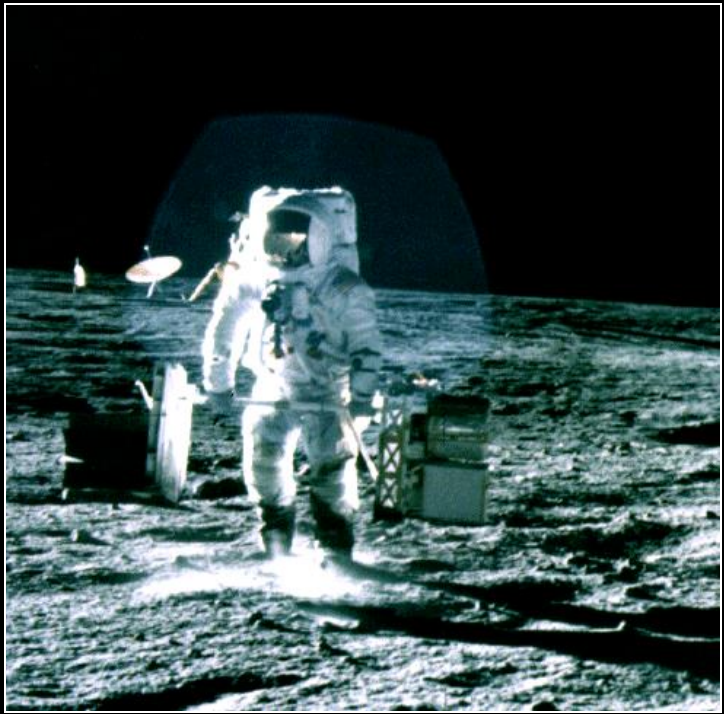
Venera 14:

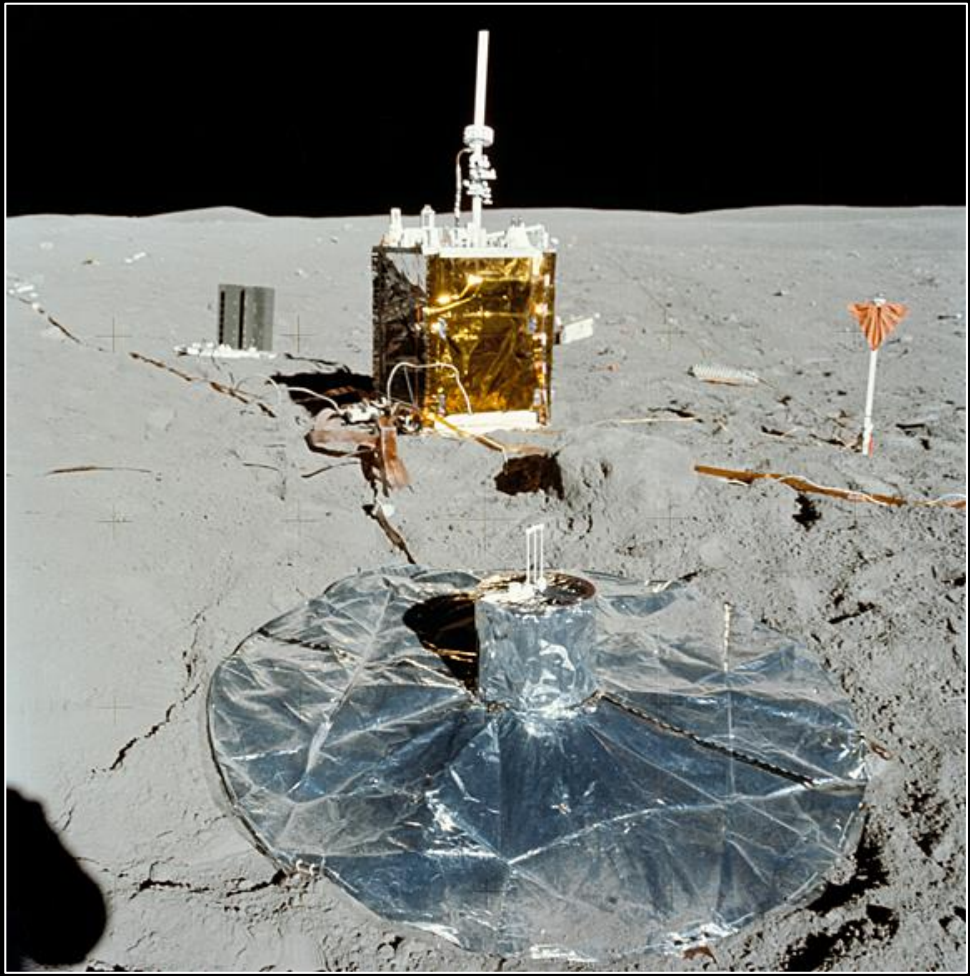
- 2 microseisms were recorded , found to be distinct from wind signals
- Amplitudes consistent with source distance ~3000 km, coincident with volcanically active region



Moon: Apollo

ALSEP: Apollo Lunar Surface Experiment Package

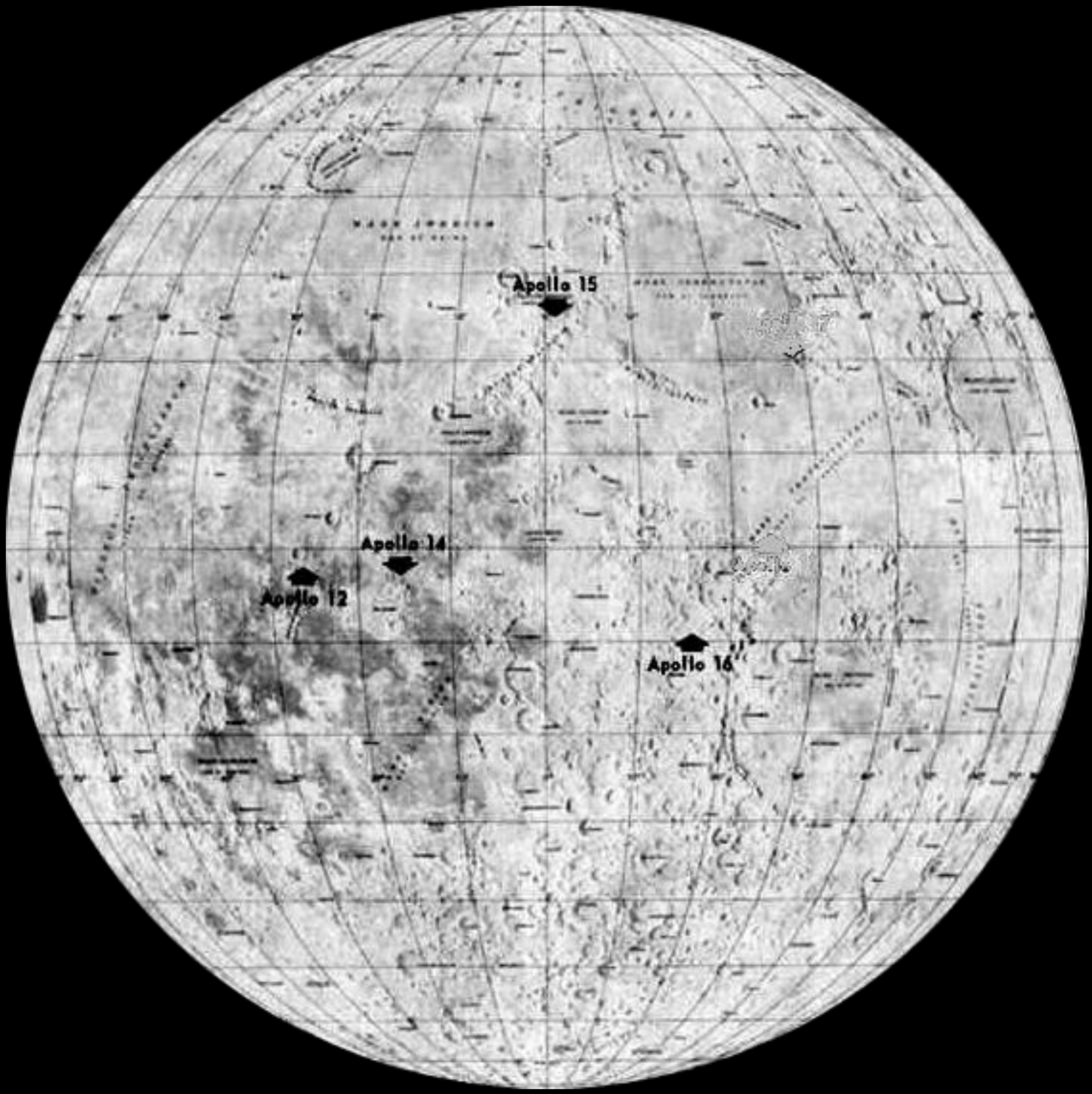




Moon: Apollo

The Apollo Passive Seismic Experiment

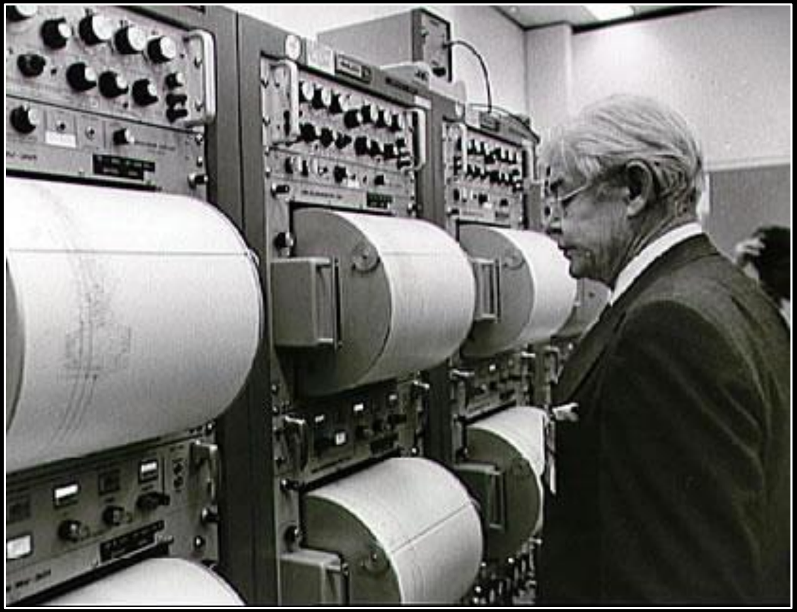
- Four stations deployed on the lunar near side during the Apollo 12/14/15/16 missions.
- Operated from inception until mid-1977.



Moon: Apollo

Apollo PSE history

- Original event detection was done by eye
- Recent re-analyses focused on application of modern computer capabilities and techniques not available in the 60’s and 70’s (analysis of the continuous data, event identification and classification)



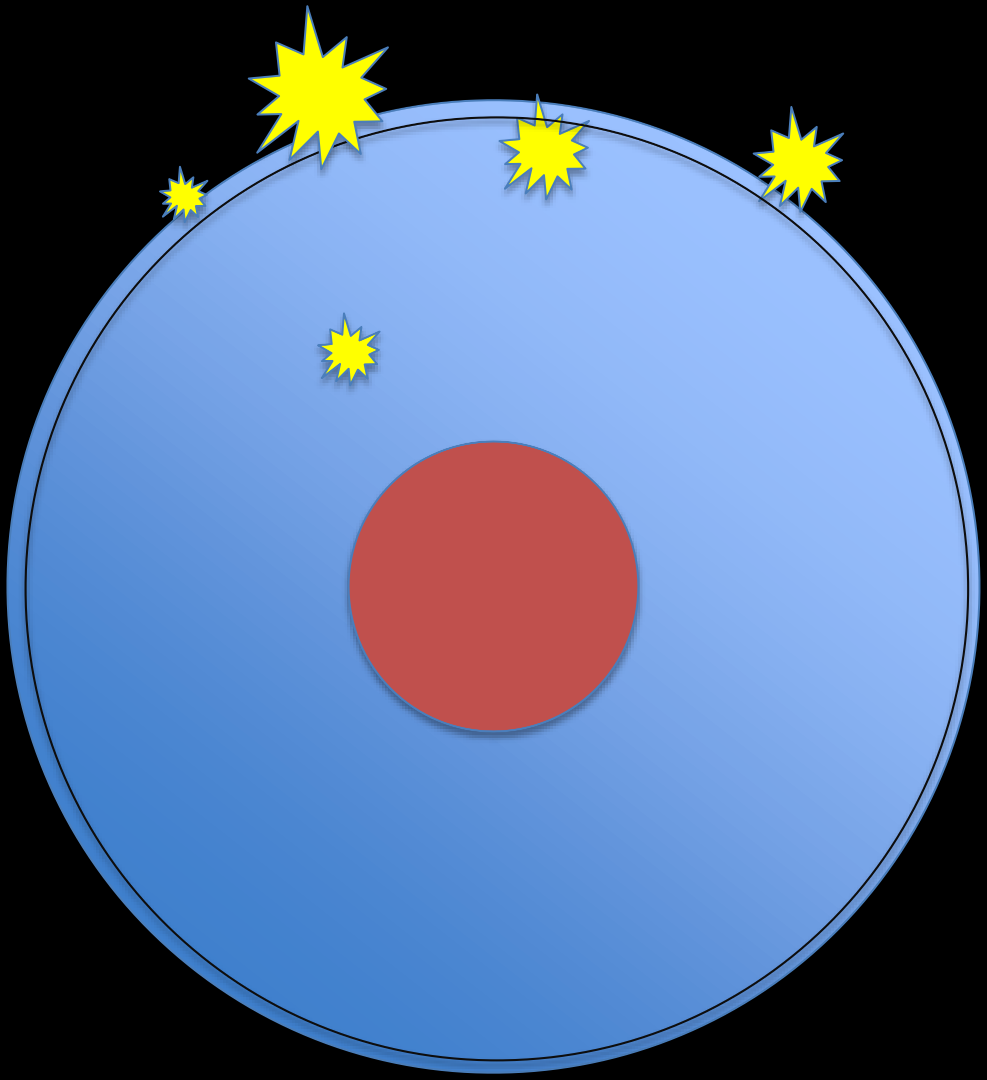
Moon: Apollo

- Modern computer technology permits more advanced studies than were initially possible given computer capabilities of the era

