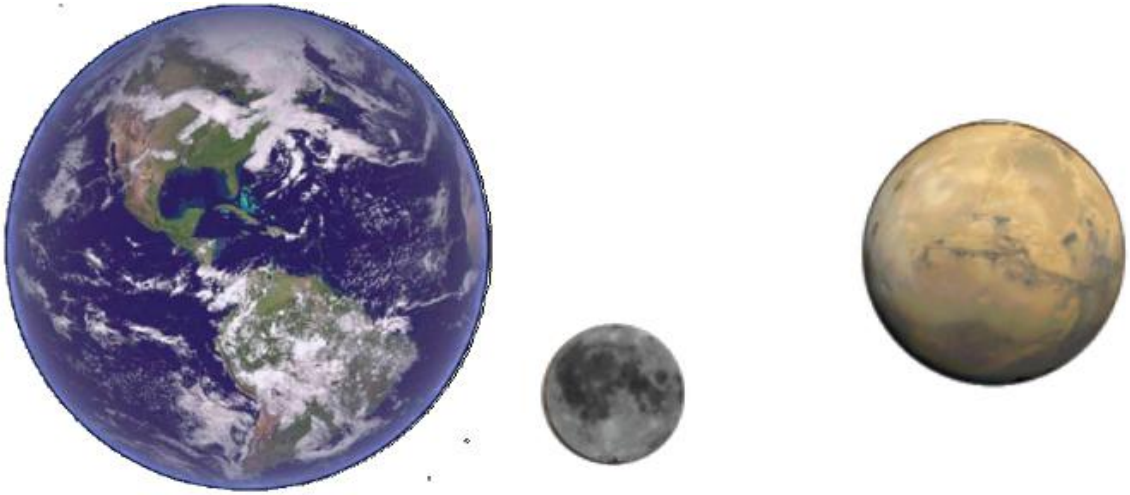


Seismology and the interior of rocky planets: Earth, Moon, Mars?

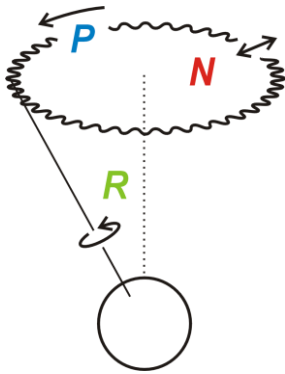
Barbara Romanowicz
UC Berkeley and Collège de France, Paris

19th century: is the earth's interior fluid or solid?

- Shape of the Earth: flattening suggests an equilibrium (fluid?) figure under rotation

- Hopkins (1793-1866): earth nutations and precessions observed astronomically imply a solid envelope of at least 1000 km thickness.

- Lord Kelvin (1824-1907) estimates a thickness of 2000-2500km for the solid envelope (tides, nutations)
  - Earth's rigidity comparable to that of steel.

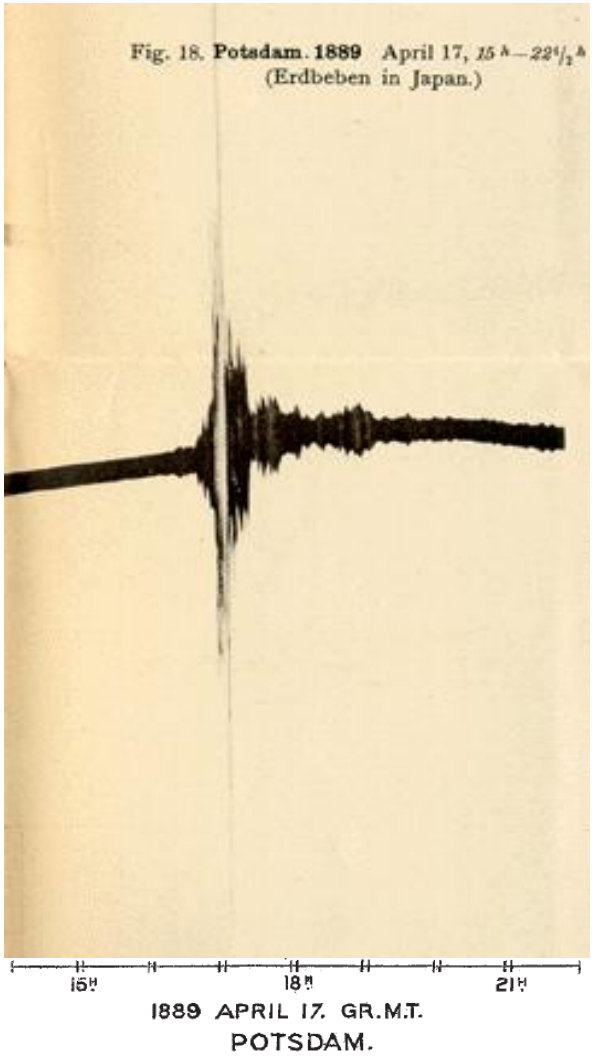


- 1891: Discovery of Chandler wobble (earth's free nutation)

- Mean density of earth: 5.515 kg/m^3 larger than typical density of rocks at the surface ~3 kg/m^3 => Earth cannot be made entirely of rocks (Wiechert?)

- E. Wiechert (1896) suggests that the Earth is like a giant meteorite with a core made of Fe-Ni
  - Not a continuous density increase from compression
  - 2 layer models

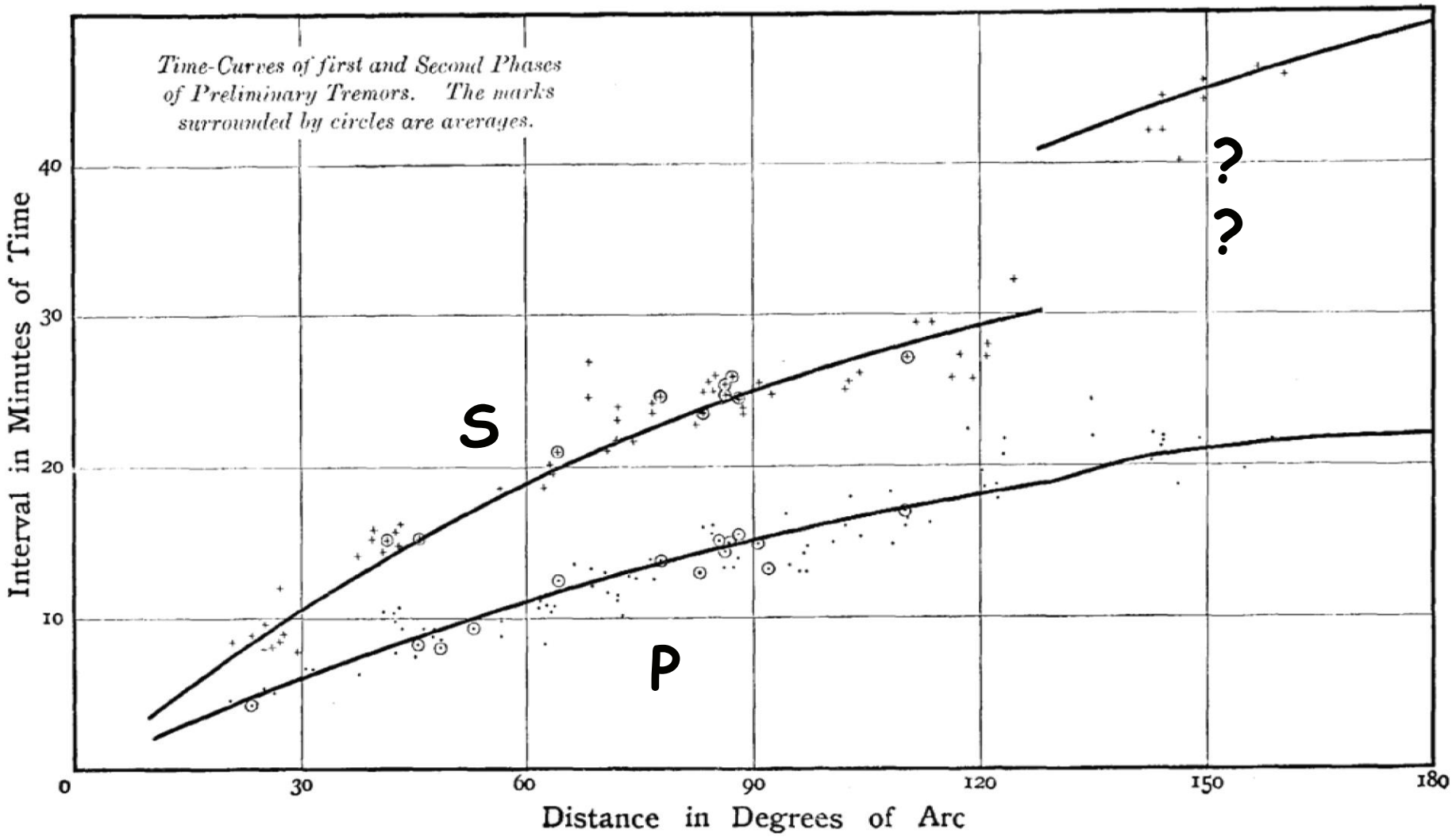
VonReubeur Paschwitz
1889



"Reading the report on this earthquake in NATURE (June 13, p. 162), I was struck by its coincidence in time with a very singular perturbation registered by two delicate horizontal pendulums at the Observatories of Potsdam and Wilhelmshaven."
VonRebeur Paschwitz, E., Nature, 40, July 25, 1889

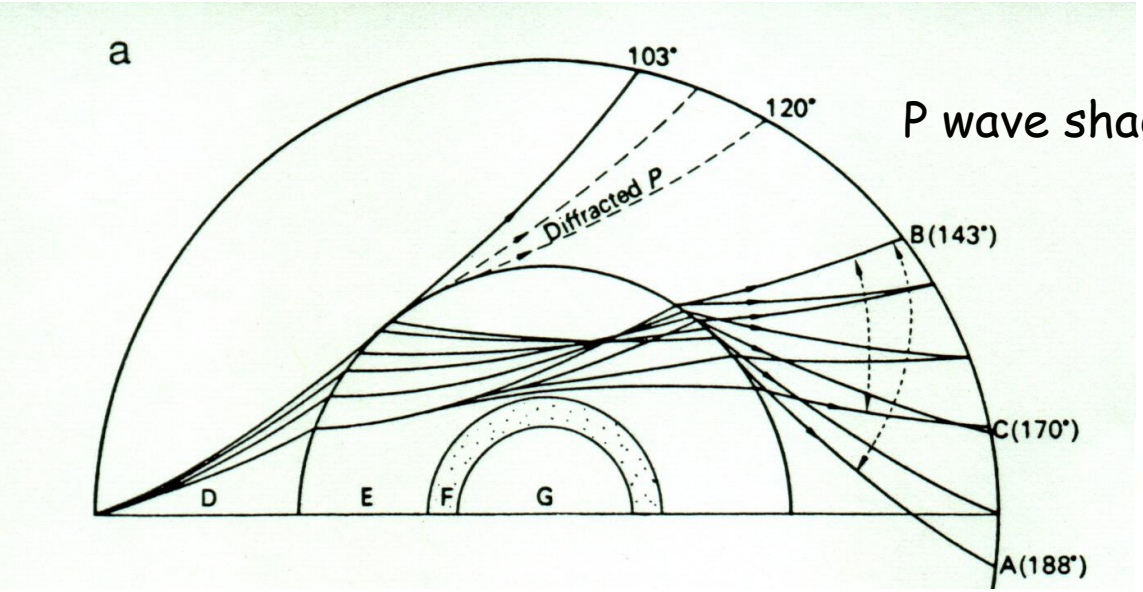
The earth's core…

- **1906** – Oldham discovers liquid core
- **1936** - Inge Lehmann discovers inner core
-
- **1940** – Birch suggests that the inner core is solid and corresponds to the solidification of iron.
- **1950-51** – Bullen suggests that if the inner core is solid, we should observe PKJKP waves.
- **1970** - Confirmation of the solidity of the inner core from normal mode eigenfrequency measurements (*Dziewonski and Gilbert*)
- **1986** – Discovery of inner core anisotropy



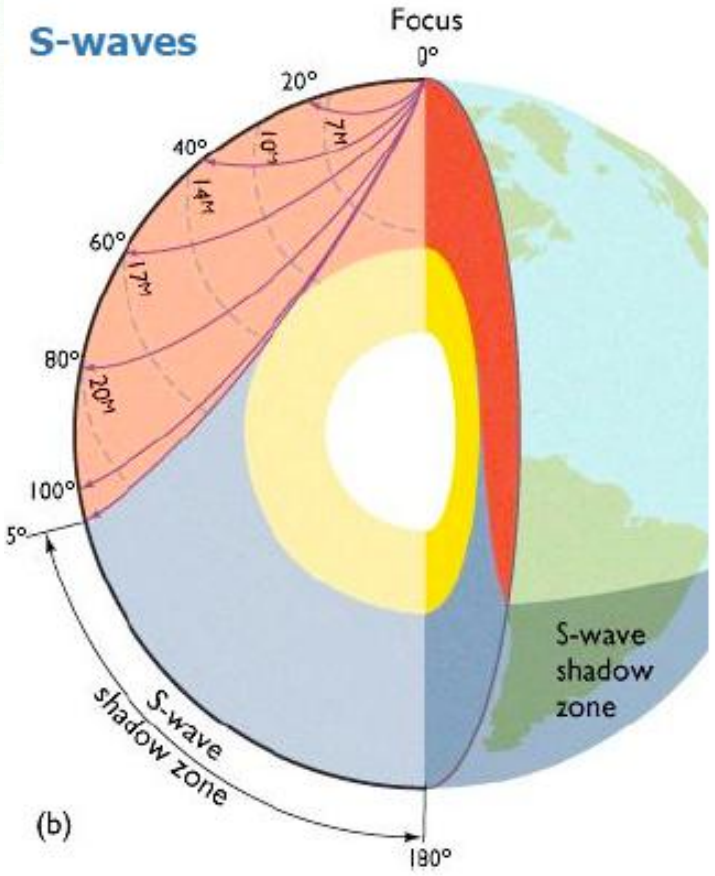
Radius of the core estimated by Oldham: ~2600km

