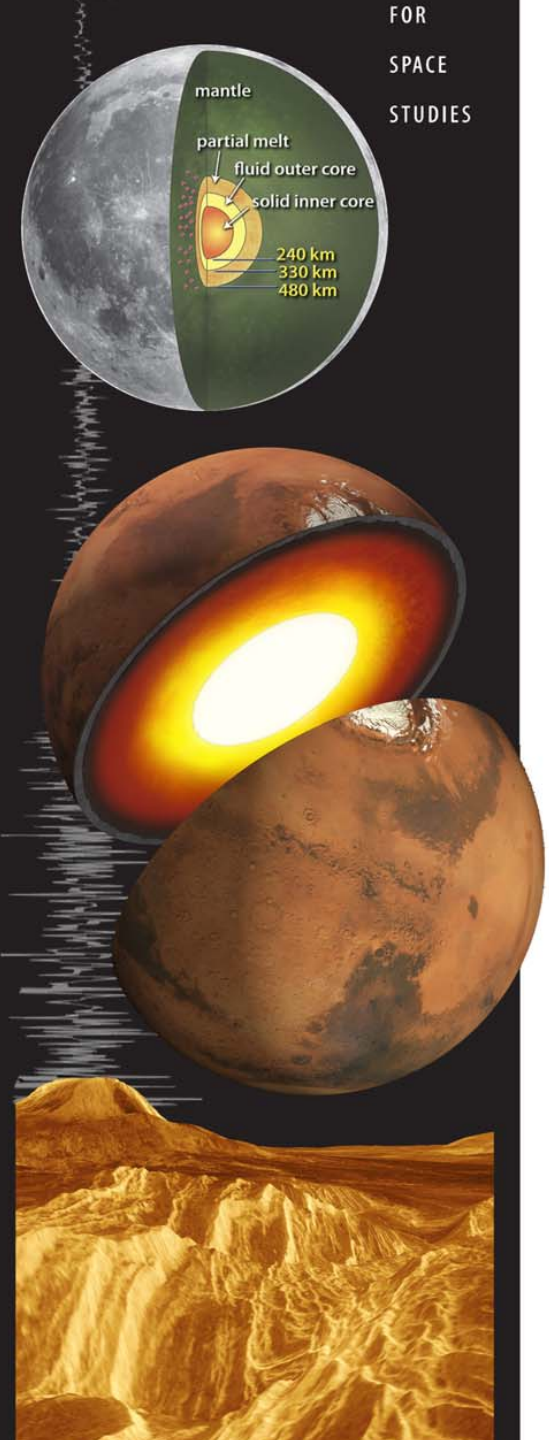
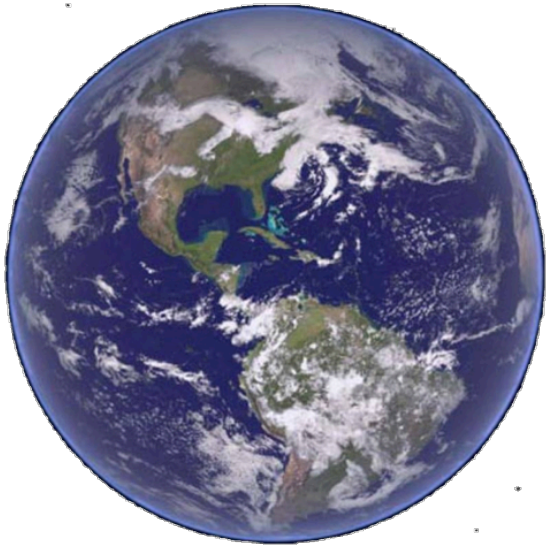
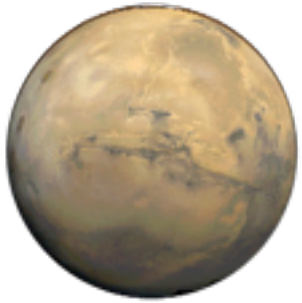


Seismology 3: Extra-terrestrial Seismology on telluric planets

Philippe Lognonné
Université Paris Diderot-Sorbonne Paris Cité
Institut de Physique du Globe de Paris

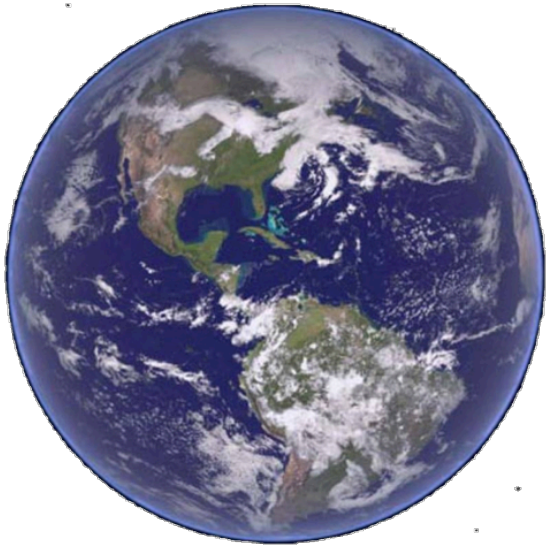
New frontiers of Planetary seismology

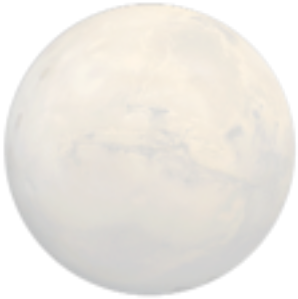



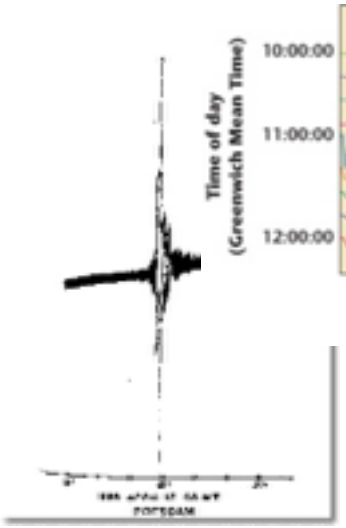


The interior of the terrestrial planets…

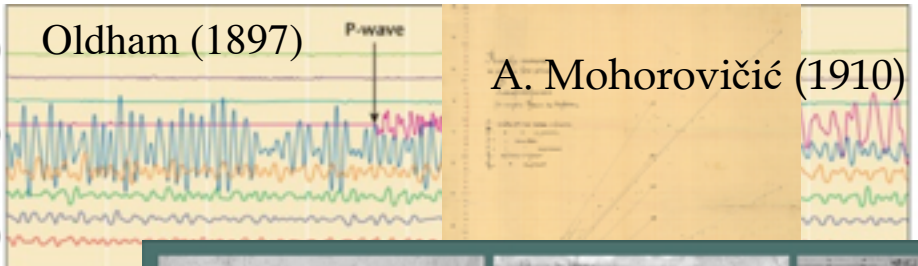
The first success story





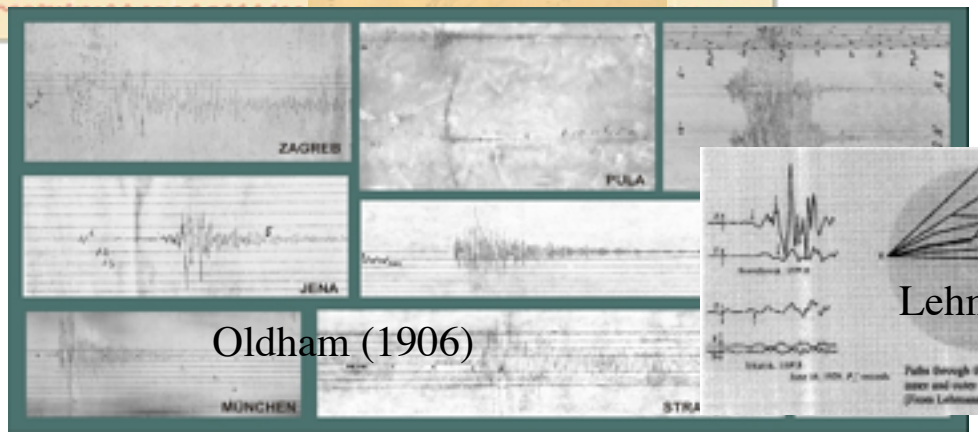


von Rebeur-Pacshwitz (Nature, 1889)

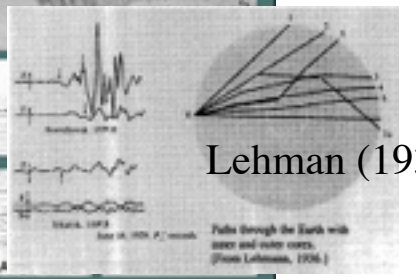


Oldham (1897)

A. Mohorovičić (1910)

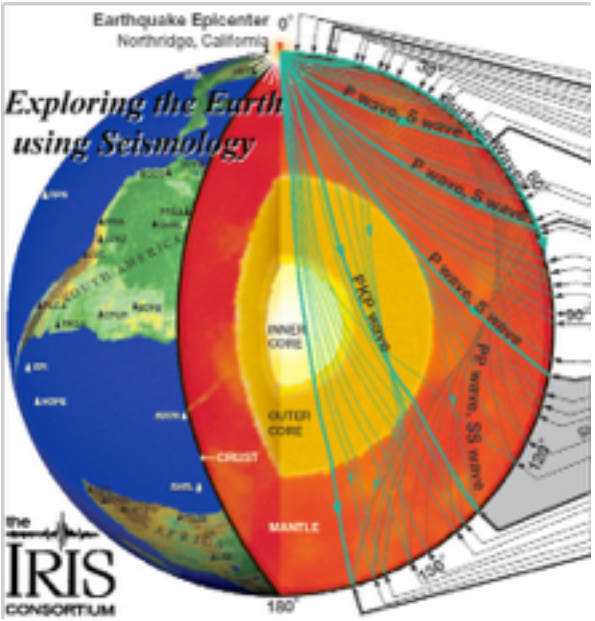


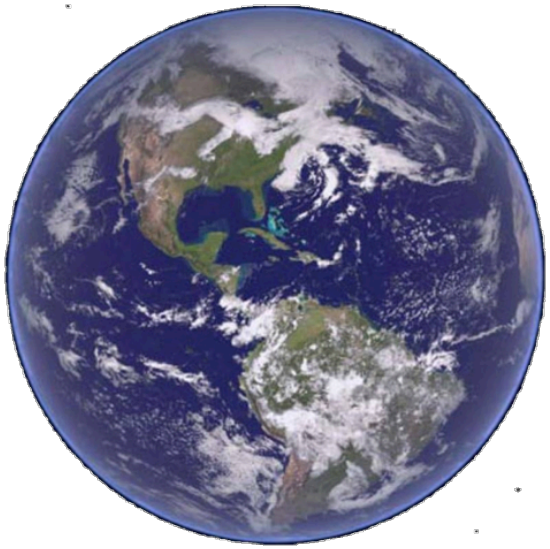
Oldham (1906)

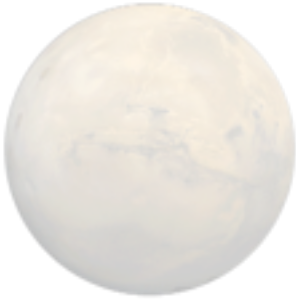


Lehman (1936)

The first success story

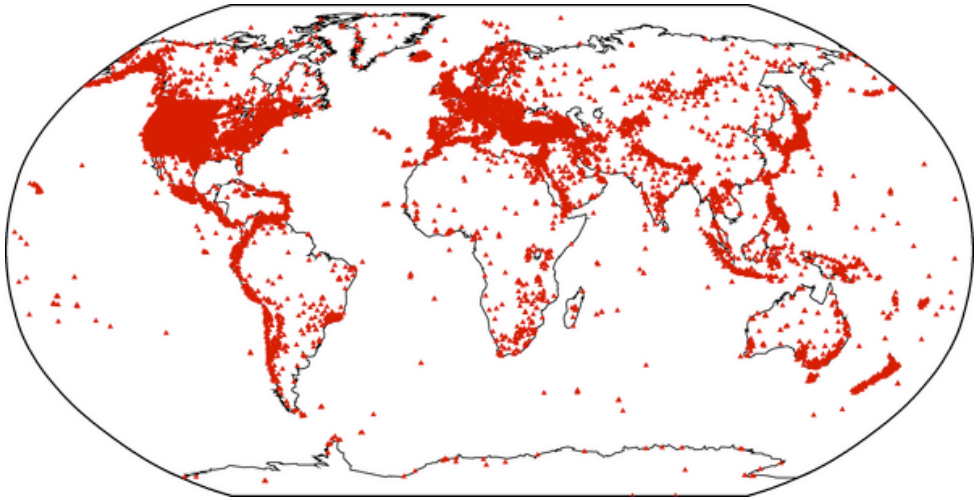






1980-90

geoscope



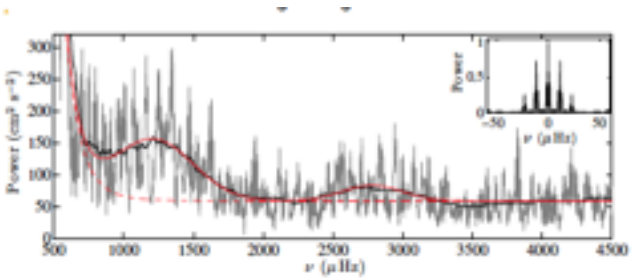
>20000 stations, many of them with direct access to data

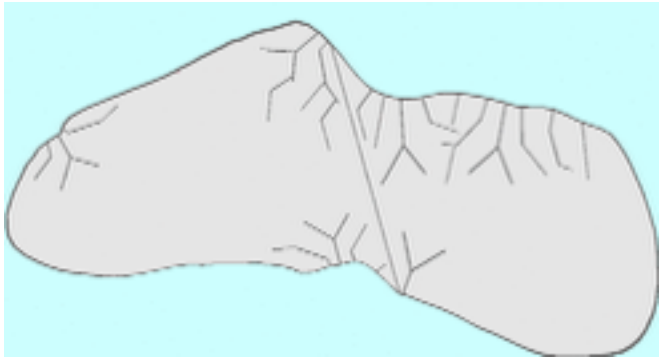
New frontiers of Planetary seismology

- Forget Earth dense Network…
  - Goals of planetary seismology are those of the early 1890-1920 on Earth…
- Past Seismology with 4-5 seismometers….. The Moon
- Near future Seismology with one seismometer…… Mars
- Further future Seismology without seismometer …Venus or maybe Moon

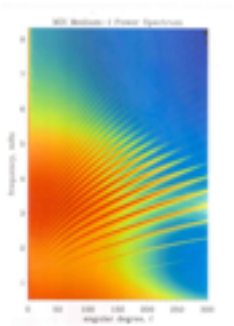
Not in this talks…

- Jupiter
  - growing evidence that normal modes are excited continuously to a level close or above from the detection threshold (Gaulme et al., 2011)
- The Jovian satellites
  - Europa, Io might be interesting place to go in some decade of this century (see Panning et al., 2006)
- The small bodies
  - where seismic waves generate seismic shaking and change the surface morphology (Richardson et al, 2004)
- The Sun
  - where normal modes are monitored with a detail we do not have on Earth (e.g. Gizon et al., 2010)





