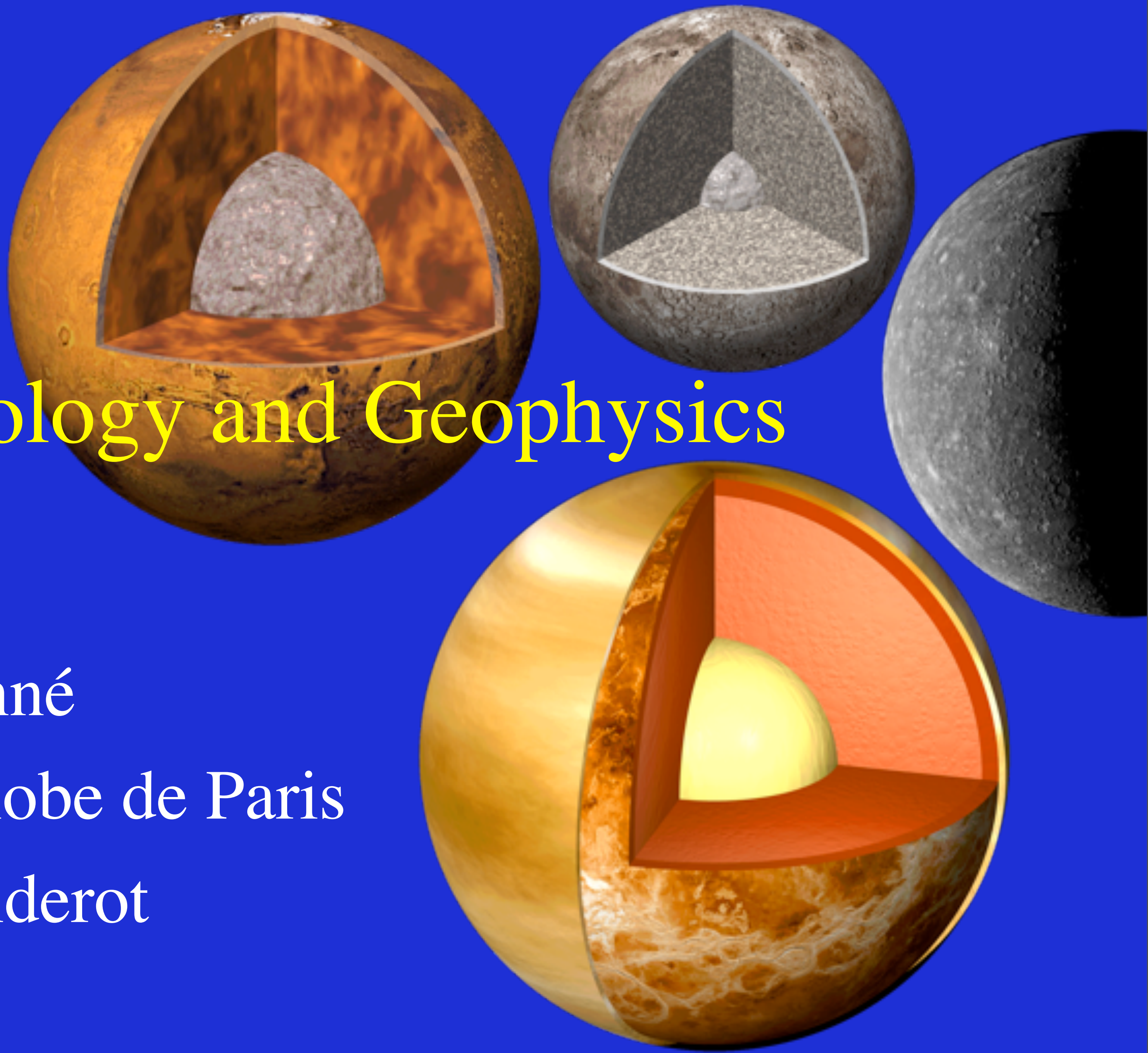

Planetary Seismology and Geophysics

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France

Presentation's outline

- What can we get from geophysical exploration and sounding of a planet other than Earth?
  - A complete illustration with the Moon

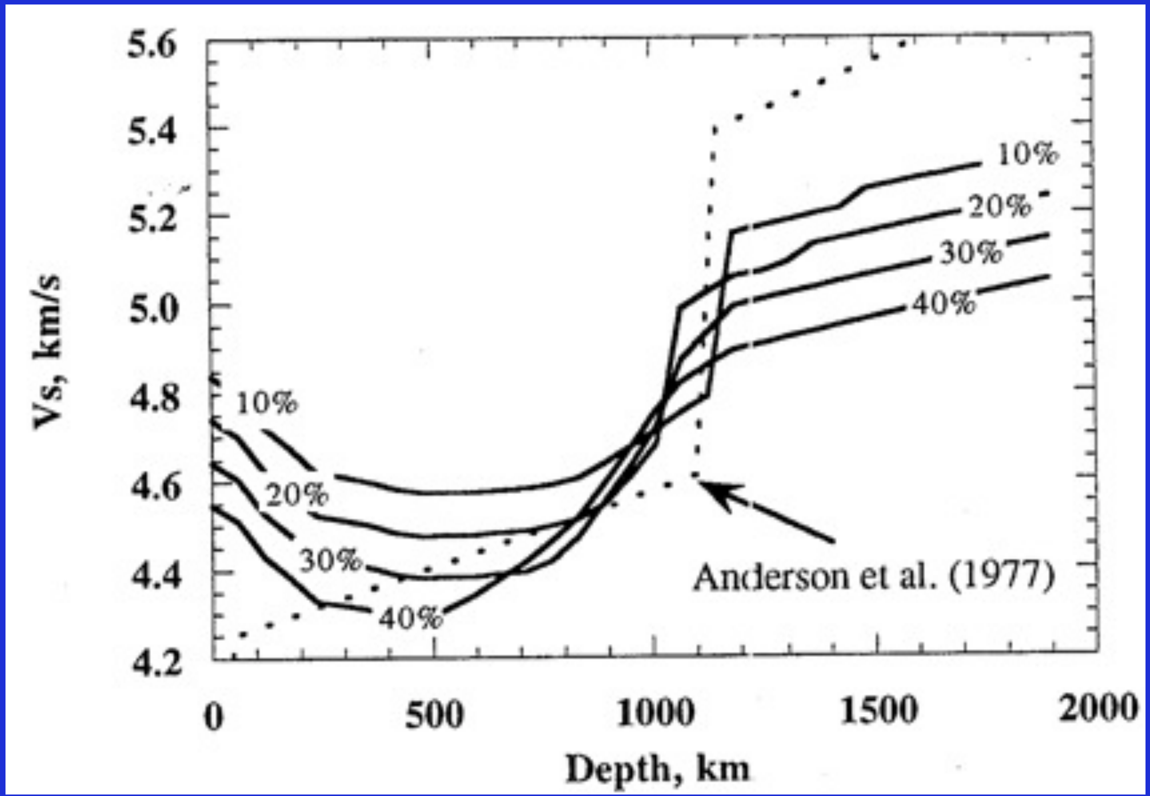
- What can we imagine from geophysical exploration and sounding of a planet other than Earth?
  - Dreams for Mars, the Moon and Venus...

In situ geophysical exploration

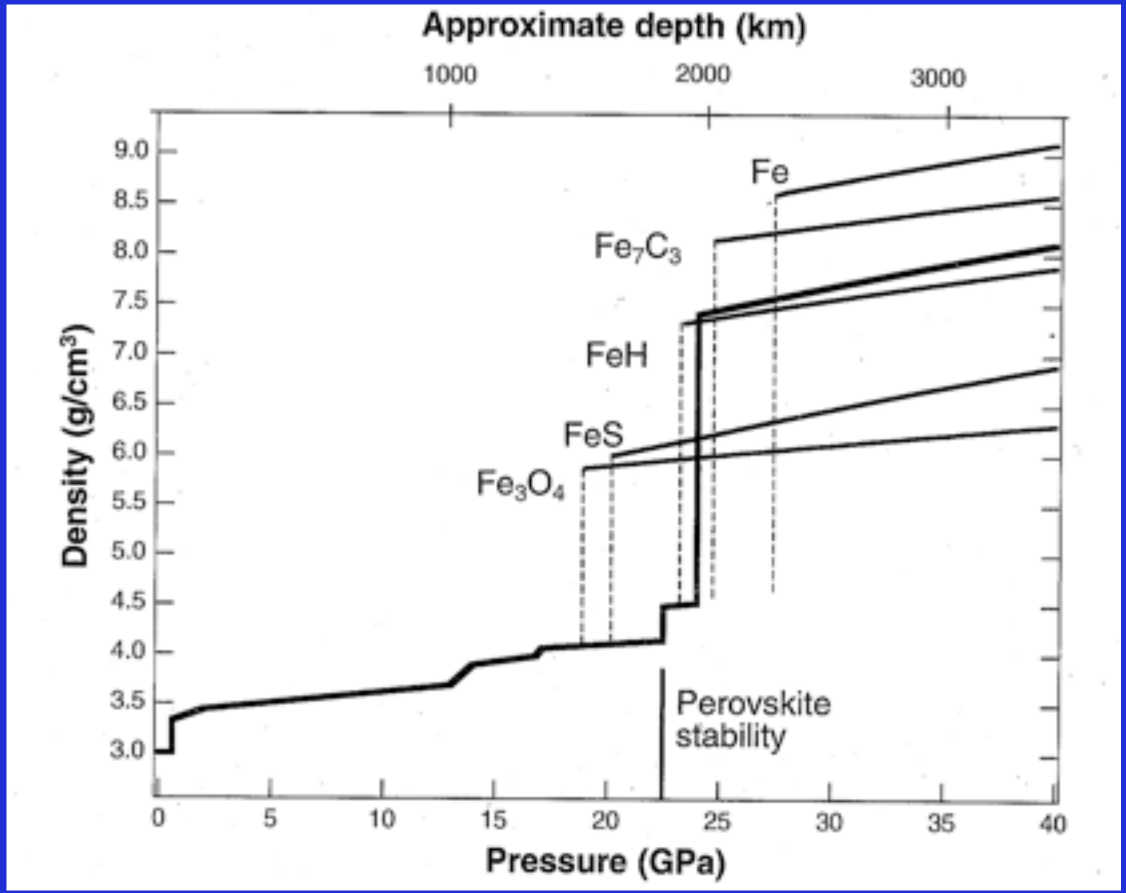
- Goal of in situ geophysical exploration is to determine the Internal structure of a planet
- Internal structure is
  - Therrmodynamical state (pressure and temperature)
  - Mineralogy
- The approach is based
  - On geophysical methods determining the profile with depth (or the 3D models, for the earth case) of geophysical parameters such as
    - Seismic velocities
    - Shear modulus
    - Density
    - Electrical conductivity
    - For subsurface, permittivity
  - On remote sensing, in situ and sample analysis of the crustal radioactive material PLUS situ heat flow measurement to get the heat (and temperature) surface budget
  - On laboratory and theoretical studies determining the dependence of these geophysical parameters with respect to temperature and mineralogy (PLUS thermal evolution models)
  - On mineralogical and geochemical analysis constraining directly or indirectly the mineralogy with depth

- A geophysical field must penetrate in the planet, must be reflected/ transmitted and then recorded
  - Magnetic sounding (electrical conductivity)
  - Seismic sounding (seismic velocities, seismic attenuation)
  - Electro-magnetic sounding (permittivity, electrical conductivity)
- A geophysical signal must be produced by the planet with amplitude depending on its properties with depth
  - Gravity (density)
  - Heat flux (temperature, radioactivity, thermal conductivity)
- An external force deform the planet with a response depending on its properties with depth and the shape (or deformations) of the planet is recorded
  - Tidal deformation, Precession, nutation, etc (density and elastic modulus)
  - Plate flexure (density, elastic thickness)
- In planetology, data are generally limited…. All sources of information must be used

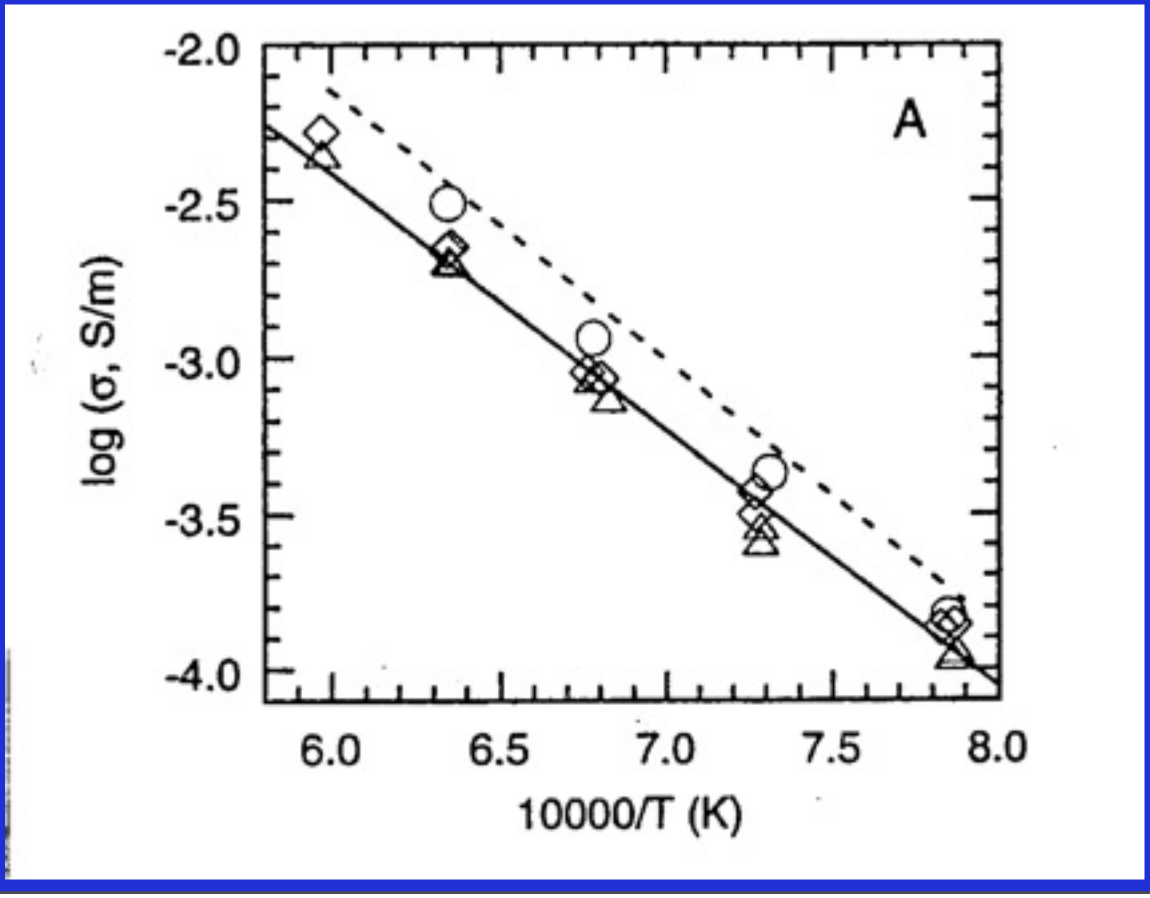
What is the mineralogy, structure and temperature?



Mantle seismic velocities versus Mantle iron content
(Mocquet et al., 1996)



Core density versus core composition
(Bertka and Fei, 1998)



Mantle electrical cnductivity versus electrical conductivity
(Xu et al., 1998)

Magnetic sounding

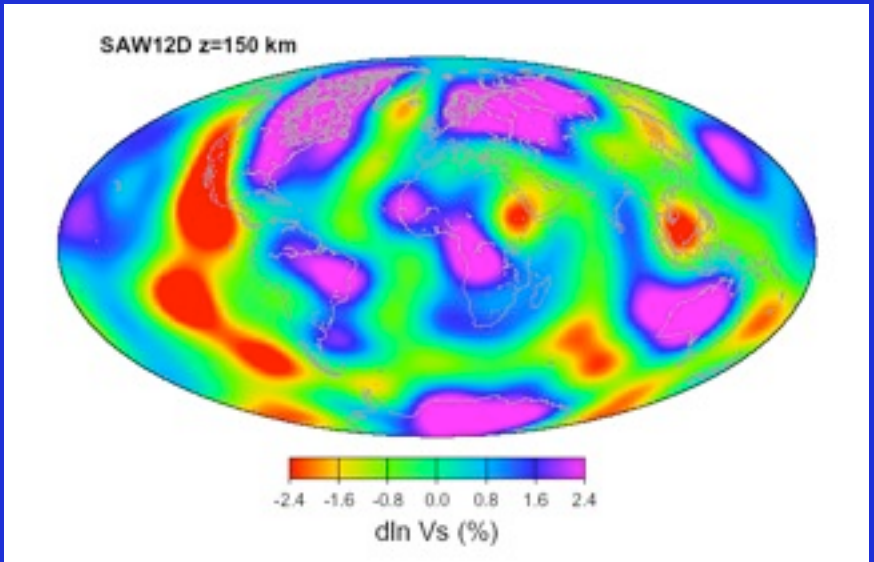
- Principle:
  - An external, time dependant, magnetic field penetrates in an planet
  - Time variation of the magnetic field inside the planet generates currents in the conductive areas canceling partially the field
  - The induced magnetic field is measured by magnetometers
- Limitation
  - Magnetic field is diffusing inside the body

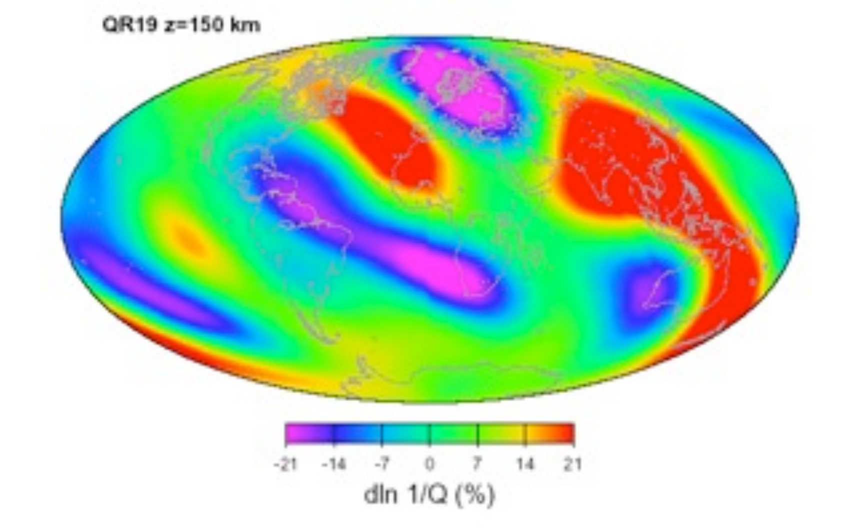
$$\nabla^2 \mathbf{B} = \mu\sigma \frac{\partial \mathbf{B}}{\partial t},$$

  - Only long periods magnetic field (hours) are sounding deep
  - Diffusion makes the reconstruction of discontinuities difficult
- Success
  - Detection of highly conducting part of a planet (iron metallic core, low velocity zone in a mantle associated to partial melting, liquid in the crust or below a crust)
- Sources
  - Moon: Magnetic field variations associated to the displacement of the Moon in the Earth magnetosphere
  - Moon: Magnetic field variations associated to the solar wind
  - Jovian satellites: Magnetic field variations associated to the tilted rotating Jovian magnetosphere

Seismic sounding

- Principle
  - Use active (impactors, explosive) or passive (quakes, meteorite impacts, crack) seismic sources
  - Record and analyse the seismic signals
- Key dates
  - Earth:
    - Von Reben Paschwitz, 1889, first signal
    - Oldham, 1906, discovery of the core
    - 1960, discovery of the normal modes
    - 1980+ Tomographic models (i.e. details of a few %)
  - Sun:
    - Leighton et al., 1962, discovery of the normal modes
  - Moon:
    - Latham et al., 1969, Apollo 11, first records and deep moonqu
  - Jupiter:
    - Hammel et al., 1995, observation of Atmospheric Tsunamis
  - Mars:
    - Anderson et al., 1976, First installation of seismometer, single observation of a «quake» possibly not associated to wind burst…





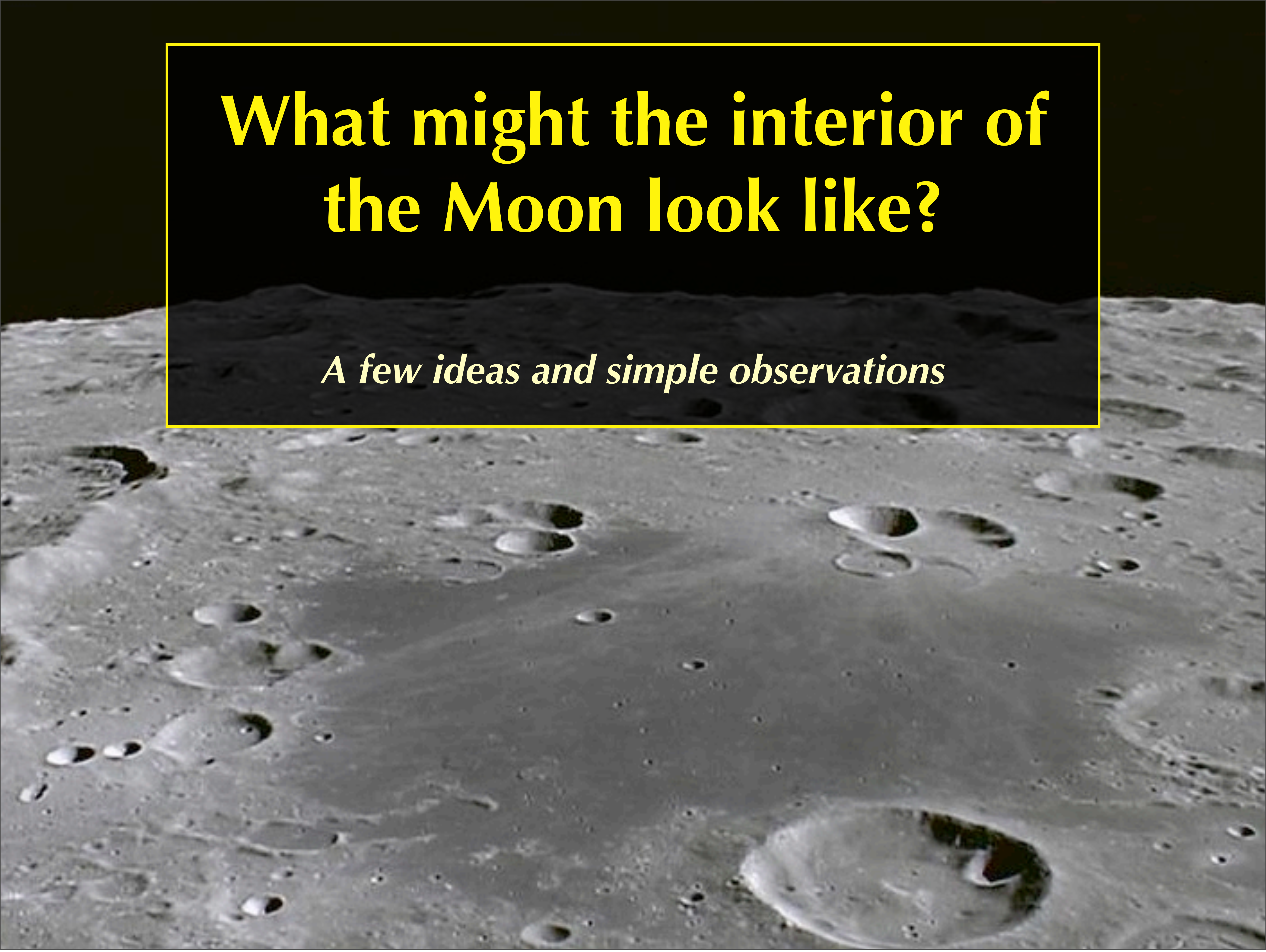
The interior structure of the Moon

What did seismology and geophysics?

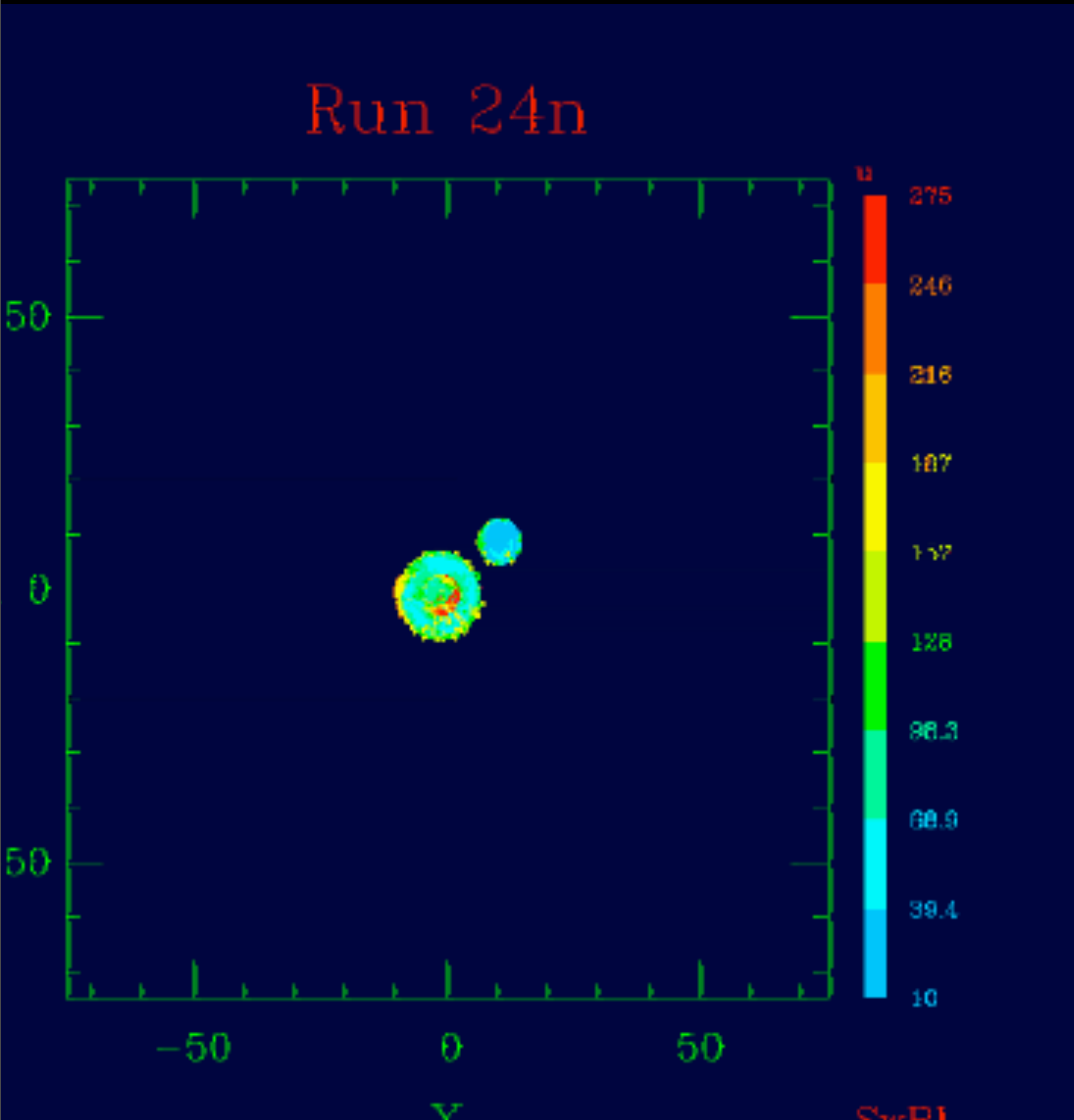
with contributions of
Mark Wieczorek, Jeannine Gagnepain-Beyneix, Tamara Gudkova, Catherine Johnson, Taichi Kawamura and other

What might the interior of the Moon look like?

A few ideas and simple observations



The origin of the Moon: The first 24 hours



anup and Asphaug (2001)

A Mars-sized object is postulated to have collided with the Earth 4.5 B.y.a.

The material put into circum-terrestrial orbit re-accretes to form the Moon on the time scale of about 1 month to 100 years.

As a result of the energy liberated during the impact, the energy associated with re-accretion, and the short re-accretion time scales, the Moon could have formed completely molten.

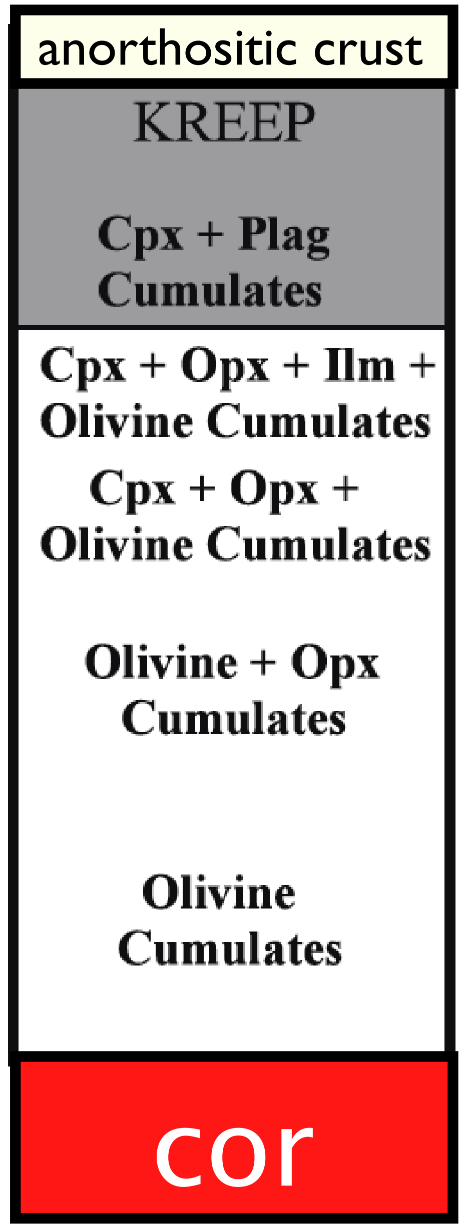
Magma Ocean Crystallization

initial state

completely or partially molten magma ocean

→ fractional crystallization →

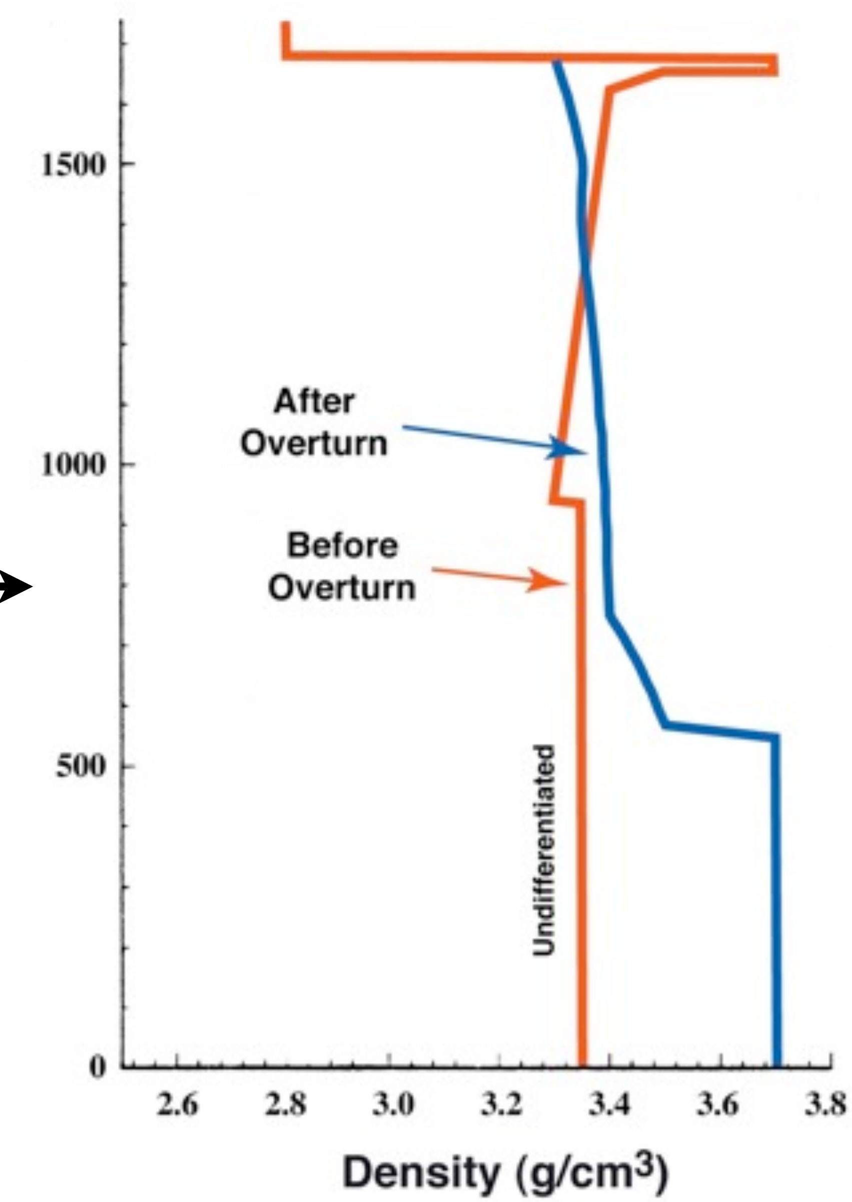
intermediary



Shearer et al. (2006)

→ gravitational overturn? →

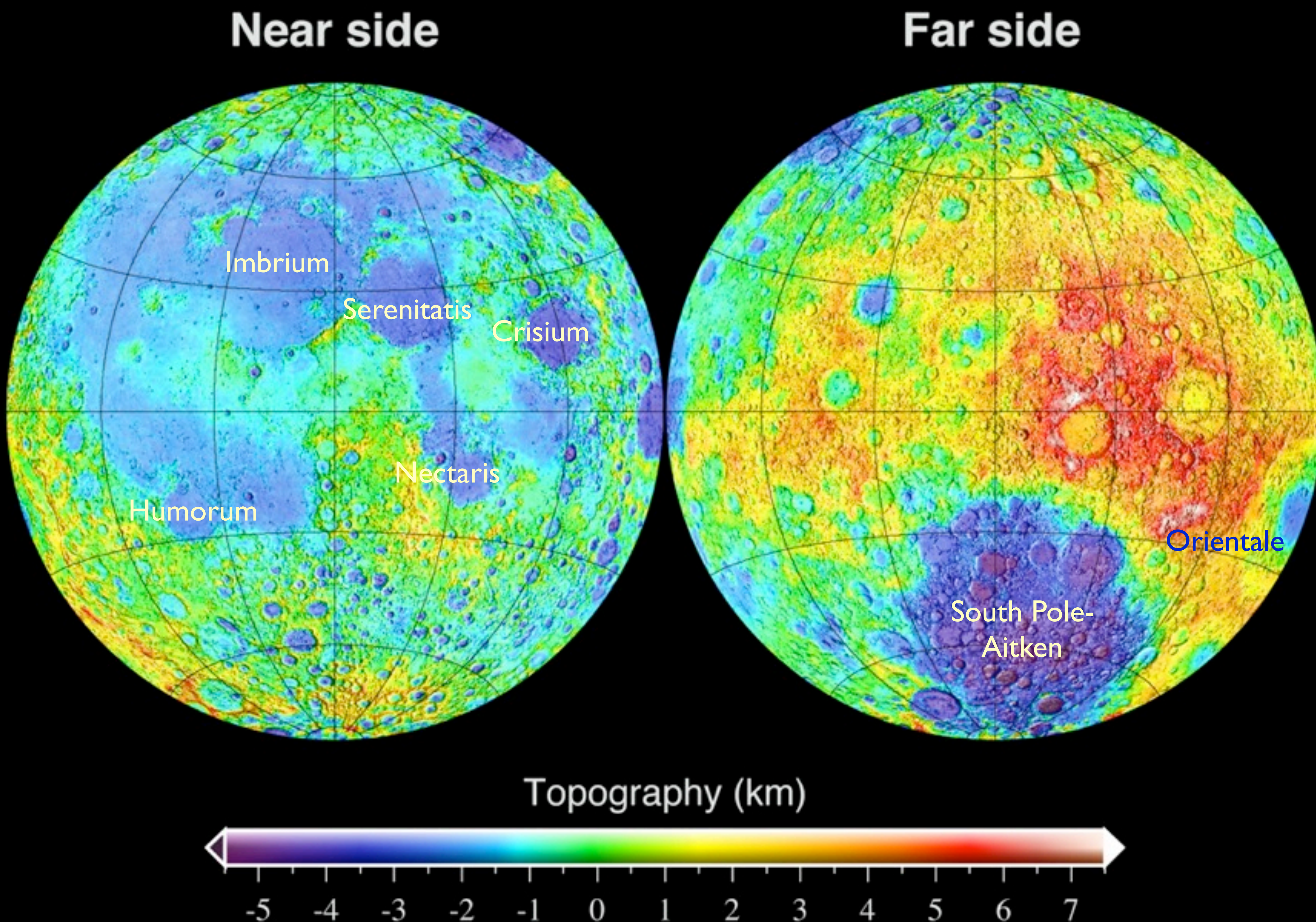
final state?



Hess and Parmentier (1995)

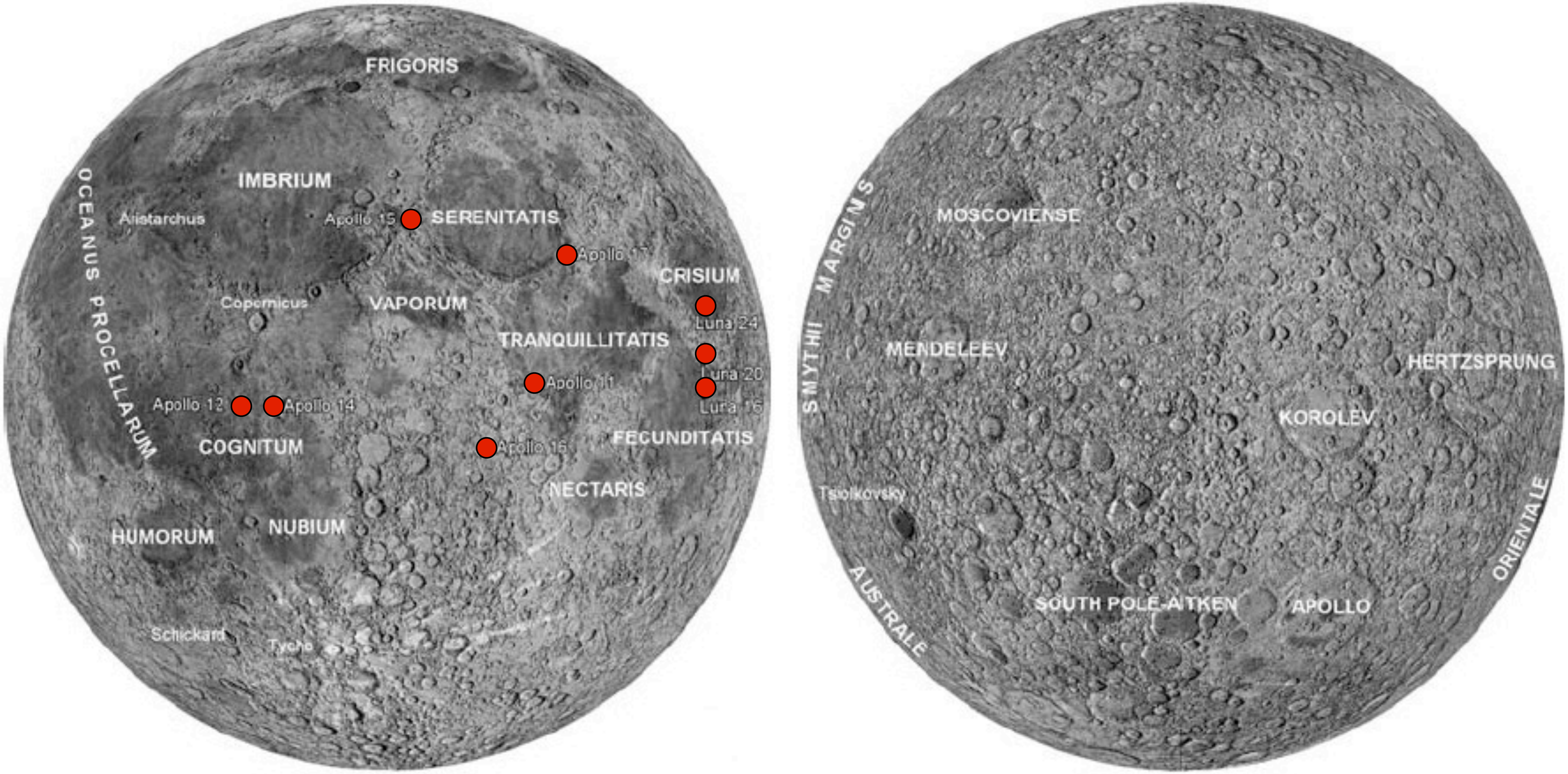
Crystallizing a magma ocean could have given rise to a layered mantle. The cumulates would have been gravitationally unstable and might have overturned.

Impact Cratering



Asteroidal and cometary impact events excavated deep into the crust. Large lateral variations in crustal thickness

Mare Volcanism



Almost all volcanic flows erupted on the near-side. Are there large variations in composition (i.e., heat producing elements) between the two hemispheres?

Geophysical investigations of the lunar interior

The Crust

Composition, average thickness, lateral variations in thickness, magnetization.

The Mantle

Composition, layering, lateral variations in composition, temperature.

The Core

Composition, size, geodynamo.

Gravity

Crustal thickness variations, time variable gravity signatures related to the tides and core.

Seismology

Crustal thickness, seismic discontinuities in the mantle, core size.

Magnetics

Crustal magnetizations, electrical conductivity of the mantle and core.

Lunar Laser Ranging

Energy dissipation in the mantle (Q) and at the core-mantle boundary.

Heat flow

Distribution of heat producing elements in the crust and mantle.

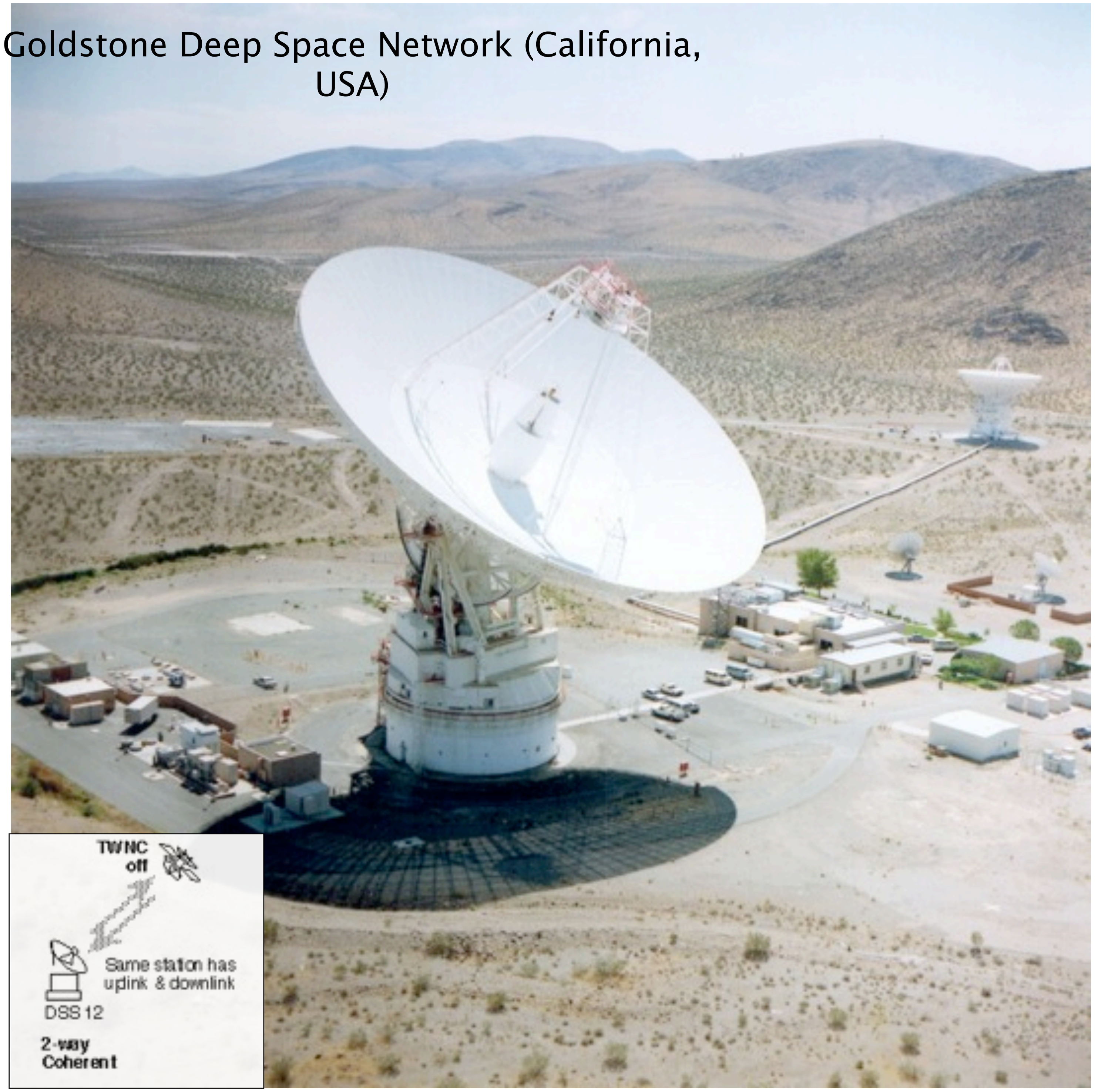
Gravity

$$\mathbf{g}(\mathbf{r}) = \nabla U(\mathbf{r})$$

$$U(\mathbf{r}) = \int_V \frac{G\,\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}\,dV'$$

The gravity field depends upon the distribution of mass within the planet.

Measurement principle



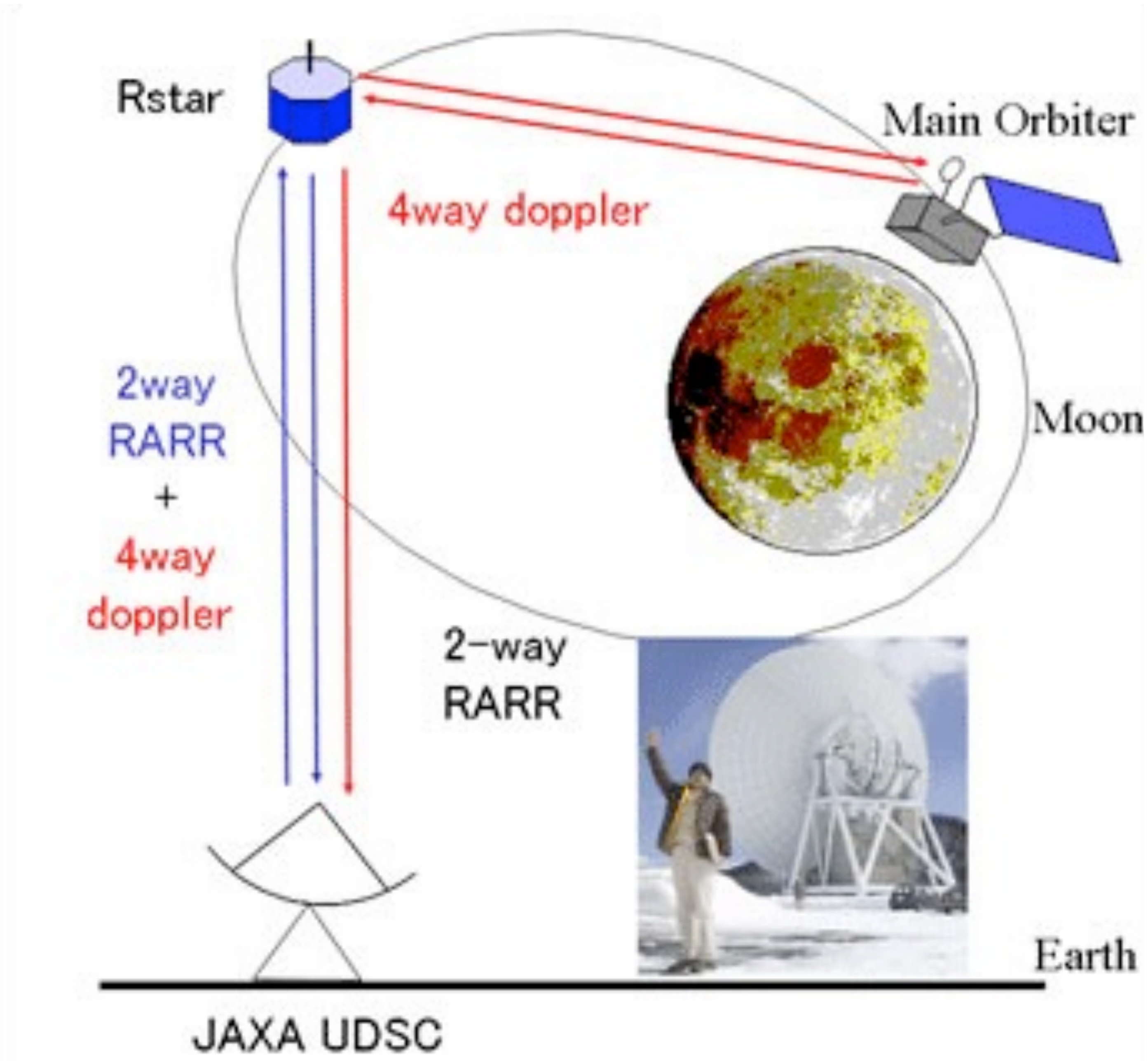
1. The frequency of radio signals transmitted by a spacecraft is doppler shifted according to the relative velocity.
2. The time-of-flight of the radio signal is related to the distance between the antenna and spacecraft.

These two measurements are used to reconstruct the orbit of a spacecraft, and the “residuals” are modeled as spatial variations in the gravity field of the planet.

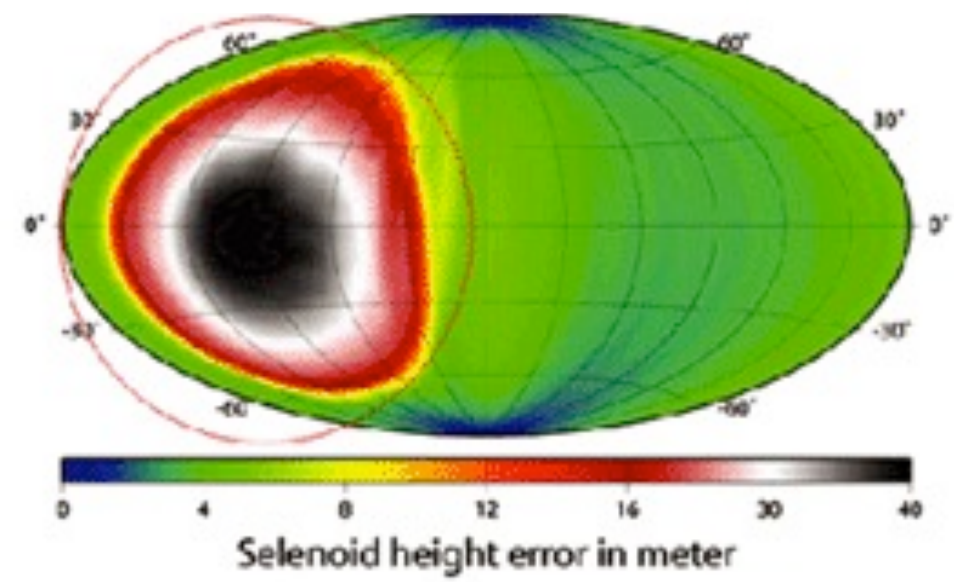
No data is available over the far-side hemisphere of the Moon when using a single satellite!

Kaguya (SELENE, Japan)

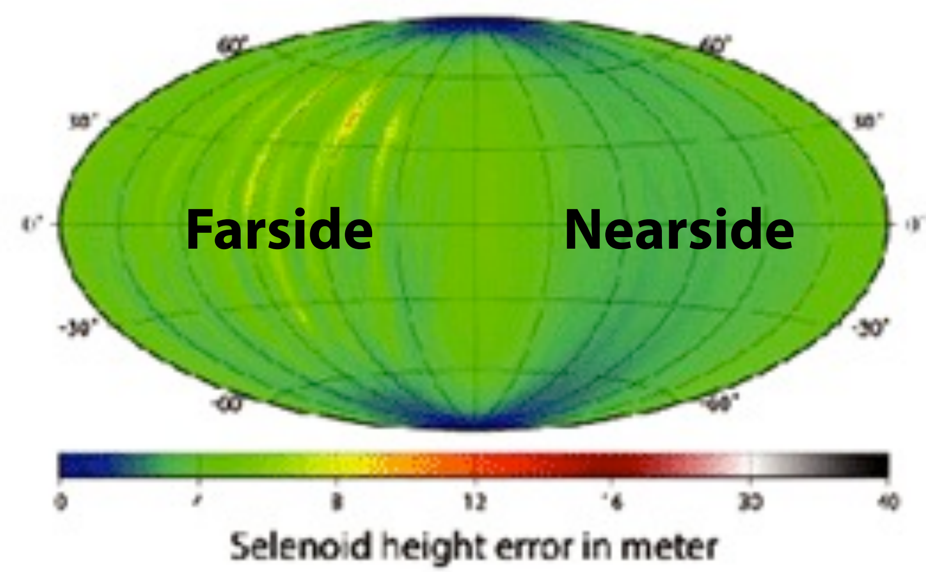
4-way tracking



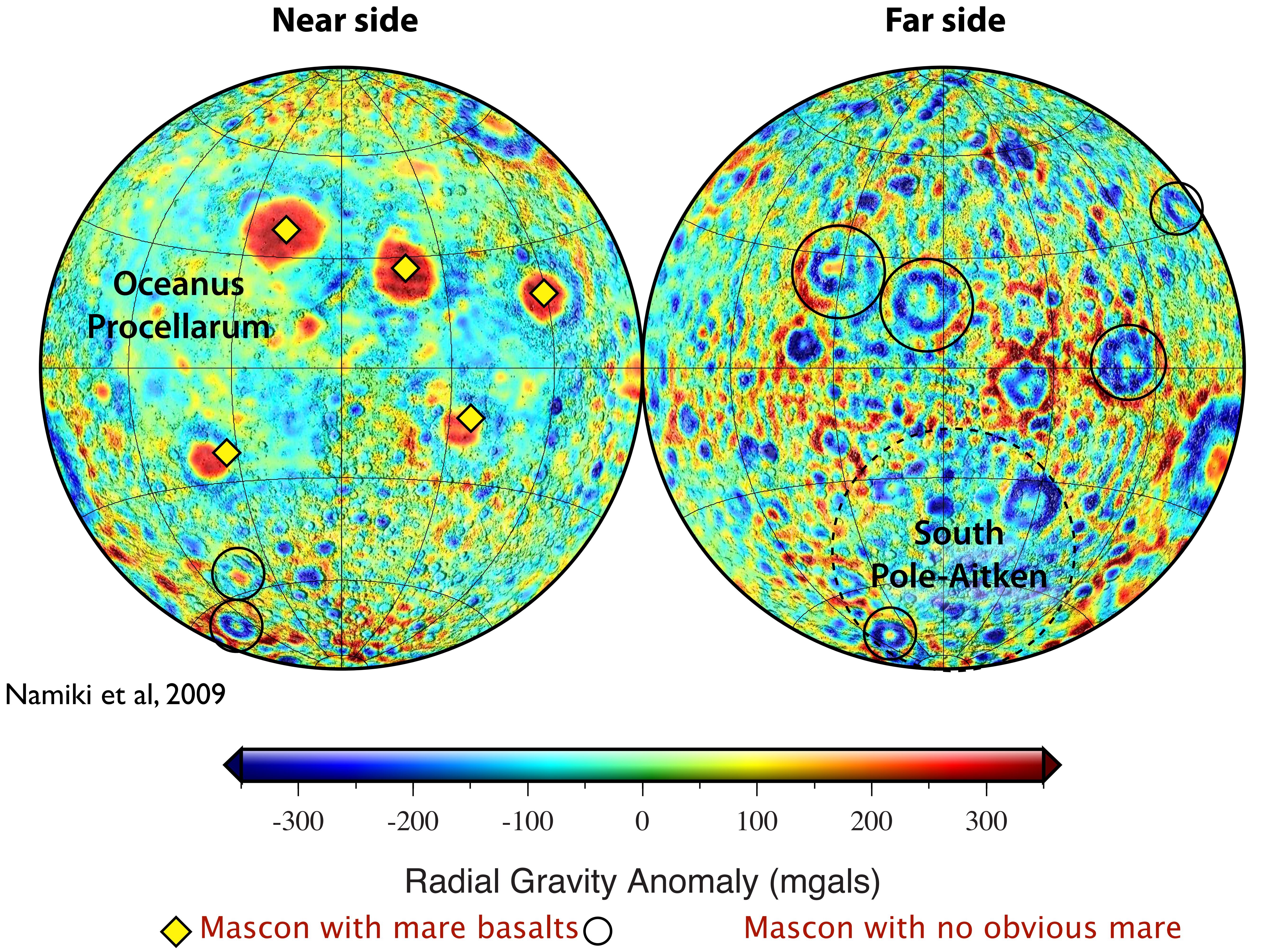
previous gravity uncertainty



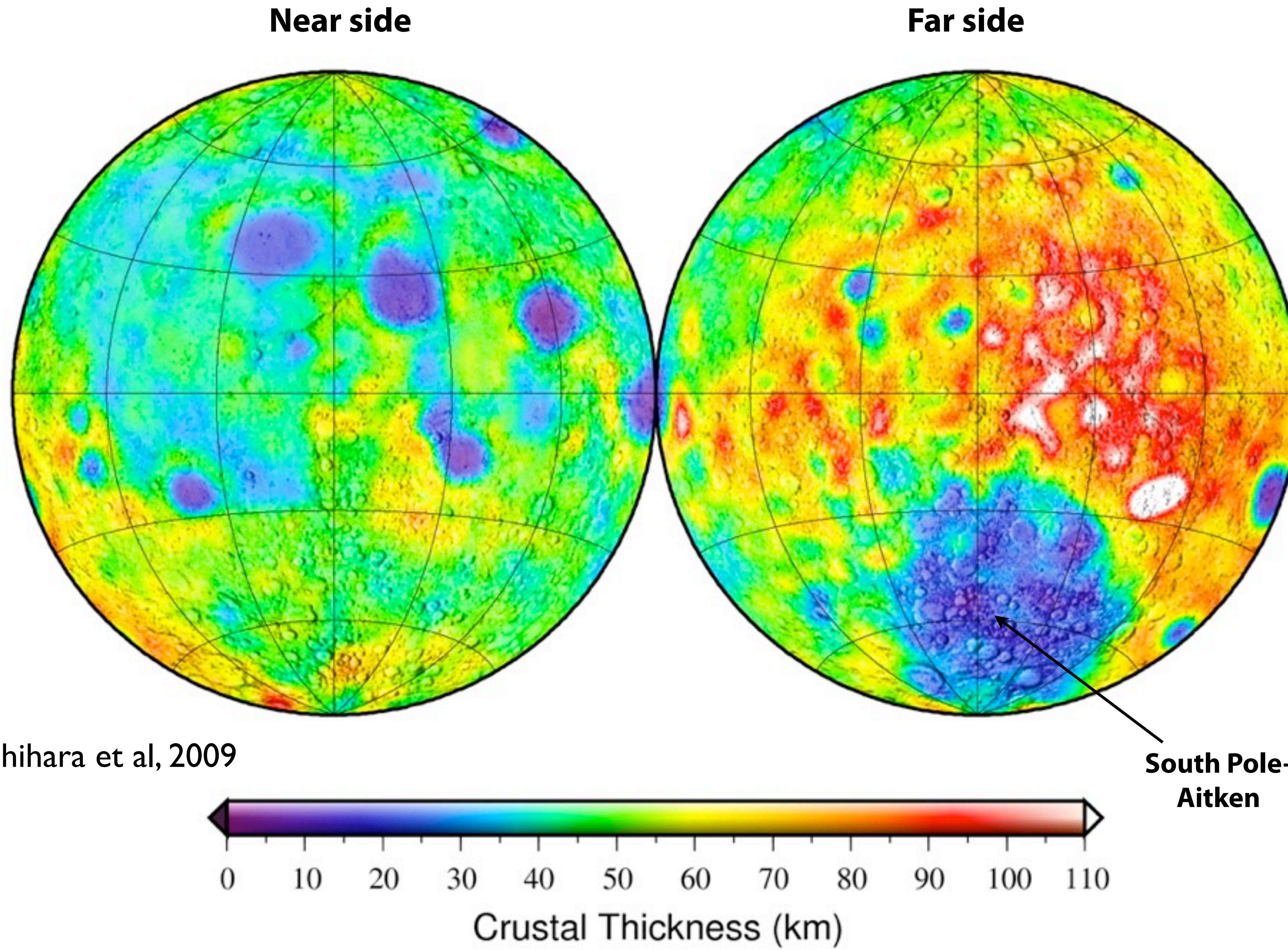
Kaguya gravity uncertainty



4-way tracking using two satellites has obtained data over the far-side hemisphere for the first time.


Near side
Far side
Oceanus Procellarum
South Pole-Aitken
Namiki et al, 2009
-300
-200
-100
0
100
200
300
Radial Gravity Anomaly (mgals)
Mascon with mare basalts
Mascon with no obvious mare

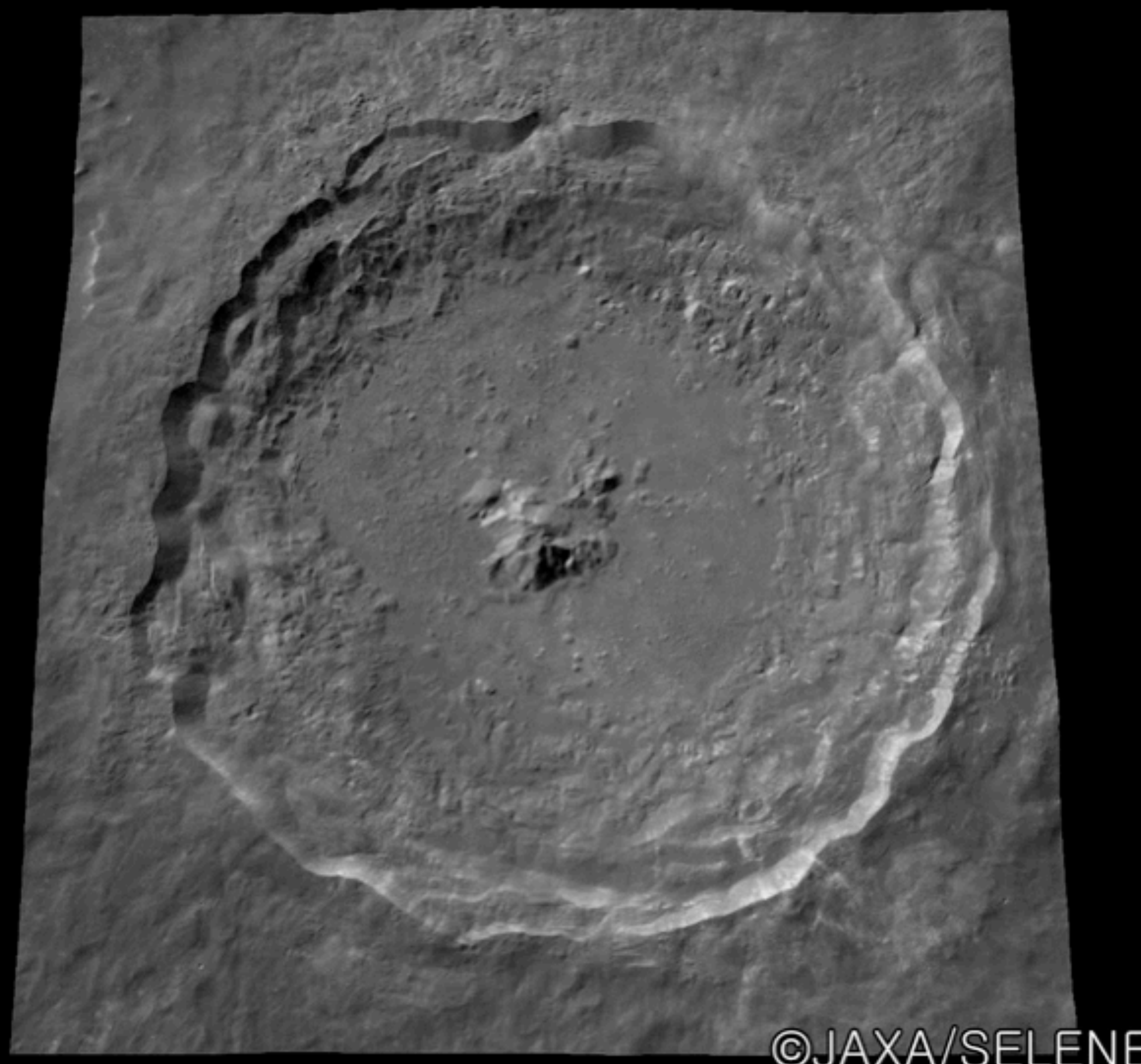
Crustal thickness modeling



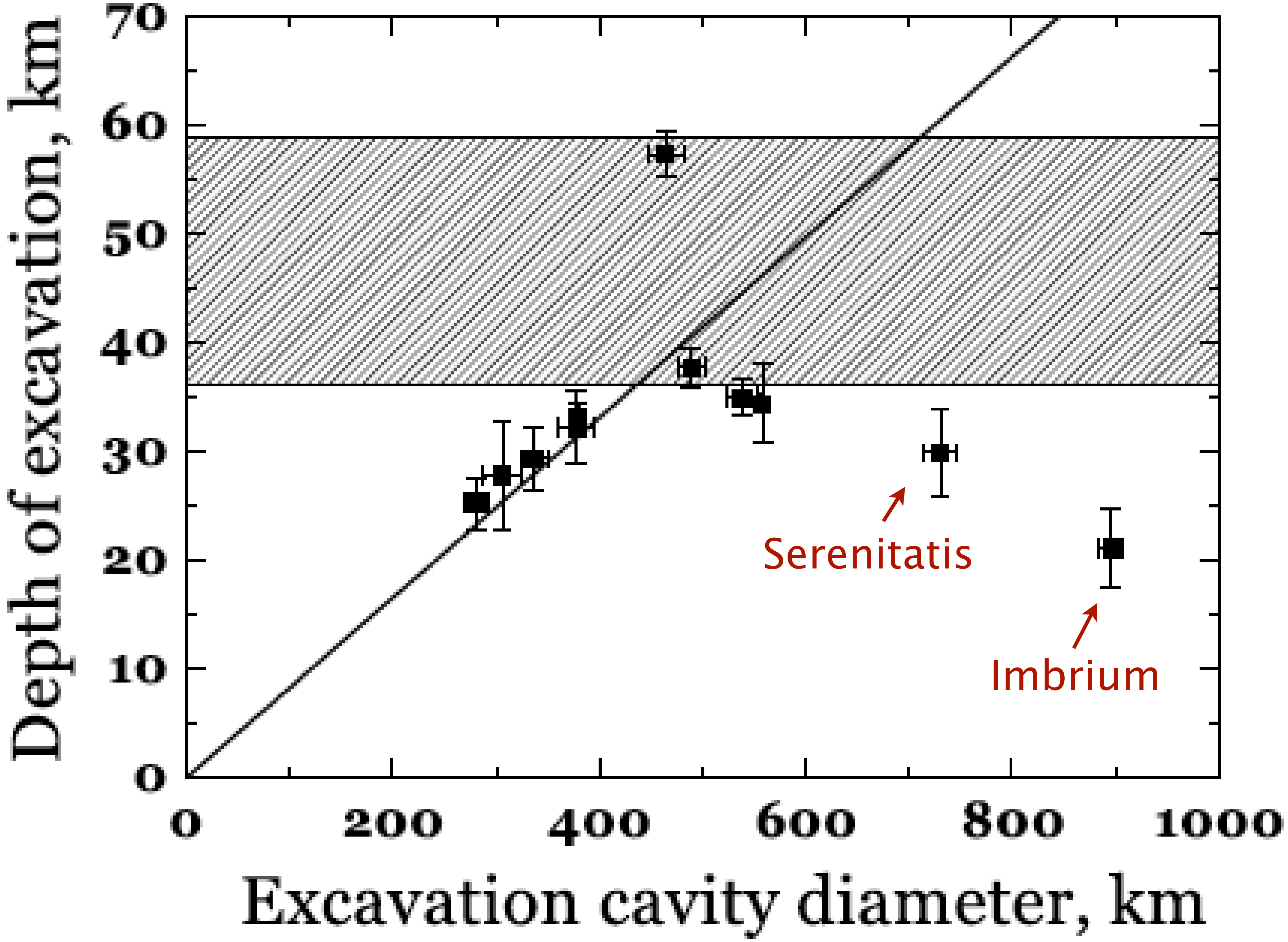
Ishihara et al, 2009

Large impact events excavated deep into the crust (and mantle?).

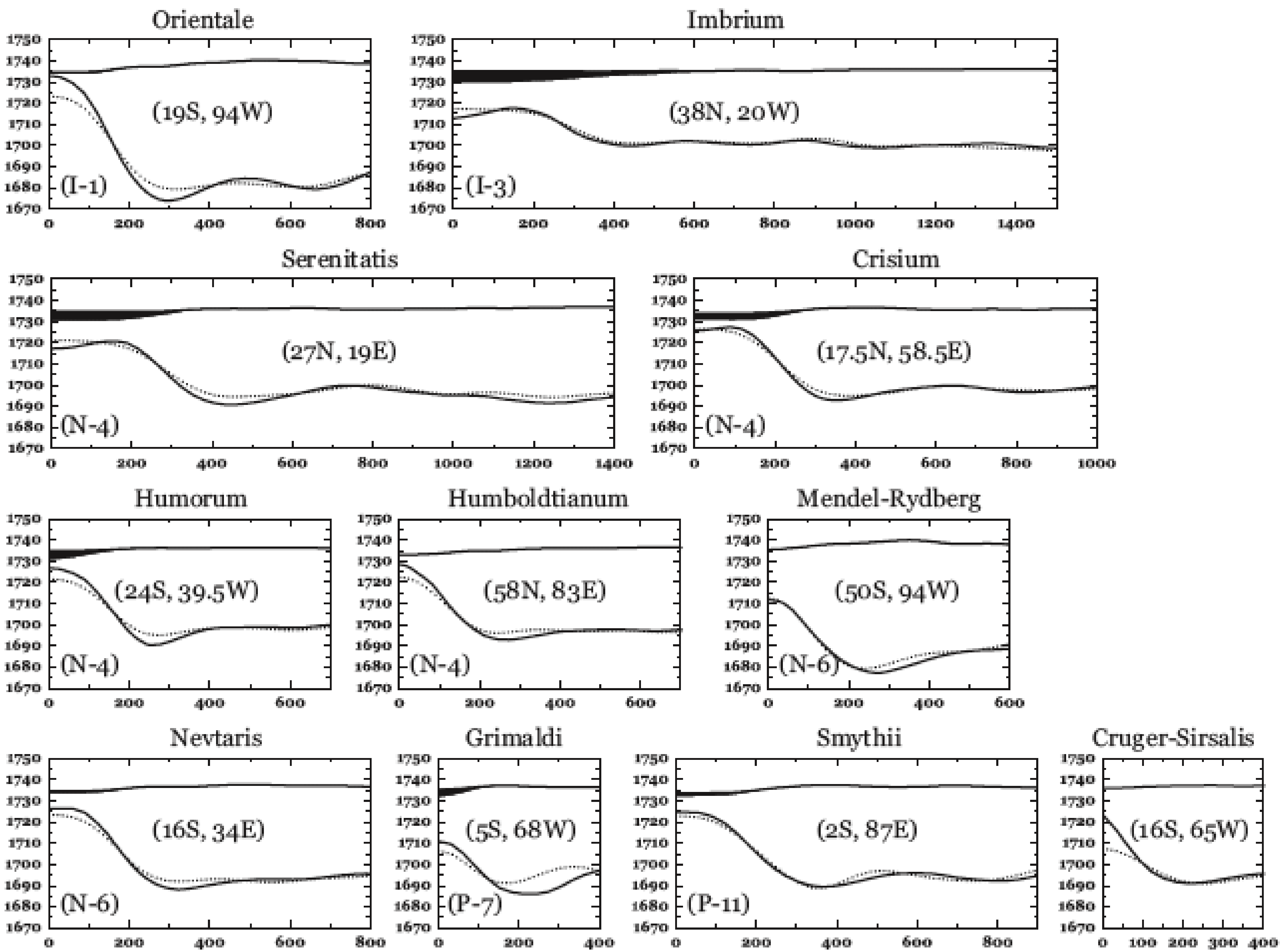
Tycho Crater: 85 km diameter



The central peak could represent materials derived from about 10 km below the surface


Depth of excavation, km
70
60
50
40
30
20
10
0
0
200
400
600
800
1000
Excavation cavity diameter, km
Serenitatis
Imbrium

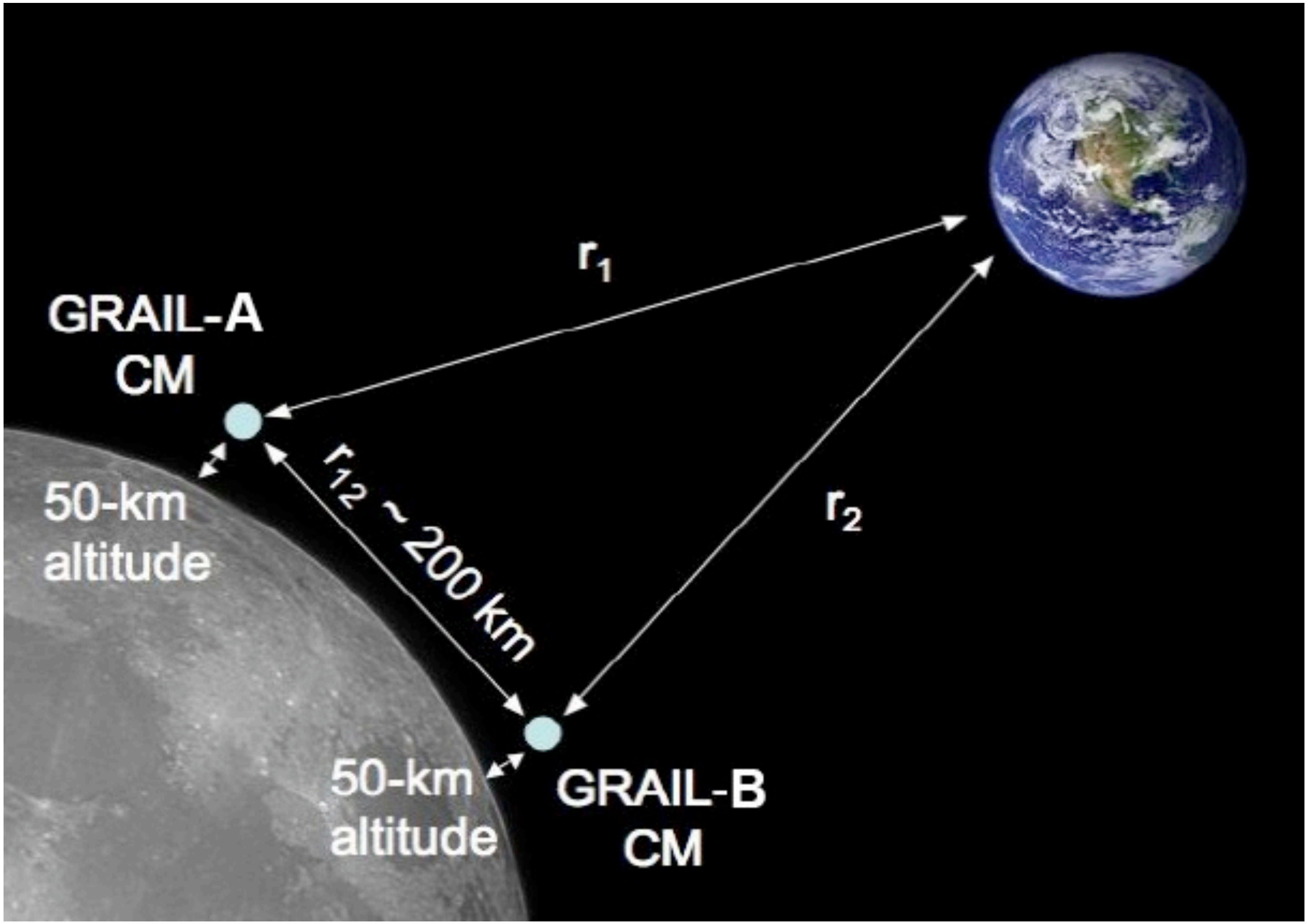
Structure of lunar impact basins



Hikida and Wieczorek (in press)

GRAIL (NASA)

Gravity Recovery and Interior Laboratory

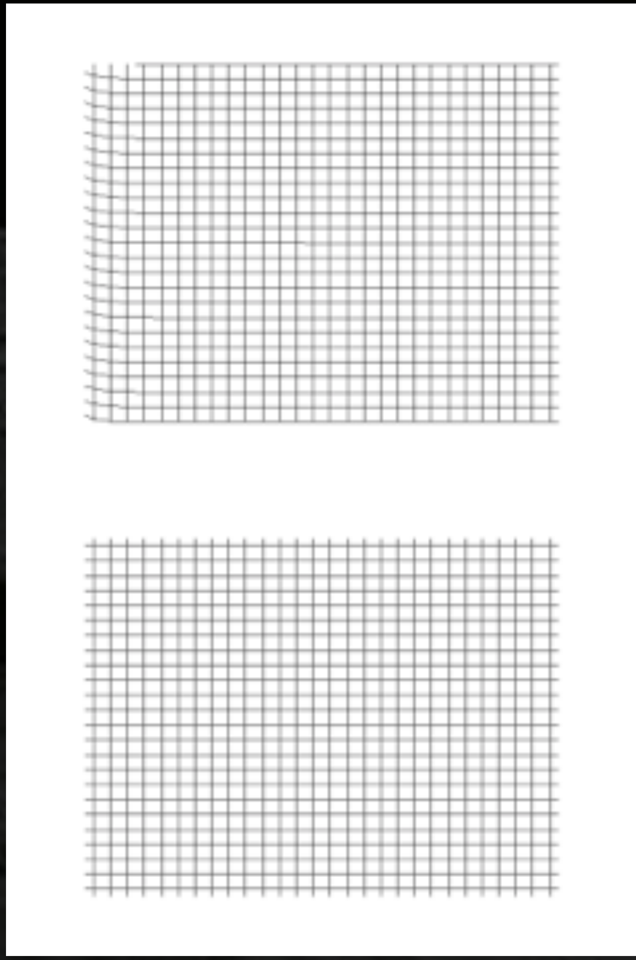


Tracking between two satellites will be obtained over the entire surface of the Moon, similar to the current Earth mission GRACE.

Seismology

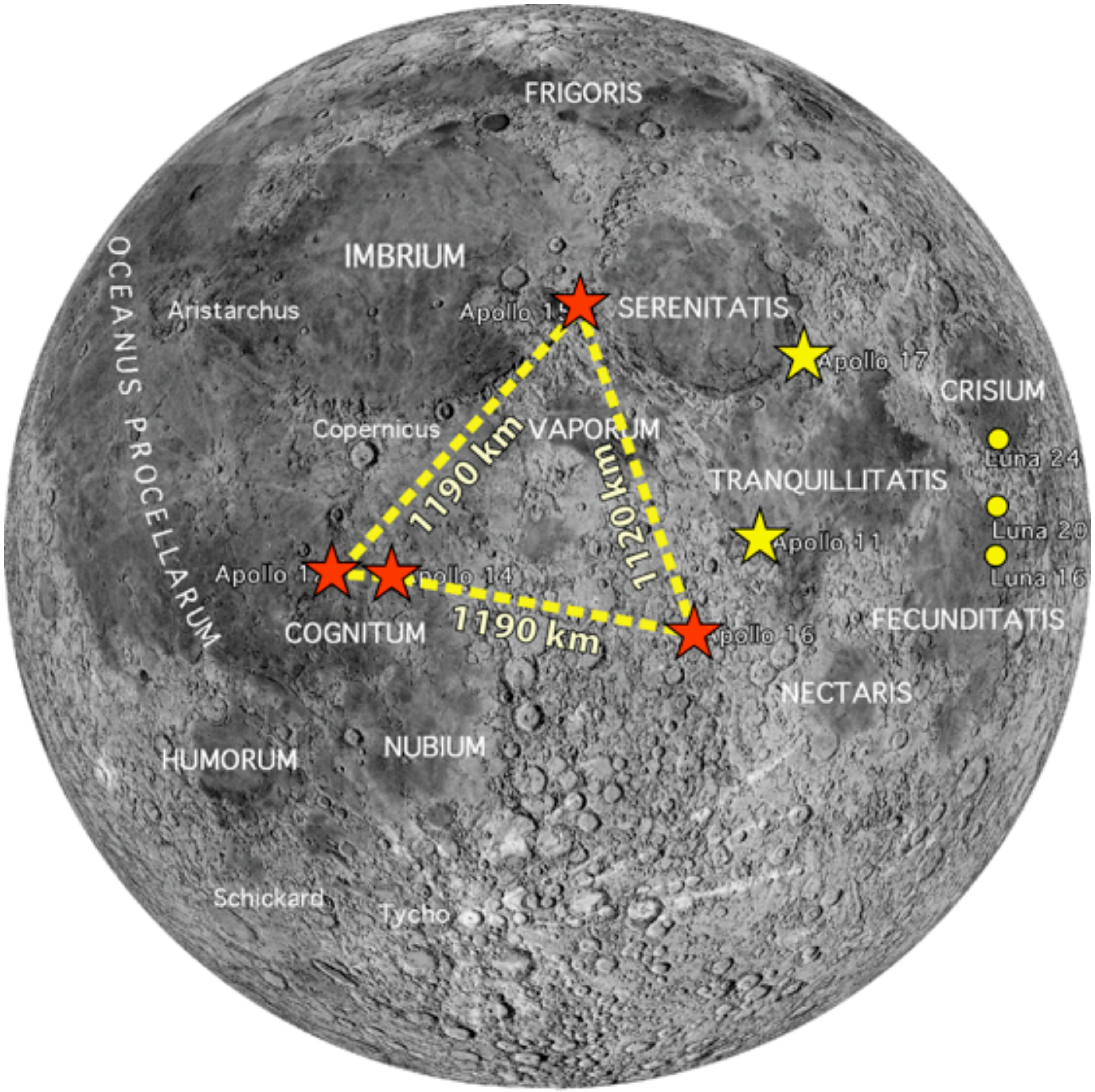
$$V_s = \sqrt{\frac{\mu}{\rho}}$$

$$V_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$$



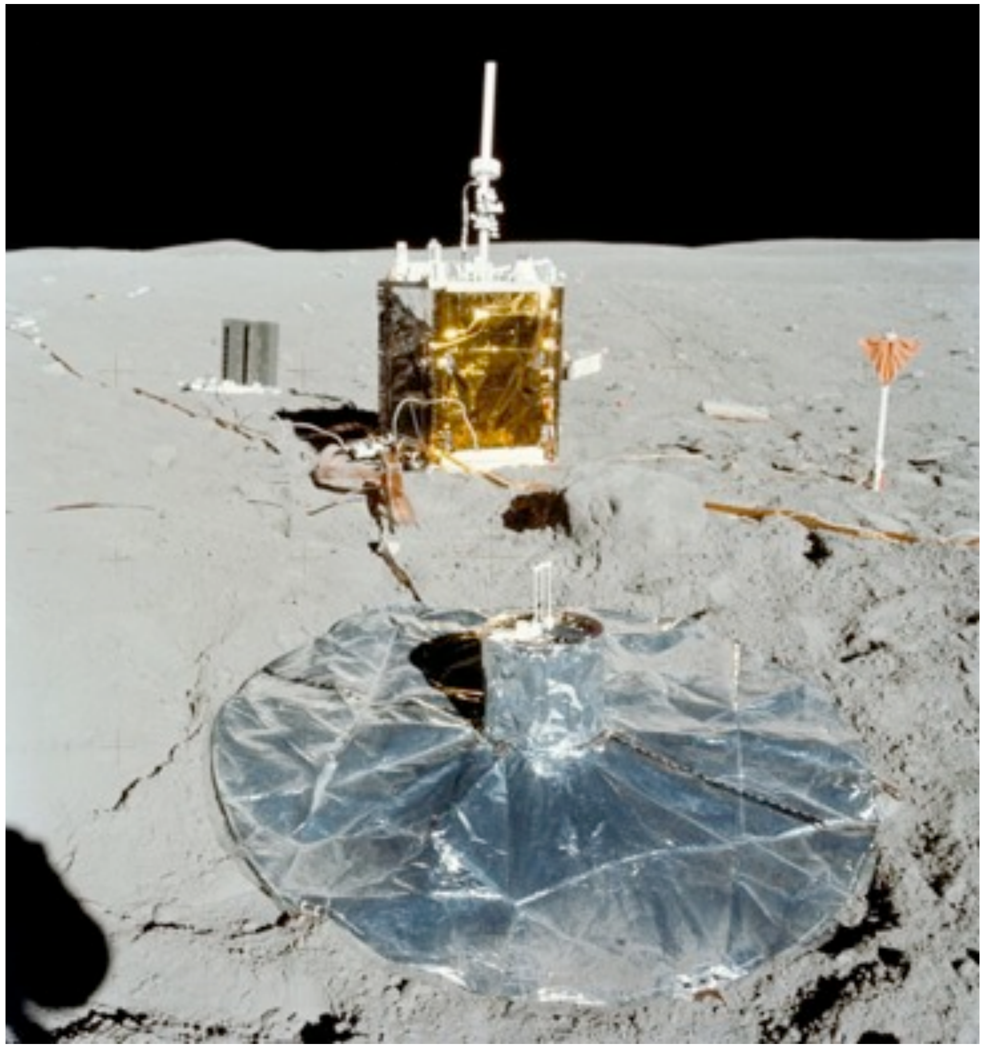
Seismic velocity depends upon both composition and temperature.

The ALSEP Network



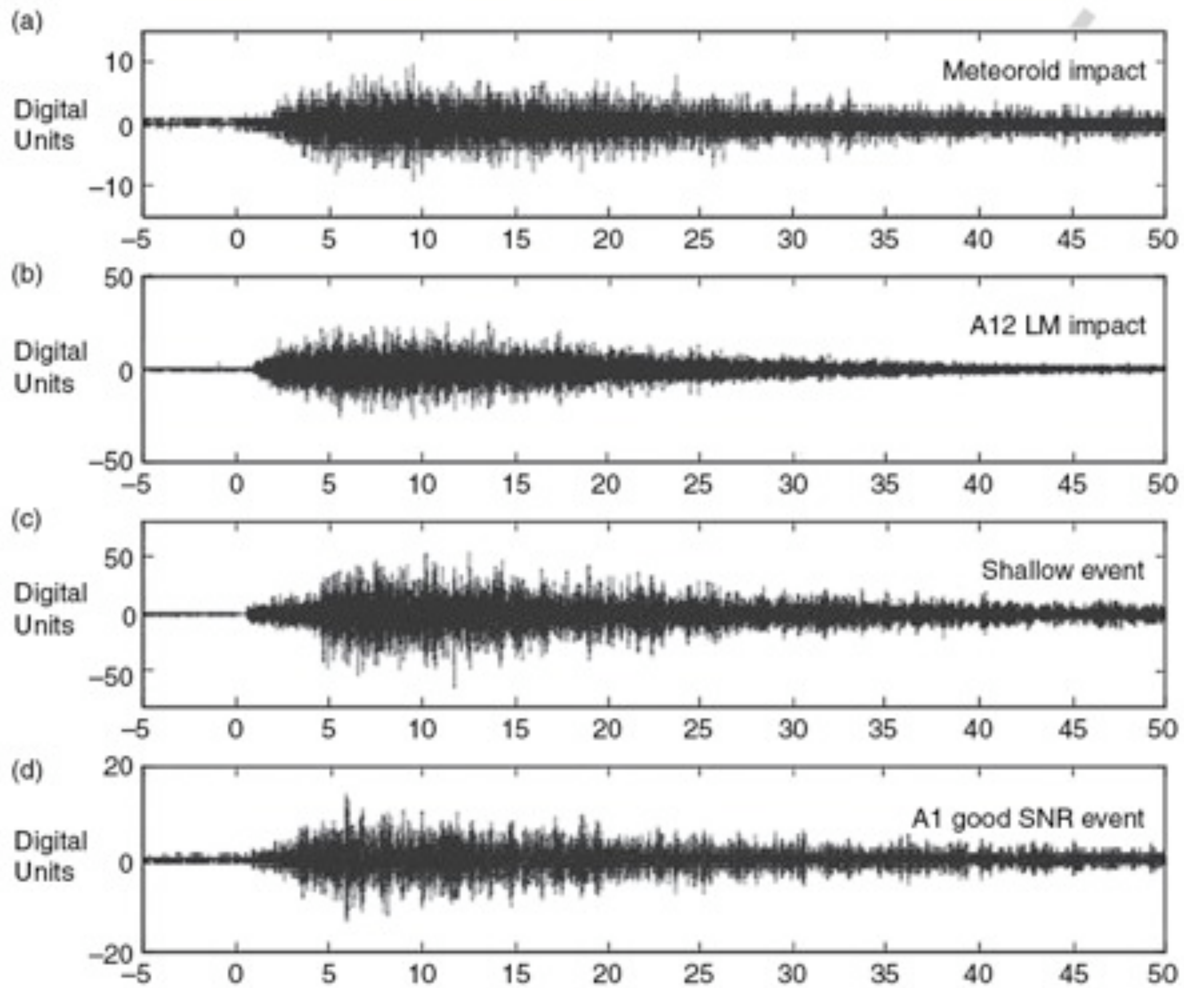
The ALSEP seismic network covered only a small portion of the near-side hemisphere.

Apollo 16 seismometer



The Apollo Lunar Surface Experiment Packages (ALSEP) operated concurrently from ~1972 to mid-1977.

Characteristics of moonquakes



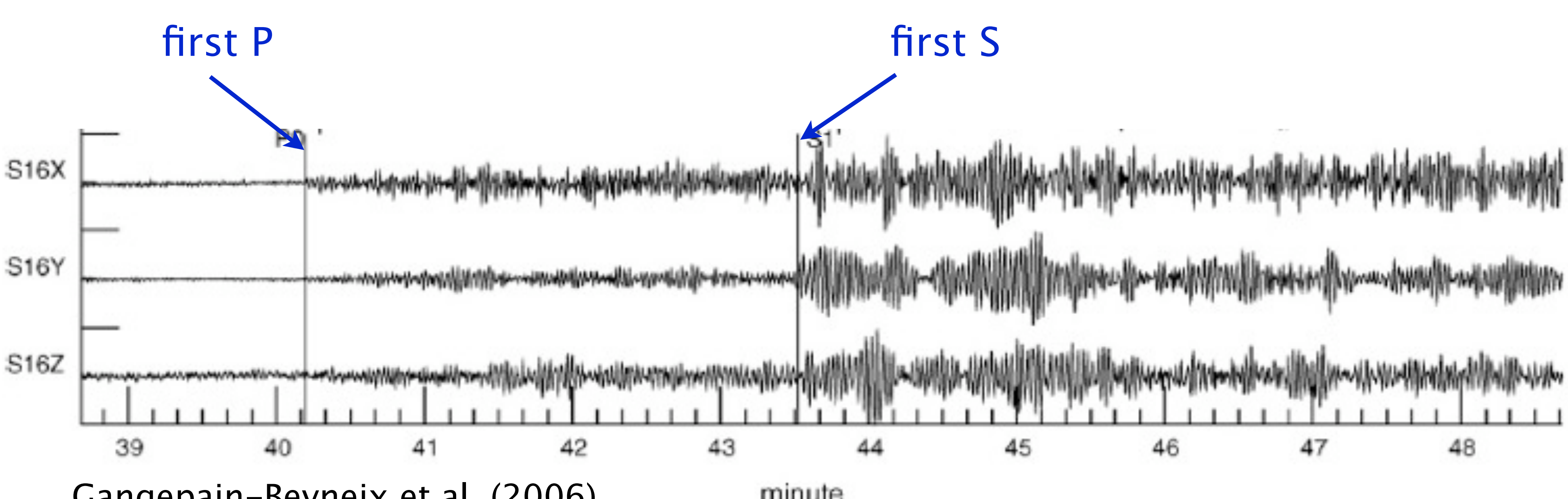
Lognonné and Johnson (2007)

~1700 meteoroid impacts.