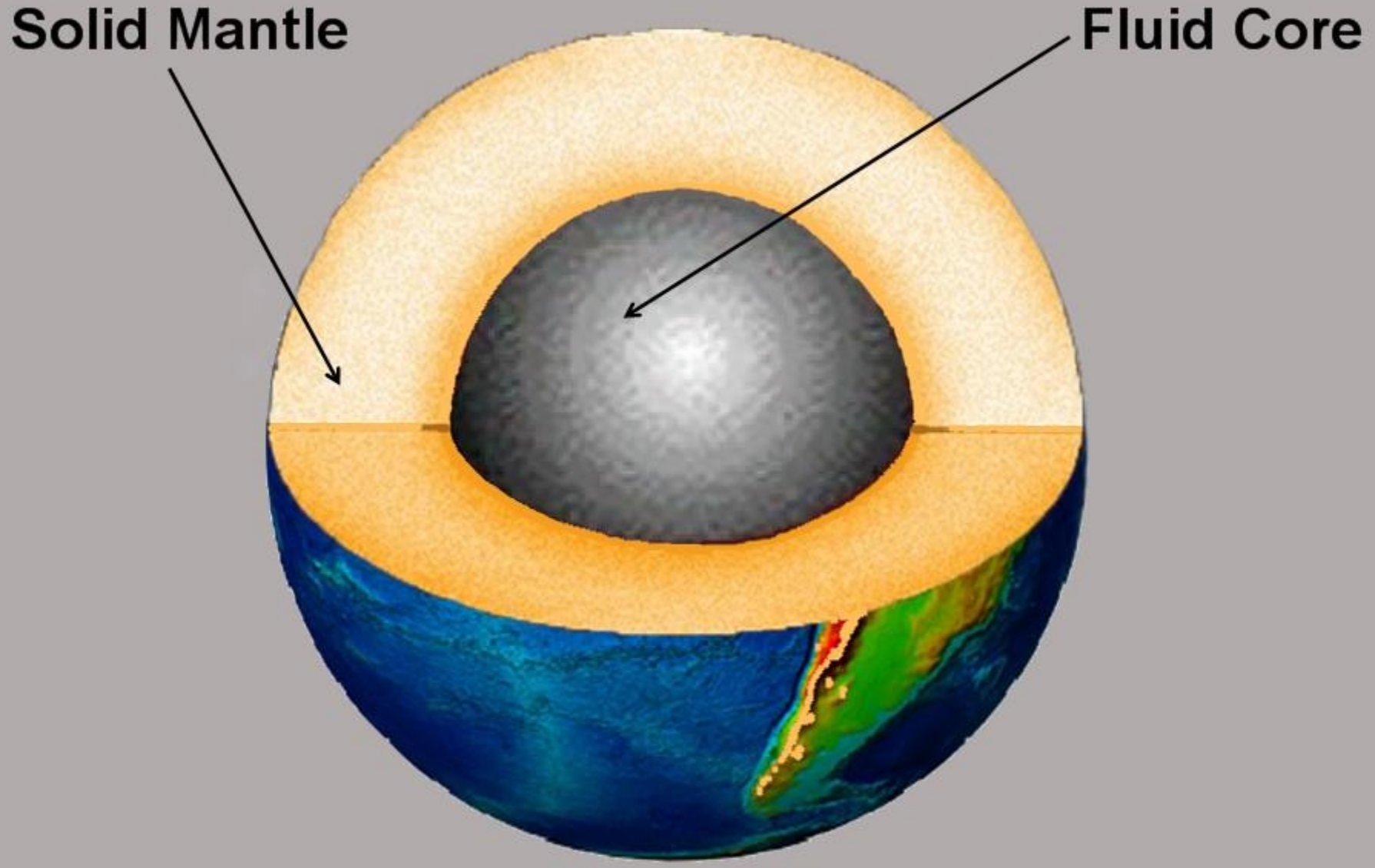
Oldham, 1906



P wave shadow zone

Shadow zones due to the presence of the liquid core





The earth as seen ~1910

Inge Lehmann 1888-1993

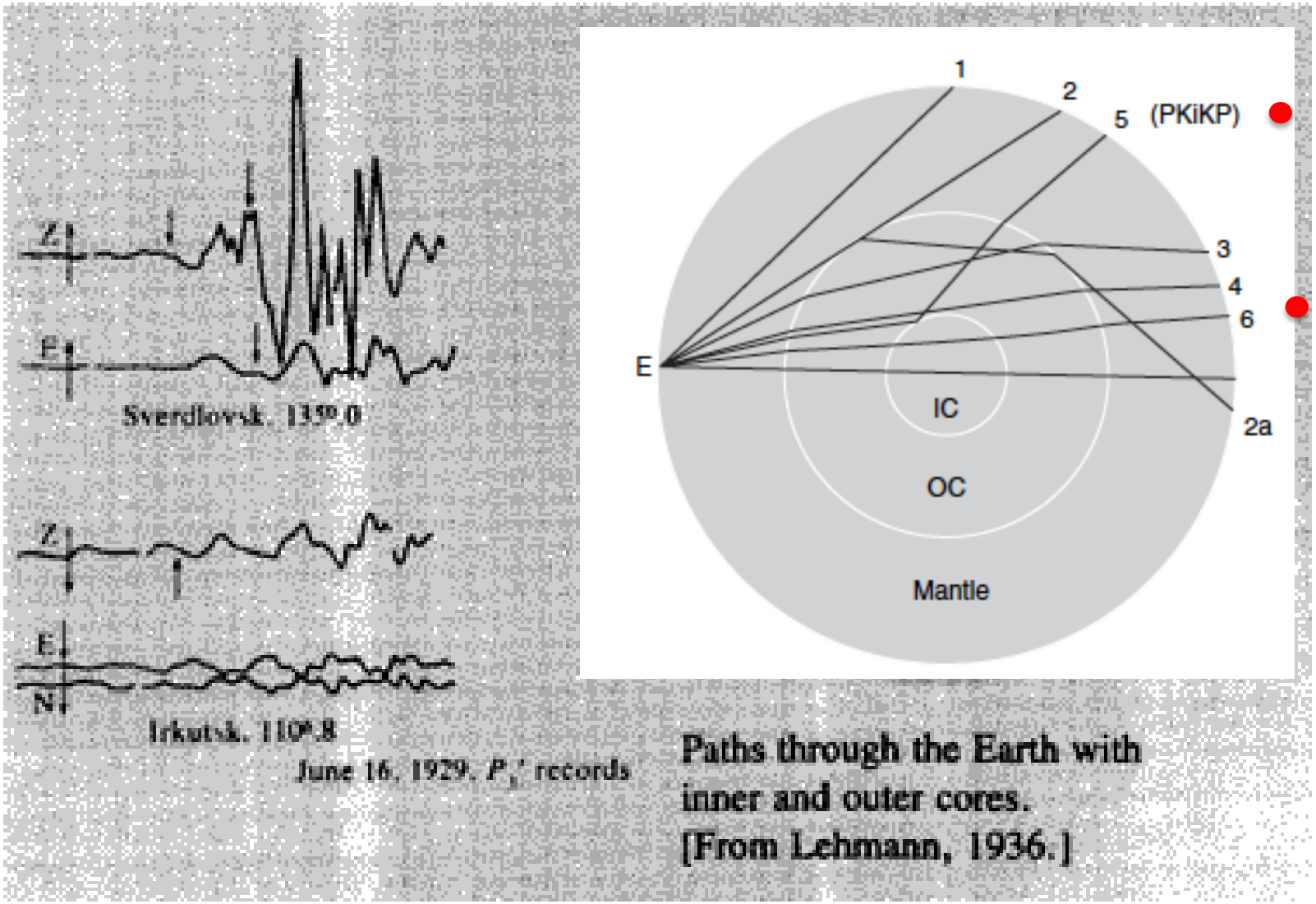
Discovery of the inner core 1936

Observes "P-like" phases in the shadow of the core

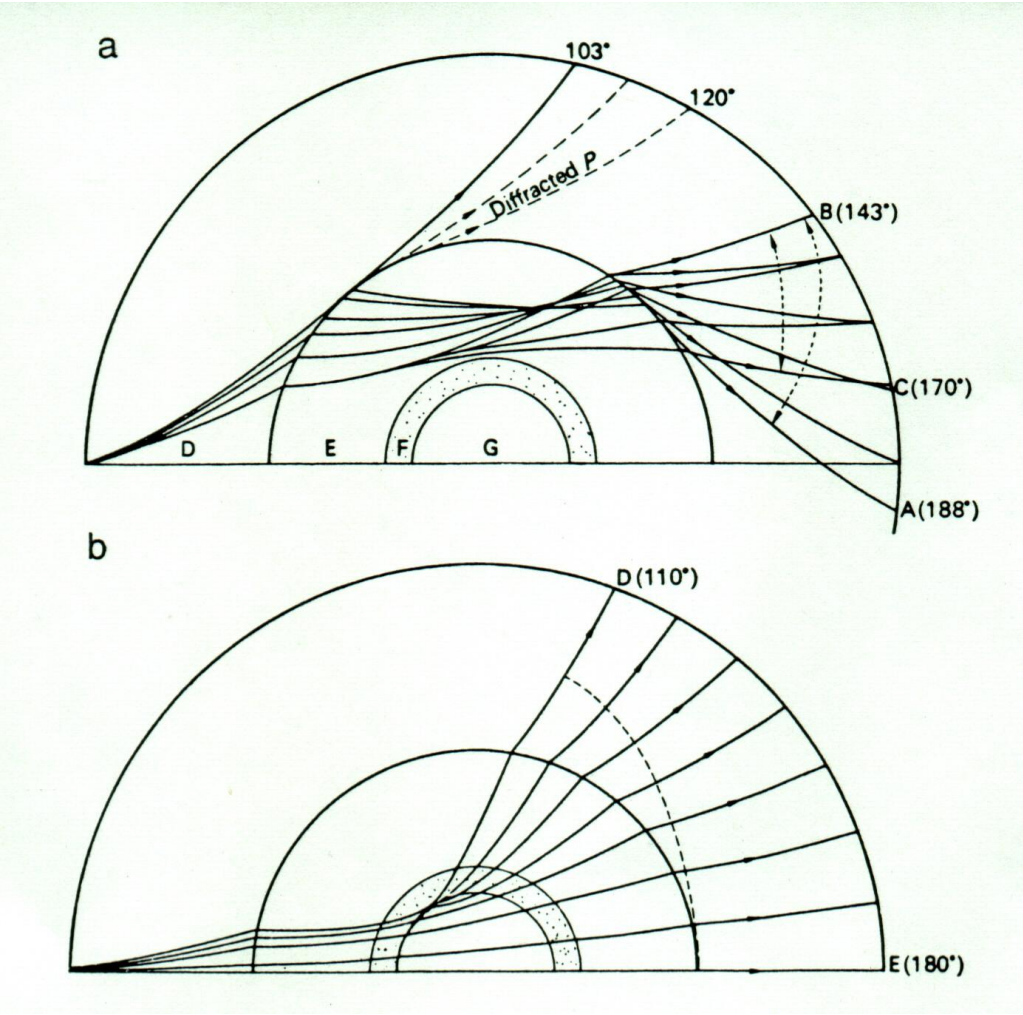
Calls the new seismic phase P'

Writes a paper whose title is the shortest ever: " P' "

->Existence of a region at the center of the core with different elastic properties than the external part of the core.



Lehmann, 1936



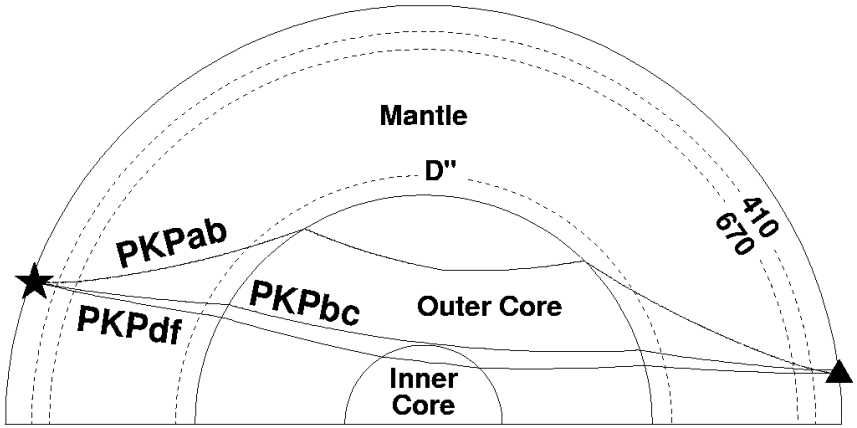
Shadow zone

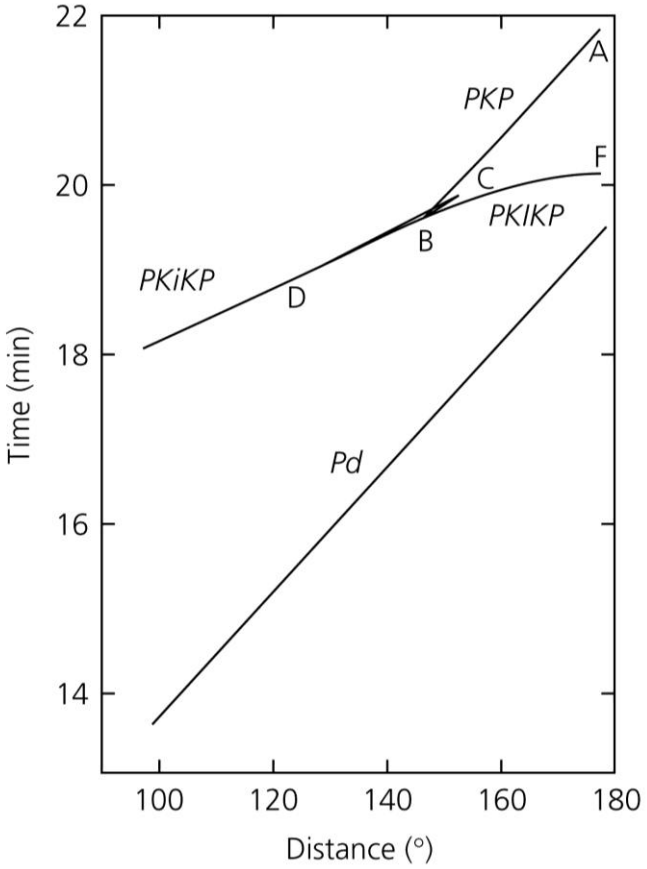
PKIKP
also noted:
PKP(DF)

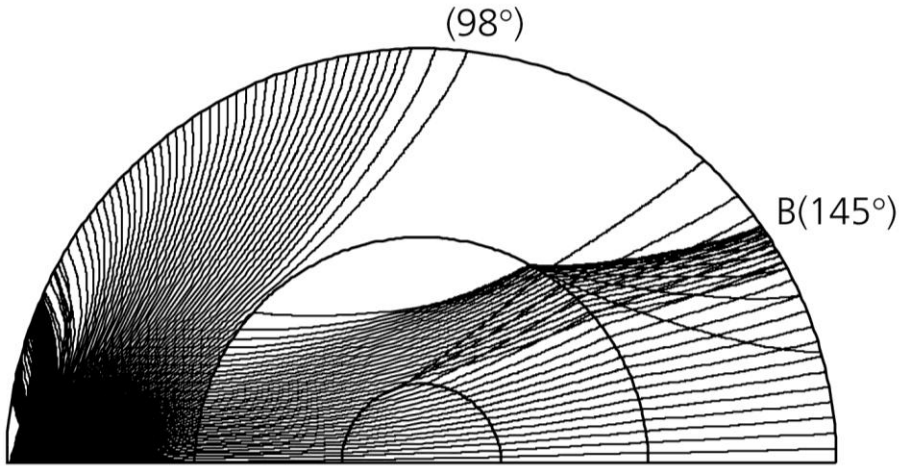
(after B. Gutenberg)

PKP= Refracted waves in the core

There are 3 branches: PKPbc, PKPab, and PKPdf=PKIKP

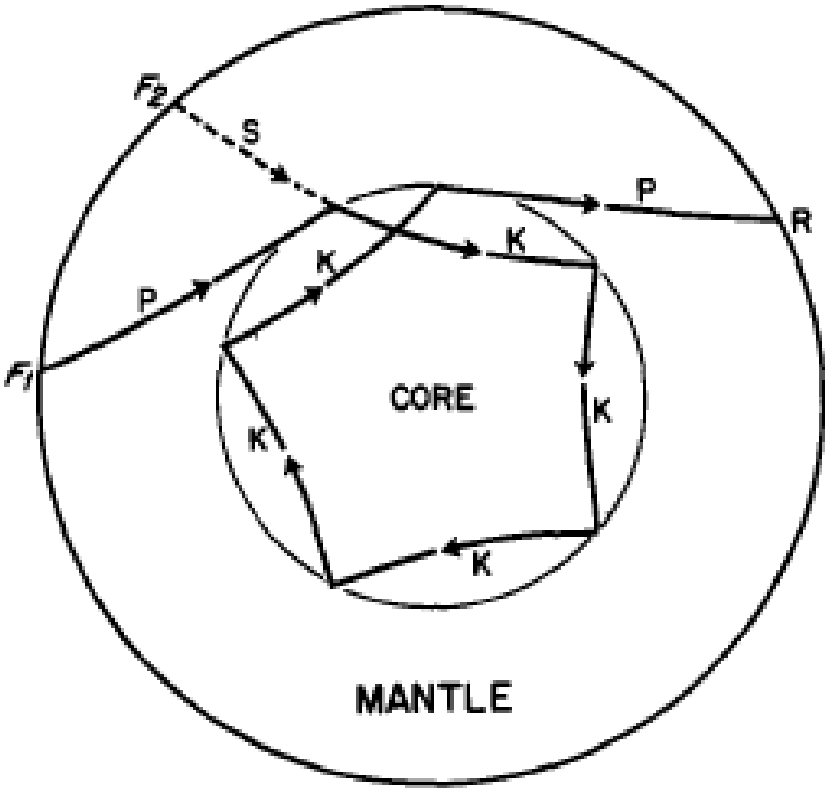






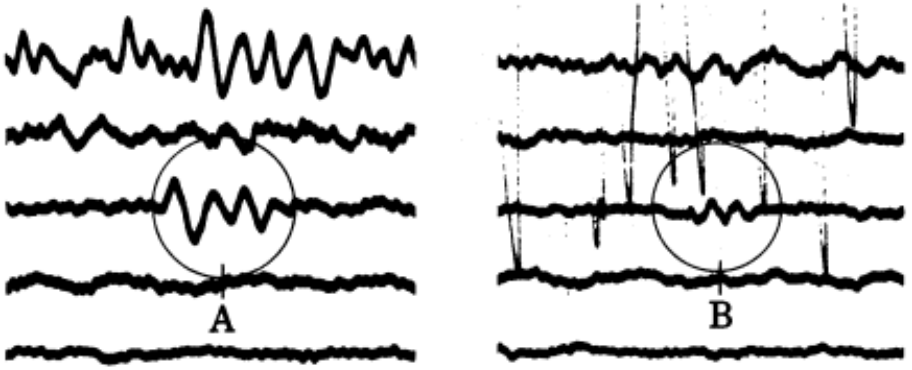
Pd is a diffracted wave around the CMB

PnKP

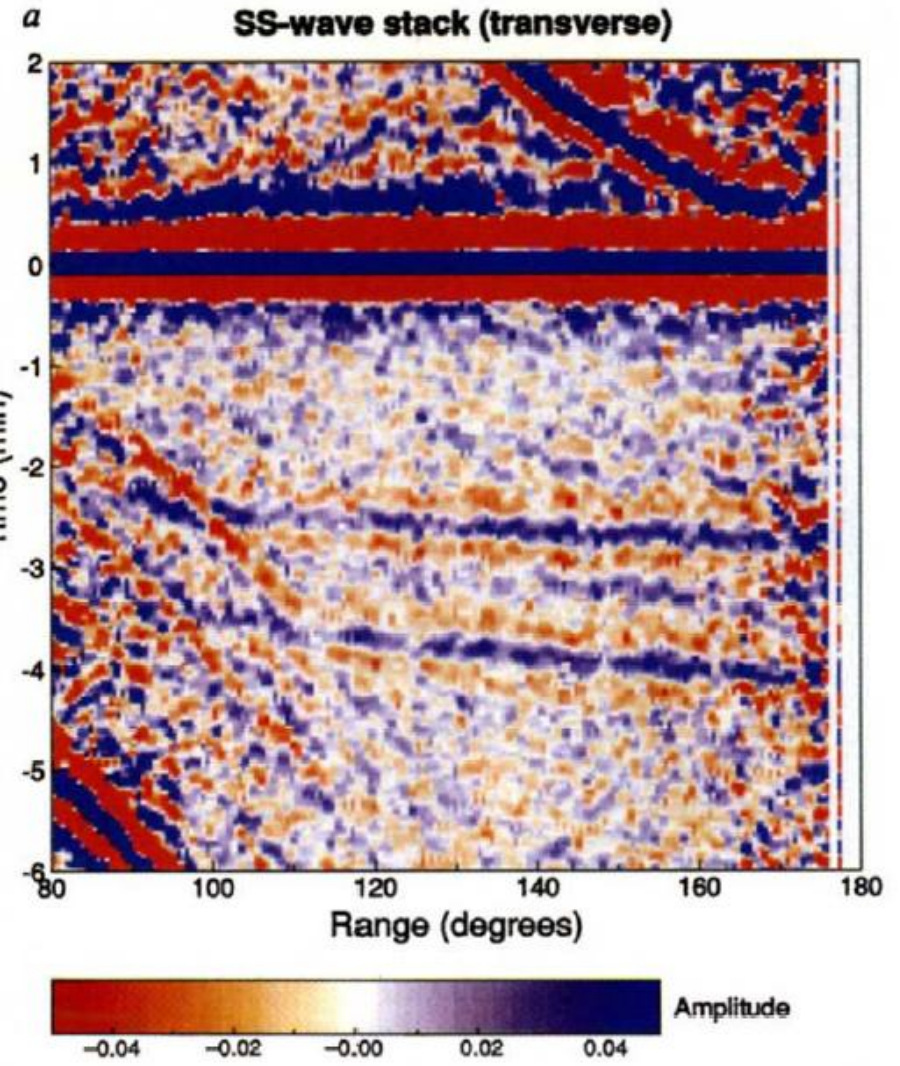


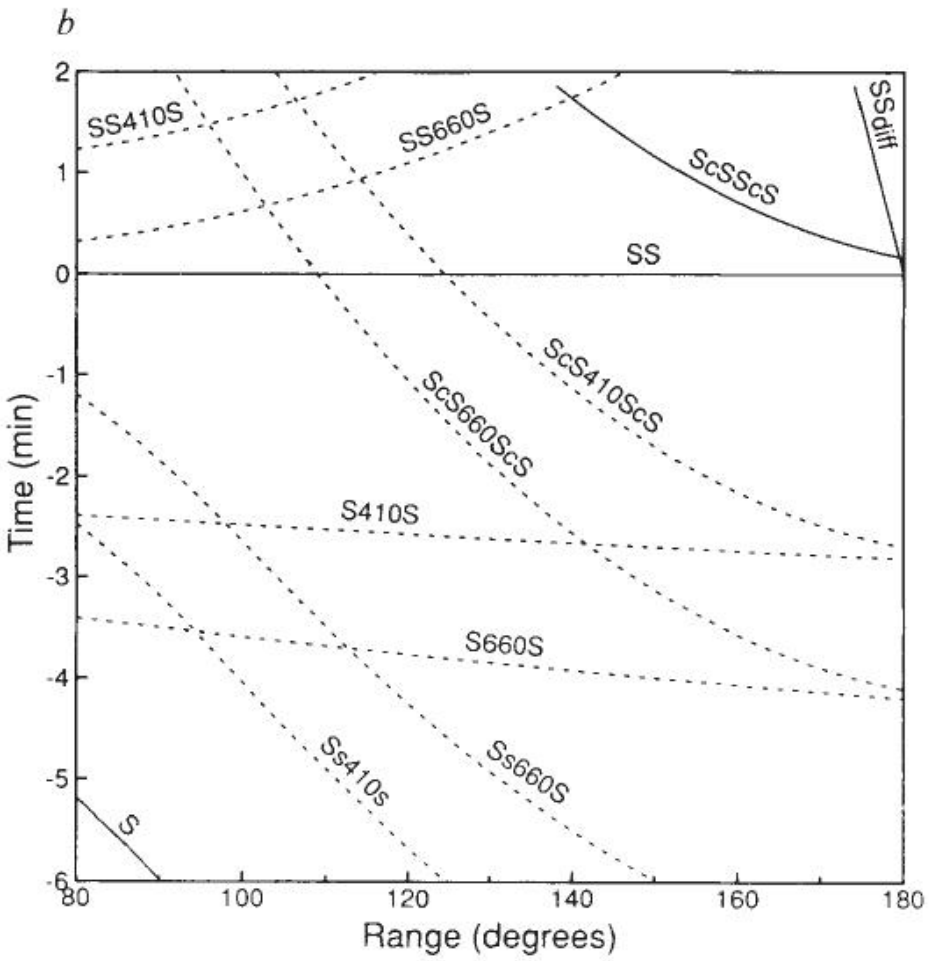
P4KP

P7KP

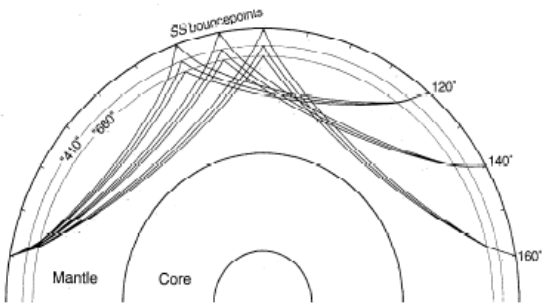


Global Transverse Component Stacks





with (*b*) travel-t … lines) and
upper-mantle dis … are shown
in blue, negative … .05 of the



