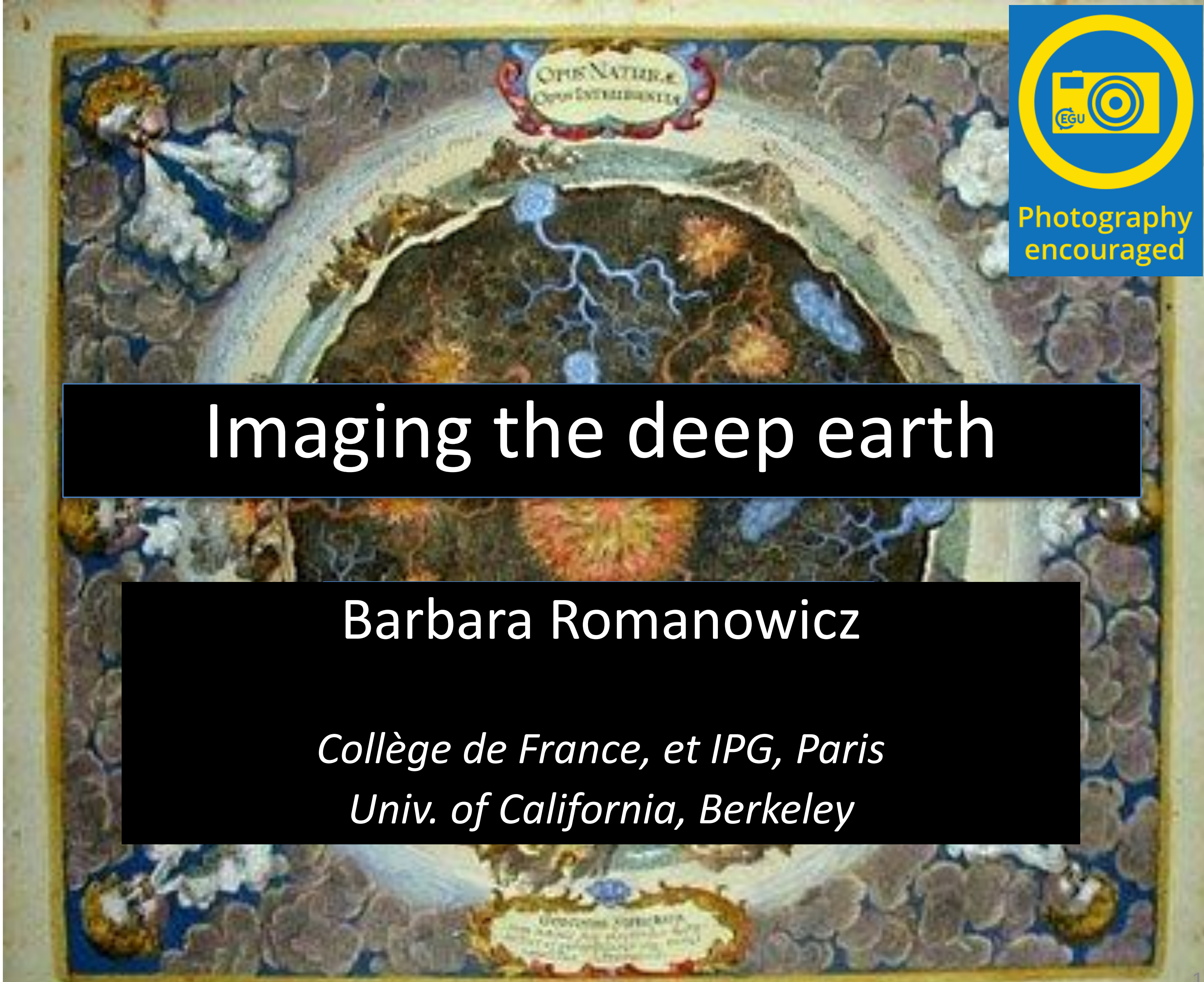


Imaging the deep earth

Barbara Romanowicz

Collège de France, et IPG, Paris

Univ. of California, Berkeley

Photography encouraged

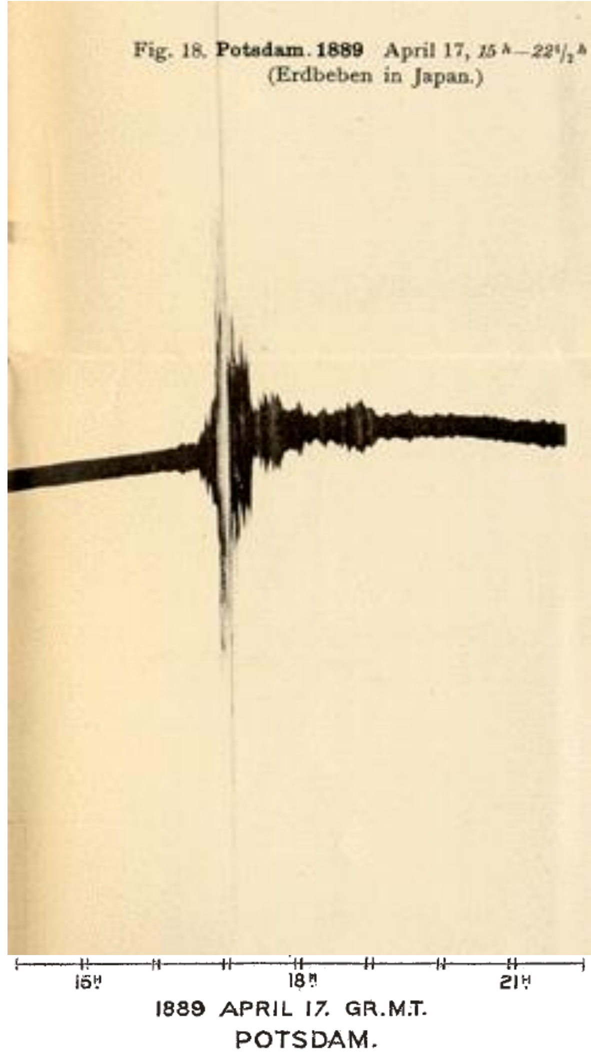
Athanasius Kircher – (1664) *Mundus subterraneus*

Kola 1970-1989 – profondeur: 12.3 km

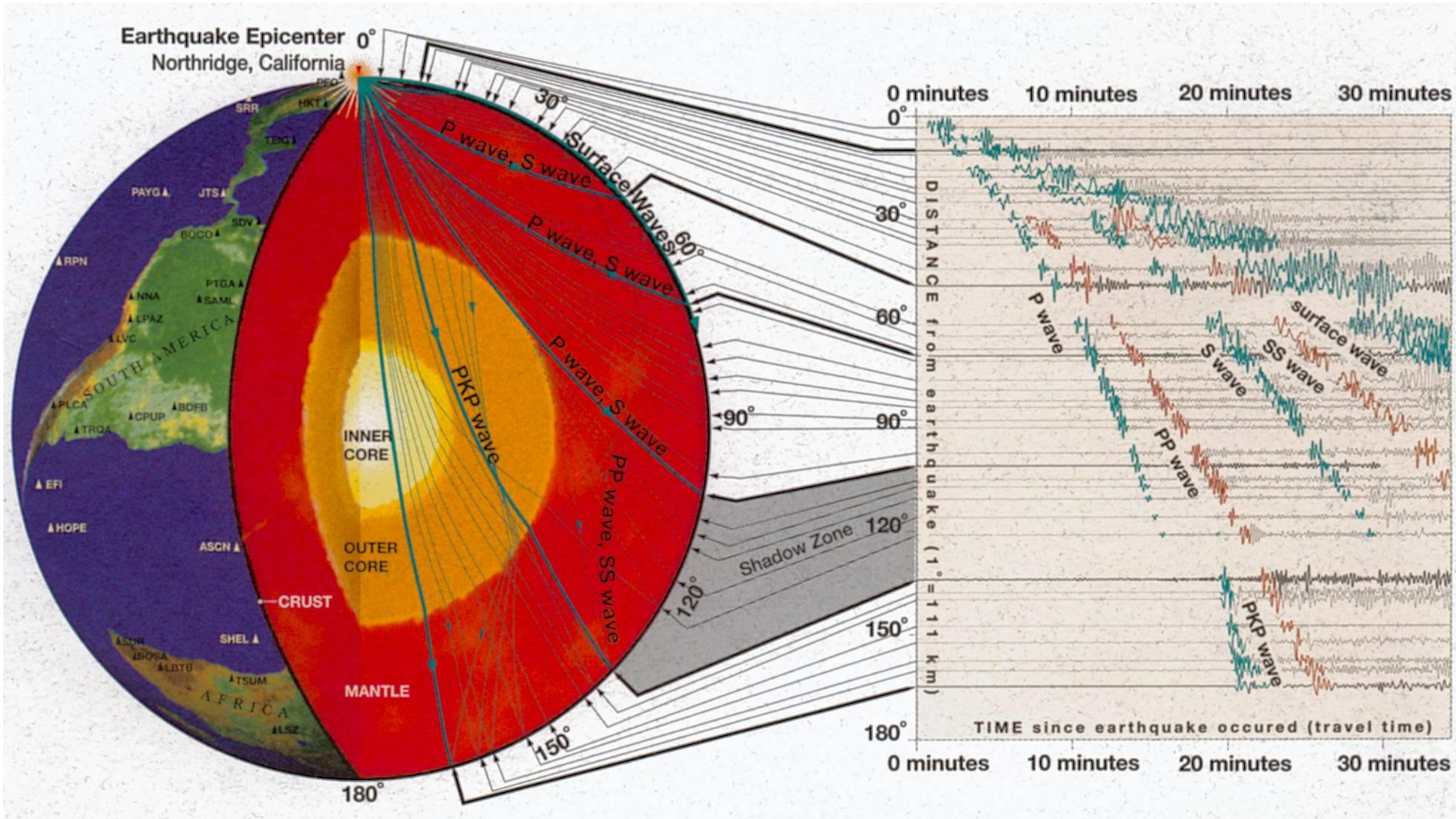
Photographié en 2007

Rayon de la terre: 6,371 km

VonReubeur Paschwitz
1889

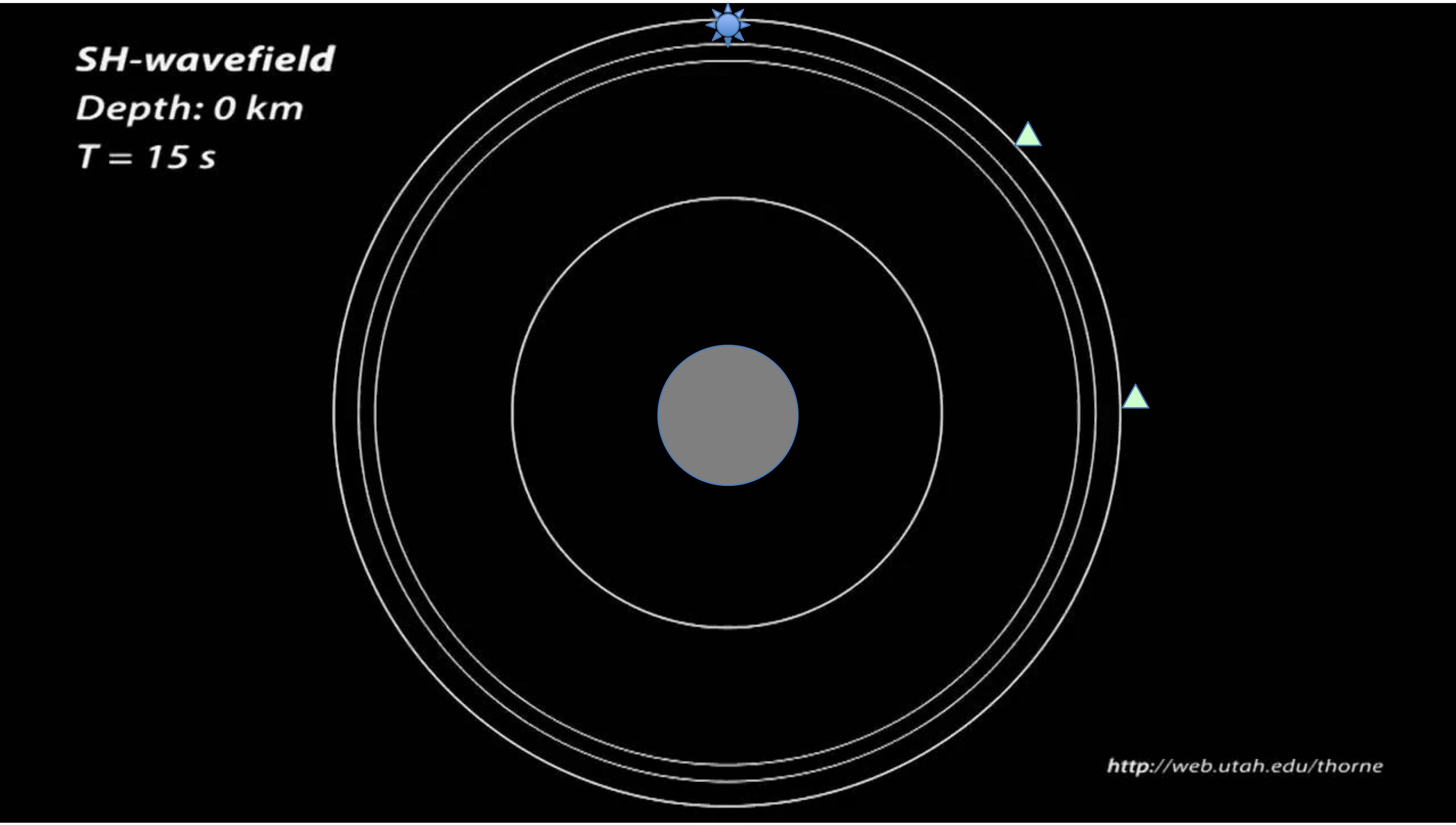


"Reading the report on this earthquake in NATURE (June 13, p. 162), I was struck by its coincidence in time with a very singular perturbation registered by two delicate horizontal pendulums at the Observatories of Potsdam and Wilhelmshaven."
VonRebeur Paschwitz, E., Nature, 40, July 25, 1889

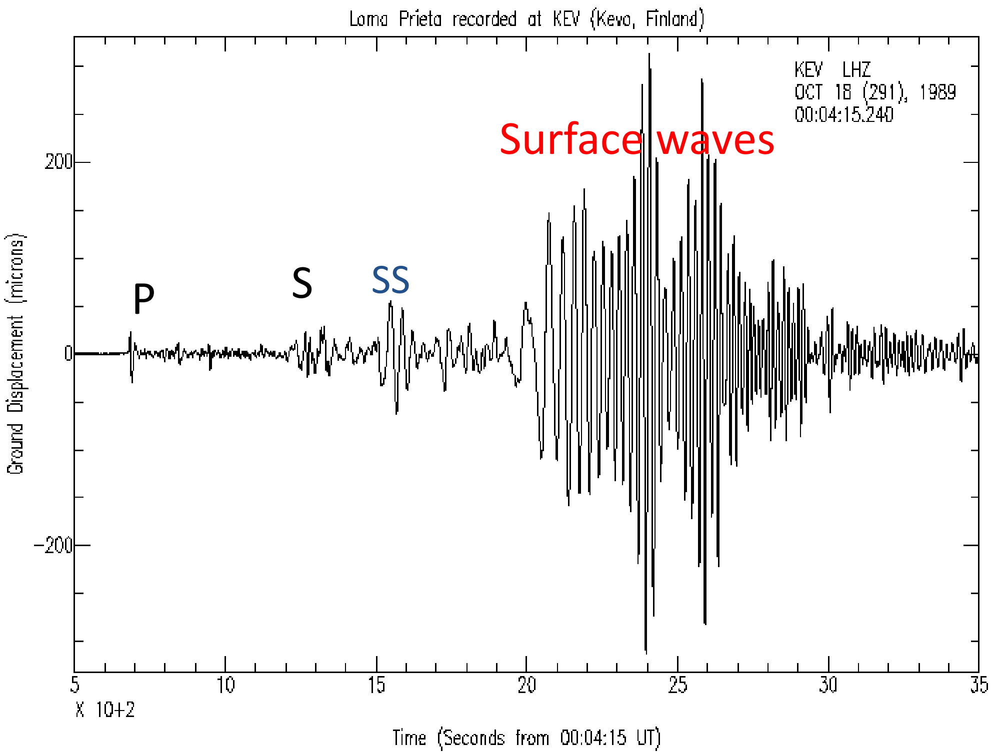


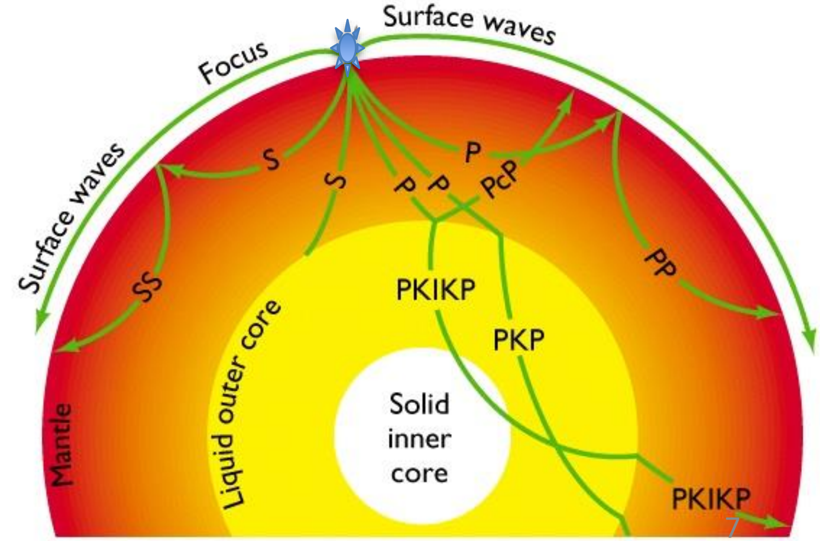
->Seismic waves propagate at different speeds through different materials –speed depends on temperature and composition

