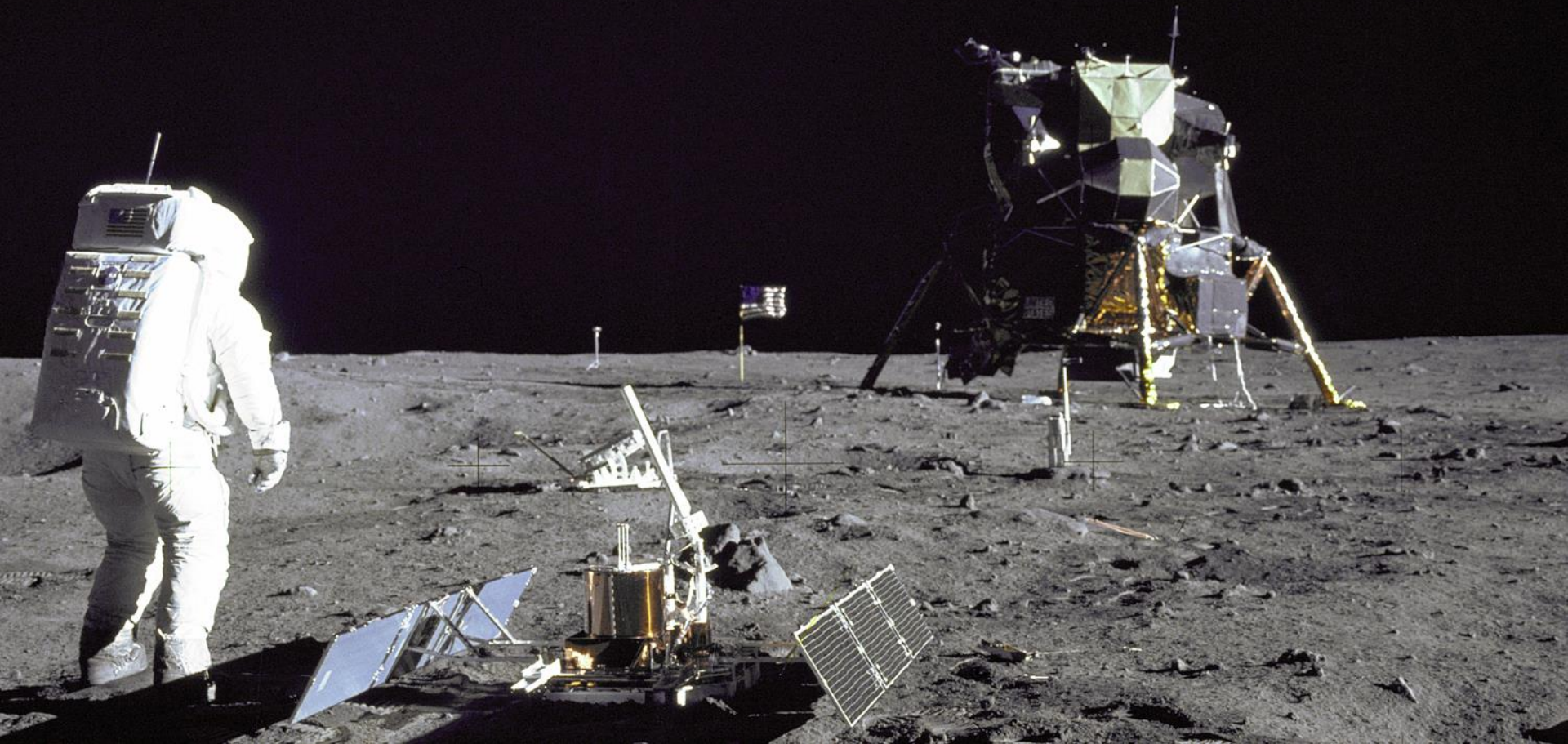


# Planetary seismology



Renee Weber  
NASA Marshall Space Flight Center



# Seismology:

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

## Exploring the Earth Using Seismology

### THE WORTHWHILE EARTHQUAKE



In the last century, at least 17,000,000 people have been killed by earthquakes. The number of people killed and injured is also estimated to be 100 million. The damage to buildings, bridges, and other structures is estimated to be \$100 billion. The damage to the environment is also estimated to be \$100 billion.



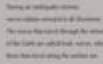
### NOW ARE EARTHQUAKES RECORDED?



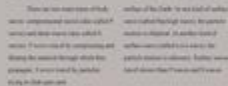
The seismometer is a device that records the motion of the ground during an earthquake. It consists of a mass on a spring that is suspended from a frame that is fixed to the ground. When the ground moves, the mass moves relative to the frame, and this motion is recorded by a pen or a digital sensor.



### SEISMIC WAVES

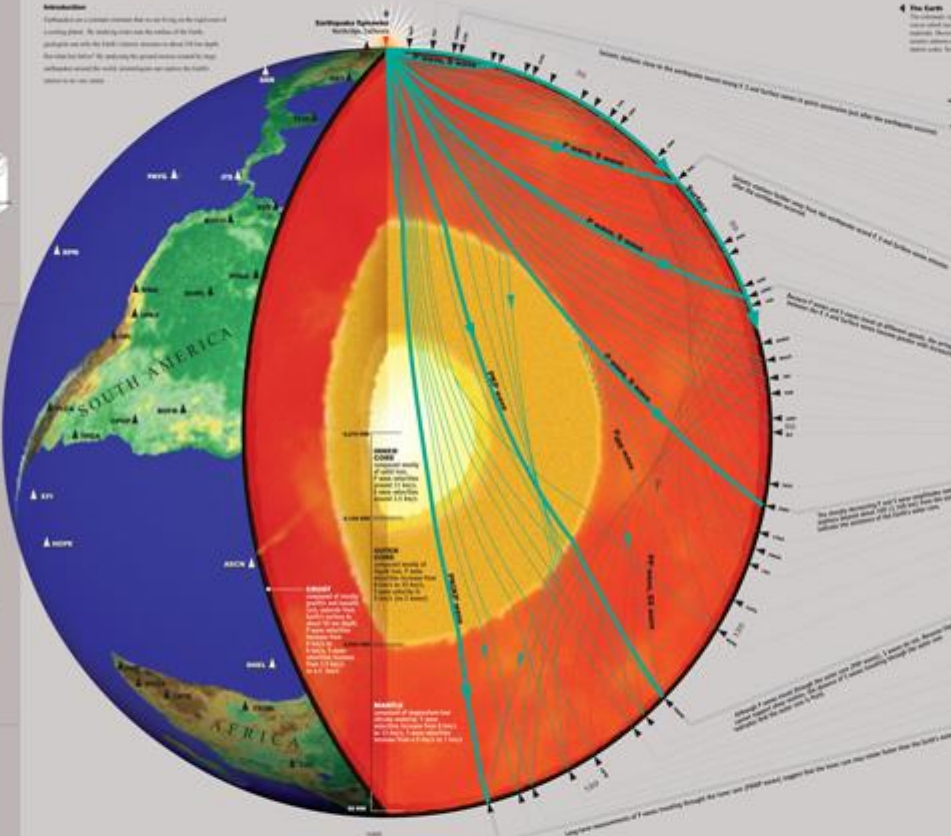


Seismic waves are vibrations that travel through the Earth. They are caused by the sudden release of energy in the Earth's crust, which creates seismic waves. There are three main types of seismic waves: P-waves, S-waves, and surface waves.



### Introduction

Earthquake is a sudden release of energy in the Earth's crust that creates seismic waves. The energy is released as a result of the sudden slip along a fault. This is called the focus or hypocenter of the earthquake, and is usually located at a depth of about 10 km below the surface of the Earth. The point on the surface of the Earth directly above the focus is called the epicenter. The distance from the epicenter to the seismometer is called the epicentral distance.

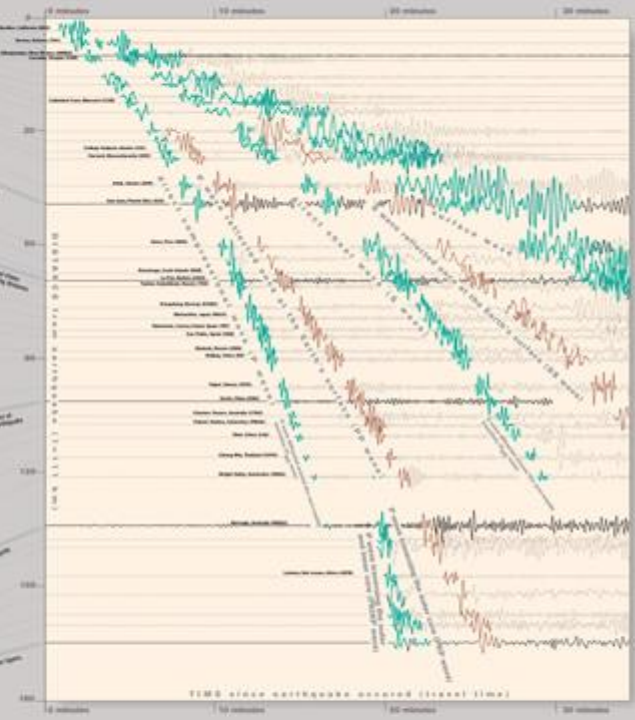


### The Earth

The Earth is a planet that is composed of several layers. The outermost layer is the crust, which is about 10 km thick. Below the crust is the mantle, which is about 2,900 km thick. The innermost layer is the core, which is about 7,000 km in radius. The core is divided into the inner core and the outer core. The inner core is about 1,200 km in radius, and the outer core is about 5,400 km in radius.

### The Seismogram Section

A seismogram is a record of the motion of the ground during an earthquake. It is produced by a seismometer, which is a device that records the motion of the ground. The seismogram shows the amplitude of the seismic waves as a function of time. The amplitude is measured in millimeters, and the time is measured in seconds. The seismogram is a valuable tool for studying earthquakes and for determining the location and depth of the focus.



### GLOBAL SEISMOGRAPHIC NETWORK



The Global Seismic Network is a worldwide network of seismometers that record the motion of the ground during earthquakes. The network is operated by the International Seismological Centre (ISC) and the International Earthquake Service (IES). The network is essential for studying earthquakes and for determining the location and depth of the focus.

### HOW OFTEN DO EARTHQUAKES OCCUR?

Earthquakes occur all over the world, and they occur at different depths. The frequency of earthquakes is highest in the Pacific Ocean and the Atlantic Ocean. The frequency of earthquakes is also highest in the West Indies and the San Andreas Fault. The frequency of earthquakes is lowest in the interior of the continents. The frequency of earthquakes is also lowest in the deep ocean. The frequency of earthquakes is highest in the shallow ocean, and it decreases with depth. The frequency of earthquakes is also highest in the shallow ocean, and it decreases with depth.

### Energy Release



### WHERE DO EARTHQUAKES HAPPEN?



### WATCH EARTHQUAKES AS THEY OCCUR



17th International Symposium on Seismology and Earthquake Engineering

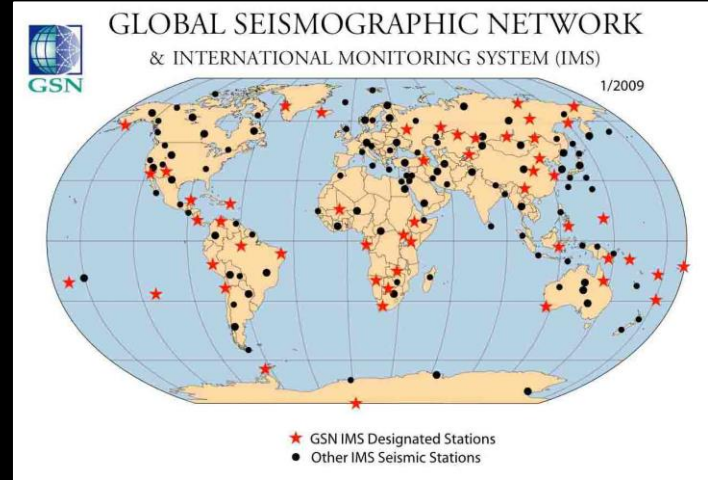
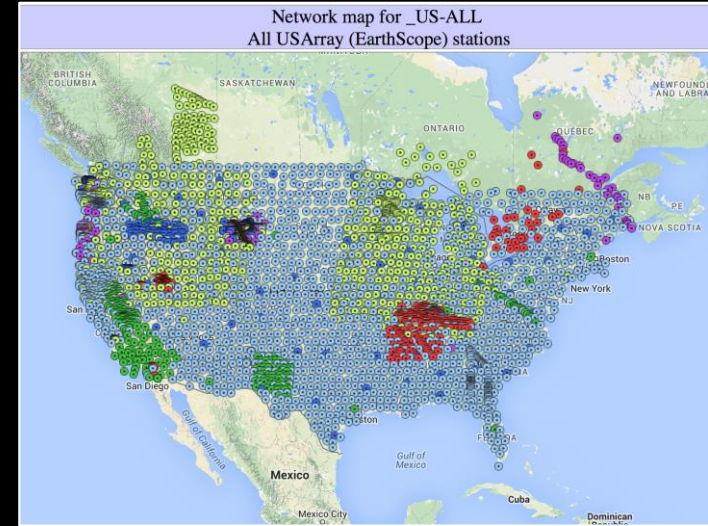
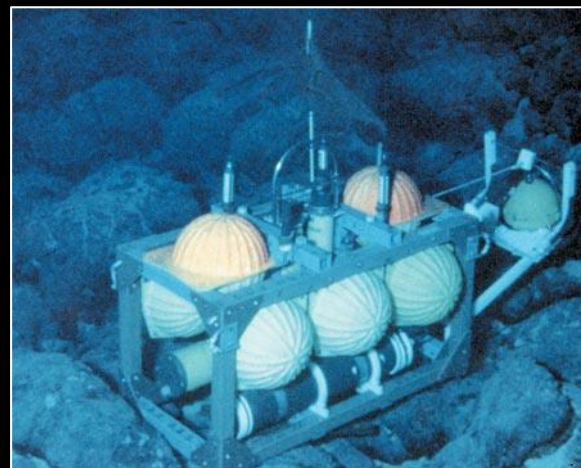
**IRIS**  
CONSORTIUM

University of California, Berkeley  
University of Colorado, Boulder  
University of Illinois, Urbana-Champaign  
University of Michigan, Ann Arbor  
University of Oregon, Eugene  
University of Pennsylvania, Philadelphia  
University of Texas at Austin, Austin  
University of Washington, Seattle  
University of Wisconsin-Madison, Madison  
University of Wisconsin-Minneapolis, Minneapolis  
University of Wisconsin-Stevens Point, Stevens Point  
University of Wisconsin-Stout, Stout  
University of Wisconsin-La Crosse, La Crosse  
University of Wisconsin-Oshkosh, Oshkosh  
University of Wisconsin-River Falls, River Falls  
University of Wisconsin-Superior, Superior  
University of Wisconsin-Stevens Point, Stevens Point  
University of Wisconsin-Stout, Stout  
University of Wisconsin-River Falls, River Falls  
University of Wisconsin-Superior, Superior

USGS

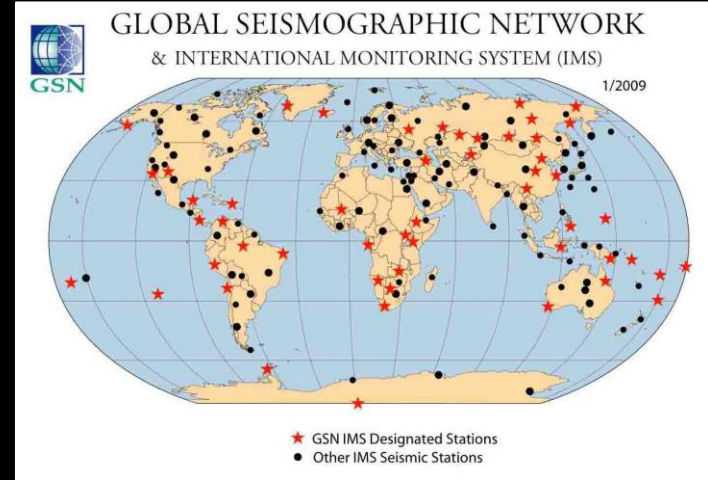
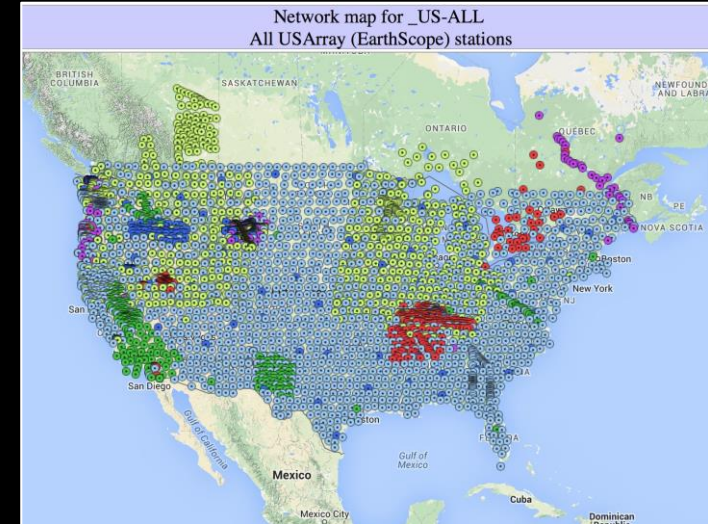
# Characteristics of a “good” seismic network:

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



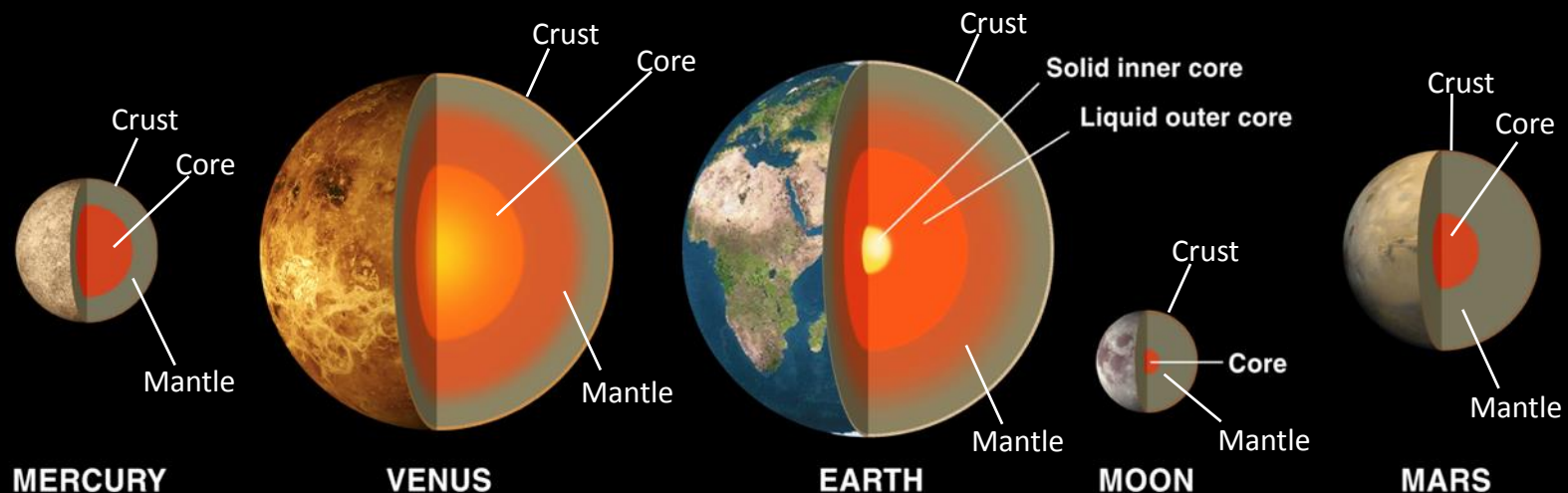
# Characteristics of a “good” seismic network:

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

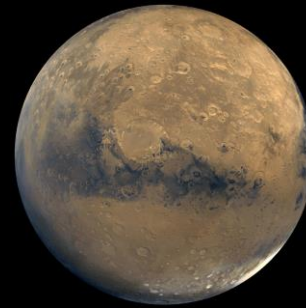


# Why planetary seismology?

- 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

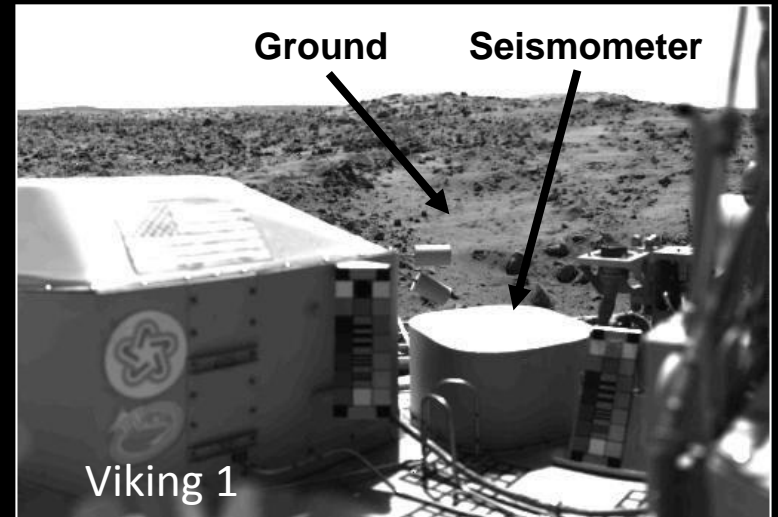
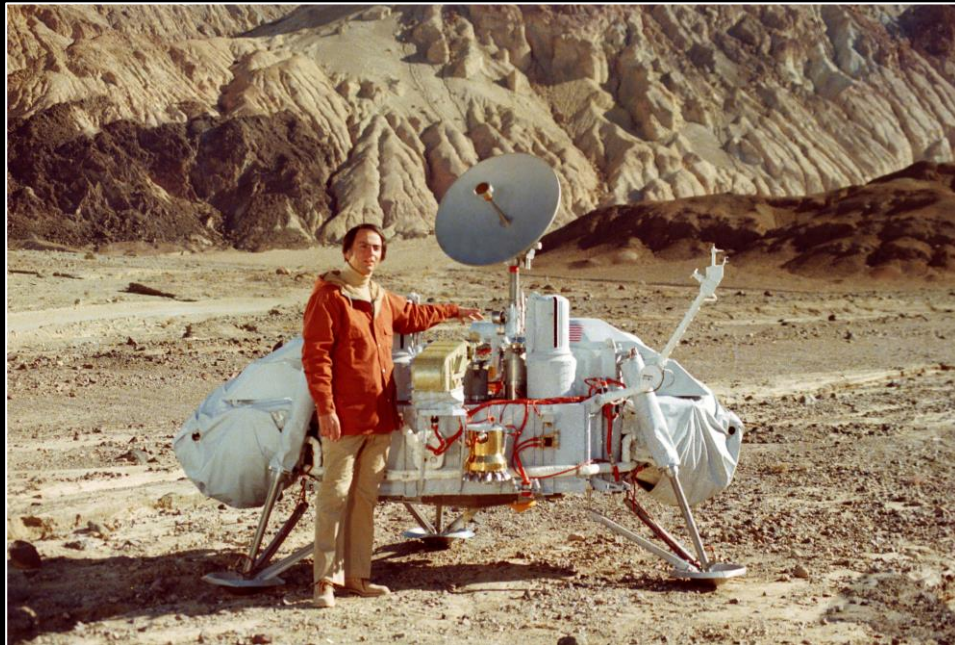
# Mars: Viking

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



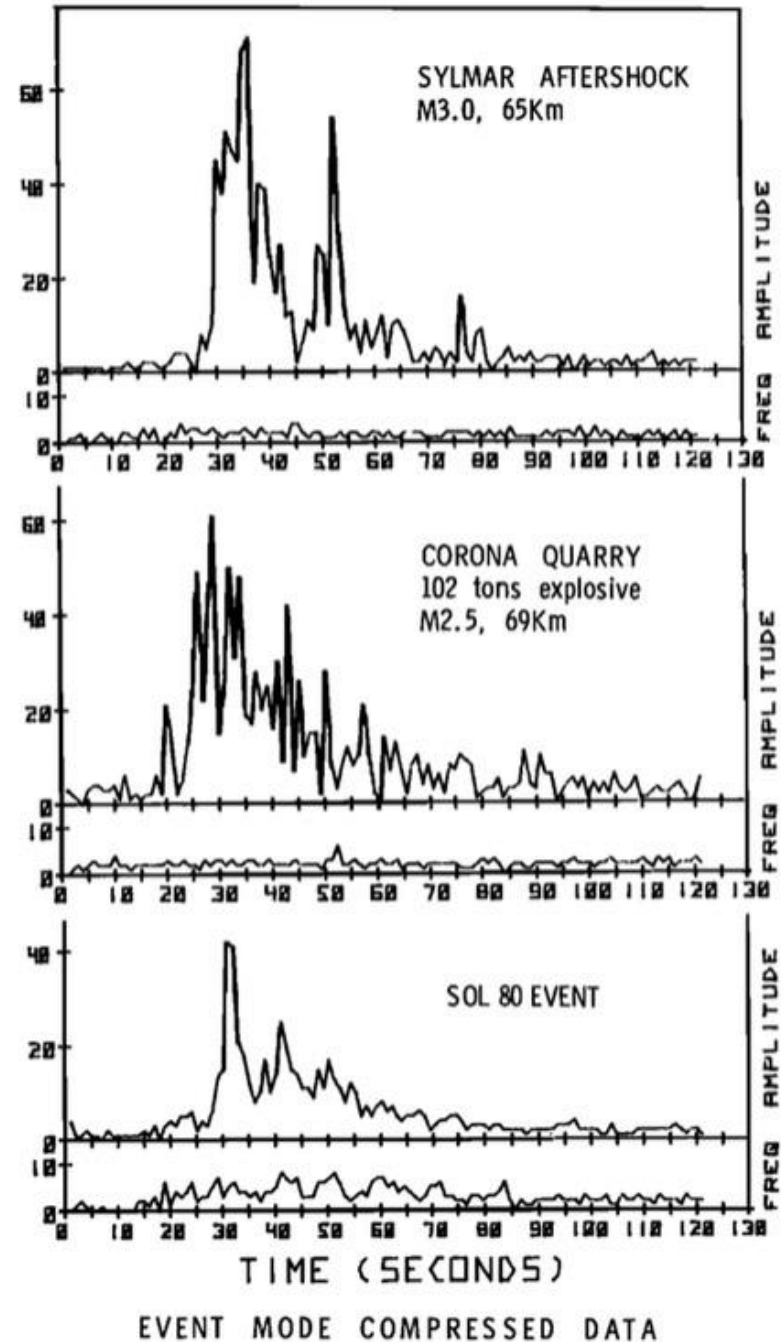
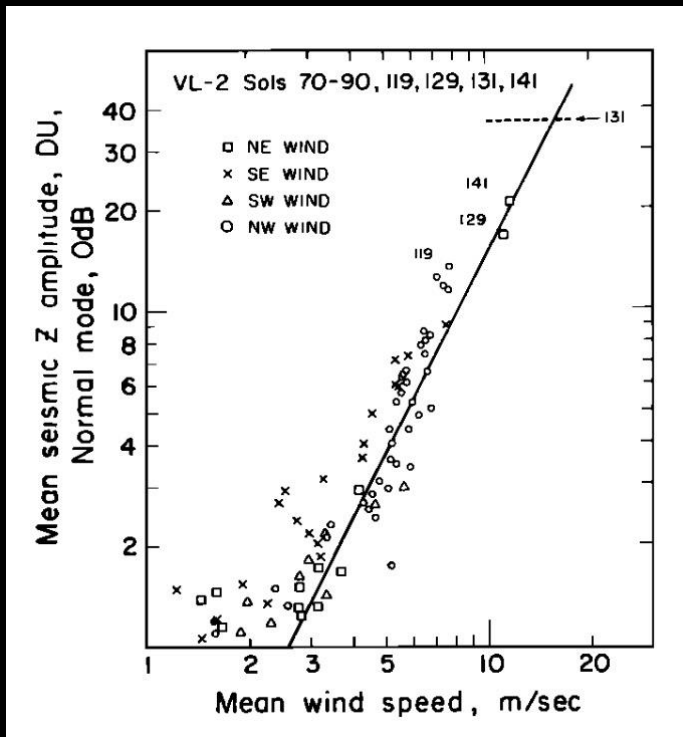
problem: poor ground coupling!

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)

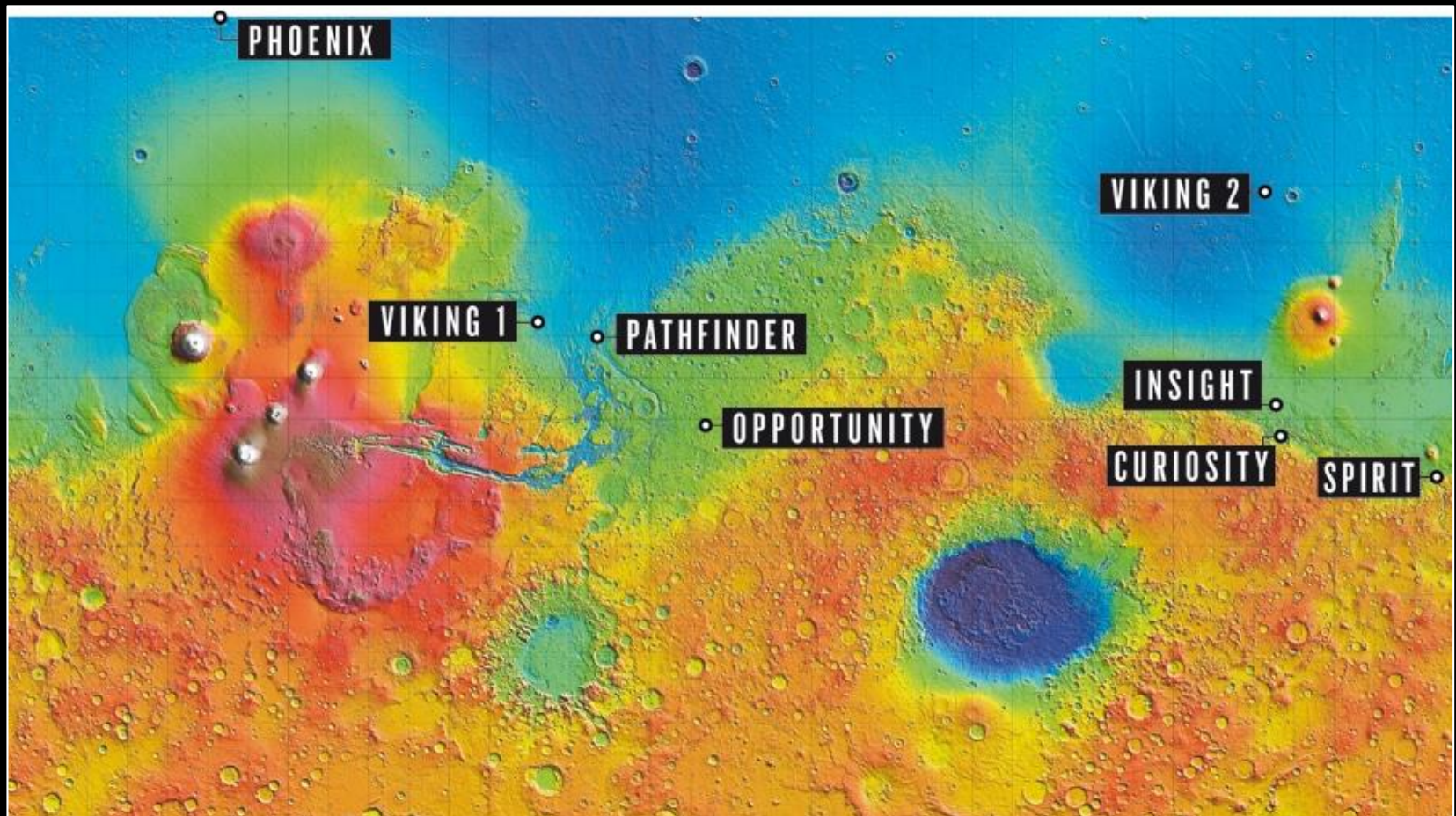




# Mars: Viking

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!