Shearer, 1991

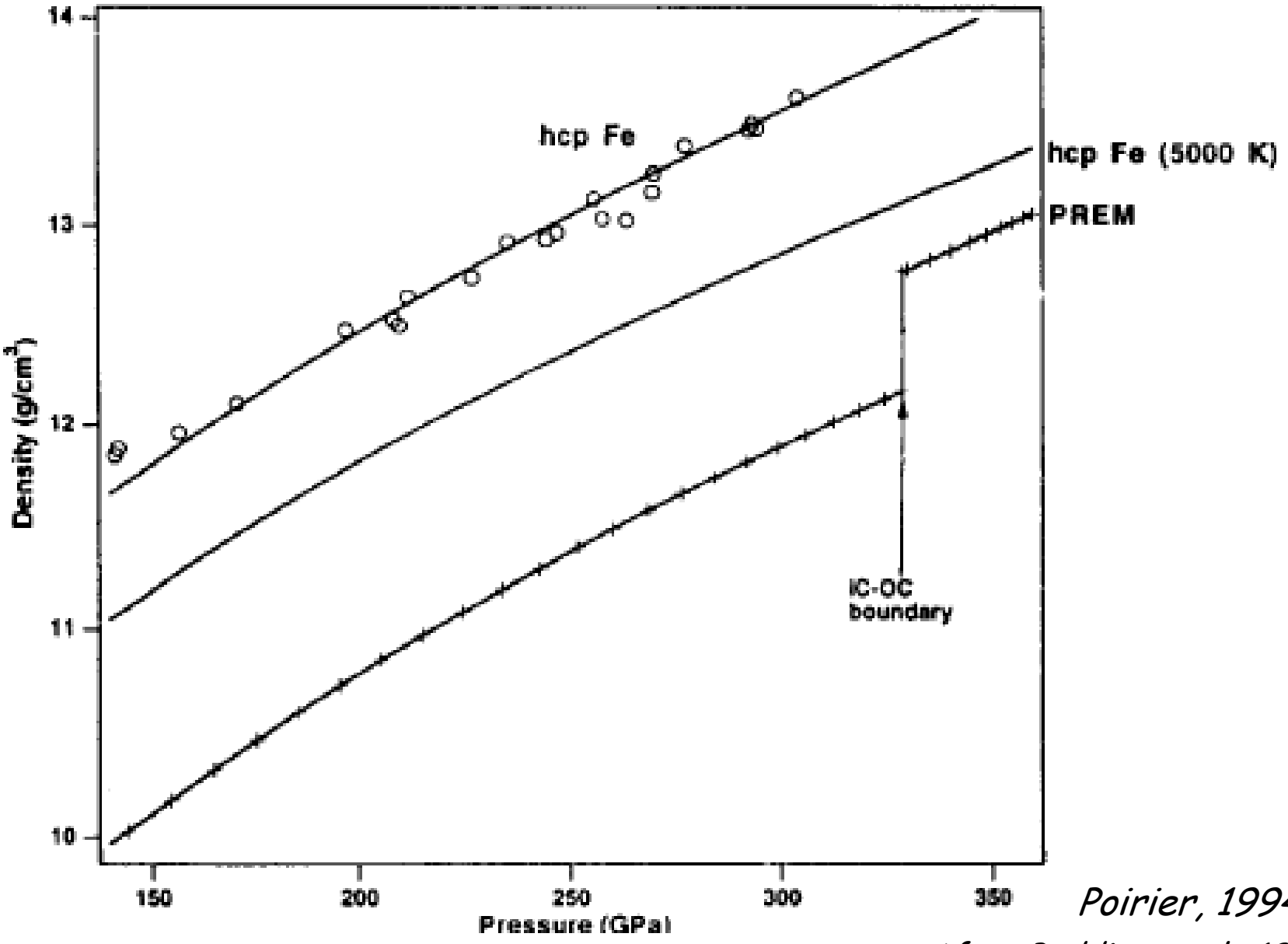
Composition of the core

Francis Birch – 1903-1992

- Francis Birch demonstrates in 1952 that the earth's mantle is composed of silicates, the outer core of liquid iron and the inner core of solid, cristalline iron (*Birch, 1952, JGR*).
- He confirms in 1961 that the density of the core is ~10% lower than that of iron at the pressure (P) and temperature (T) conditions of the core.

outer core is..
"liquid iron, perhaps alloyed with a small fraction of light elements" (C and Si)

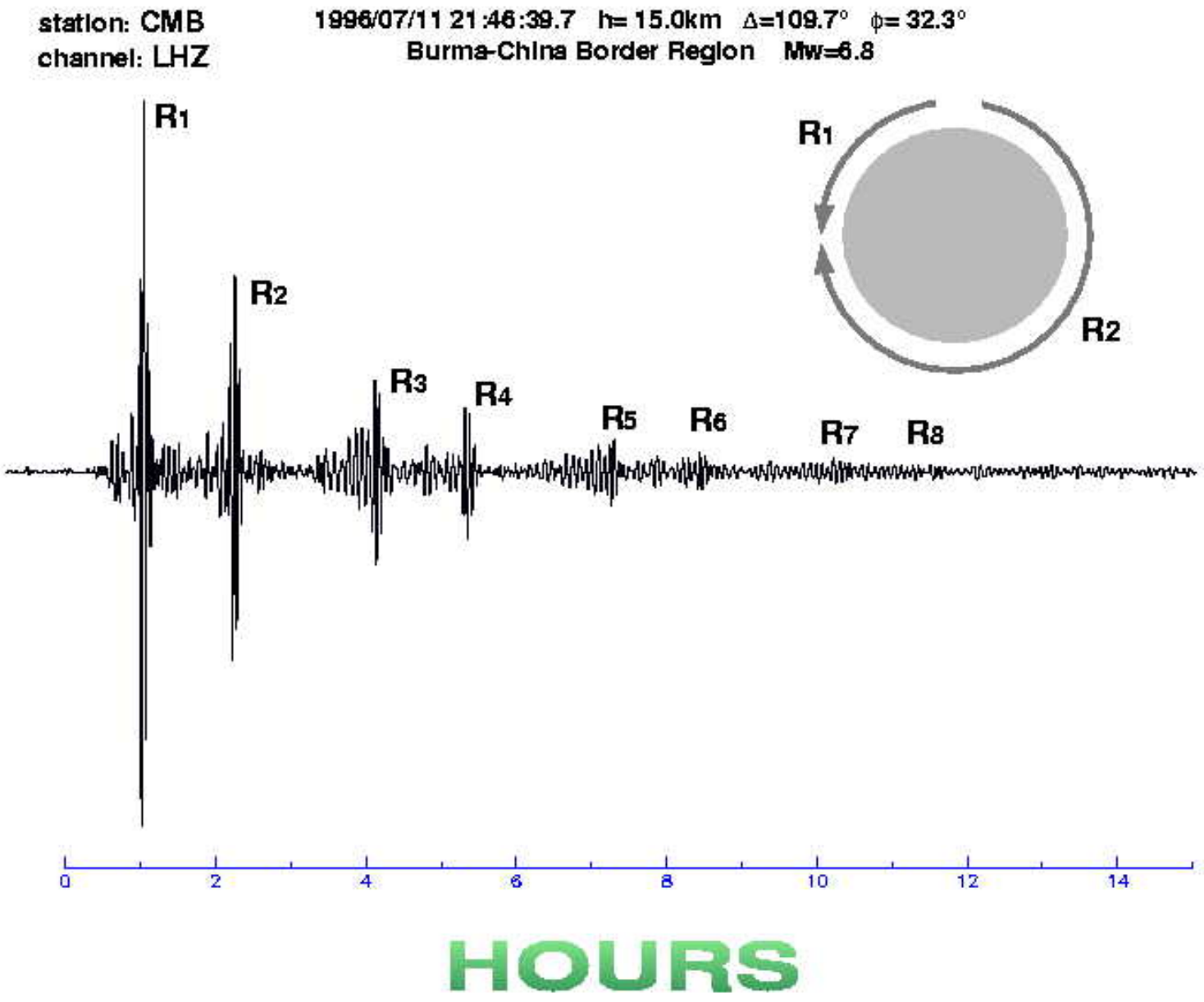
Hcp iron density versus pressure – comparison with PREM

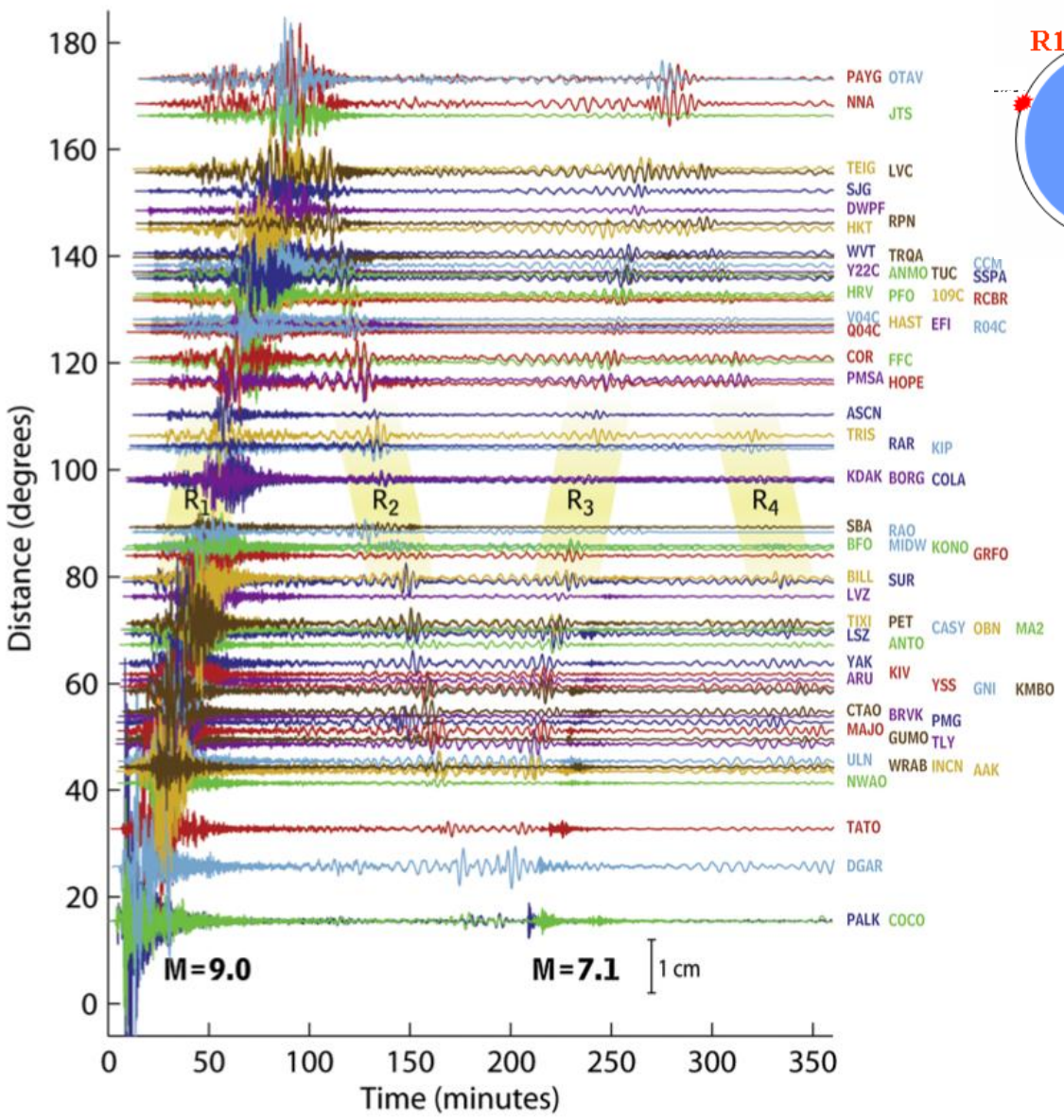


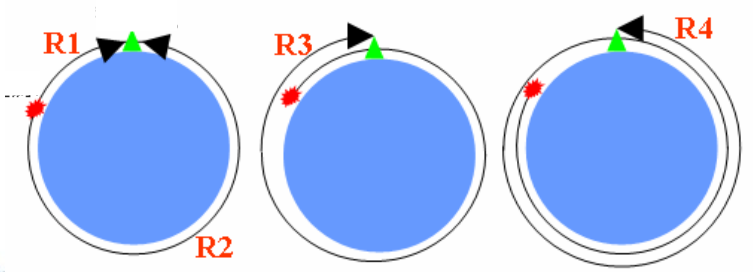
Poirier, 1994

From in situ measurements

After Badding et al., 1991

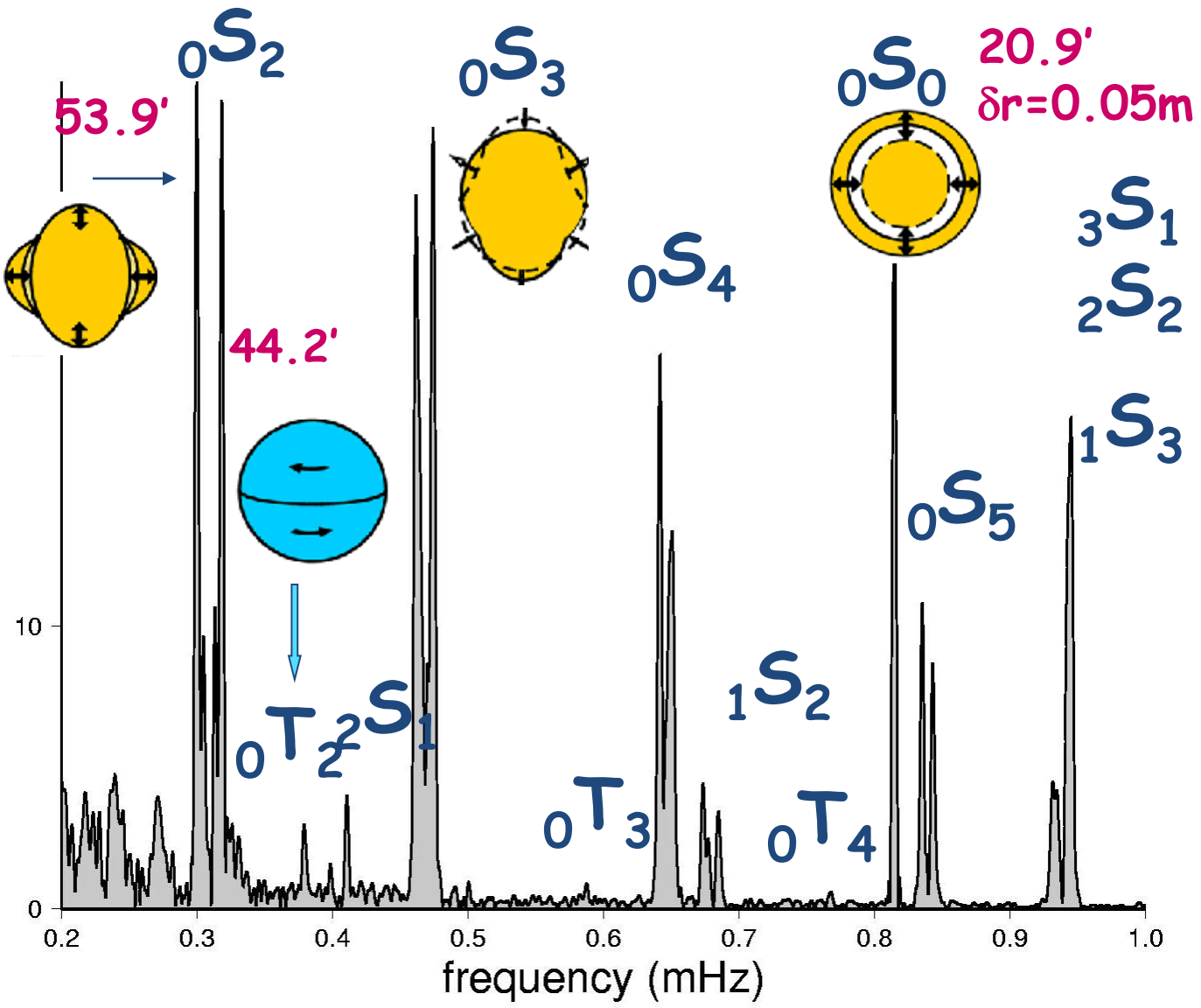

station: CMB
channel: LHZ
1996/07/11 21:46:39.7 h= 15.0km Δ=109.7° ϕ= 32.3°
Burma-China Border Region Mw=6.8
R1
R2
R3
R4
R5
R6
R7
R8
R1
R2
0
2
4
6
8
10
12
14
HOURS