Peter et al., 2011



Lunar seismology…. started in 1962…

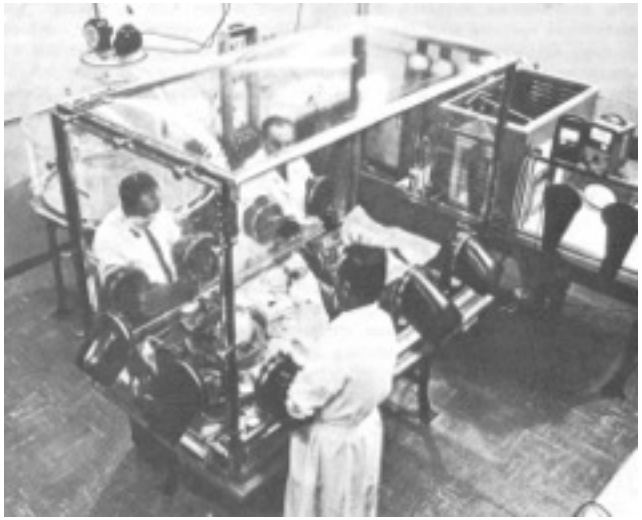
Seismometer and Ranger at JPL

Apollo 14 crew training the ALSEP (and seismometer) deployment

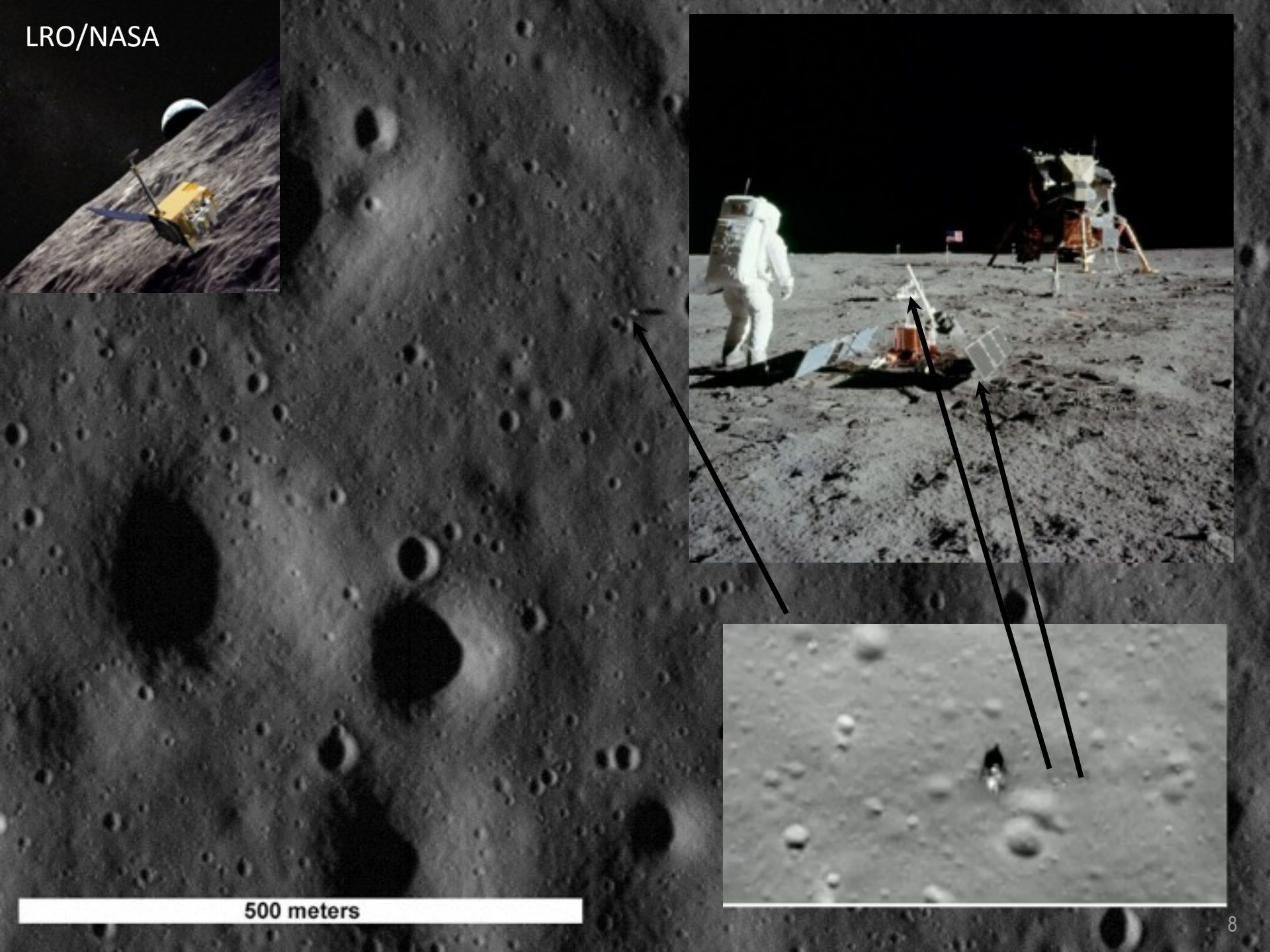
Ranger 3
1/26/1962

Ranger 4
4/23/1962

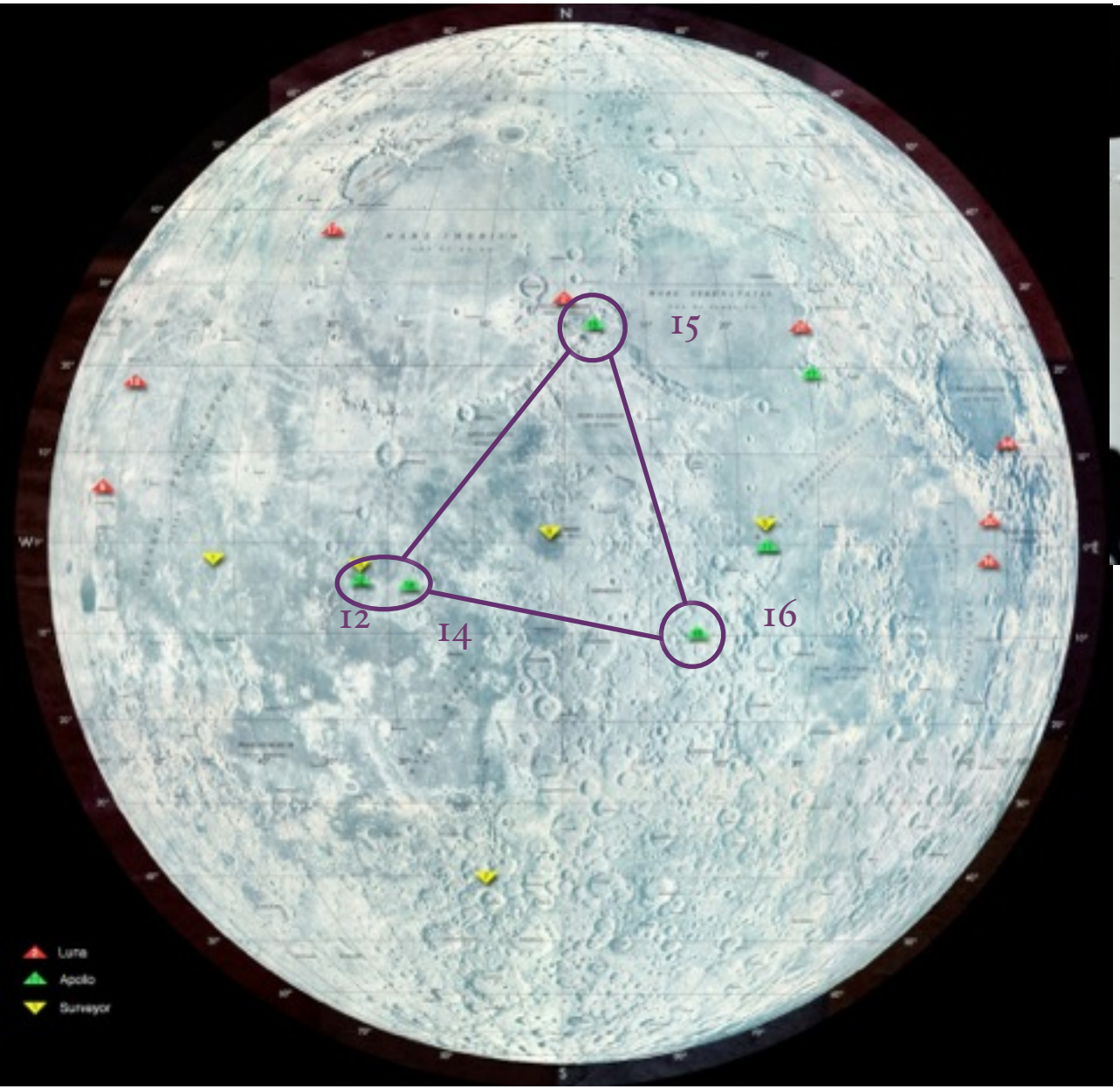
Ranger 5
10/18/1962

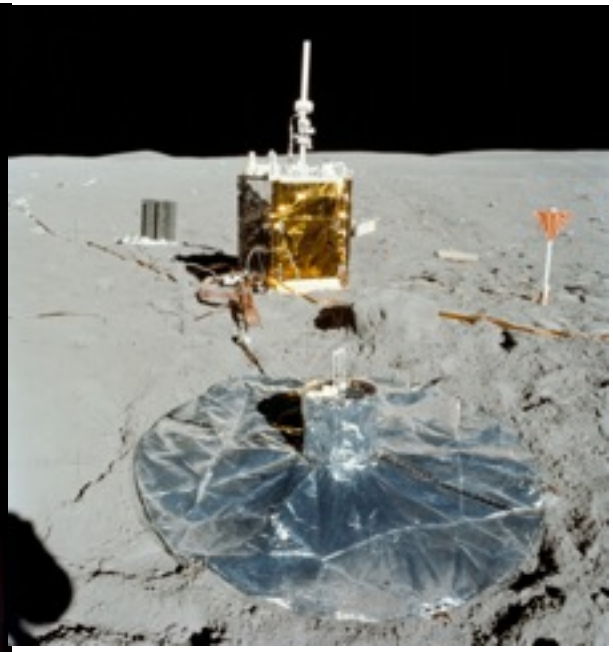


Sterile seismometer assembly at Aeronutronic

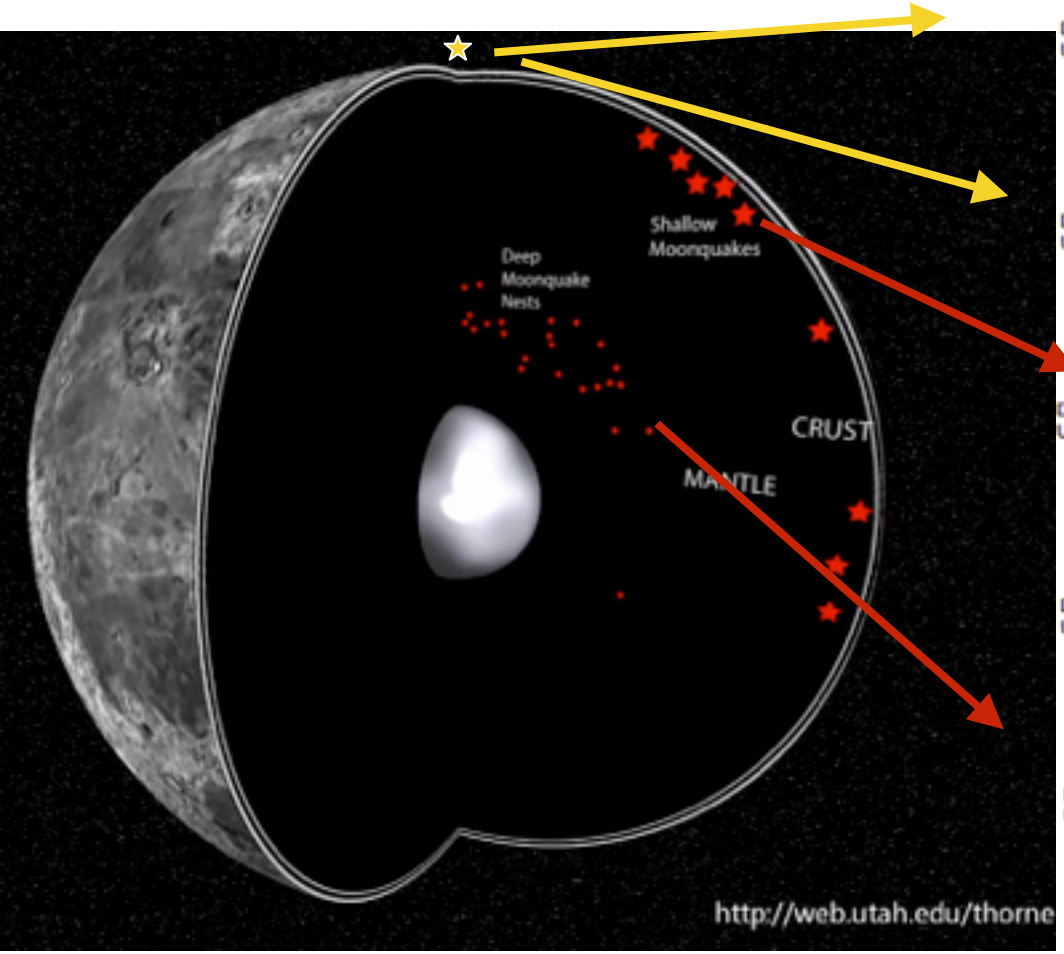

LRO/NASA
500 meters

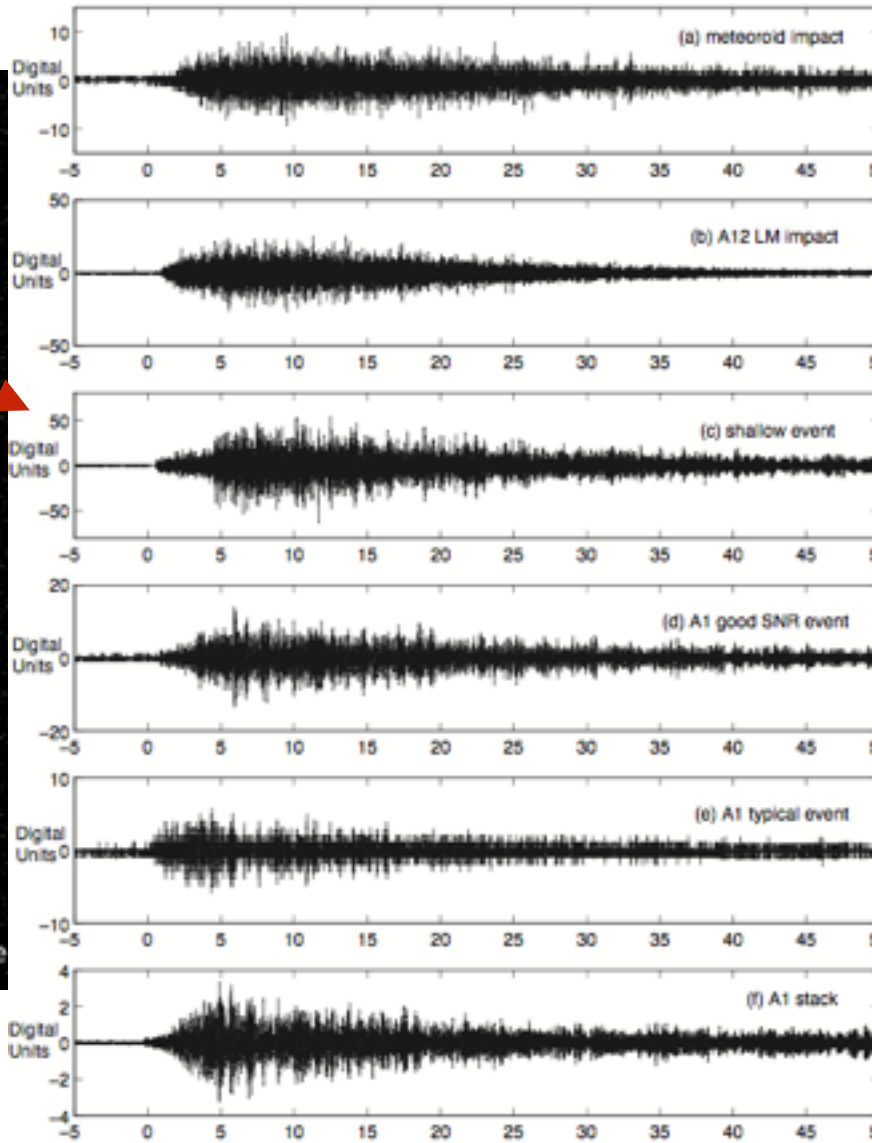
Apollo seismic network





Lunar quakes zoology

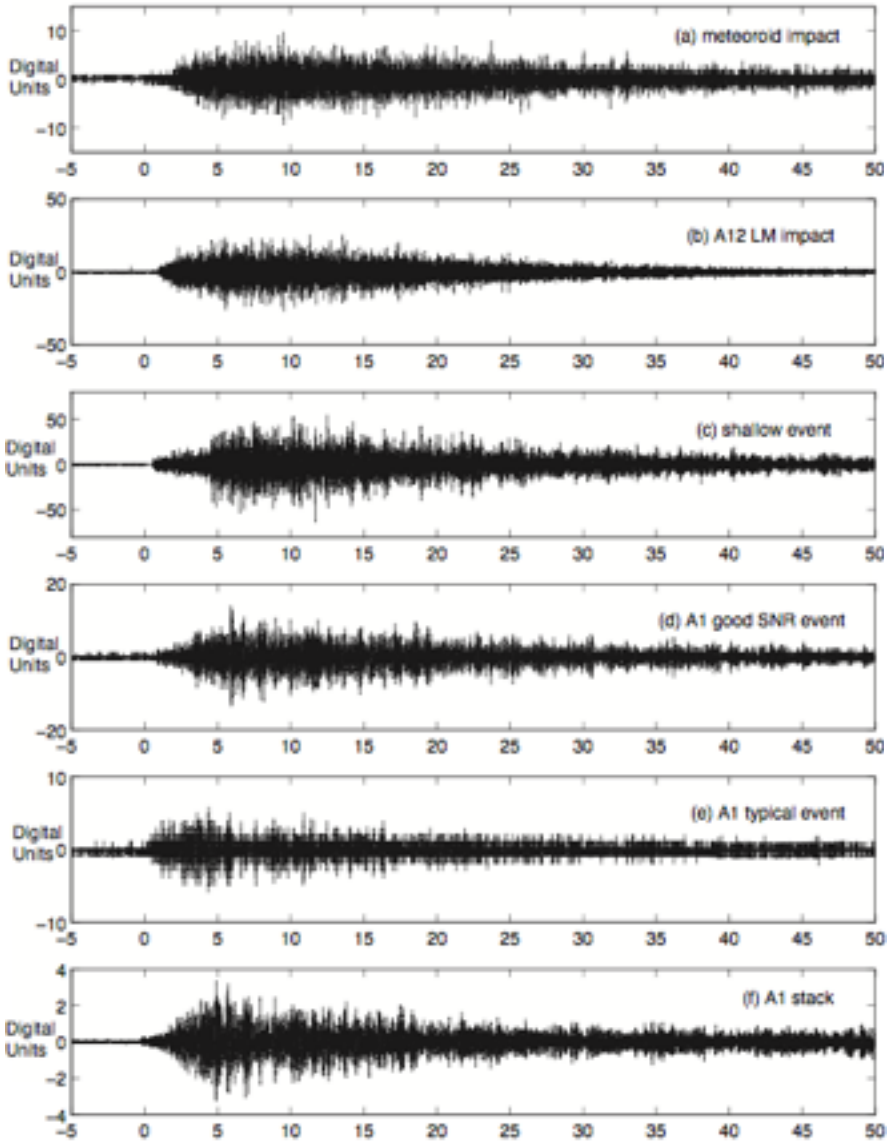


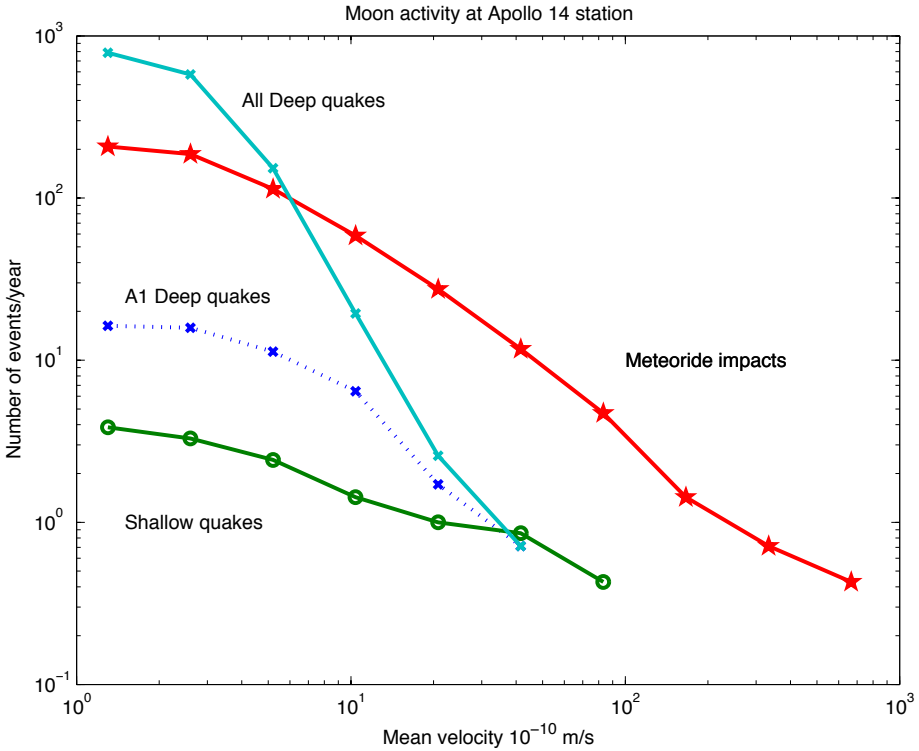


1 Digital Unit (DU) = 0.5 10^{-10} m at 2 sec

Lognonné & Johnson, 2007

Lunar quakes zoology

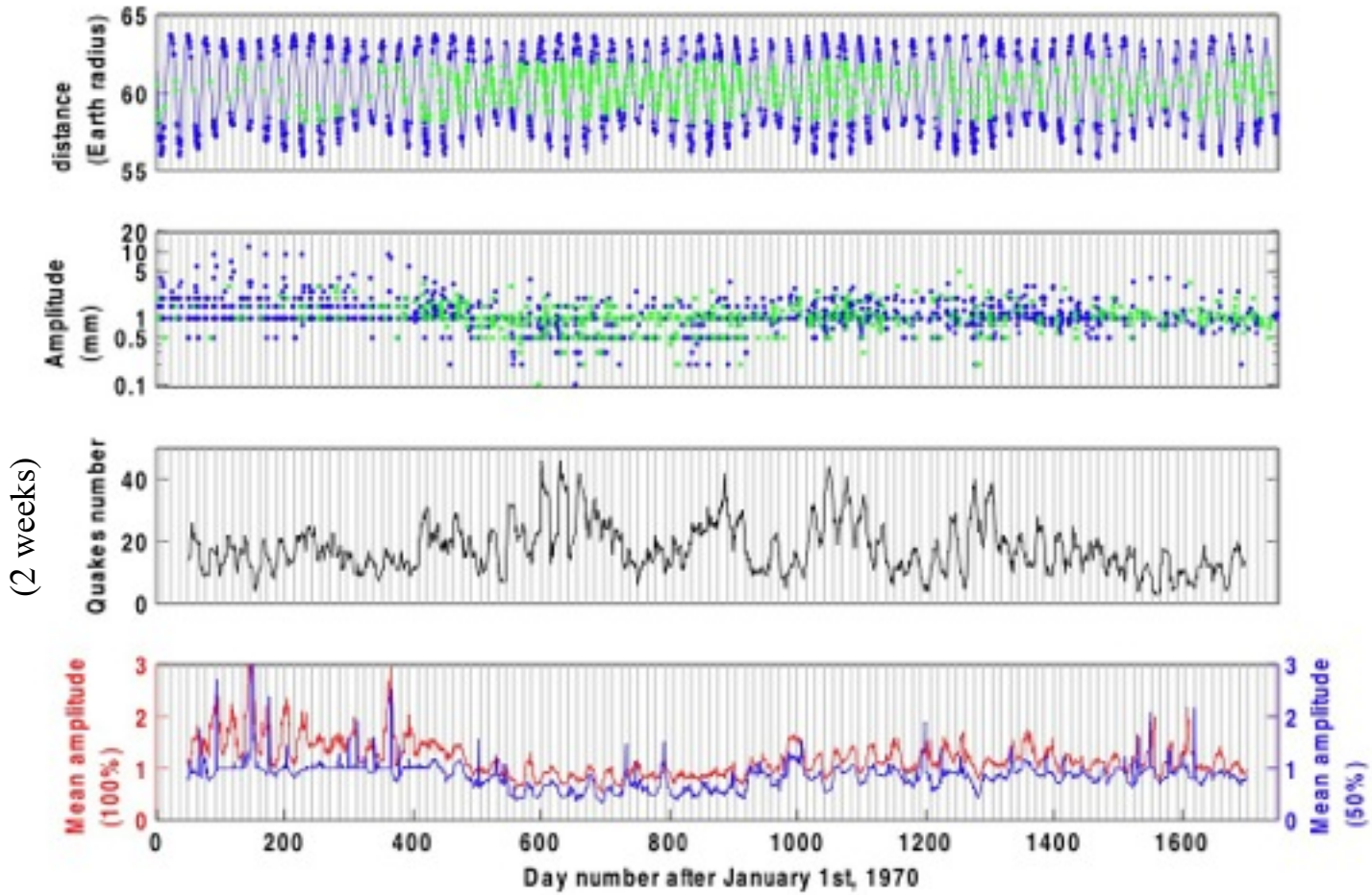




Lognonné & Johnson, 2007

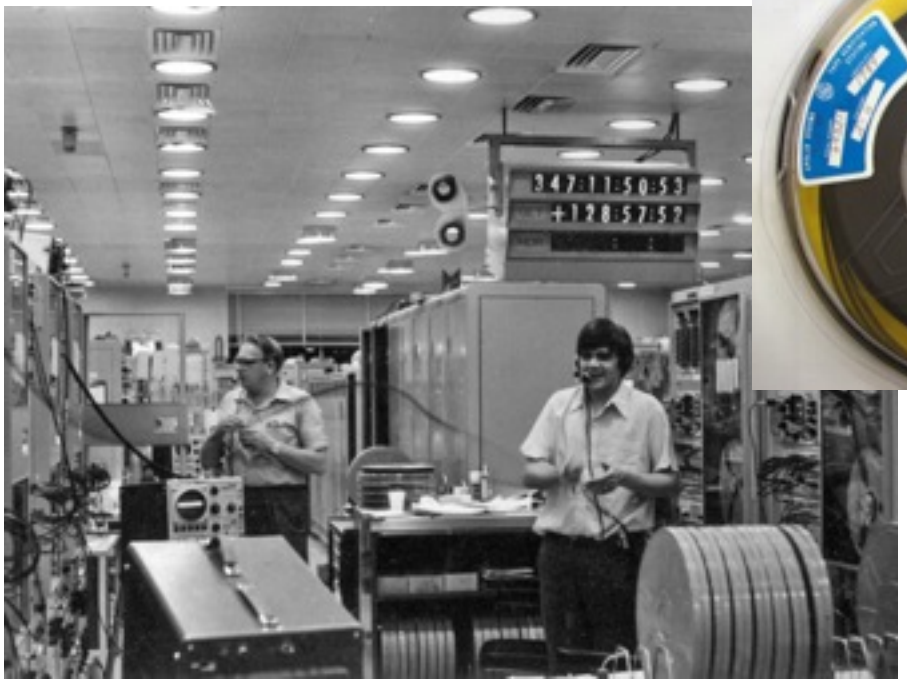
Deep Moonquakes

- Over 10 000 quakes detected in 7 years
- Small to very small amplitudes
- Triggered by the Earth's tide



Modern Apollo seismology: painful gift of Lunar A

- In the late 1990, JAXA decided to transfer the “old” tape recorded Apollo data on exabytes in the frame of the Lunar-A penetrator mission
- Lunar-A was cancelled in 2007, but this effort lead to a renew of the Apollo seismic data analysis….
- Data are now available in various electronic forms and recovery effort continue…



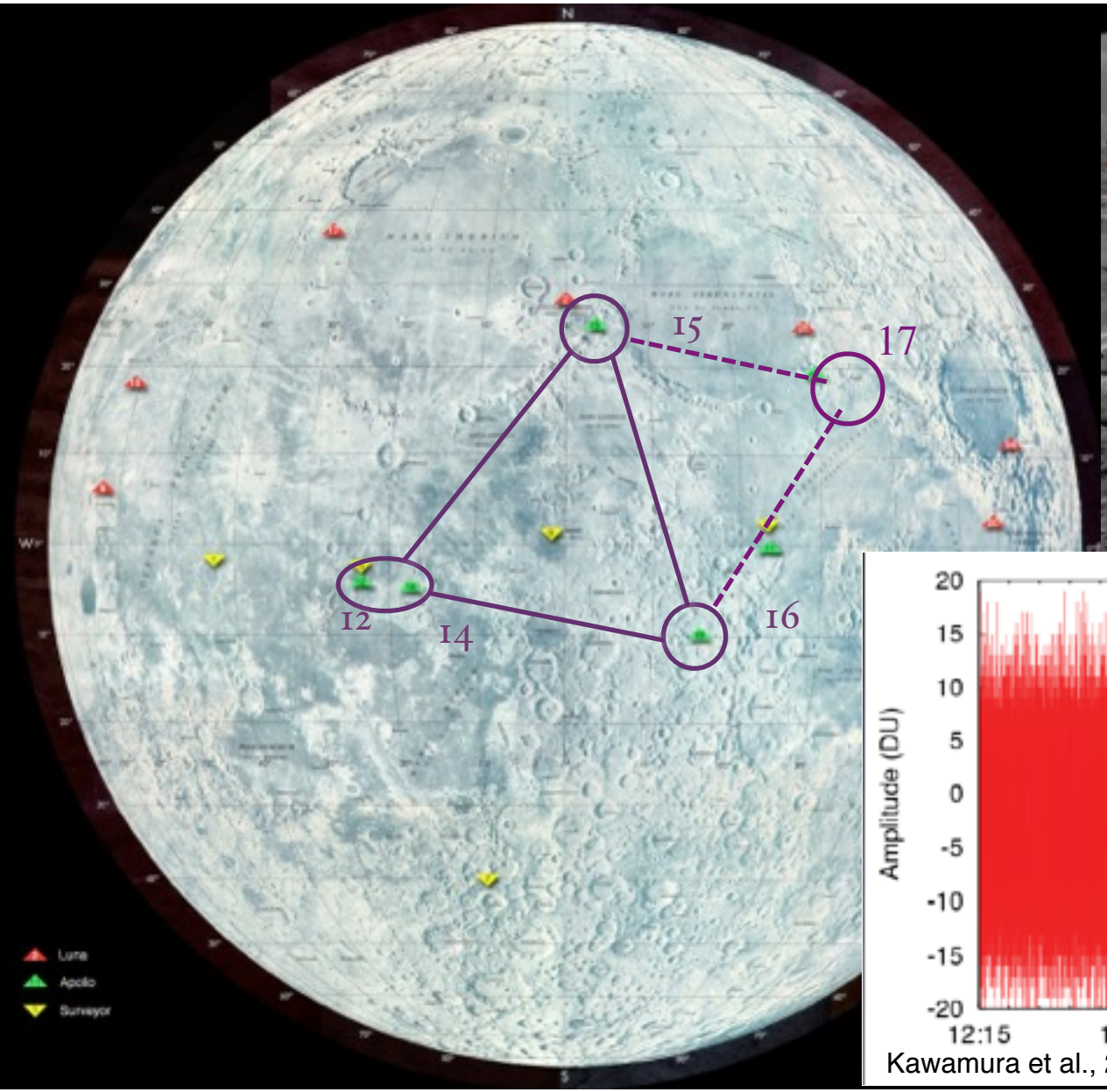
Apollo 17 data facility…

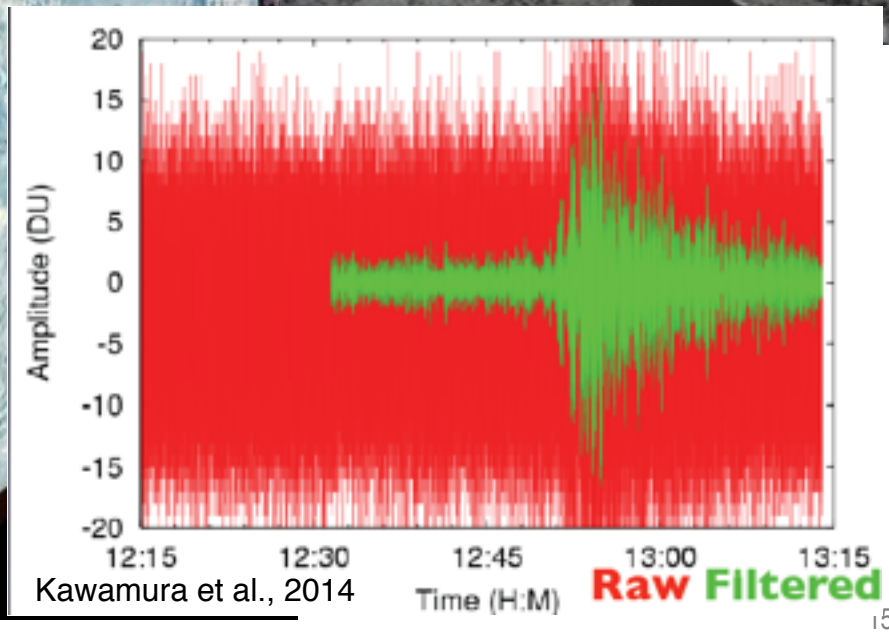
Original ALSEP data

Lunar-A penetrator


The most recent Apollo seismic data….

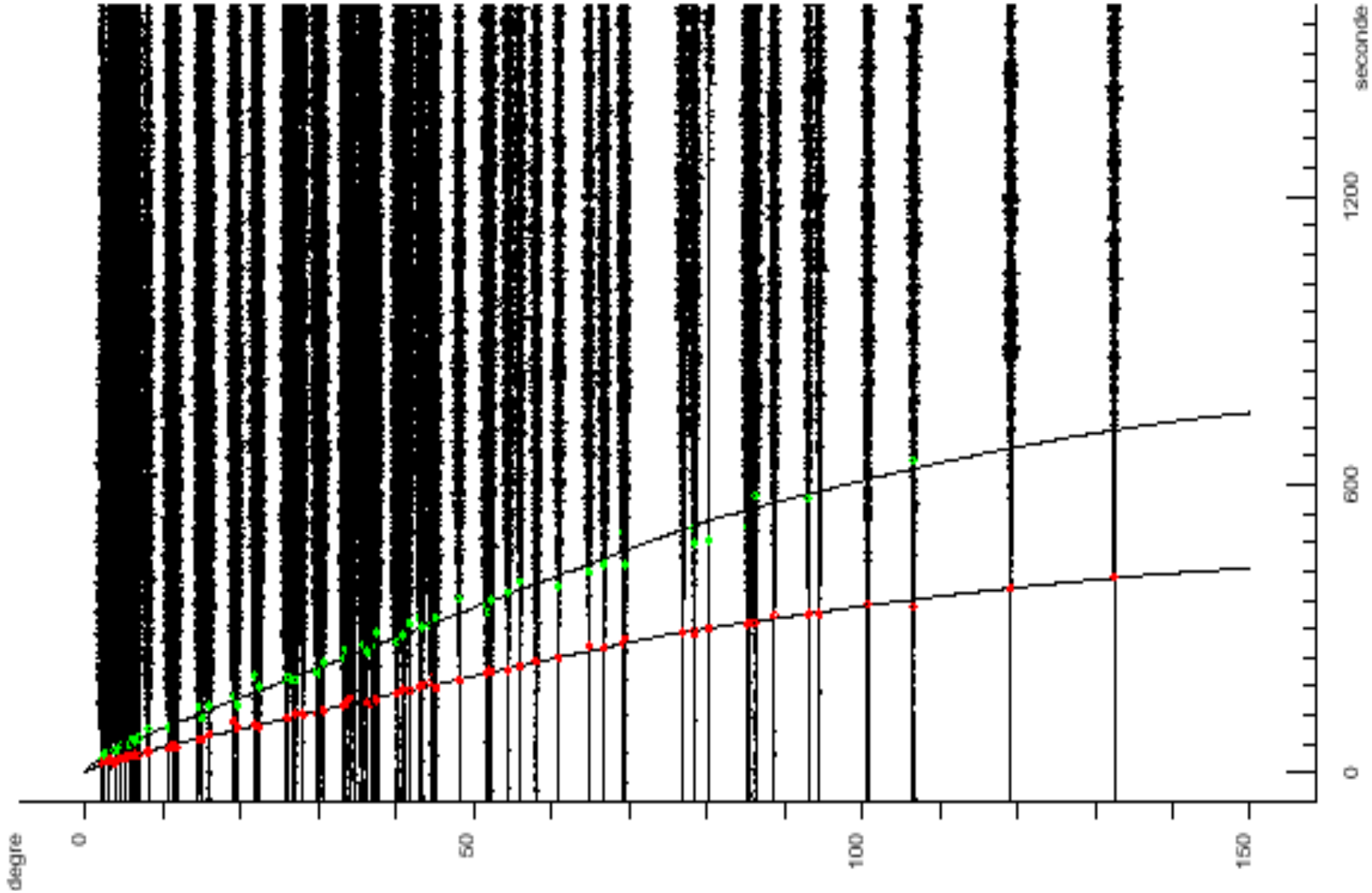
Apollo seismic network





Kawamura et al., 2014

Impact collection and arrival time measurement “noise” or “error”



Typical Inversion in the Apollo case

Seismic data, i.e. arrival times at the stations (3 most of the time)
N_{events} x 6

Source parameters, i.e. position and times of the quakes
N_{quake} x 4
N_{impact} x 3
$N_{event} = N_{quake} + N_{quake}$

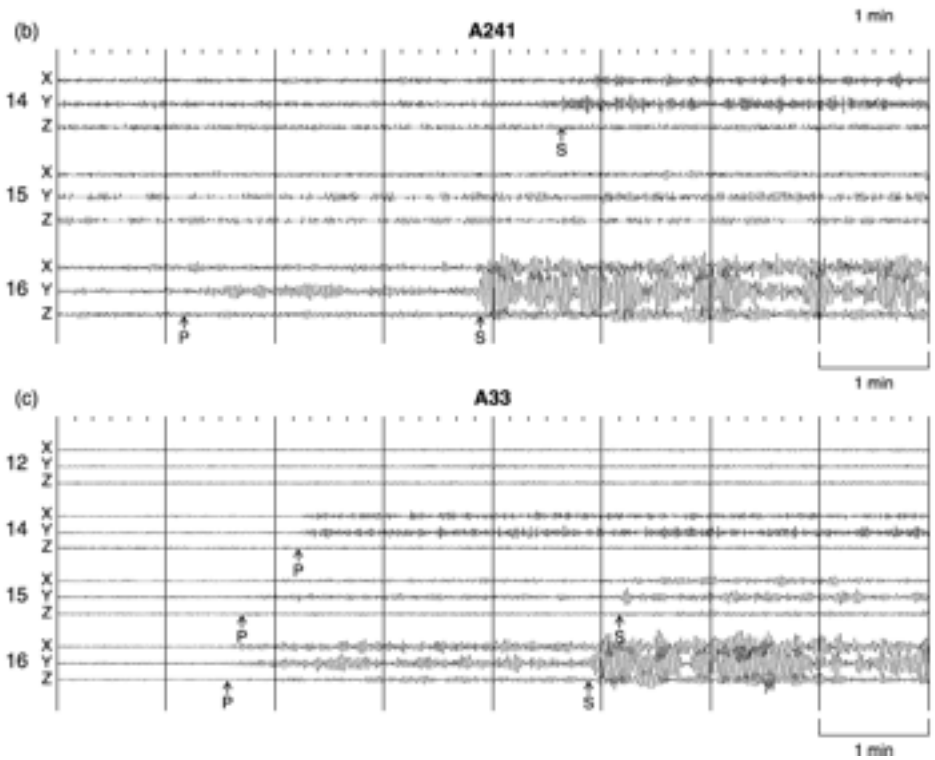
Model parameters, i.e. P and S seismic velocities with depth
$N_{parameters}$

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
Large errors for arrival times…

2 approaches:
- get noisy inversions with high resolution
- get less noisy inversion with low resolution by reducing the number of parameters (or layers) and/or by injecting a priori mineralogy

Typical travel time measurement error

Nakamura, 2005



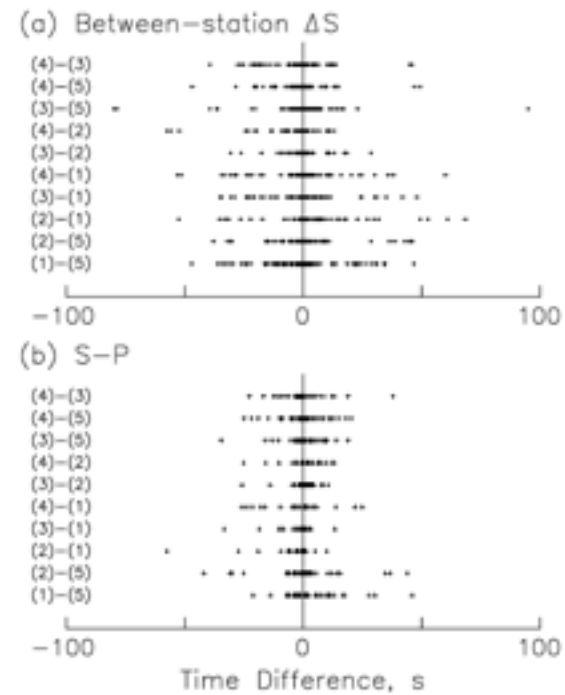


Figure A1. (a) Distribution of differences among different sets of between-station S wave arrival-time differences. (b) Similar distribution for S-P arrival-time differences. Numbers (1)–(5) refer to different sets as indicated in the footnote of Table A1.

(1) Lammlein (1977)
(2) Goins (1978)
(3) Nakamura (1983)
(4) Lognonné et al. (2003)
(5) Nakamura (2005)

2 approaches:
- get noisy inversions with high resolution
- get less noisy inversion with low resolution by reducing the number of parameters (or layers) and/or by injecting a priori mineralogy

The Lunar Seismic models (with error bars…)

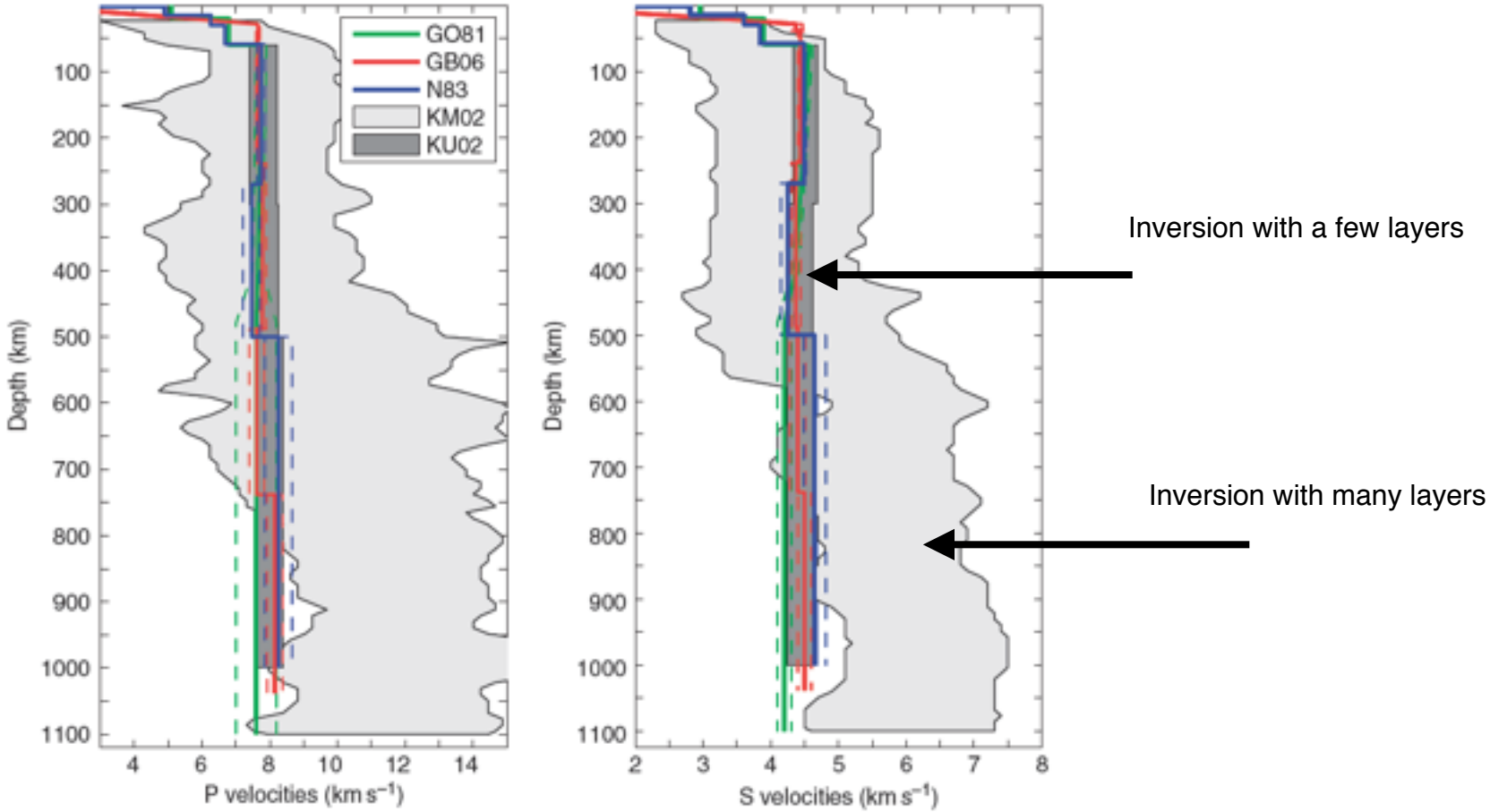
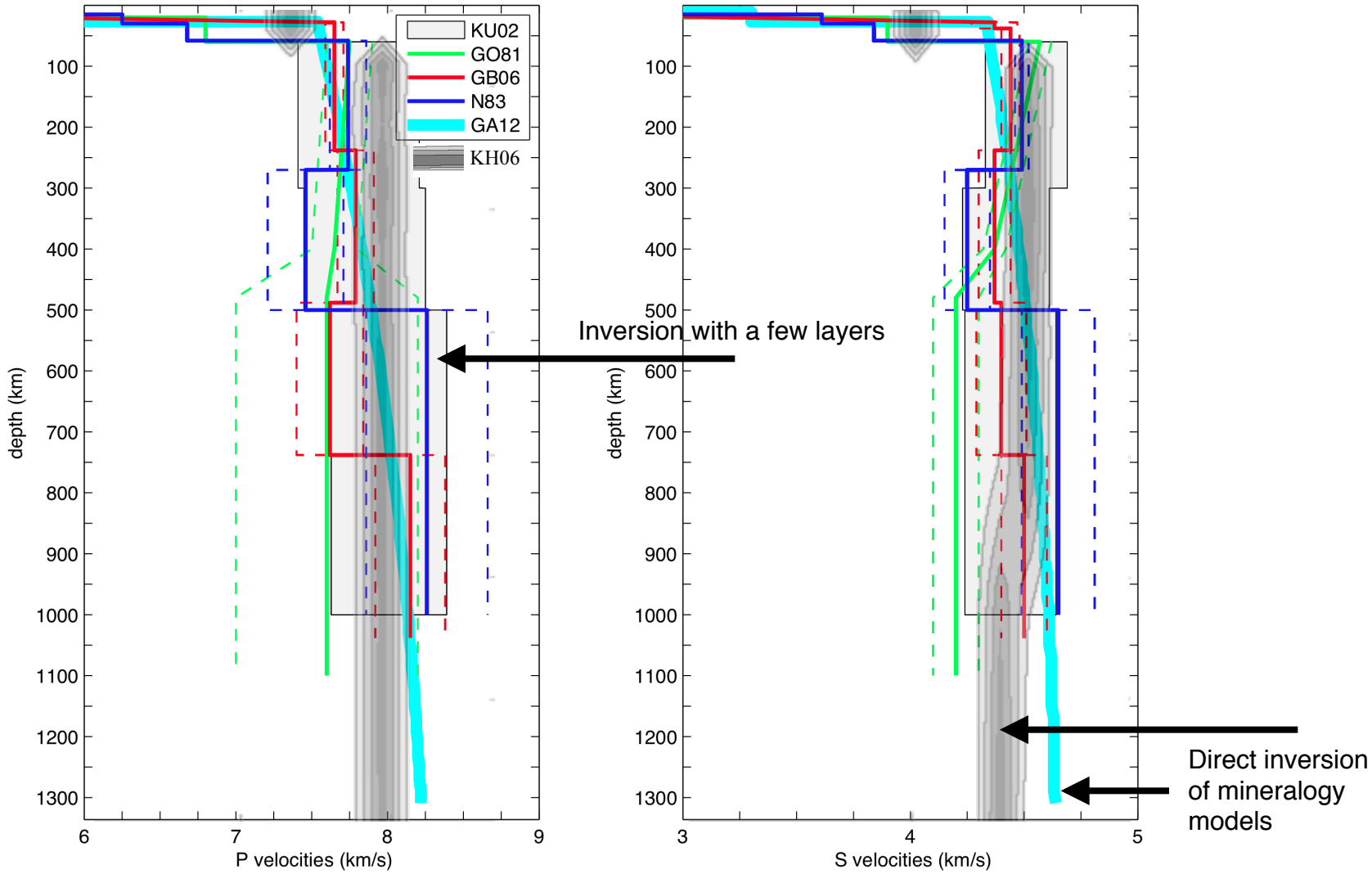


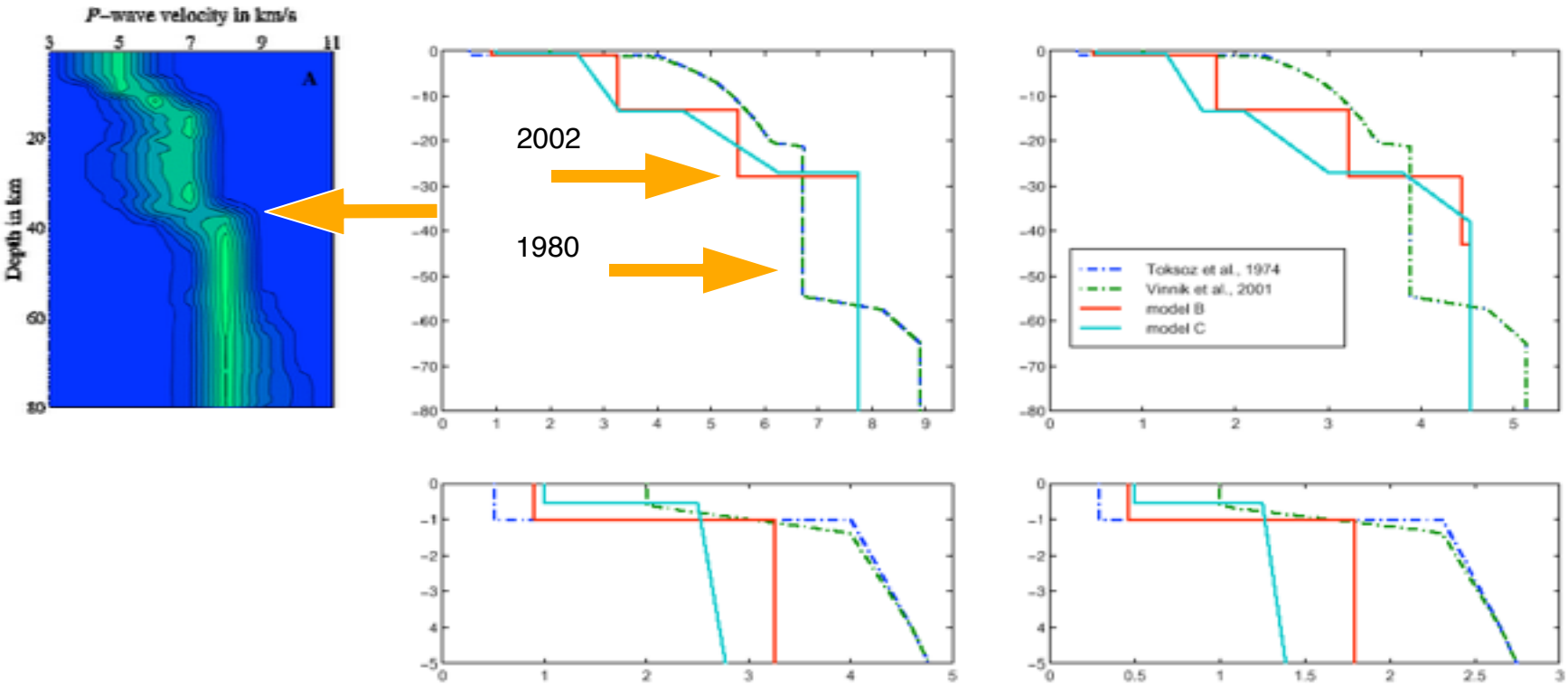
Figure 5 P- and S-wave velocity models vs depth: green, Goins *et al.* (1981b), red, Ganepain-Beyneix *et al.* (2006), blue, Nakamura (1983). The light gray zone is the 80% probability zone of Khan and Mosegaard (2002); The dark gray is the petrology/geochemistry model of Kuskov *et al.* (2002). Values for mantle velocities and associated 1σ uncertainties for each model can be found in table 1 of Lognonné (2005) and are plotted as colored dashed lines with the same colors for the three first models.