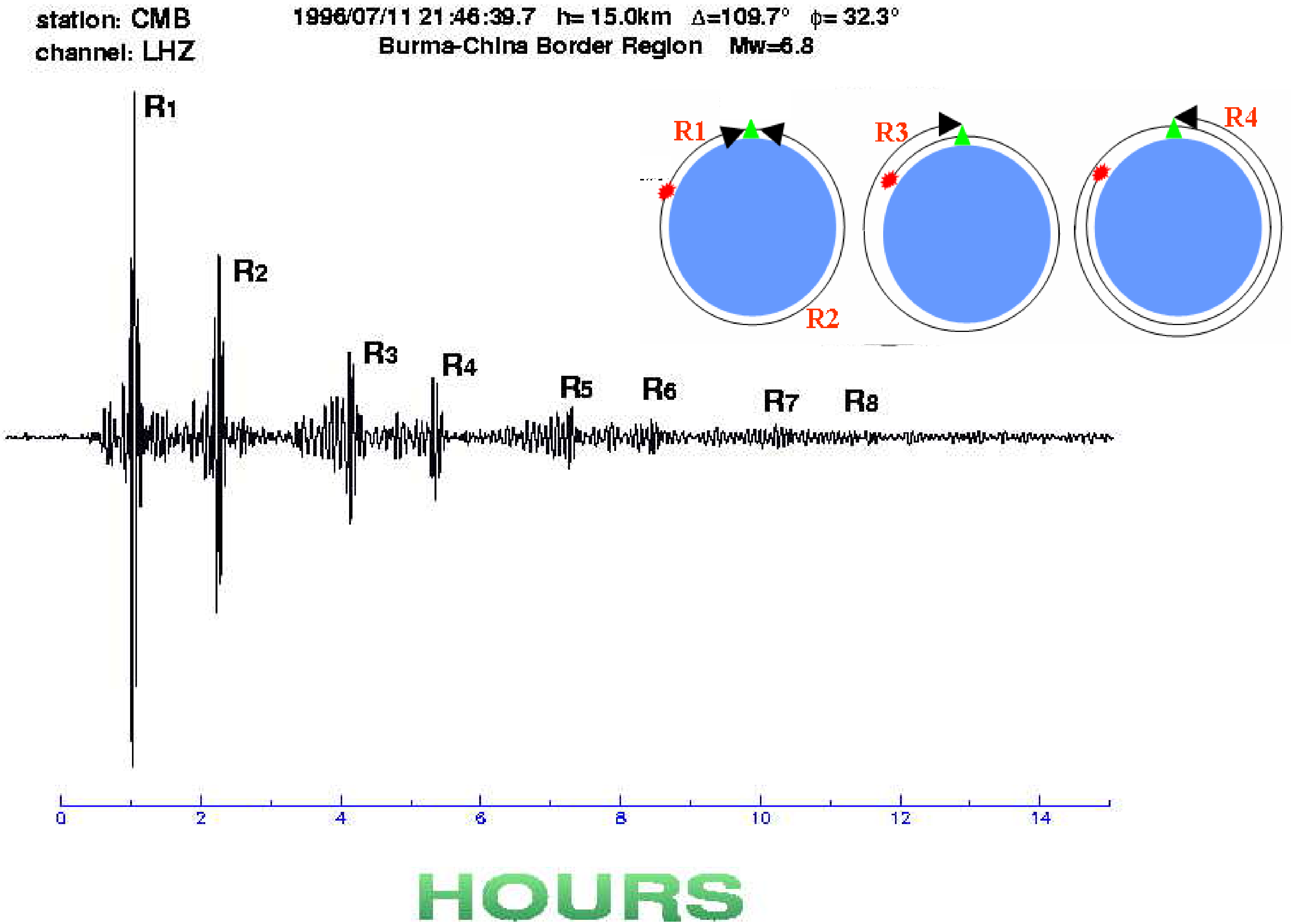
->They reflect and refract on discontinuities of structure such as the core-mantle boundary, the earth's surface, phase change related discontinuities in the upper mantle etc…


SH-wavefield
Depth: 0 km
T = 15 s
http://web.utah.edu/thorne

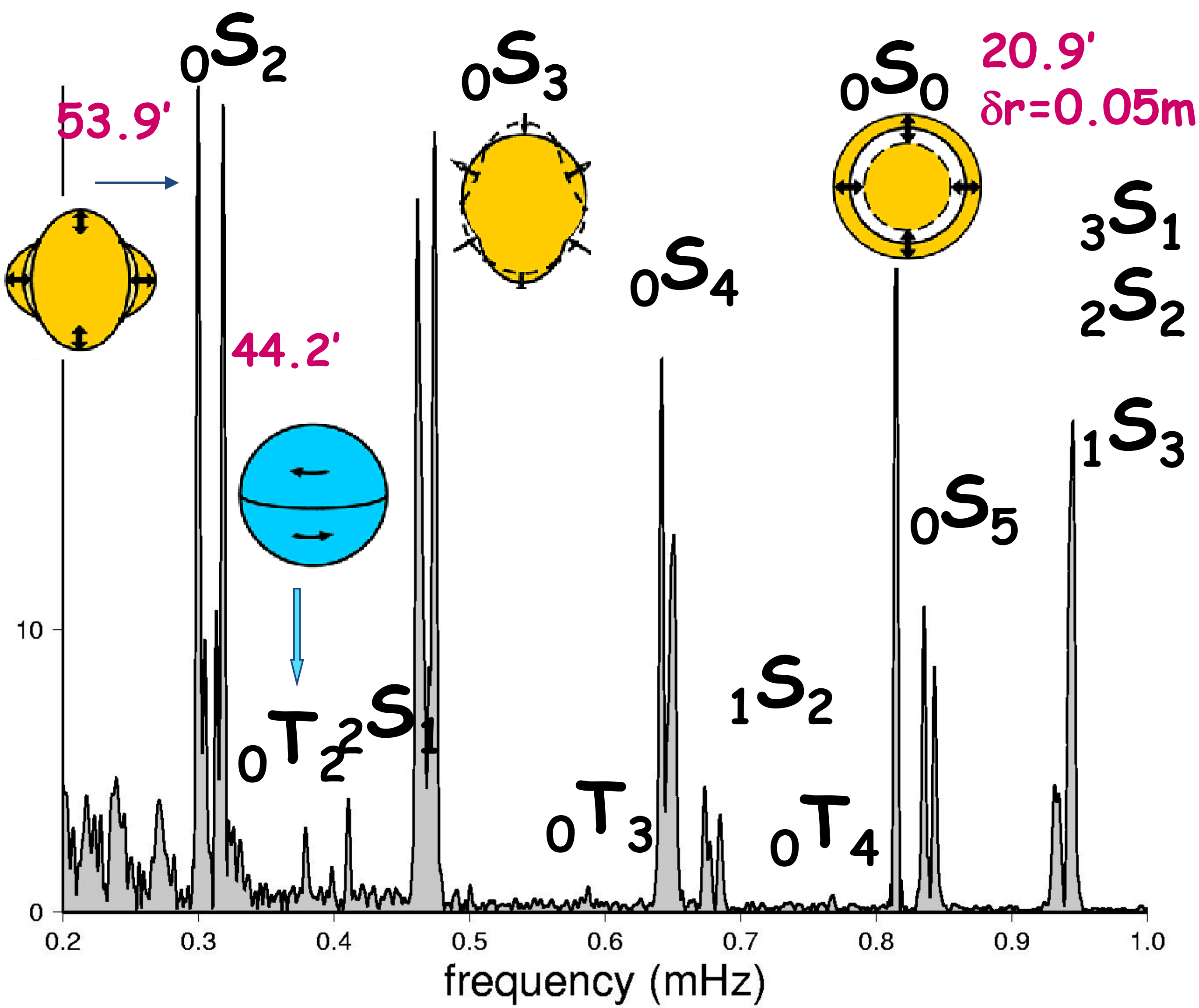
Séisme de Loma Prieta (CA) 1989 M 7 observé à KEV, Finlande



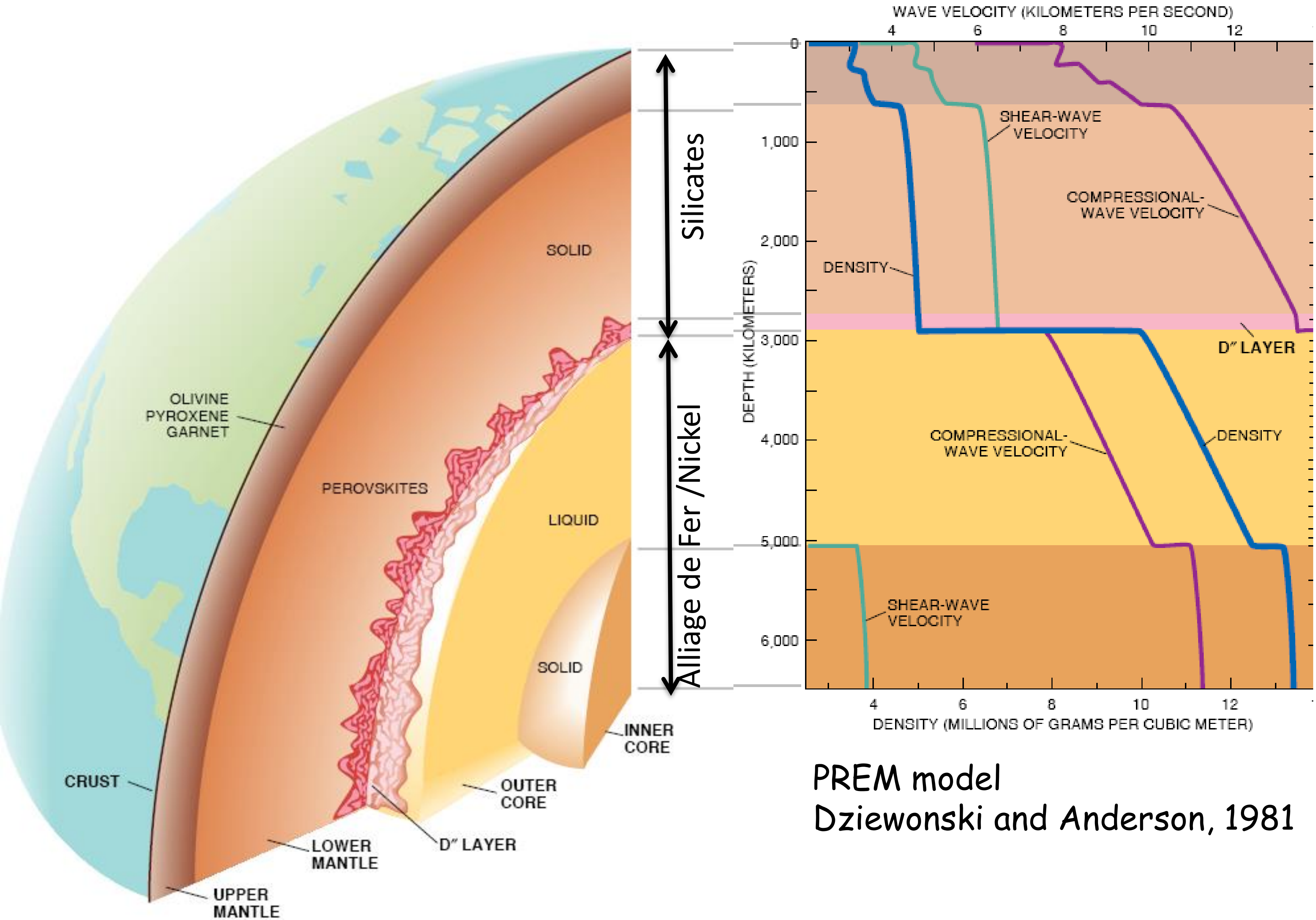



station: CMB
channel: LHZ
1996/07/11 21:46:39.7 h= 15.0km Δ=109.7° ϕ= 32.3°
Burma-China Border Region Mw=6.8
R1
R2
R3
R4
R5
R6
R7
R8
R1
R2
R3
R4
0
2
4
6
8
10
12
14
HOURS

Earth's free oscillations recorded after the giant Sumatra earthquake of December 26, 2004, M_w 9.2

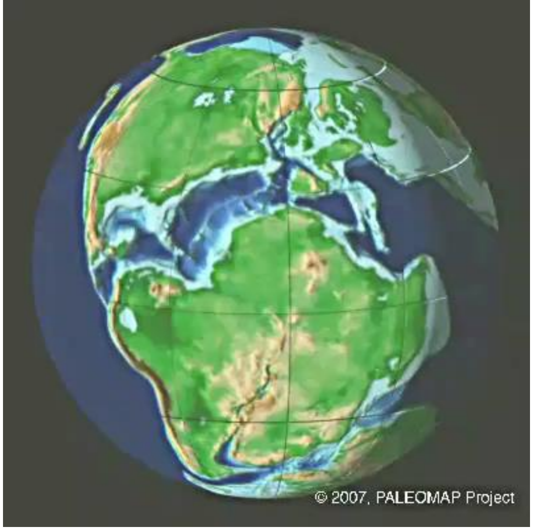


Courtesy of G. Roult

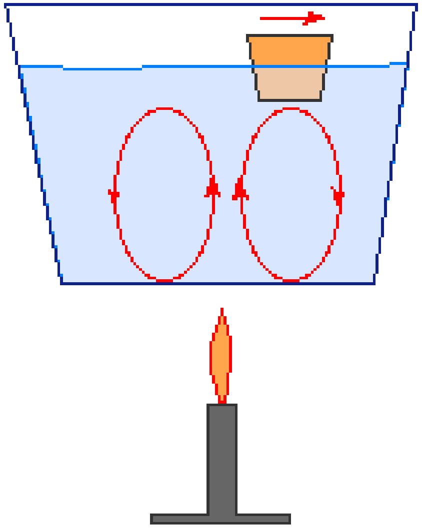


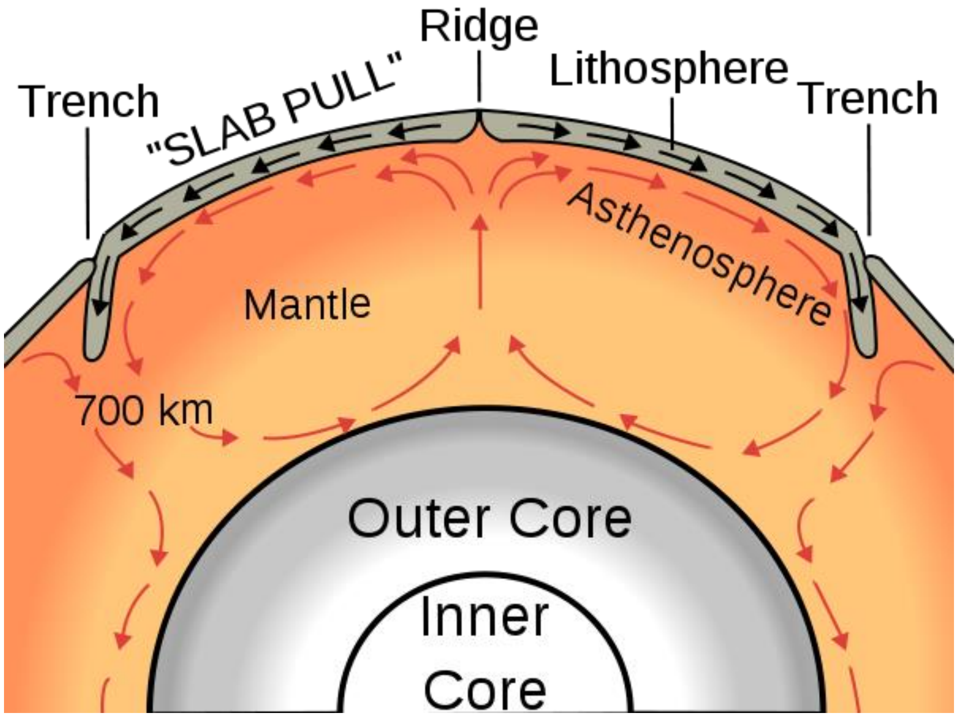
PREM model
Dziewonski and Anderson, 1981

Jeanloz and Lay, Sci. Amer., 1993



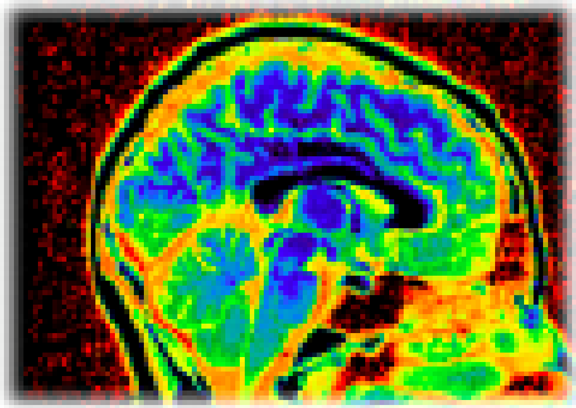
2015: 100th anniversary of the theory of continental drift,
~2018: 50 th anniversary of acceptance of Plate Tectonics Theory



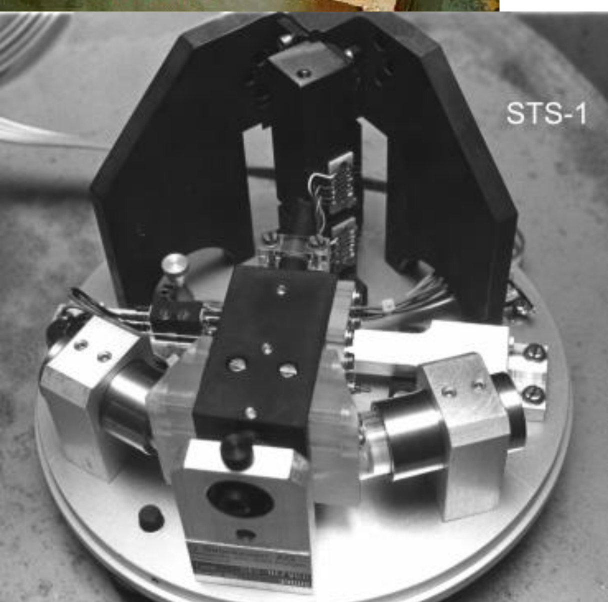


Seismic tomography
e.g. Medical imagery

-> Non invasive investigation
-> Using sources of waves



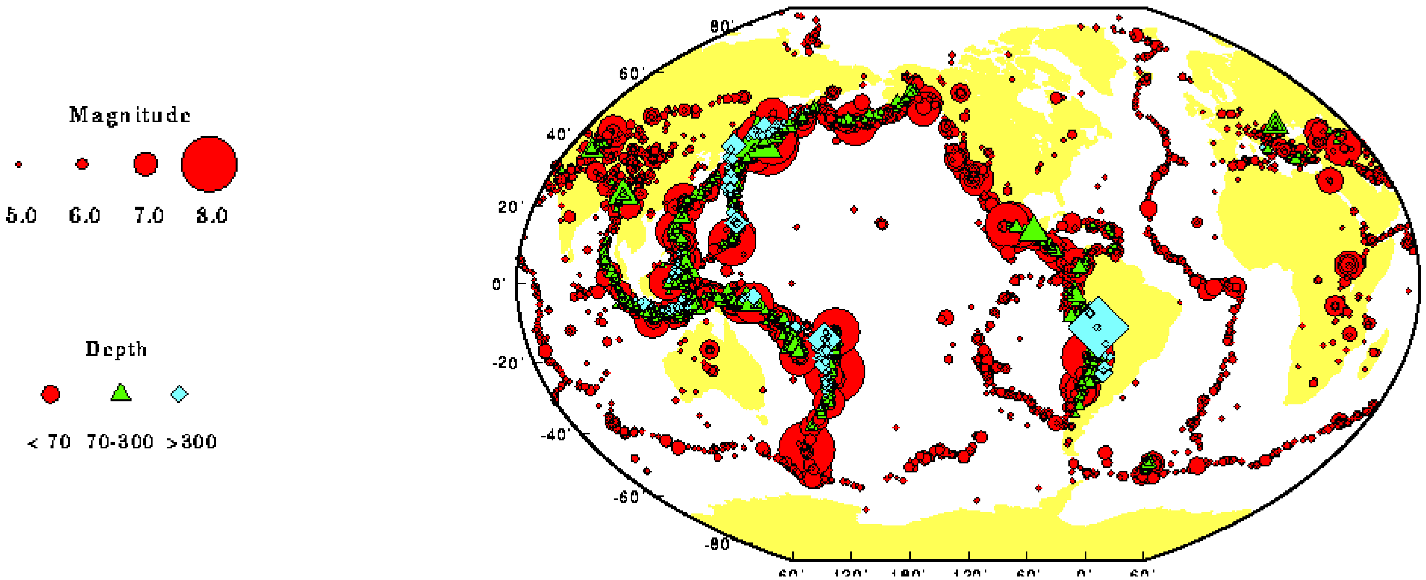
Very broad band seismometer installations (e.g. global GEOSCOPE network)