9 artificial impacts.

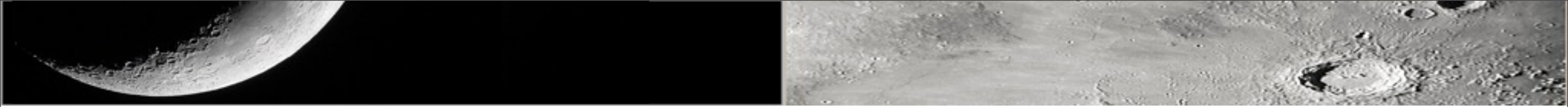
28 shallow "tectonic" moonquakes. (Most energetic, having magnitudes up to 5).

~7000 deep moonquakes originating from about 300 distinct source regions that are correlated with the tides.

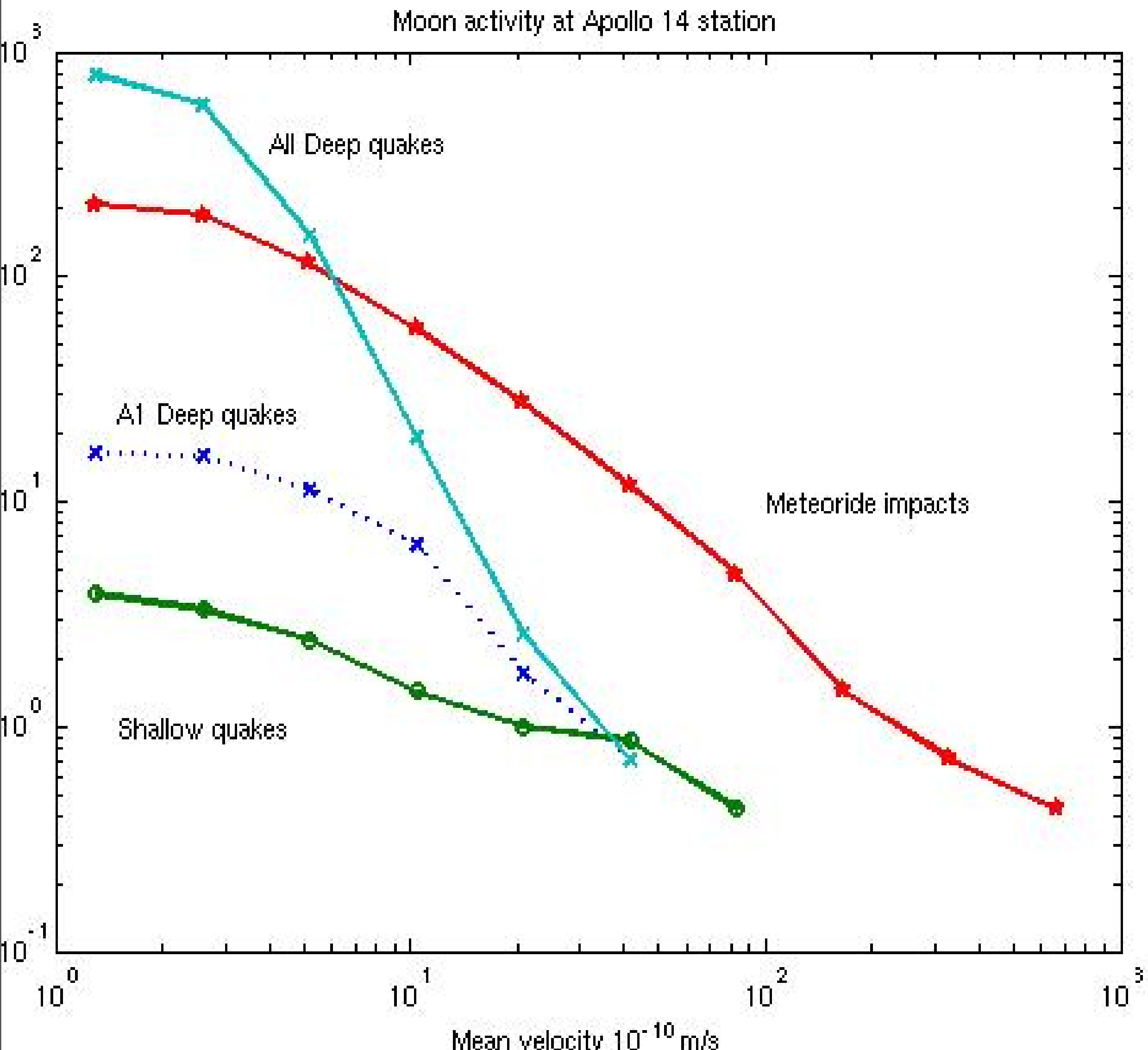


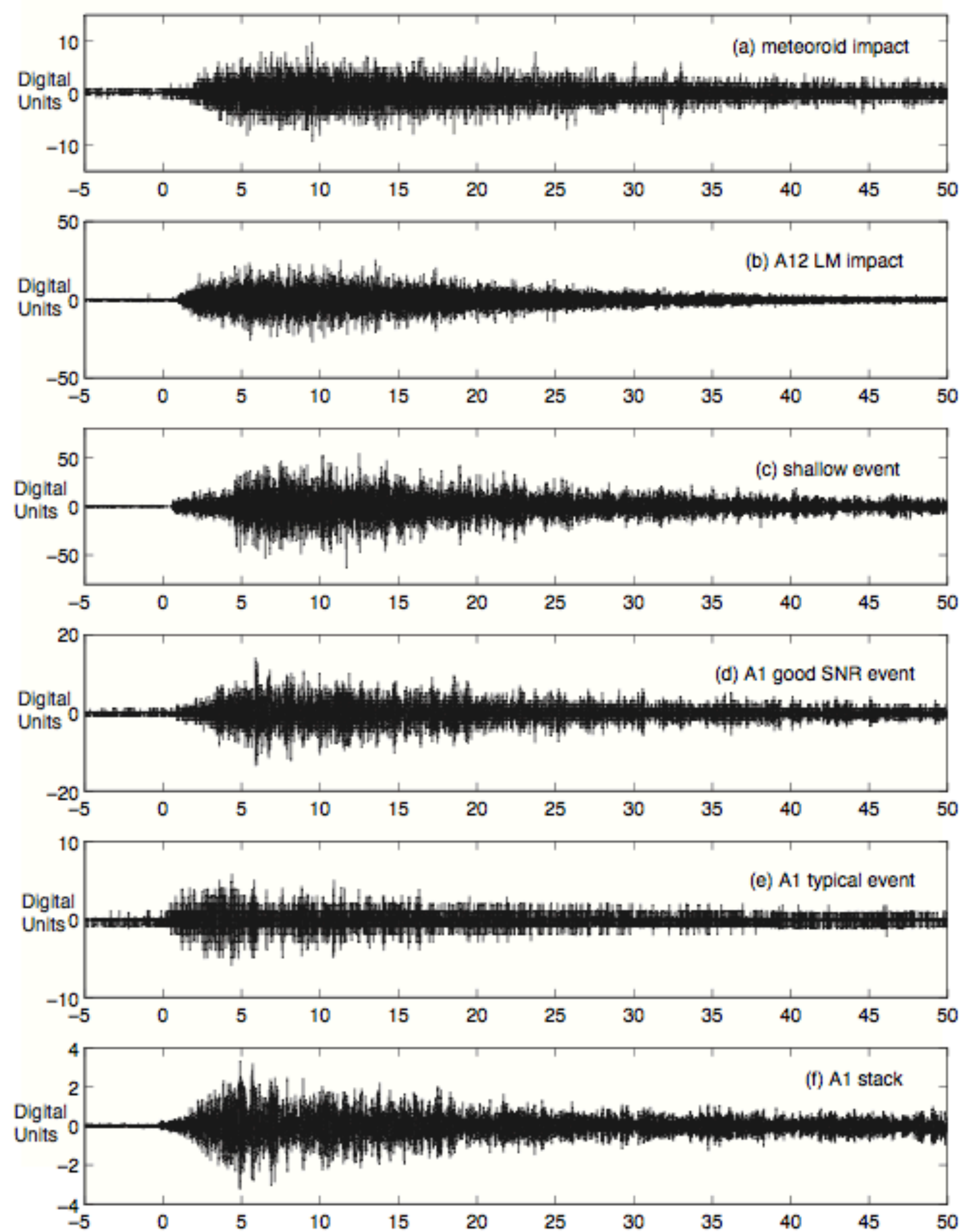
Gangepain-Beyneix et al. (2006)

Picking P and S first-arrival times is subjective; uncertainties can be up to 10 seconds.



But very small amplitudes....



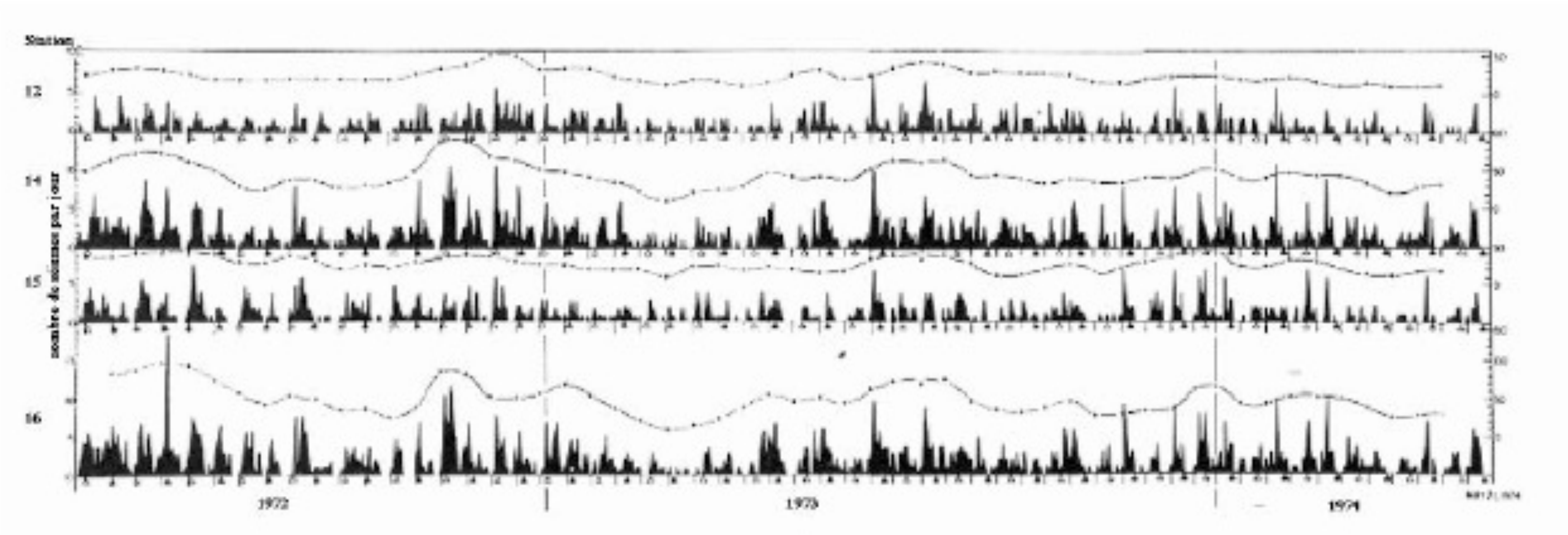


Lognonné and Johnson, 2007

Lunar specific seismic events

- Deep Moon quakes (Quakes occuring at the same locations)
- Impacts (on the Earth, most of the impacting meteorites are burned in the atmosphere)

Deep moonquakes



• Number and amplitude of quakes is related to the amplitude of tide
• About 50 active faults detected
• Quakes occur at the same fault regularly but with very low amplitudes, with ground displacement of a few Angströms at 2 sec (0.5 10^{-9} ms^{-2} of ground acceleration)

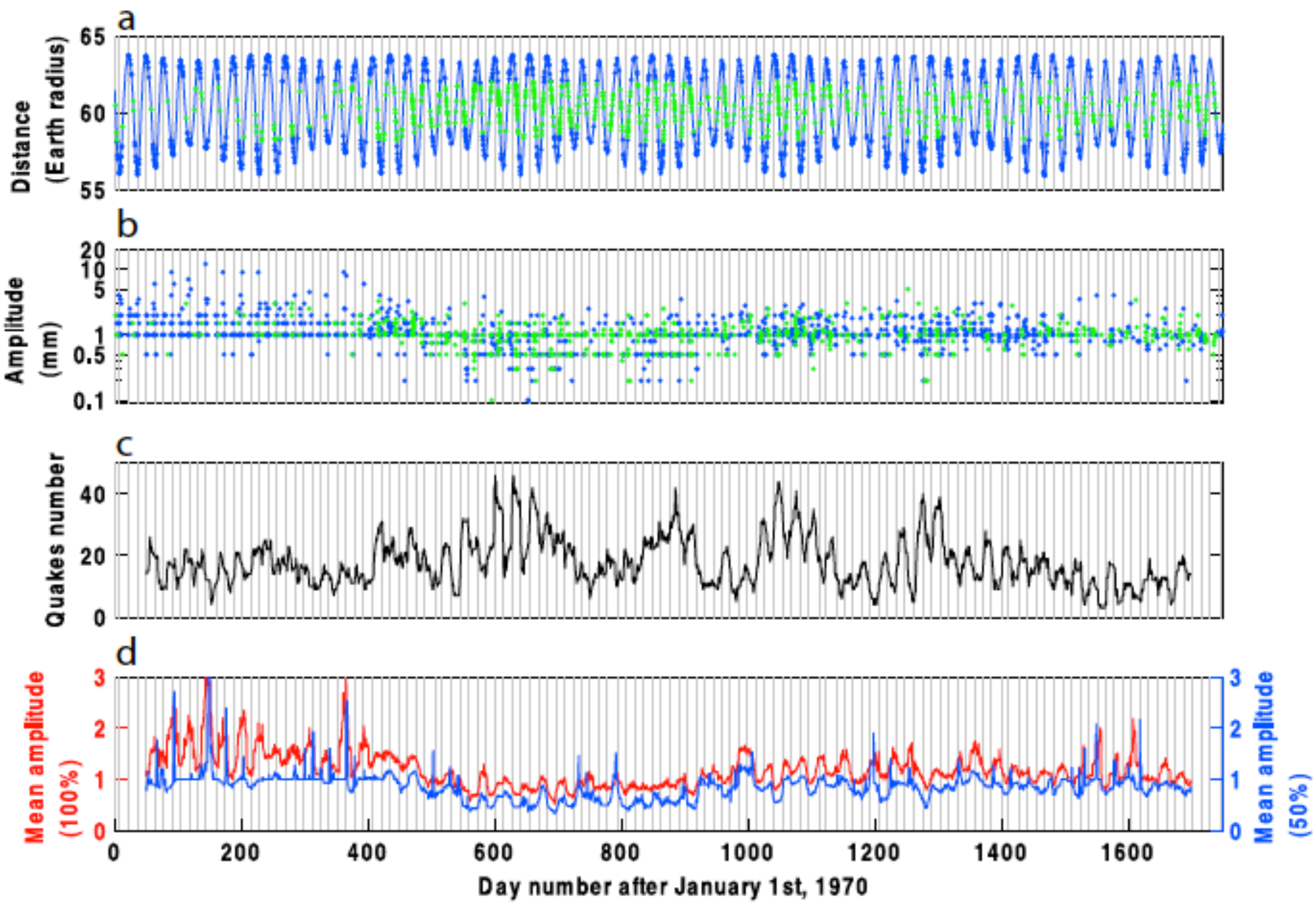
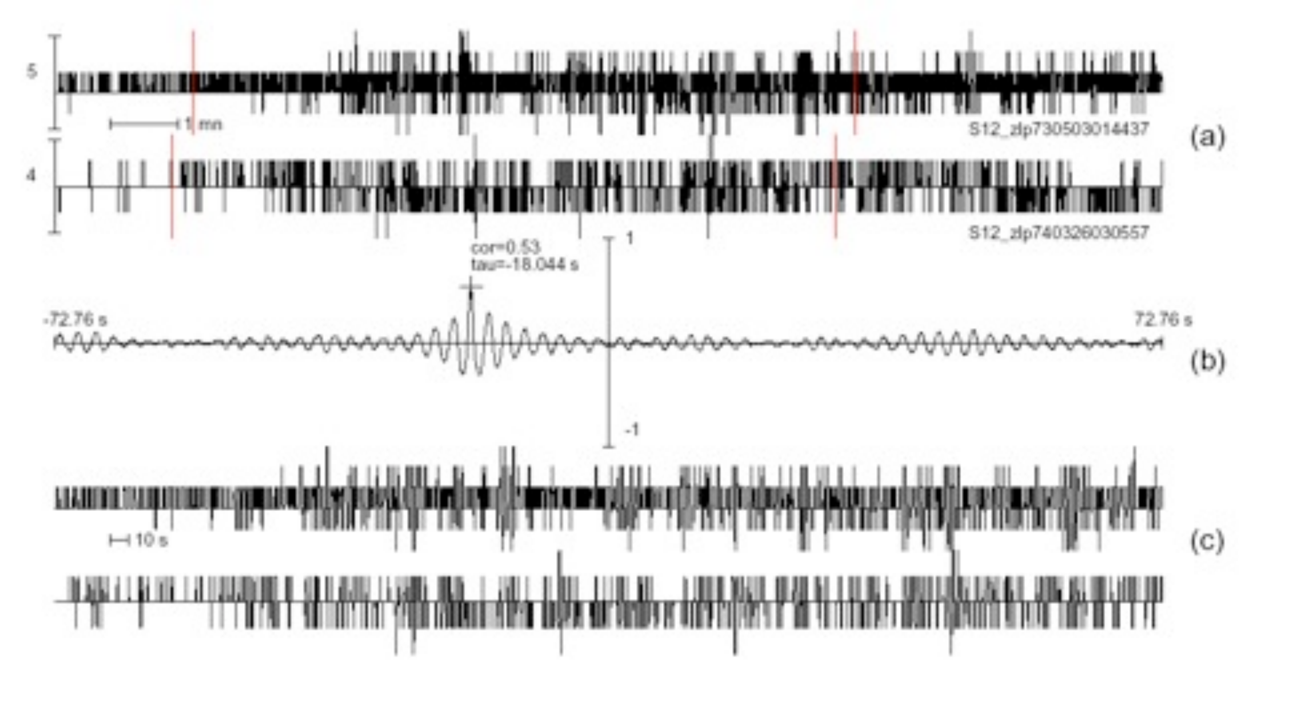
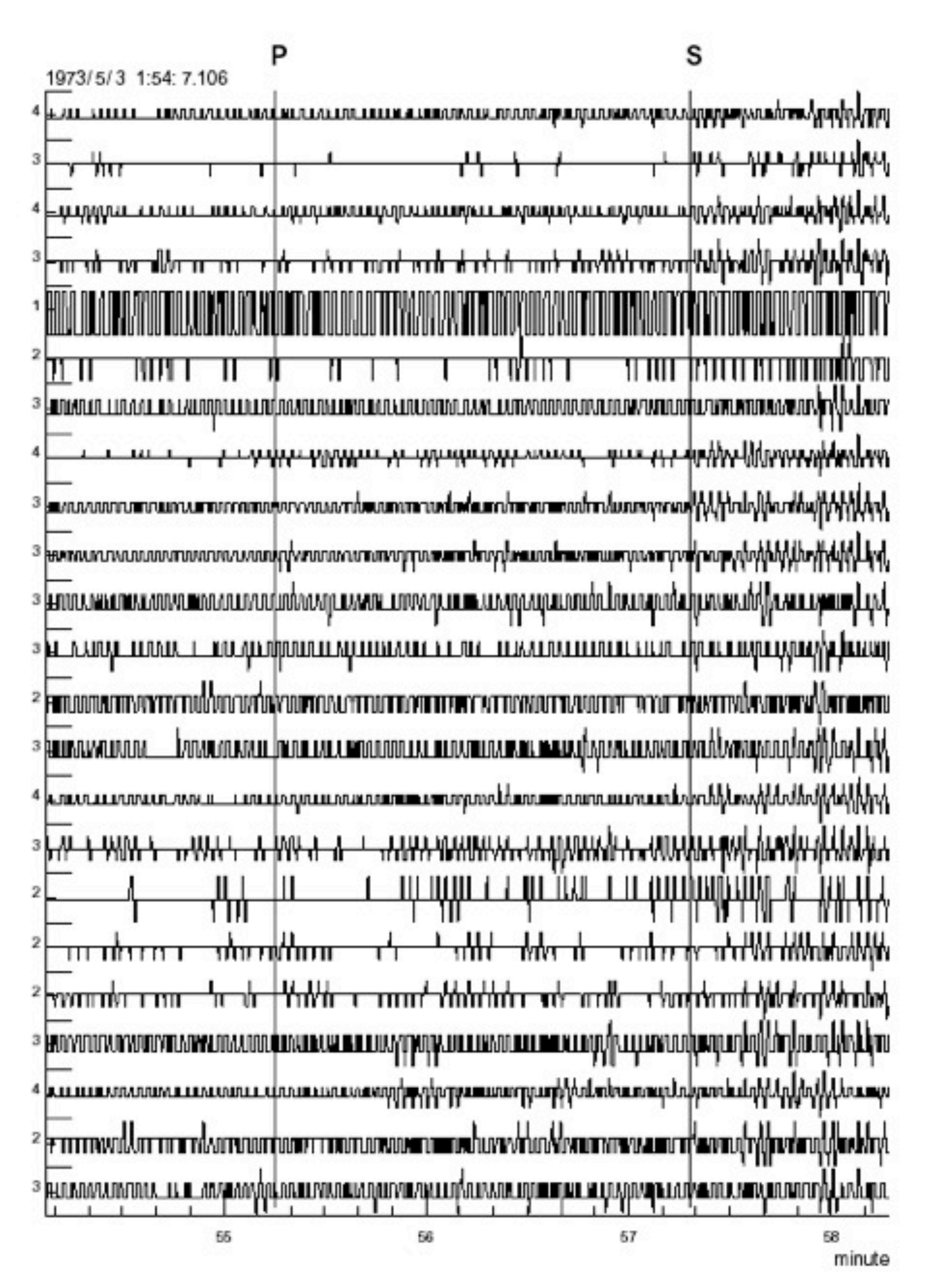


Figure 4. (a) Occurrence times of deep moonquakes plotted on the Earth-Moon distance curve. The green (blue) stars are used for events occurring when the Earth-Moon distance is smaller (greater) than 50% of its maximum excursion from the mean distance. (b) The corresponding amplitudes. (c) The number of moonquakes occurring in a 2 week period centered on any given day. (d) The mean amplitude of all events (red line) in this 2 week period, and the mean amplitude of the smallest 50% of events in the same period (blue line). We note variations in the latter between 0.5 to 1 mm.

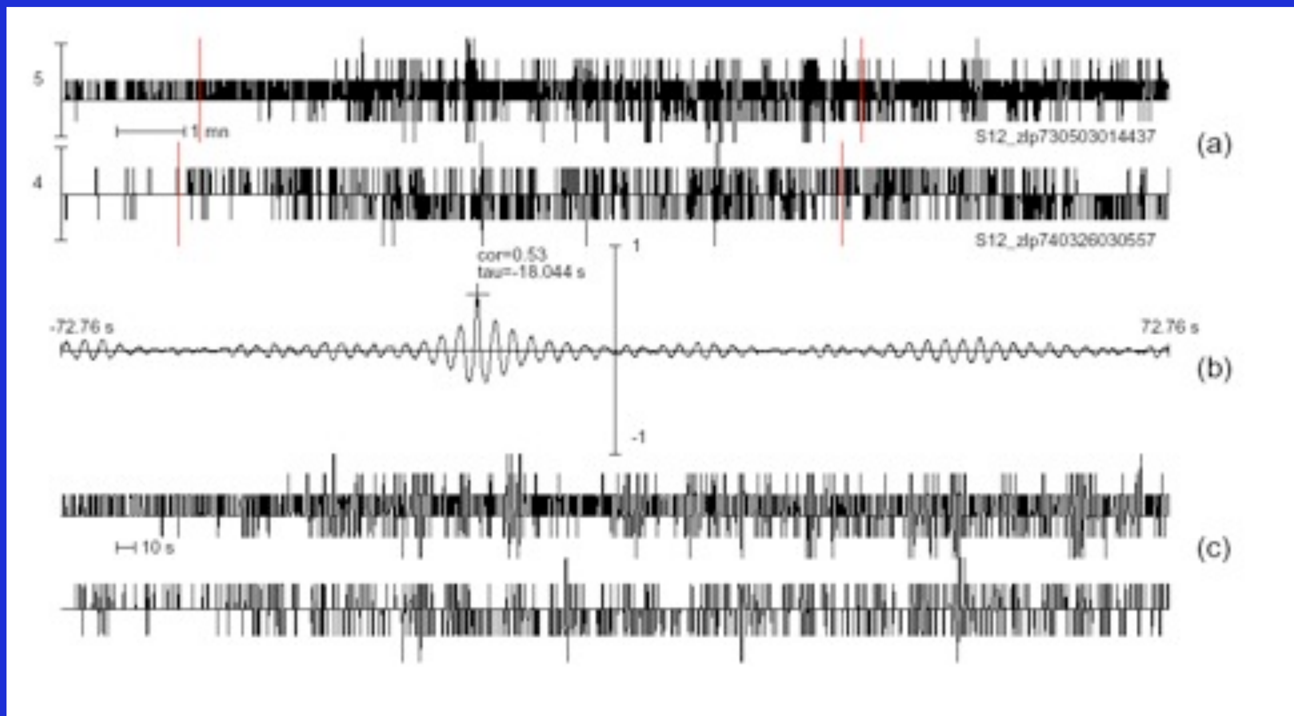
Deep Moonquake

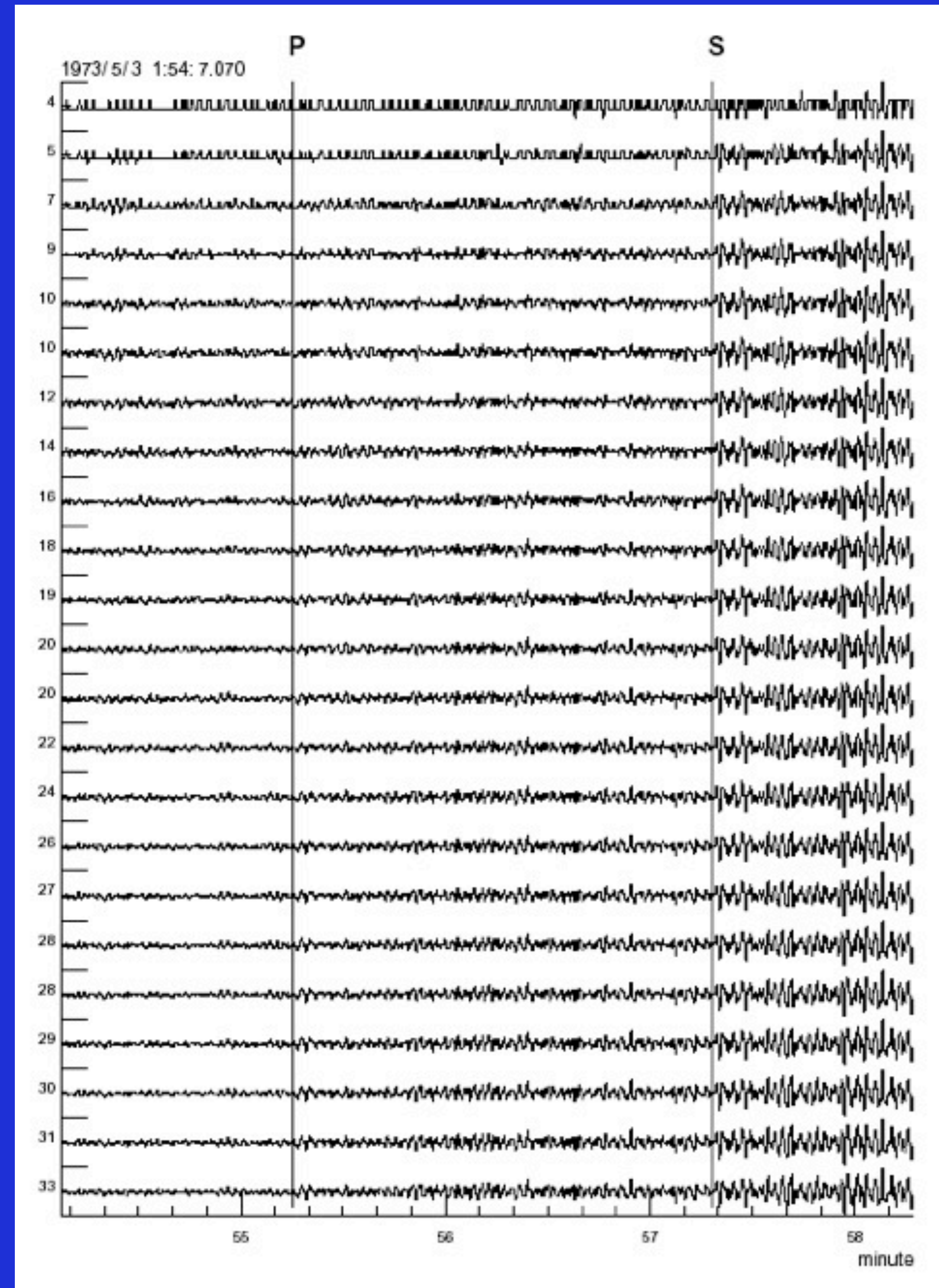


- example of two quakes (in 1973 and in 1974) from the same deep focus and their cross-correlation
- cross-correlation provides the time shift necessary to align the arrival times
- stacking can then be done



Deep Moonquake





- example of two quakes (in 1973 and 1974) from the same deep focus and their cross-correlation
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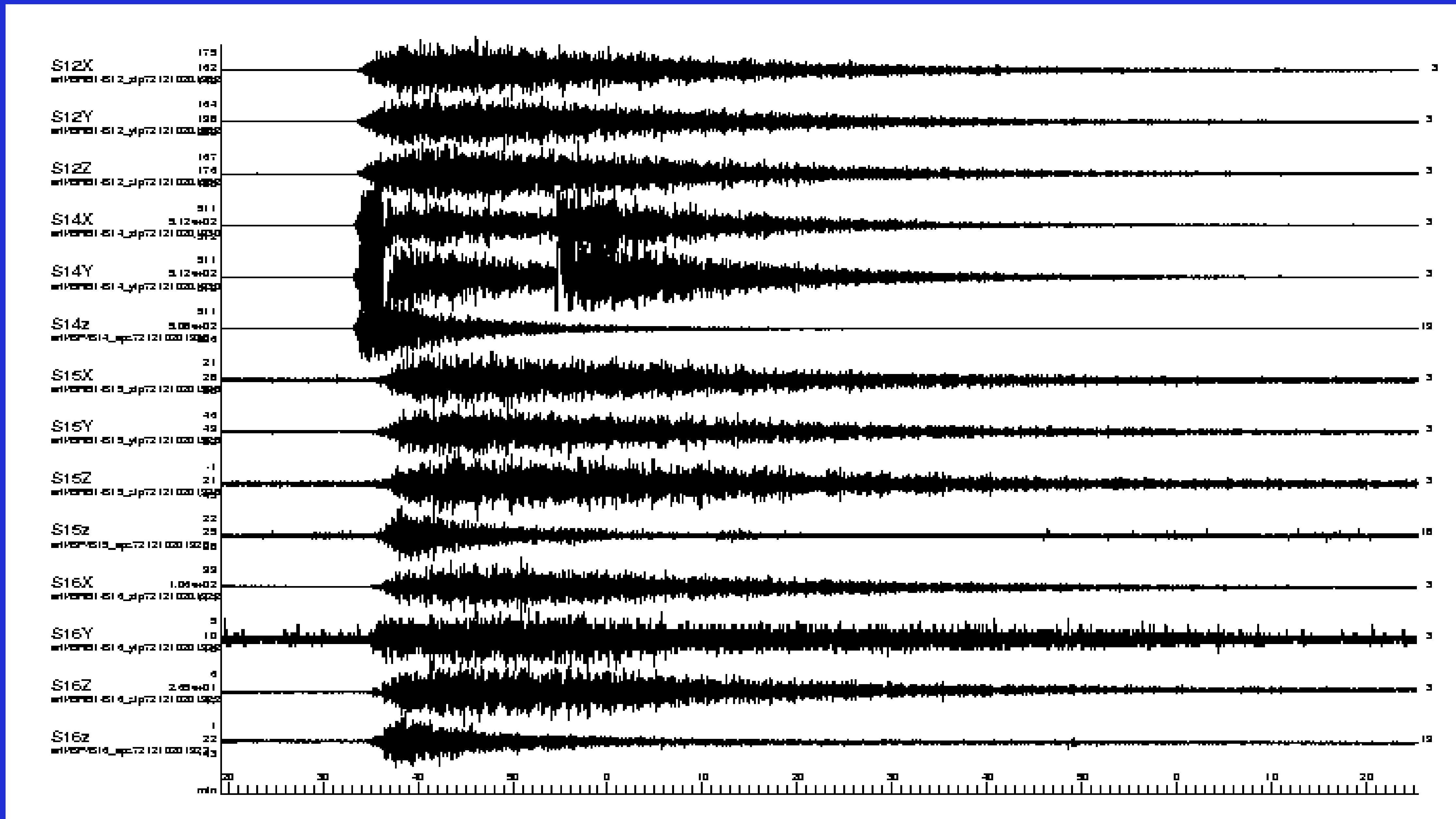
Active source: impacts

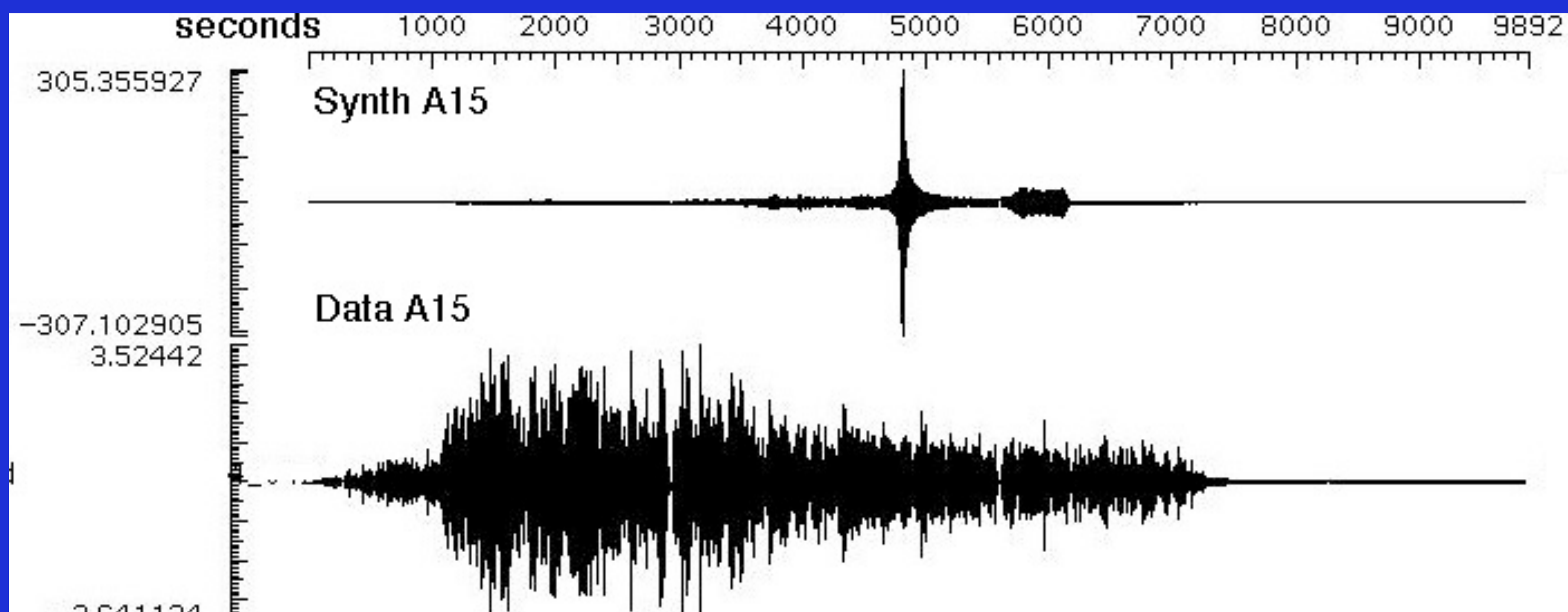


- Impact of the Apollo 17 Saturn V upper stage (Saturn IVB) on the Moon on 10 December 1972 at distances of 338, 157, 1032 and 850 km from the Apollo 12, 14, 15 and 16 stations, respectively. Amplitudes at Apollo 14 station, 157 km from impact, reach about 10^{-5} m s^{-2}
- Known time and location: all arrival times give information on the structure

Diffraction: the modelling chalenge!

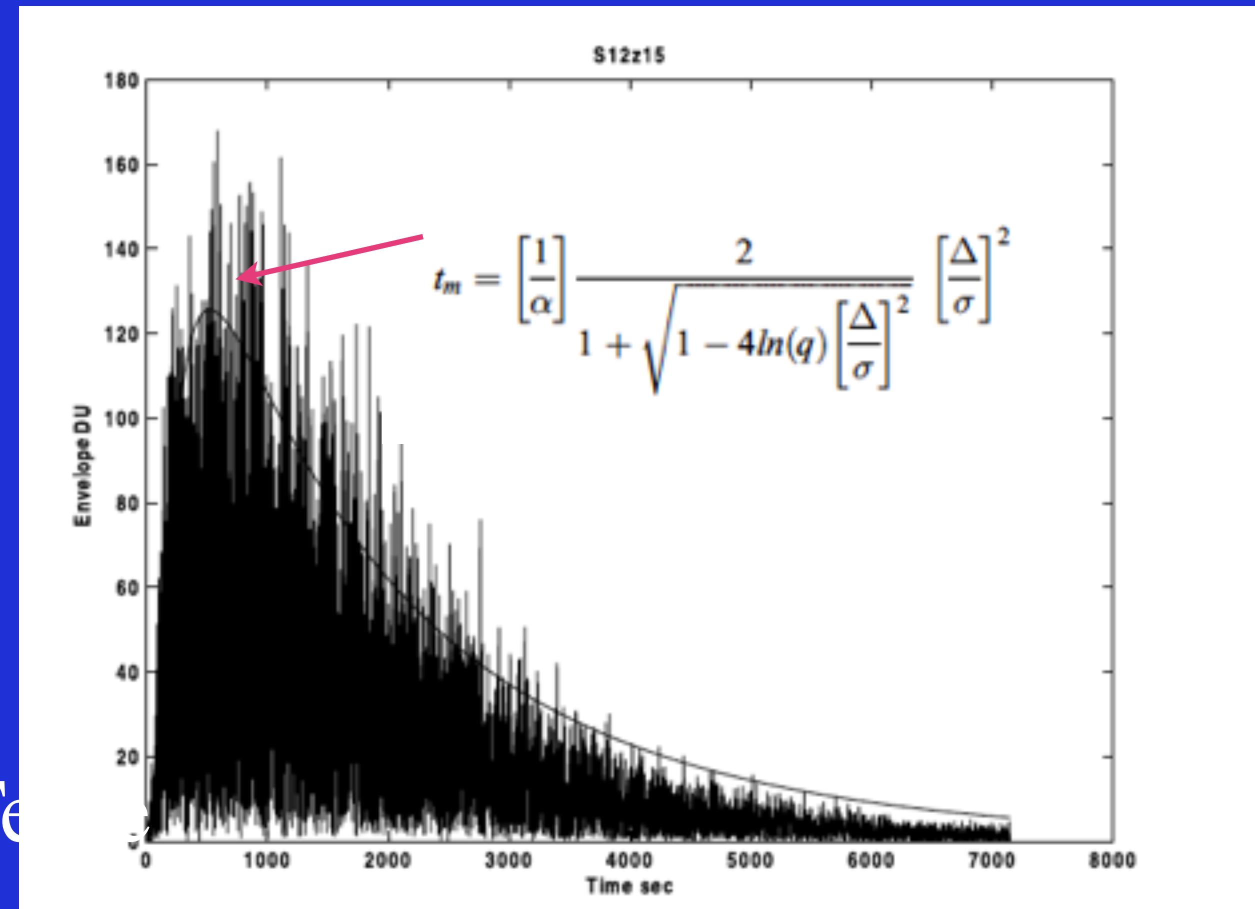
- The Moon subsurface is highly fracturated, as a results of non-resurfacing and of a long impacting history
- Propagation equation is not valid anymore for waves propagating in the crust and diffusion equation must be used
- Scattering destroy short period surface waves and is able to transfer energy from P to S waves up to an equipartition given by $E_p= v_s^3/ v_p^3 E_s/2$, where E_p, E_s are the energy of P and S waves, v_p , v_s are the velocities of P and S waves

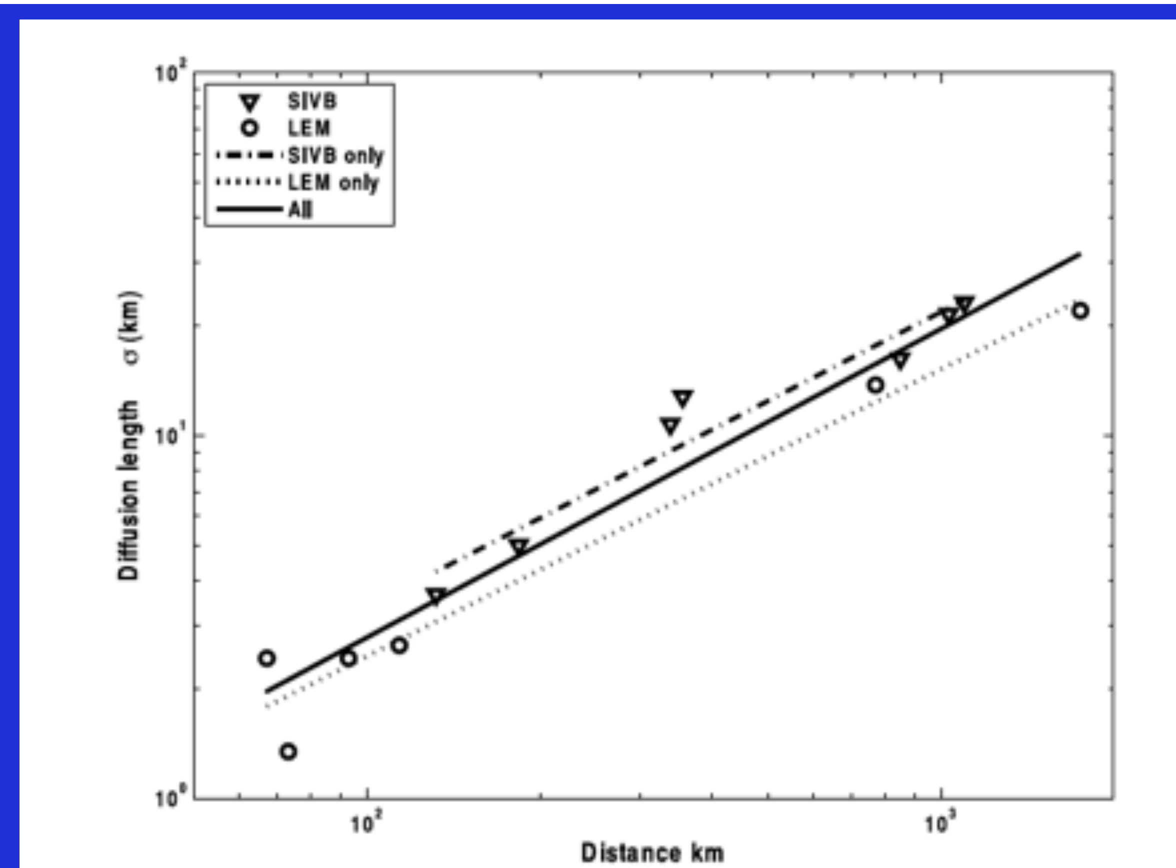
Example a known artifical impact



$$e(t) = A^2 q^{\alpha t} \frac{1}{\alpha t} e^{-\frac{1\Delta^2}{\alpha t \sigma^2}}$$

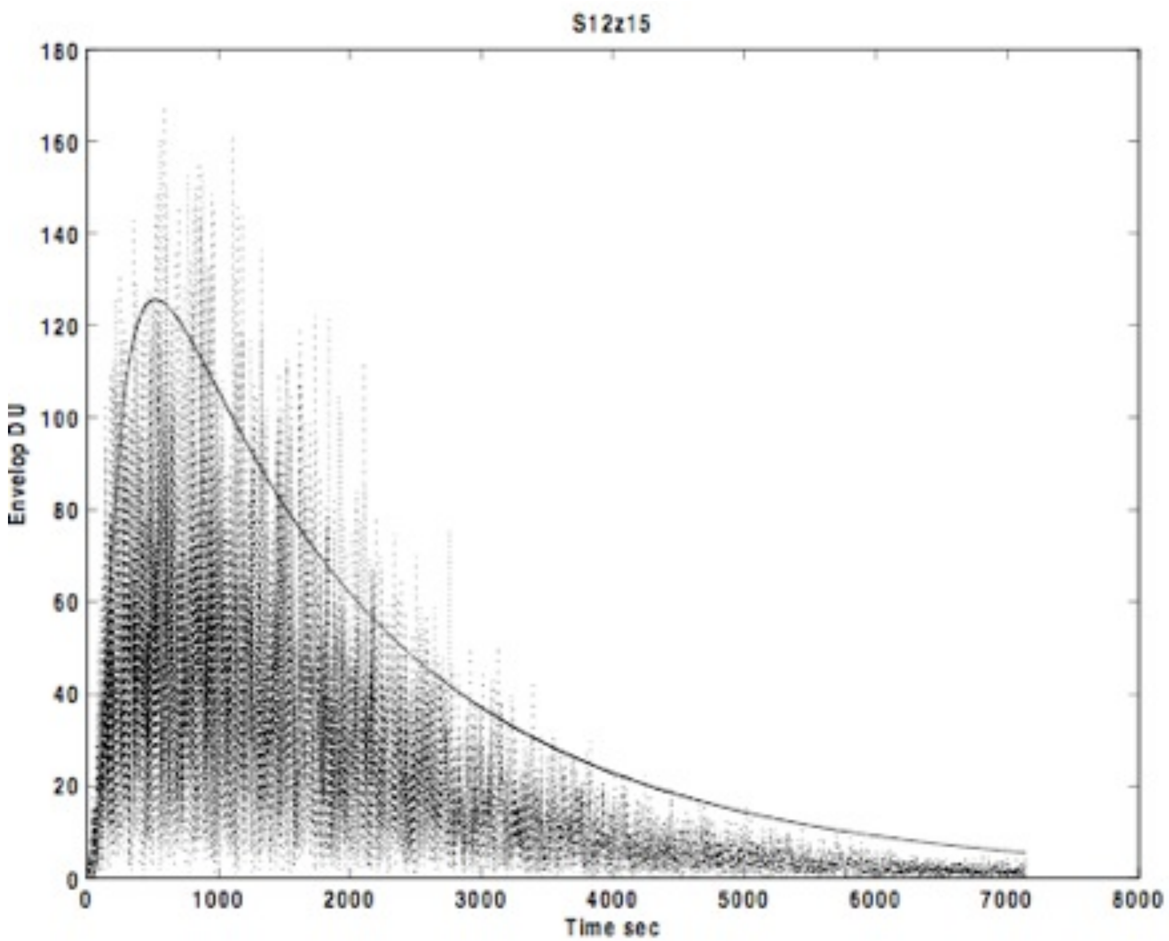
Te

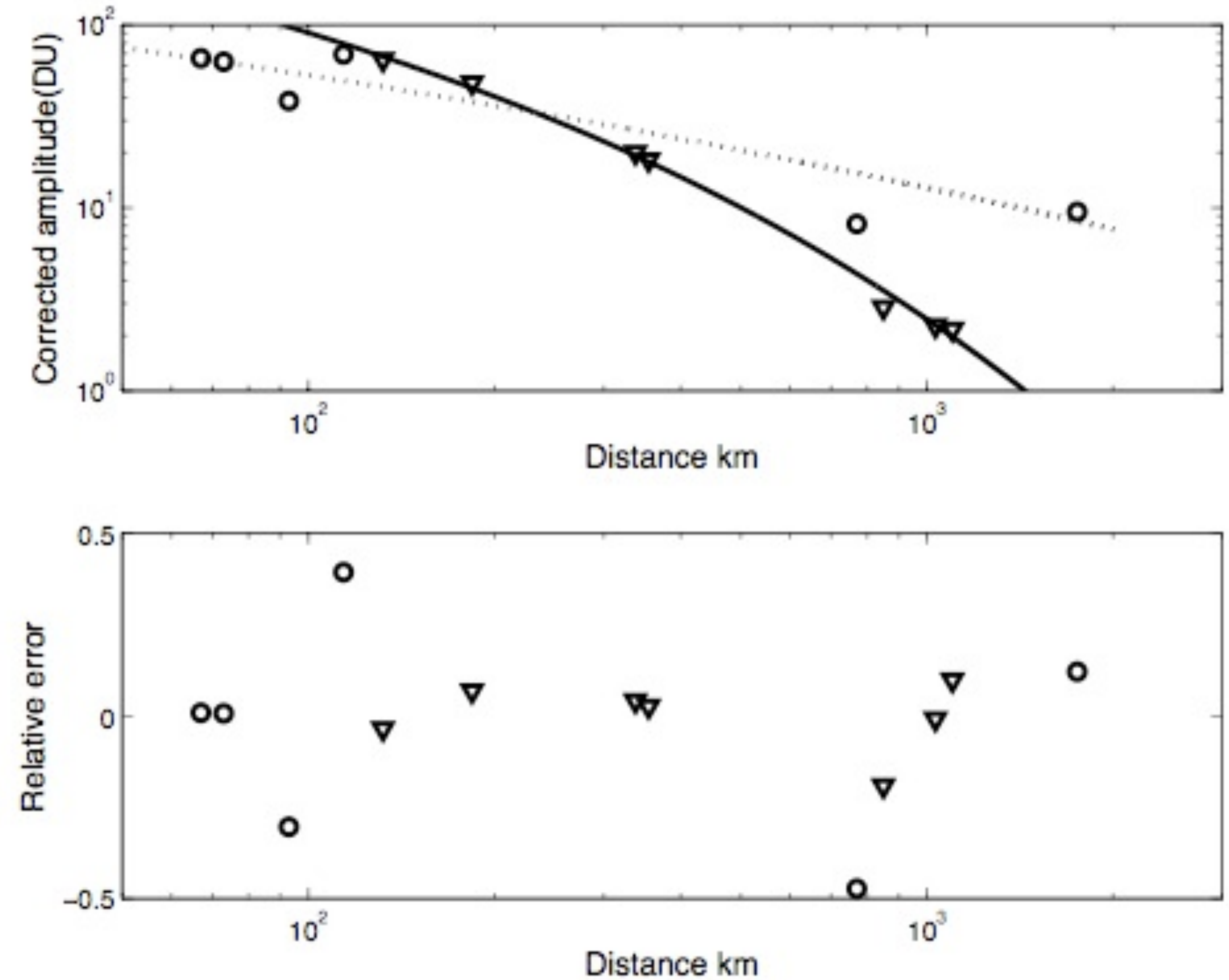


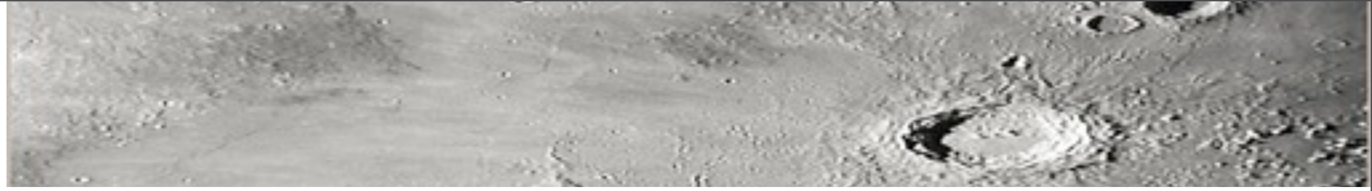


- Simple Diffusion theory (Strobach, 1970)

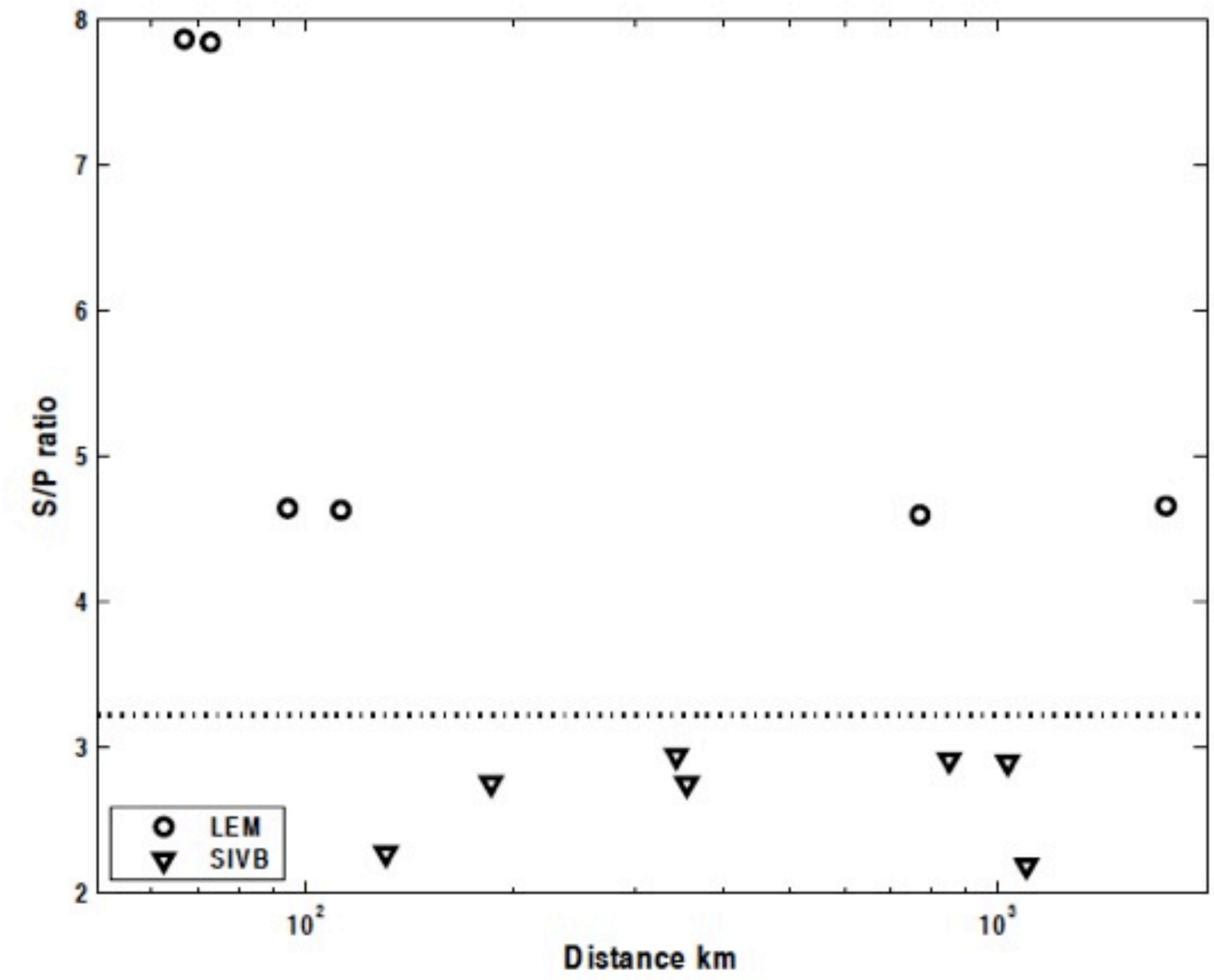
Excitation differences between the LEM and S4B impacts







A signature of a different diffusion regime?



Modeling without the diffracted surface waves

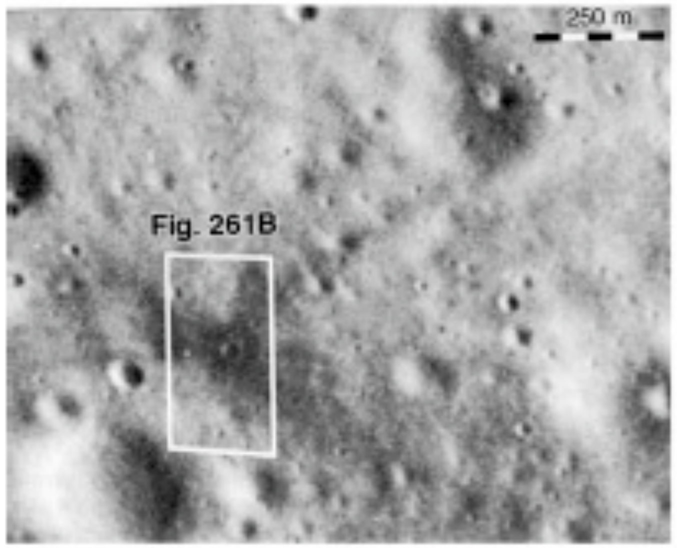
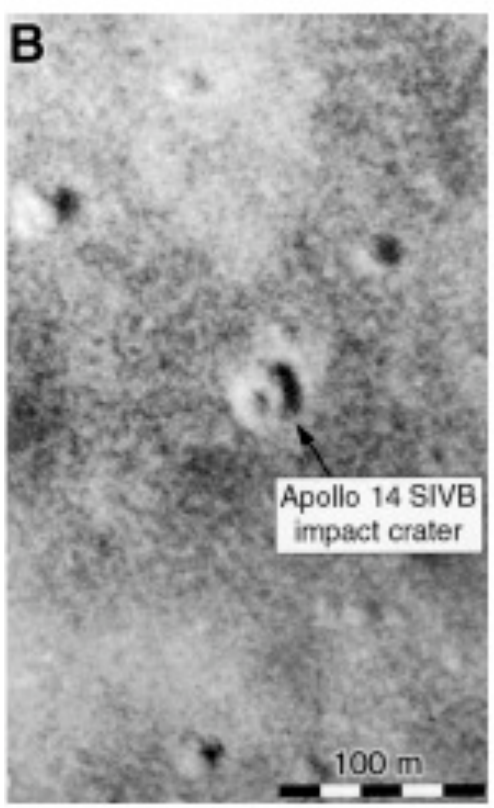
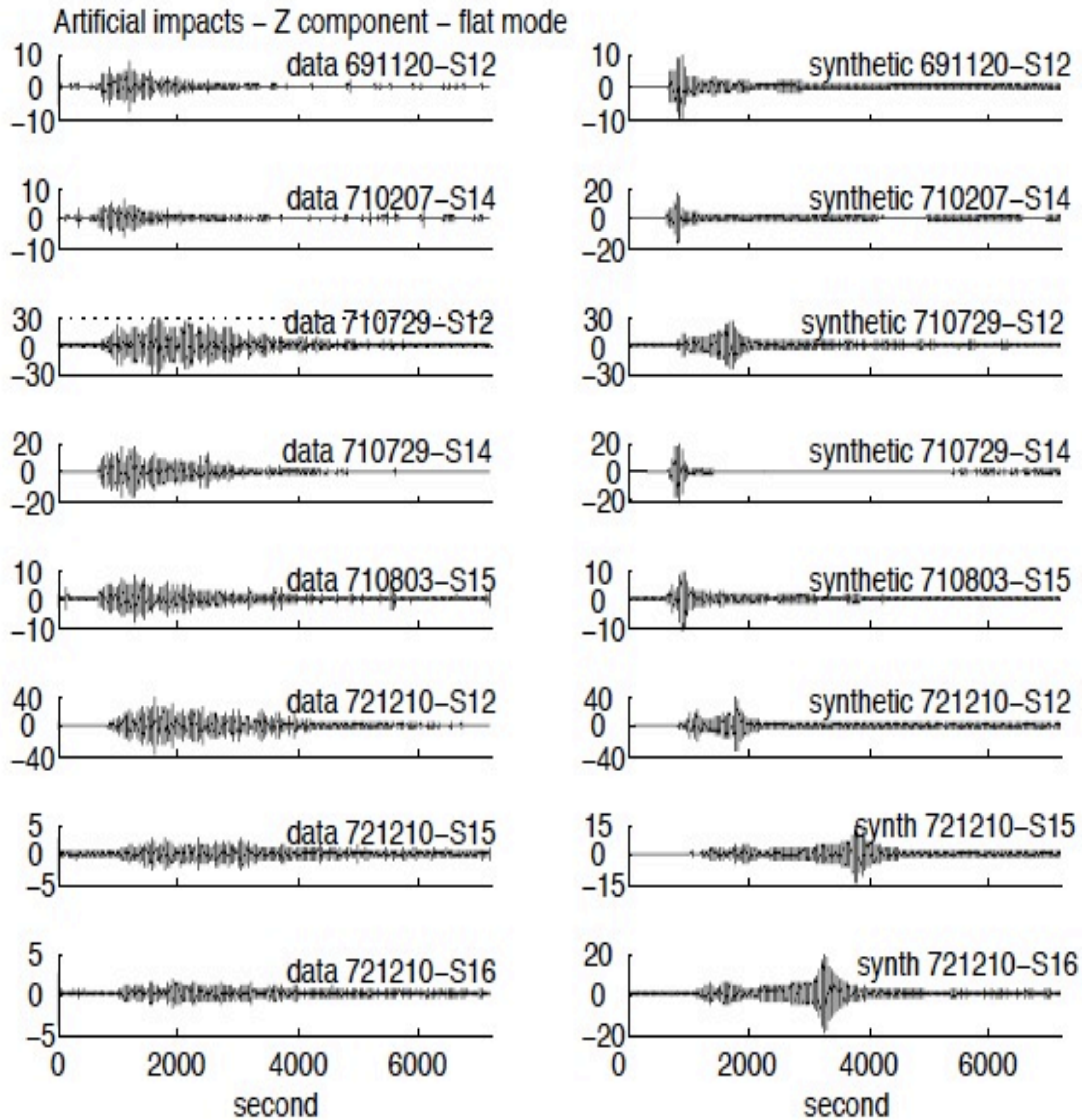
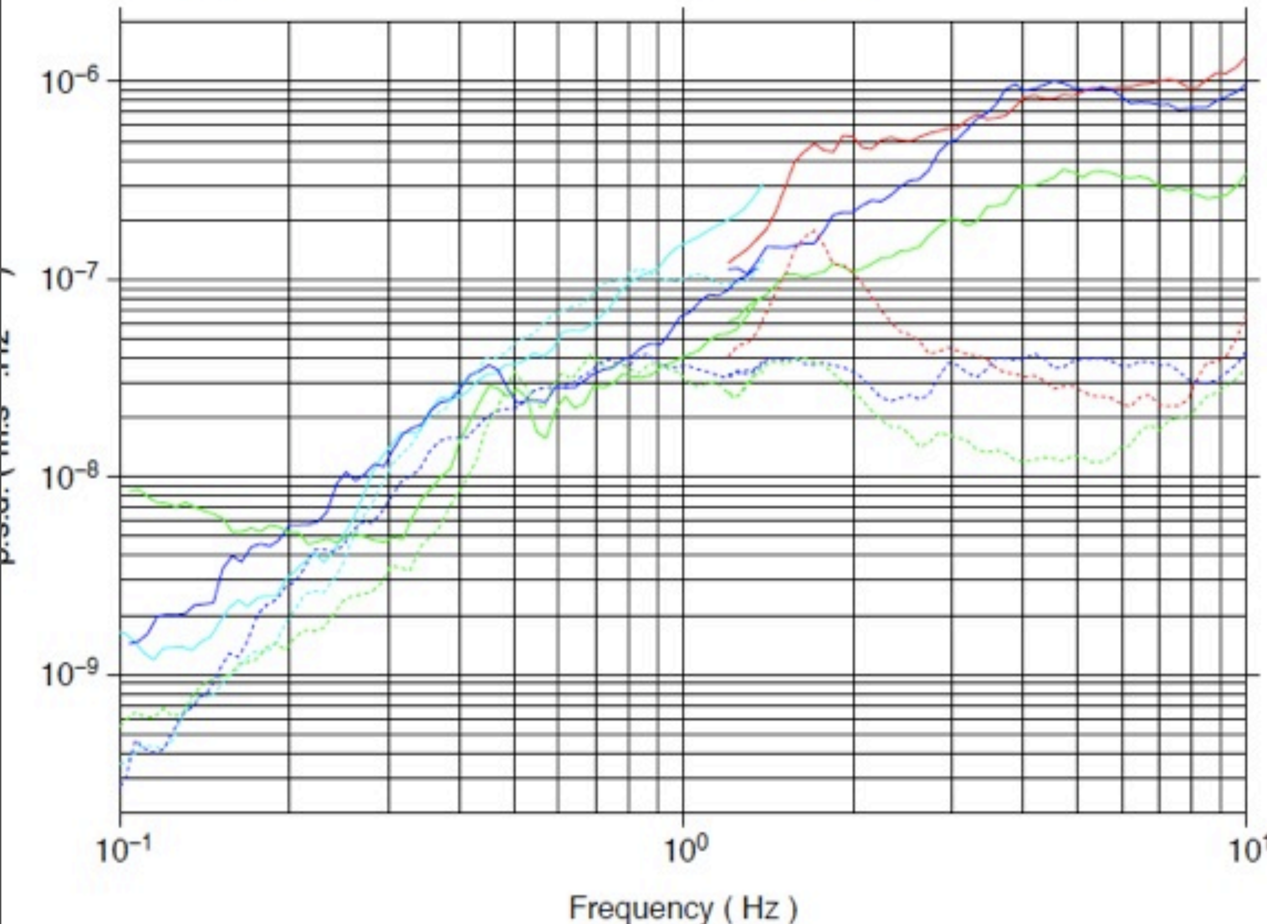


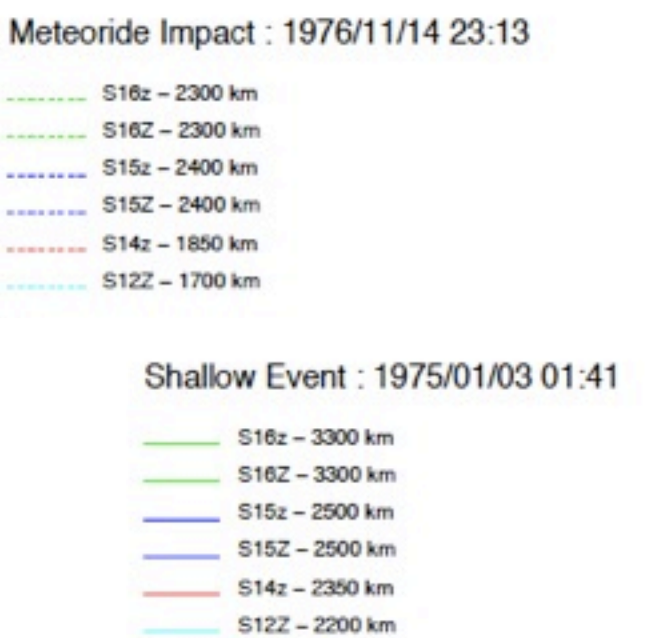
Fig. 1: Apollo 14 SIV/B impact site, images taken from [4]

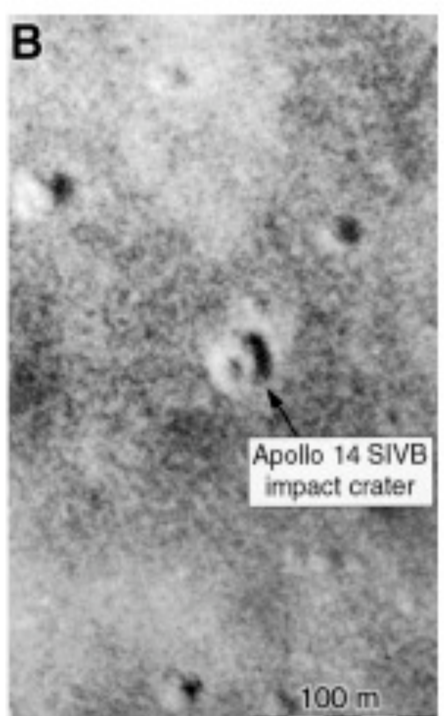




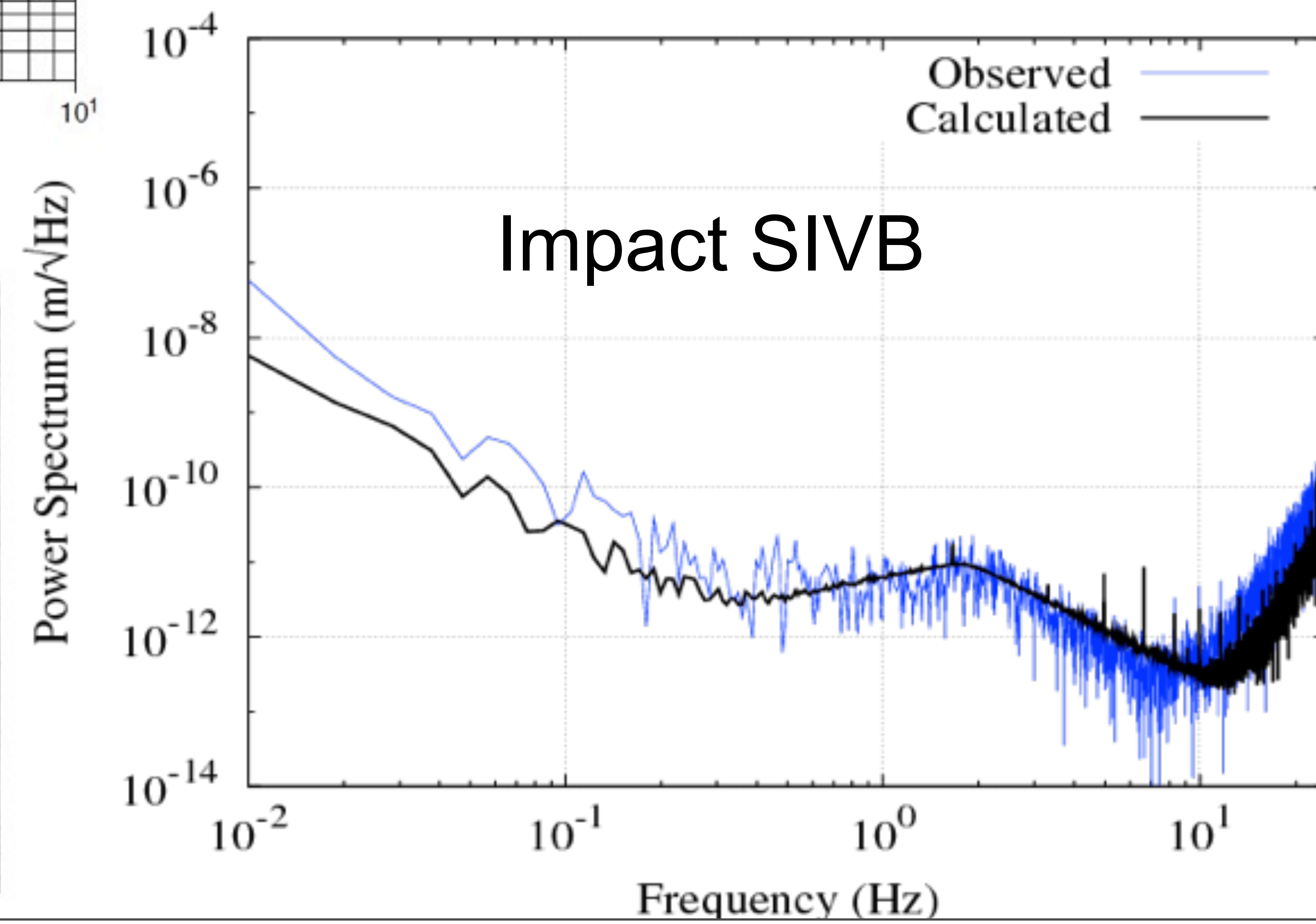
Impacts



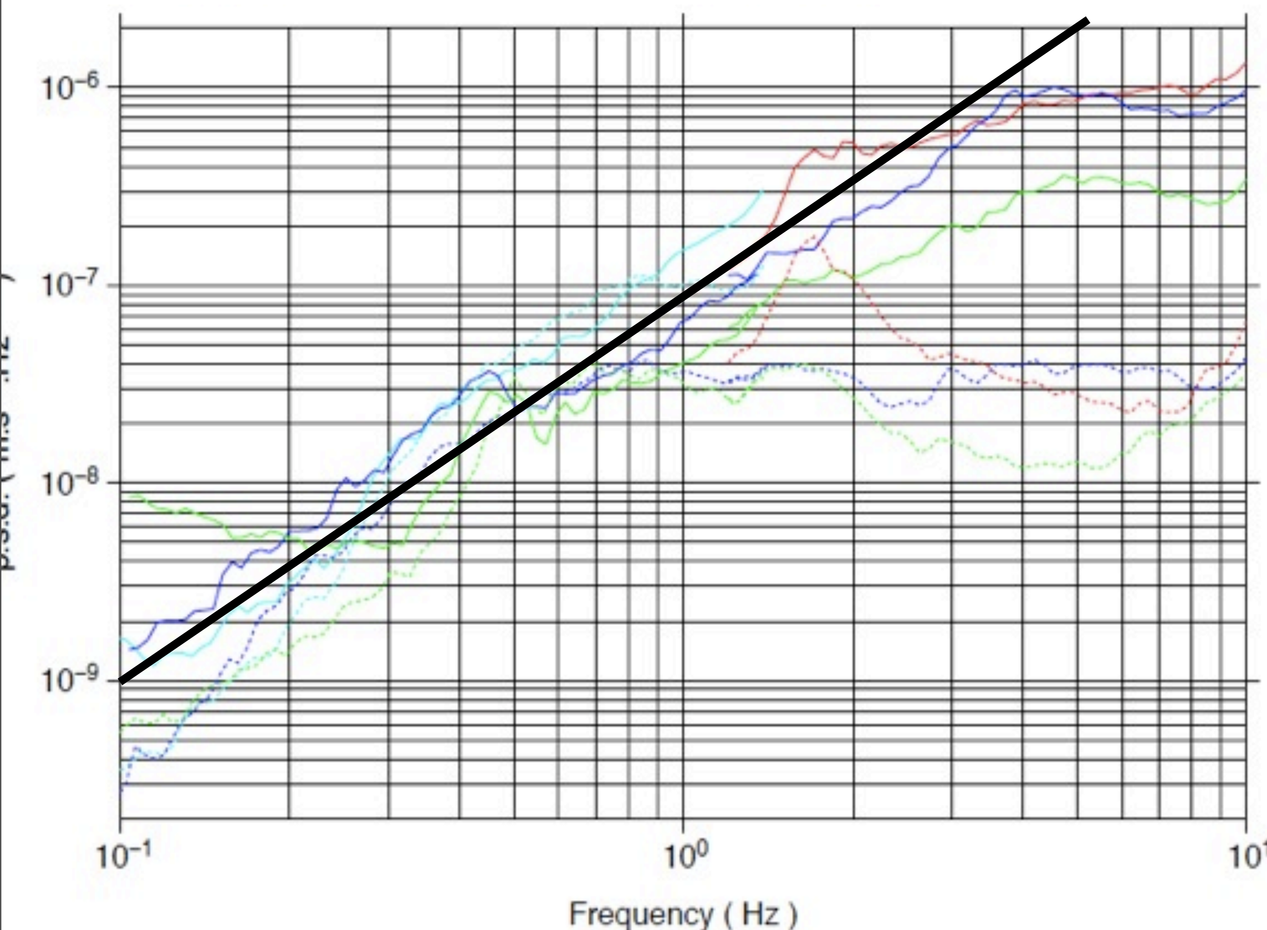


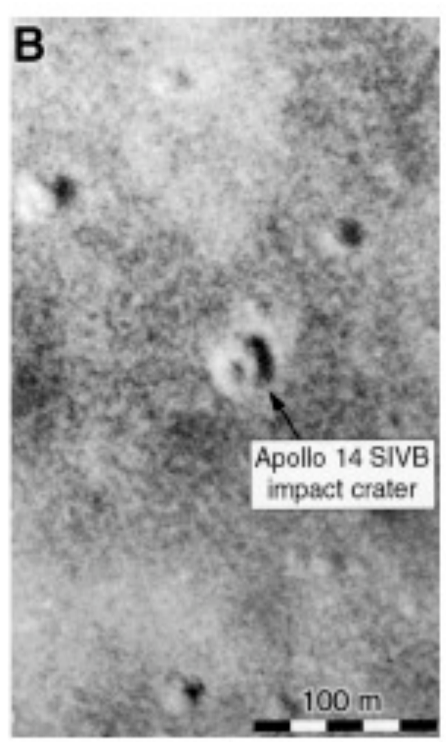


Impacts DO not generate high seismic frequencies!

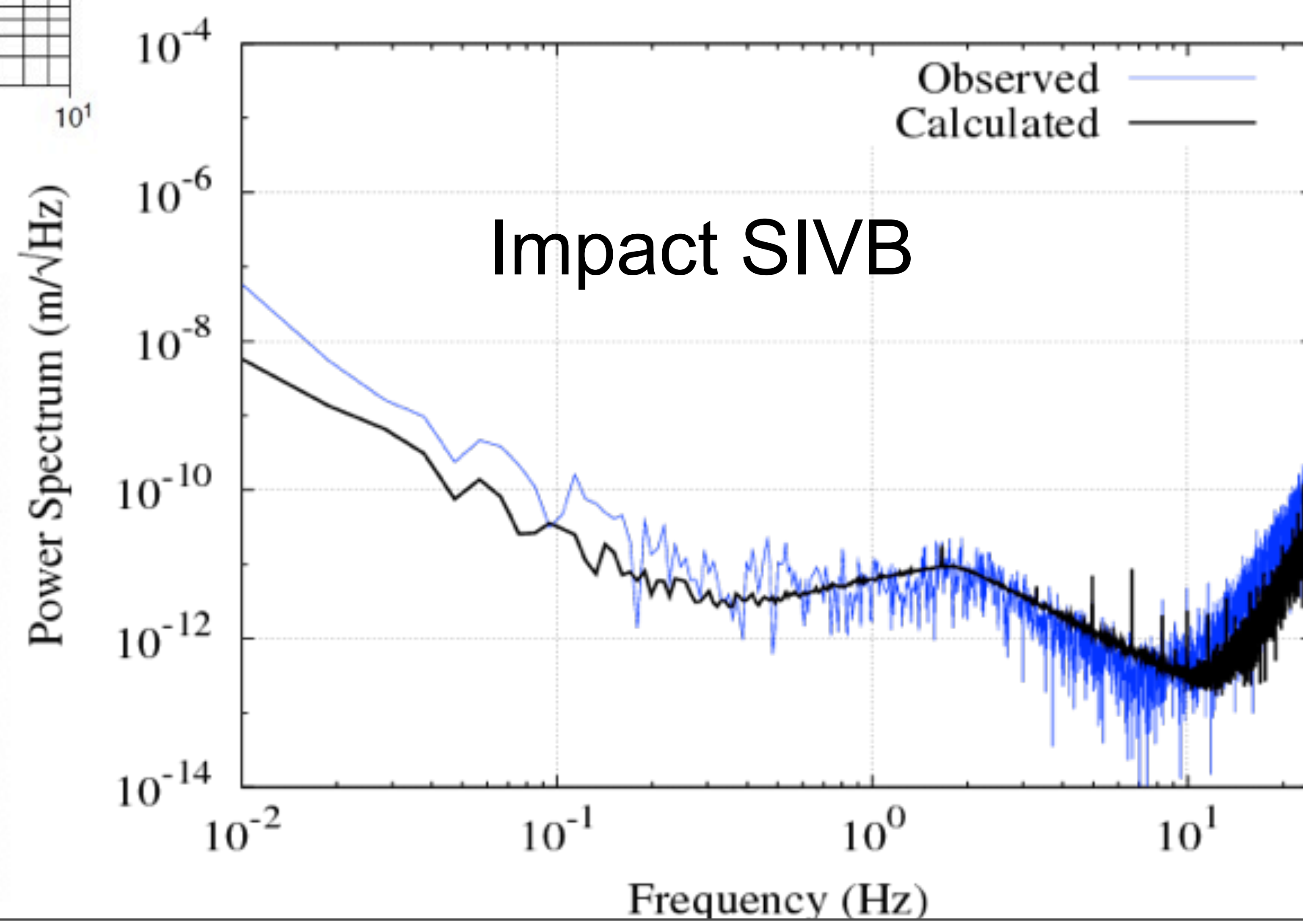


Quake

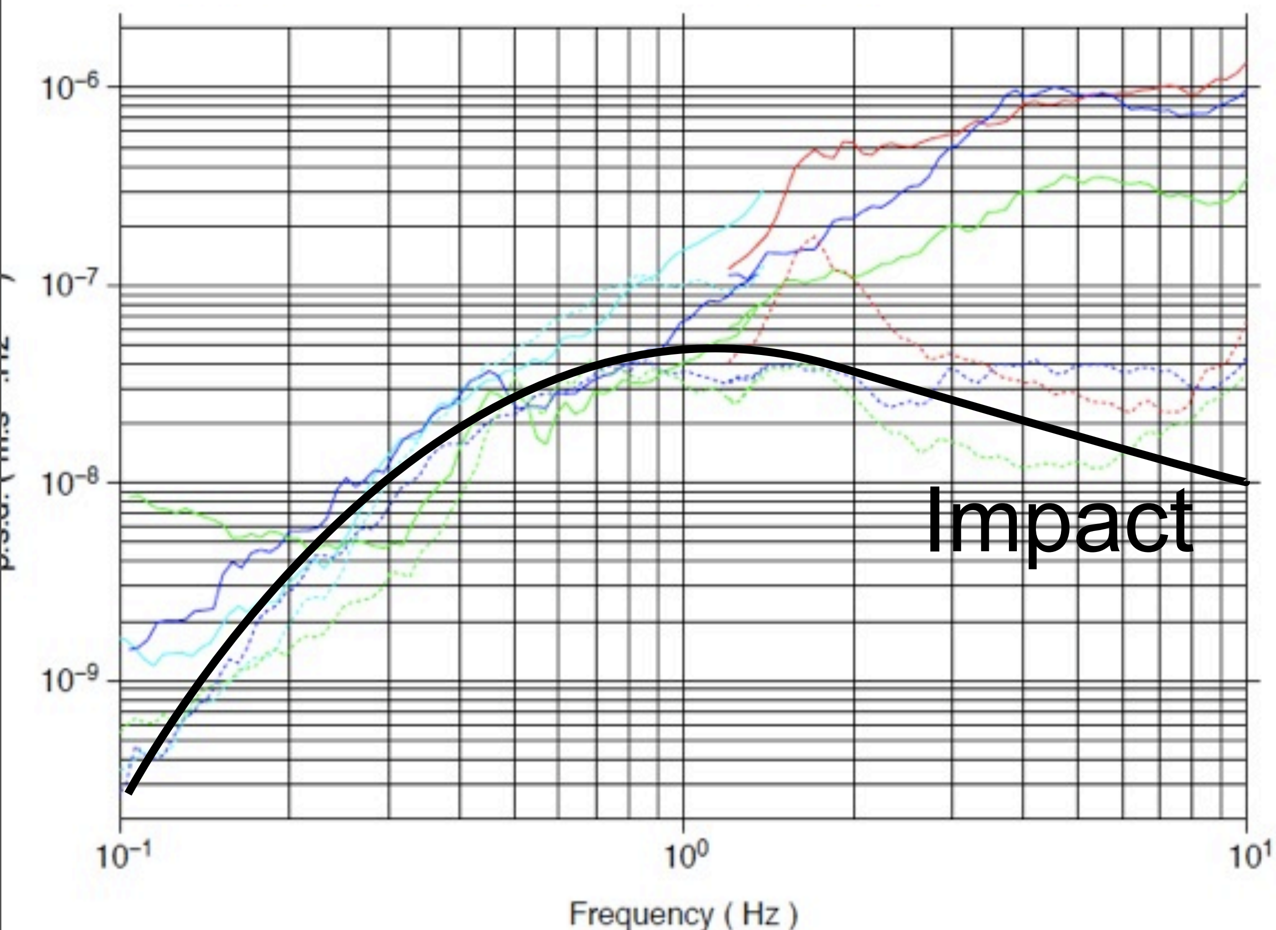


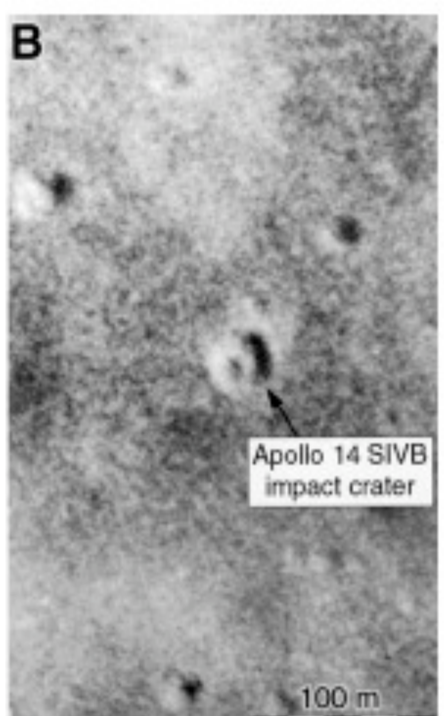


Impacts DO not generate high seismic frequencies!

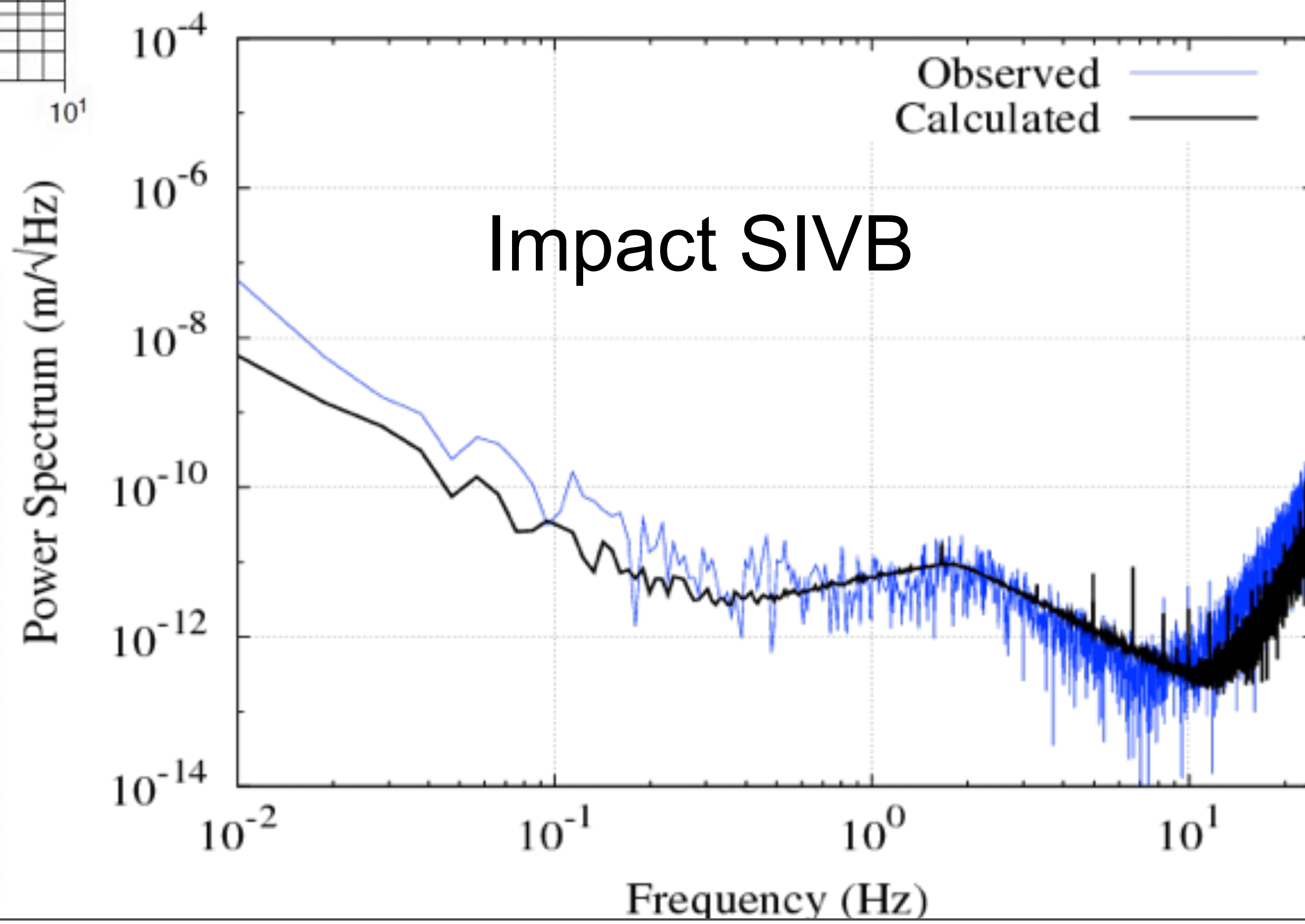


Impacts

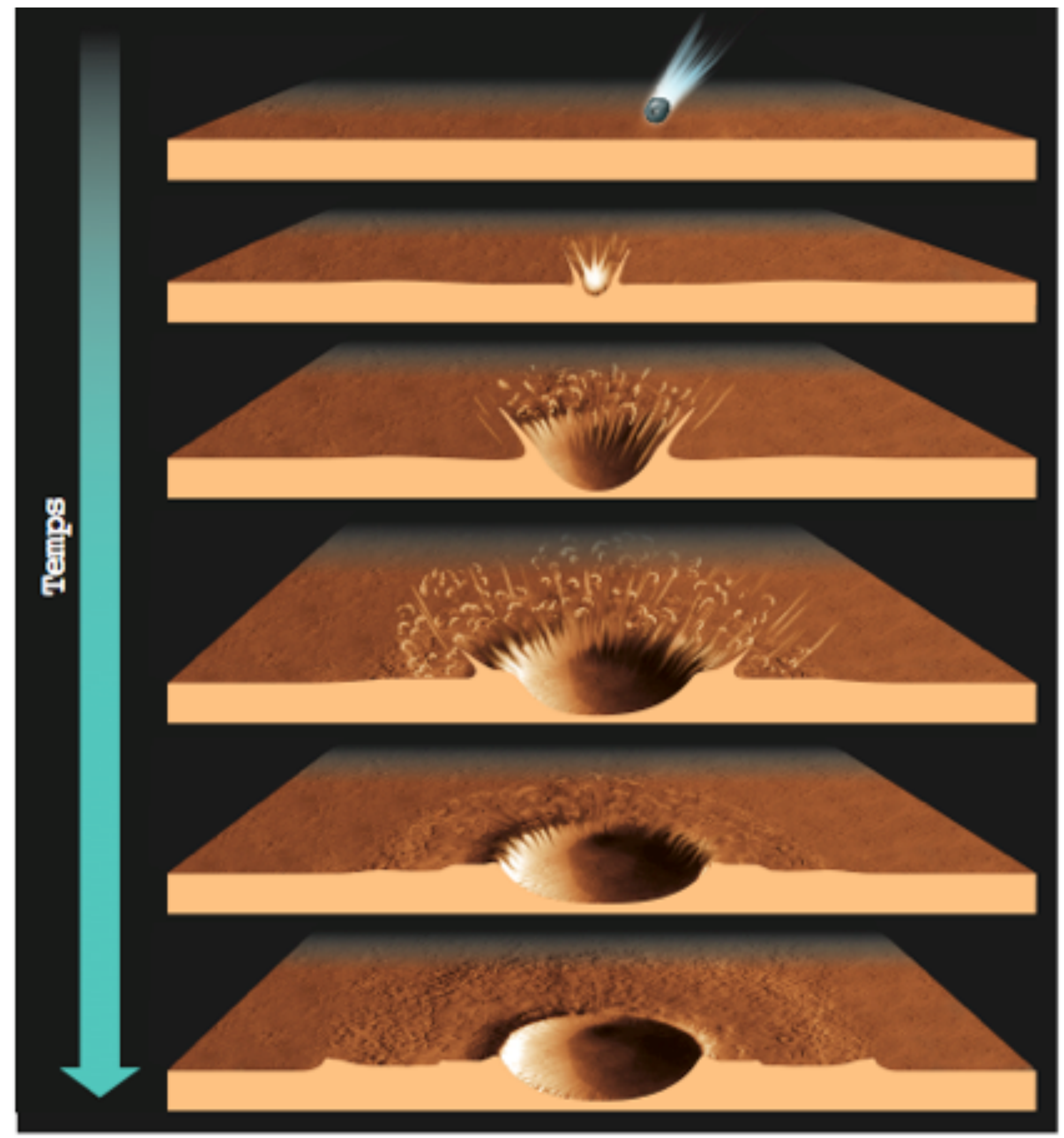




Impacts DO not generate high seismic frequencies!
Why?



