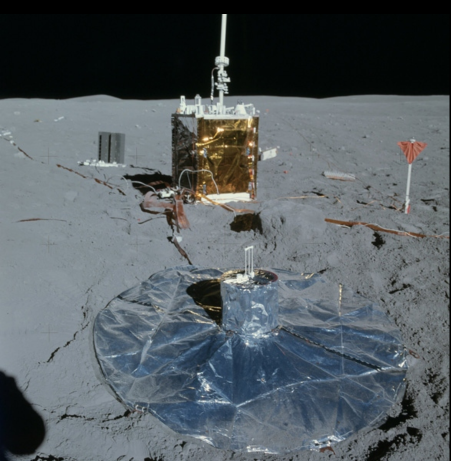
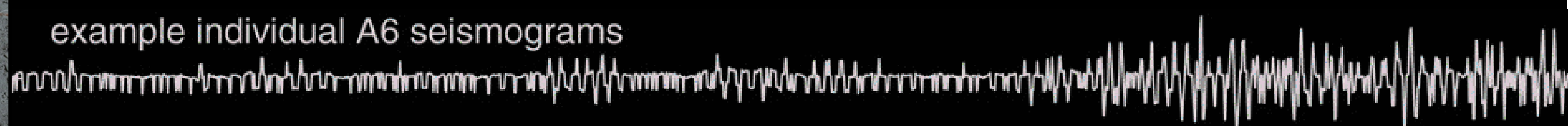
Moon internal structure from Apollo seismic data:
A corner stone for planetary seismology

R. F. Garcia

ALSEP station



example individual A6 seismograms



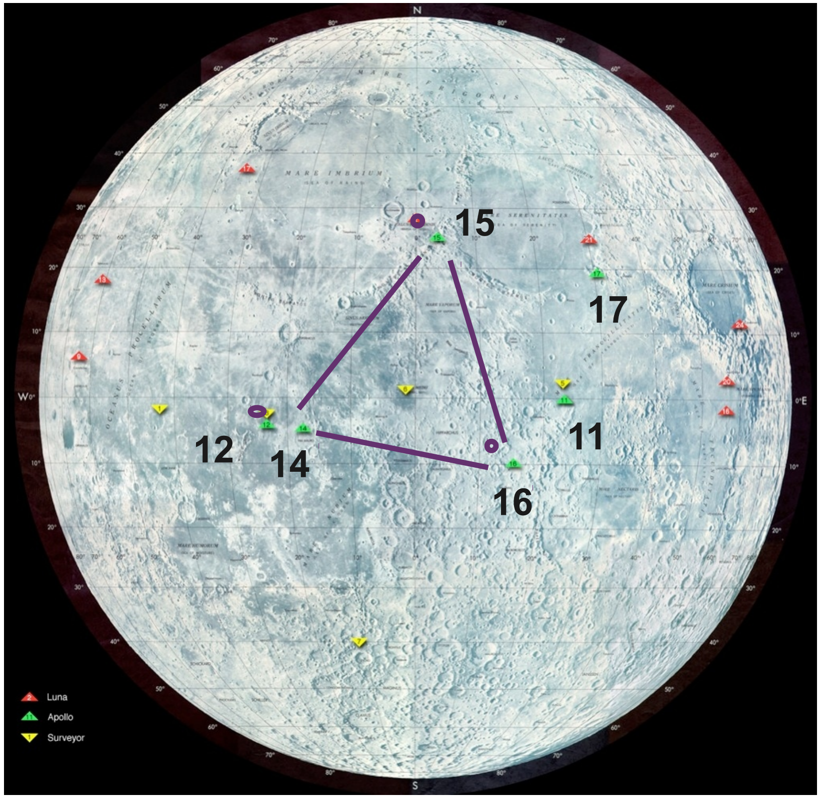
Institut Supérieur de l'Aéronautique et de l'Espace
Institut de Recherche en Astrophysique et Planétologie
Toulouse University

Outline

- Apollo seismic experiments
- Constraints on internal structure from top to bottom
  - Sub-surface
  - Crustal structure
  - Mantle and deep structures
- Other geophysical constraints
- Hot debate : structure of the lowermost mantle
- Preparing new observations

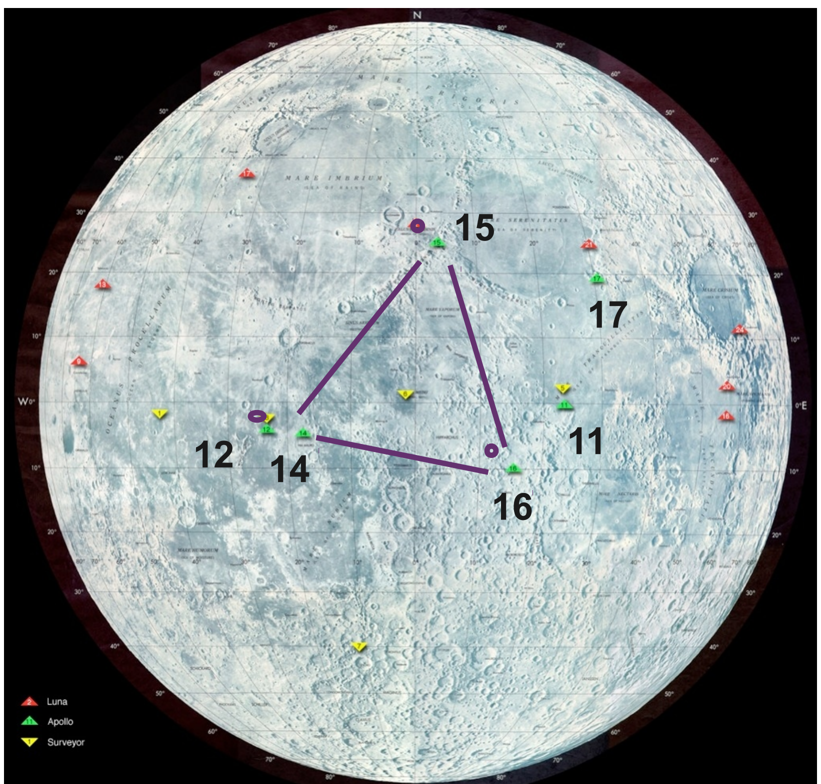
ALSEP experiment

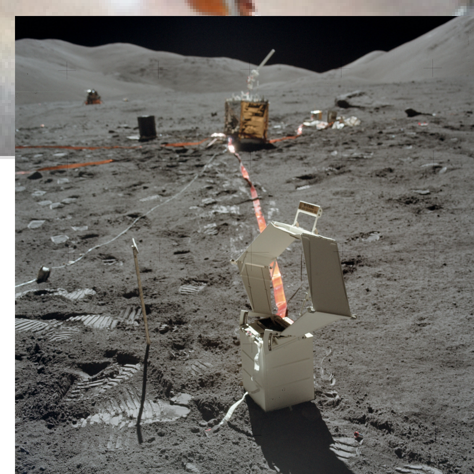
- 7 years of continuous recordings
- Very good sensors but poor A/D converters
- Very limited bandwidth (0.3-1.2 Hz), strong scattering

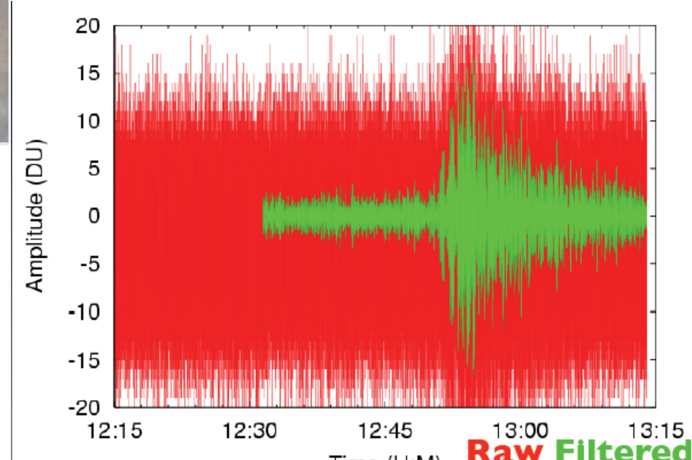


ALSEP experiment

- 7 years of continuous recordings
- Very good sensors but poor A/D converters
- Very limited bandwidth (0.3-1.2 Hz), strong scattering
- Temporary experiments + gravimeter (Apollo 17)

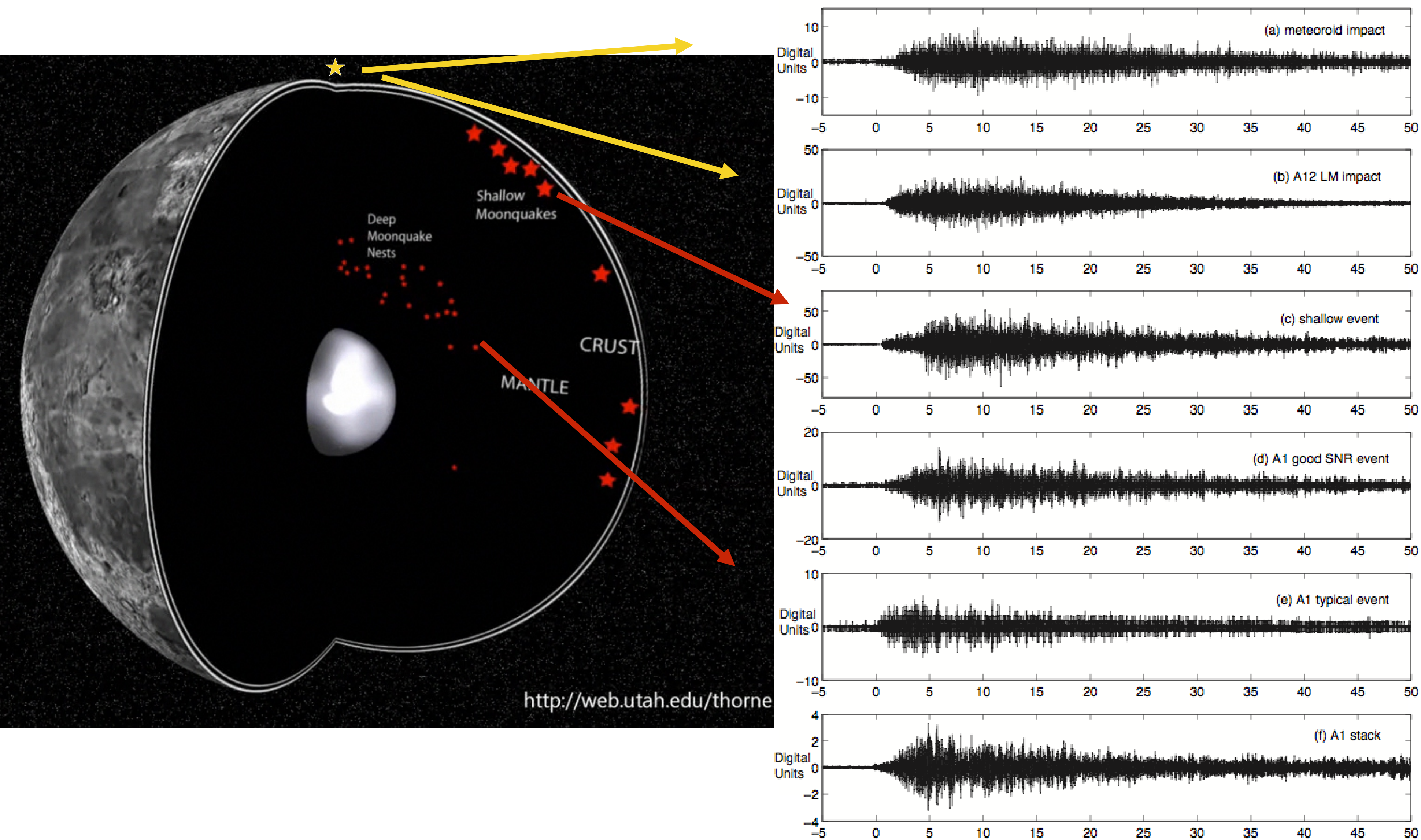






Kawamura et al., 2014

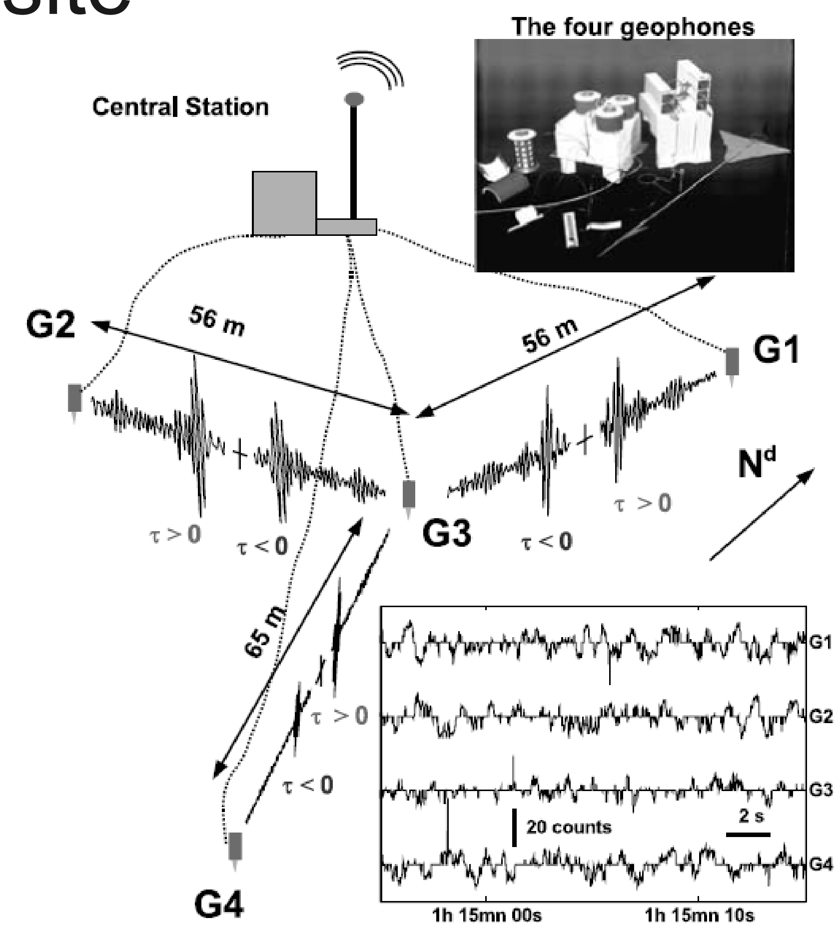
Lunar quake zoology



Lognonné & Johnson, 2007

Sub-surface exploration by seismic studies

- Recent re-processing by passive monitoring methods → 2 meters of fine dust at Apollo 17 site



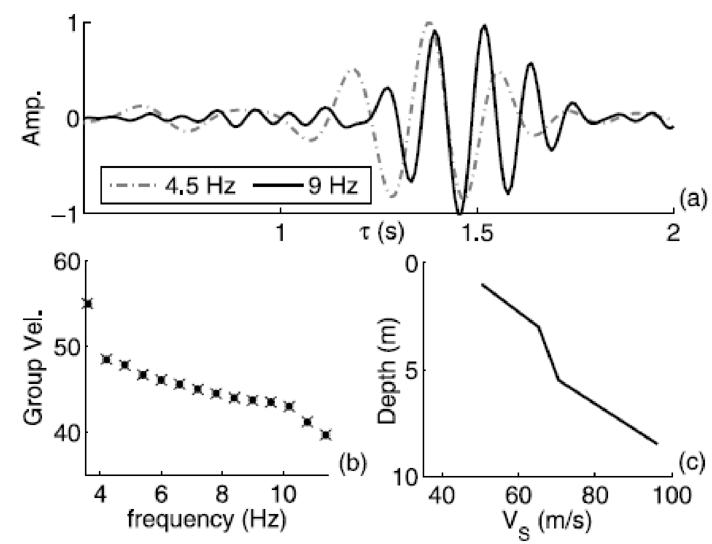


Figure 2. Dispersion analysis of the Rayleigh pulse. (a) The wave packet is filtered in two non-overlapping frequency bands (around 4.5 Hz and 9 Hz). (b) Observed dispersion curve of the Rayleigh wave group velocity. Dots: observations. Crosses: calculated data from the profile shown in (c). (c) Result of the inversion of the dispersion curve showing the upper 10 m of the shear wave velocity profile. See color version of this figure in the HTML.

Larose et al. (2005)

Sub-surface exploration by seismic studies

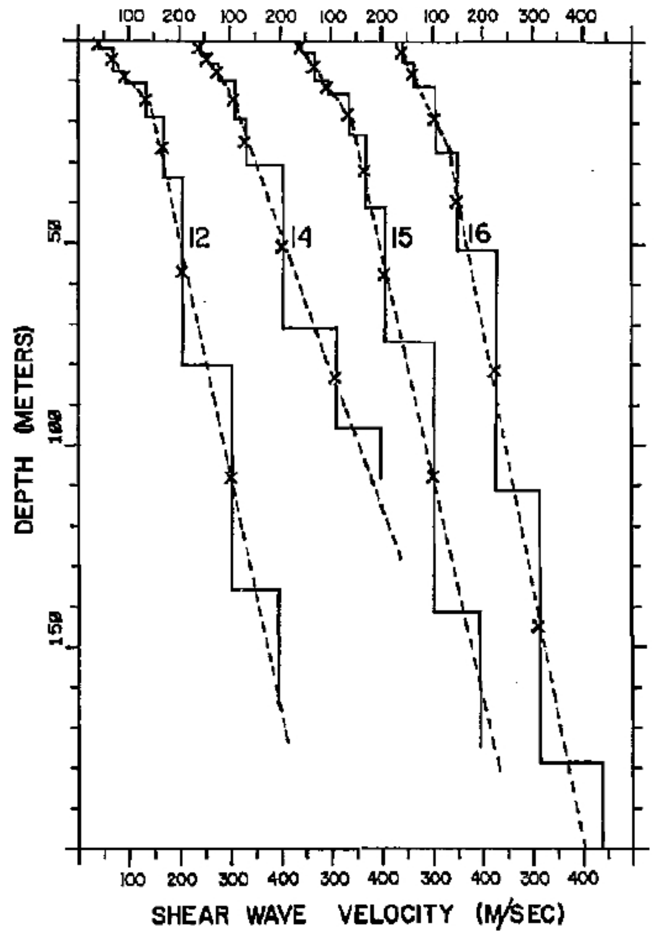


Fig. 6. Shear velocity profiles of model B obtained for the Apollo 12, 14, 15, and 16 landing sites. The center of each layer is marked with a cross; the dashed line is the piecewise linear shear velocity function given in Table 5.

Horvath et al. (1980)

- This layer appears below all the ALSEP seismic stations, but
- Significant variations betwen the stations
- Large uncertainties in the first meters due to bandwidth and resolution of Apollo seismometers.