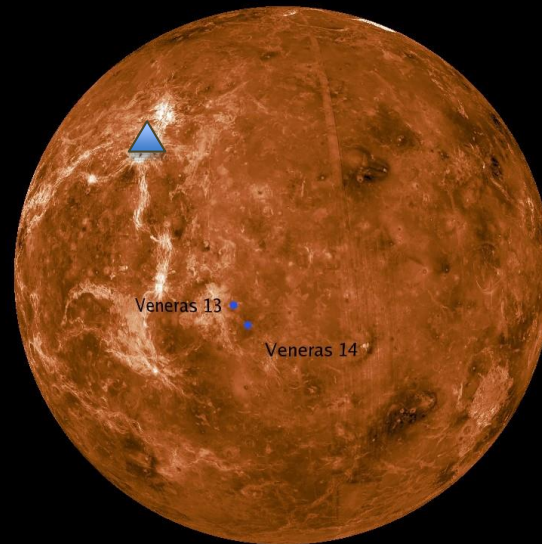
(inhospitable surface conditions: high temperature, high pressure, corrosive atmosphere)



# Venus: Venera

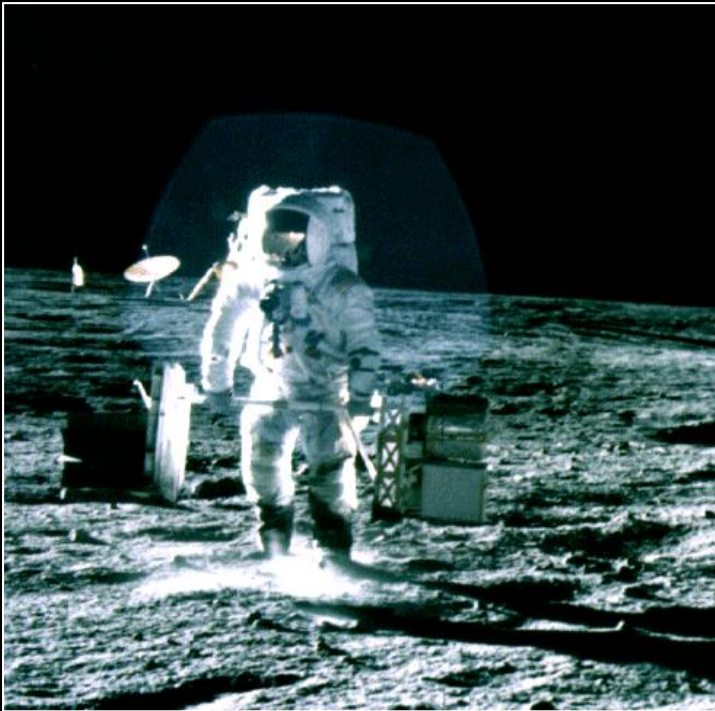
## Venera 14:

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



# Moon: Apollo

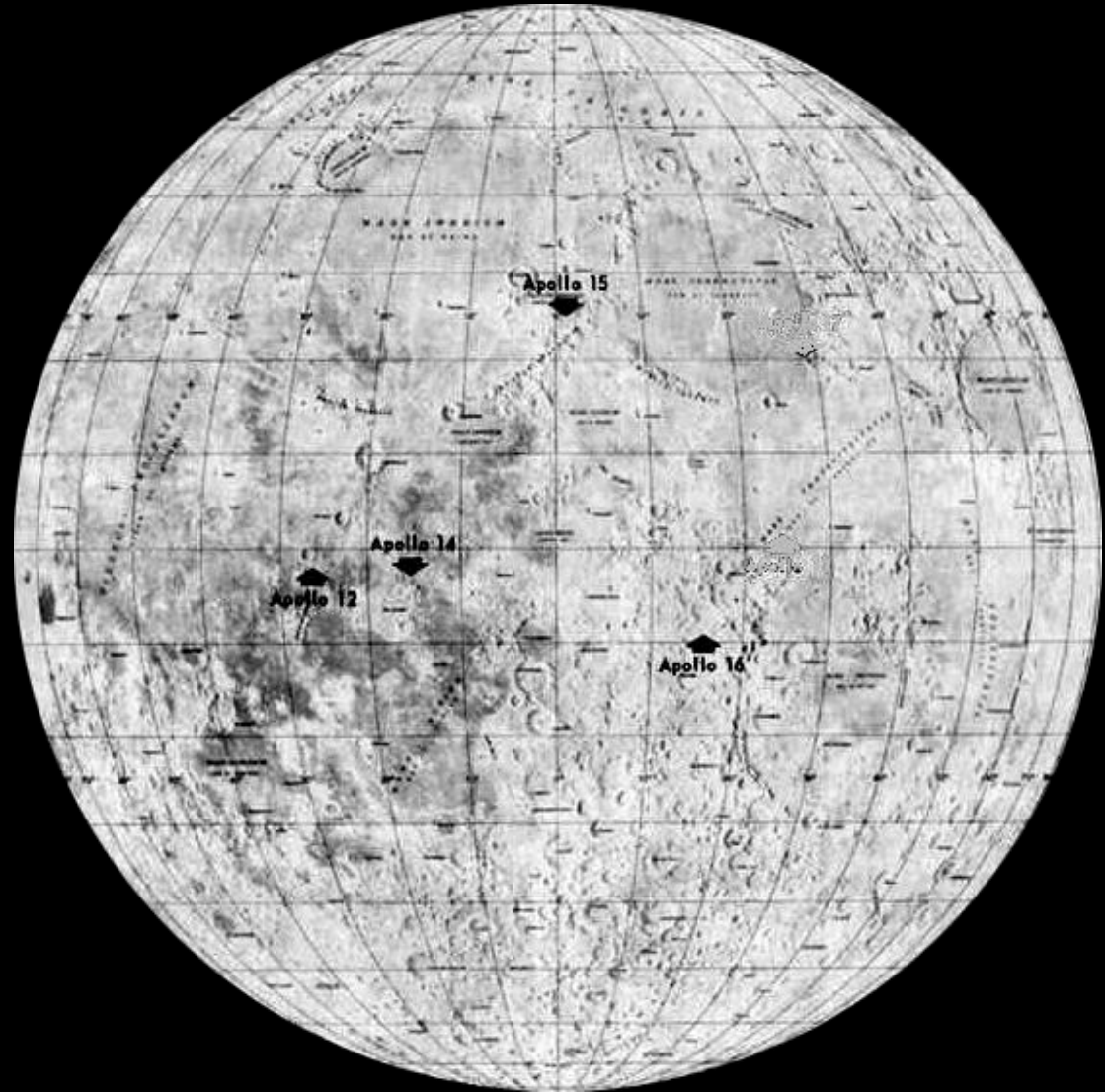
## ALSEP: Apollo Lunar Surface Experiment Package



# Moon: Apollo

## The Apollo Passive Seismic Experiment

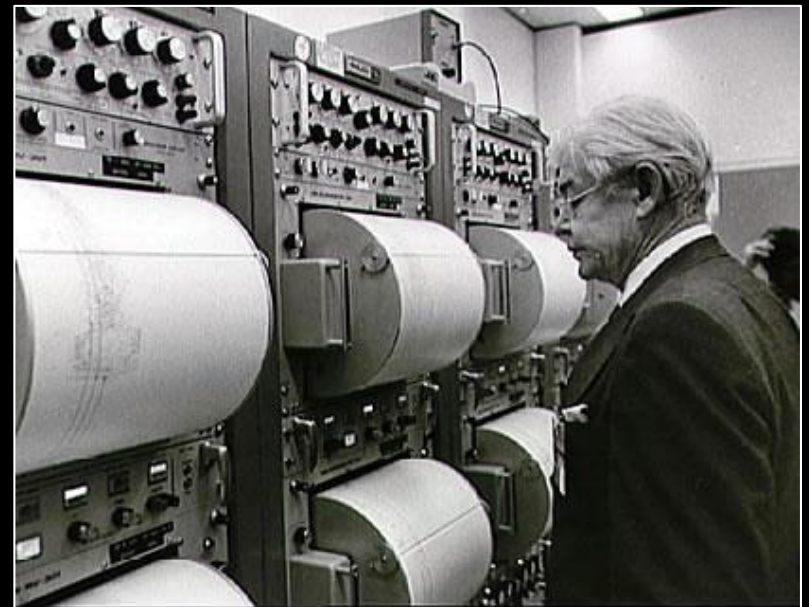
- Four stations deployed on the lunar near side during the Apollo 12/14/15/16 missions.
- Operated from inception until mid-1977.



# 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

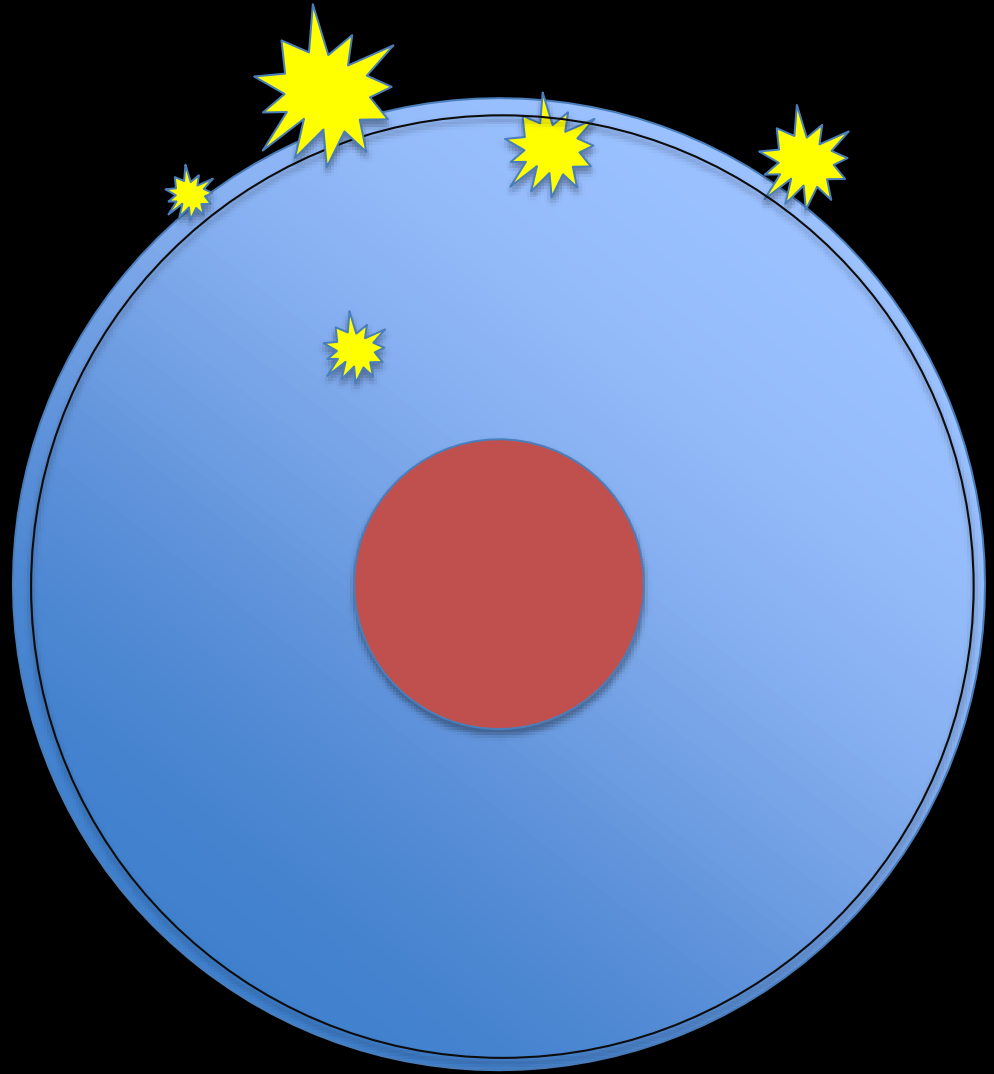
- Modern computer technology permits more advanced studies than were initially possible given computer capabilities of the era



# Moon: Apollo

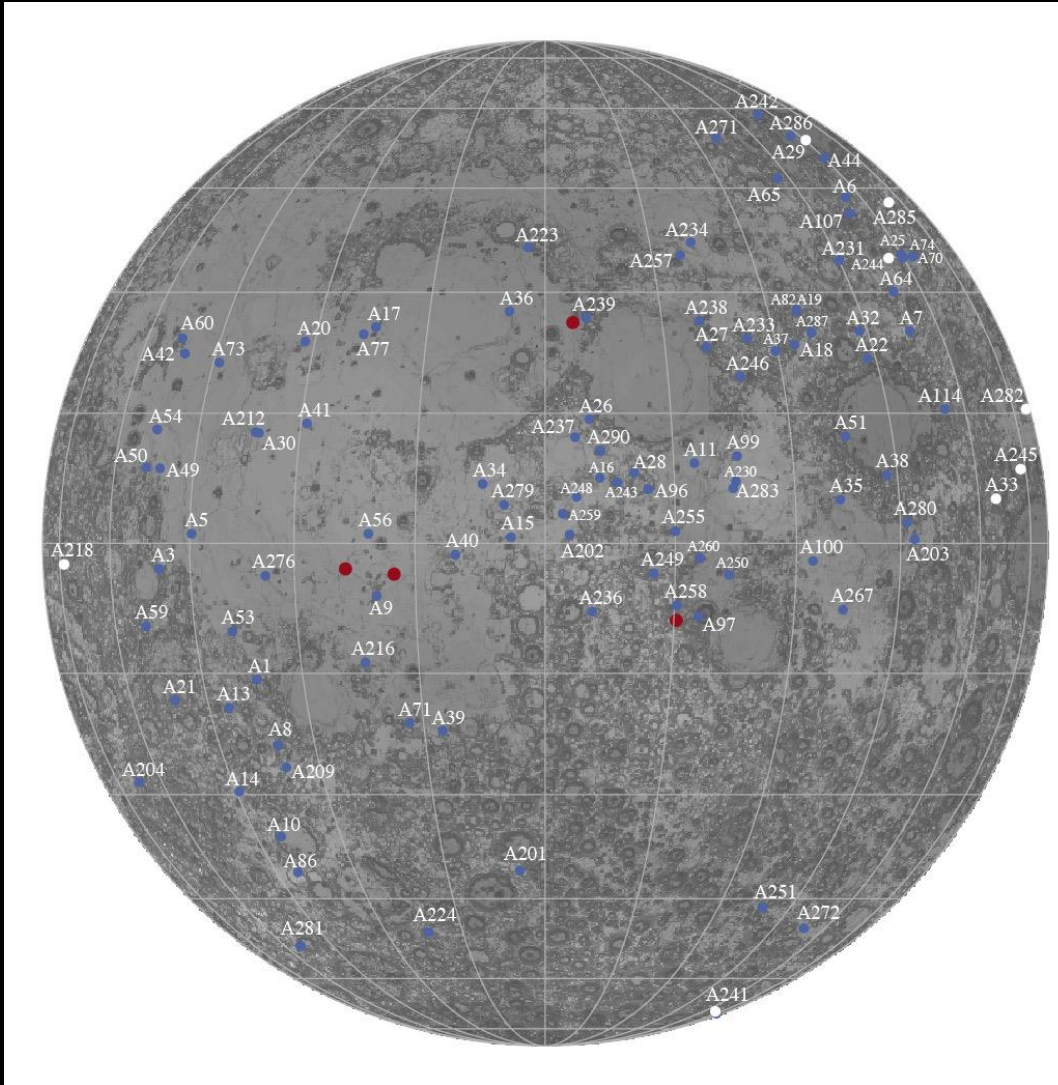
## Lunar seismicity:

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





# Moon: Apollo

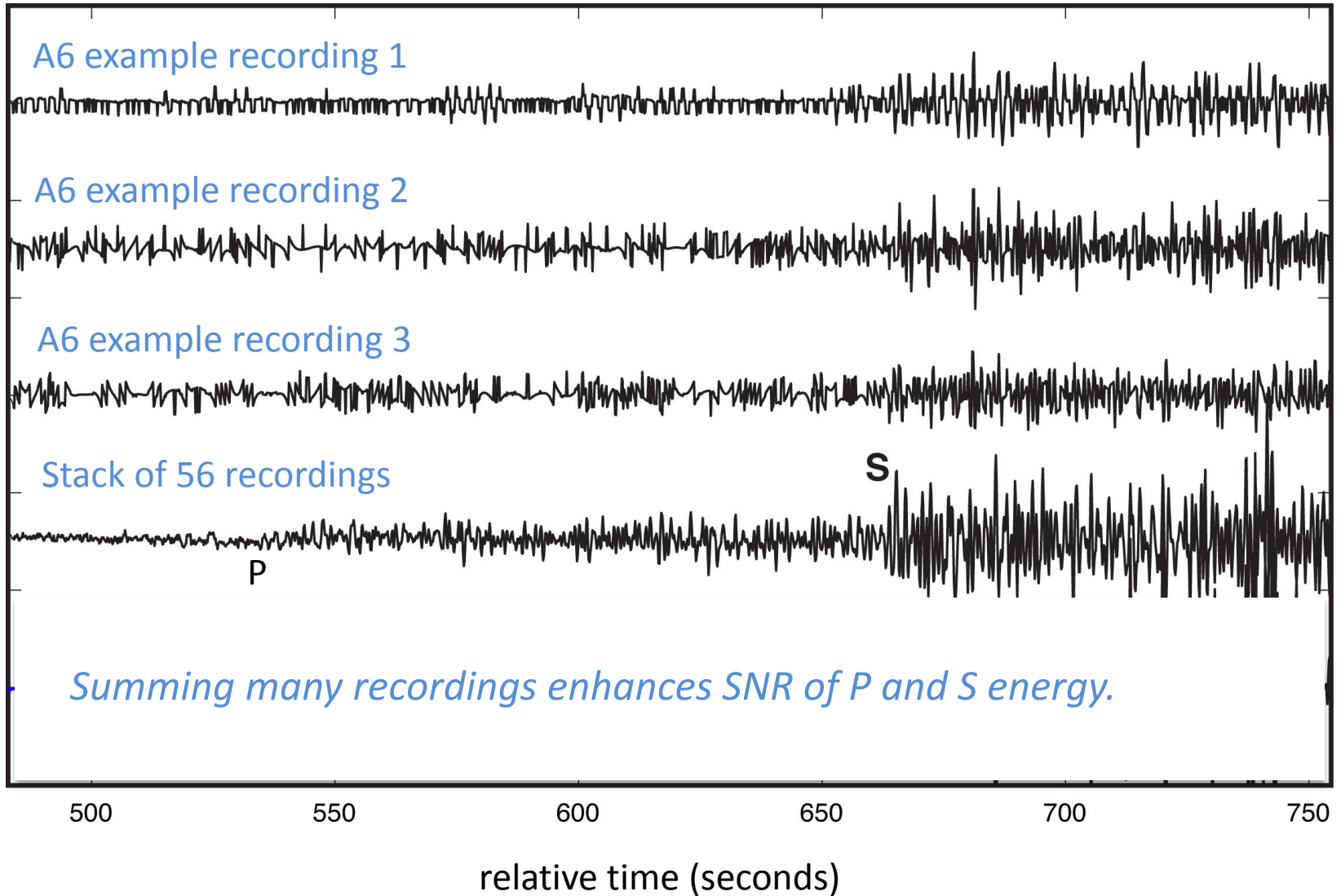


## Deep moonquakes:

- 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

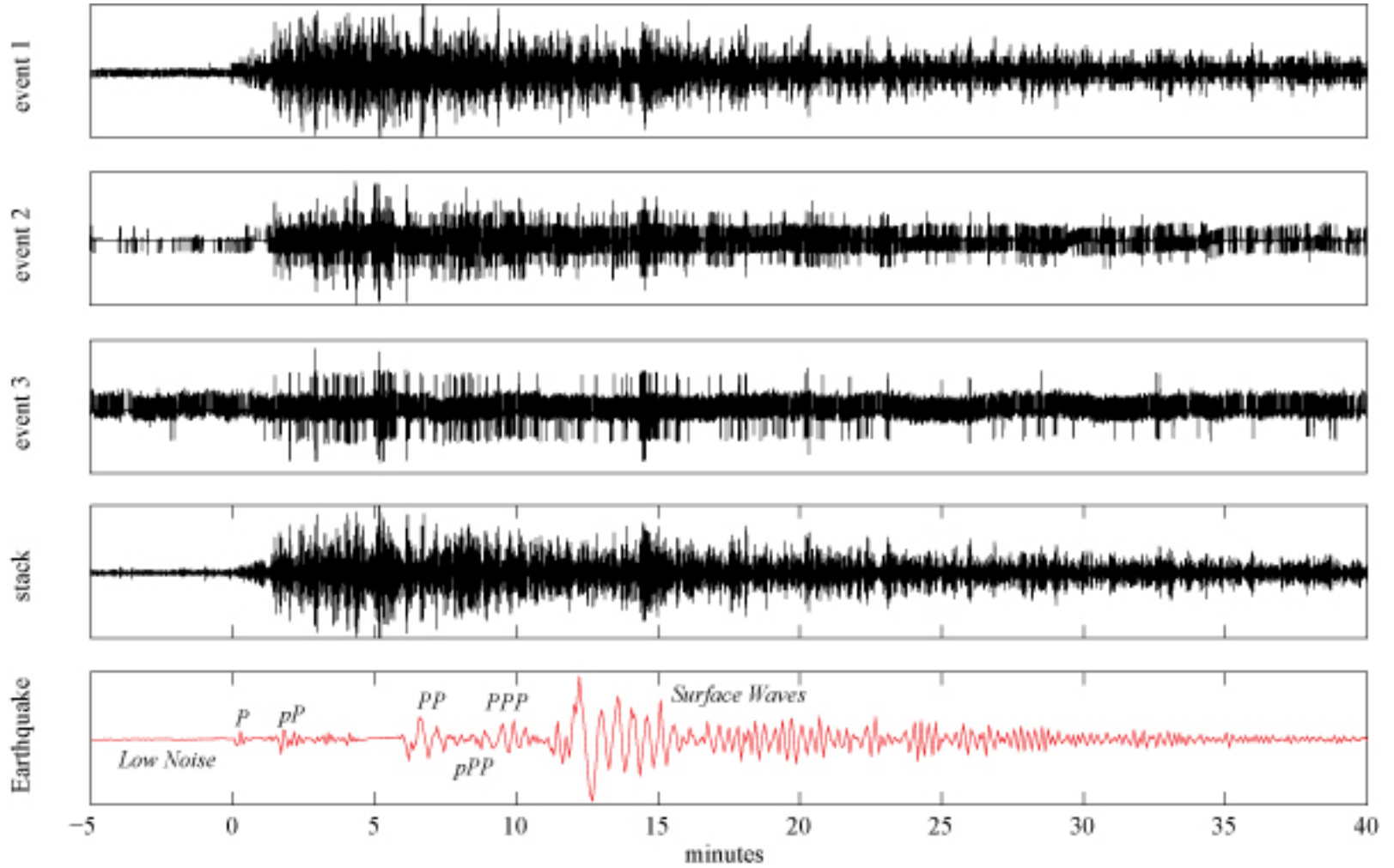
# Moon: Apollo

## Station 15 recordings of A6 cluster moonquakes



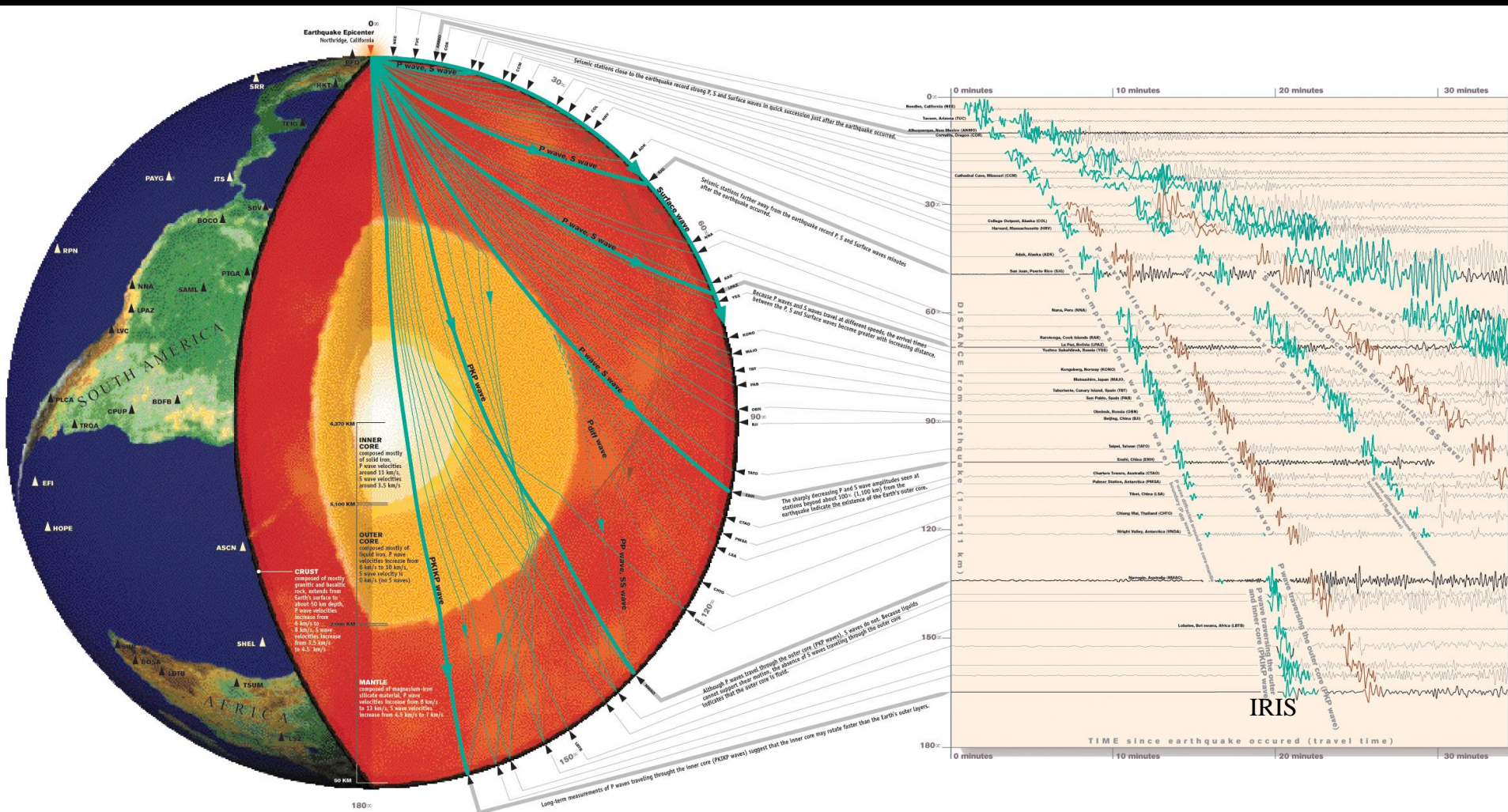
# Moon: Apollo

comparison to Earth – secondary phases are masked



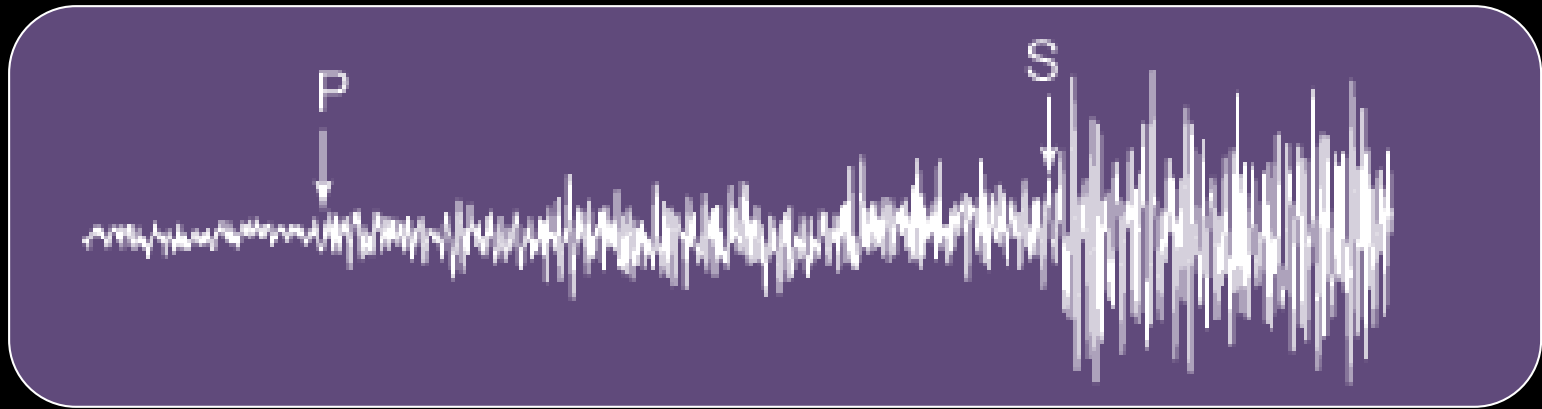
# Moon: Apollo

secondary phases contain information on deep structure



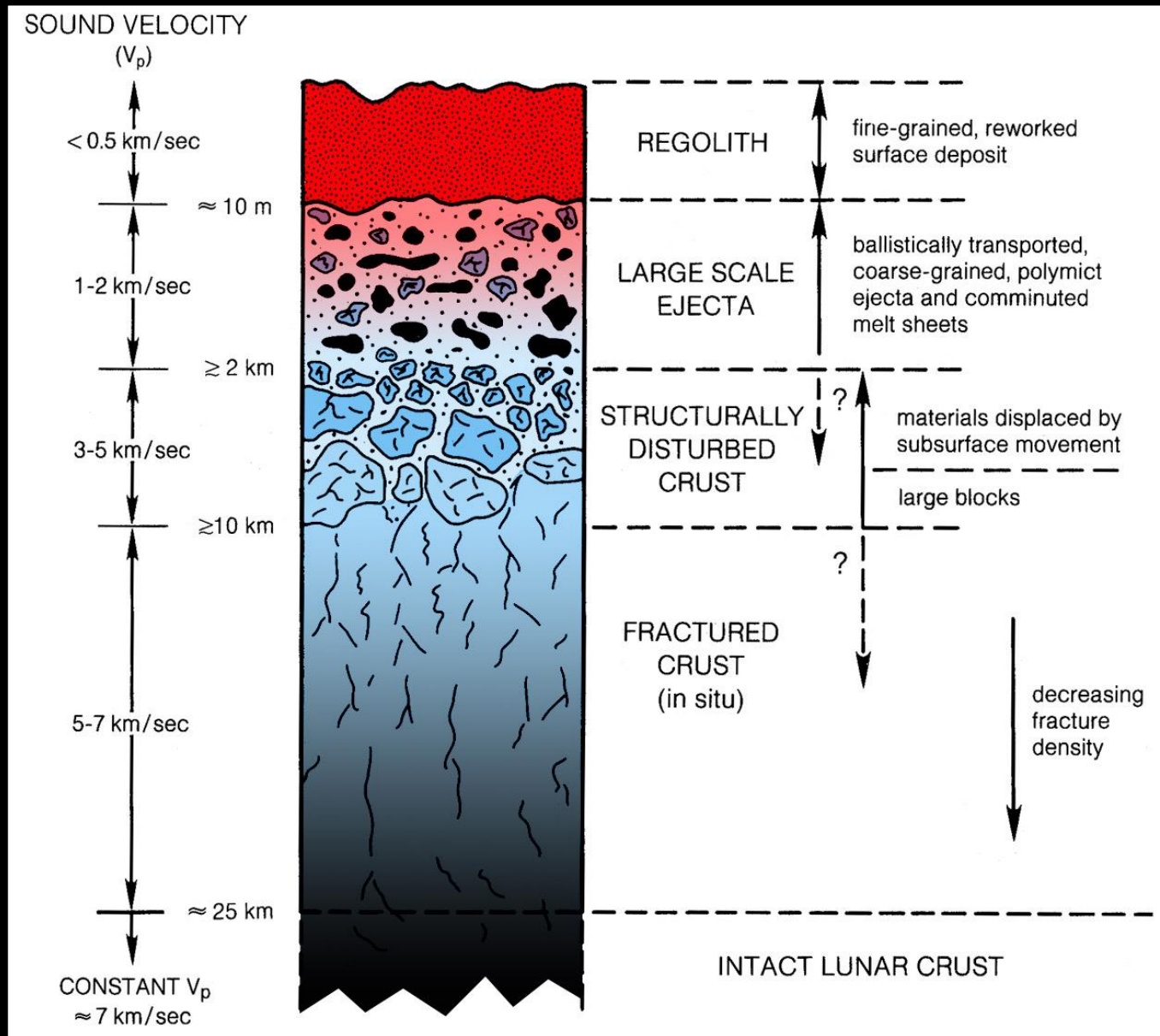
# Moon: Apollo

- 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.