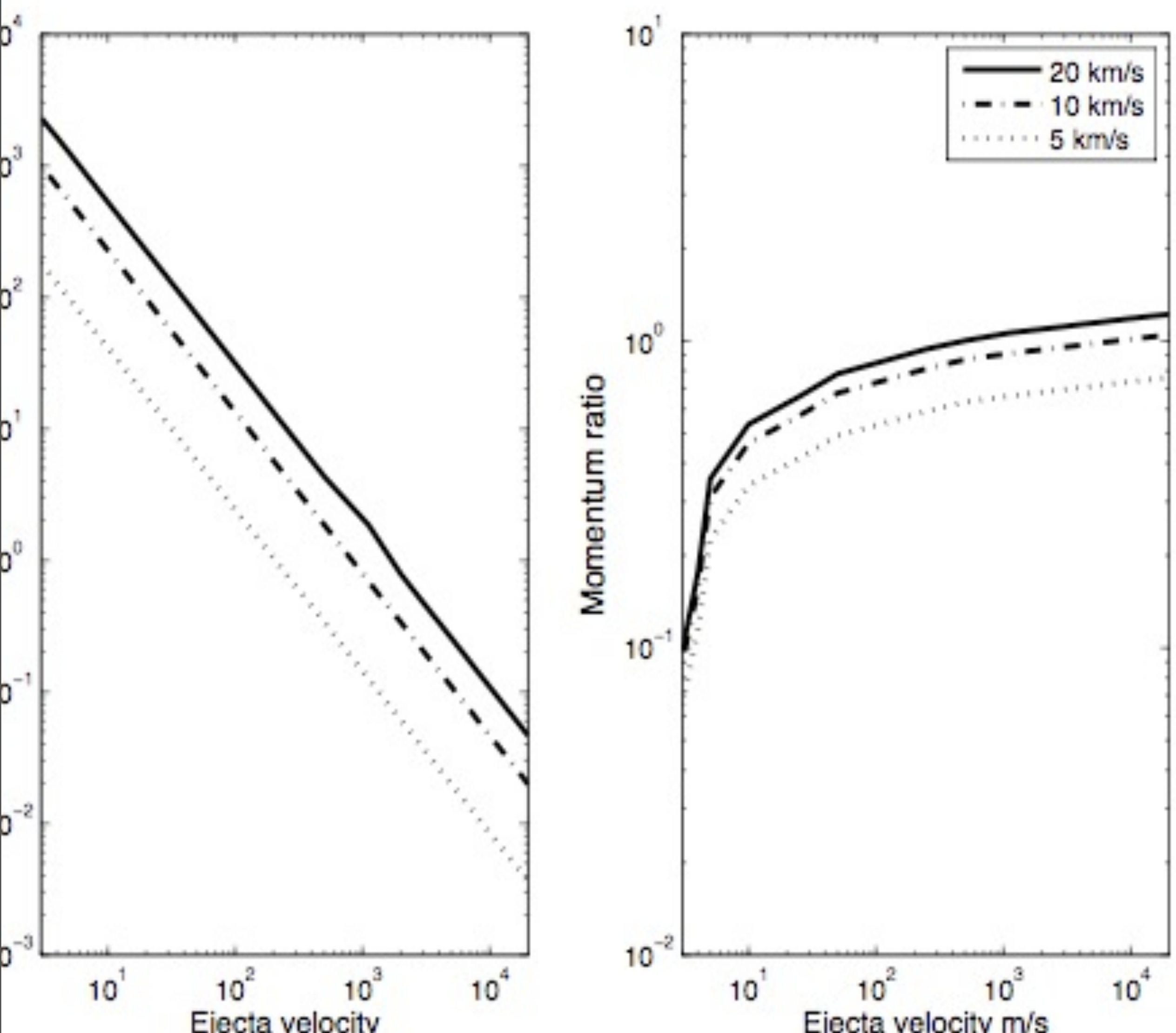
- Seismic source must take into account both the ejecta and the formation time of the crater
  - Ejecta mass are much larger than impactor mass
  - Momentum of the ejecta is significant and increase the force
  - Formation time leads to cutoff in the 1Hz-10hz range

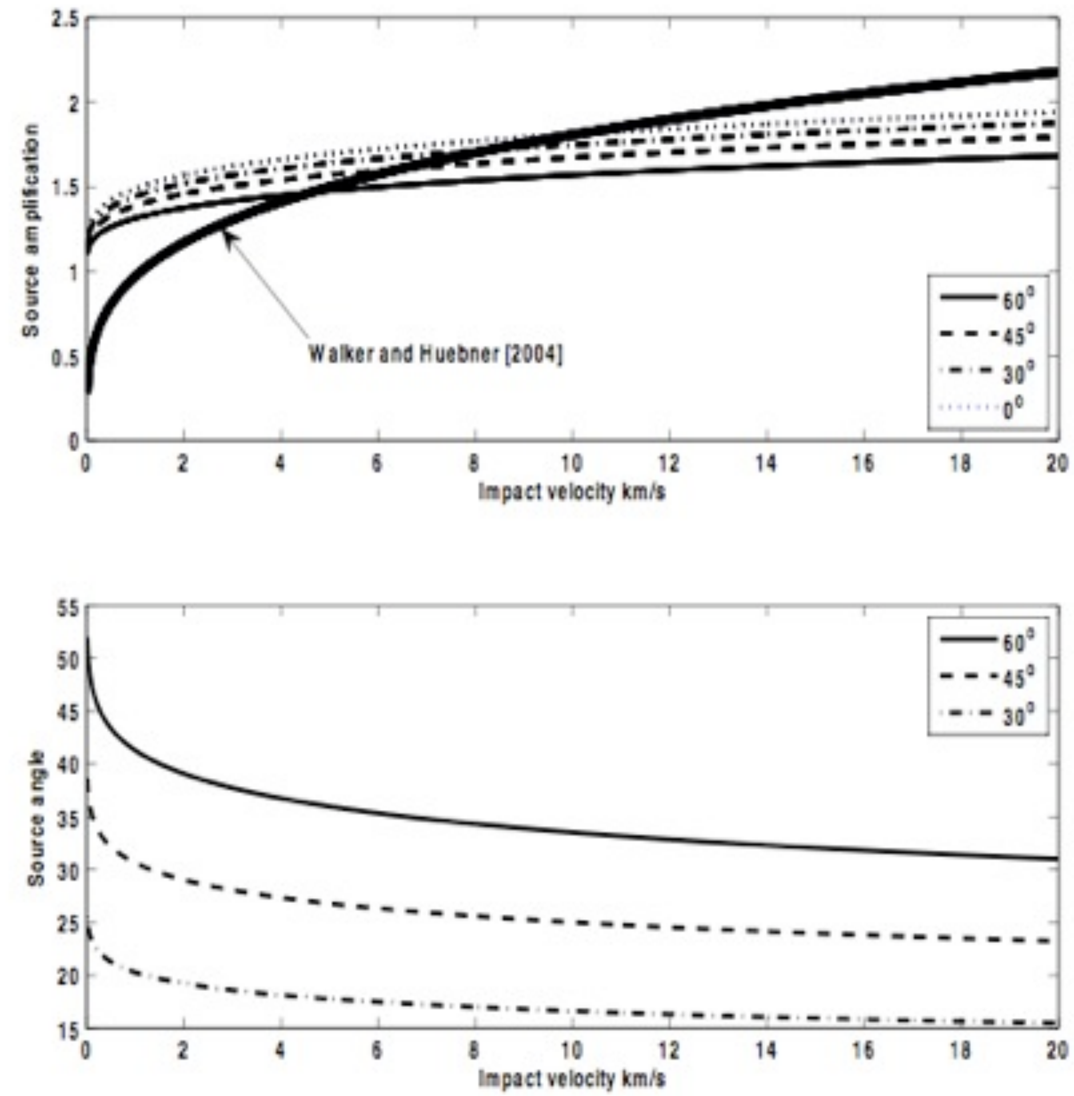


$$\vec{f}_0(t) = (m\vec{v} - \vec{p}_{eject})\delta(t)$$

$$\vec{f}(t) = \vec{f}_0(t) * g(t)$$

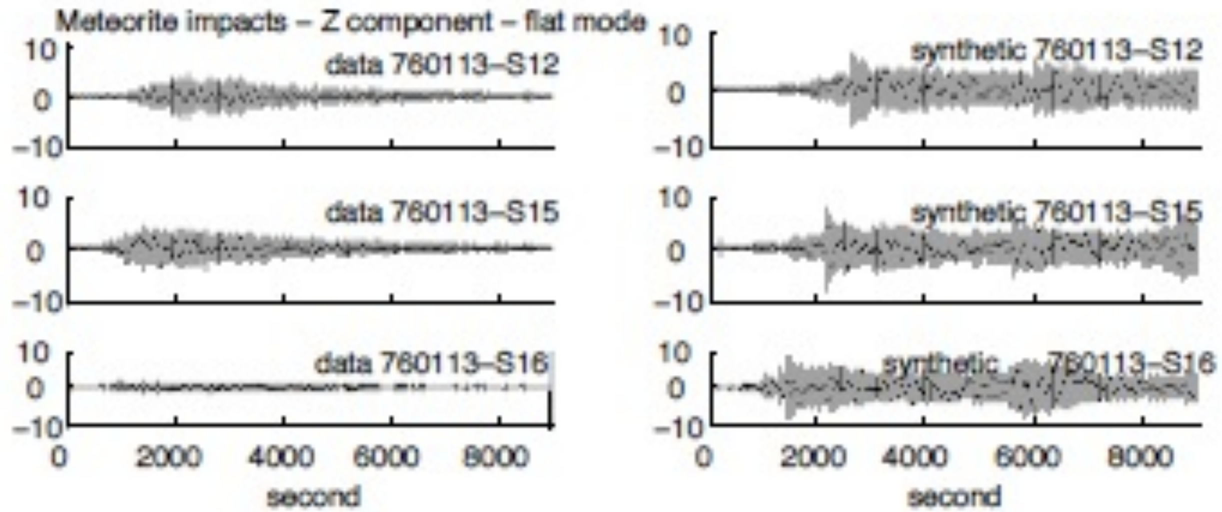
Ejecta amplification

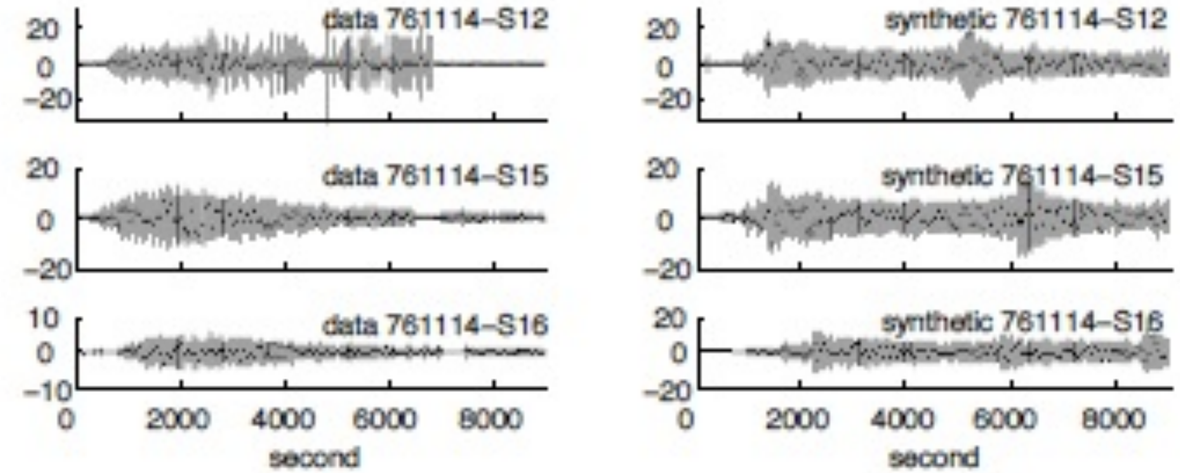


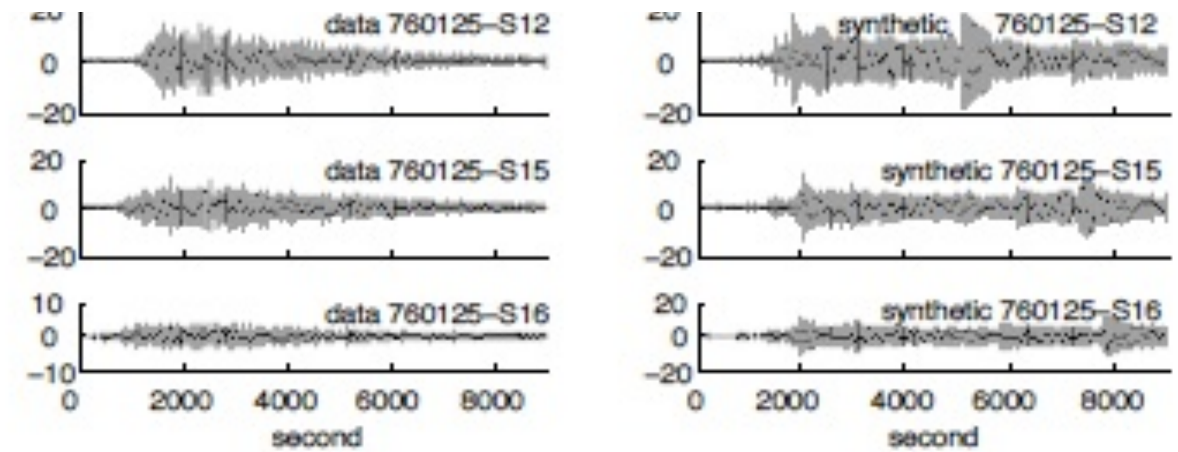


Ejecta mass and momentum

Ejecta seismic amplification







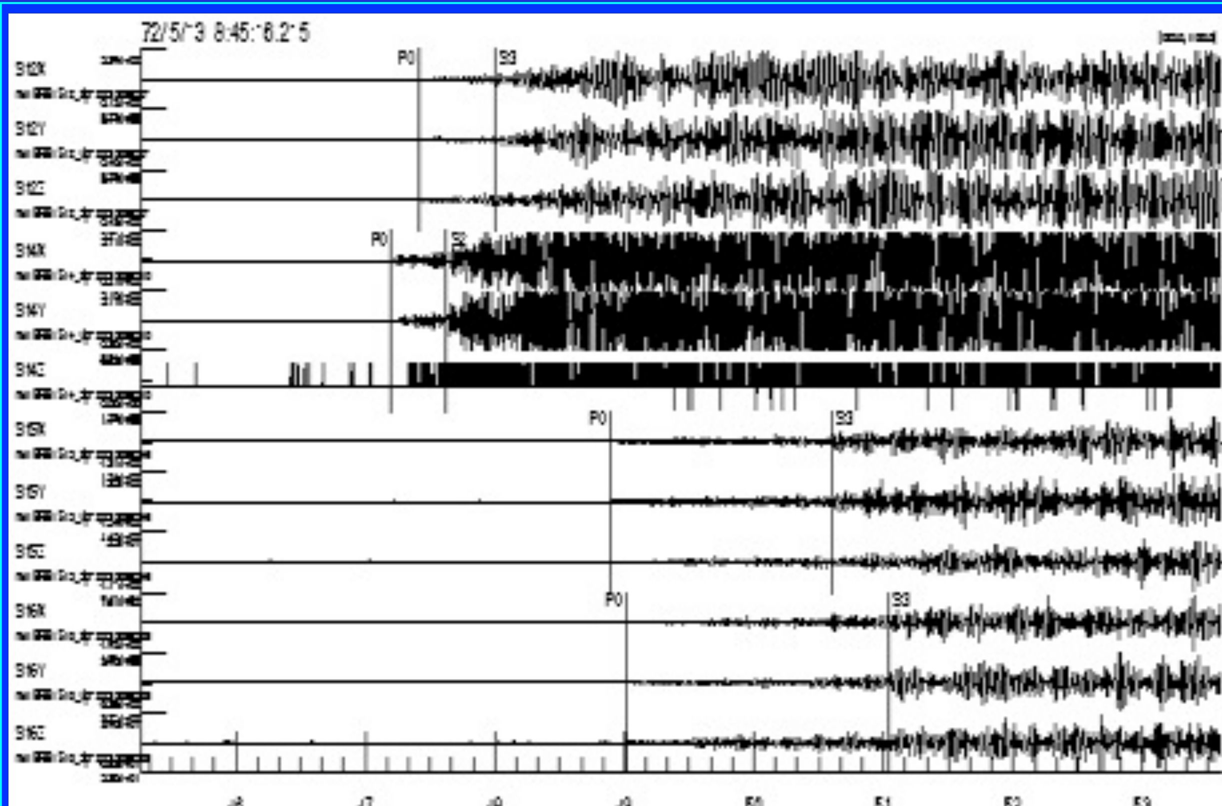
3 large impact

Date	I (kg m/s)	mv_M (kg m/s)	Mass (10^3 kg)	Diameter of meteoroids (m)	Crater diameter (m)	Crater depth (m)	Crater formation time (s)
13 Jan 1976	5×10^8	**(2.9-3.6)x10^8**	**15-18**	**2.1-2.3**	**52-62**	**14-17**	**3.0-3.3**
25 Jan 1976	8×10^8	**(4.7-5.7)x10^8**	**24-29**	**2.5-2.6**	**60-70**	**16-19**	**3.2-3.5**
14 Nov 1976	9×10^8	**(5.3-6.4)x10^8**	**27-32**	**2.6-2.7**	**61-73**	**17-20**	**3.3-3.6**

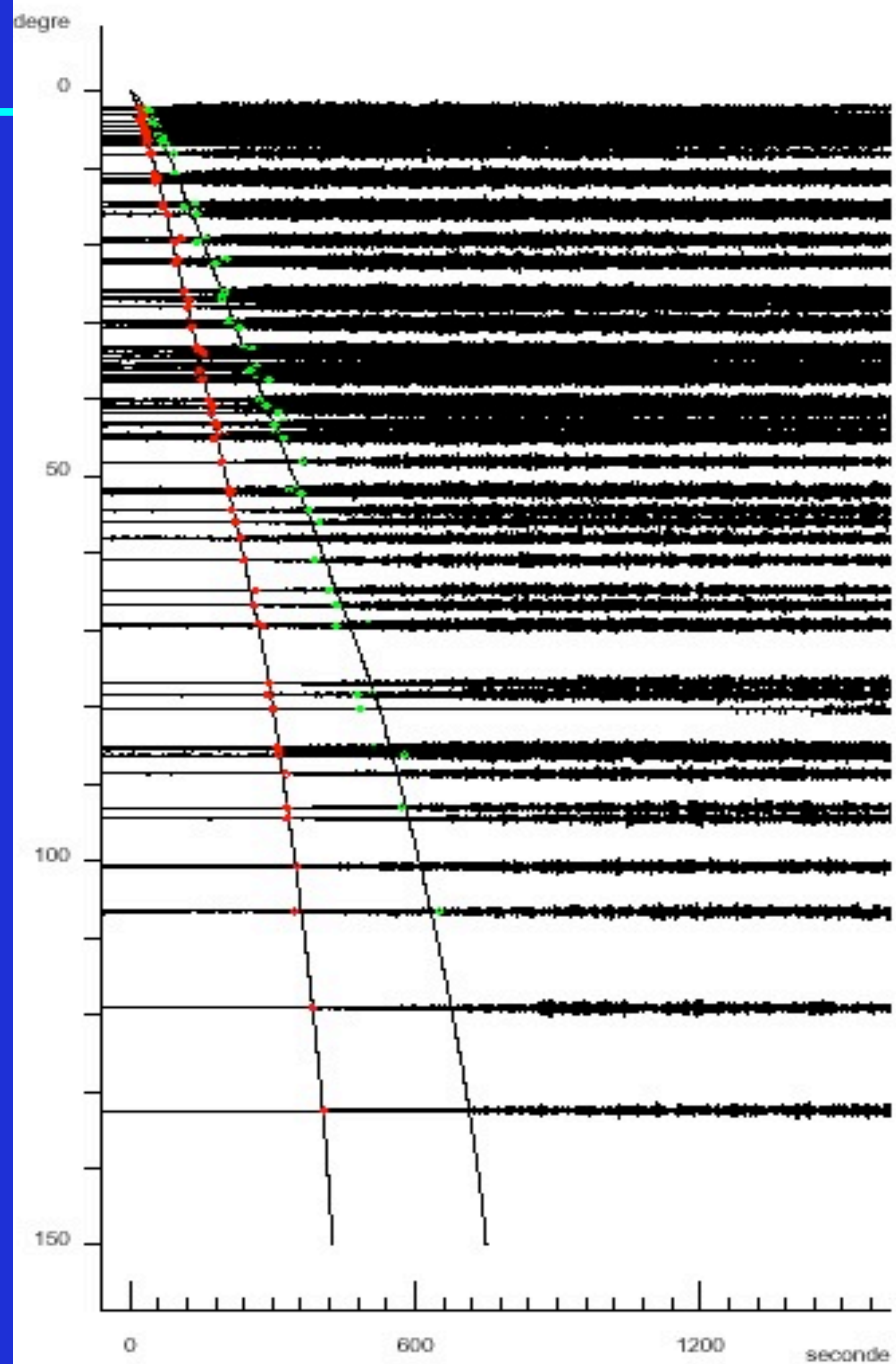
What can be done?

- Like on Earth?
- Interior models with travel times to invert
  - crust
  - mantle
  - core
  - 3D lateral variation, tomography....

Example of arrival time determination

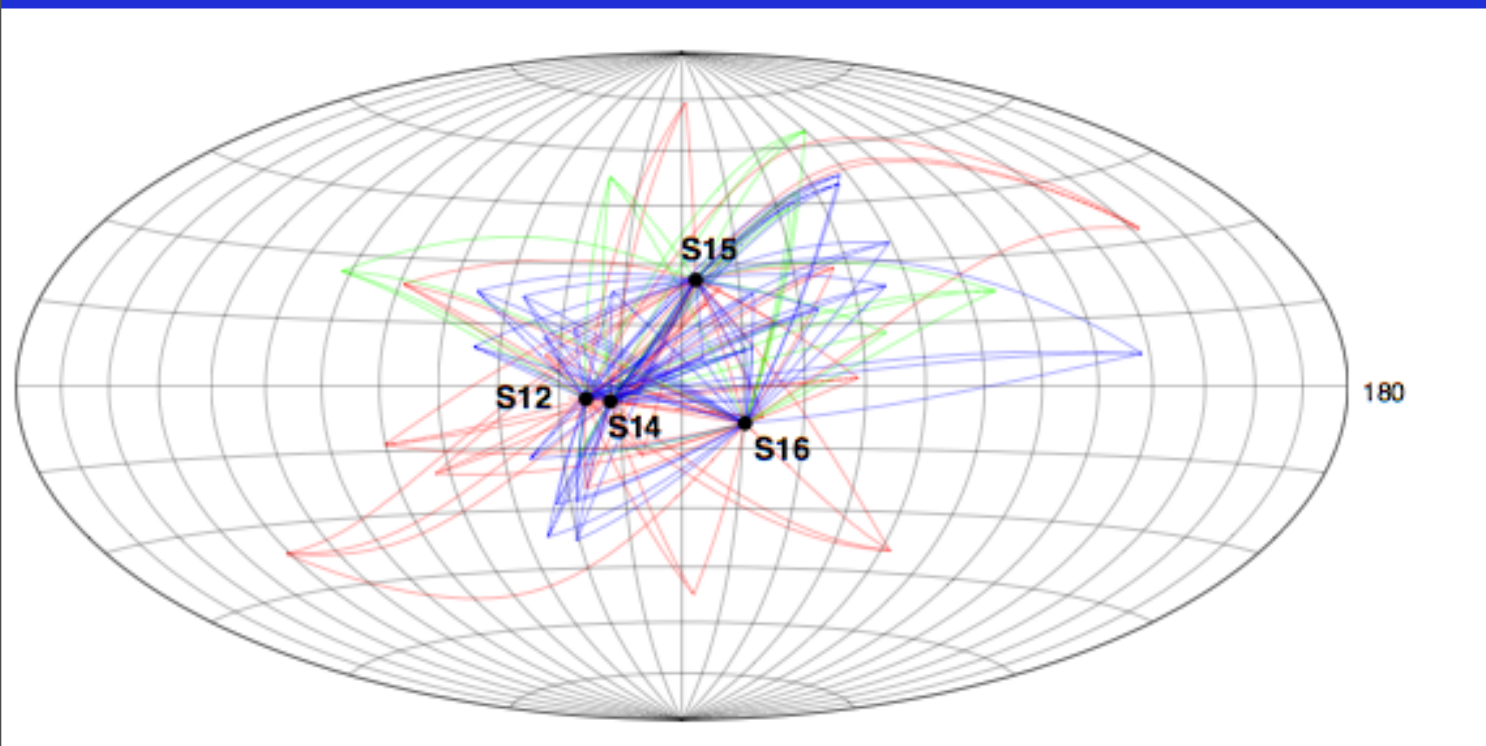


Example of seismic traces : a near impact recorded at all stations on 3 components



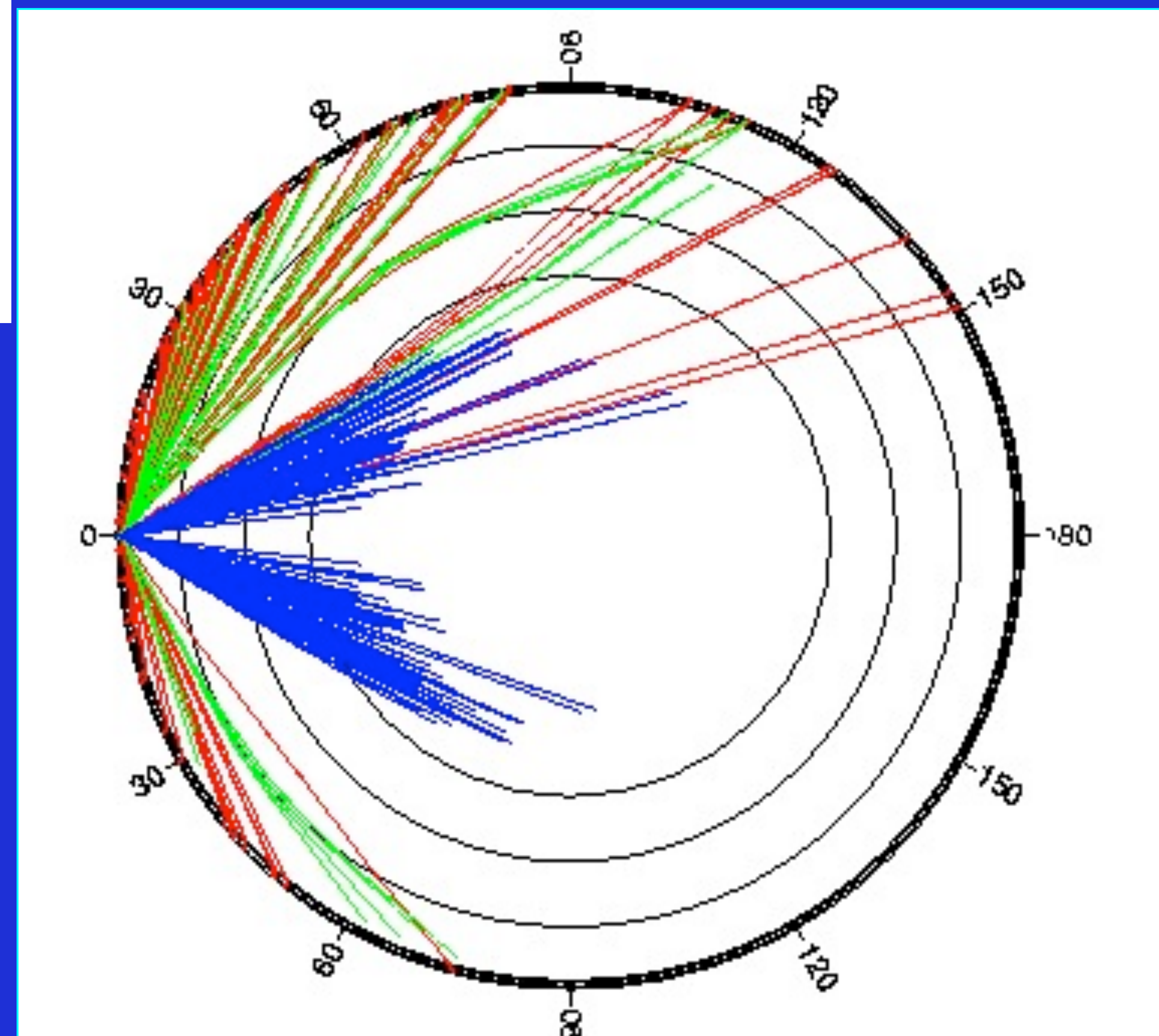
- In many case, diffraction is making the determination of arrival times difficult, with error up to 10sec (mean error is about 2s)

Rays sampling



• recording events with different epicentral distances give access to the structure with depth

• the inverted model is however not a mean model of the planet, but a mean model of the area where the network is deployed



All ray paths available in the Moon. Blue is for deep events, red for impacts, green for superficial moonquakes.

Principle of the inversion

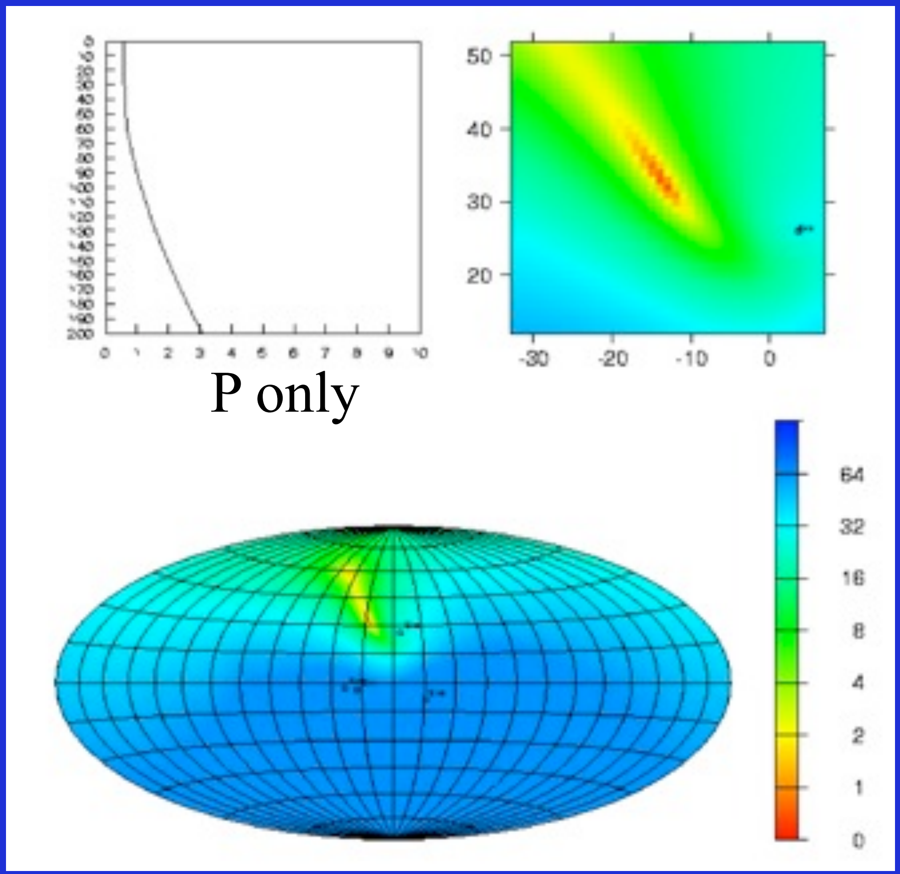
Seismic data, i.e. arrival times at the stations

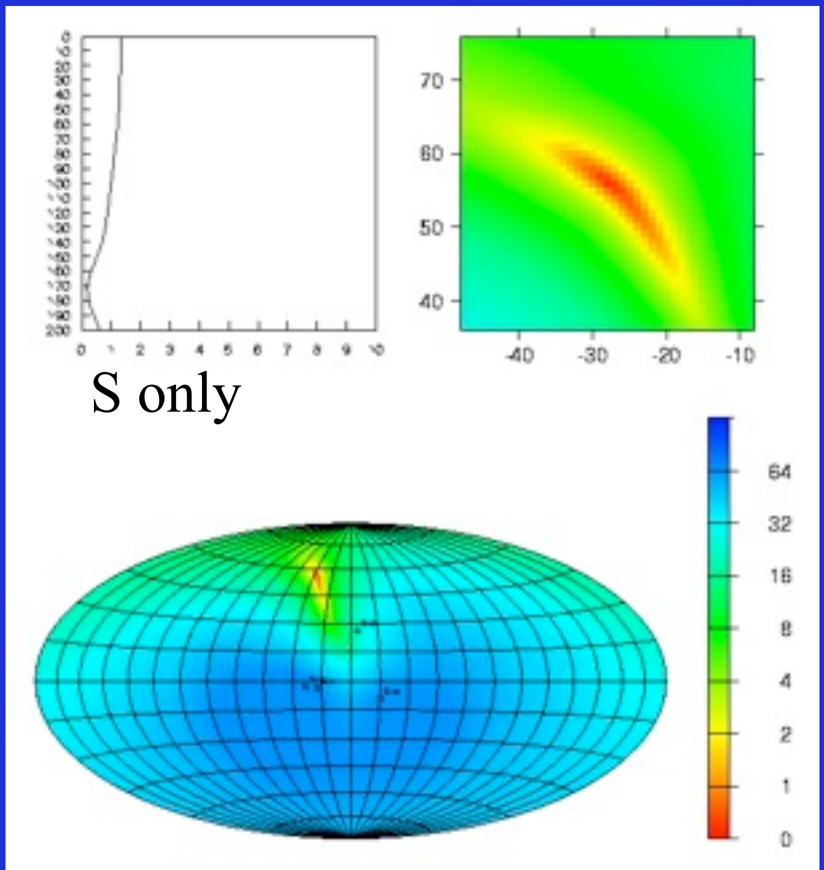
Source parameters, i.e. position and times of the quakes

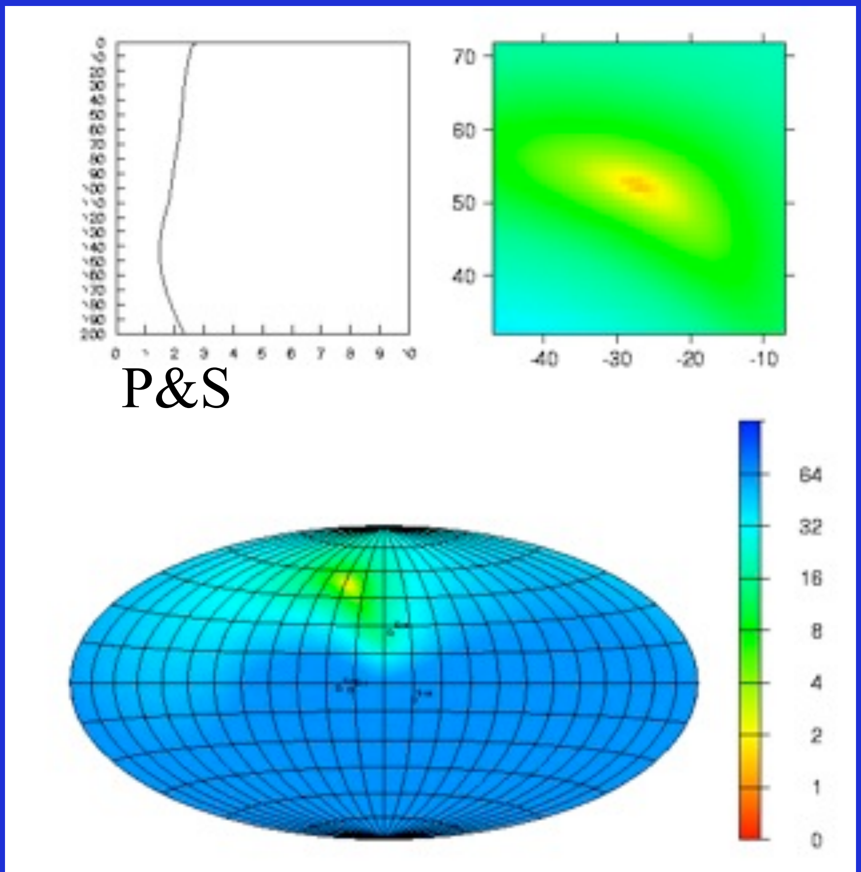
Model parameters, i.e. P and S seismic velocities with depth

Sources relocalisation

- Source localisation is done iteratively in the inversion: for each new structure new model, a new localisation of the sources is done and then used for next inversion of structure







Principle of the inversion

Seismic data, i.e. arrival times at the stations
Nx6

Source parameters, i.e. position and times of the quakes
Nx4

Model parameters, i.e. P and S seismic velocities with depth
< 2N

- N is the number of quakes
- The seismic model must
  - be limited to depth seen by the seismic rays
  - if errors are high, an oversampling is mandatory to reduce the impact of errors on the data
  - Number of layers with V_p and V_s inverted is therefore $N_l << N$

Inversion in the Appolo case

Seismic data, i.e. arrival times at the stations
Nx6

Source parameters, i.e. position and times of the quakes
Nx4

Model parameters, i.e. P and S seismic velocities with depth
< 2N

-Practically, in total 319 P & S arrival time data where used to constrains 59 seismic sources, including 185 source parameters and 134 degree of freedom available for internal structure

-Mean error is 2 sec for arrival times

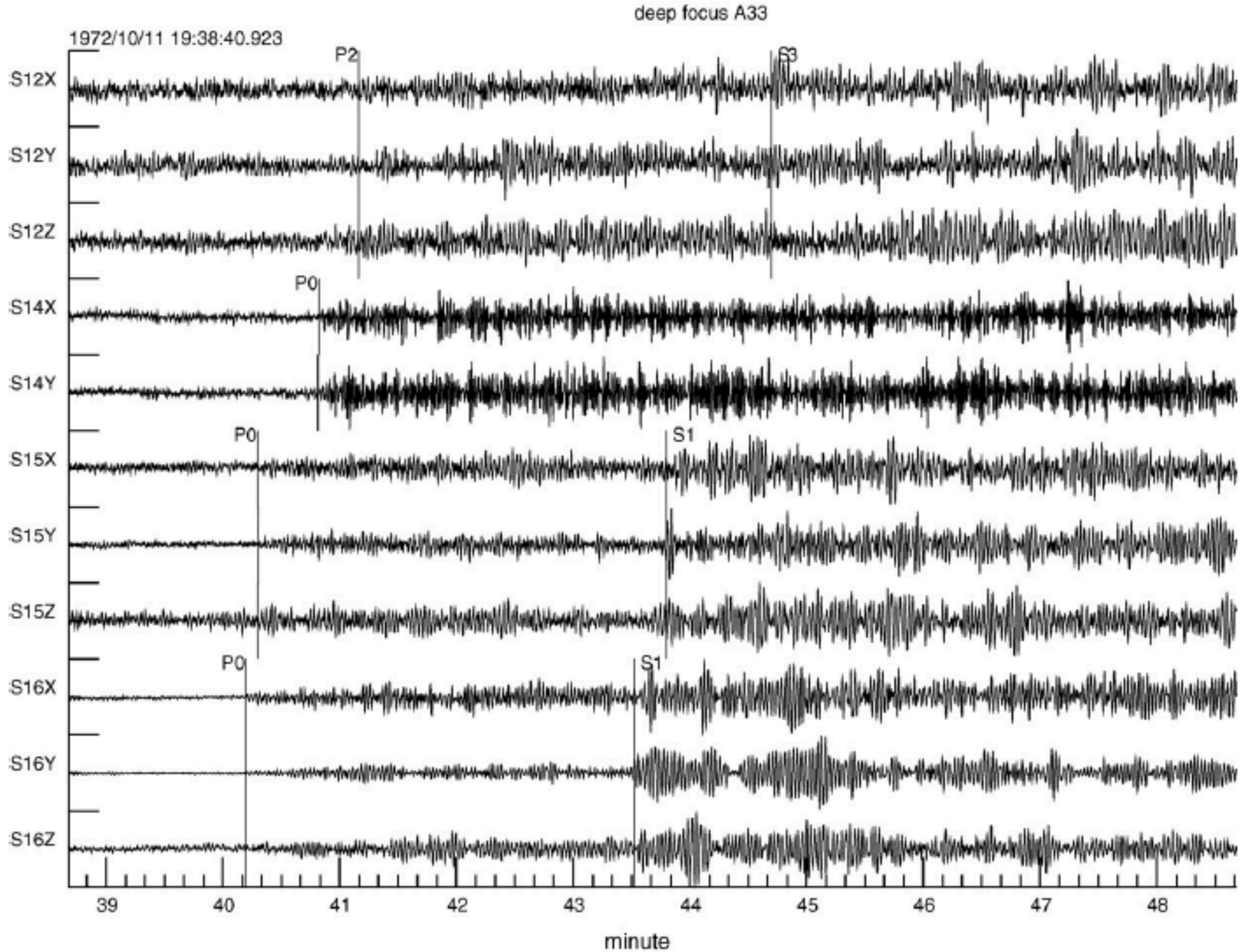
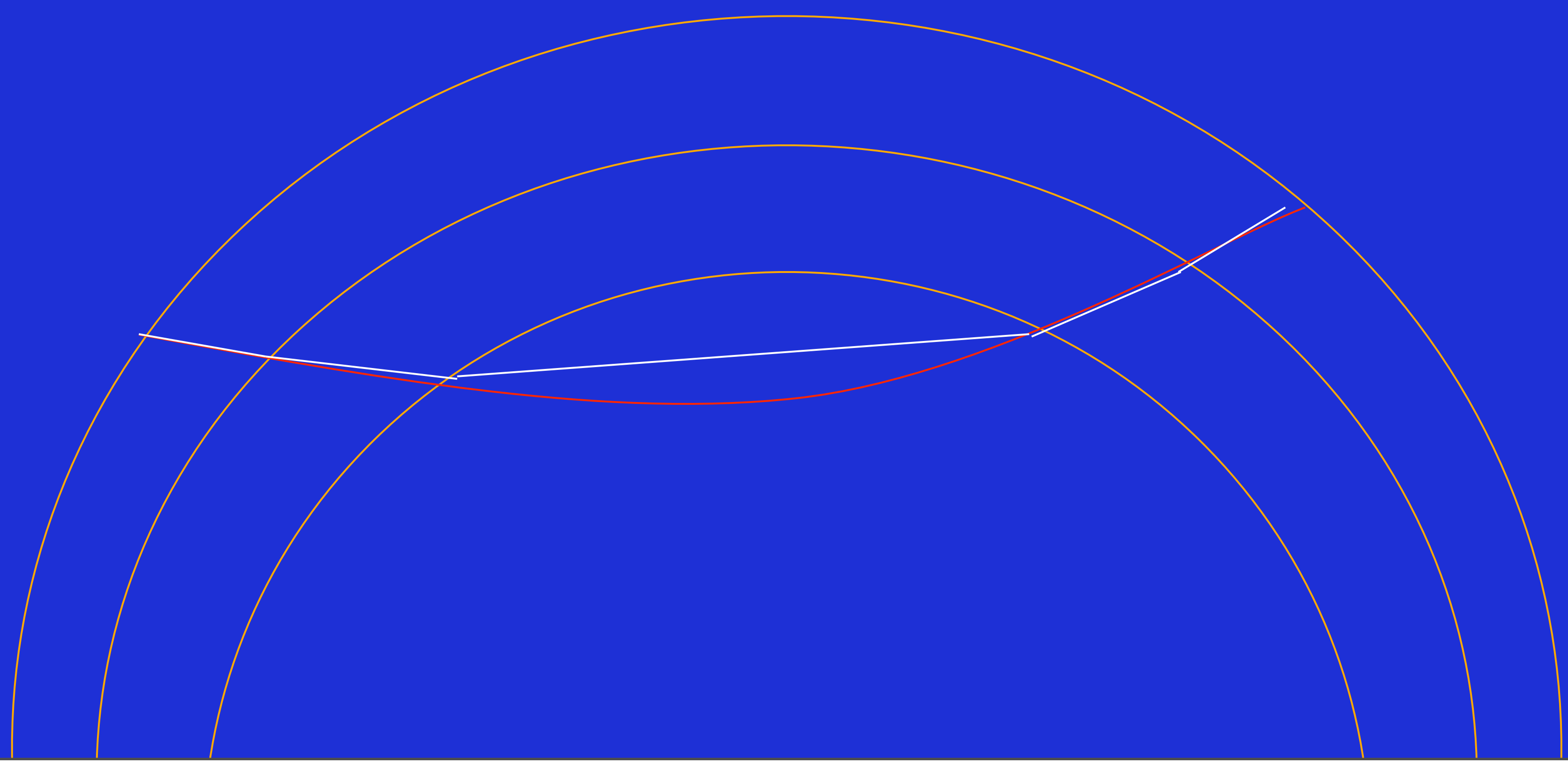
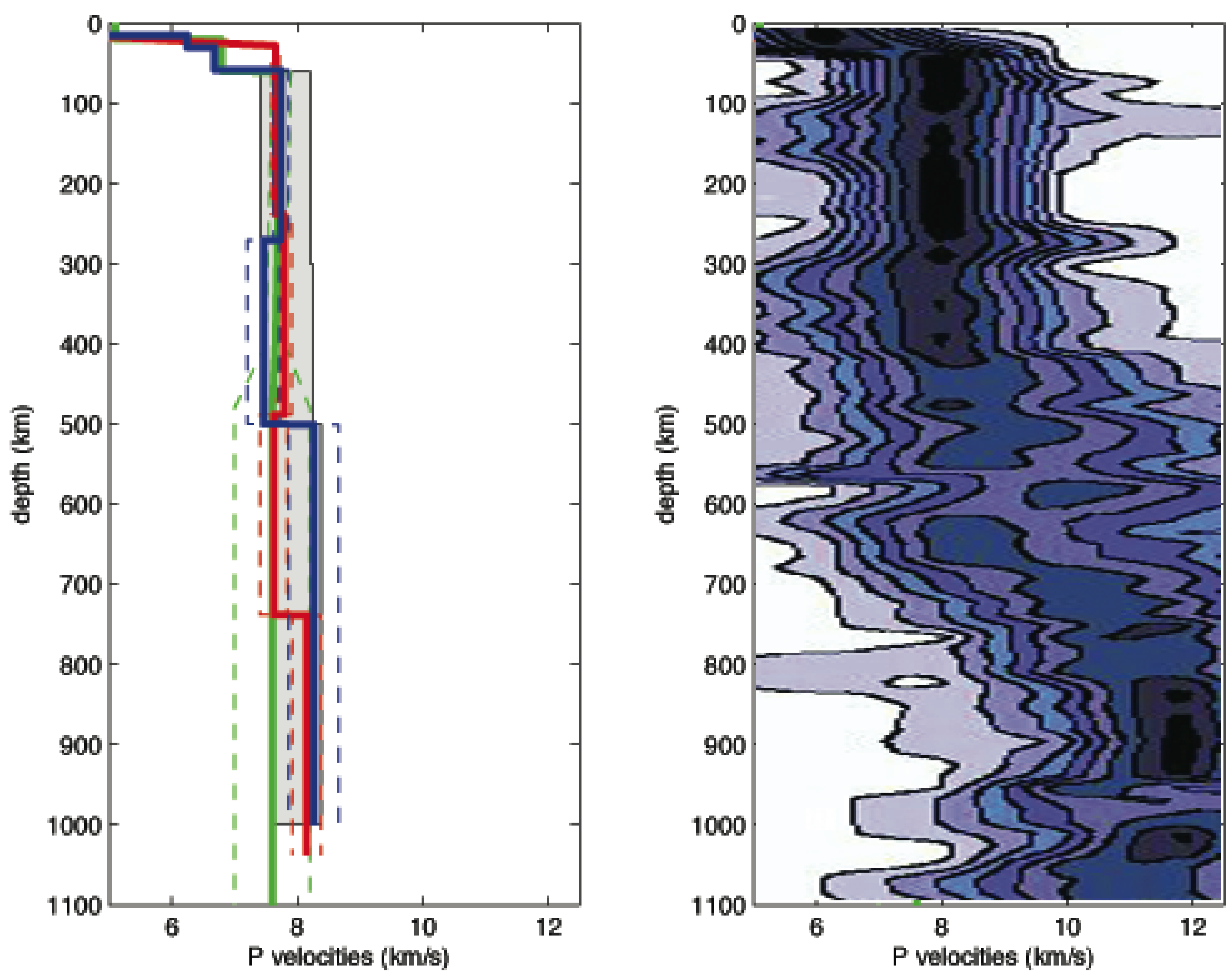


Fig. 3. Example of arrival time pickings for deep focus A33. The index 0, 1, 2 and 3 correspond respectively to uncertainty about 1, 3, 10, 30 s.

- 2 possible inversion strategy
- Inversion with a limited number of layers (typically about 5-10)
  - Inverted parameters are not the true velocities but the mean velocities in a layer
  - Some error is done in the theory
  - When sdata > stheory, the error on the inverted models is improved
- Inversion with a large number of layers (typically 50)
  - Inverted velocities have error directly related to the mean quality of data

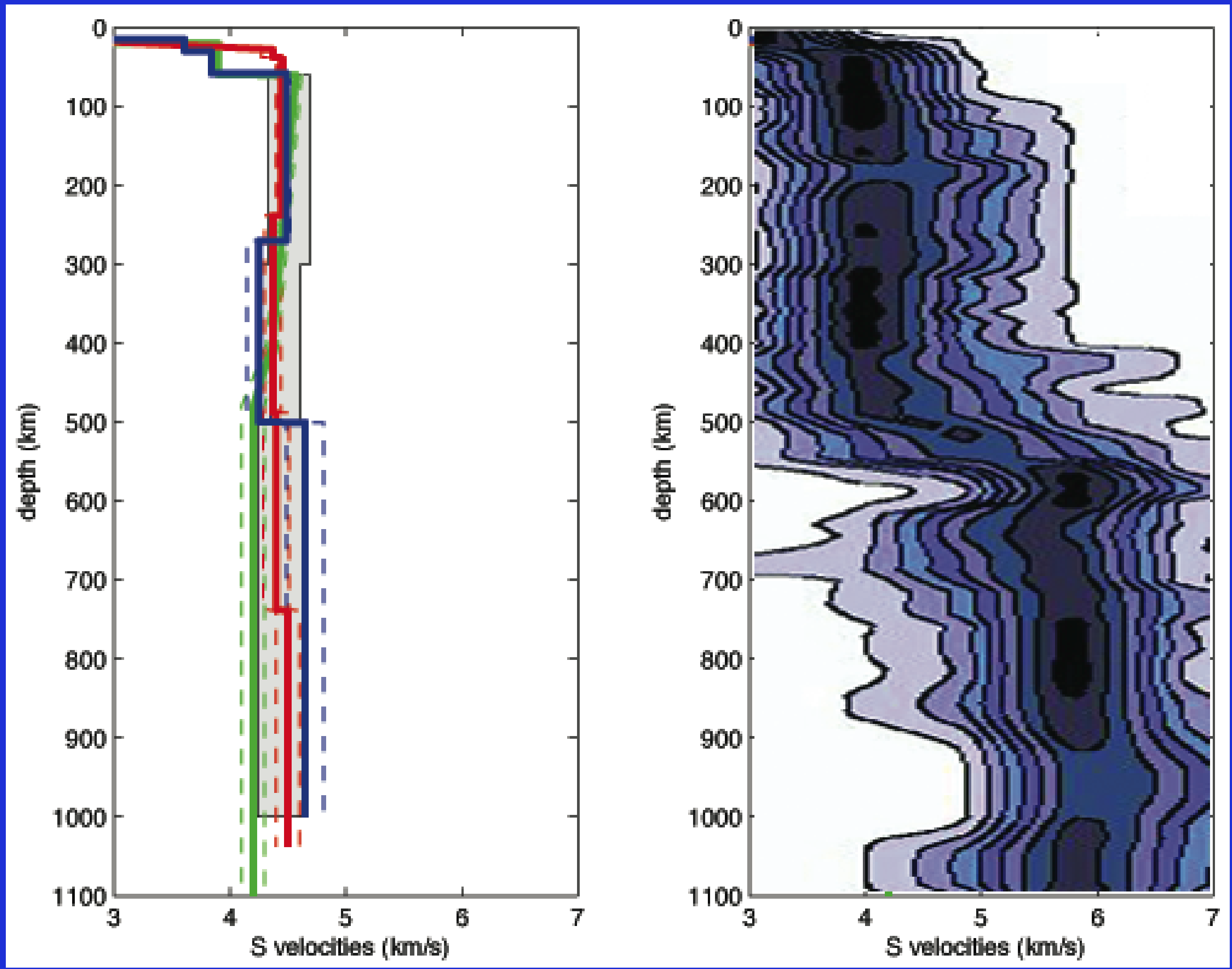


Inversion results

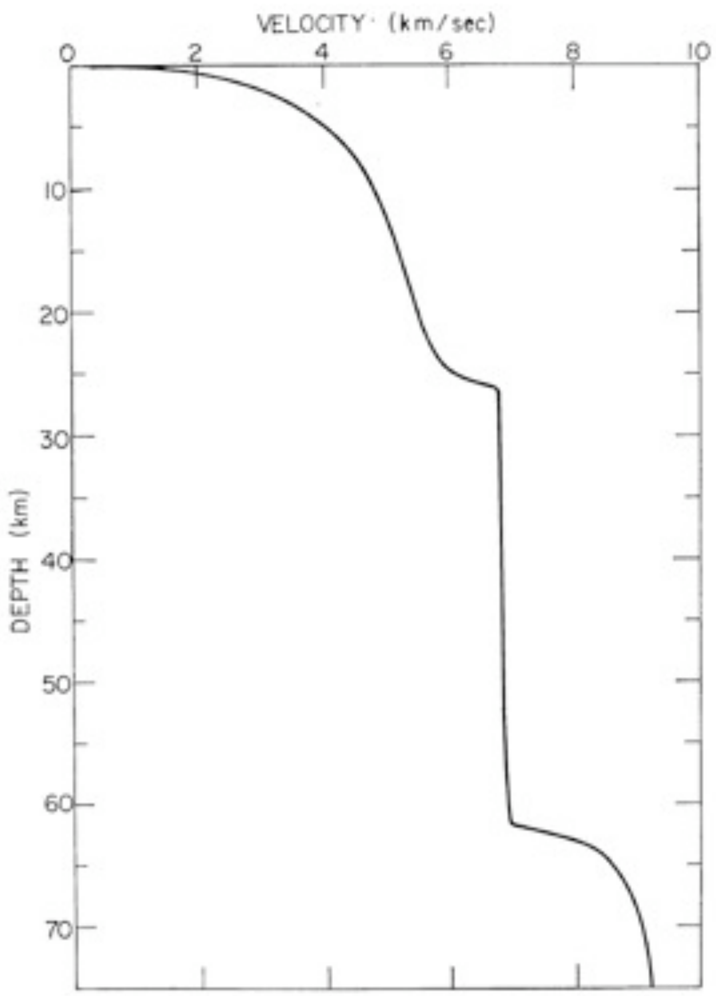


- right: highly layered model (Khan et al., 2000, 2002)

- left: weakly layered model (Lognonné et al., 2003)

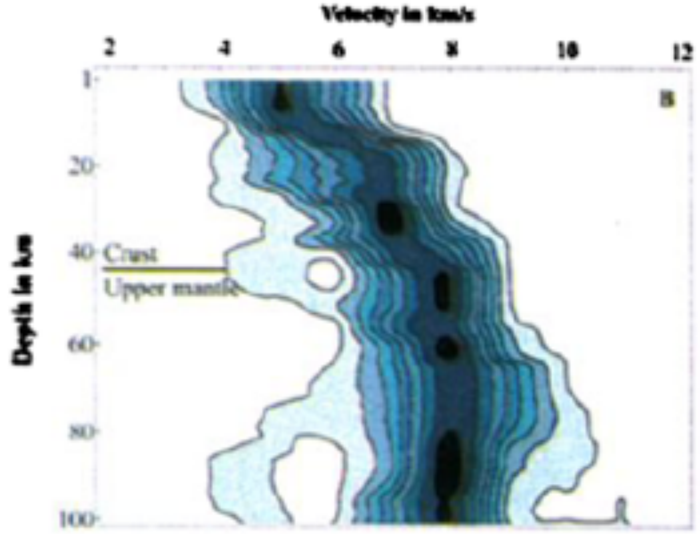


Results: Thickness of the crust



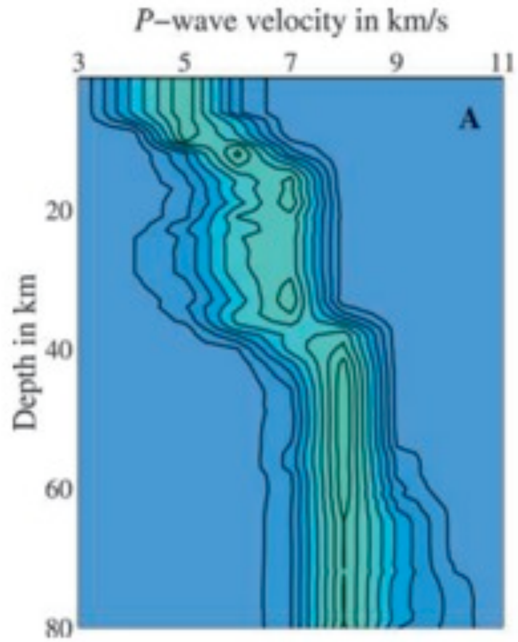
Toksöz et al. (1972)

~60 km



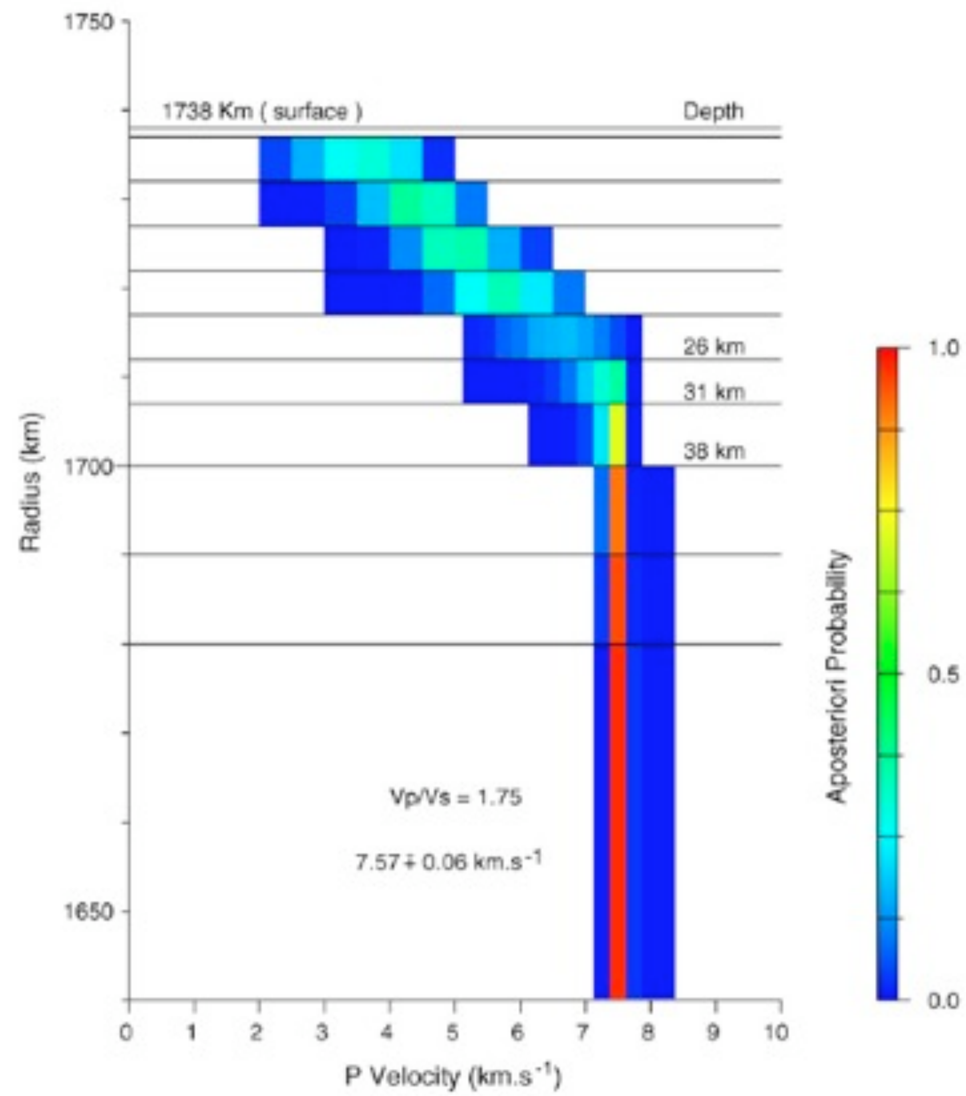
Khan et al (2000)

45±5 km



Khan and Mosegaard (2002)

38±3 km



Lognonné et al. (2003)

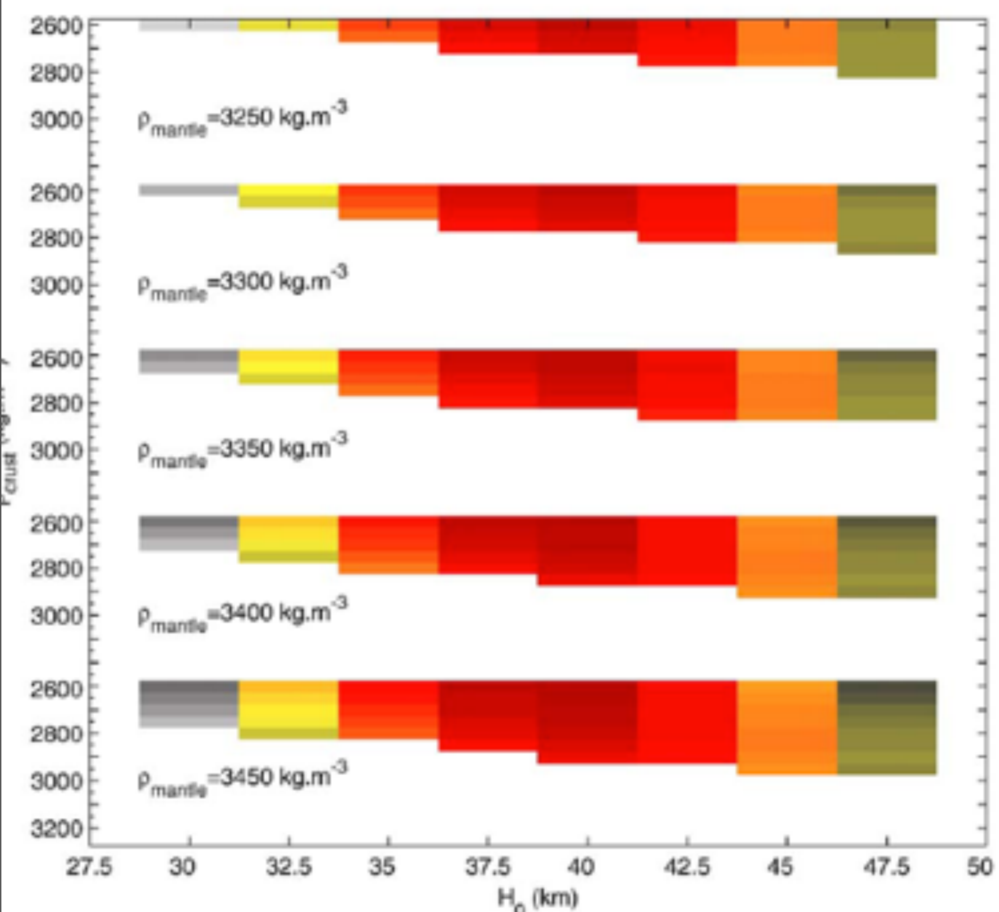
30±3 km

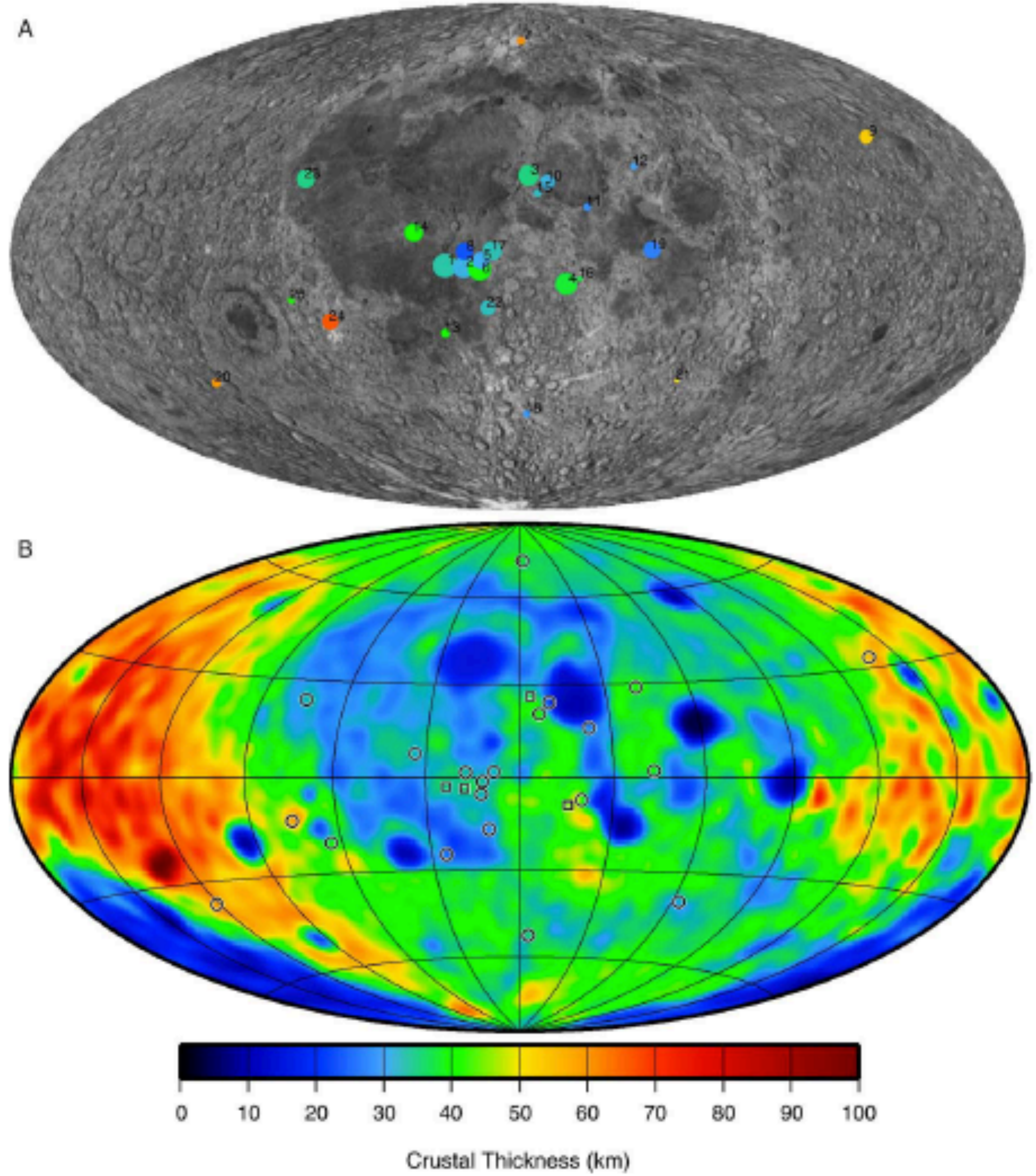
Each study used different seismic events, seismic arrival times and analysis techniques... and thickness do not always fit the gravity one

Joint crustal inversion: gravity plus seismic

Chenet et al (2006)

40±5 km





Why so much differences?

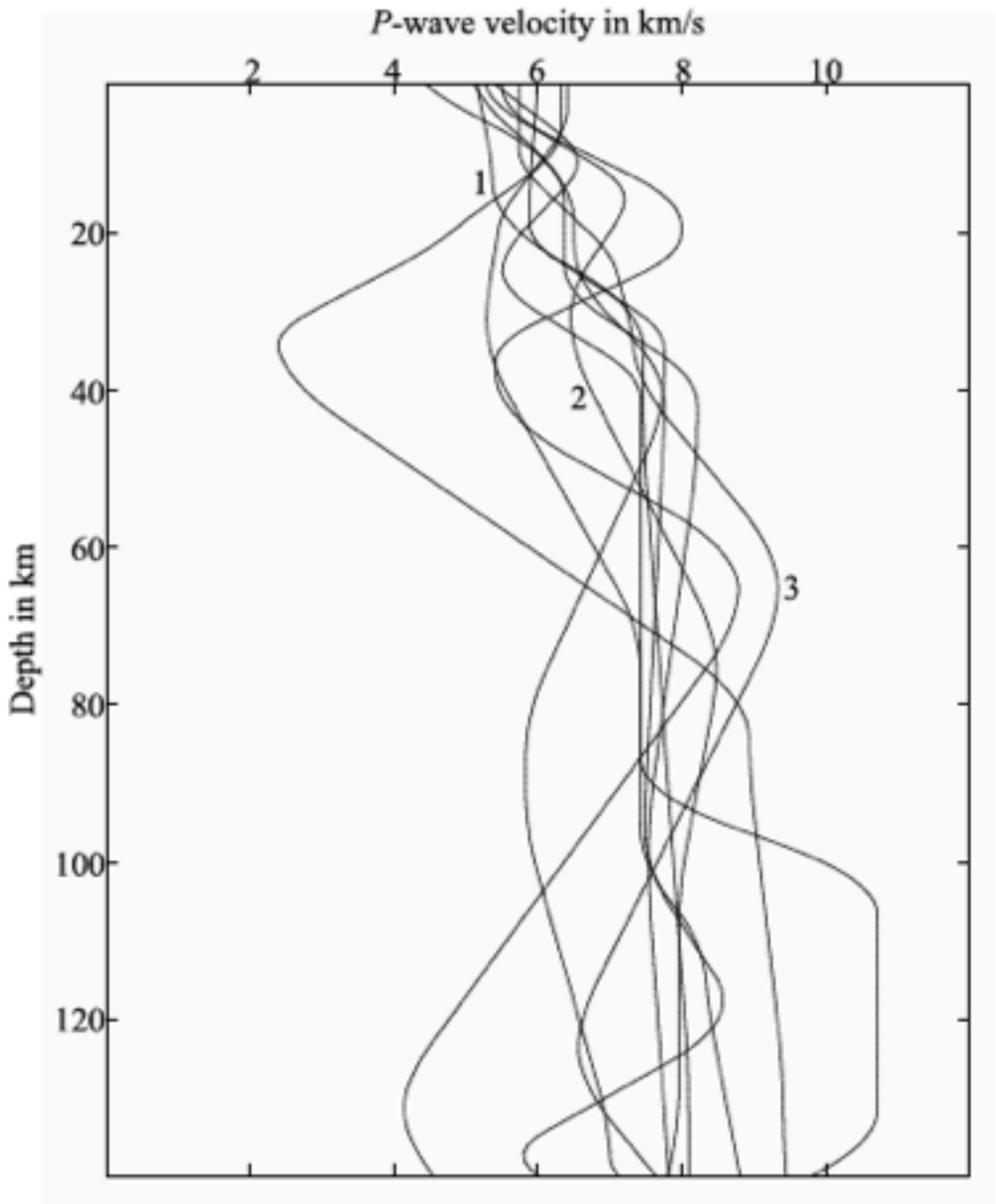
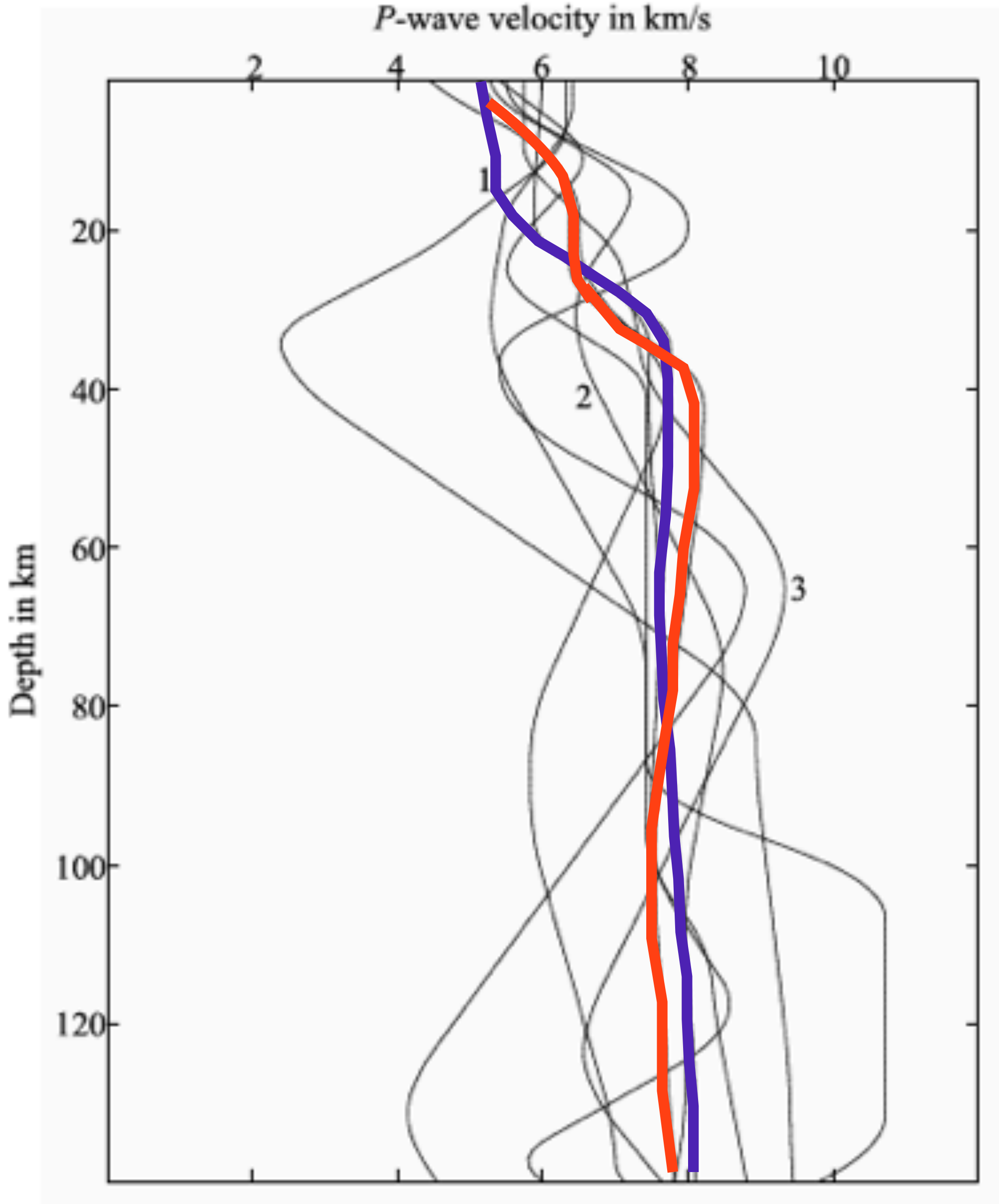


Figure 5. A smoothed version of 10 samples from the posterior distribution, each one obtained by sampling a different extremum in the model space. The models shown here emphasize only the crustal and upper mantle part. The three models numbered 1–3 have been taken as examples of models which individually highlight seemingly different structures but nonetheless are models that all produce a fairly large likelihood value, that is, produce a good fit to the observed data (see Table 1).

- seismology is mainly sensitive to the travel times, which means integration of the slowness along ray
- gravity does not constrains the mean crustal thickness if the mass of the mantle is not known
- gravity lateral variation is to first order sensitive to the surface density

Khan et al, 2002

Real differences?



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Khan et al, 2002

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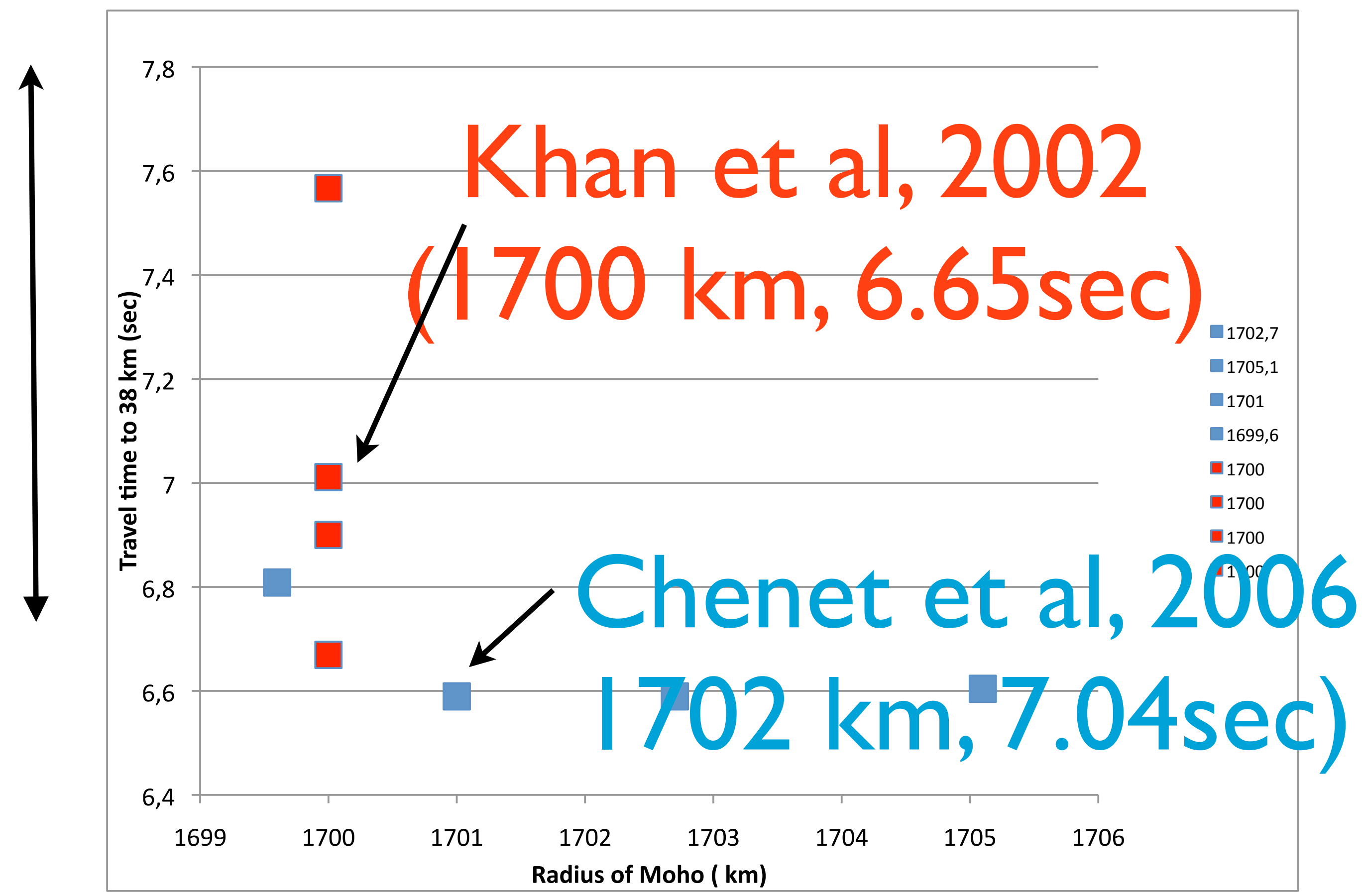
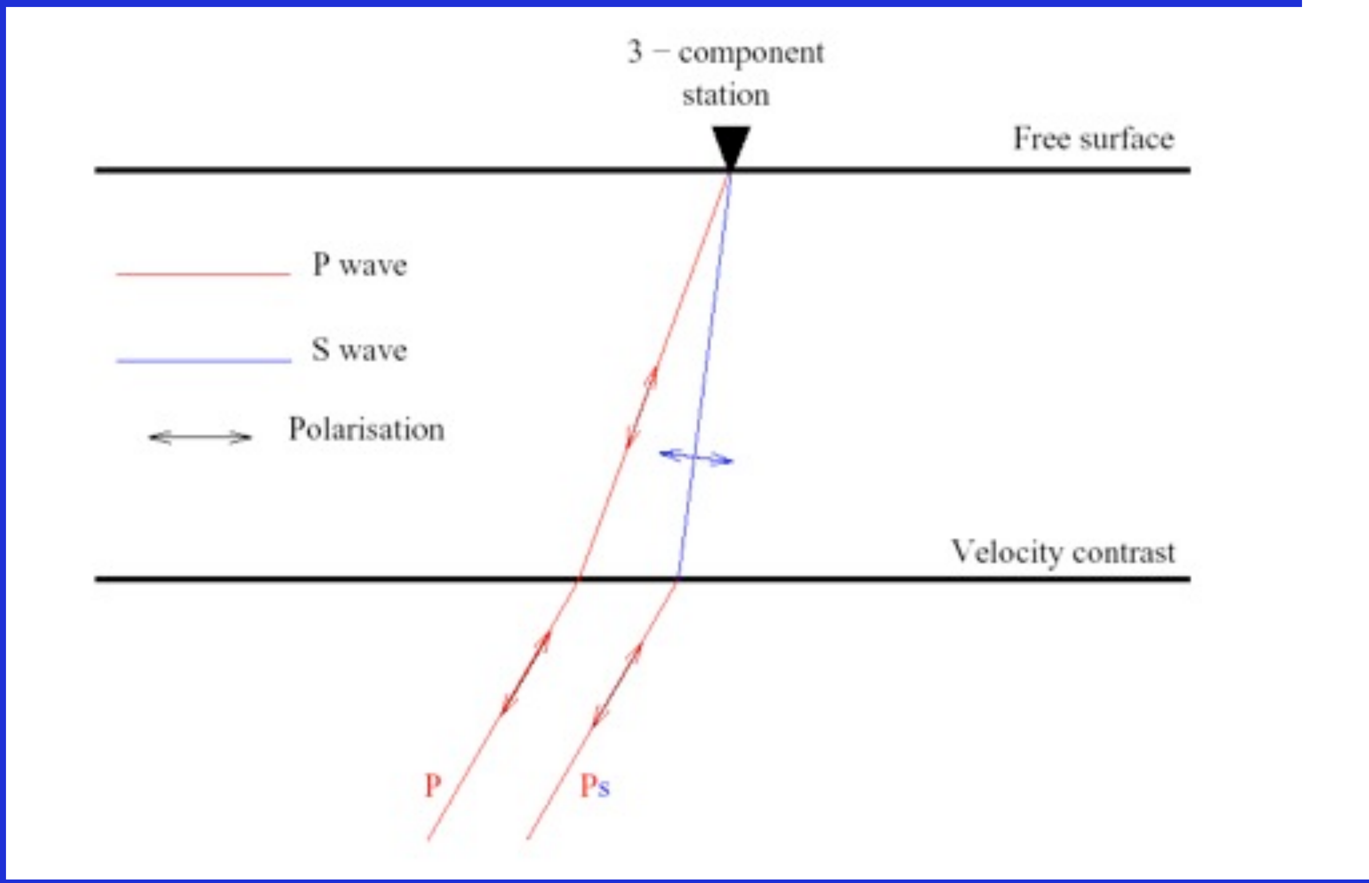
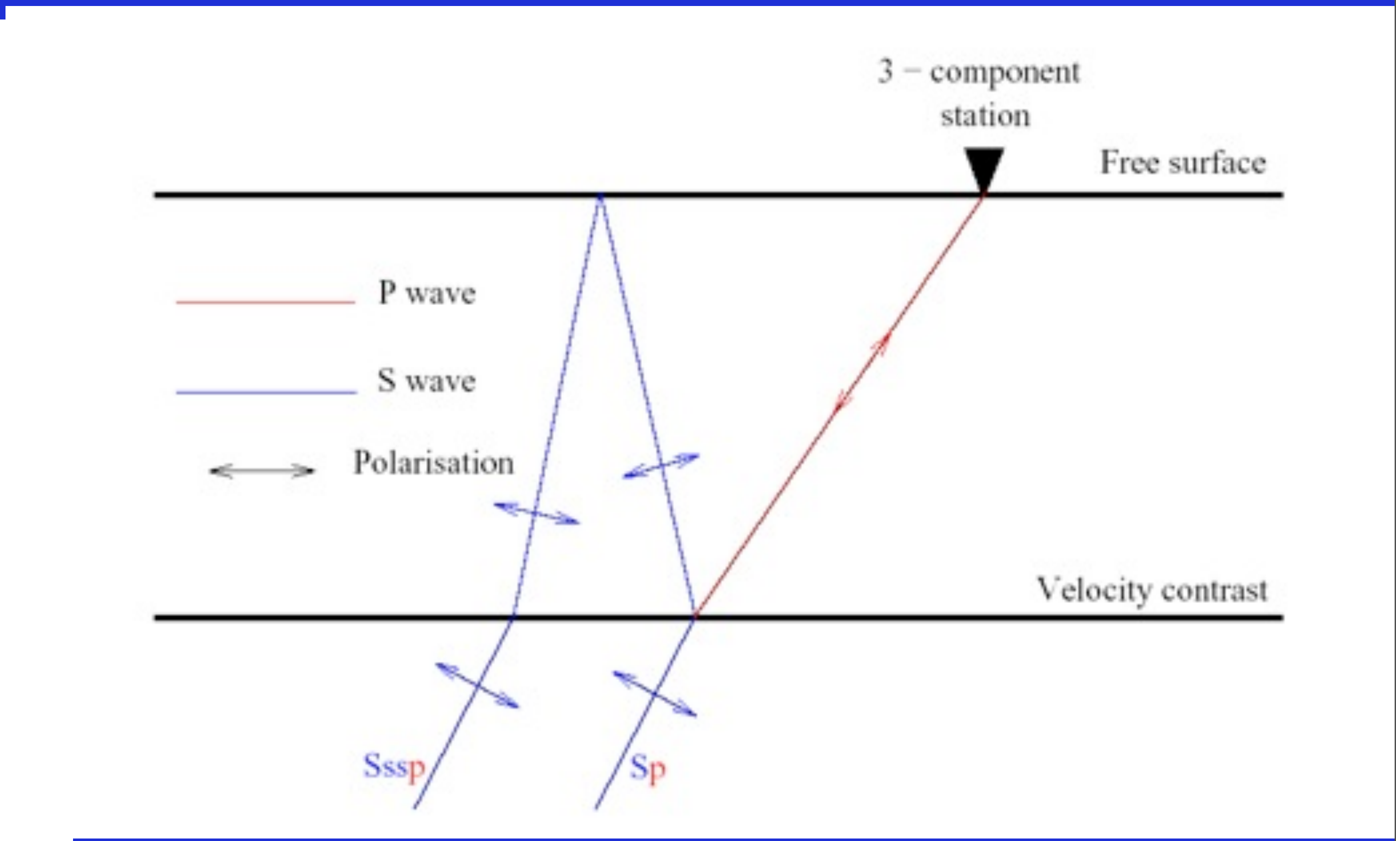


- typical error ± 5km, ±1sec

Inversion with some 3D effects: crustal structure

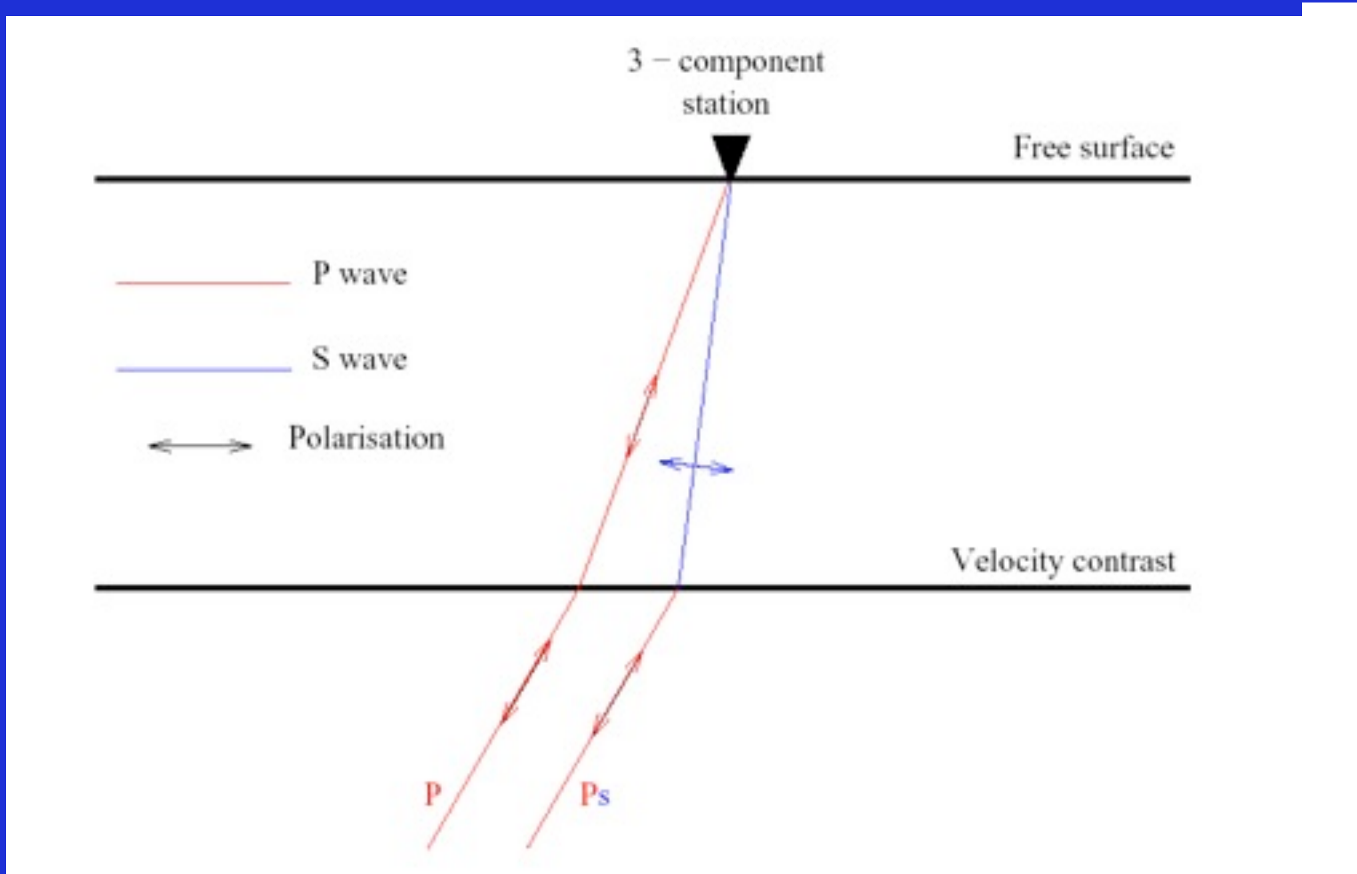
- The crustal structure leads to conversion and reverberations
  - Primary wave arrival ~$P(t-t_p)$ x T
    - P(t) is the amplitude in of the P wave below the crust, depending on the mantle propagation and of the seismic source, T the transmission coefficient to the crust and tp the transmission time through the crust
  - Converted wave ~$P(t-t_c)$ c C
    - C is the transmission coefficient of the crust from Primary wave to converted wave and tc the transmission time through the crust