The Lunar Seismic models (with error bars…)



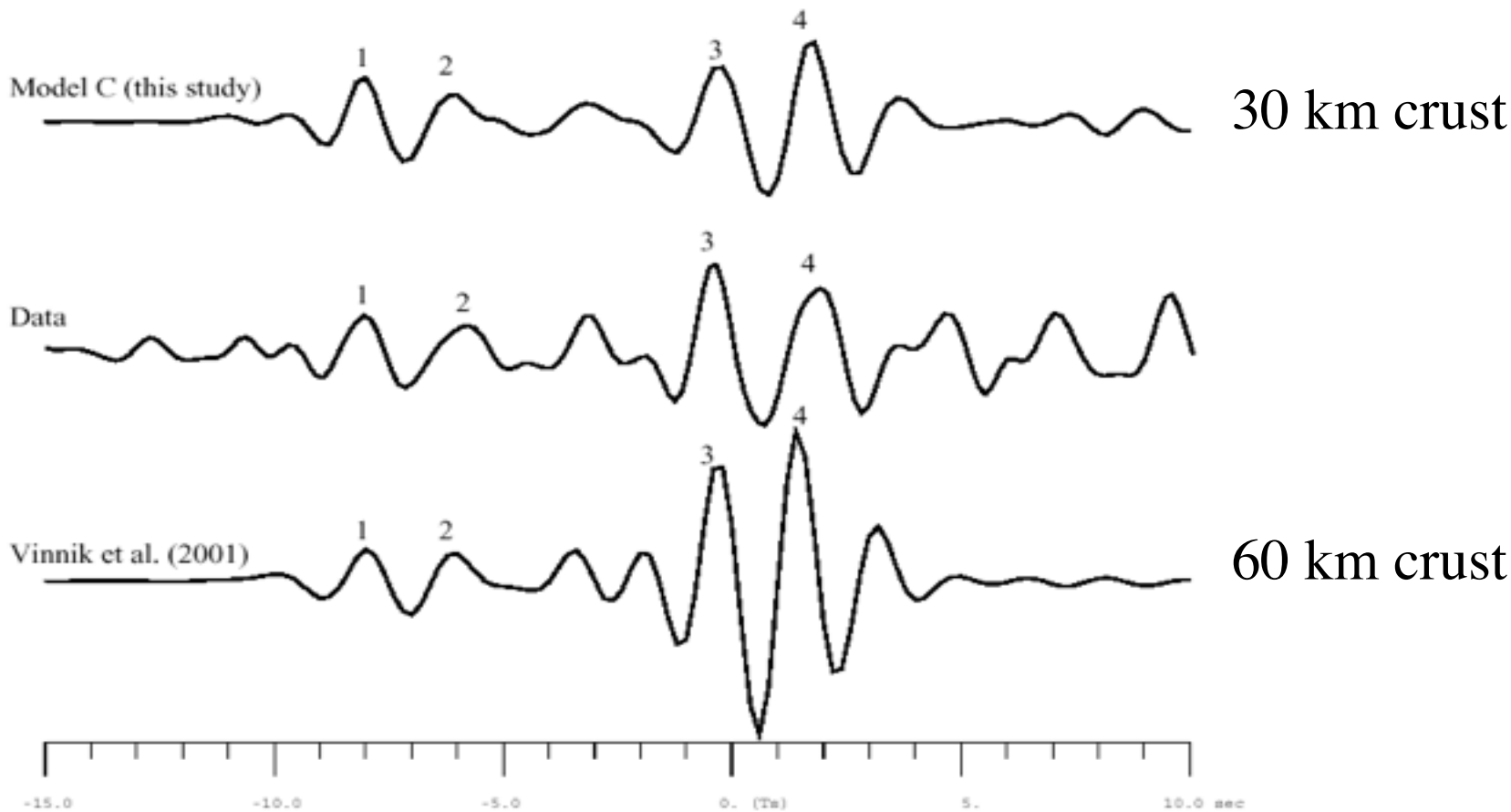
Modern Apollo seismology: a new crust

- Crustal thickness was estimated to 60 km between 1970-1980 by Toksoz et al. and Nakamura et al.
  - This implied large volume of primary crust and an bulk U content much larger than Earth
- All re-estimations were however providing thinner crust, from 30 km (Lognonné et al., 2003, Beyneix et al., 2007) to 38 km (Khan et al, 2002)



Moon receiver function (Apollo 12 site)

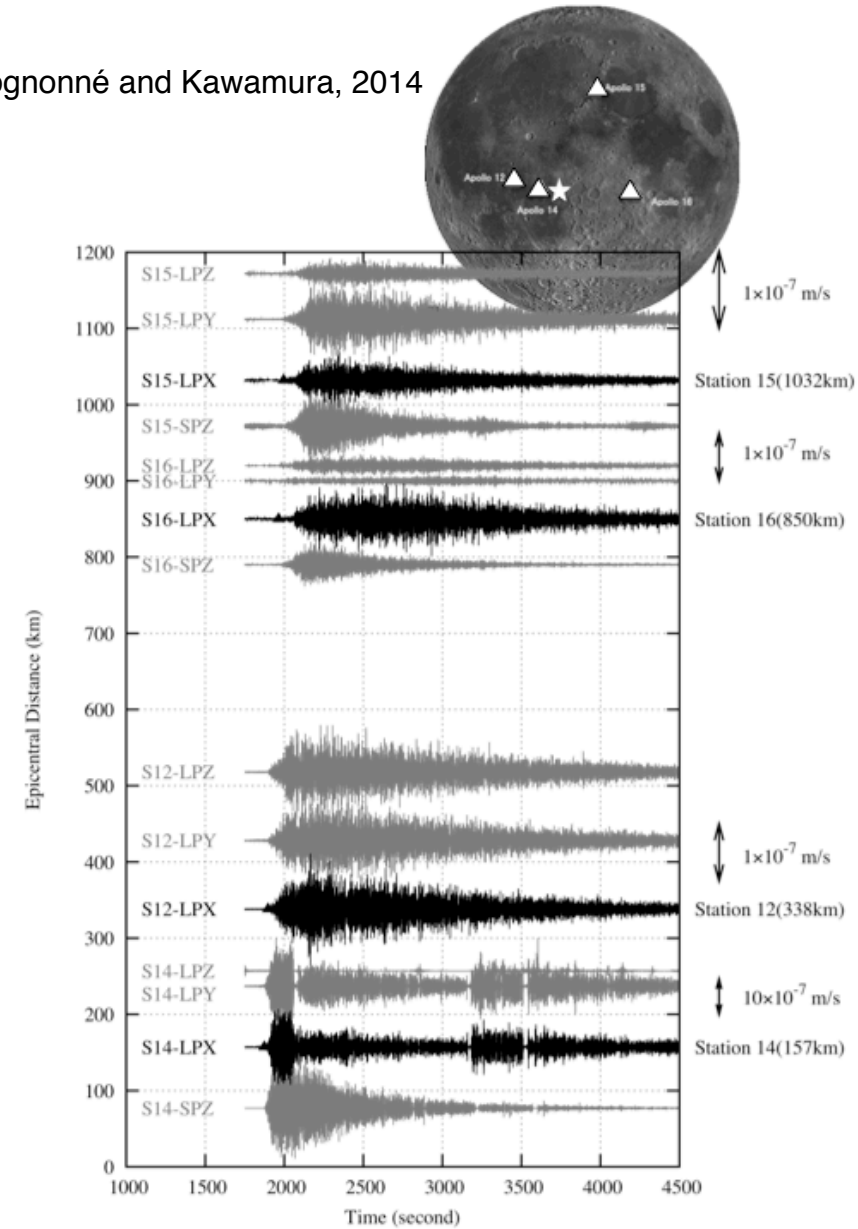
- This apparent contradiction is mainly related to two different models family having *similar travel times*…

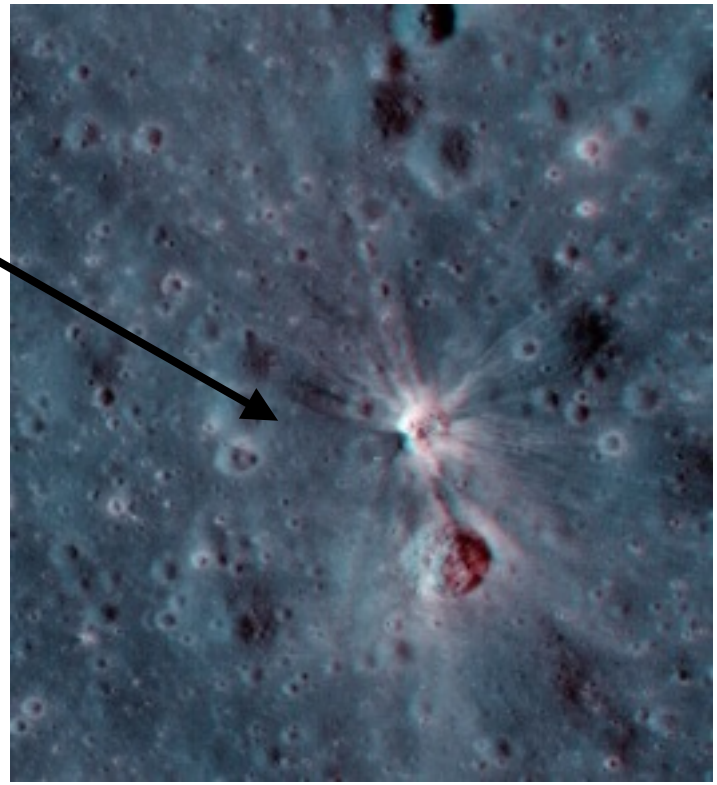


Vinnik et al., 2001

Lunar impacts… Lightening the crust

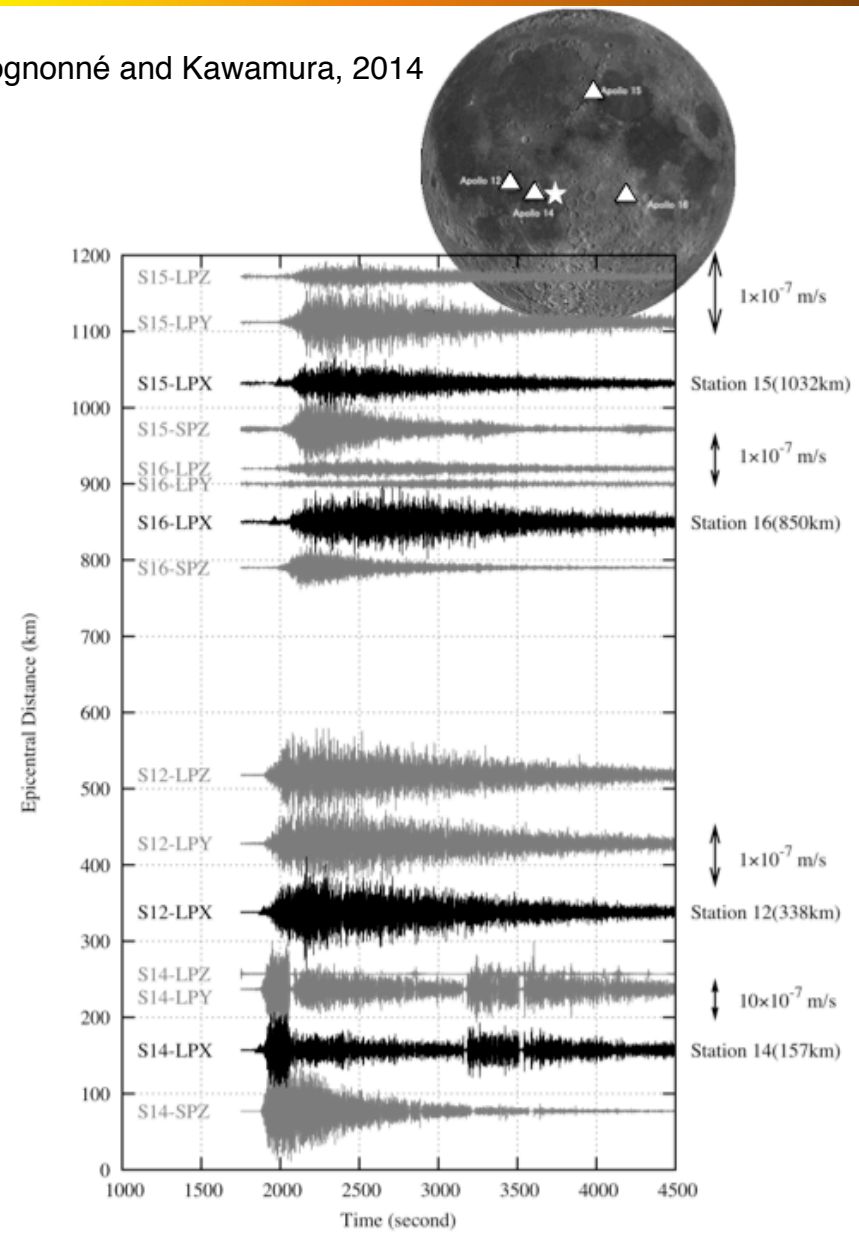
Lognonné and Kawamura, 2014

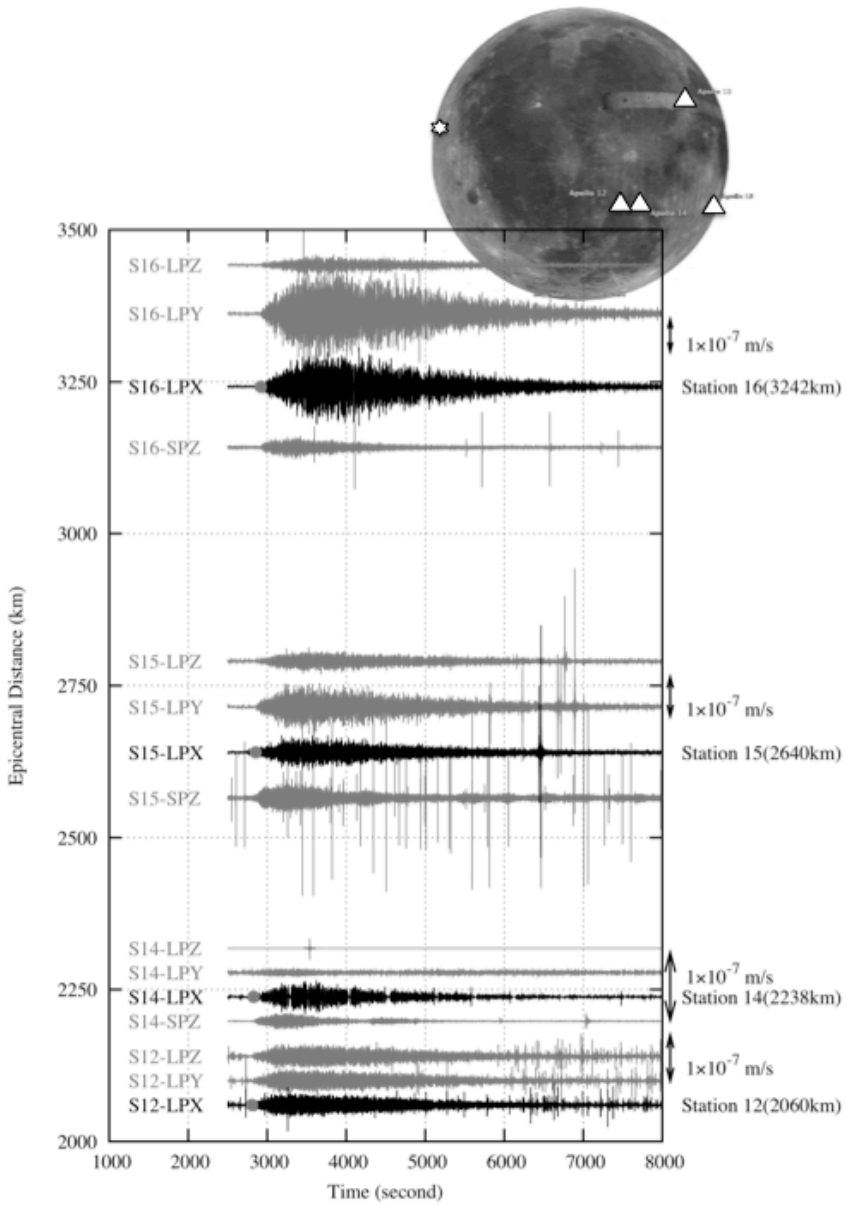


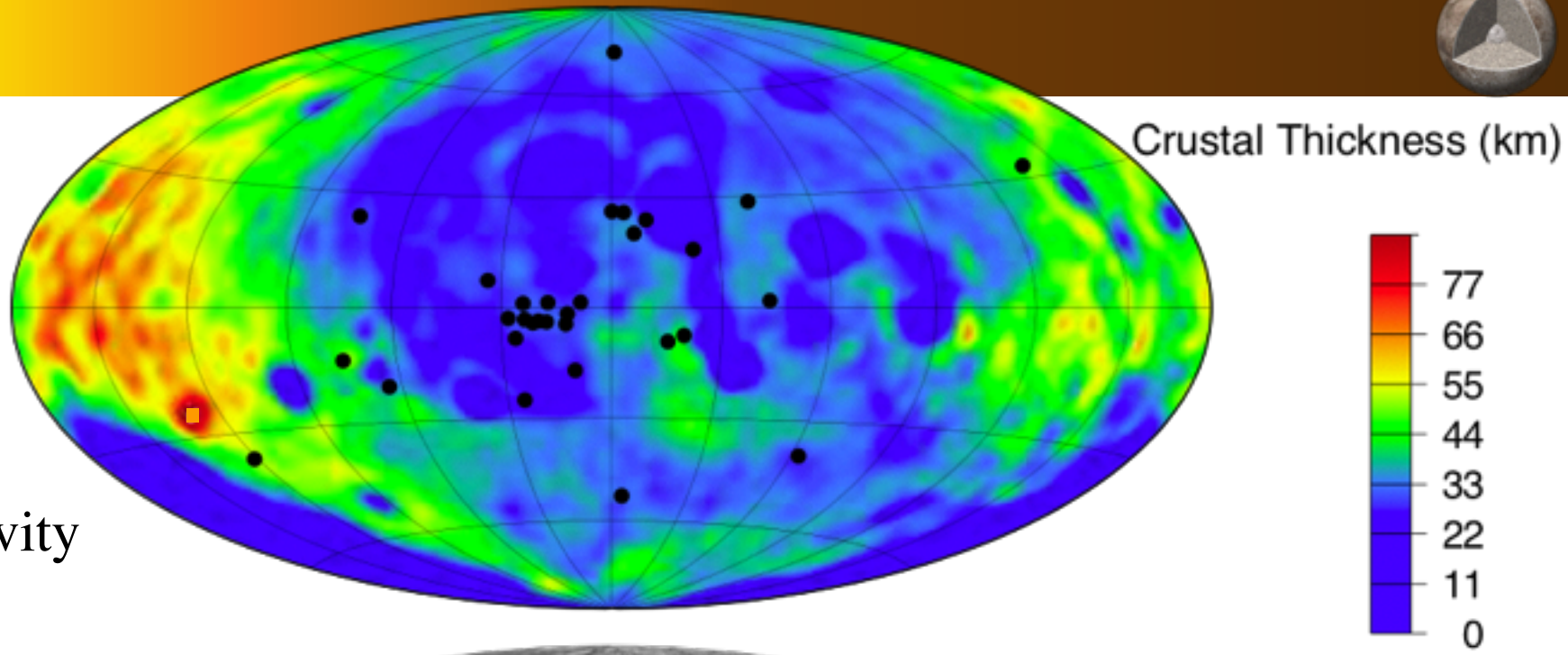


Lunar impacts… Lightening the crust

Lognonné and Kawamura, 2014

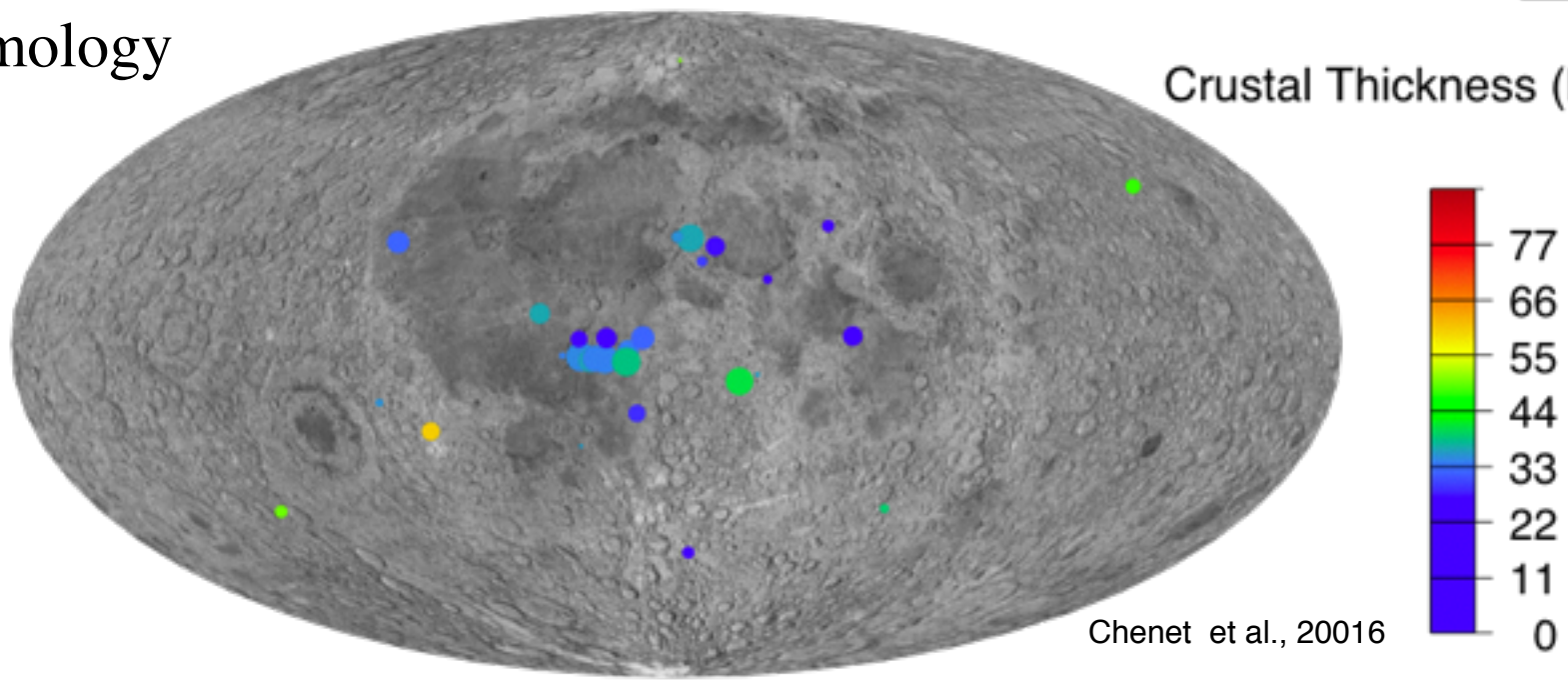






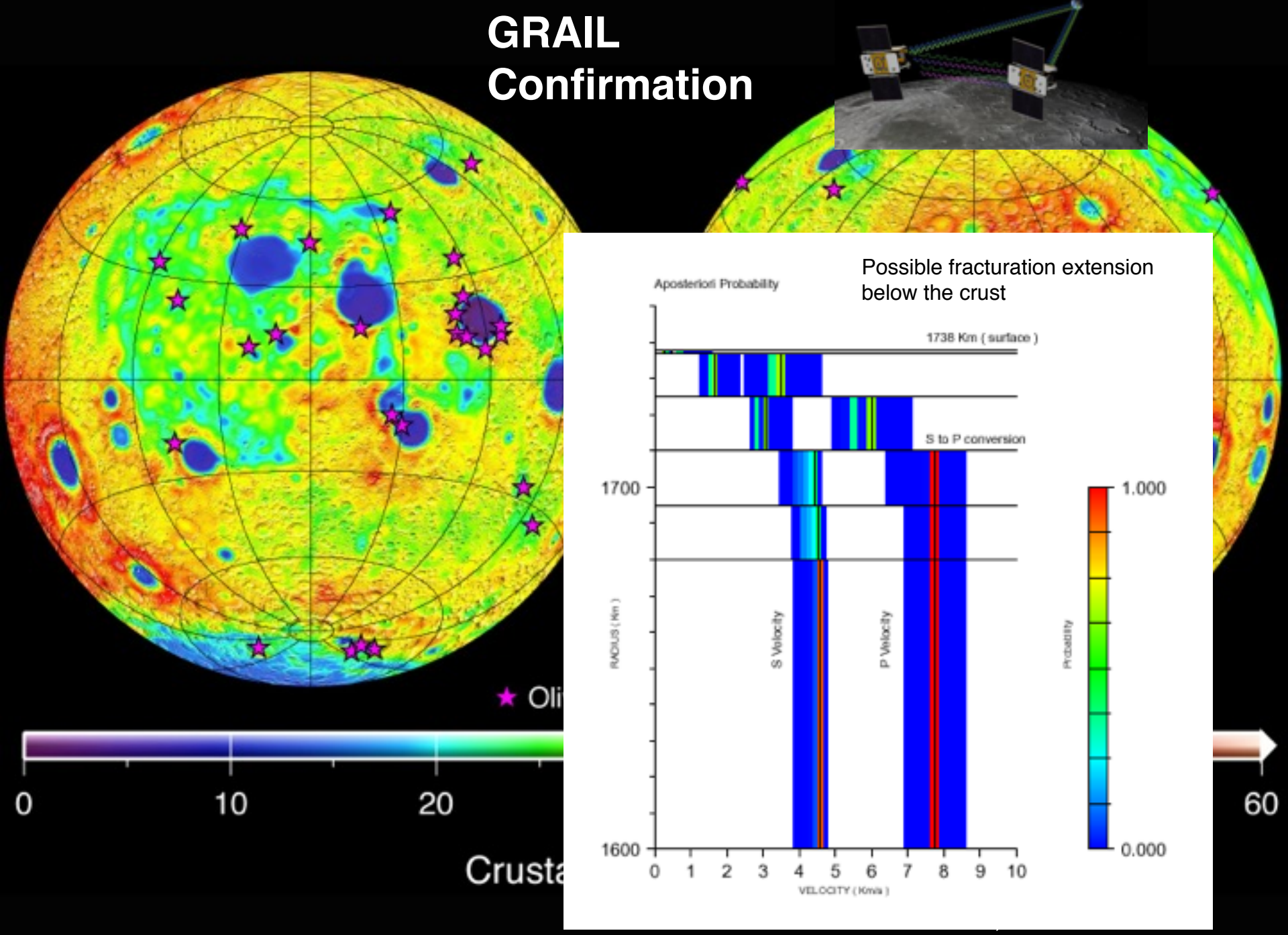
Gravity

Seismology



Chenet et al., 20016

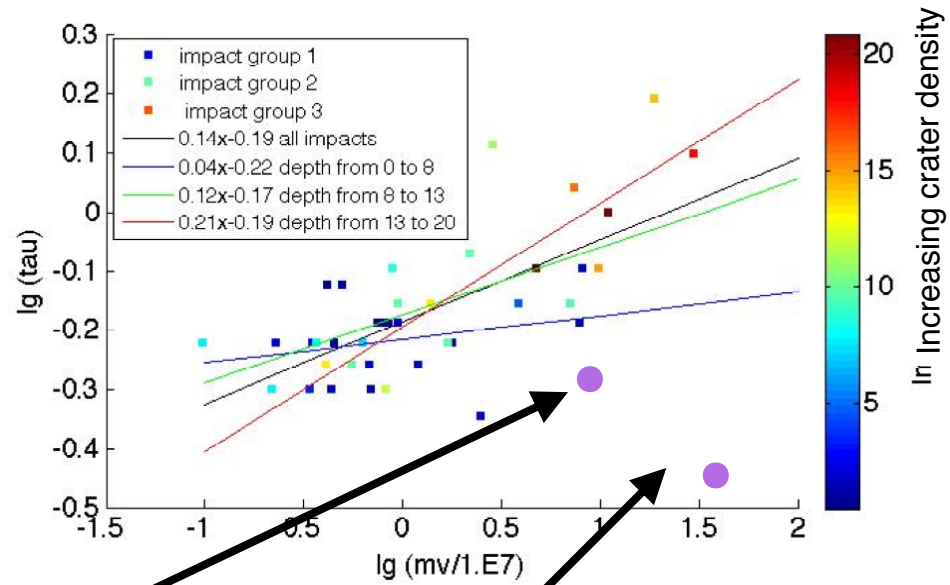
GRAIL Confirmation

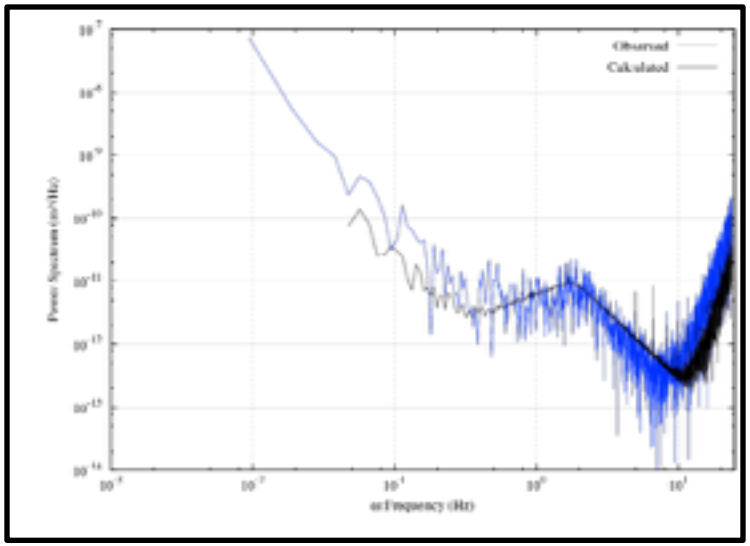


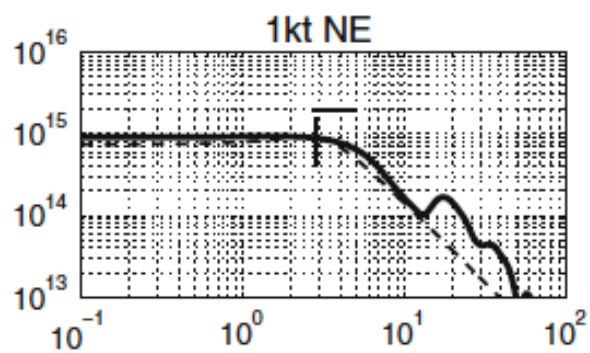
Impact source properties….

- Natural impacts have a long lasting seismic source likely due to the low seismic velocities of the surface and high (20km/s) impact velocities

Gudkova et al, 2014



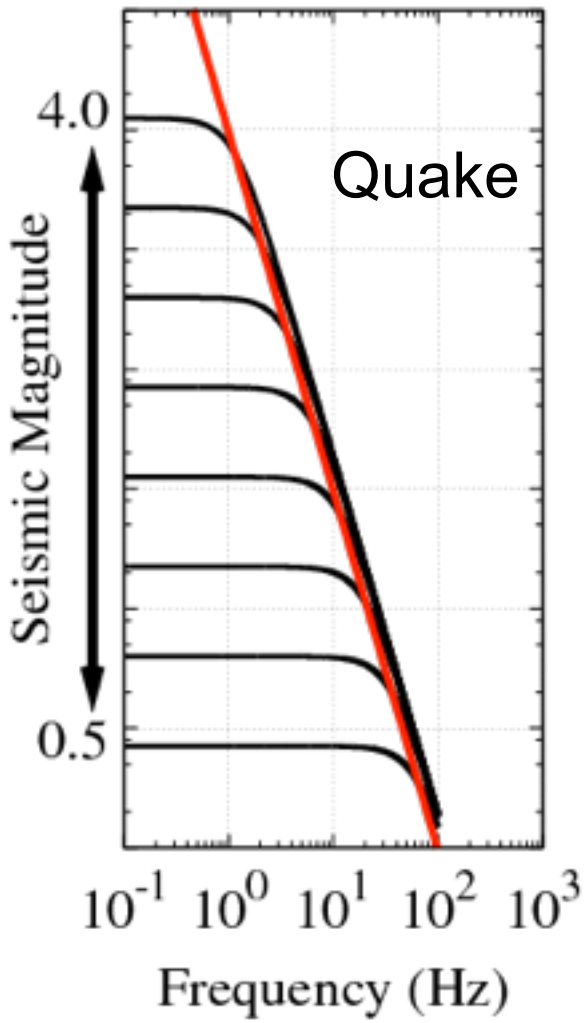


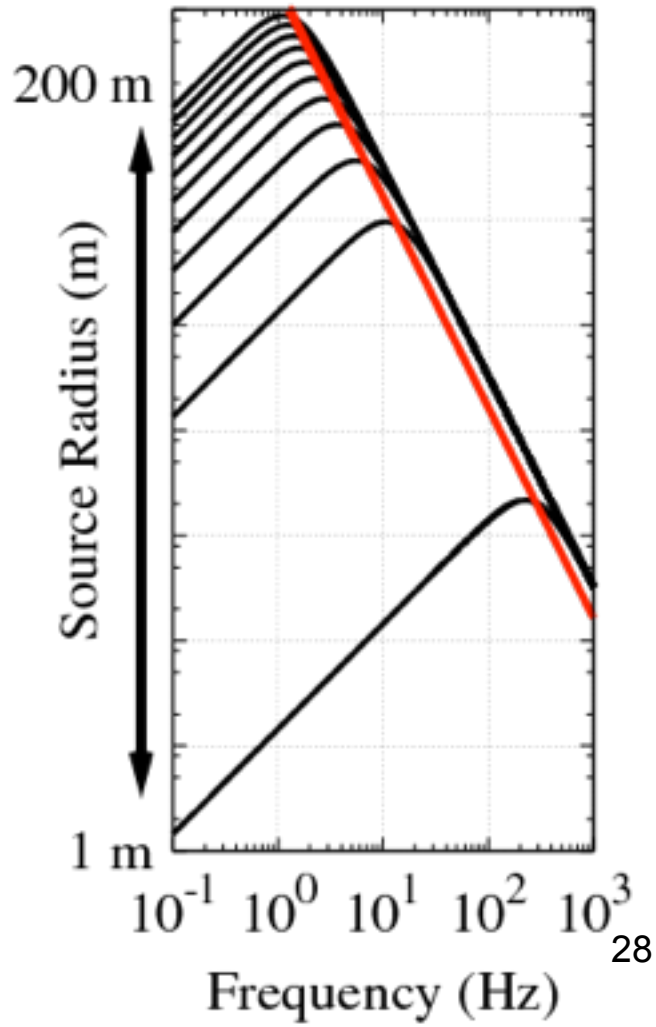


1 kT nuke in Granit (Xu et al, 2014)

Source model (in frequency)

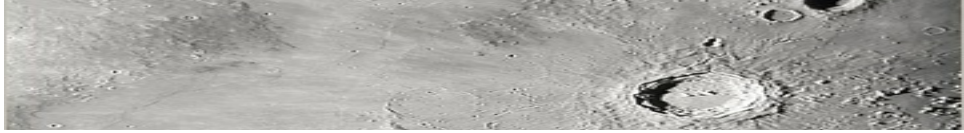
- Low frequency displacement = > moment or impulse
- Frequency integral of displacement= > energy





Impacts

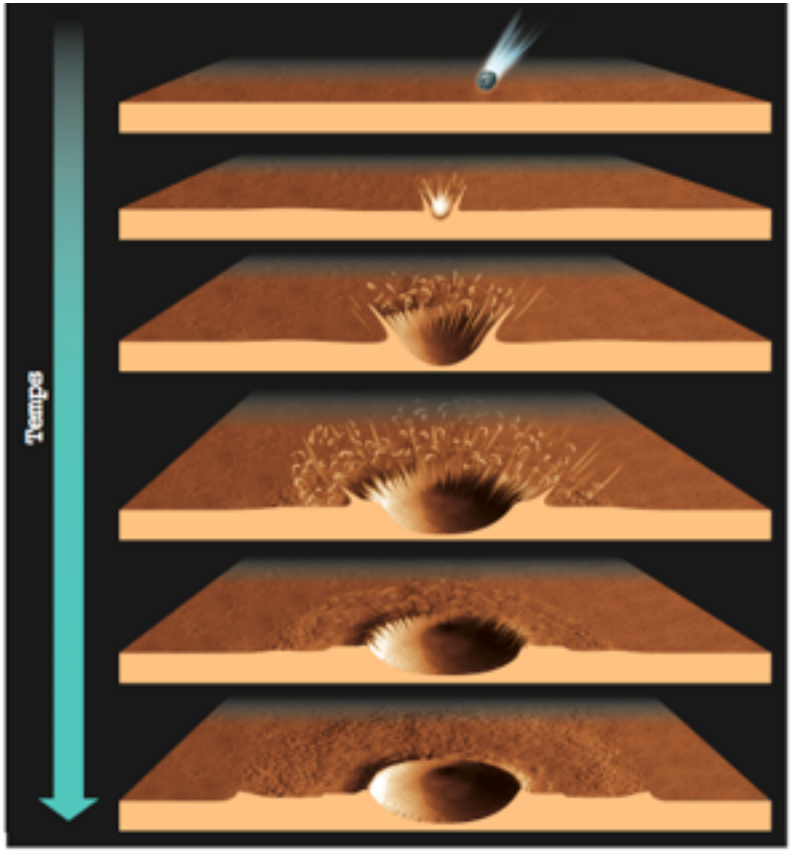
Lognonné et al., 2009



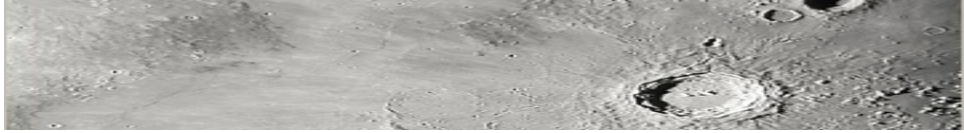
- Seismic source must take into account both the ejecta and the formation time of the crater
  - Ejecta mass are much larger than impactor mass
  - Momentum of the ejecta is significant and increase the force
  - Formation time leads to cutoff in the 1Hz-10hz range