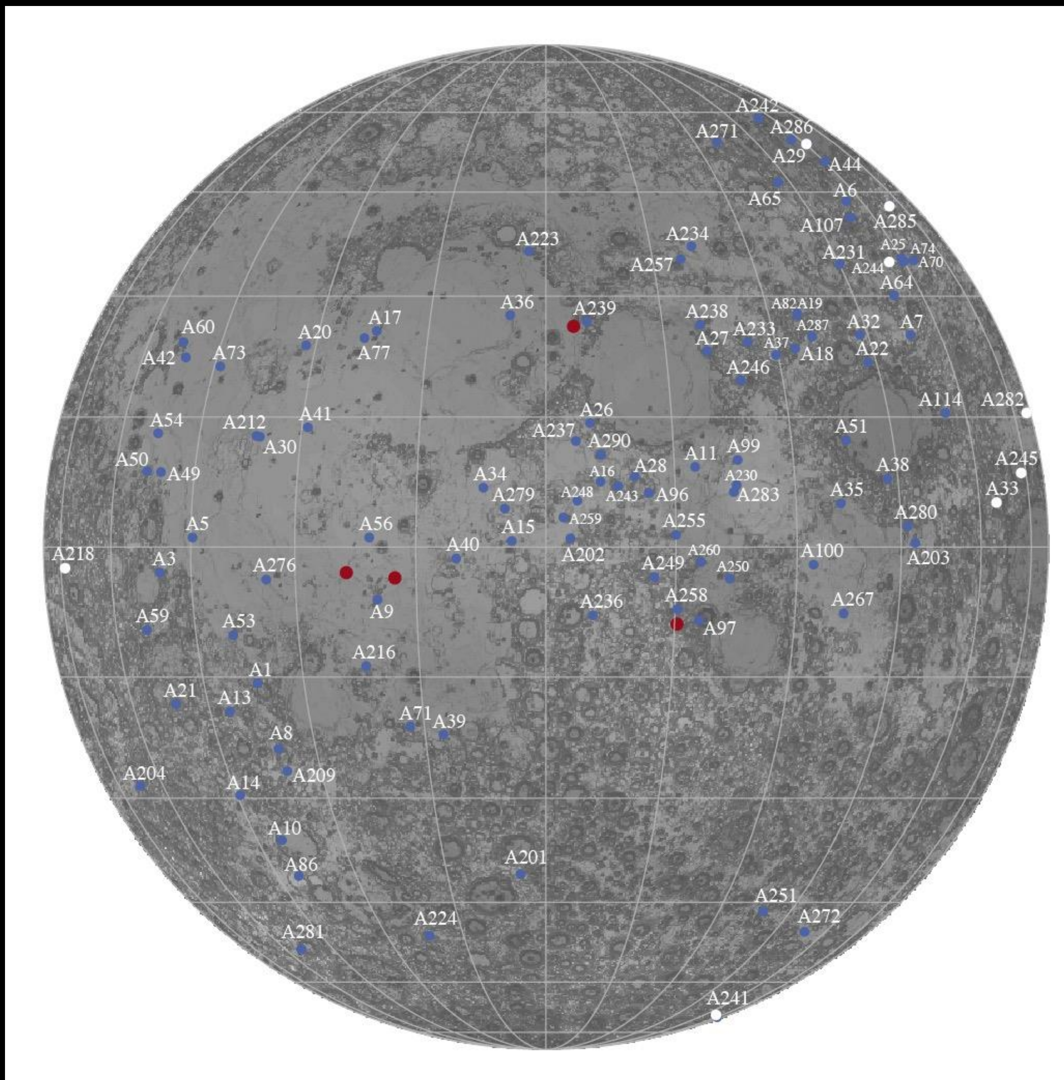
Moon: Apollo

Lunar seismicity:

- Surface events
  - Meteorite impacts
  - Artificial impacts (SIV-B booster rockets, LM impacts)
  - Thermal events
- Shallow events
  - “tectonic” moonquakes
- Deep events
  - “tidal” moonquakes



Moon: Apollo

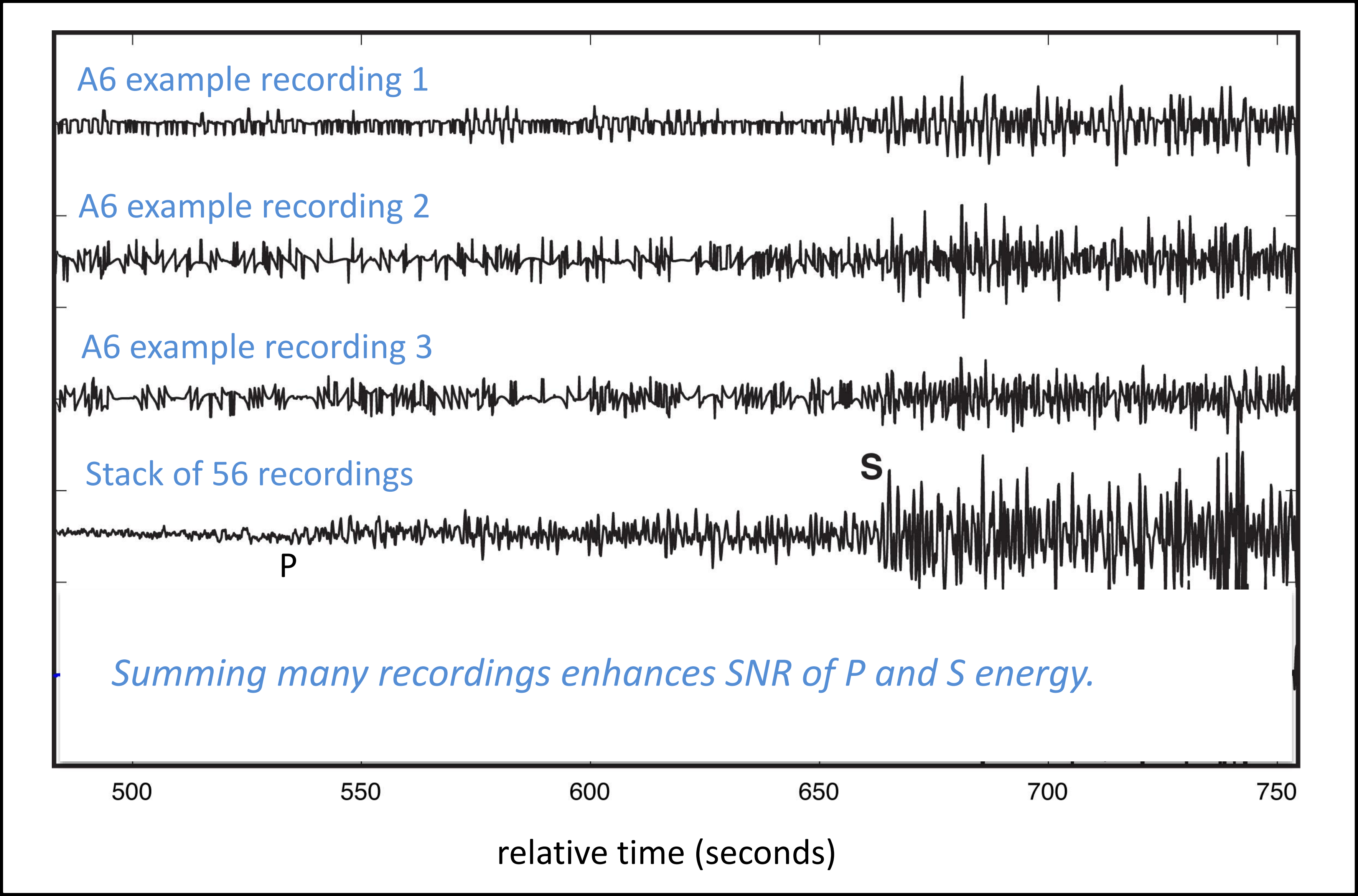


Deep moonquakes:

- 106 clusters with constrained locations and depths (Nakamura, 2005)
- Each cluster produces its own repeatable waveform, so single event seismograms from a given cluster at a given station can be stacked

