Seismic detection of the layers of the lunar core

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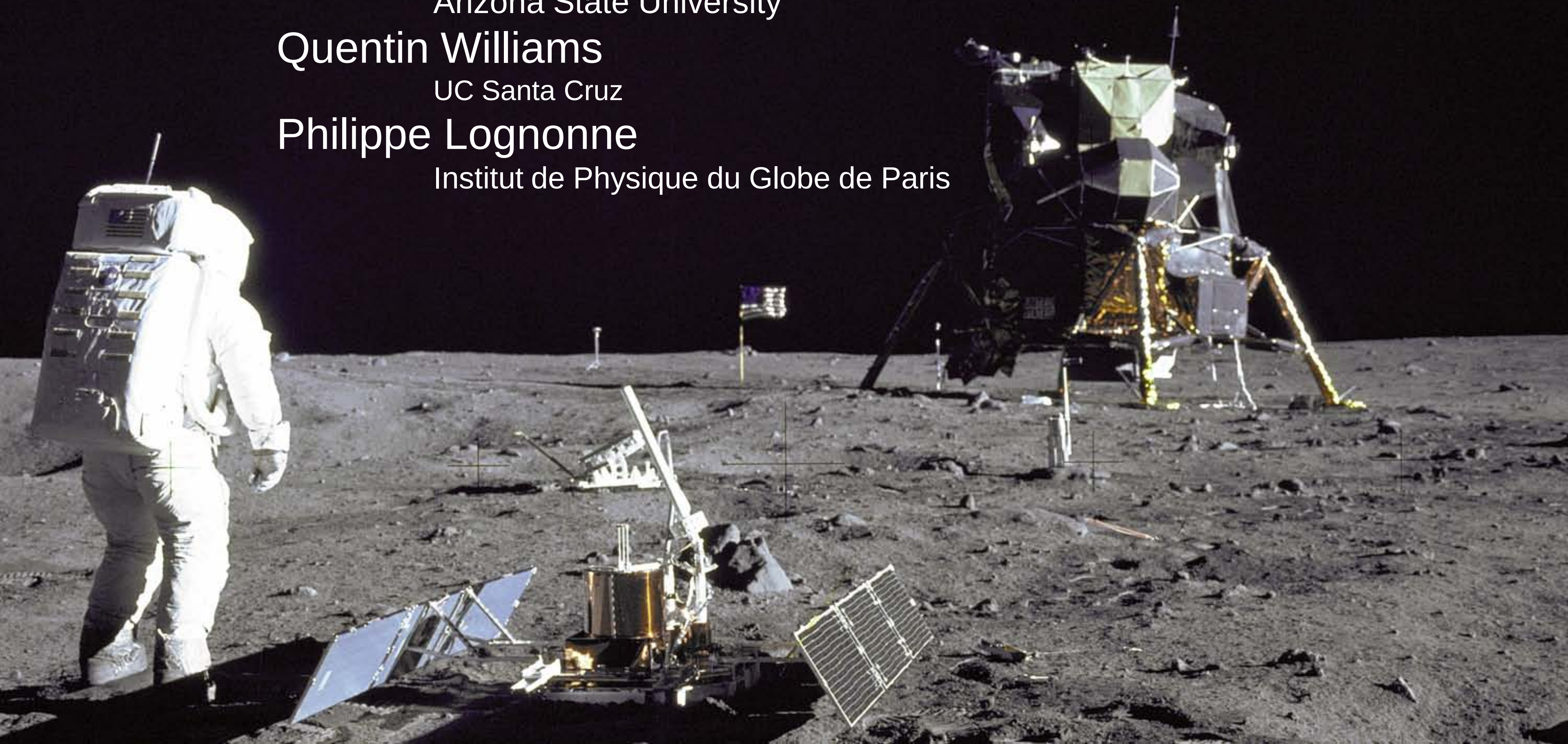
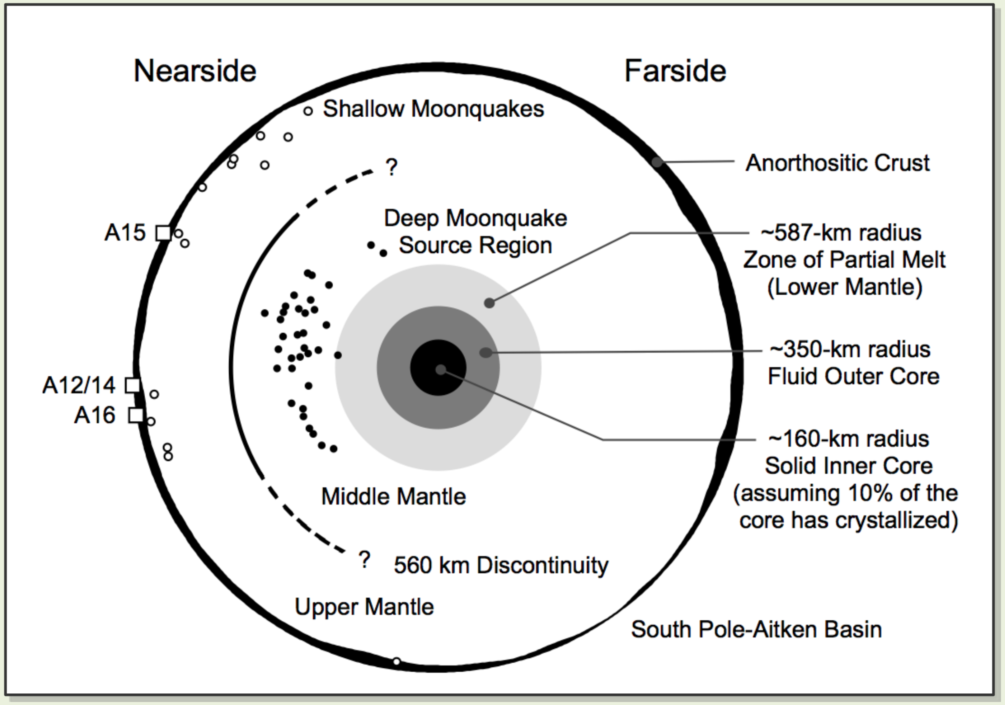


Introduction

- Core properties (size, composition, seismic velocity and density, state: liquid vs. molten) provide important constraints in lunar formation and evolution models, as well as possible indicators of an early dynamo for magnetic field generation.

- Current constraints on core properties arise from moment of inertia considerations, lunar laser ranging, magnetic induction studies, and analyses of elemental abundances in mare basalts. These estimates vary widely.

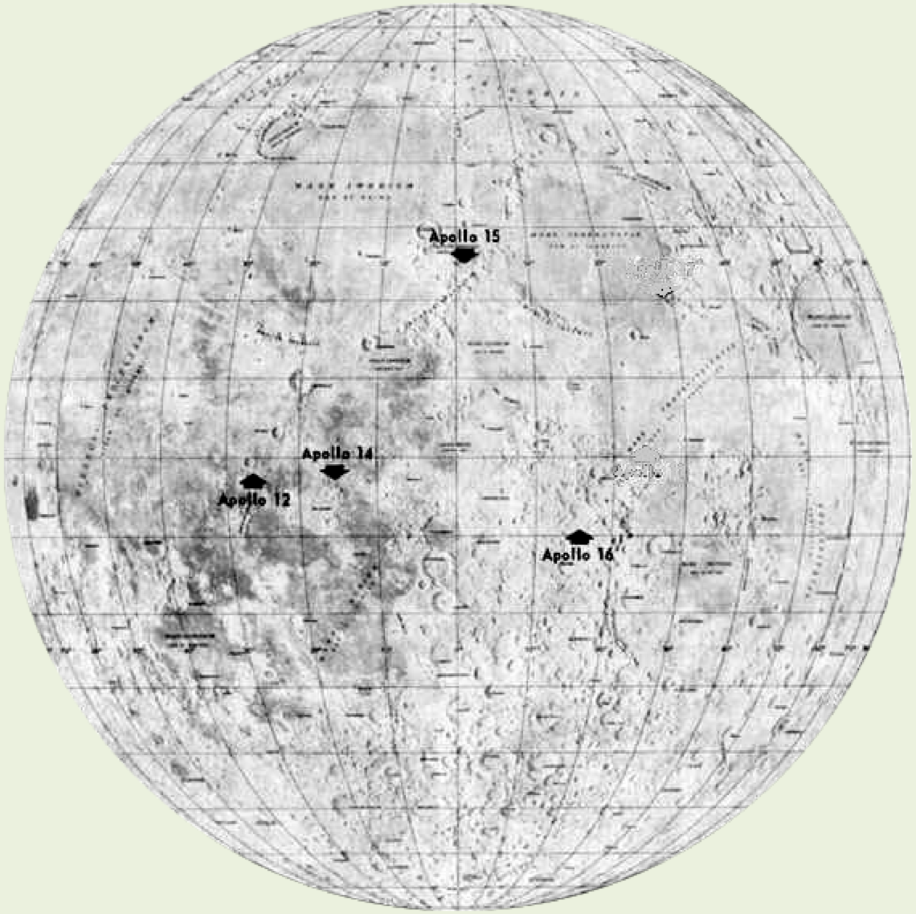
- Direct seismic constraint on core size is desirable.



Wieczorek et al., 2006

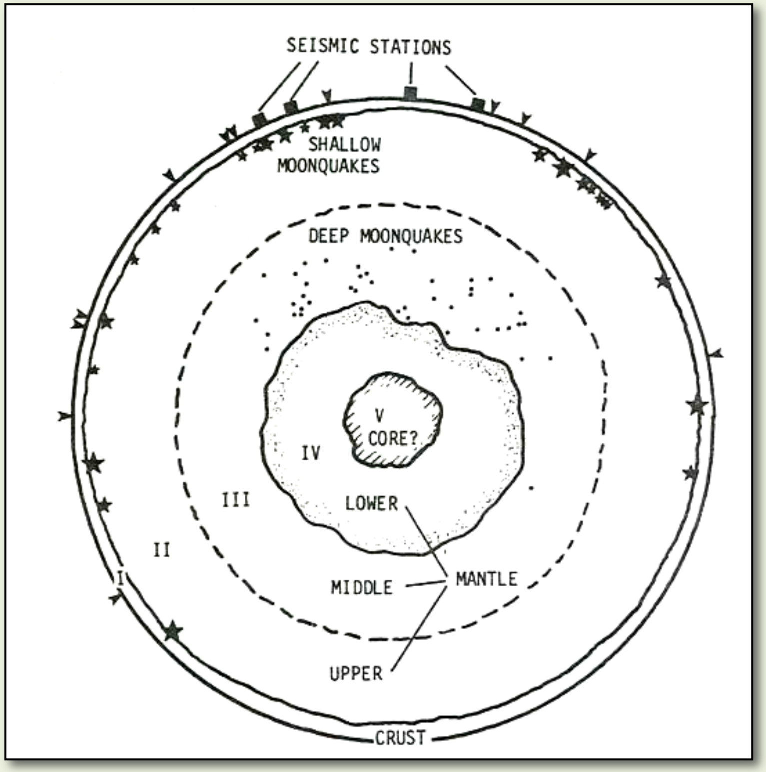
The Apollo Passive Seismic Experiment

- Four stations deployed on the lunar near side during the Apollo 12/14/15/16 missions.
- Operated from inception until mid-1977.
- Several different types of naturally-occurring seismic events were observed, including meteorite impacts, surface thermal events, shallow “tectonic” moonquakes, and deep “tidal” moonquakes.