Sub-surface exploration by seismic studies

- Apollo 17 deployed an active a small scale seismic network → meter scale dust layer with very low seismic velocities

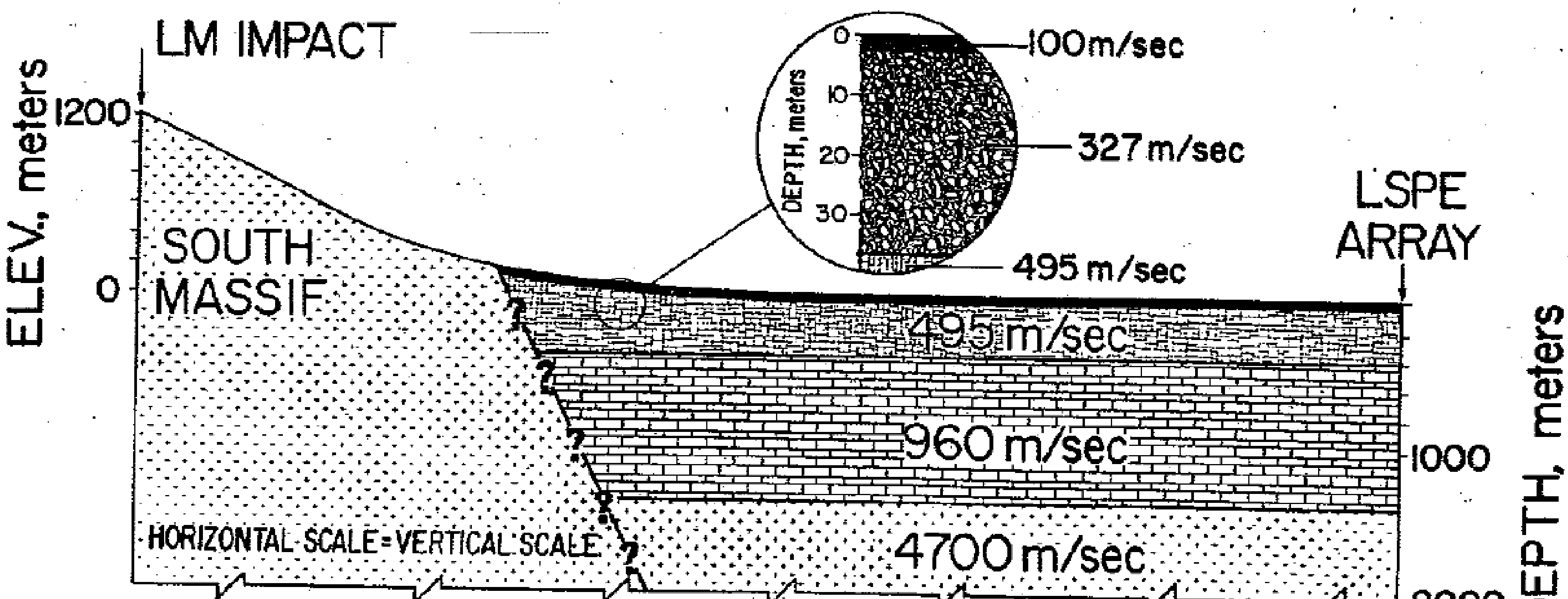
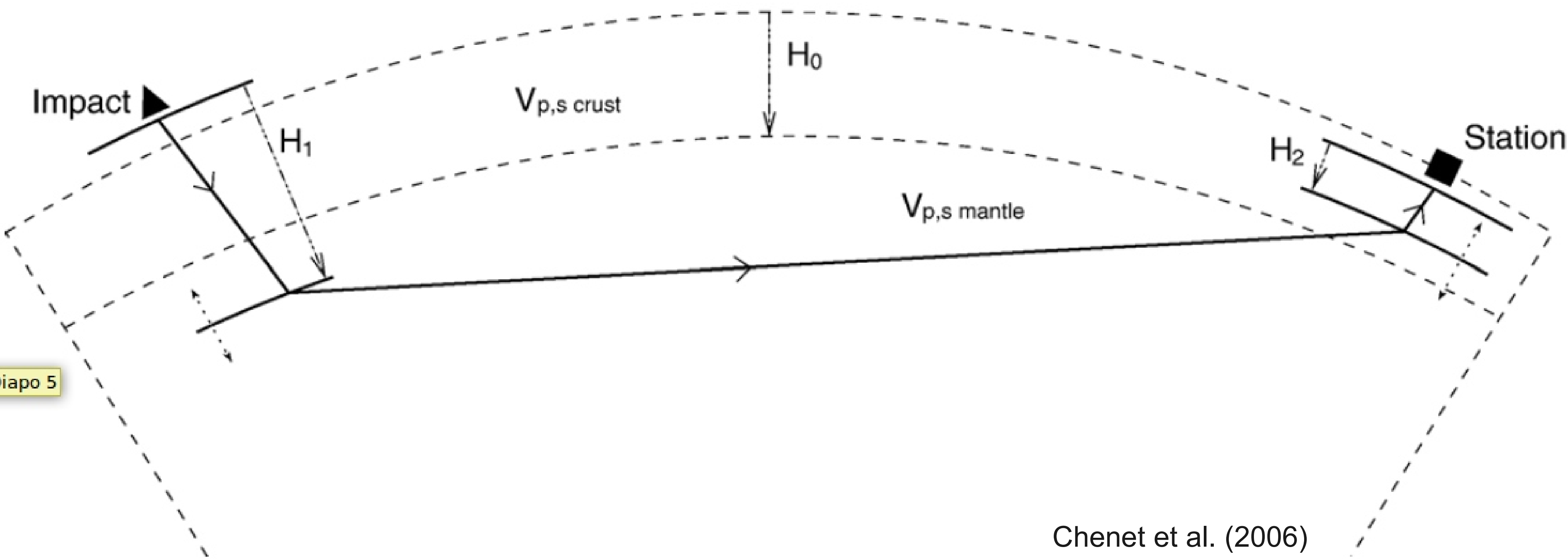


Fig. 15. Schematic cross section of the regional structure at the Apollo 17 landing site in the Taurus-Littrow valley.

Cooper et al. (1974)

Crust Structure (below Apollo Stations)

- Mainly constrained from direct phases
- Single SP conversion below S12 (Vinnick et al., 2001)

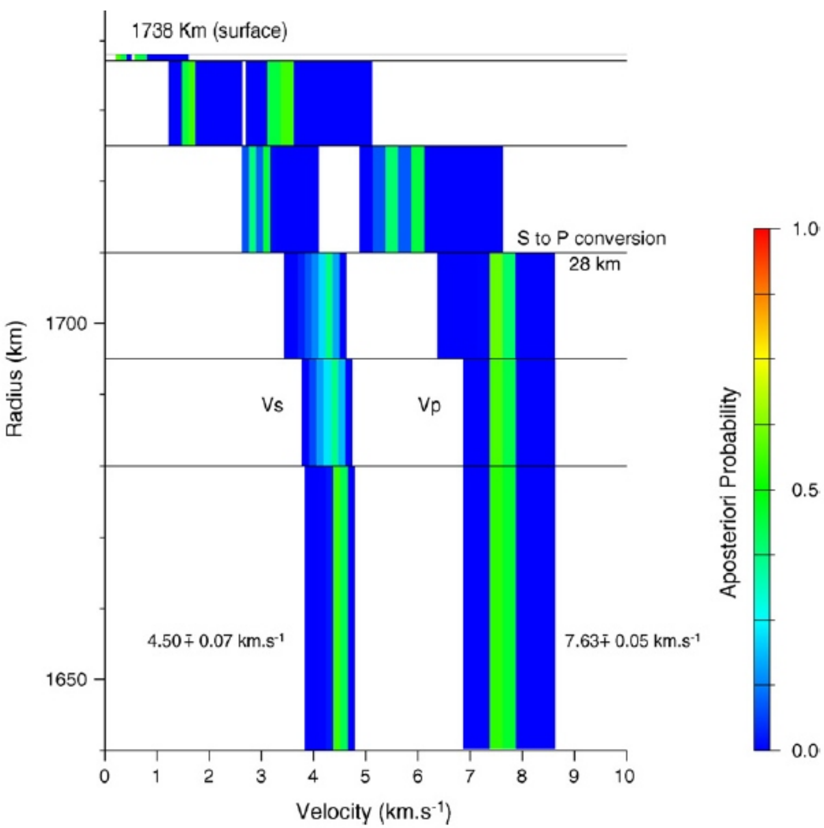


Diapo 5

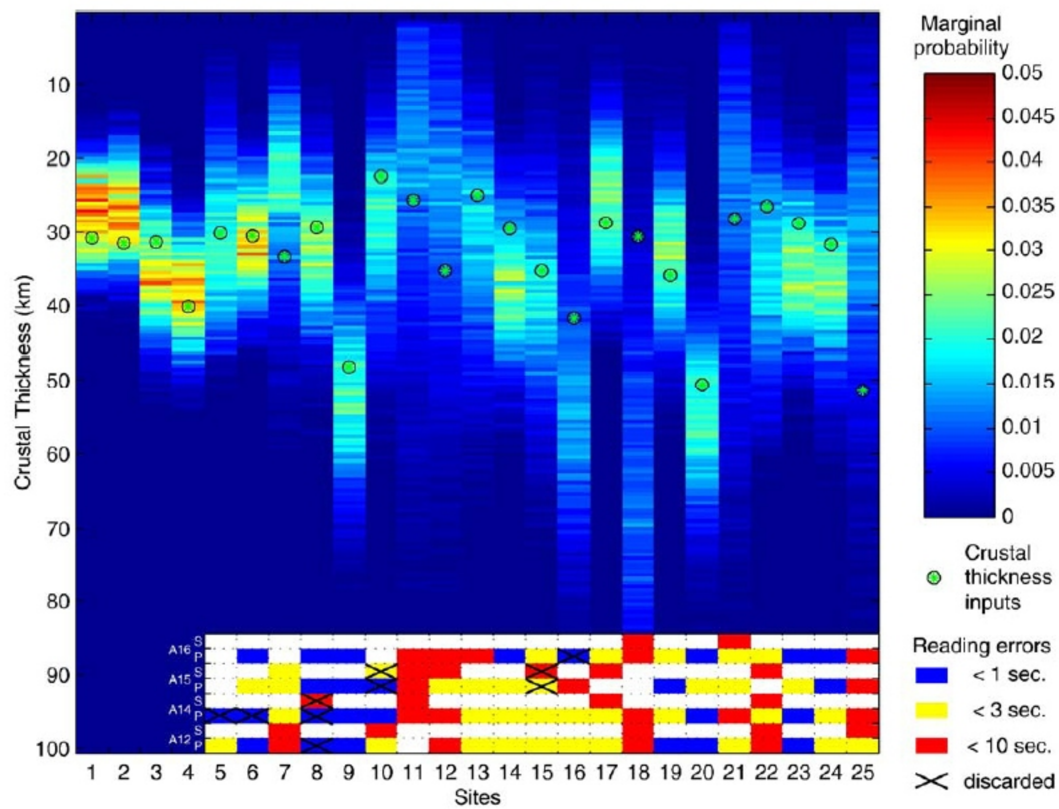
Chenet et al. (2006)

Crust Structure (below Apollo Stations)

- Average crustal thickness of 28 km
- Strong lateral variations consistent with gravity data



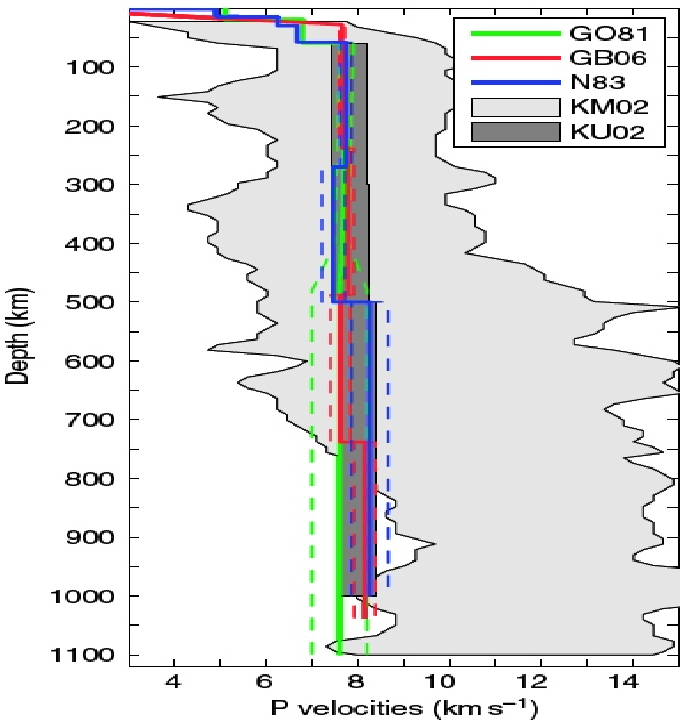
Beyneix et al. (2006)



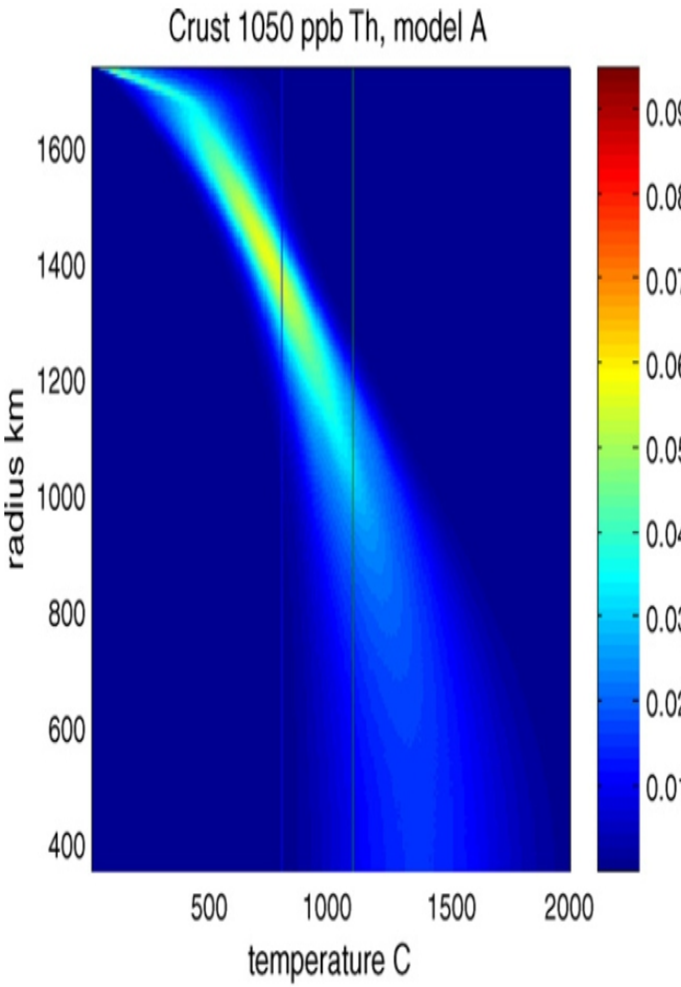
Chenet et al. (2006)

Mantle structure and thermal profile

- From seismic models to thermal structure assuming mineralogy



Lognonné et al. (2007)



Beyneix et al. (2006)

Mantle structure and thermal profile

- From geophysical observations to thermal structure inverting for mineralogy

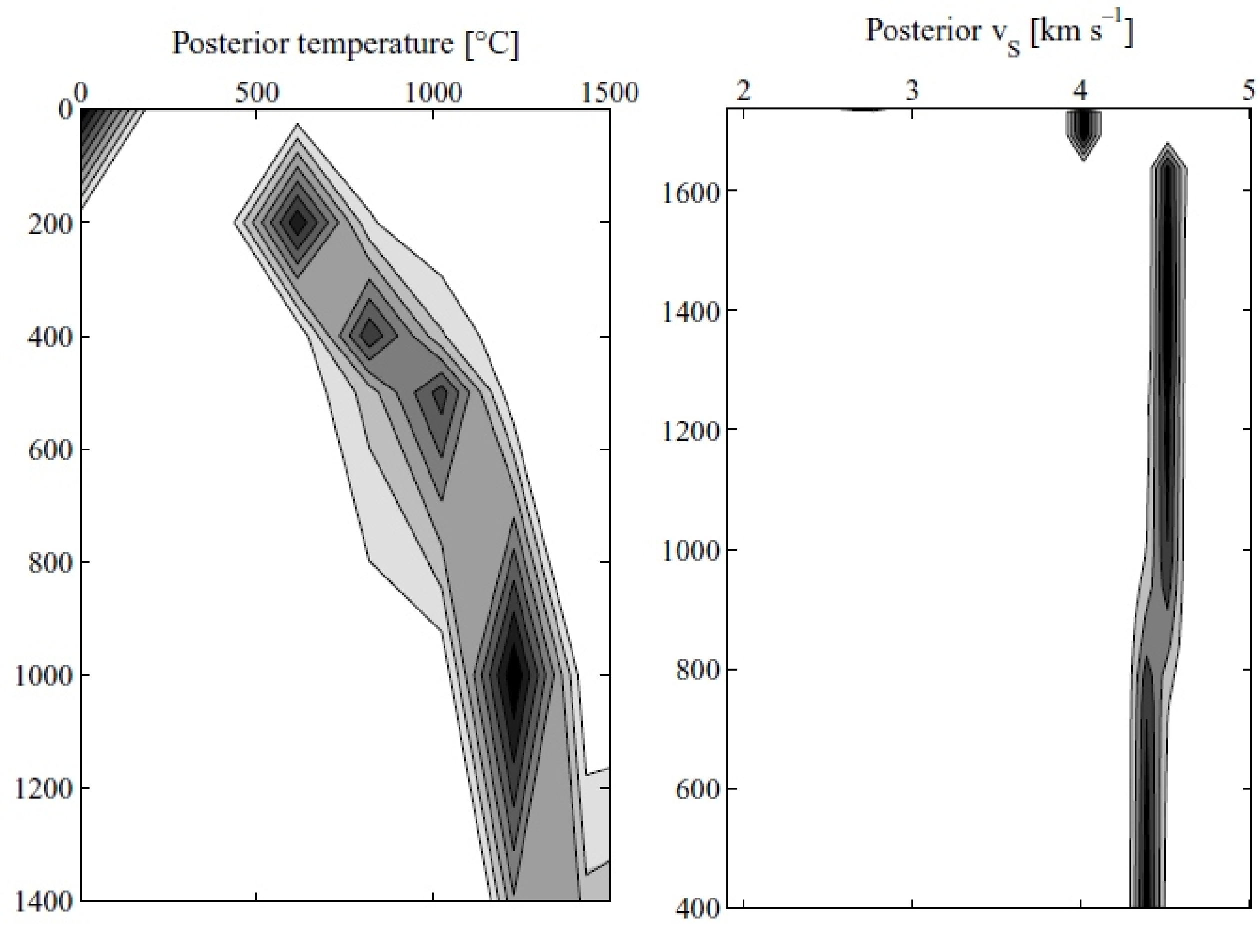
Travel times

Mass, MoI

Elec. Conductivity

=> chemistry

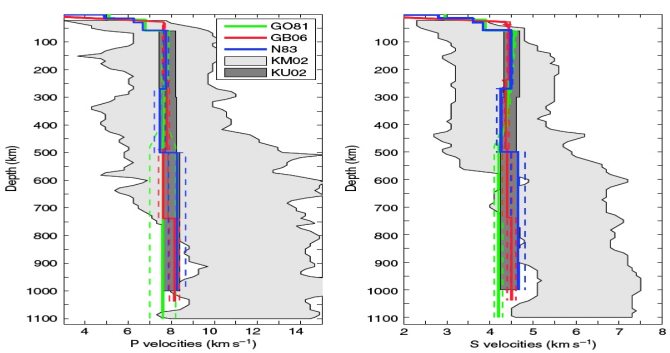
=> Temperature



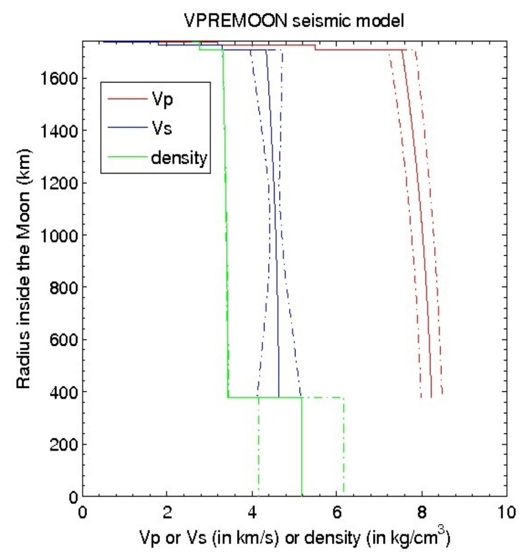
Khan et al. (2007)

Seismic imaging of the deep moon

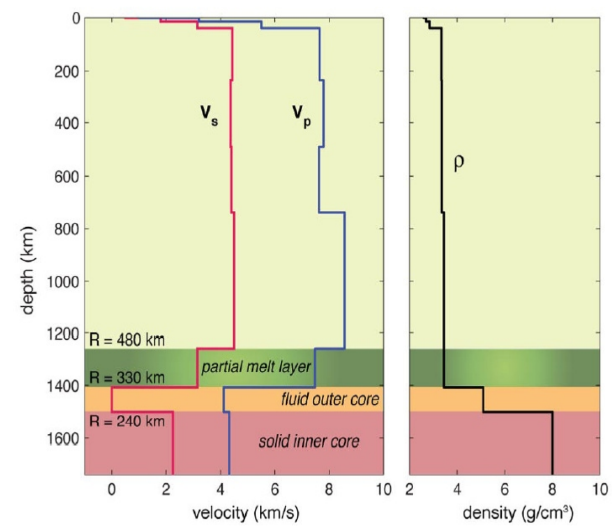
- Recent Apollo data reprocessing present detection of core reflected waves for core radii in the 330-380 range but large error bars.