After Park et al., 2005

Sumatra Andaman earthquake 12/26/04 M 9.3



Observed on the vertical component

Free Oscillations of the Earth

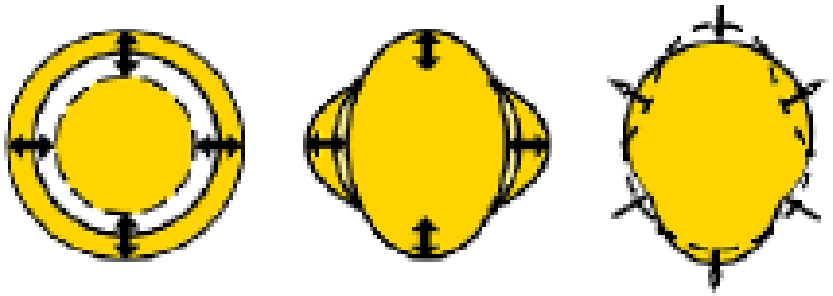
- Normal modes of the Earth:

- Standing waves
- Periods 100s to 1 hour (54 mn)

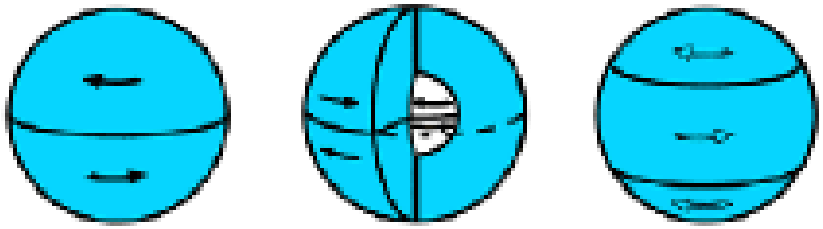
- Two types:

- Spheroidal, S
  - vertical and radial motion
  - correspond to Rayleigh waves

- Toroidal, T
  - observed on the tangential component
  - correspond to Love waves



Spheroidal modes ${}_0S_0$ (20.5 min), ${}_0S_2$ (53.9 min) and ${}_0S_3$ (25.7 min)



Toroidal modes ${}_0T_2$ (44.2 min), ${}_1T_2$ (12.6 min) and ${}_0T_3$ (28.4 min)

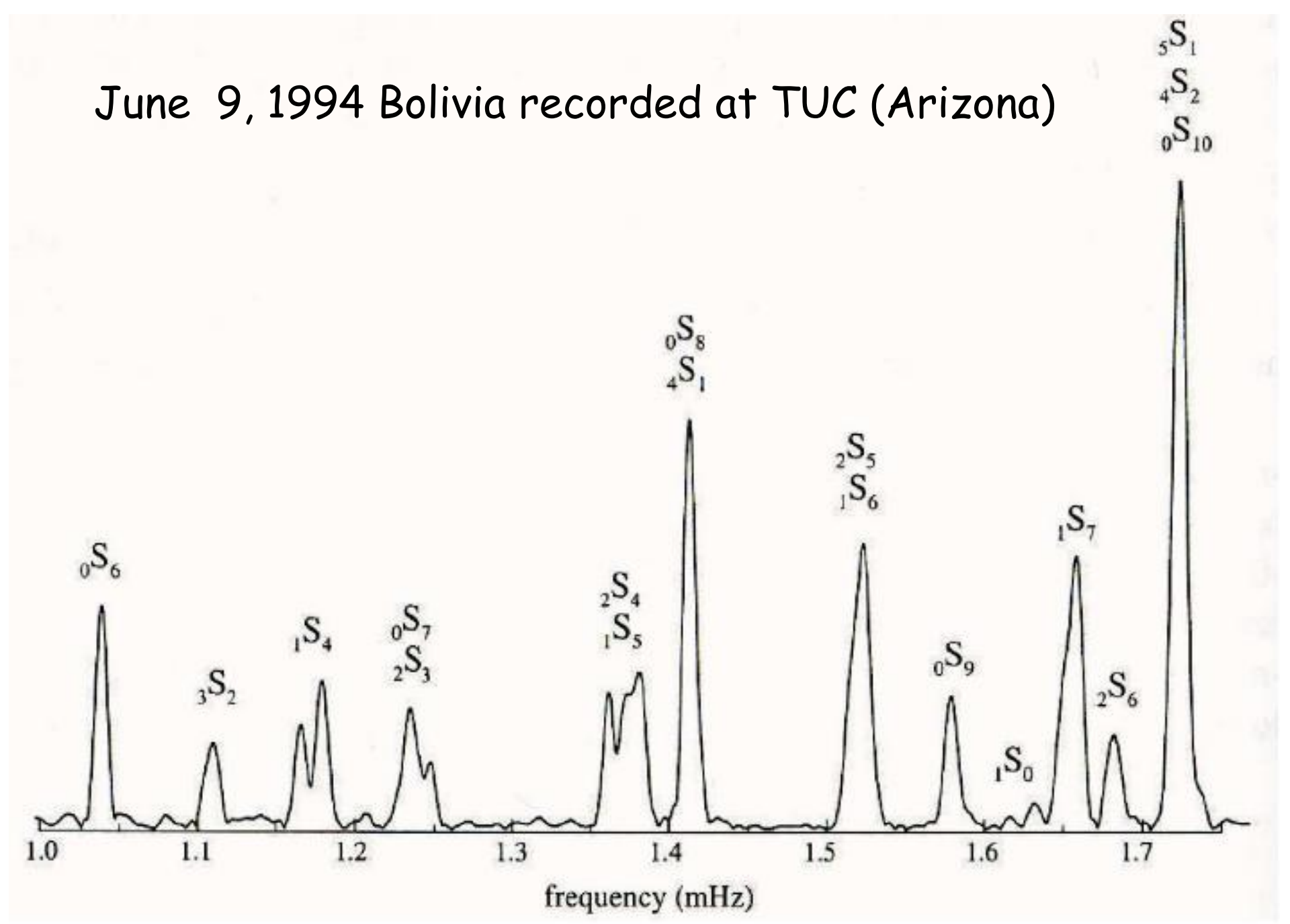
- Nomenclature:

${}_nS_{l,\,n}T_l$

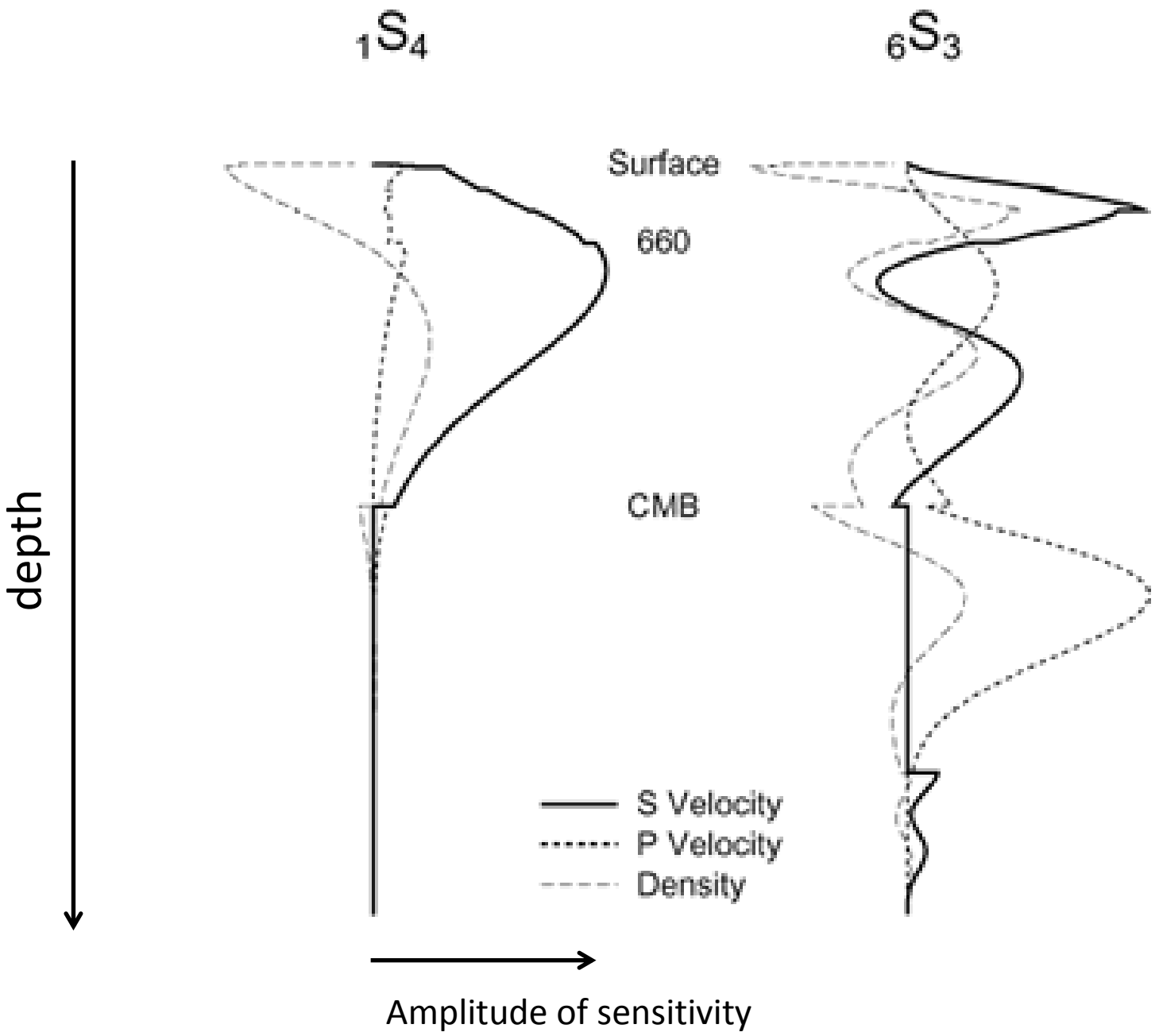
l = number of nodes in latitude

n = number of nodes with depth

June 9, 1994 Bolivia recorded at TUC (Arizona)



Depth sensitivity kernels of earth's normal modes



Group 1

Group 2

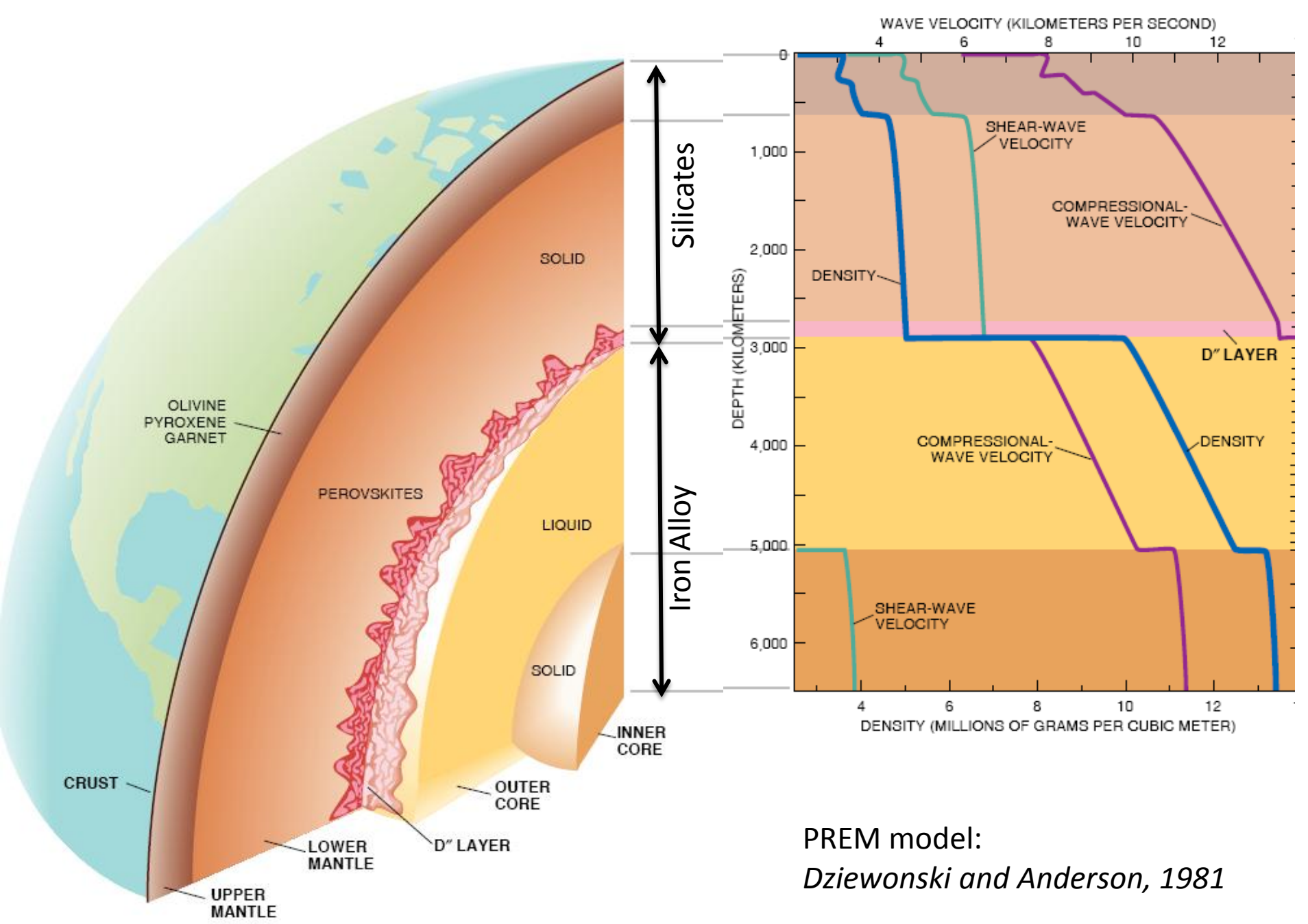
Mode	Mean period (s)	No. of observations	s.e.m. (s)	UTD124B′—Solid inner core Comp. period	Rel. error (%)	Inner core energy Compr.	Shear
$_1S_0$	613.57	11	0.236	614.59	0.17	0.181	0.000
$_2S_0$	398.54	40	0.084	397.59	−0.24	0.206	0.001
$_3S_0$	305.84	7	0.129	306.00	0.05	0.233	0.003
$_4S_0$	243.59	12	0.067	243.80	0.09	0.192	0.007
$_2S_2$	904.23	21	0.487	904.43	0.02	0.001	0.080
$_5S_2$	397.36	11	0.157	397.03	−0.09	0.015	0.102
$_6S_1$	348.41	21	0.046	348.23	−0.05	0.068	0.011
$_7S_3$	281.37	11	0.113	281.59	0.08	0.004	0.022
$_8S_1$	272.10	11	0.144	271.79	−0.11	0.115	0.052
	Nine modes—r.m.s.						

UTD124B′—Liquid inner core 5.08M

Comp. period	Rel. error (%)	Comp. period	Rel. error (%)
607.39	−1.02	610.06	−0.57
392.31	−1.59	391.42	−1.81
301.36	−1.48	301.84	−1.31
241.11	−1.03	241.55	−0.84
914.94	1.17	917.80	1.50
399.93	0.67	398.20	0.21
347.10	−0.38	347.38	−0.30
282.77	0.50	283.34	0.70
271.00	−0.40	270.92	−0.43