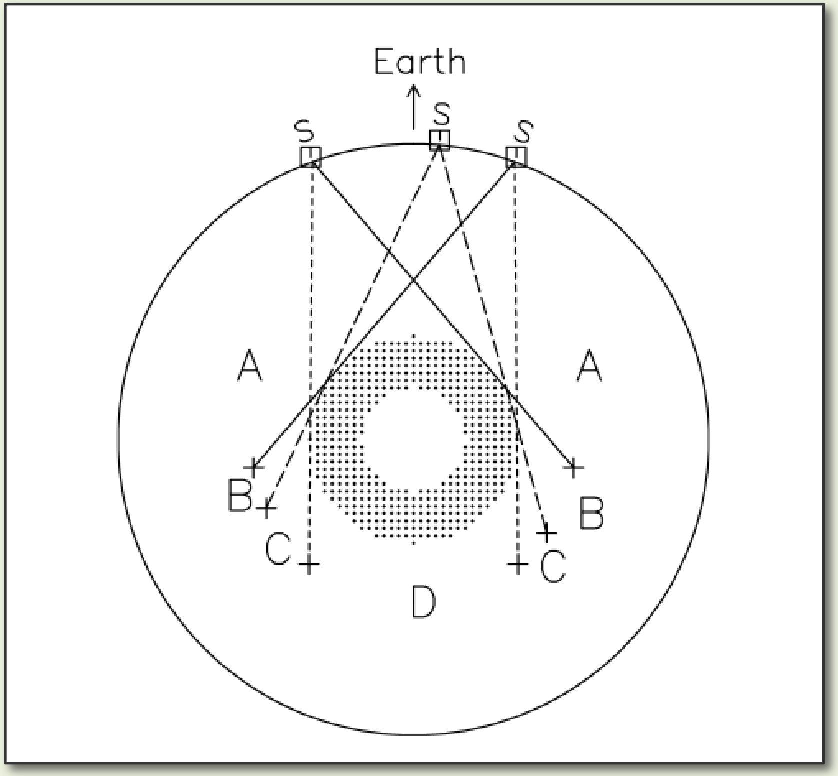


Imaging the lunar interior

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



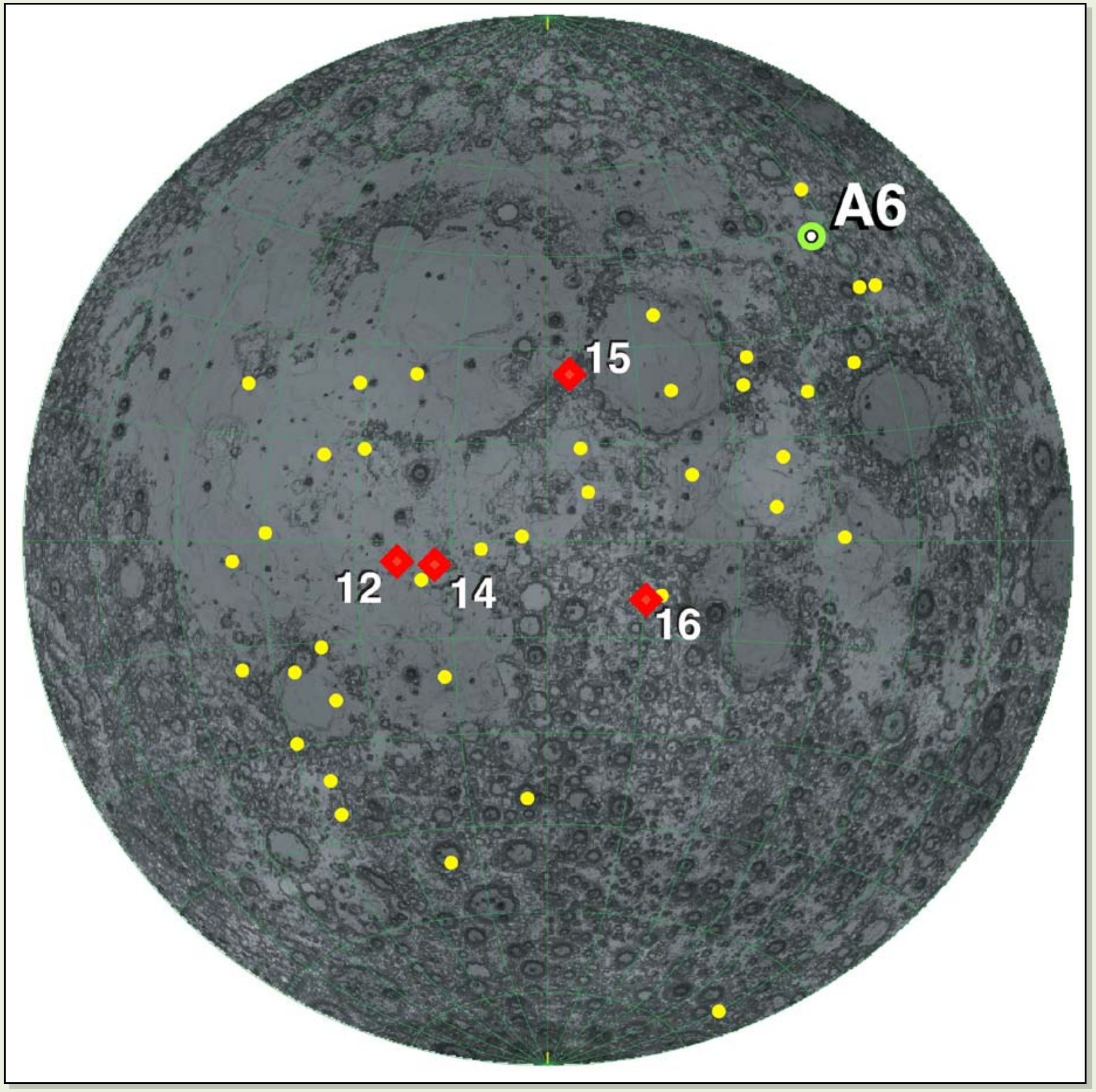
Nakamura et al., 1982



Nakamura, 2005

- We present new analysis techniques that enable re-evaluation of legacy data

Data set - deep moonquakes

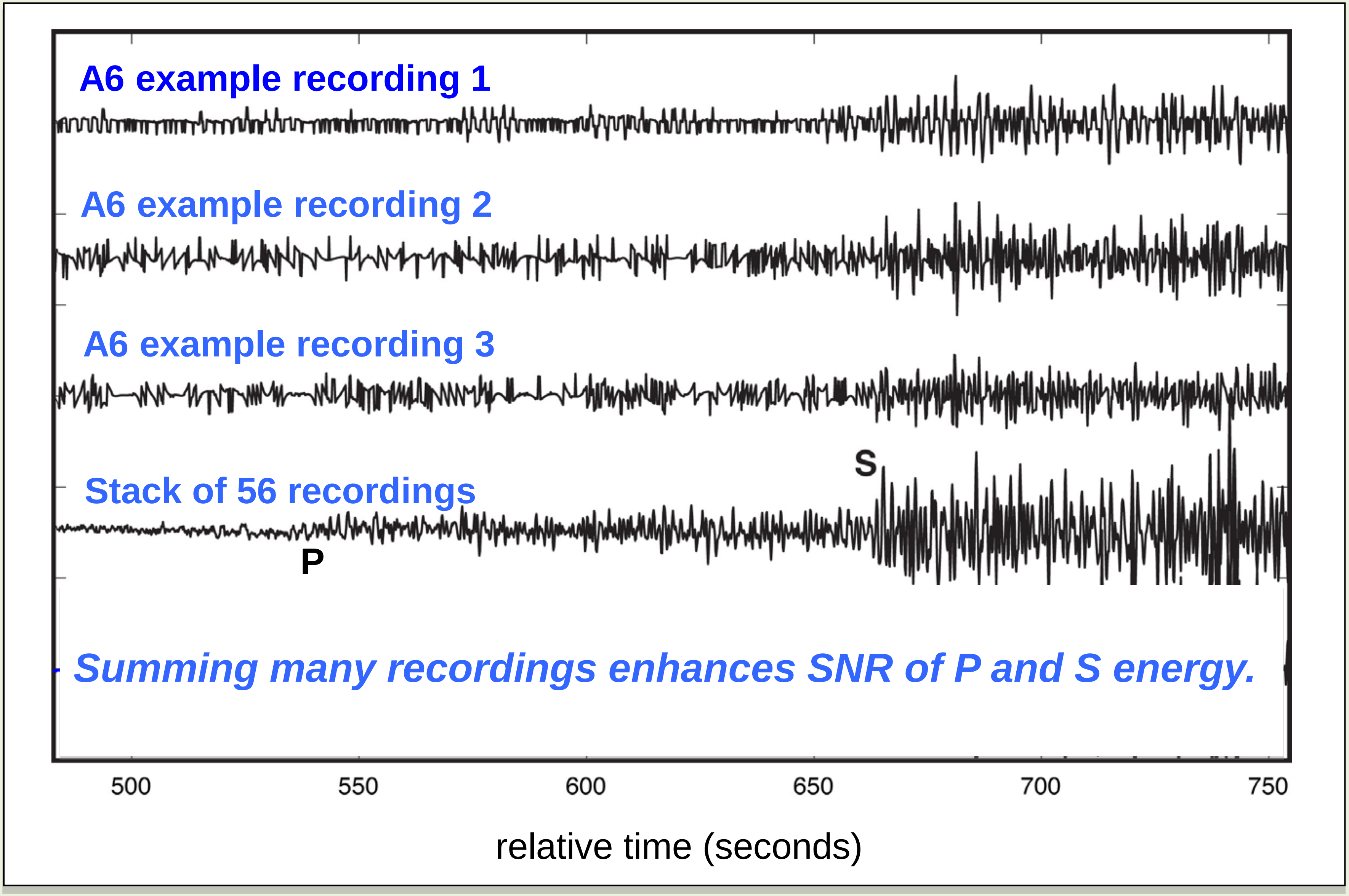


There are 106 clusters with constrained locations and depths (Nakamura, 2005)

Each cluster produces its own repeatable waveform, so single event seismograms from a given cluster at a given station can be stacked

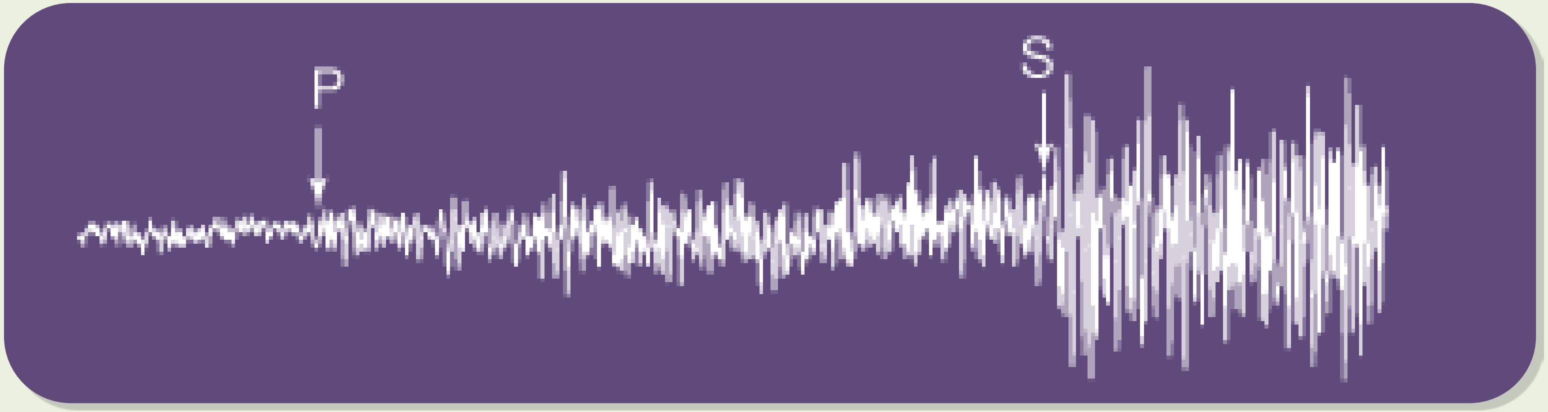
We selected 38 clusters having clear S (shear) arrivals on one or more station stacks, resulting in 62 traces for use in our array methods

Station 15 recordings of A6 cluster moonquakes

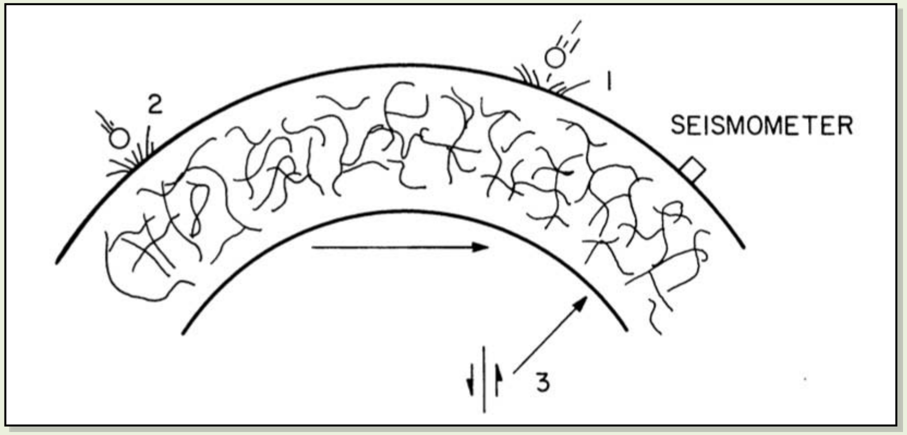


Deep moon seismic phases

- 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.