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

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

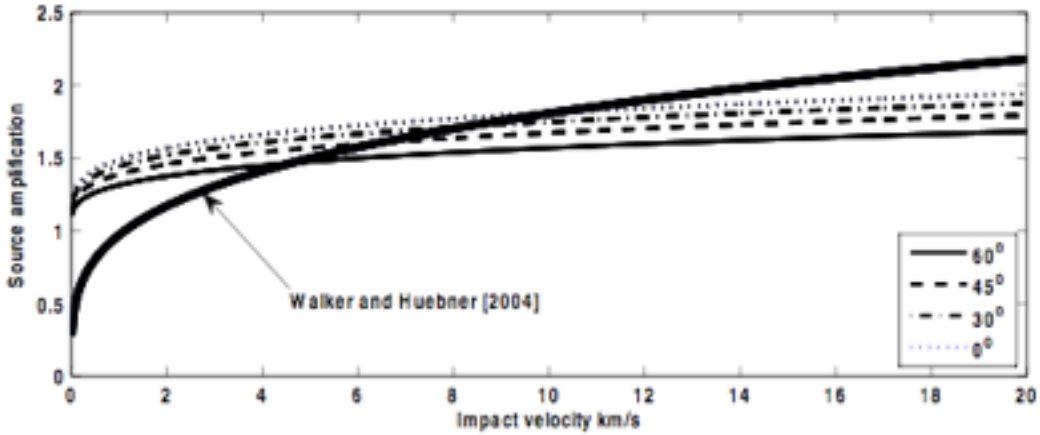


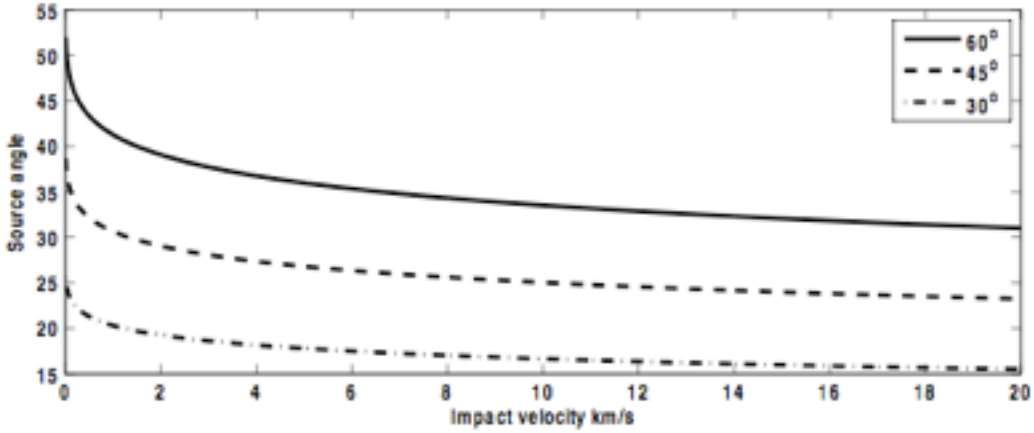
Lognonné et al., 2009



Ejecta and Seismic source

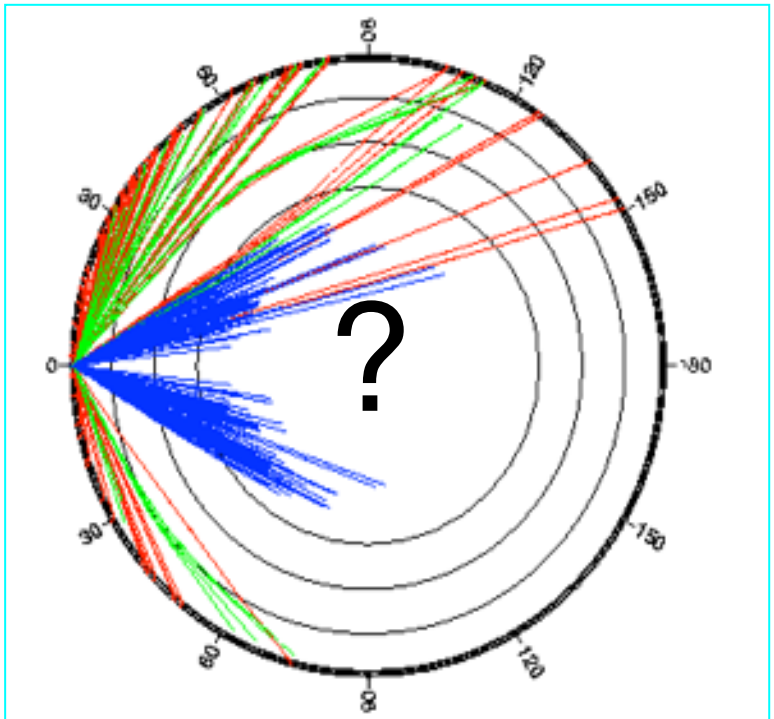
- Provide an amplification of the point force amplitude (~m v)
- Low effects for the Apollo artificial impacts
- Significant effect for high velocity impacts, leading to vertical source
- Linearity to the source impulse is found below .5Hz





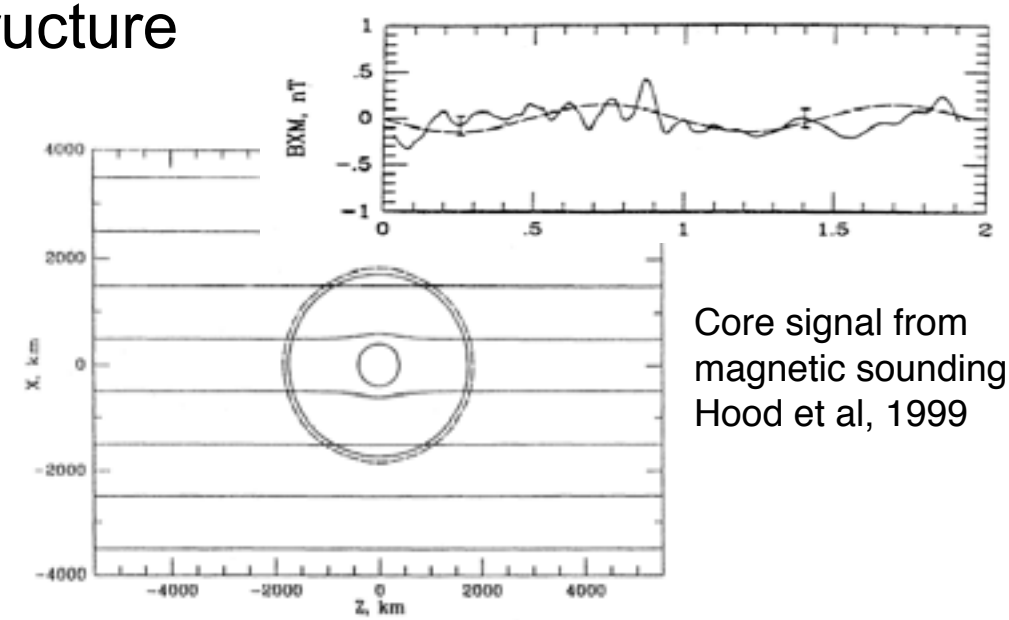
Core…?

- Until 2010, Seismology was in a pre-Oldham configuration regarding the lunar core structure



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

Lognonné and Johnson, 2007



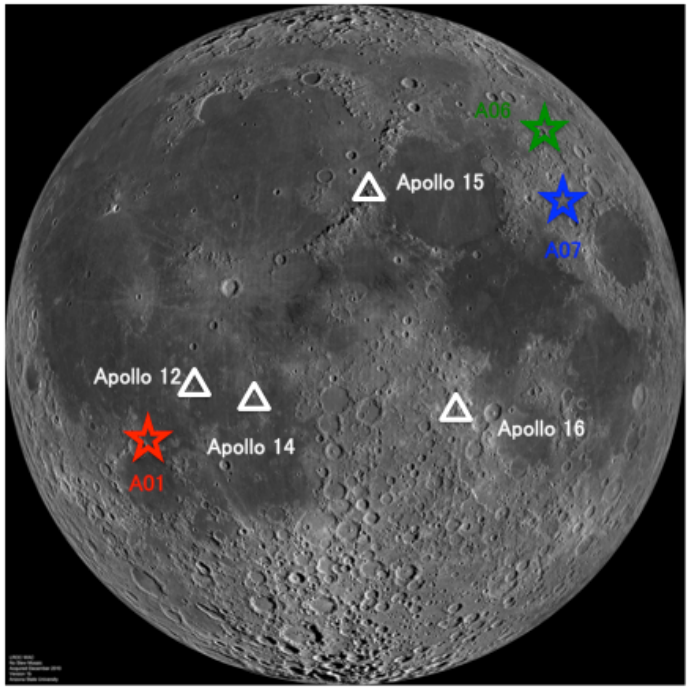
Core signal from magnetic sounding, Hood et al, 1999

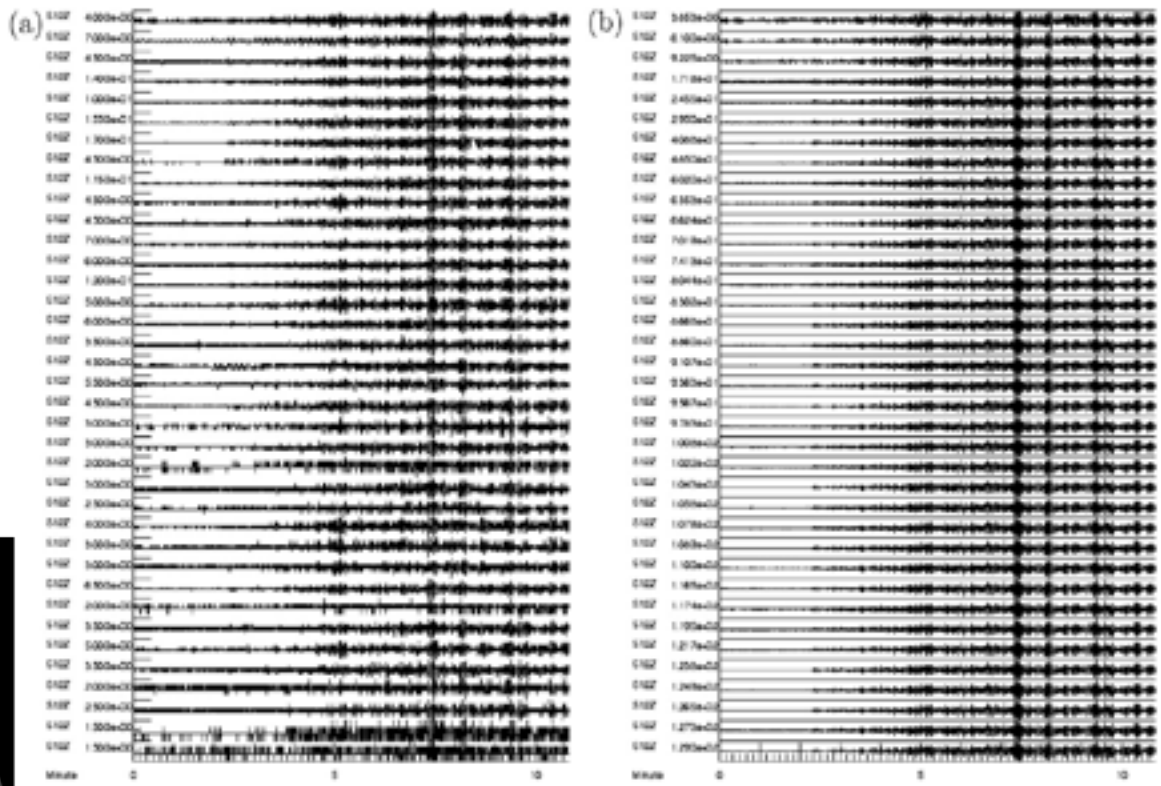
Core signal from libration monitoring, William et al, 2001

Back to the Deep Moonquakes

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

Kawamura et al, 20134

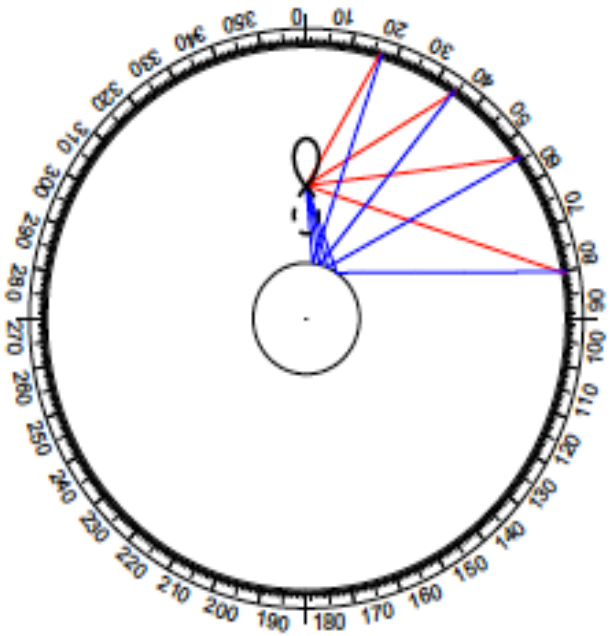


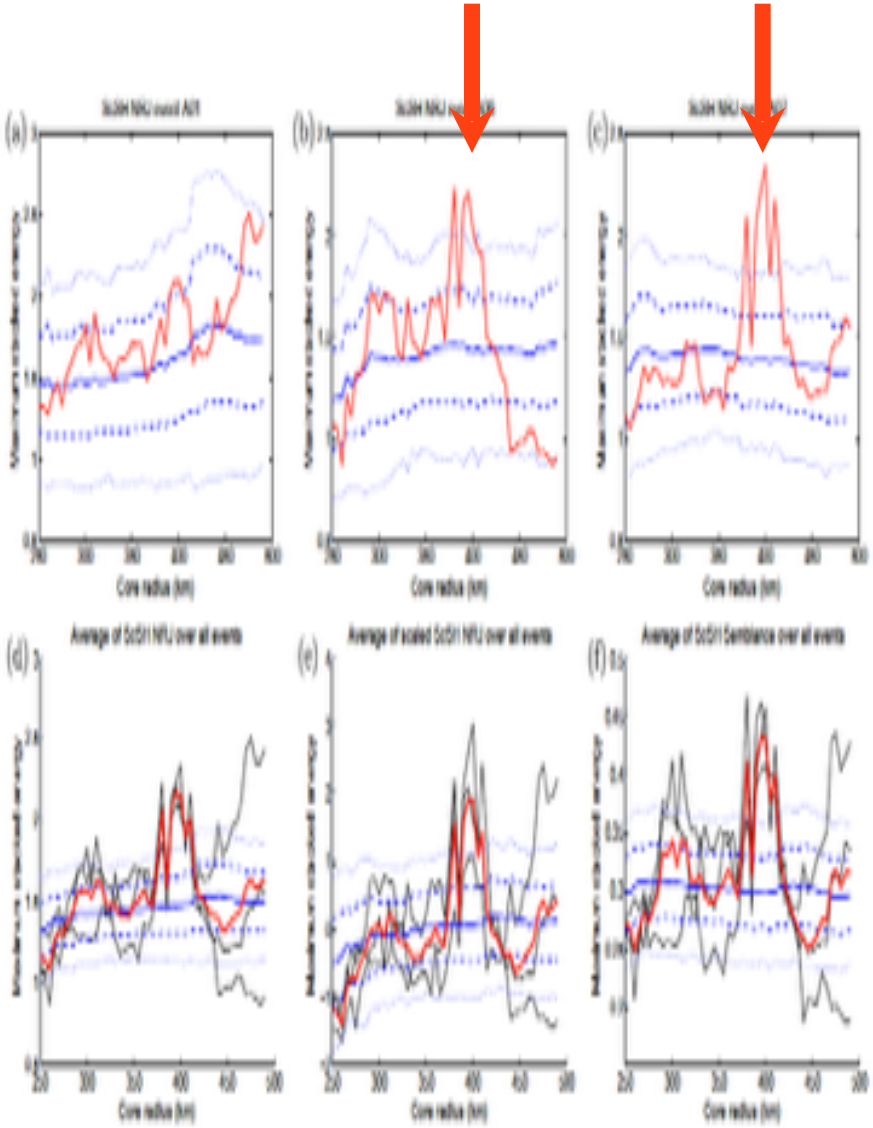


Garcia et al, 2013

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

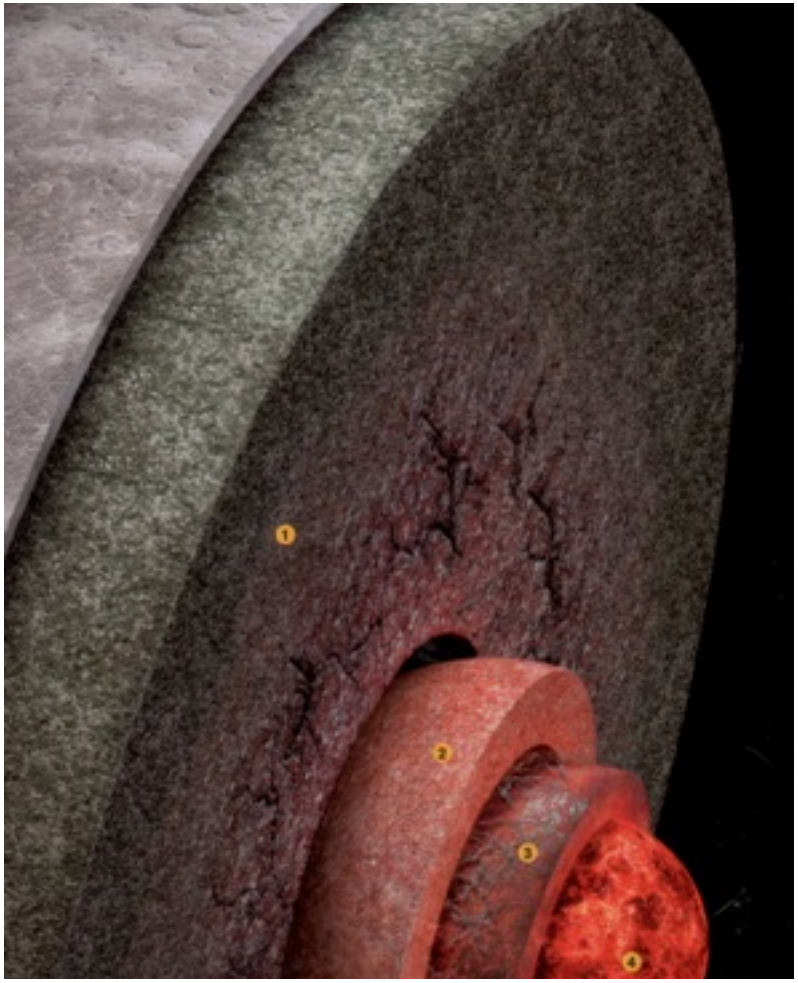
Seismic discovery of the core (1/2)

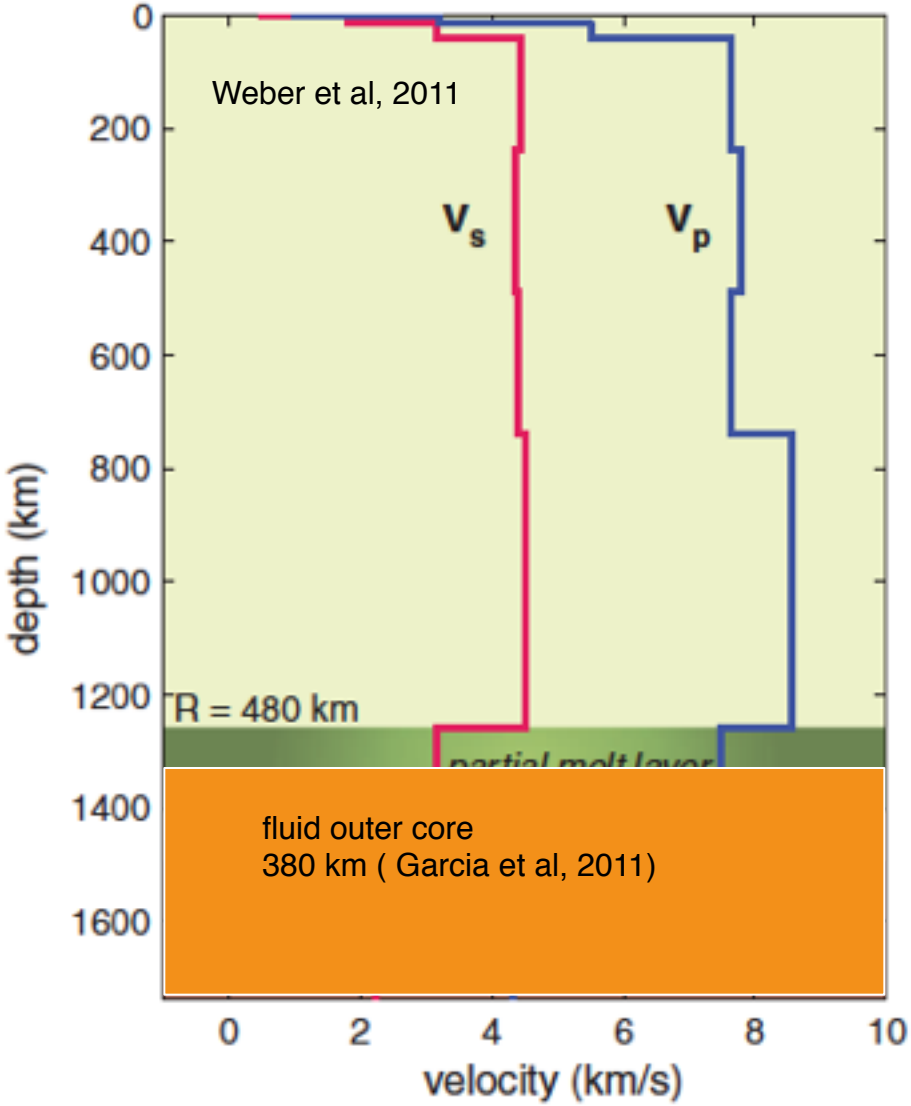




Garcia et al., 2011
Weber et al, 2011

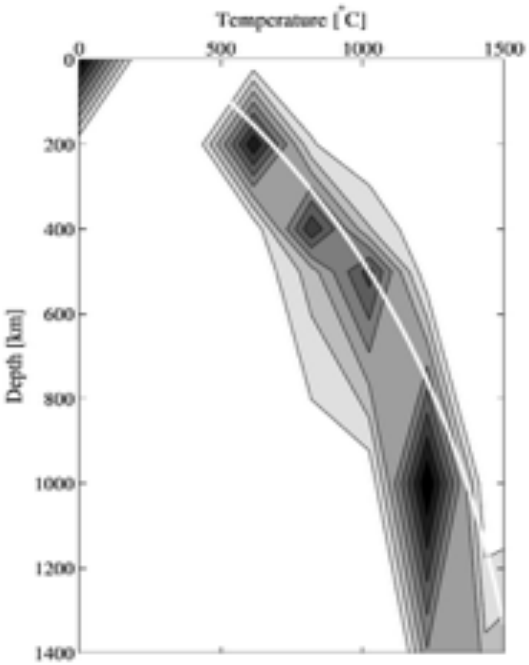
Seismic discovery of the core (2/2)

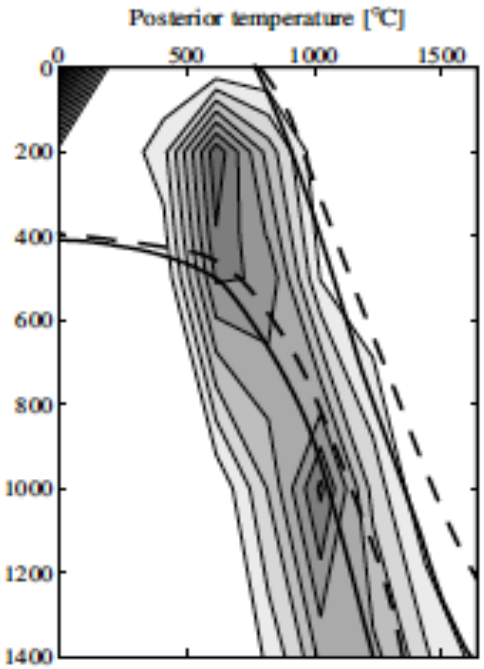




Weber et al, 2011

Core temperature and composition (1/2)

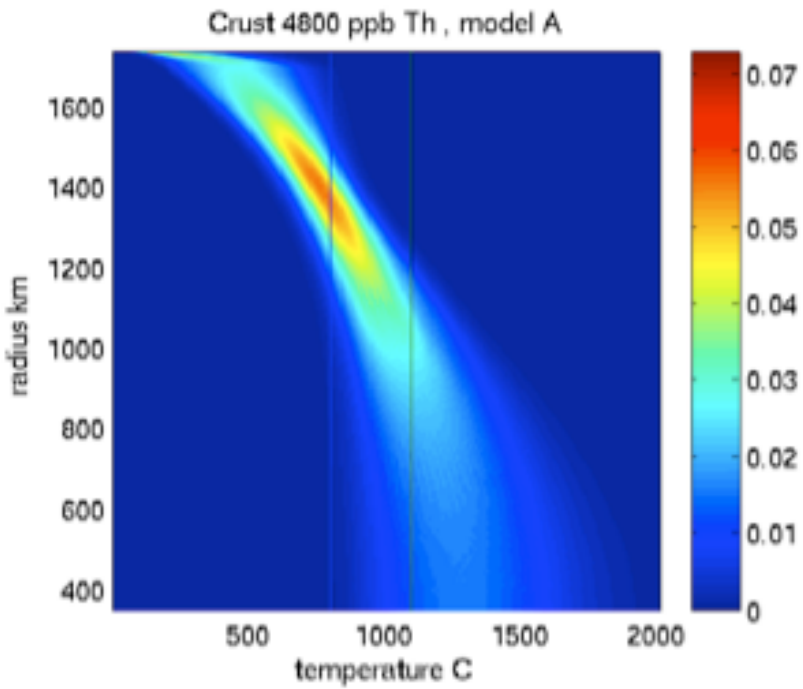




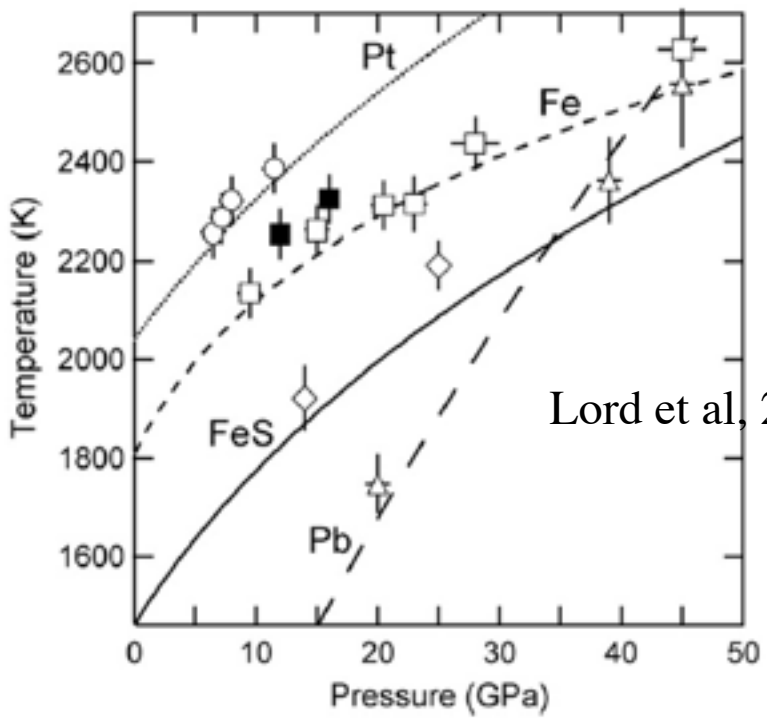
Gagnepain-Beyneix et al, EPSL, 2006

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

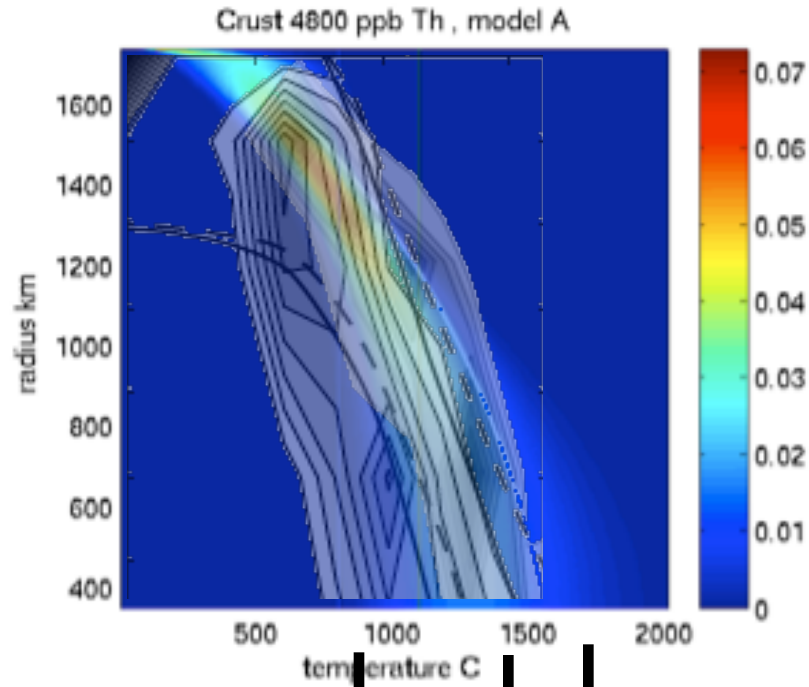
Khan et al, 2007
(direct inversion of magnetic data)



Core temperature and composition (2/2)



Lord et al, 2010

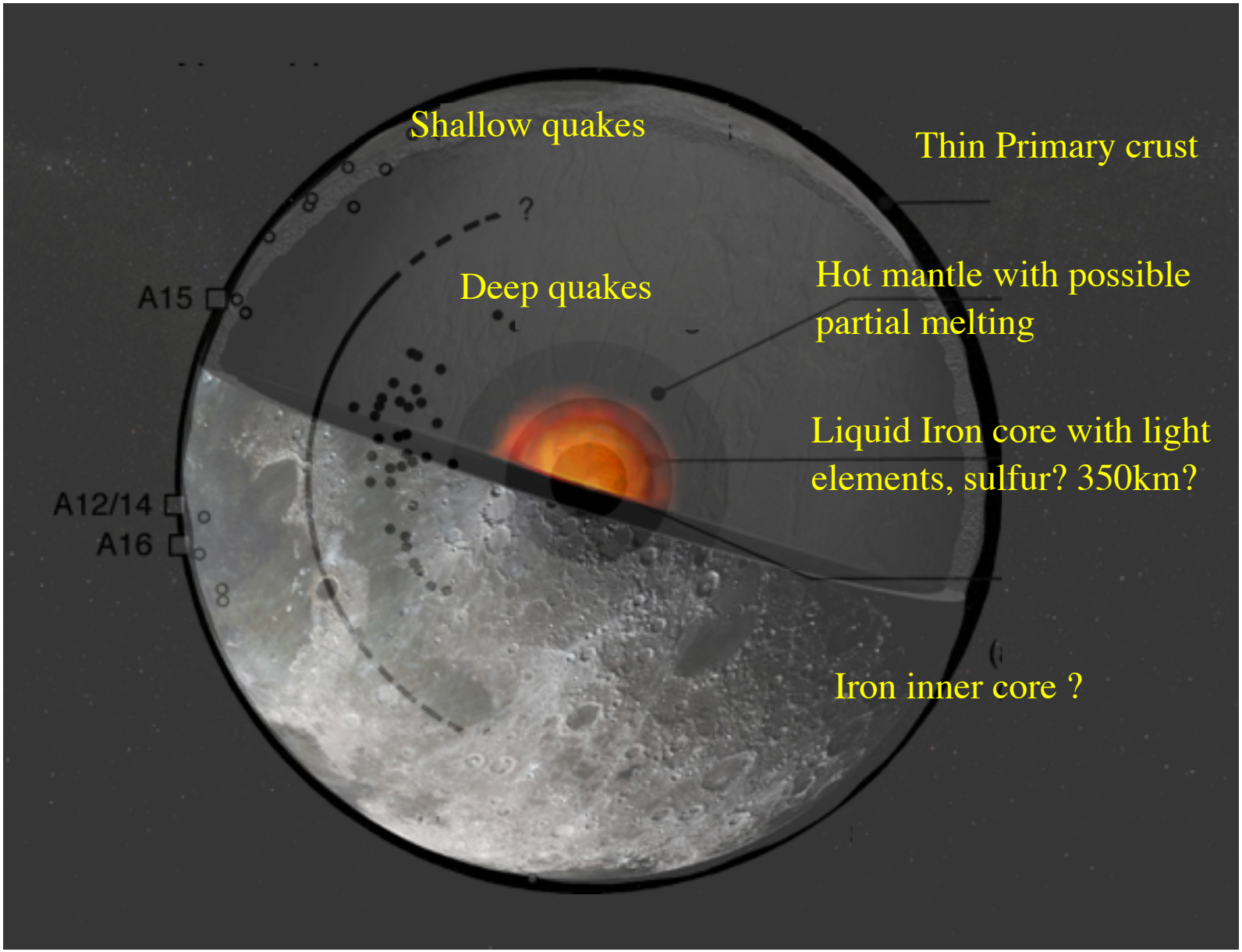


1620°C (Fe, Anderson and Isaak, 2000)

1490°C (29° Ilmenite, 71% clinopyroxene, Wyatt, 1977)

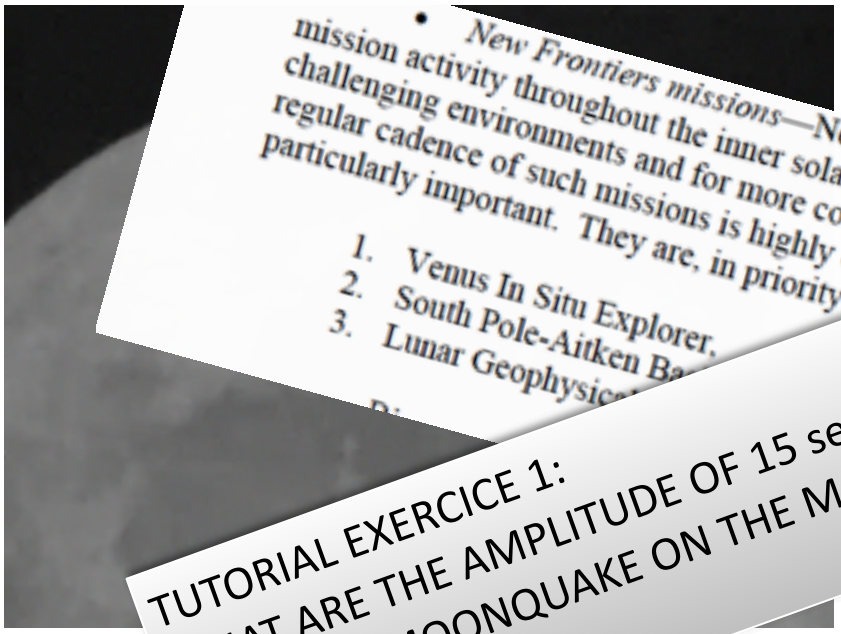
950°C (Fe-S Eutectic, Fei et al, 1997)

Our view of the Moon



Moon Future directions…

- SELENE2 (JAXA)
- NF Lu[illegible] Network (NASA)



• *New Frontiers missions*—New Frontiers missions
mission activity throughout the inner solar system, providi
challenging environments and for more comprehensiv
regular cadence of such missions is highly desirab
particularly important. They are, in priority o

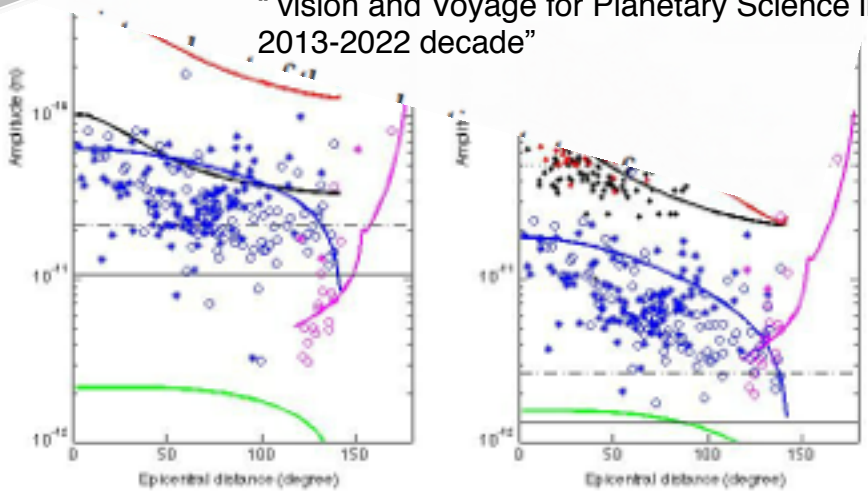
1. Venus In Situ Explorer,
2. South Pole-Aitken Ba
3. Lunar Geophysic

TUTORIAL EXERCICE 1:
WHAT ARE THE AMPLITUDE OF 15 sec SEISMIC WAVES GENERATED BY A SHALLOW MOONQUAKE ON THE MOON ?