Lognonné et al. (2007)



Garcia et al. (2011)

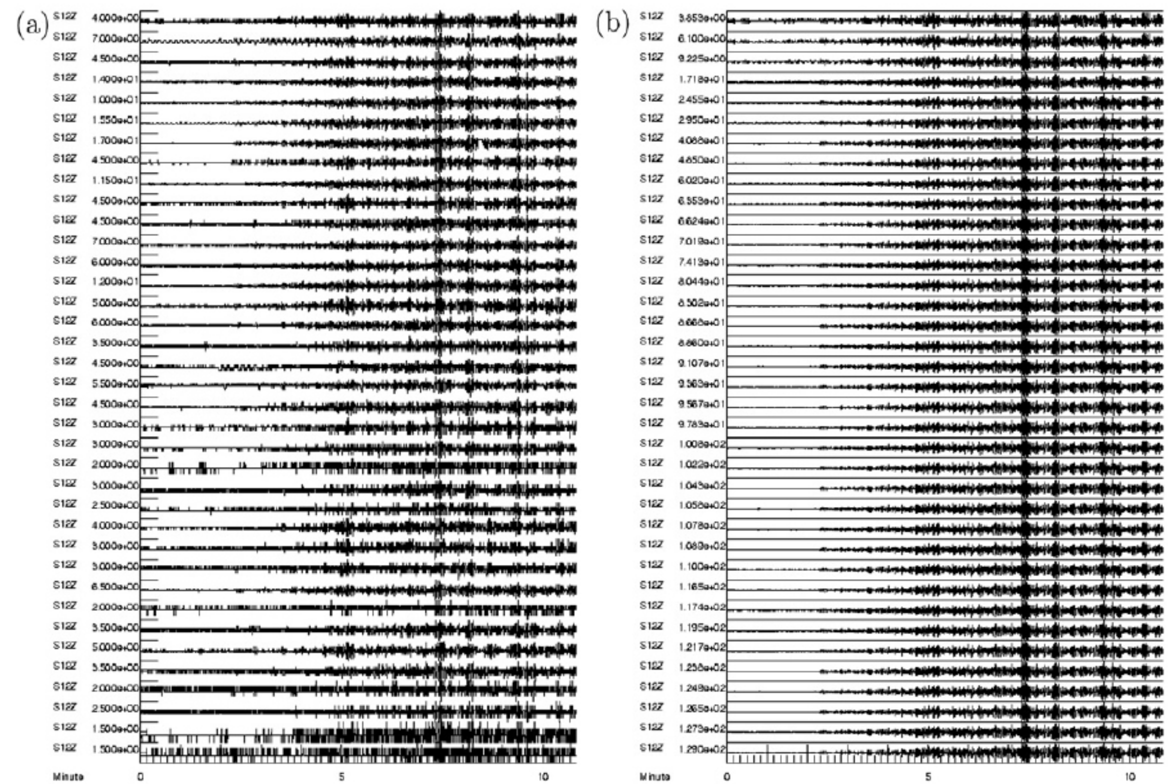


Weber et al. (2011)

- Main discrepancies on the deep mantle S wave velocity structure and on the core structure
- Agree on the existence of a liquid core

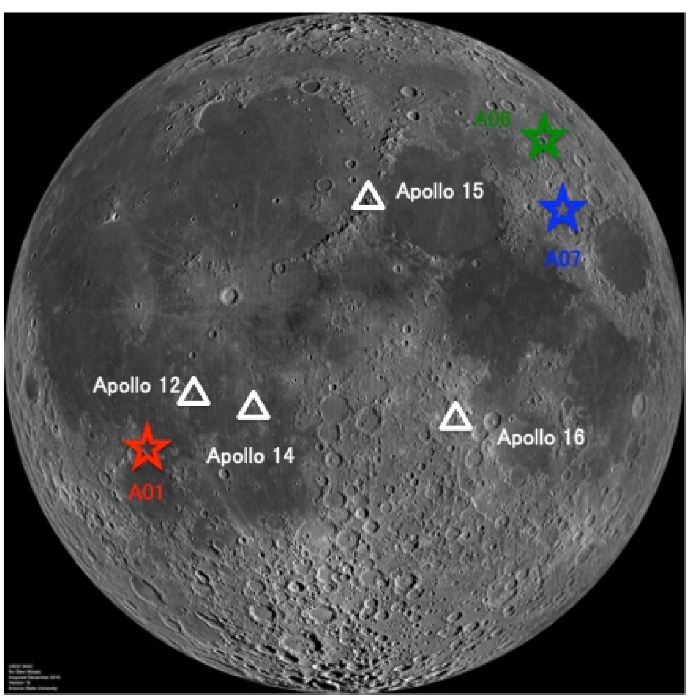
Deep moonquakes lighten the core

- Deep Moonquakes repeat at the same fault at rate of several per months
  - Are triggered by the Earth tide

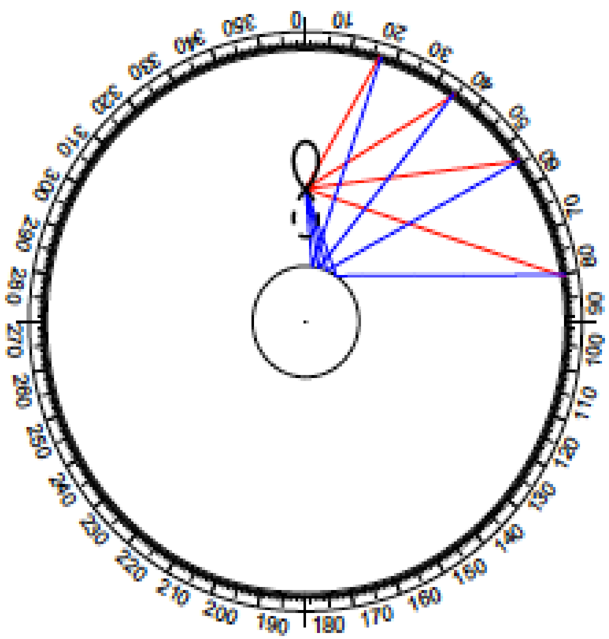


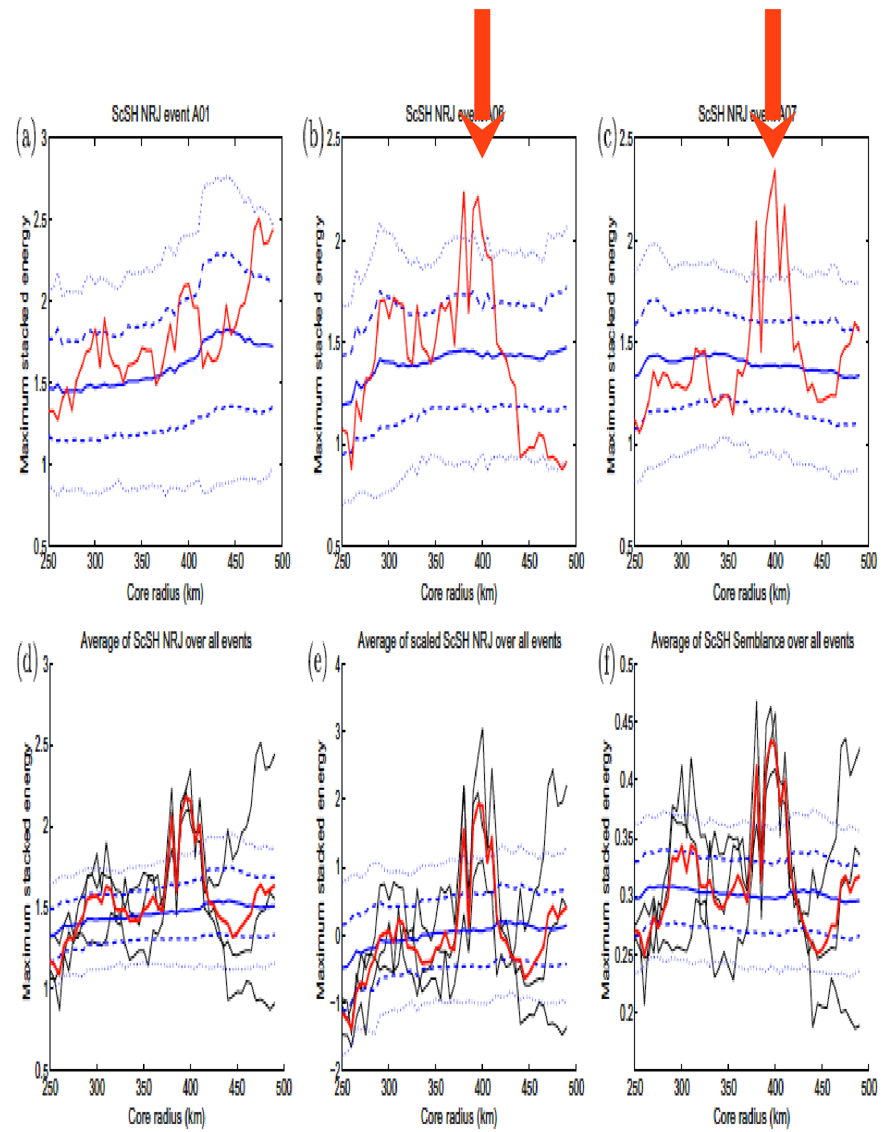
Garcia et al, 2011

- Are beneath the Apollo stations and lighten the deep Moon interior



Seismic evidence for a lunar core





Garcia et al., 2011
Weber et al, 2011

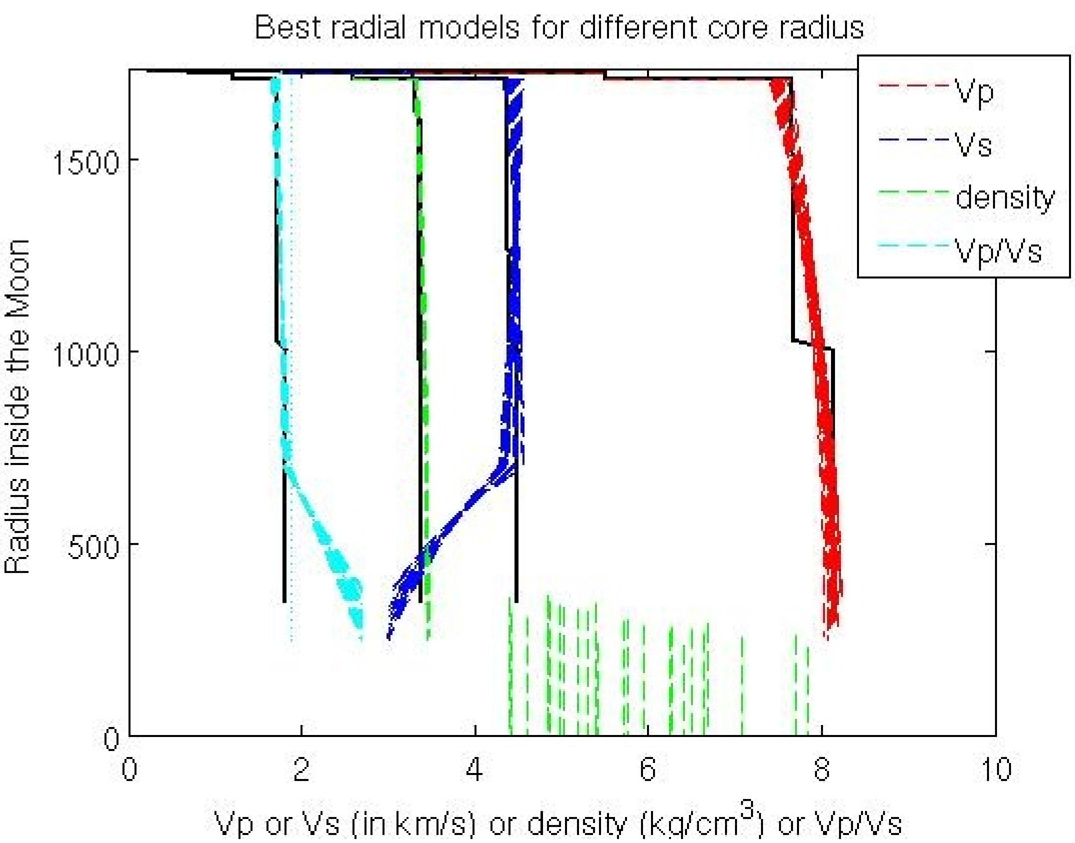
Other geophysical constraints
New results

- Love numbers, mass and moment of inertia of the Moon revisited by GRAIL mission + LLR
  - K2 increase → need for a less viscous region
- Crust density constrained by GRAIL to 2600 kg/m3
- High pressure and temperature studies of iron alloys :
  - Vp in liquid core ~4.0 km/s (Nishida et al.,2013)
  - Solid core density (~7500 kg/m3), Vp~5400 kg/m3 and Vs~3000kg/m3 better constrained (see next talk)
  - Outer core density strongly dependent on light element involved
- Magnetic induction to constrain core size => more from ARTEMIS mission results

Hot debate : Structure of lowermost mantle

- If love number k2 (measured at 1 month period) is assumed identical to the one at 1s period

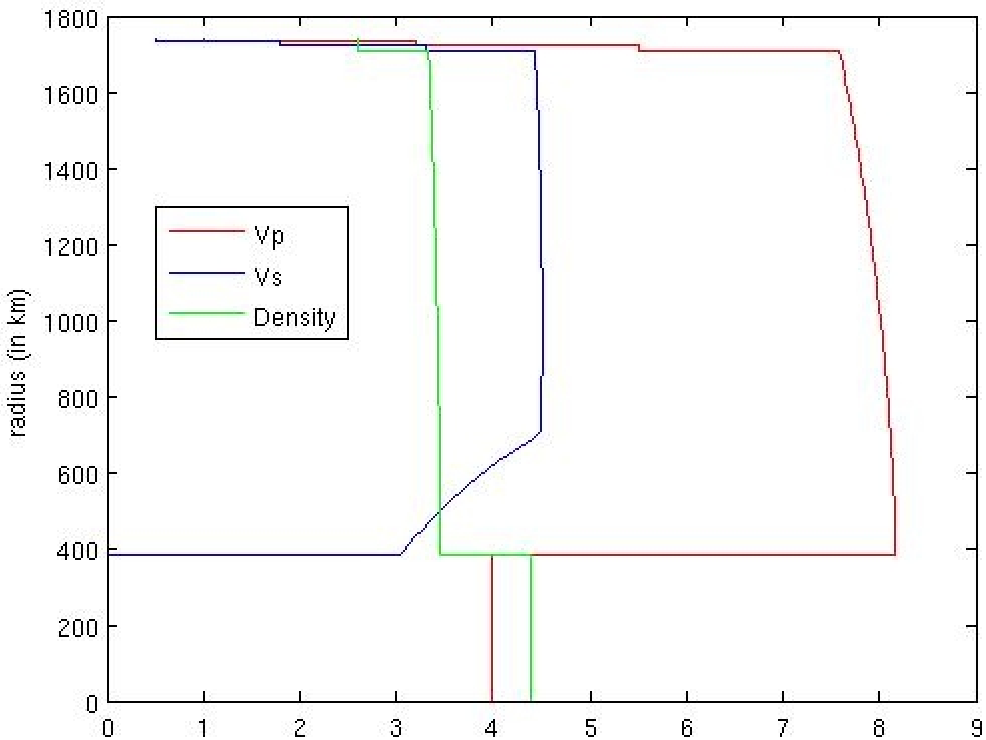
=> need low S wave velocities at mantle base

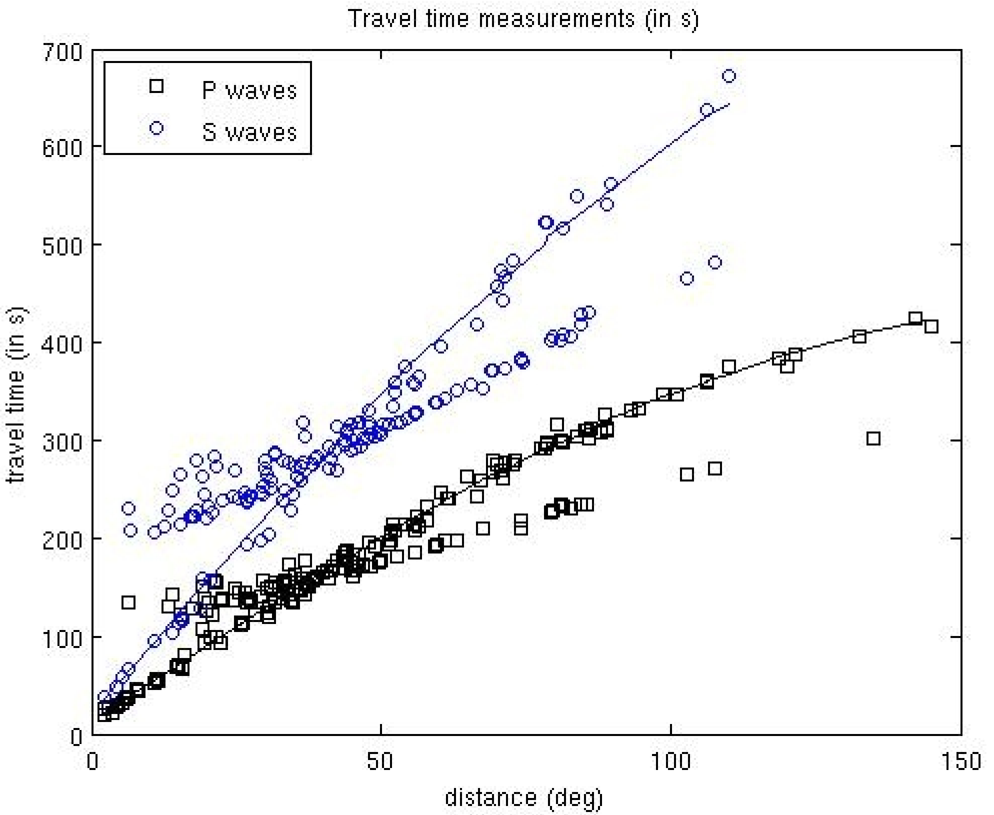


Hot debate : Structure of lowermost mantle

- Low S wave velocities in the lowermost mantle?