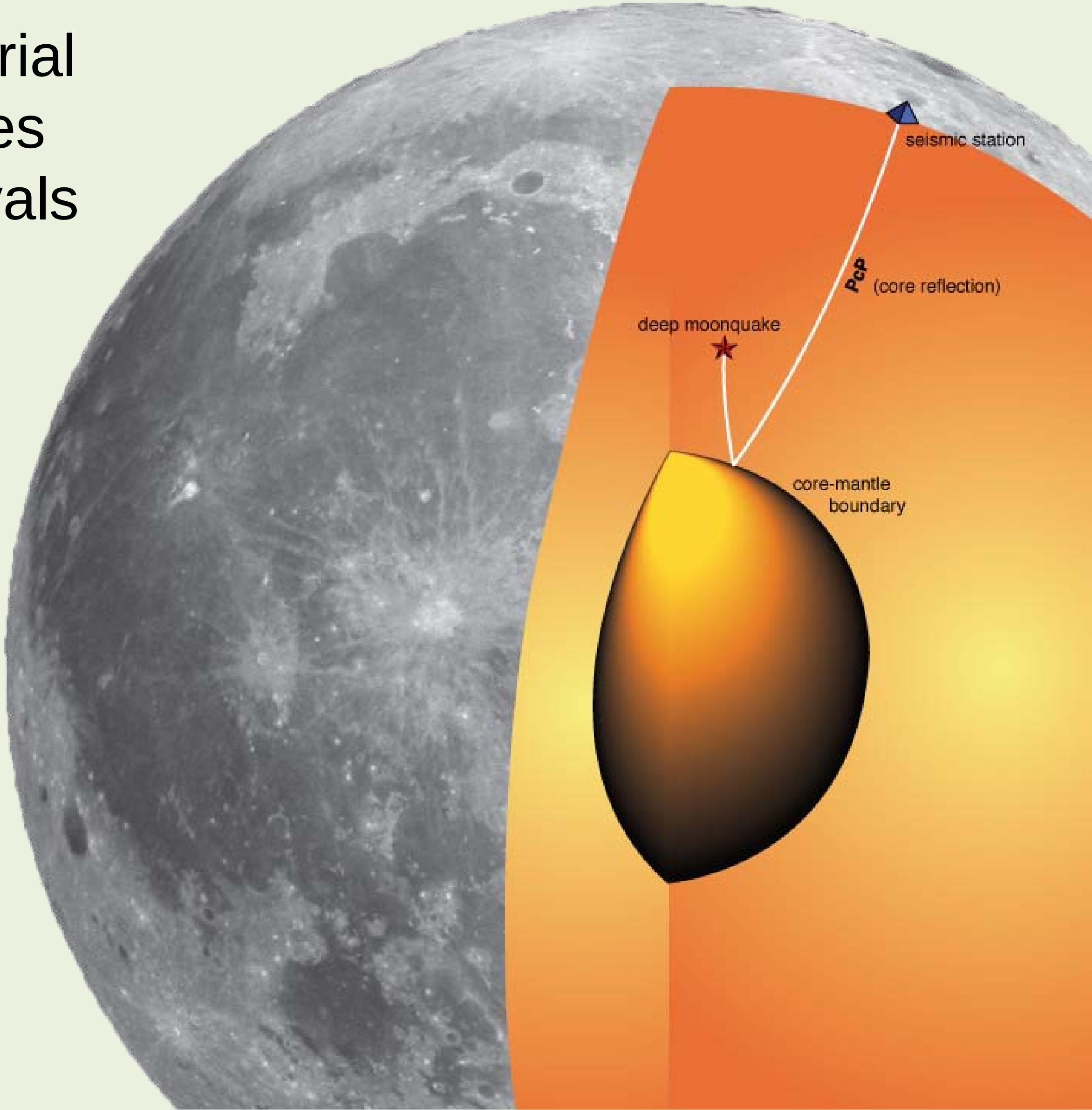
- Long, ringy coda is due to scattering and strong reverberations in the regolith.



Our goal

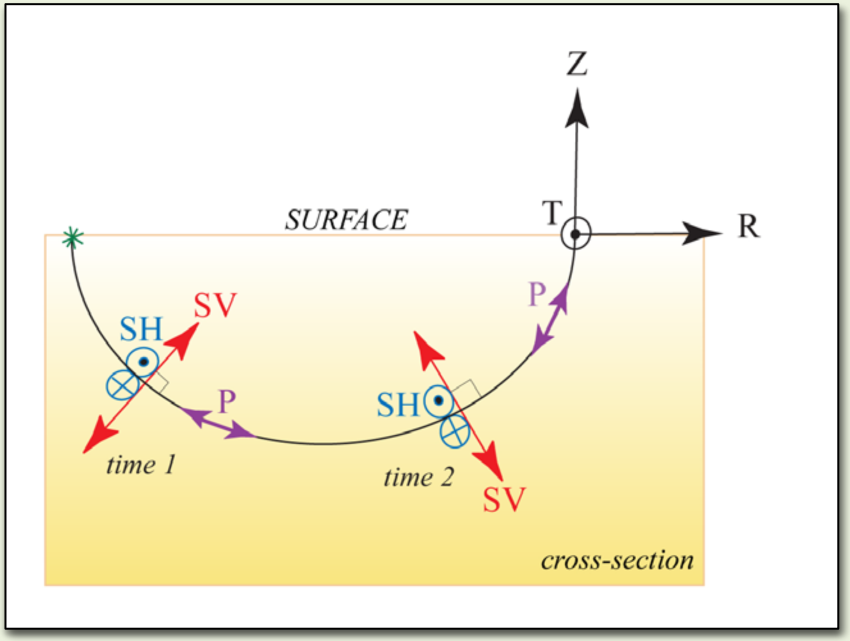
Apply modern terrestrial seismology techniques to enhance core arrivals in the Apollo seismograms

- Polarization filter
- Double array stacking



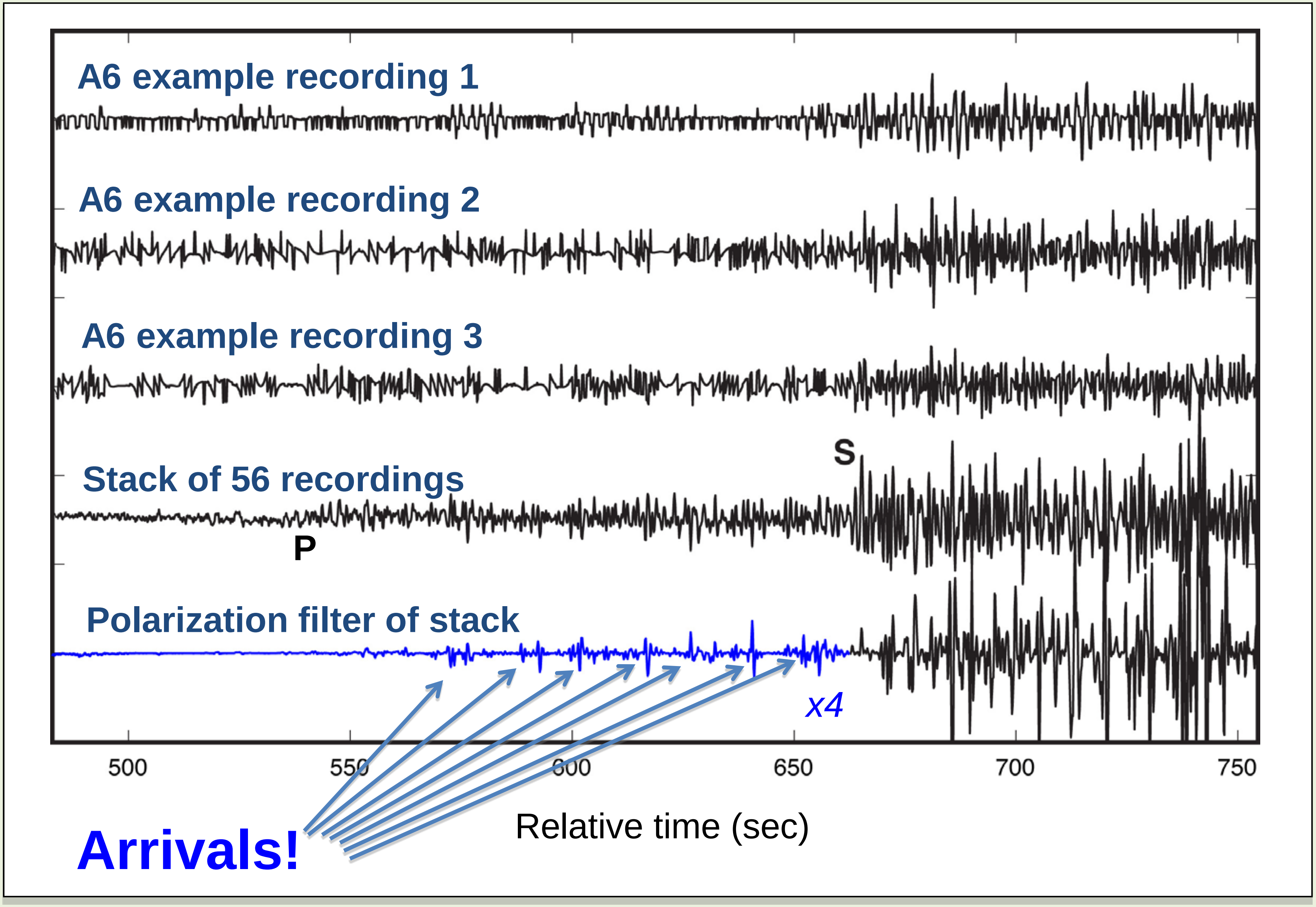
The polarization filter

Many seismic waves are naturally polarized onto just the vertical (Z) seismometer component of motion, the Z and radial (R) components, or the tangential component (T).

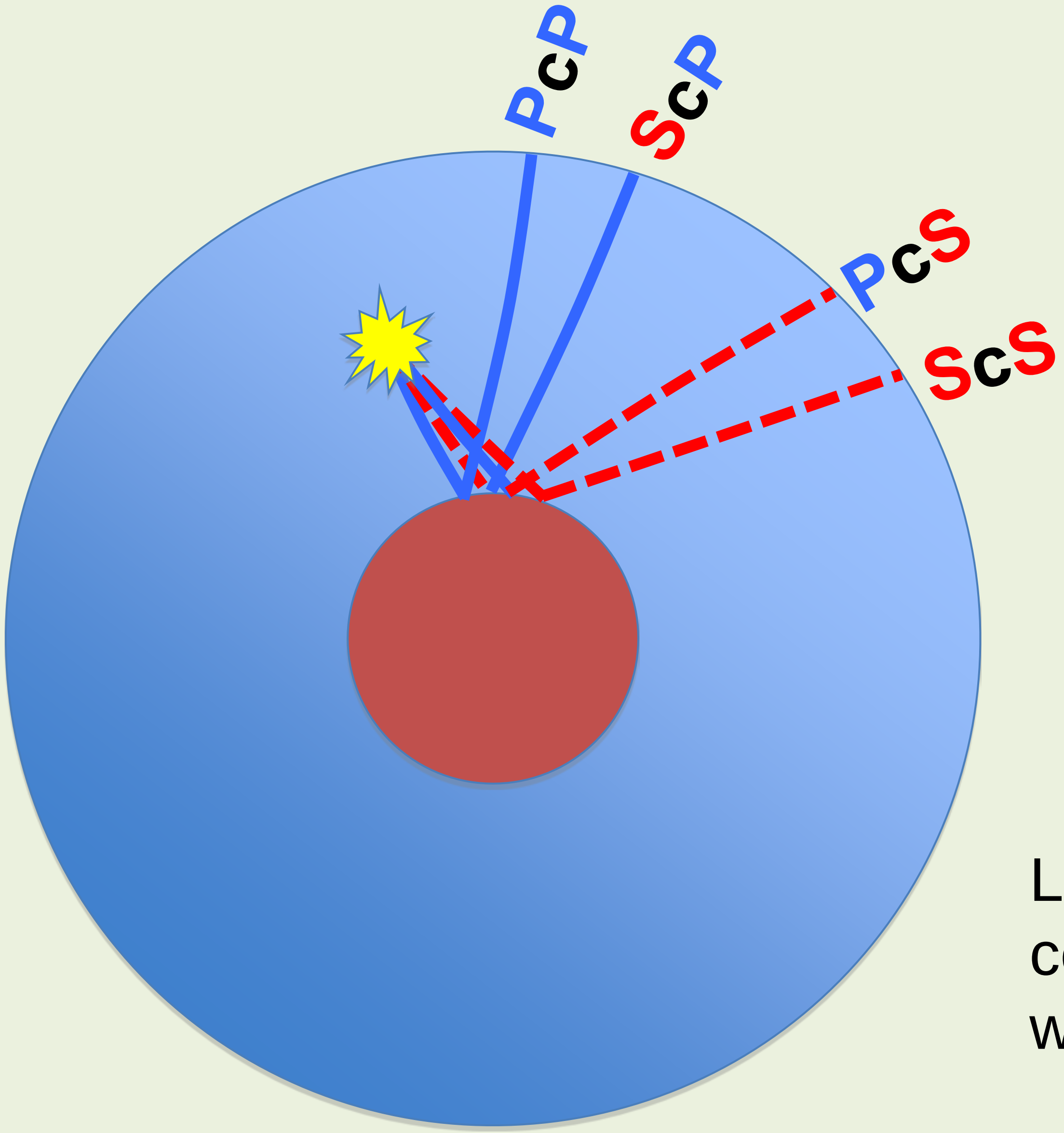


However, scattering tends to partition energy onto all 3 components of motion. The polarization filter enhances energy that is “smeared” onto orthogonal components of motion.