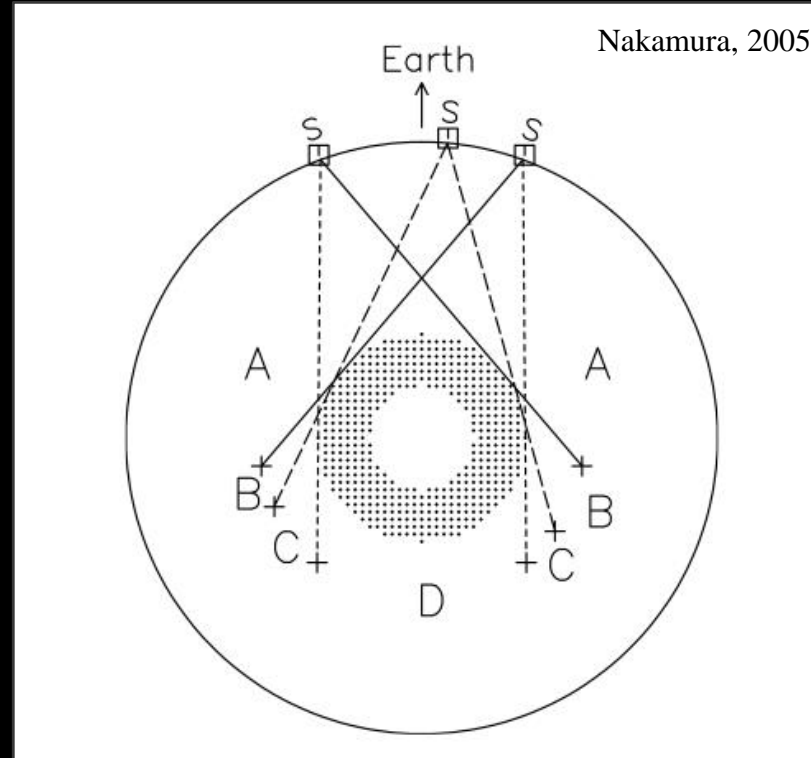
# Moon: Apollo



# 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

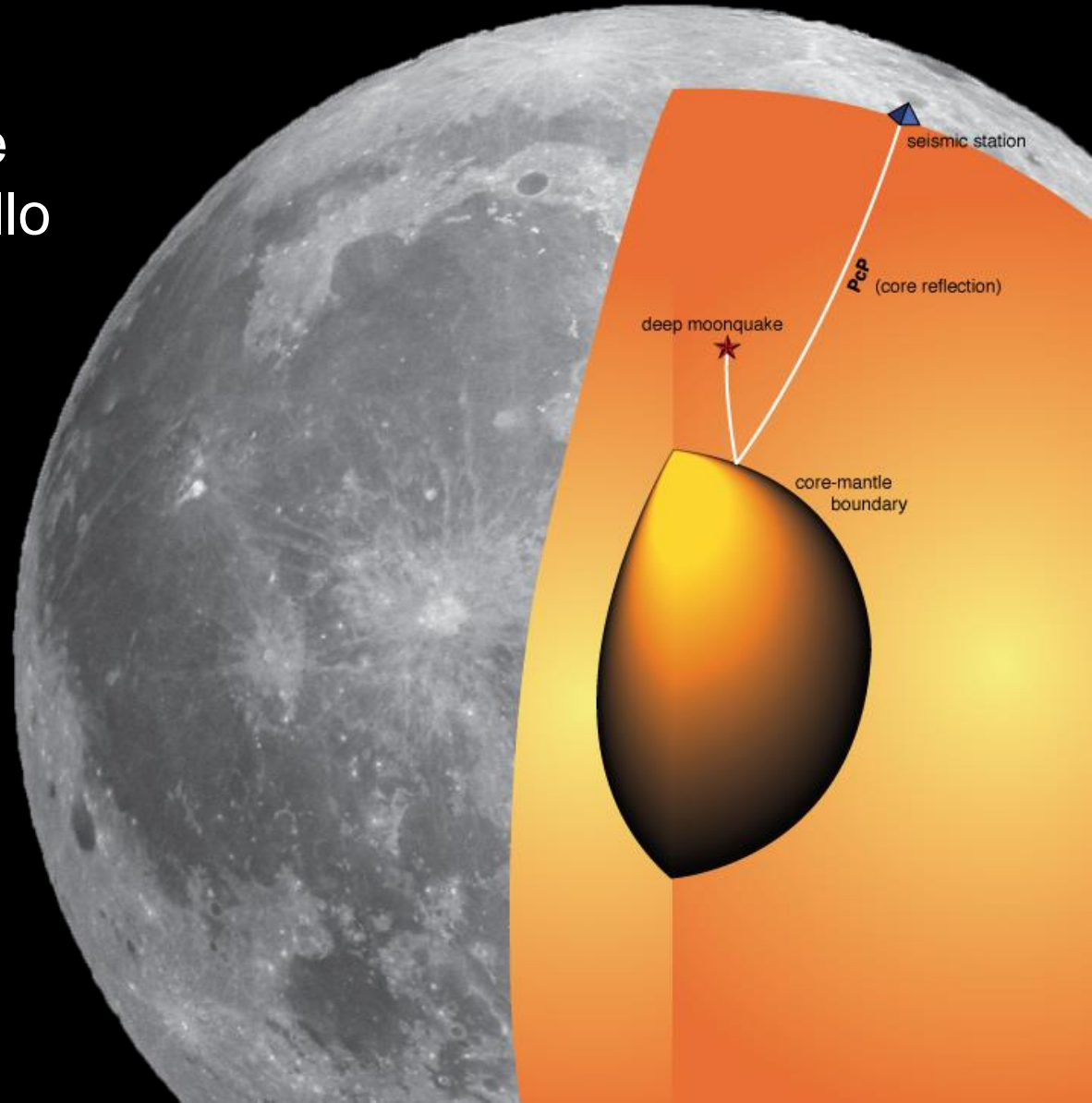
D: No shear arrivals

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

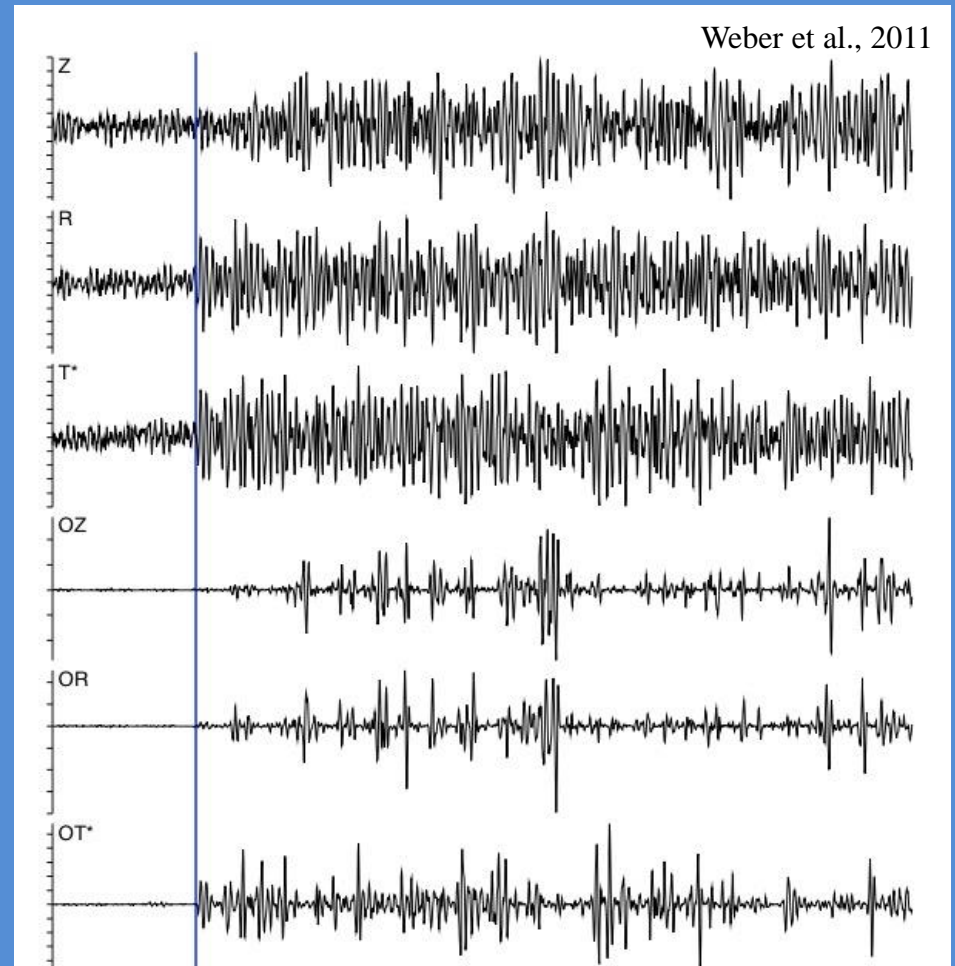
$$M_j = \mathring{a} \prod_{i=-n}^n Z_{j+i} R_{j+i}$$

filter output

$$OZ_j = Z_j M_j$$

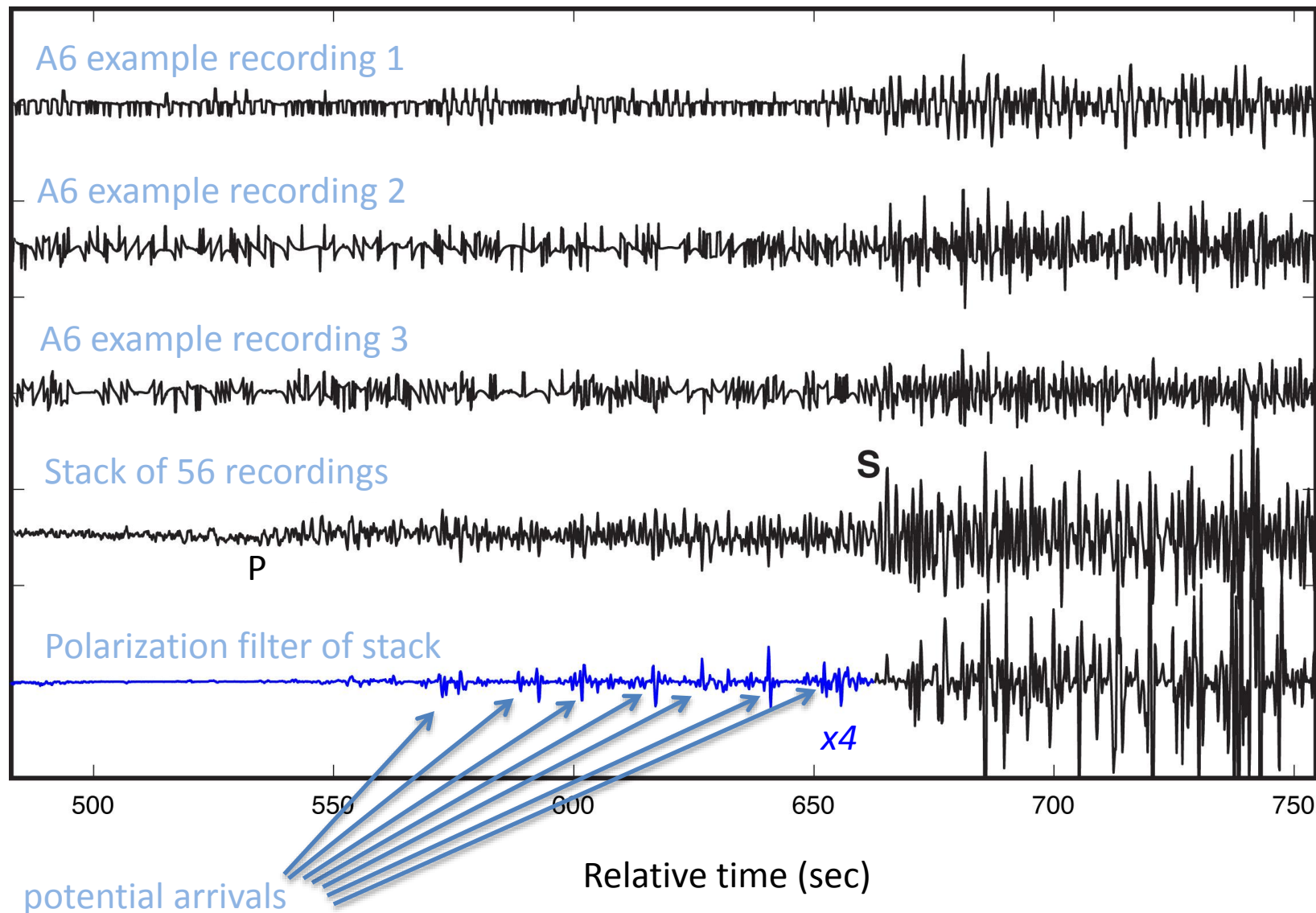
- Enhances larger amplitudes relative to smaller amplitudes from the triple product of seismograms
- Enhances energy that is rectilinearly partitioned onto the R and Z components of motion (while suppressing noise)

$n = 6$  samples (window length  $\sim 2.8$ sec)