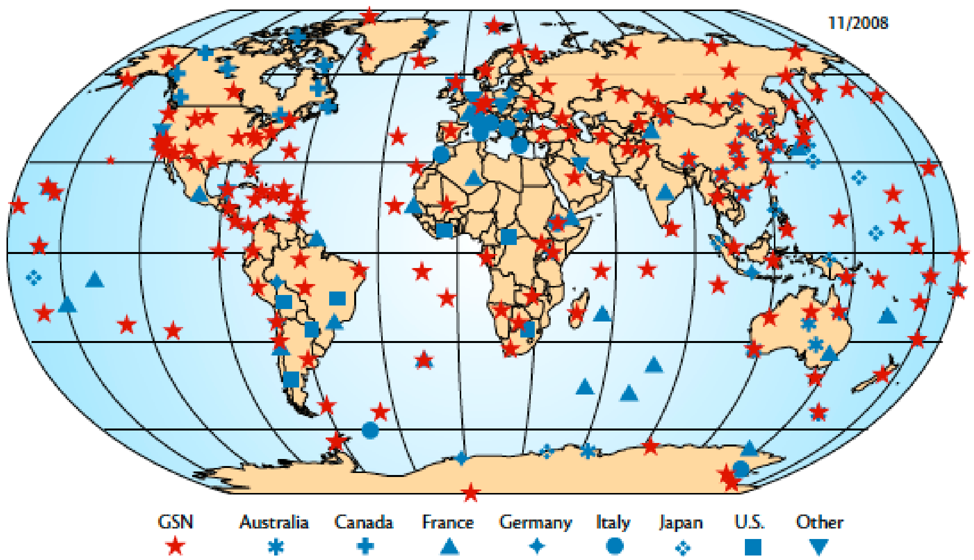
VBB seismometer+
Accelerometer
> >200 dB dynamic range

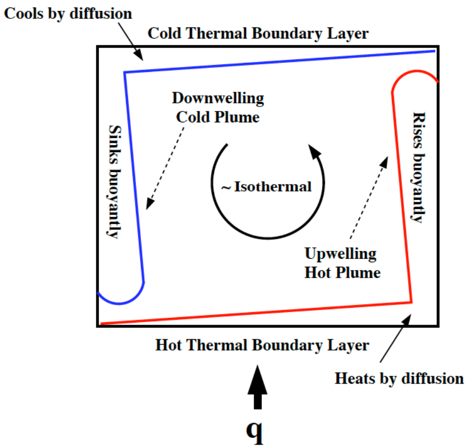
Datalogger + time
Power supply and conditioning,
Telemetry equipment,
OTHER

Earthquakes >Magnitude 5.0, 1985 - 1996 From NEIC

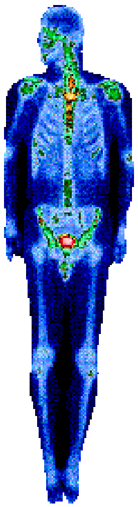


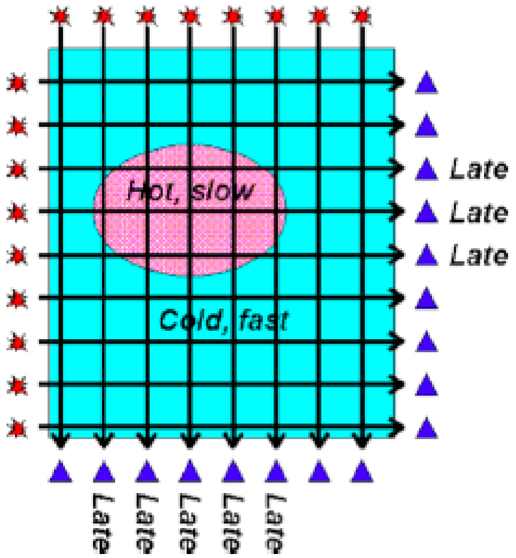
International Federation of Digital Seismograph Networks

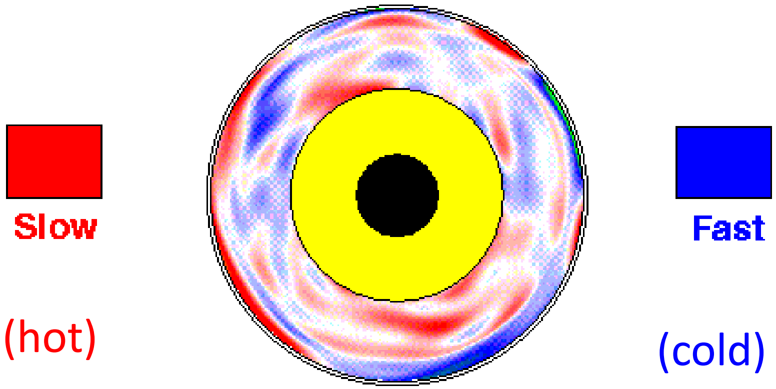


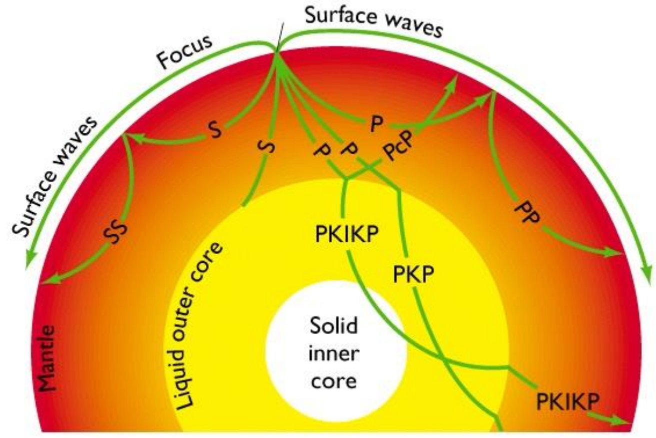


Medical Imagery





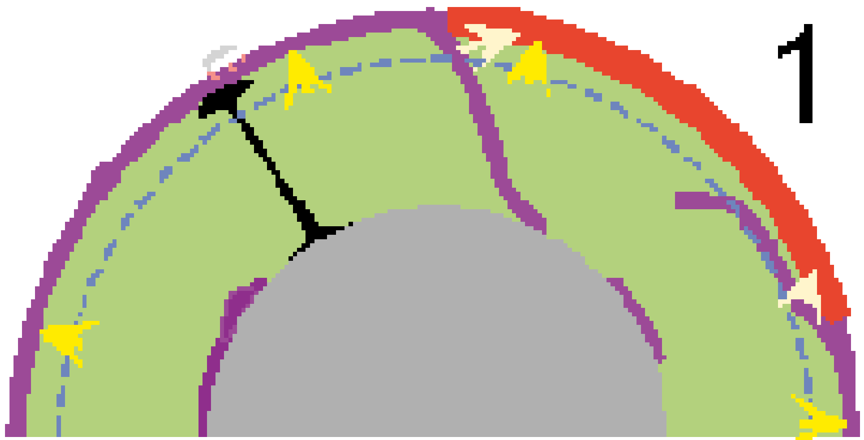




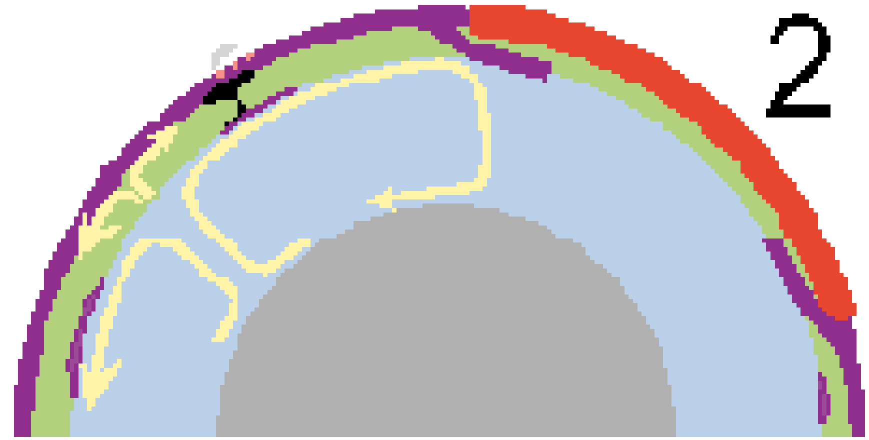
Seismic Tomography

Measure travel times of seismic waves through the Earth

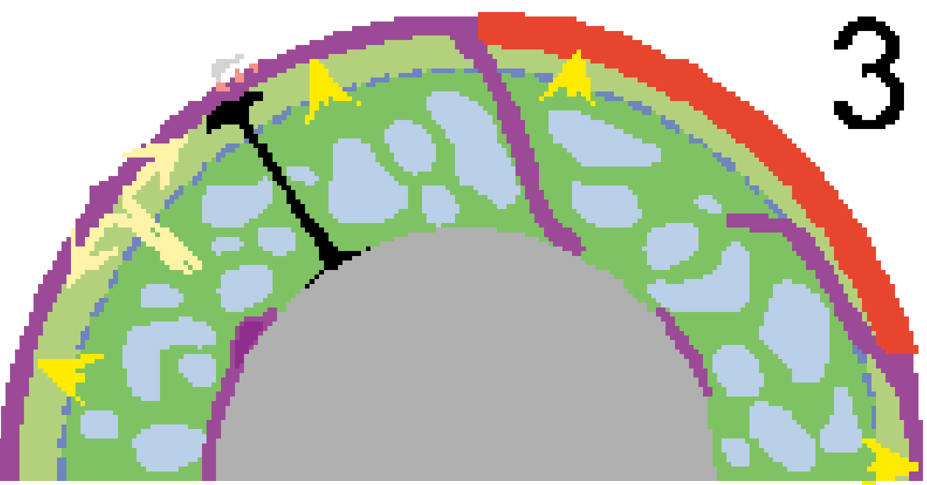
Whole mantle convection



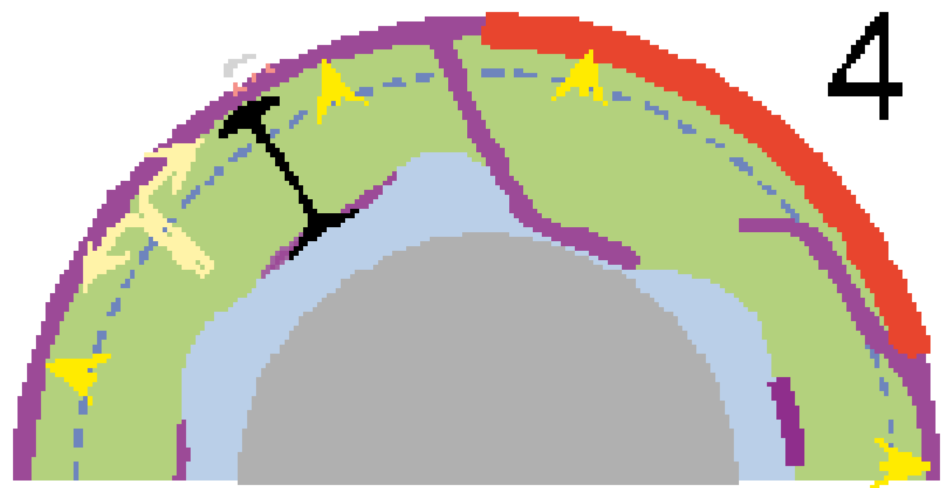
Two layer convection



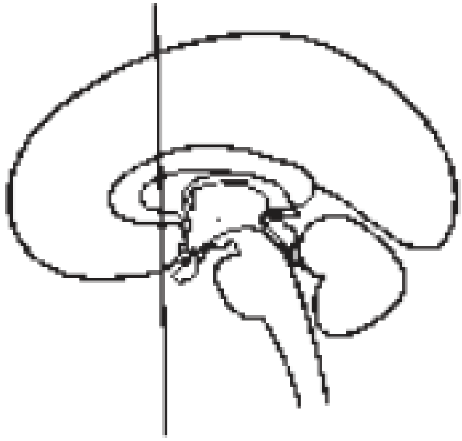
"Marble cake mixing"

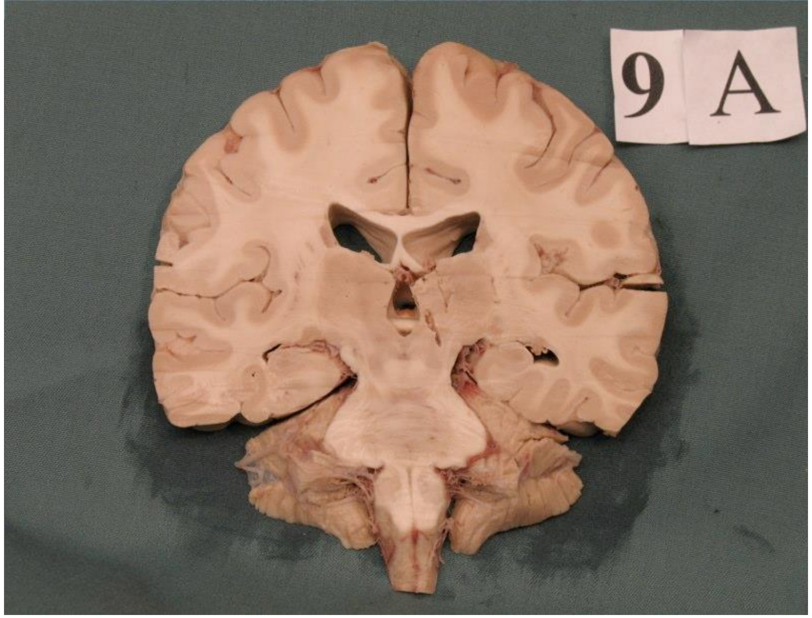


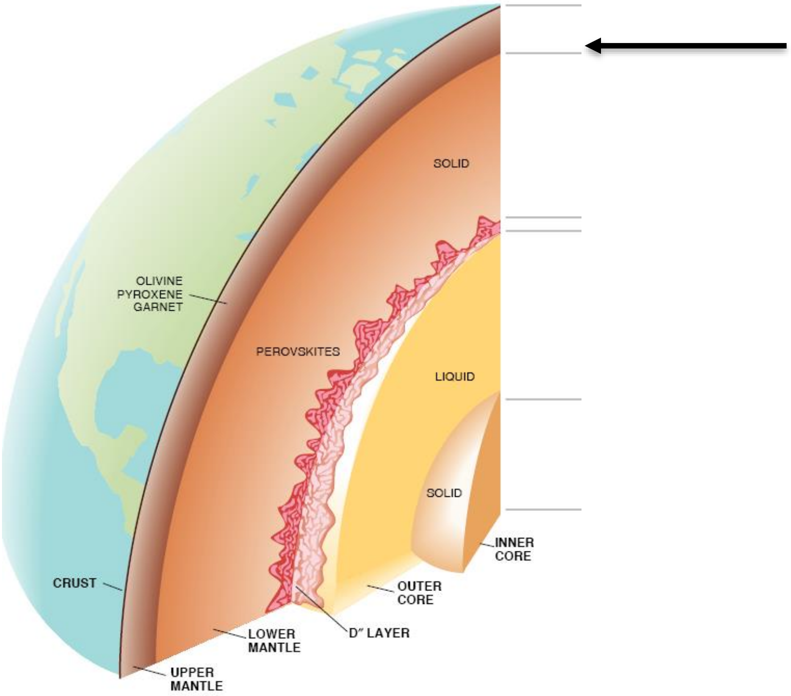
"Abyssal Layer"



After Albarède et Van der Hilst, 1999





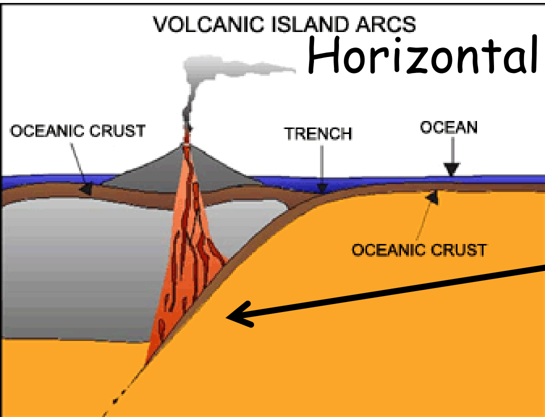


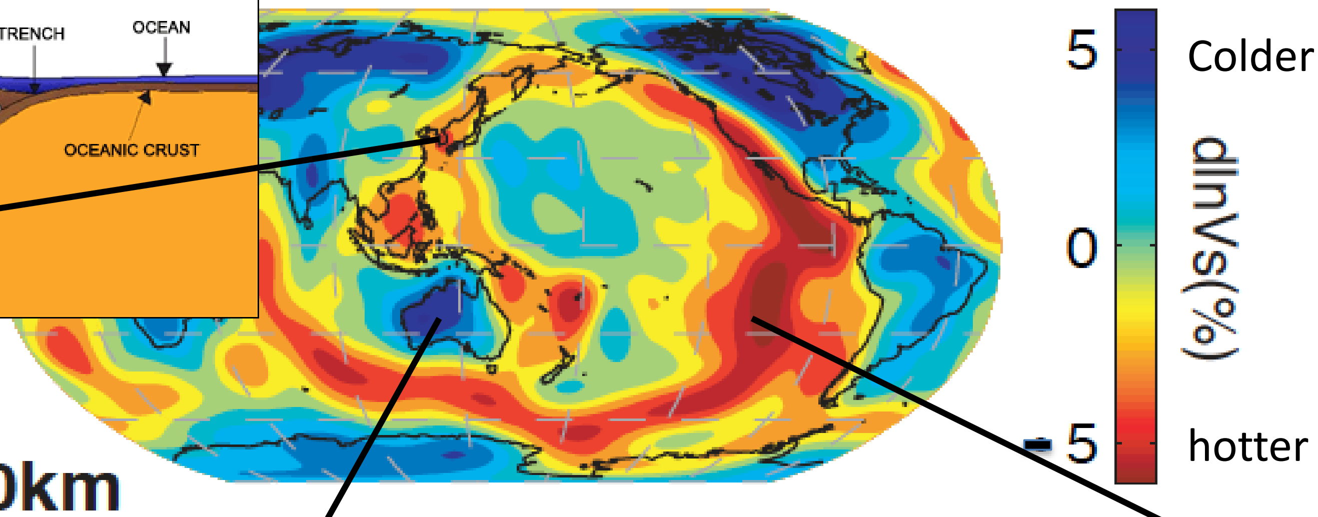
Global maps at specific depths in the mantle