  => because no seismological constraints ! :

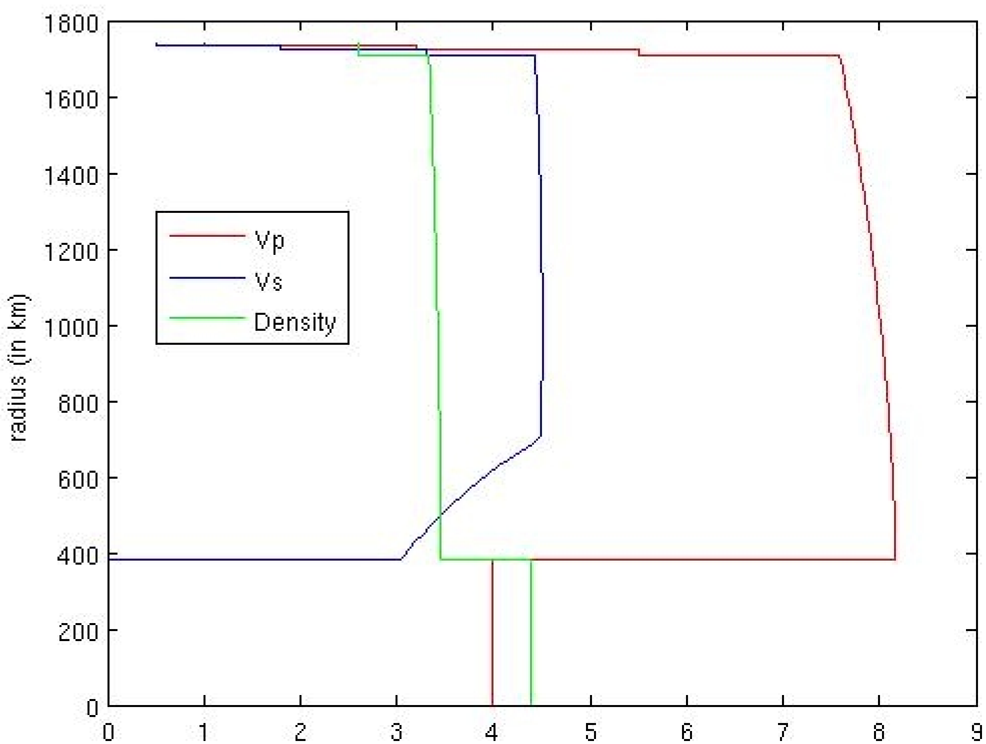


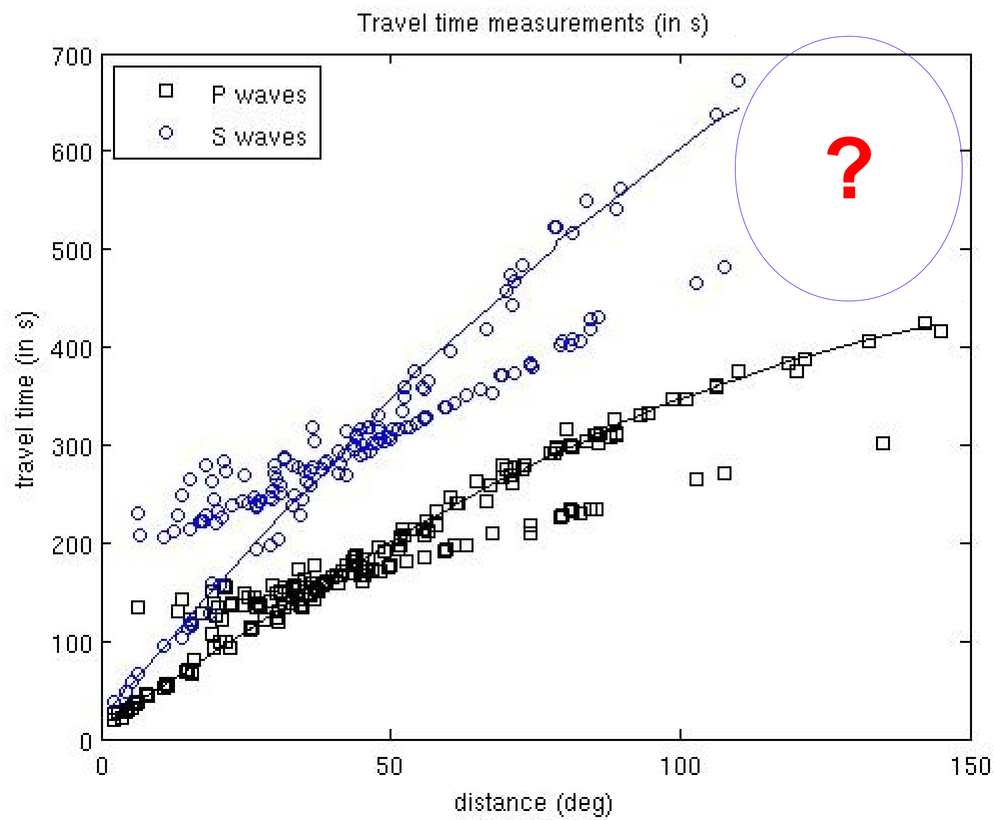


Hot debate : Structure of lowermost mantle

- Low S wave velocities in the lowermost mantle?

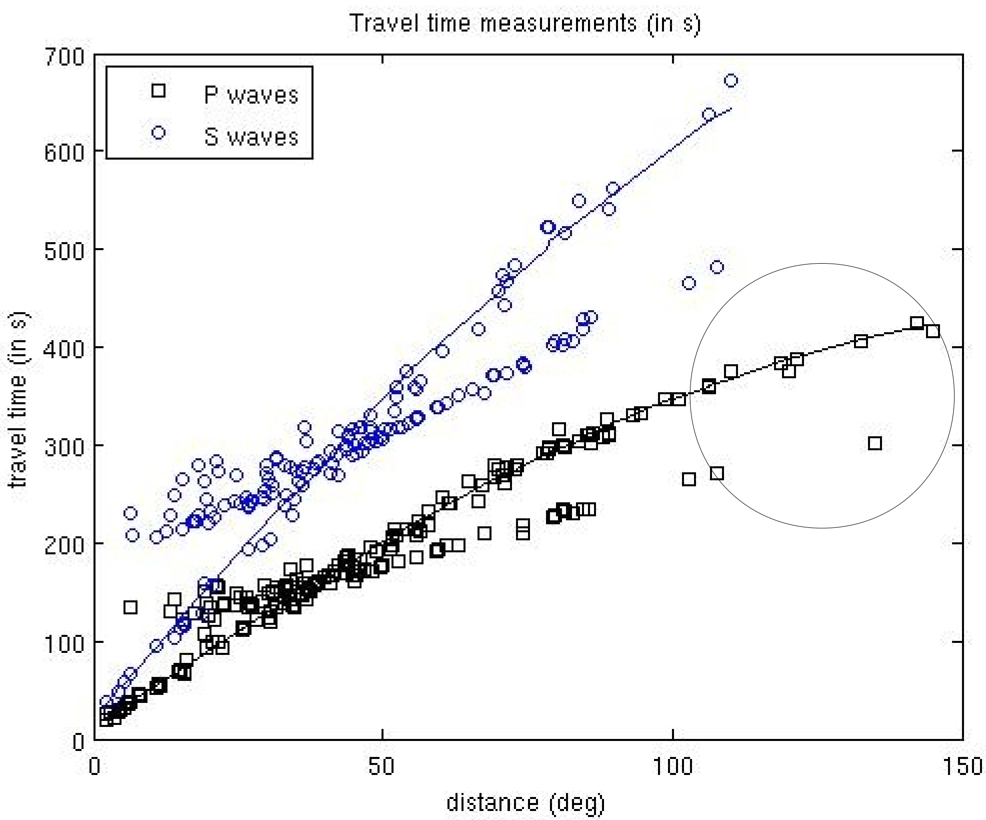
  => because no seismological constraints ! :
  No S wave arrivals at large distances

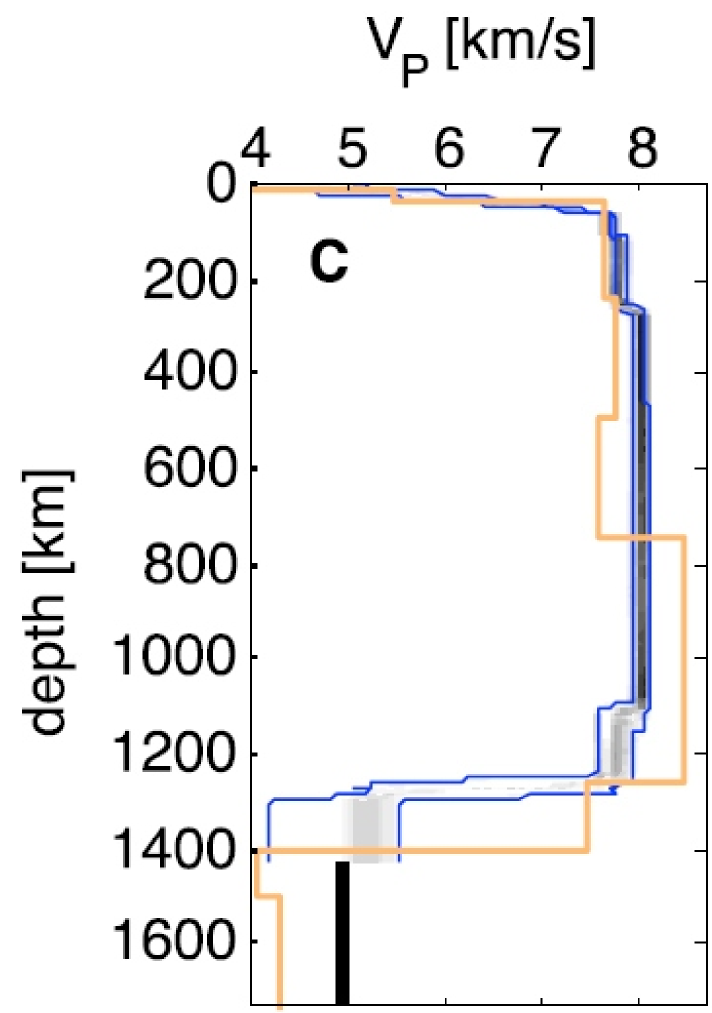




Hot debate : Structure of lowermost mantle

- But P wave arrivals are **not consistent** with a decrease in P wave velocity



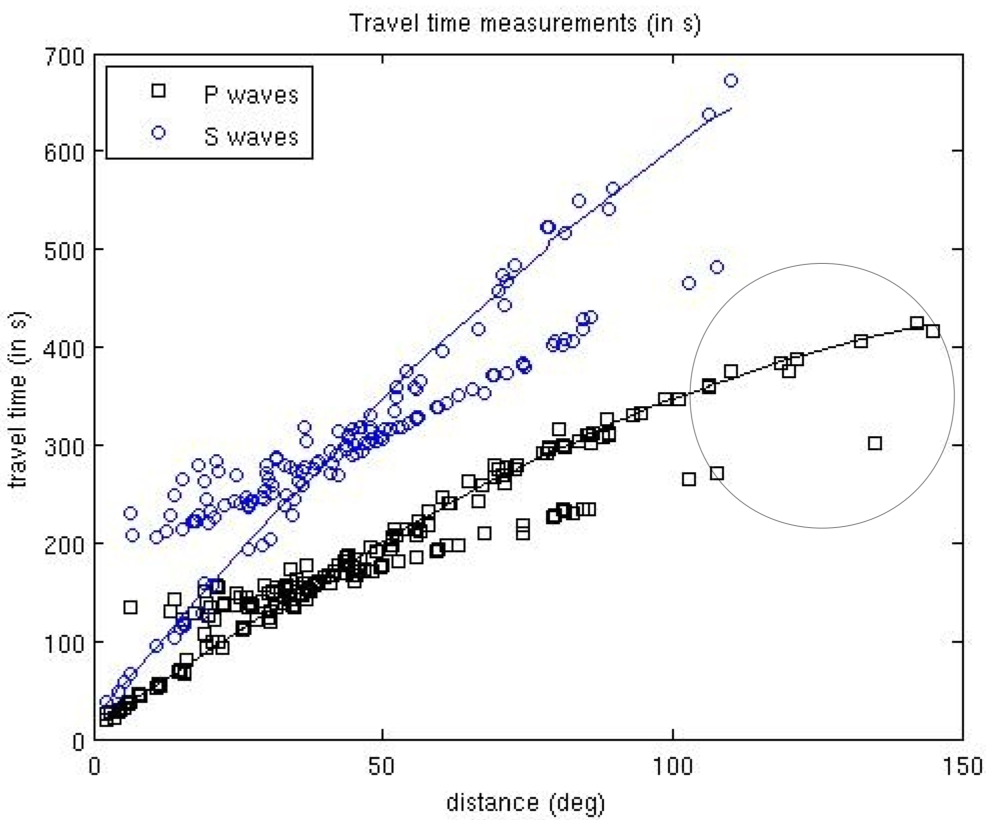


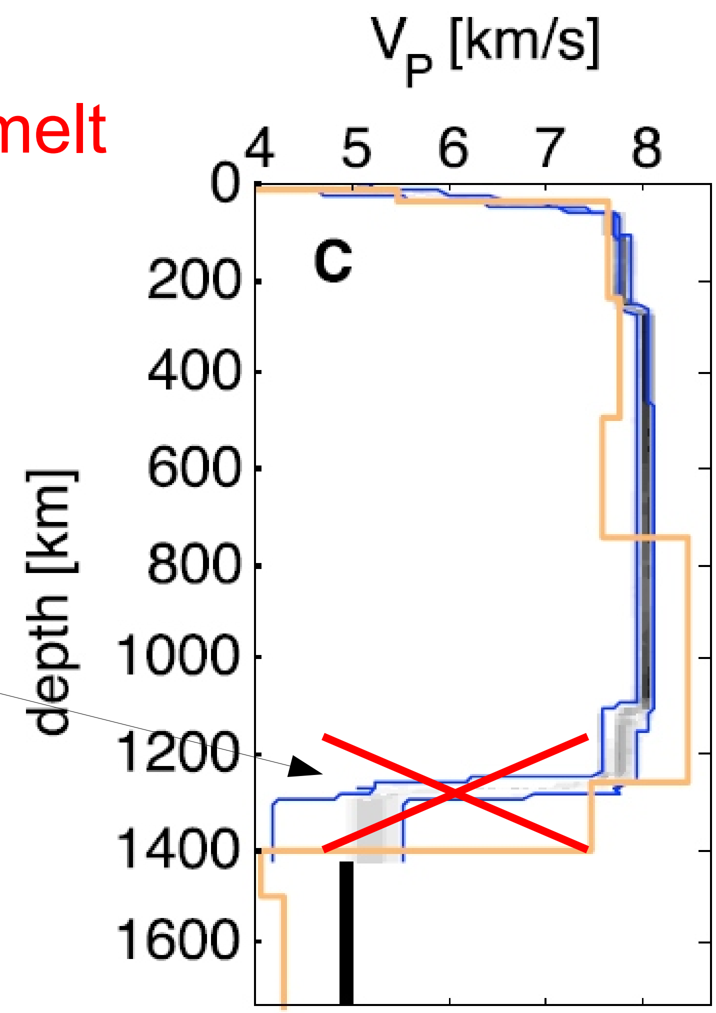
Khan et al. (2014)

Hot debate : Structure of lowermost mantle

- But P wave arrivals are **not consistent** with a decrease in P wave velocity

=> no models with large amounts of melt



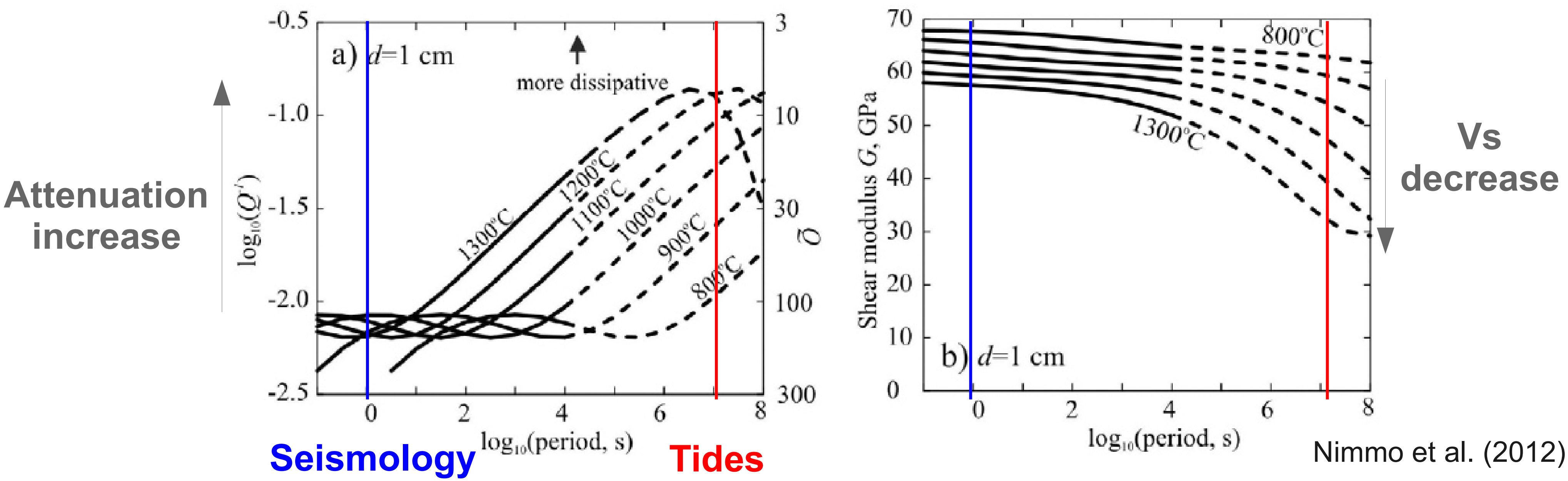


Khan et al. (2014)

Hot debate :
Structure of lowermost mantle

- What's wrong with k2 ?

=> interpolation of k2 over 7 orders of magnitude in period



Nimmo et al. (2012)

=> very different anelastic phenomena at 1 month period and 1 second period => over contributions to k2 from tides

Hot debate : Structure of lowermost mantle

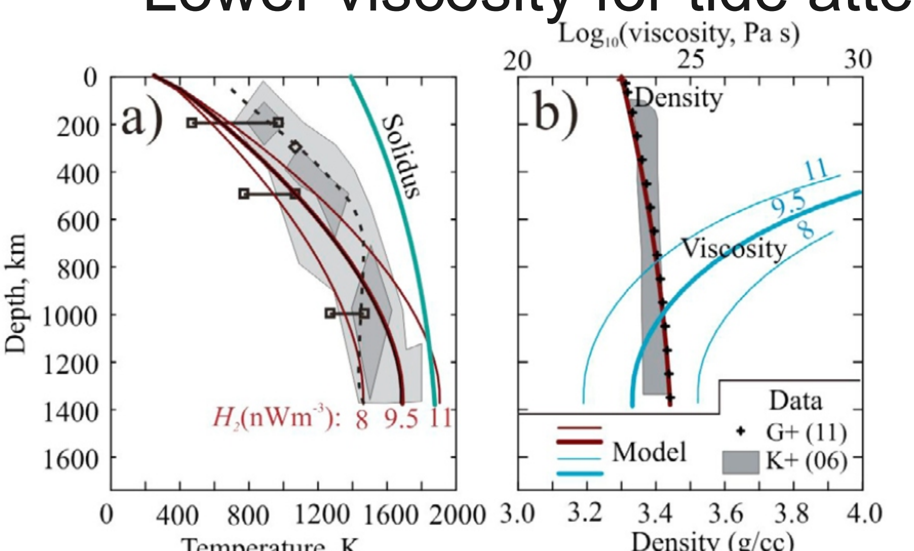
- The lowermost part of the mantle (below deep moonquakes or below 1100 km depth) may be the lithosphere/asthenosphere boundary of the Moon

=> do not require melt (temperature effect only)

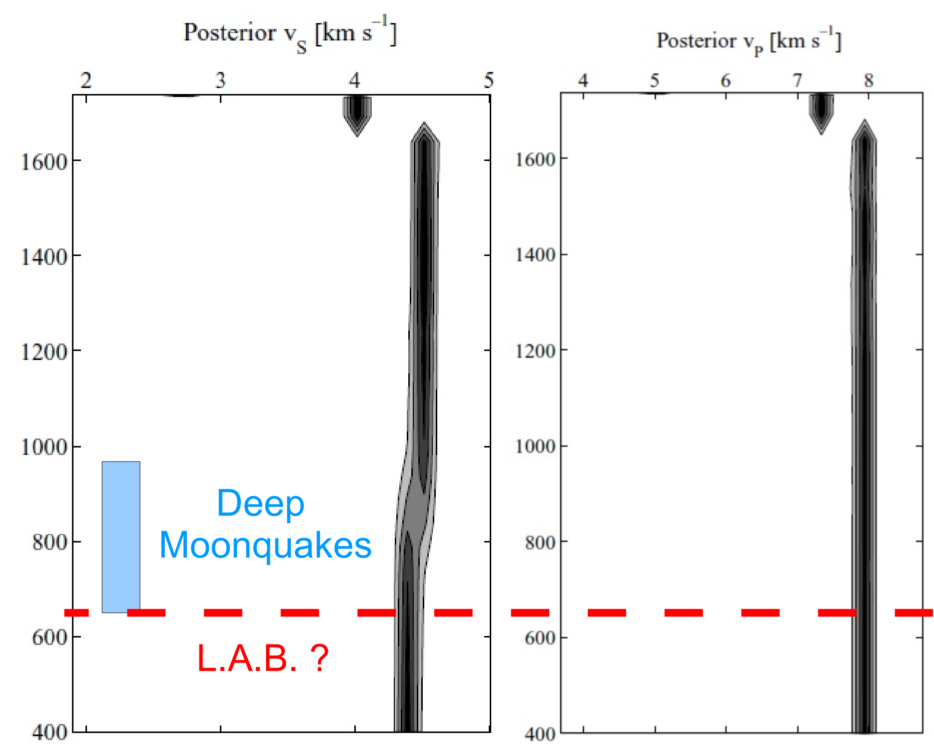
Vs decrease but not Vp

Increase of S wave attenuation

Lower viscosity for tide attenuation



Nimmo et al. (2012)



Khan et al. (2007)