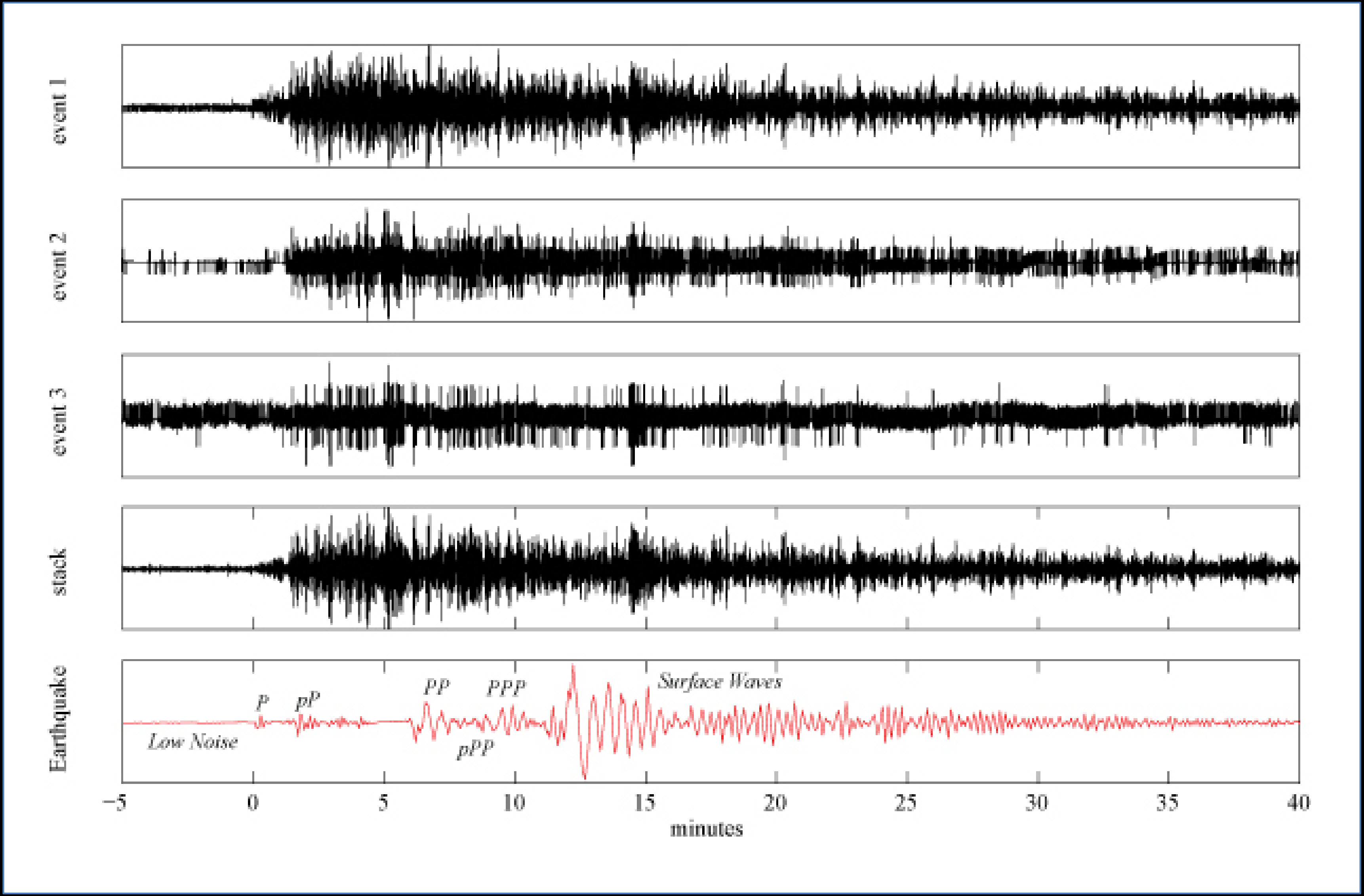
Moon: Apollo

Station 15 recordings of A6 cluster moonquakes



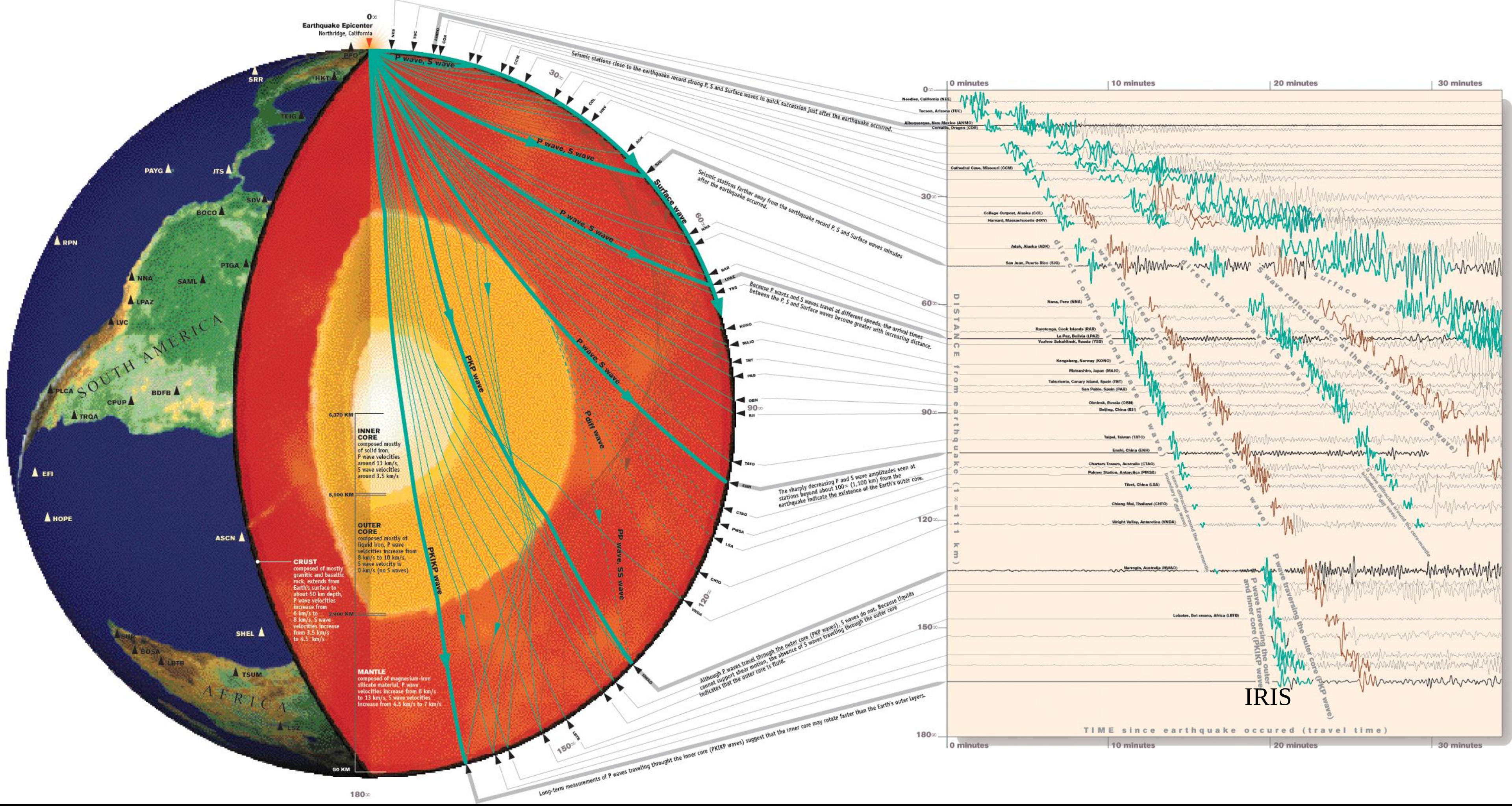
Moon: Apollo

comparison to Earth – secondary phases are masked



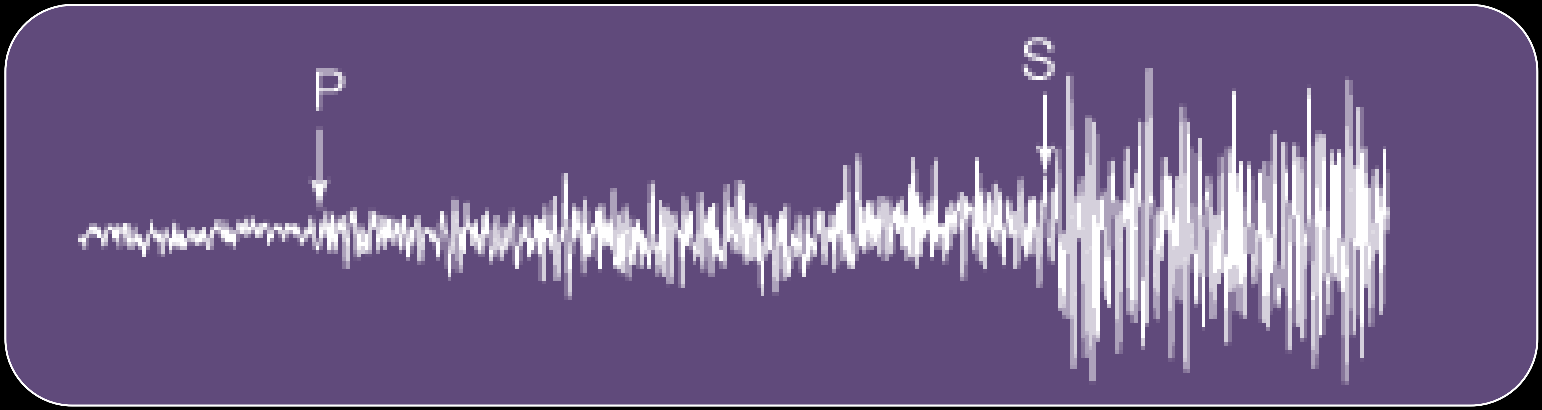
Moon: Apollo

secondary phases contain information on deep structure



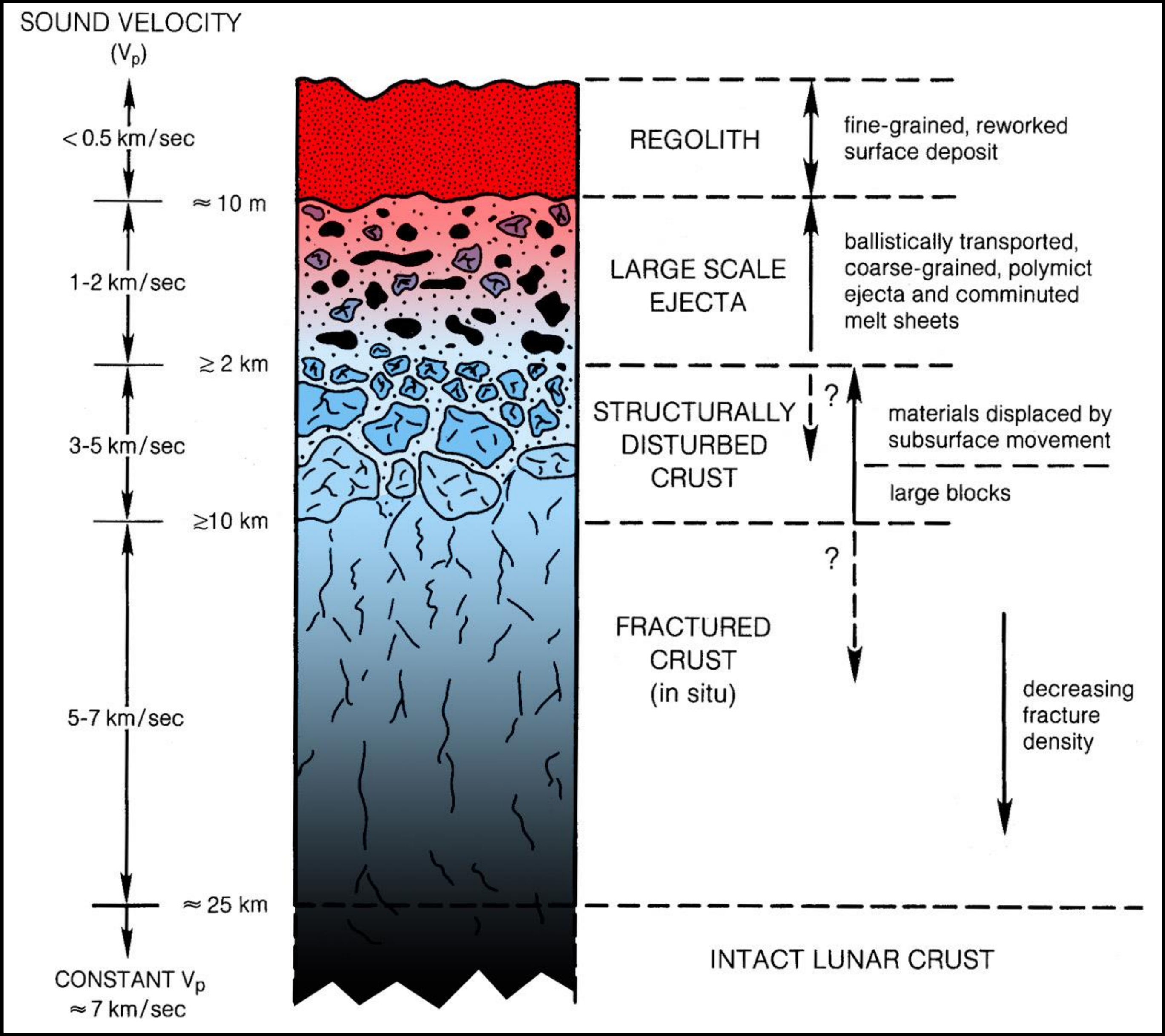
Moon: Apollo

- Seismic waves that travel deep into the Moon arrive after the first arriving P-wave, and hence are obscured by the P coda. Some of these deep phases arrive after the S-wave.



- Long, ringy coda is due to scattering and strong reverberations in the regolith.

Moon: Apollo

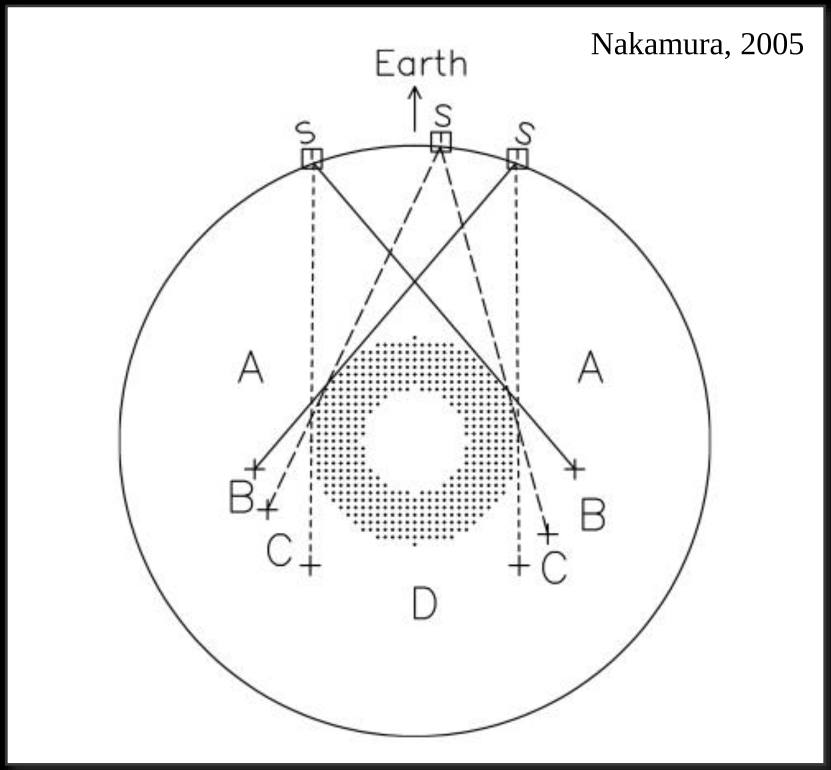


The Lunar Sourcebook

Moon: Apollo

Imaging the lunar interior with deep moonquakes:

- Previous analyses of Apollo seismic data provide first-order constraints on crust and mantle, but not deeper.