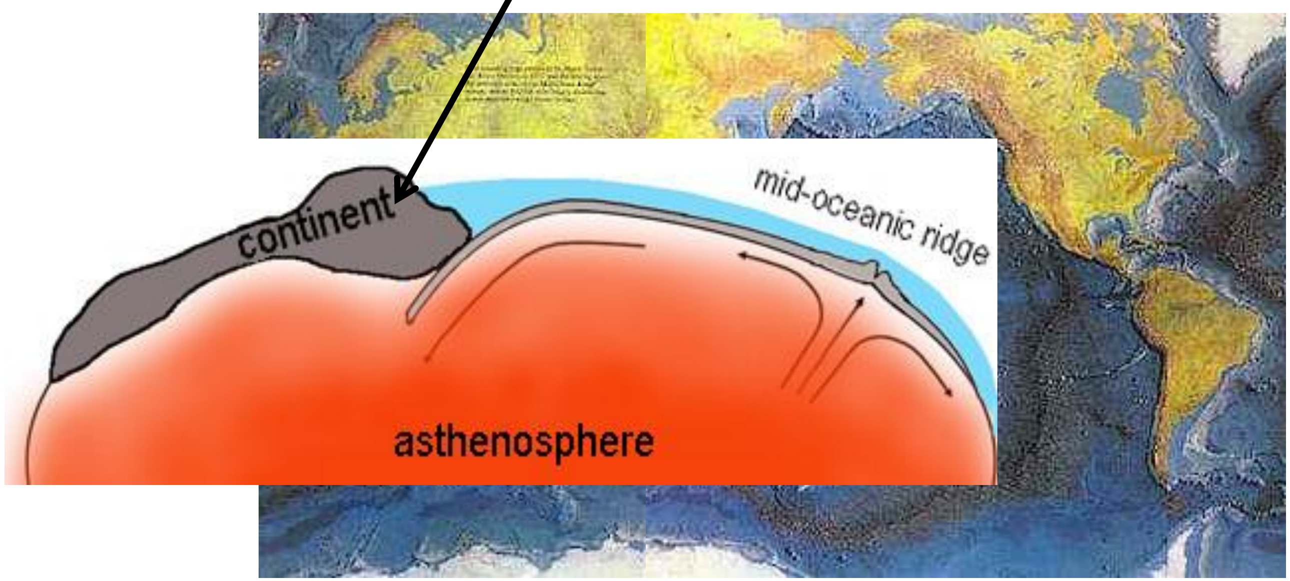
Shear wave velocity with respect to Average at that depth

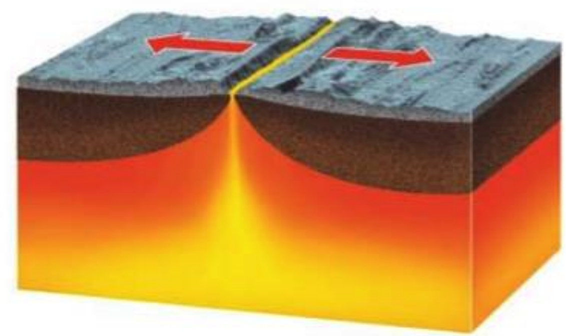
Can be interpreted in terms of temperature variations and composition

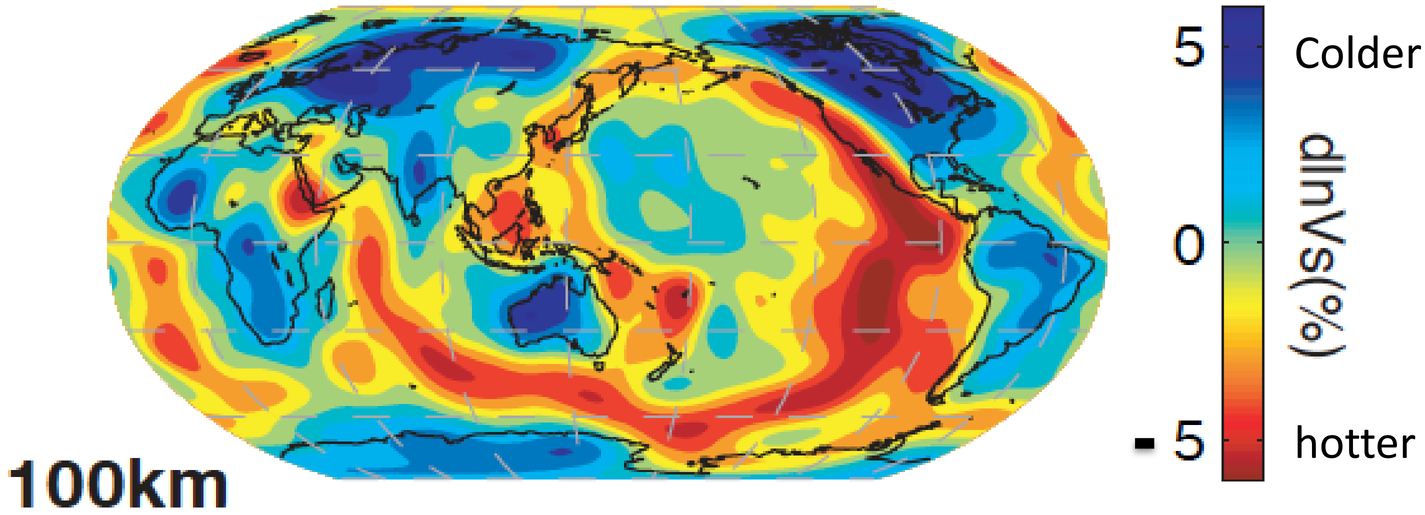
Horizontal slice at 100 km depth below the earth's surface