Remaining uncertainties

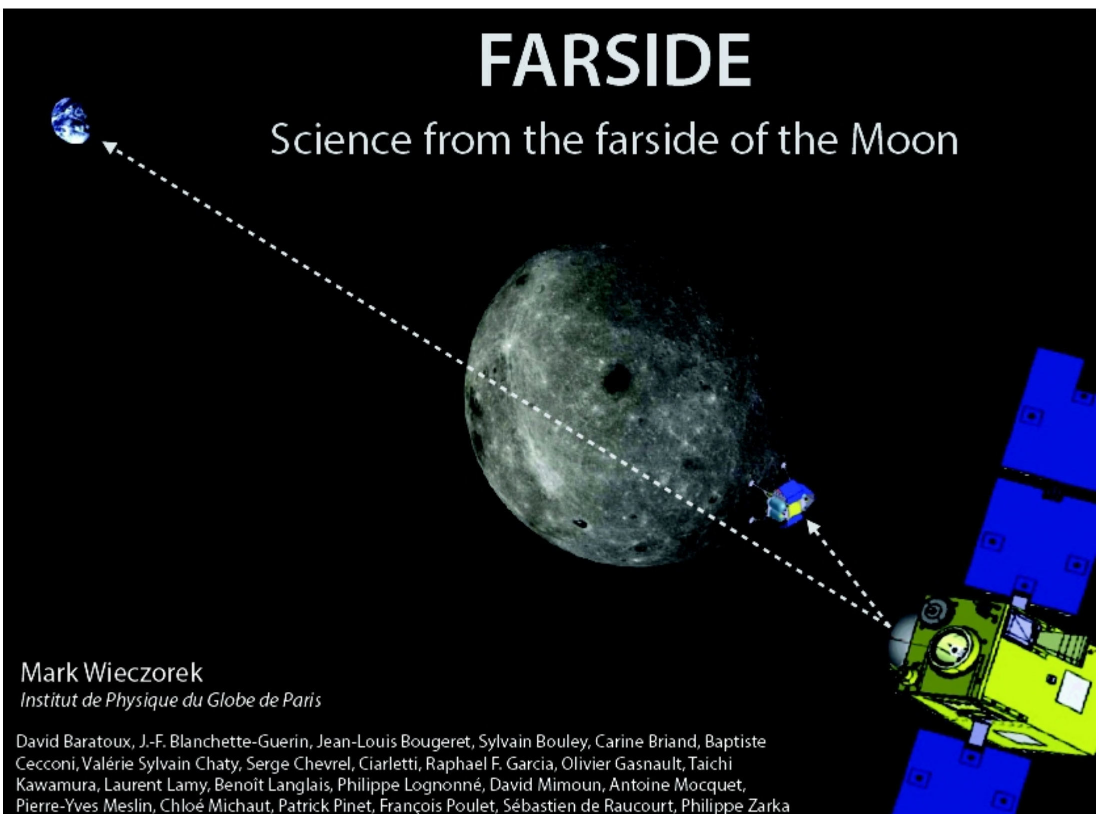
- Large lateral variations of seismic properties are expected
- Source mechanisms of deep moonquakes is unknown, but faults lubricated by quakes acting during millions years is favoured (Frohlich and Nakamura, 2009)
- Direct seismic detection of Moho
- Seismic waves passing through the core

Nimmo et al. (2012)

Khan et al. (2007)

Future observations

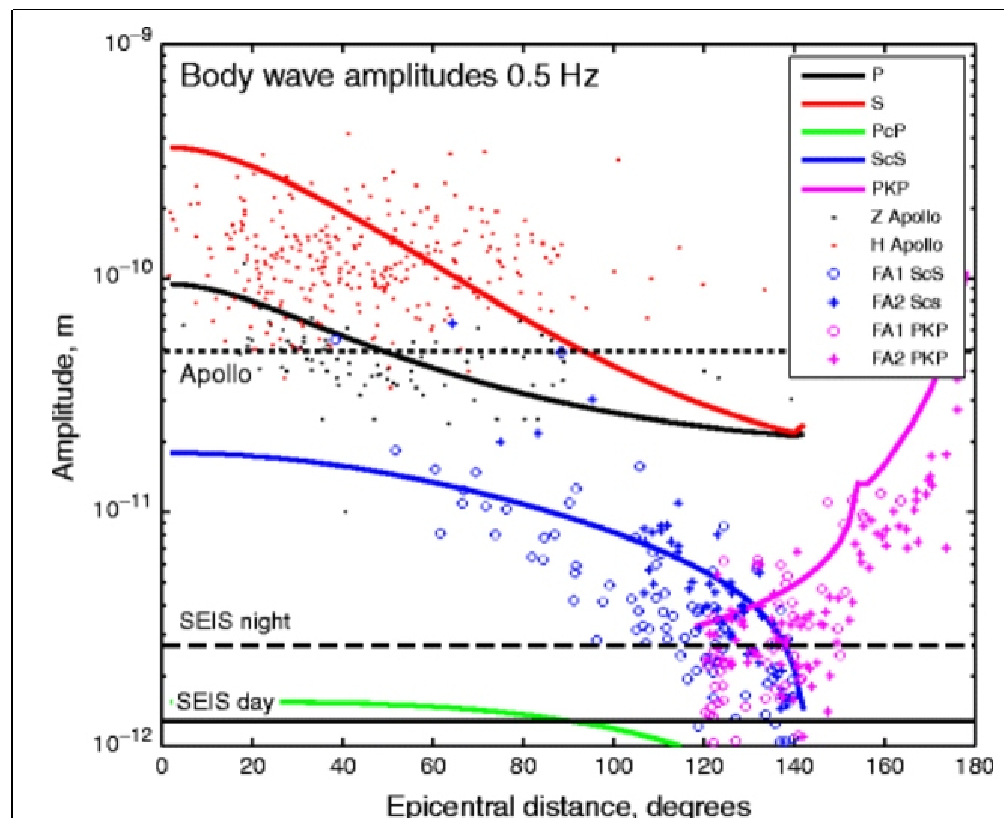
- Go to the farside and monitor impacts (known seismic sources)



Bouley et al., 2014

Future observations

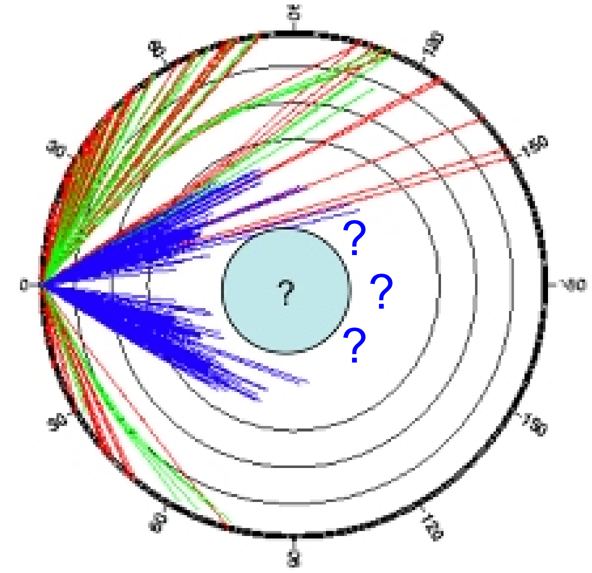
- Go to the farside and monitor impacts (known seismic sources)
- Increase sensitivity and enlarge bandwidth to lower frequencies

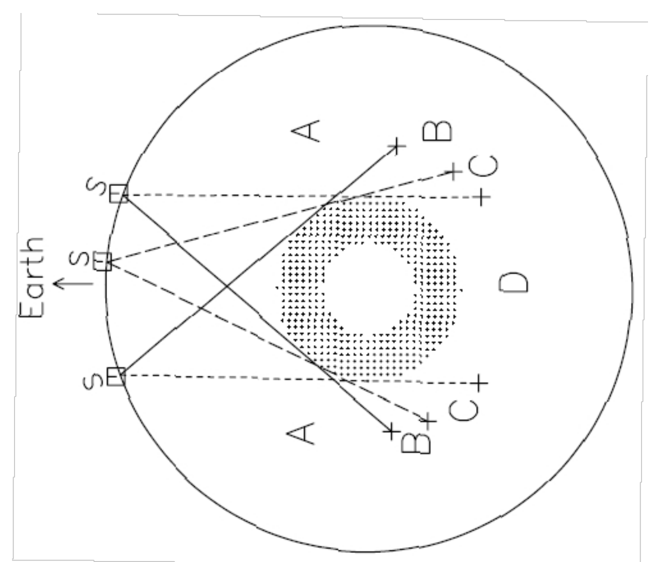


Mimoun et al. (2013)

Far side station advantages

- Detect already known deep moonquakes and far side ones → new core information

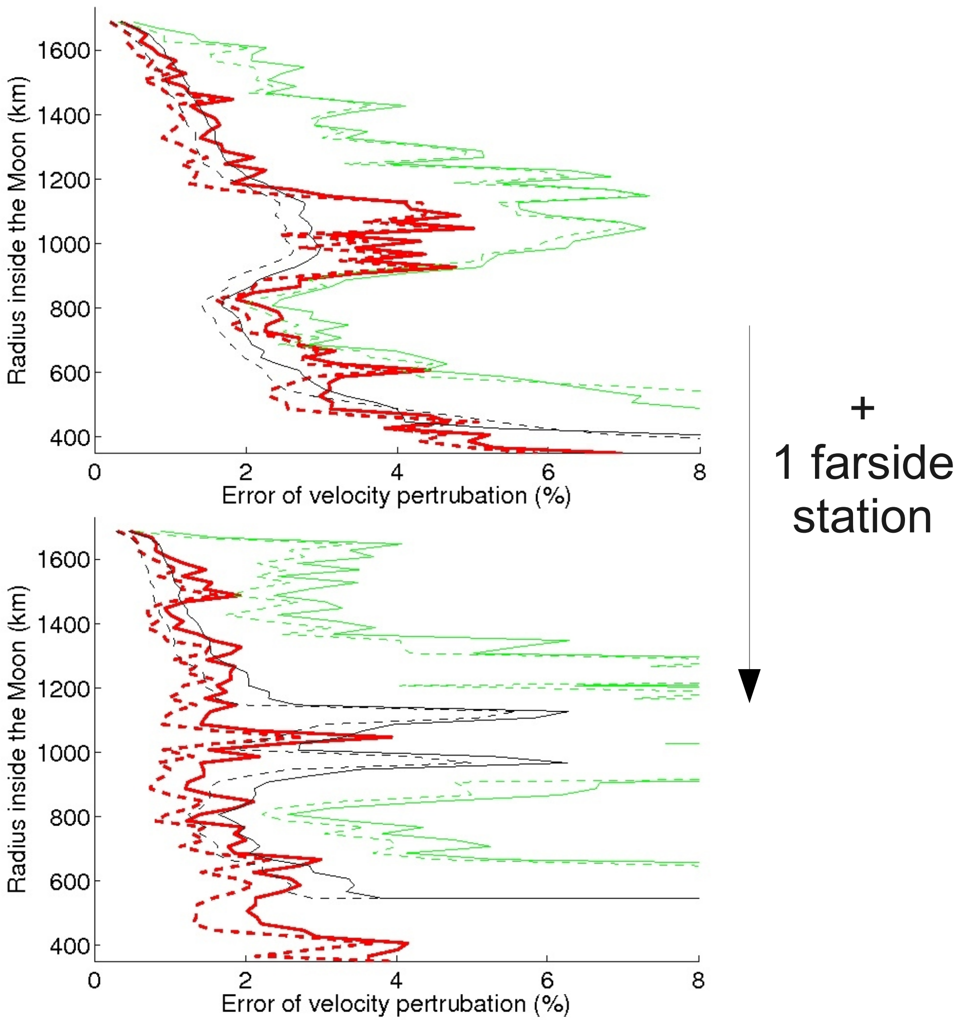




Nakamura et al. (2005)

Far side station advantages

- Detect already known deep moonquakes and far side ones → new core information
- Adding a farside side station to an existing 3 nodes network divide by 2 the error bar of deep internal structure models



Error bar (in %)

Yamada et al. (2011)

Conclusion

- First extra-terrestrial seismic network allowed **imaging from sub-surface to the core.**
- Discrepancy between love numbers at tidal periods and seismic observations not solved, but **lowermost mantle melting is not favoured**.
- **New constraints** (GRAIL, HP/HT experiments...) should be integrated in future models.
- **Going to the farside** with new planetary geophysics instrumentation will solve the uncertainties on the deep Moon structure.

Back up slides

Construction of radial Moon internal structure models

- Fit P and S wave travel times, Love numbers, mass and moment of inertia of the Moon
- Seismic events relocated inside each model
- A priori information and physical constraints:
  - Average crustal thickness is fixed at 40 km
  - Vp and Vs crustal model of Beyneix et al. 2006
  - Density model is imposed to fit exactly lunar mass
  - Birch law, Adams Williamson equation and Vp/Vs ratio linearly varying inside the mantle → Vp, Vs and density inside the mantle

Construction of radial Moon models

- Only 6 parameters:
  - Crust density
  - $Vp(r)=a+b*\rho(r)$: birch law
  - $Vp/Vs=A+B*r$: linear in radius
  - Core radius
  - Crust/mantle density jump fixed to 550 kg/m3

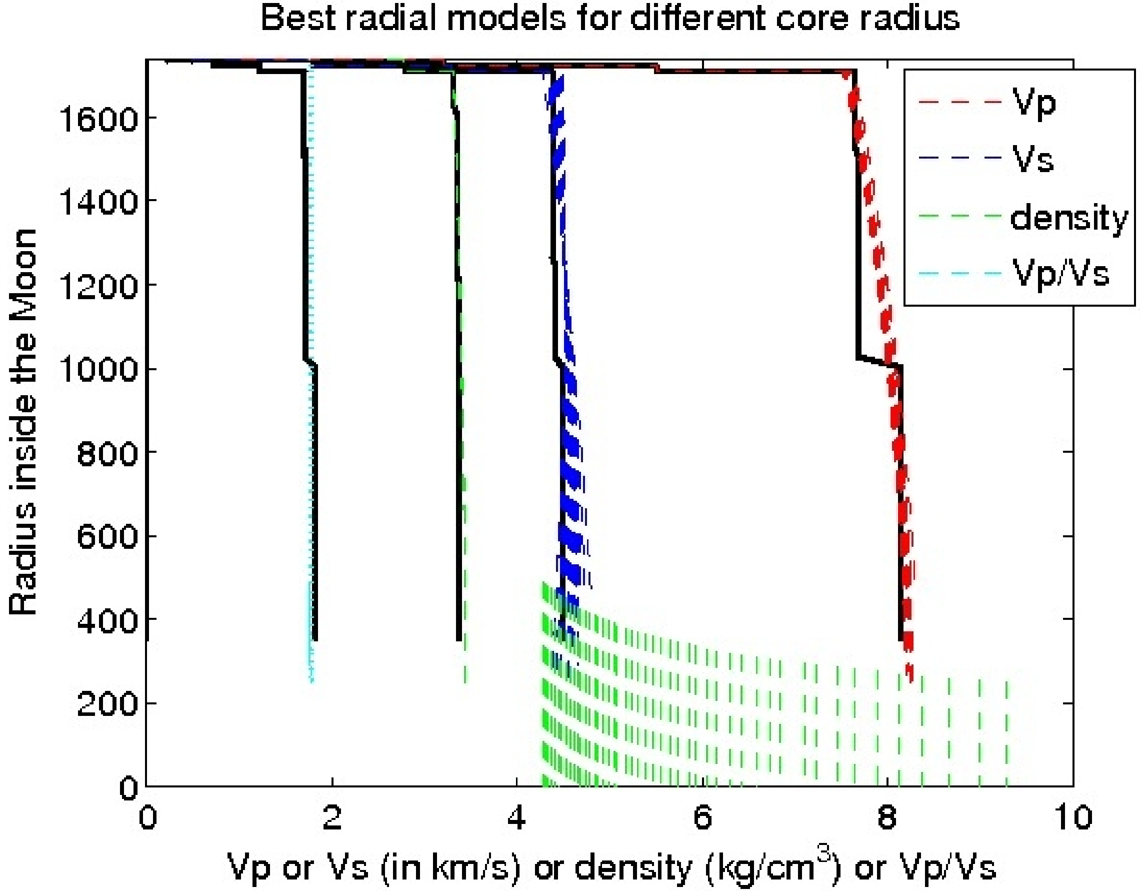
  } Vp(r)
  Vs(r)
  Density : $\rho(r)$

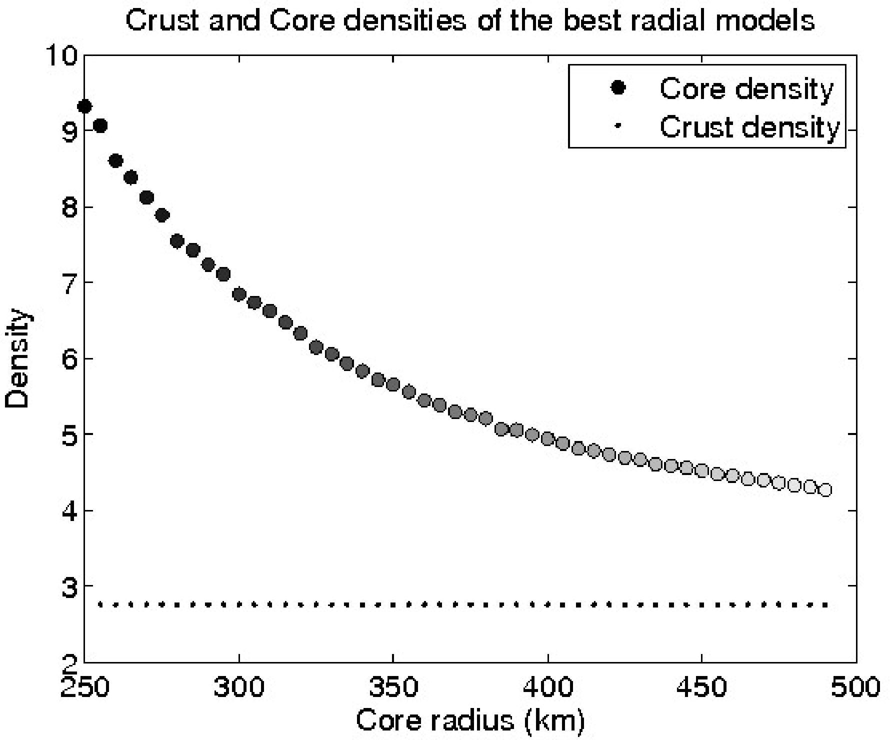
- Strategy:

  Find the best model for each core radius (5 km step), and use these models for searching core reflected seismic phases

- Inversion by Neighbourhood Algorithm

Best radial Moon models

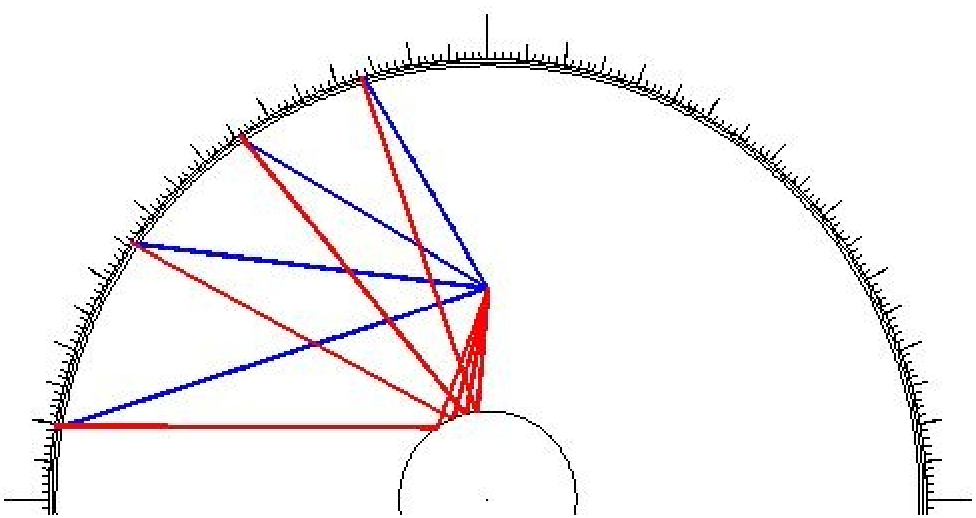


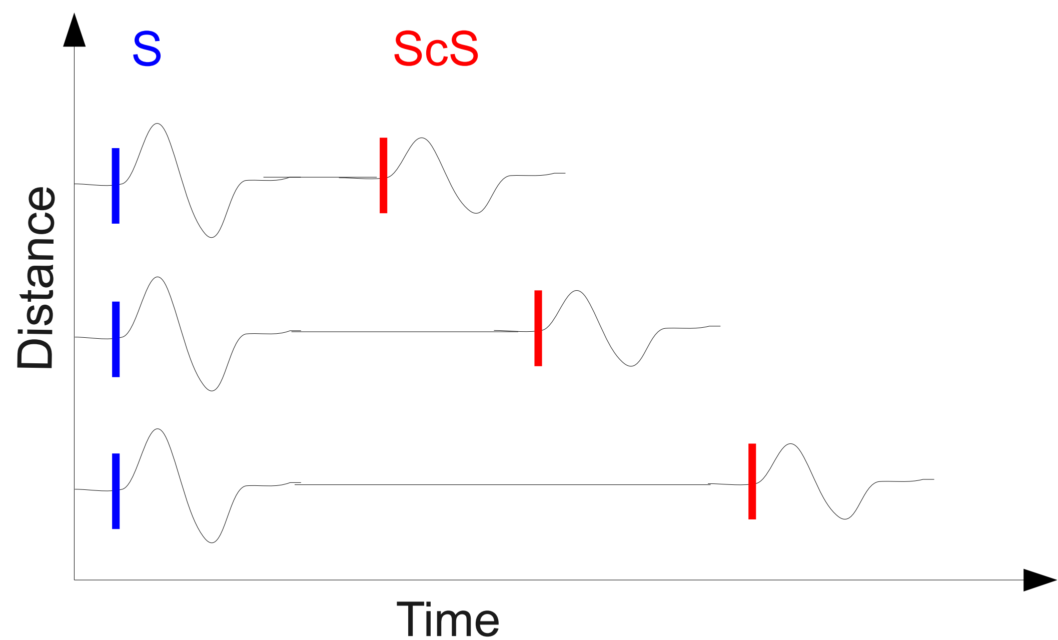


- Smooth variations in the mantle
- Vs larger than before at the base of the mantle
- Core density deduced from core size