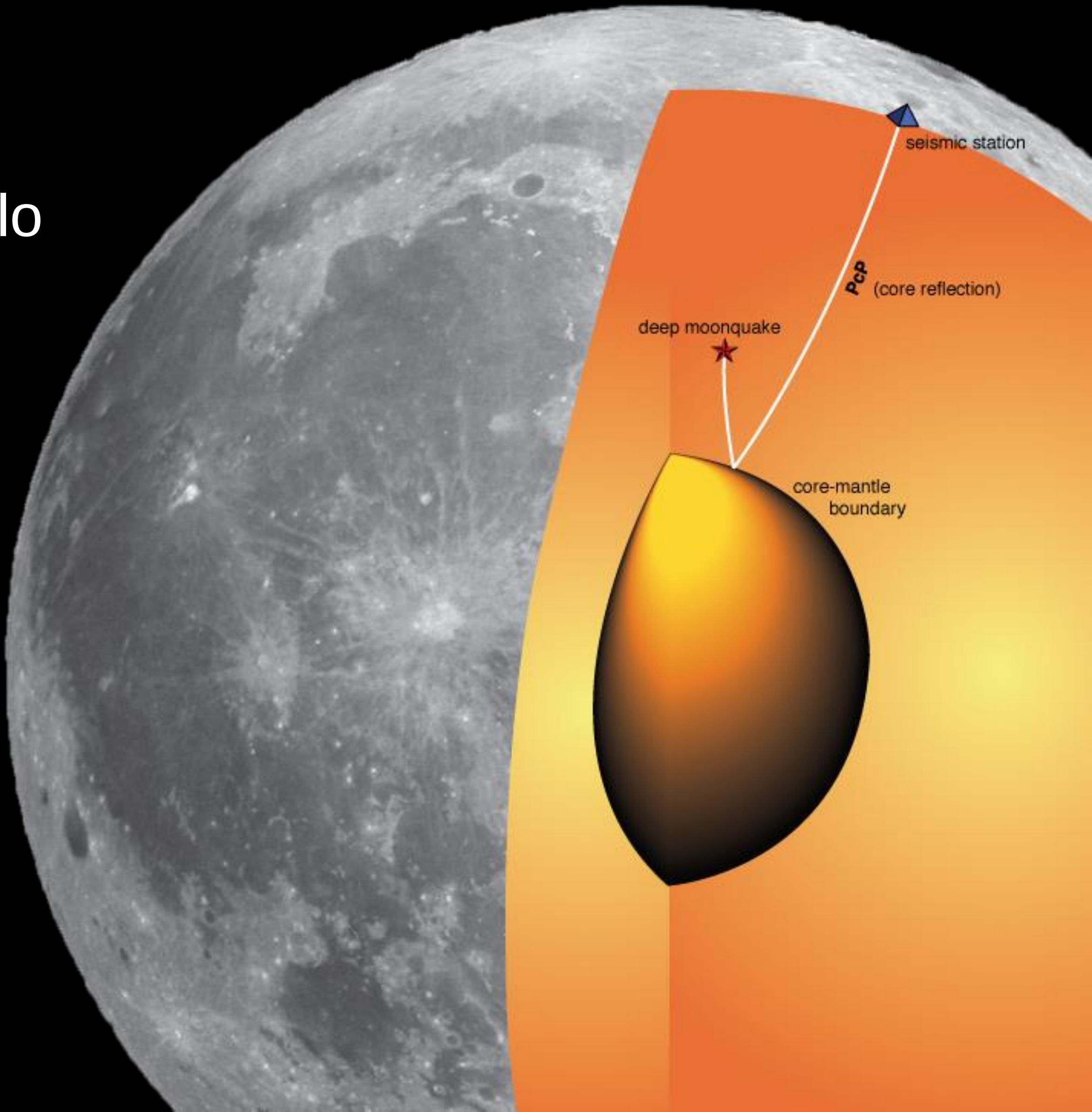
A: S arrivals at all 3 corners of Apollo array
B: S arrivals at 2 corners
C: S arrival at 1 corner
D: No shear arrivals

Zone D – aseismic?
or attenuating core

Moon: Apollo

Goal:

Identify and/or enhance core arrivals in the Apollo seismograms



Moon: Apollo

polarization filter

polarization function

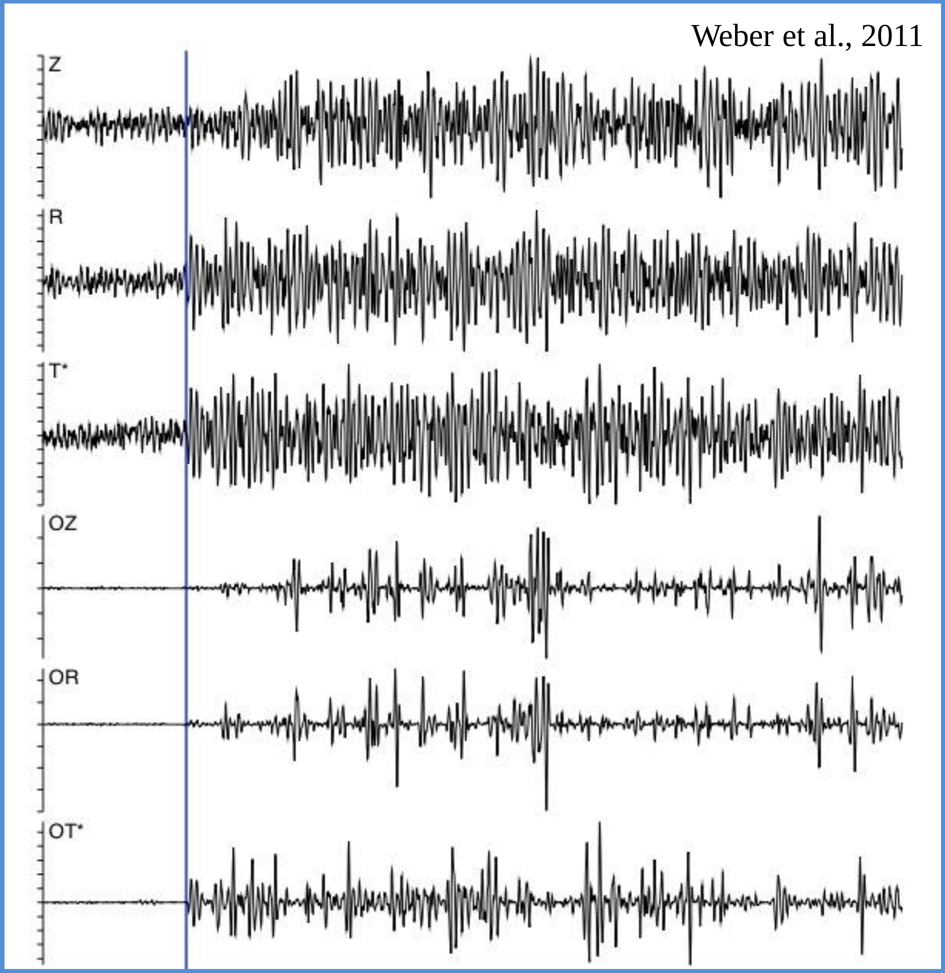
$$M_j = \sum_{i=-n}^{n} Z_{j+i} R_{j+i}$$

filter output

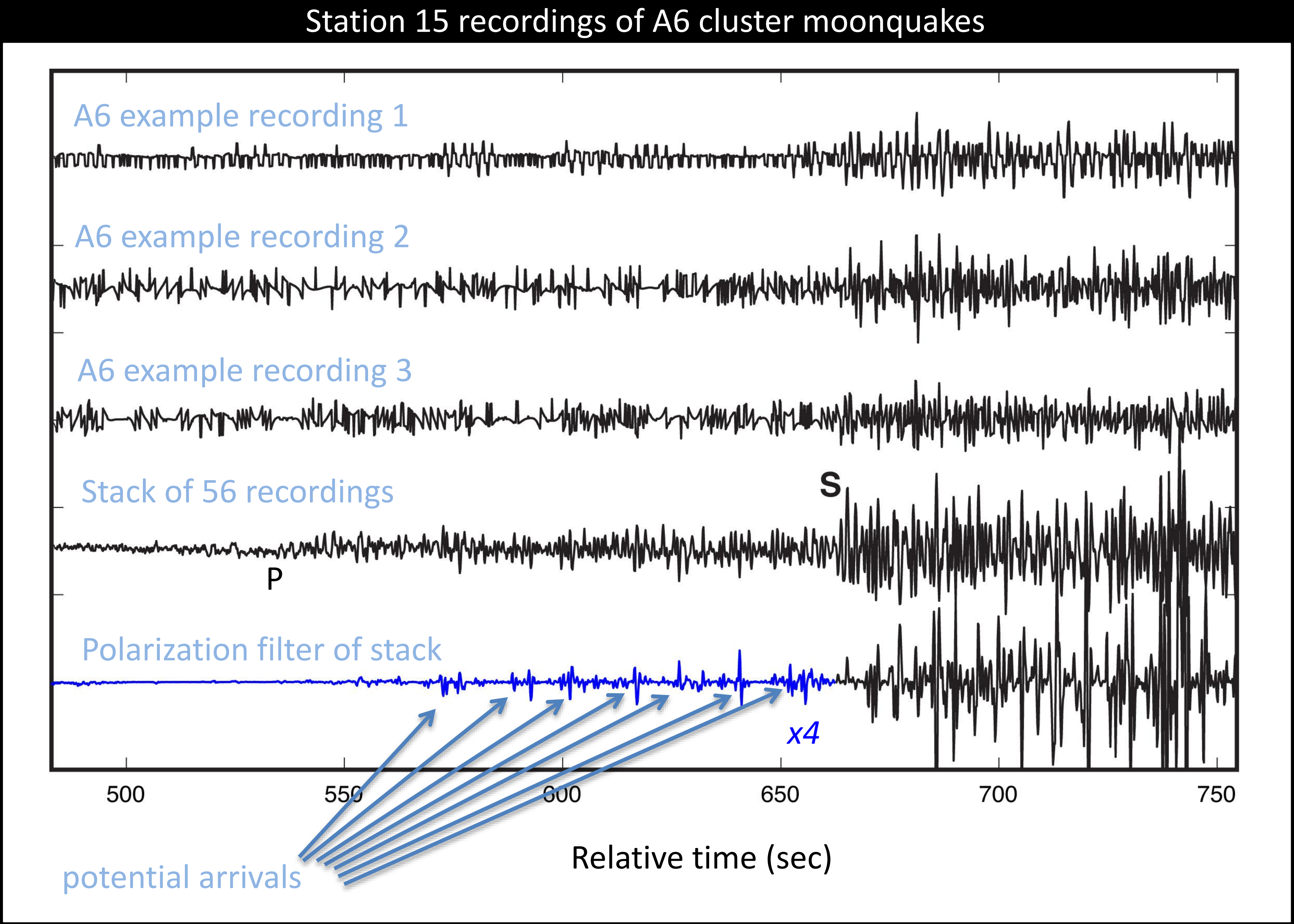
$$OZ_j = Z_j M_j$$

- Enhances larger amplitudes relative to smaller amplitudes from the triple product of seismograms
- Enhances energy that is rectilinearly partitioned onto the R and Z components of motion (while suppressing noise)

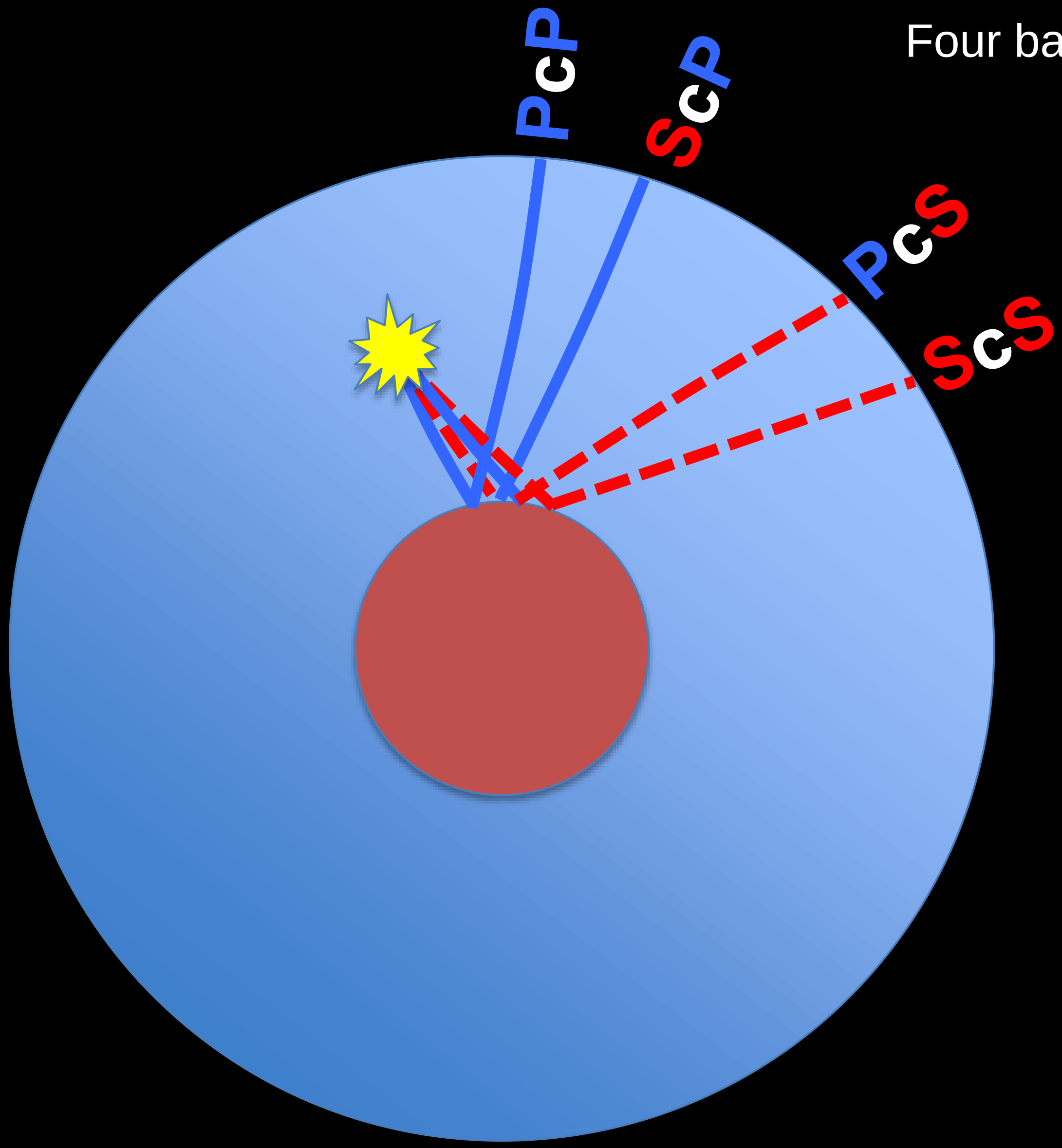
n = 6 samples (window length ~ 2.8sec)