Station 15 recordings of A6 cluster moonquakes



What can reflect off the Moon’s core?



Four basic reflections are possible:

S-to-P

P-to-P

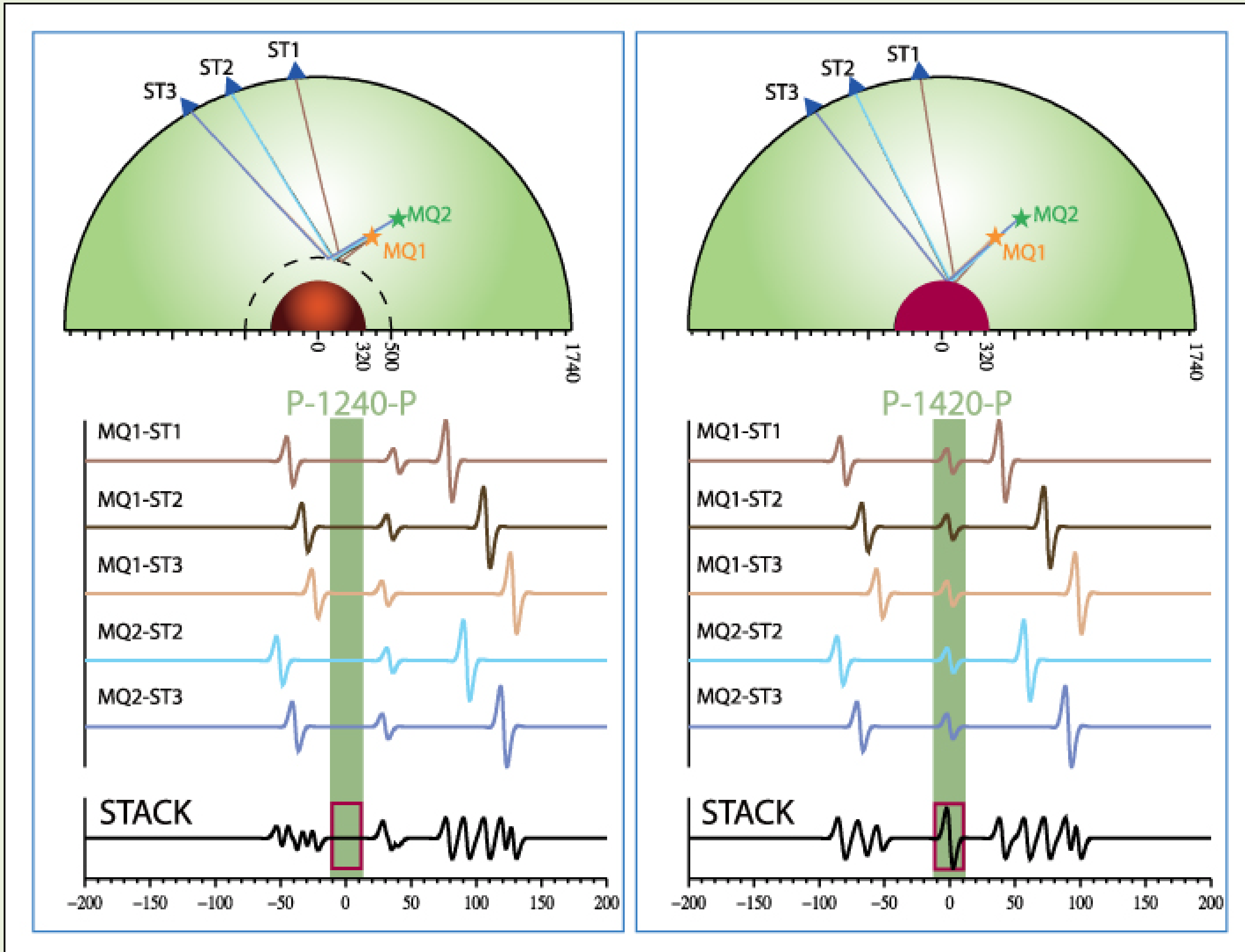
P-to-S

S-to-S

Look for results that are common to the different wave types

Double array stacking

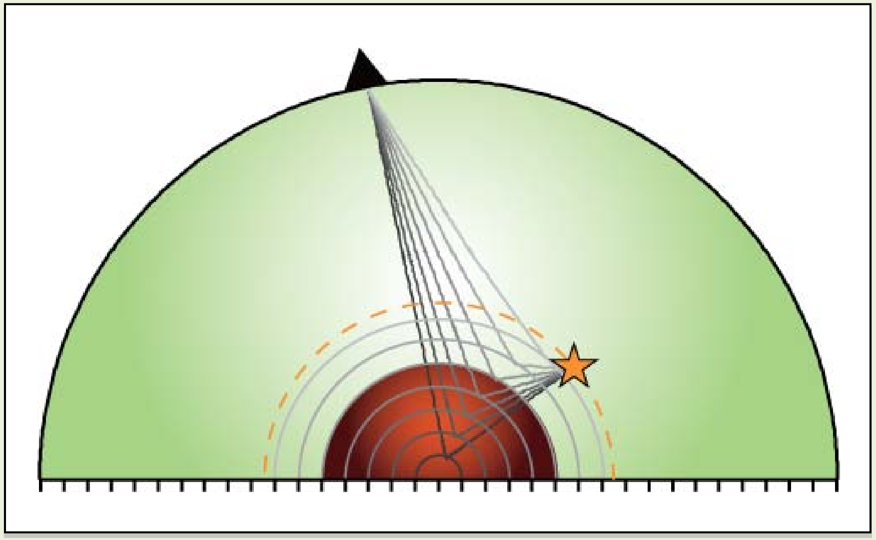
Array processing methods enhance subtle seismic arrivals by stacking seismograms that have been time-shifted to predicted core arrival times.



We search for lunar core reflections by time-shifting deep moonquake-cluster traces according to predictions associated with different possible layer depths, then summing the traces.

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 (core-mantle boundary)