Objective: detection of core reflected SH waves

- Total reflection of SH waves if a liquid core
- Use of deep moonquakes to reduce the effect of scattering inside the crust





Objective: detection of core reflected SH waves

- Total reflection of SH waves if a liquid core
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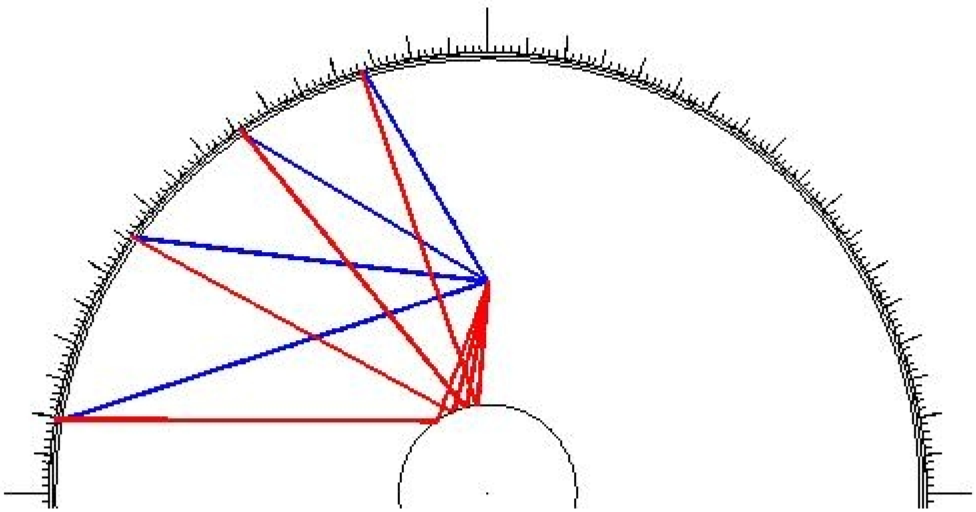
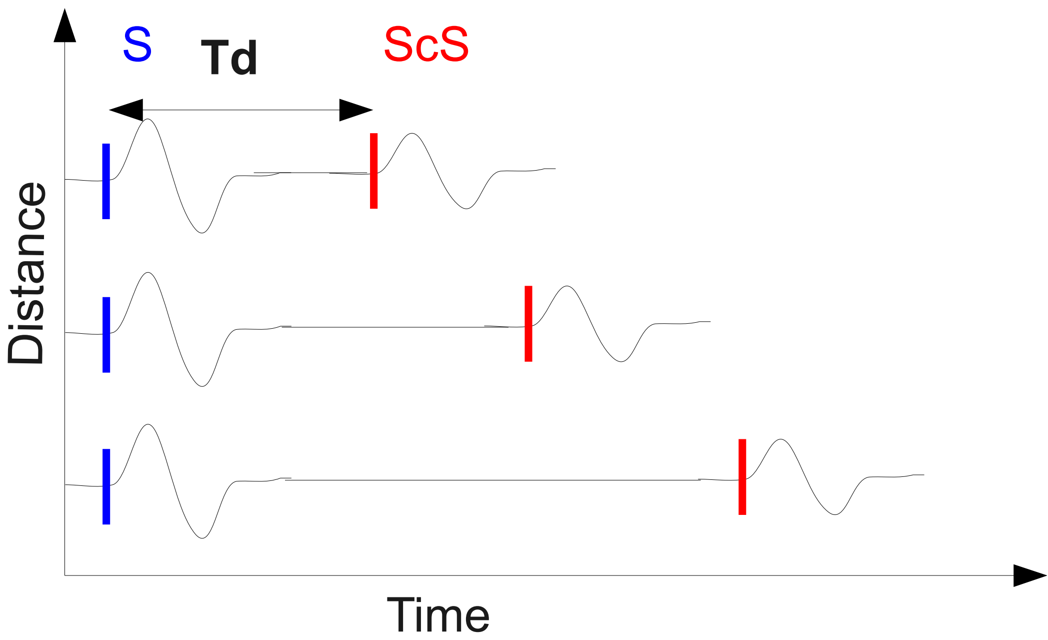
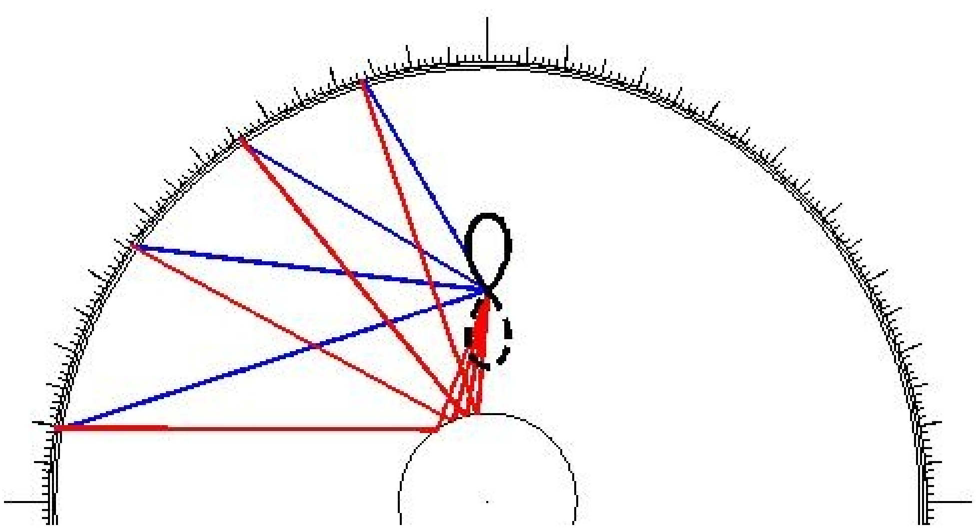
- Use ScS-S diff. Time (Td) to avoid crust effects

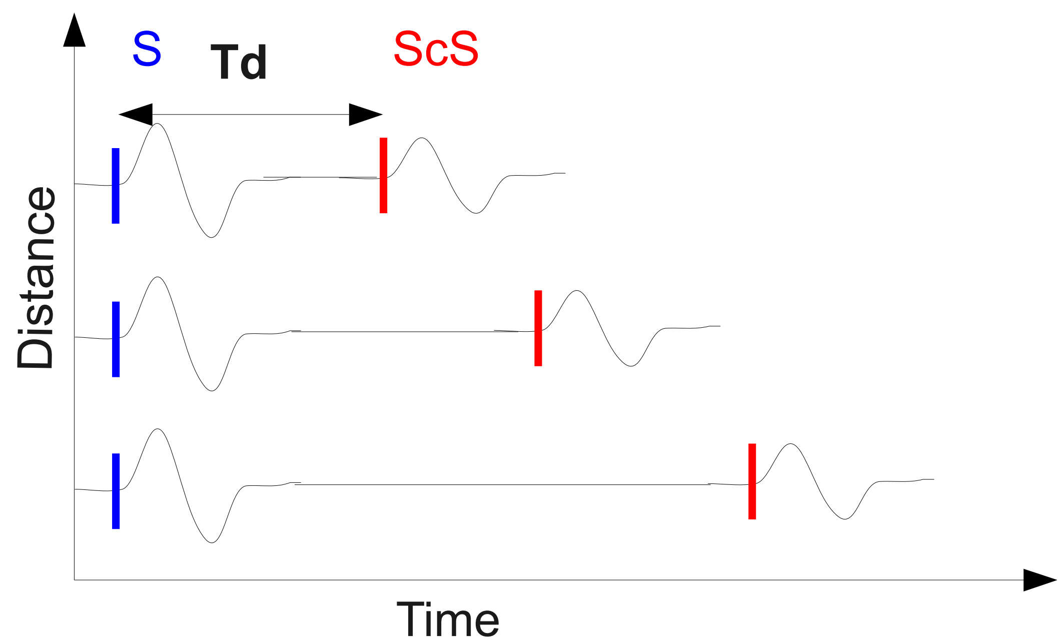




Objective: detection of core reflected SH waves

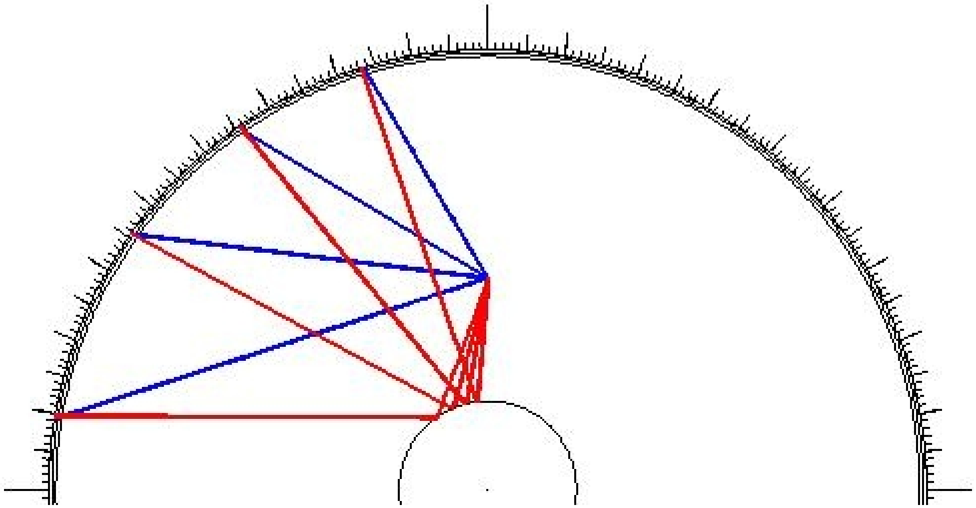
- Total reflection of SH waves if a liquid core
- Use of deep moonquakes to reduce the effect of scattering inside the crust
- Use ScS-S diff. Time (Td) to avoid crust effects
- Deep quakes radiate more energy along the vertical

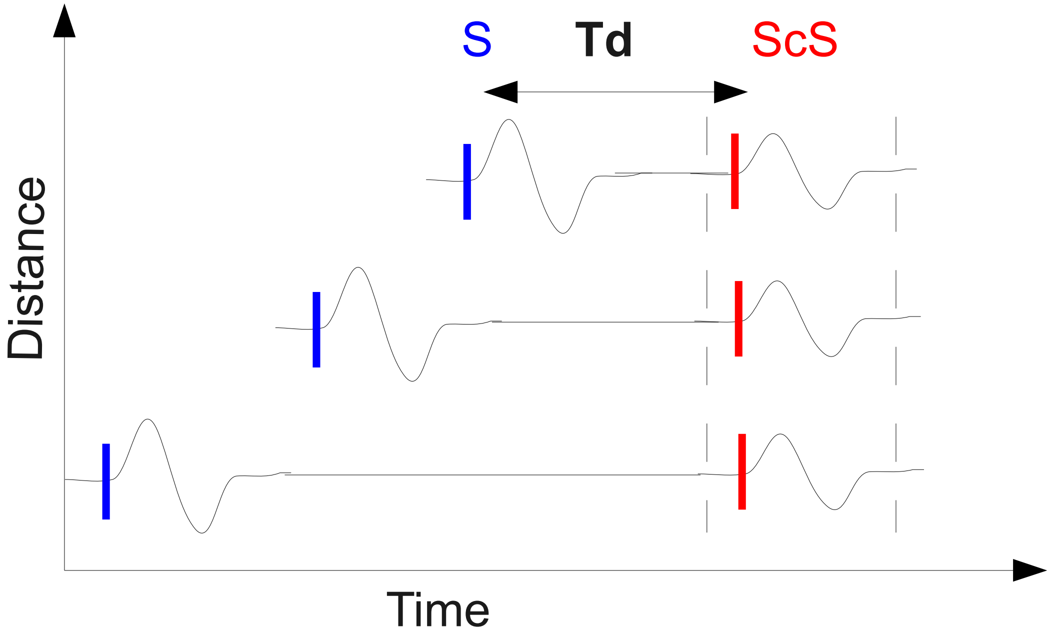




Linear summation of transverse records depends on ScS-S time

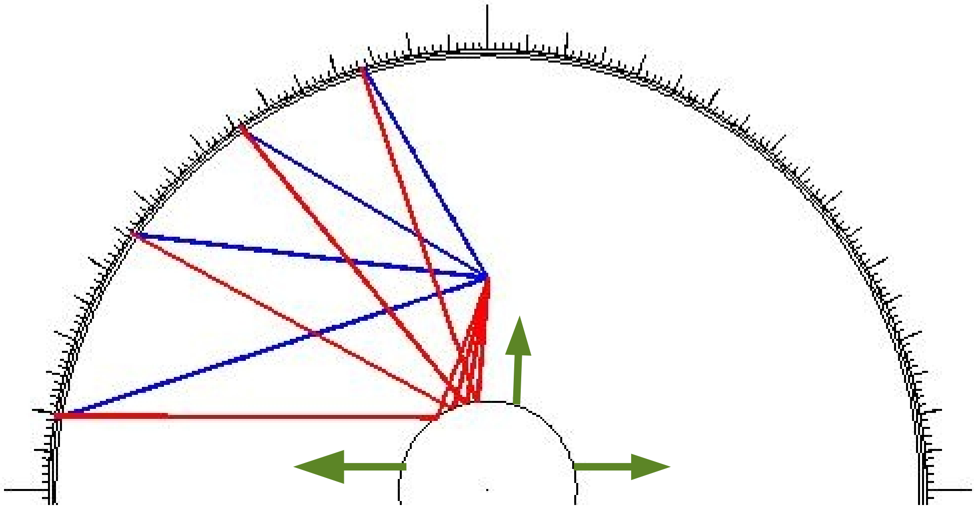
- Pick S wave arrivals
- Compute ScS-S differential times (Td)
- Align on ScS arrivals and sum the waveforms
- Compute stack energy in a window around ScS

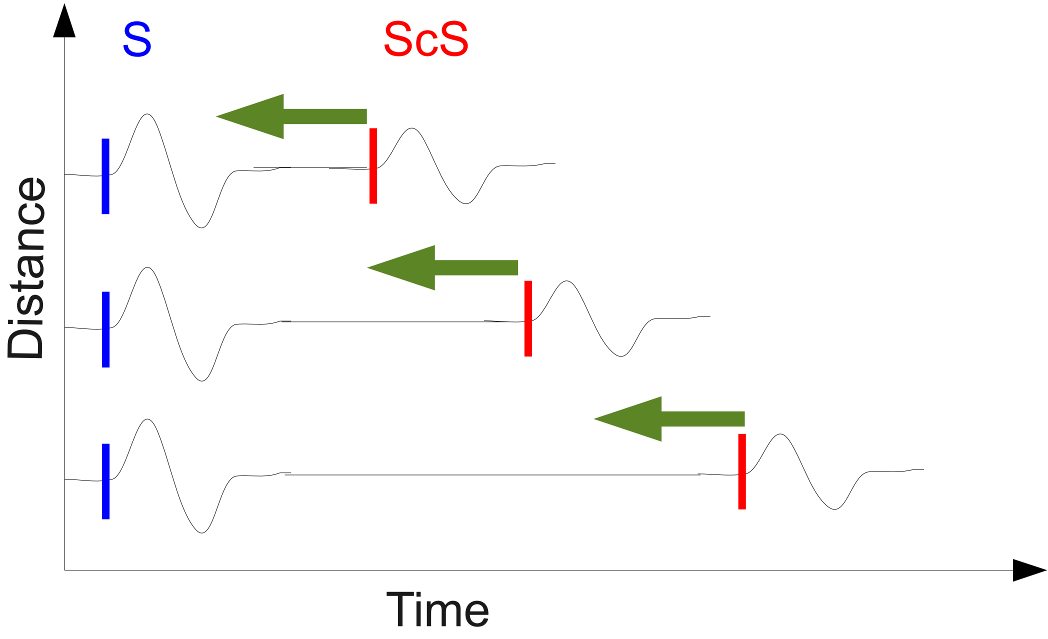




Differential time depends on core radius

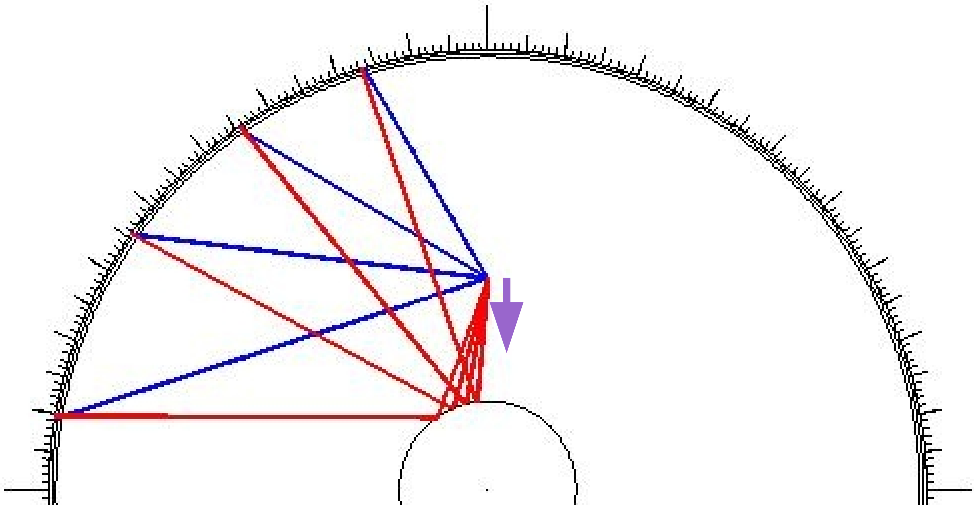
- Increase in core radius reduces Td

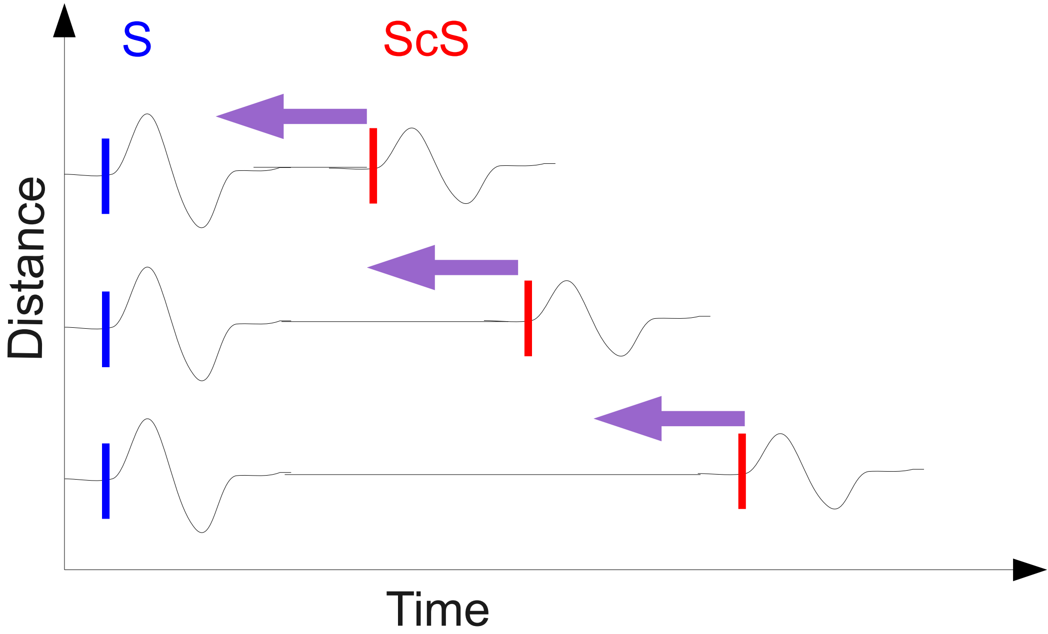




Differential time depends on event depth

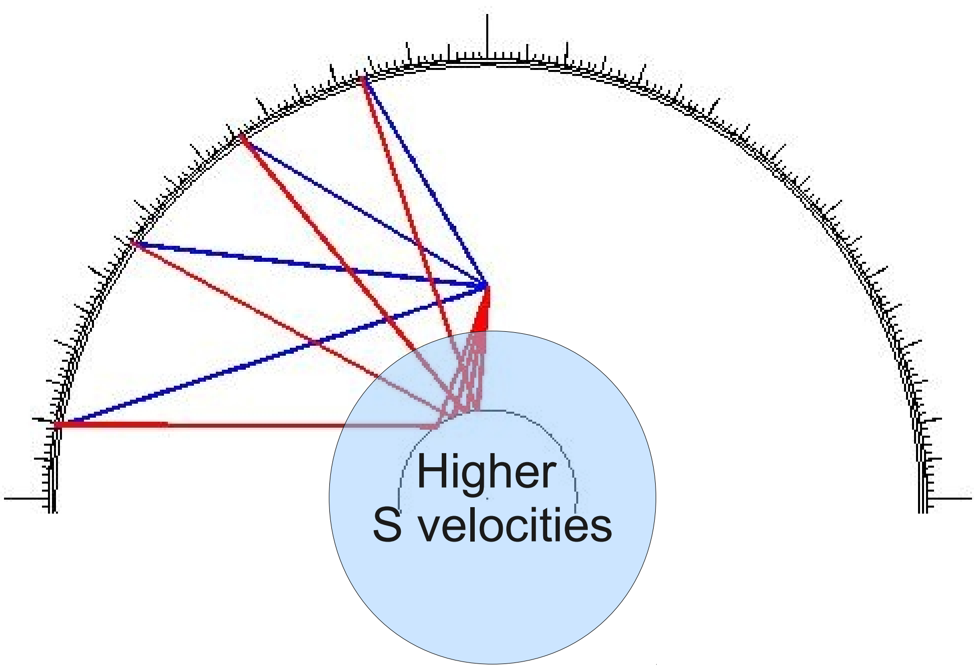
- Increase in event depth reduces Td
- Almost the same effect as core radius
- Parameter investigated in stacking process