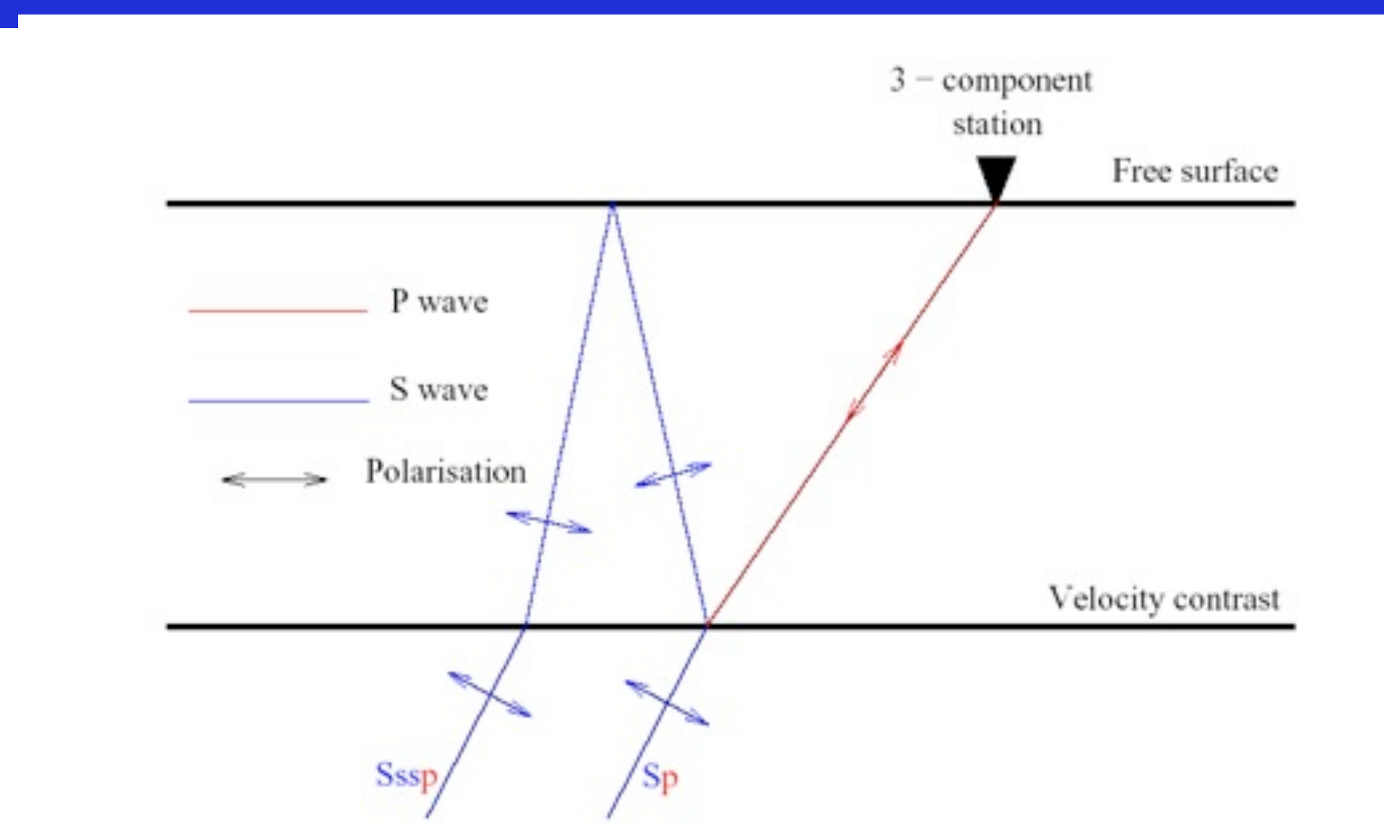




Receiver function method

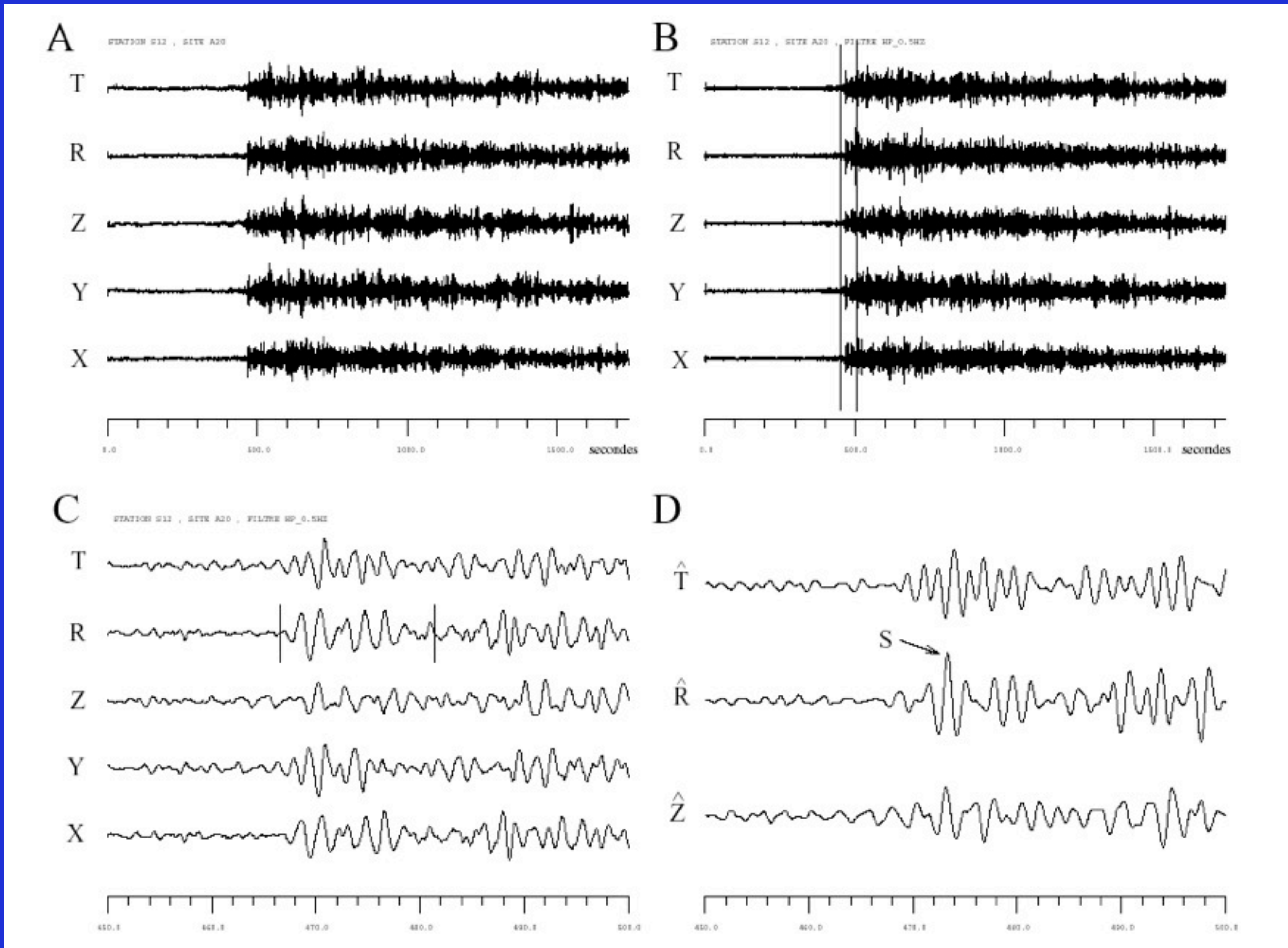
- 1st step : make the Fourier transformation of the arrivals
  - Primary wave arrival Fourier Transformation ~ T $P(\omega) \exp(i\omega t_p)$
  - Converted wave ~C $P(\omega) \exp(i\omega t_x)$
- 2nd step: perform the deconvolution of the converted wave by the primary wave in frequency domain
  - $R(\omega)= [T\, P(\omega) \exp(i\omega t_p)] / [C\, P(\omega) \exp(i\omega t_x)] = T/C \exp(i\omega(t_p - t_x))$
- 3rd step: perform the inverse Fourier transformation
  - $R(t)=T/C\, \delta((t_p - t_x)$



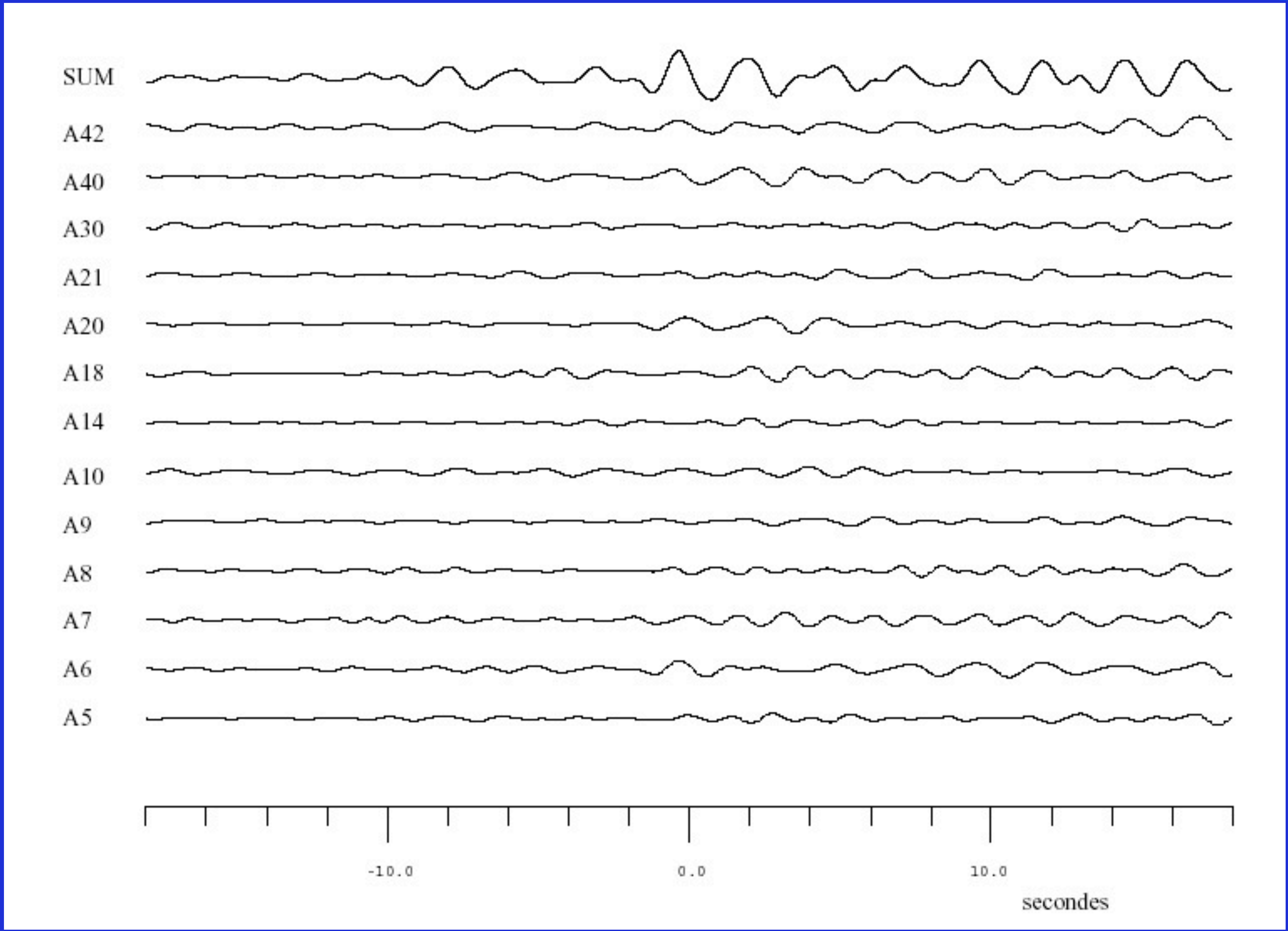


2012年7月9日月曜日

Deconvolution process



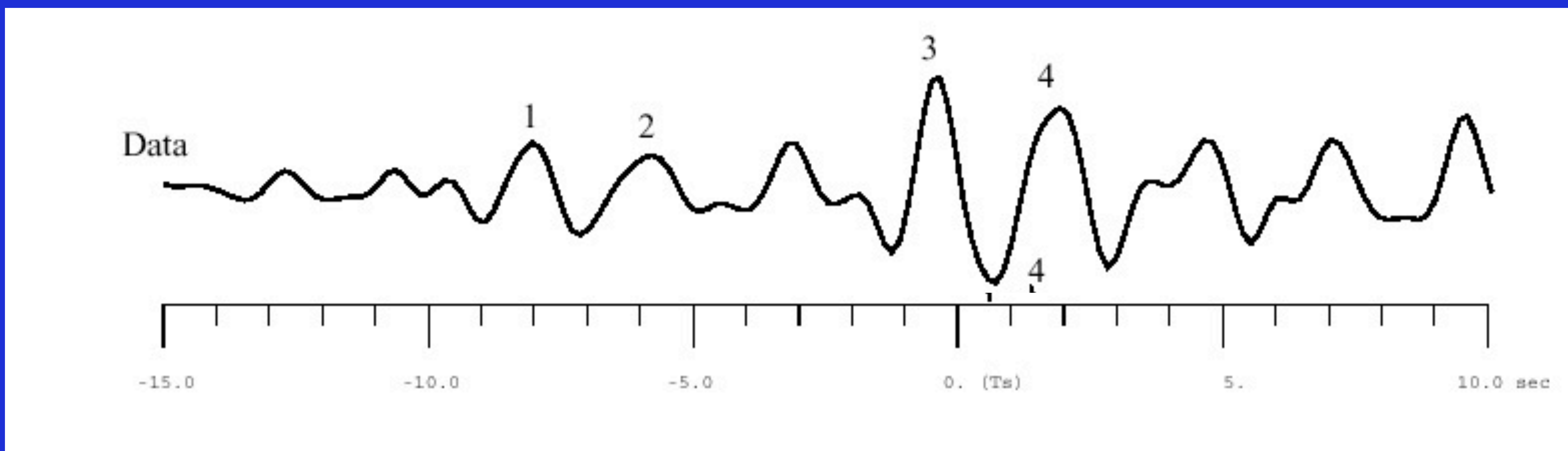
Improving the signal to noise ratio with stack



Moon receiver function (Apollo 12 site)

S->P conversion at the Base of the crust

Subsurface/regolith delay and reverberation

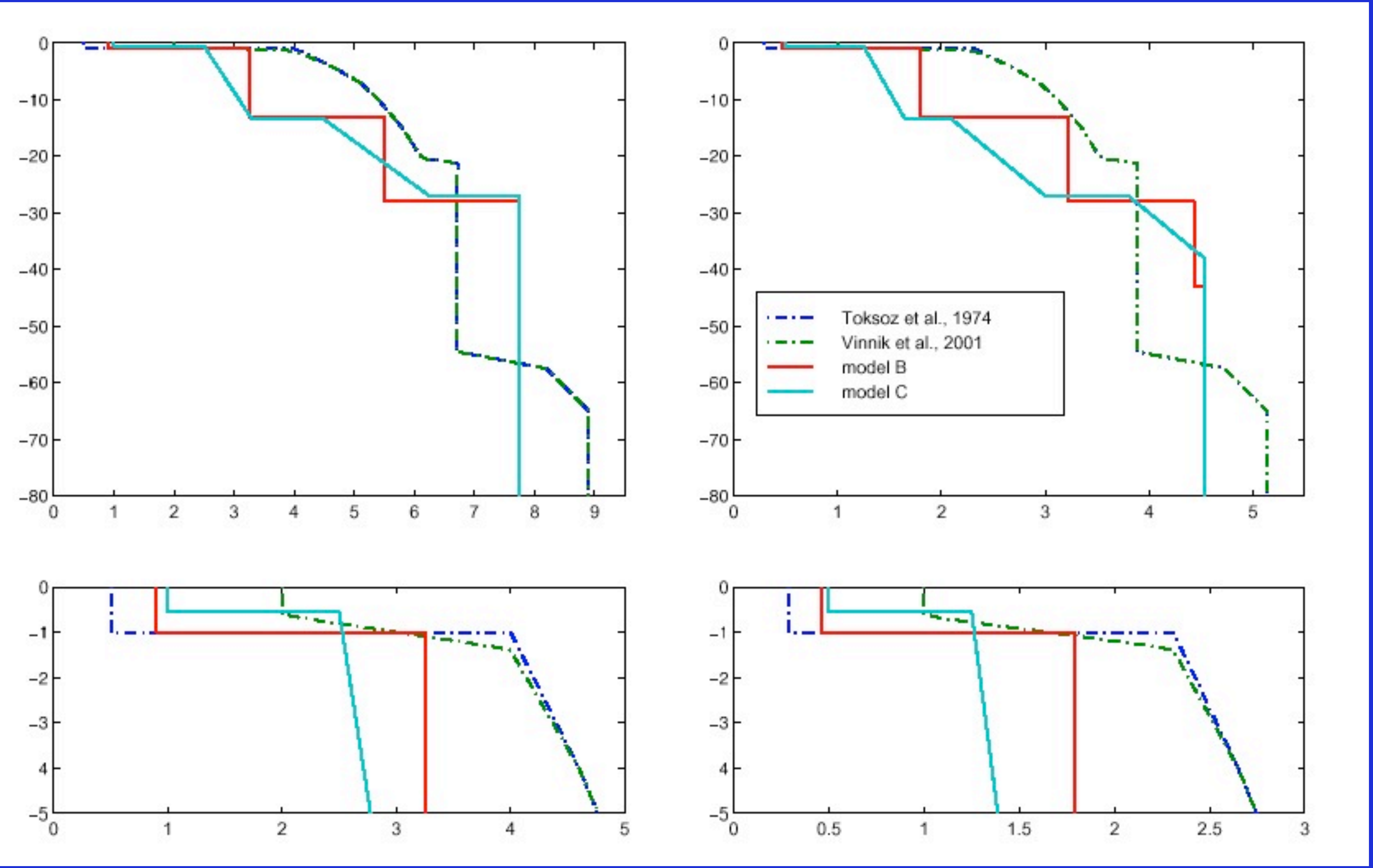


- S-P delay is equal to

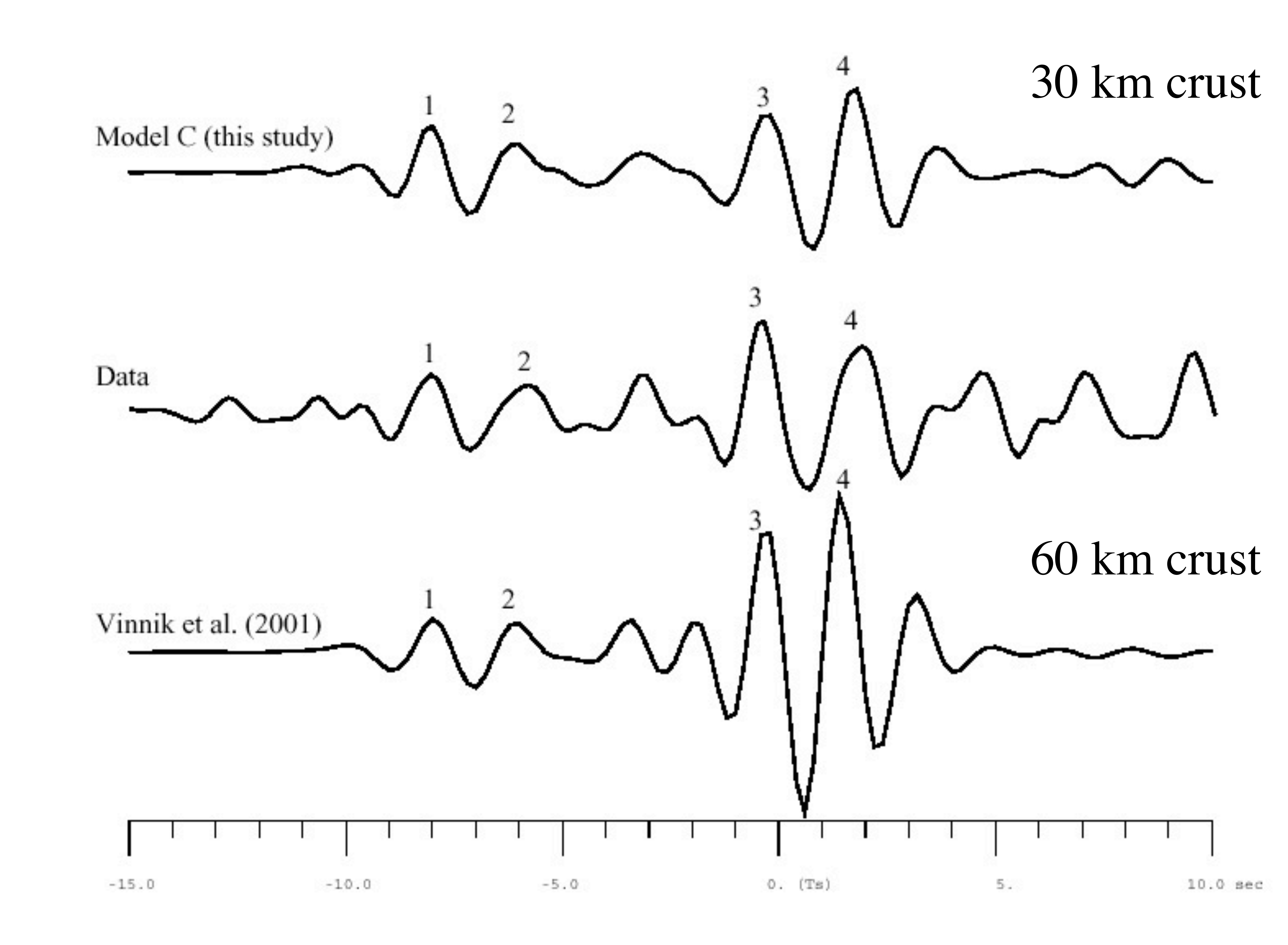
$$\Delta t = t_s - t_p = D(\frac{1}{v_s} - \frac{1}{v_p})$$

And therefore does not give a unique solution

- other informations are needed (amplitude conversion coefficient)


Toksoz et al., 1974
Vinnik et al., 2001
model B
model C

Moon receiver function (Apollo 12 site)

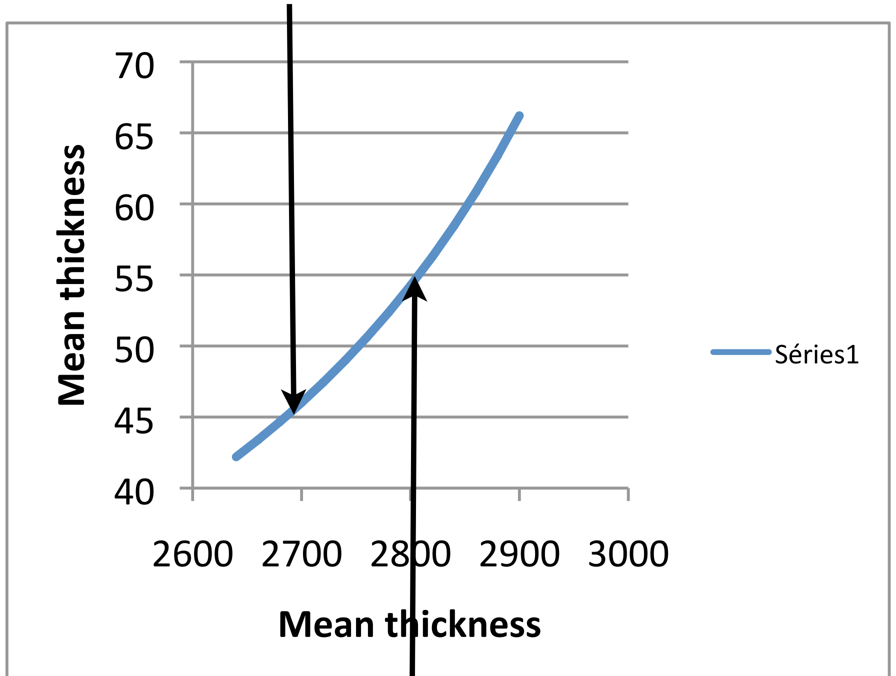


Surface fracturation ?

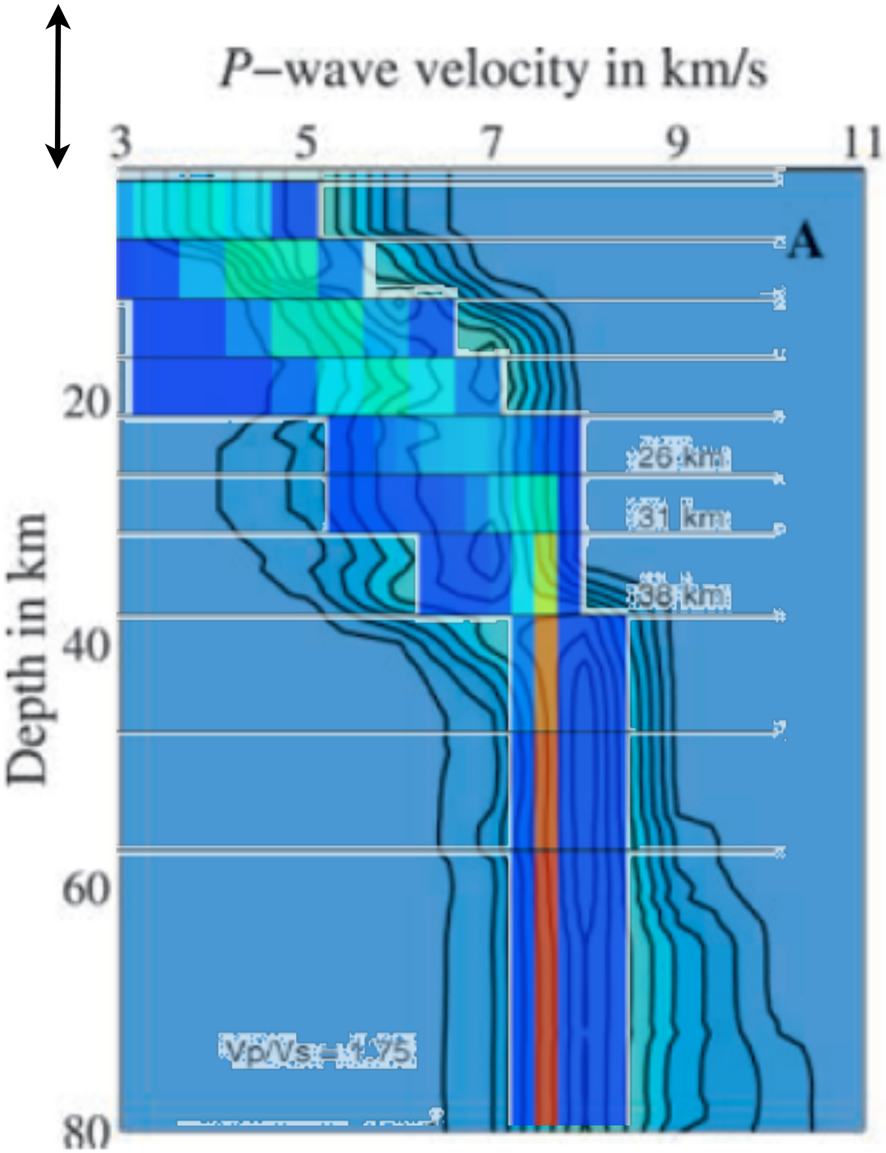
- Many recent evidence for higher porisity
- Possibly a key issue for more precise crustal estimation

Huang and Wieczorek,2012

constant mass

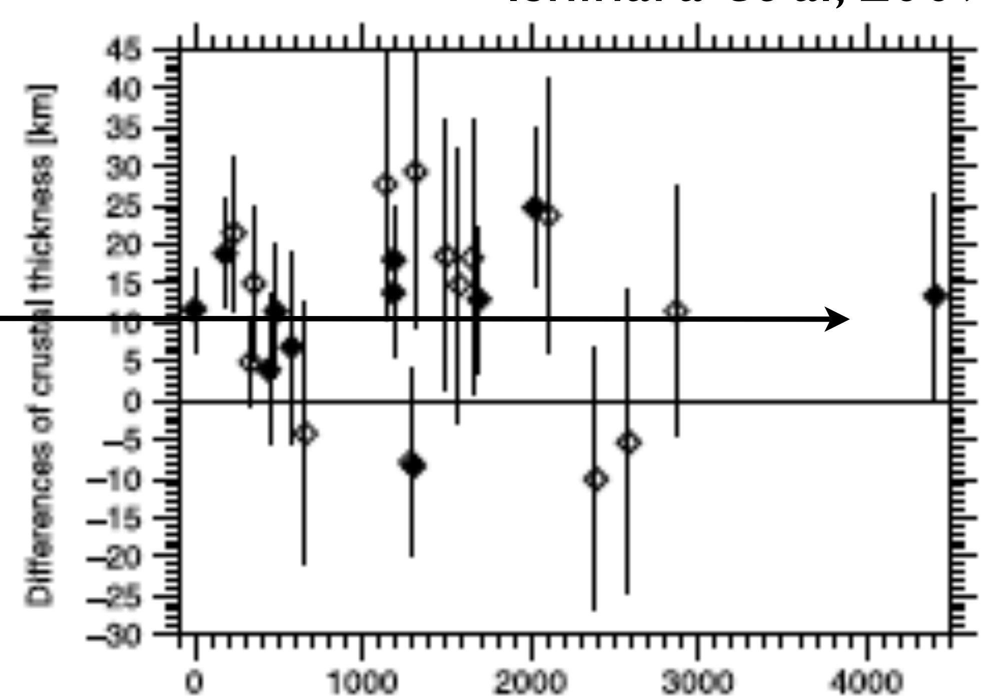


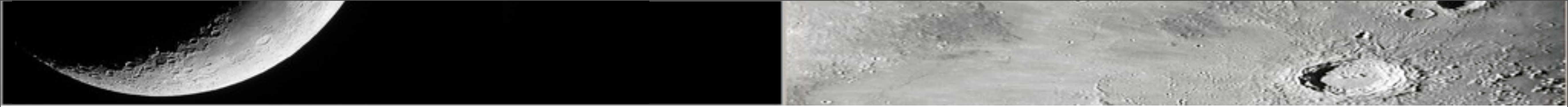
1 km vp at least down to 3.3 km at Apollo17 , i.e. 2.4 km/s(Nakamura , 2011)



Ishihara et al, 2009

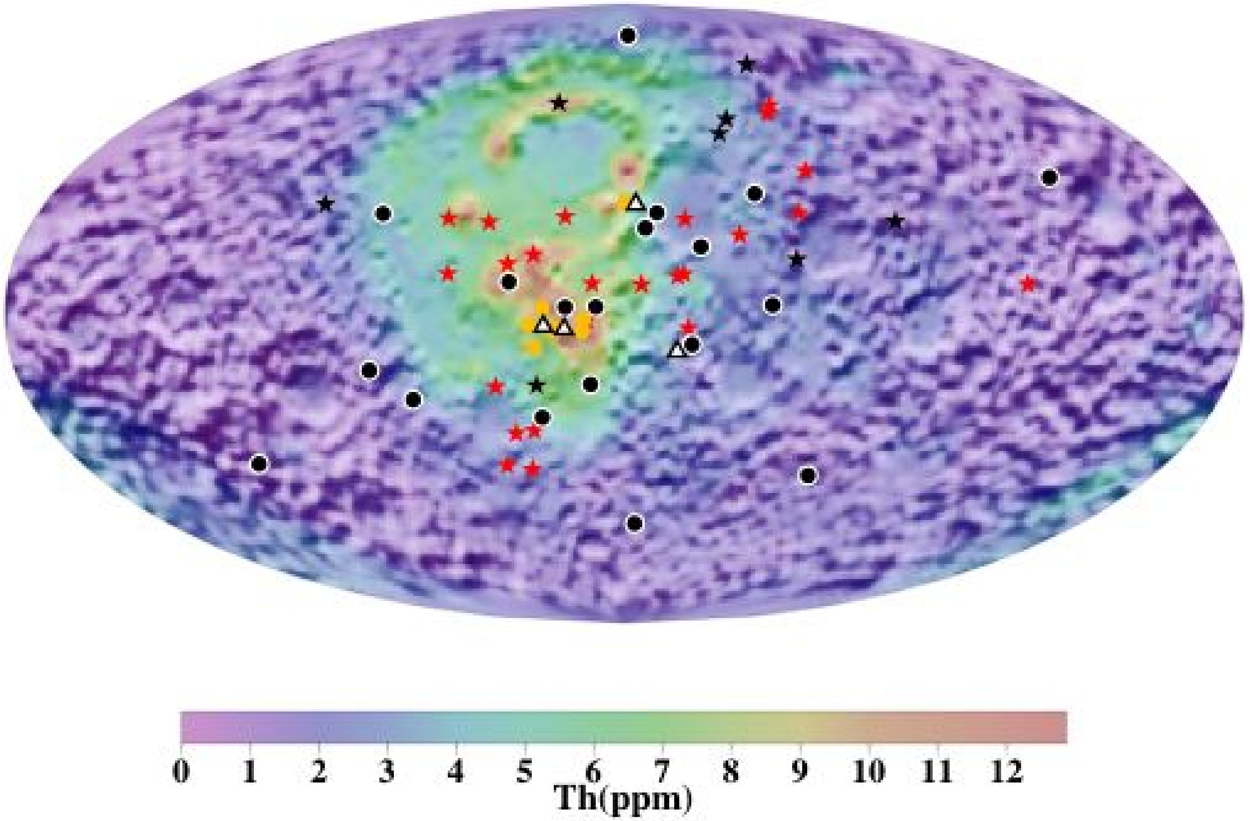
Porisity effect?

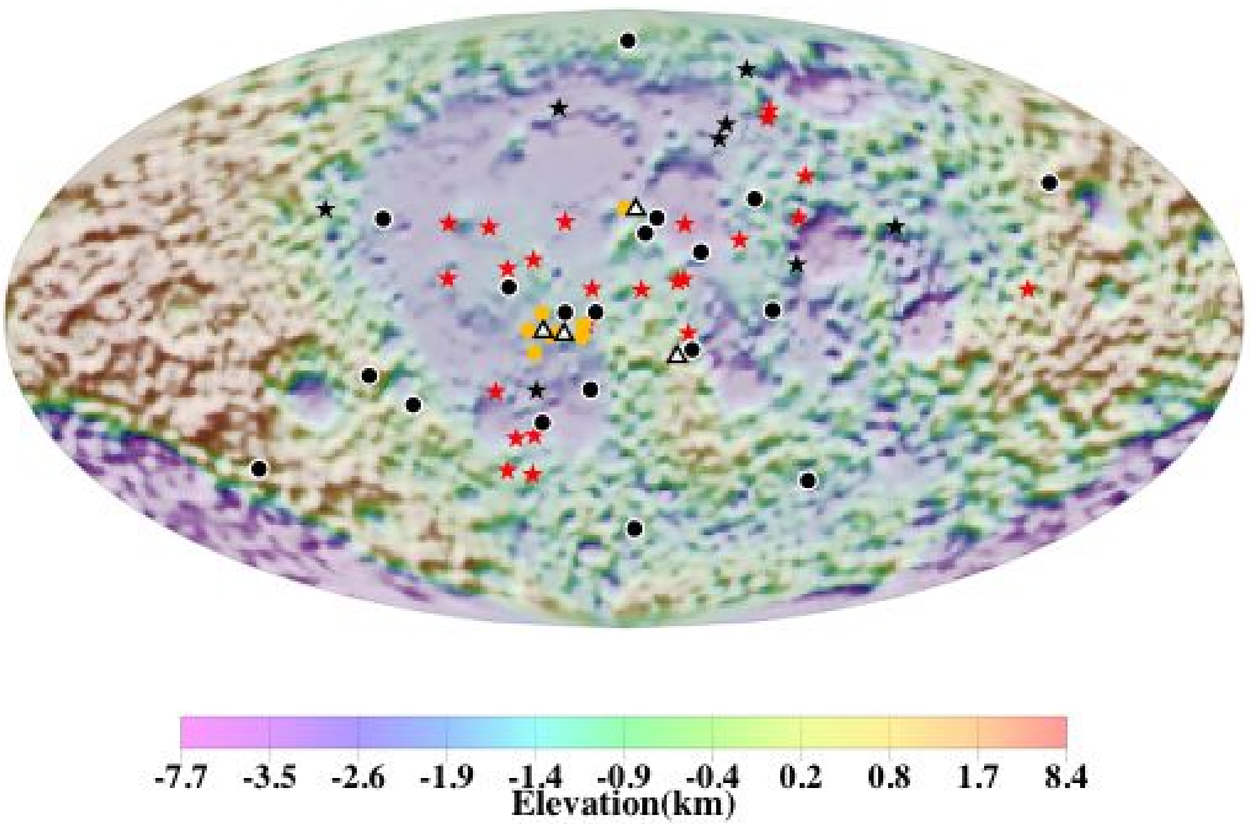




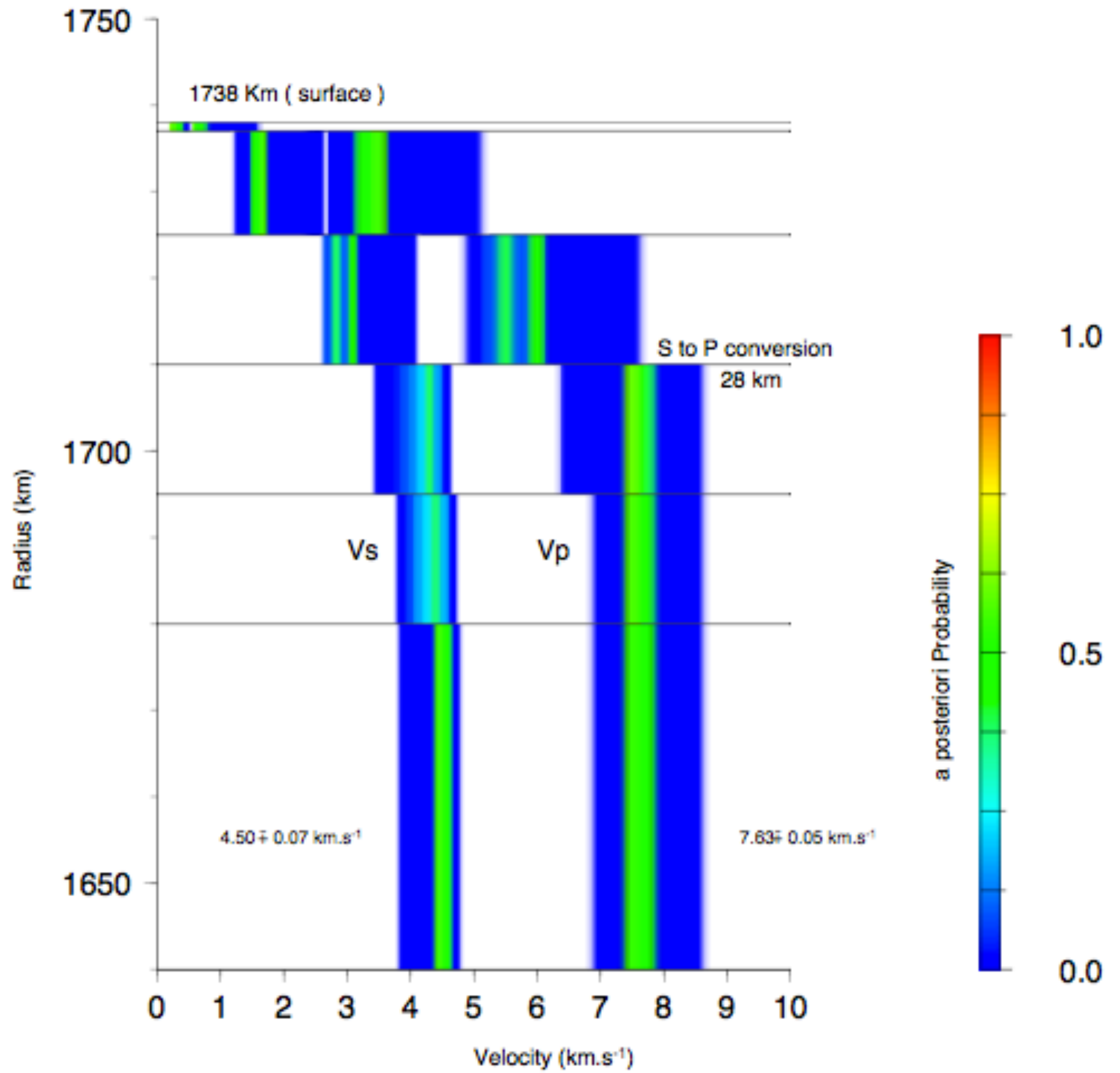
3D crustal structure

- The structure sampled by the Apollo seismic network is not providing a mean Moon model but a regional model associated to the Procellarum Kreep Terrane
  - Thiner crust
  - Probable High Th content



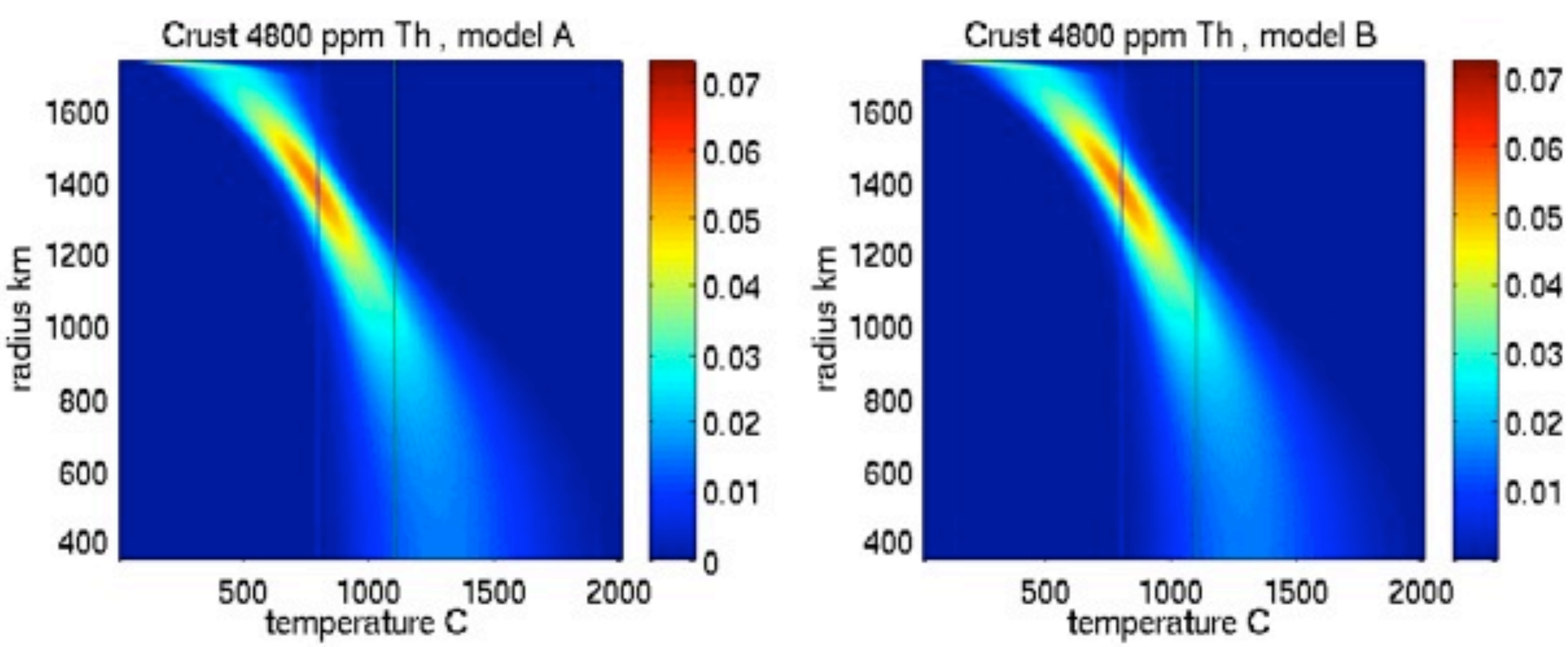


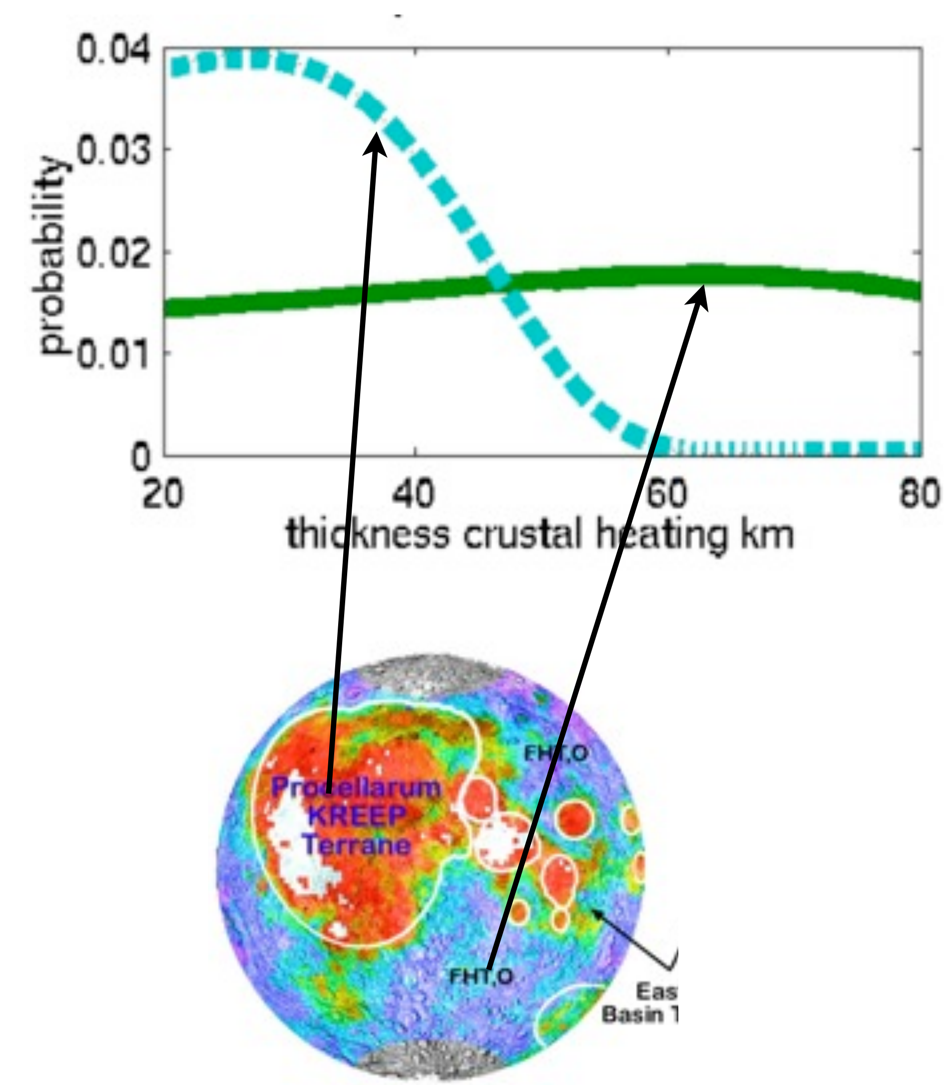
Down to Moho?


1750
1700
1650
Radius (km)
1738 Km (surface)
S to P conversion
28 km
Vs
Vp
4.50 ∓ 0.07 km.s⁻¹
7.63∓ 0.05 km.s⁻¹
0
1
2
3
4
5
6
7
8
9
10
Velocity (km.s⁻¹)
a posteriori Probability
1.0
0.5
0.0

Joint crustal inversion: seismic plus mineralogy

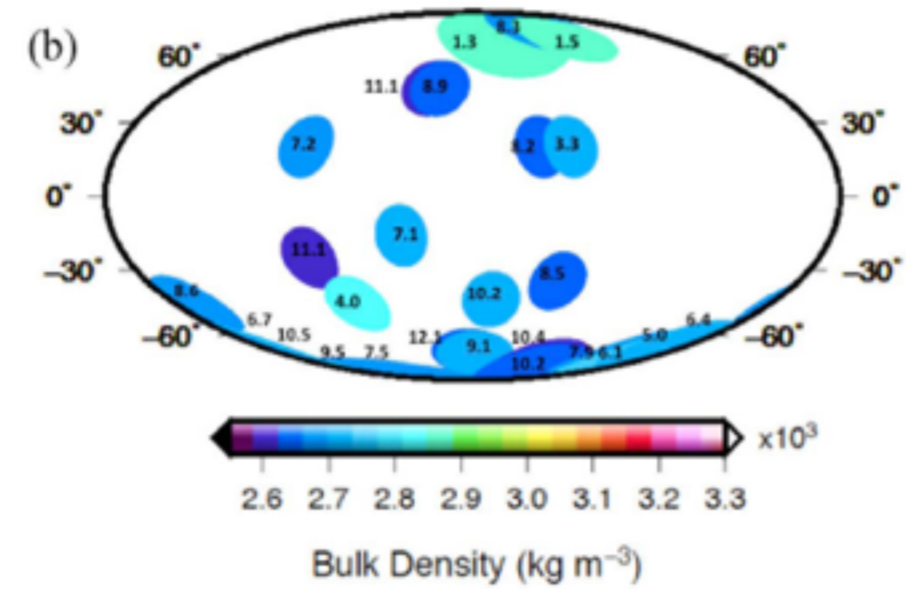
- Use lunar samples to fix the mineralogy of the upper mantle
- Use the upper mantle seismic velocity as «thermometer» to constrain the thickness of the radioactive heating crust





Further effects: Lateral density variations ....

- Typical lower crustal density is 2900-3040 kg/m^3
- Typical upper mantle density is 3300-3400 kg/m^3
- Difference is therefore ~12%
- 5 km of crustal thickness increase (negative mass) is therefore equivalent to crustal porosity increase by 6% in the upper 10 km

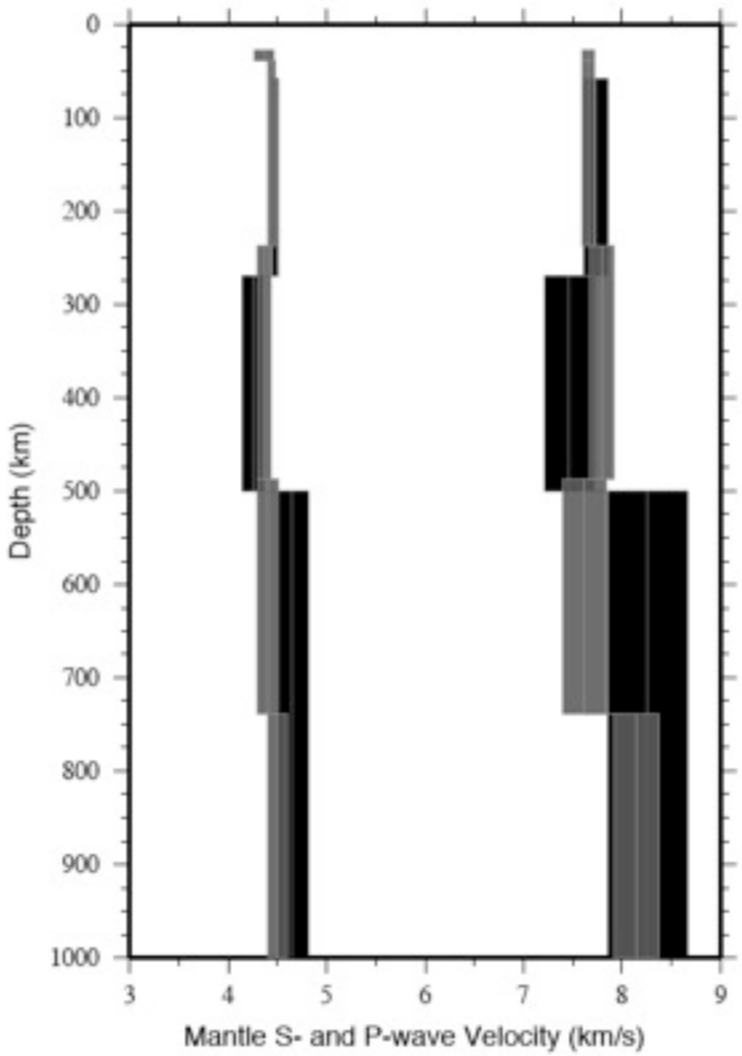


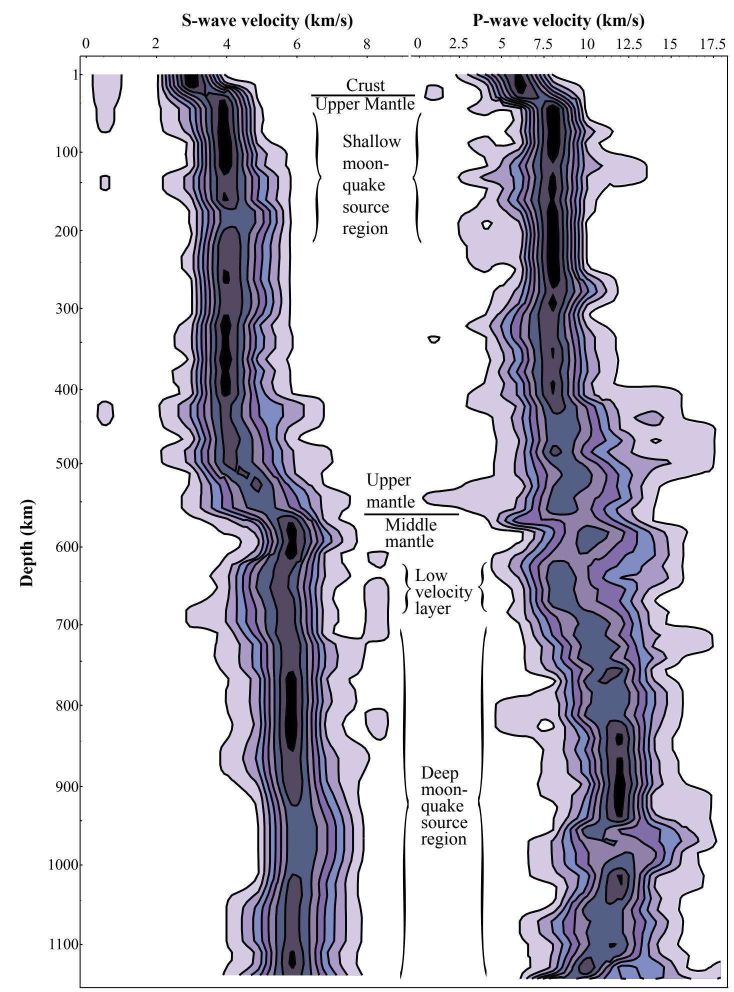
- Positive Thermal crustal-upper mantle feedback

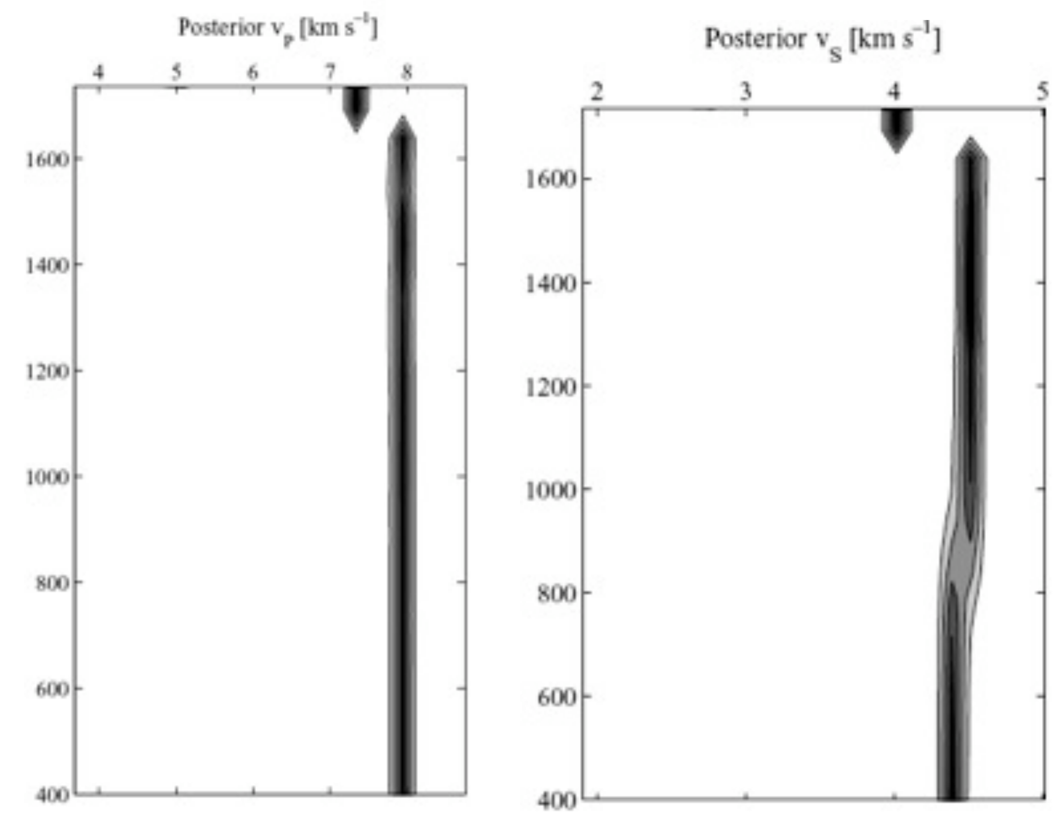
  - negative crustal mass
    - increased porosity (better isolation)
    - Larger thickness (more heating)

  - negative mantle mass
    - hotter upper mantle

Is there a seismic discontinuity in the mantle?







Nakamura et al. (1982), Lognonné et al. (2003)

Maybe: ~500 km

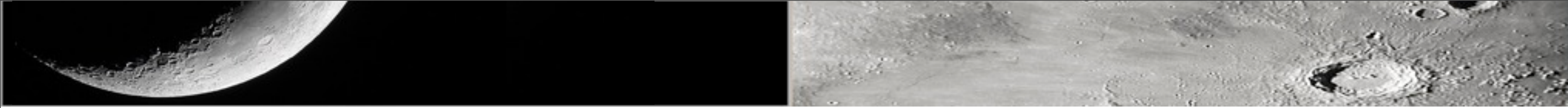
Khan and Mosegaard (2002)

Yes: 550 km depth

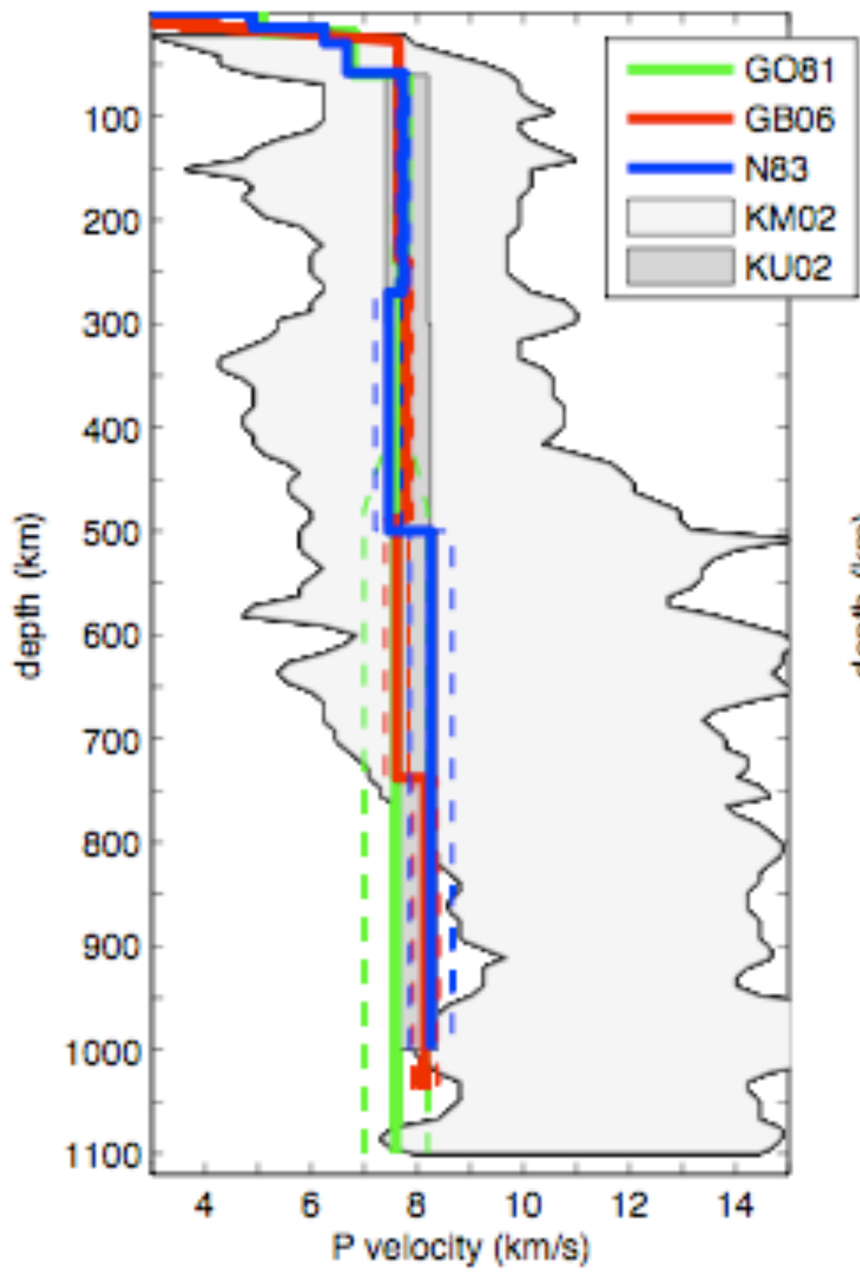
Khan et al. (2007)

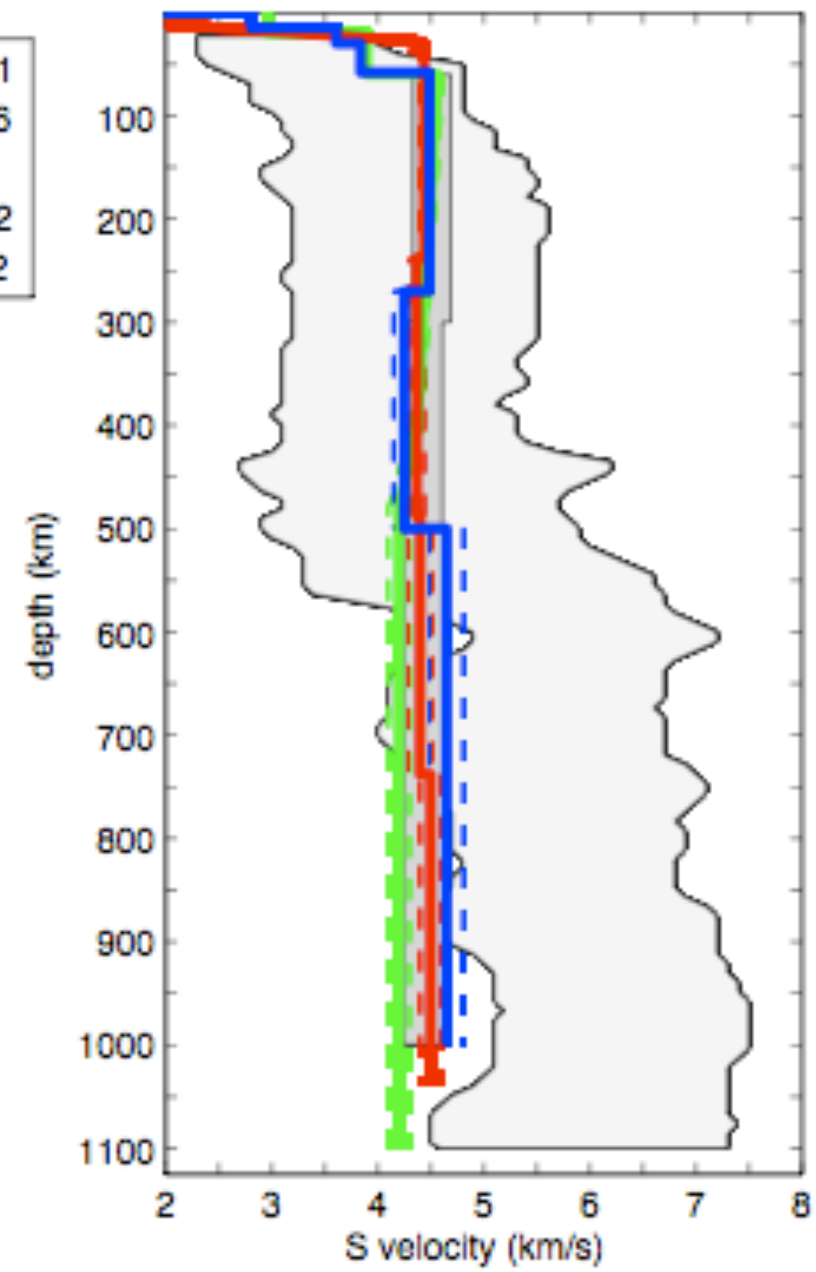
NO? or 850 km depth?

Each study used different seismic events, seismic arrival times and analysis techniques...

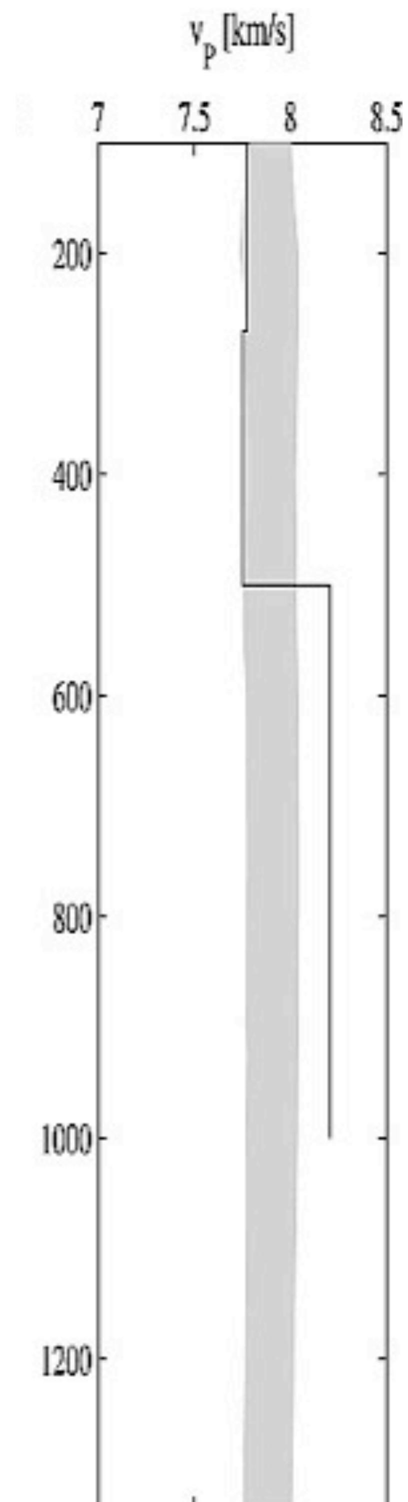


Direct inversion of seismic velocities





Direct inversion of mineralogy



Khan et al., 2006

Nakamura, 1983

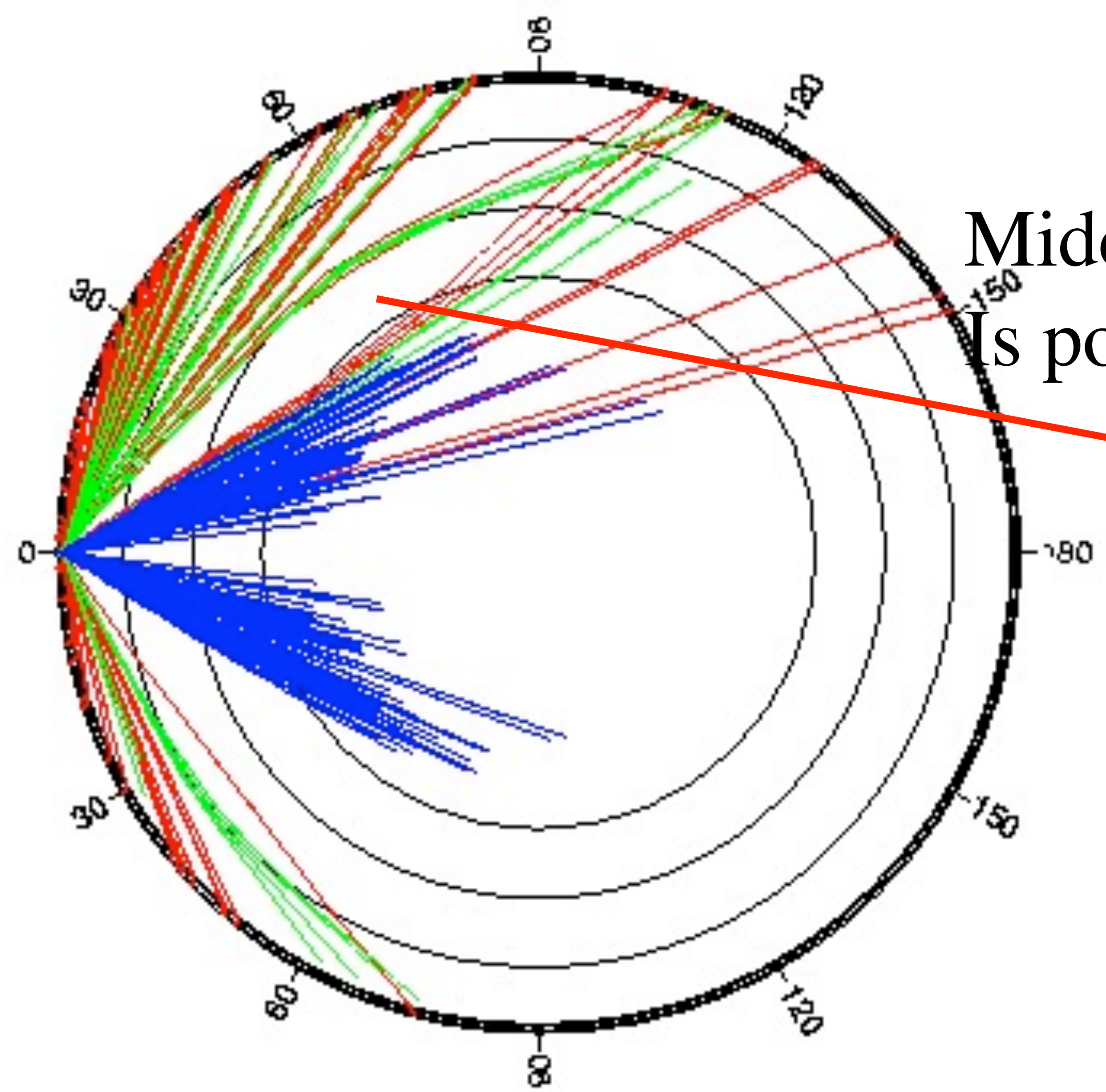
Goins, Dainty and N.Toksöz, 1981

Lognonné, 2003, Gagnepain-Beyneix 2006

Kuskov et al, 2002

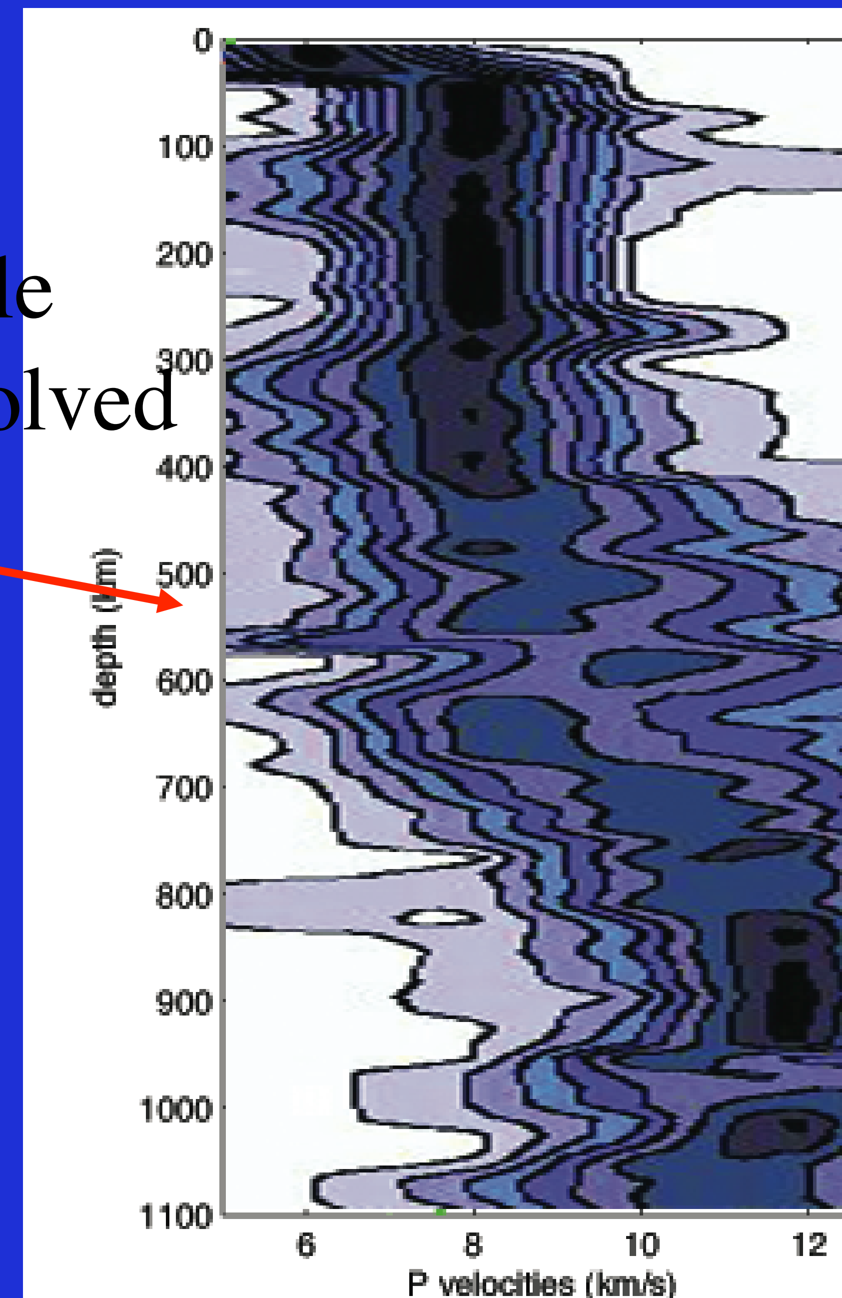
Khan et al, 2000

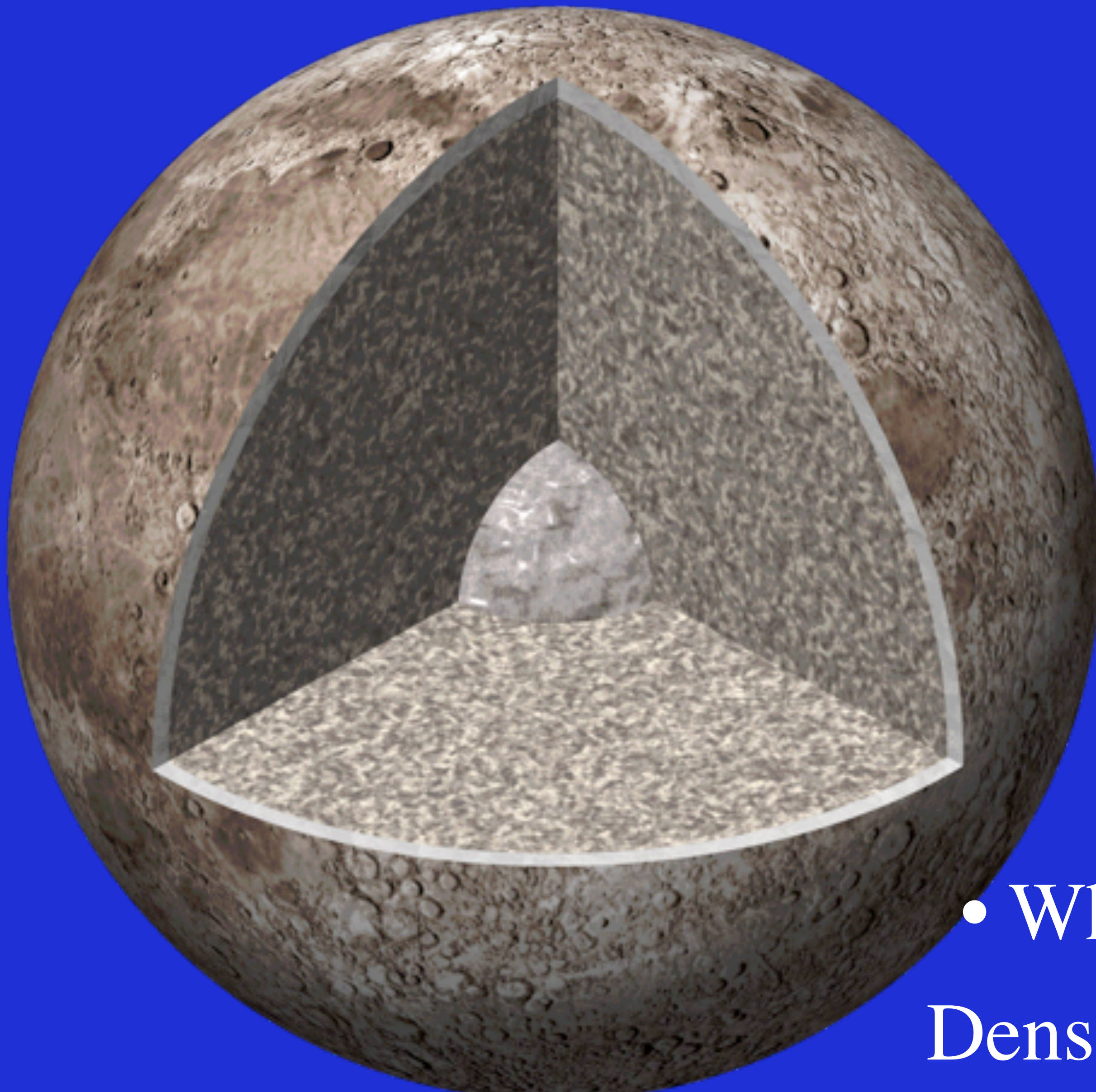
Khan and Mosegard, 2002



All ray paths available in the Moon. Blue is for deep events, red for impacts, green for superficial moonquakes.

Middle mantle
Is poorly resolved





Sounding the Lunar core

- What we knew 2 years ago

Density and moment of inertia

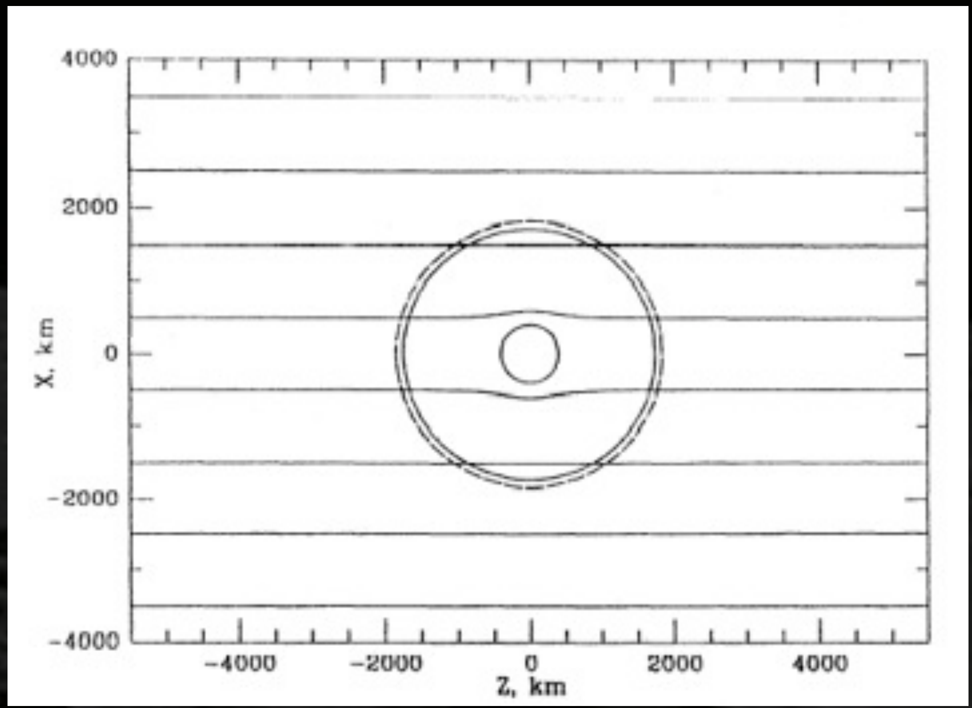
Magnetic sounding

- What we know today

Coffee break

Magnetic Induction

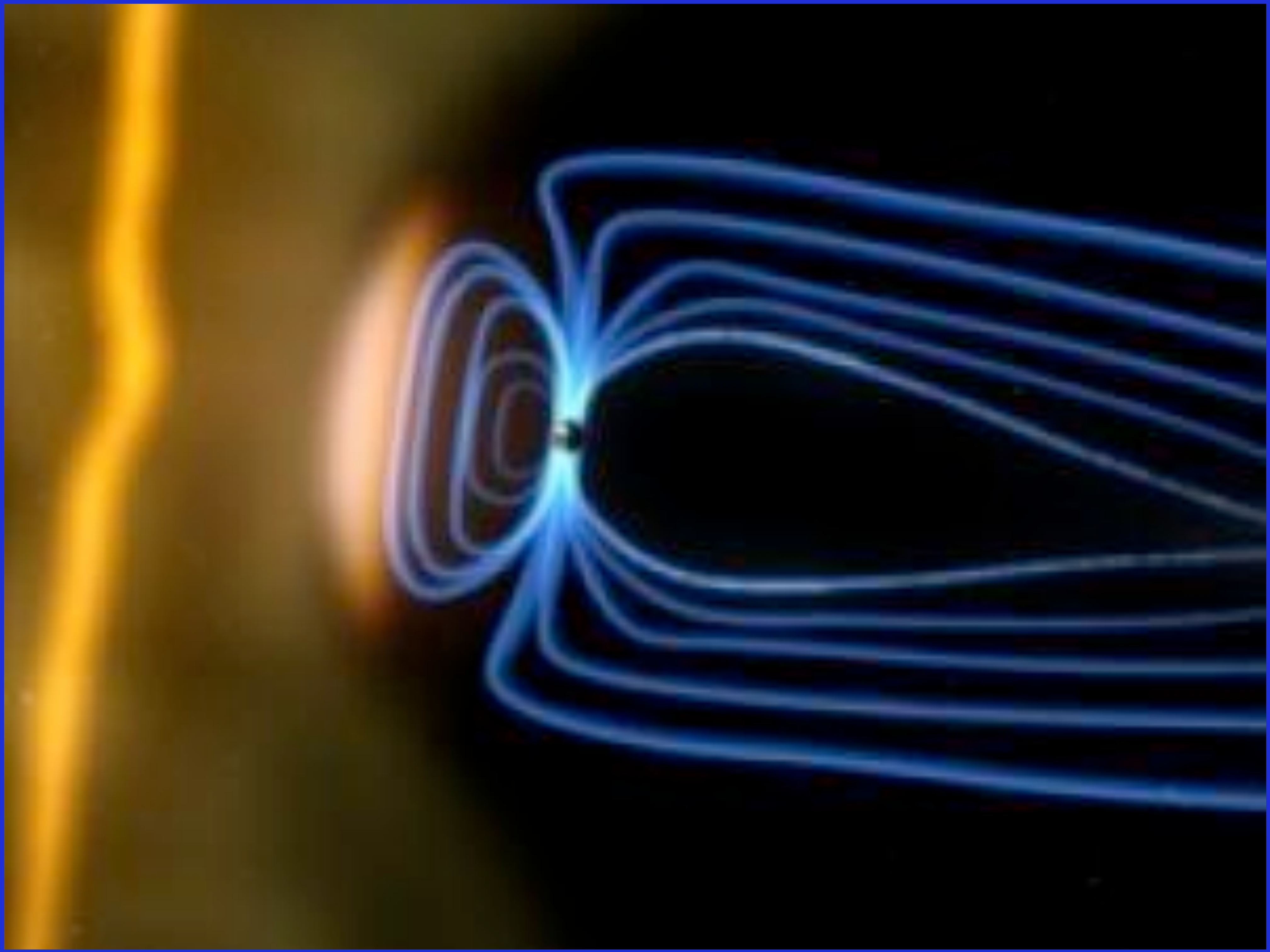
$$\nabla^2 \mathbf{B} = \mu\sigma \frac{\partial \mathbf{B}}{\partial t},$$

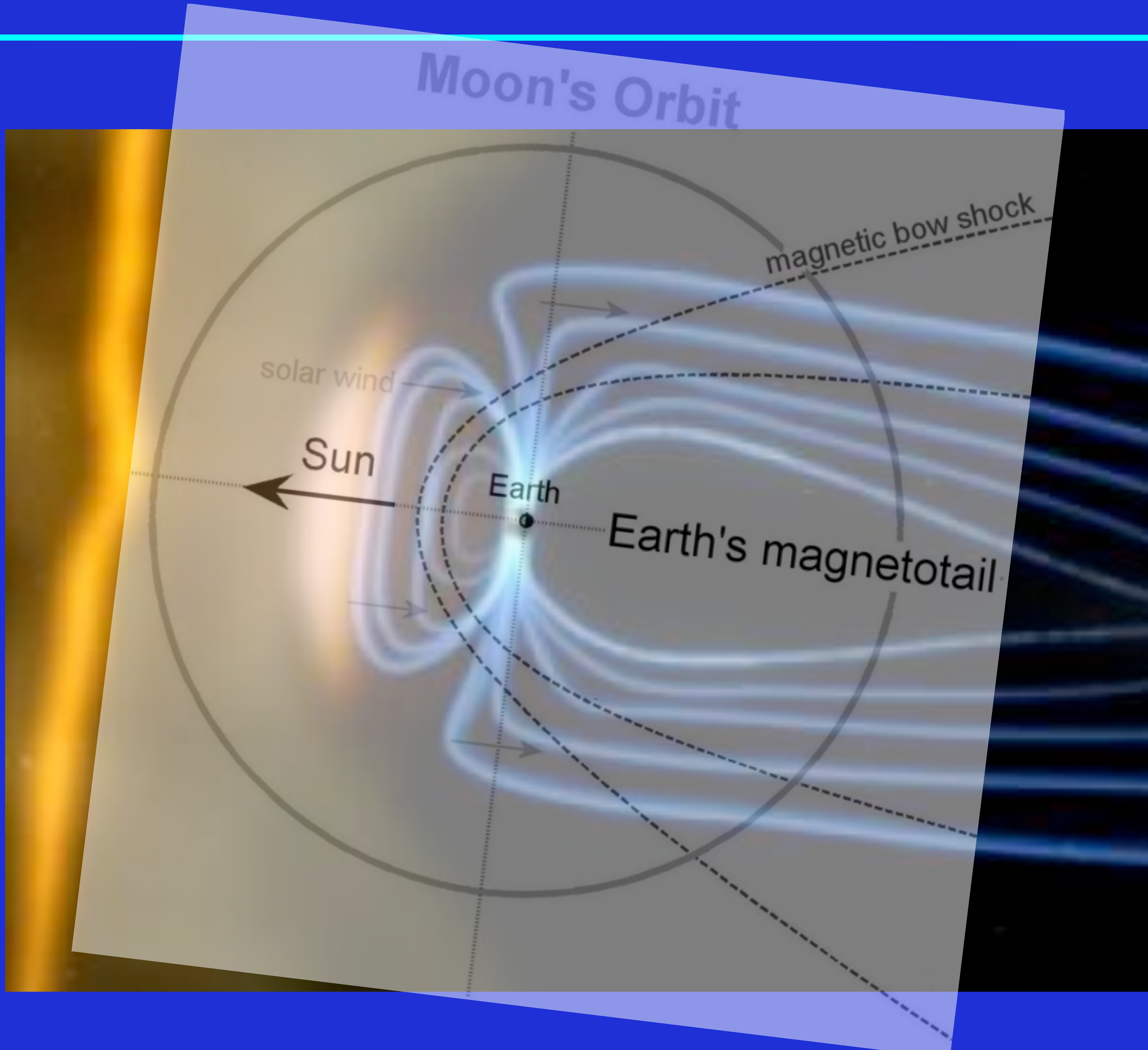


What is the (conductive) size of the Lunar Core?

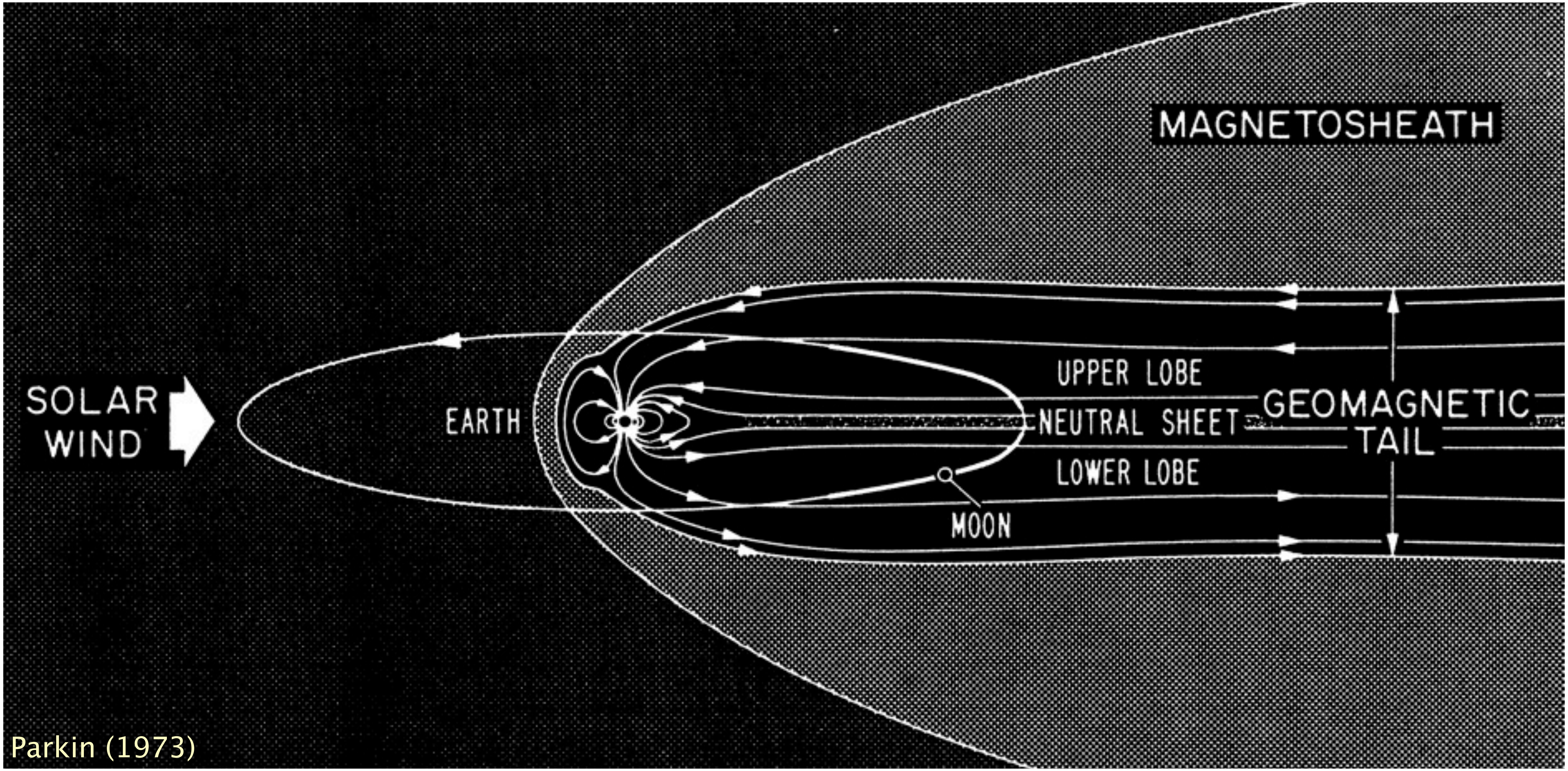
What is the mantle conductivity ?