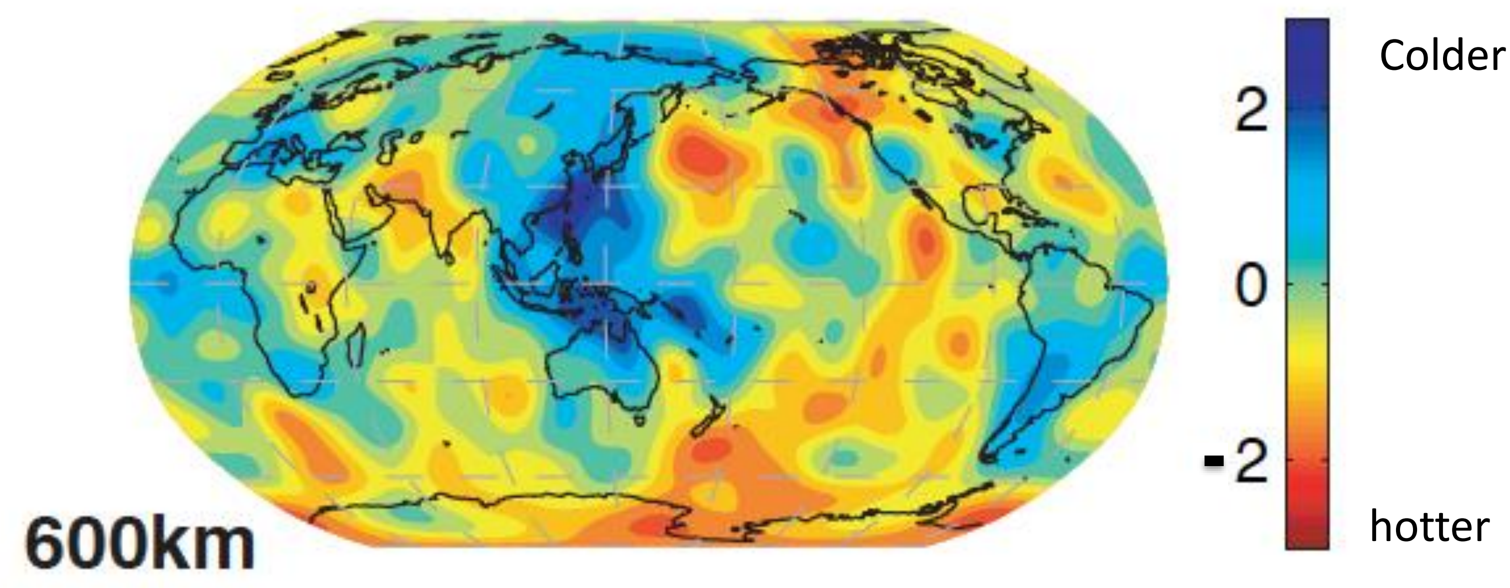




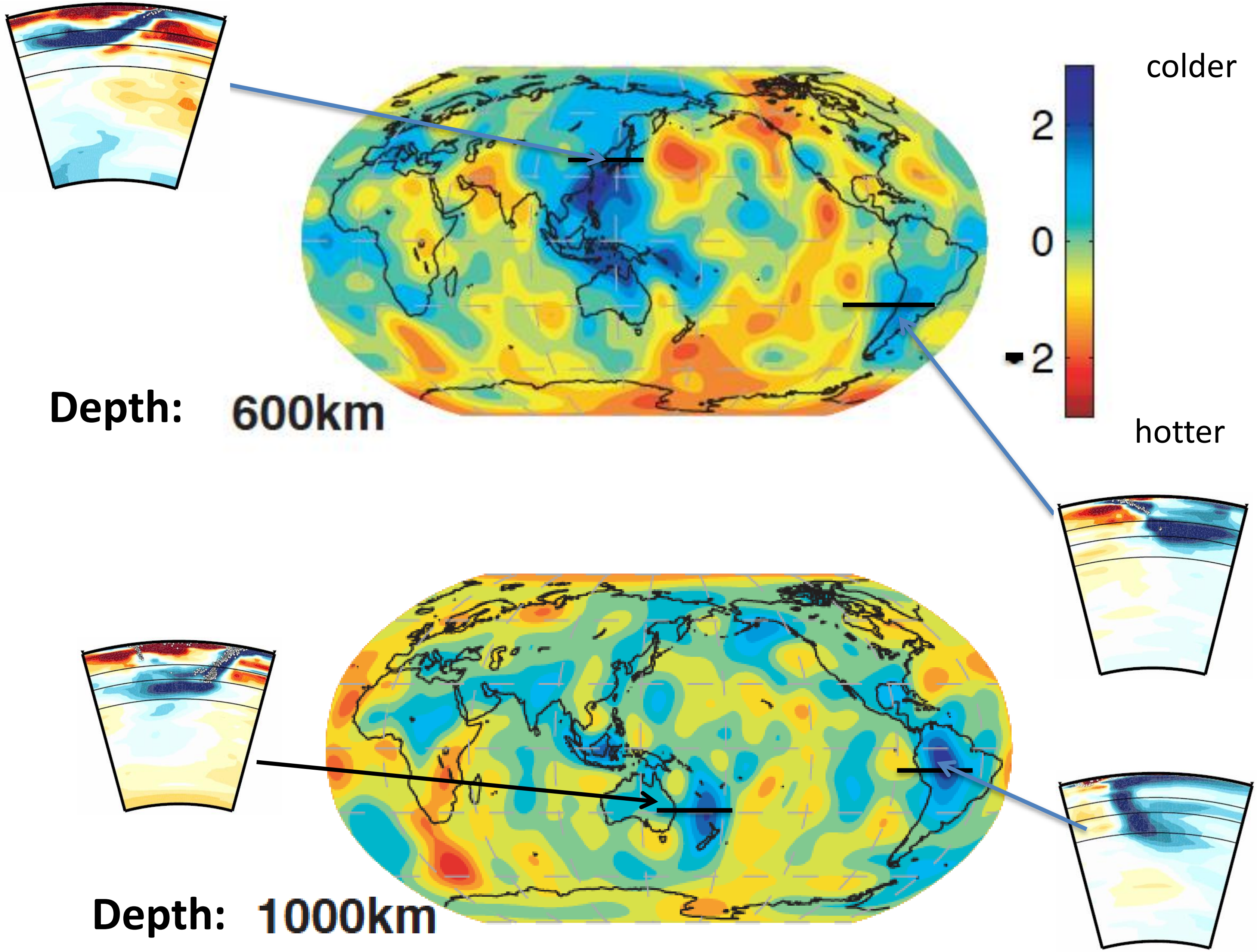




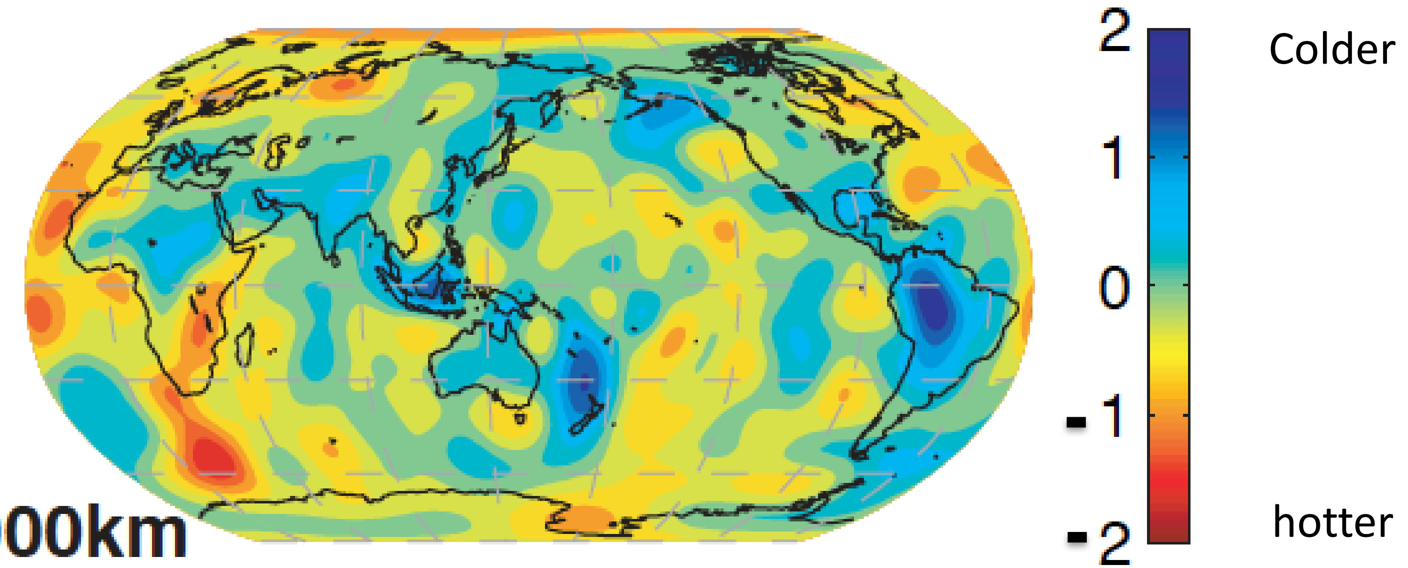




Horizontal slide at 600 km depth below the earth's

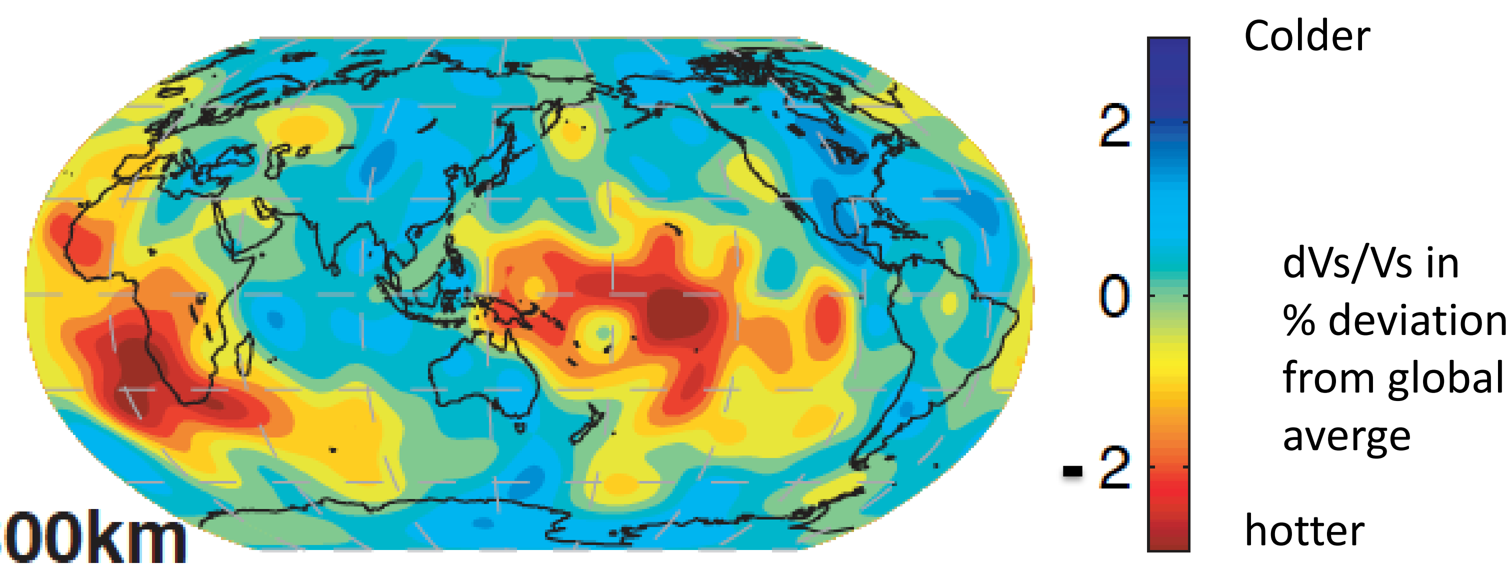


Shear velocity, in % deviation from the global average at each depth



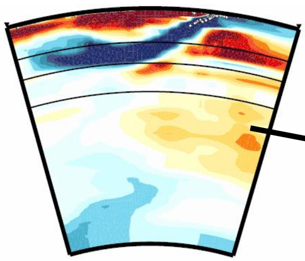
Depth: 1000km

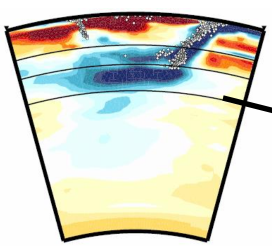
Large
Low
Shear
Velocity
Provinces

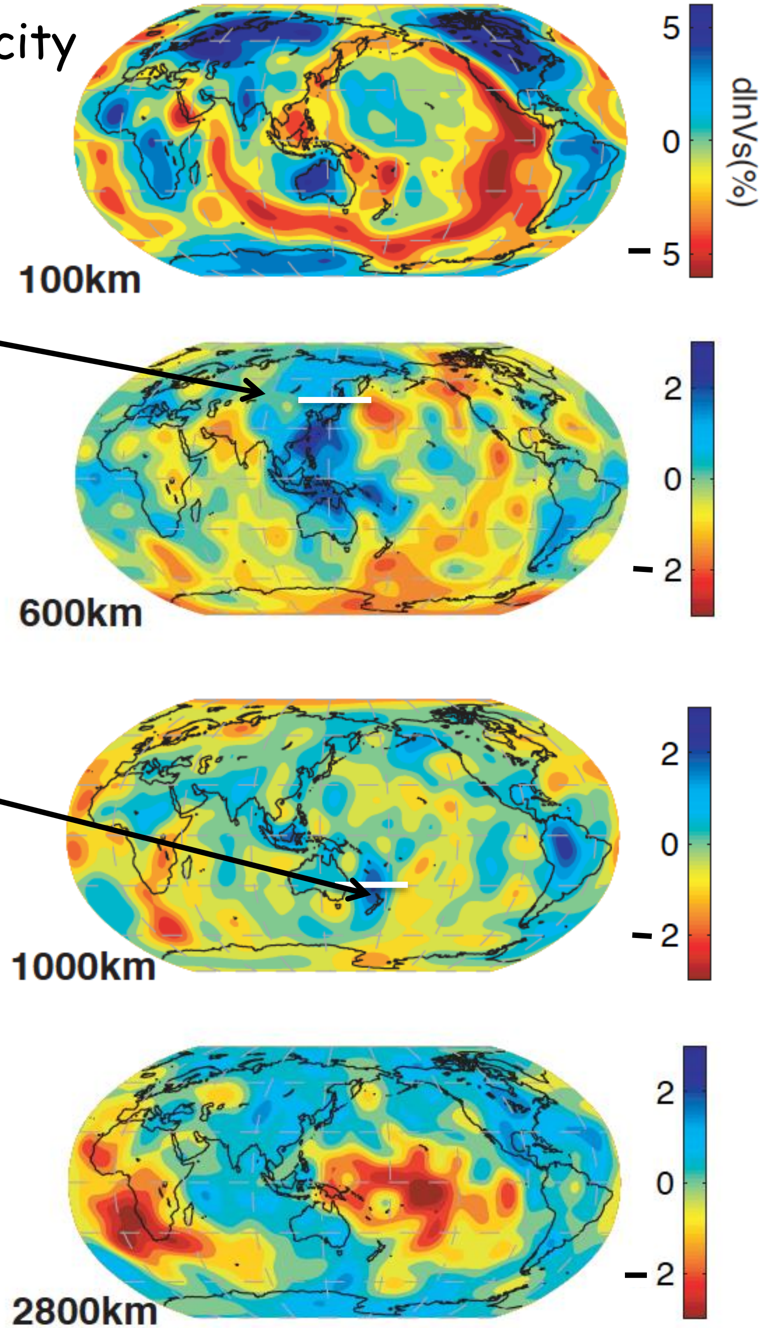


Depth: 2800km

Shear velocity maps

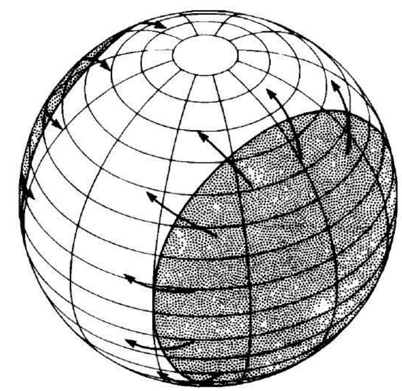


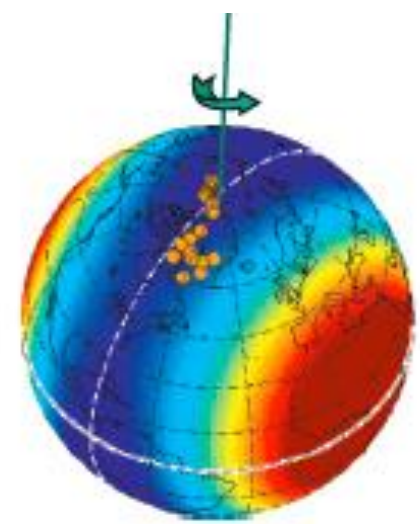




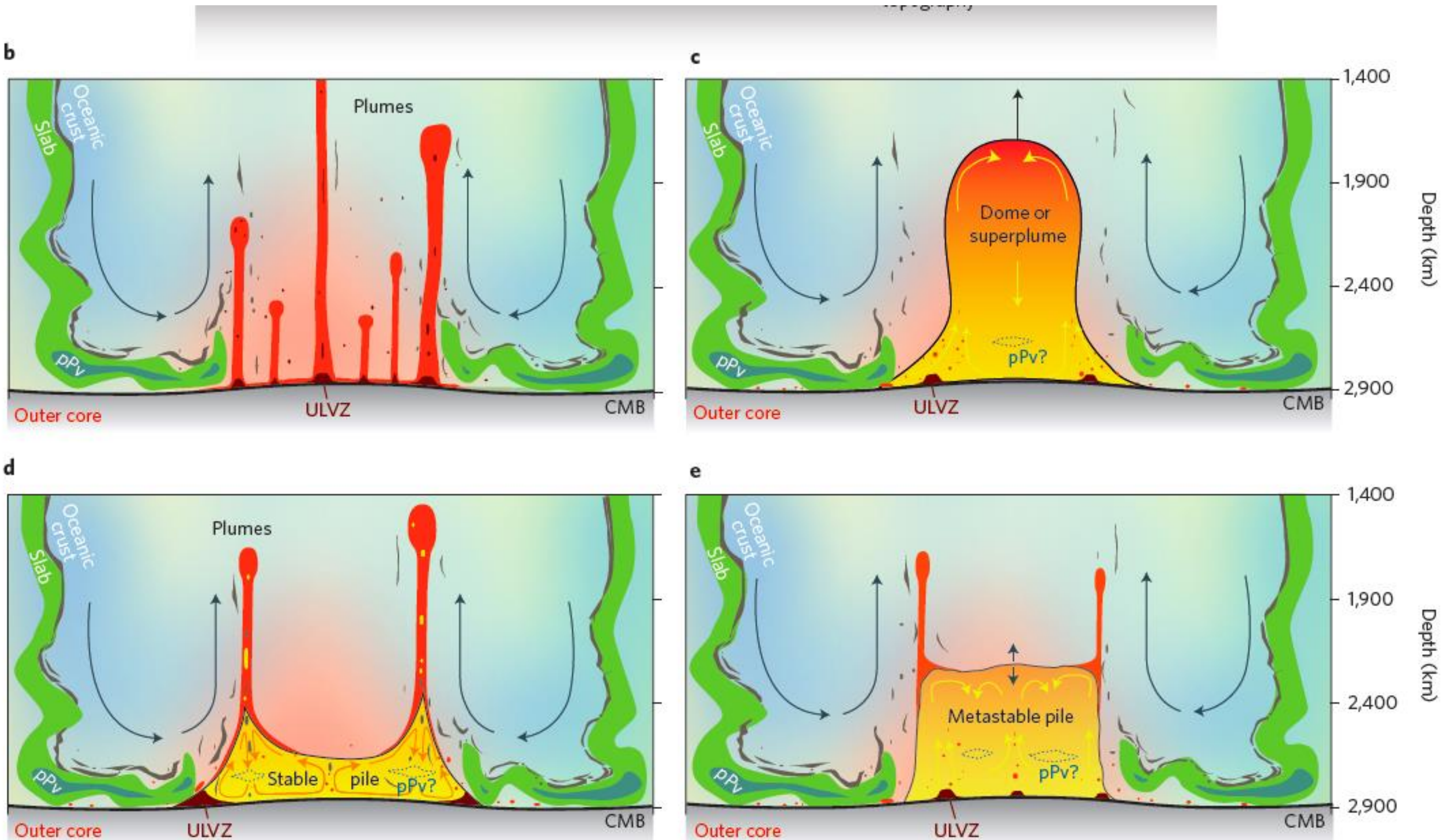
LLSVPs

Degree-2 convection proposed by Busse (1983)



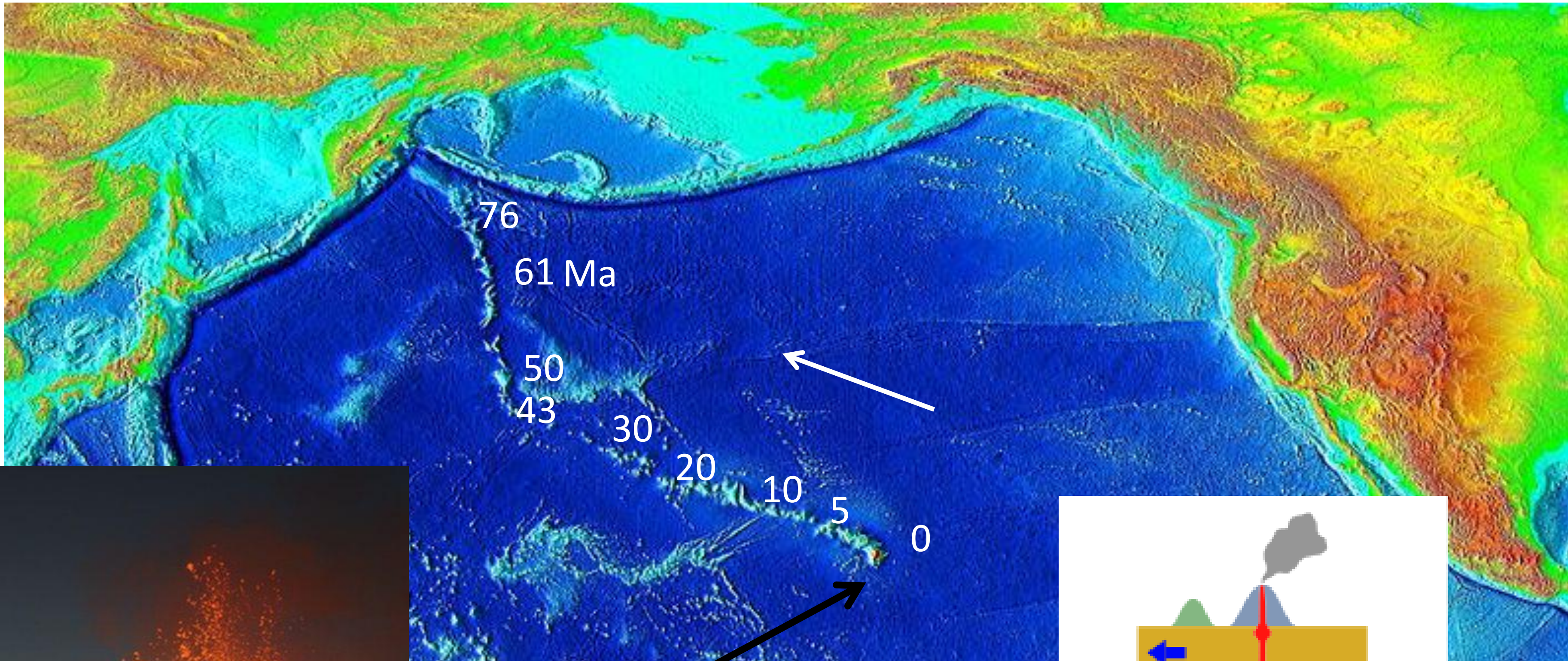


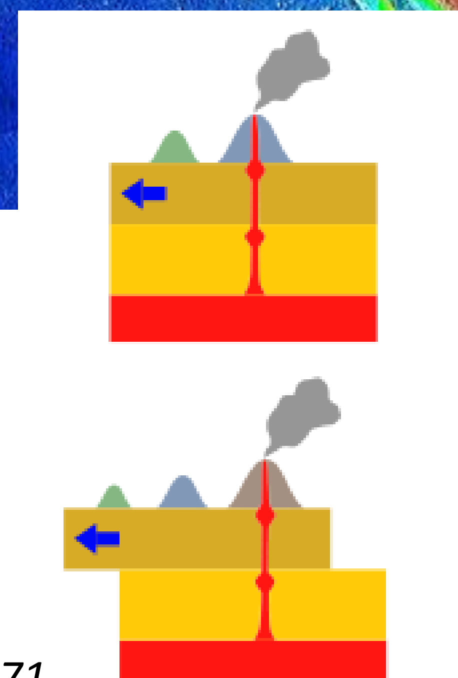
Paleo-pole locations (Besse and Courtillot, 2002)