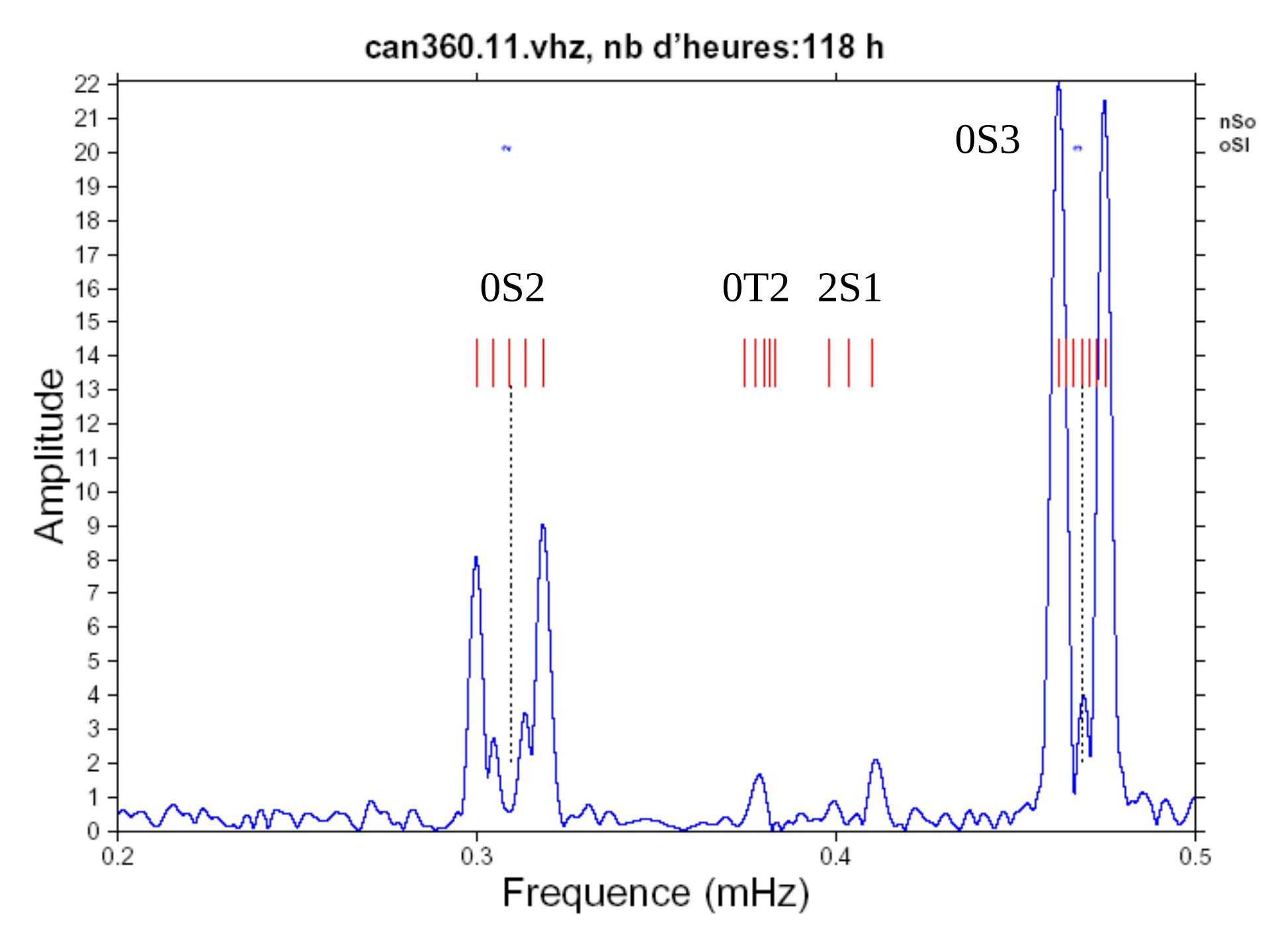
-→ Vs-ic=3.517 km/s

Dziewonski and Gilbert, Nature 1971
Also Dziewonski, Science, 1971- radial modes

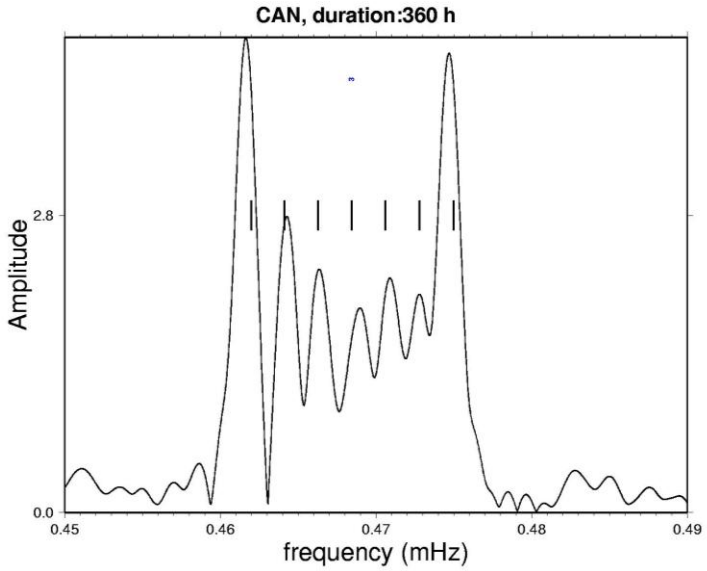


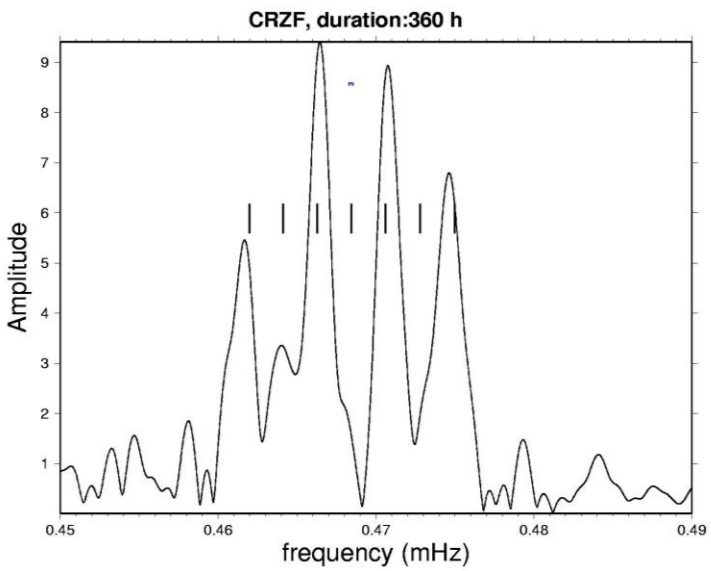
PREM model:
Dziewonski and Anderson, 1981

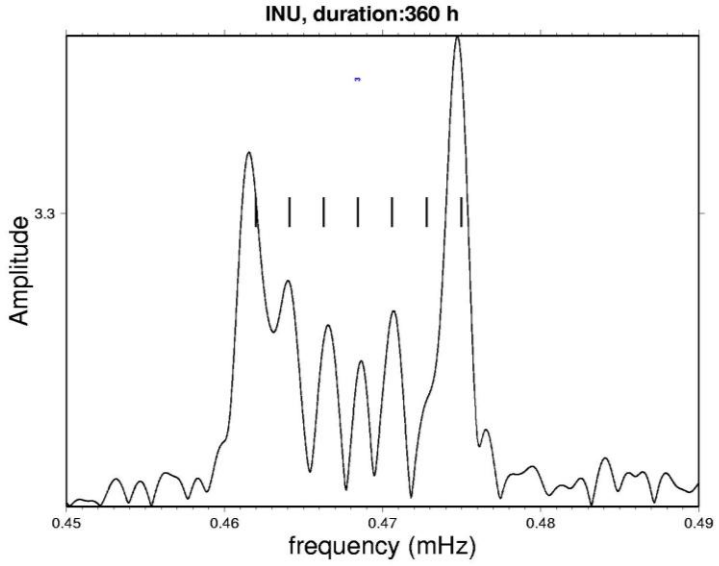
Graphics from Jeanloz and Lay, Sci. Amer., 1993

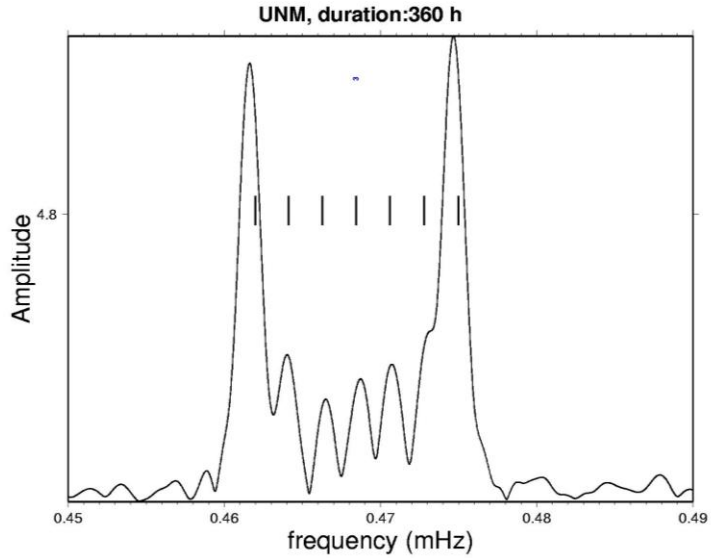

can360.11.vhz, nb d'heures:118 h
0S3
0S2
0T2
2S1
nSo
oSl
Amplitude
Frequence (mHz)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
0.2
0.3
0.4
0.5

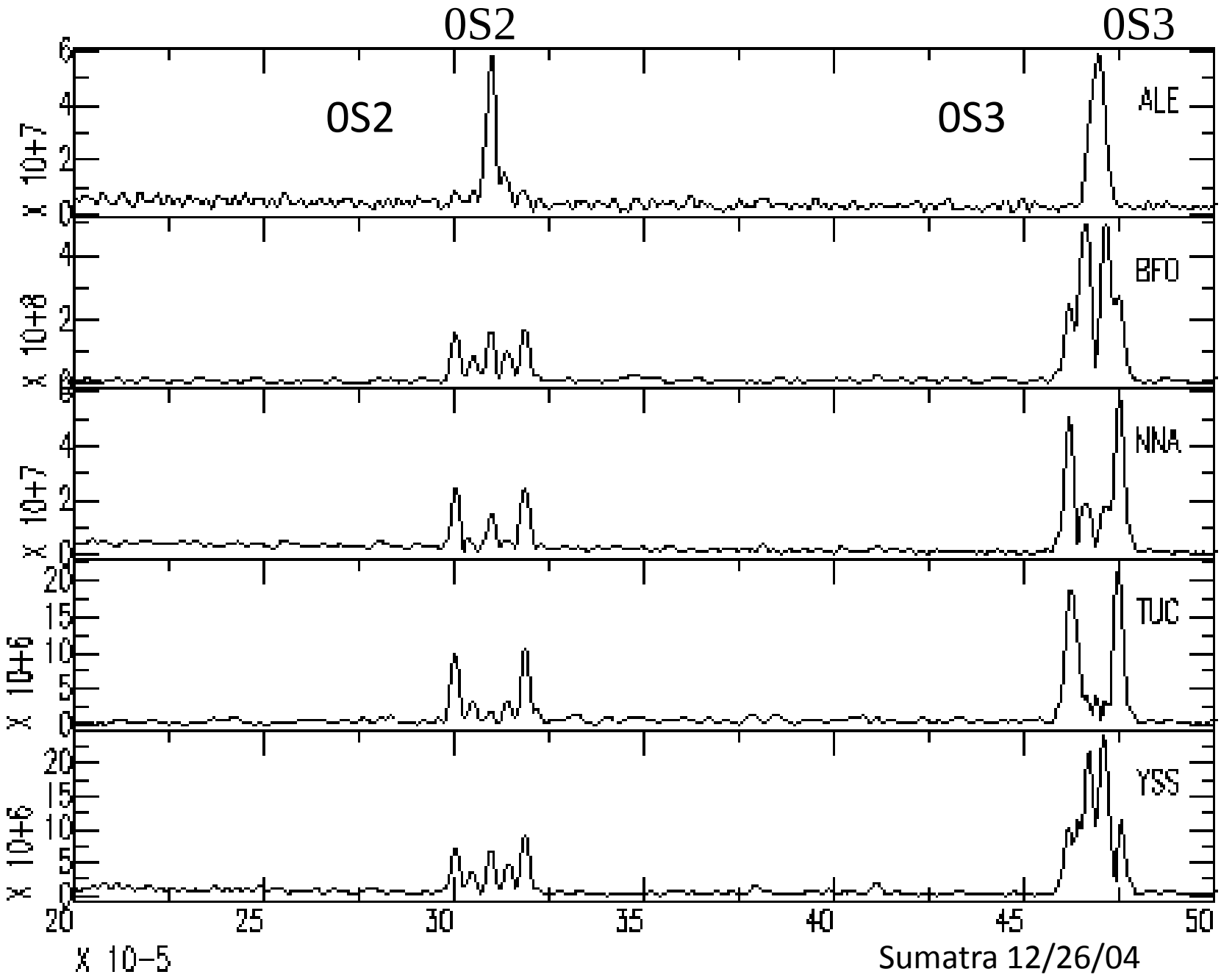
mode $_0S_3$ 7 singlets

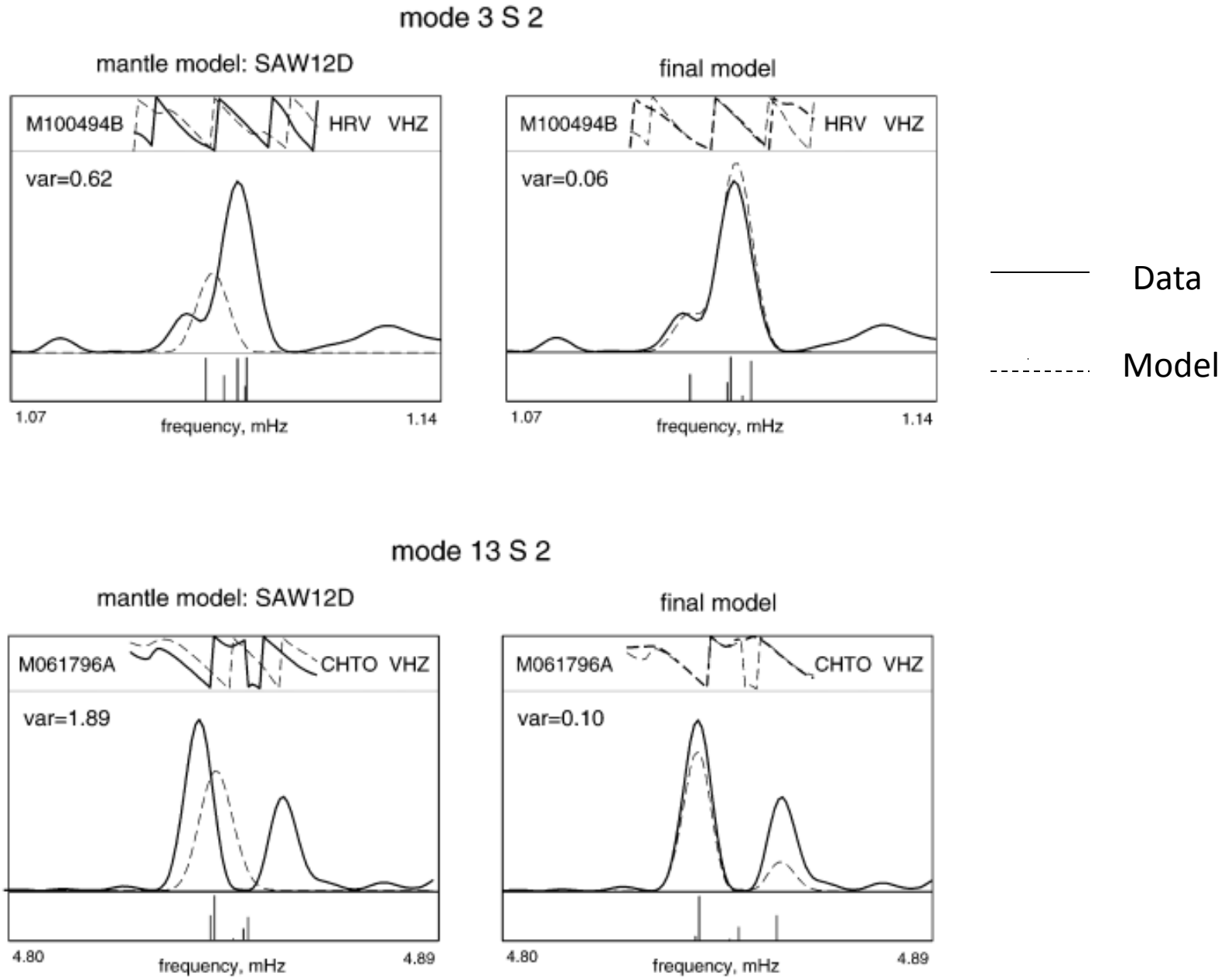








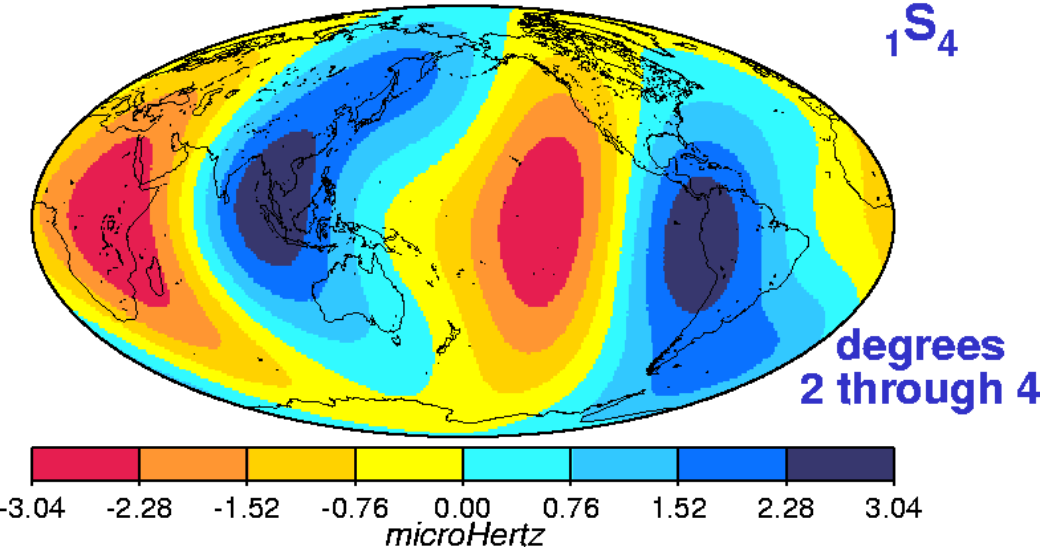

0S2
0S3
0S2
0S3
ALE
BFO
NNA
TUC
YSS
x 10+7
x 10+8
x 10+7
x 10+6
x 10+6
X 10-5
20
25
30
35
40
45
50
Sumatra 12/26/04



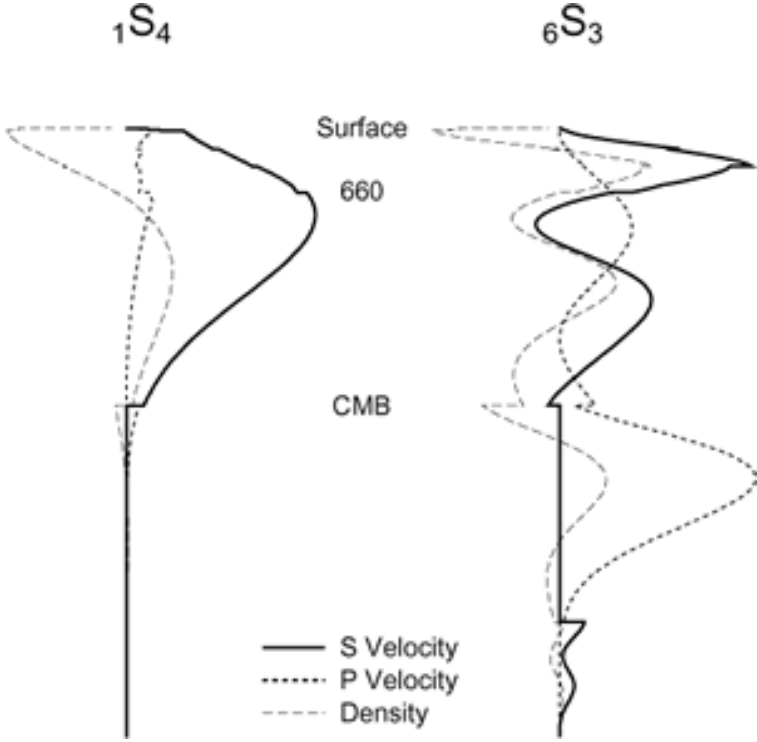
Anomalous splitting of core modes 3S2 and 13S2