1997: Moon sounding with the Earth

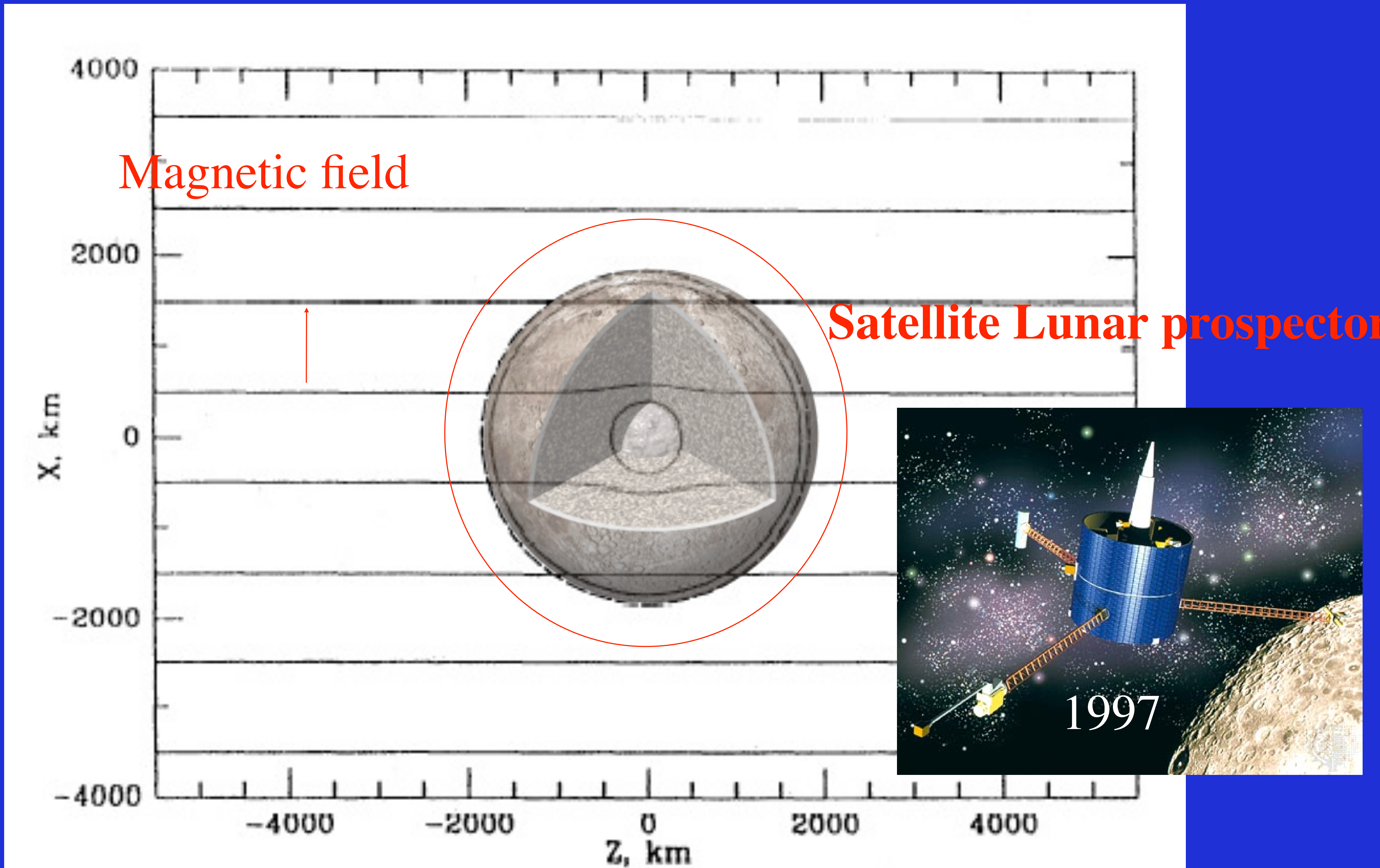



Moon's Orbit
magnetic bow shock
solar wind
Sun
Earth
Earth's magnetotail

The magnetic environment of the Moon

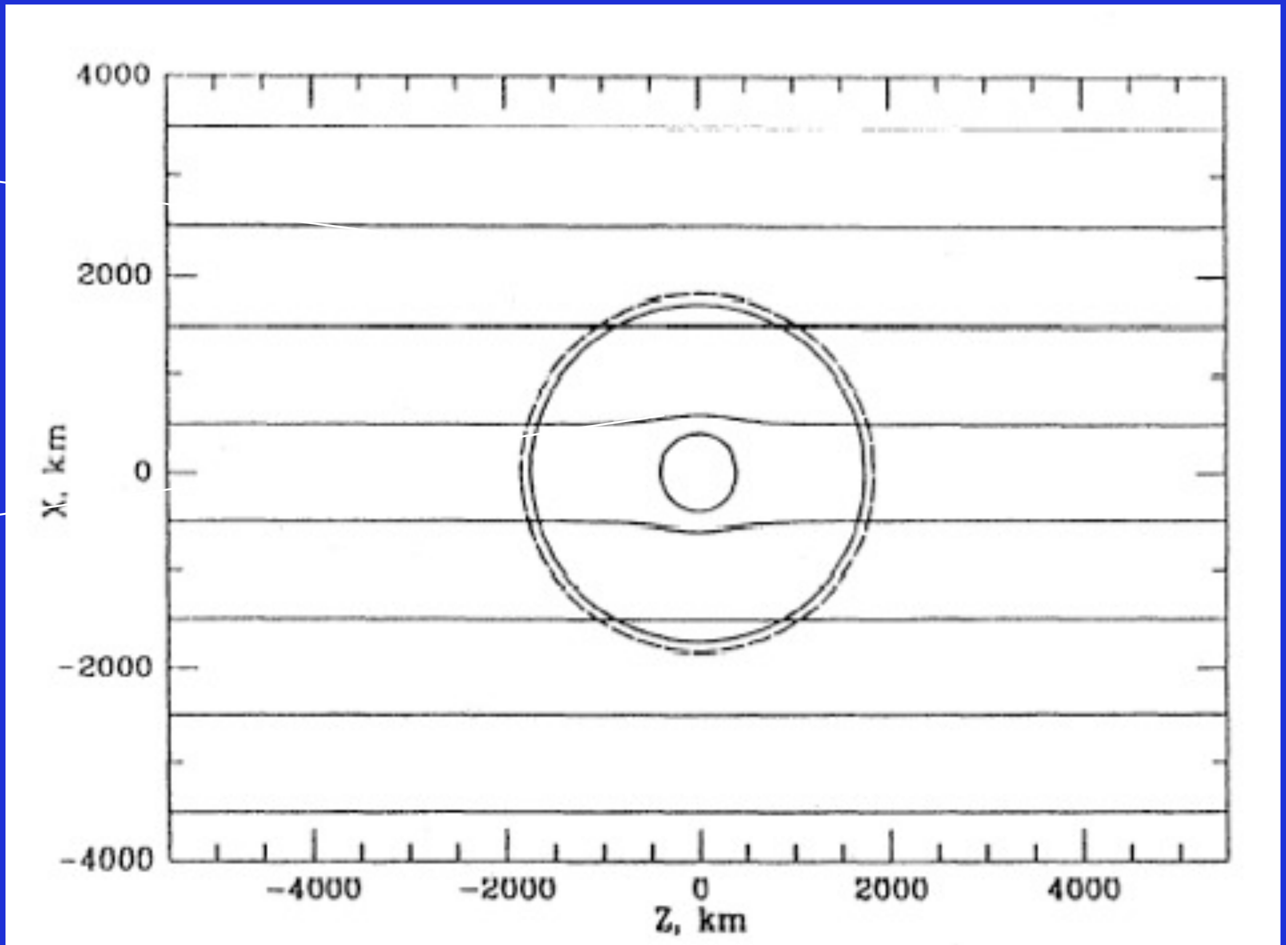


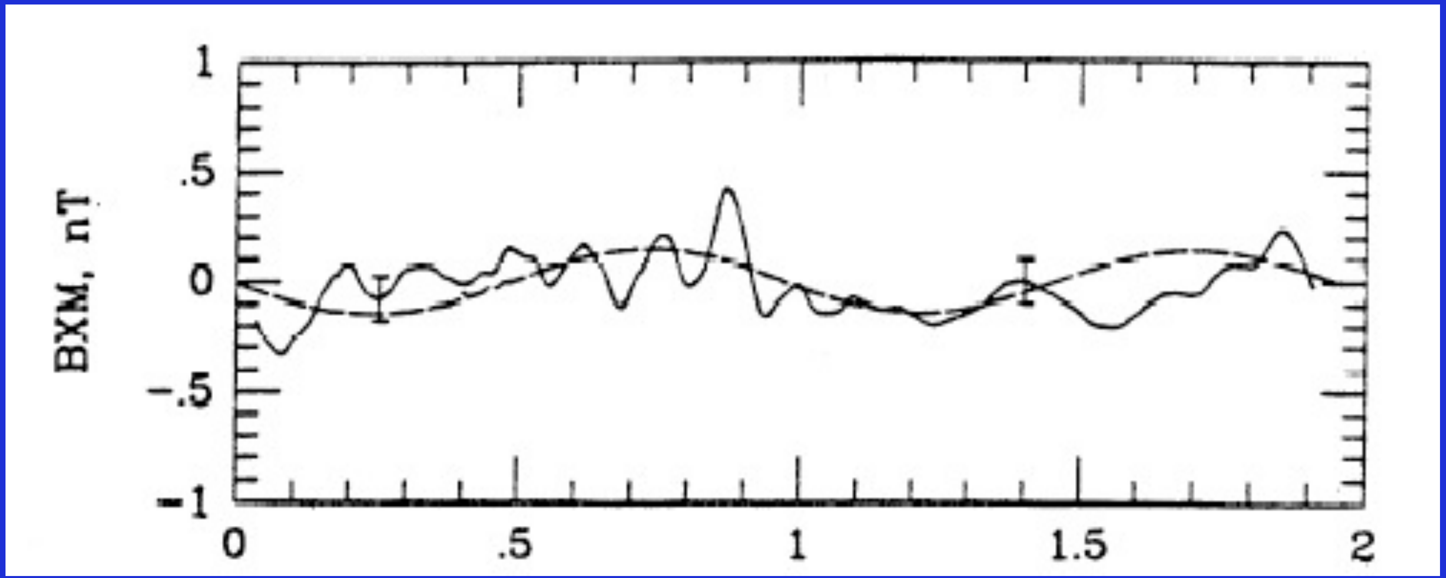
The most precise measurements of the Moon's field are made on the hemisphere that is partially shielded against the solar wind, and for about 2 days per month when the Moon passes through the Earth's geomagnetic tail lobe.


4000
2000
0
-2000
-4000
X, km
-4000
-2000
0
2000
4000
Z, km
Magnetic field
Satellite Lunar prospector
1997

Lunar prospector magnetic sounding

- Primary magnetic field is the magnetic field of the geotail (12-16nT)
- Magnetic field is slighly expulsed from the iron moon core
- A low altitude orbiting satellite with magnetometer (Lunar Prospector) measure the small (0.4 nT) perturbation
- Best fit is achieved with a metallic core of 400 km





Lunar prospector magnetic sounding

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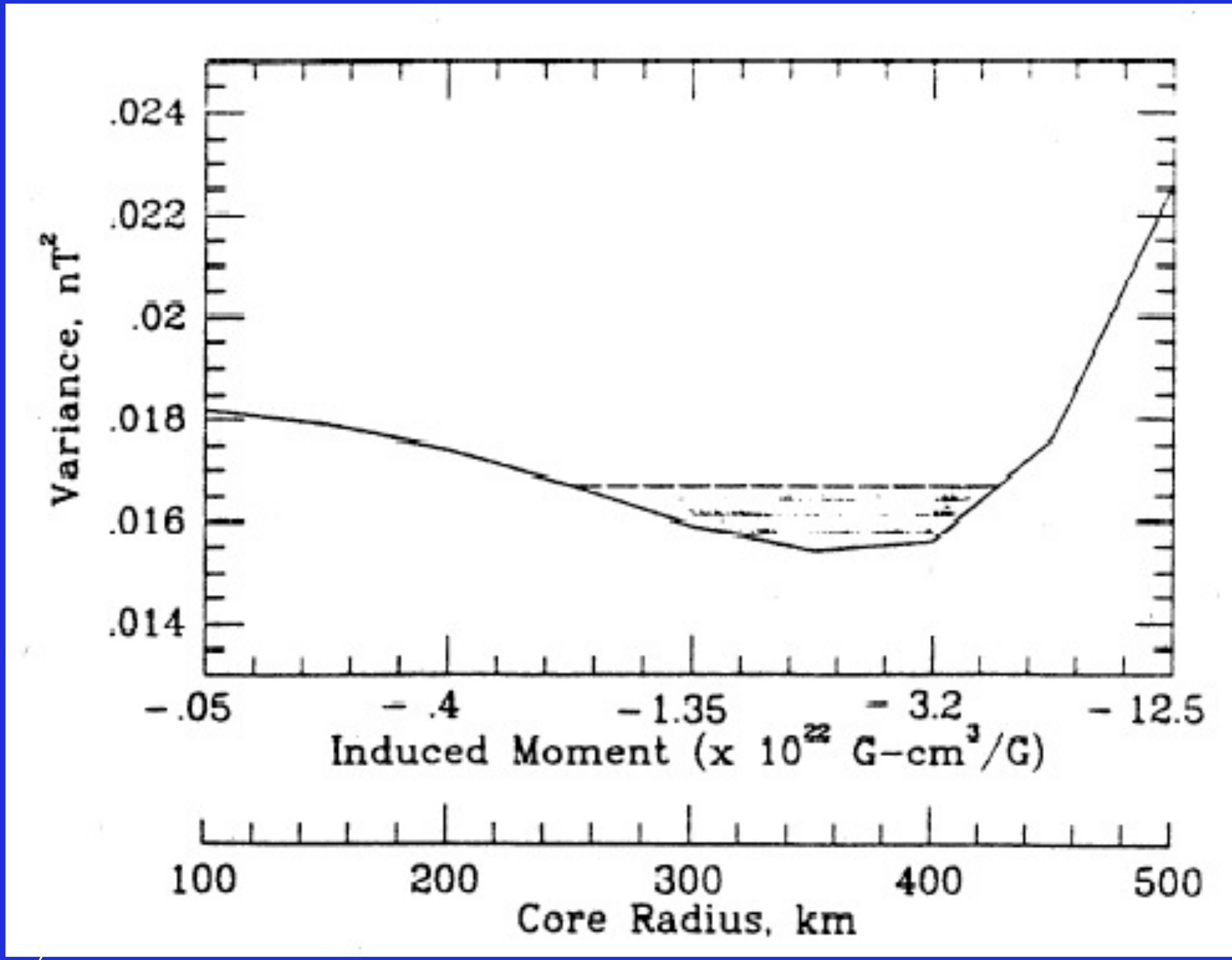
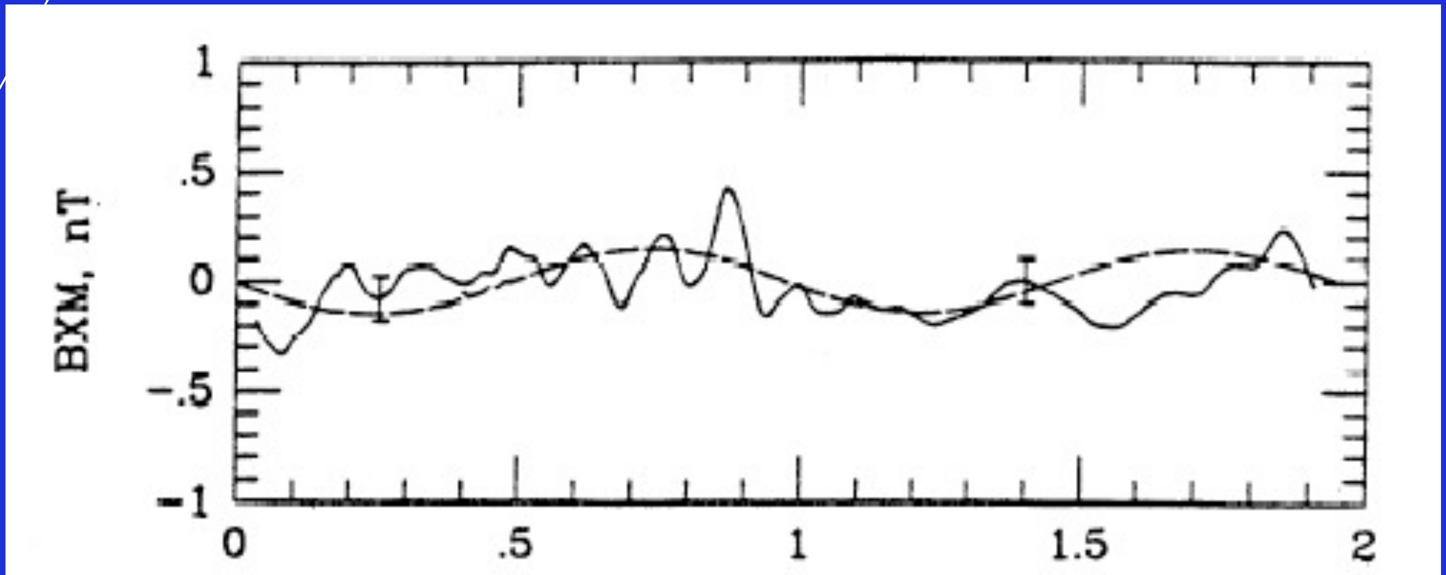
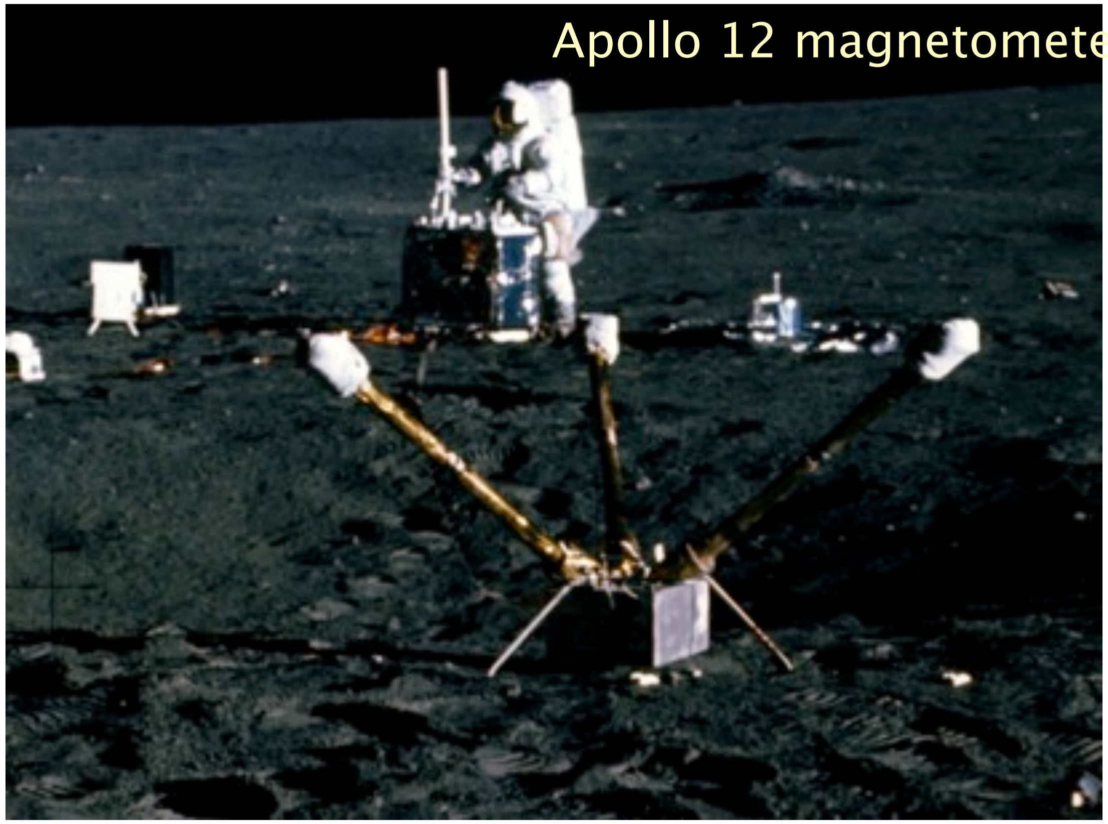
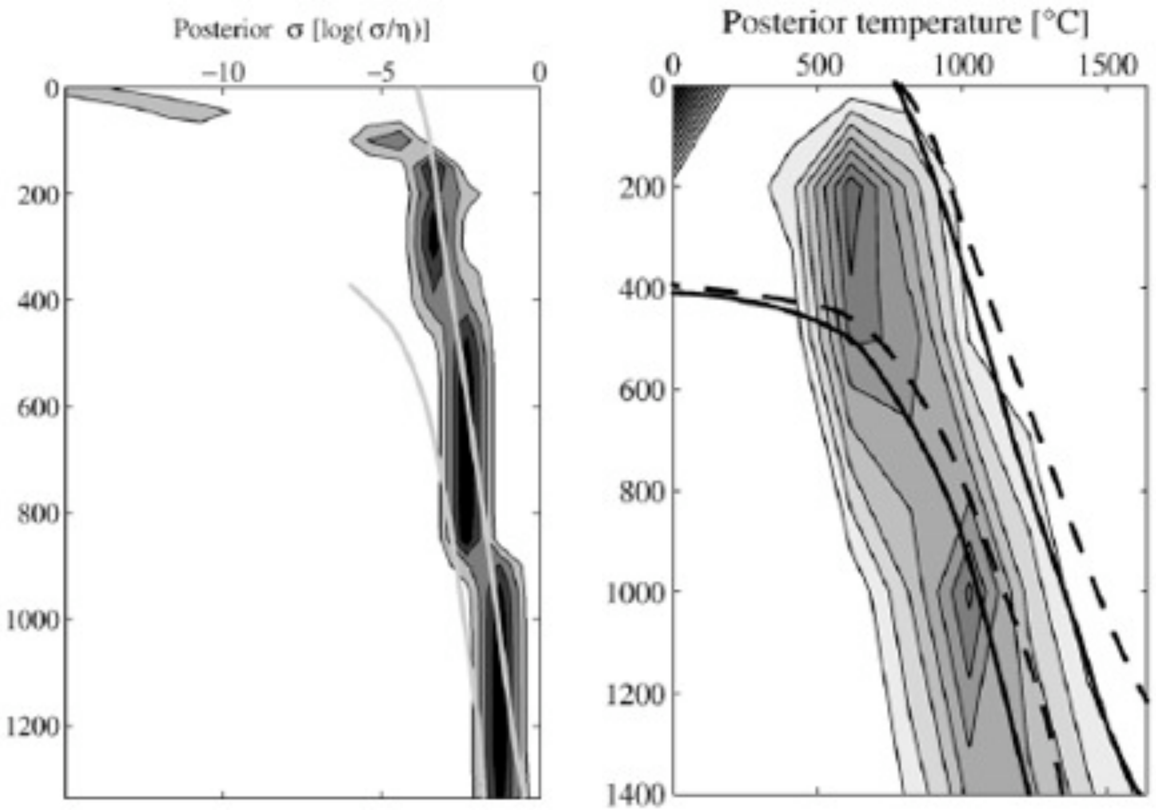




Time-variable magnetic induction signals



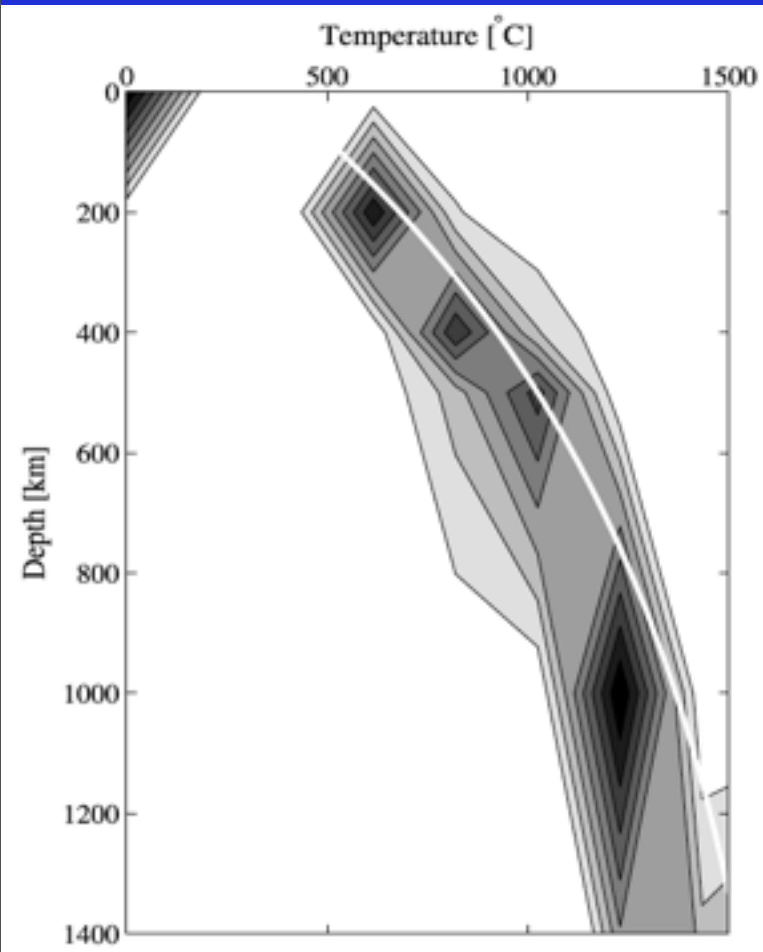
The electrical conductivity profile can be obtained by measuring the inducing field from orbit and the resulting magnetic field on the surface.

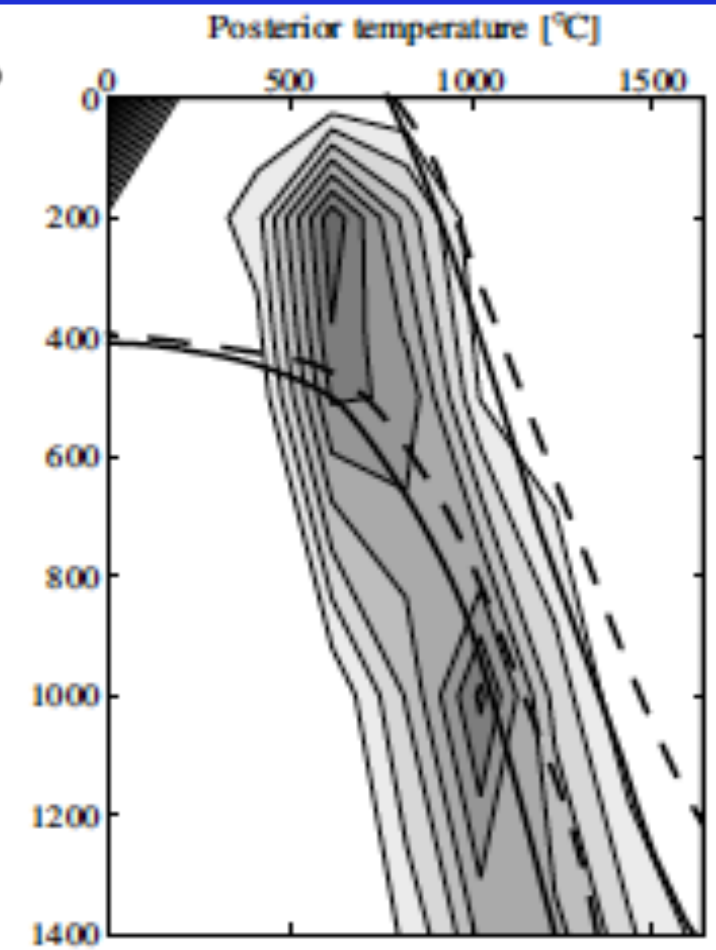


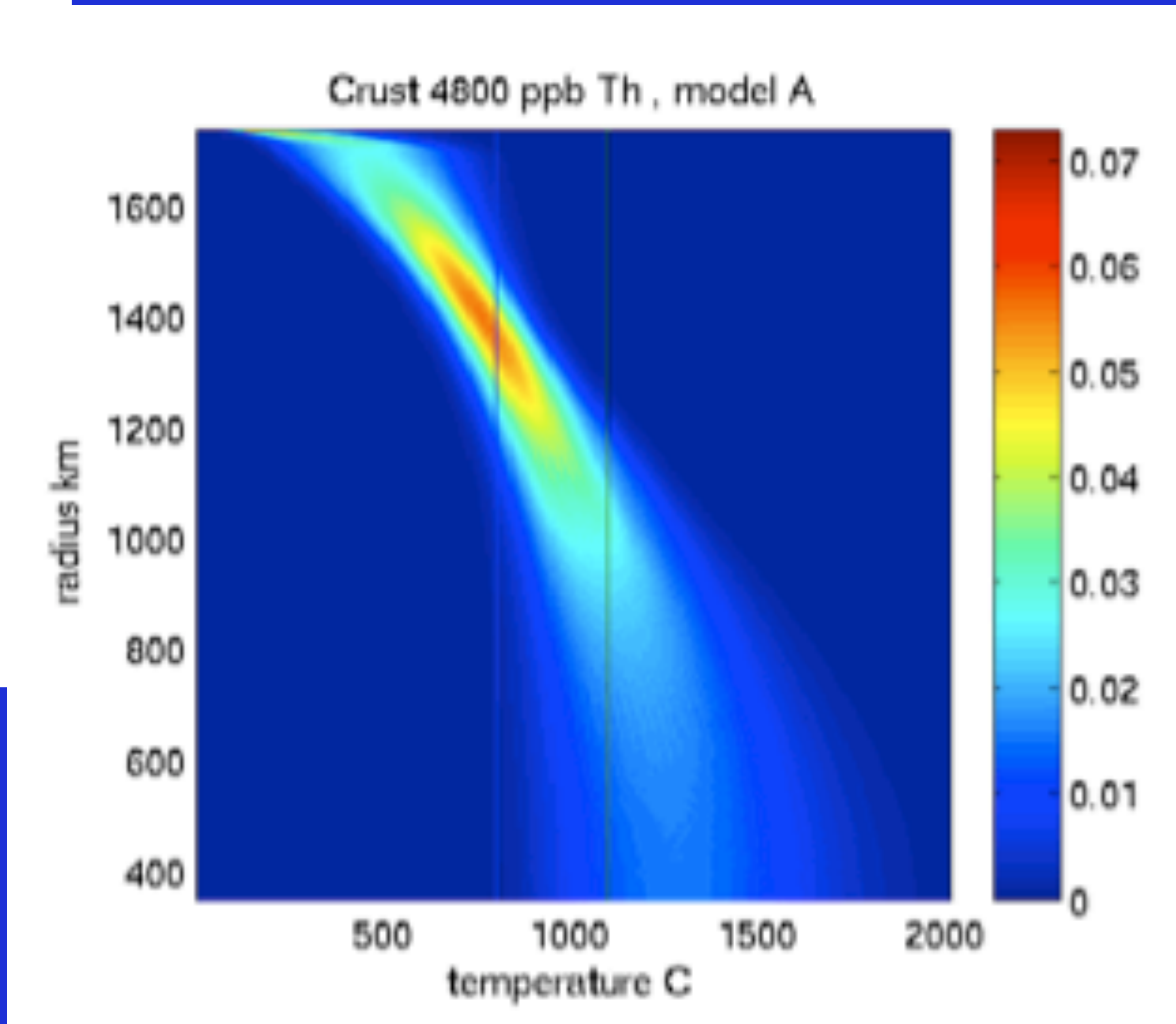
Khan et al. (2006)

Inferred temperature profile depends upon a limited number of electrical conductivity measurements.

Other temperatures



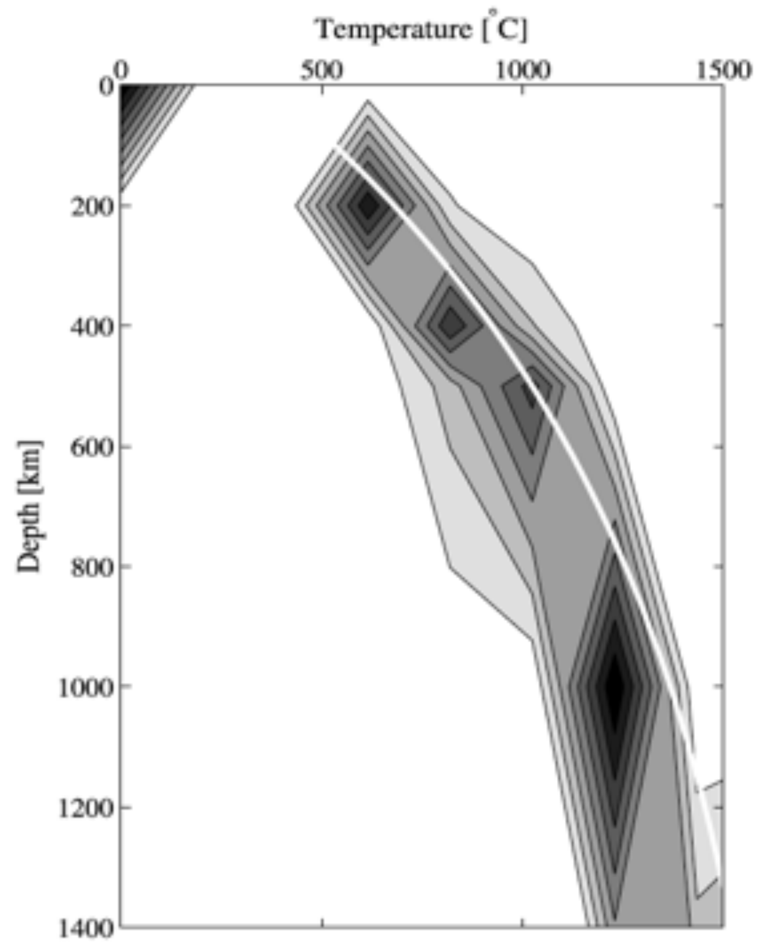


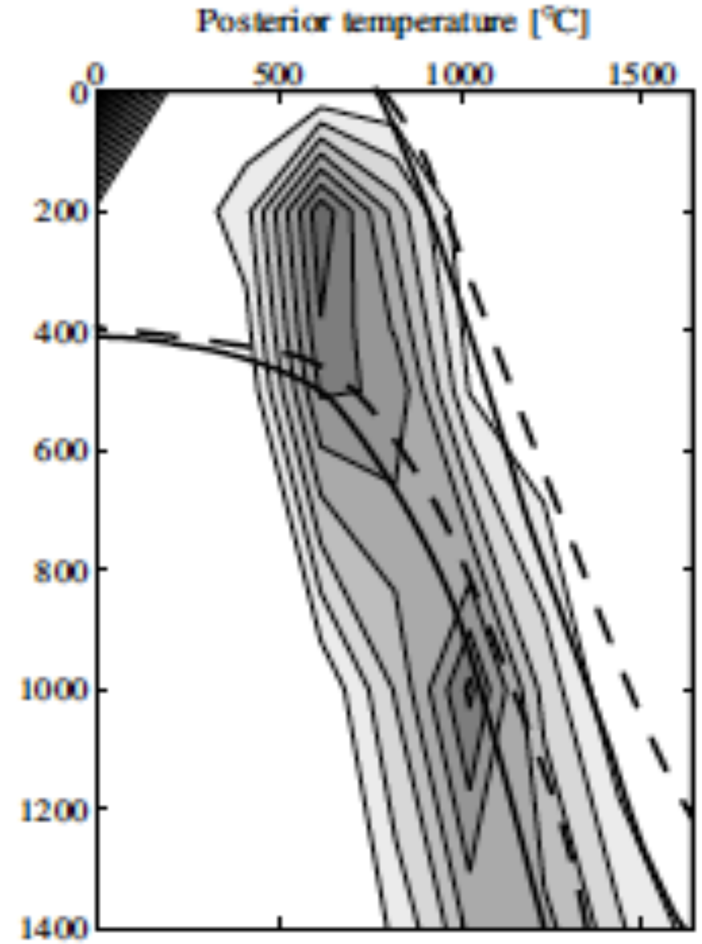


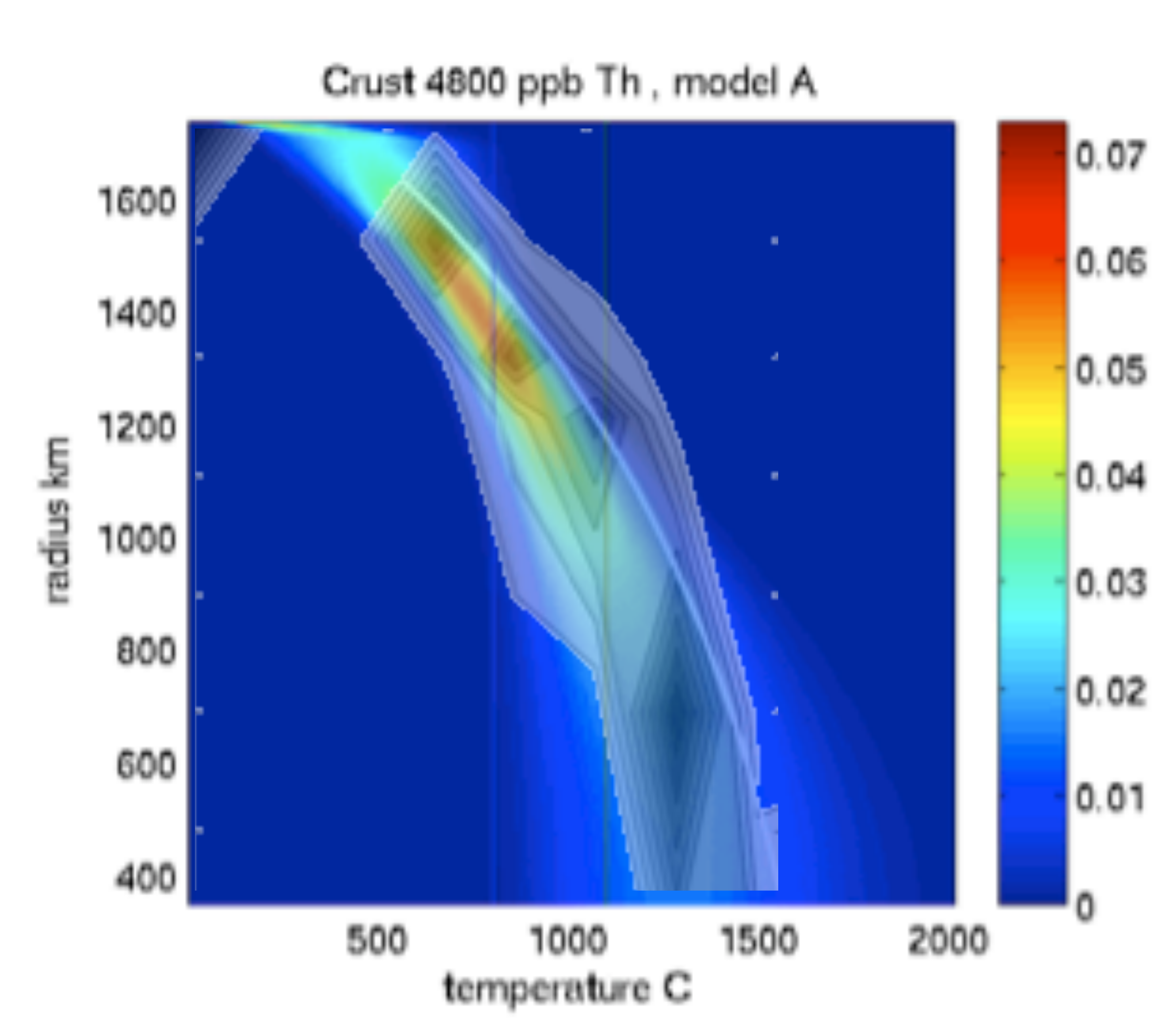
Khan et al, 2006
(direct inversion
of seismic data)

Khan et al, 2007
(direct inversion
of magnetic data)

Other temperatures







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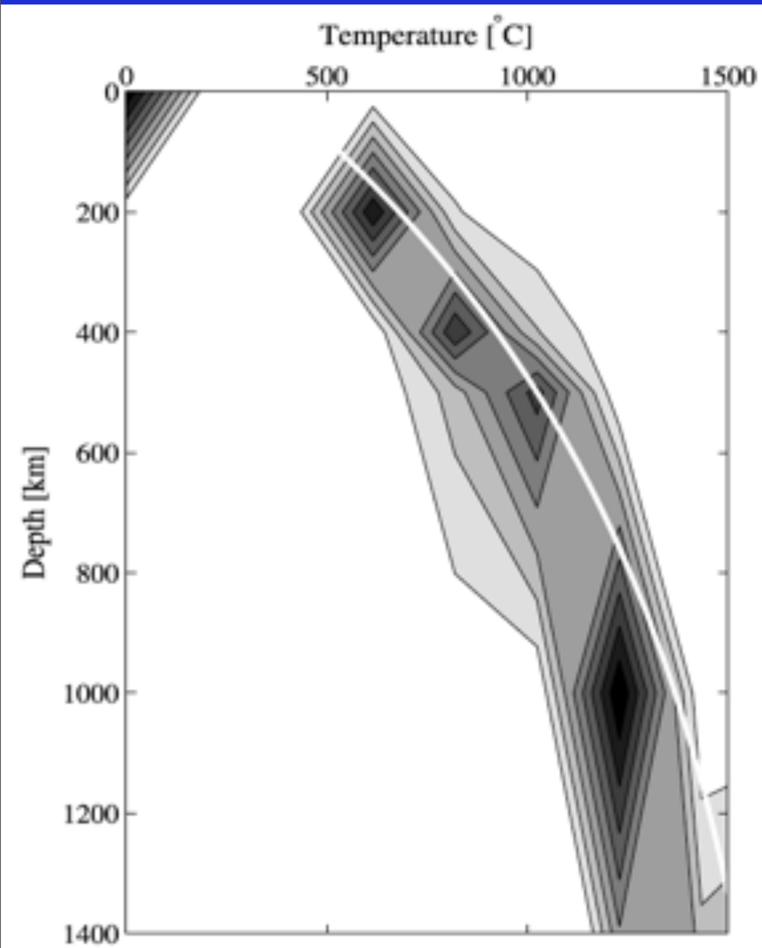
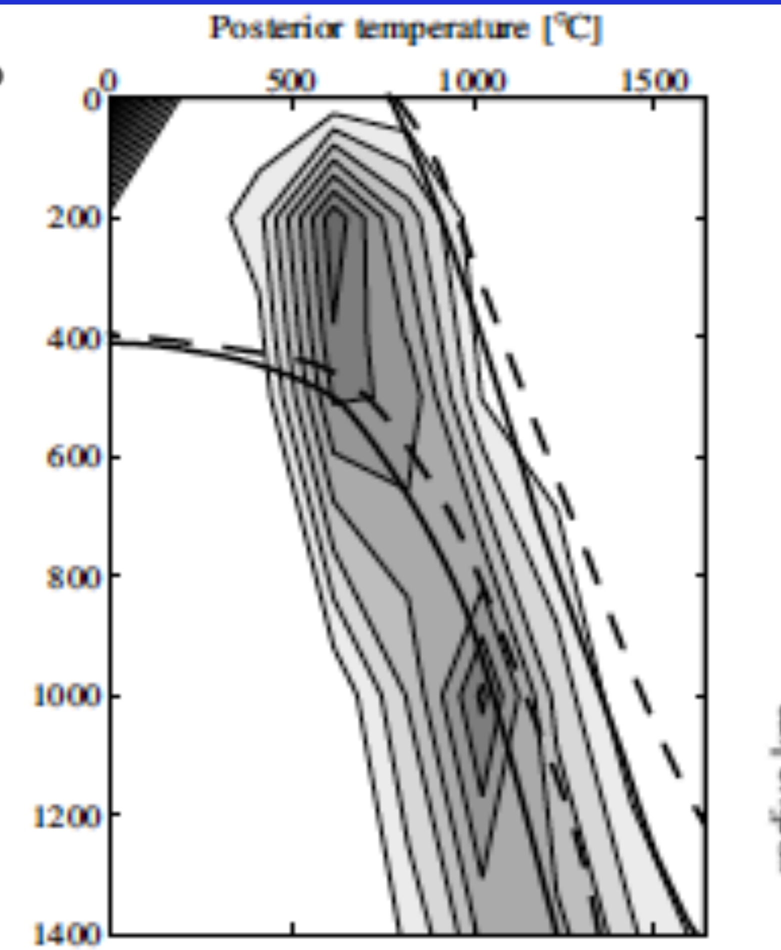
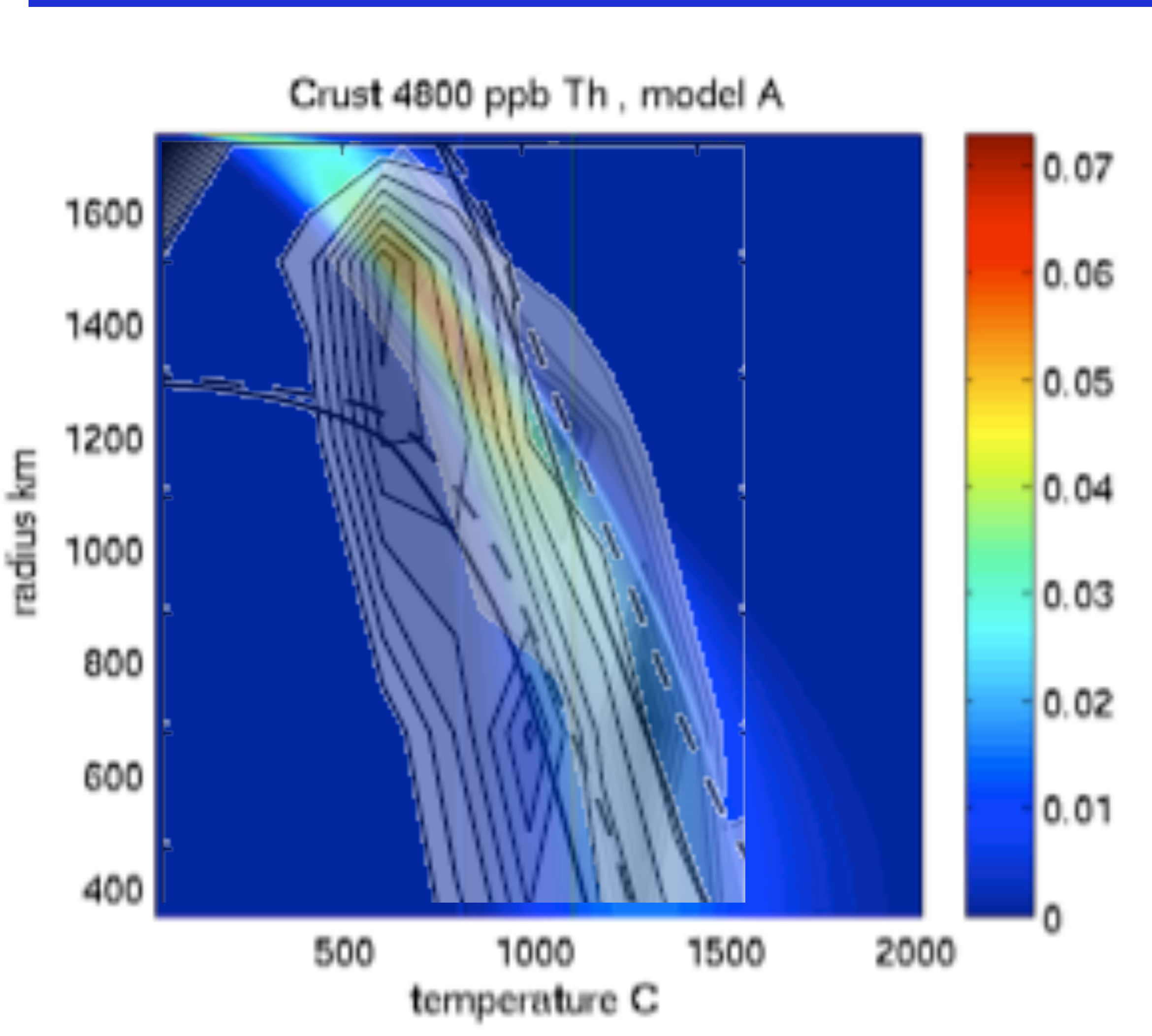
Other temperatures



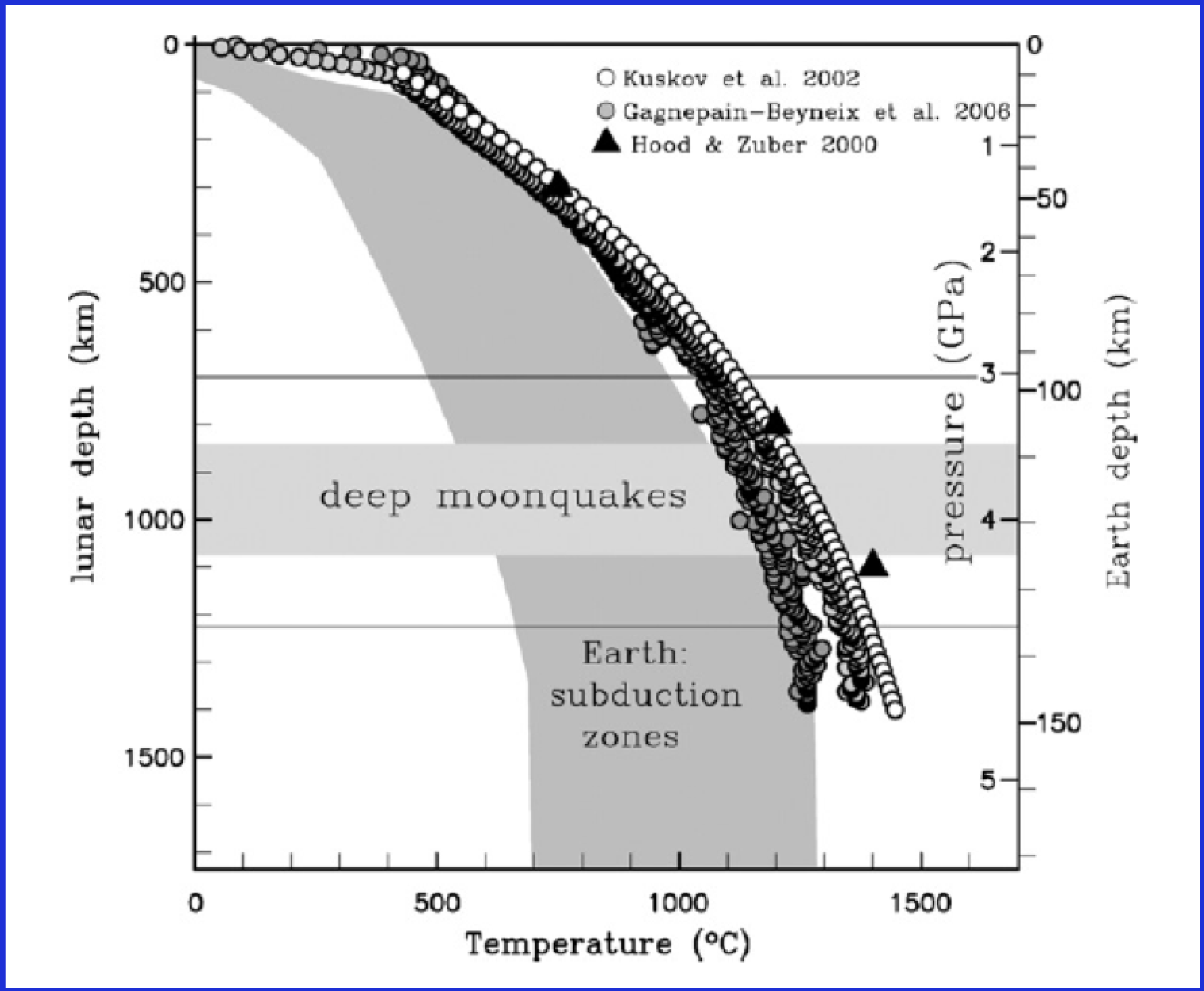


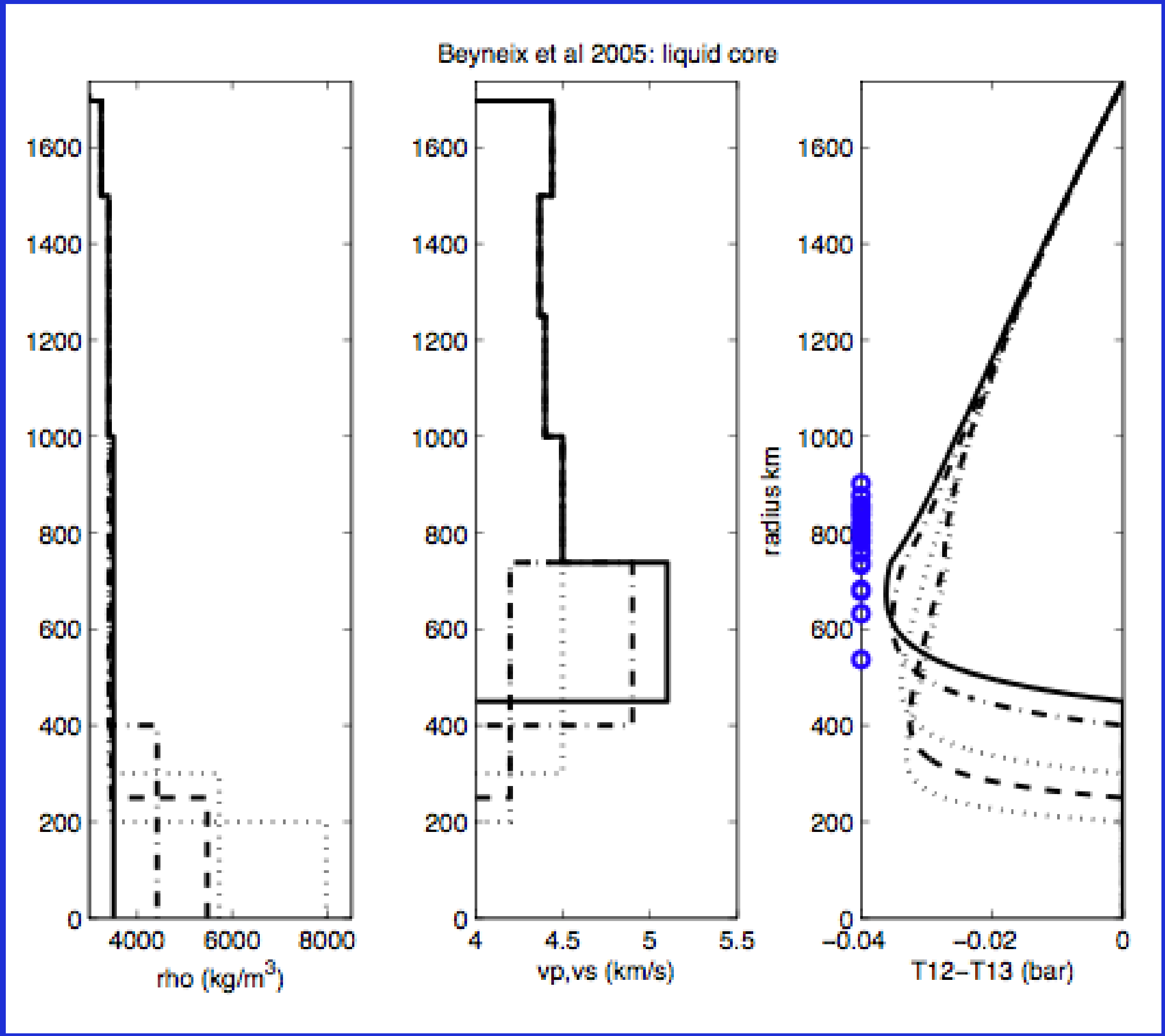


Khan et al, 2006
(direct inversion
of seismic data)

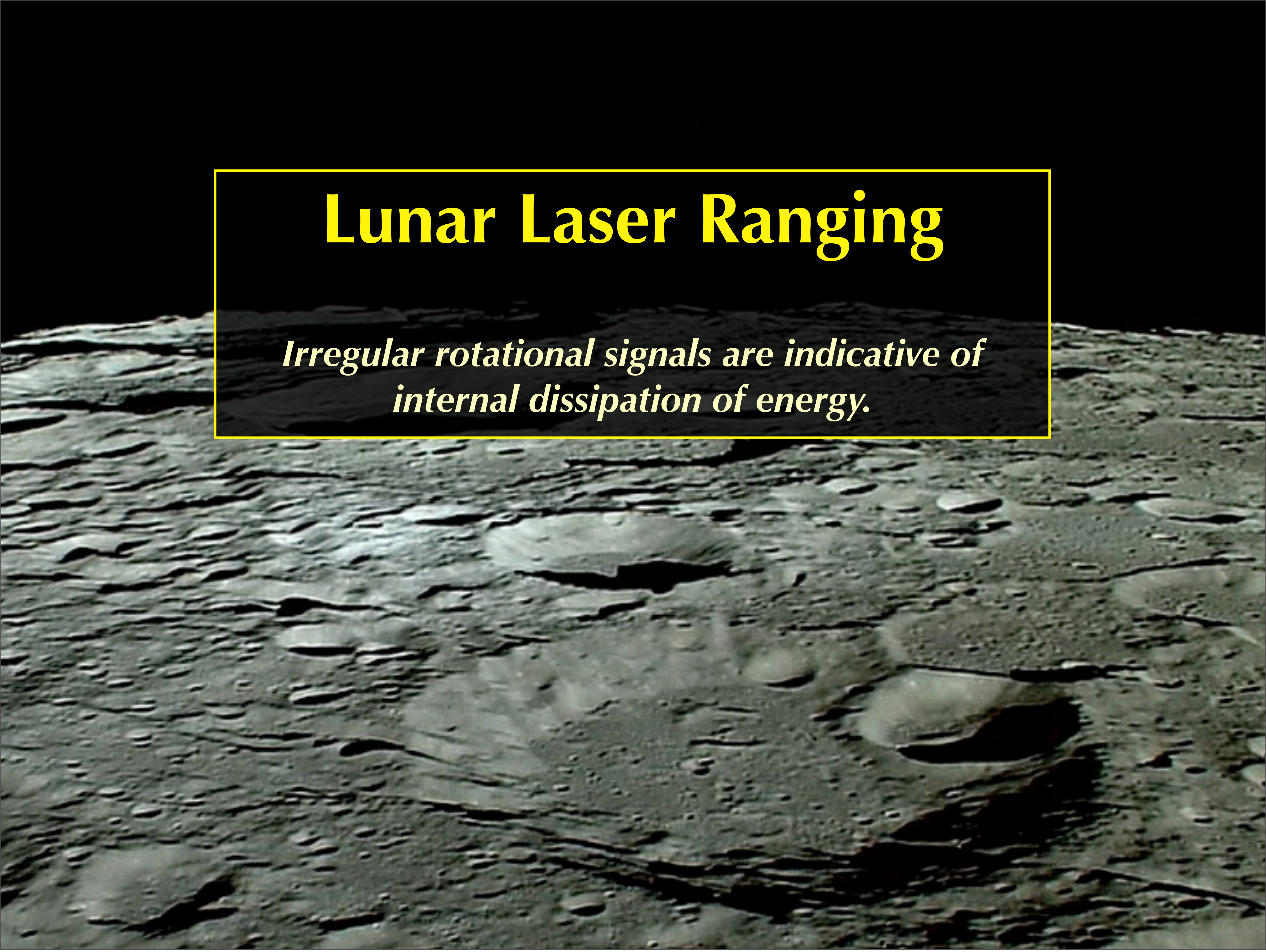
Khan et al, 2007
(direct inversion
of magnetic data)

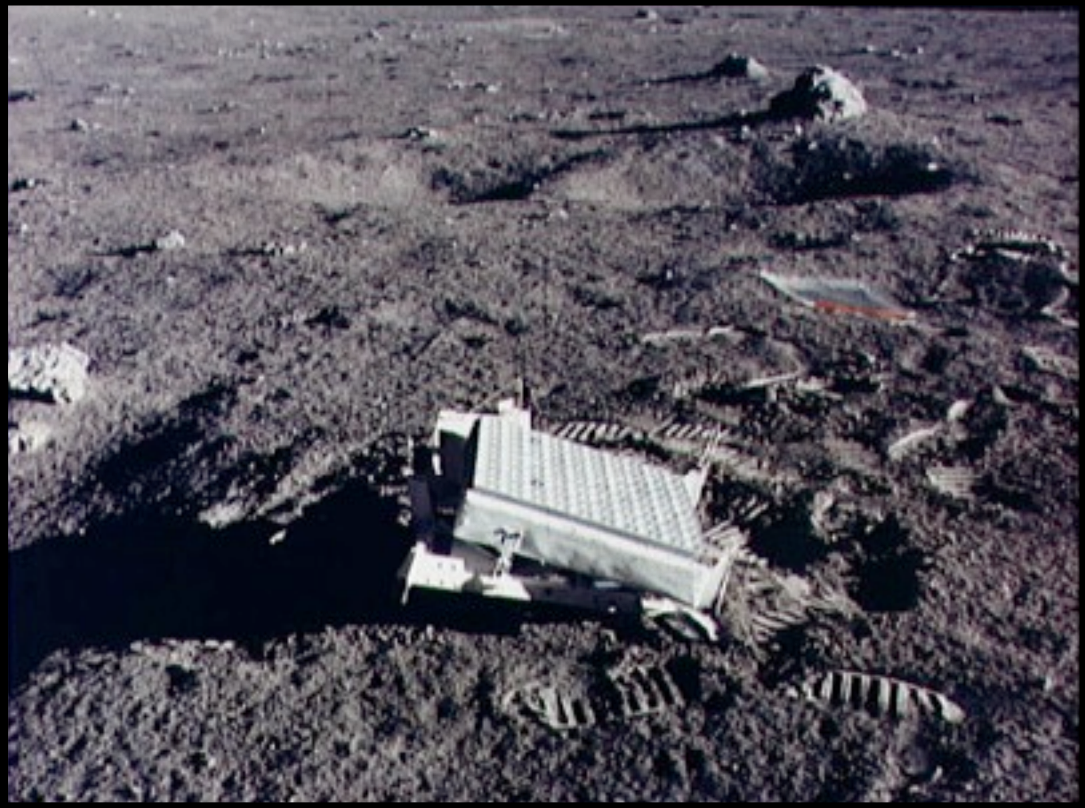
Tidal stresses and core size



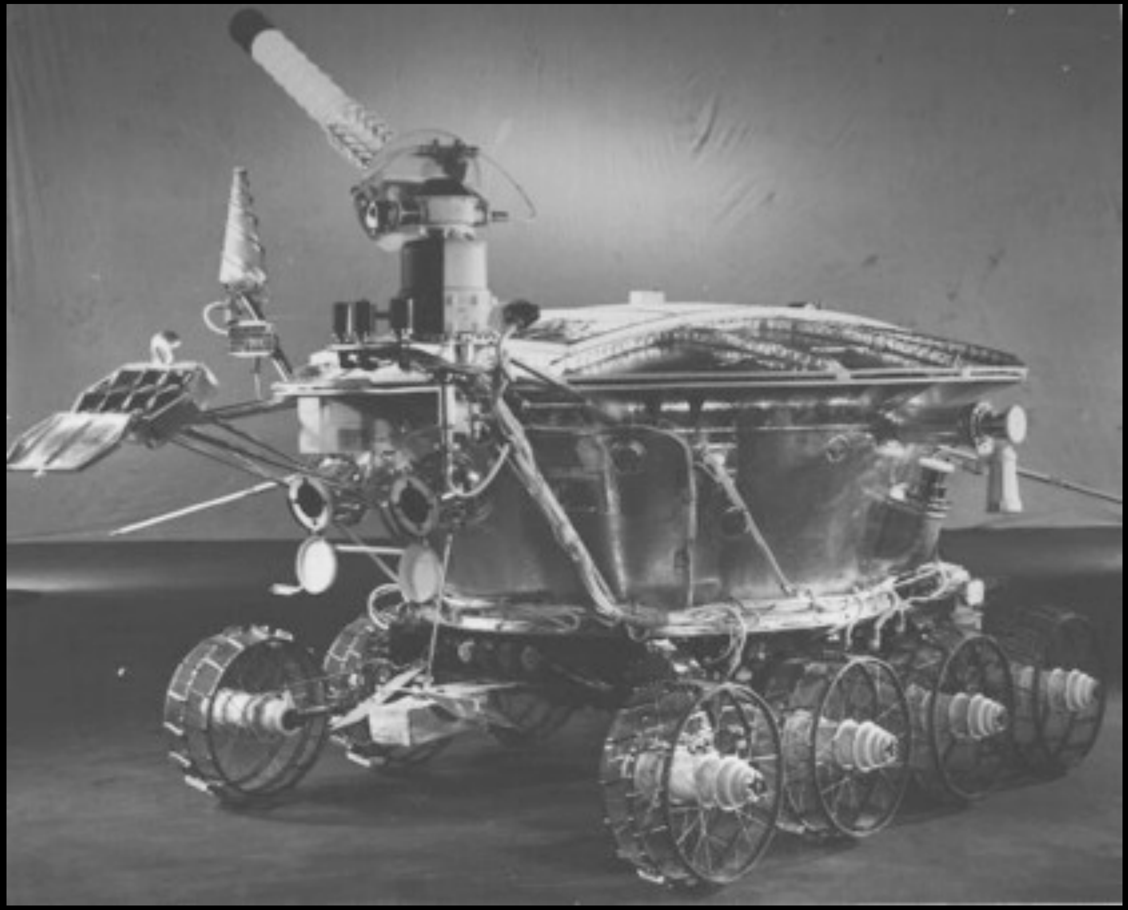


- Focal mechanism of the deep moonquakes remains to be better known but liquid core provide maximum stress at the deep moonquake depth
- Large core need a high (and maybe too high) Vs velocity in the lower mantle to match with the k_2 value
- Temperature are above the maximum temperature of subduction zone but in a possible dryer mantle than subduction zone or Earth upper mantle (Qs ~300 on the deep Moon, Qs~150 on Earth)


Lunar Laser Ranging
Irregular rotational signals are indicative of internal dissipation of energy.



Lunar Laser Ranging can determine the Earth-Moon distance to an accuracy of ~2 cm.



By using ranges to several stations, it is possible to reconstruct the orientation of the Moon.

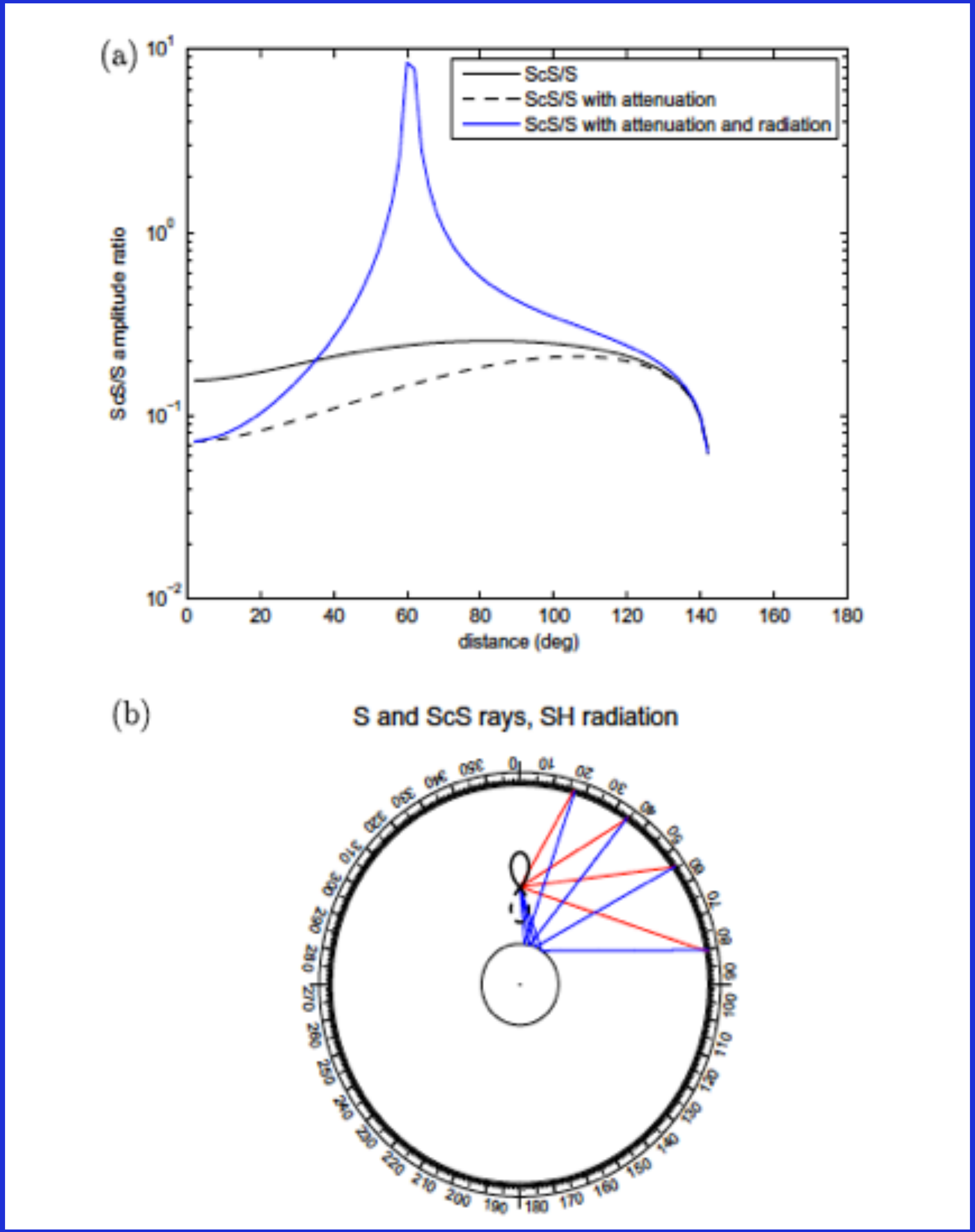
Rotational signals

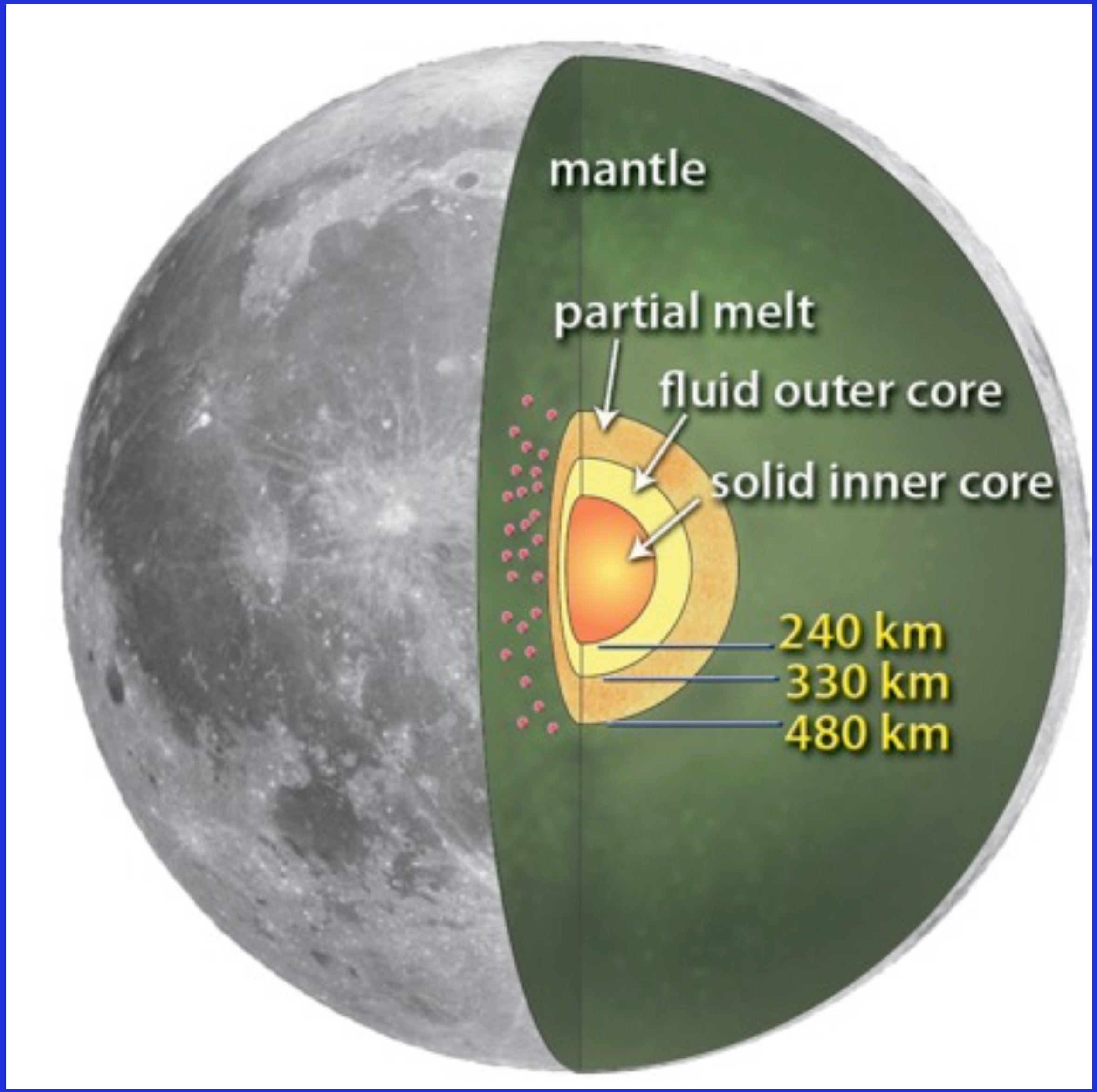
<u>Optical librations</u> are caused by the Moon's eccentric and inclined orbit.

<u>Physical librations</u> are caused by torques on the solid body of the Moon by Earth's gravity field. Velocity differences at the core-mantle boundary, as well as dissipation within the solid body, give rise to a distinctive rotational signatures.

The Moon possesses a molten core. Dissipation of energy is also occurring deep in the solid portion of the lunar mantle (Q=37-60). Is the deep mantle partially molten?

Core Seismic Phases





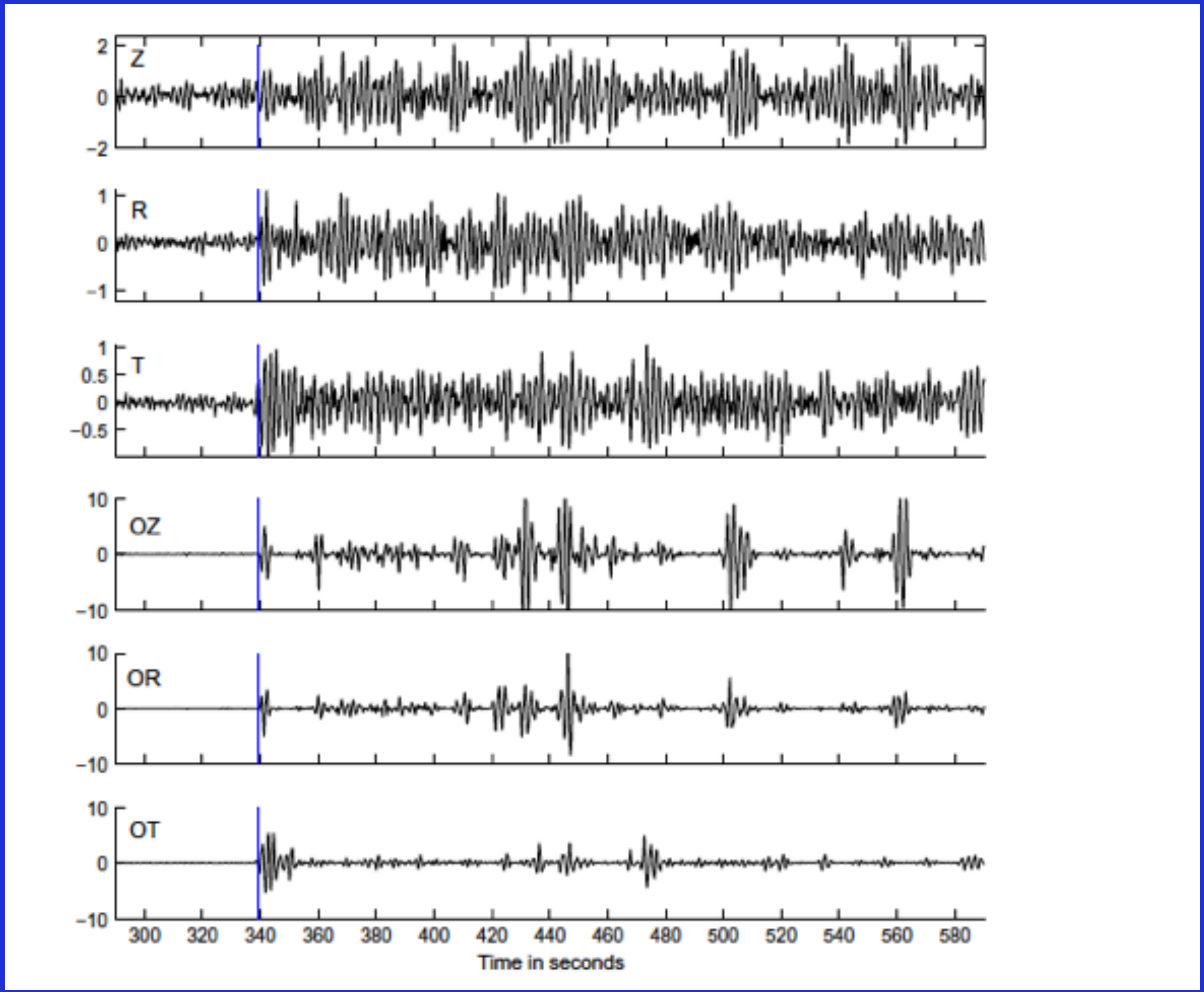
Weber et al, 2011

Garcia et al, 2011

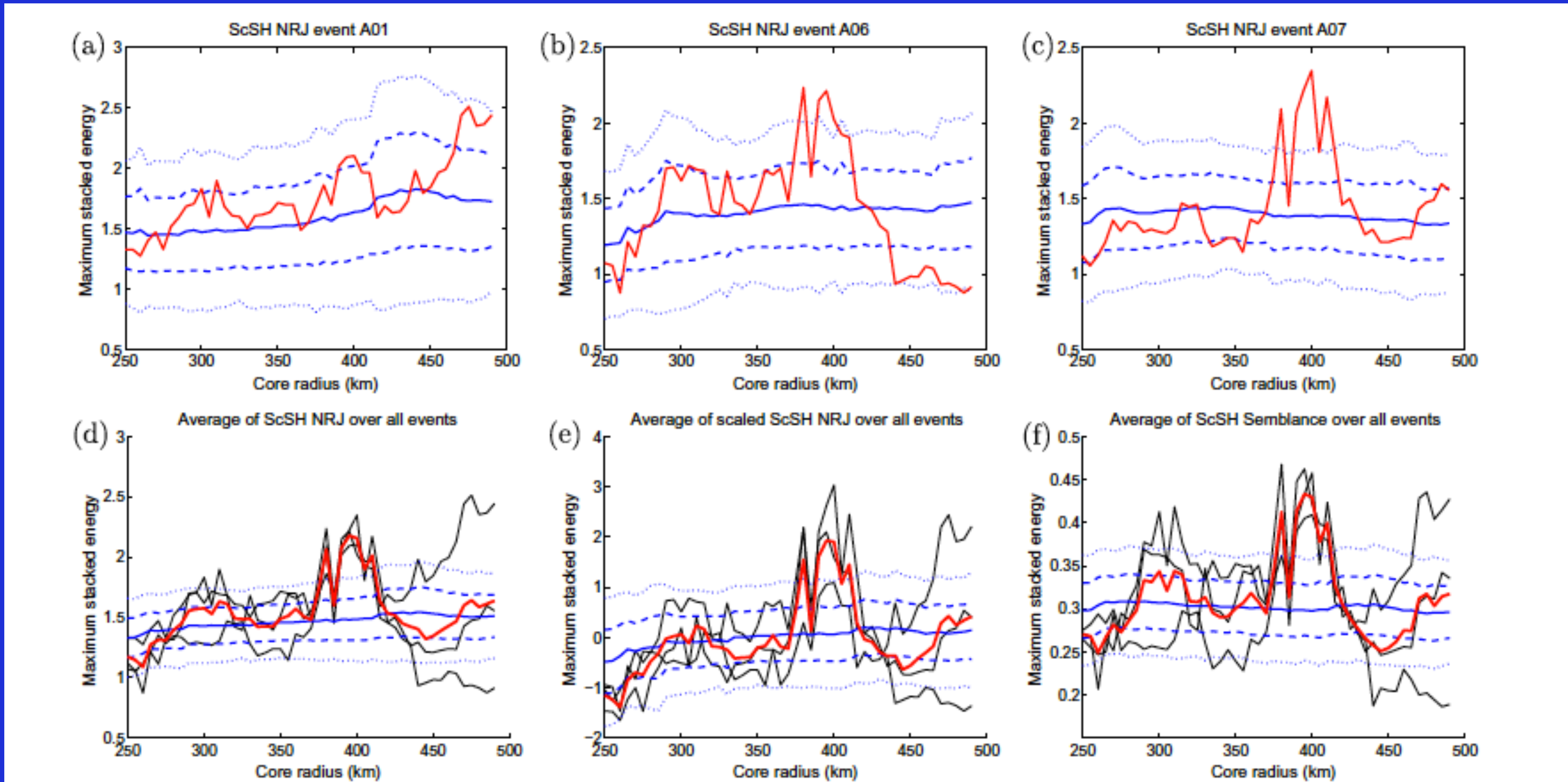
2012年7月9日月曜日

Methodology

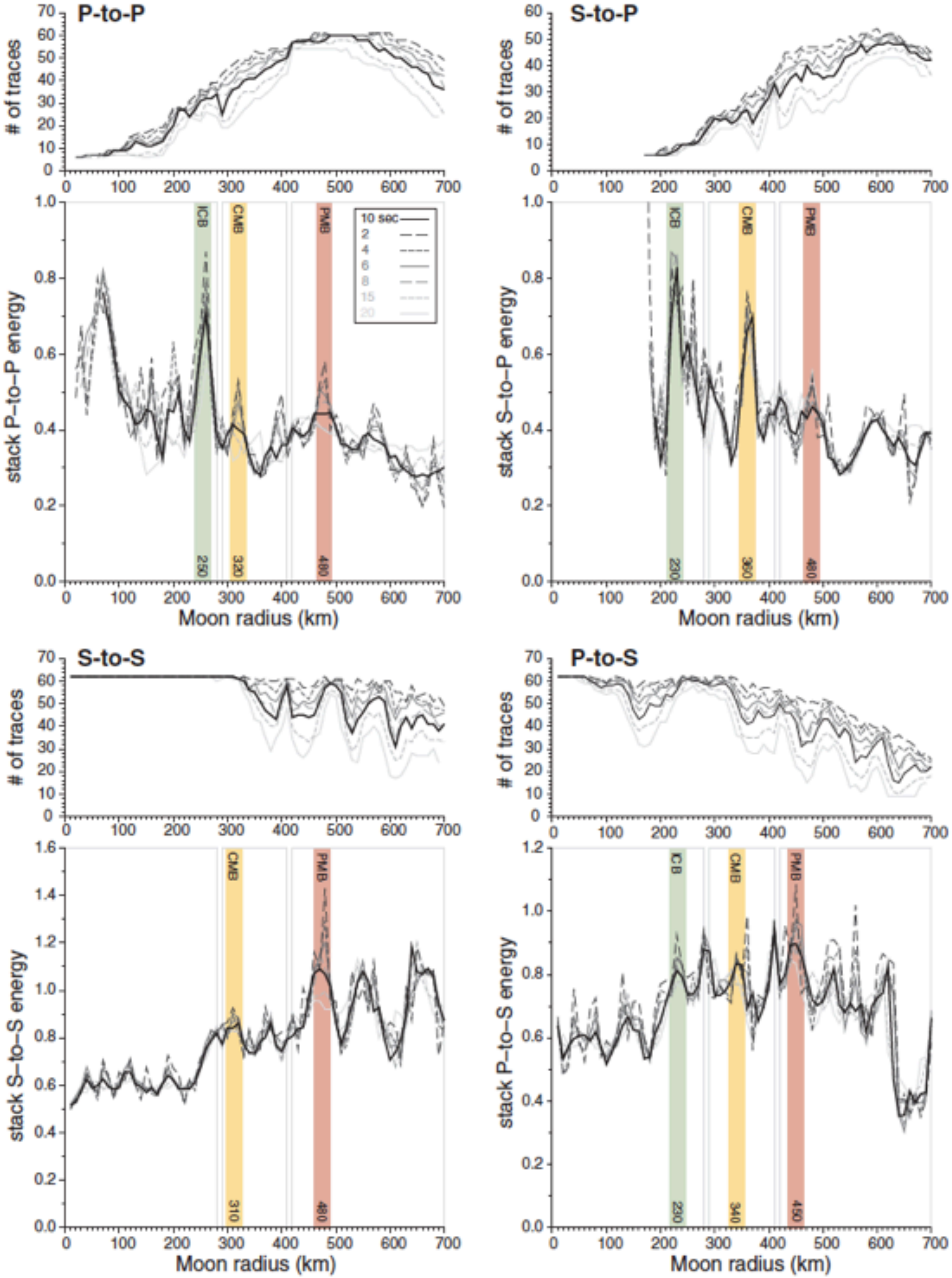
- Core phases are weak signals
  - DMQ stacking + All stations stacks
  - Use of Polarisation filters + Stations corrections

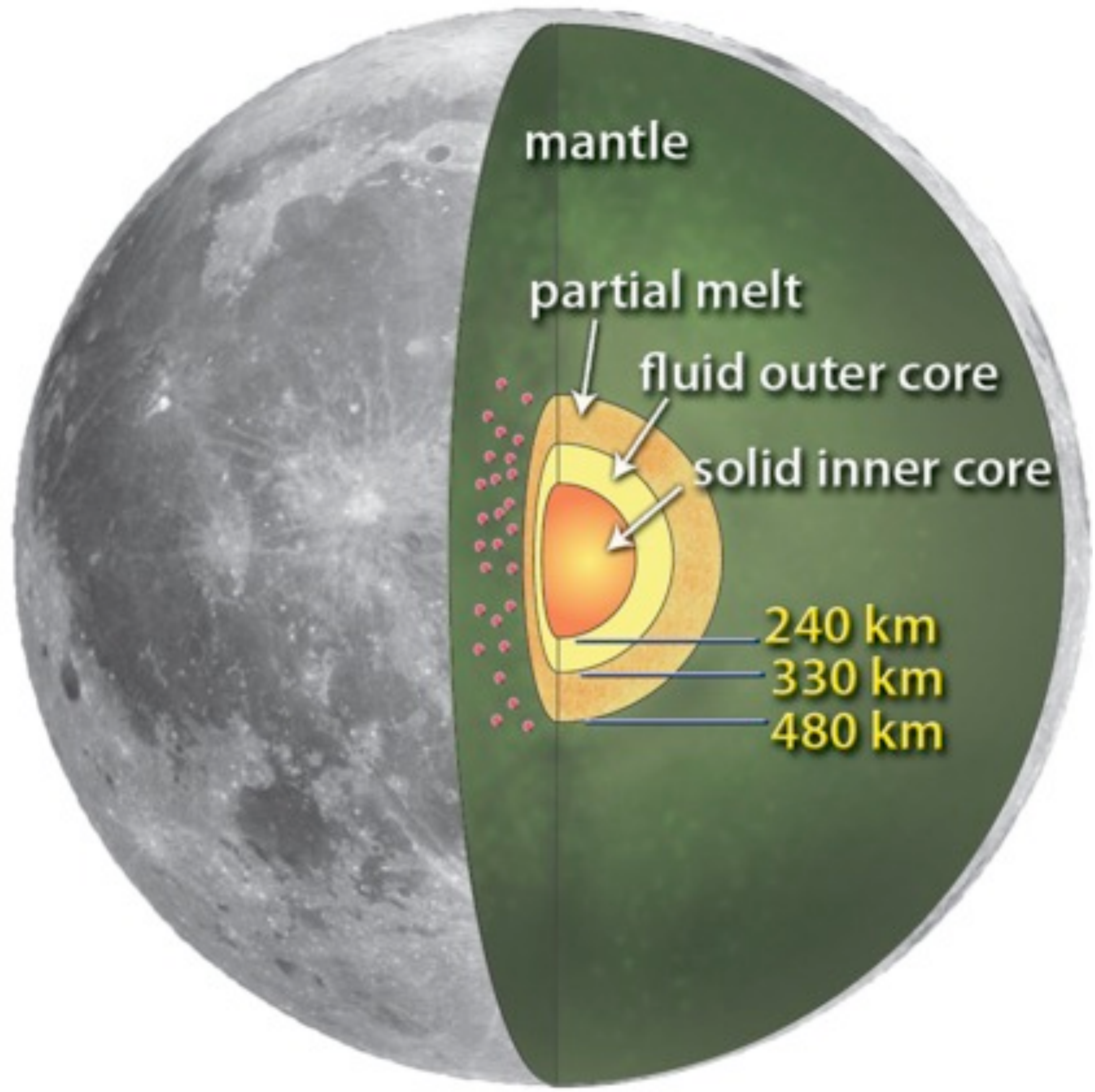


Results



- Clear identification of reflected energy from a 350-400 km radius reflctor





Weber et al. 2011

Deep interior and state of core

- Upper structure is constrained by seismic data
- Invert only for the structure not resolved by seismic data

Garcia et al 2011:

380 km ± 40 km

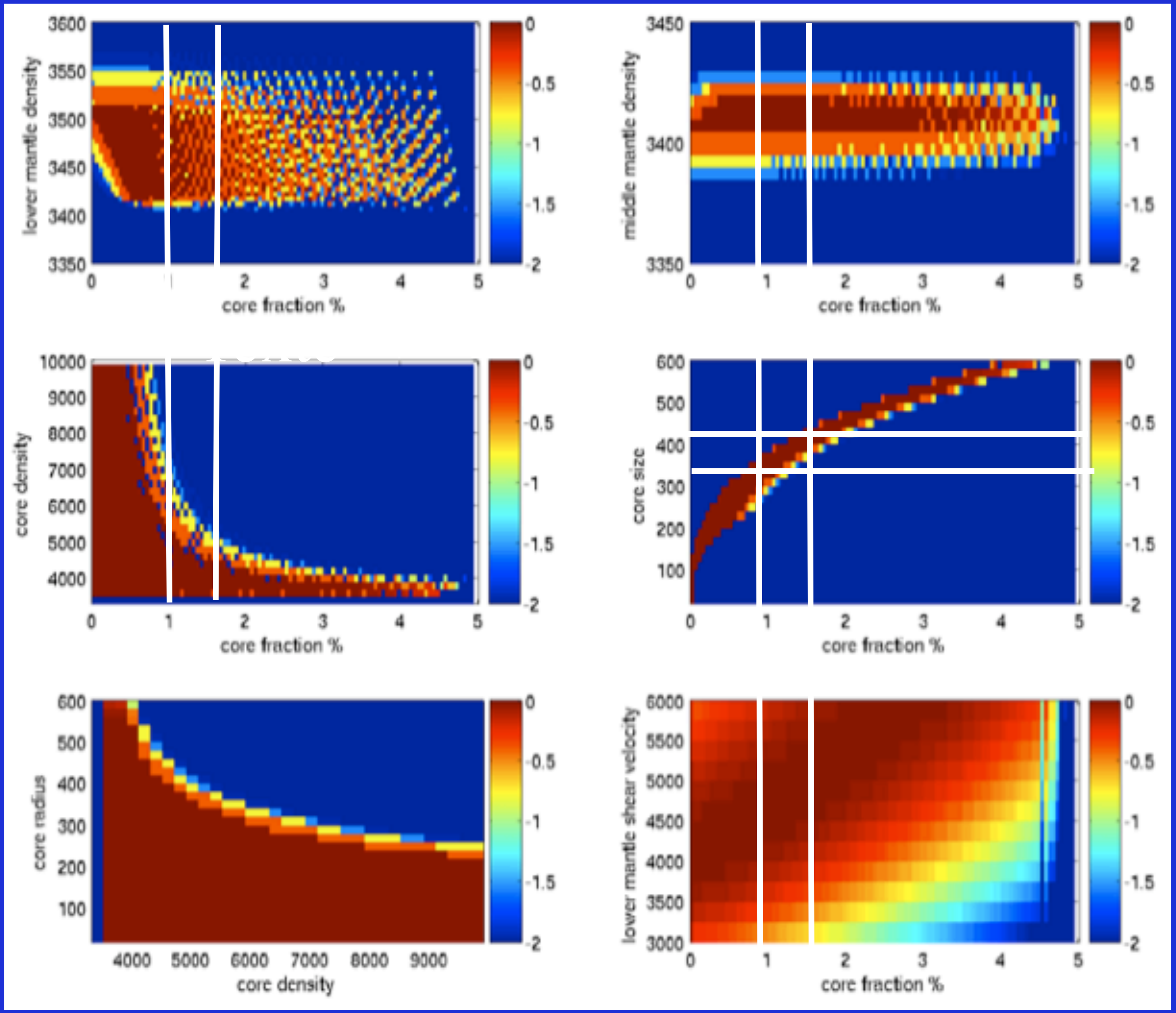
5200±1000 kg/m³

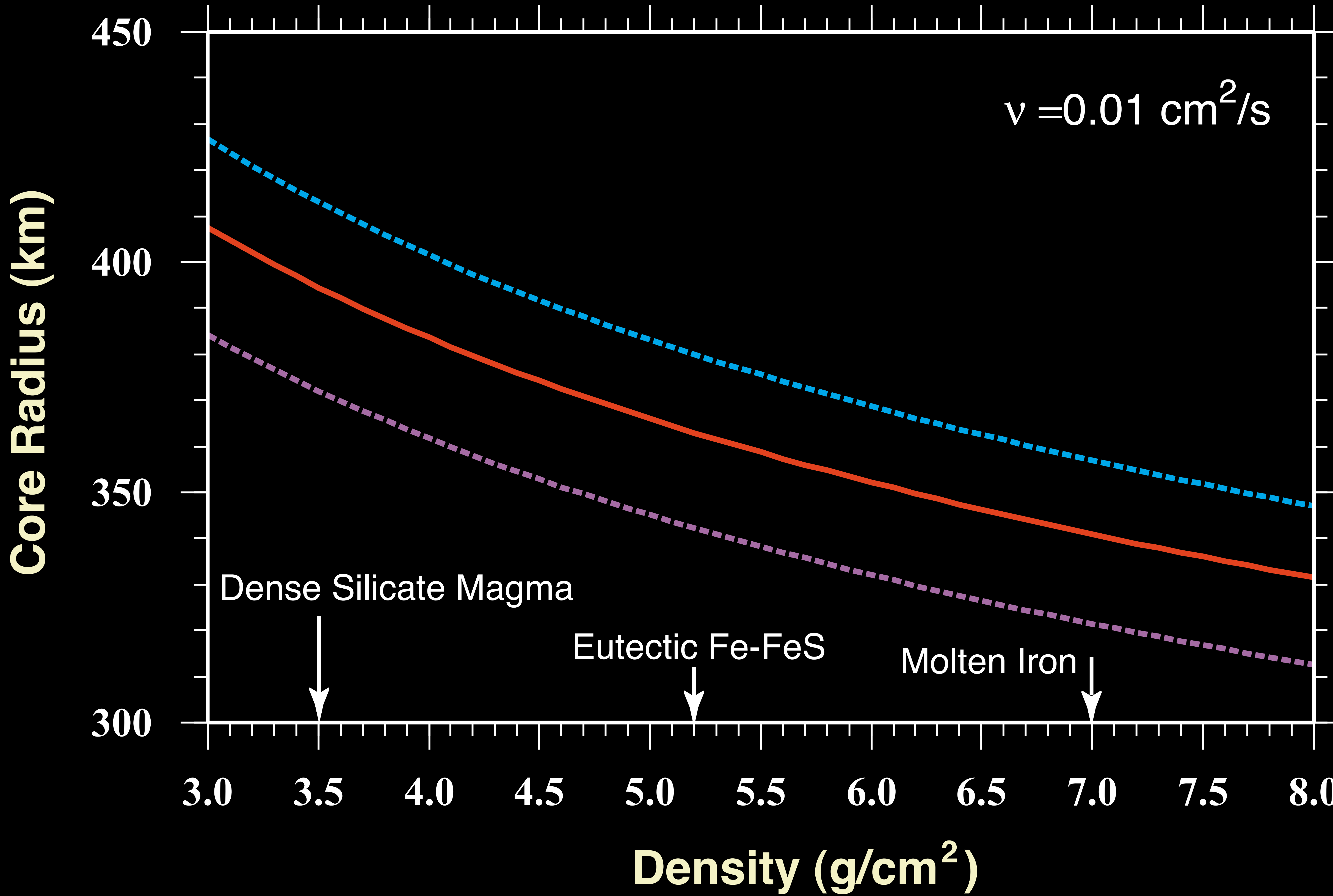
Weber et al 2011:

330 km ± 20 km

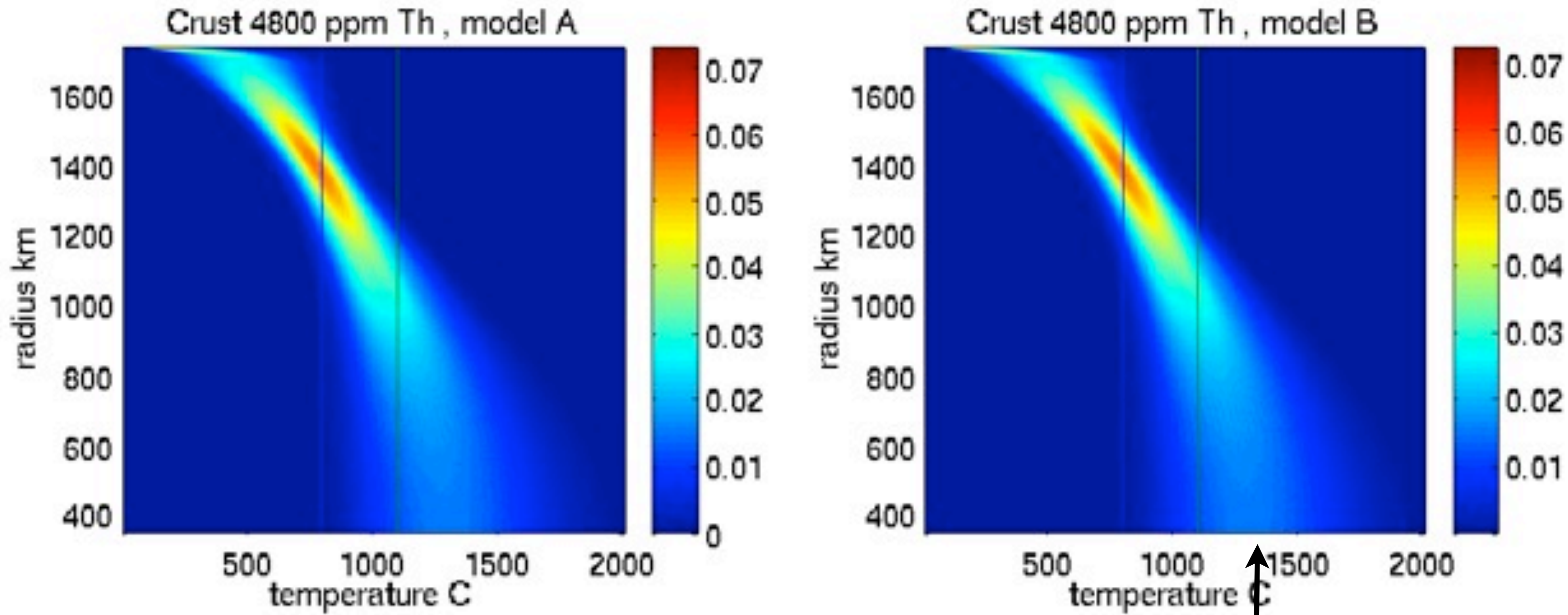
6200±1000 kg/m³

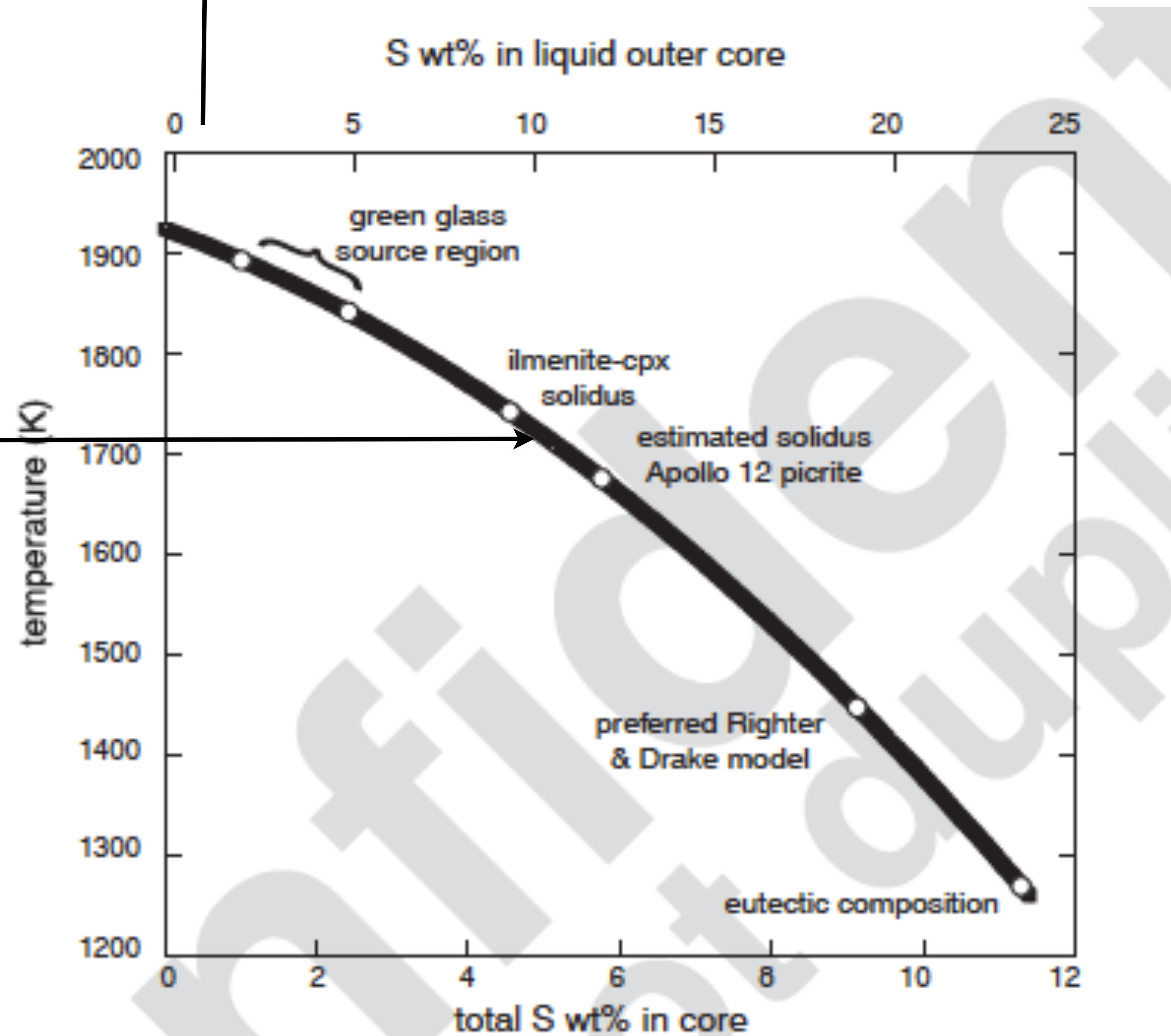
Crust 40 km (Beyneix et al., 2005)





ν =0.01 cm²/s
Core Radius (km)
450
400
350
300
Dense Silicate Magma
Eutectic Fe-FeS
Molten Iron
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
Density (g/cm²)

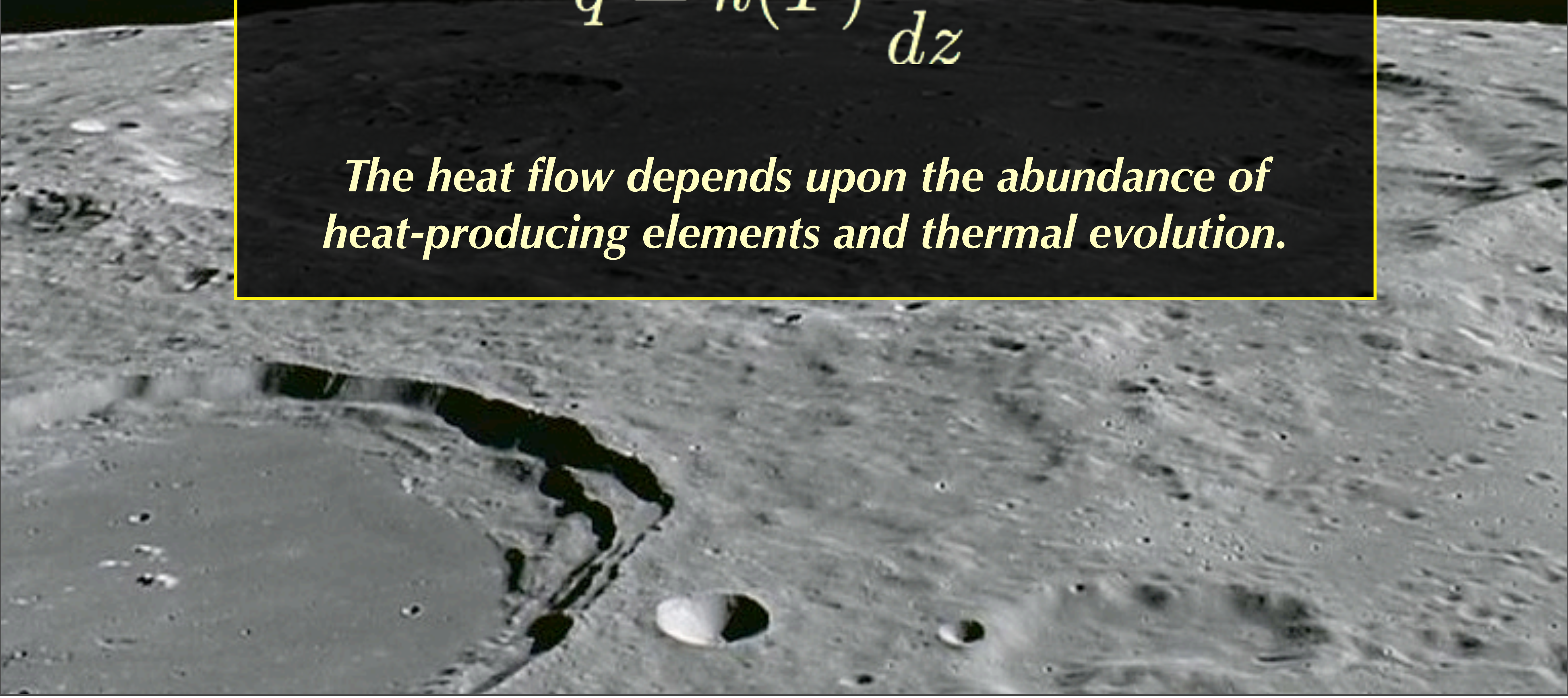

Crust 4800 ppm Th , model A
radius km
temperature C
Crust 4800 ppm Th , model B
radius km
temperature C


S wt% in liquid outer core
temperature (K)
total S wt% in core
green glass
source region
ilmenite-cpx
solidus
estimated solidus
Apollo 12 picrite
preferred Righter
& Drake model
eutectic composition

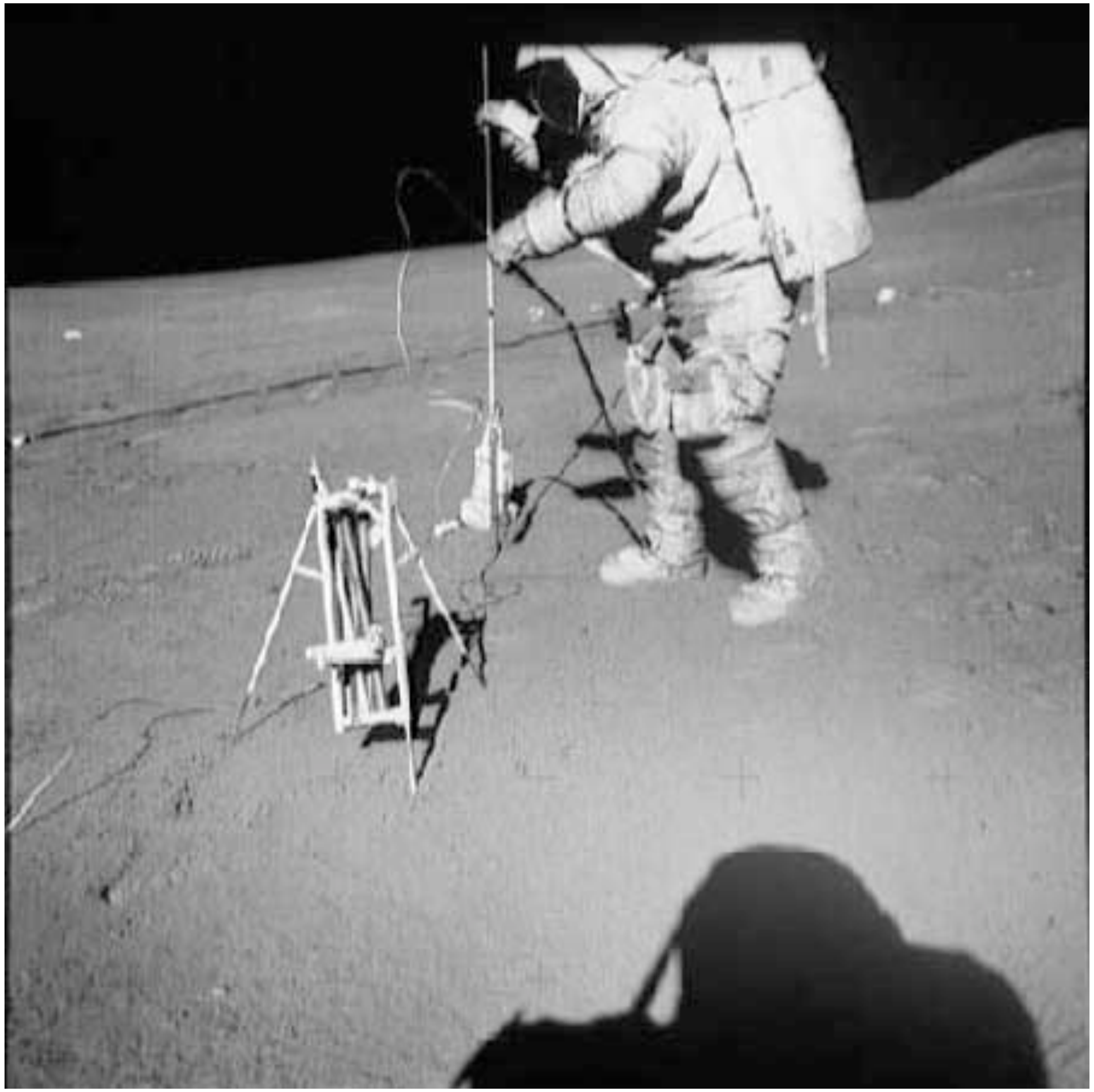
Heat Flow

$$q = k(T)\frac{dT}{dz}$$

The heat flow depends upon the abundance of heat-producing elements and thermal evolution.

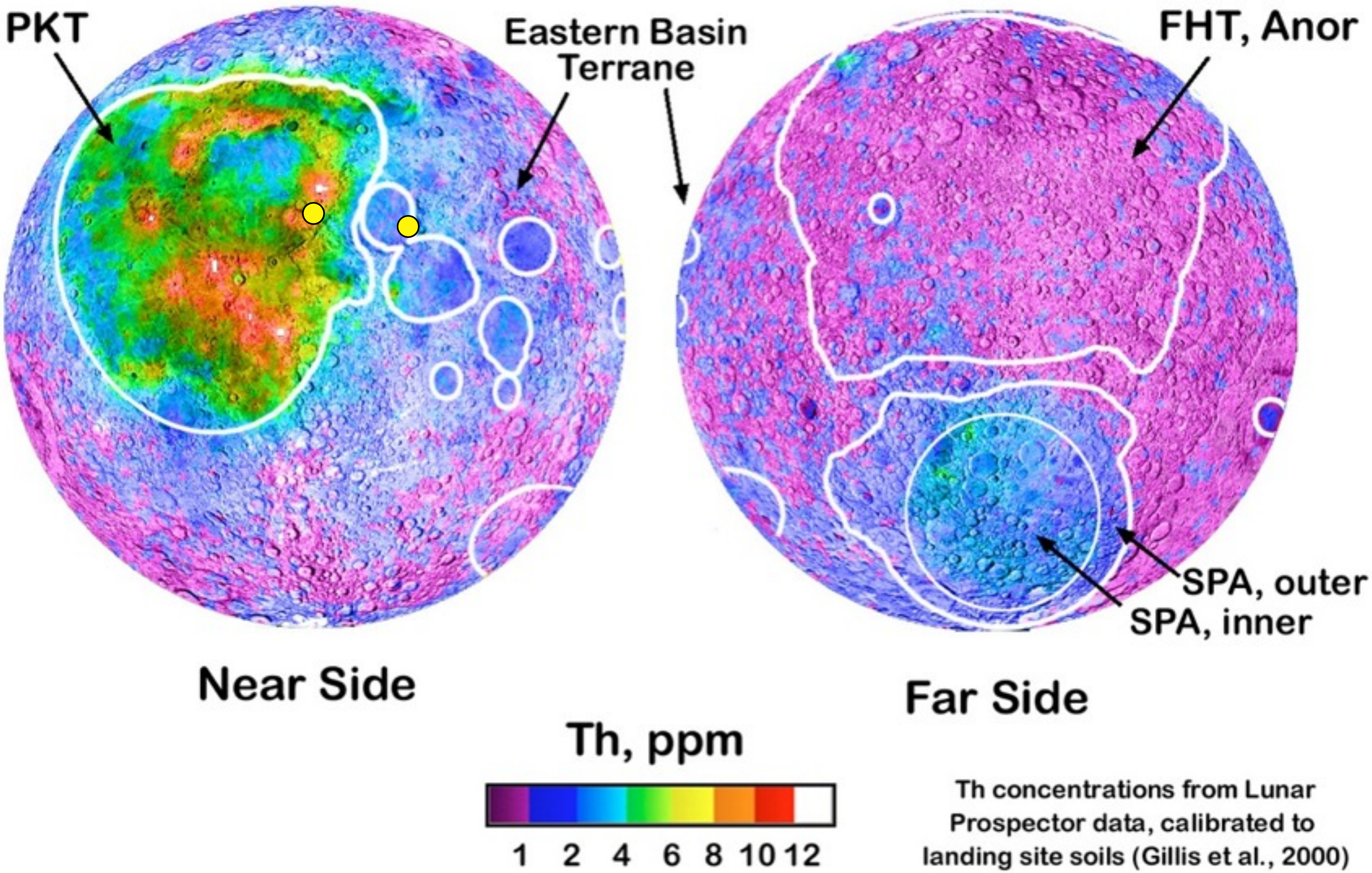


The heat flow was measured at two locations on the Moon: Apollo 15 and 17



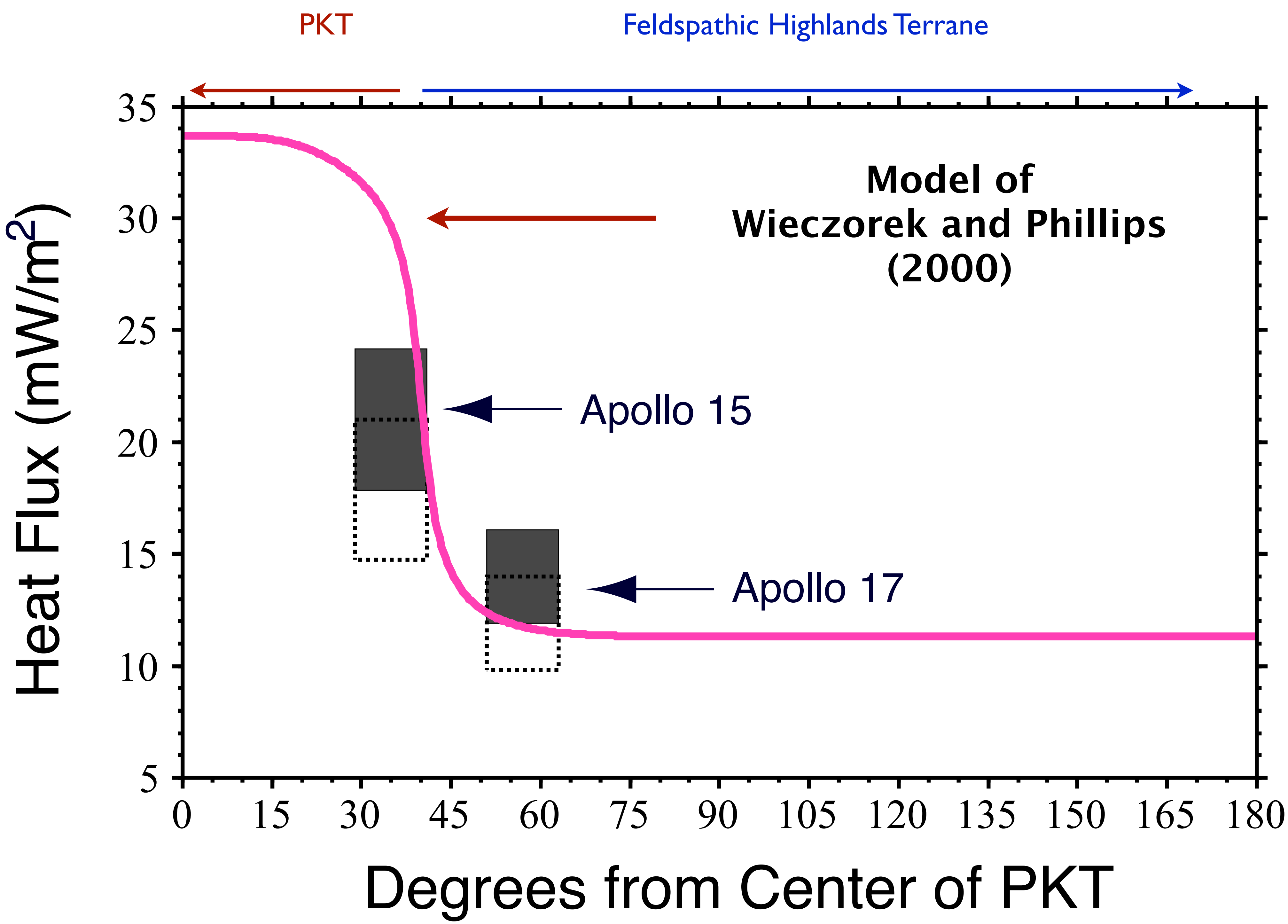
Final emplacement of the Apollo 15 heat flow probe

Geologic context of the heat flow measurements



Heat-producing elements are highly concentrated in a small near-side crustal province where the majority of mare basalts erupted.

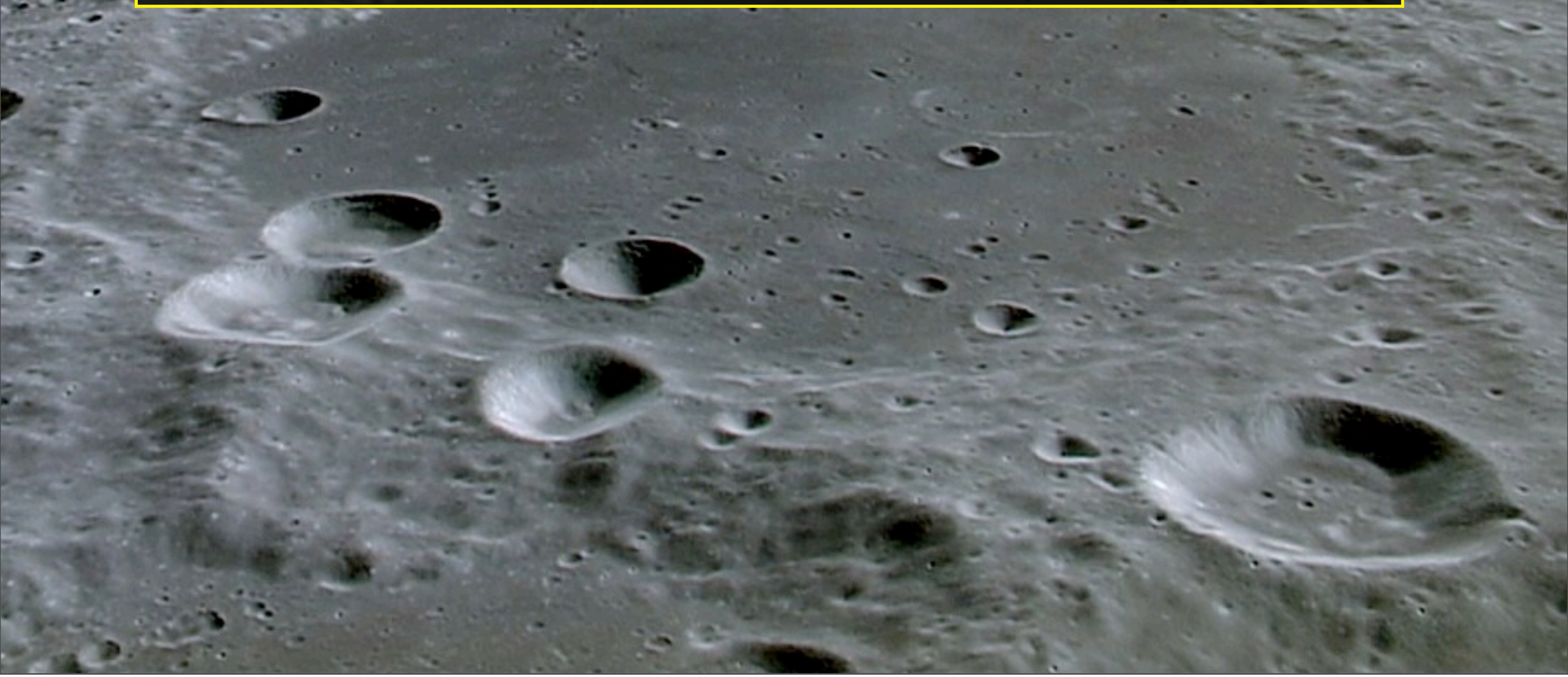
The measurements....



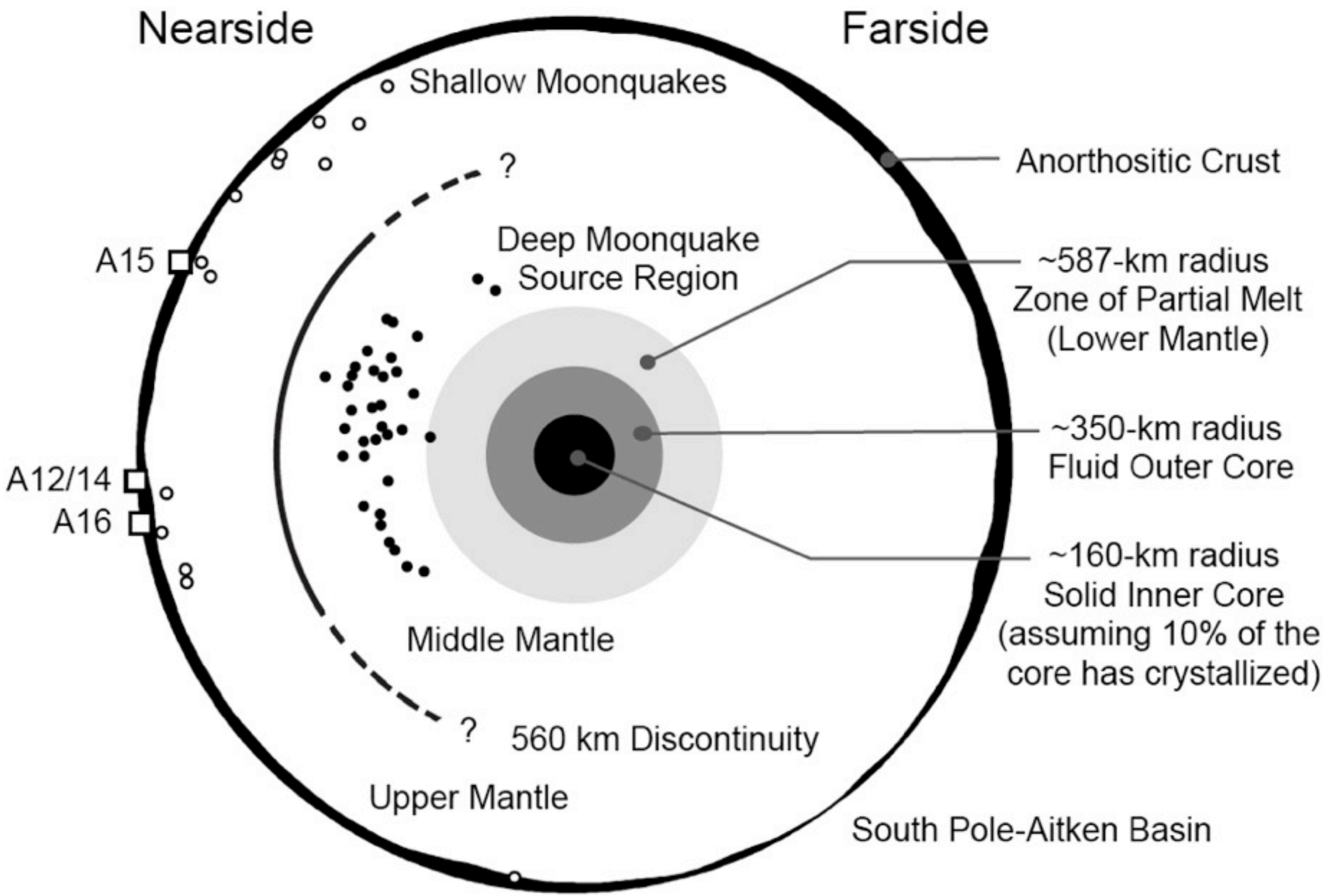
The heat flow is predicted to be about 3 times higher in the center of the Procellarum KREEP Terrane than in the Feldspathic Highlands Terrane.

Conclusions

What do we know?
And what is the future of lunar geophysics?



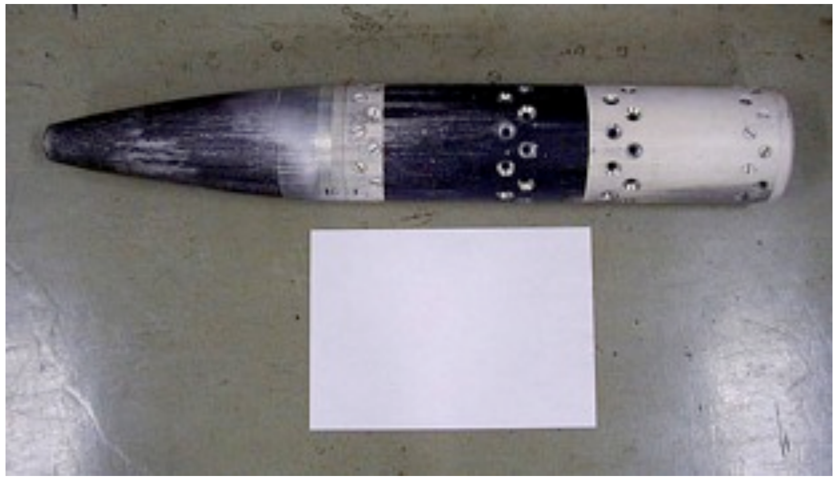
Our best guess



Wieczorek et al. (2006)

We need more data!

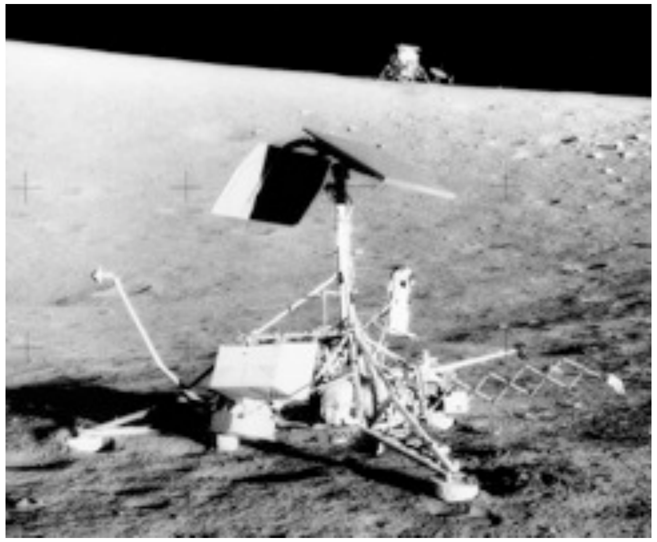
Several future seismic missions are being investigated.



Penetrators
(Japan, UK)

We need global coverage!
10+ stations on both the near- and far-side hemispheres.

Landers
(Japan,Europe, China, US)



Human
(US)

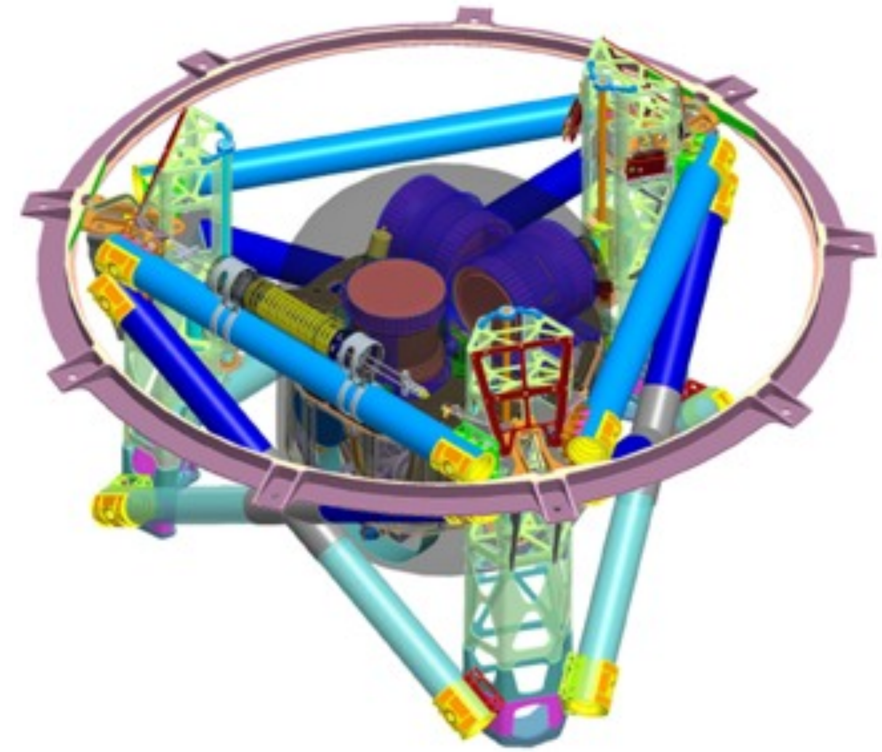
The activity of deep moonquake nests is correlated with the tides (27 days, 6 years, 9 years, and 18.6 years). We need long time spans of data!


Lunar near
Future

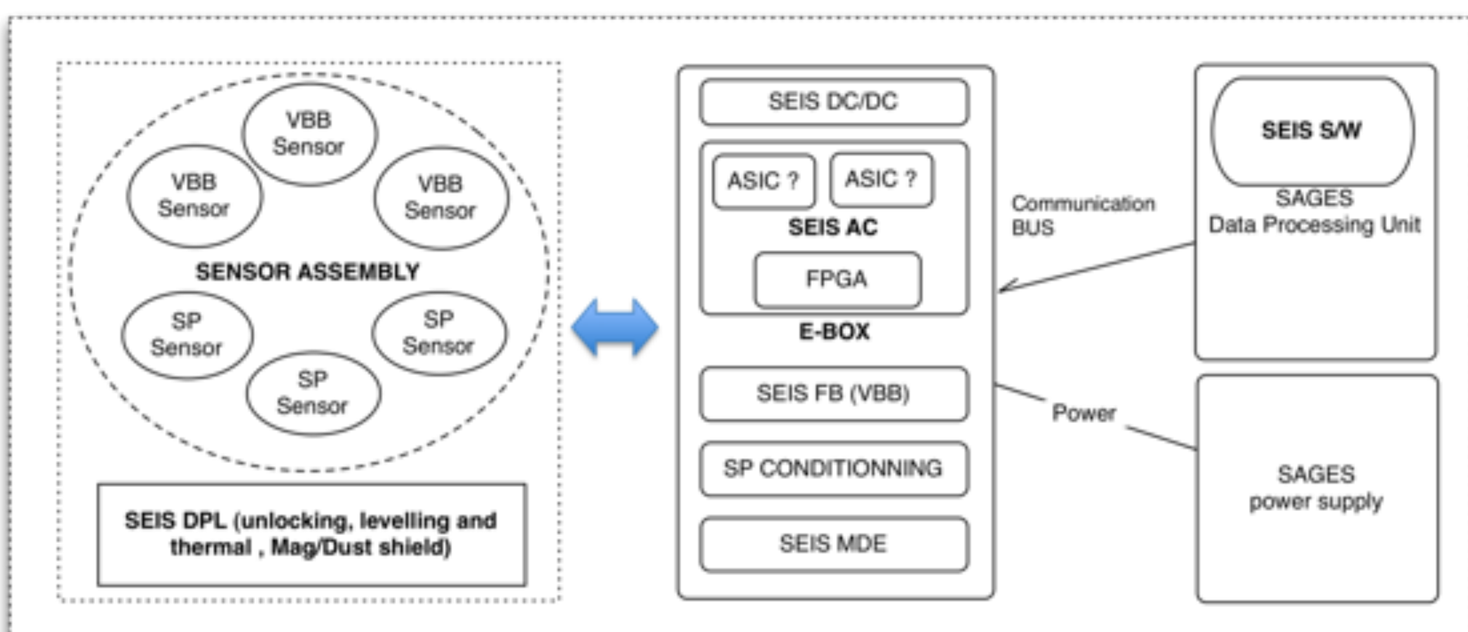
SELENE2

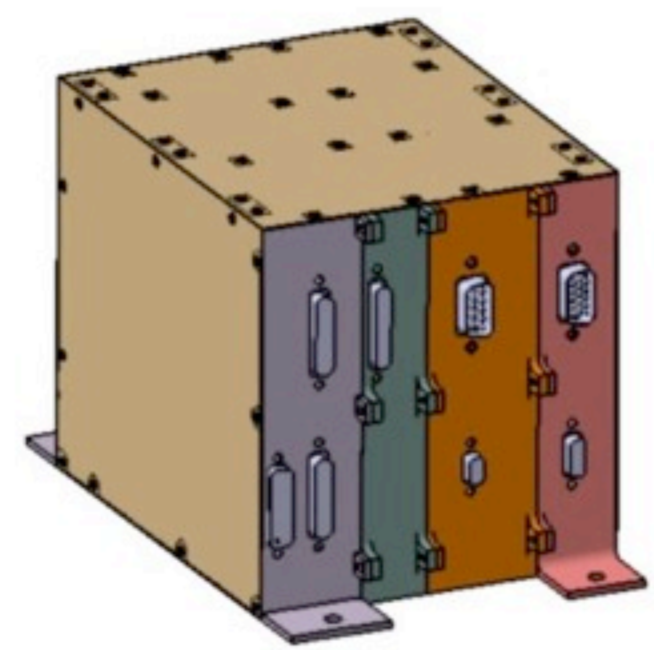
Lunar SELENE2 seismometer

- The Seismometer Experiment is composed of :
  - Three Short period seismometers (ISAS,J, N.Kobayashi)
  - Three Very Broad Band seismic sensors (IPGP/CNES, F)
  - An installation and leveling system (MPS, D)
  - An acquisition electronics (ETHZ, CH)



- The seismometer shall be serviced by a survival module
  - Provides power, data storage, communication with Earth
  - Maintain the seismometer in an adequate thermal range



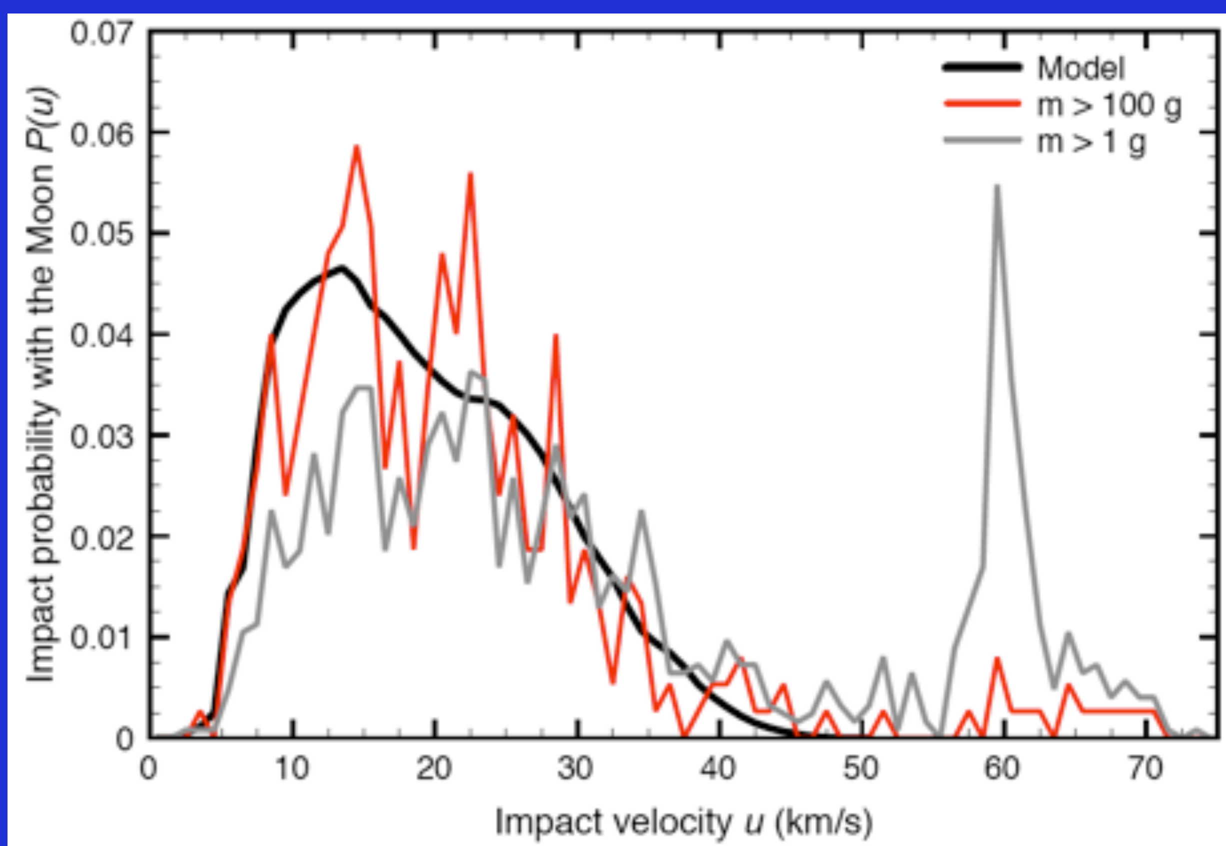


Lunar seismic Seismic Noise

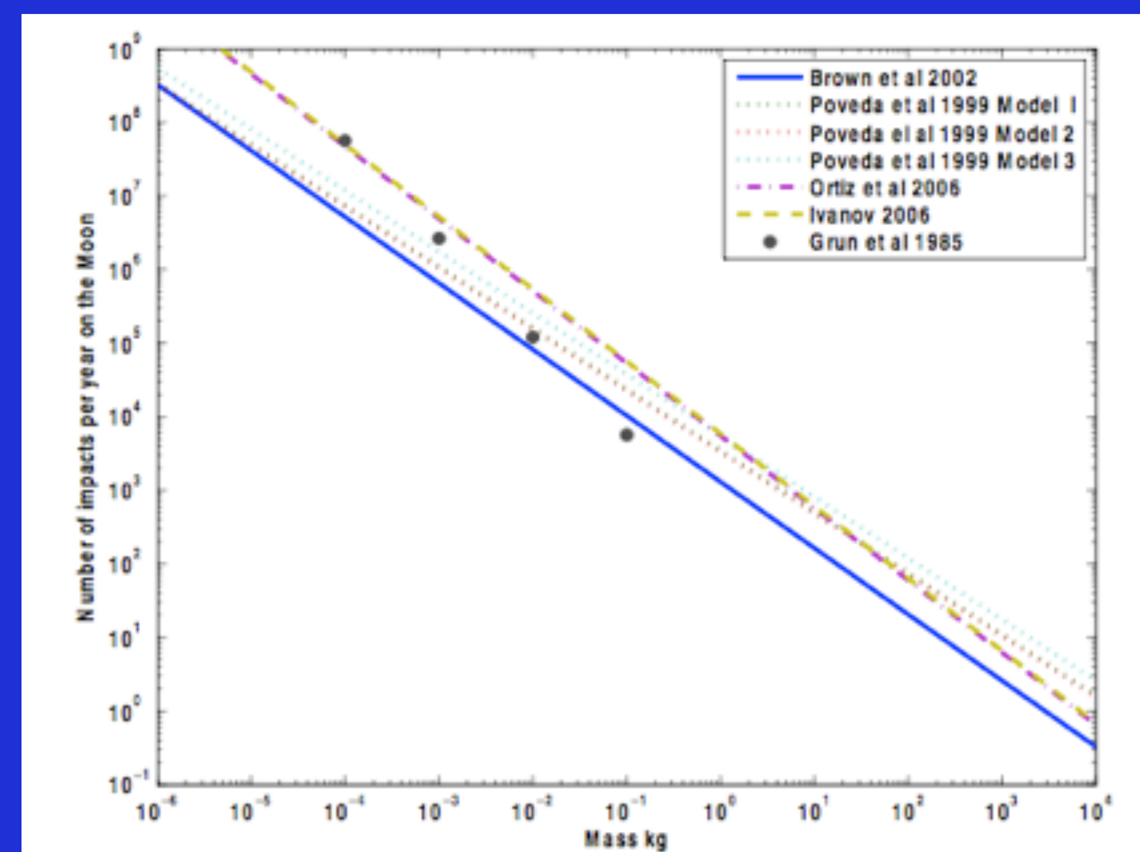
No atmosphere but continuously impacting meteorites…

Impacting rates

- The Moon, as all other planetary or small bodies without atmosphere is impacted continuously by meteorites.
  - Scattering and low attenuation are generating a “long” time diffusion
  - Direction of impacts are given by a priori distribution of NEO in the internal solar system (Bottke et al., 2002)
  - Mass/frequency of impacts are given by different models, but typically 3000/5000 impacts > 1 kg on the Moon

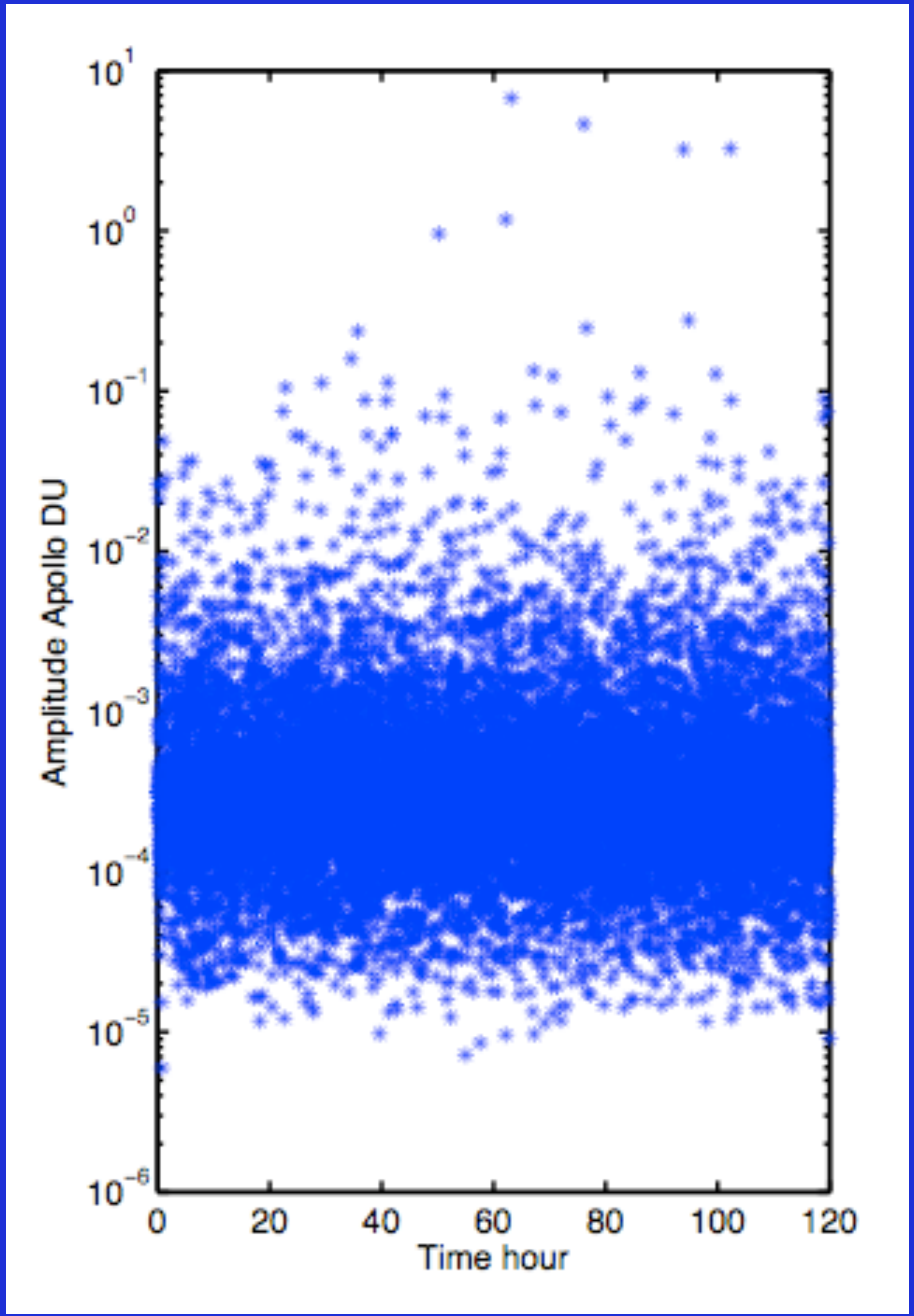


velocities

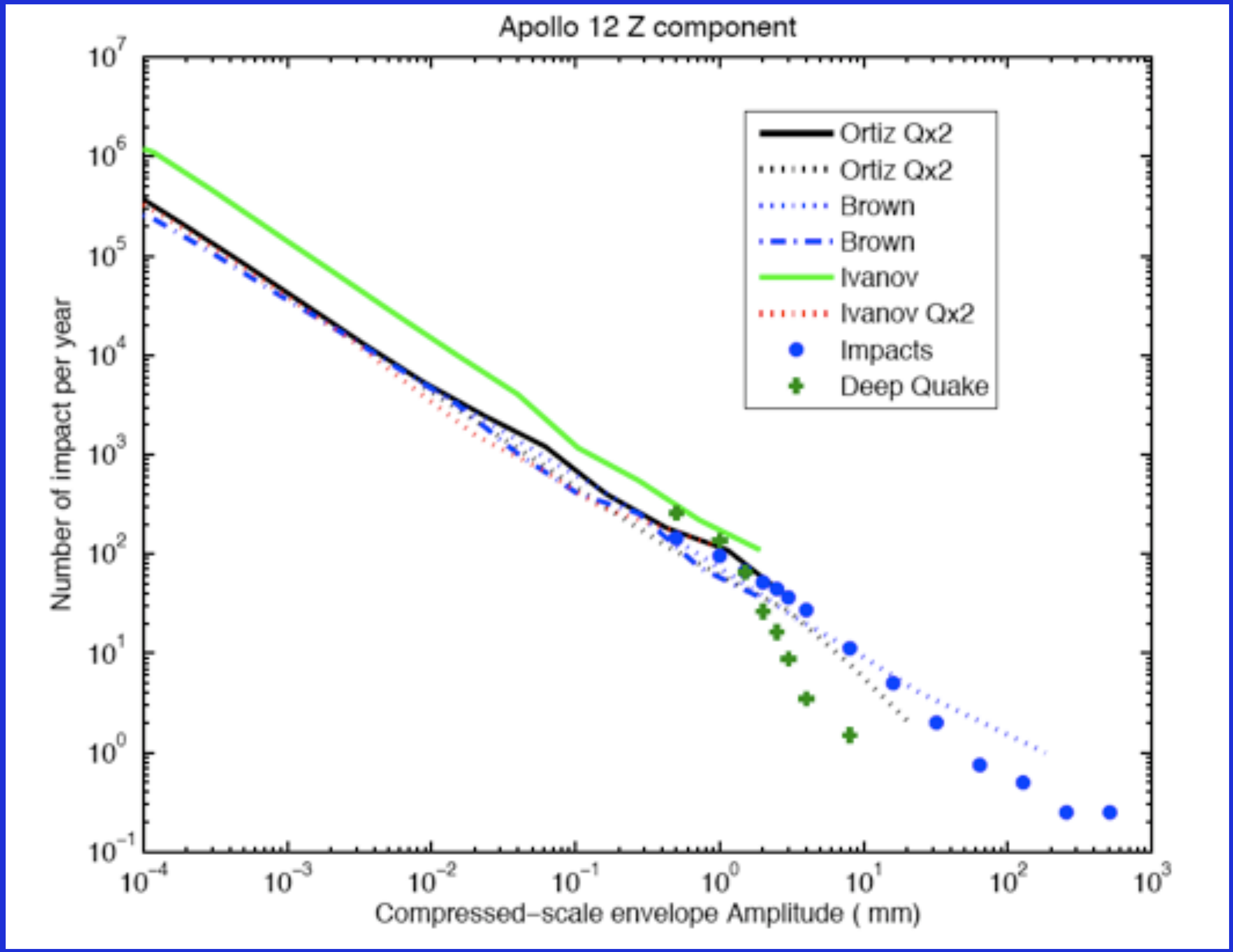


mass

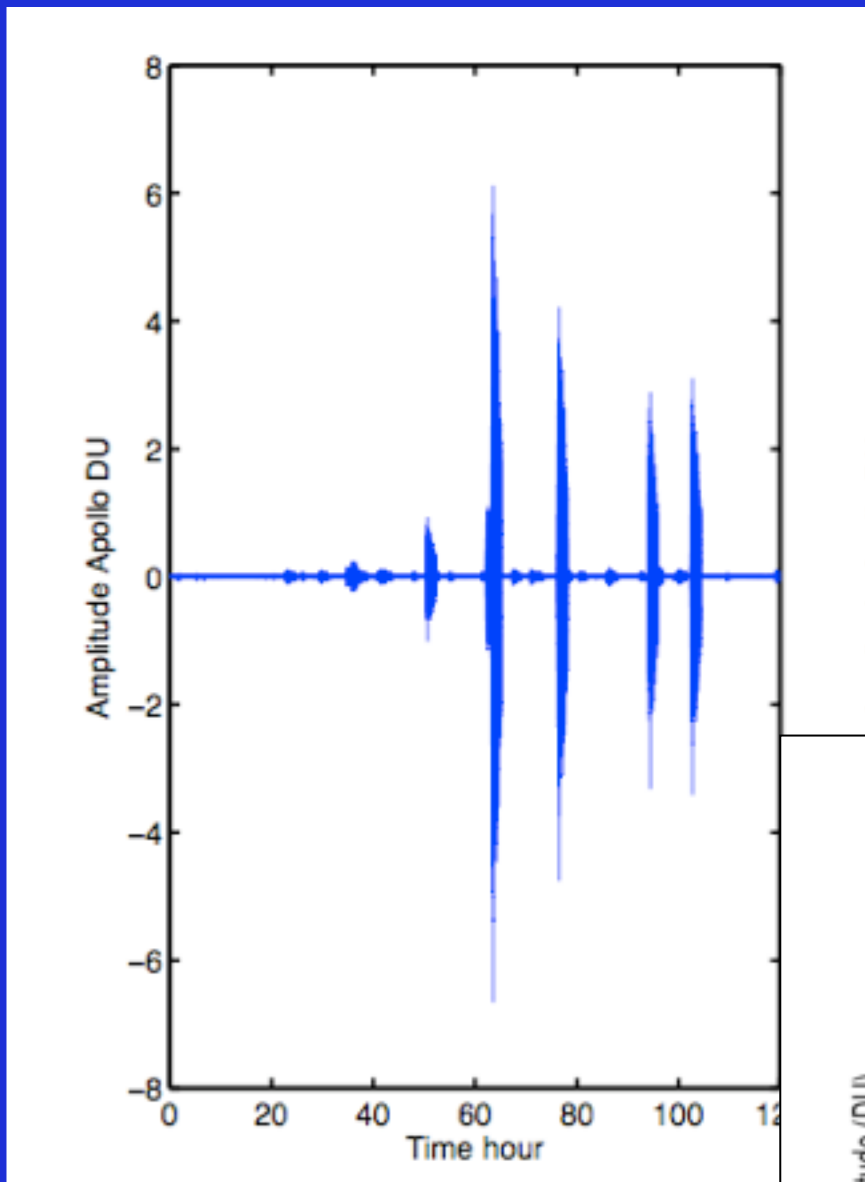
Impact/hum transitions



Maximum amplitudes



Event frequency

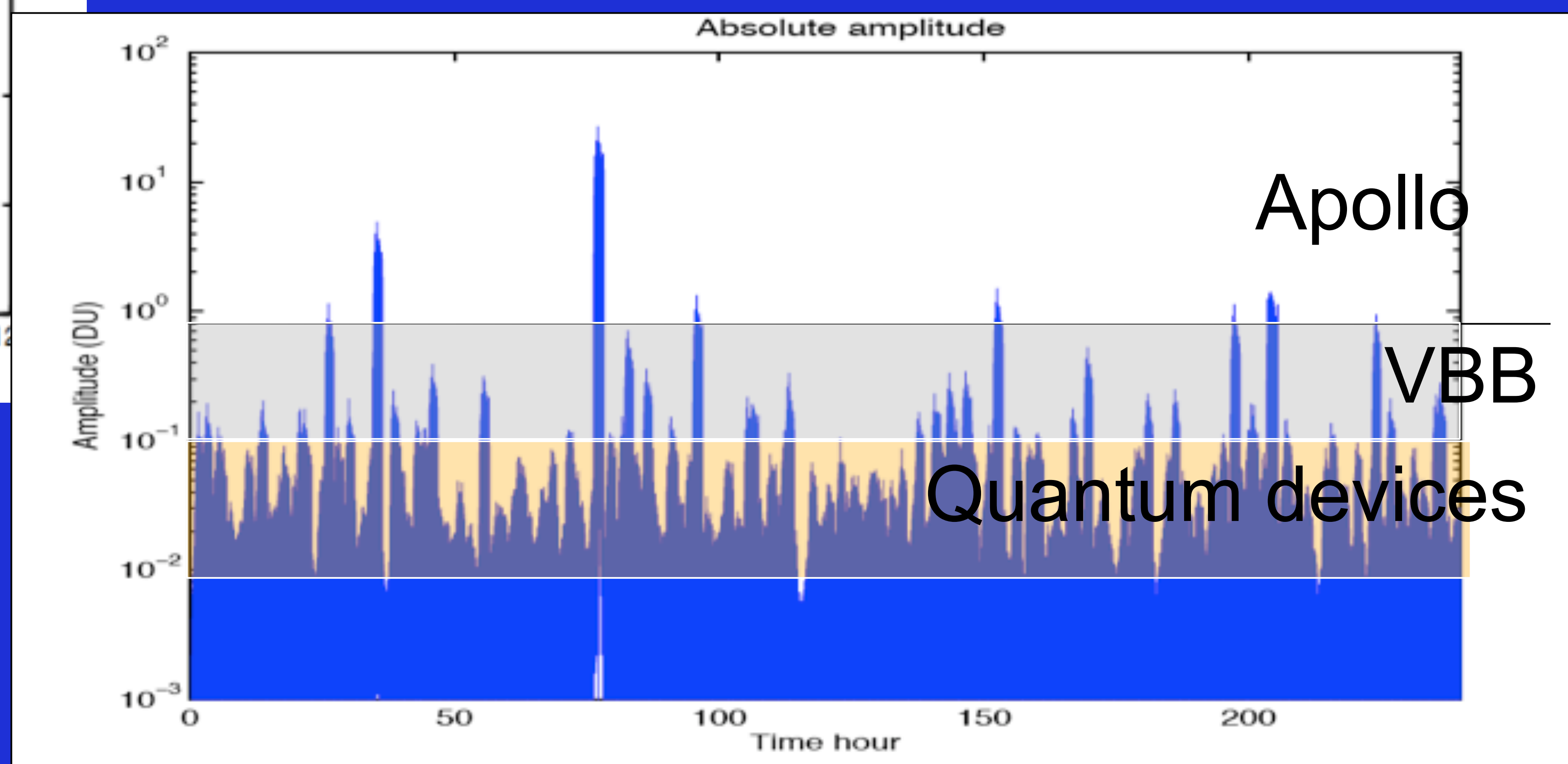


Apollo

DU= 5 x 10^{-10} ms^{-2}

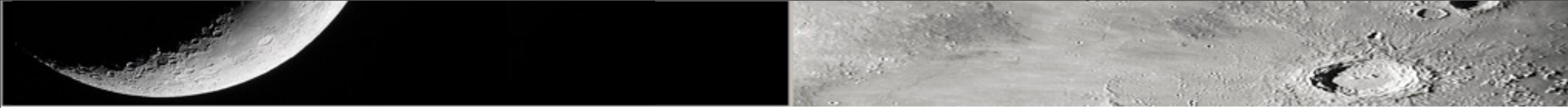
VBB:

rms= $5x10^{-11}$ ms^{-2}



Active seismology using impacts

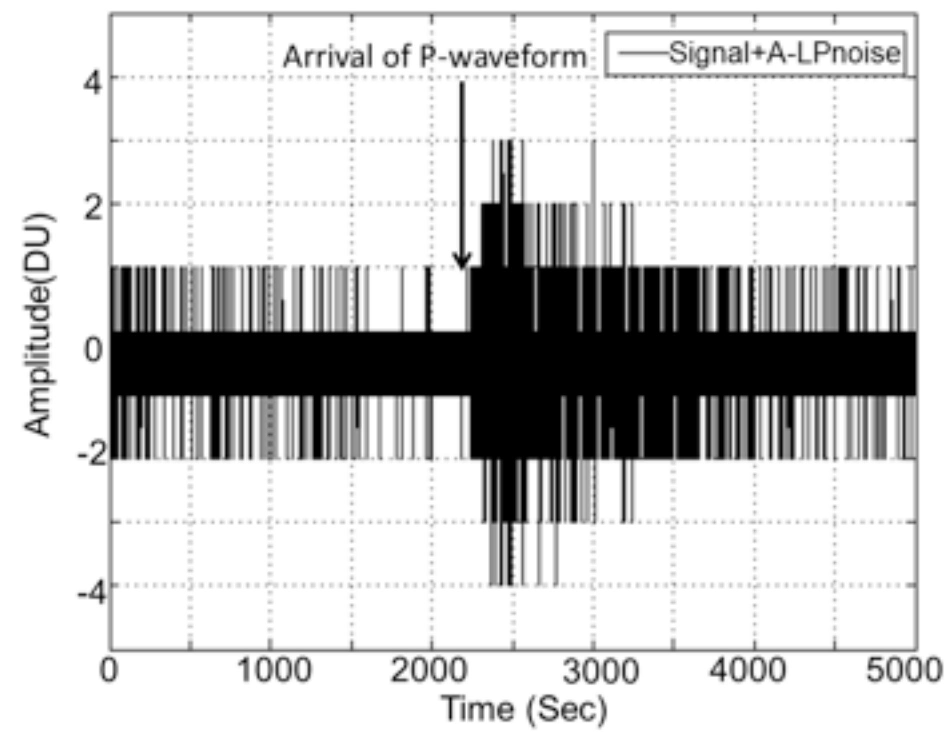
Impact monitoring gives the source position and time of the seismic event, allowing seismic investigations with a single station.



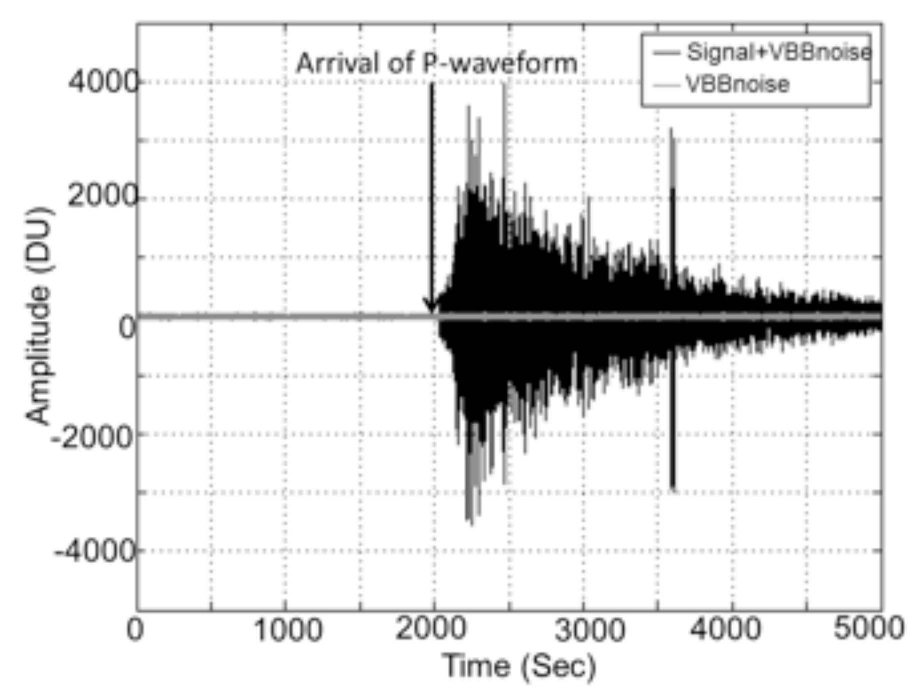
Expected improvement with respect to Apollo will enable new seismic discoveries

- Core phases and core size
- High resolution crustal model from joint Earth/ Moon impacts monitoring
- Detailed seismic source dynamics of impacts and DMQ

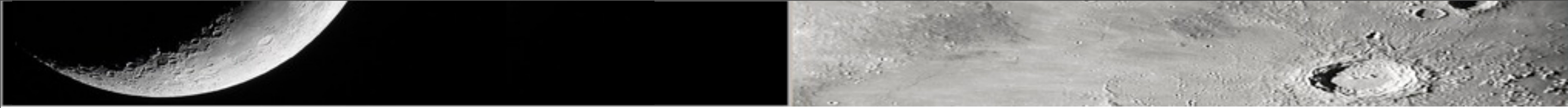
Apollo LP



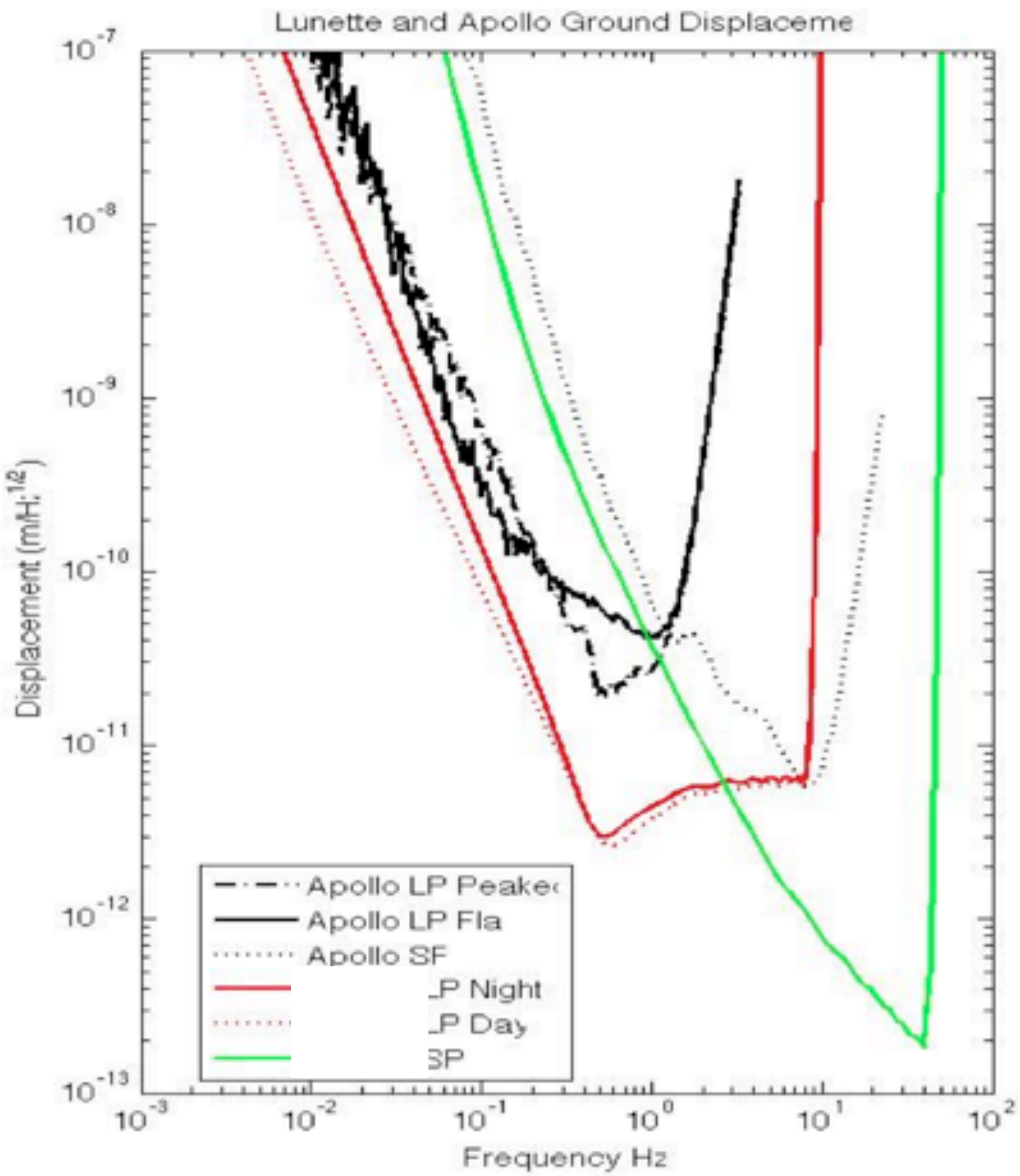
SELENE LP

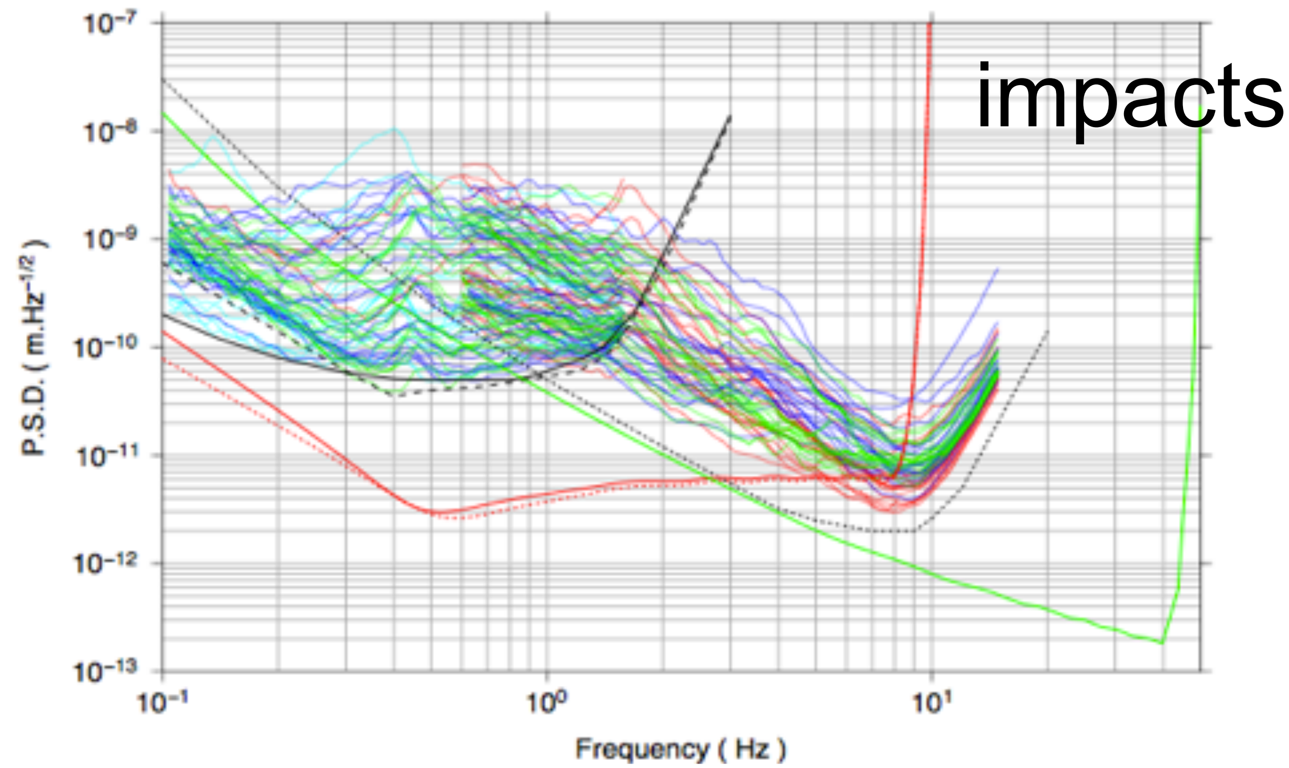


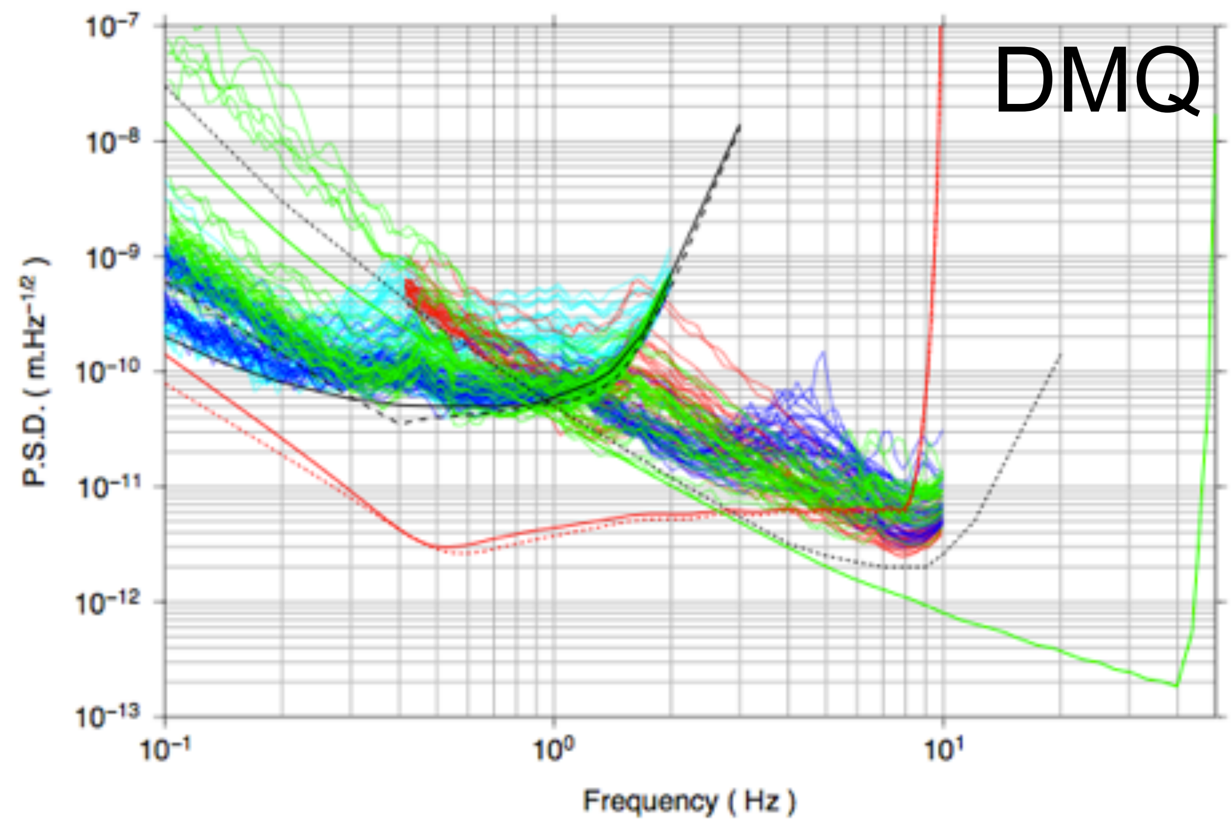
Yamada et al., 2012

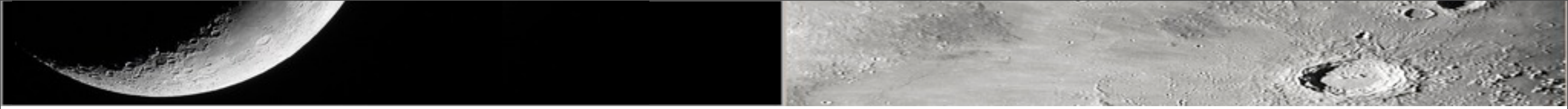


Performances improvements…

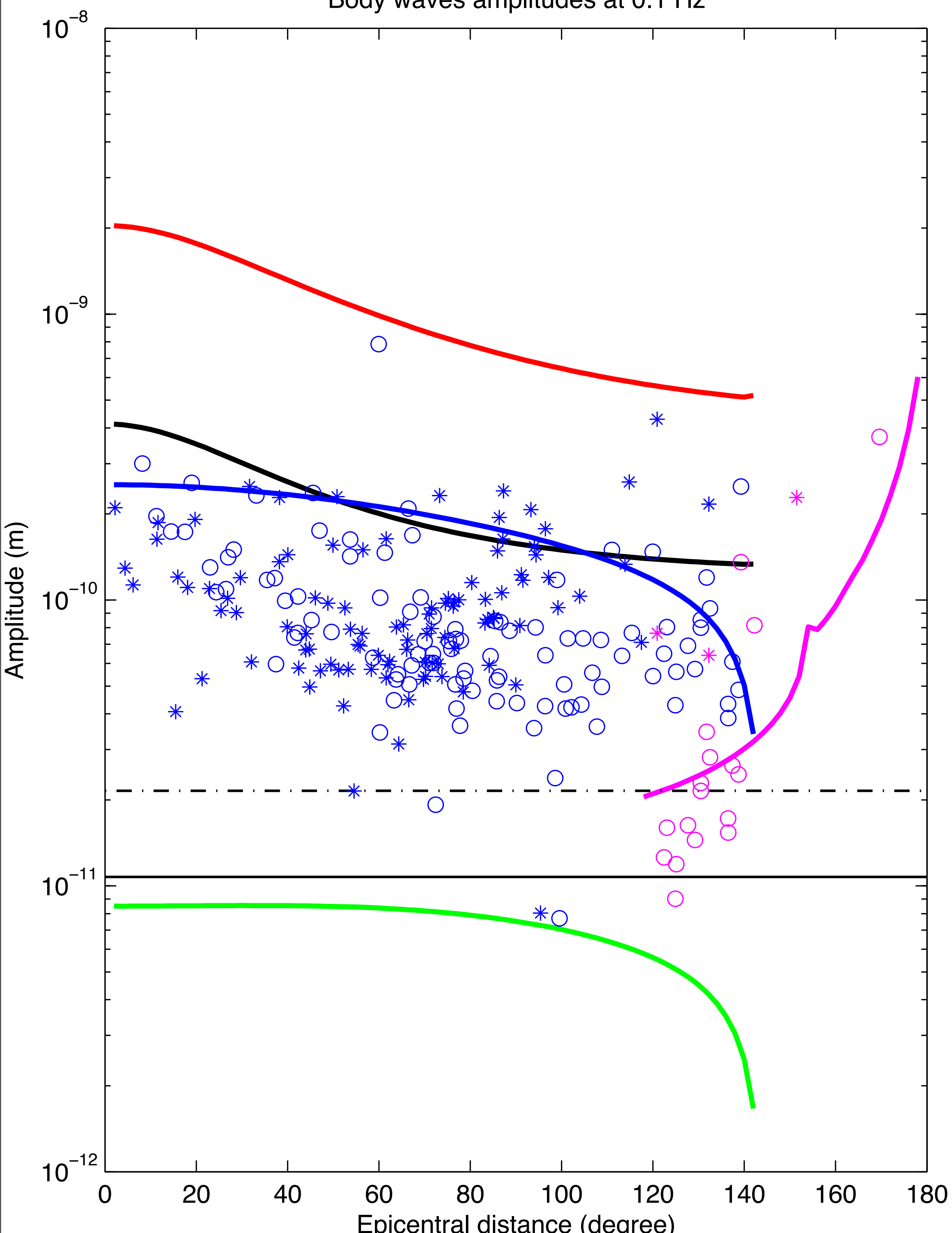


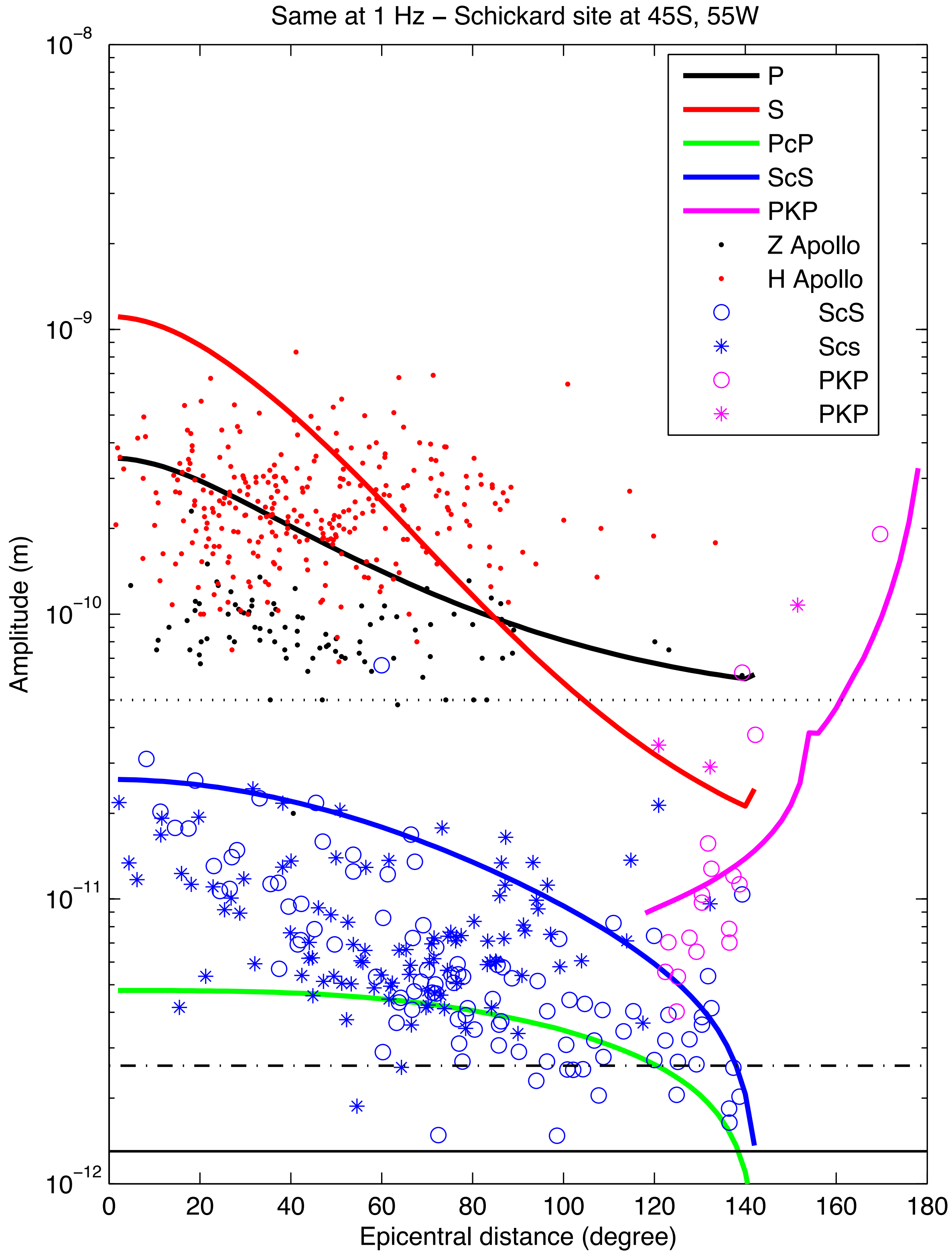


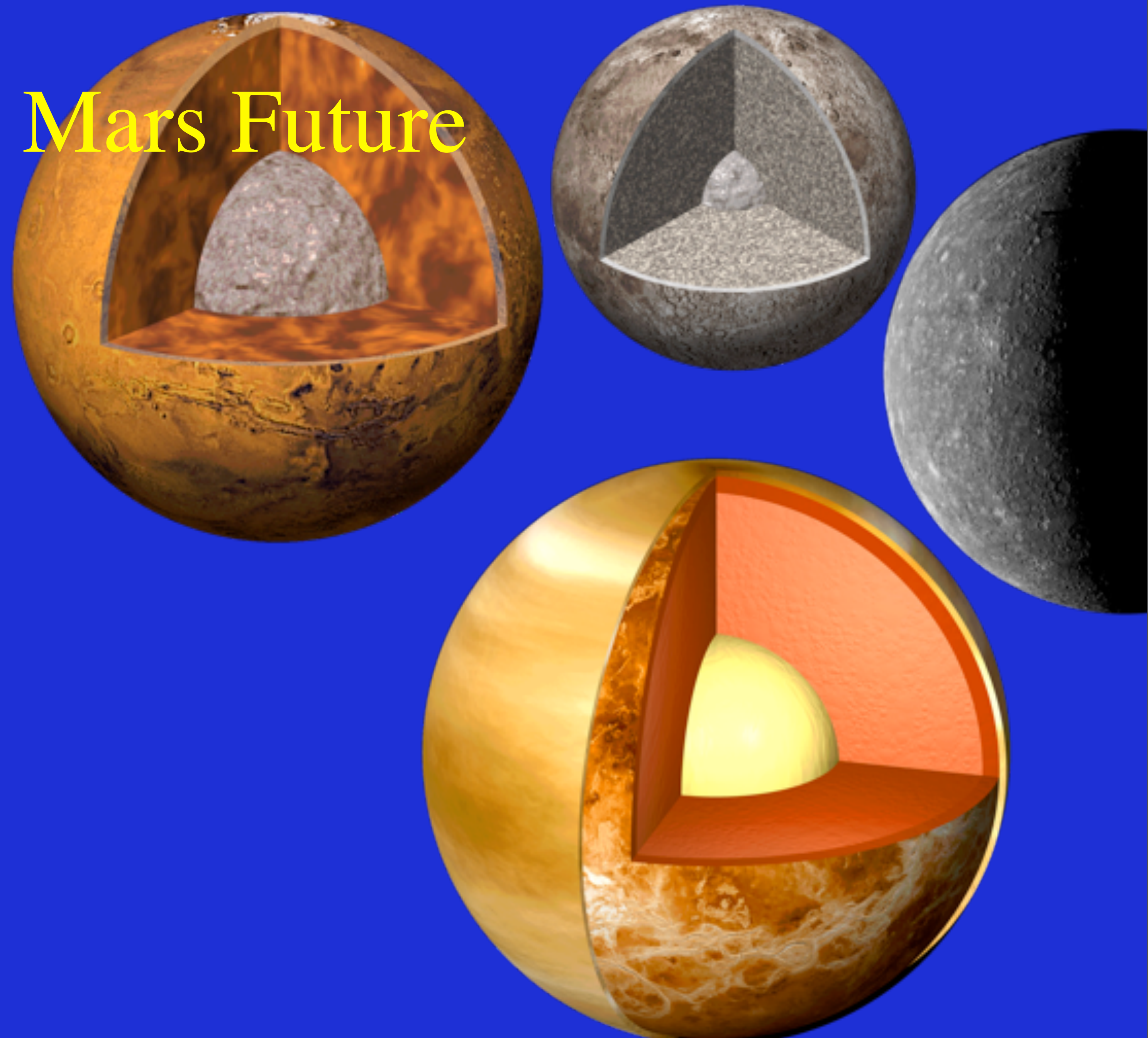




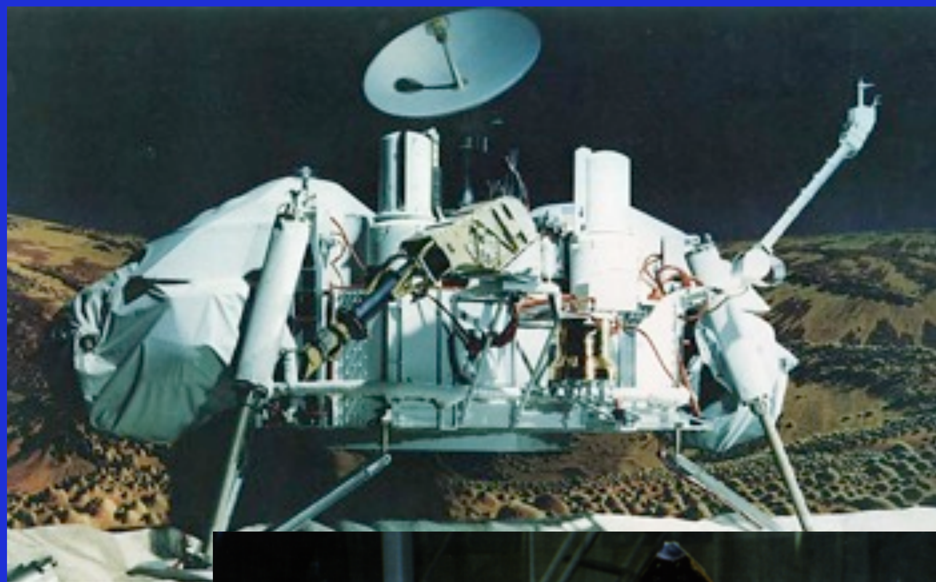
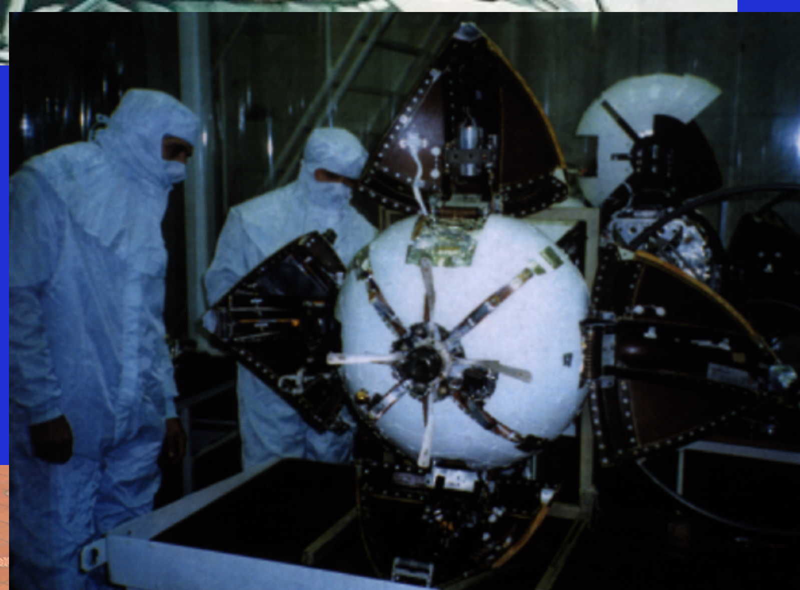
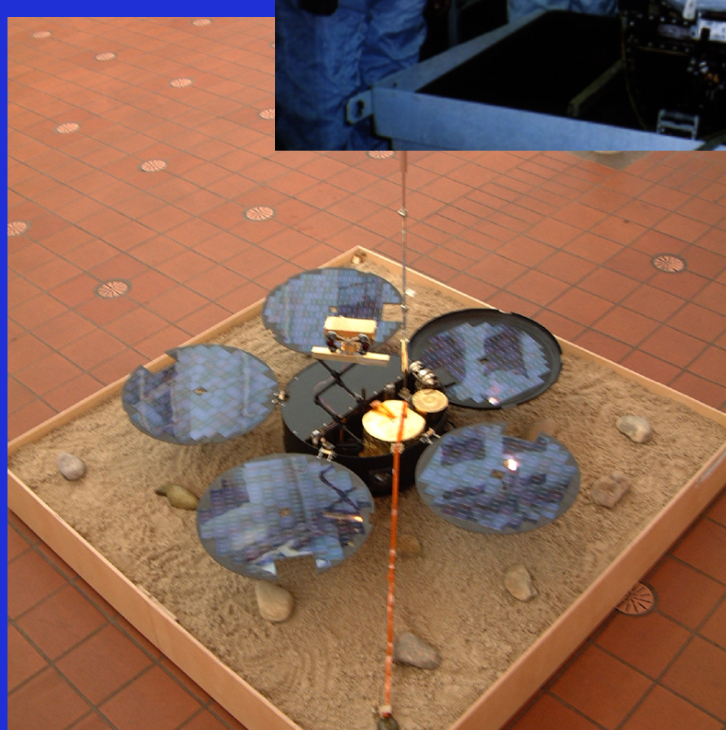
Better detection of core phase...