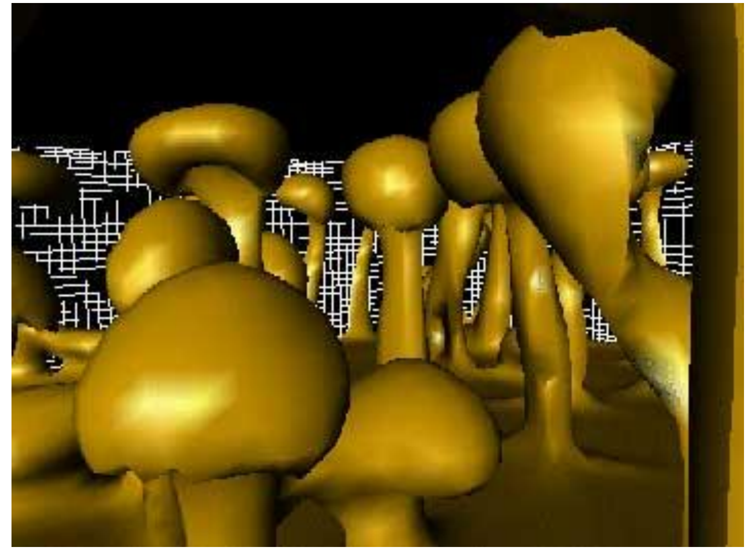
Garnero et al., 2016

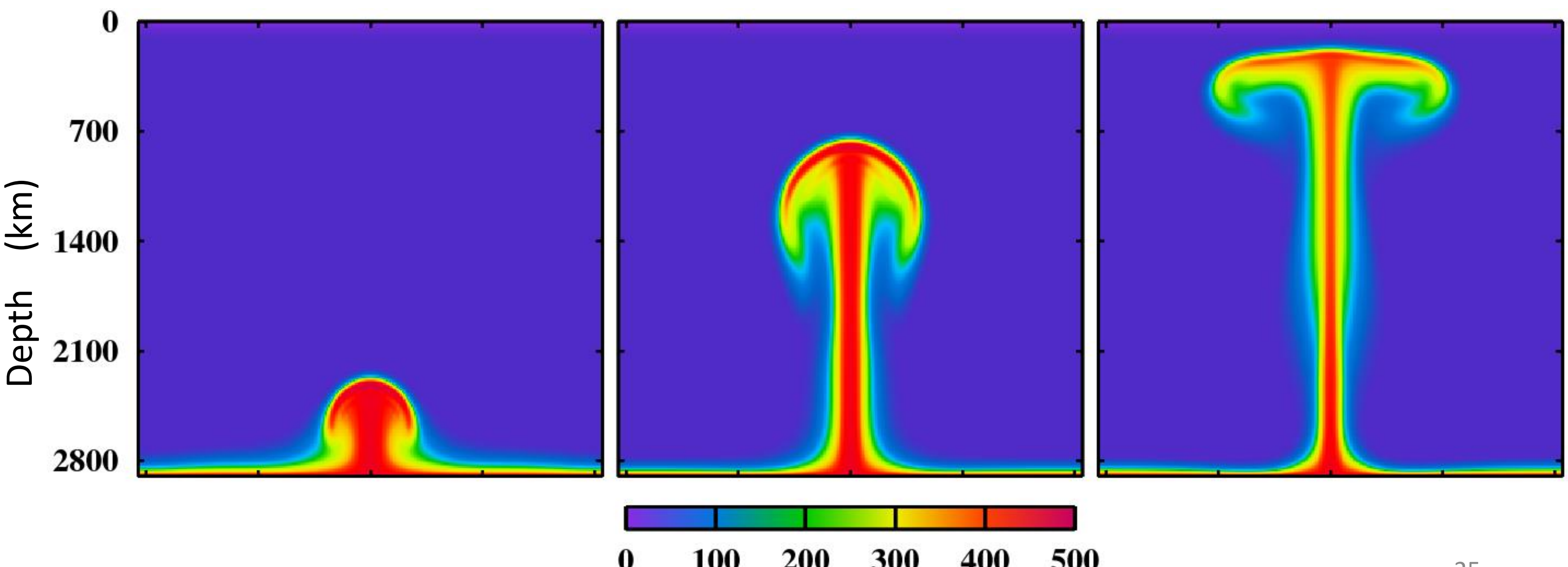
Points chauds et panaches



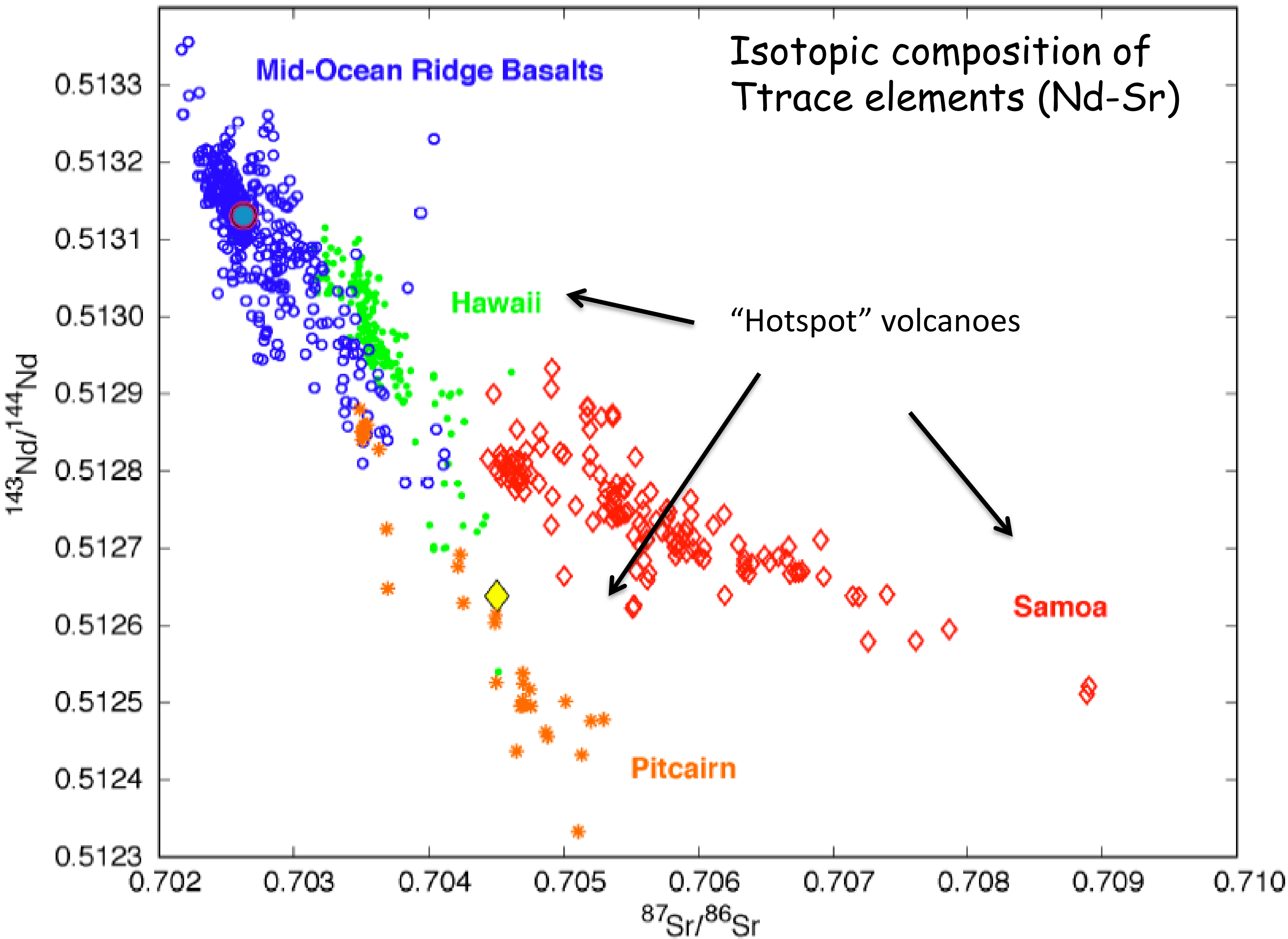


Morgan, 1971



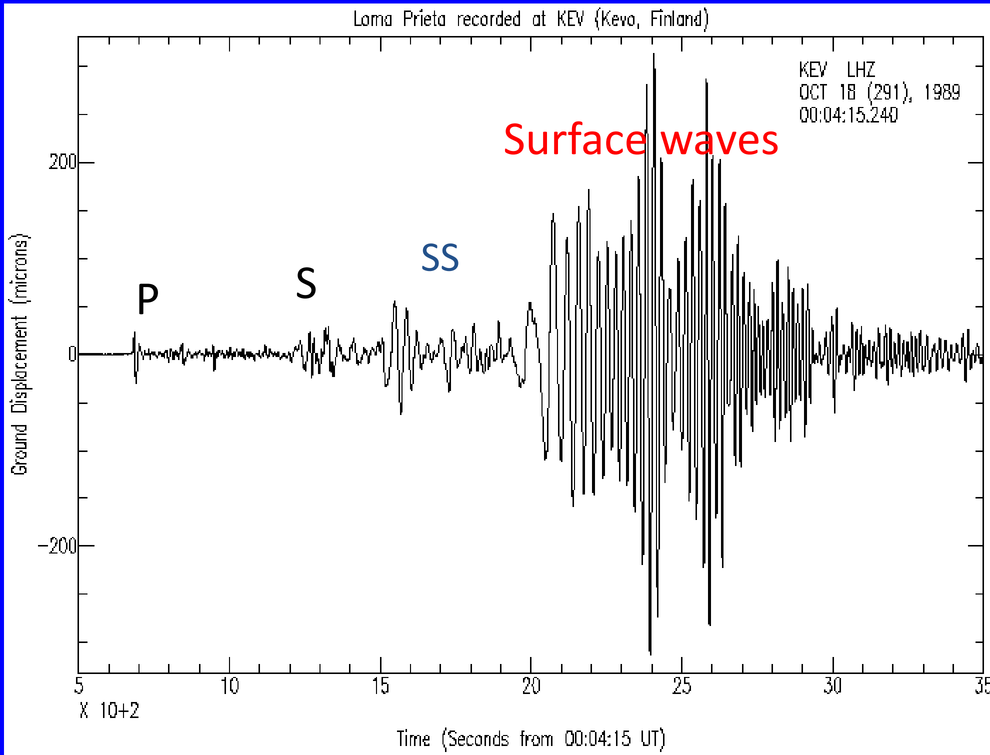


Courtesy of Cinzia Farnetani

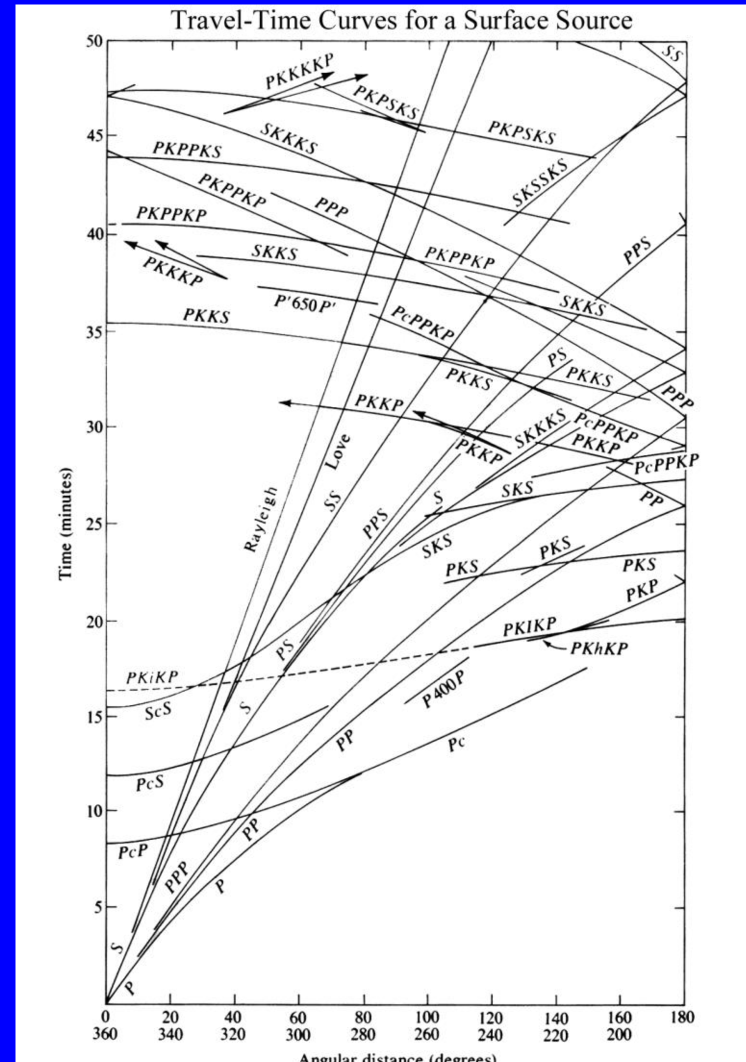


Workman, 2005

There is more information in seismic records than that provided by travel times of first arriving or isolated "phases"



← 50 mn →

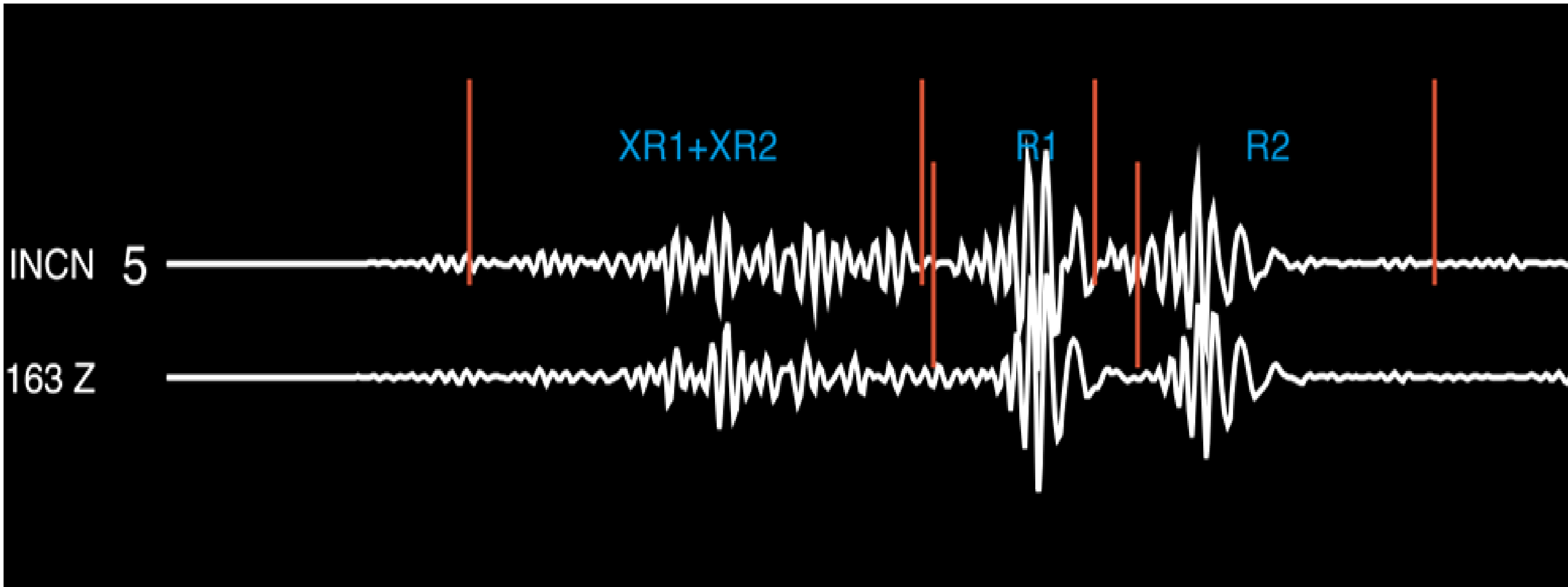


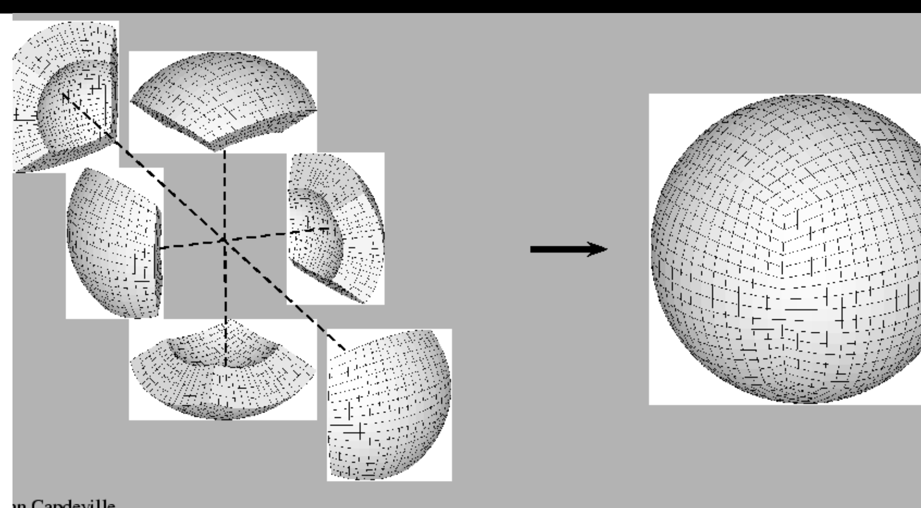
From Bolt, B., *Inside the Earth*, San Francisco: W.H. Freeman, 1982.

Until recently, seismic tomography was based
Mostly on travel times of seismic waves that can
Be isolated unambiguously on seismic records

P, PP, S, SS, fundamental mode of surfae waves

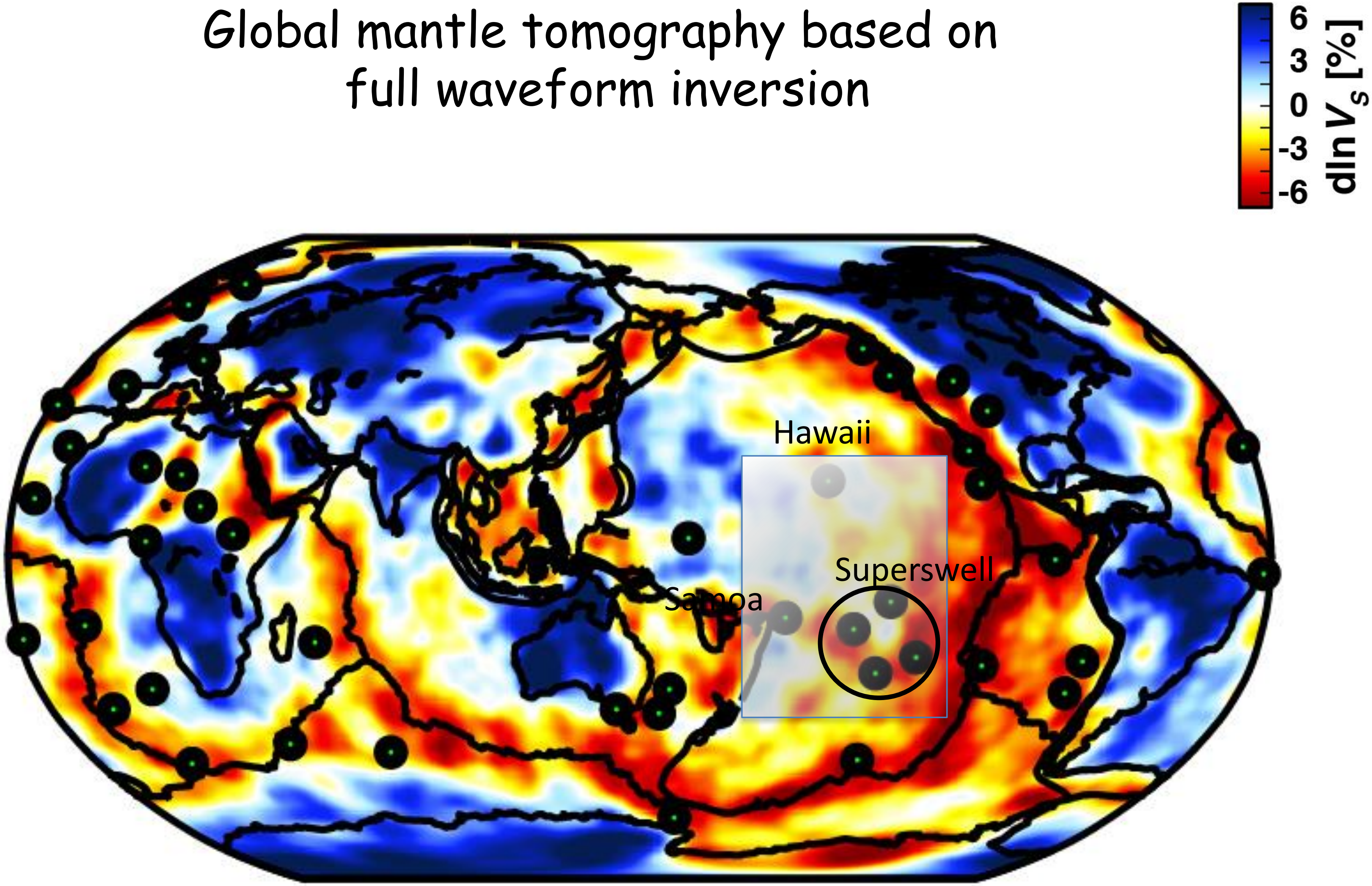
Numerical wavefield computations





Spectral element method
and the “cubic sphere”

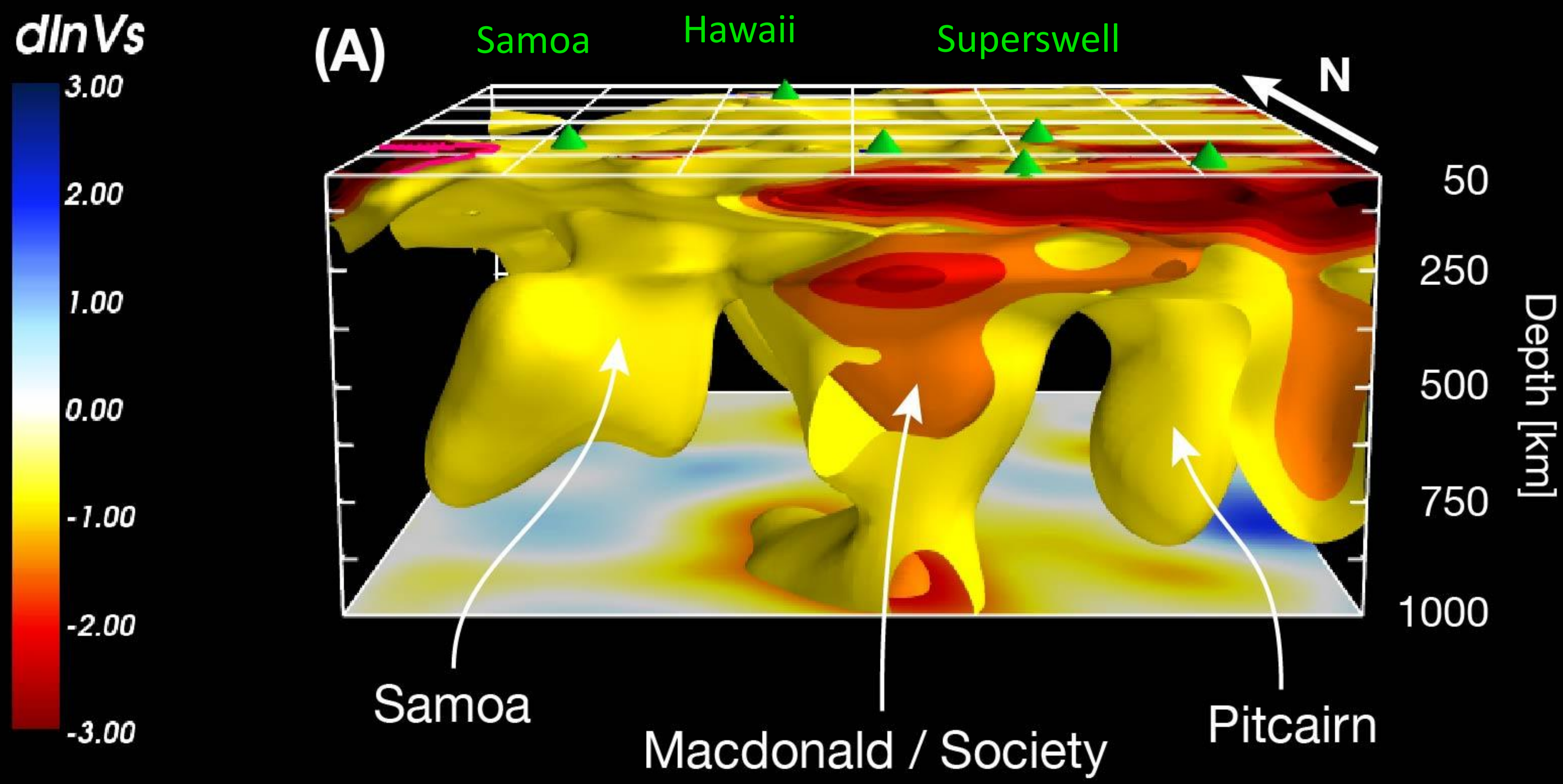
Global mantle tomography based on full waveform inversion