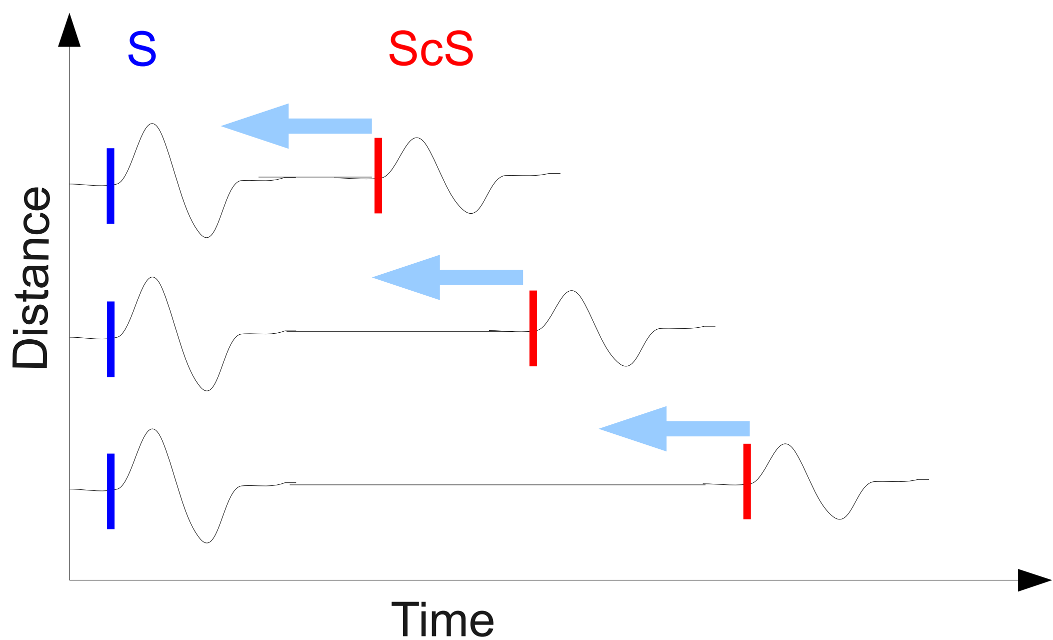




Differential time depends on velocity model

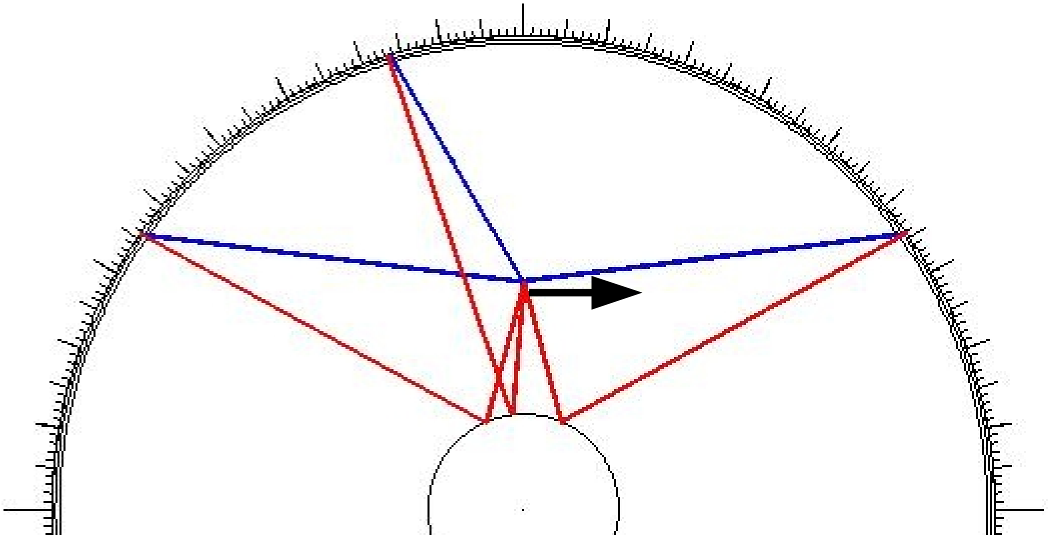
- Increase of velocity below the quake reduces Td
- Very poor knowledge of S wave velocities in the deep Moon.

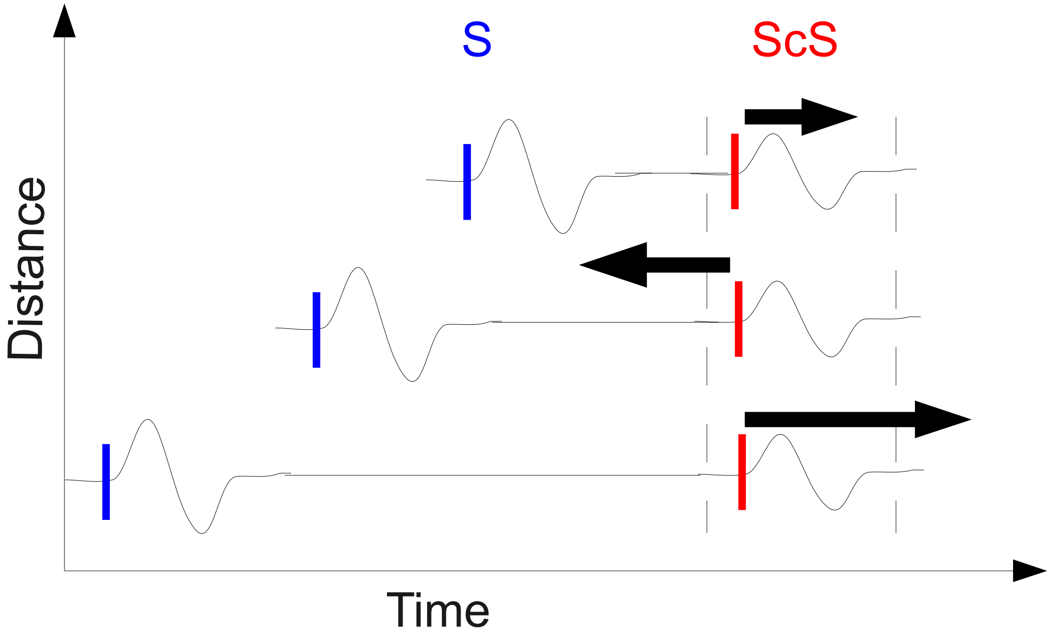




Differential time depends on lateral event location

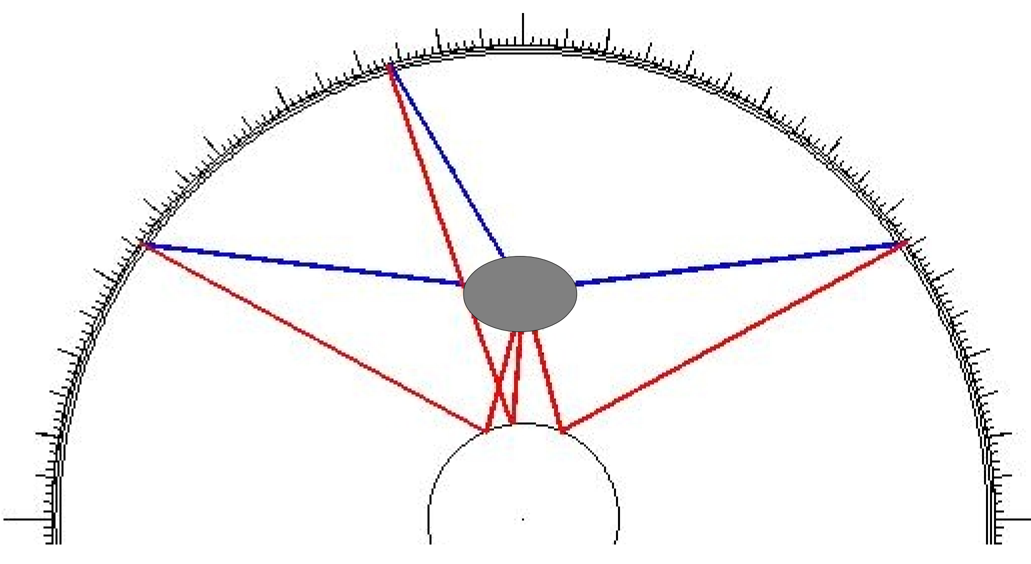
- Second order effect, but cannot be corrected from ScS-S differential times and makes the stacking process inefficient.

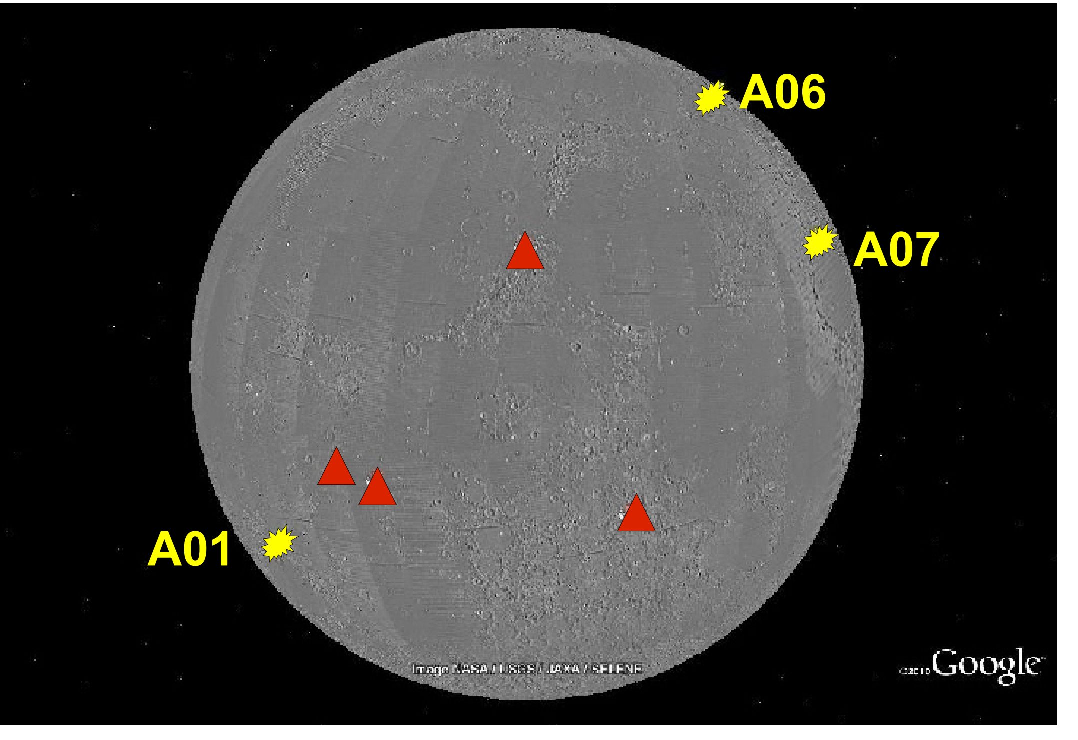




Differential time depends on lateral event location

- Second order effect, but cannot be corrected from ScS-S differential times and makes the stacking process inefficient.
- Due to large lateral location error, only 3 deep moonquakes can be used!!!



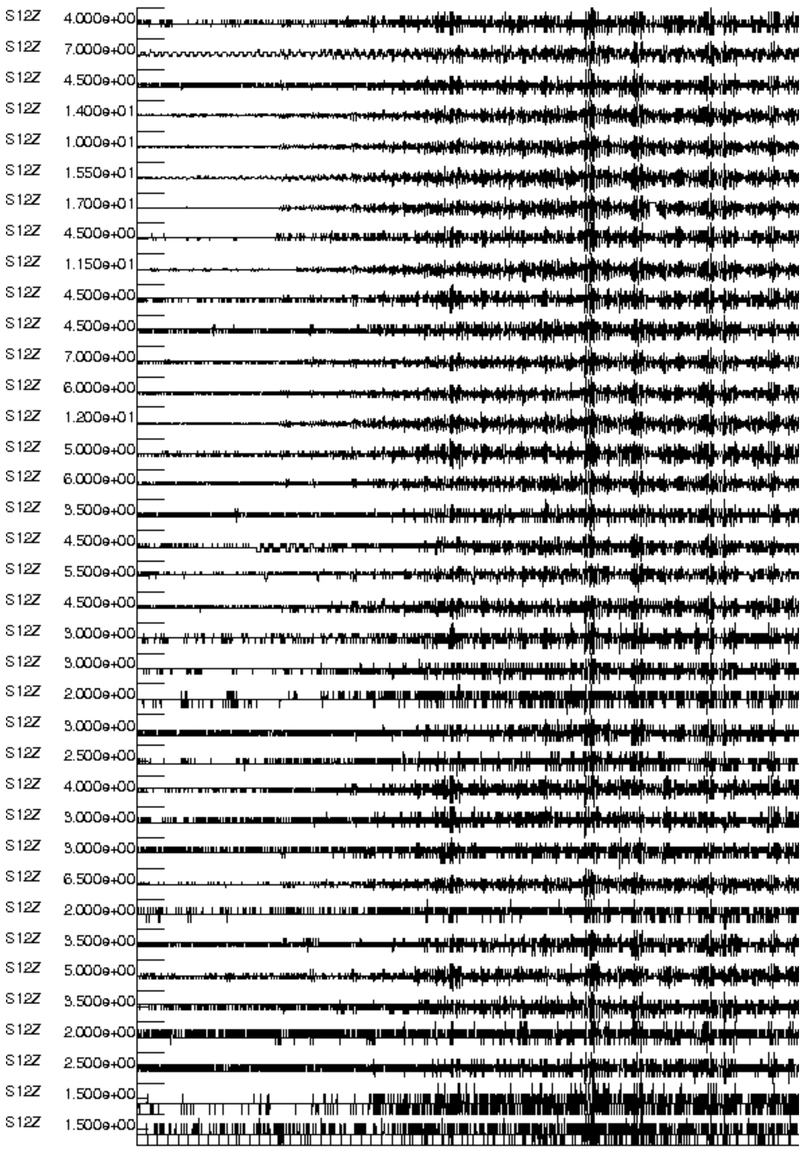


Data pre-processing

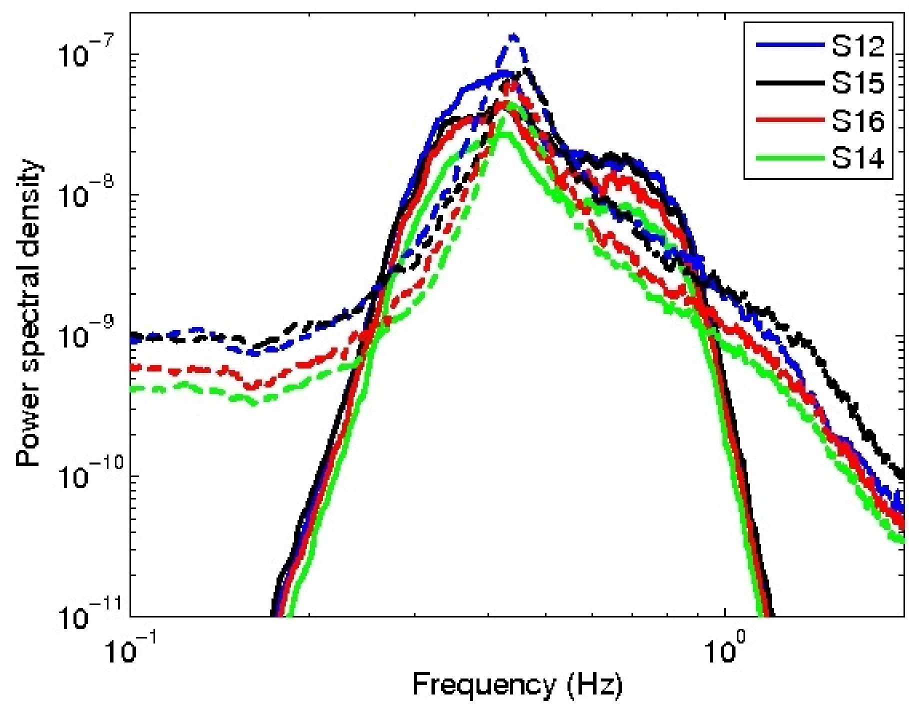
- Differential times are computed inside the best radial models in order to stack the waveforms
- Moon data require pre-processing
  - Summation of deep moonquake records
  - Correction of horizontal component (X and Y) gains
  - Correction of site and instrument frequency responses

Data pre-processing

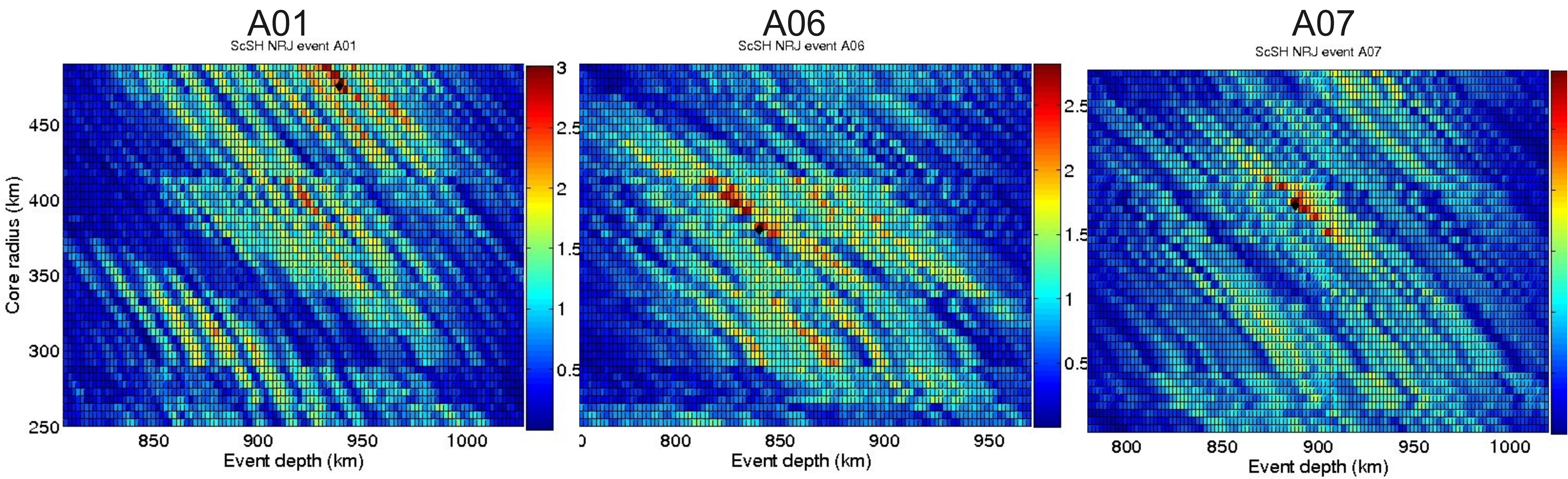
Individual deep moonquake records :
Station S12 event A01