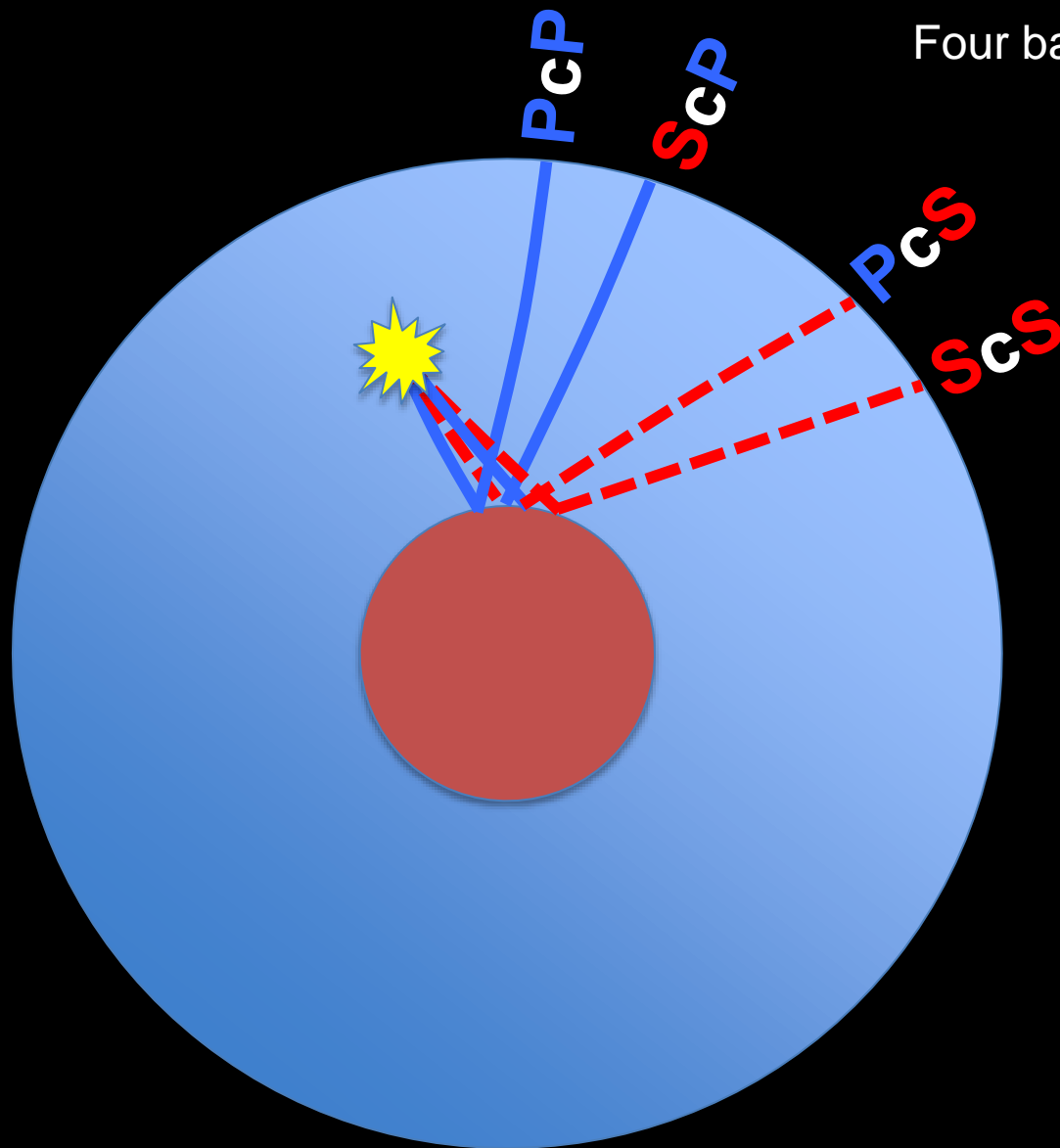


# Moon: Apollo

## Station 15 recordings of A6 cluster moonquakes



# 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:

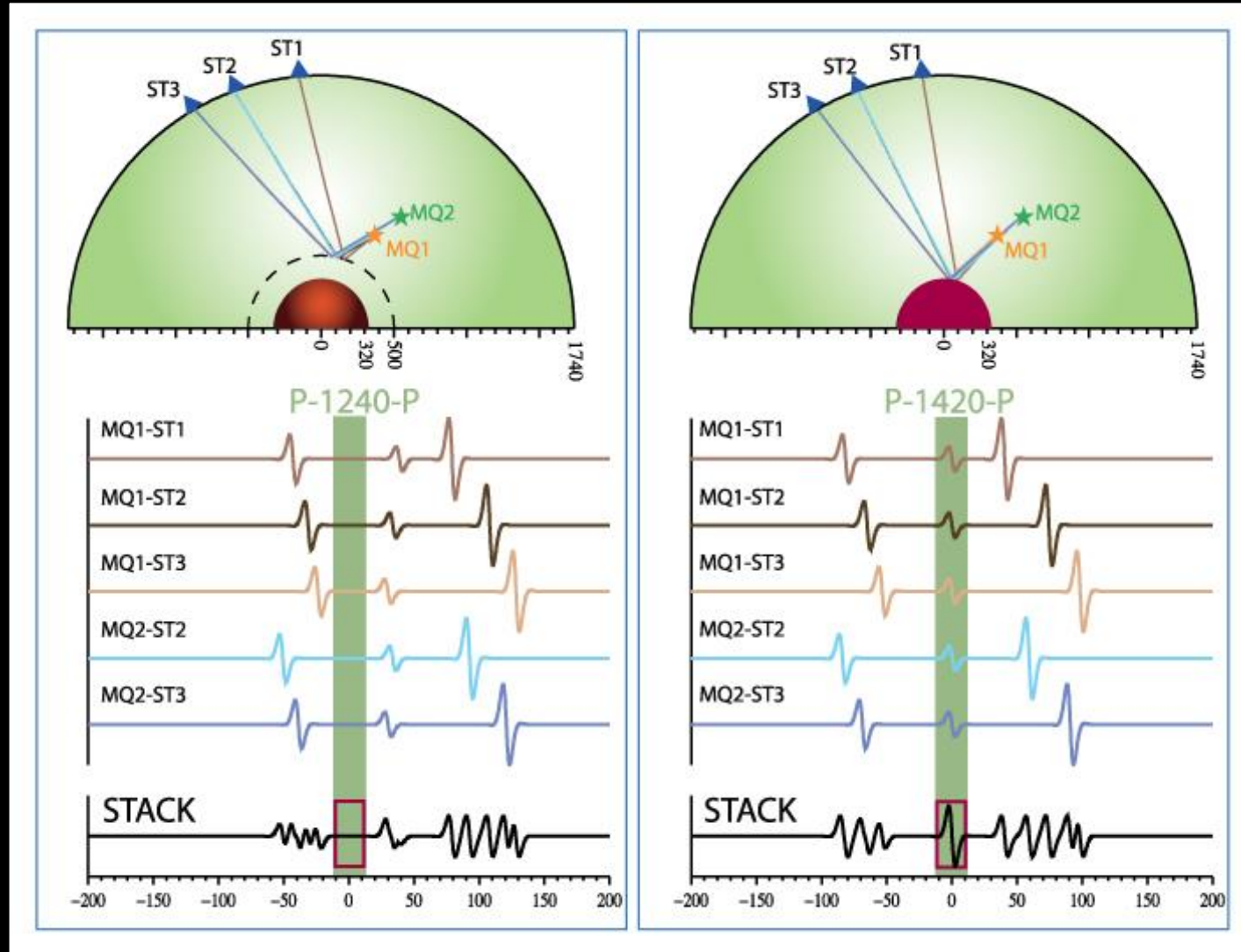
S-to-P: OZ  
P-to-P:

P-to-S: OR (vertically polarized)

S-to-S: OT (horizontally polarized)

# Moon: Apollo

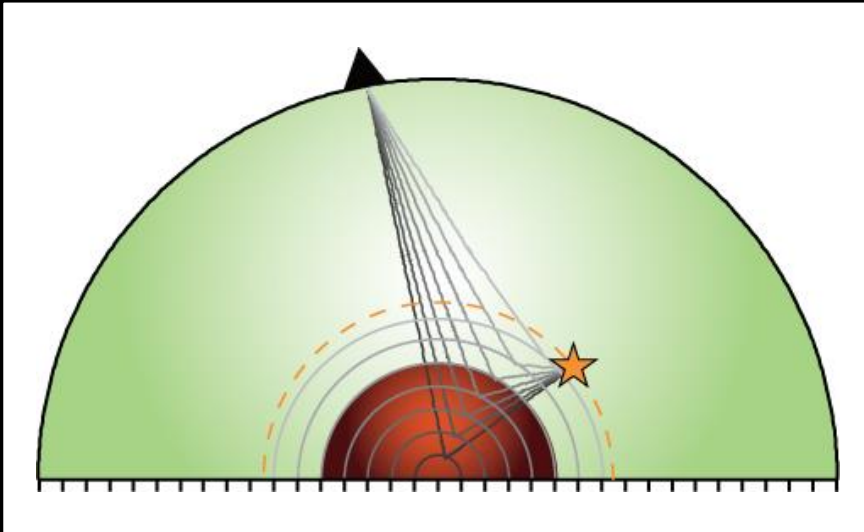
Double array stacking: Array processing methods enhance subtle seismic arrivals by stacking seismograms that have been time-shifted to predicted core arrival times.



# 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:

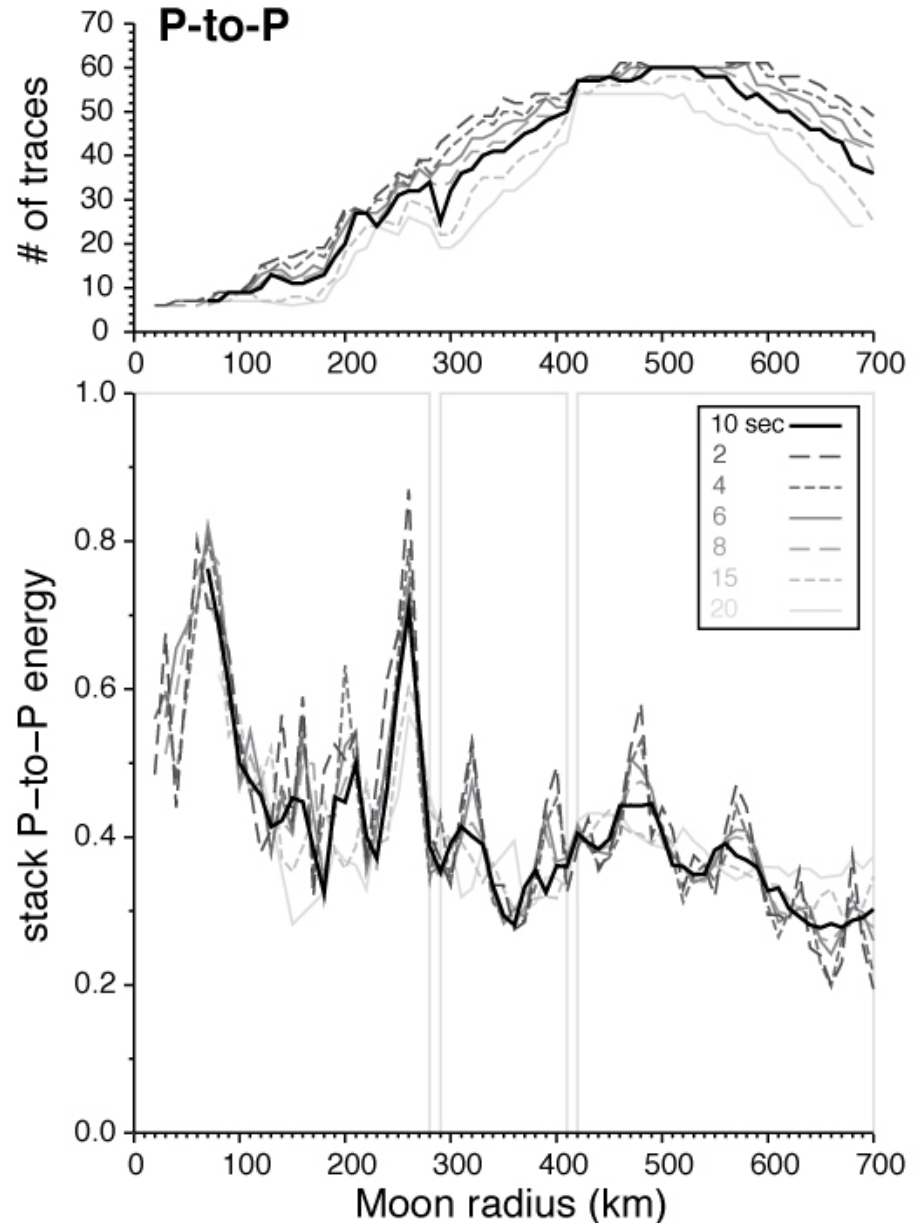
- 420-700 km (partial melt region)
- 290-410 km (CMB)
- 0-280 km (ICB)

# Moon: Apollo

## Initial results for P-to-P reflections

### 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

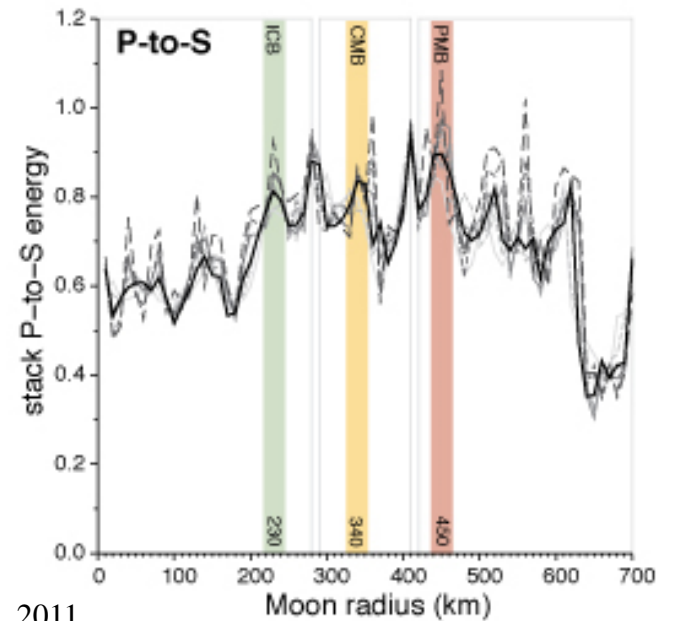
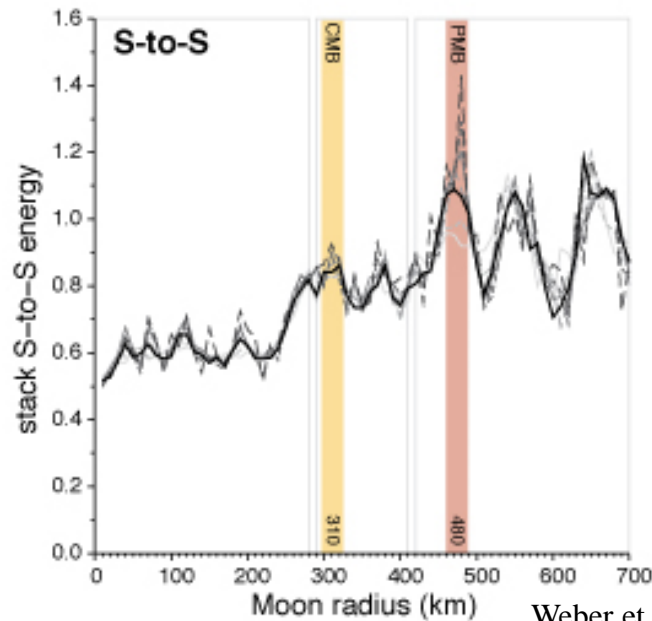
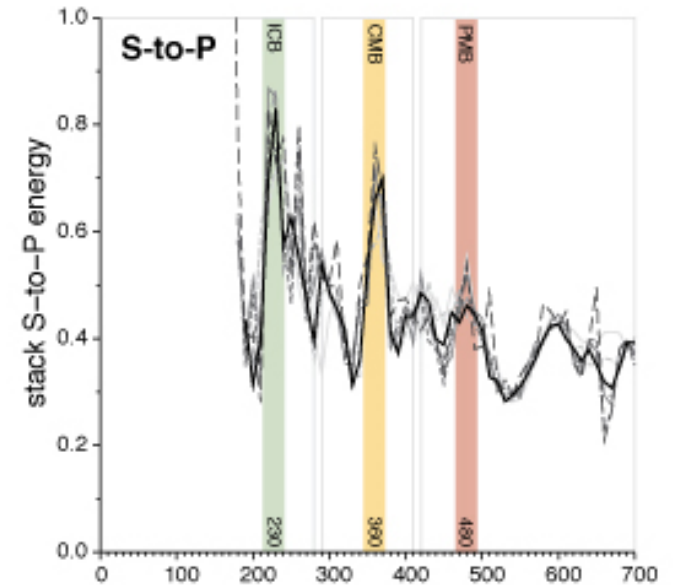
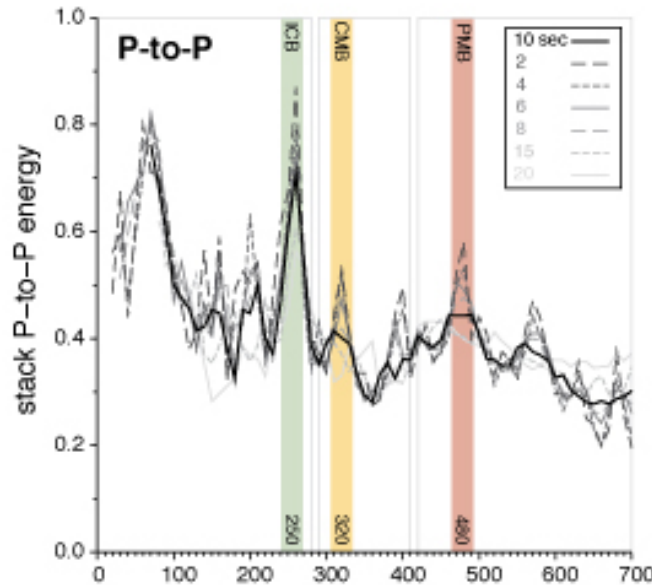