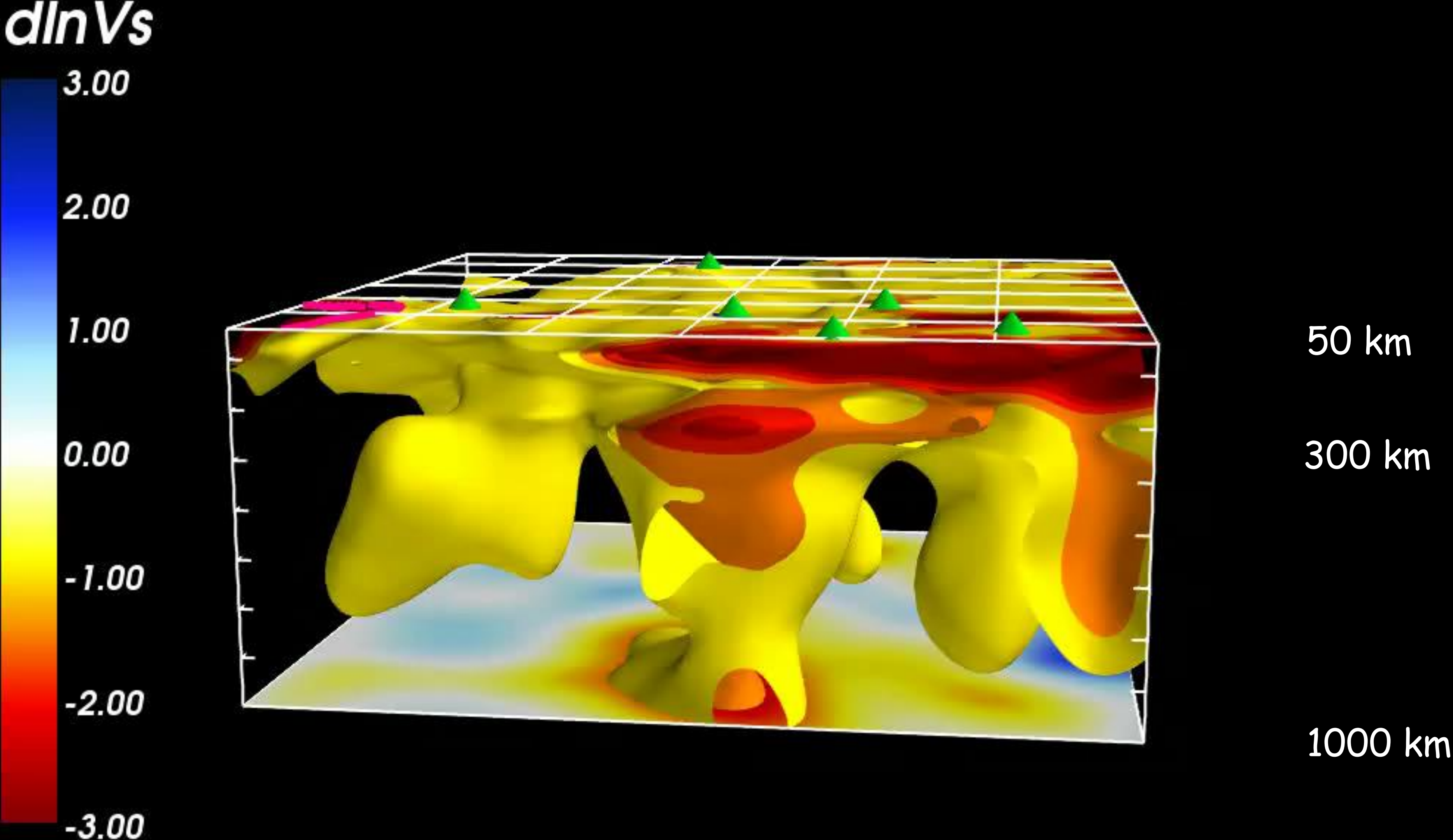


"SEMum2" at 100 km depth

French et al., 2013

Isosurface levels:
-1-> -3%%

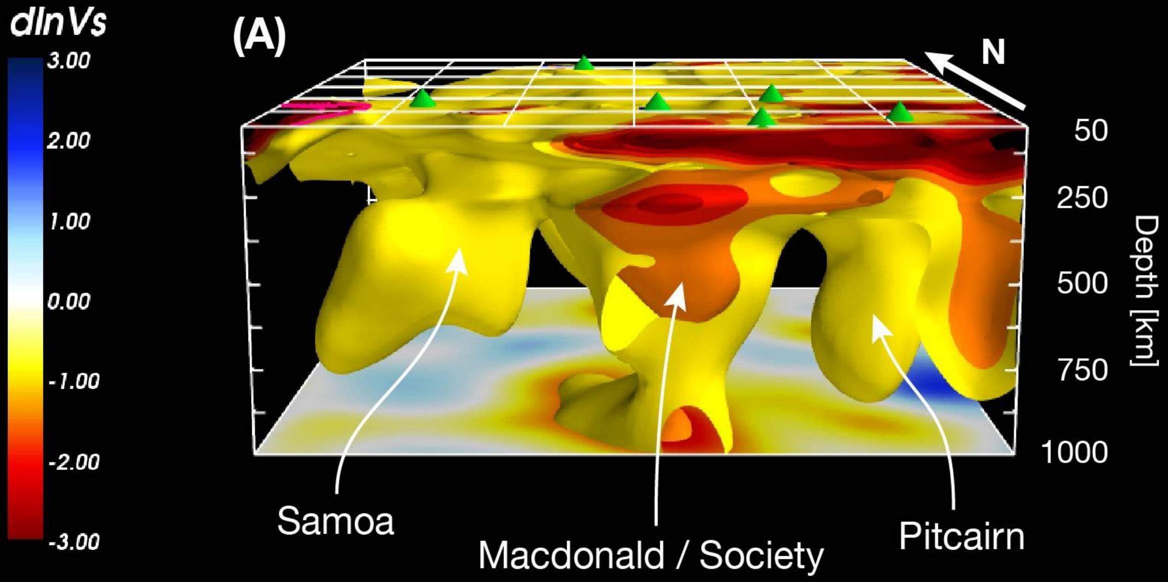


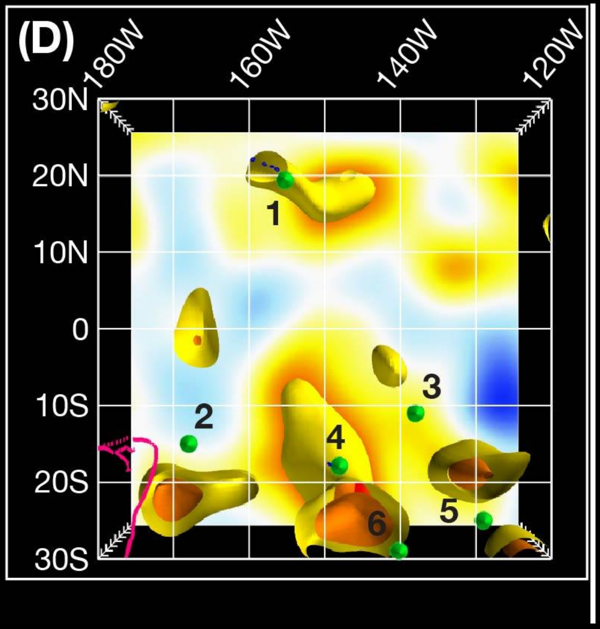


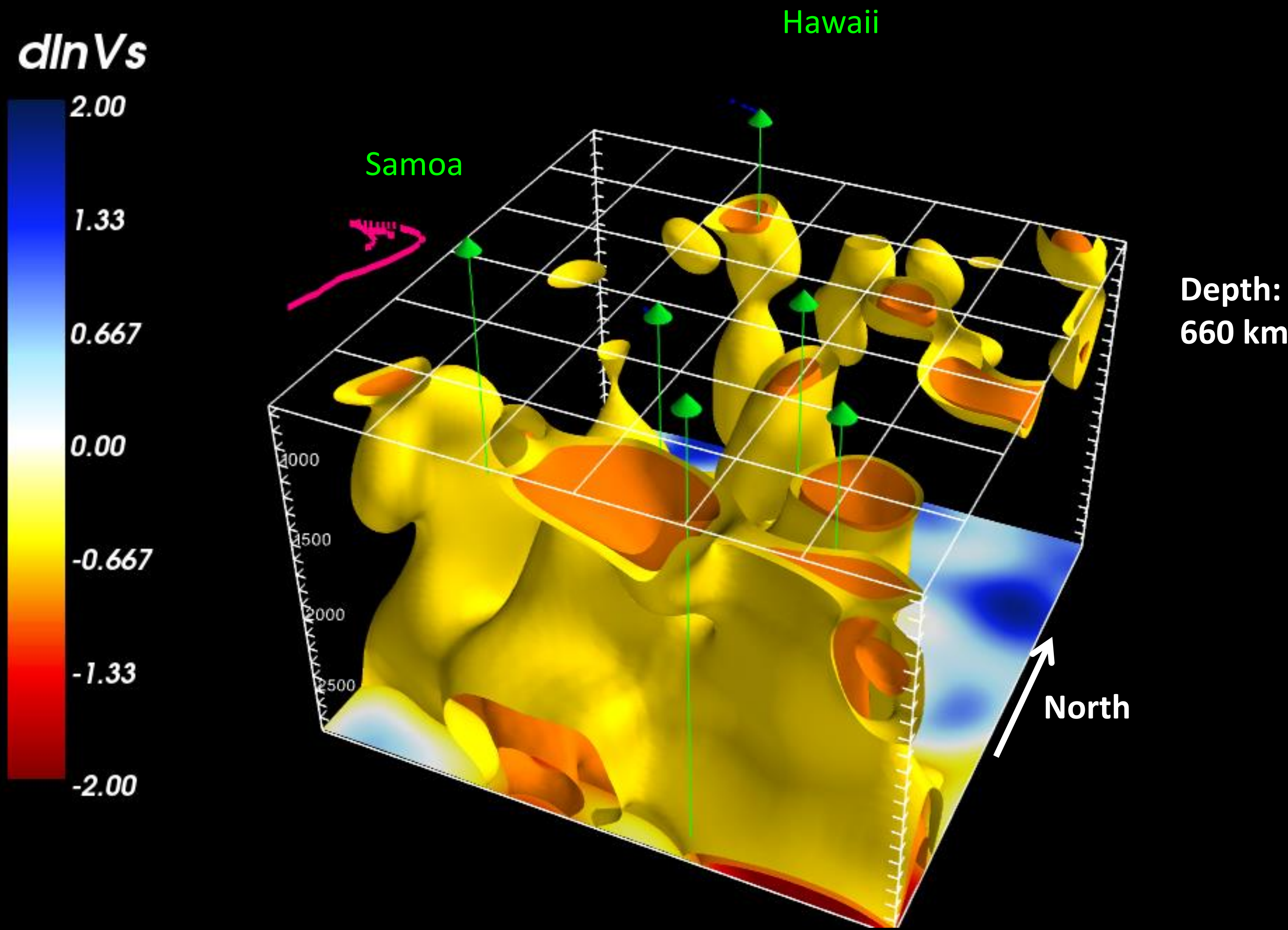
dlnVs
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
50 km
300 km
1000 km

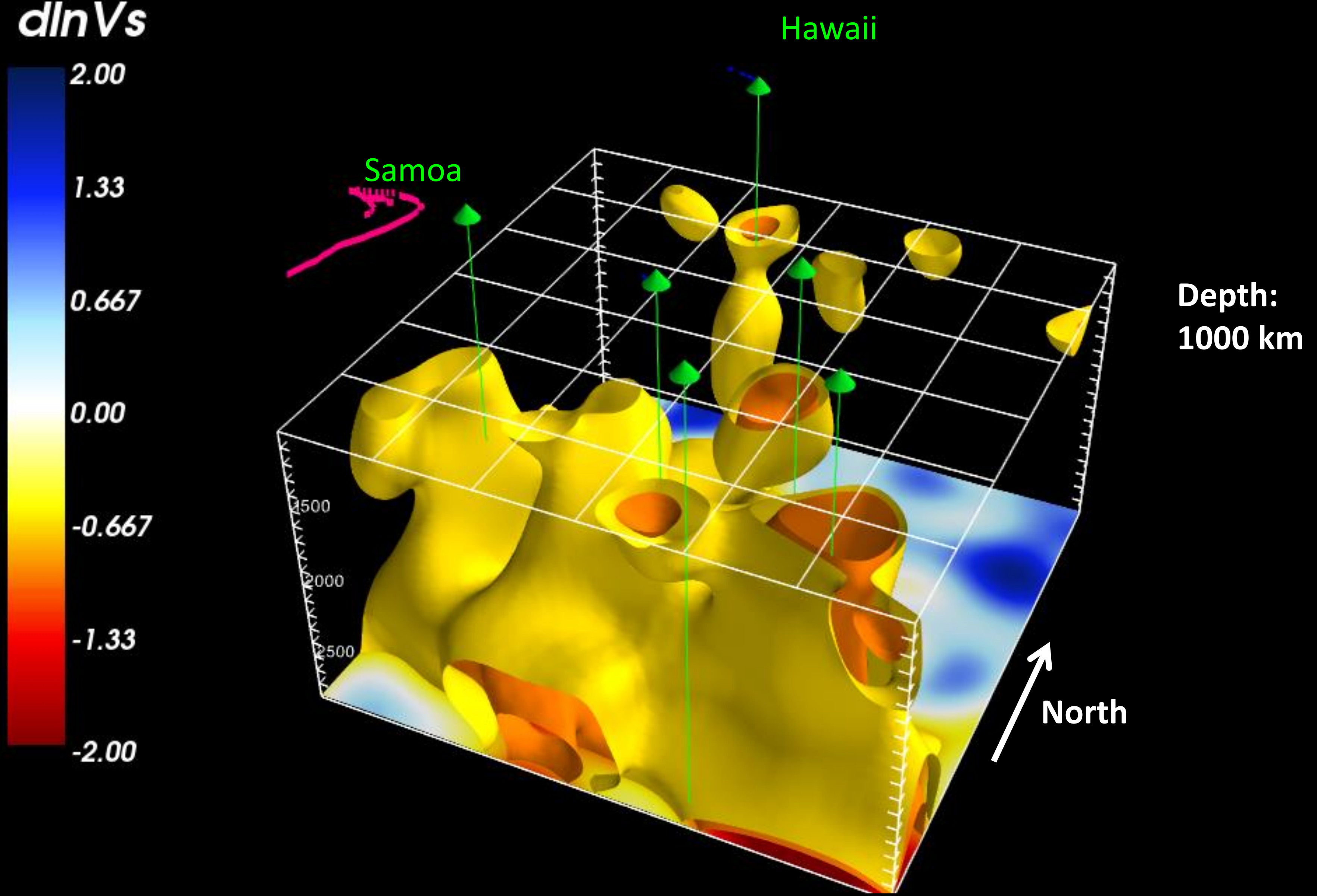
View from the south…..

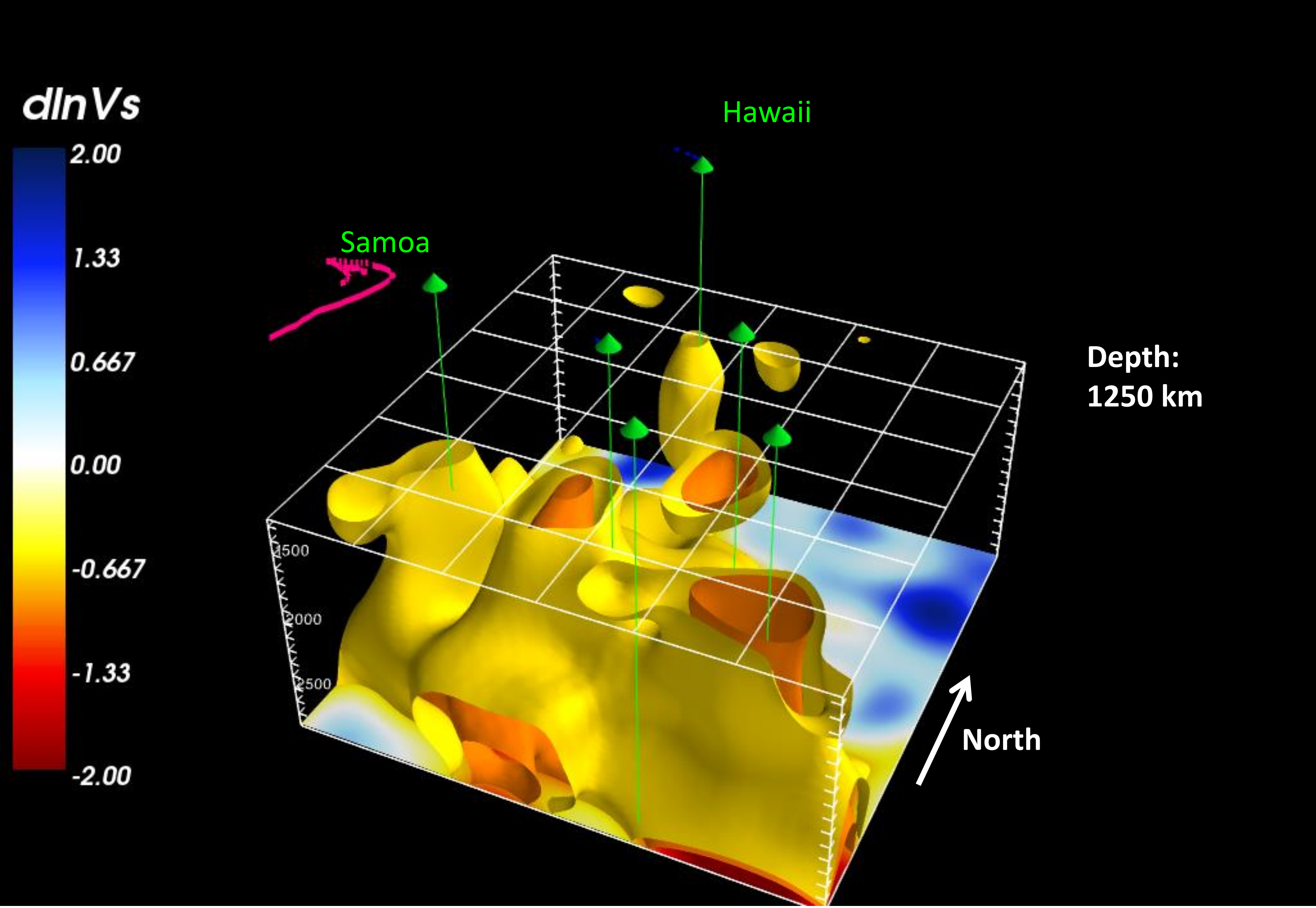
View from the top Starting at 500 km depth