Moon: Apollo


Station 15 recordings of A6 cluster moonquakes
A6 example recording 1
A6 example recording 2
A6 example recording 3
Stack of 56 recordings
S
P
Polarization filter of stack
x4
500
550
600
650
700
750
Relative time (sec)
potential arrivals

Moon: Apollo



Four basic reflections are possible:

S-to-P
P-to-P
P-to-S
S-to-S

Look for results that are common to the different wave types:

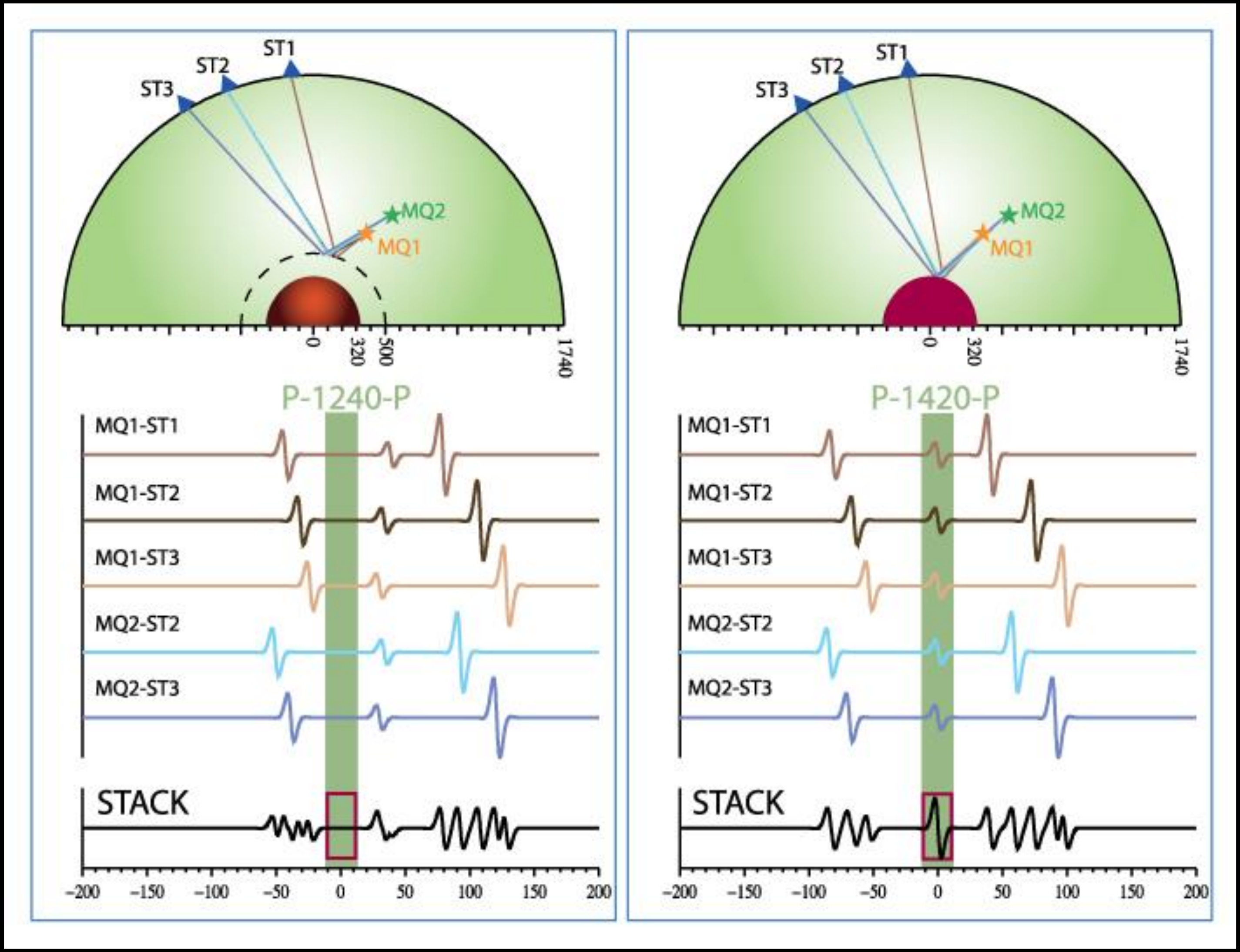
S-to-P
P-to-P: OZ

P-to-S: OR (vertically polarized)

S-to-S: OT (horizontally polarized)

Moon: Apollo

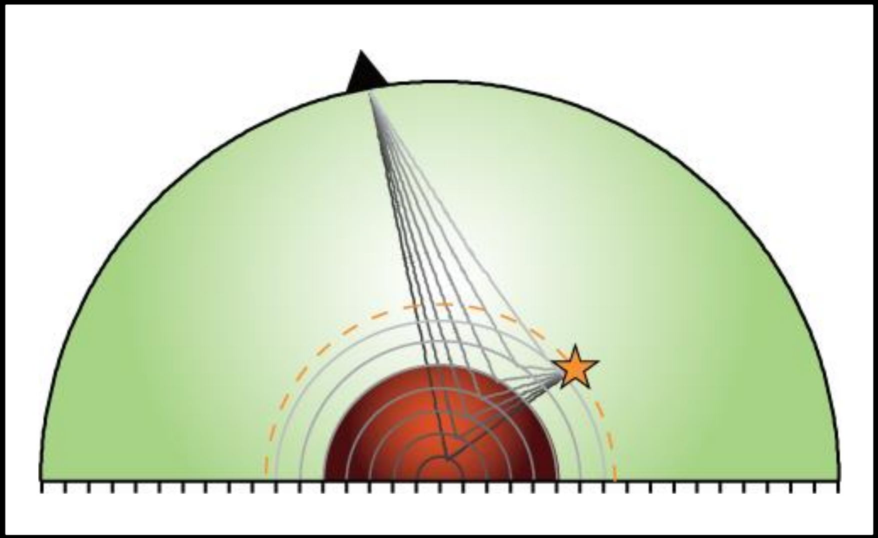
Double array stacking: Array processing methods enhance subtle seismic arrivals by stacking seismograms that have been time-shifted to predicted core arrival times.



Moon: Apollo

Double array stacking in a multi-layer model:

- Iterative approach that seeks the best-fit radii and overlying P- and S-wave speeds of each layer



10-km depth increments in three depth ranges:

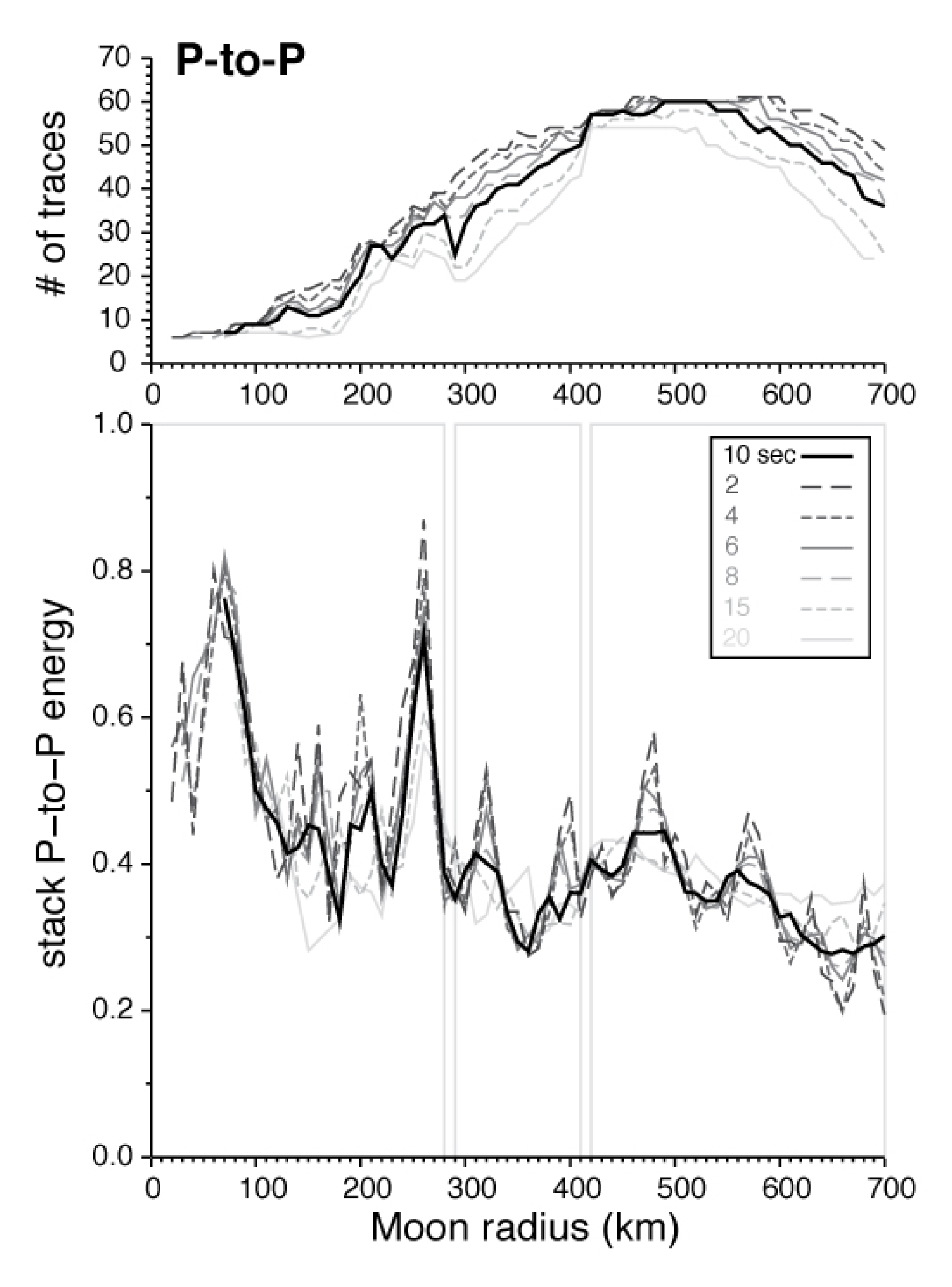
- 420-700 km (partial melt region)
- 290-410 km (CMB)
- 0-280 km (ICB)

Moon: Apollo

Process:

- At each depth increment, estimate the energy associated with each stack
  - ➢ Energy = area under the envelope of the stack
- Test different stack window lengths to allow for possible moonquake origin time and location errors