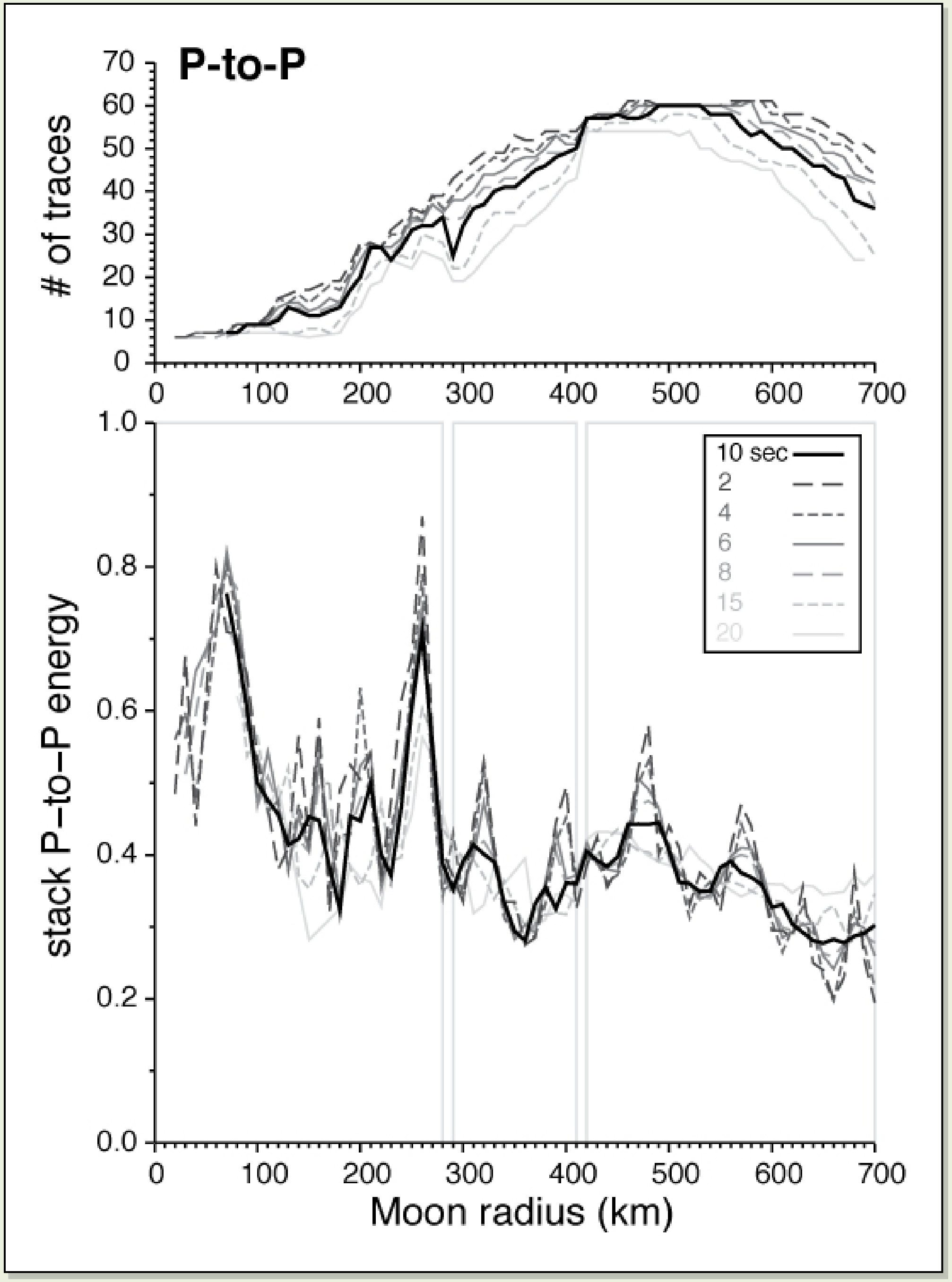
•0-280 km (inner core boundary

Initial result: P-to-P reflections

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

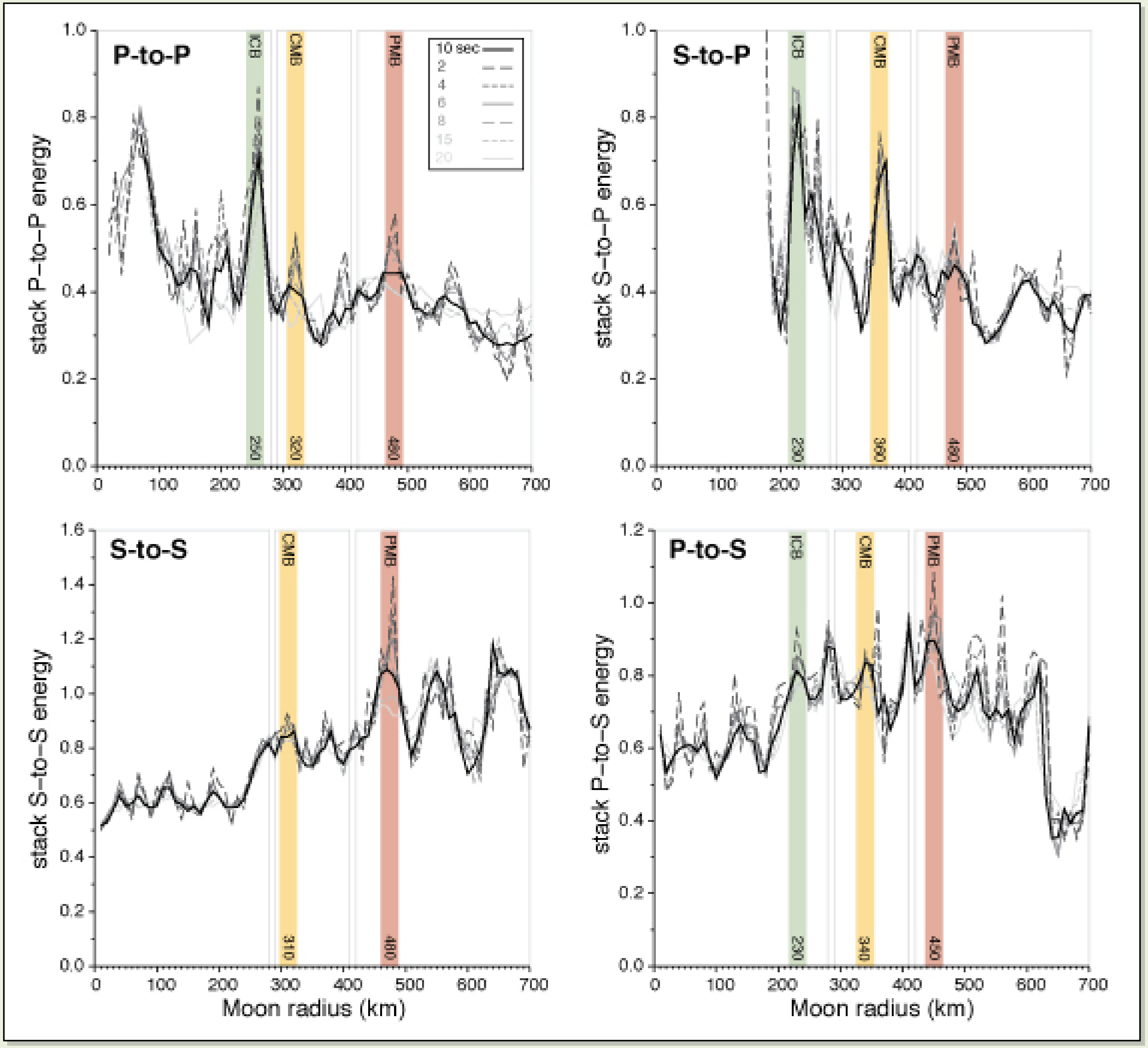


Results

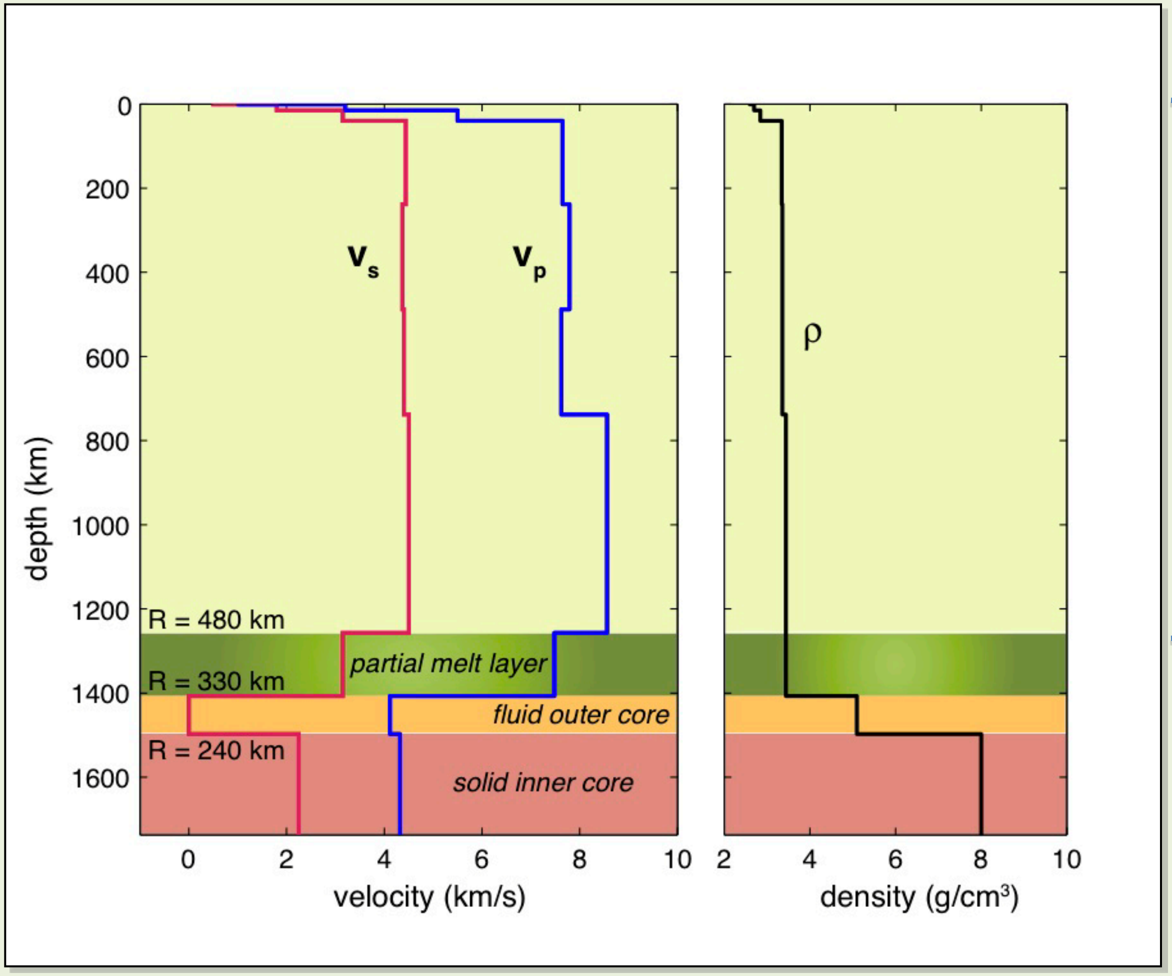
PMB:
480 km

CMB:
330 km

ICB:
240 km



Velocity/density structure with depth



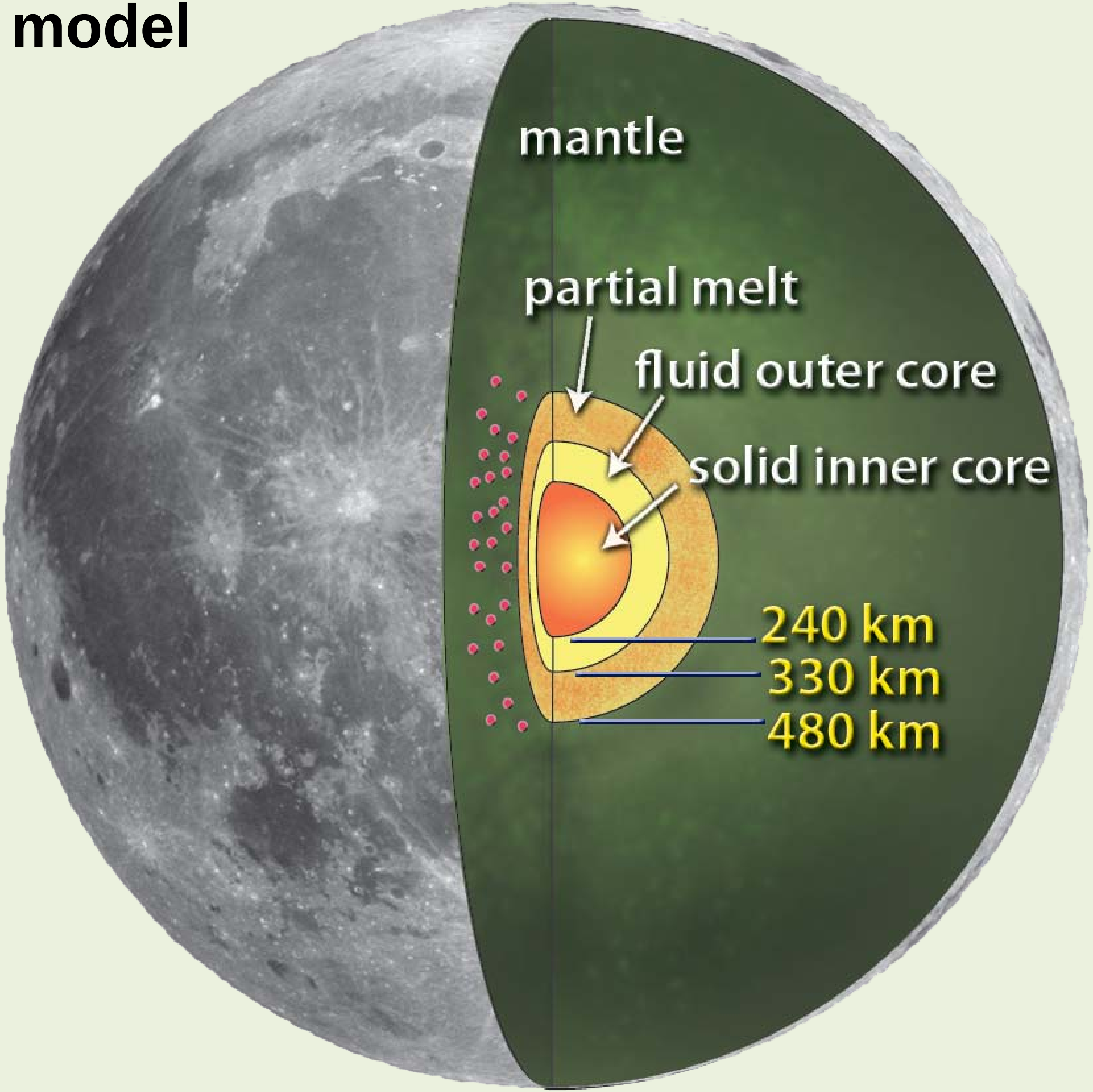
From Lognonne et al., 2003

Our new results

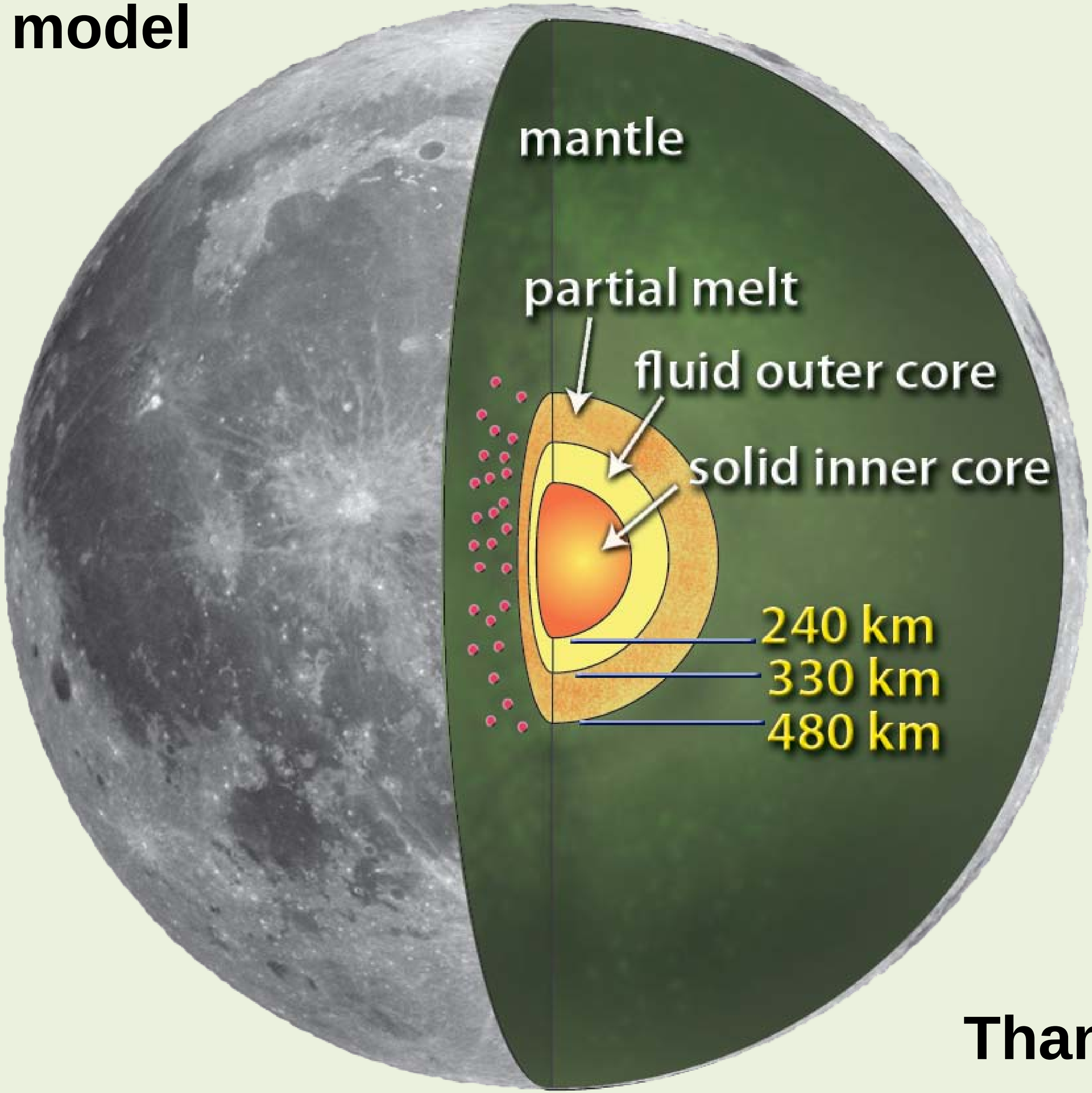
Interpretation

- While our layer depths and velocities are consistent with those of other studies and satisfy constrains on the Moon's mass and mean density, they are not constrained. The depth of any reflector has a 1-to-1 trade-off with the velocity above the interface. We emphasize the qualitative agreement between the different types of reflections.
- Deep mantle v_p of 8.5 km/sec consistent with presence of garnet.
- Melt v_p of 7.5 km/sec corresponds to 5-30% partial melt, depending on its spatial distribution.
- Liquid outer core v_p of 4.1 km/sec consistent with liquid iron alloy at lunar pressure conditions; transition from liquid to solid at this depth implies the Moon's core is ~40% solidified.

Final model


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