even-degree normal mode splitting function

Generalized Spectral Fitting Estimate

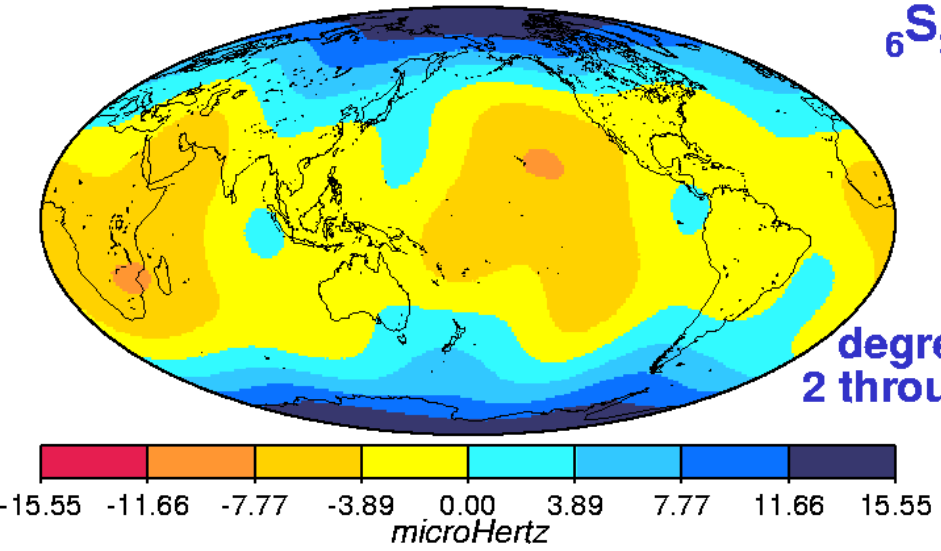


Mantle mode



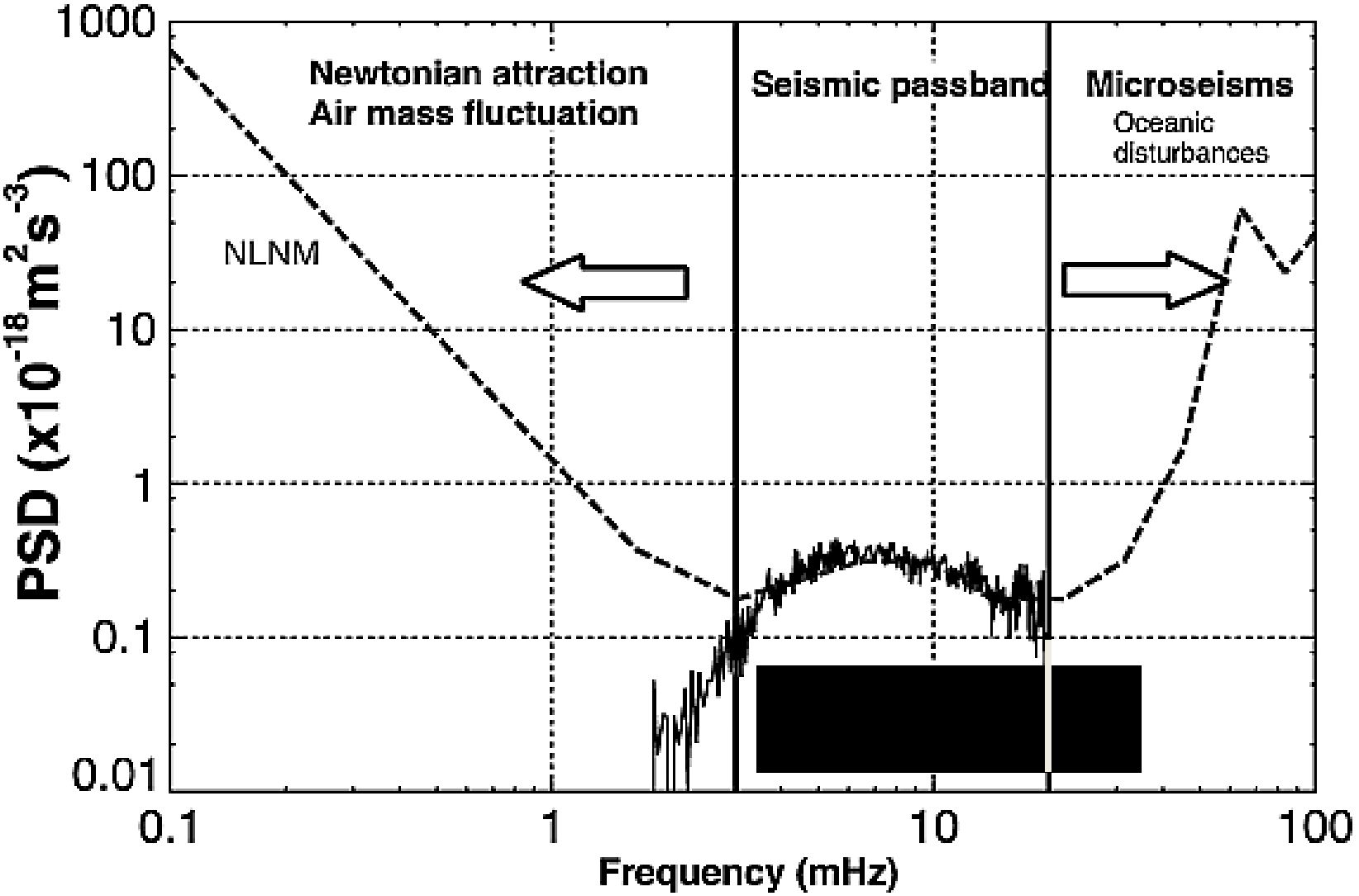
even-degree normal mode splitting function

Generalized Spectral Fitting Estimate



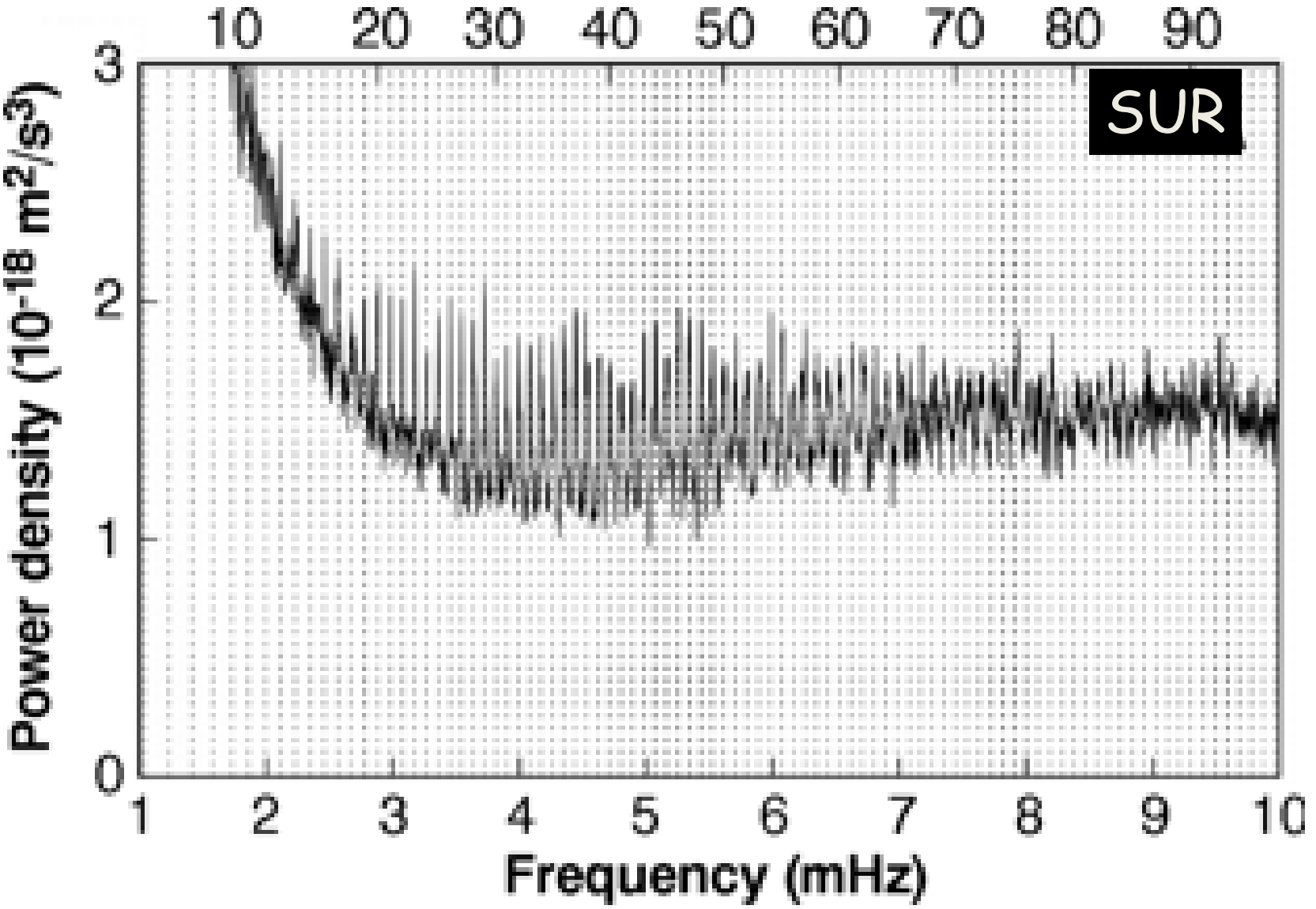
Core mode

Seismic Noise Power Density Spectrum



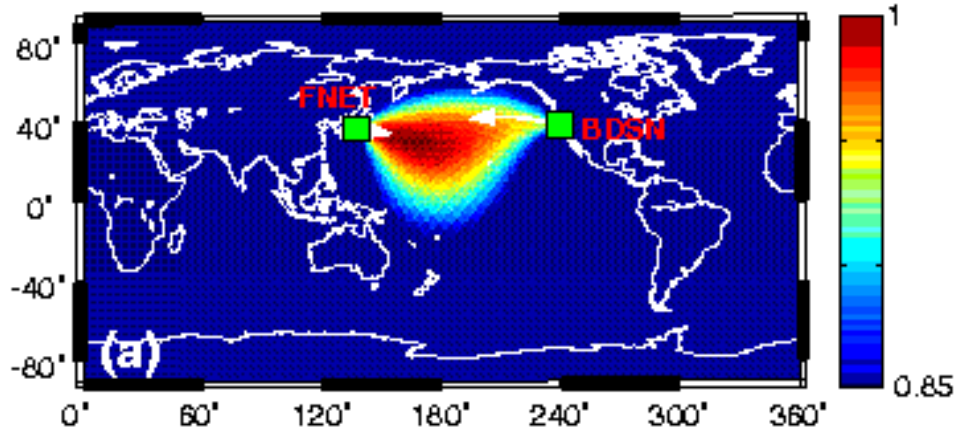
After Nishida et al., GRL, 2002

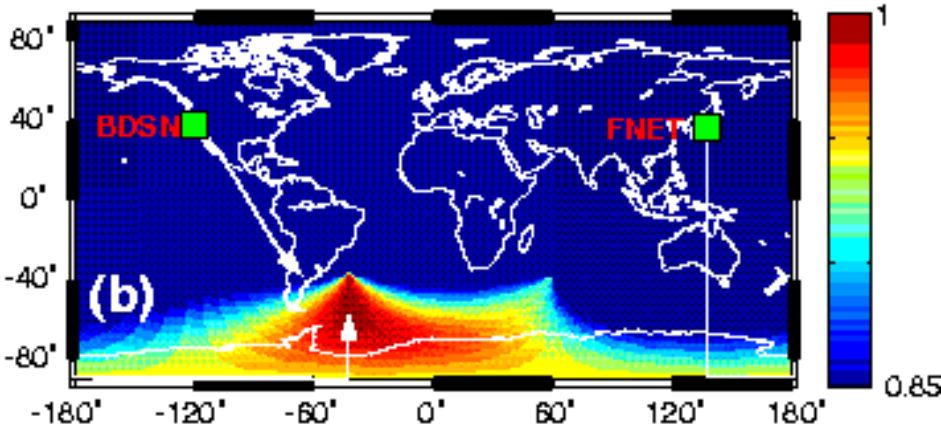
Observed noise spectra stacks
437 days without earthquakes



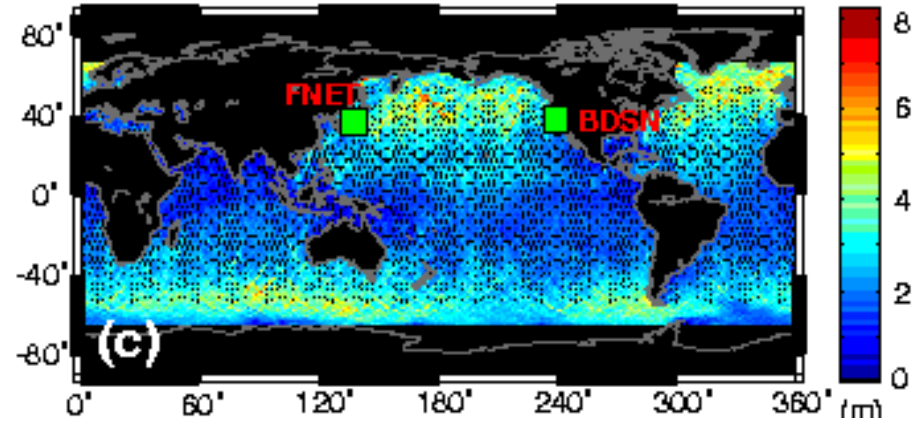
Suda et al., 1998

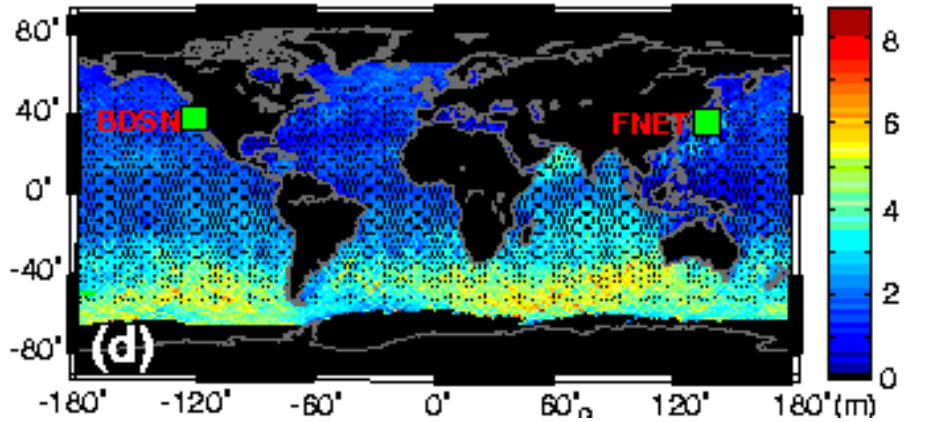
Seismic Data





Significant Wave Height (Topex-Poseidon)



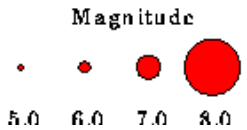


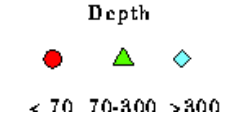
Winter

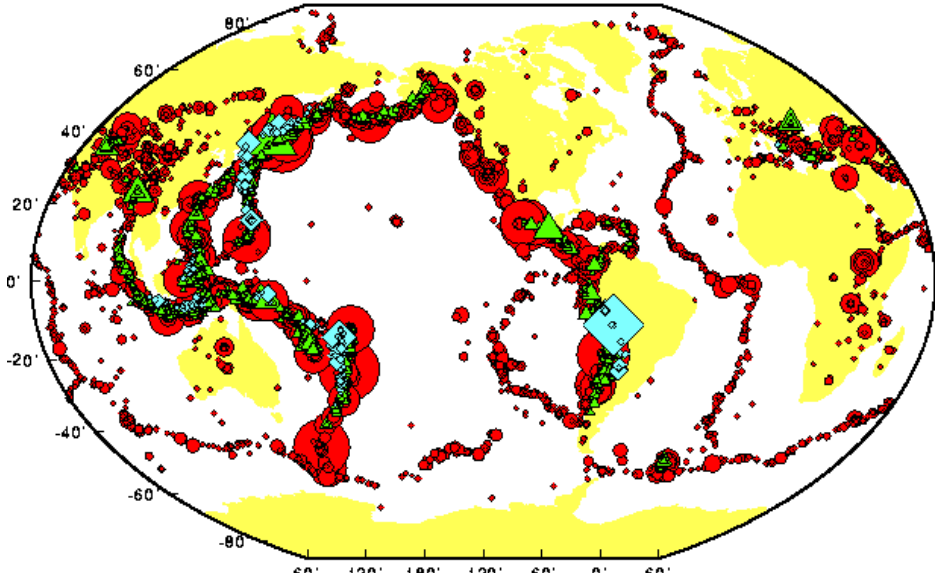
Summer

Rhie and Romanowicz, Nature, 2004

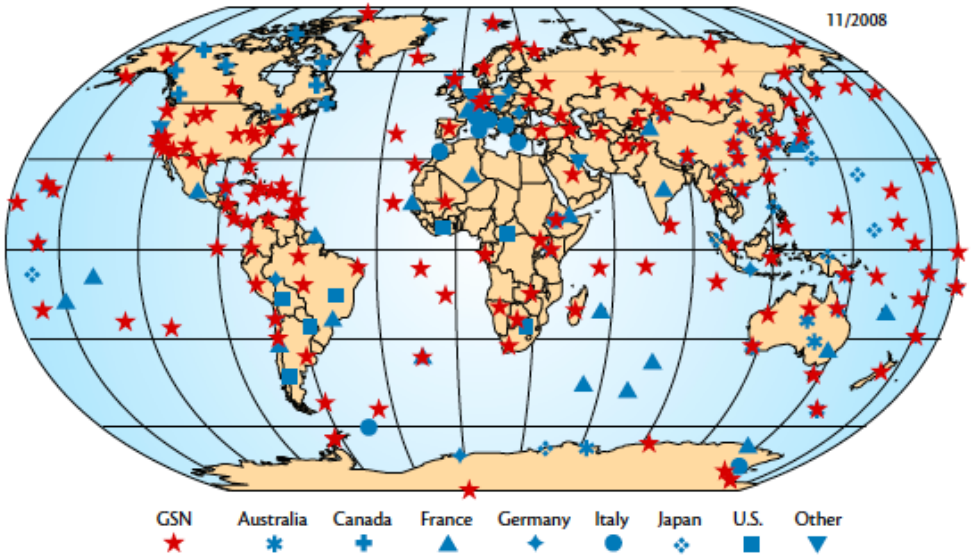
Earthquakes >Magnitude 5.0, 1985 - 1996 From NEIC