Initial results for P-to-P reflections

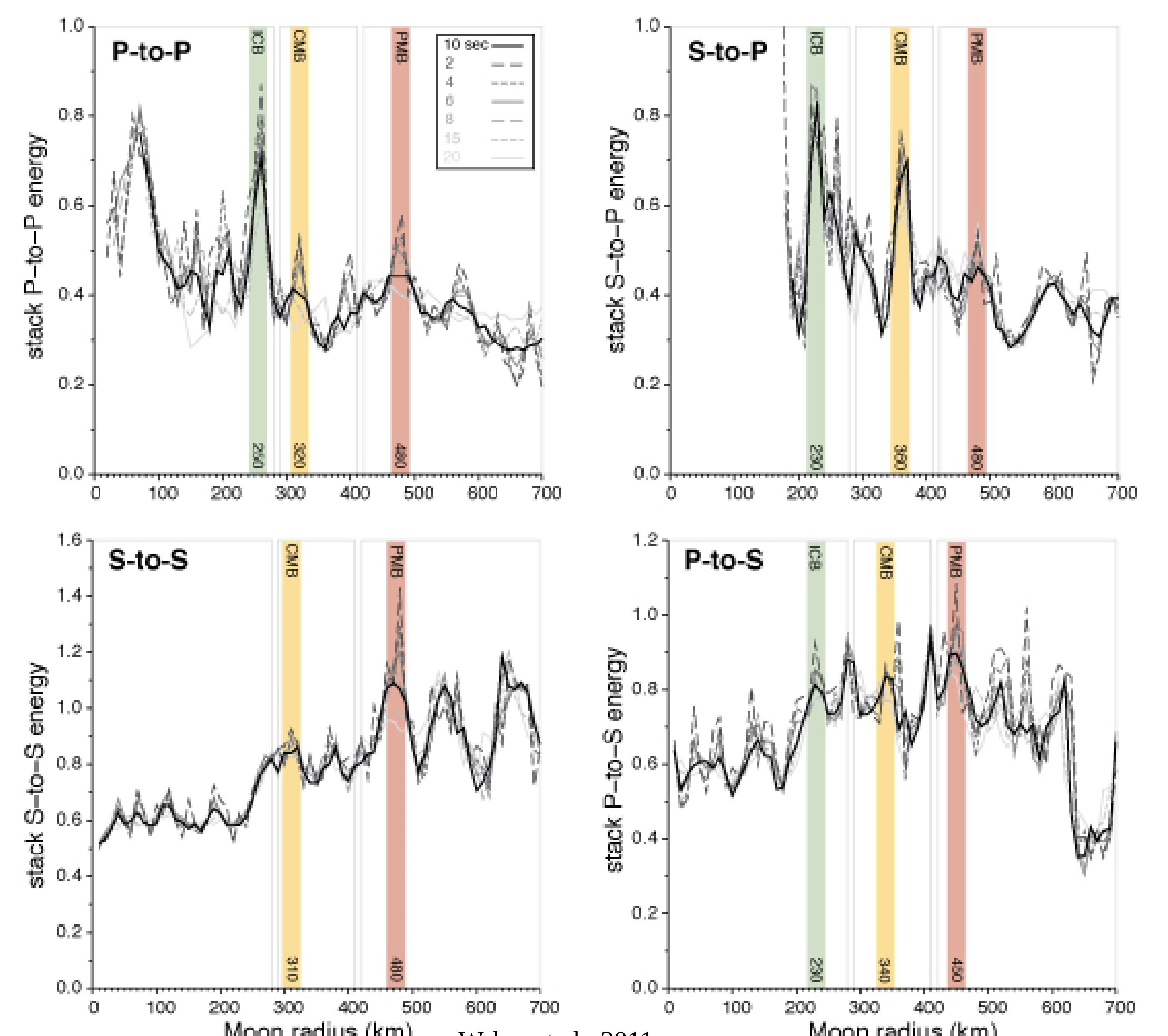


Moon: Apollo

PMB:
480 km

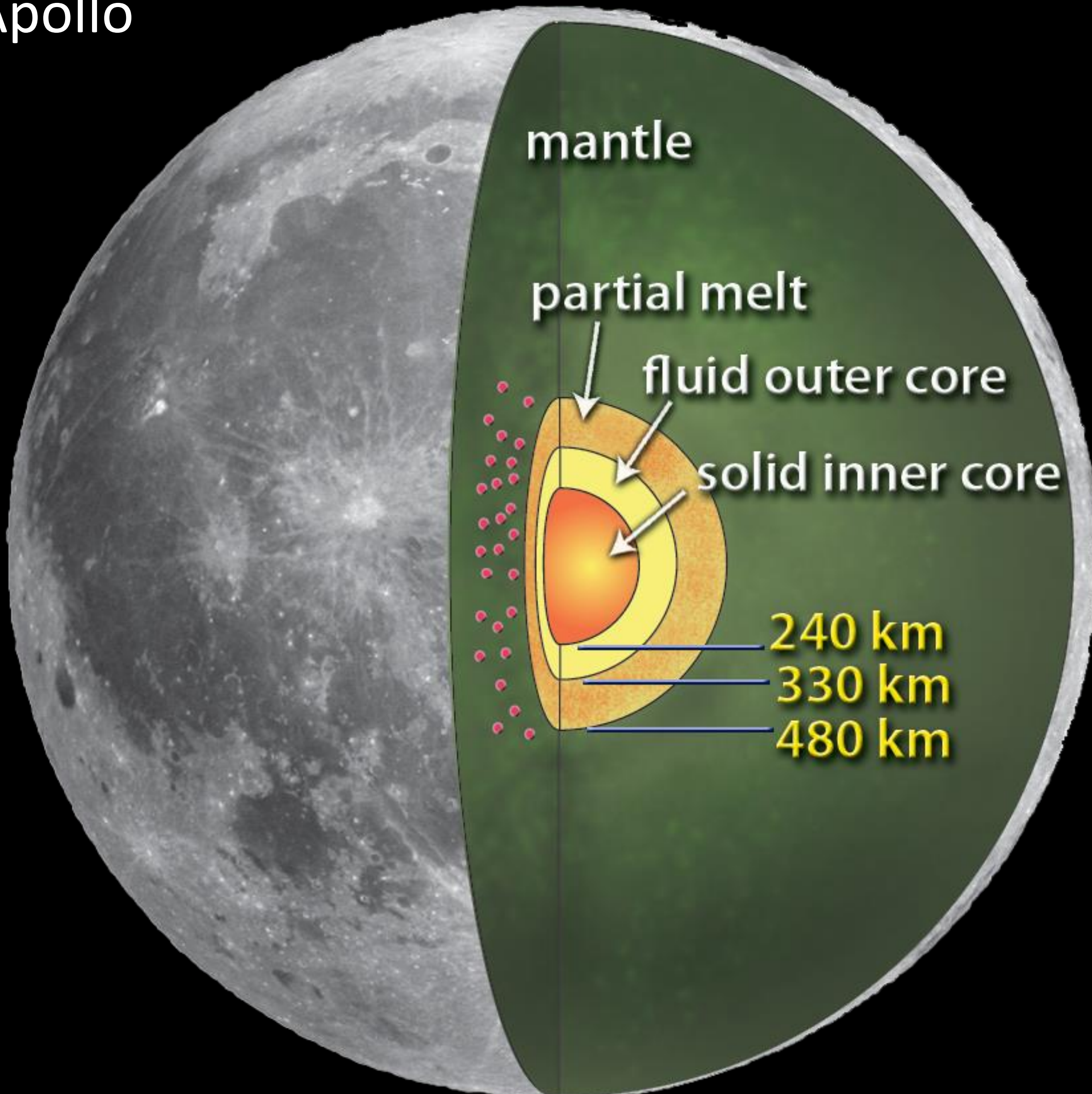
CMB:
330 km

ICB:
240 km



Weber et al., 2011

Moon: Apollo

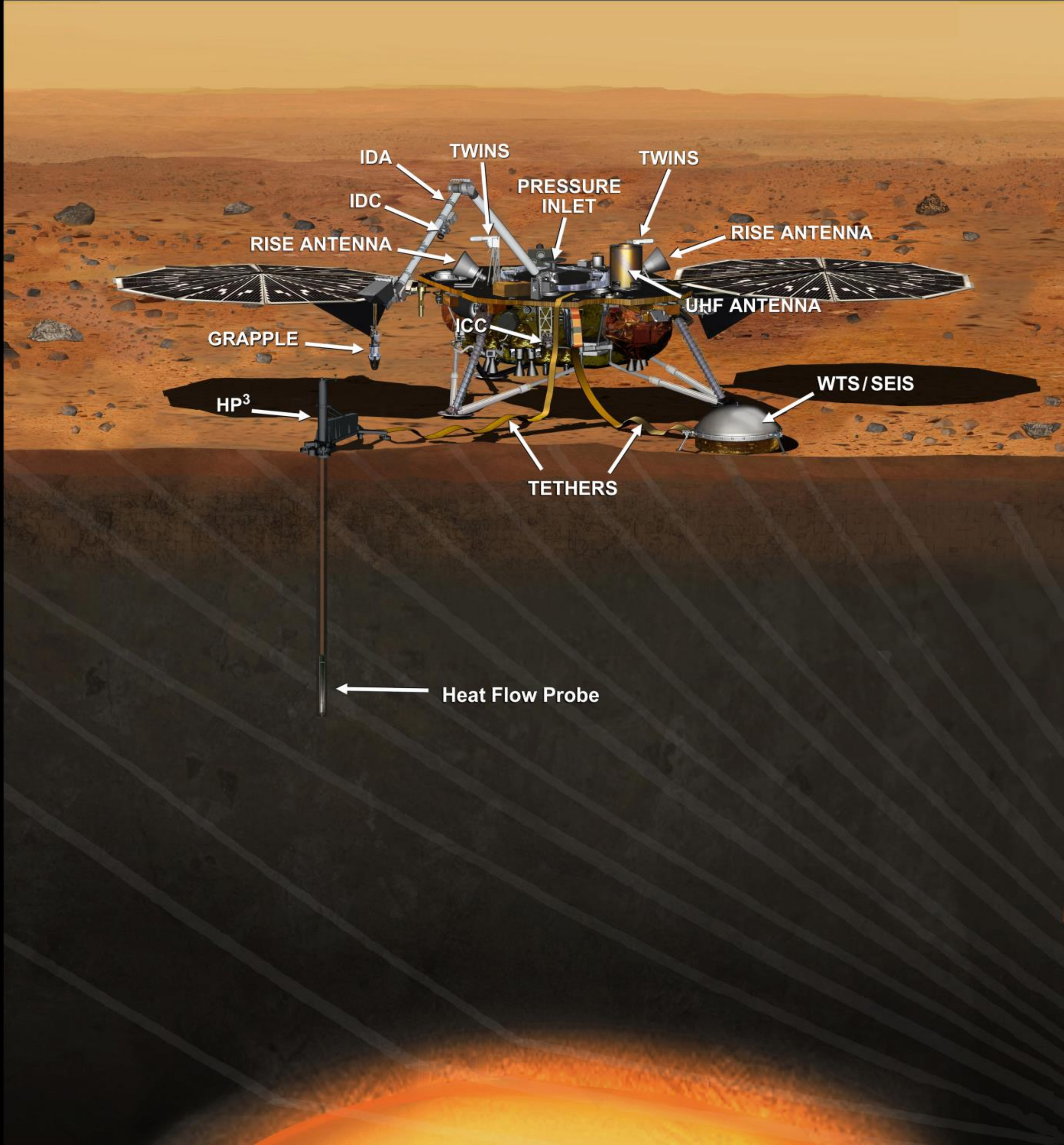

mantle
partial melt
fluid outer core
solid inner core
240 km
330 km
480 km

Coming soon:
More Mars seismology!

A Discovery Mission to Explore the Deep Interior of Mars

InSight

Interior Exploration using Seismic Investigations, Geodesy and Heat Transport

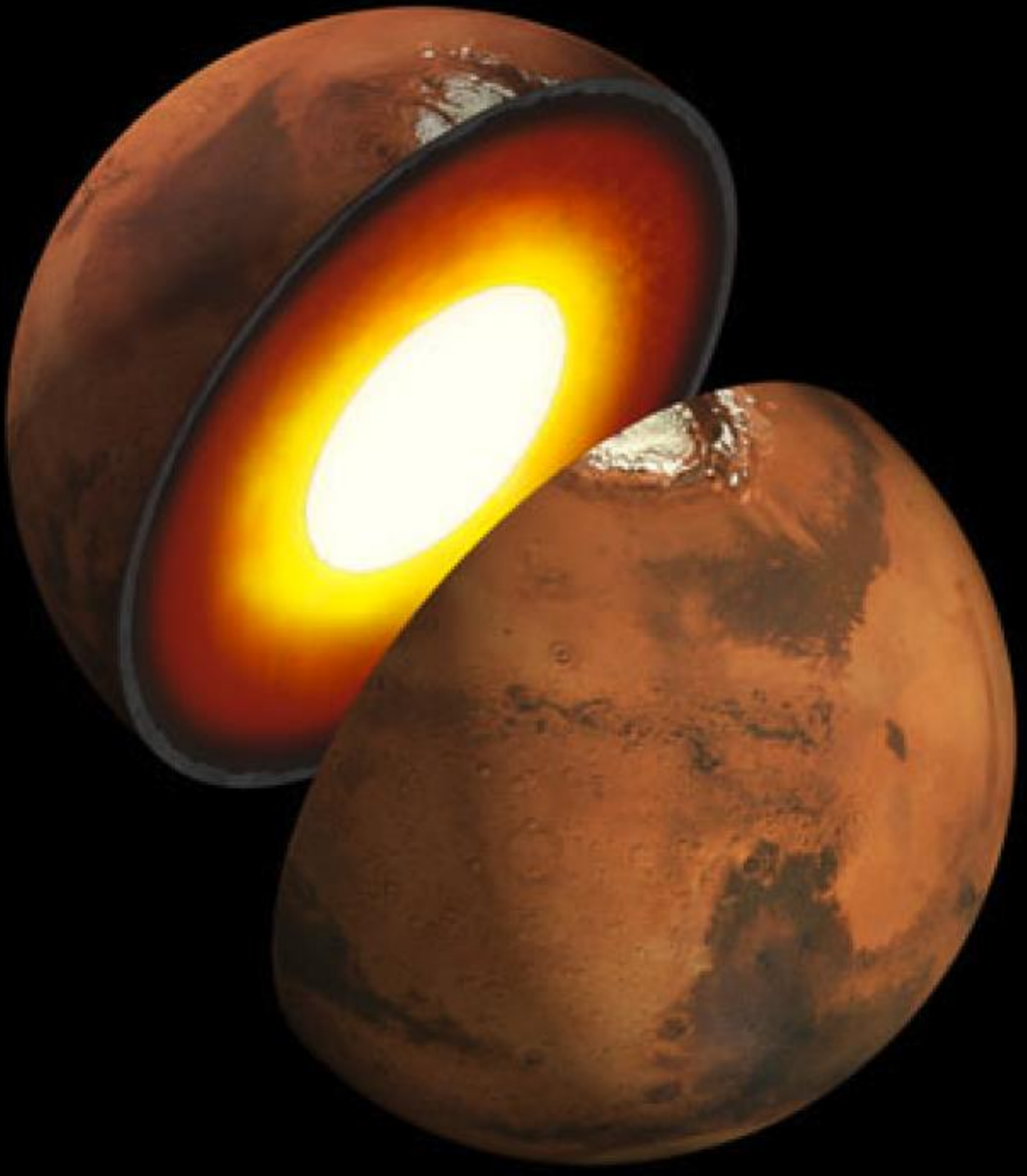


Launch: May 2018

Mars: InSight

Goal:
Understand the formation and evolution of terrestrial planets through investigation of the interior structure of Mars