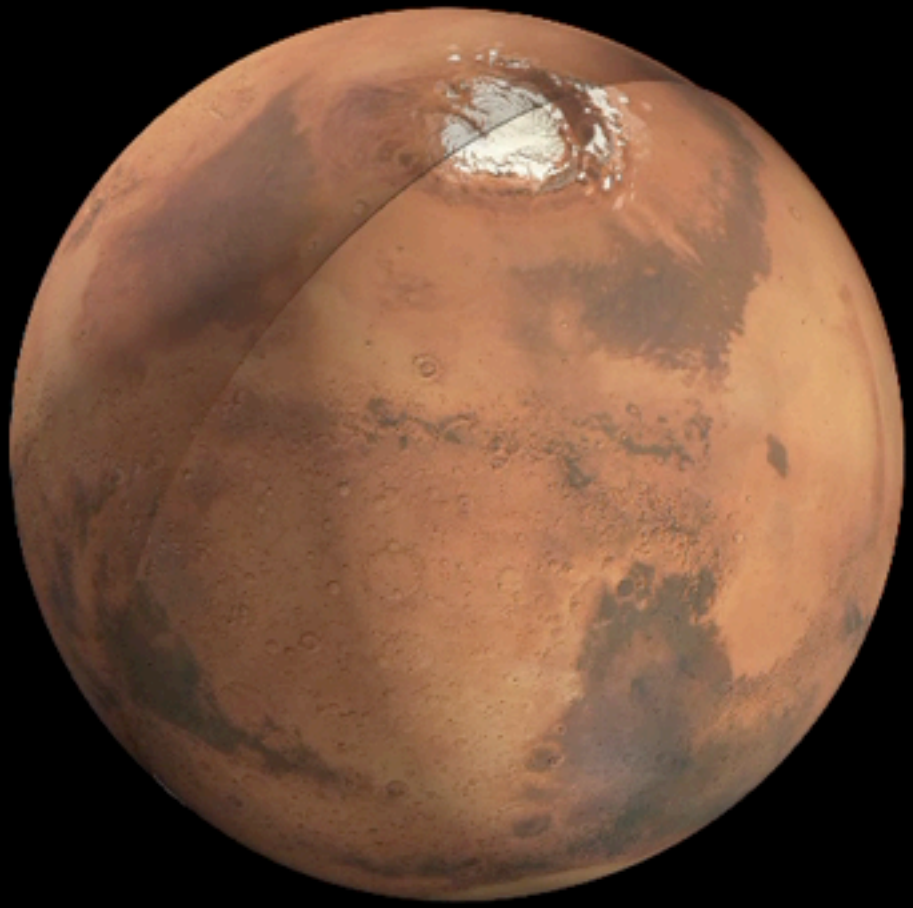
- Impacts: Can now be observed also from Earth and will therefore provide fr[illegible] active seismic exp[illegible] th 100th

[illegible] am of
[illegible] ce in more
[illegible] der Discovery. A
[illegible] missions as being

NRC Decadal report
" vision and Voyage for Planetary Science in the 2013-2022 decade"

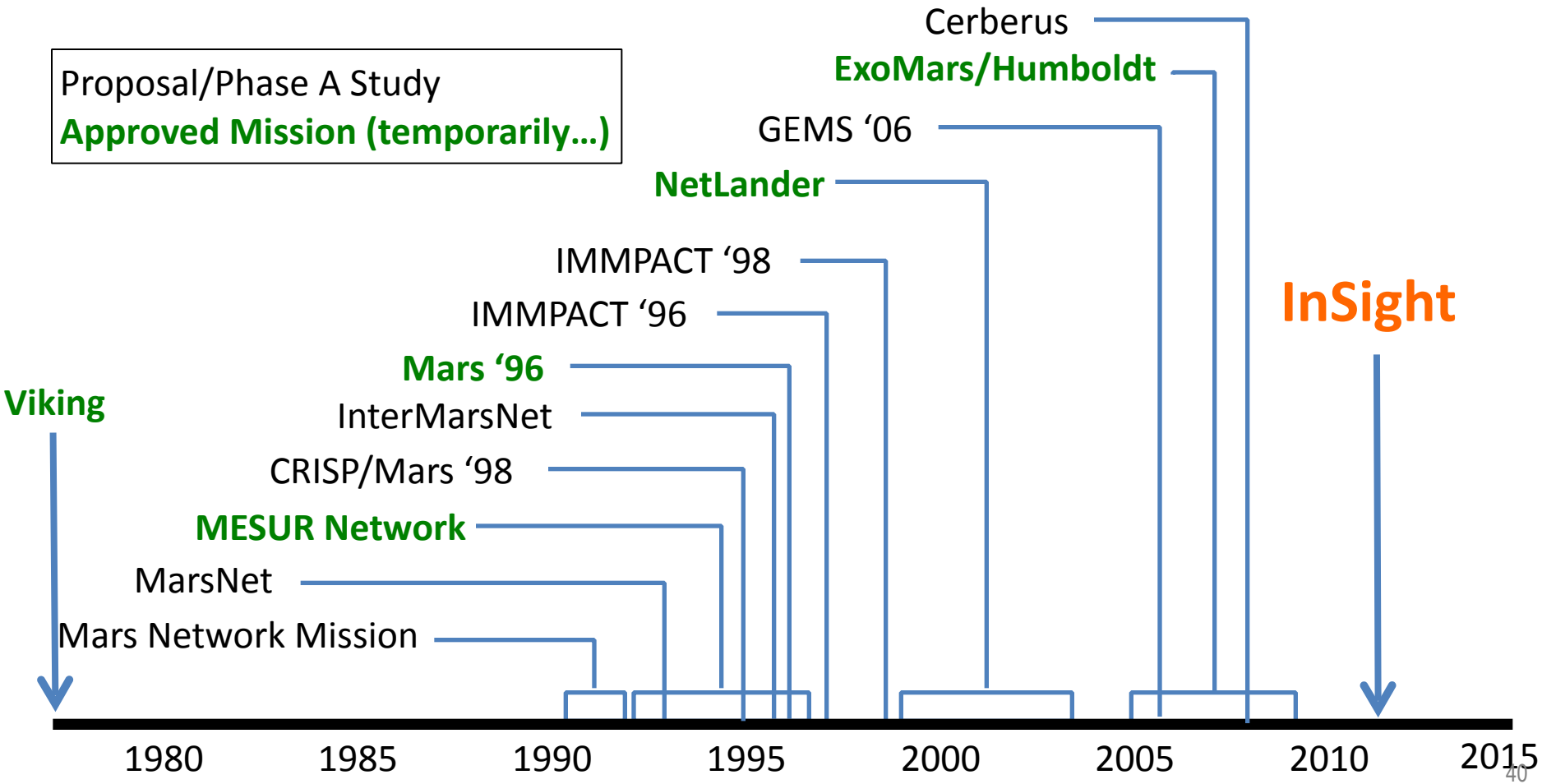


- Core. [illegible] sensitivity will allow the detection of core phases on single seismograms



1977 – Present

- Over the 35 years since Viking and Apollo, despite many proposals and several mission starts, there have been no further seismic investigations of the interior of any planet… until now!

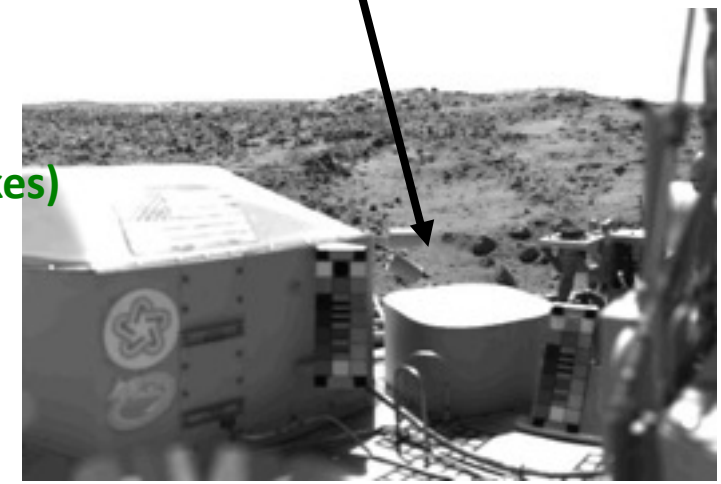


1977 – Present

- Over the 35 years since Viking and Apollo, despite many proposals and several mission starts, there have been no further seismic investigations of the interior of any planet… until now!

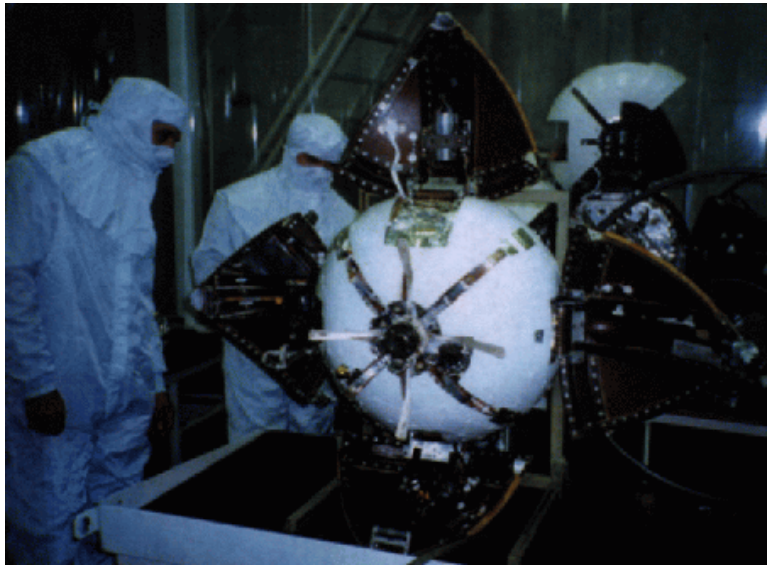
Launched Mission

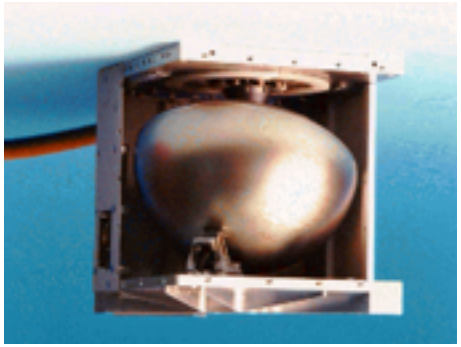
Seismometer



Viking (no quakes)

Mars '96 (lost)

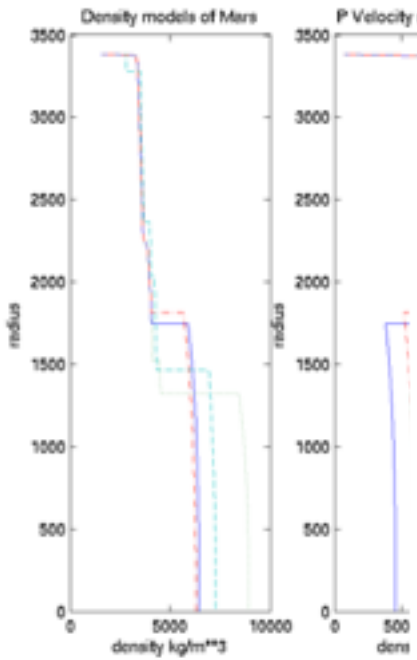




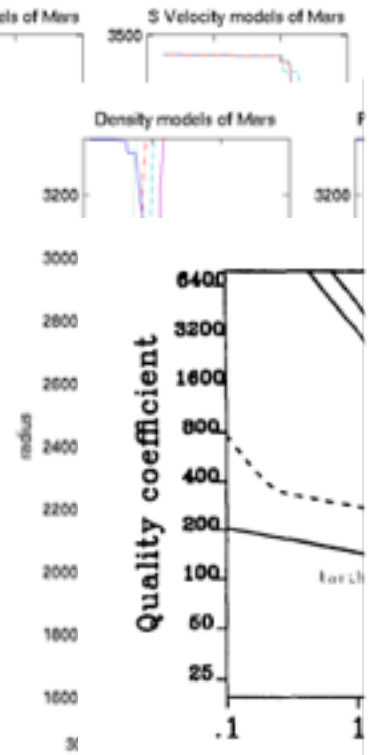
InSight

1980 1985 1990 1995 2000 2005 2010 2015

A priori seismic models

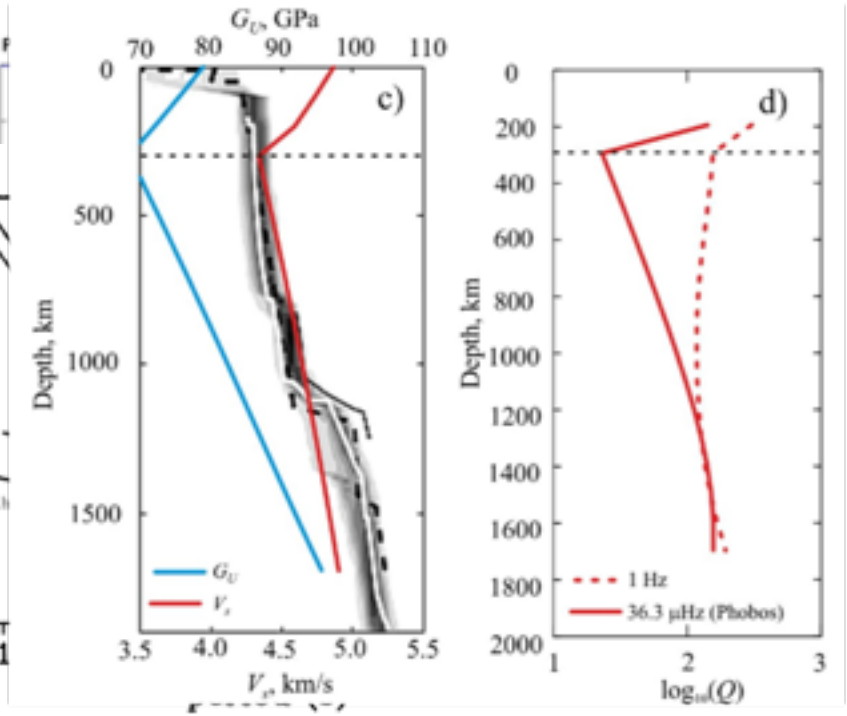


Dashed line Sohl and Spohn [1997]
Gudkova & Zharkov (2004]
Solid line 50%H, 14% S
Dotted line 70% H, 14% S
Dashdotted line 35% S



Mocquet et al., 1998

Nimmo, 2012

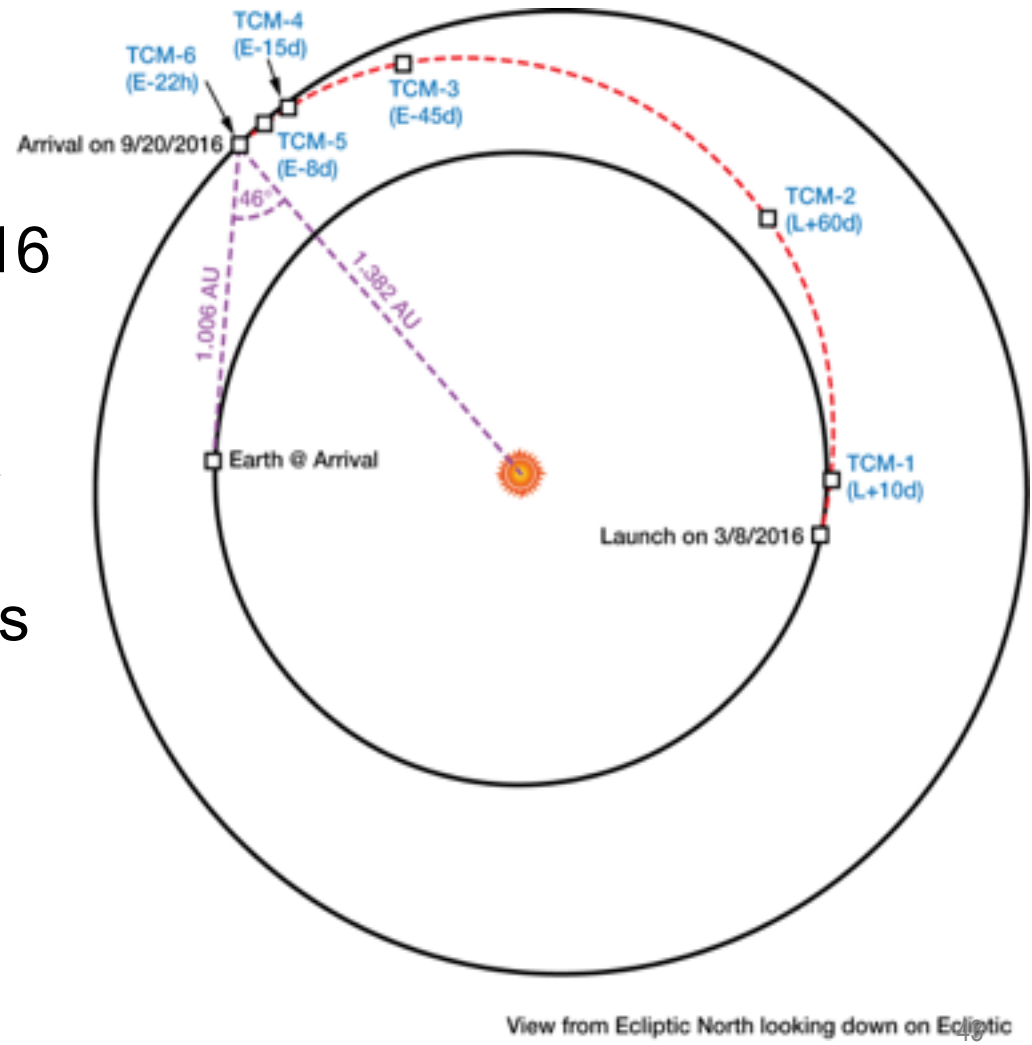


Earth like Q dependance
Lognonné and Mosser., 1993

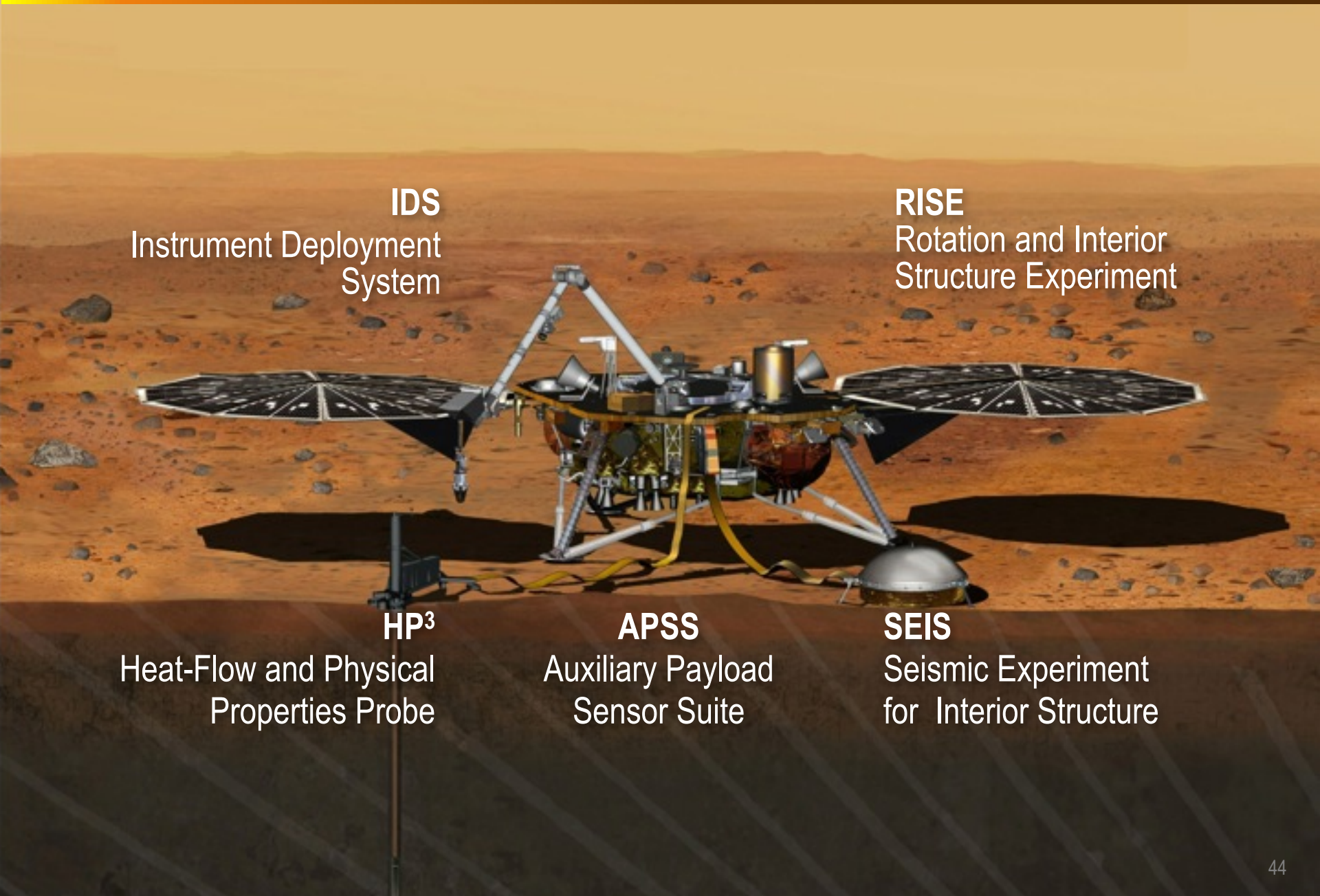
InSight Mission Design Summary

Only 1 year, 7 months, 21 days from now!

- Launch: March 4, 2016
- Fast, type-1 trajectory, 6.5 month cruise to Mars
- Landing: September 28, 2016
- 67-sol deployment phase
- One Mars year (two years) science operations on the surface; repetitive operations
- Nominal end-of-mission: October 6, 2018

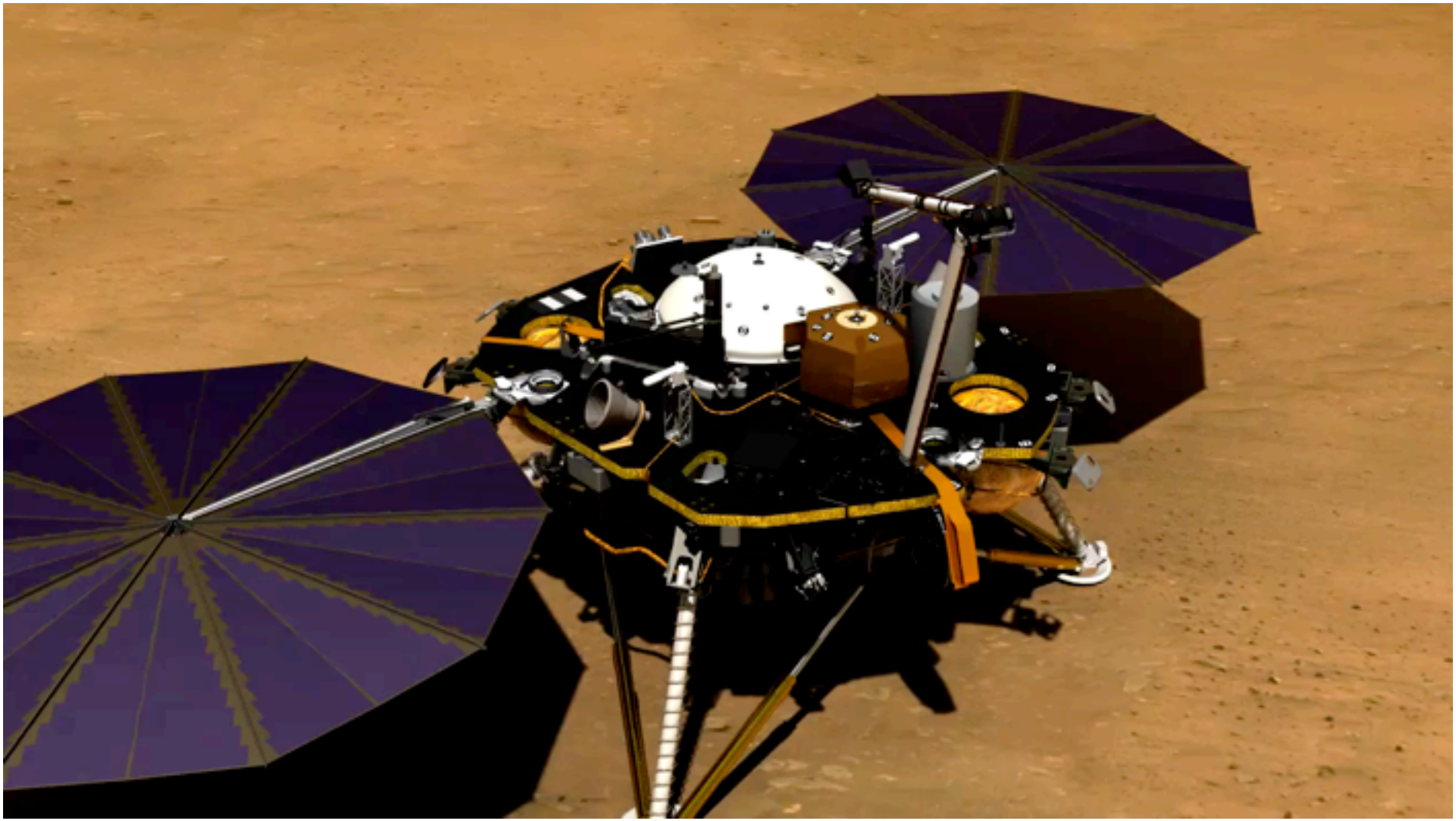


Payload Elements

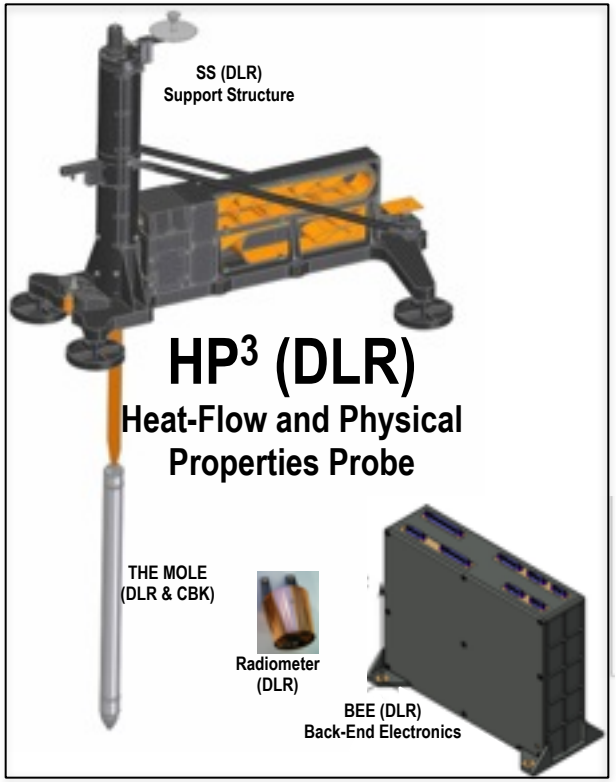


Payload Elements Deployment challenge: Apollo

Payload Elements Deployment challenge: InSight

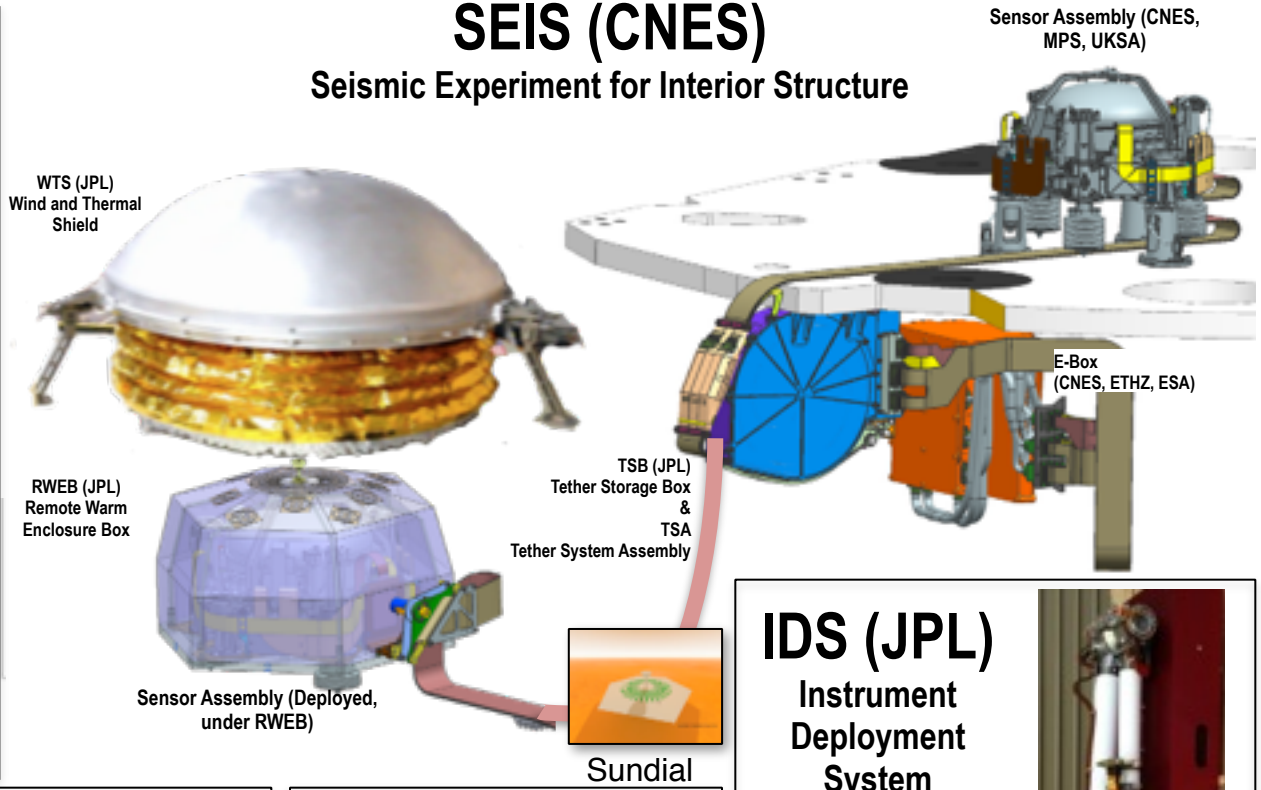


The InSight Payload



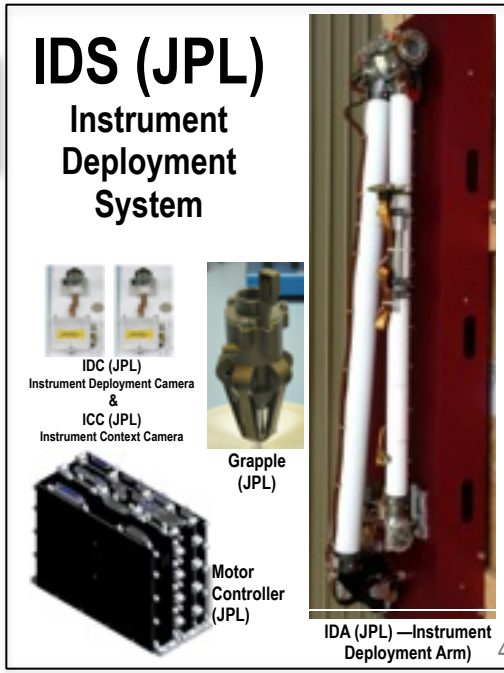
SEIS (CNES)

Seismic Experiment for Interior Structure



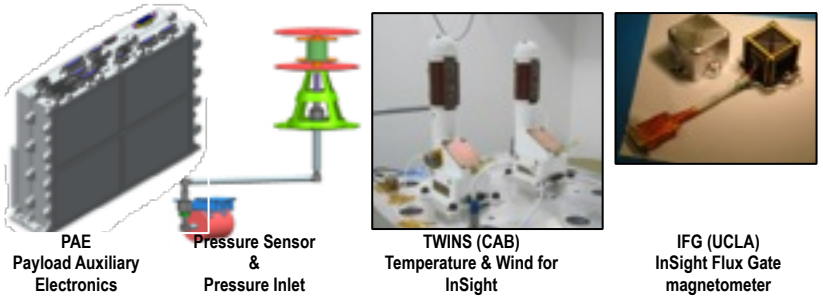
IDS (JPL)

Instrument Deployment System



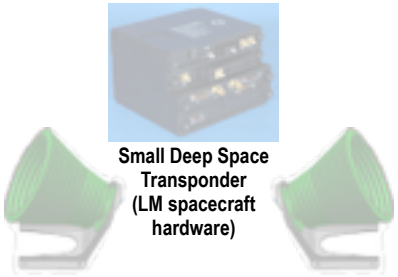
APSS (JPL)

Auxiliary Payload Sensor Suite

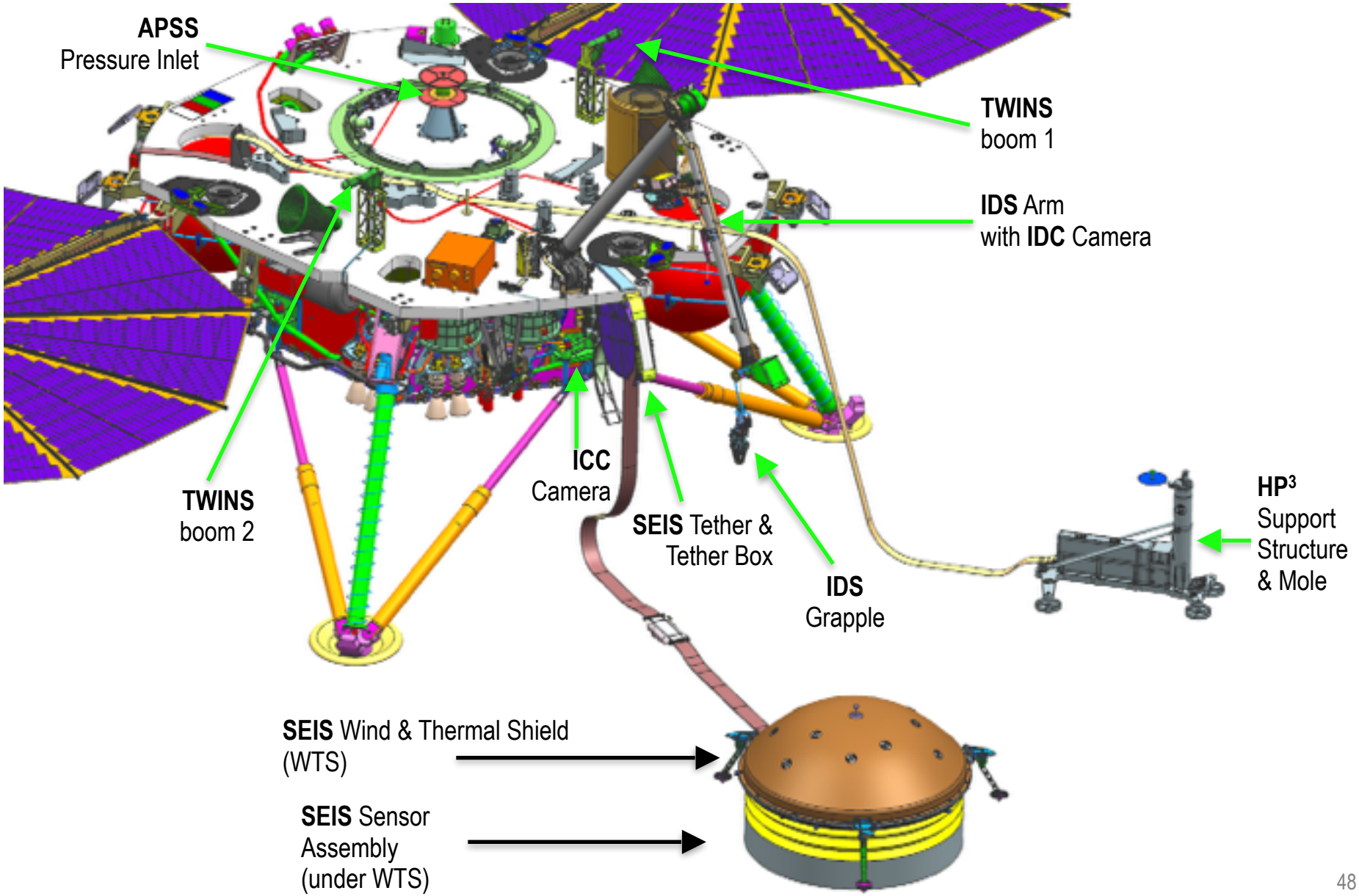


RISE (S/C)