International Federation of Digital Seismograph Networks



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

Lunar seismology…. started in 1962…

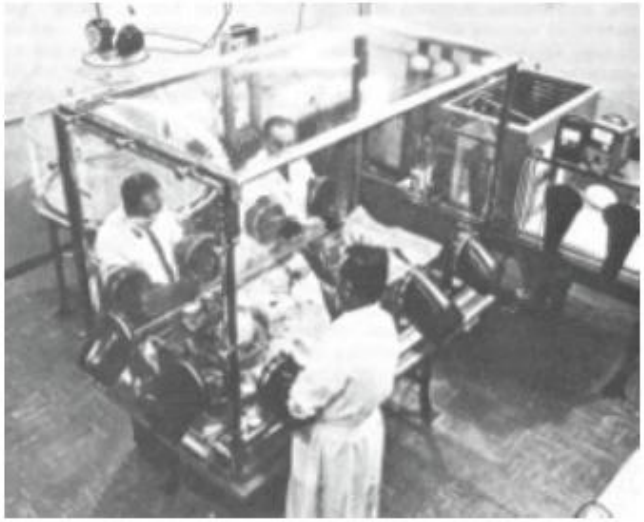
Seismometer and Ranger at JPL

Apollo 14 crew training the ALSEP (and seismometer) deployment

Ranger 3
1/26/1962

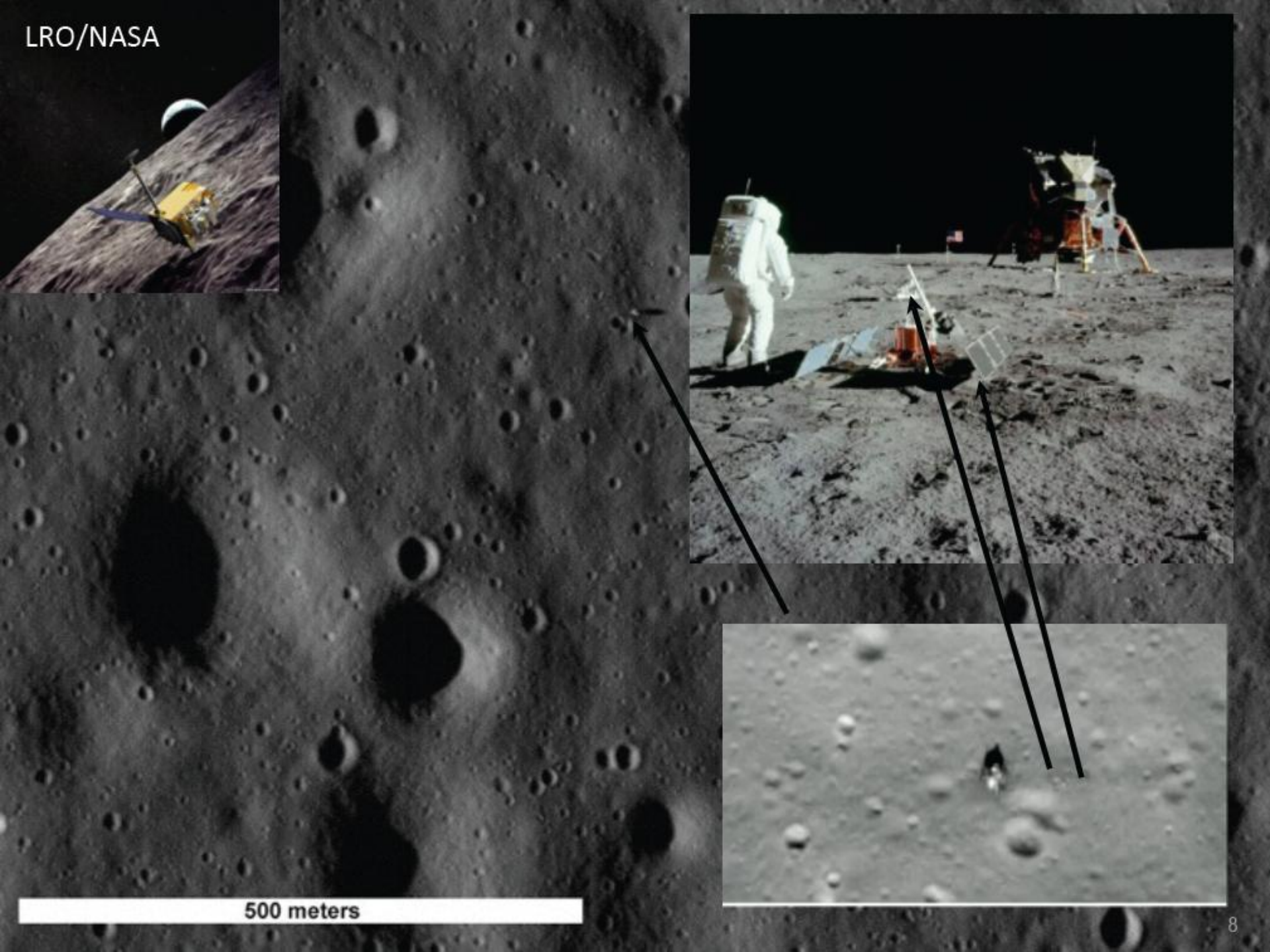
Ranger 4
4/23/1962

Ranger 5
10/18/1962

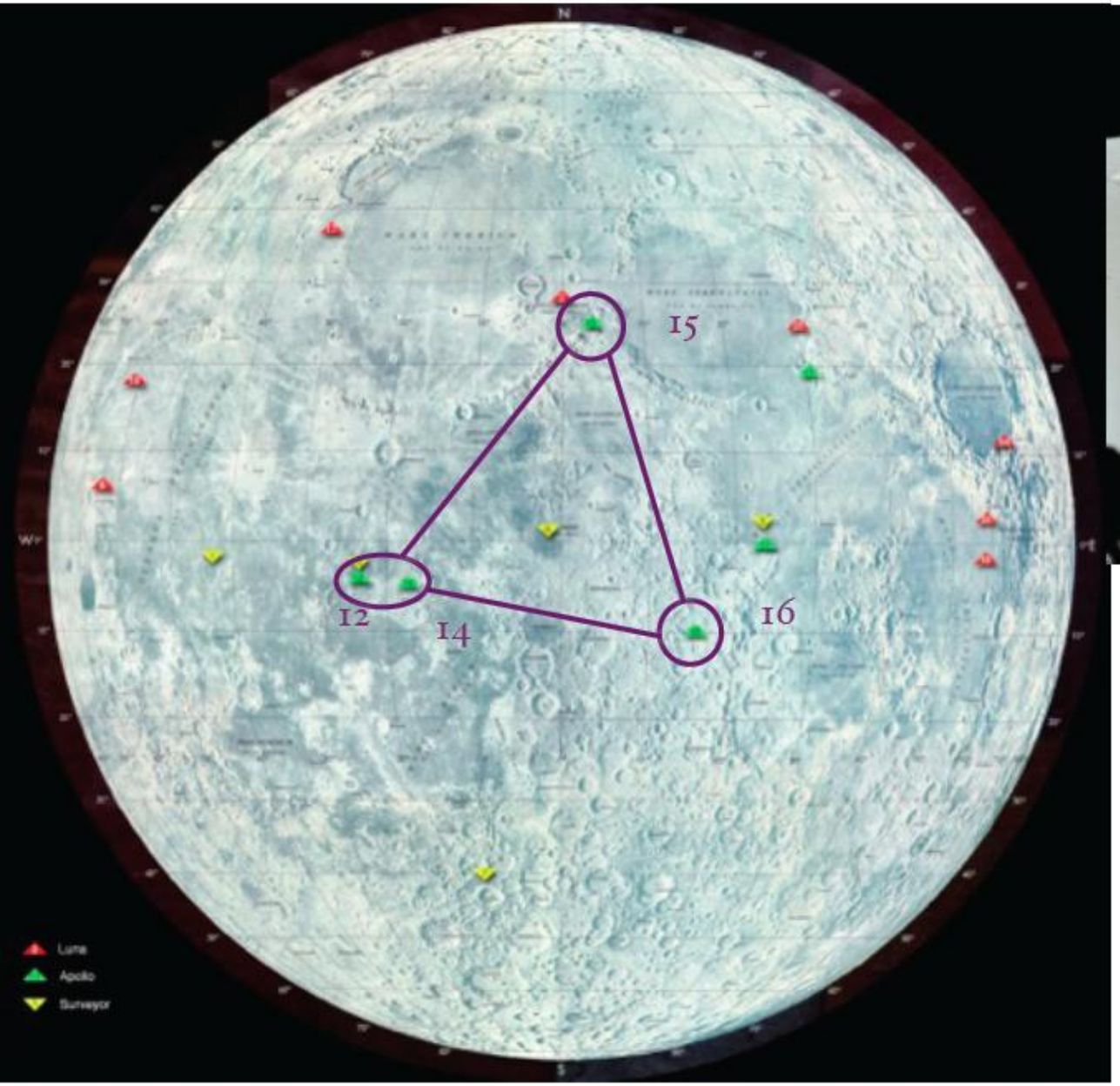


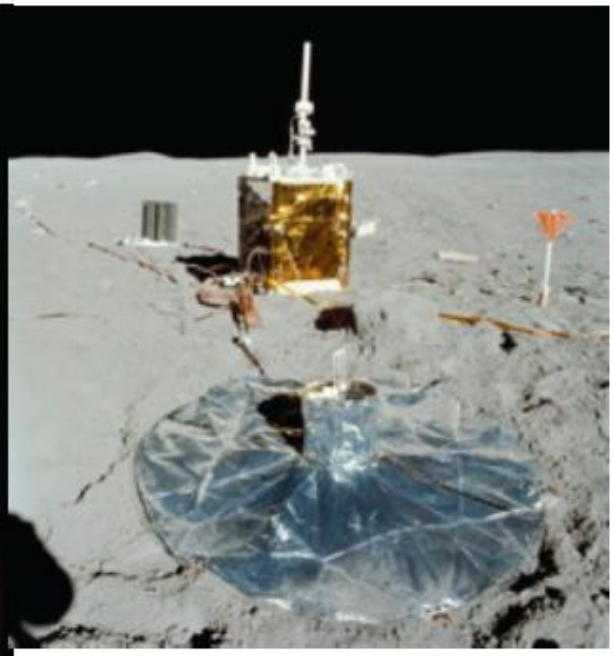
Sterile seismometer assembly at Aeronutronic

Ph. Lognonné, CIDER 2014


LRO/NASA
500 meters

Apollo seismic network





Apollo Network

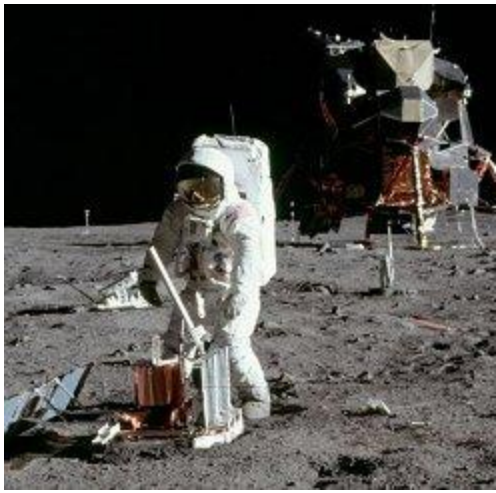


Image source: NASA

-Passive Seismic Experiment (PSE):

4 stations: Apollo sites 12, 14, 15 and 16
installed between 1969 and 1972
turned off in 1977

-Long Period Seismometer– 3 axis

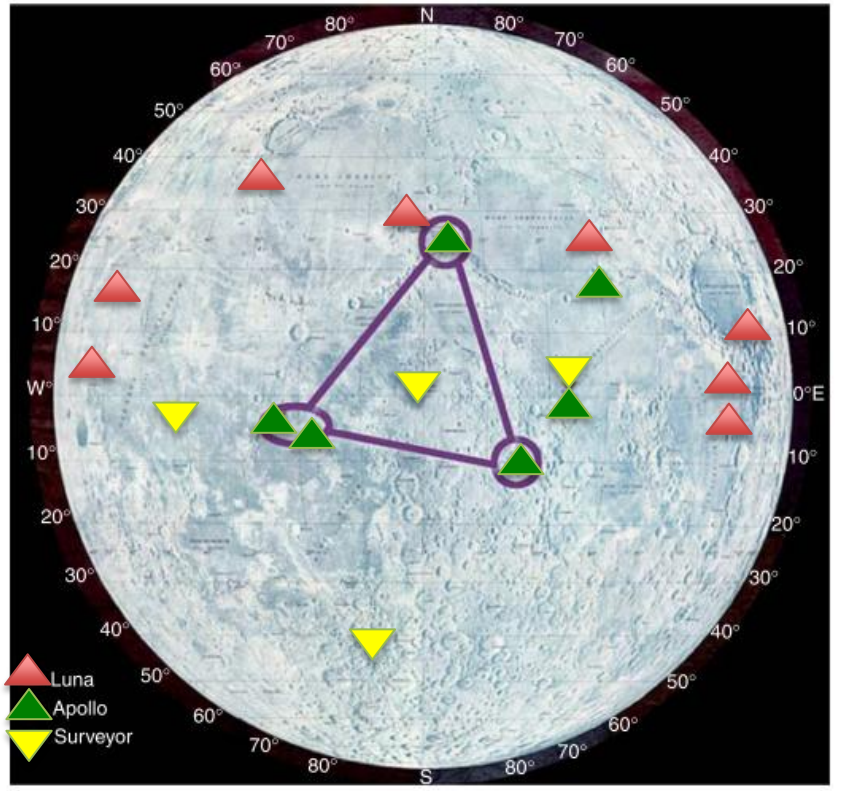
- 3 x 10^{-10} m, 0.1-1 Hz

-Short Period – Vertical only

- 0.5 x 10^{-10} m, 8 Hz

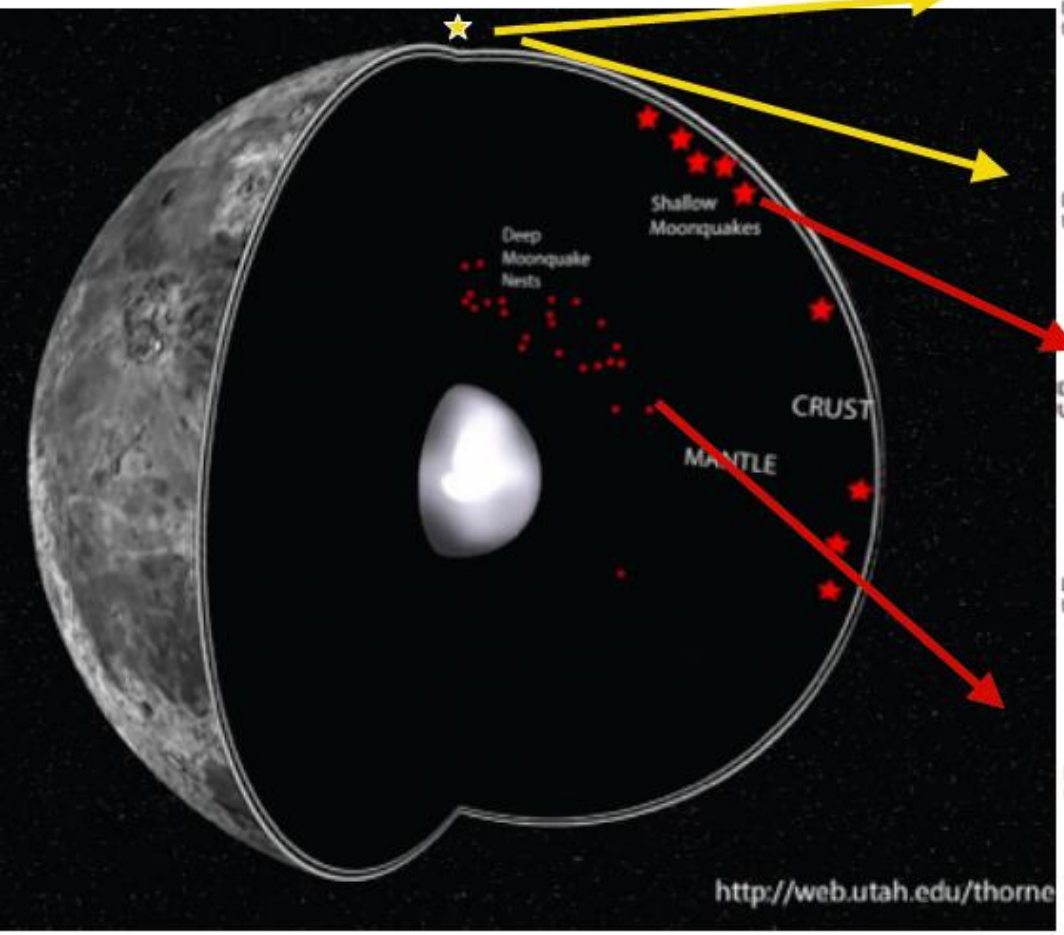
>12,500 observed cataloged events

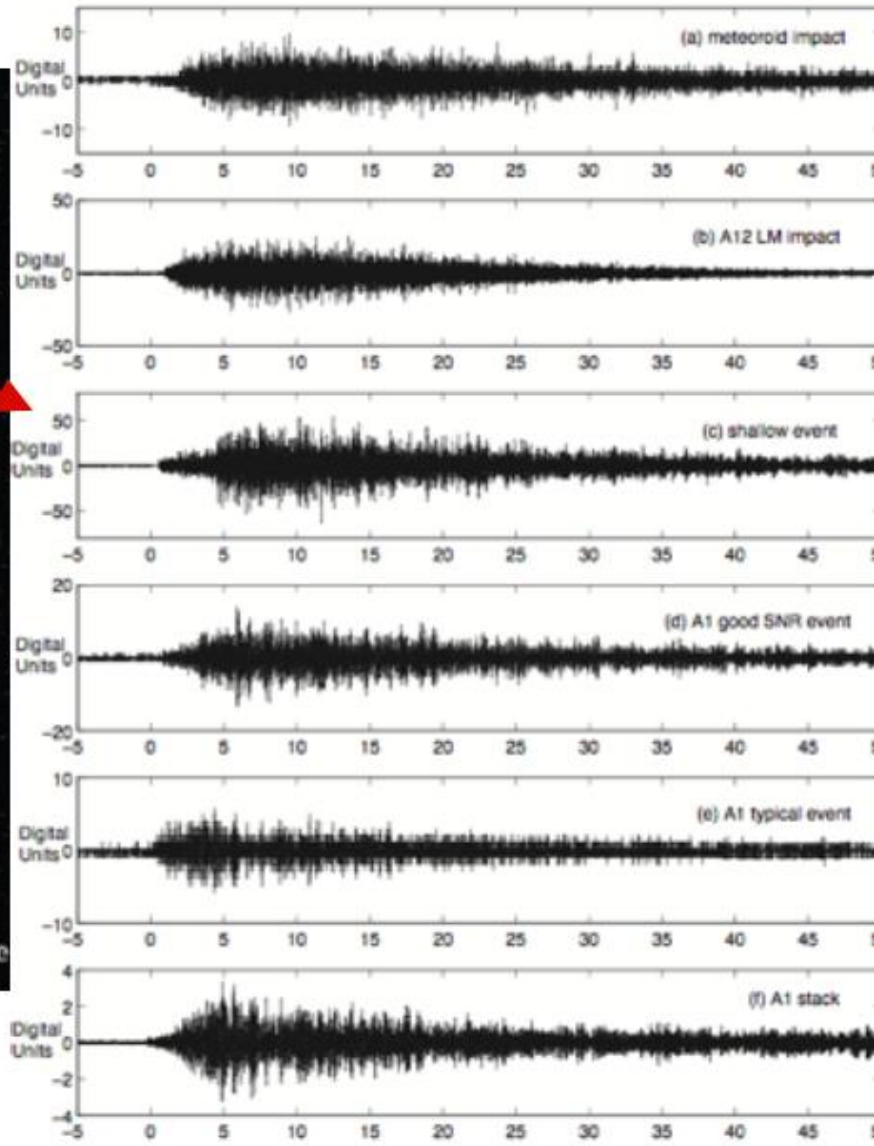
1. Shallow Moonquake
2. Deep Moonquake
3. Meteoroid Impact
4. Artificial Impact
5. Thermal