# Moon: Apollo

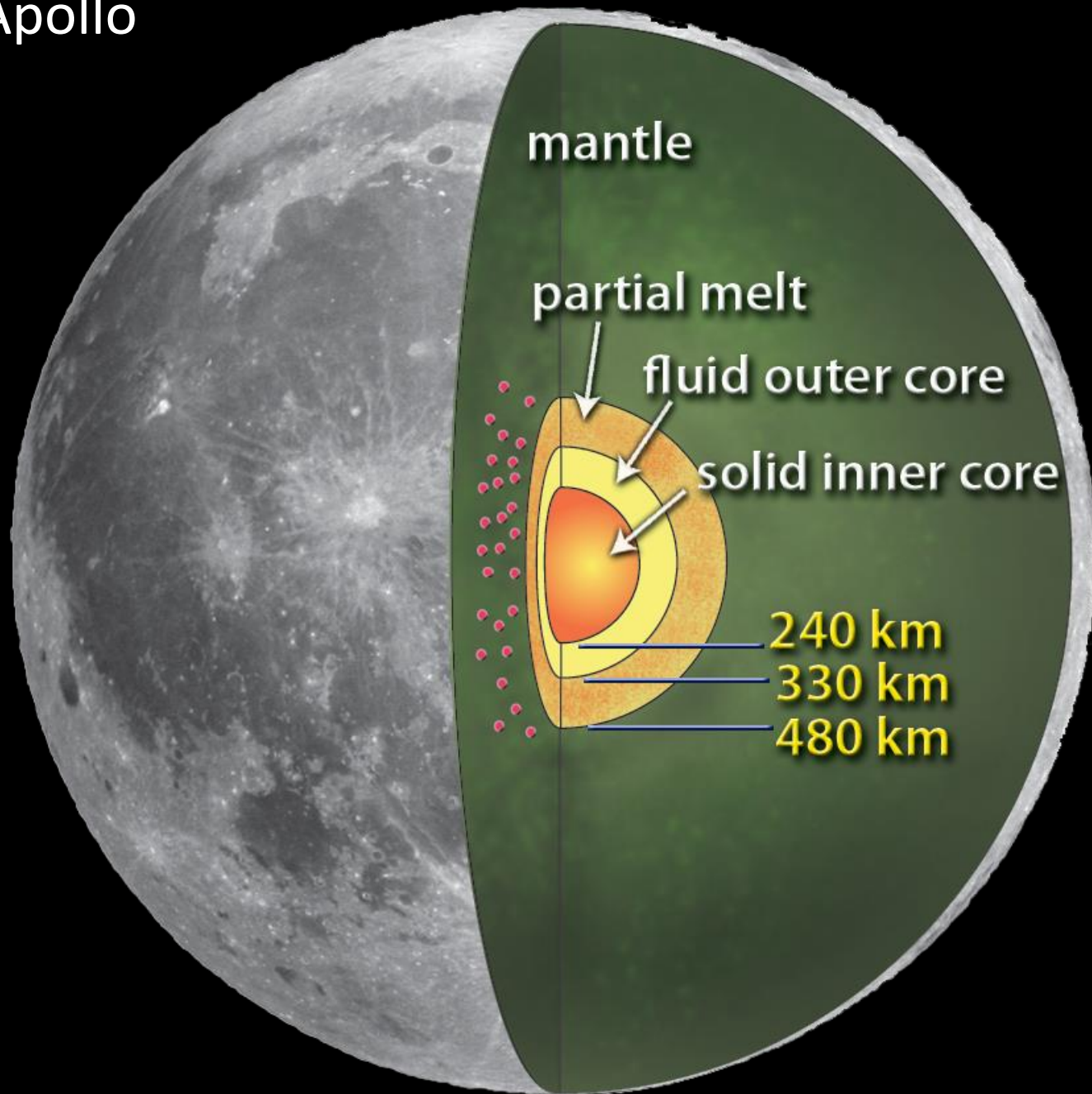
PMB:  
480 km

CMB:  
330 km

ICB:  
240 km



# Moon: Apollo



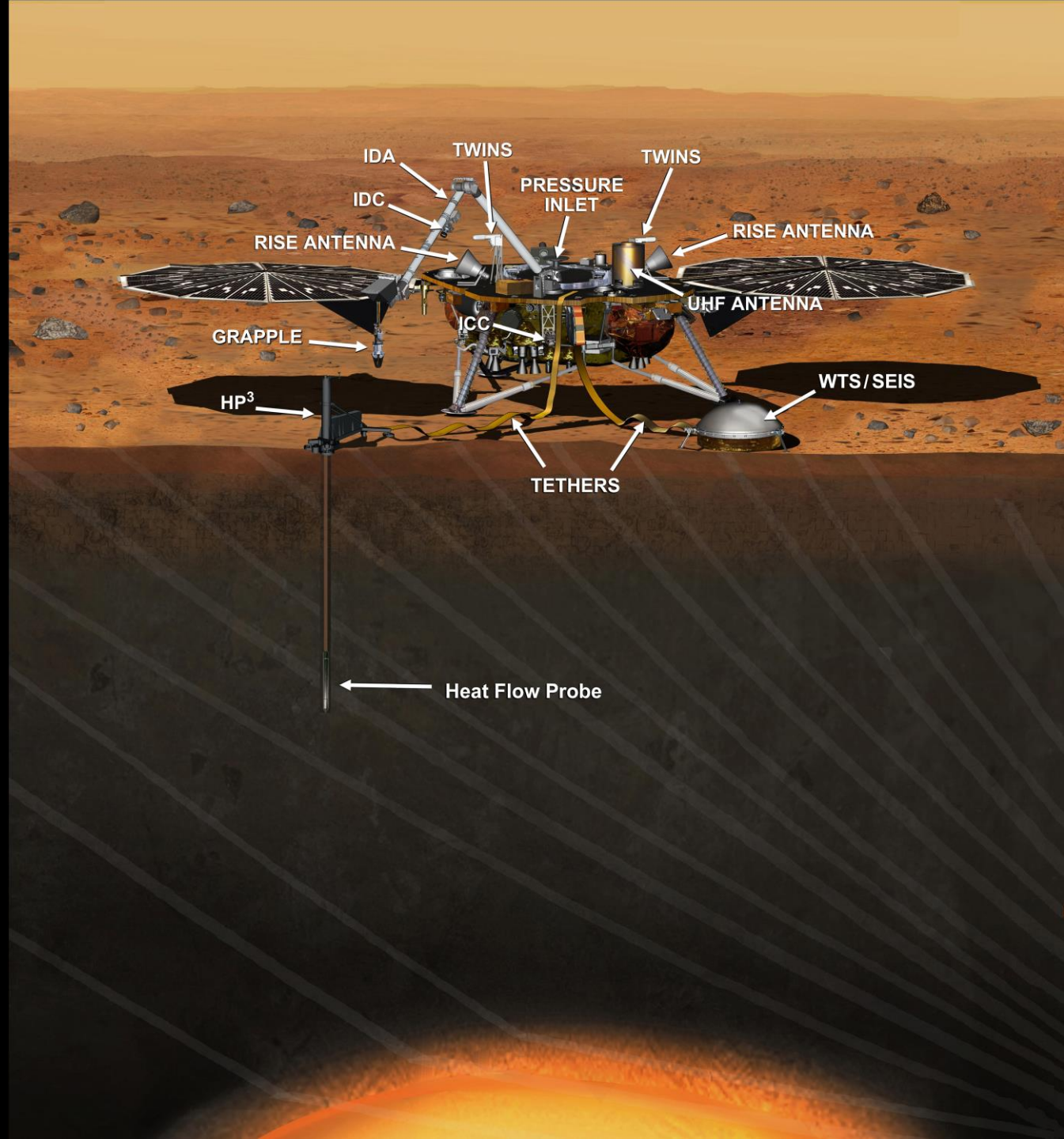


Coming soon:  
More Mars seismology!



Interior Exploration  
using Seismic  
Investigations,  
Geodesy and Heat  
Transport

Launch: May 2018

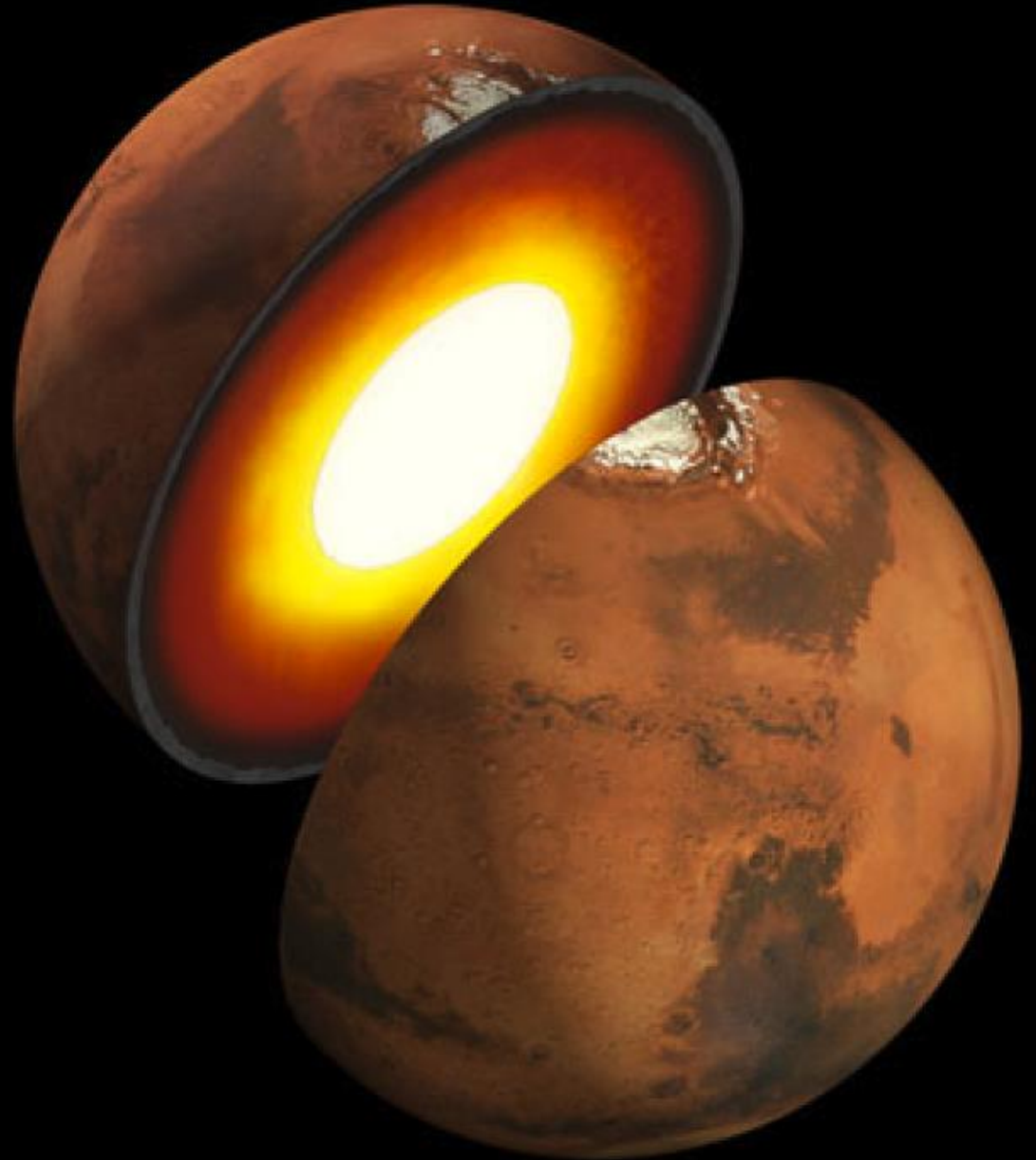


# Mars: InSight

## Goal:

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

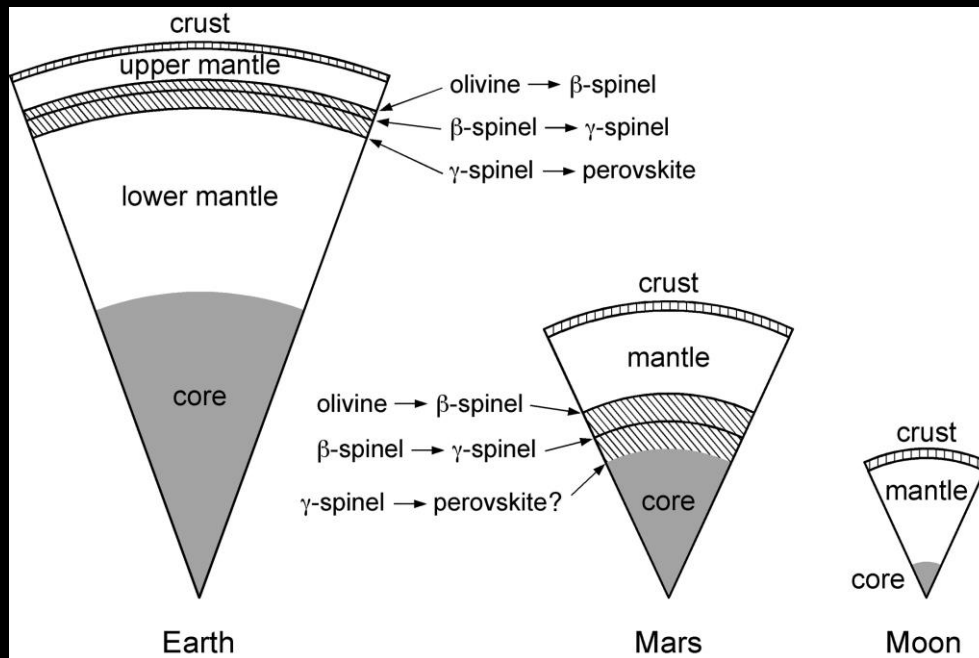
- Seismology
- Geodesy
- Heat flow
- Magnetics



# Mars: InSight

## Why Mars?

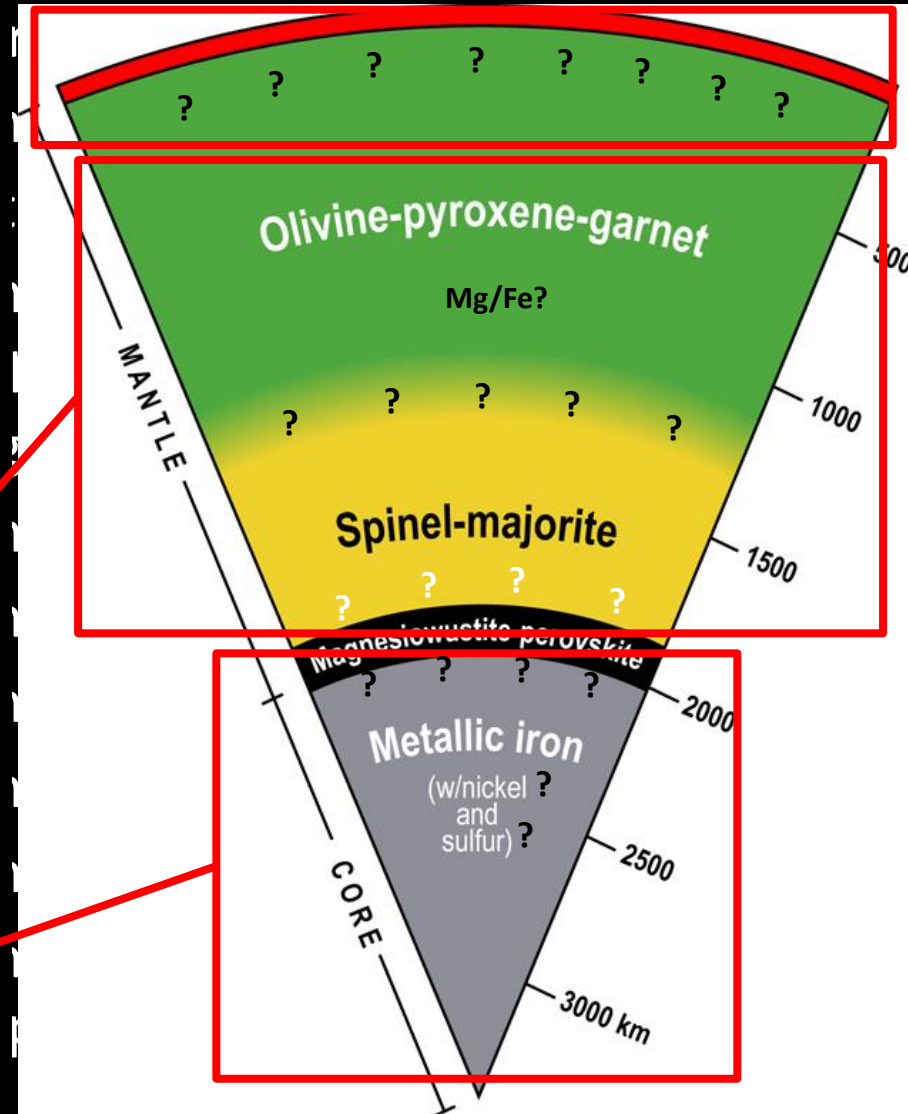
- The Moon was formed under unique circumstances and with a limited range of P-T conditions (<200 km depth on Earth)
- Mars is large enough to have undergone most terrestrial processes, but small enough to have retained evidence of its early activity.
- Mars is uniquely well-suited to study the common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

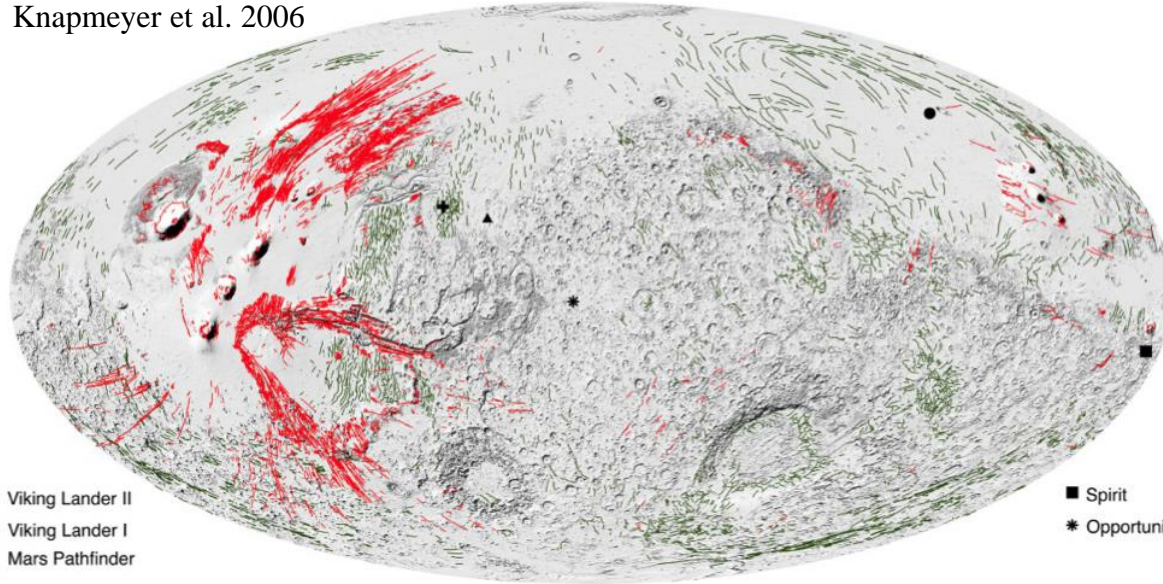
# Mars: InSight

- **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

Knapmeyer et al. 2006

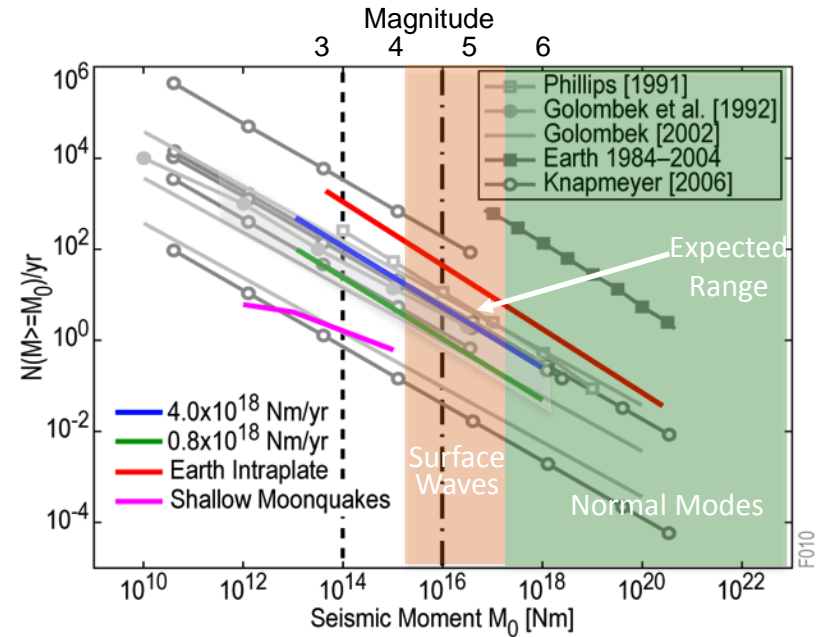


Seismic sources:

- faulting



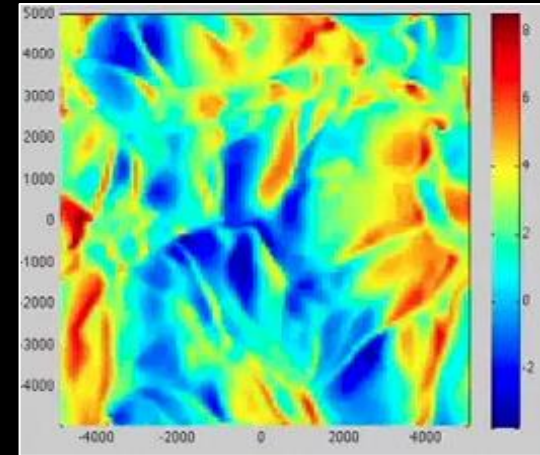
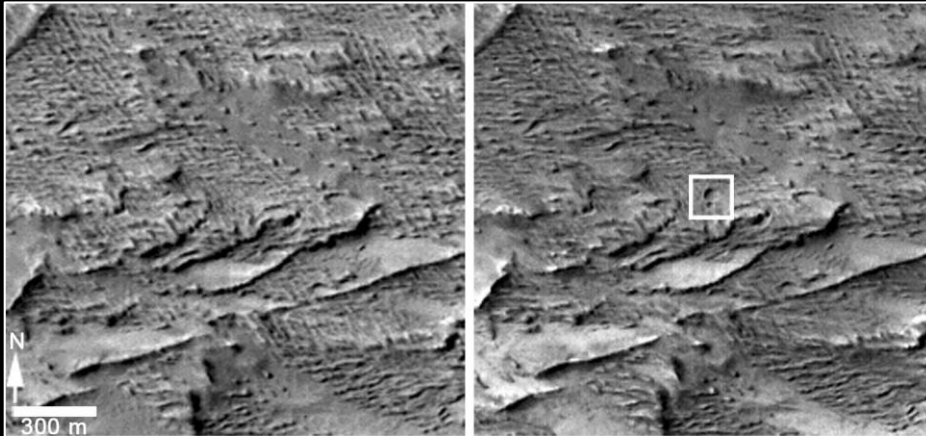
## Rate of Seismic Activity



# Mars: InSight

Seismic sources:

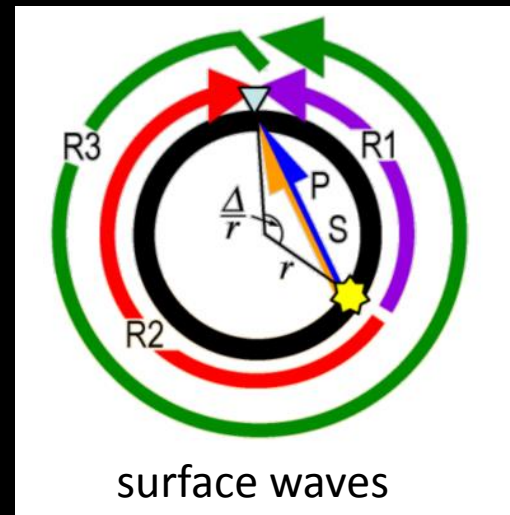
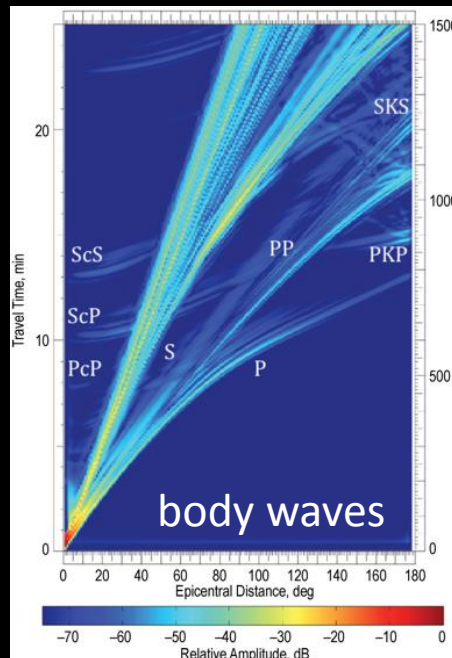
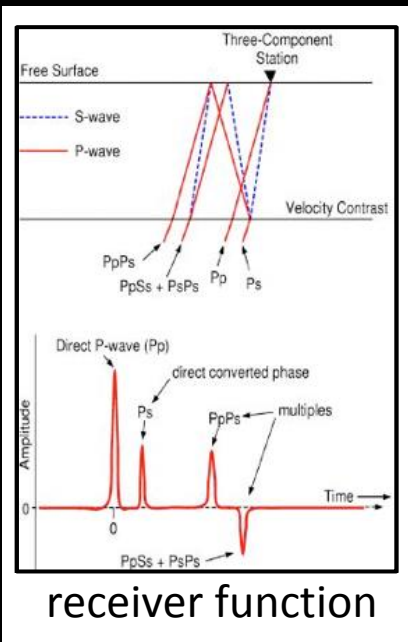
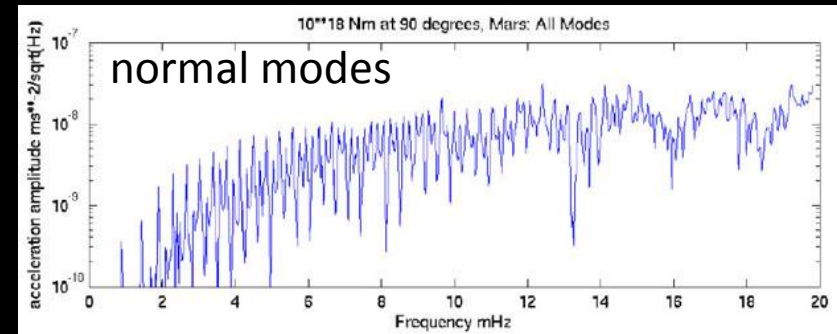
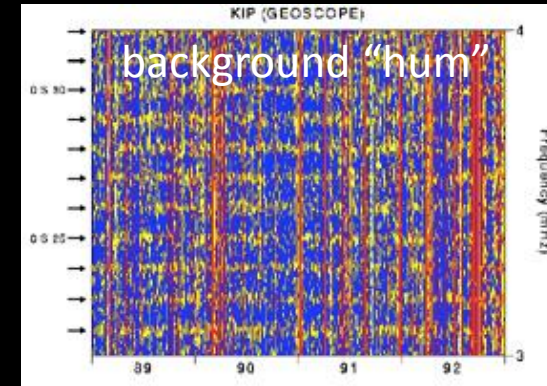
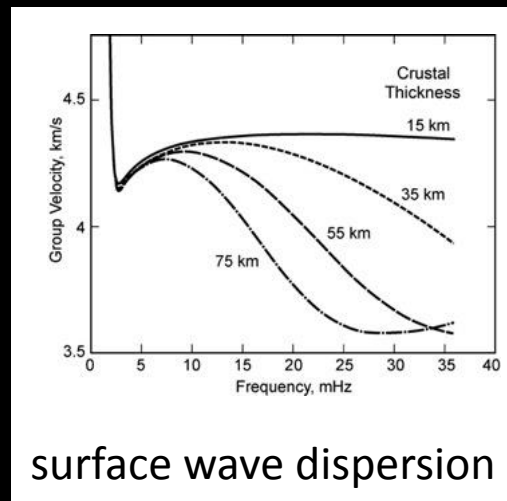
- Impacts
- Atmospheric excitation
- Phobos tide



# Mars: InSight

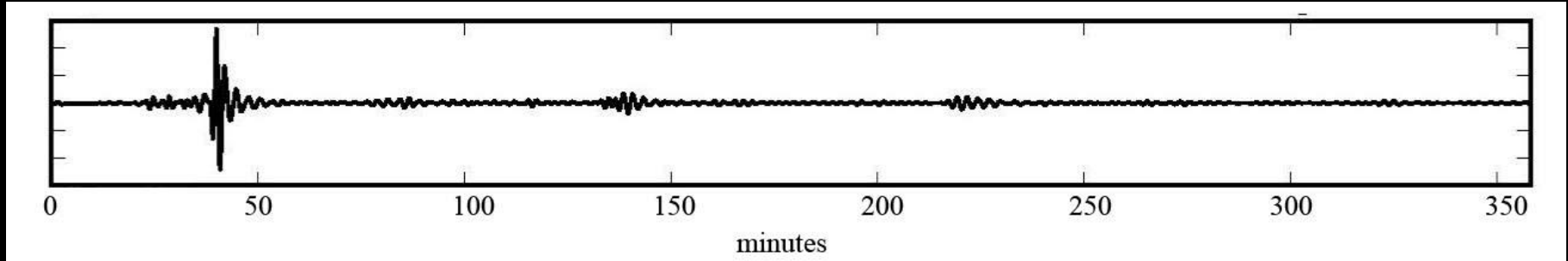
## Single-station analysis techniques:

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

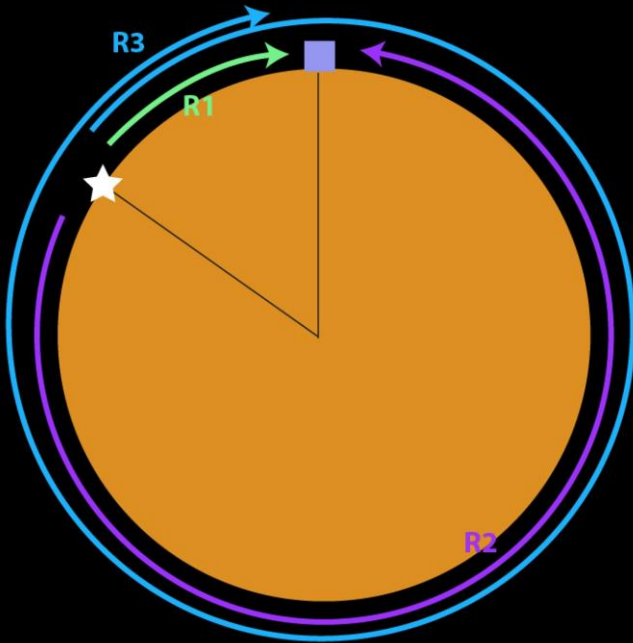


# Mars: InSight

epicentral distance from Rayleigh waves



vertical component



angular group velocity

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

epicentral distance

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

origin time

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



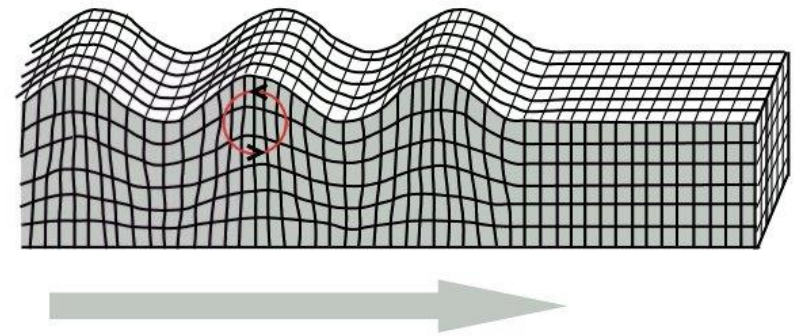
# Mars: InSight

## back azimuth from Rayleigh waves

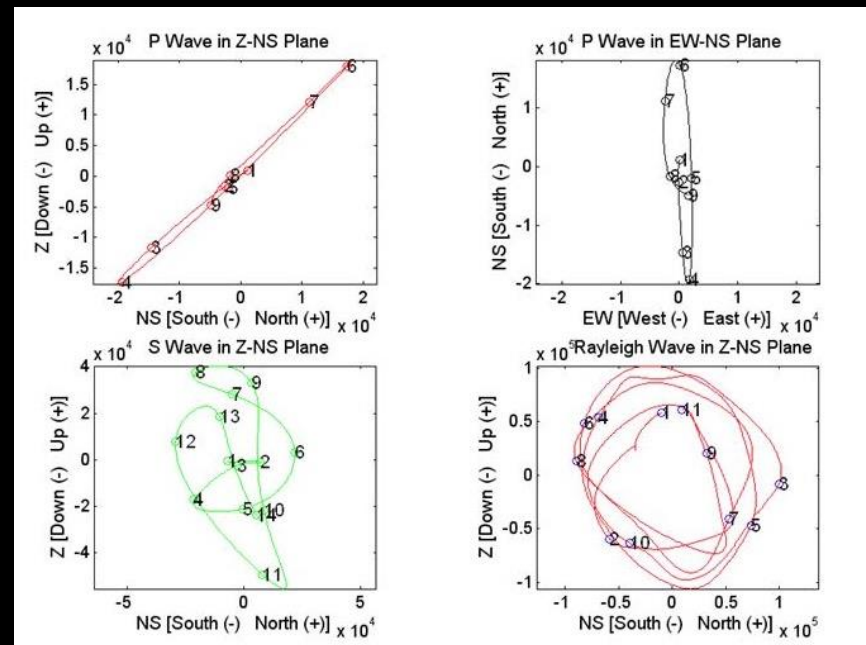
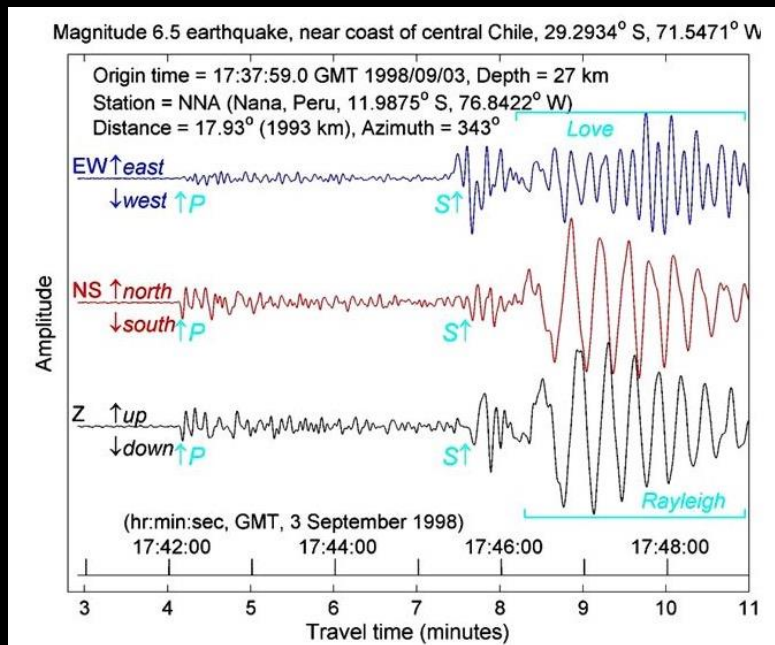
determined from analysis of 3-component seismograms: P-SV phases are polarized in the great-circle plane containing the source & receiver

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

## Rayleigh Wave



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



# Mars: InSight