Final model



Thank you

Supplementary slides

The polarization filter

The polarization function M is a moving sum of the product of two seismogram components. Here it is defined with R and Z:

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

The polarization function M is then multiplied by the component of motion of interest, yielding S, ***the polarization filtered data***:

$$S_j = R_j M_j$$

For stacking on PcP

- PcP, ScP energy should appear on radial and vertical components
- (Z,R)*Z

For stacking on PcS

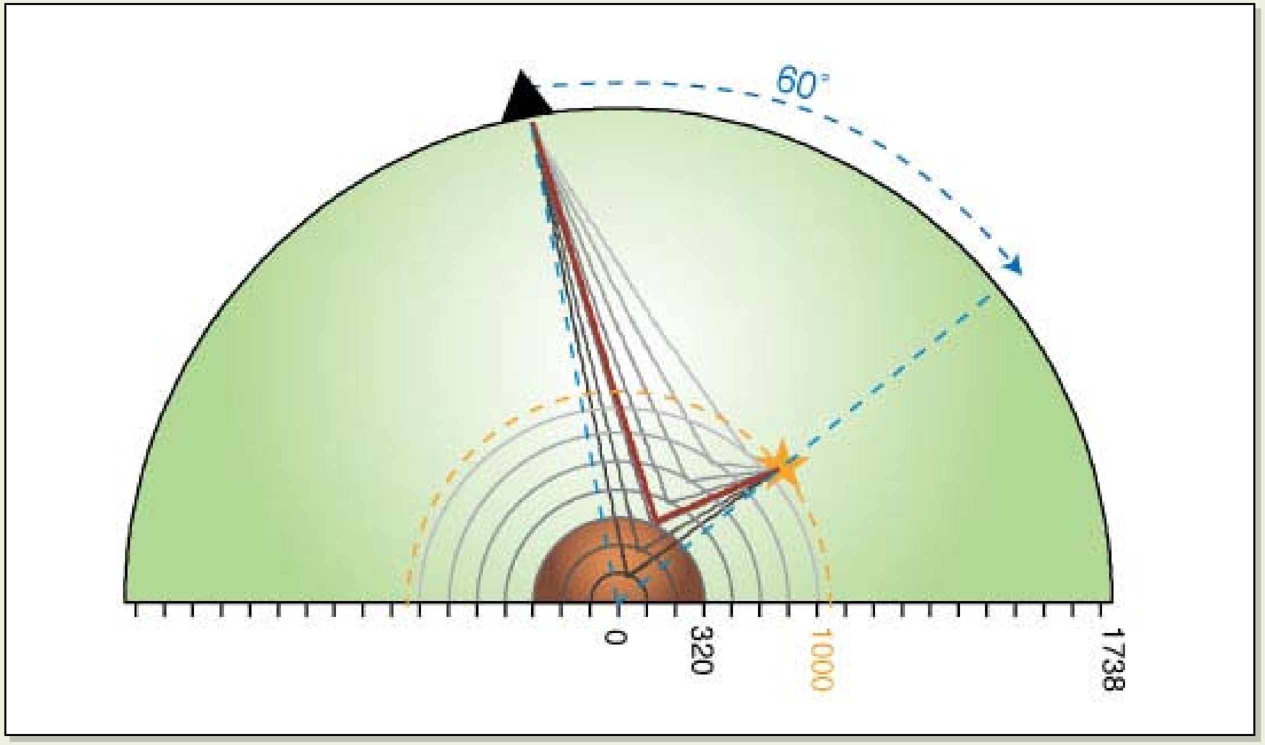
- SV energy should appear on radial component
- (Z,R)*R

For stacking on ScS

- SH energy should appear on transverse component
- (T,T)*T

The double array stacking procedure

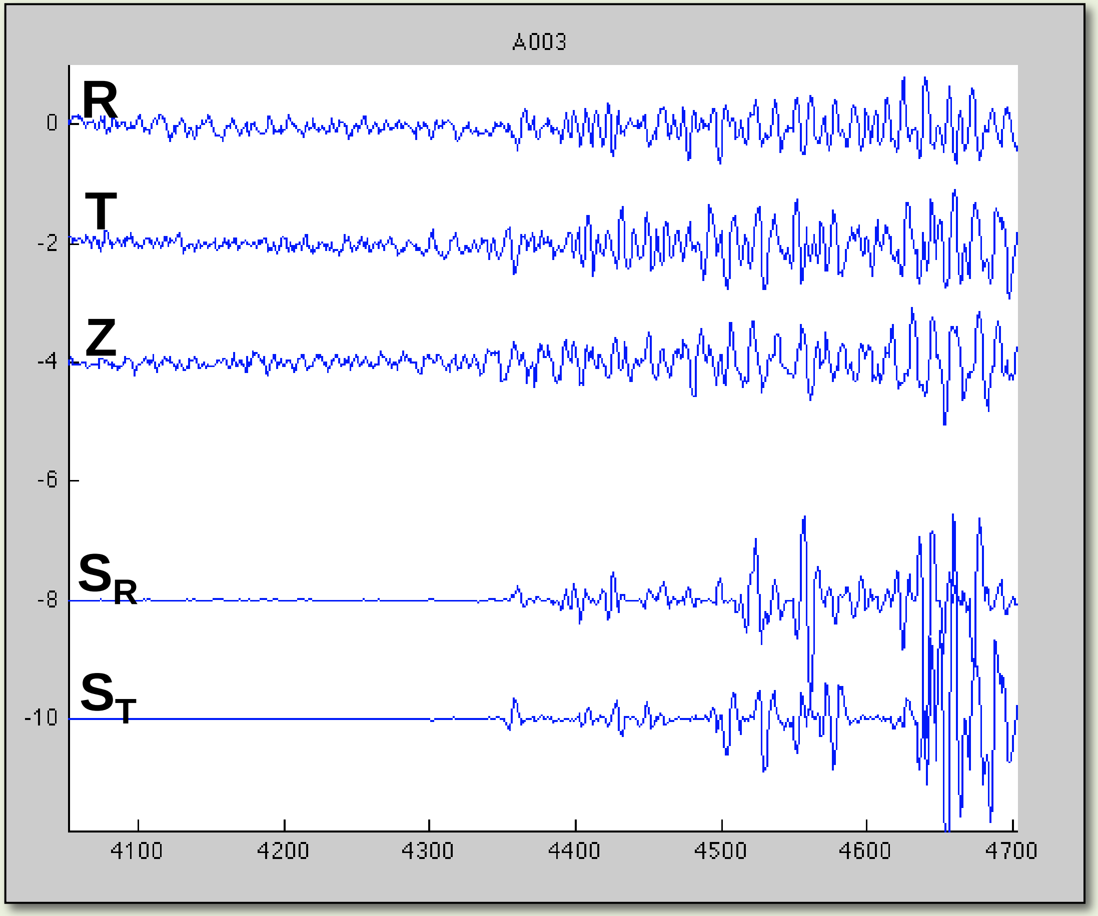
1. Hand pick reference S arrival time
2. Predict core arrival times from ray theory
3. Apply normalization, if necessary
4. Remove possible interfering arrival time windows
5. Discard data with source depth below core depth
6. Shift each trace so phase of interest aligns at time t=0



7. Stack iteratively based on suite of core radii

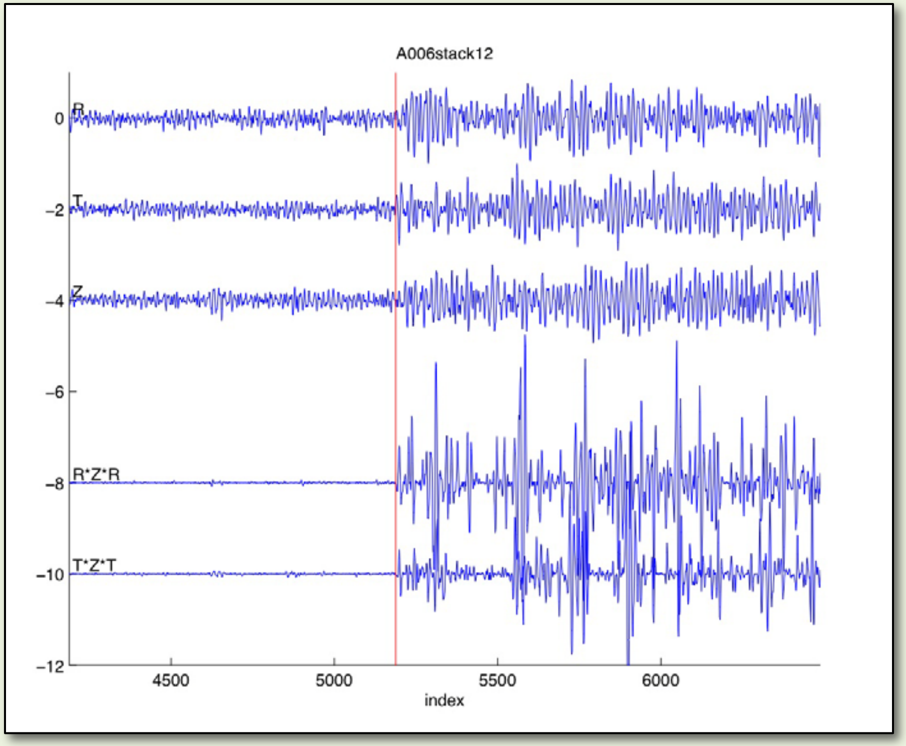
1) Picking

On each trace, pick the S arrival for reference (implement quality control).