Rotation and Interior Structure Experiment

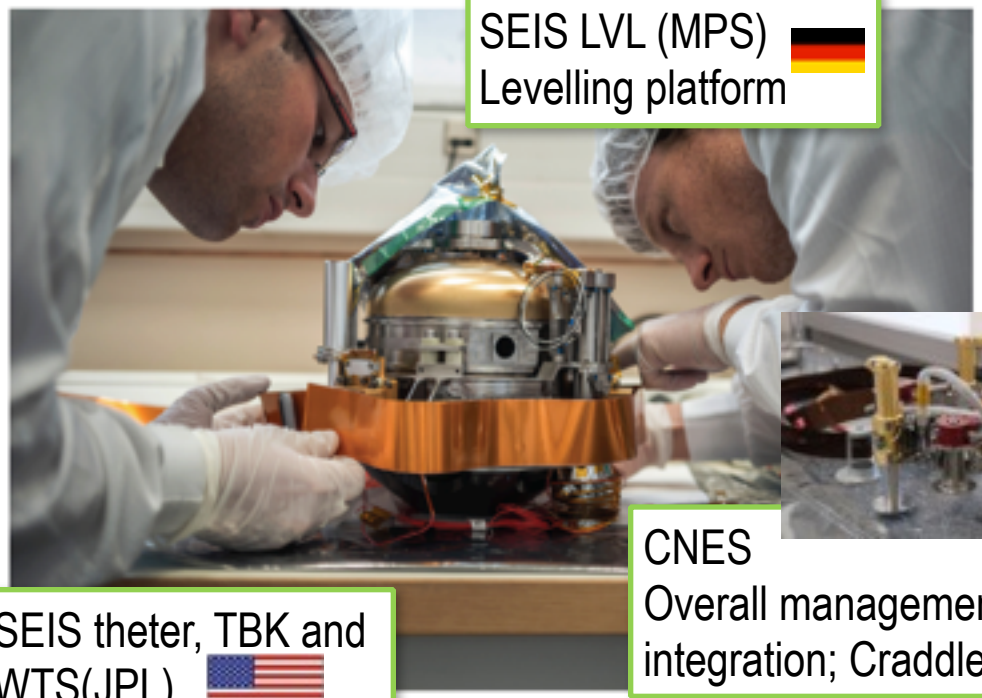


Payload Configuration on Deck—Deployed



SEIS Overview/Description

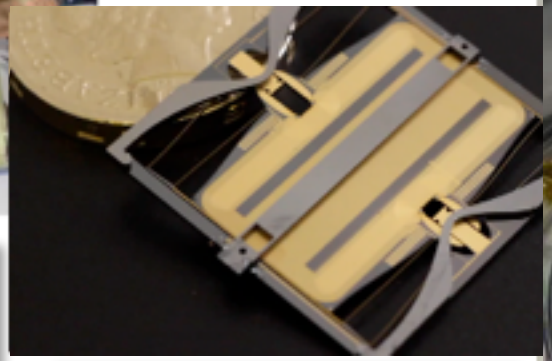
SEIS Electronics (ETHZ)
10x24 bits + 72x12 bits data logger



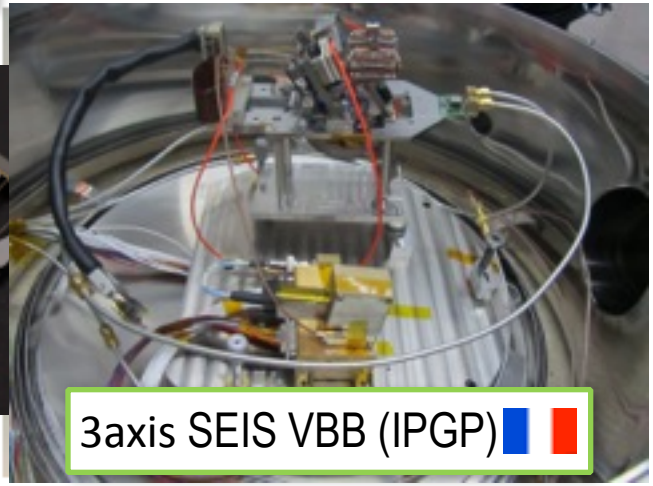
SEIS LVL (MPS)
Levelling platform

SEIS theter, TBK and WTS(JPL)

CNES
Overall management and integration; Craddle



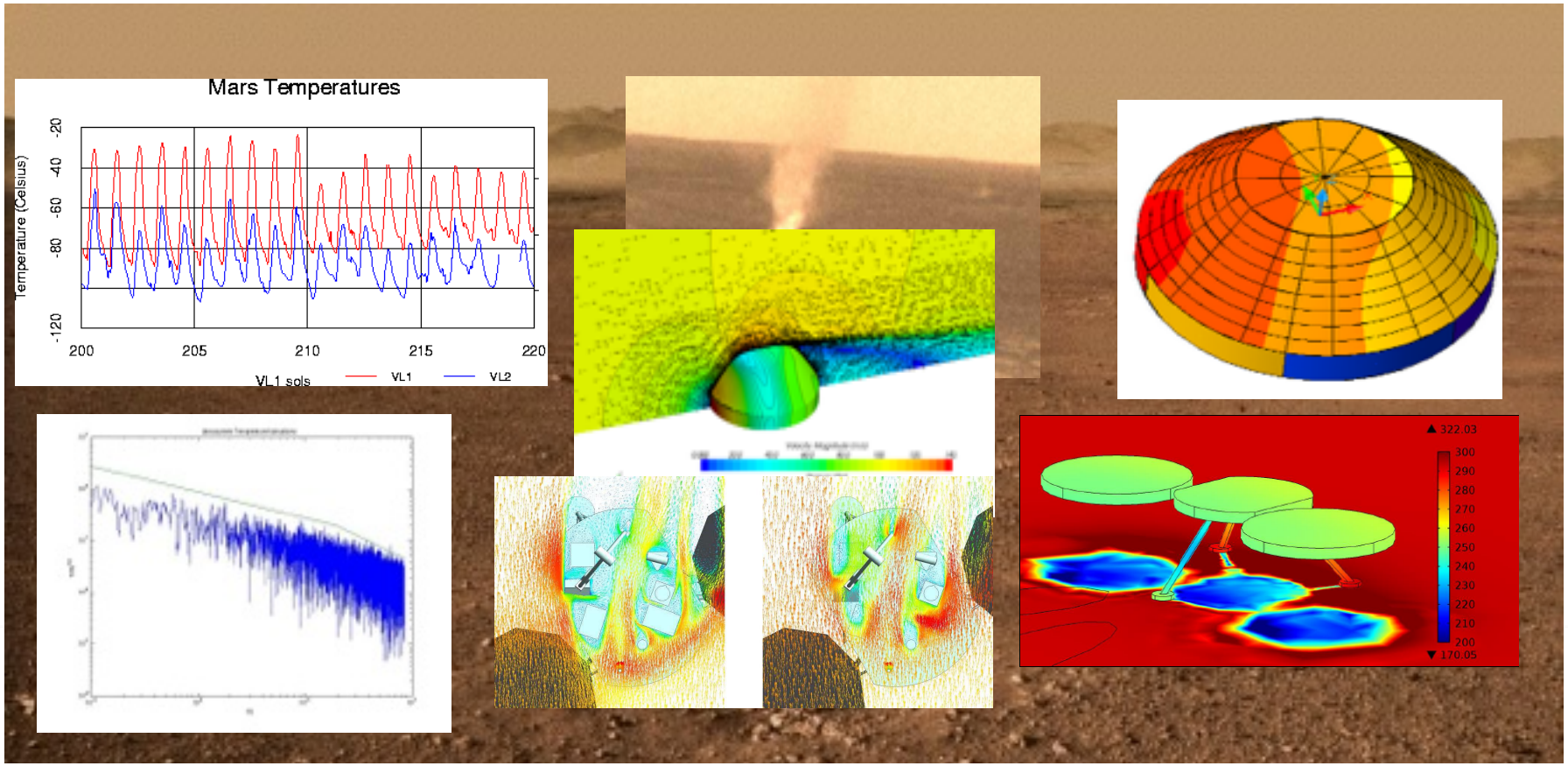
3 axis SEIS SP (IC)



3axis SEIS VBB (IPGP)

Environmental noise

- We are here……



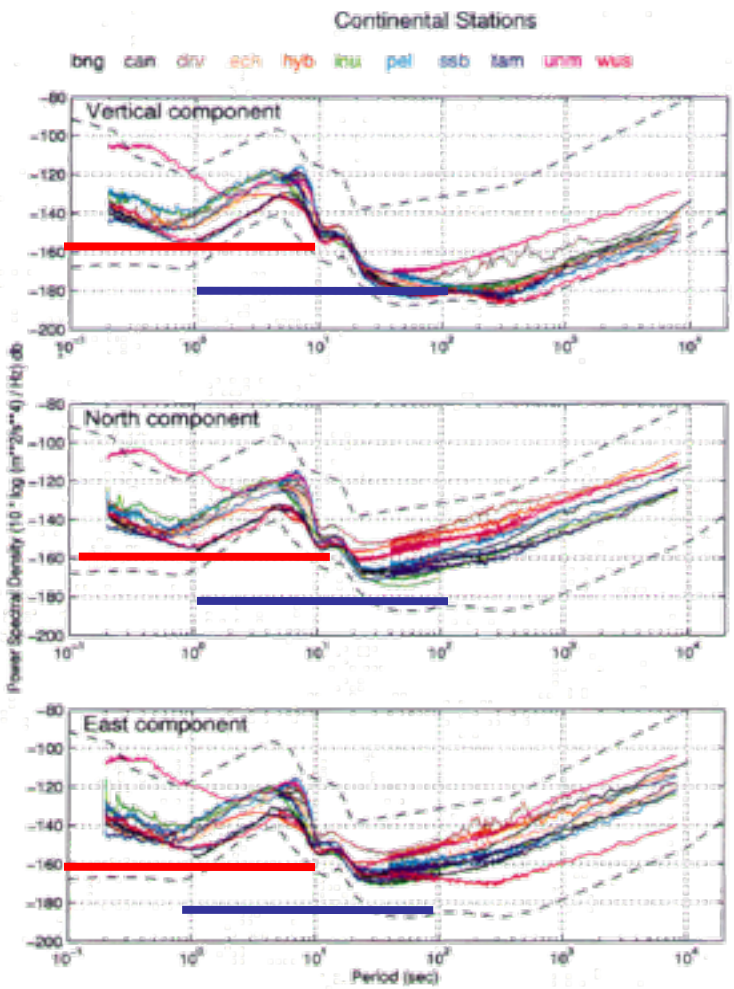
Environmental noise

- but would like to be there……

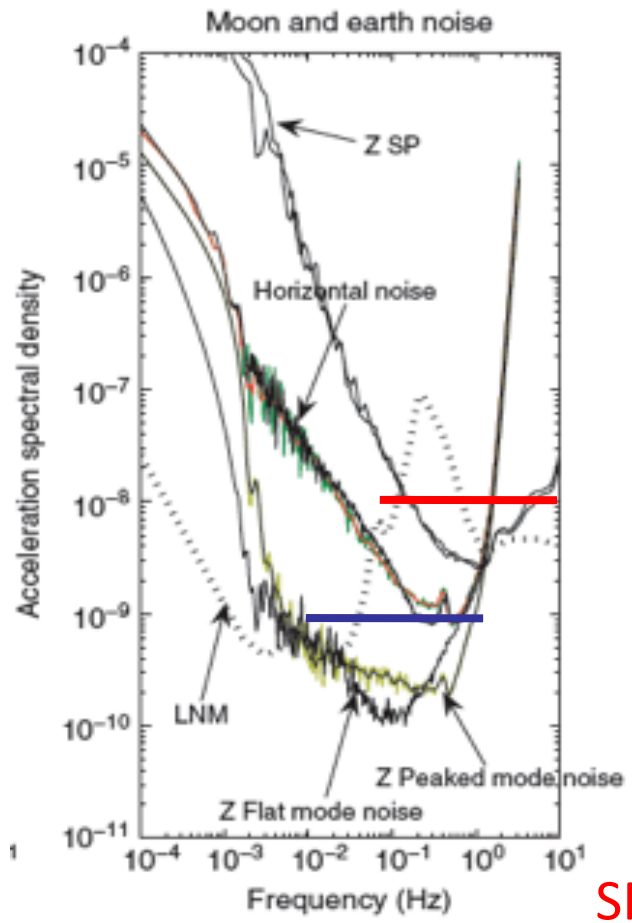
Seismic vault

Environmental noise: installation goals

Planet with Ocean and Atmosphere



Planet without atmosphere and ocean

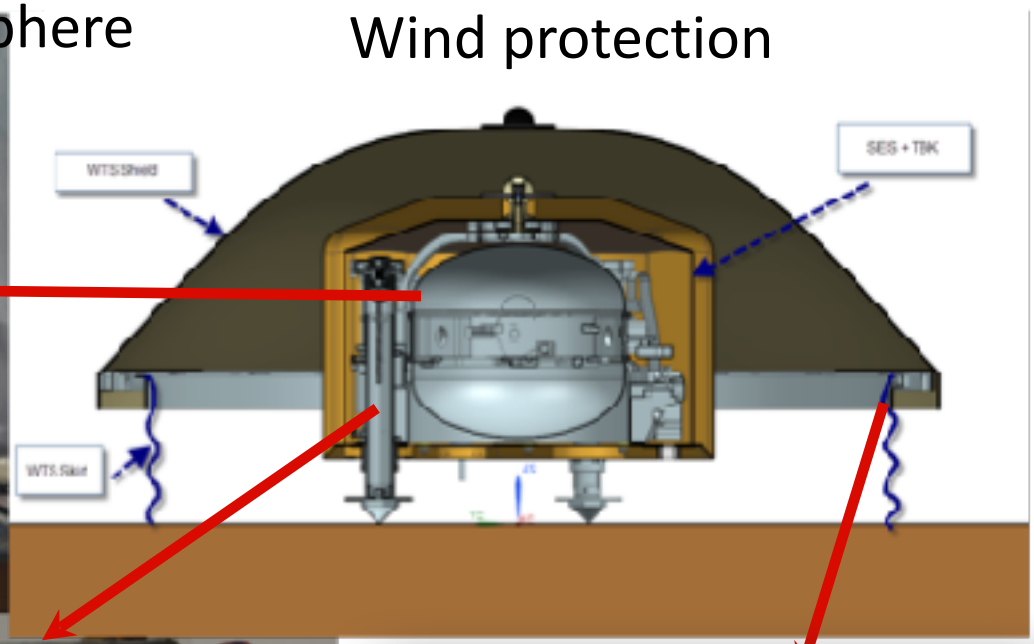


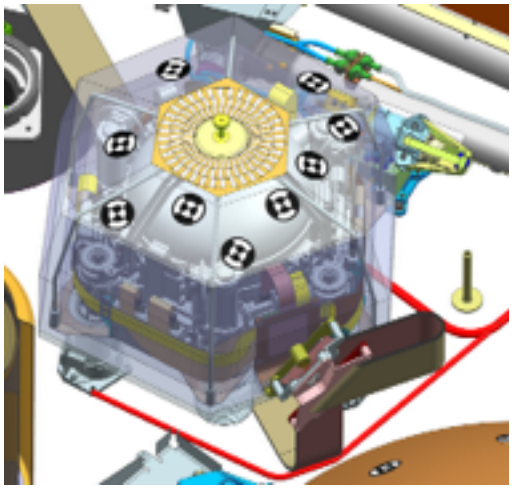
SP VBB

Temperature and wind protection

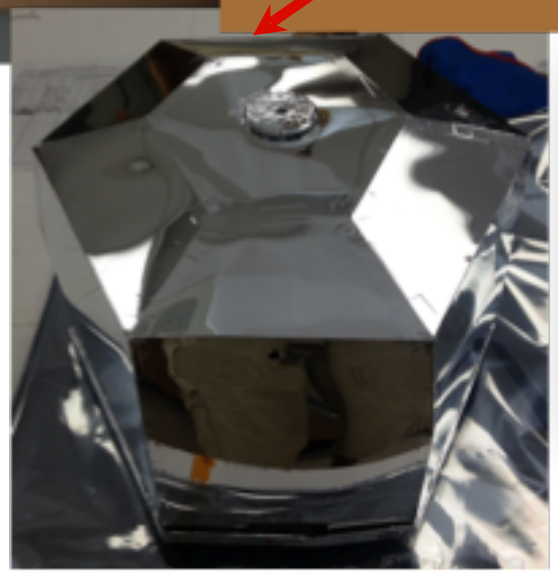
Evacuated sphere

Wind protection

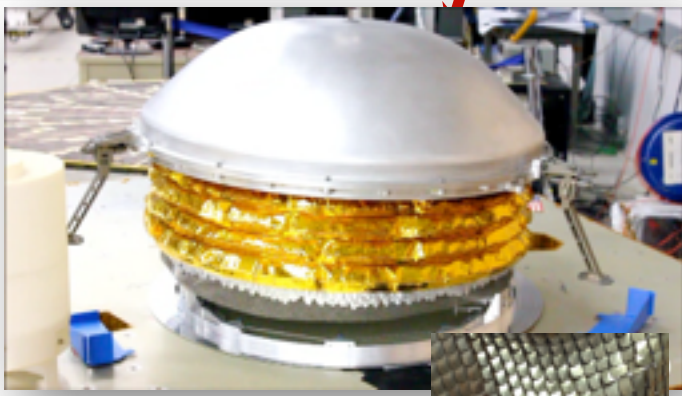




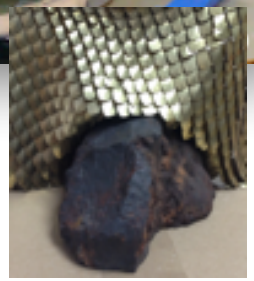
Thermo-elastic service loop



Thermal shield



Sealing skirt



SEIS Expected Natural signals

M~5.5 1-2/yr

Global

M~4.5 ~ 10/

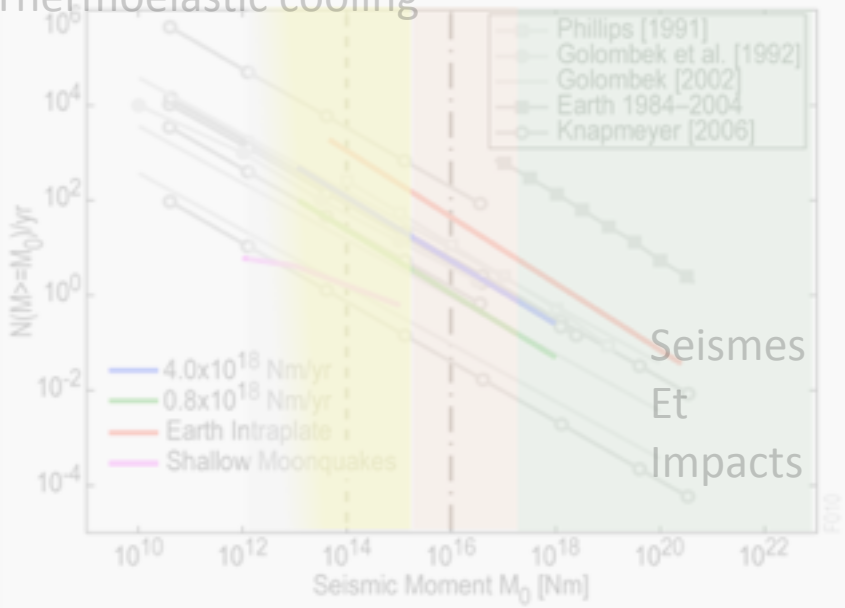
Global to regional

M~3.5 ~100/

regional

Impacts 10-15/

Thermoelastic cooling



Seismes

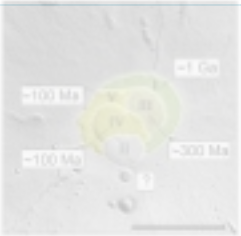
Et

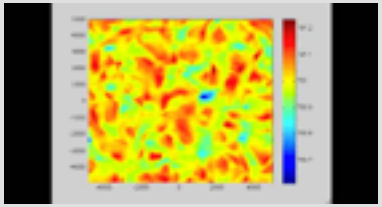
Impacts

Phobos tide

Bonus:

Tectonic activity





Atmospheric loading

Atmospheric generated seismic noise

Wind/pressure generated seismic waves and static loading

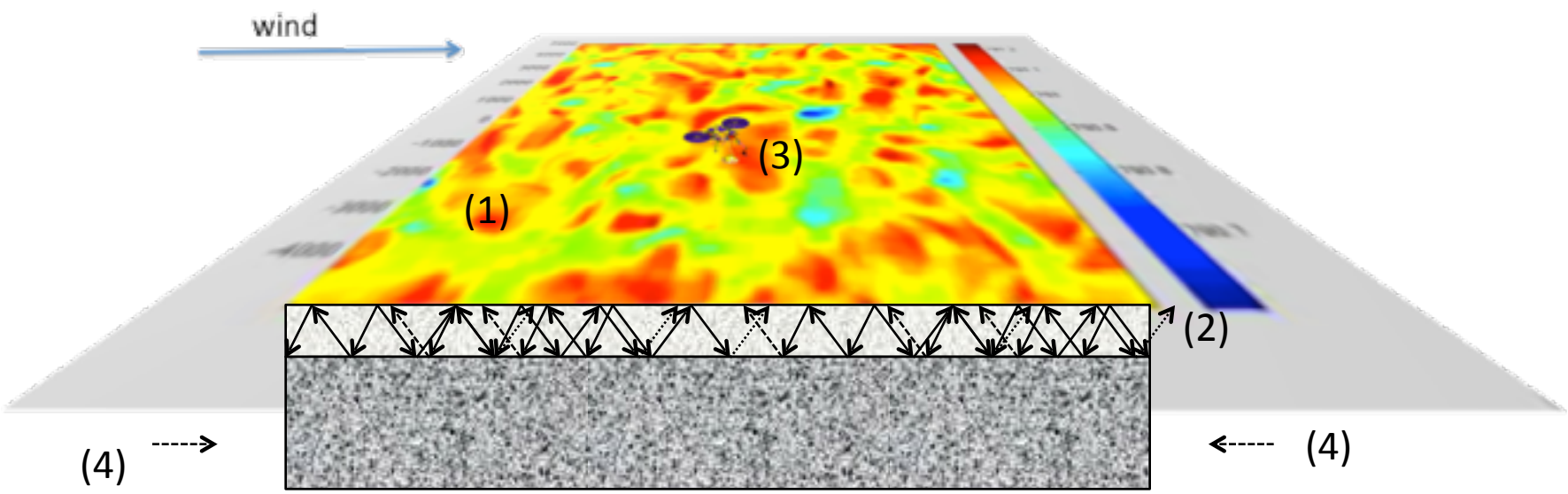
The atmosphere and wind/pressure fluctuations will be a major source of ground displacement for frequencies > 0.02 Hz with:

(1) At long period, static deformations of the surface, associated to wind generated pressure waves **(static loading)**

(2) At short period, dynamic ground acceleration, associated to local and possibly regional subsurface trapped surface waves excited by wind dynamic pressure **(short period seismic waves)**

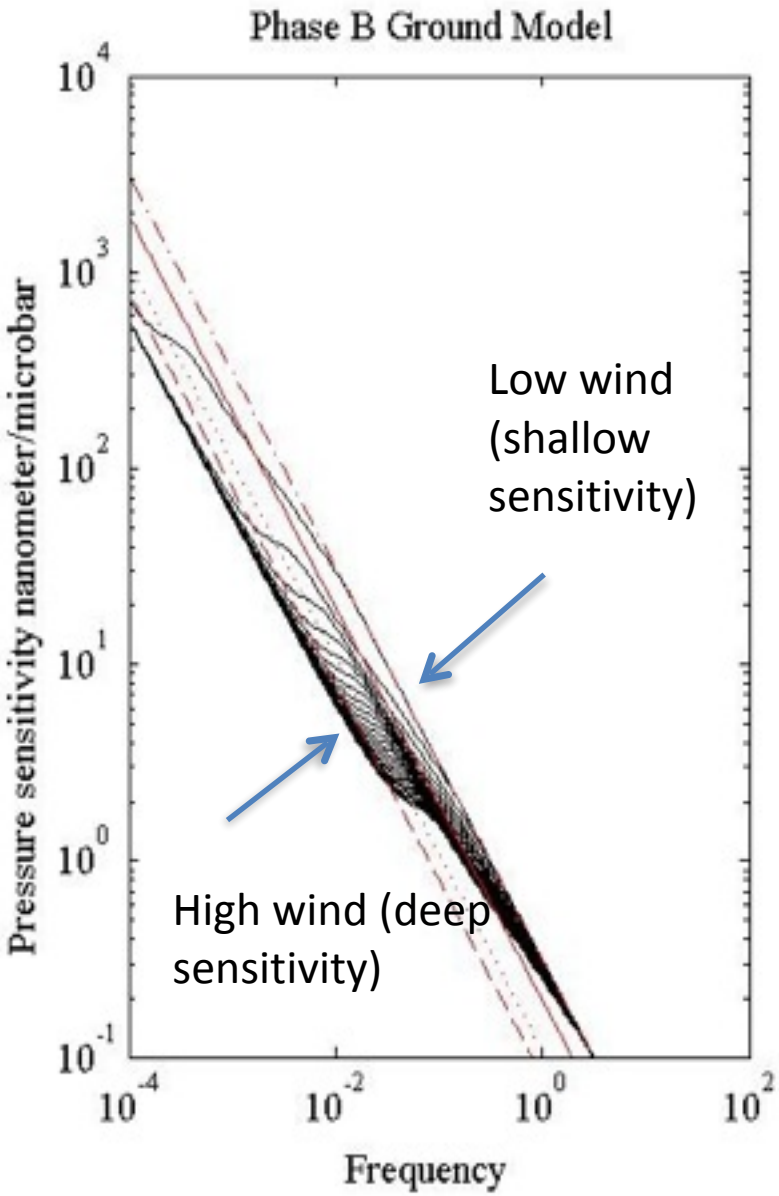
(3) again at short period, wind interaction with the shield and the lander **(seismic noise)**

(4) on the global scale and at long period, surface waves excited by the global weather pressure fluctuations **(long period seismic waves and normal mode hum)**

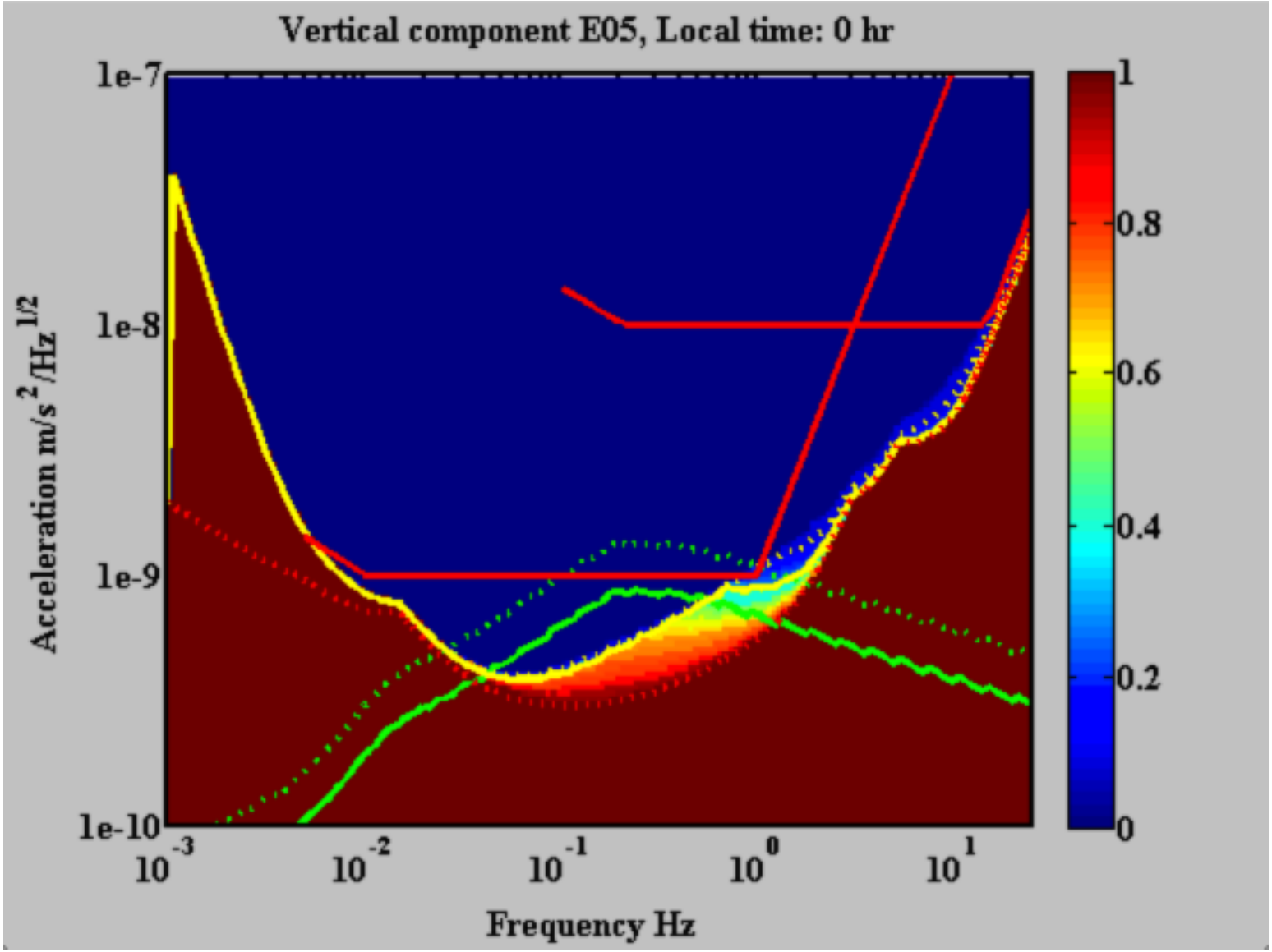


Theoretical background: ground response

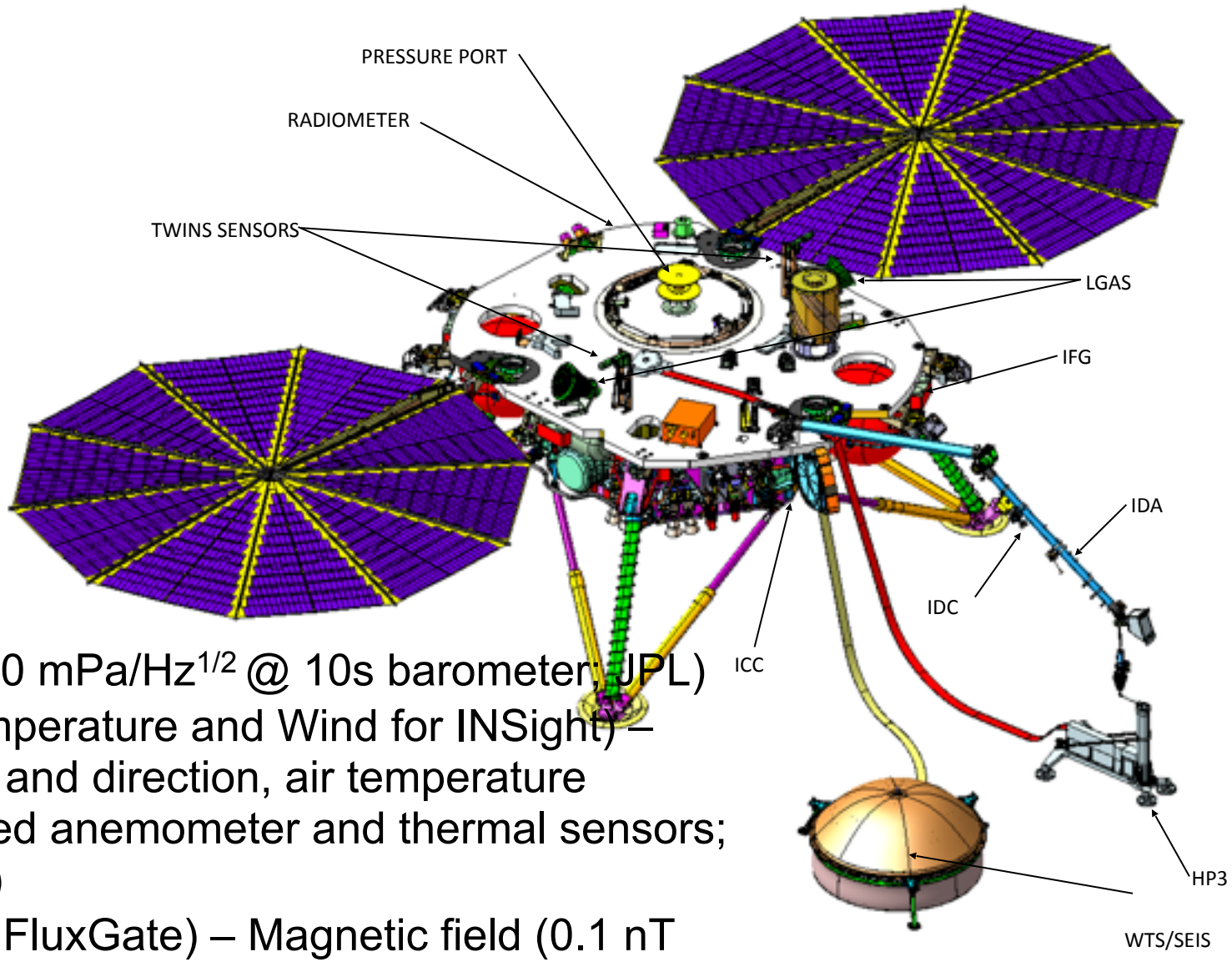
- At 10 sec, the typical expected ground deformation are expected to be ~5 nm/μbar for 5.7 m/s wind
- Sensitivity decrease to 2 nm/μbar for larger wind (deeper sounding) and is 1/f dependent
- 10^{-9} $ms^{-2}/Hz^{1/2}$ Ground acceleration is equivalent to 50 $mPa/Hz^{1/2}$ in pressure (at 10 sec)



Planet breathing estimation



Environmental sensors for SEIS support



- **Pressure** (10 mPa/Hz$^{1/2}$ @ 10s barometer; JPL)
- **TWINS** (Temperature and Wind for INSight) – Wind speed and direction, air temperature (REMS-based anemometer and thermal sensors; CAB, Spain)
- **IFG** (Insight FluxGate) – Magnetic field (0.1 nT