Mars Future

Mars seismology: history

- 1975: 2 Viking landers equipped with seismometers. Possible detection of one quake on one lander
- 1996: Failure of the launch of Mars96, with 2 surface stations equipped with BRB Z axis seismometers and 2 penetrators with SP geophones
- 2003: The NetLander mission is stopped by CNES and NASA before phase B completion.
- 2008: Humbold/ExoMars project is stopped by ESA after phase B

Mars seismology: history

The Discovery Insight

- **Science**
  - InSight (former GEMS) is investigating the interior of an Earth-like planet for the first time.
  - Scientific payload is highly focused on geophysics
    - ✓3 axis Seismometer
    - ✓Heat flow
    - ✓geodesy experiment
  - Will utilize sophisticated single-station analysis techniques to derive geophysical information from one site on Mars.
  - InSight is a necessary pathfinder for any future Mars geophysical network.
- **Mission**
  - Low risk development and mature Instruments, Phoenix spacecraft
  - InSight mission is nearly identical to Phoenix from launch to landing and stays within all Phoenix capabilities except mission duration.
  - After a short deployment period, surface operations require very little interaction (Deploy & Forget).

Final NASA decision is expected in about 3 weeks!

Pathway to (science) success

- How can a single lander perform the seismic monitoring of a whole planet:
  - Installation and noise of the seismometer will be critical
  - What will be the detection threshold and how many quakes can be detected?
- How can single seismic record of quakes can be used to constrain the interior
  - How well can be the seismic source and interior structure determined?

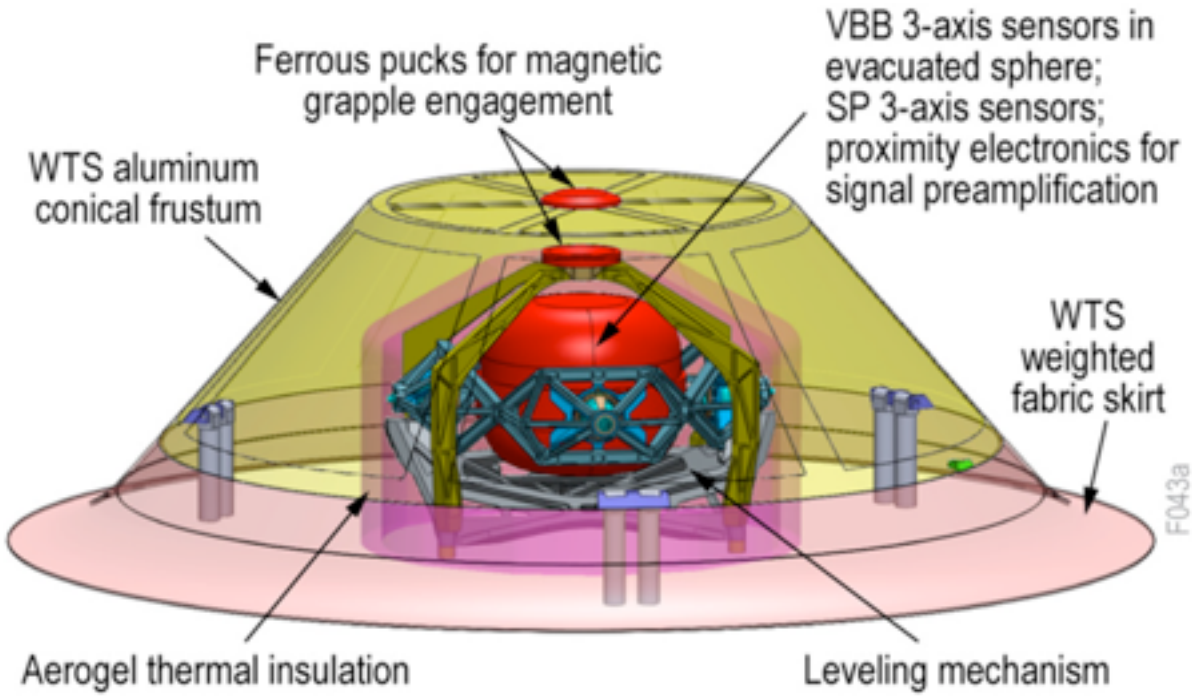
InSight

Deploying a seismic vault on Mars : why?

- Most of the quality of an Earth seismic station is directly associated to the quality of the seismic vault
- Most of the Viking seismometer failure was related to the bad installation of the seismometer (on the lander deck, e.g. on a suspension...)
- Most of the success of the Apollo seismometers

Imperial College London

Deploying a seismic vault on Mars : how?



- Request a large mass made available by the Phoenix-type lander capability
- Will put the expected direct wind and thermal noise below the capability of space qualified VBB seismometers (see posters 1493 and 2025)
- Will allow to reach the (surface) micro-seismic noise of the planet

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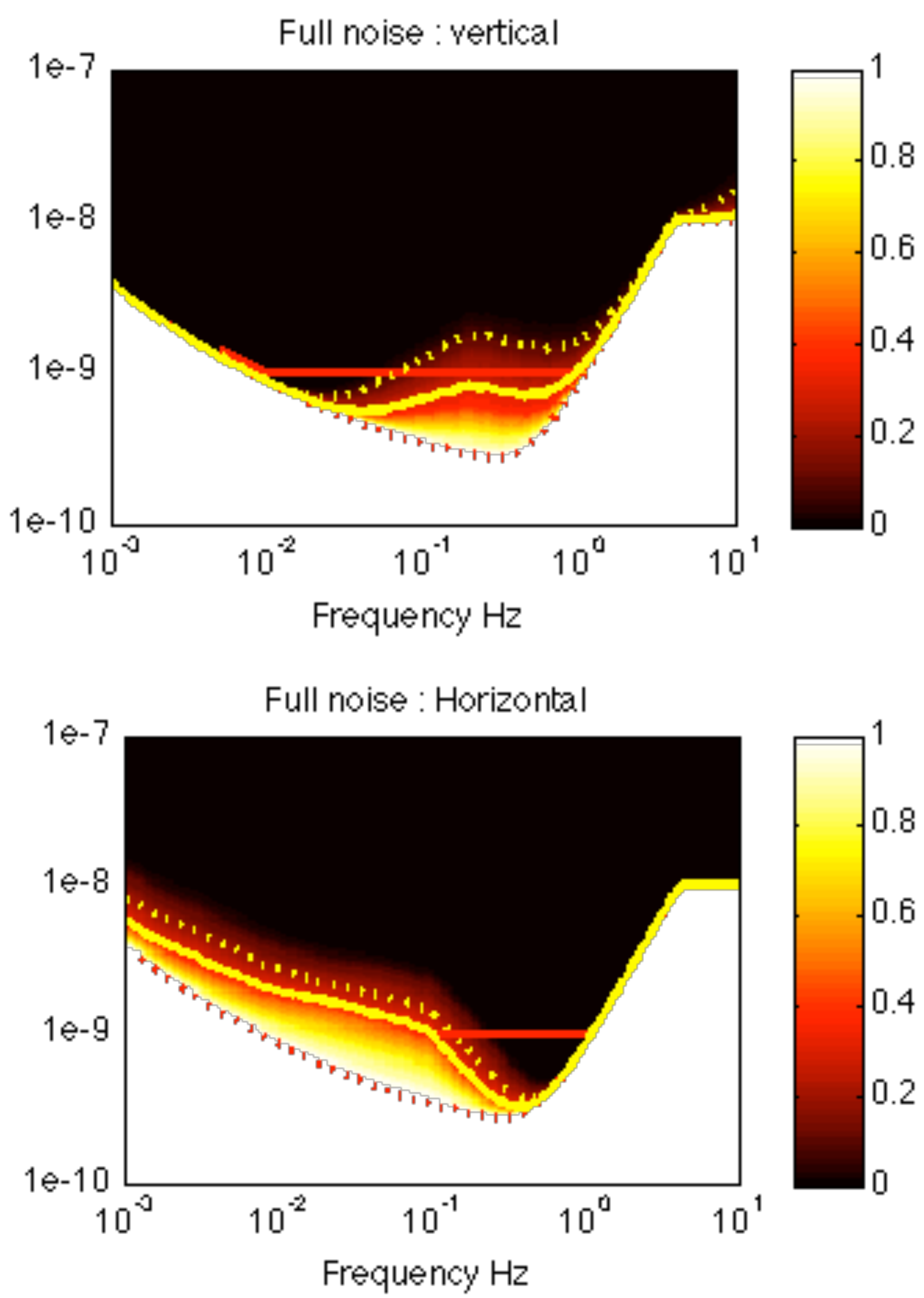
Mars Micro-seismic noise estimation



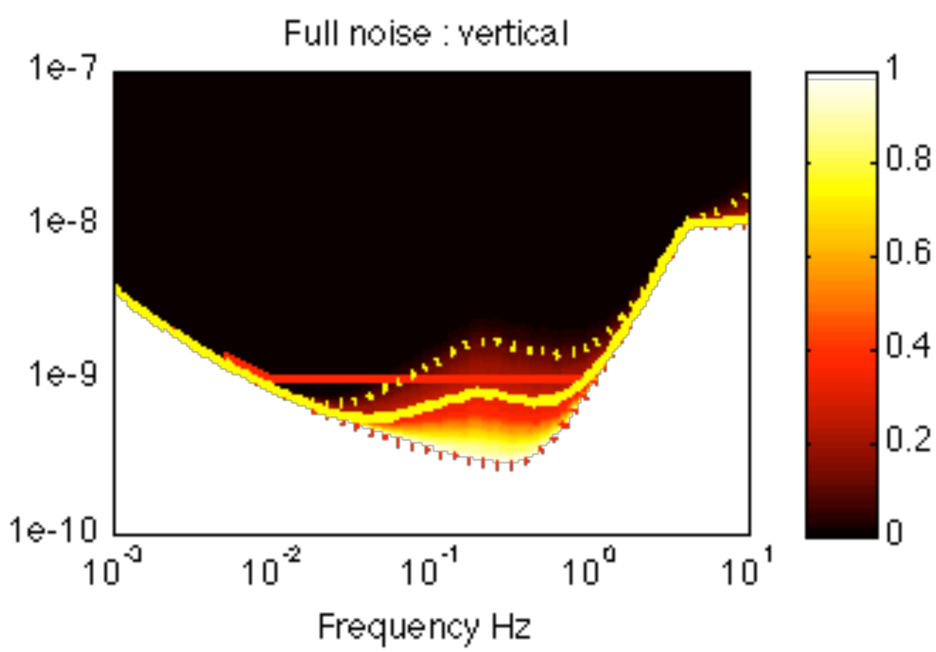
- Can be estimated with GCM and Large Eddies simulation
- Is expected to be below 10^{-9} $ms^{-2}/Hz^{1/2}$ 70% of the time (10^3 less than Viking)
- Is expected to reach Apollo level with pressure decorrelation (10 x more)

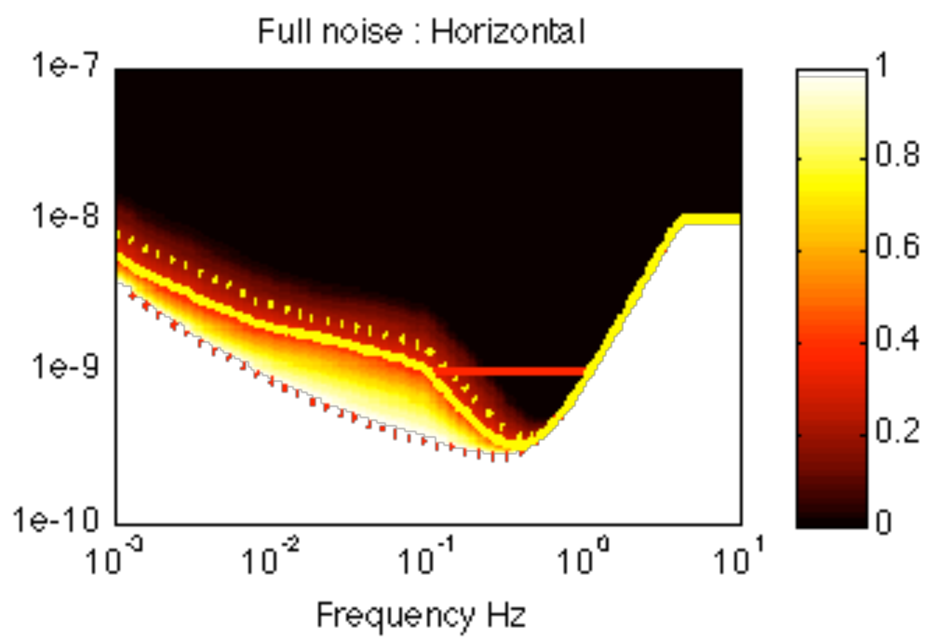
Pressure fluctuation on the ground => ground tilt

InSight

2012年7月9日月曜日

Mars Micro-seismic noise estimation





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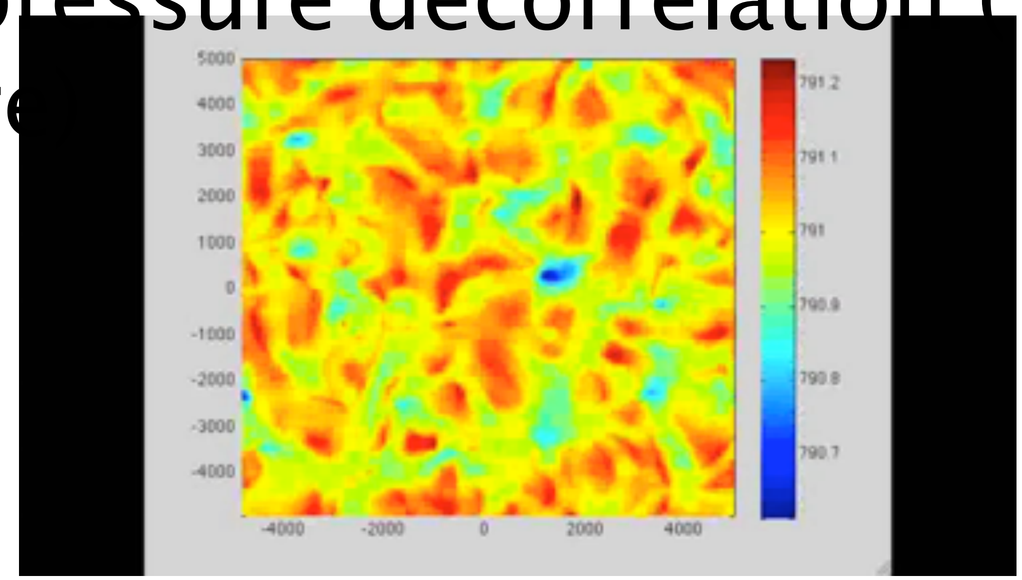
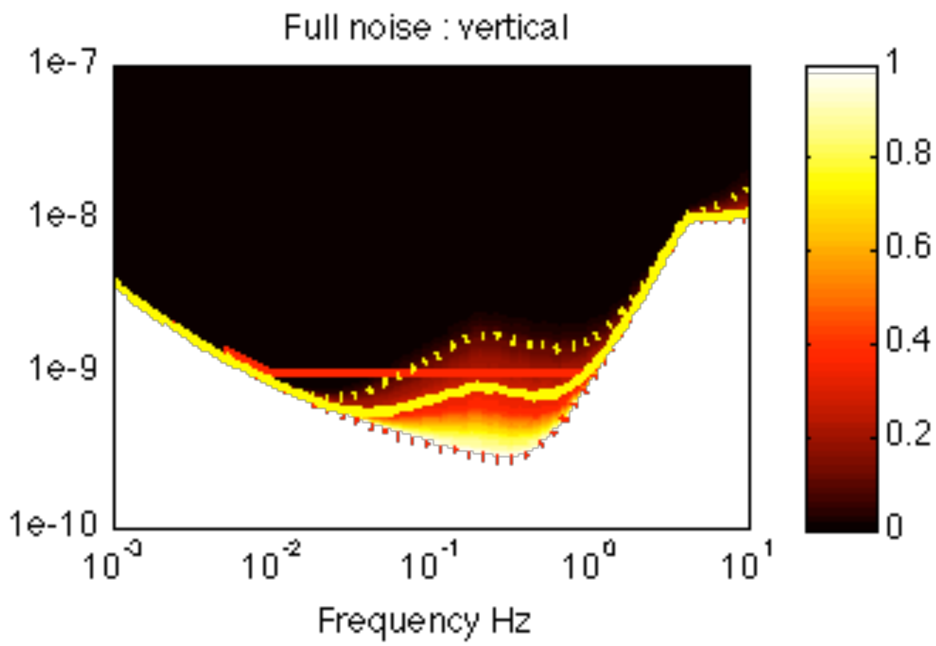
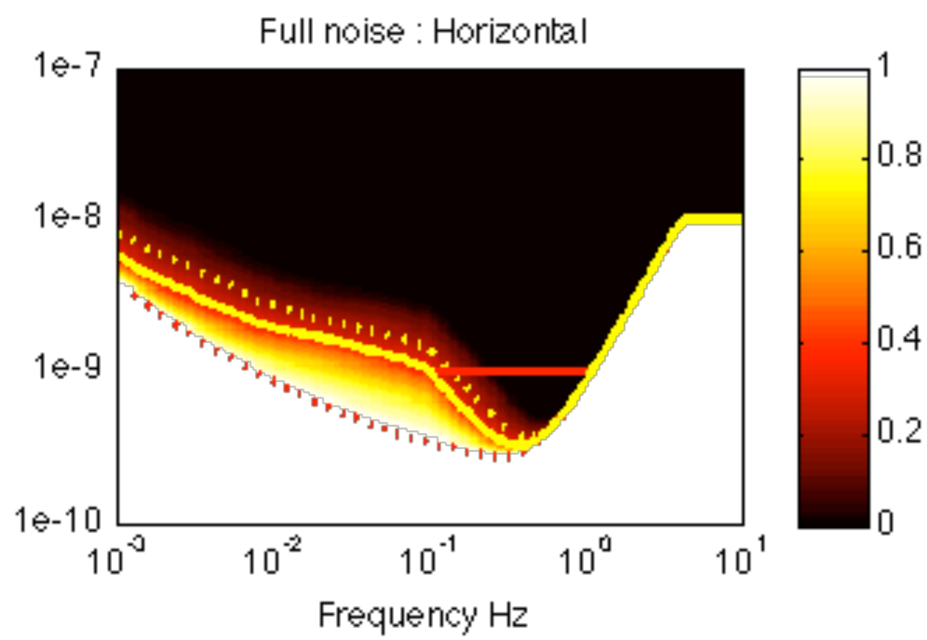


Pressure fluctuation on the ground => ground tilt

Mars Micro-seismic noise estimation





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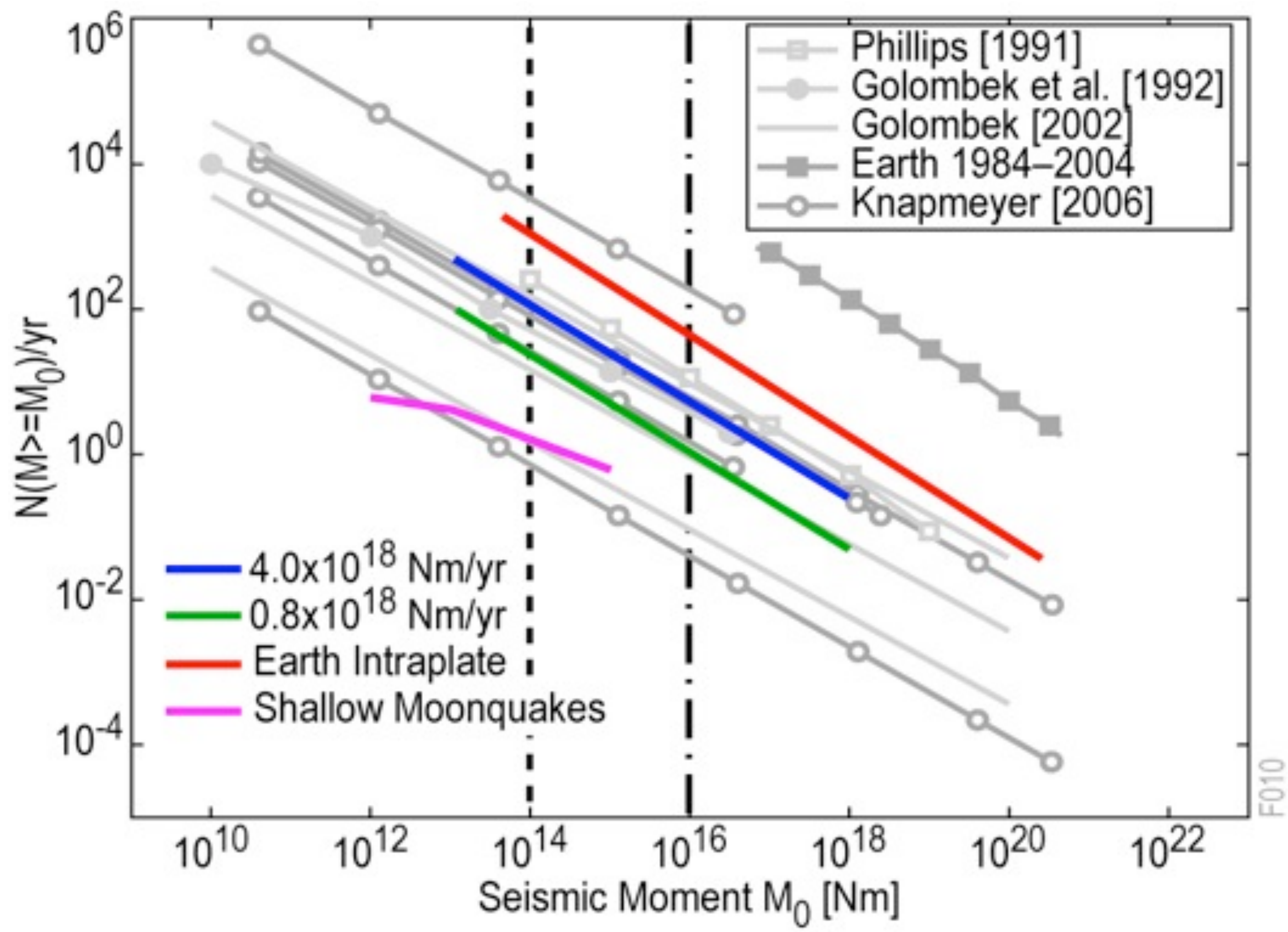
Pressure fluctuation on the ground => ground tilt

Mars seismicity



- Seismicity of Mars remains unknown, even if MRO has brought back some indications on present activity with avalance and fallen boulder (e.g. Roberts et al., 2012)

Seismic targets

M~5.5 a few/yr

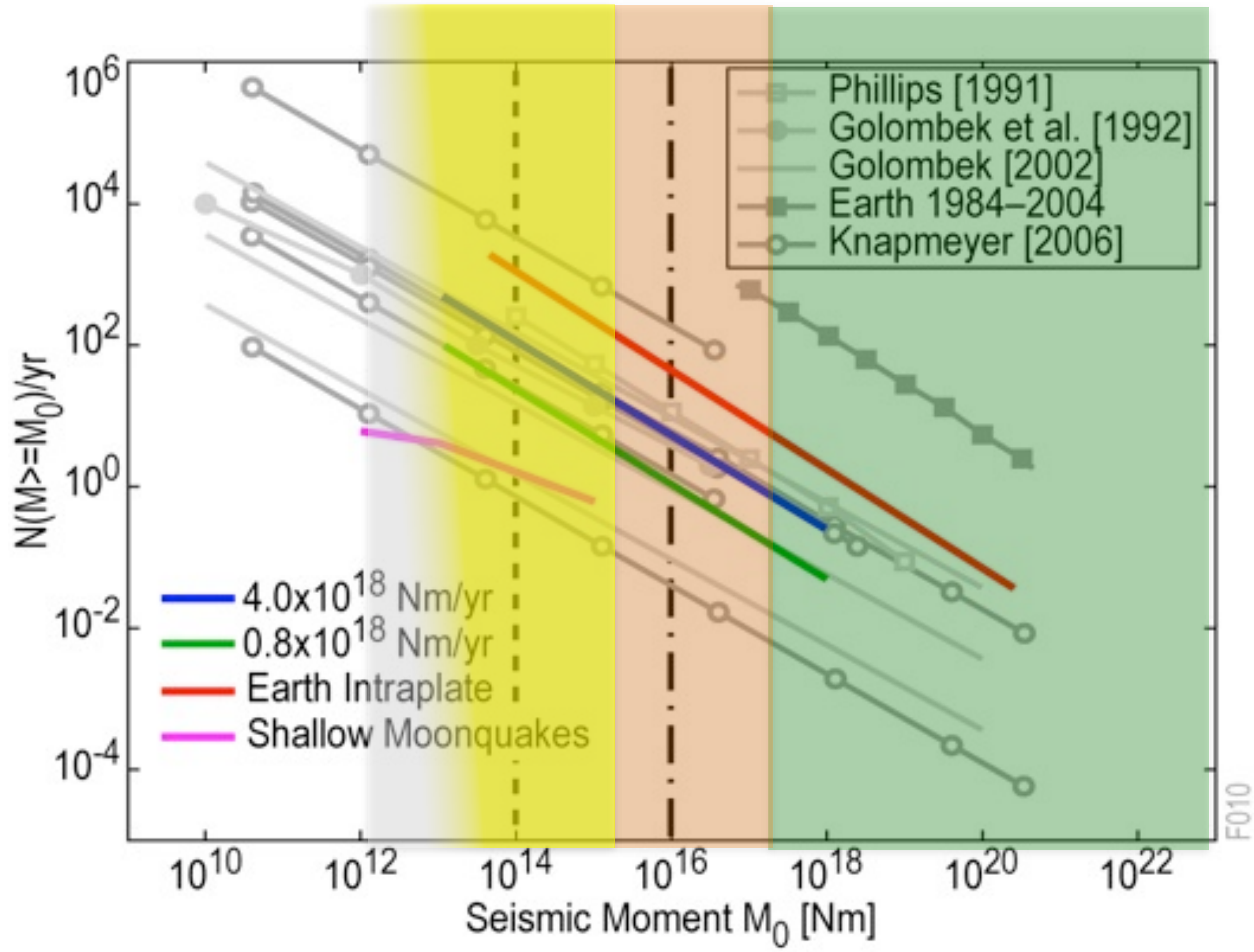
Global

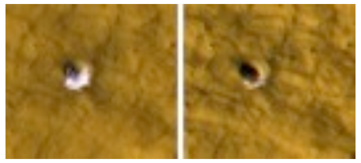
M~4.5 ~ 10/yr

Global to regional

M~3.5 ~100/yr

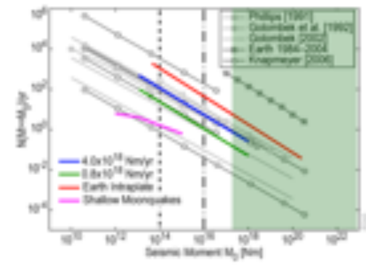
Regional



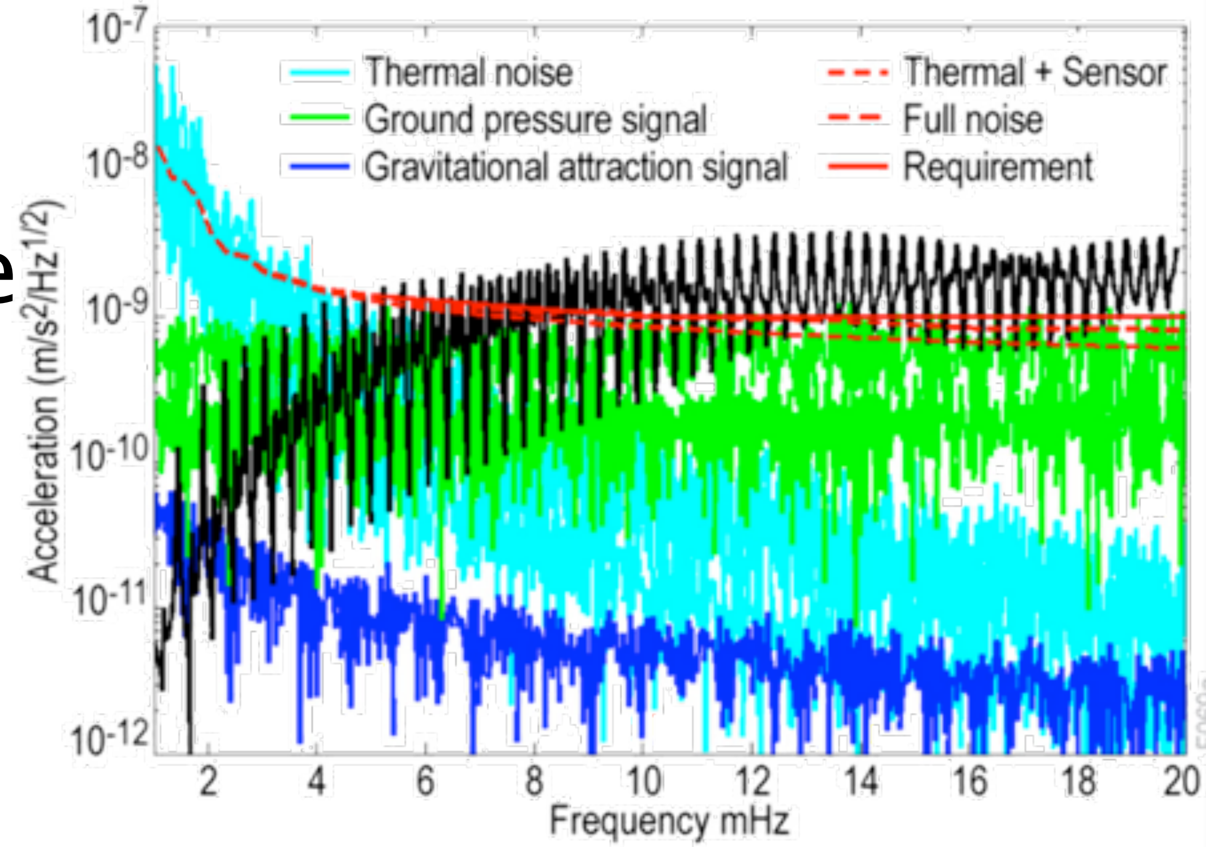


Plus impacts…

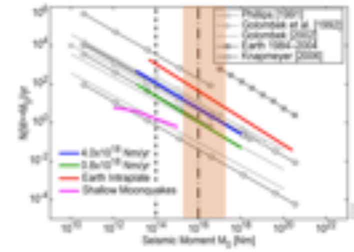
Seismic target #1:



- Normal modes of a 2×10^{17} Nm quake
- « spectroscopy » seismology: does not need the knowledge of the source location
- will constrain the upper mantle with the normal modes frequency inversion (e.g. PREM on Earth)



Seismic target #2:



- Epicentral distance will be determined from Surface waves arrival of R1, R2
- Most of the error in the Distance will be related to the 3D structure as seen by the surface waves
- Full great circle travel time (e.g. $T_R = T_{R3} - T_{R1}$) will be determined from analysis of the largest events (and refined from joint analysis of all events)
- Analysis principle:

$$t_{R1} - t_0 = \frac{\Delta}{v_R}$$

$$t_{R2} - t_0 = \frac{2\pi a - \Delta}{v_R}$$

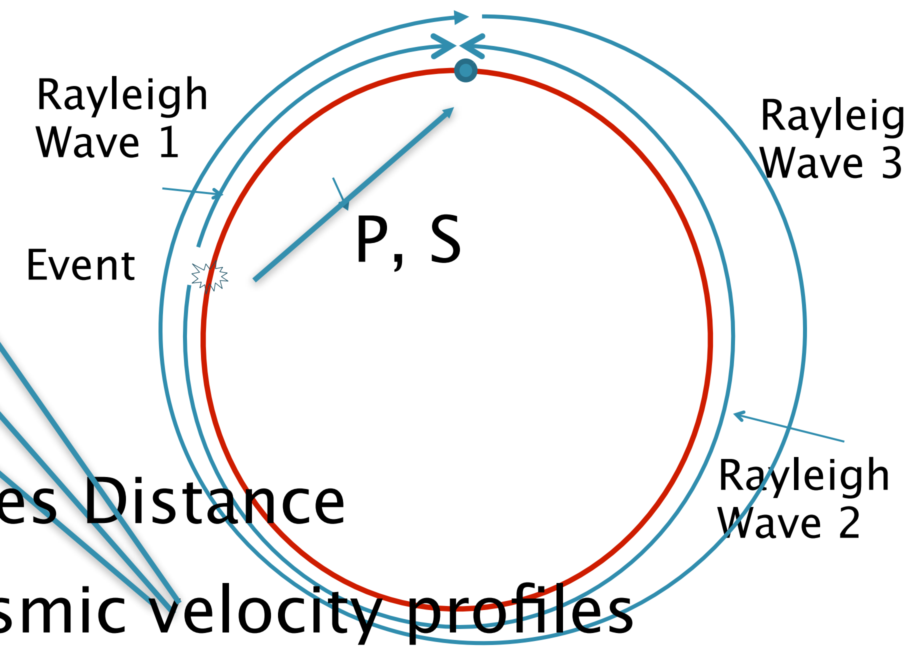
$$t_{R3} - t_{R1} = \frac{2\pi a}{v_R}$$

$$\frac{\Delta}{\pi a} = 1 - \frac{t_{R2} - t_{R1}}{T_R}$$

$$t_S - t_P = f_1(\Delta, v_s, v_p)$$

$$t_R - t_P = f_2(\Delta, v_s, v_p)$$

$$T_R = f_3(f, v_s, v_p)$$



Depends on lateral variations: gives Distance

Depend on both lateral and depth variations: gives seismic velocity profiles

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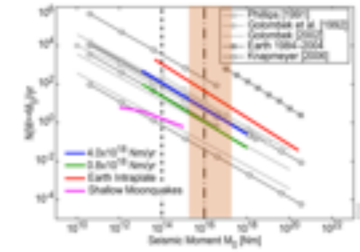
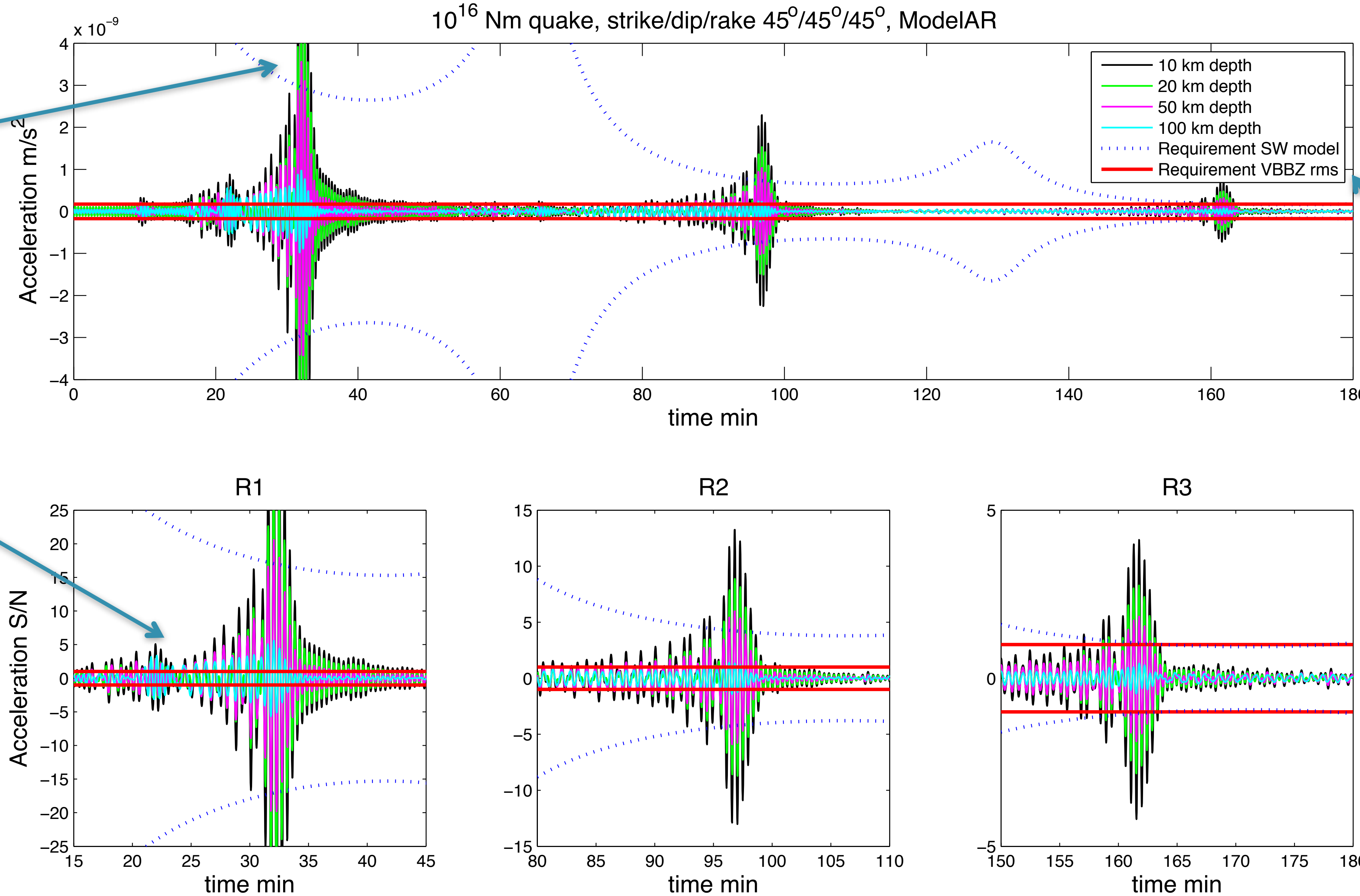
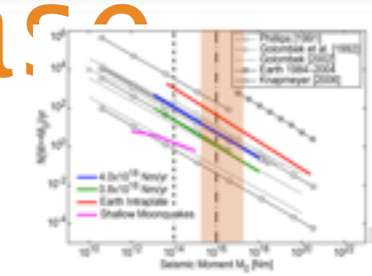
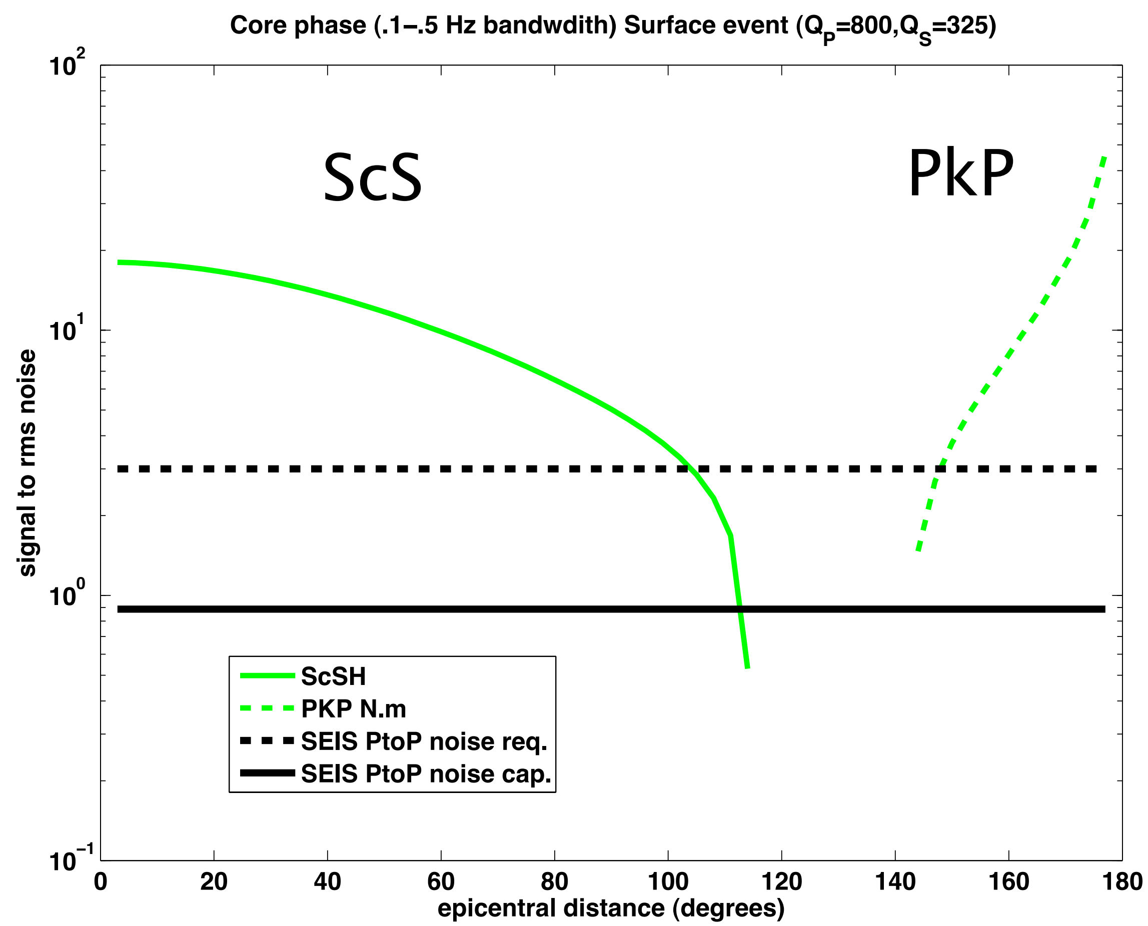
Typical Signal to noise : Rayleigh

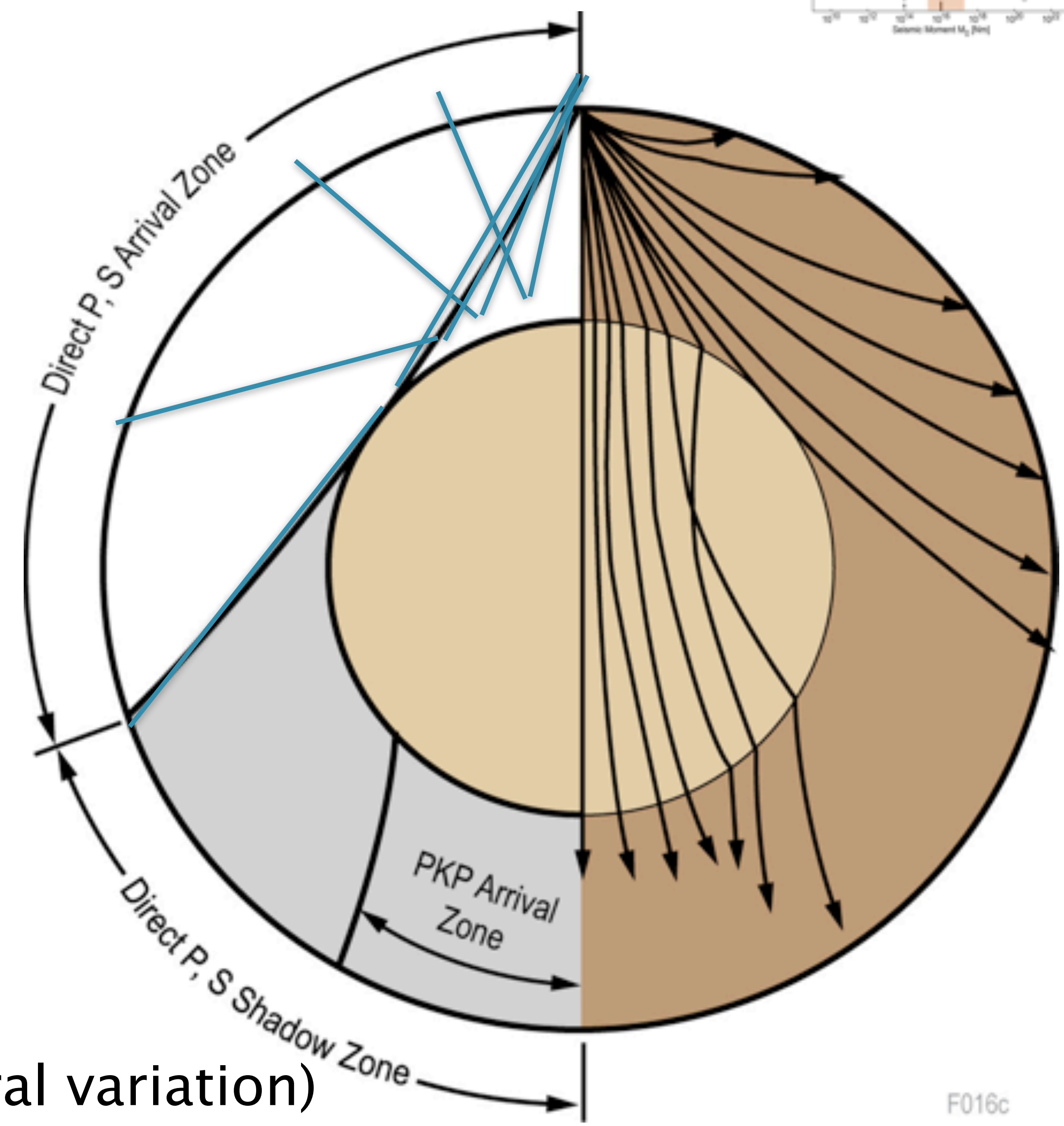




Typical Signal to noise : core phase



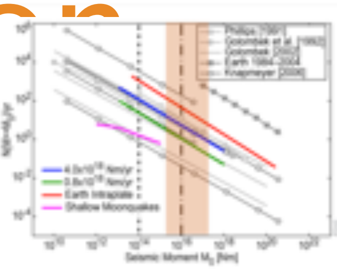




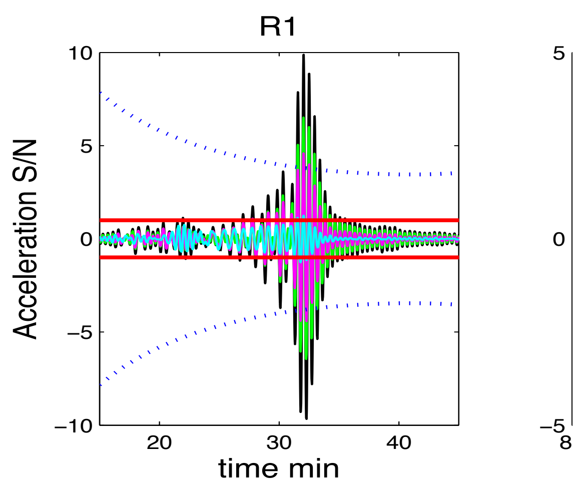
Expected Distance error ~10%
(less with a priori on crustal lateral variation)

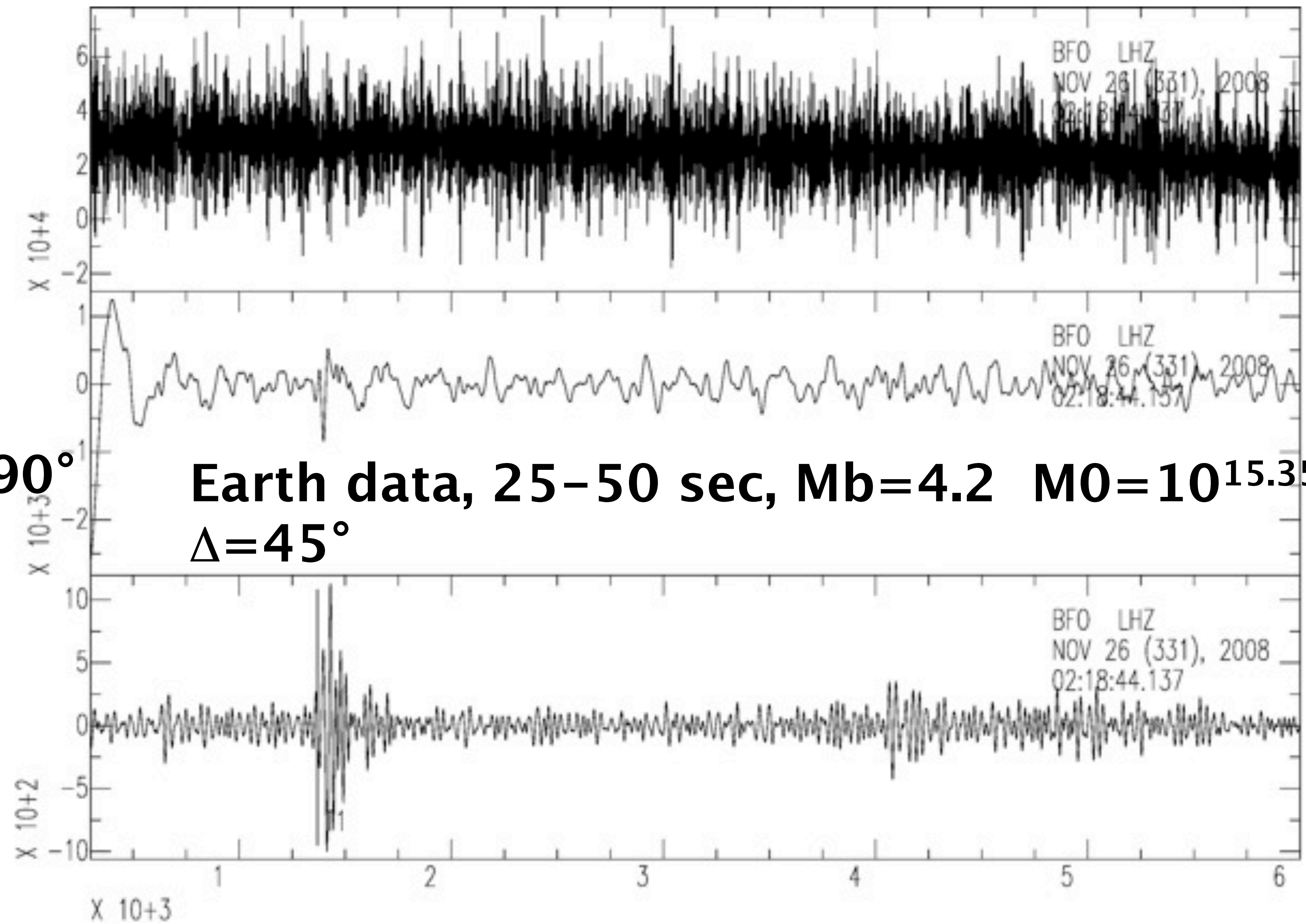
Earth data/Mars Model validation

Body waves non observed due to Earth noi



Mars synt data, $\Delta=90°$



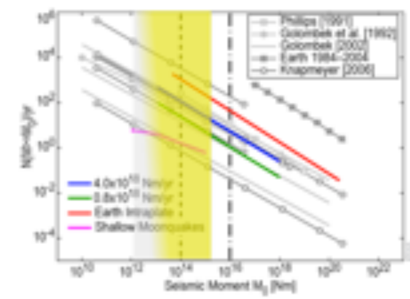


Earth data, 25-50 sec, Mb=4.2 M0=$10^{15.35}$ nm, $\Delta=45°$

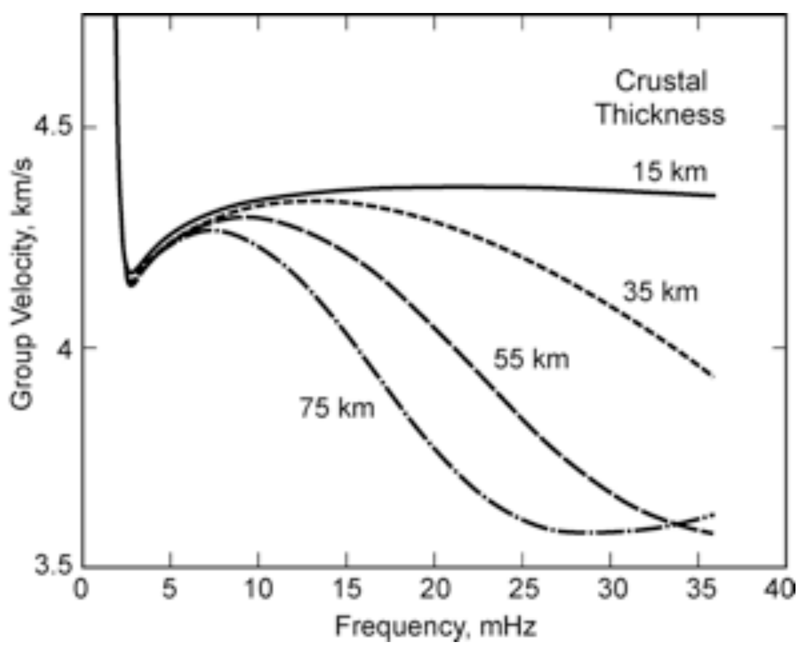
Noise level ~10^{-9} $ms^{-2}/Hz^{1/2}$

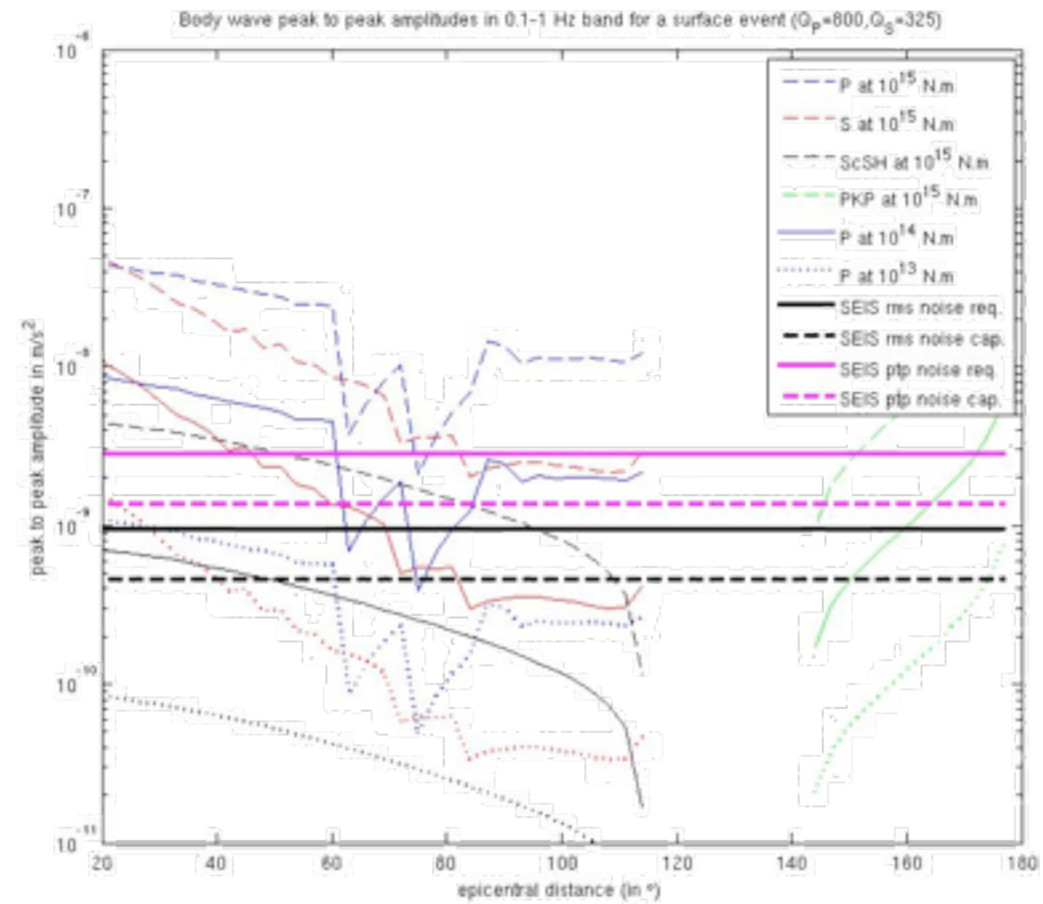
More in poster 1515

Seismic target #3:



- 10^{14}–10^{15} Nm quakes will provide P,S and Surface waves records enabling
  - Regional crustal inversion from surface waves and receiver functions analysis for the 10^{15} Nm quakes
  - Quake location for the ≤ 10^{14} Nm quakes





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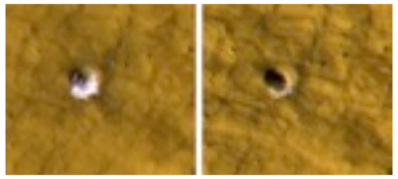
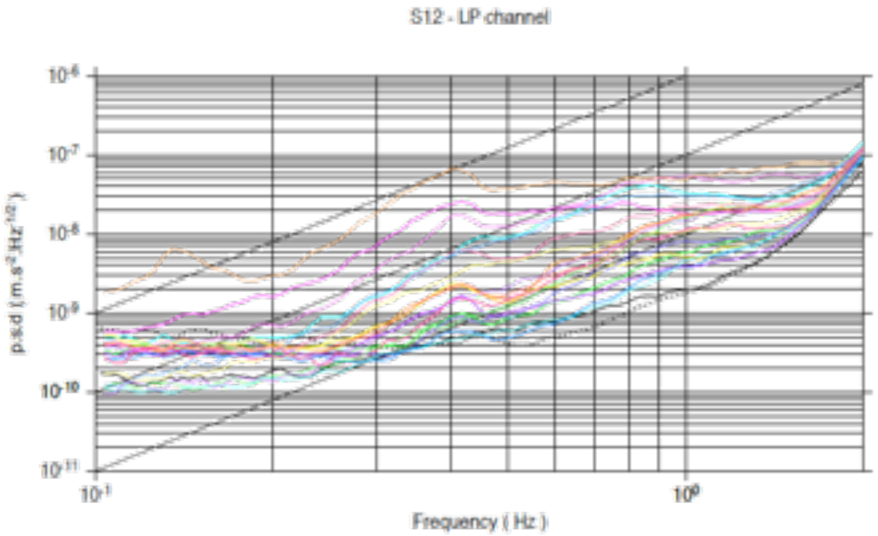
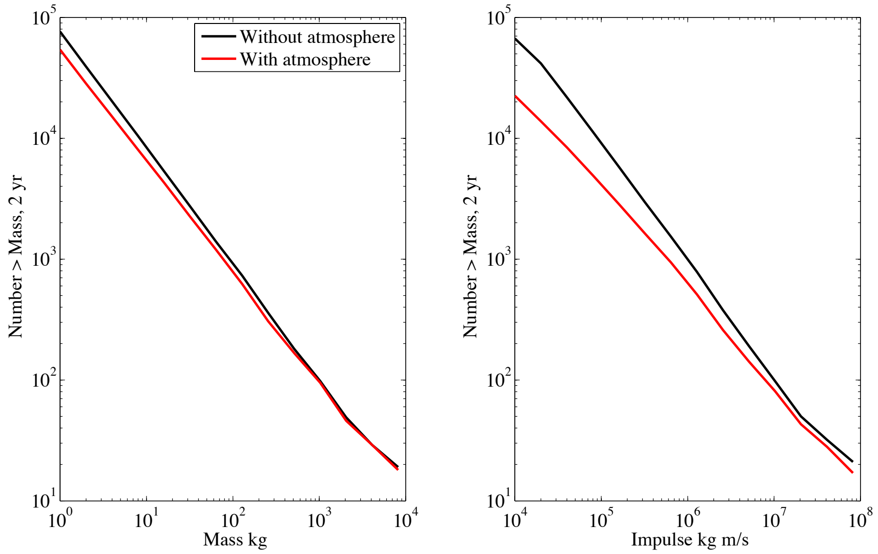
Seismic target #4:

- Seismic signals generated by impacts can be calibrated with Moon Apollo data
  - Amplitude must be corrected by the larger a priori mantle and crust attenuation
- Impactor flux can be estimatec with Monte-Carlo modeling
  - Ground mass/velocity must however be computed with the atmospheric ablation and shielding







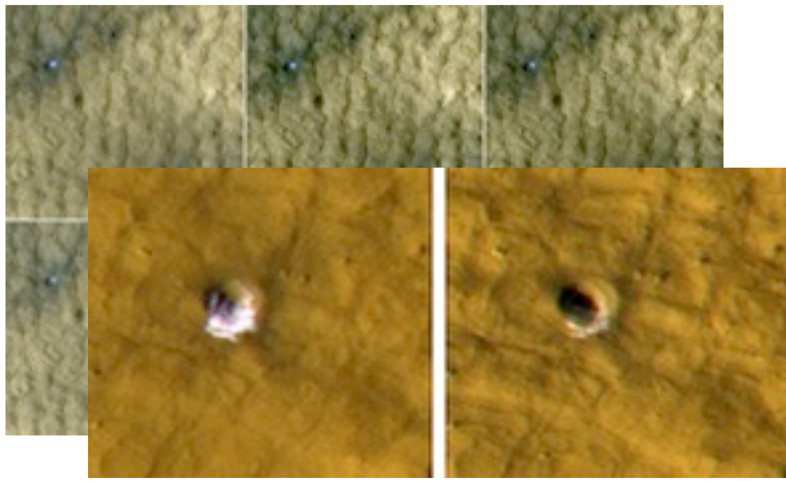
InSight

JPL ETH MPS cnes Imperial College London isae SUPAERO cnrs PARIS DIDEROT

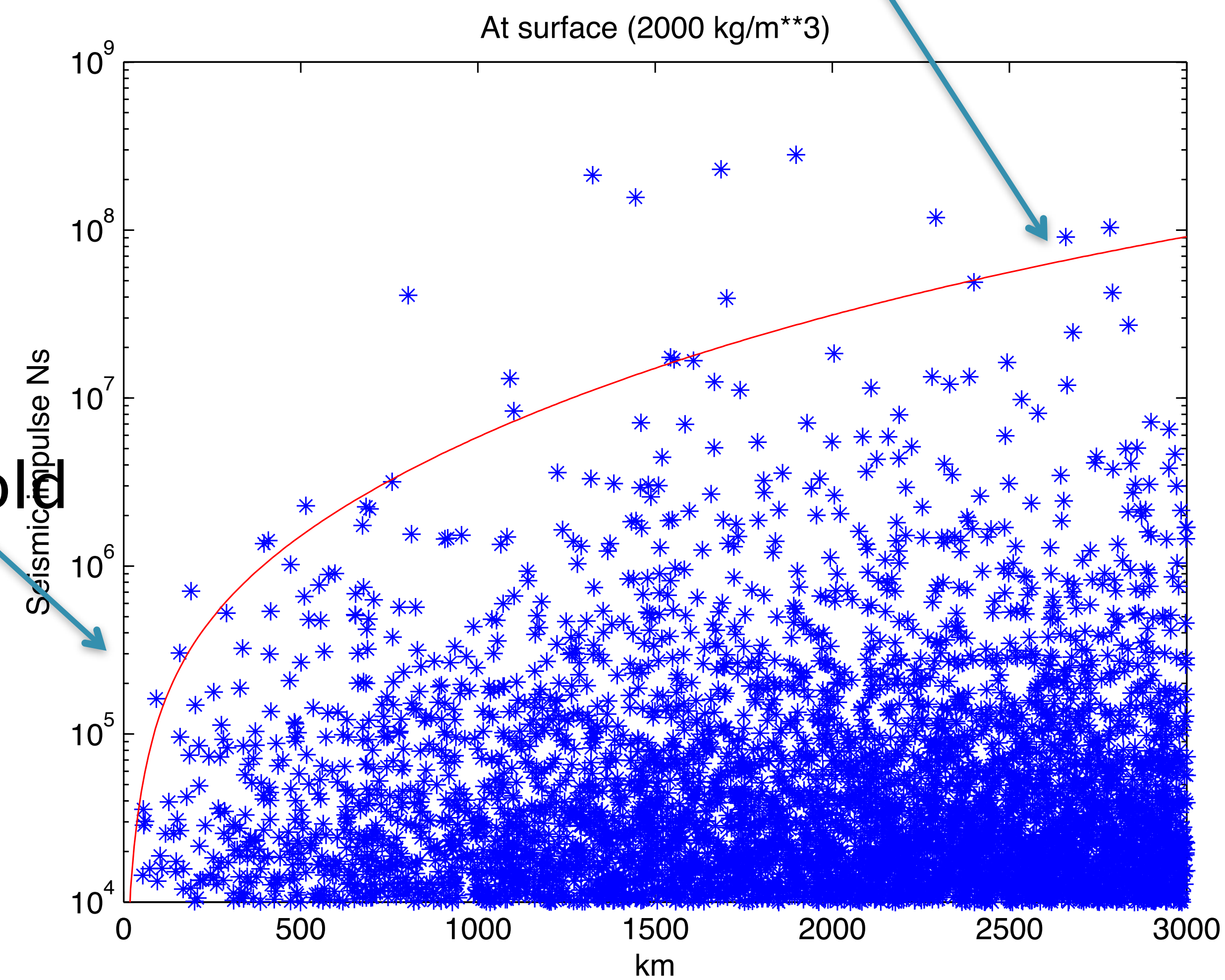
2012年7月9日月曜日

About 20 impacts in 1 Mars yrs with S/N > 3 (D < 3000 km)
(16 for D < 2000 km and 4 for D < 400 km)

Seismic SN ~3



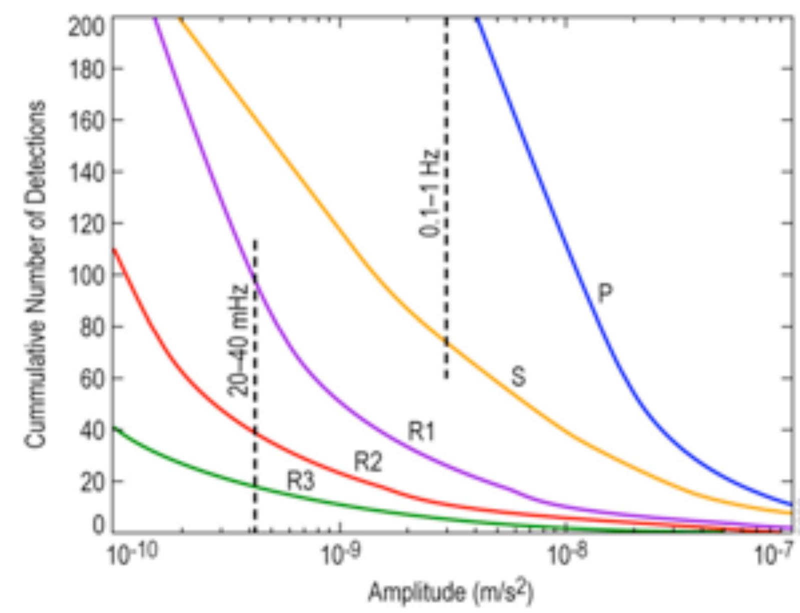
MRO Optical detection threshold

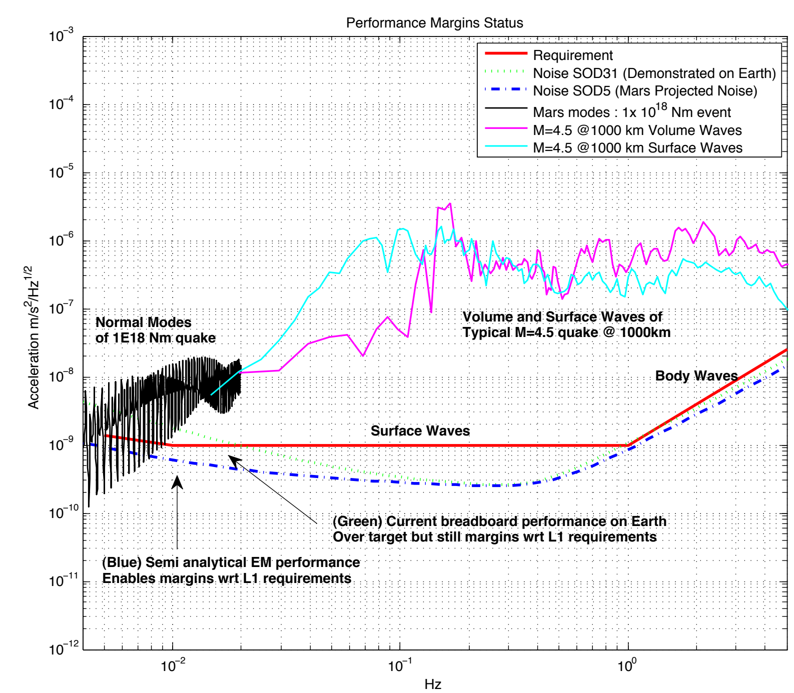


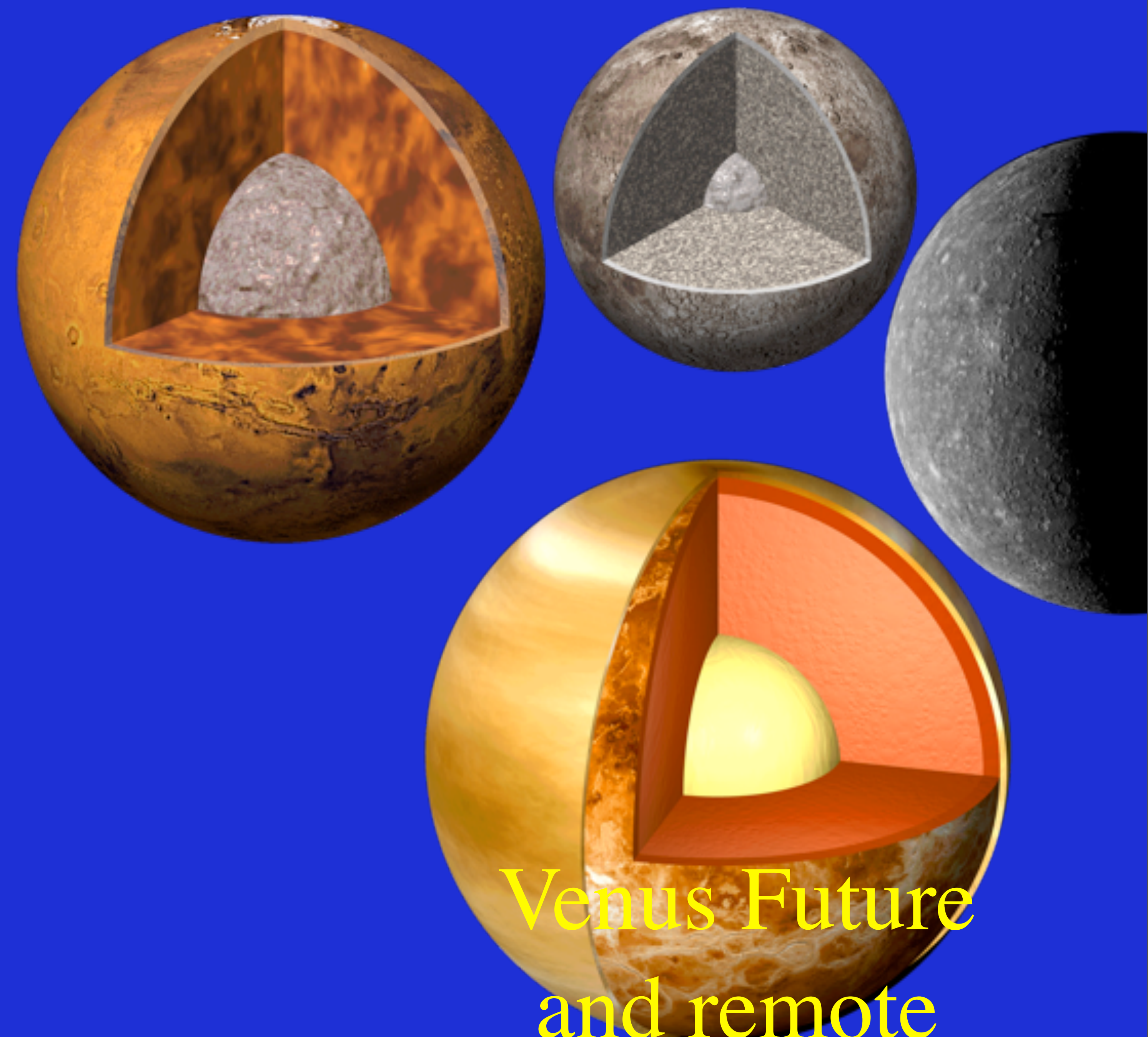
Joint MRO/InSight impacts observation will allow location constrained seismic analysis and amplitude constrained impact analysis with science return similar to the artificial impacts of Apollo!

Summary

- Modeling indicate that a Low noise (e.g. $<10^{-9}$ $ms^{-2}/Hz^{1/2}$) can be reached on Mars
- Such a low noise enable in 0.7 Mars yr
  - > 10 quakes with R3 and core phases
  - > 40 quakes with P,S,R1 including > 25 with R2
- Such a data set will made possible (with margin of 100%)
  - The determination of the absolute crustal thickness to ±10 km
  - The determination of the seismic velocities of the upper mantle to ±0.25 km/s
  - And the determination of the rate and location of Marsquakes (location within



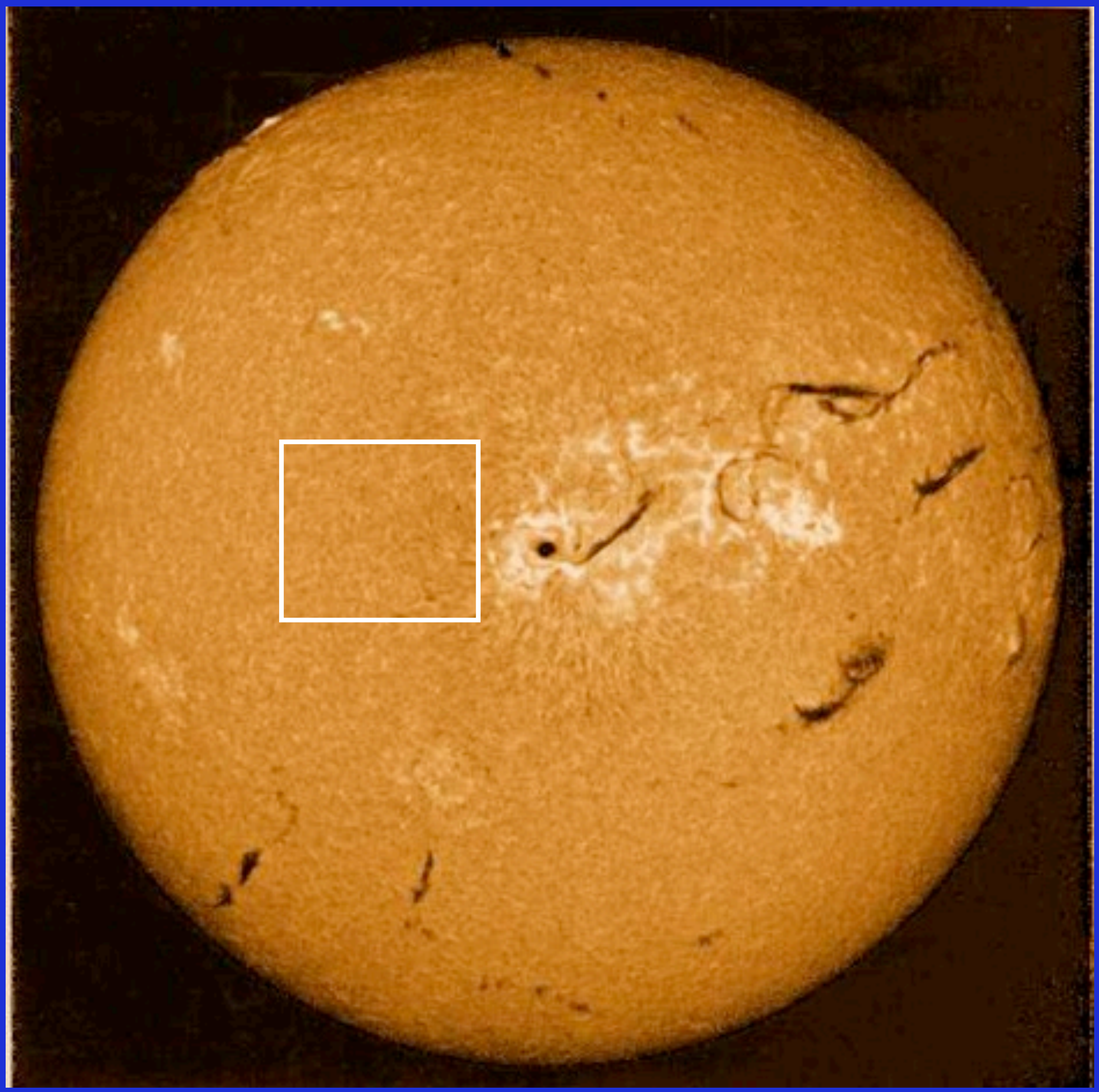




Venus Future and remote sensing

Remote sensing planetology

Exemple 1: seismic remote sensing of the Sun

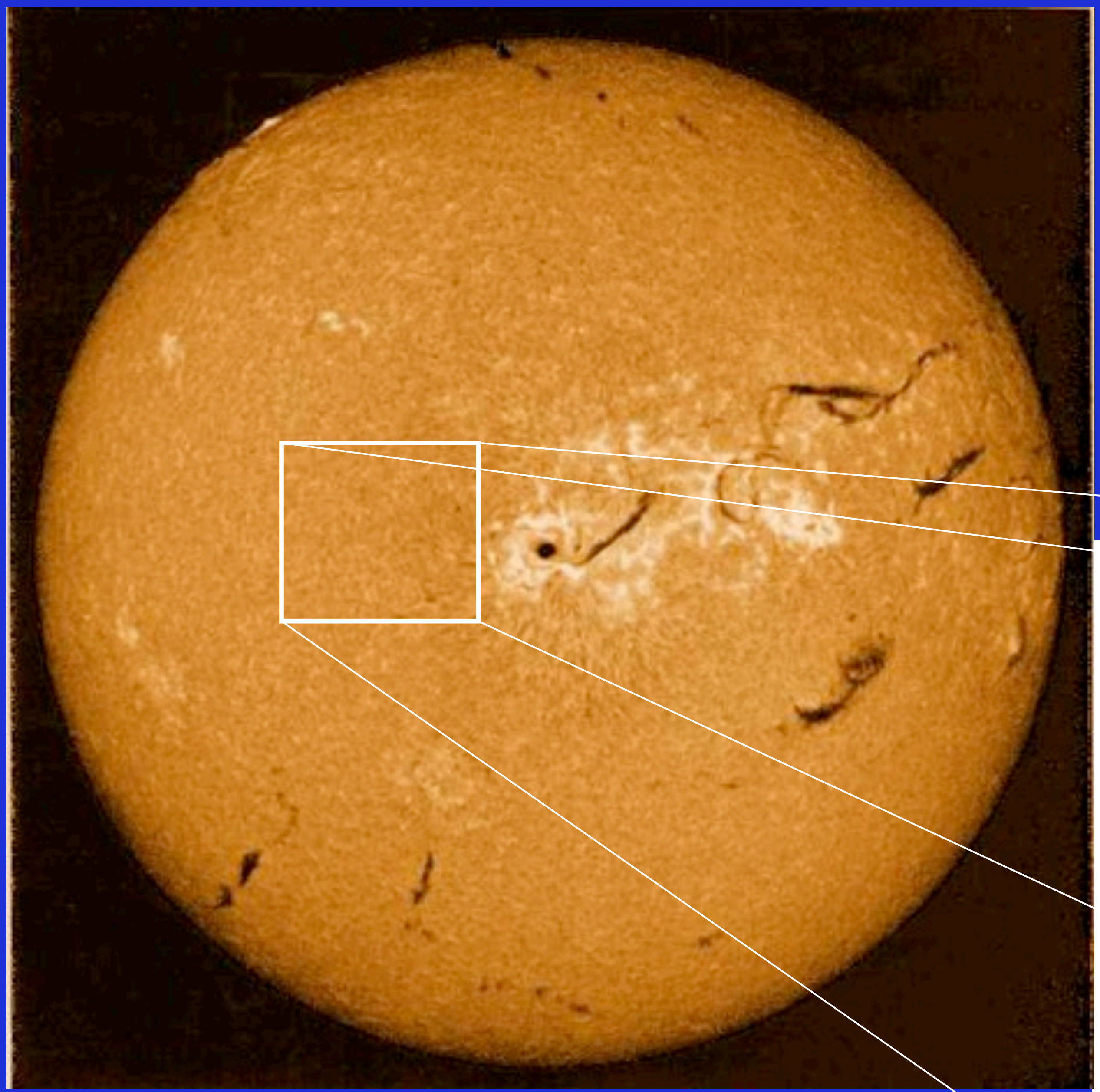


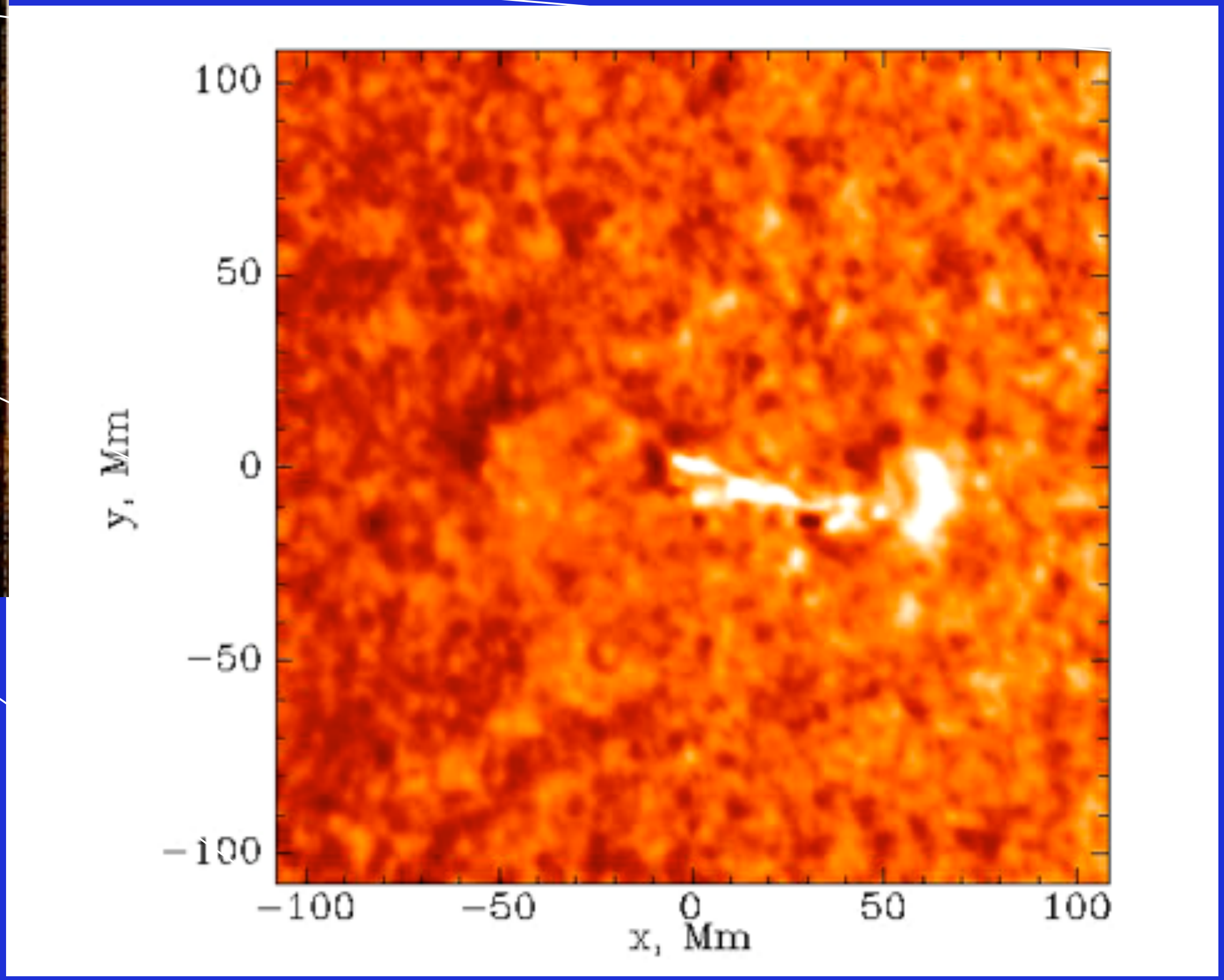
1,400,000 km

- ESA/NASA spacecraft observation with MDI (Michelson Doppler Interferometer Instrument)
- Sun velocity is measured by a using emission of Ni in the photosphere
- 1024x1024 pixels provide the vertical velocity of the Sun every 60 sec with 20 m/s of error

Exemple 1: seismic remote sensing of the Sun

- July 9, 1996 solar flare
- Quake equivalent magnitude M=11
- Vertical displacement of about 3 km

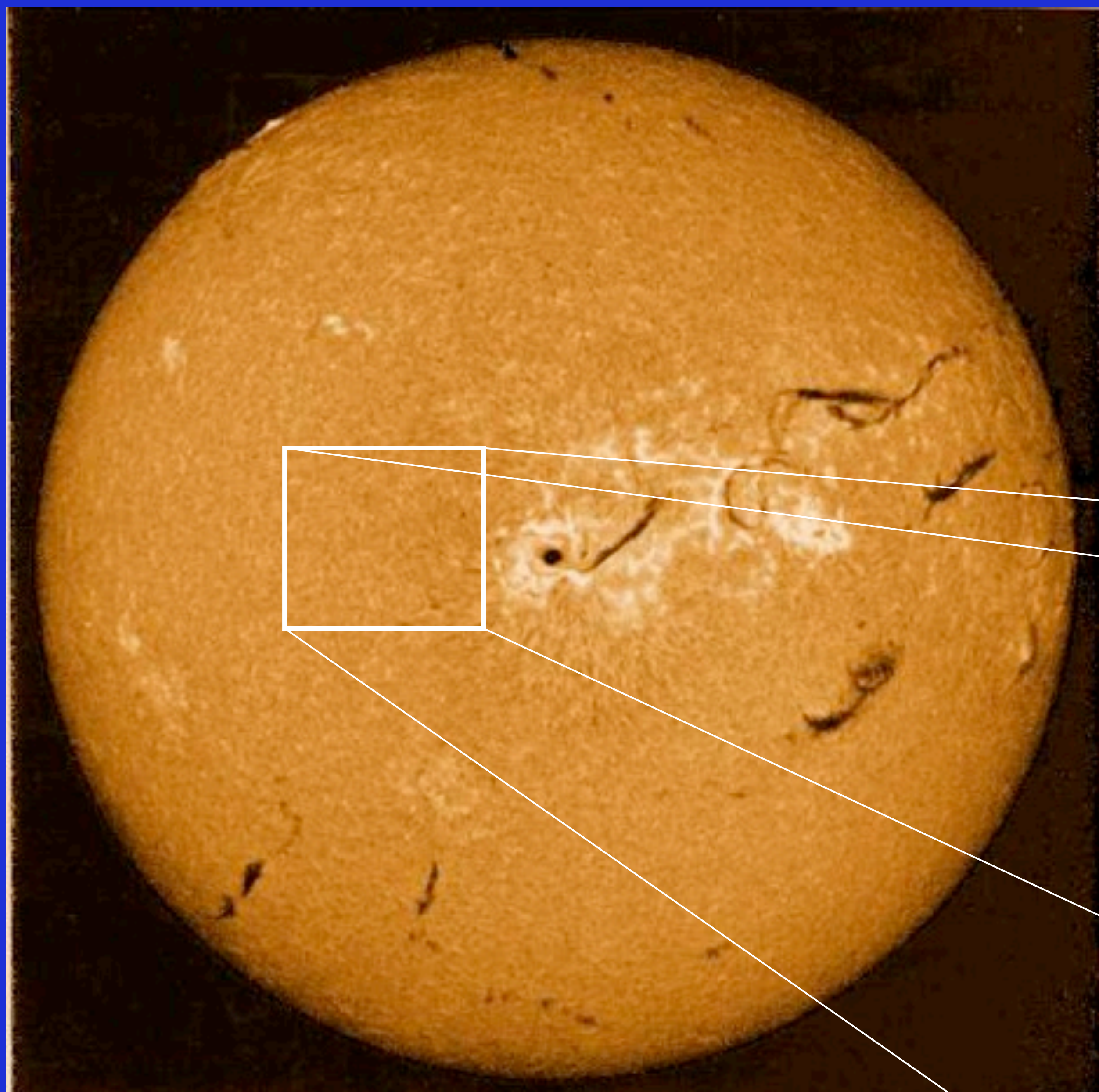




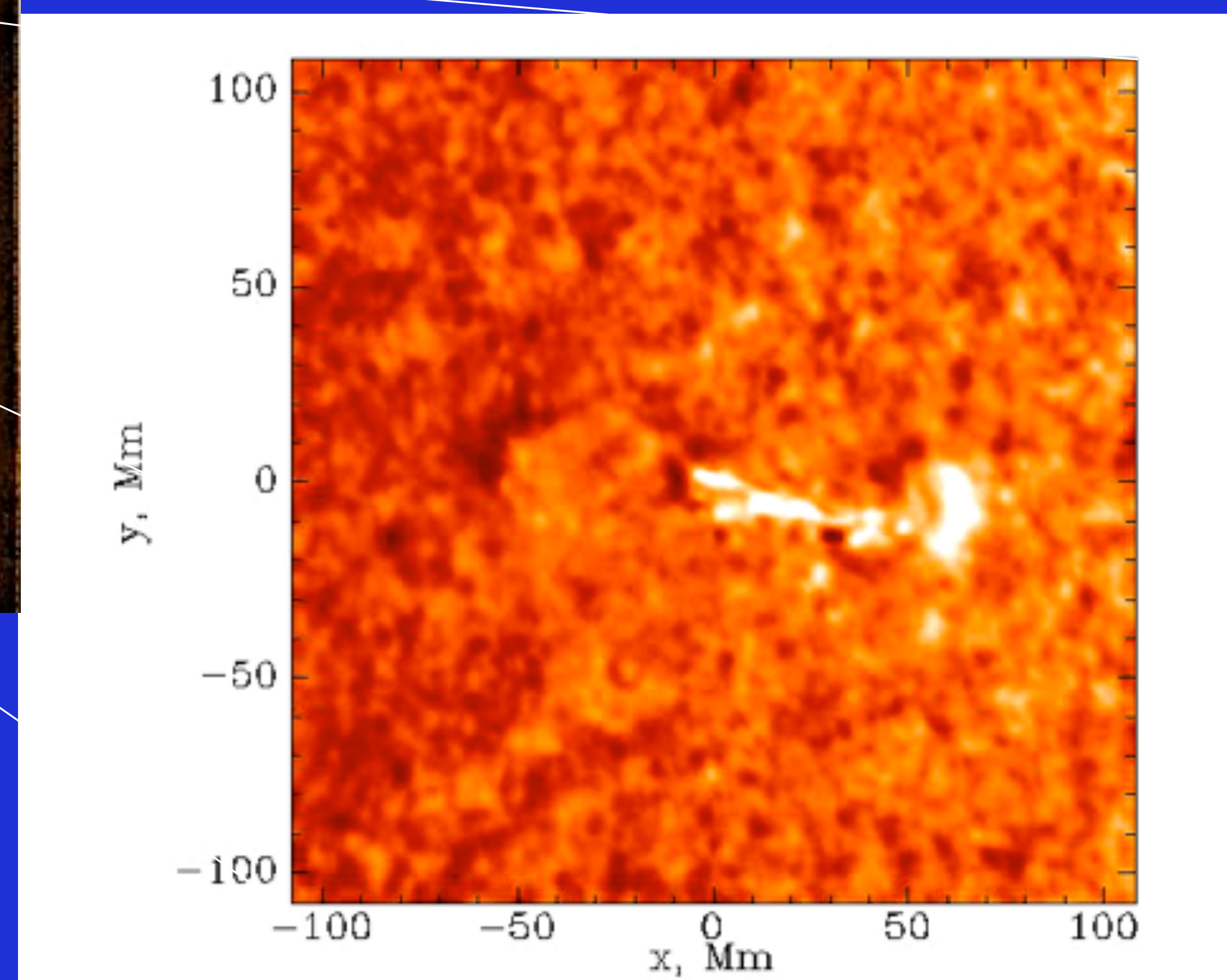
1,400,000 km

A. G. Kosovichev, V. V. Zharkova, Stanford Un.

Exemple 1: seismic remote sensing of the Sun



- July 9, 1996 solar flare
- Quake equivalent magnitude M=11
- Vertical displacement of about 3 km



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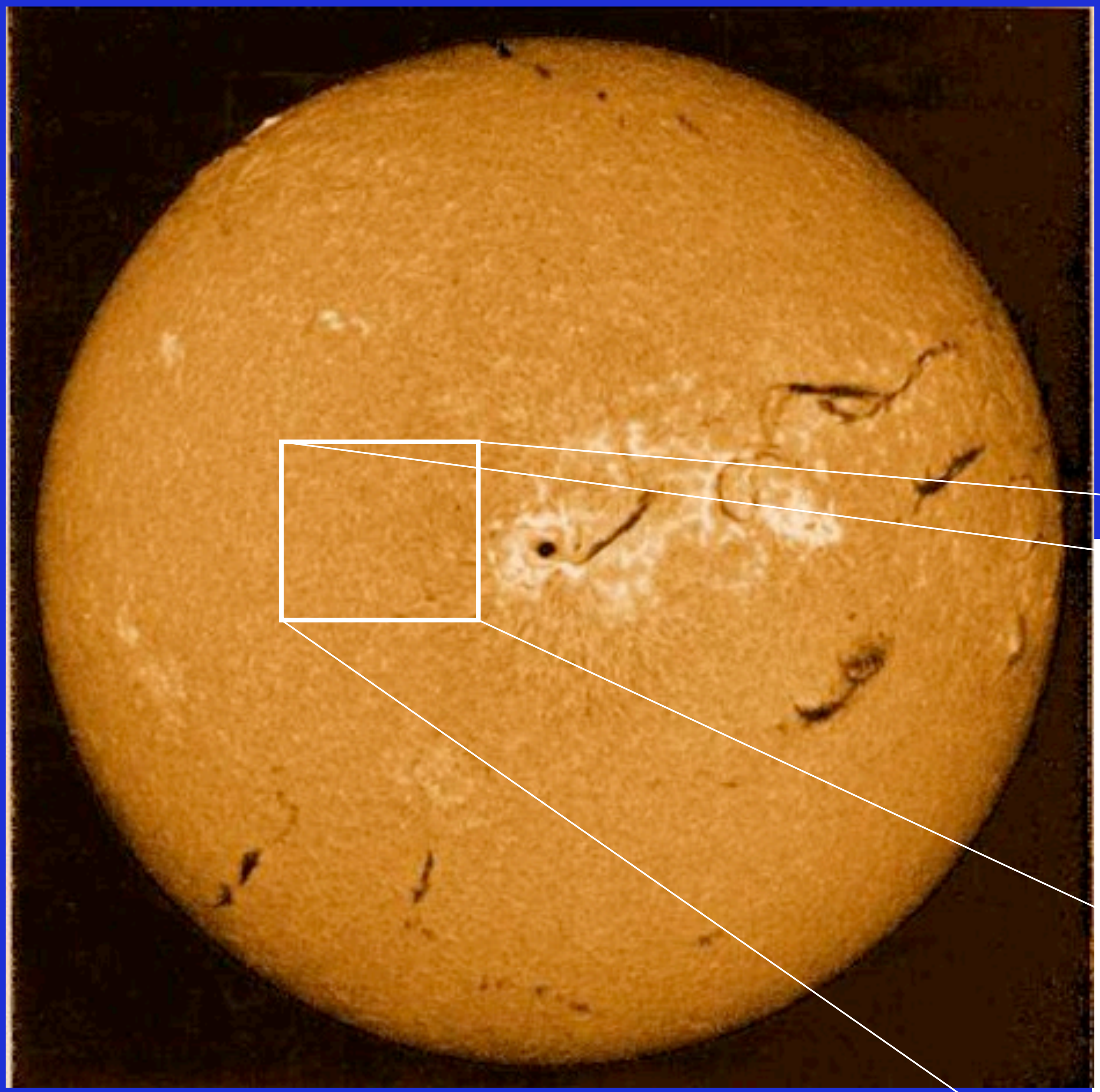
A. G. Kosovichev, V. V. Zharkova, Stanford Un.