Lognonné, 2007, 10.03 Planetary Seismology, p. 73

Lunar quakes zoology

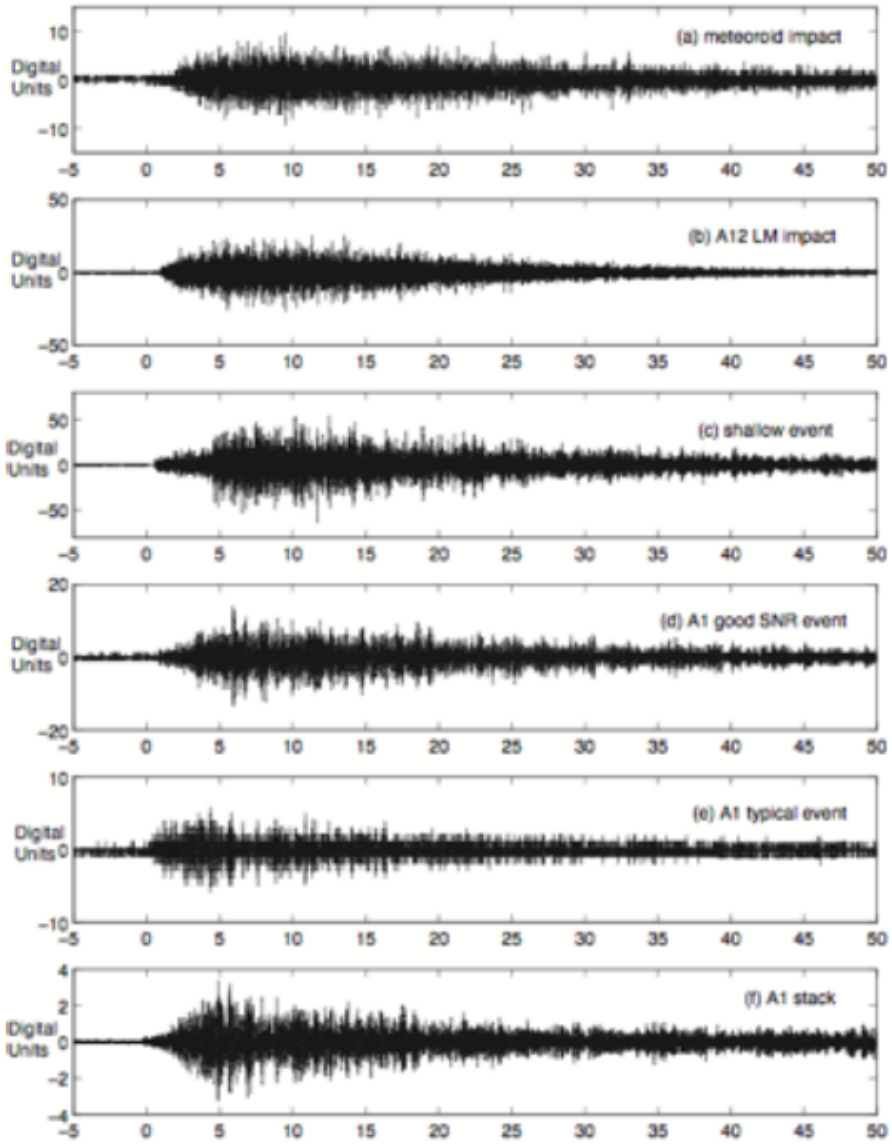


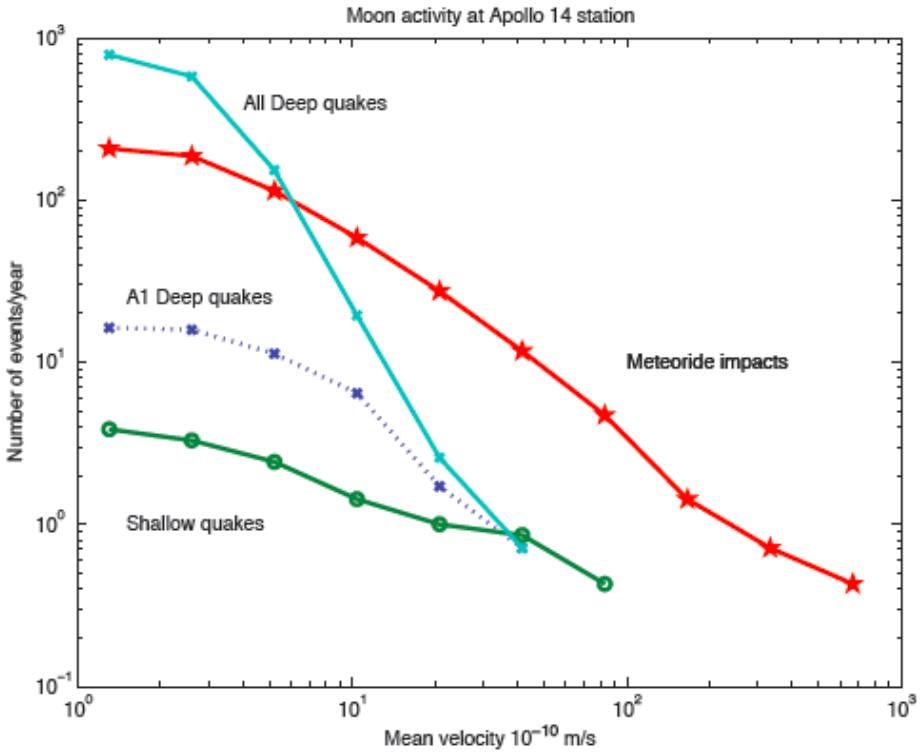


1 Digital Unit (DU) = 0.5 10^{-10} m at 2 sec

Lognonné & Johnson, 2007

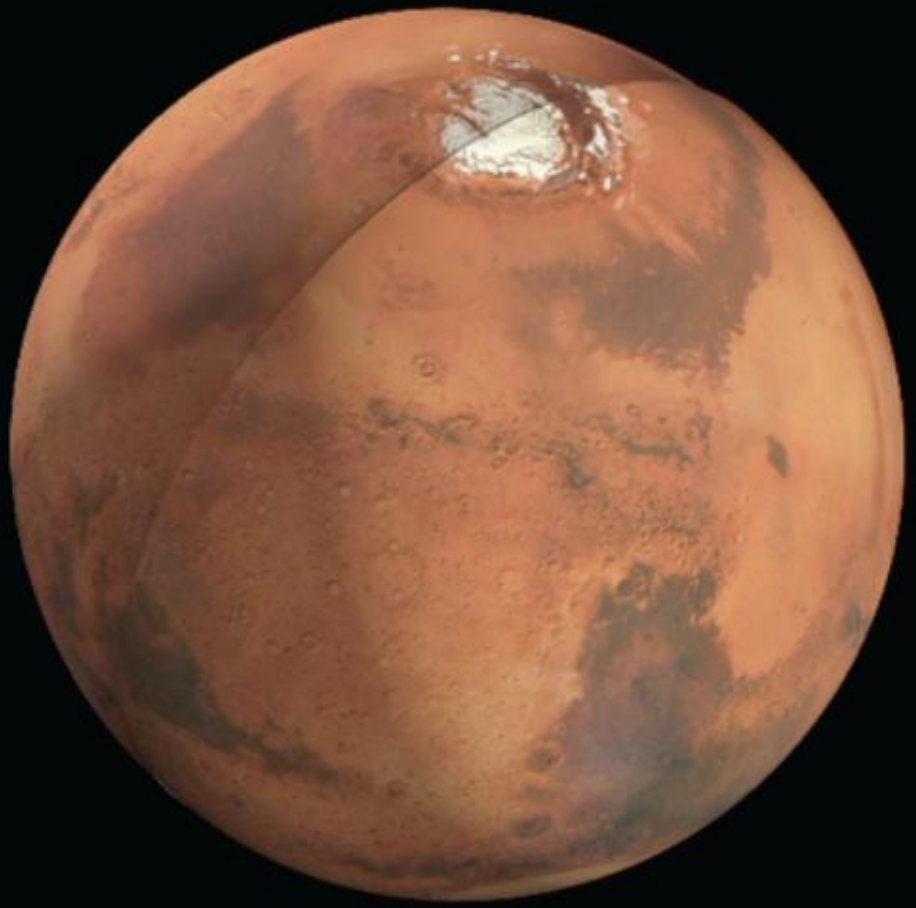
Lunar quakes zoology





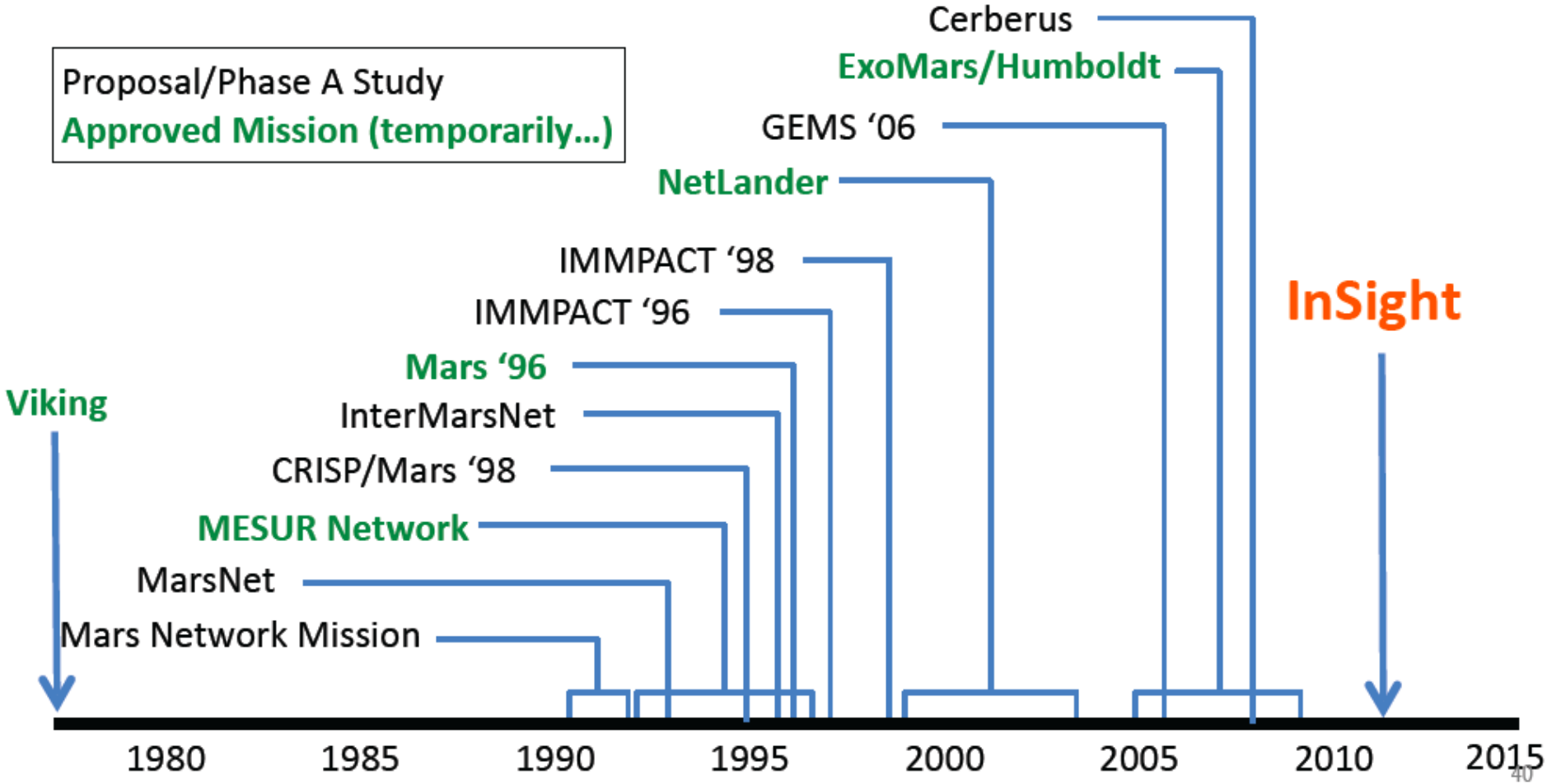
Lognonné & Johnson, 2007

MARS…



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!



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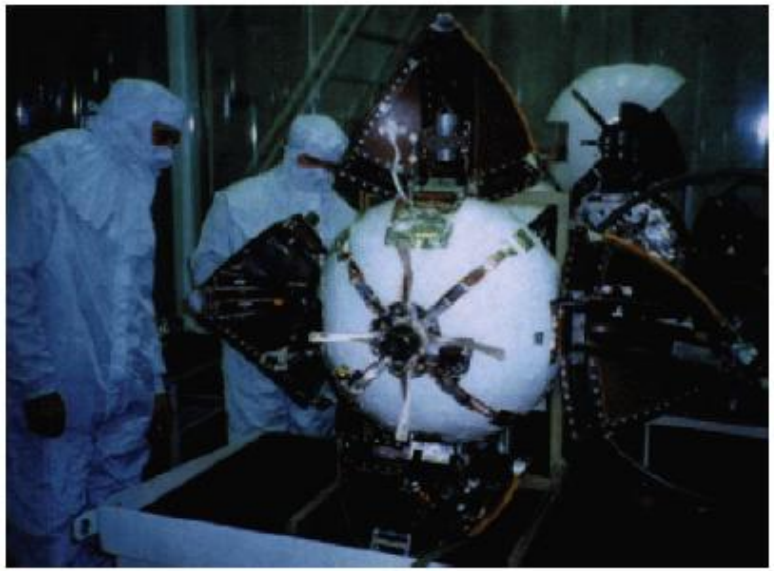
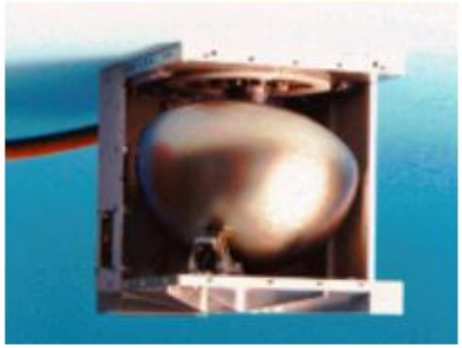


Launched Mission

Seismometer

Viking
(no quakes)

Mars '96
(lost)

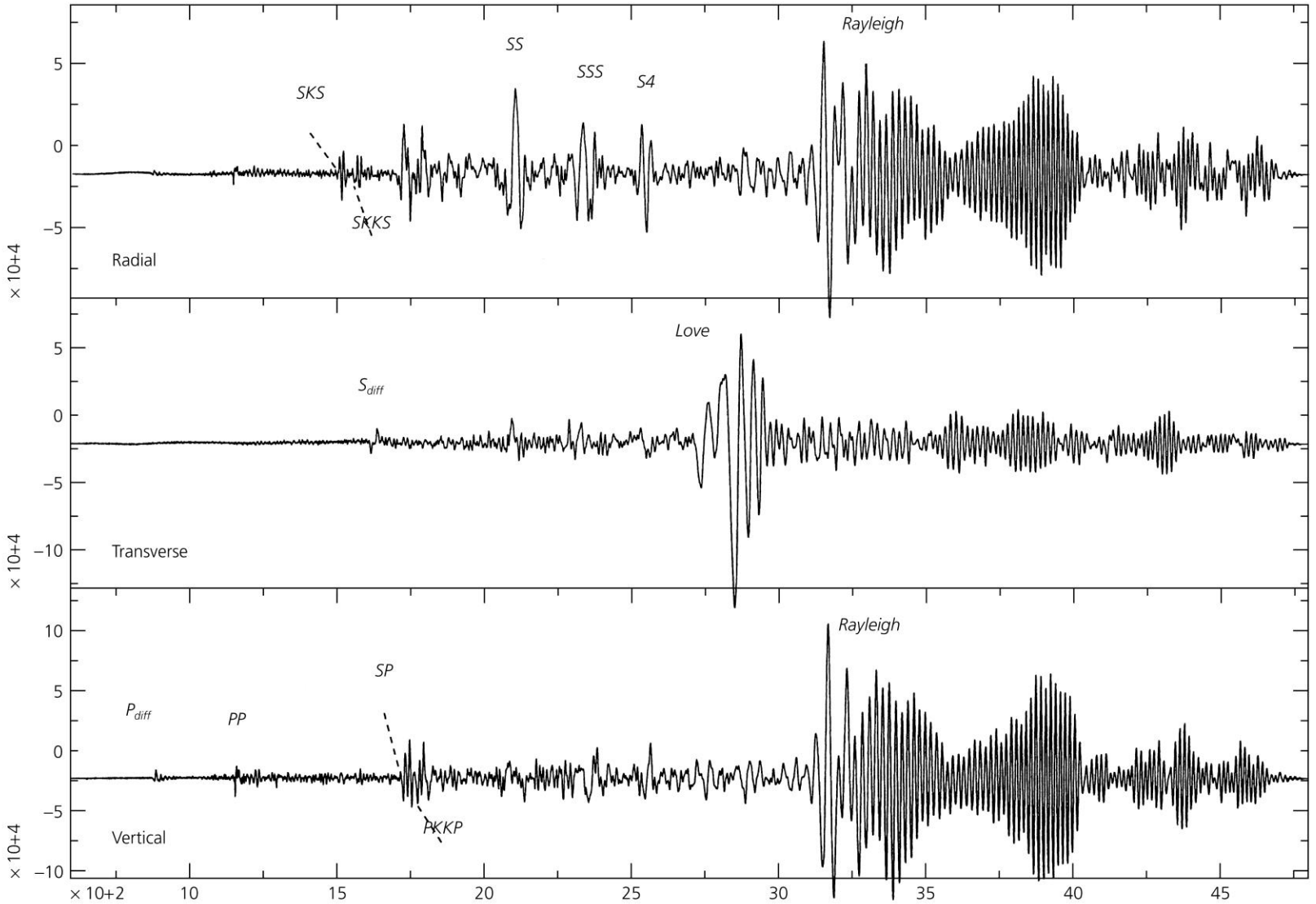


InSight

1980 1985 1990 1995 2000 2005 2010 2015

On Earth: Shallow earthquake

Figure 2.7-1: Seismograms recorded at a distance of 110°, showing surface waves.



From Stein and Wysession, 2003