SEIS Expected Natural signals

M~5.5 1-2/yr

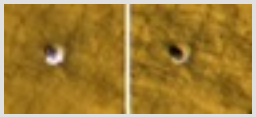
Global

M~4.5 ~ 10/yr

Global to regional

M~3.5 ~100/yr

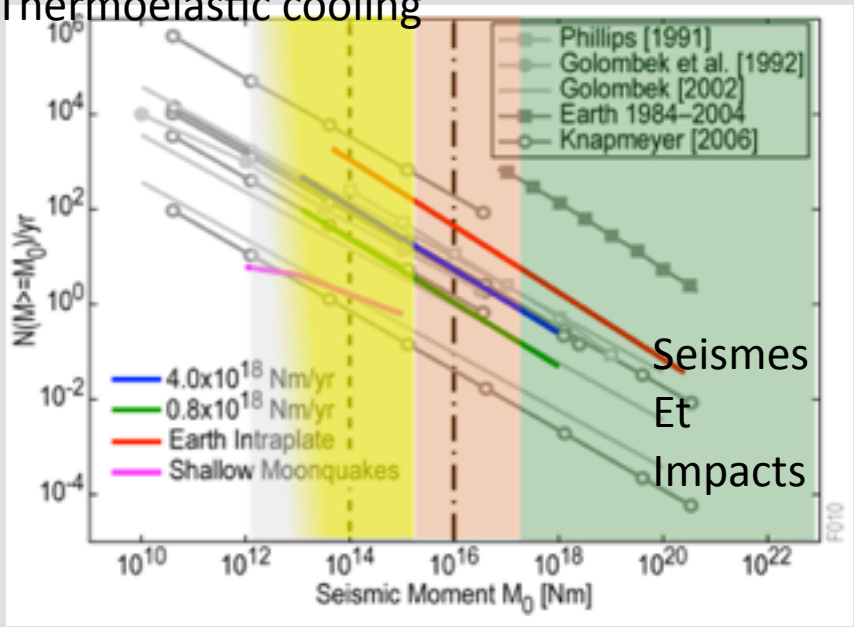
regional

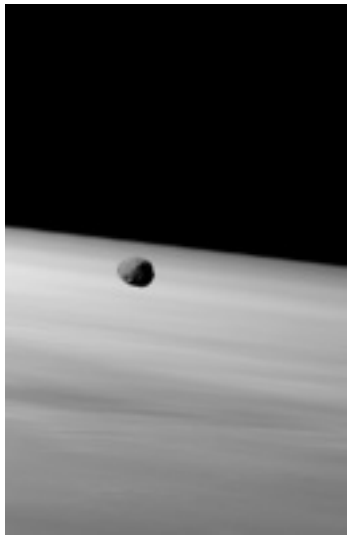


Impacts

10-15/yr

Thermoelastic cooling

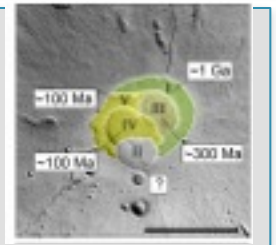


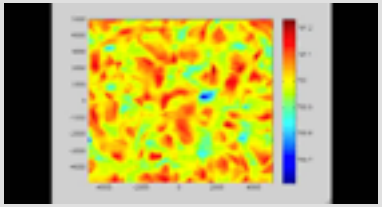


Phobos tide

Bonus:

Tectonic activity





Atmospheric loading

Atmospheric generated seismic noise

SEIS Expected Natural signals

M~5.5 1-2/yr

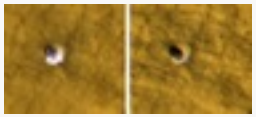
Global

M~4.5 ~ 10/

Global to regional

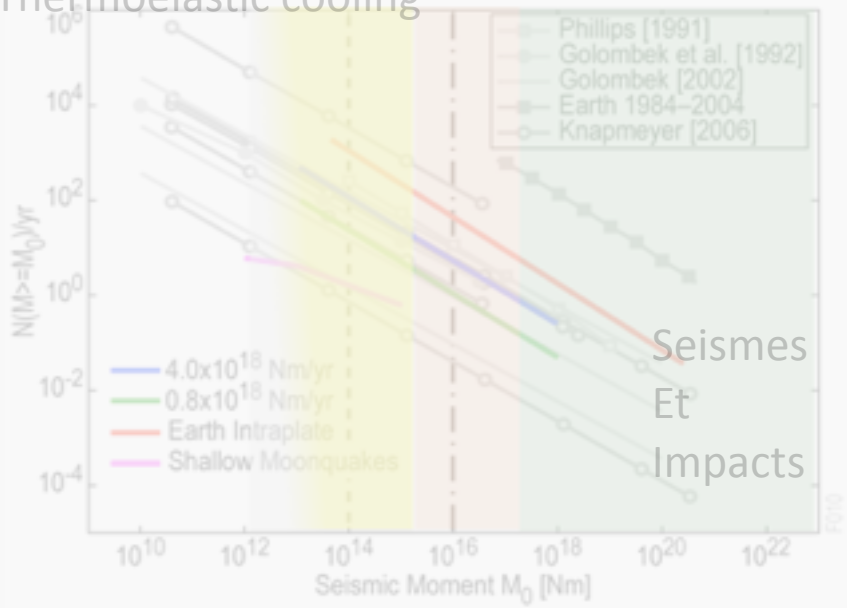
M~3.5 ~100/

regional



Impacts
10-15/yr

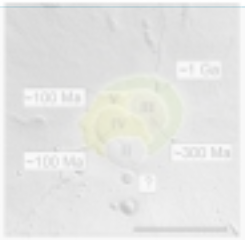
Thermoelastic cooling

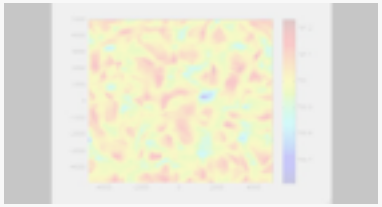


Seismes
Et
Impacts

Phobos tide

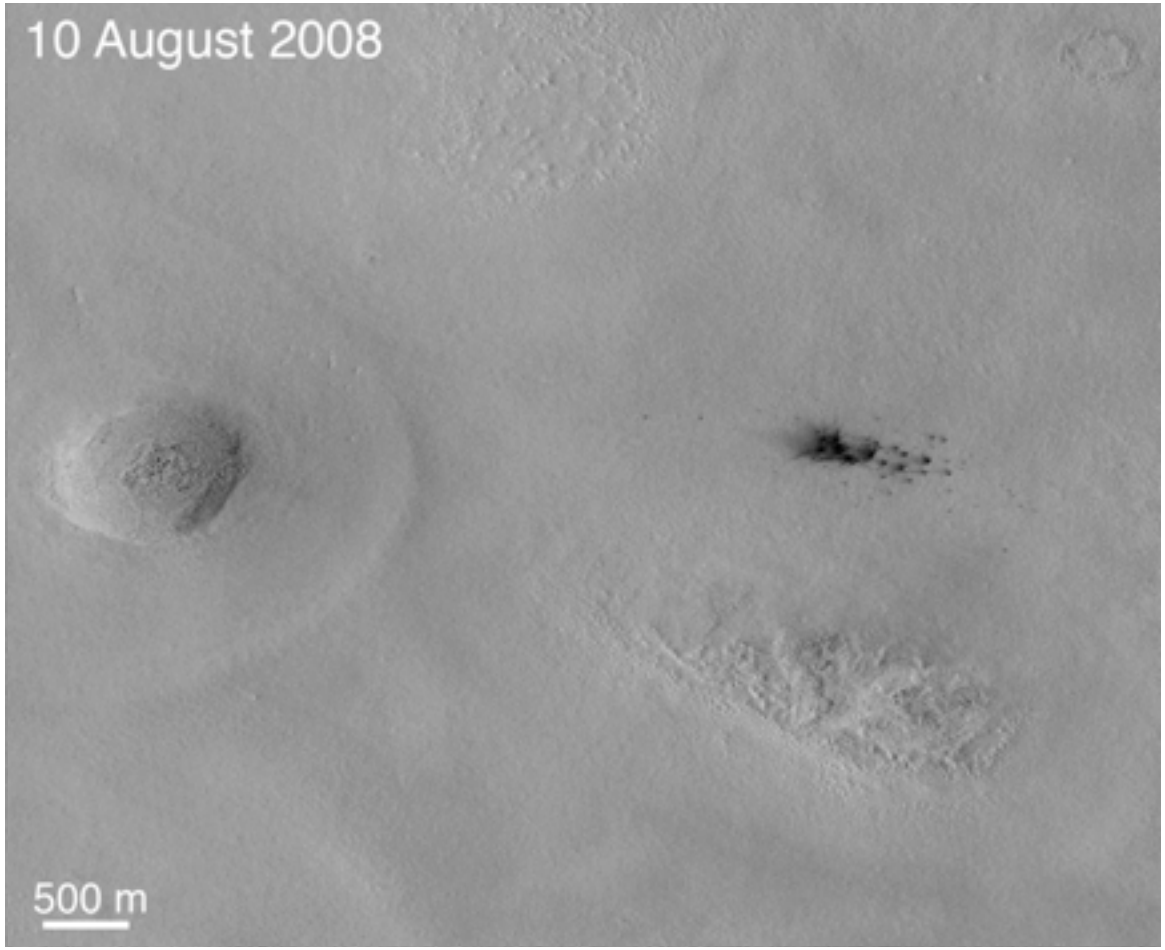
Bonus:
Tectonic
activity





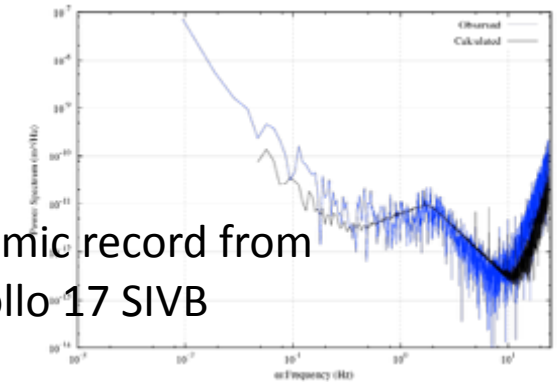
Atmospheric loading
Atmospheric generated seismic
noise

Mars impacts (1/2)



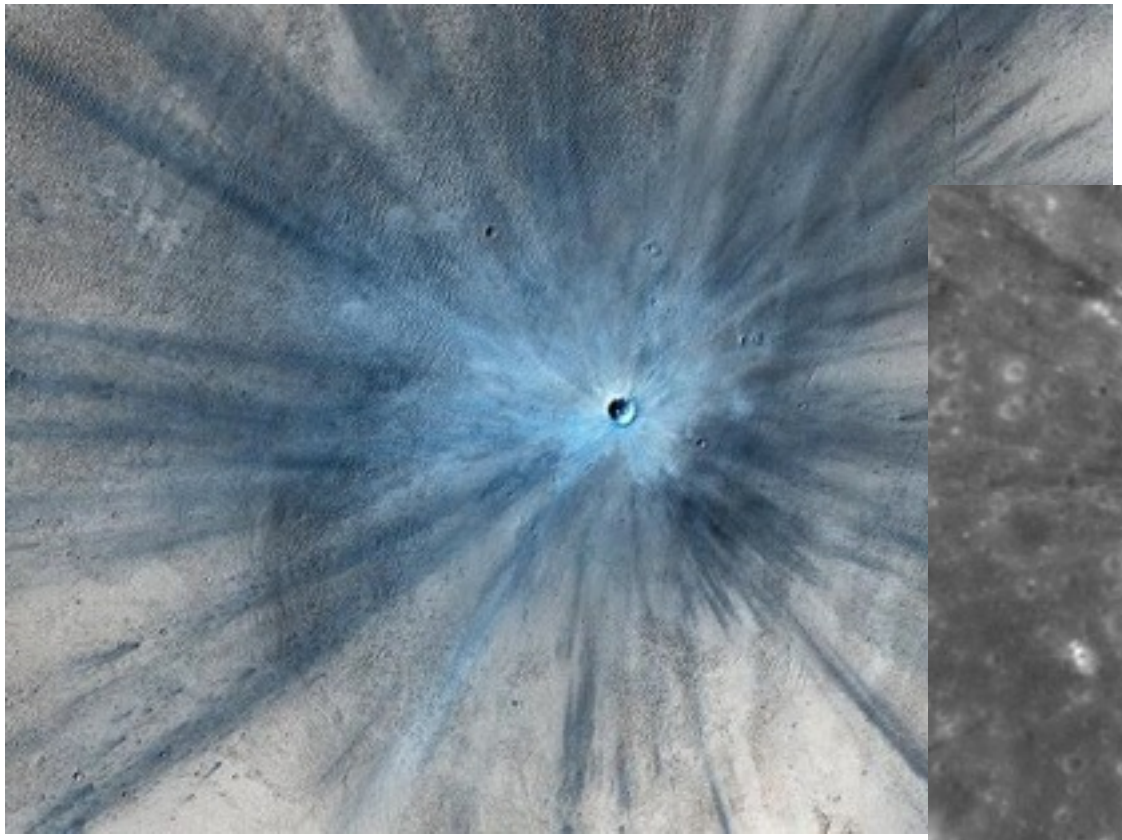
Mars impacts (2/2)

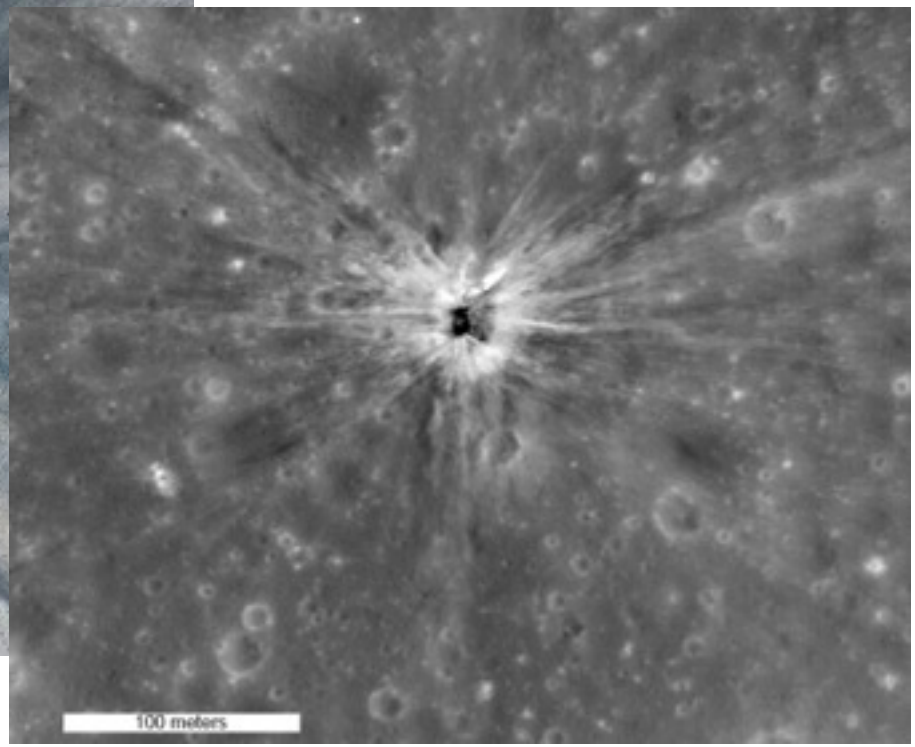
Estimation ~_5.3tons at 10 km/s => 5 10^7 Ns,
plus ejecta effects ~ 10^8 Ns



Seismic record from Apollo 17 SIVB

Apollo 13 SIVB





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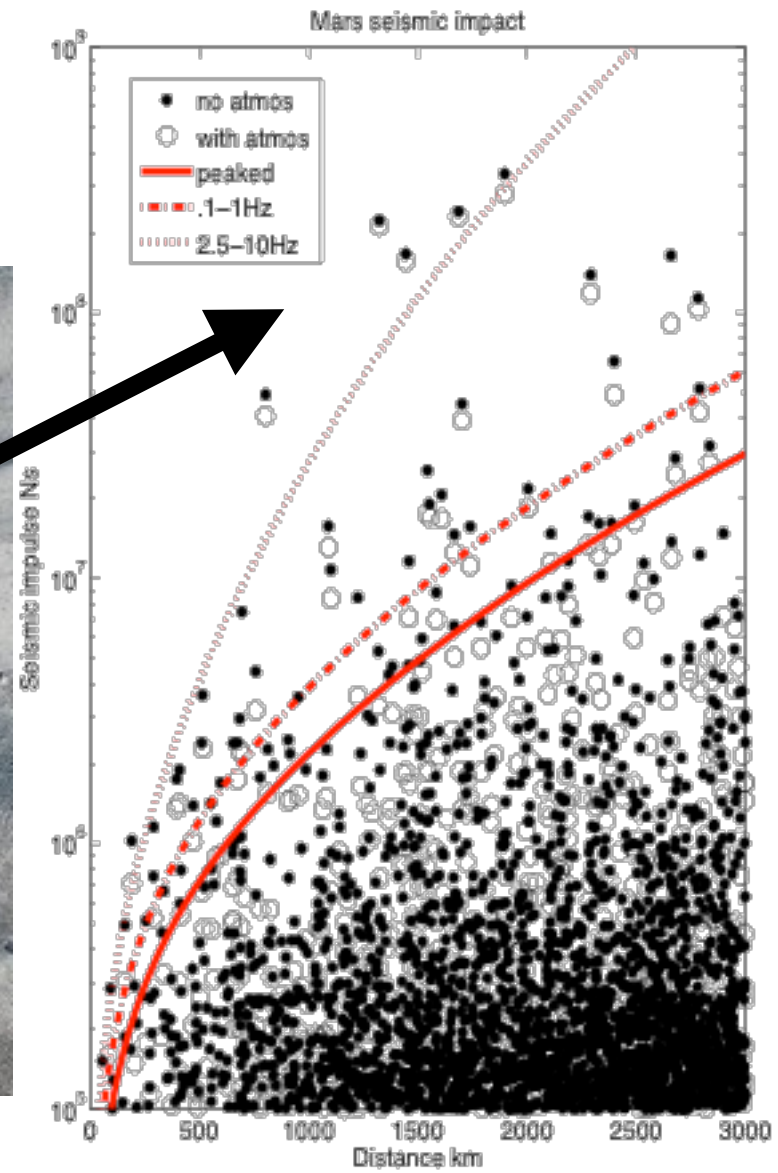


SEIS Expected Quakes…

M~5.5 1-2/yr

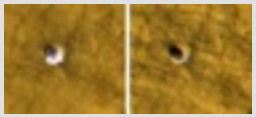
Global

M~4.5 ~ 10/yr

Global to regional

M~3.5 ~100/yr

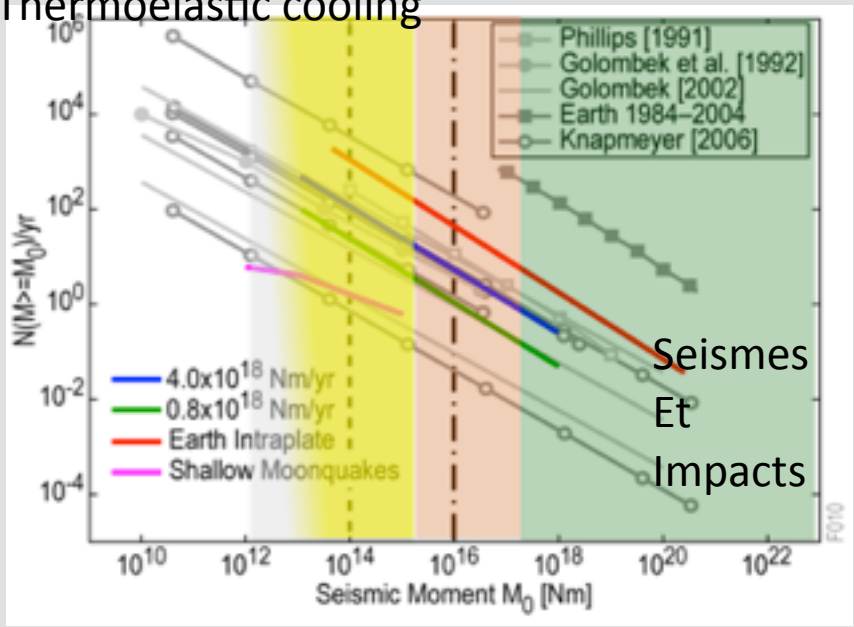
regional

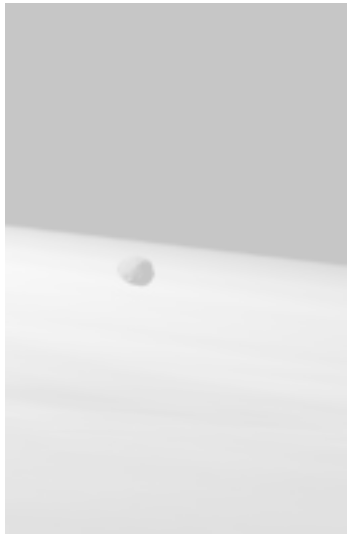


Impacts

10-15/yr

Thermoelastic cooling





Phobos tide

Bonus:

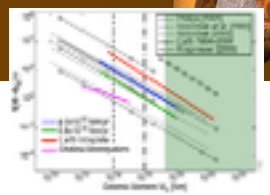
Tectonic

activity

Atmospheric loading

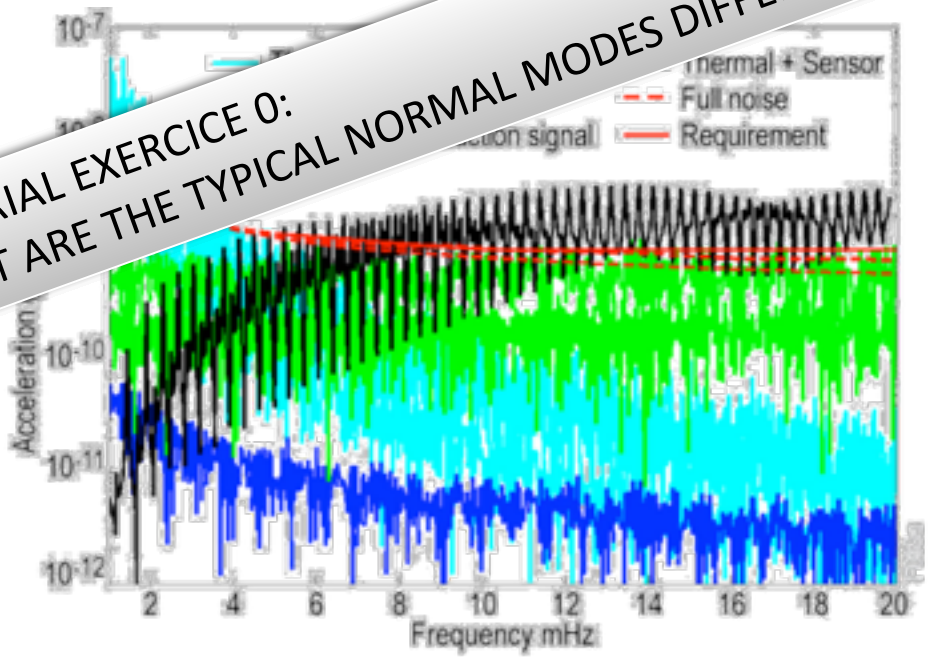
Atmospheric generated seismic noise

Largest quakes: Normal modes



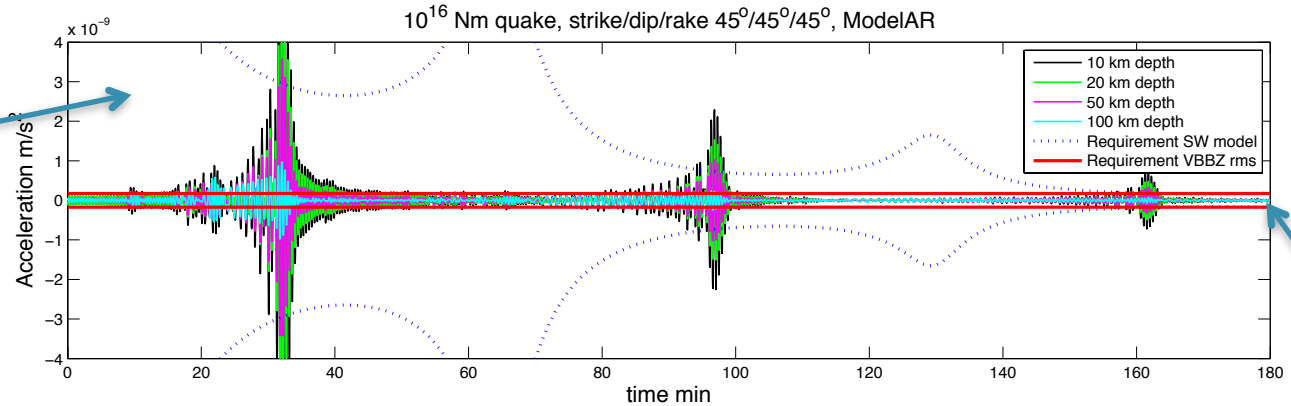
- Normal modes of a 2×10^{17} Nm quake
- « spectroscopy » seismology: does not need the knowledge of the source location
- will constrain the upper mantle with the normal mod[illegible]equency inversion (e.g. PREM on Earth)
- Might also be excited by the atm[illegible]iences

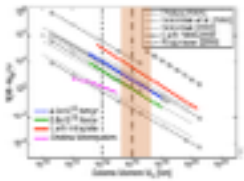
TUTORIAL EXERCICE 0:
WHAT ARE THE TYPICAL NORMAL MODES DIFFERENCES BETWEEN MODELS?



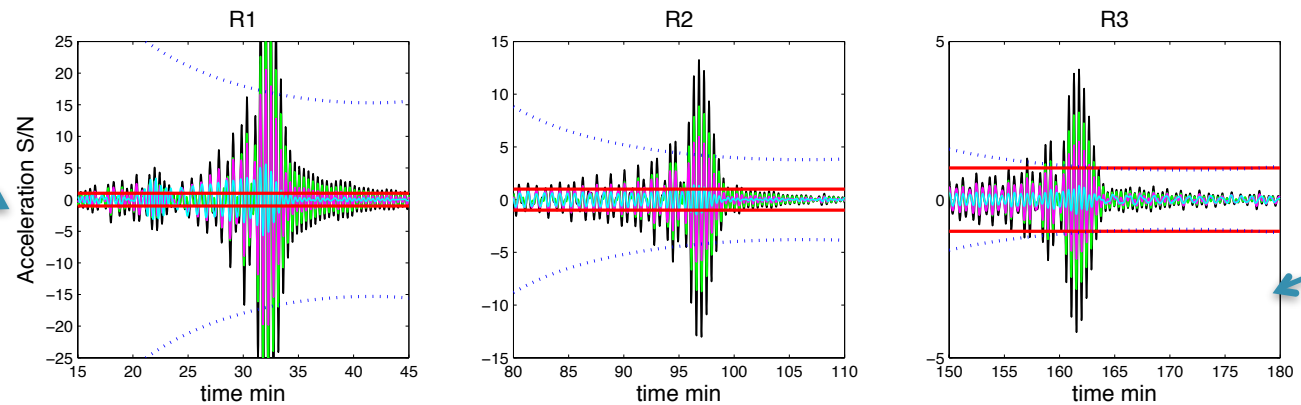
Moderate quakes: Turning waves

Rayleigh





Overtones



t_{R1} t_{R2} t_{R3}

Rms Noise in bandwidth

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

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

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

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

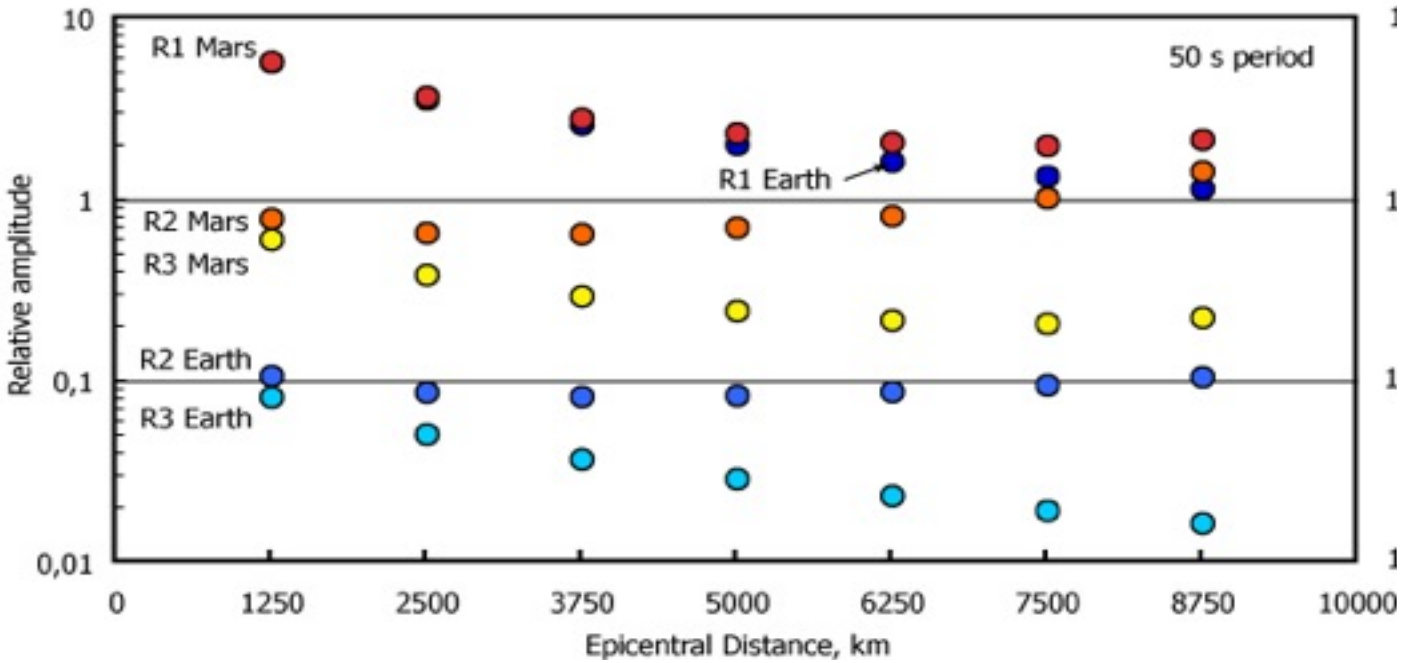
$$t_S - t_P = f_1(\Delta, v_s, v_p)$$

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

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

Model

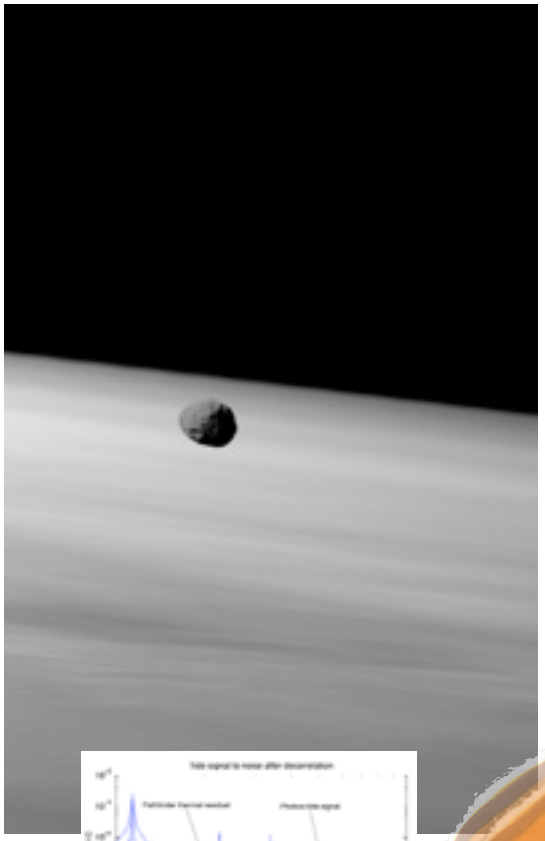
Mars-Earth comparison



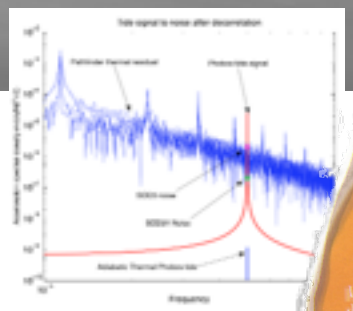
Amplitude of Rayleigh wave trains normalized by R1 amplitude at an epicentral distance of 10,000 km on Earth

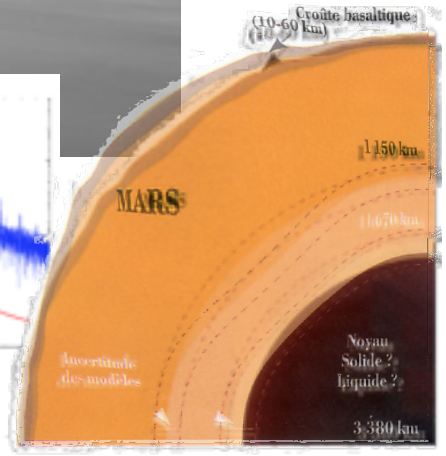
Surface waves are one order of magnitude larger on Mars for R2 and R3

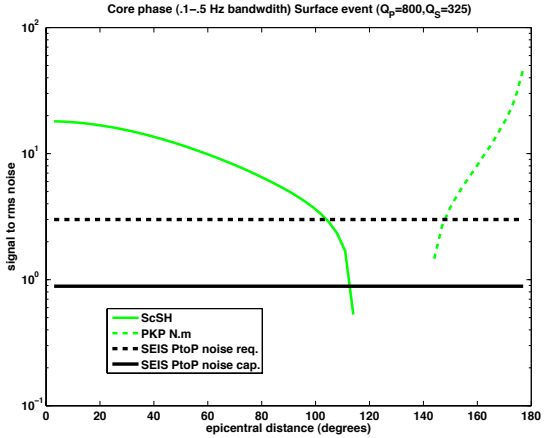
And …. the core

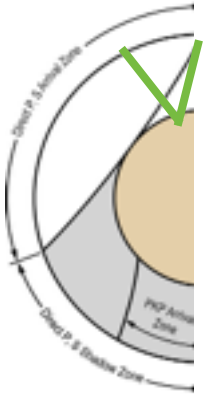


- Two ways investigation:
  - non-seismic by detection of the Phobos solid tide (~mm) and interpretation of the amplitude in term of core size
  - seismic by detection of the core reflected waves (ScS) similar Earth and Moon

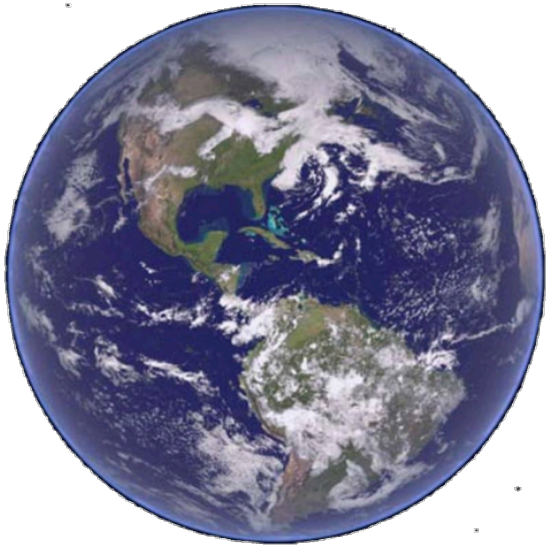


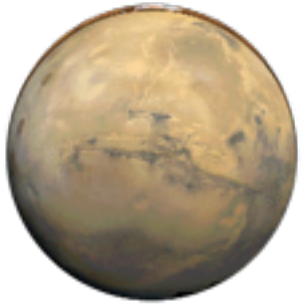






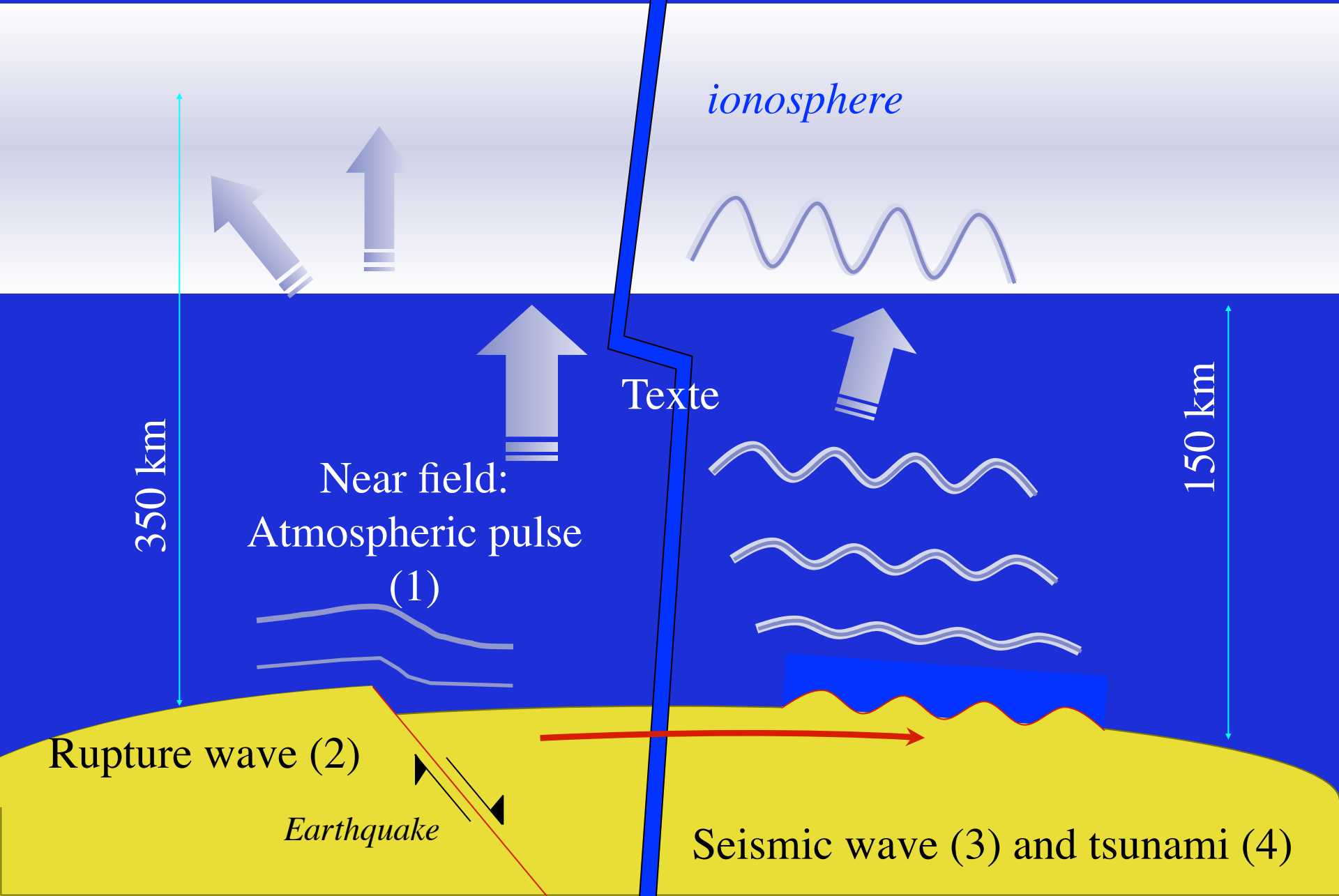
New frontiers of Terrestrial Planetary seismology

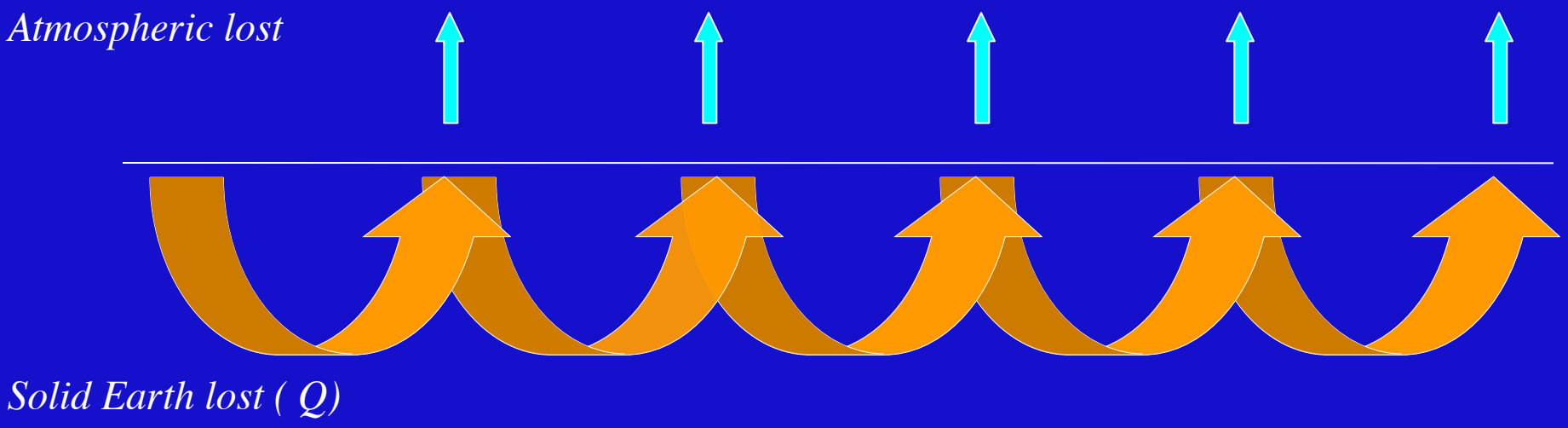


The ultimate challenge…

Back to our Earth (with atmosphere and Ocean)



Surface waves energy lost?