- Individual records of deep moonquakes are summed after alignment by cross-correlation
- Preprocessing try to enlarge the frequency band but remain in the narrow 0.3-0.9 Hz range

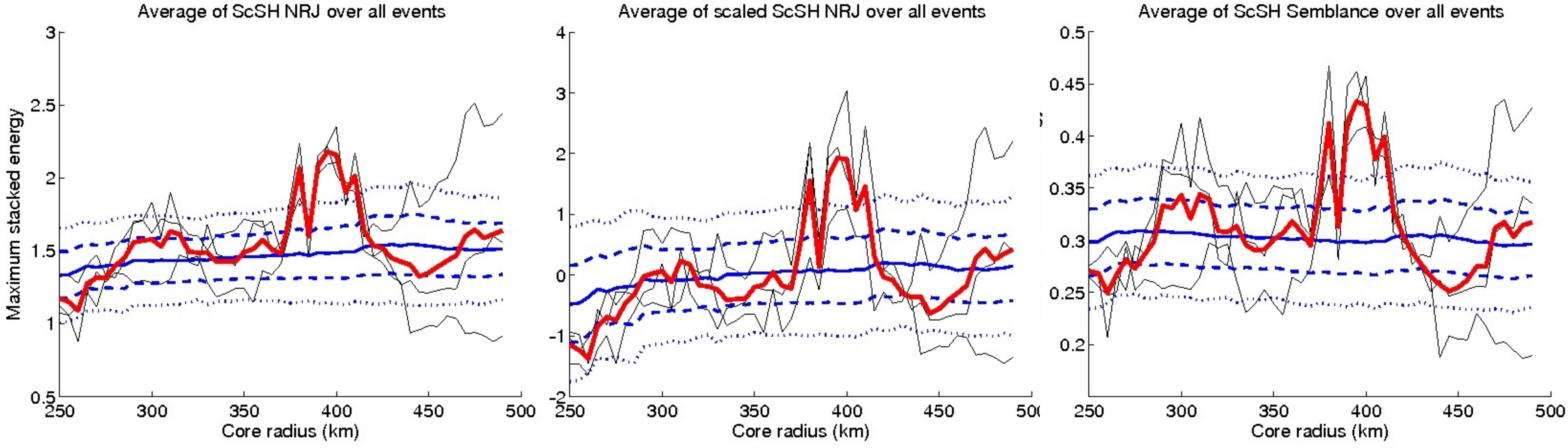


ScSH stack energy for the 3 selected quakes (small location error)

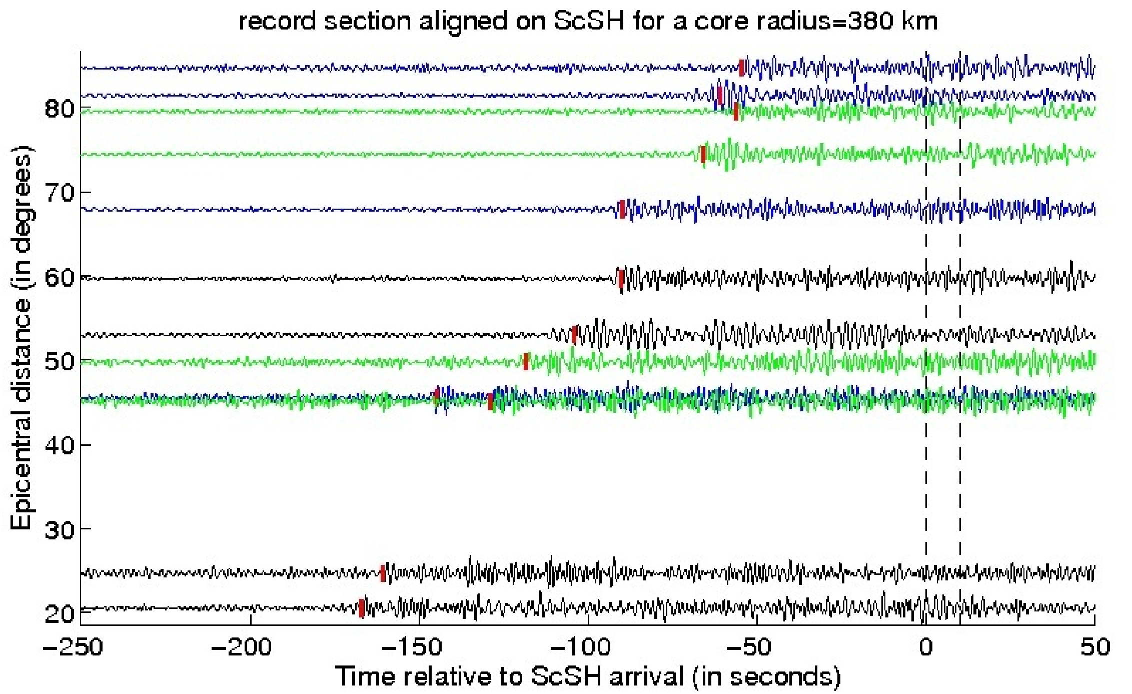


- Given the estimated depth, a maximum of ScS energy around 380-400 km core radius is observed for all deep moonquakes selected
- Extract maxima for each core radius → NRJ(Rc)
- Sum these curves for the three events

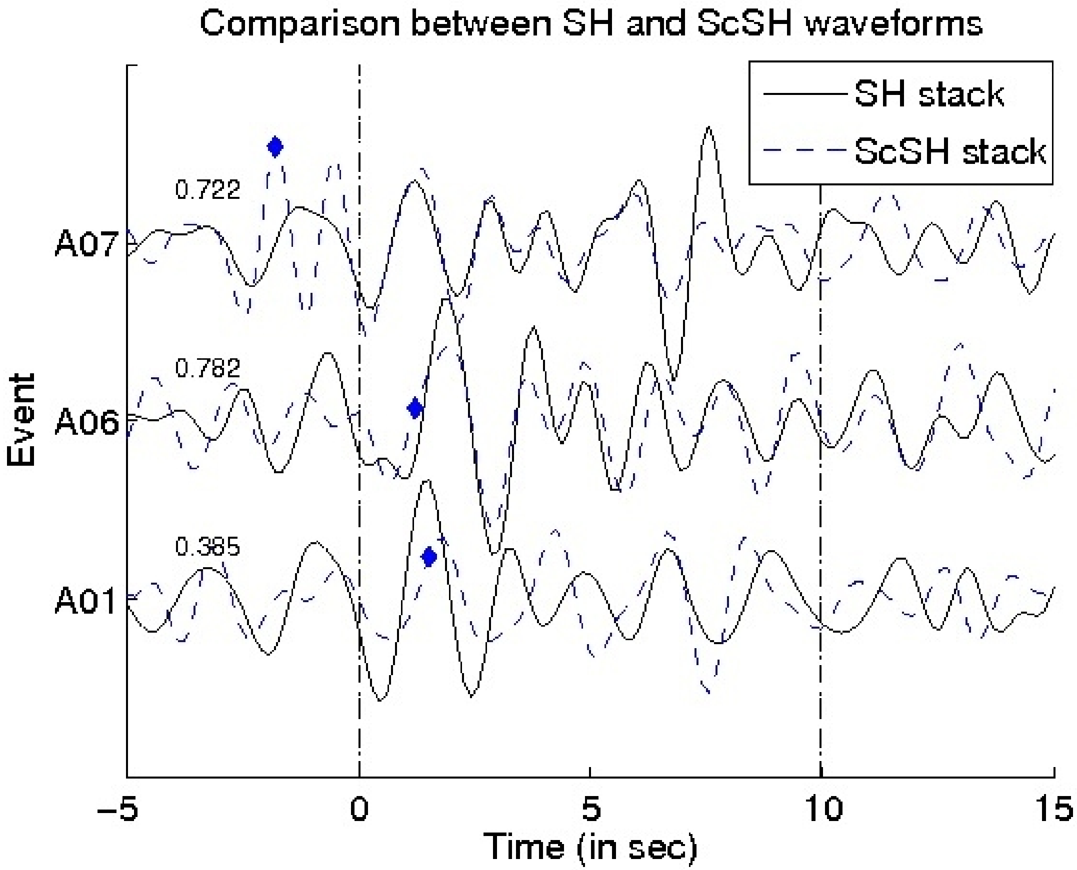
Sum of ScSH stack energy

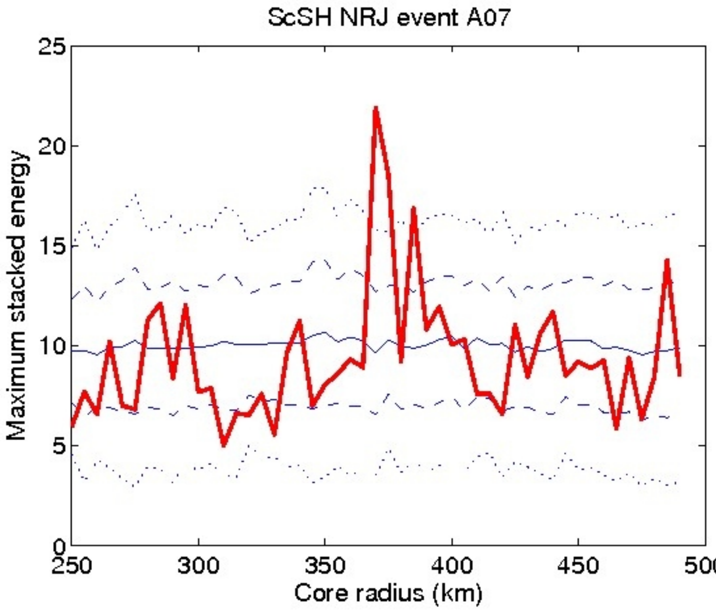


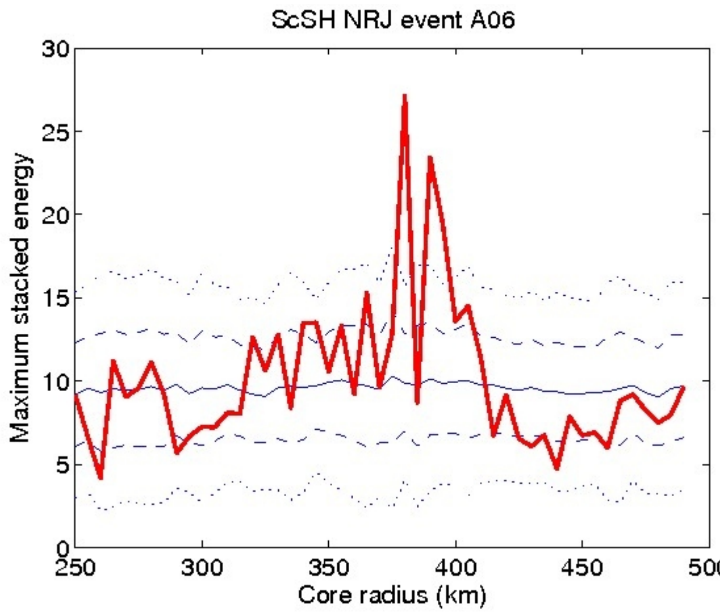
Records aligned on
ScSH arrival
For a 380km core radius
One color per quake



S and ScS waveform comparison







After deconvolution of S waveform,
A06 and A07 moonquakes present a strong stack energy ~380 km core radius

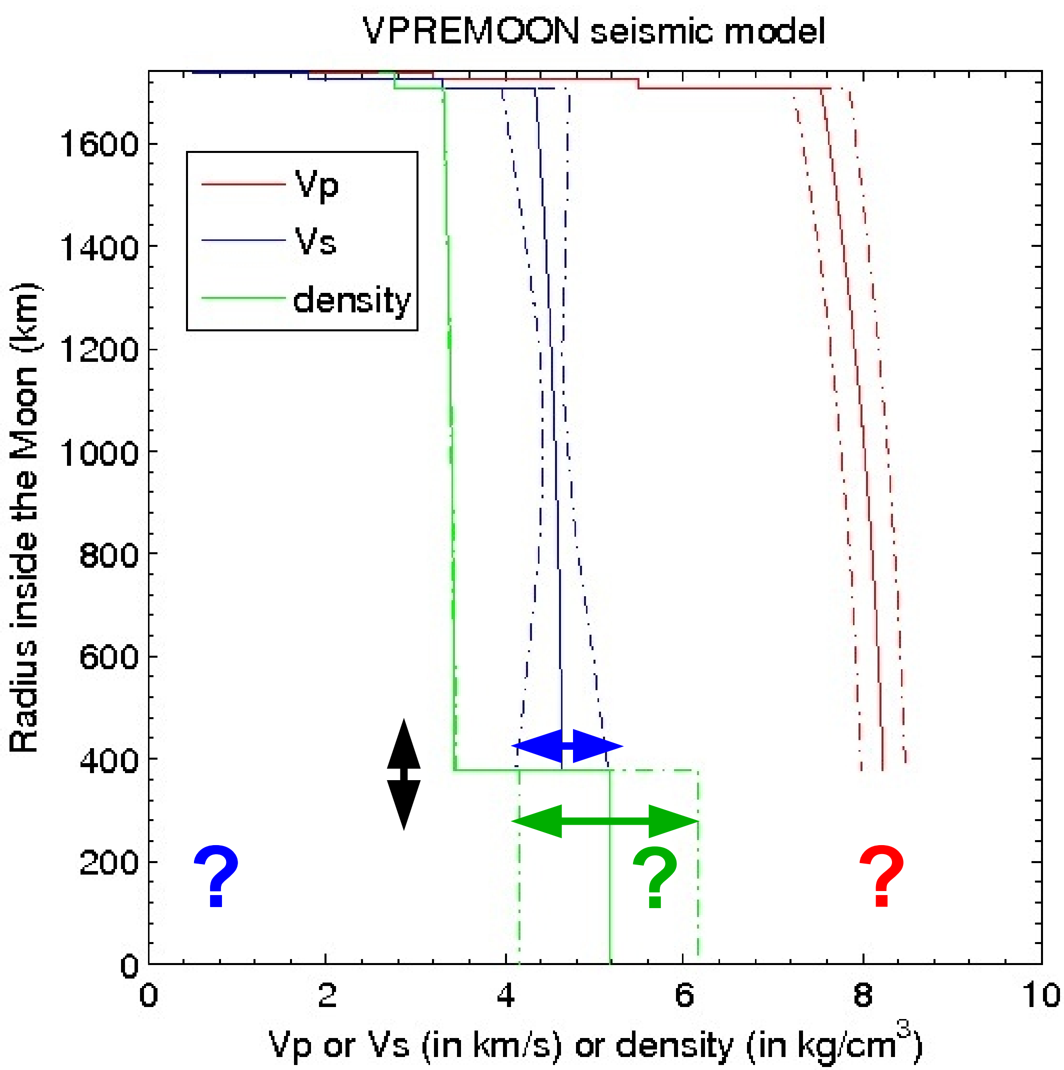
Error bar estimation

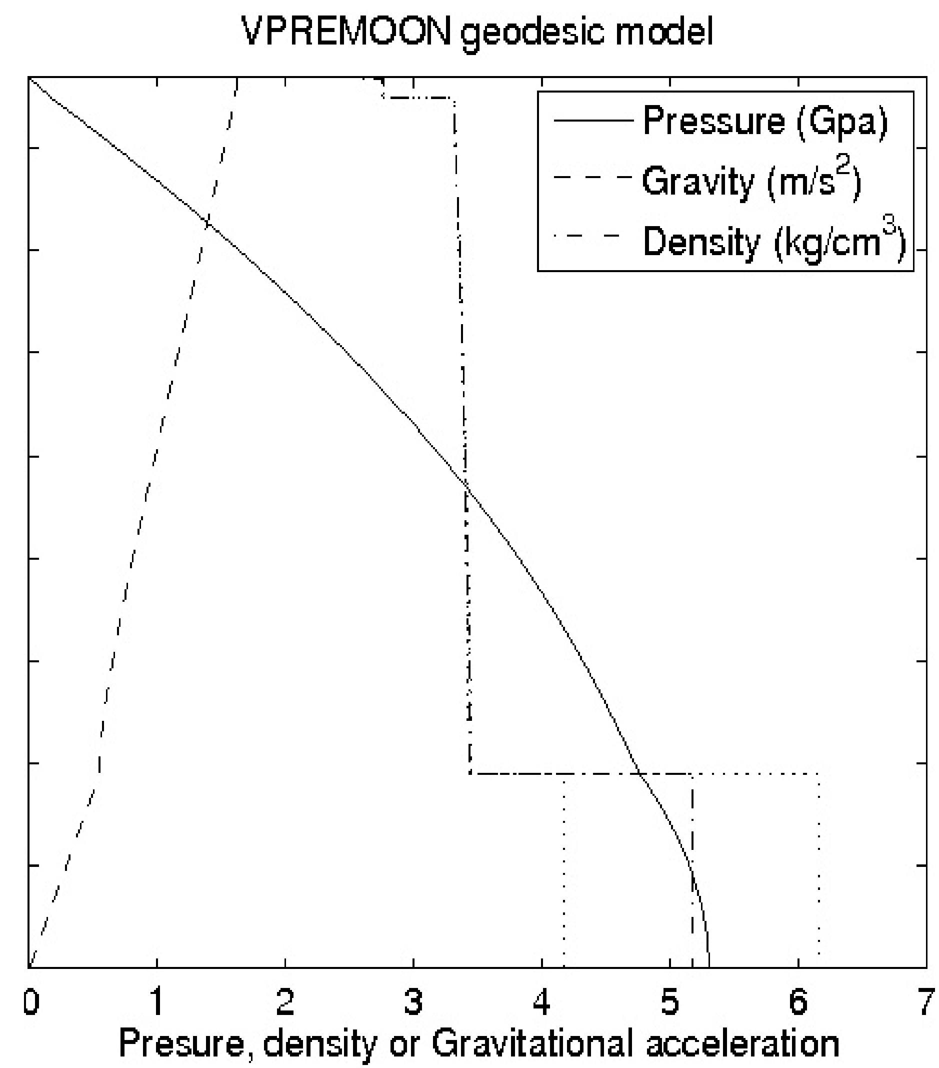
- Core radius=380±30 km according to a bootstrap analysis.
- However, additional uncertainties come from errors on the mantle model (3%-11% for seismic velocities and ~0.3% for density) and on the event location depth (~10 km).
- So, the error bar of this core radius estimate is at least 40 km
- Which traduces in a large error bar on the average core density (~1000 kg/m3)

Very preliminary **reference Moon model**

- Fit seismic and geodetic data
- Provide a density model of the mantle
- Detection of core reflected SH waves
- Core radius is 380±40 km
- Average core density is 5200±1000 kg/m3
- Estimate at the upper limit of previous studies based on lunar laser ranging and lunar induced magnetic moment.
- SV waves reflected on the core are not detected (not shown) → suggests that the outer part of the core is fluid

Very preliminary
reference Moon model





Garcia et al., PEPI, 2011 + correction

New construction of radial Moon models

- Only 8 parameters:
  - Crustal thickness
  - Vp(r)=a+b*ρ(r) : birch law
  - Vp/Vs : 3 values + linear in radius
  - Core radius
  - Crust/mantle density jump

  } Vp(r)
  Vs(r)
  Density : ρ(r)

- Fixed:
  - Crust density from GRAIL
- To be added : IC density, Vp, Vs in the core, more from gravity on moho density jump ?