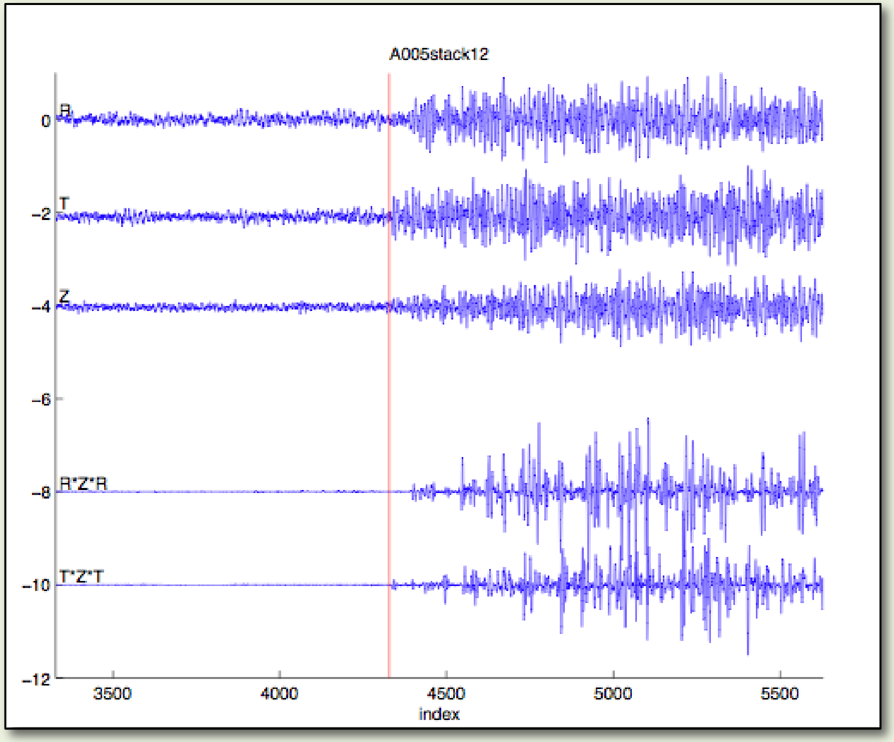


1) Picking

Stacks are weighted by the quality of the pick



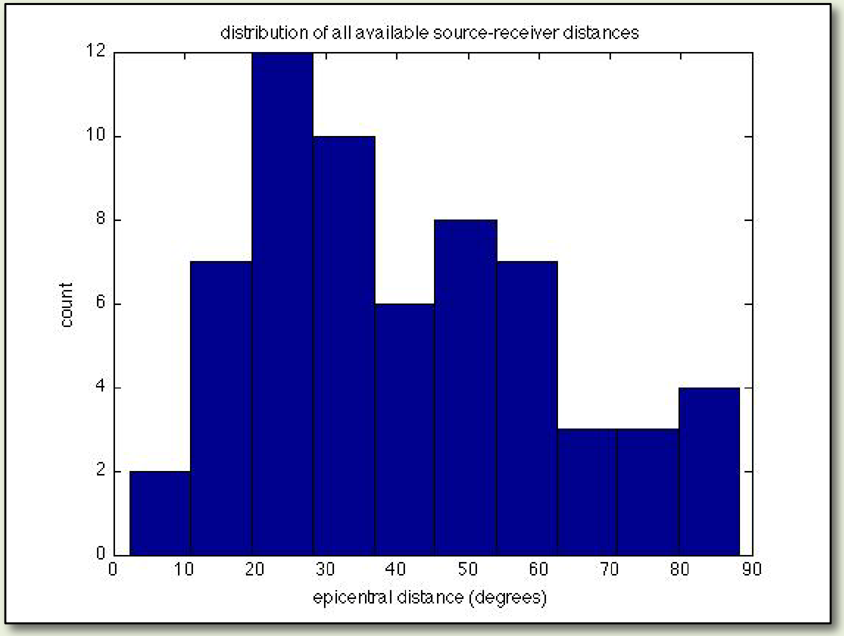
quality 1.0 = S easy to pick

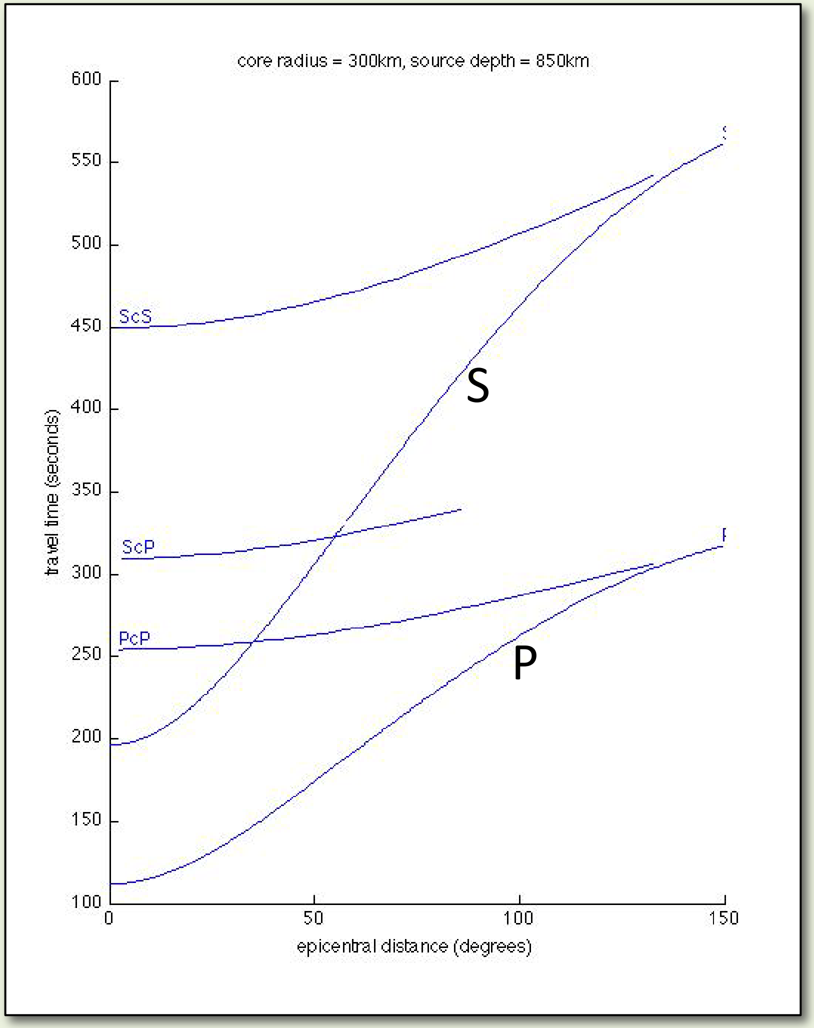


quality 0.5 = S not as clear

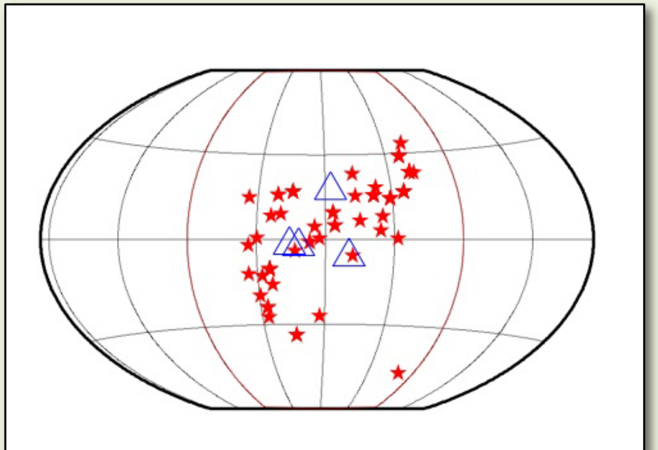
2) Core arrival times

Calculate S, PcP, ScP, and ScS arrival times for core radii ranging between 10-700 km (ray tracing through Nakamura 1983 velocity model).