Amplitude Conversion

$$t = \frac{2\rho_{\text{int}} c_{\text{int}}}{\rho_{air} c_{air} + \rho_{\text{int}} c_{\text{int}}} \approx 2$$

$$r = \frac{\rho_{air} c_{air} - \rho_{\text{int}} c_{\text{int}}}{\rho_{air} c_{air} + \rho_{\text{int}} c_{\text{int}}} \approx -1$$

Energy Conversion

$$T = \frac{\rho_{air} c_{air}}{\rho_{\text{int}} c_{\text{int}}} t^2$$

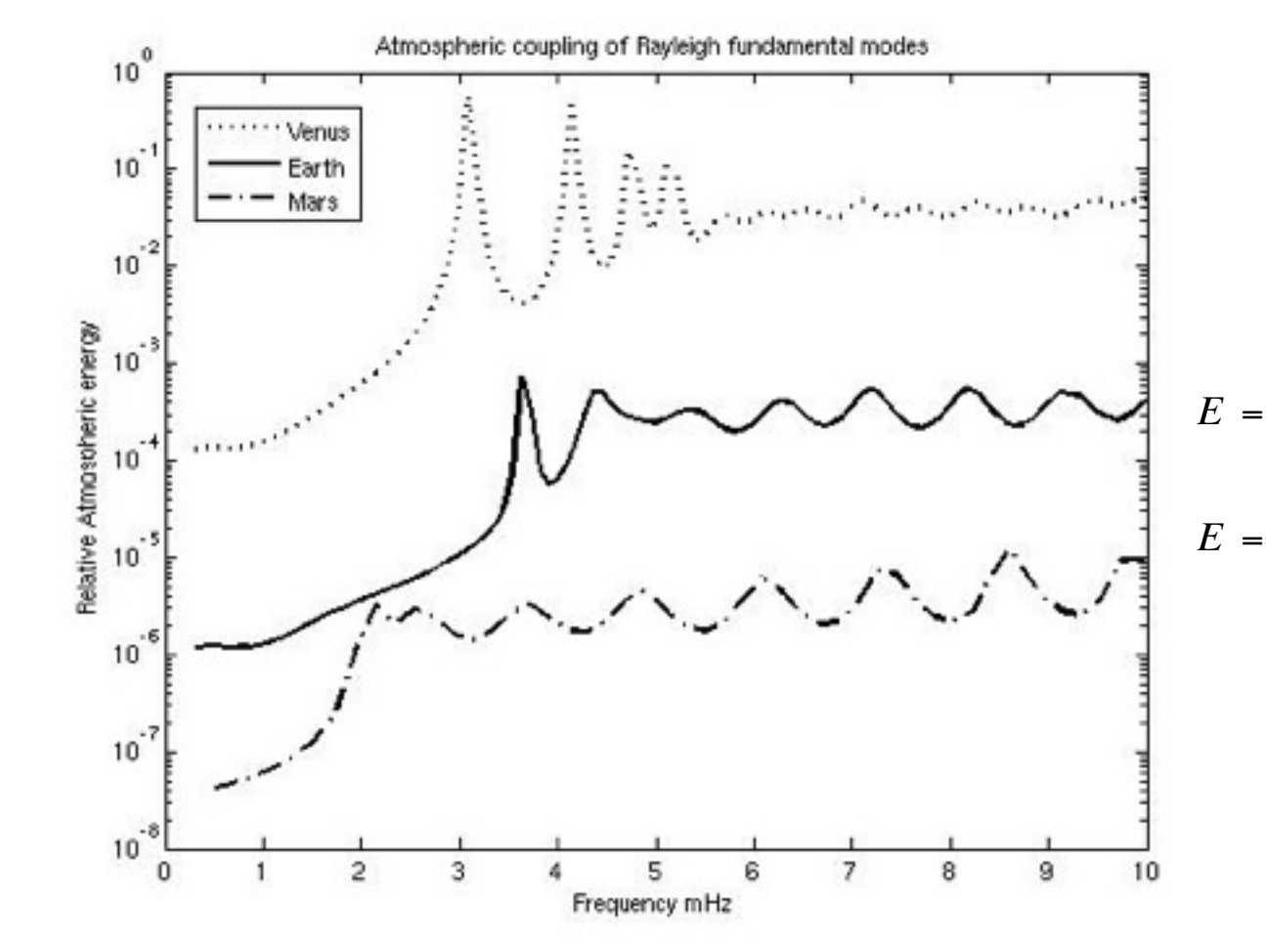
$$R = r^2$$

Energy balance

$$E = T + T\,\mathrm{Re}^{-\frac{2\pi}{Q}} + \ldots + T\left(\mathrm{Re}^{-\frac{2\pi}{Q}}\right)^p + \ldots$$

$$E = \varepsilon \frac{2Q}{\pi} \rho_{air} c_{air} \Big/ \rho_{\text{int}} c_{\text{int}}$$

Atmospheric coupling for several planets…



$$E = T + T\,\mathrm{Re}^{-\frac{2\pi}{Q}} + \ldots + T\left(\mathrm{Re}^{-\frac{2\pi}{Q}}\right)^{p} + \ldots$$

$$E = \varepsilon \frac{2Q}{\pi} \rho_{air} c_{air} \Big/ \rho_{\mathrm{int}} c_{\mathrm{int}}$$

More on atmosphere-ionosphere physics…

Ion"wind"

Seismic wave "wind

$$\frac{d\vec{v}_i}{dt} = \frac{eB}{M_i}\left(\frac{\vec{E}}{B} + \vec{v}_i \times \vec{n}\right) - \frac{k_B T \nabla N_i}{M_i N_i} + \vec{g} + \nu_{in}(\vec{u} - \vec{v}_i)$$

100 s^{-1} ~larger term

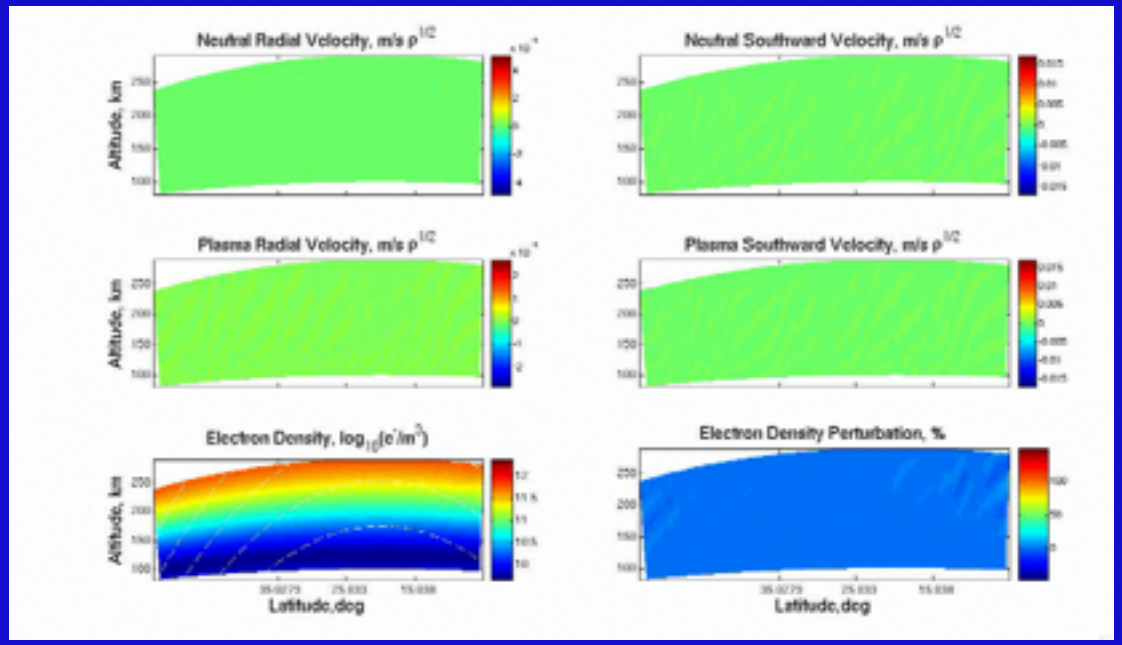
1-10 s^{-1}

Can be neglected

Can be neglected

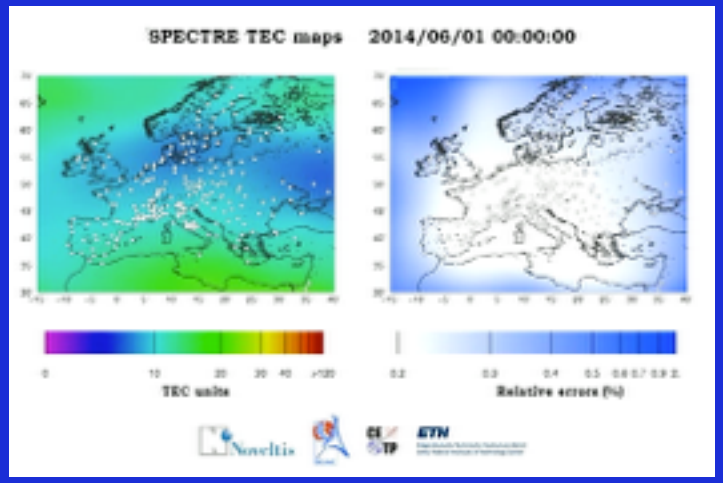
$$\frac{\partial n}{\partial t} + div(n\vec{v}_i) = 0$$

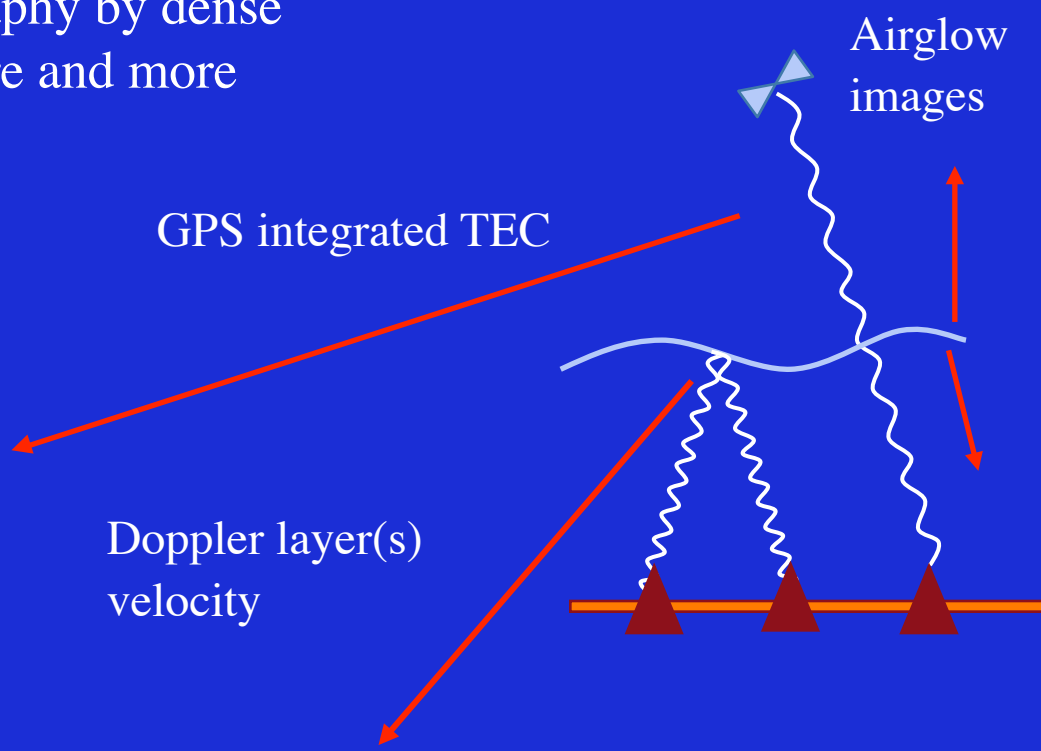
- gravity can be neglected for the time variations
- control of the ion/electrons wind is by the magnetic field diffusion and the neutral-ion collision frequency v_{in}
- Typical species :O_2+,O+,NO+, e-
- This at the end generate a charge (both + and -) flux and density n perturbations

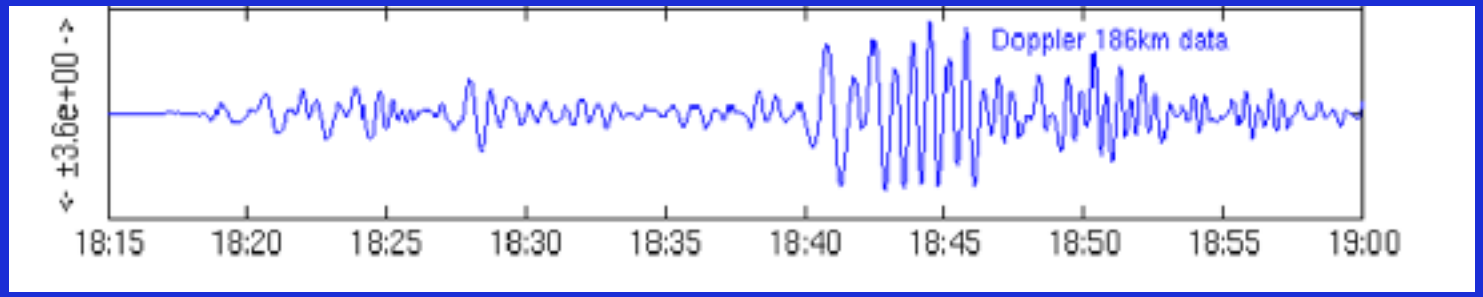


Detection tools and instruments

- Measure based on the TEC tomography by dense Networks: Dense Networks are more and more available in USA, Japan, Europe

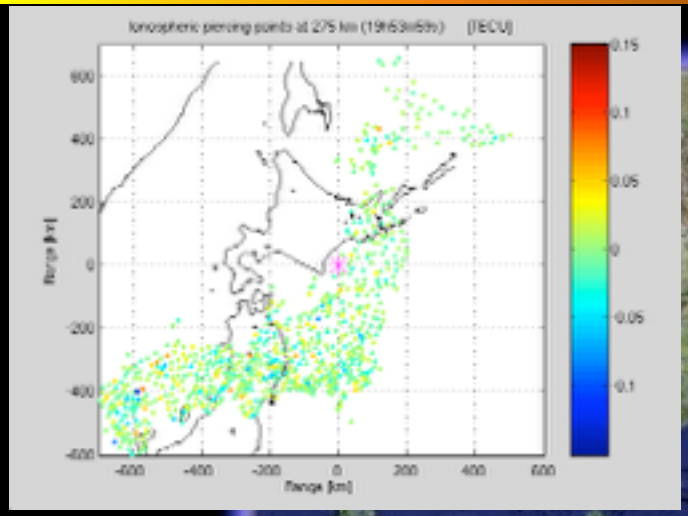




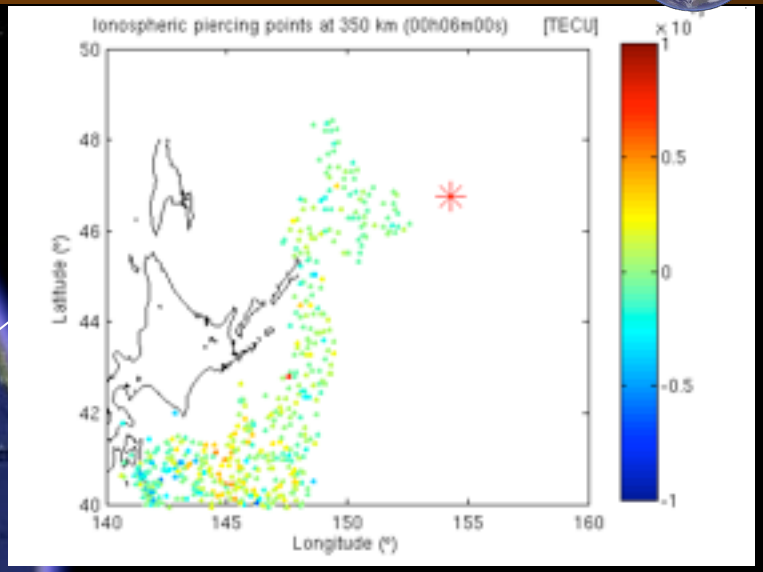


Chichi earthquake (Taiwan, 1999/09/20, M_w=7.6) - vertical velocity $m.s^{-1}$

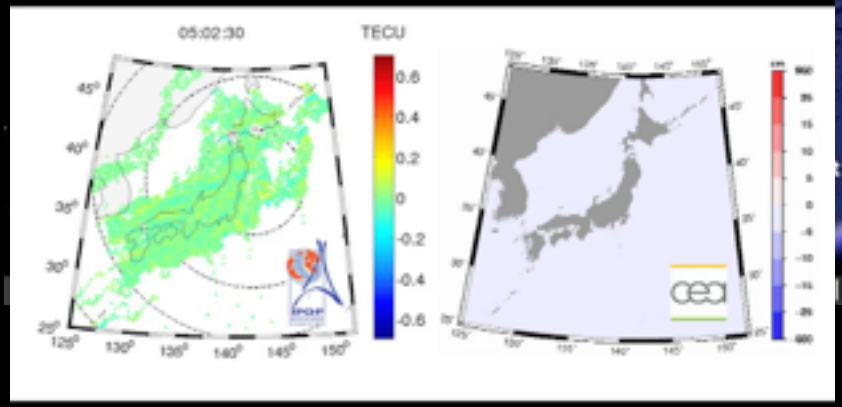
Ionospheric seismic acoustic wave



Tokacho-Oki 9/25/2003 M~8.3

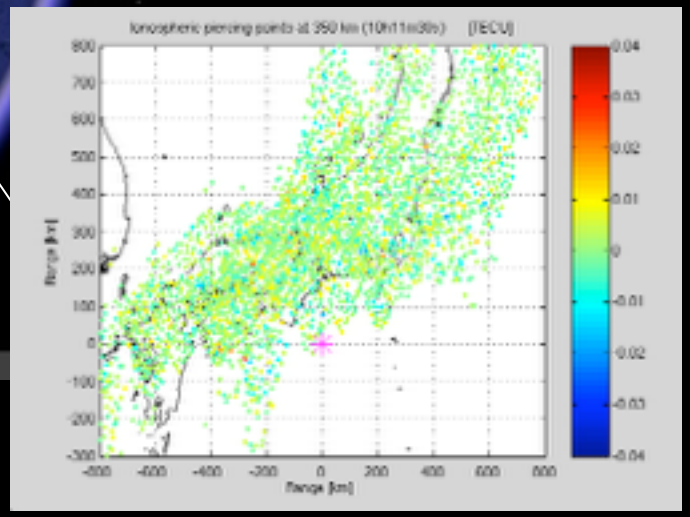


Kurils 13/1/2007 M~8.1



Tohoku 3/11/2003 M~9

Rolland et al., 2011

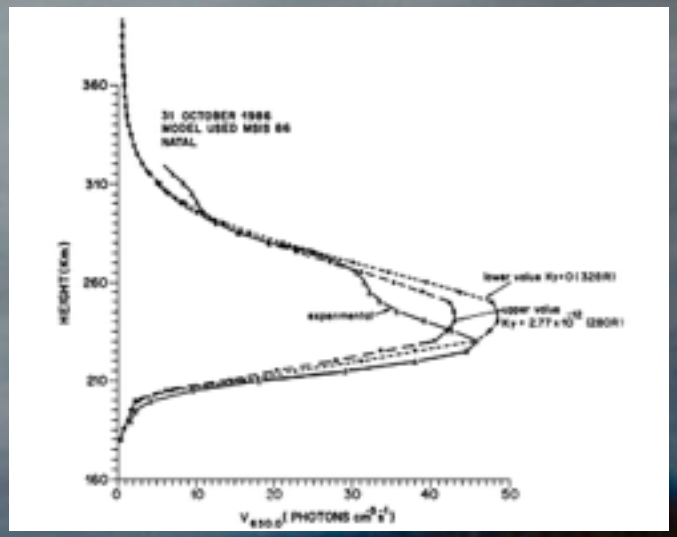


Kii 9/5/2004 M~7.4

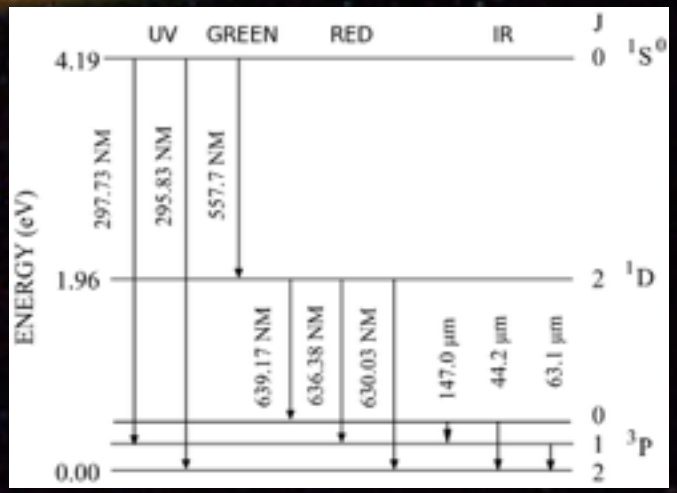
Airglow: OI red line

$$O_2 + O^+ \rightarrow O_2^+ + O$$
$$O_2^+ + e^- \rightarrow O + O(^1D)$$
$$O\,(^1D) \rightarrow O\,(^3P) + h\nu$$

Chemical reaction



250 km



630 nm

Emission peak at 250 km

quiet night 50-100 Rayleigh

about 12.5-25 mWatt/km^2 of light power

Seismic waves changes densities by 0.1-1%

$[0^+][e-]\,[O(^1D)]^{-1} = K$

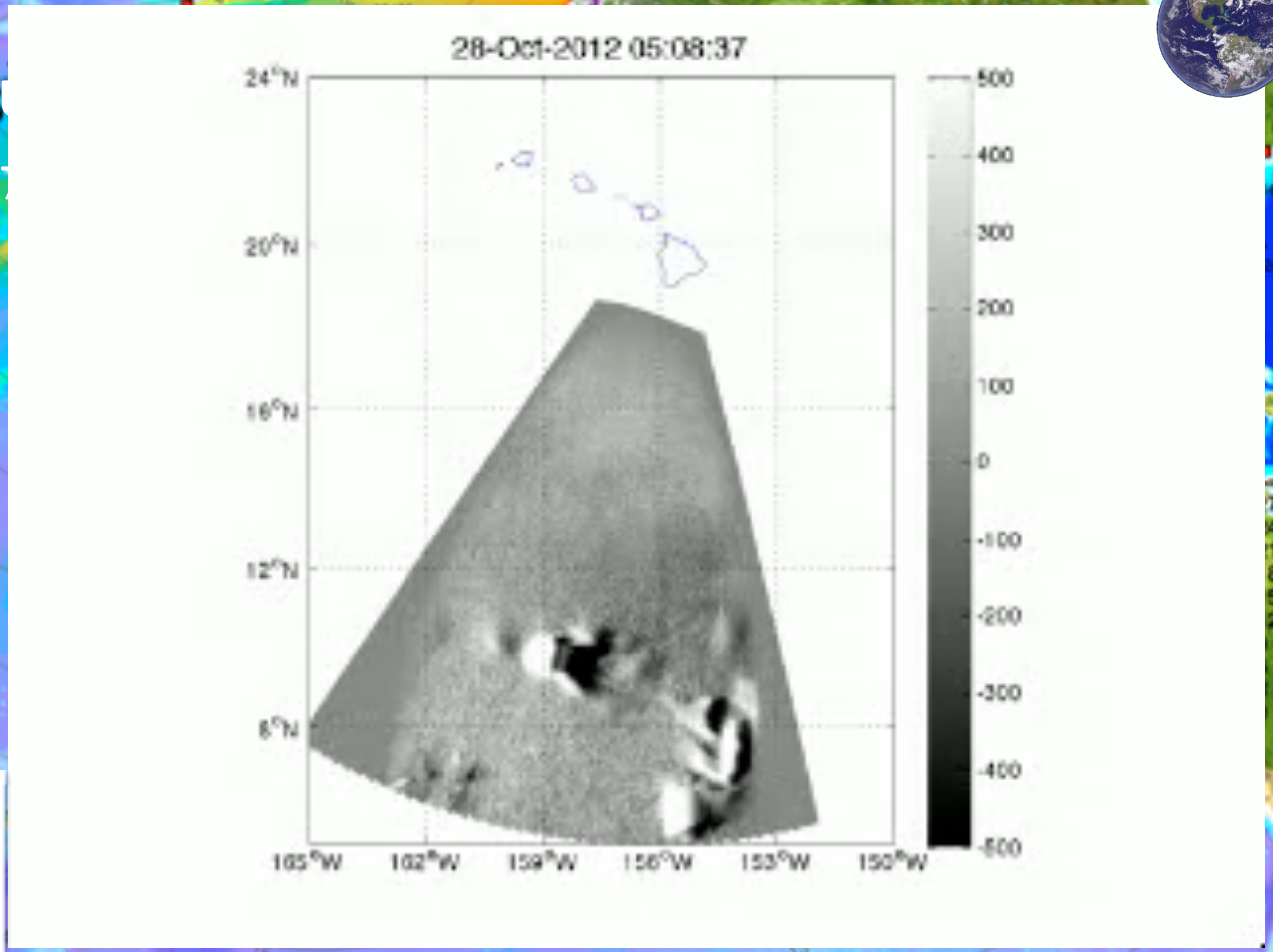
$$O_2 + O^+ \rightarrow O_2^+ + O$$
$$O_2^+ + e^- \rightarrow O + O(^1D)$$
$$O\,(^1D) \rightarrow O\,(^3P) + h\nu$$

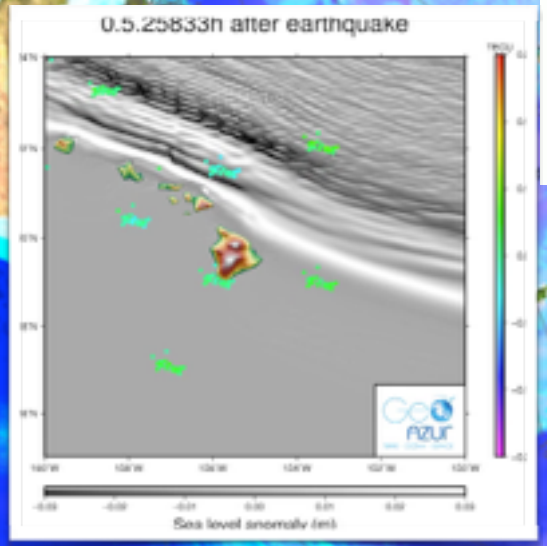
- • Seismic/tsunami waves generate 0.1-1% more or less exited oxygens, which generate photon to reach 3P level
- • this generates a seismic light of 100-100 microWatt/km^2

The Haida Gwaii ts

2012/10/28, Mw

Rolland et al., in prep



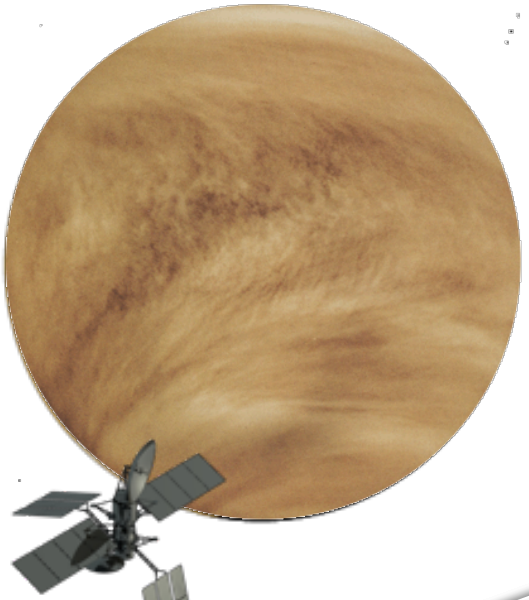


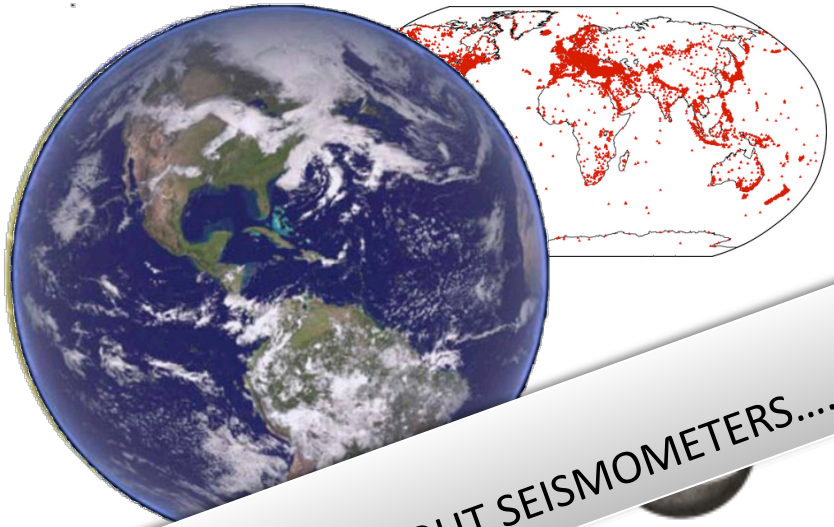
Airglow camera

GPS TEC

New frontiers of Planetary seismology

More and more data from denser seismic networks

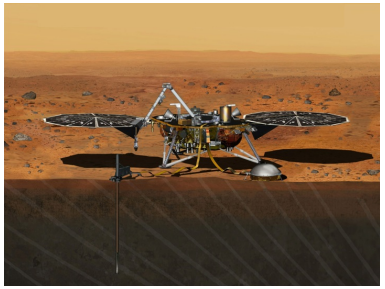




TUTORIAL EXERCICE 2:
IMAGINE SEISMOLOGY ON THE MOON WITHOUT SEISMOMETERS.....

New data : end 2016

data with new science



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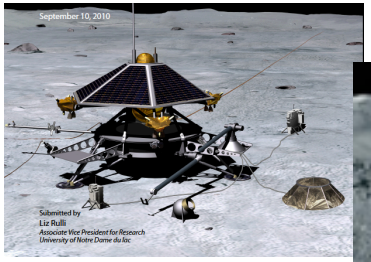
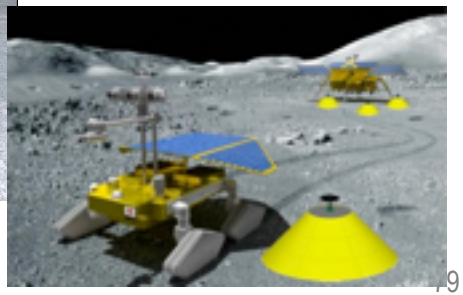
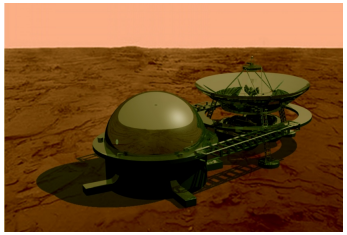
Possible First tsunami space data : 2020 -2025







Possible return: 2020-25