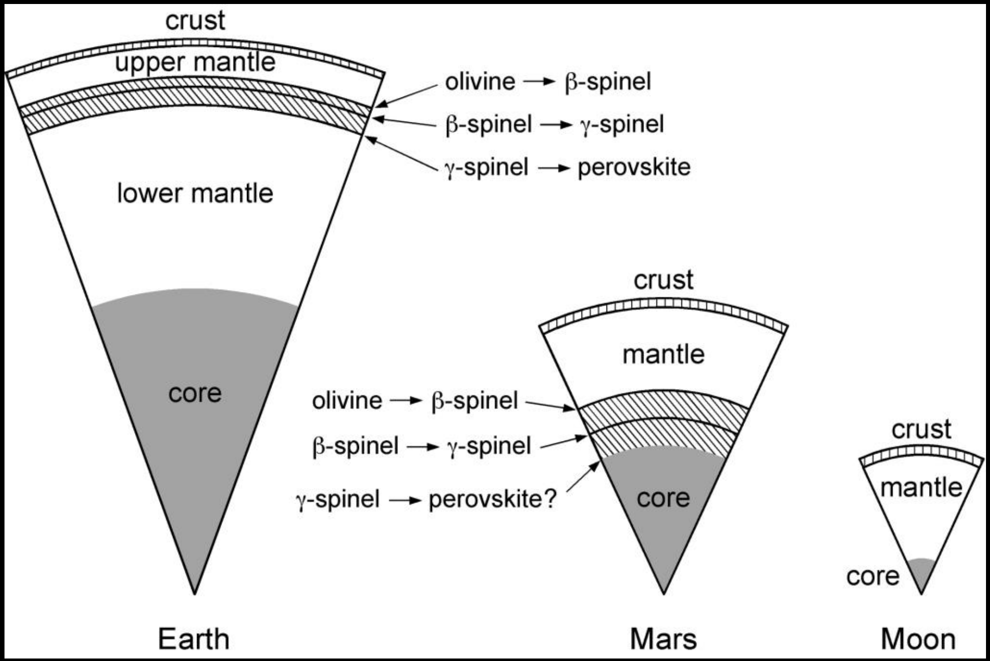
- Seismology
- Geodesy
- Heat flow
- Magnetics



Mars: InSight

Why Mars?

- The Moon was formed under unique circumstances and with a limited range of P-T conditions (<200 km depth on Earth)
- Mars is large enough to have undergone most terrestrial processes, but small enough to have retained evidence of its early activity.
- Mars is uniquely well-suited to study the common processes that shape all rocky planets and govern their basic habitability.



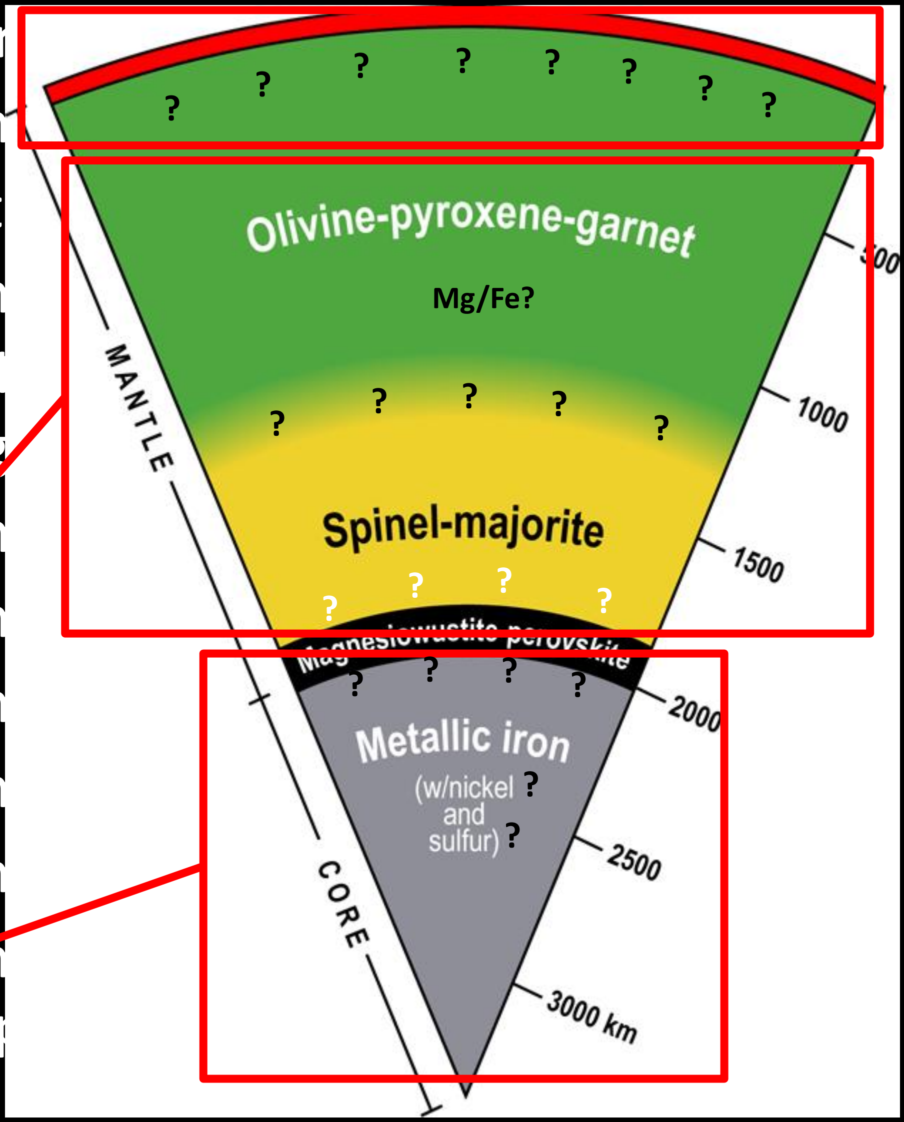
- ➢ There is strong evidence that its basic crust and mantle structure have survived little changed from the first few hundred Myr of formation.
- ➢ Its surface is much more accessible than Mercury, Venus.
- ➢ Our knowledge of its geology, chemistry, climate history provides scientific context for using interior information to increase our understanding of the solar system.

Mars: InSight

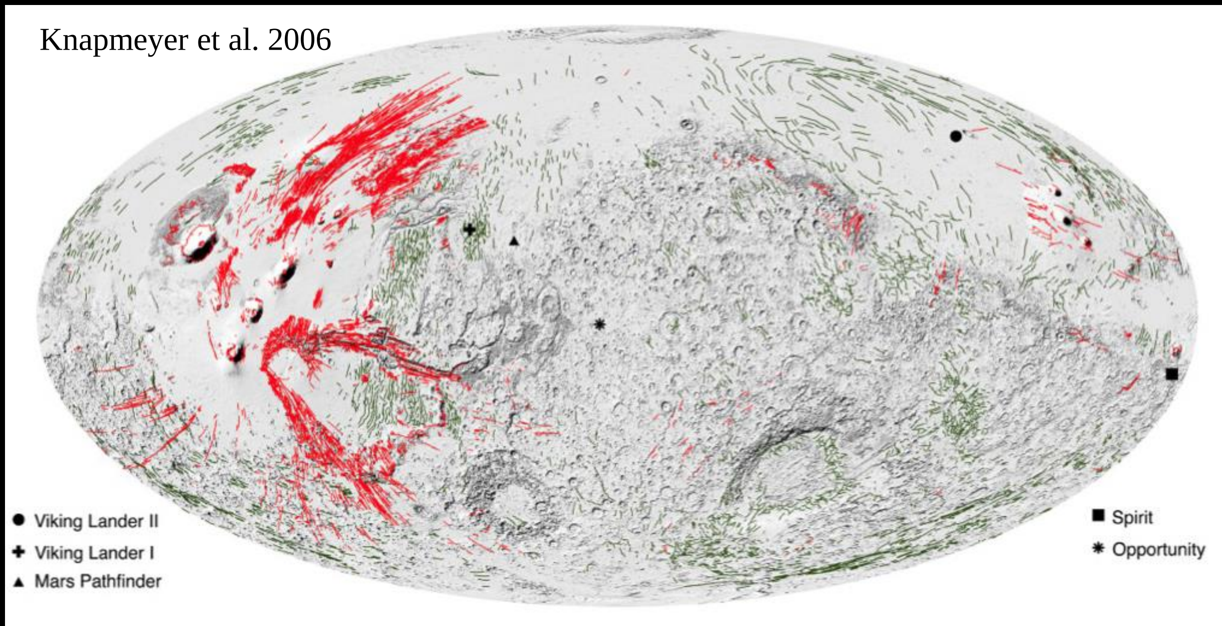
- **Crust:** Its **thickness** and vertical structure (**layering** of different compositions) reflects the depth and crystallization processes of the magma ocean and the early post-differentiation evolution of the planet (plate tectonics vs. crustal overturn vs. immobile crust vs. …).

- **Mantle:** Its behavior (e.g., convection, partial melt generation) determines the manifestation of the thermal history on a planet's surface; depends directly on its **thermal structure** and **stratification**.

- **Core:** Its **size** and composition (**density**) reflect conditions of accretion and early differentiation; its **state** (liquid vs. solid) reflects its composition and the thermal history of the planet.

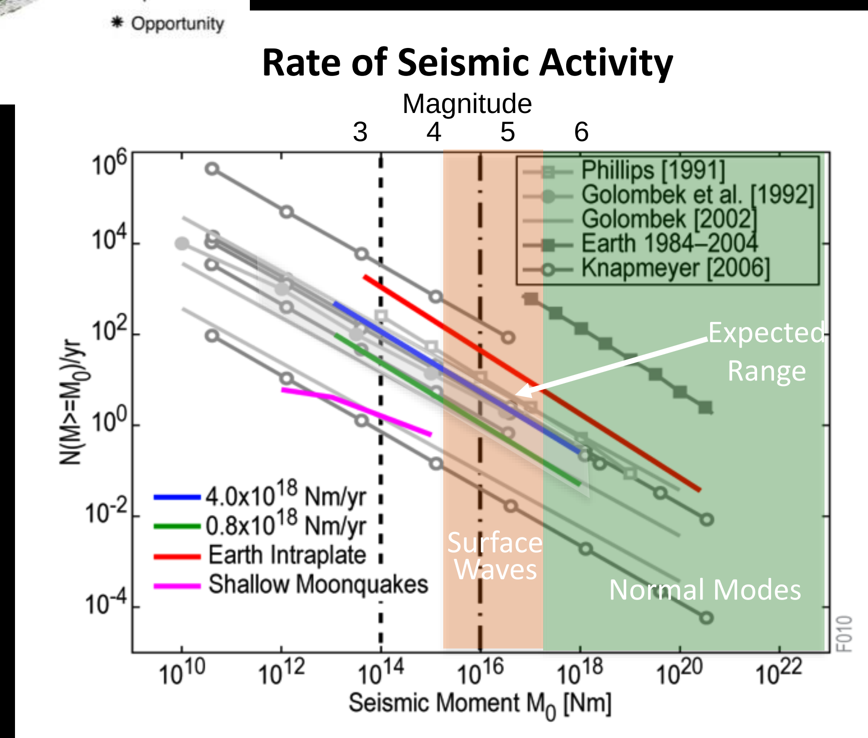


Mars: InSight



Seismic sources:

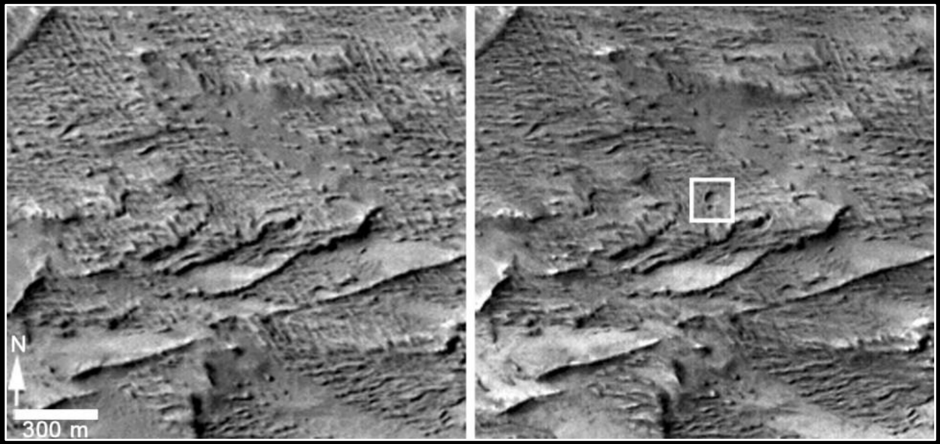
- faulting

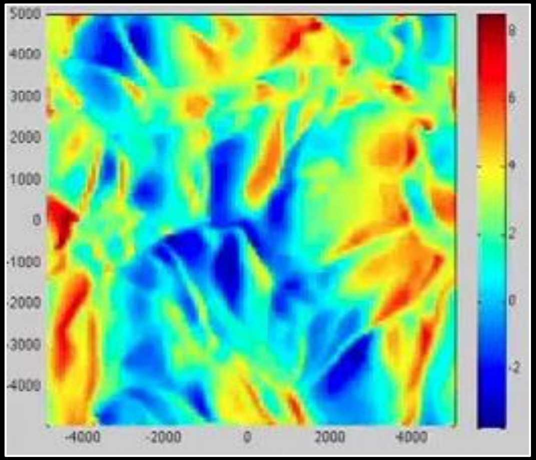


Mars: InSight

Seismic sources:

- Impacts
- Atmospheric excitation
- Phobos tide

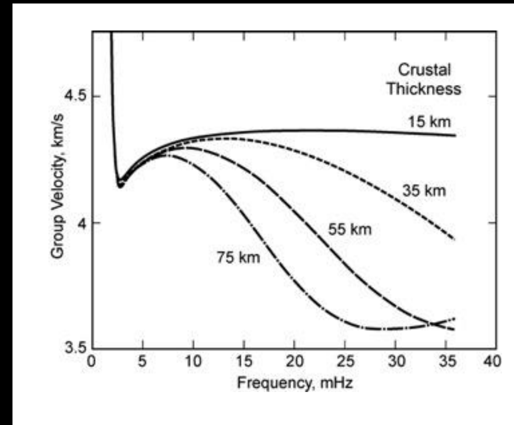




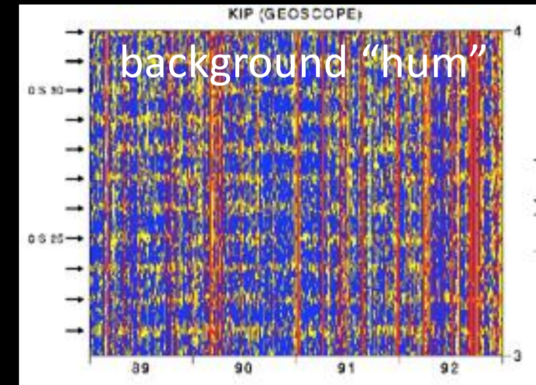
Mars: InSight

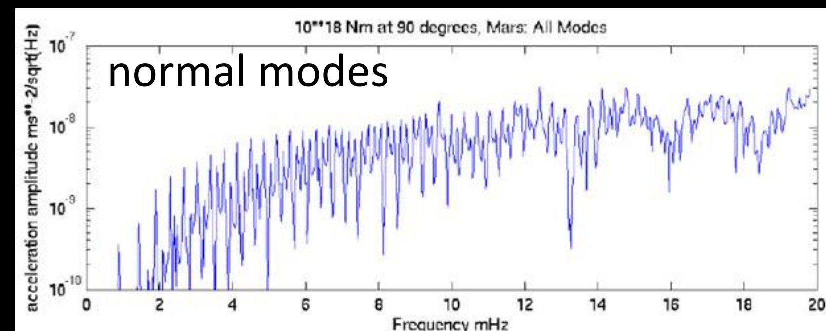
Single-station analysis techniques:

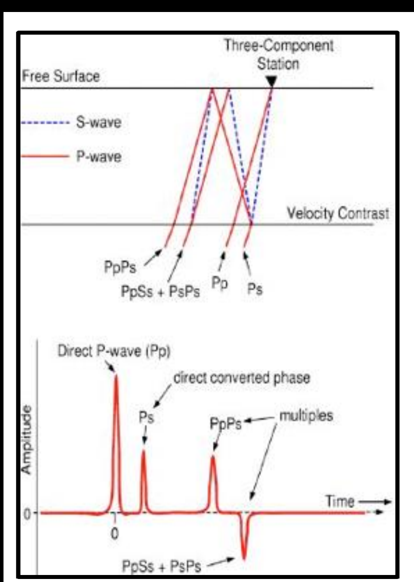
- Event location:
  - Differential travel times and back-azimuth
  - Surface wave dispersion
- Internal structure:
  - Normal modes
  - Noise analyses
  - Receiver functions
  - Body & surface waves



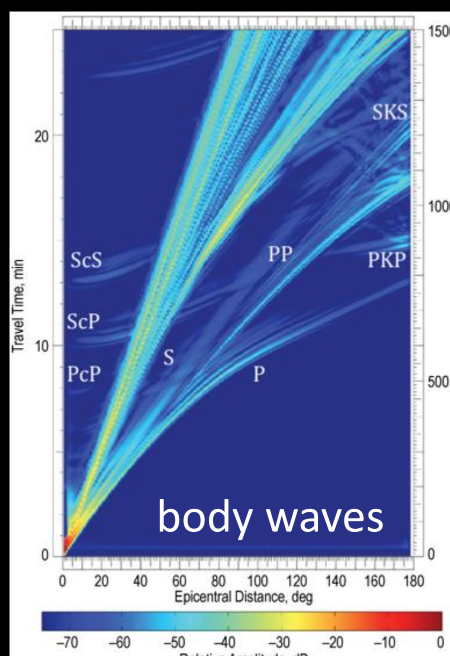
surface wave dispersion

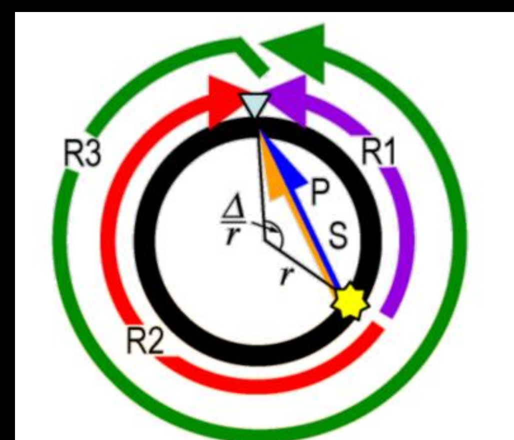






receiver function

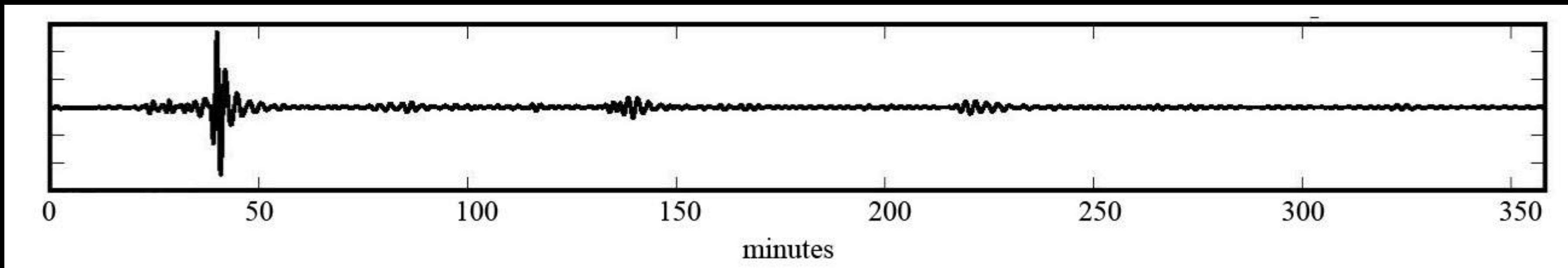




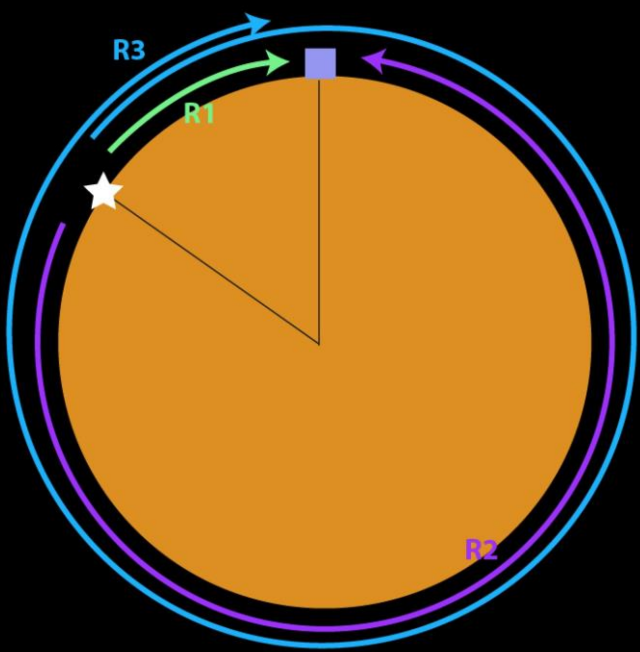
surface waves

Mars: InSight

epicentral distance from Rayleigh waves



vertical component



angular group velocity

$$U = \frac{2p}{R3 - R1}$$

epicentral distance

$$D = p - \frac{1}{2}U(R2 - R1)$$

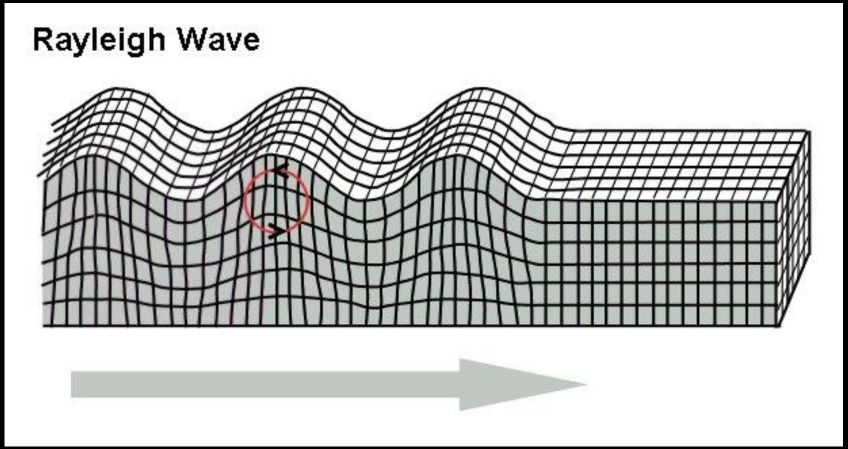
origin time

$$t_0 = R1 - \frac{D}{U}$$

Mars: InSight

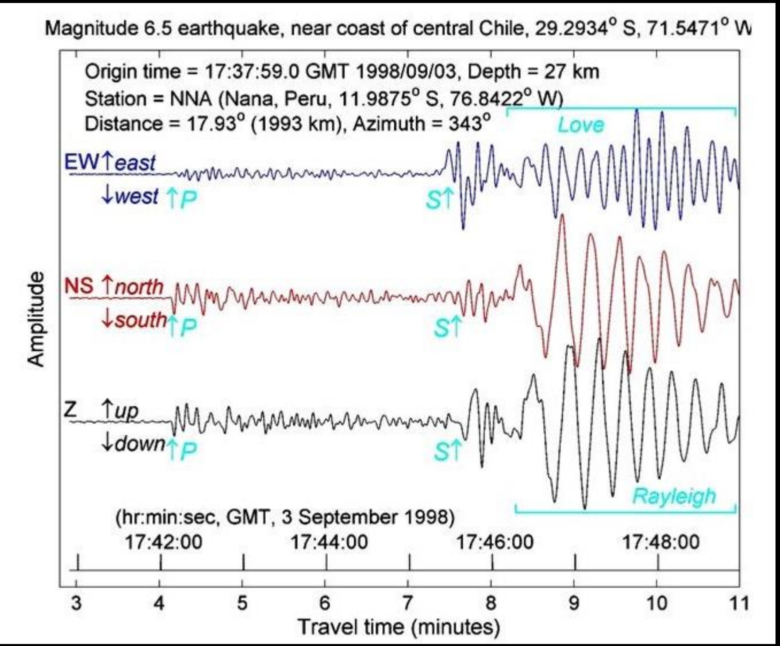
back azimuth from Rayleigh waves

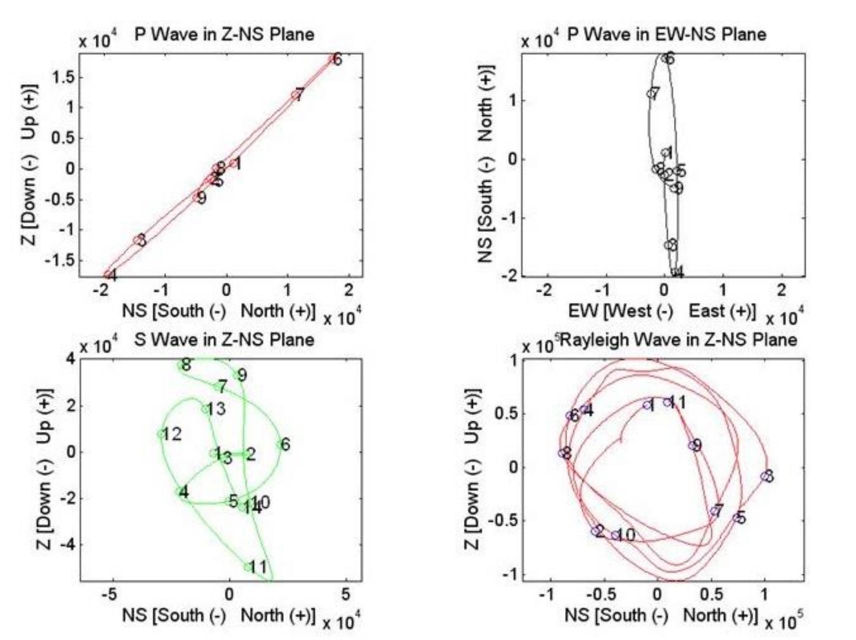
determined from analysis of 3-component seismograms: P-SV phases are polarized in the great-circle plane containing the source & receiver



plot the particle motion of a 3-component seismogram and find an azimuth for which this plot forms a retrograde ellipse in one plane

combined with body-wave arrivals, can invert for 1D mantle velocity profiles





Mars: InSight