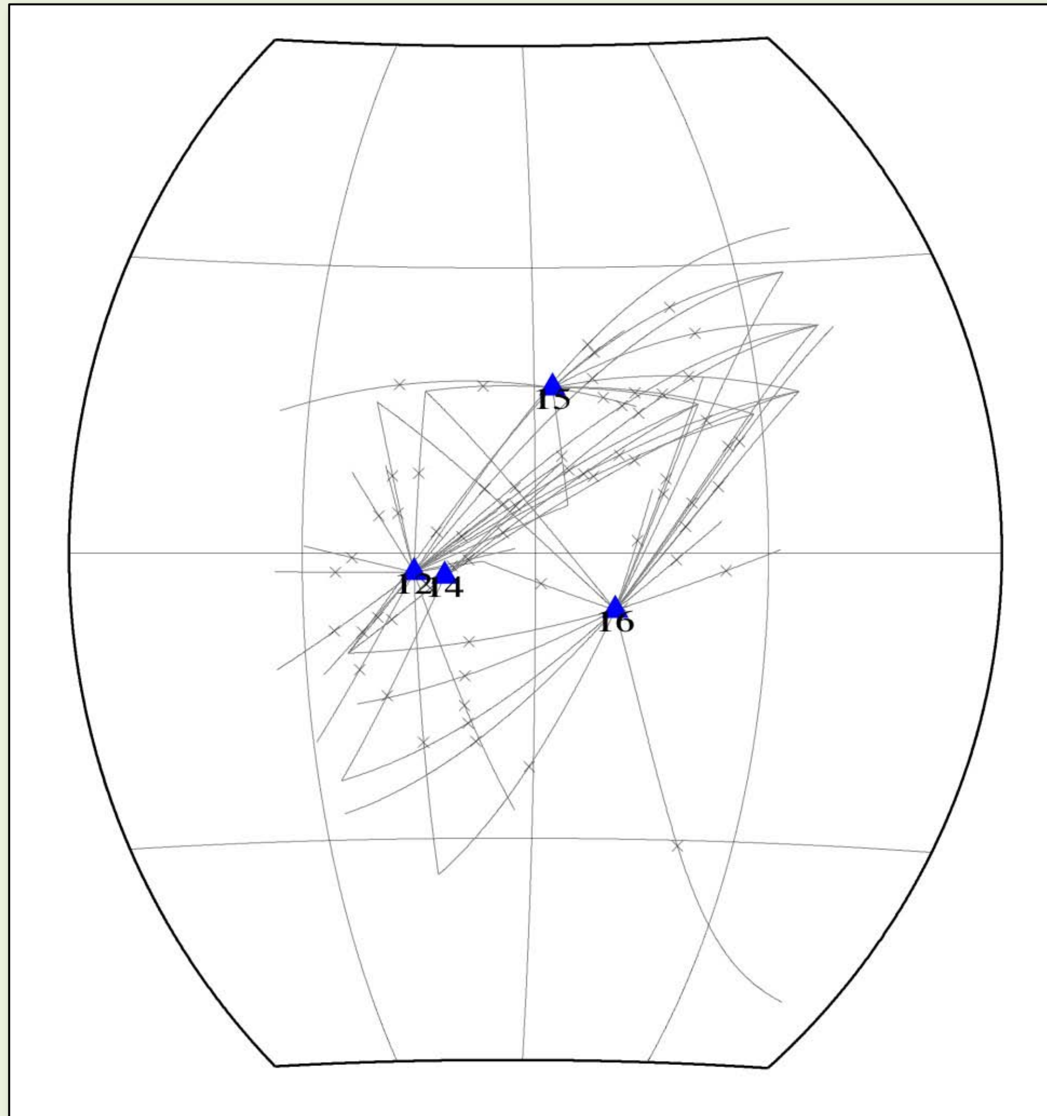




PcP bounce points



38 clusters with S picks

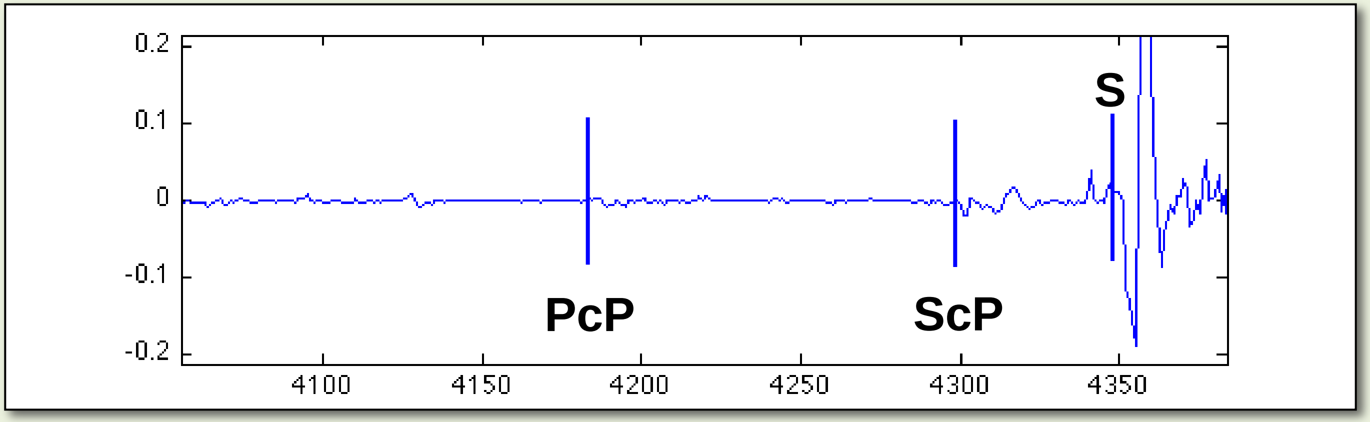


62 PcP ray paths for clusters with S picks

bounce points shown for 300-km core

3) Normalize each trace

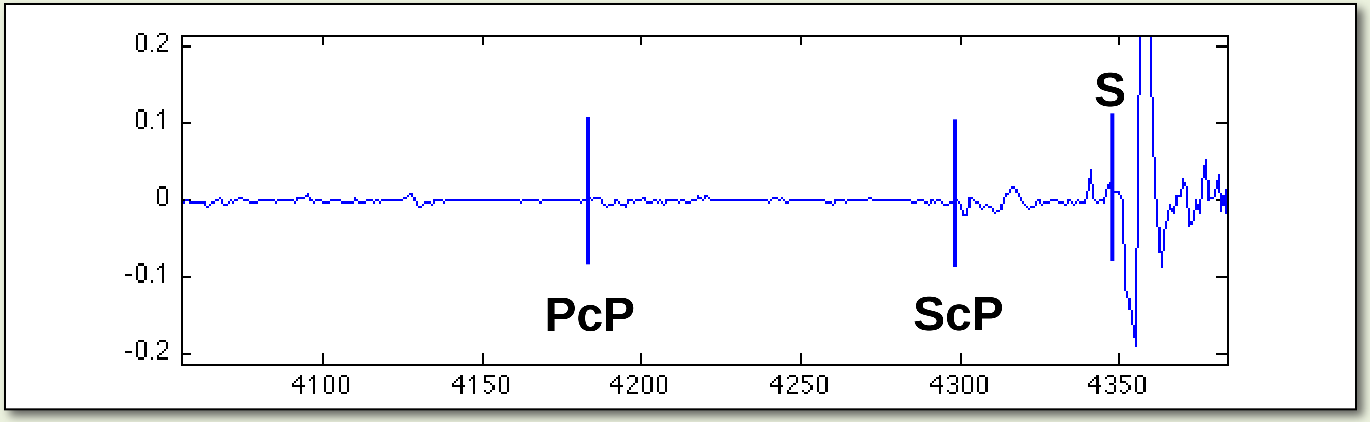
Normalize traces to one in a +/-10 second window centered on S.



4) Remove interfering arrivals

- all traces where PcP (or ScP) is closer than 3/4 of time window to S (to avoid S coda contamination).

- all traces where time between ScP and PcP is more than 1/2 of time window.

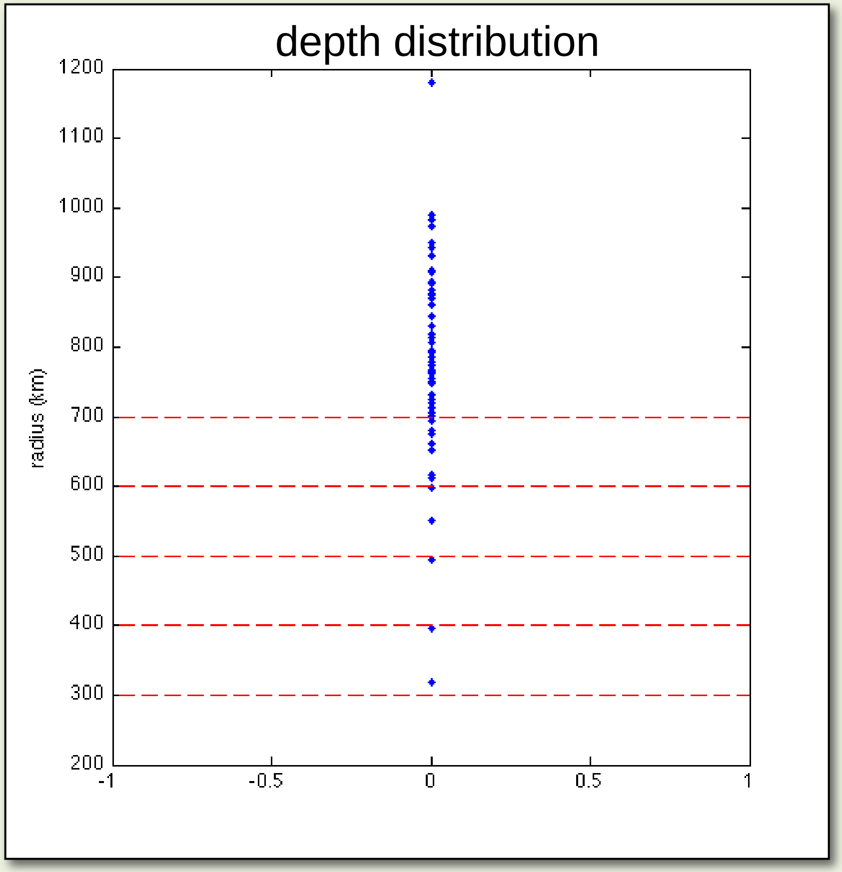


window lengths are:

2, 4, 6, 8, 10, 15, and 20 seconds

5) Throw out:

all traces where the moonquake depth is below the CMB.

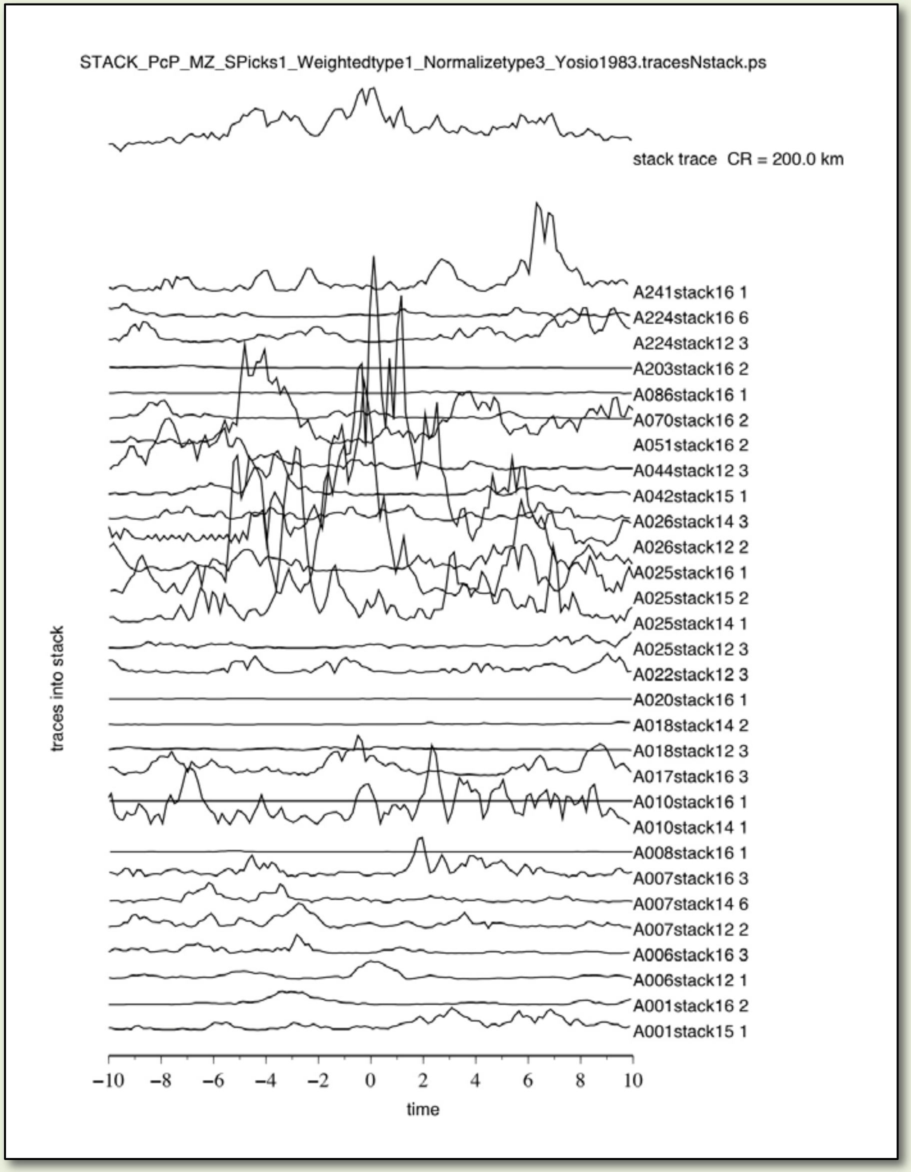


6-8) Shift, envelope, & stack

6) Shift each trace so e.g. PcP aligns at reference time t = 0.

7) Envelope each trace (to account for possible polarity differences)

8) Stack, iteratively based on core radius and window lengths.



Amplitudes

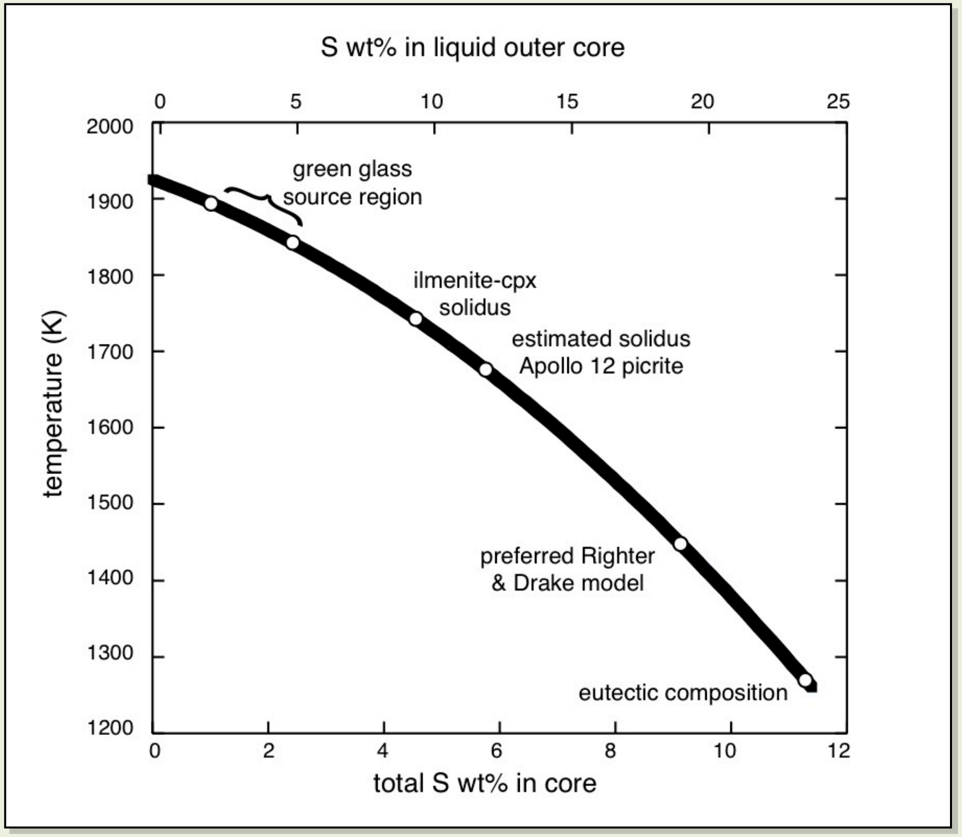
- Should the amplitudes of certain wave types adhere to some specific pattern?
  - Not necessarily.
    - » S-wave energy: the largest amplitude peak in the S-to-S stack is that which we assign to the top of the partial melt layer, hence much of the shear energy is likely reflected and is not expected to continue downwards to reflect off the CMB.
    - » P-wave energy: the relationship amplitudes of core reflections like PcP and PKiKP depend on the moonquake focal mechanism, which is not constrained. Thus either can be stronger.

Crust conversions?
Shallow scatterers?

- Crustal conversions generate delays of ~8 seconds; core arrivals are later. Surface reflections occur at different times and different move-outs for each station, so they are not expected to stack coherently.
- Structure outside our region of interest may generate coda arrivals that go into our stacks. However, we stack along the predicted arrival time move-outs of deep reflections, which do not systematically arrive at constant times, since different stations are at different distances.
- If the number of stations in any stack is high, arrivals due to unaccounted-for heterogeneity should not stack coherently, and are hence muted. The structure beneath every Apollo site is not expected to be exactly similar.

Temperature/chemistry considerations

- The temperature in the lunar interior can be derived from the depth of the ICB, coupled with the phase diagram of plausible iron alloys.



- An attenuating, partial melt-bearing layer at the base of the mantle provides a constraint on the thermal regime; current estimates typically lie above ~1650 K.
- Sulfur content of the core is ~6 wt% or less. If significant water is present in the deep Moon, solidus temperatures would be lowered in the partially molten zone, and somewhat higher sulfur contents would be permitted.