Exemple 1: seismic remote sensing of the Sun



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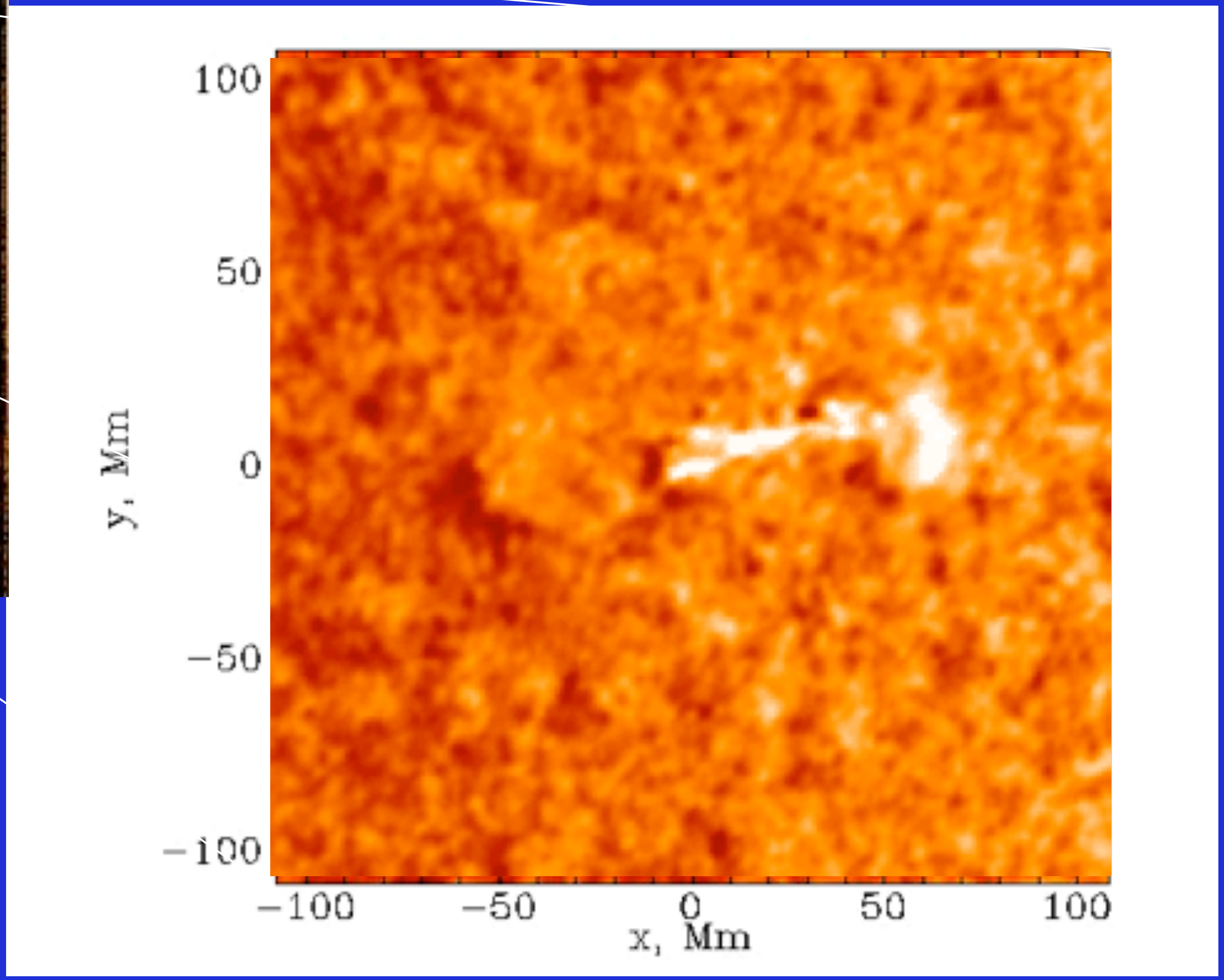
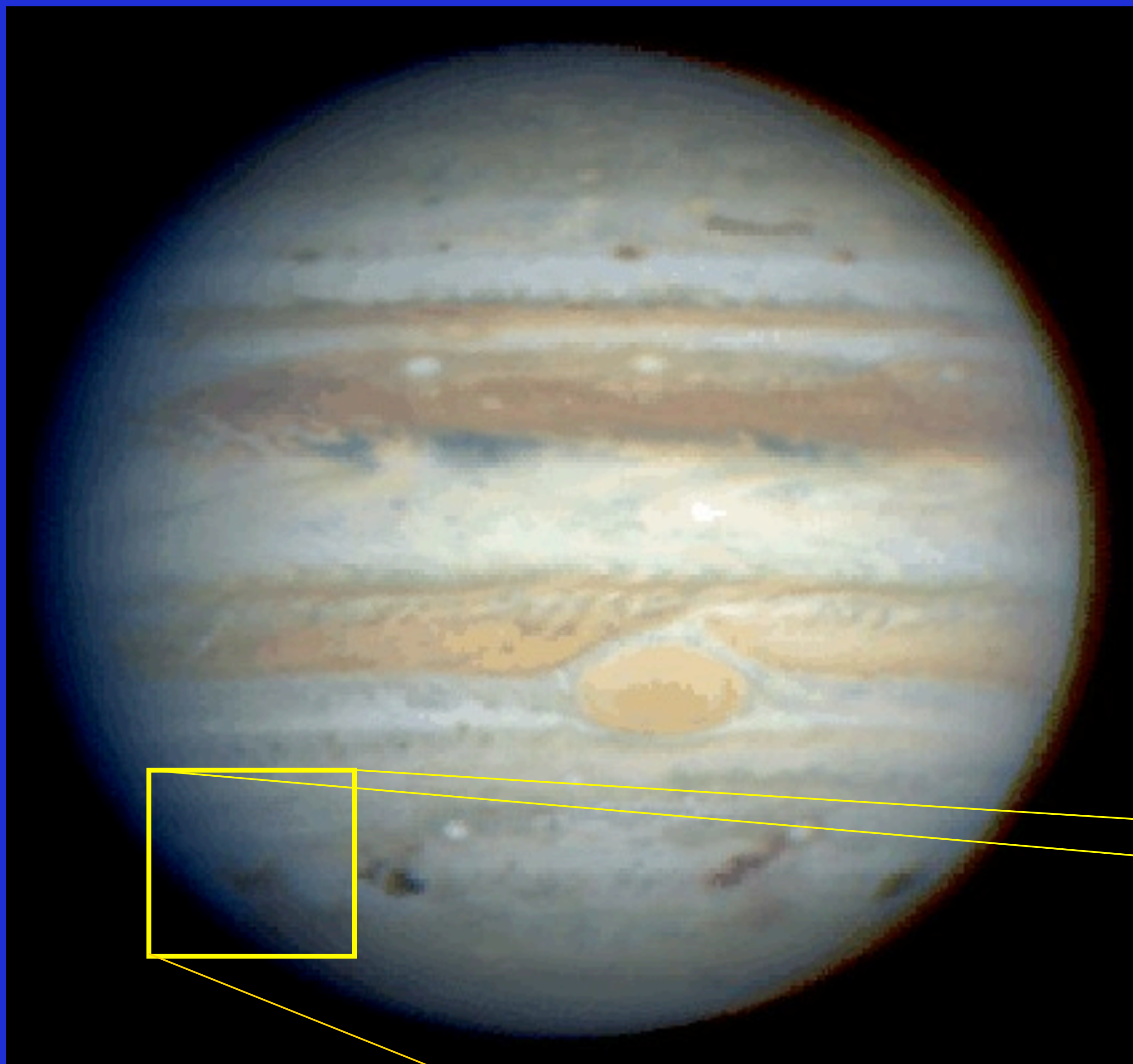


1,400,000 km

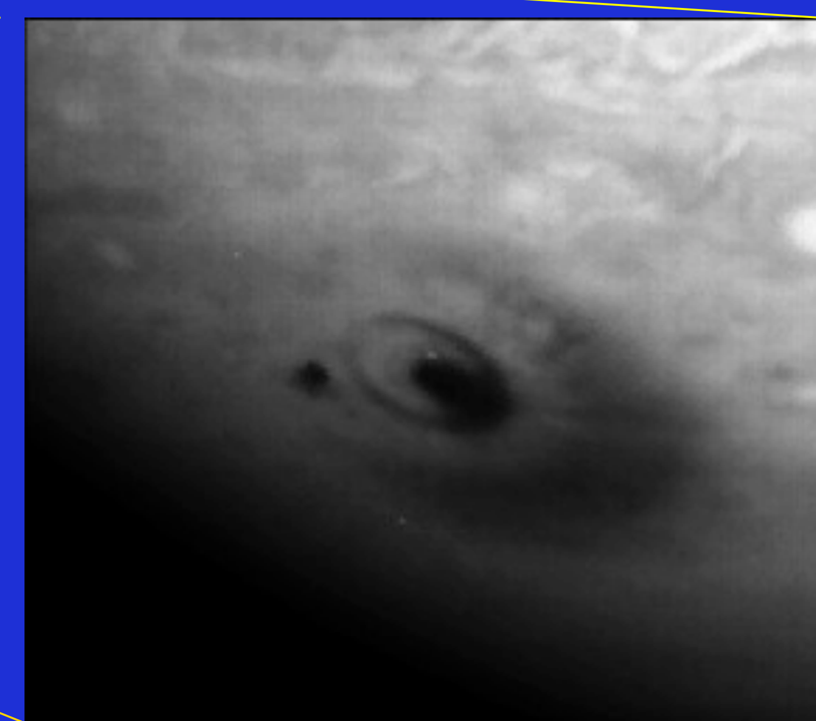
A. G. Kosovichev, V. V. Zharkova, Stanford Un.

Exemple 2: seismic remote sensing of Jupiter



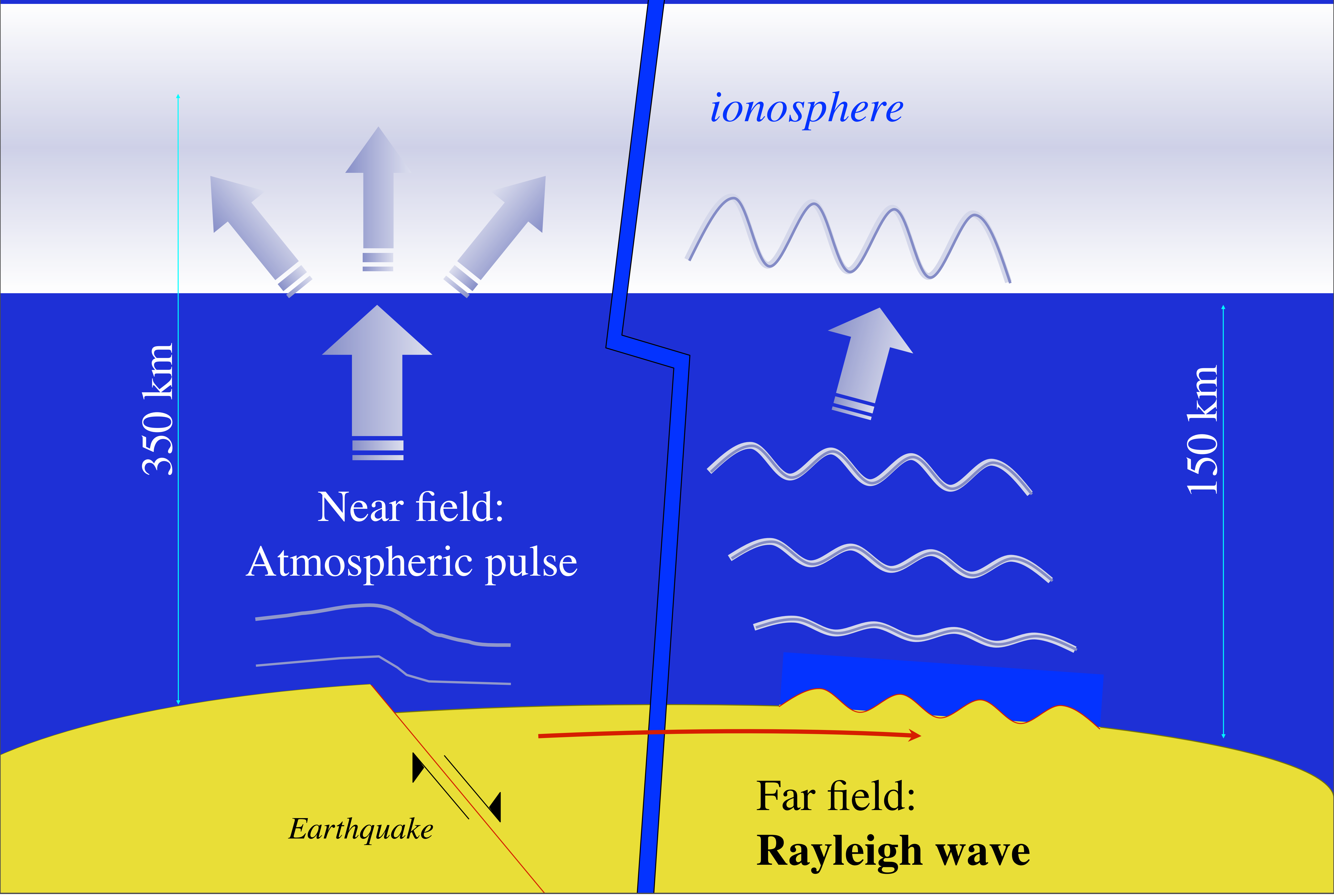
- NASA HST, WFC in optical mode
- July 22, 1994 Shoemaker-Levy 9 impact
- Quake equivalent magnitude M=9
- Vertical displacement 100m but with clouds-albedo modification
- No seismic waves observed on ground and space observations
- Tsunami/gravity waves observed

130,000 km

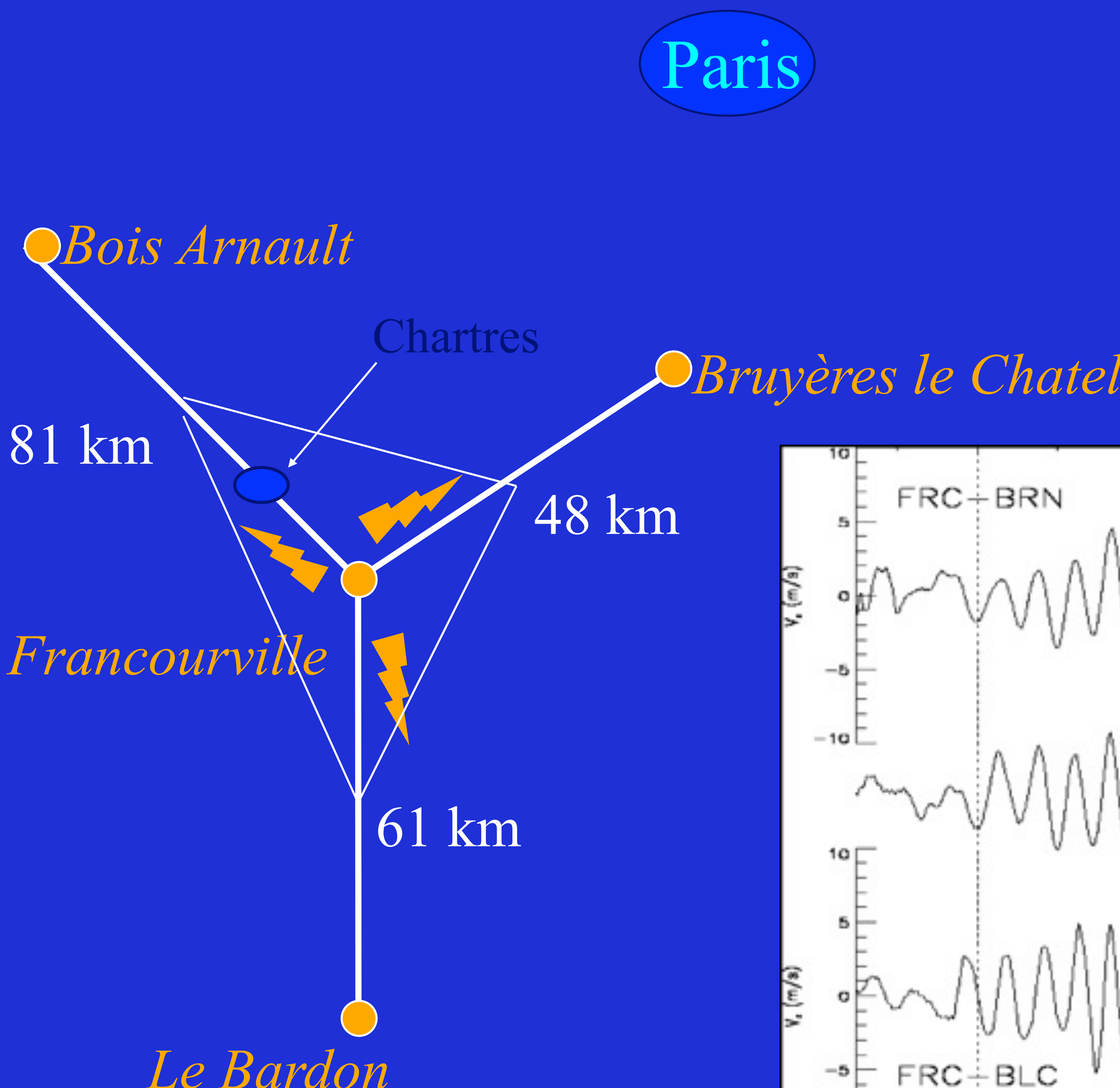


H. Hammel et al, MIT

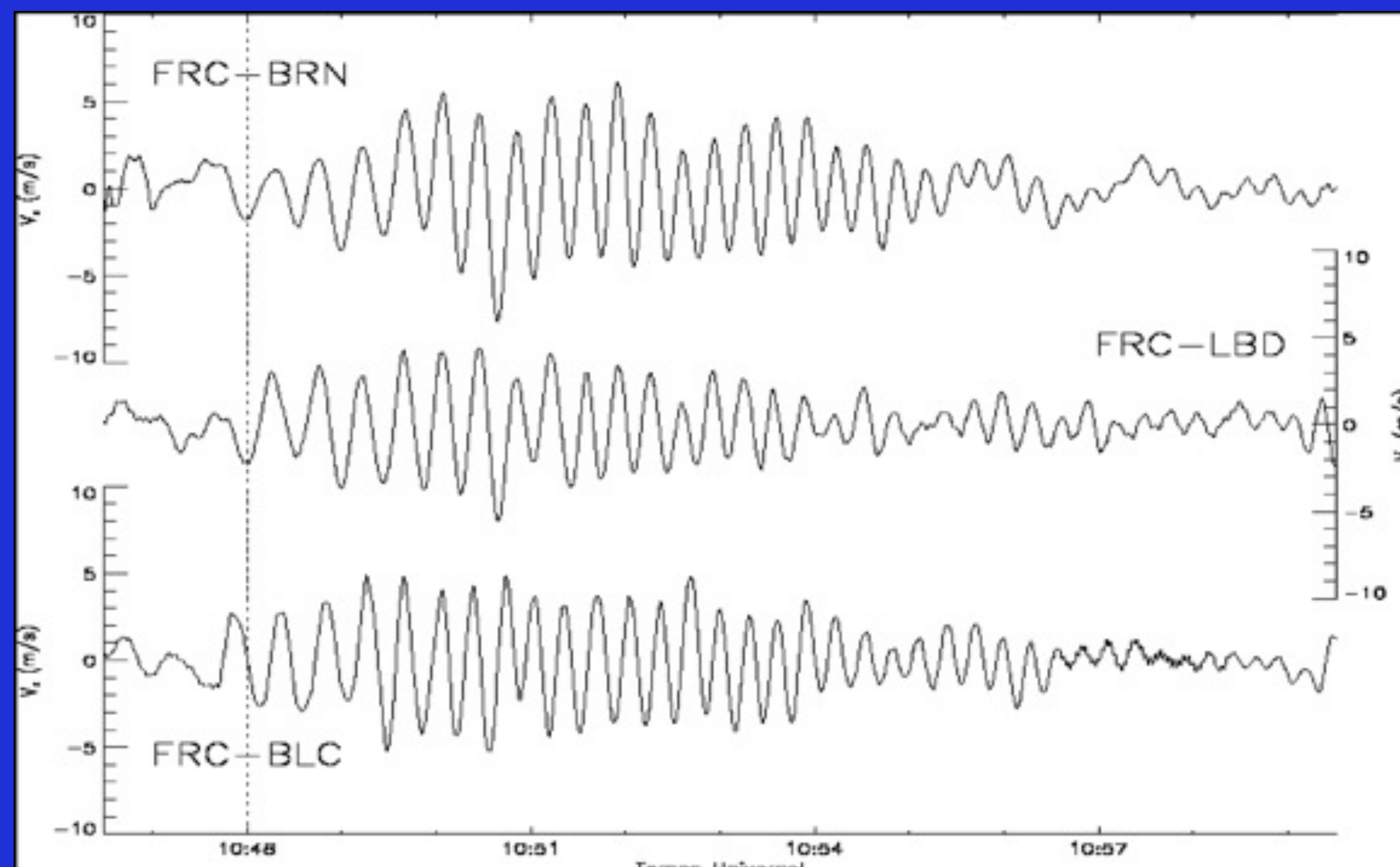
Generation mechanism of infrasonic waves by seismic waves



Francourville ionospheric sounding network



The network has been working continuously since August 1999, most of M>6.5 earthquakes have been observed.

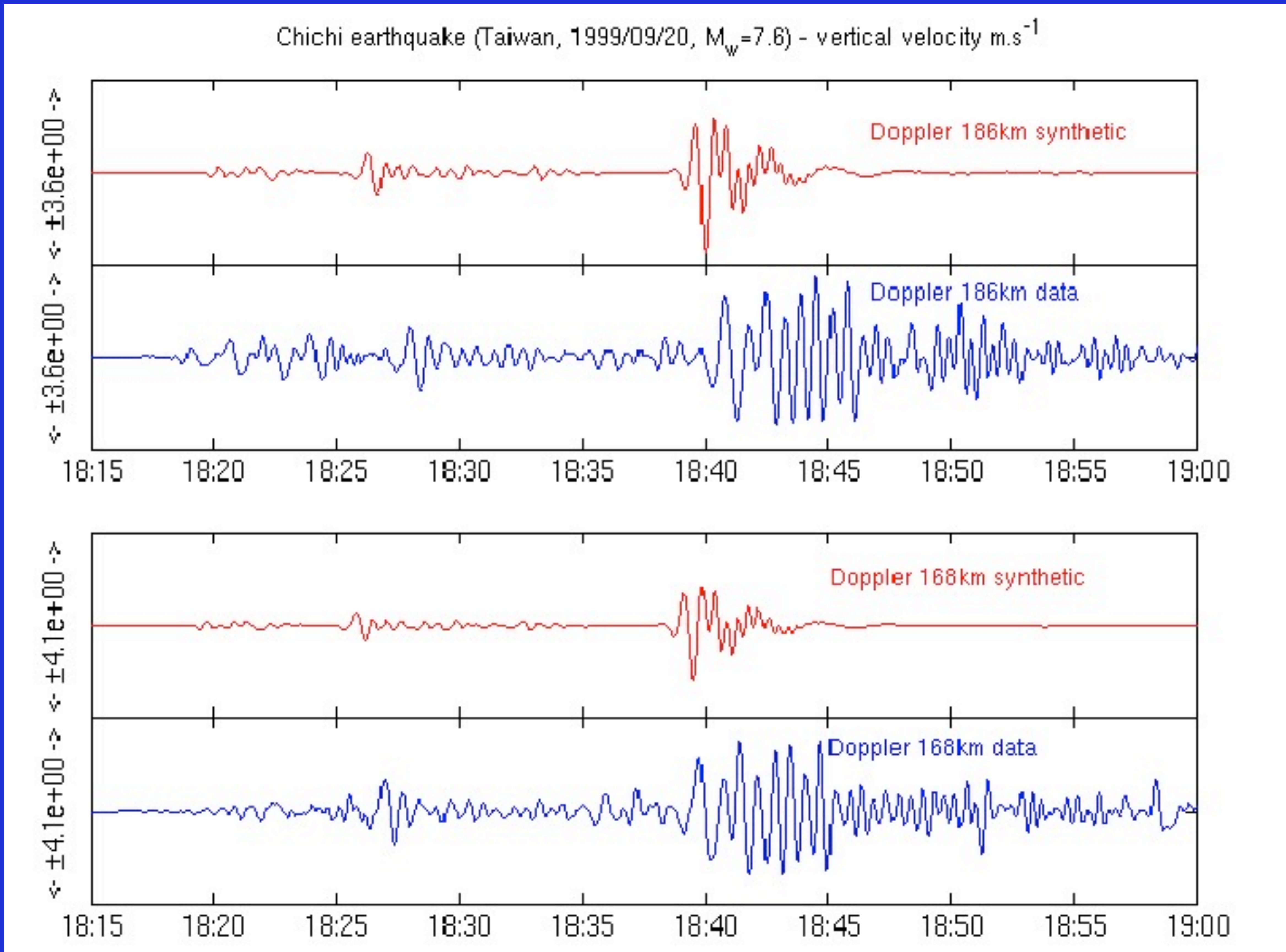


Seismic ionospheric oscillations detected at Francourville 1999/08–2000/06

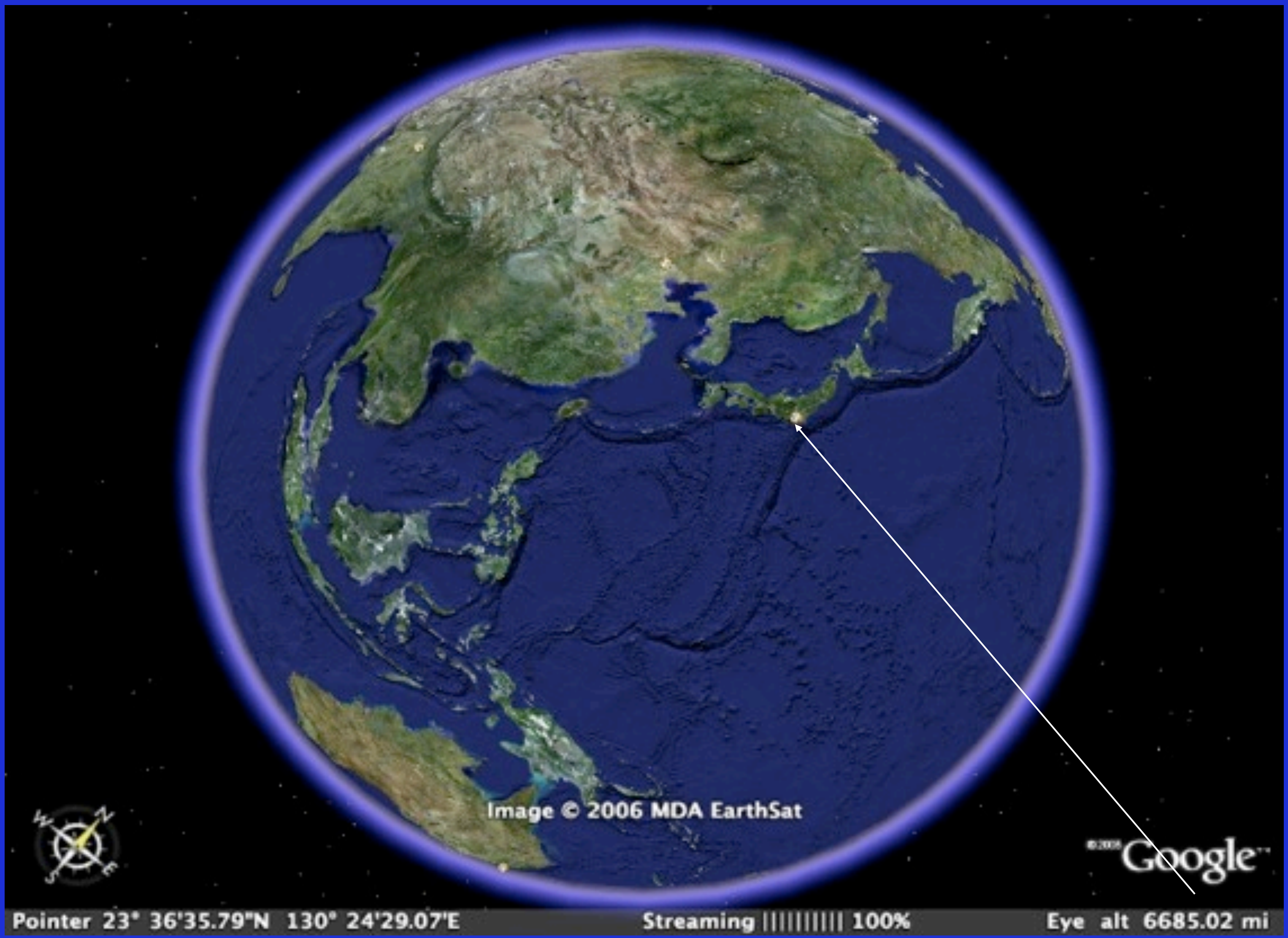
4.6 Mhz, Costa Rica, August 20, 1999
High pass at 200 sec

Artru et al, 2006

3D waveform complexity

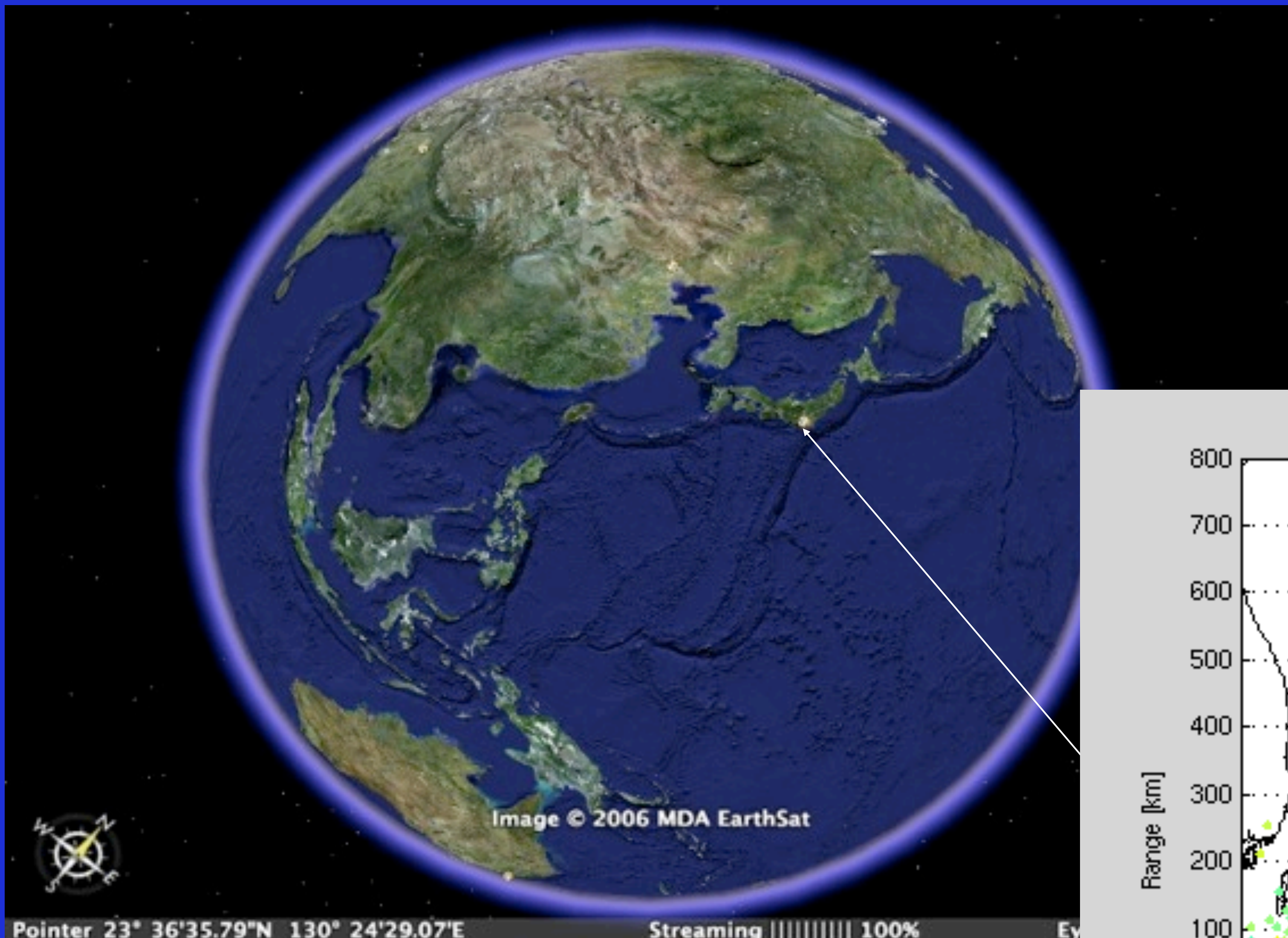


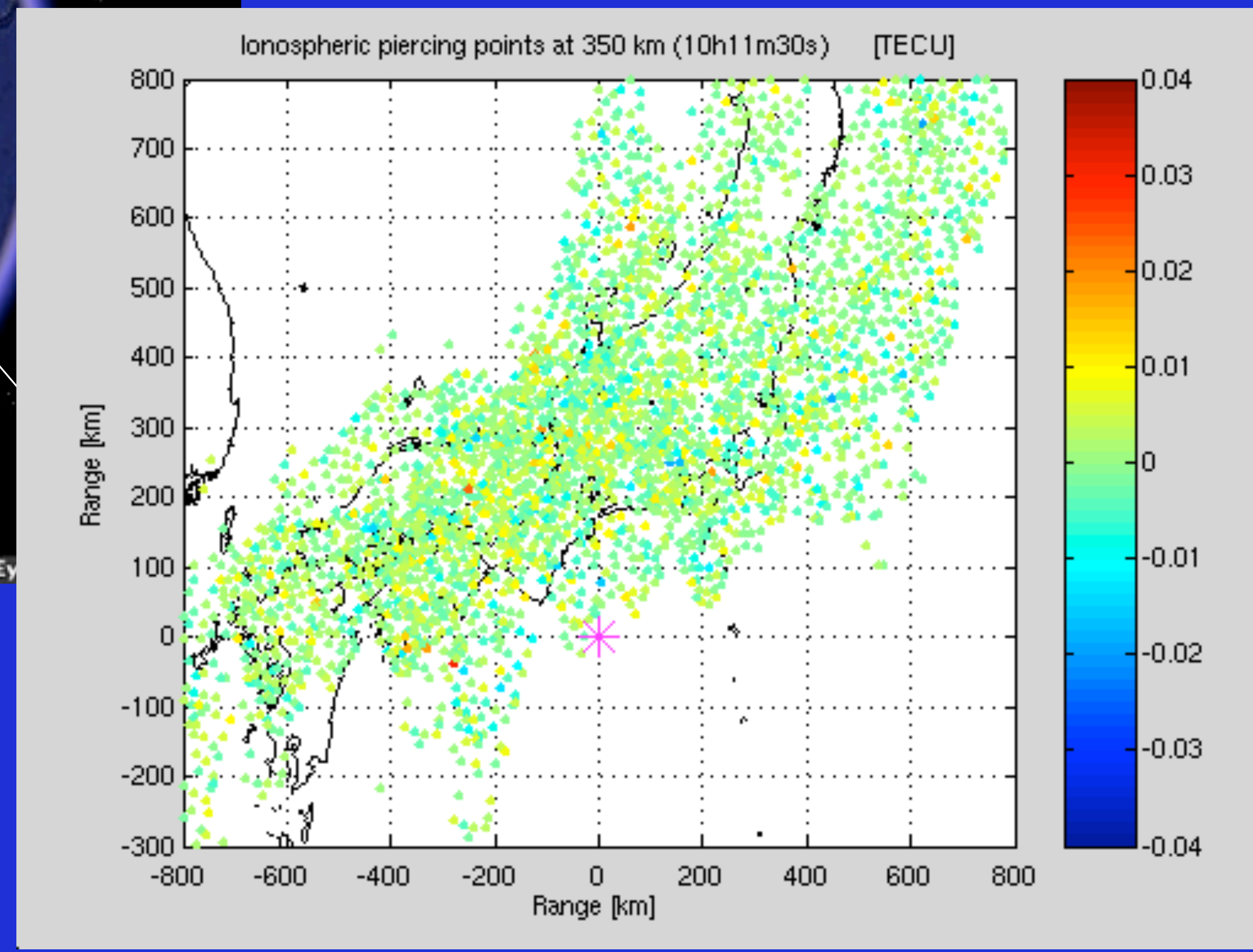
Example 3: remote sensing on Earth



Tohoku 11/3/2011 M~9

Example 3: remote sensing on Earth





Tohoku 11/3/2011 M~9

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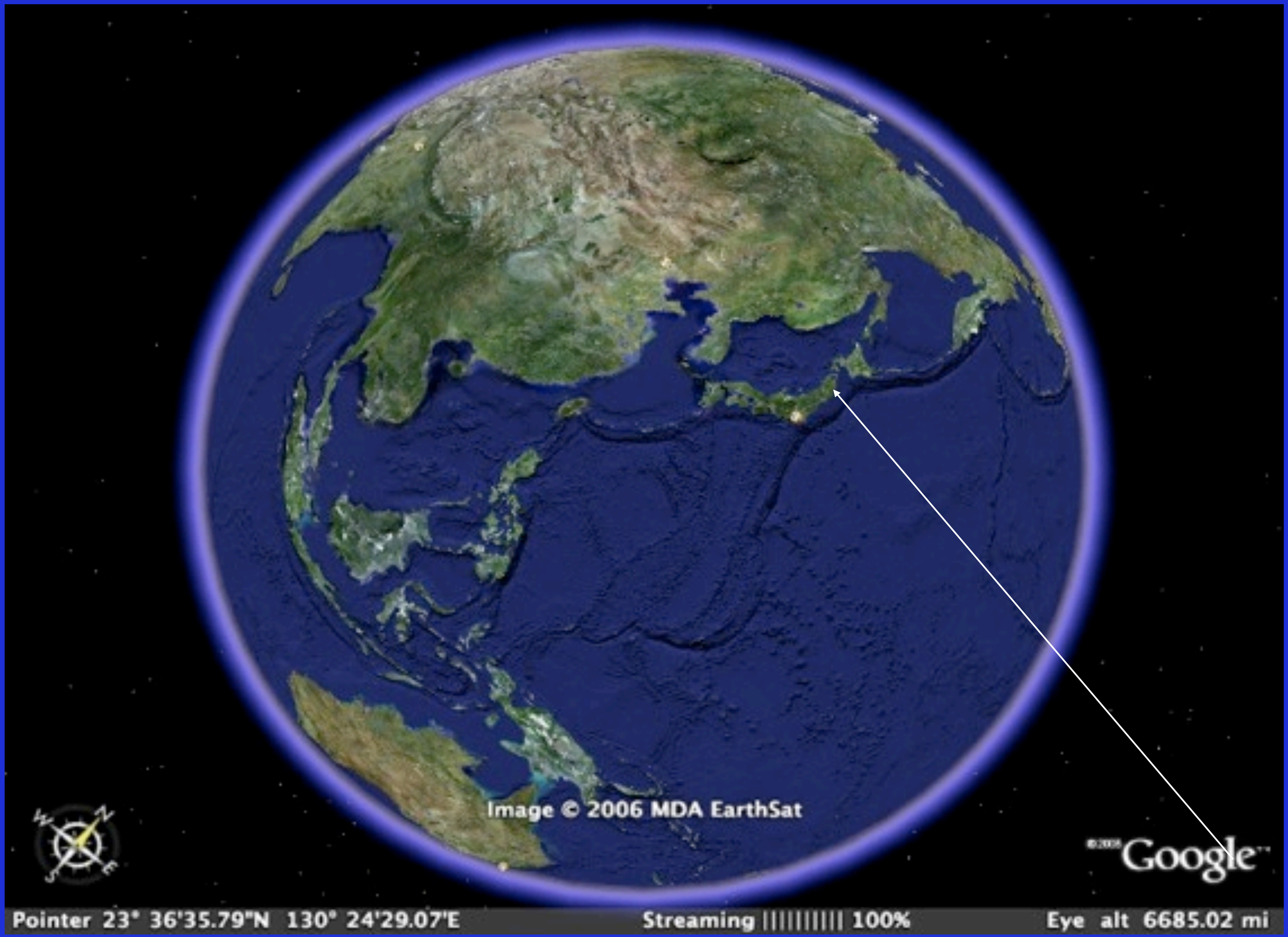
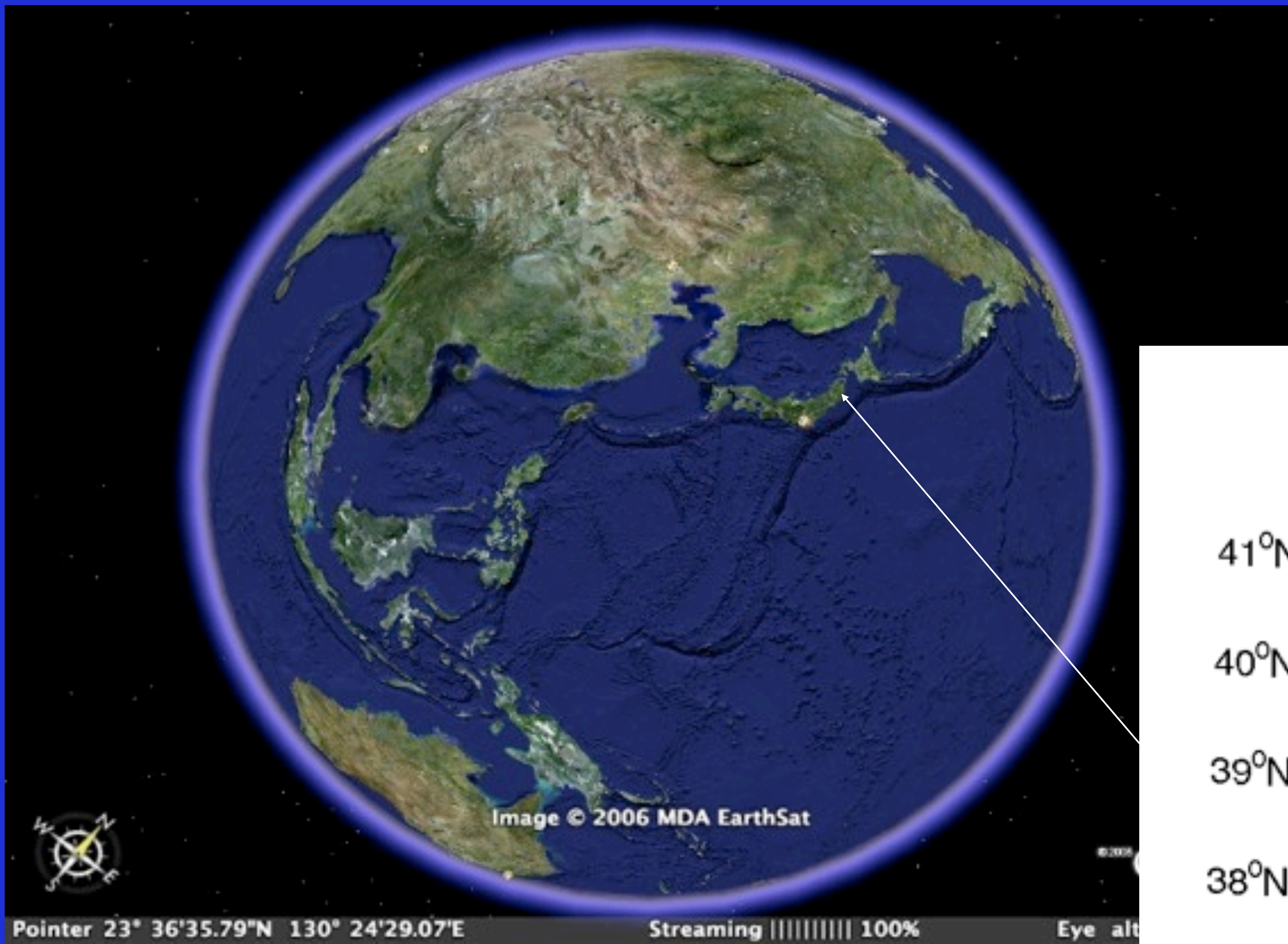
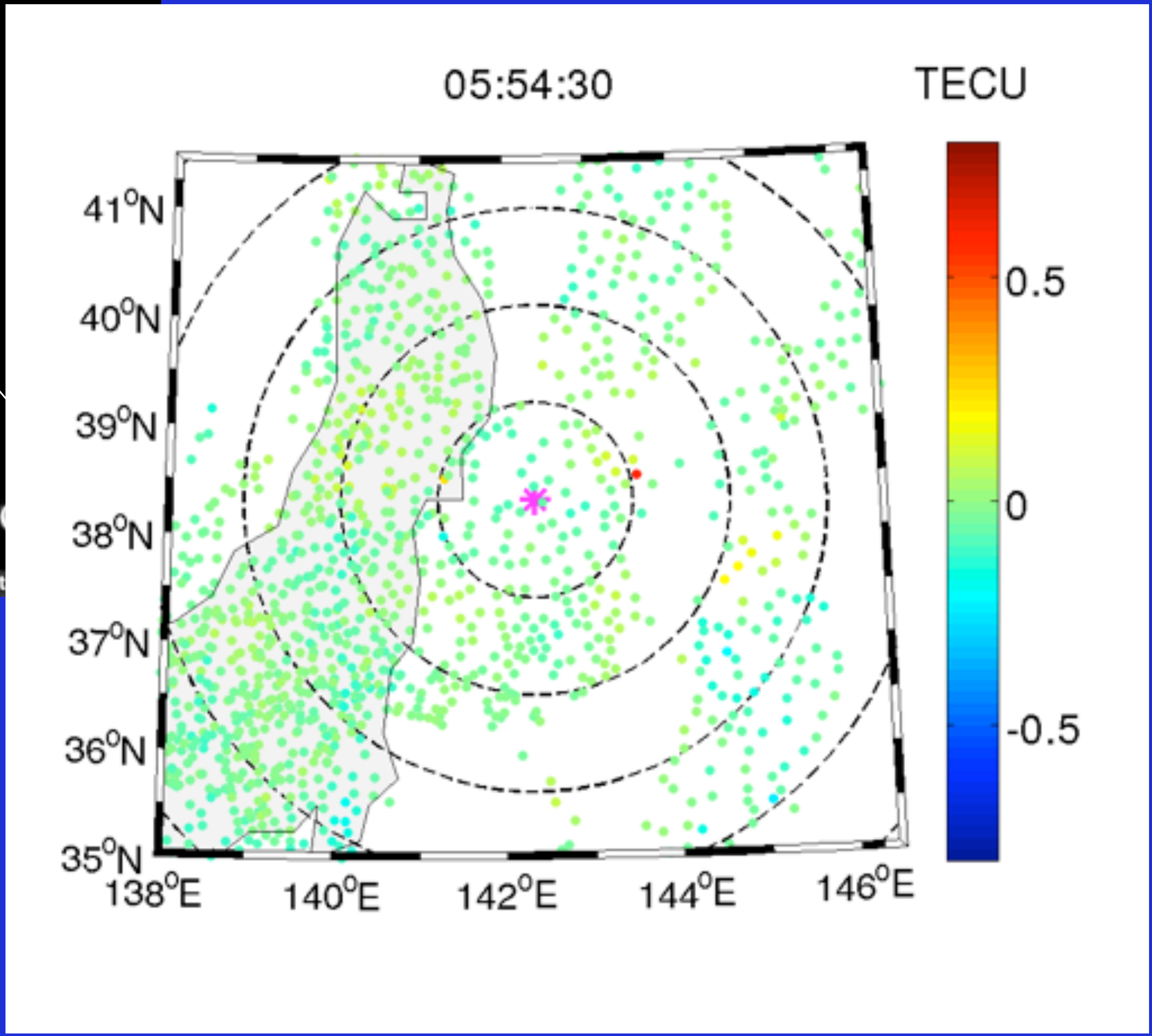


Tohoku 11/3/2011 M~9, Astafyeva et al, Rolland et al, 2011

Example 3: remote sensing on Earth





Tohoku 11/3/2011 M~9, Astafyeva et al, Rolland et al, 2011

OI red line

- 630 nm
- Emission peak at 250-300 km
- quiet night 50-100 Rayleigh

$$
\begin{aligned}
O_2 + O^+ &\rightarrow O_2^+ + O \\
O_2^+ + e^- &\rightarrow O + O(^1D) \\
O\left(^1D\right) &\rightarrow O\left(^3P\right) + h\nu
\end{aligned}
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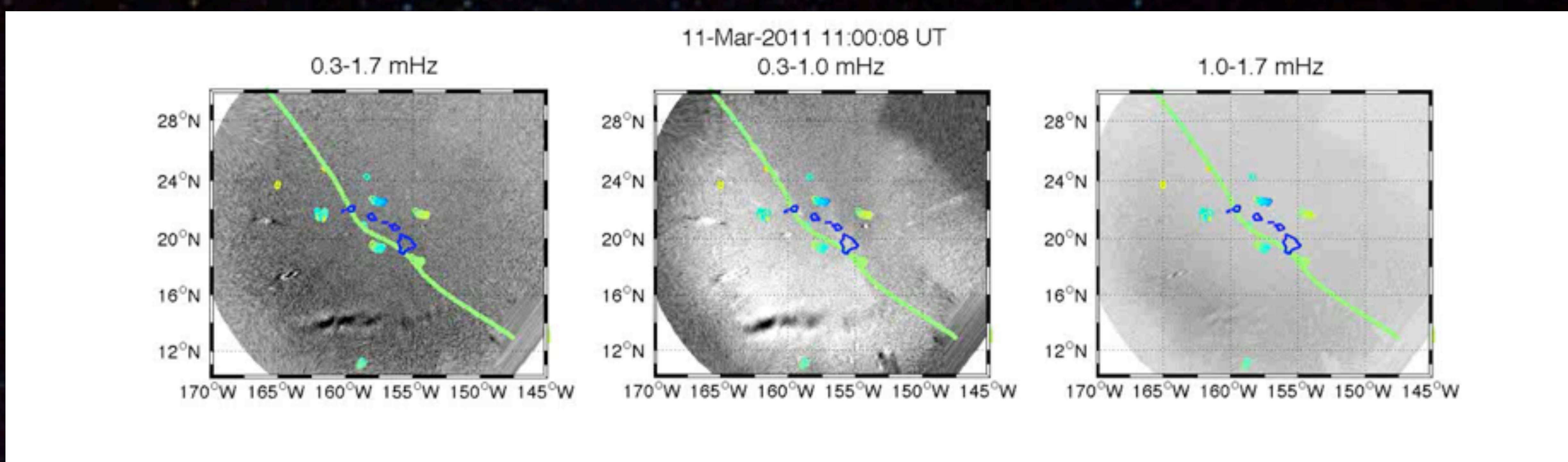
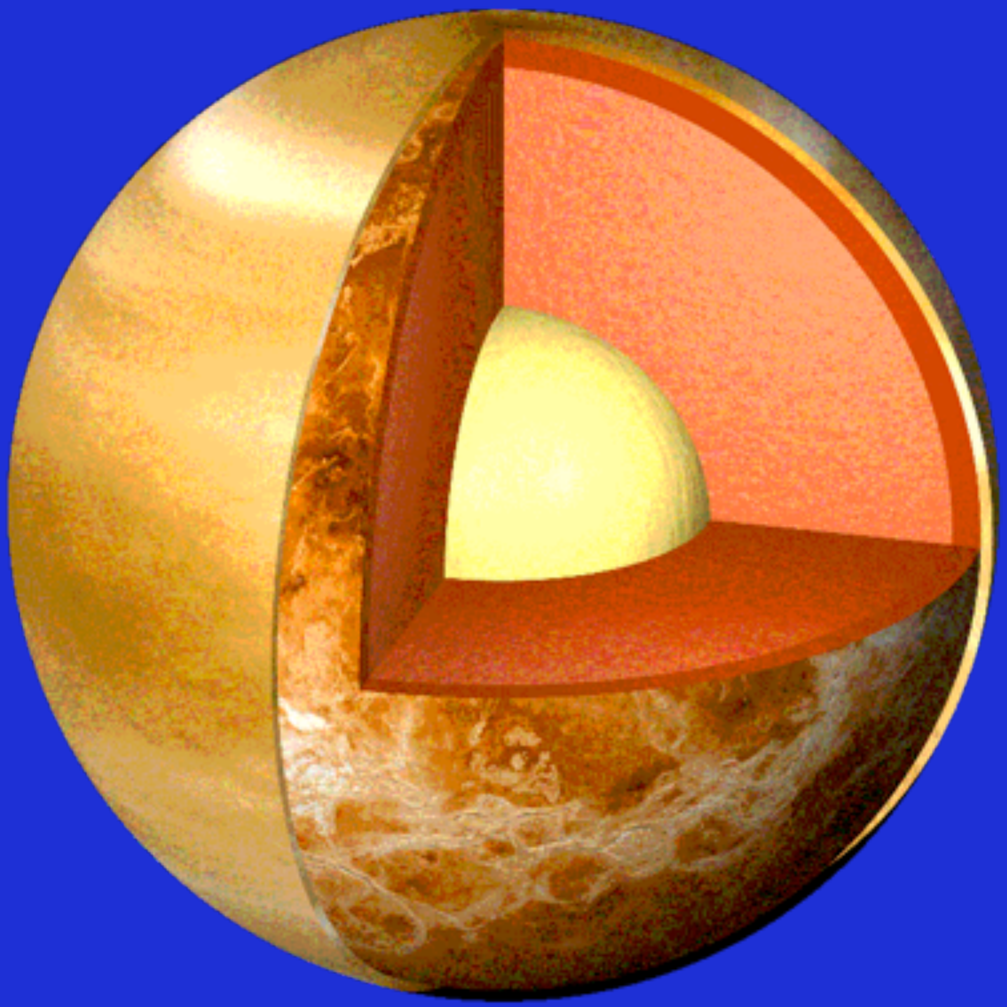
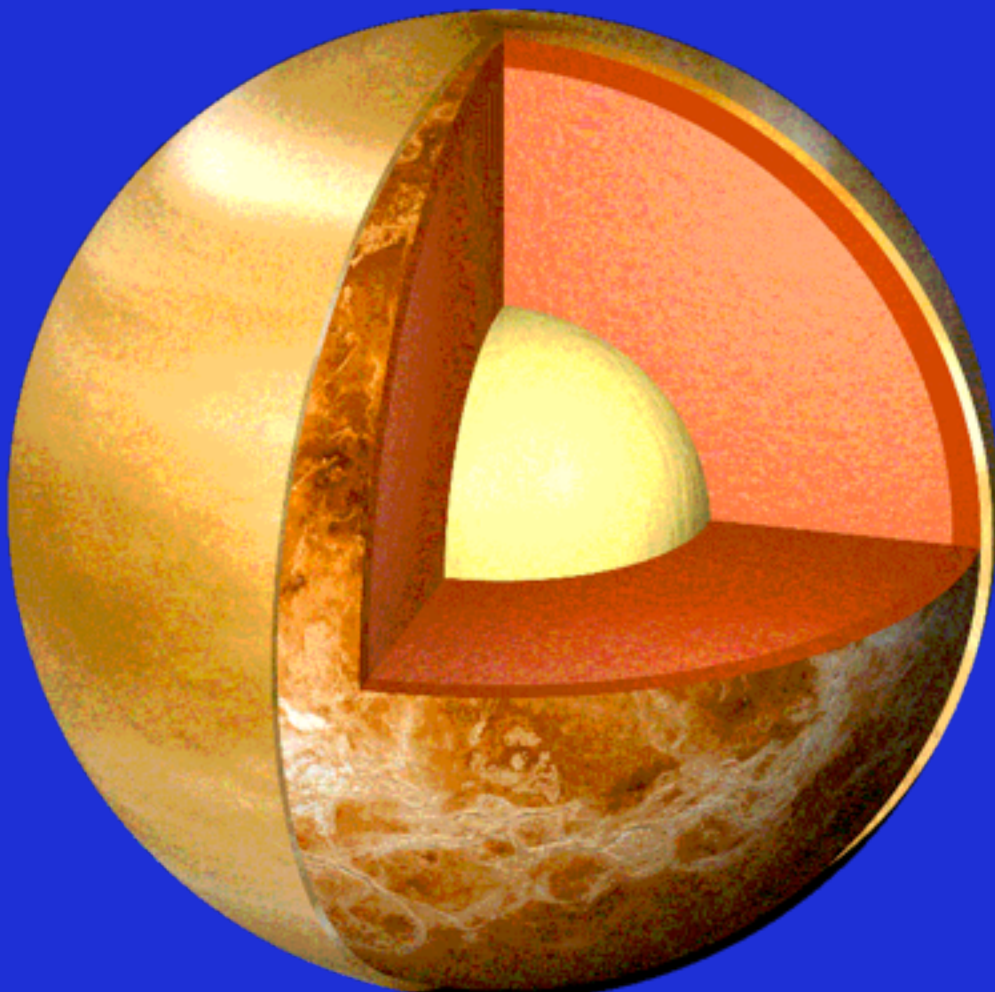
Makela et al., 2011



Example 4: Venus?



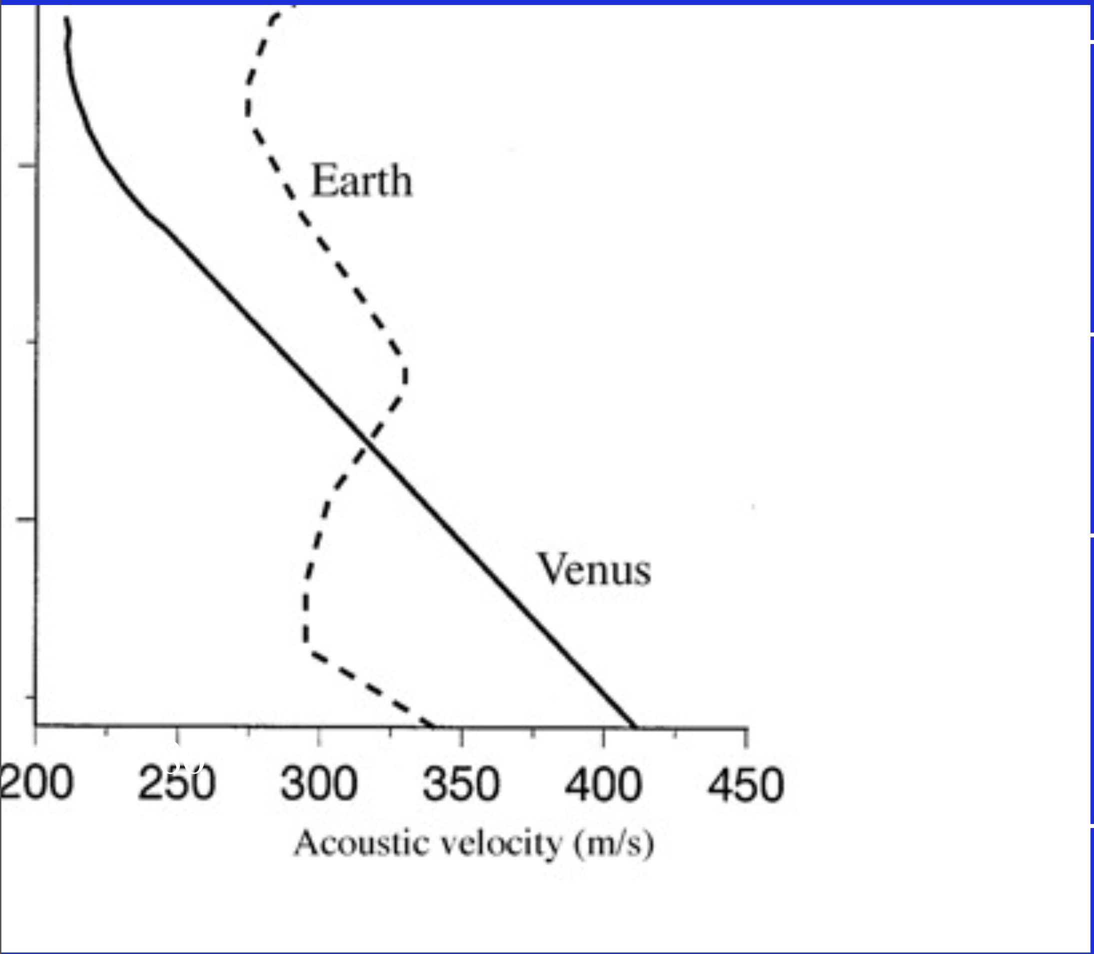
Example 4: Venus?



- The resurfacing history of Venus provide an average age of 300-500 Myears for most of the planetary surface
- Rate of volcanism comparable to Earth intraplate activity are found
- Seismic activity of Venus might generate a few Ms=6 per month
- And at the surface, pressure is about 90 bar, density of about 60 kg/m3, acoustic velocities slightly higher (410 m/s)… Ideal planet for atmospheric seismology

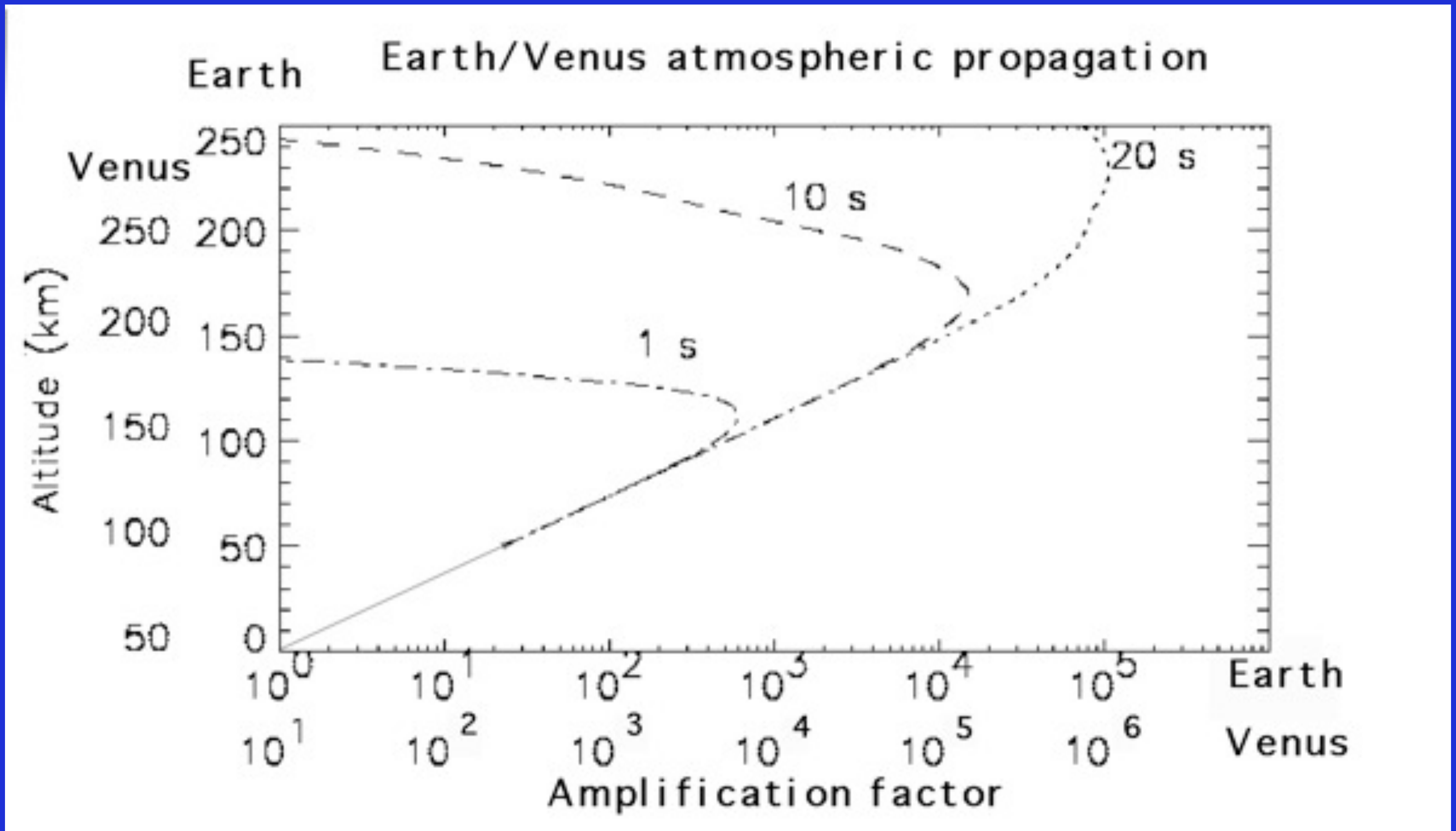
Venus Background for atmospheric seismology

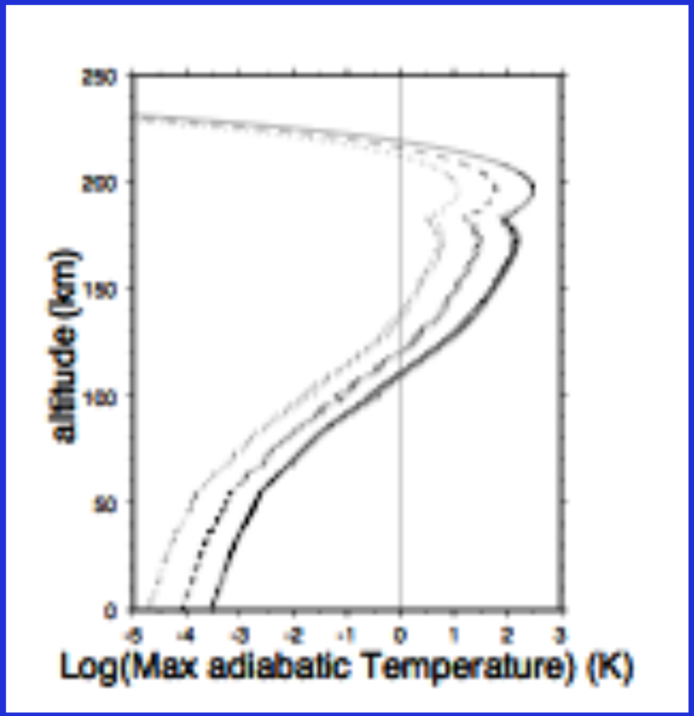
- Maximum ionisation in Venus ionosphere is reached at about 140 km, an altitude comparable to HF sounding altitude on Earth



- Ground acoustic jump is much better
  - At the surface, pressure is about 90 bar, density of about 60 kg/m3, acoustic velocities slightly higher (410 m/s)
  - Ground coupling (ρc) is about 60 greater than on Earth
  - One bar level is reached at about 50 km of altitude, after an amplification by about 10 for acoustic waves
  - Acoustic signals from ground are expected to be about 600 times greater at the same altitude and for the same quake (almost 2 magnitudes)

Body waves…. And high altitude dissipation





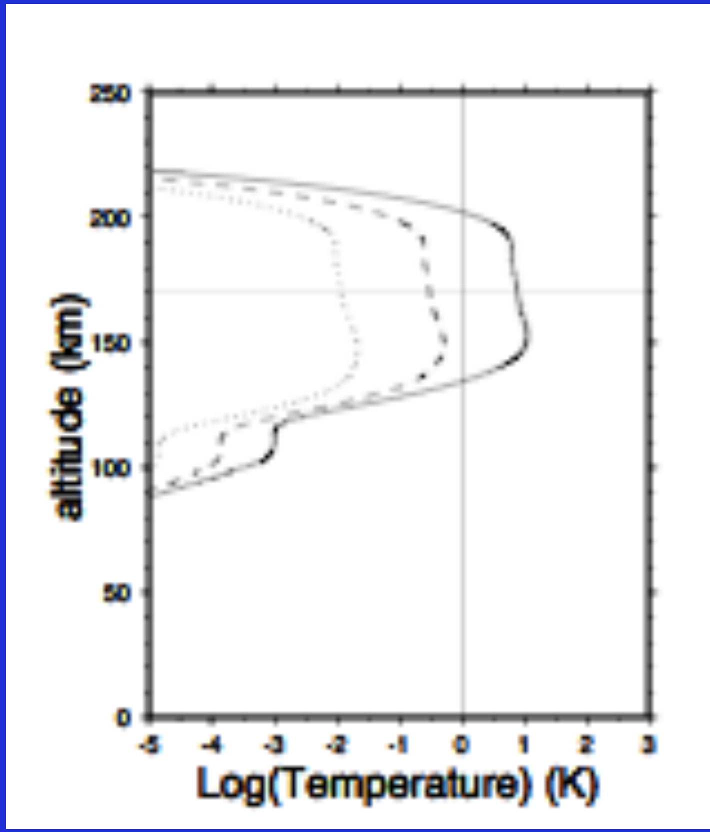
Adiabatic oscillations

- Event will be associated to a thermal signal…
- Event characteristic (Garcia et al., 2005)

  Magnitude : 5,5.5, 6

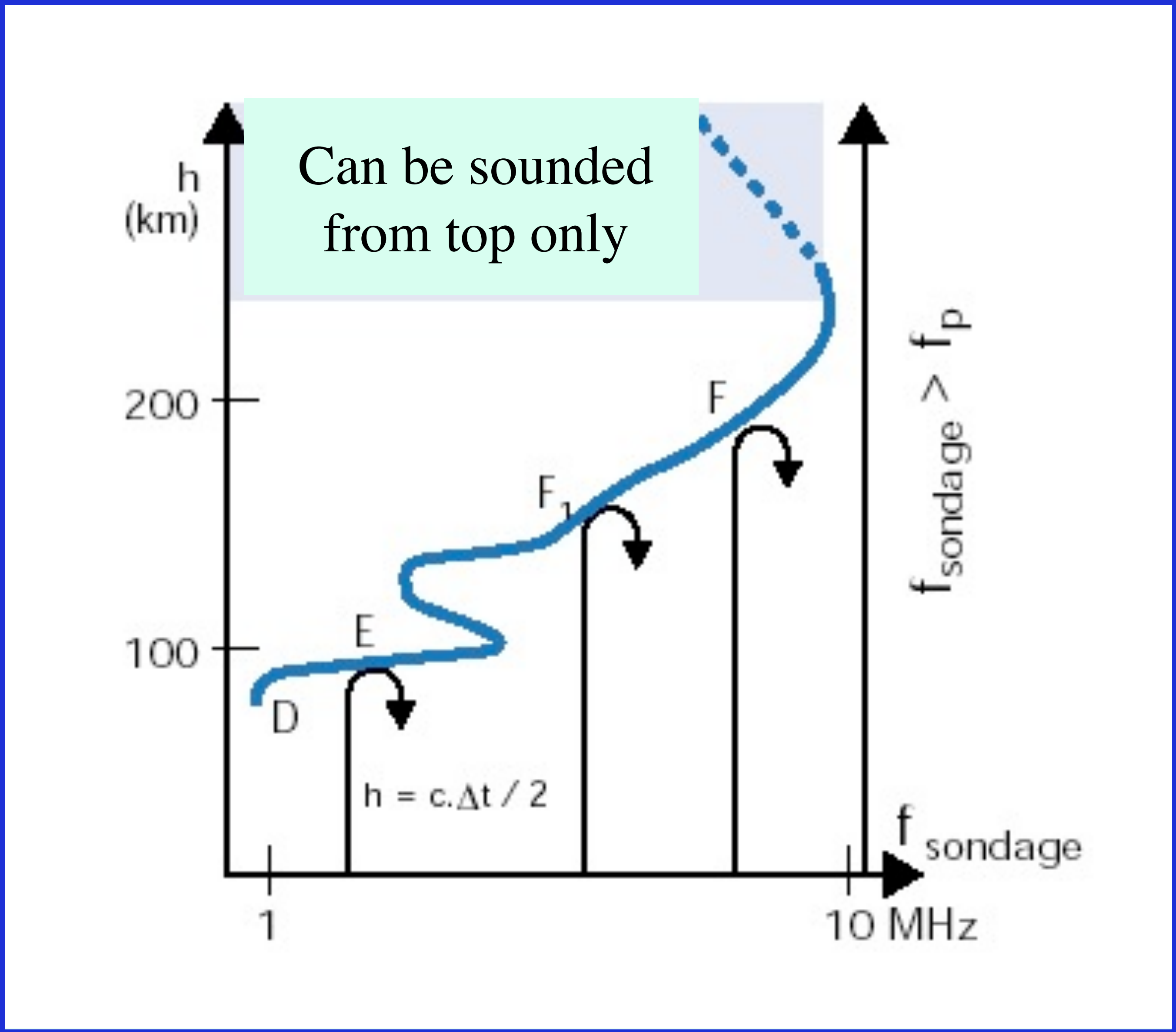
  Haskel model for rupture and frequency generation

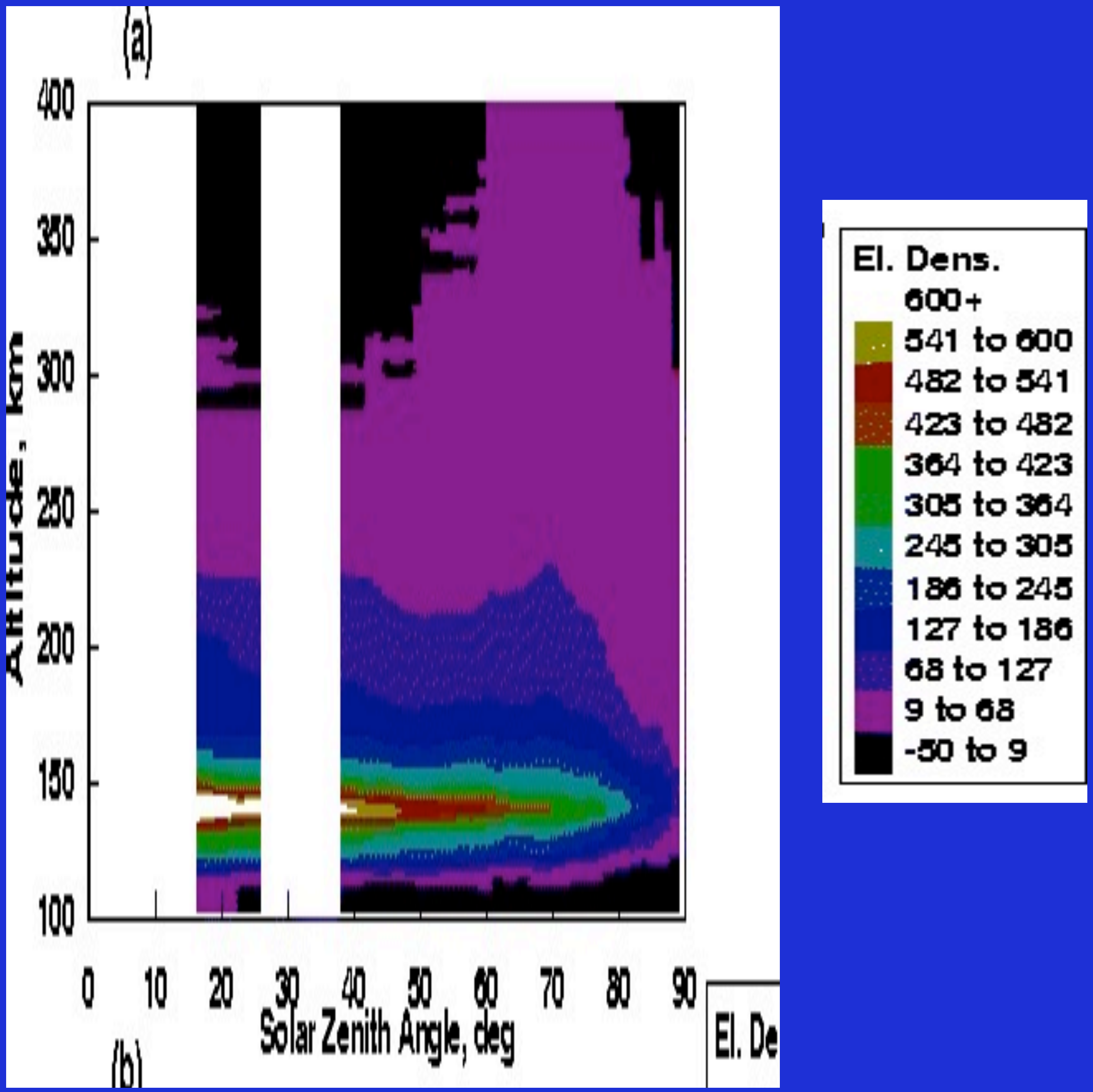
  30 km of focal depth



Non-adiabatic heating

Ionosphere and remote sensing seismology



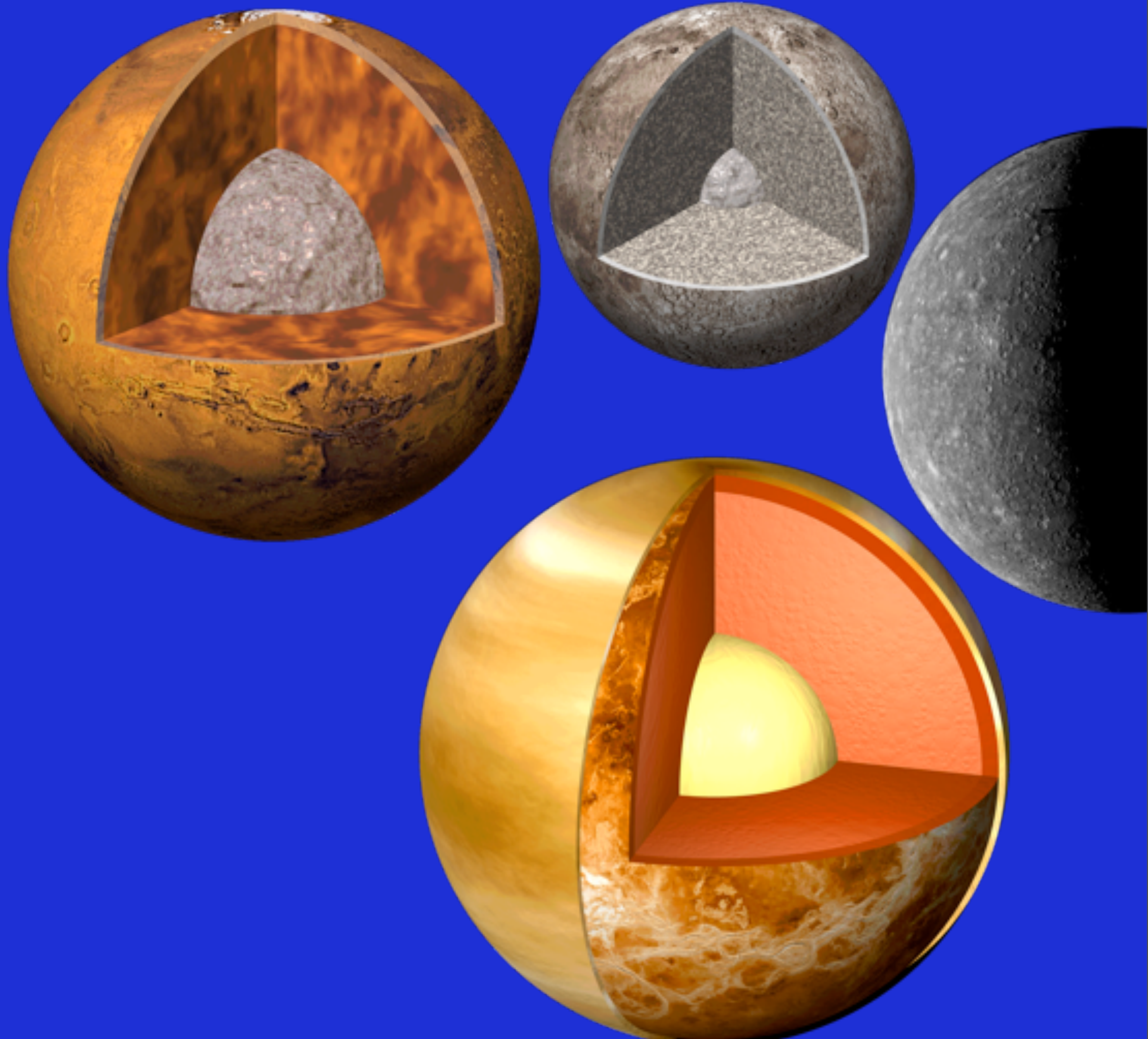


Venus

Earth

- Top side sounder might detect oscillations below 150 km

Thank you.



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