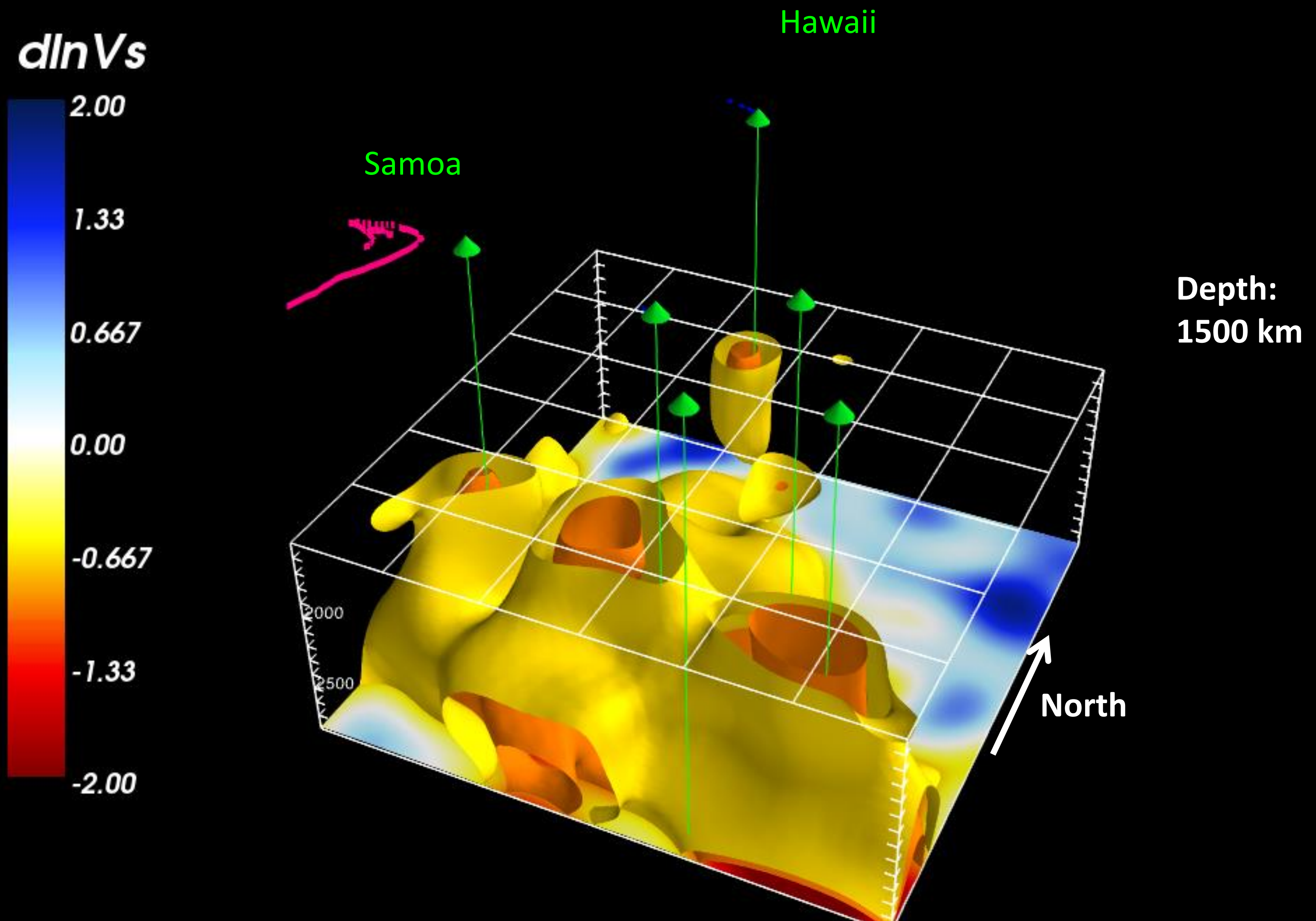


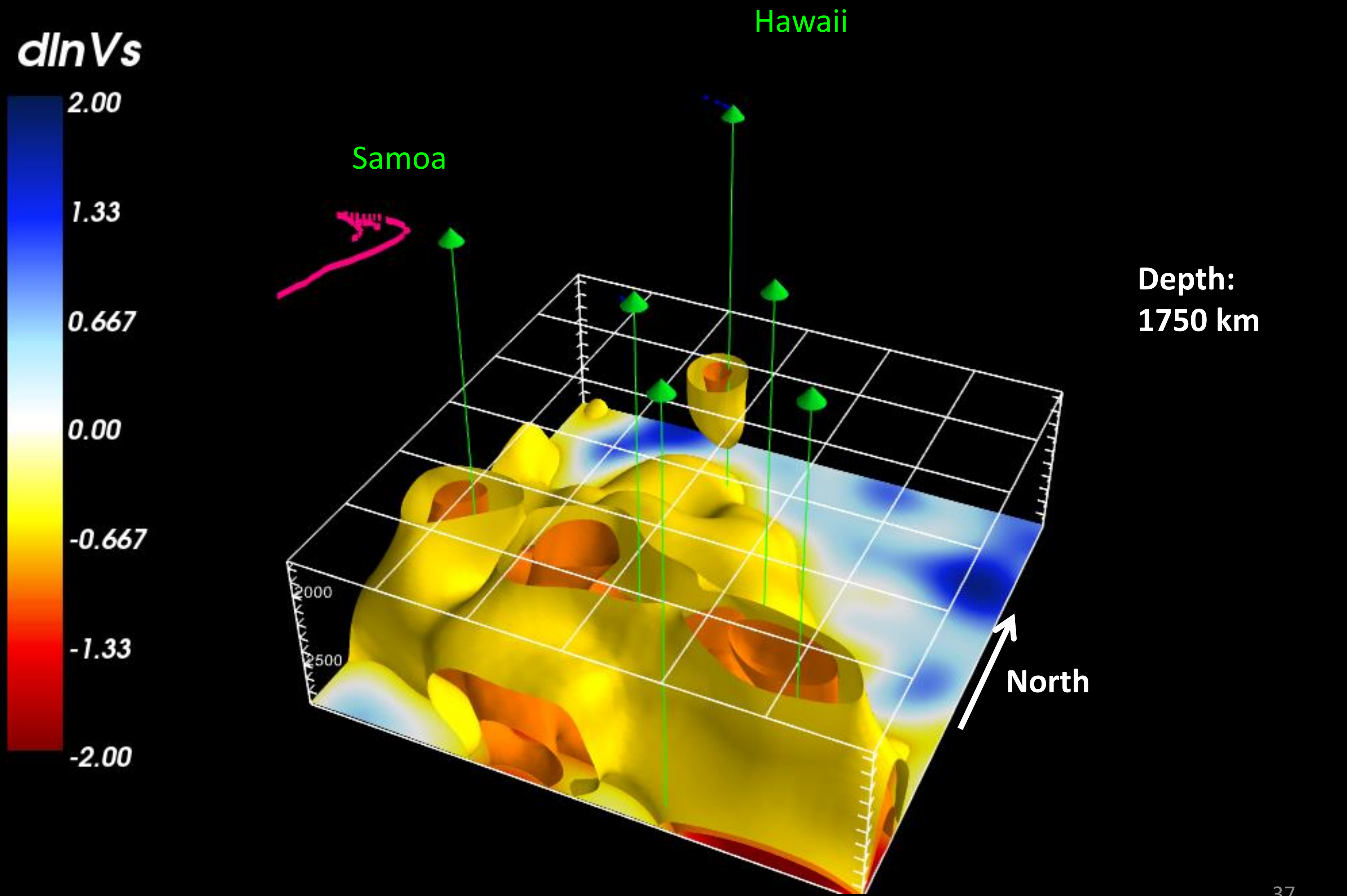


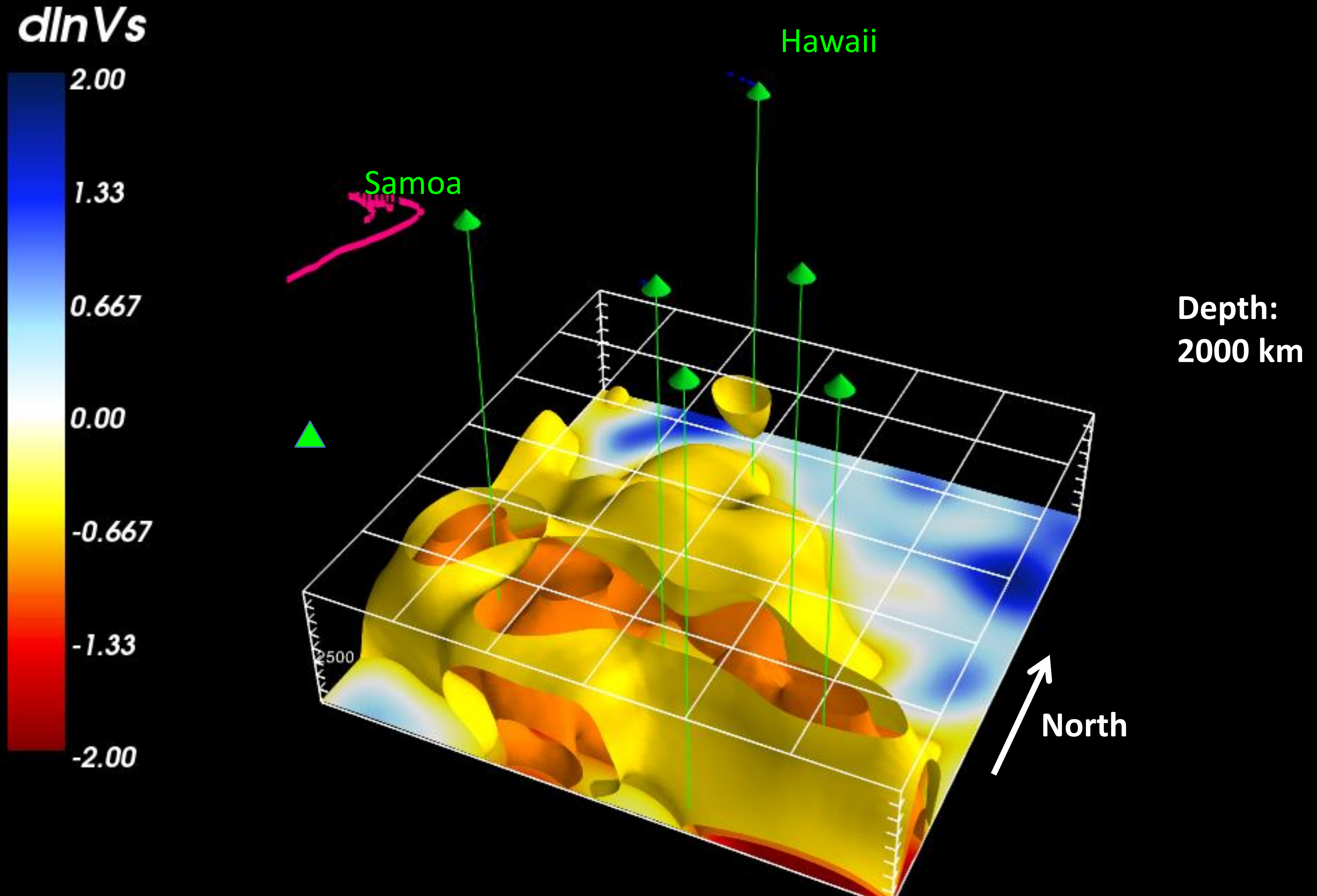

dlnVs
2.00
1.33
0.667
0.00
-0.667
-1.33
-2.00
Hawaii
Samoa
1000
1500
2000
2500
Depth:
660 km
North

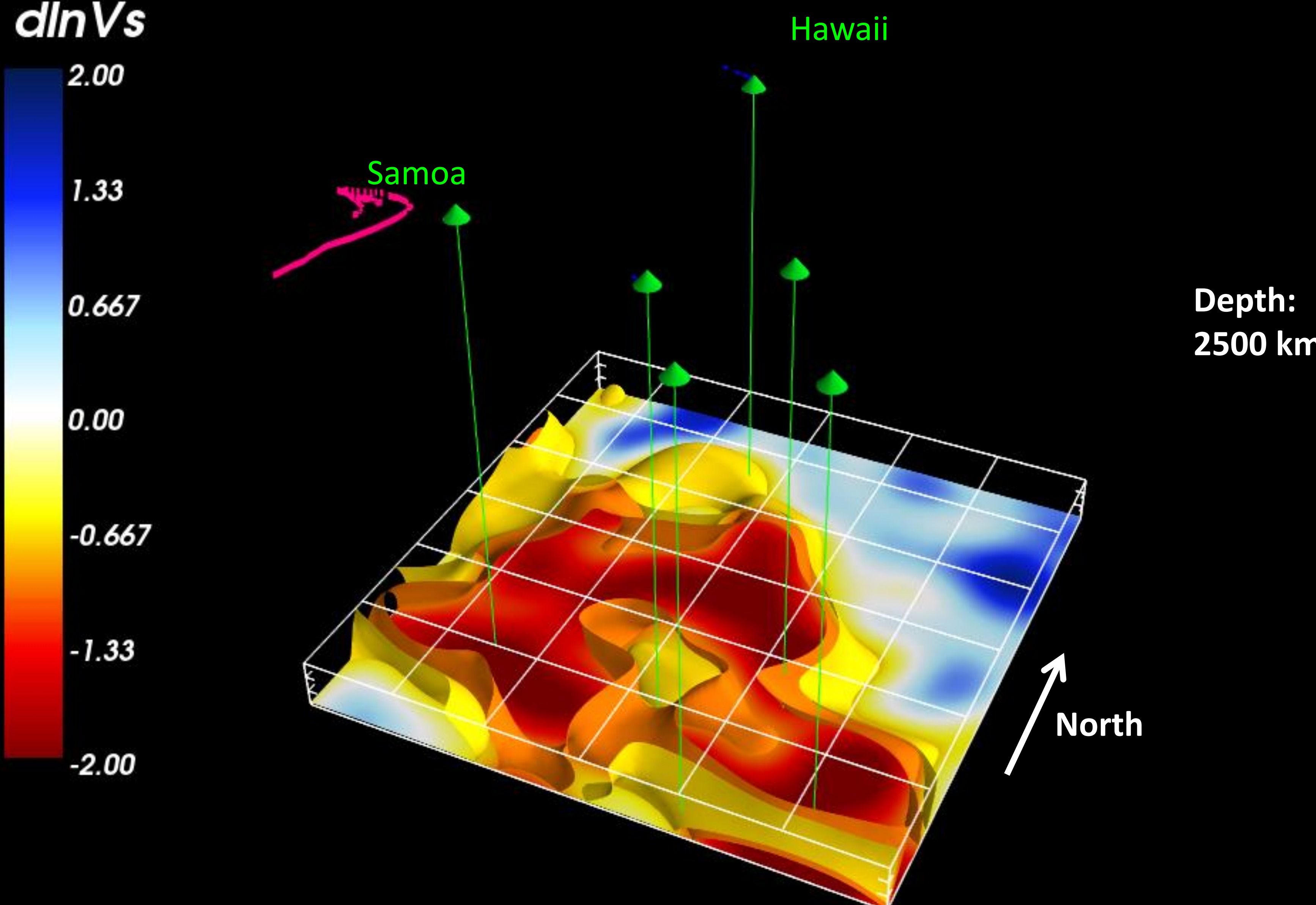

dlnVs
2.00
1.33
0.667
0.00
-0.667
-1.33
-2.00
Hawaii
Samoa
1500
2000
2500
Depth:
1000 km
North

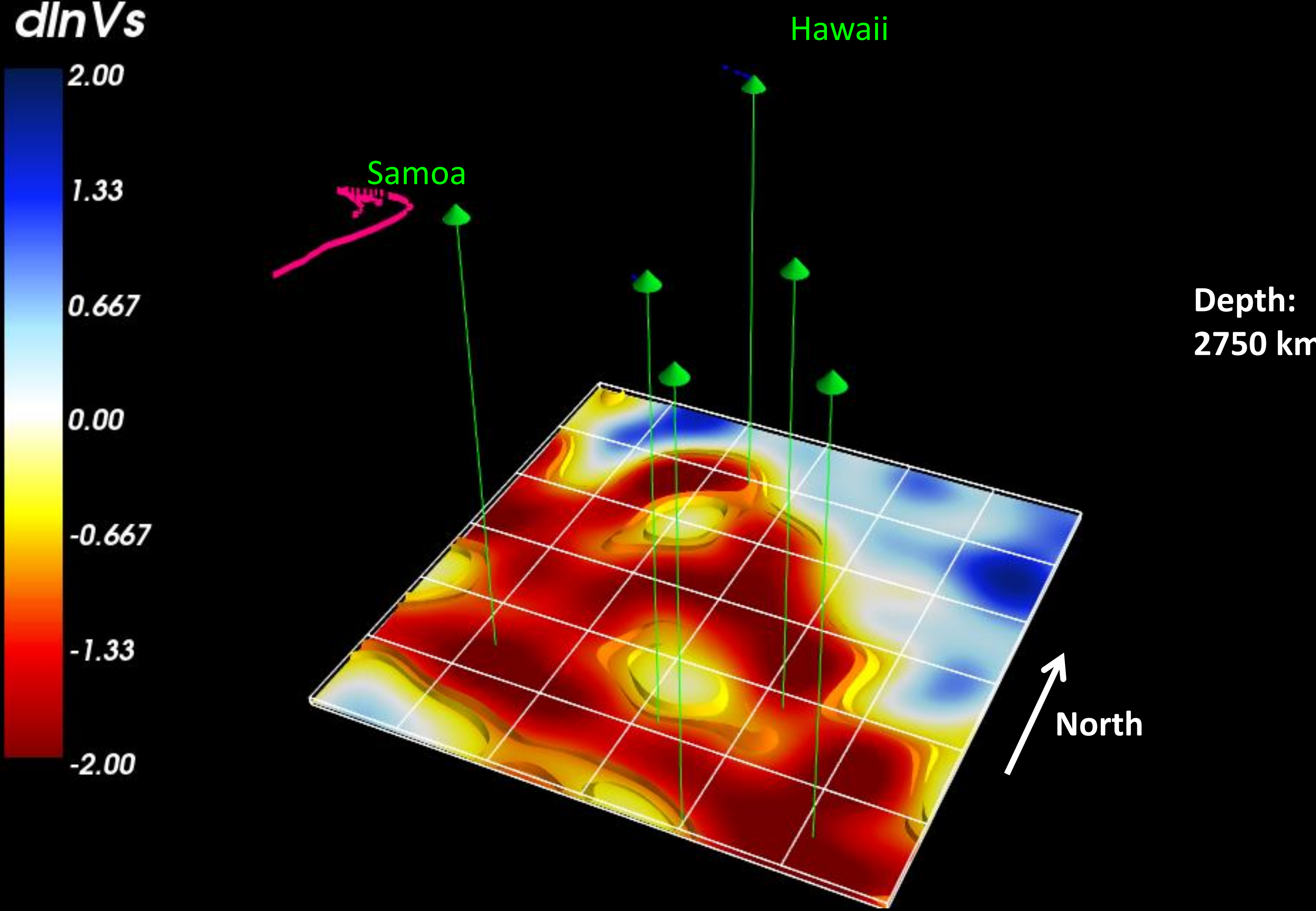

dlnVs
2.00
1.33
0.667
0.00
-0.667
-1.33
-2.00
Hawaii
Samoa
1500
2000
2500
Depth:
1250 km
North


dlnVs
2.00
1.33
0.667
0.00
-0.667
-1.33
-2.00
Samoa
Hawaii
Depth:
1500 km
2000
2500
North

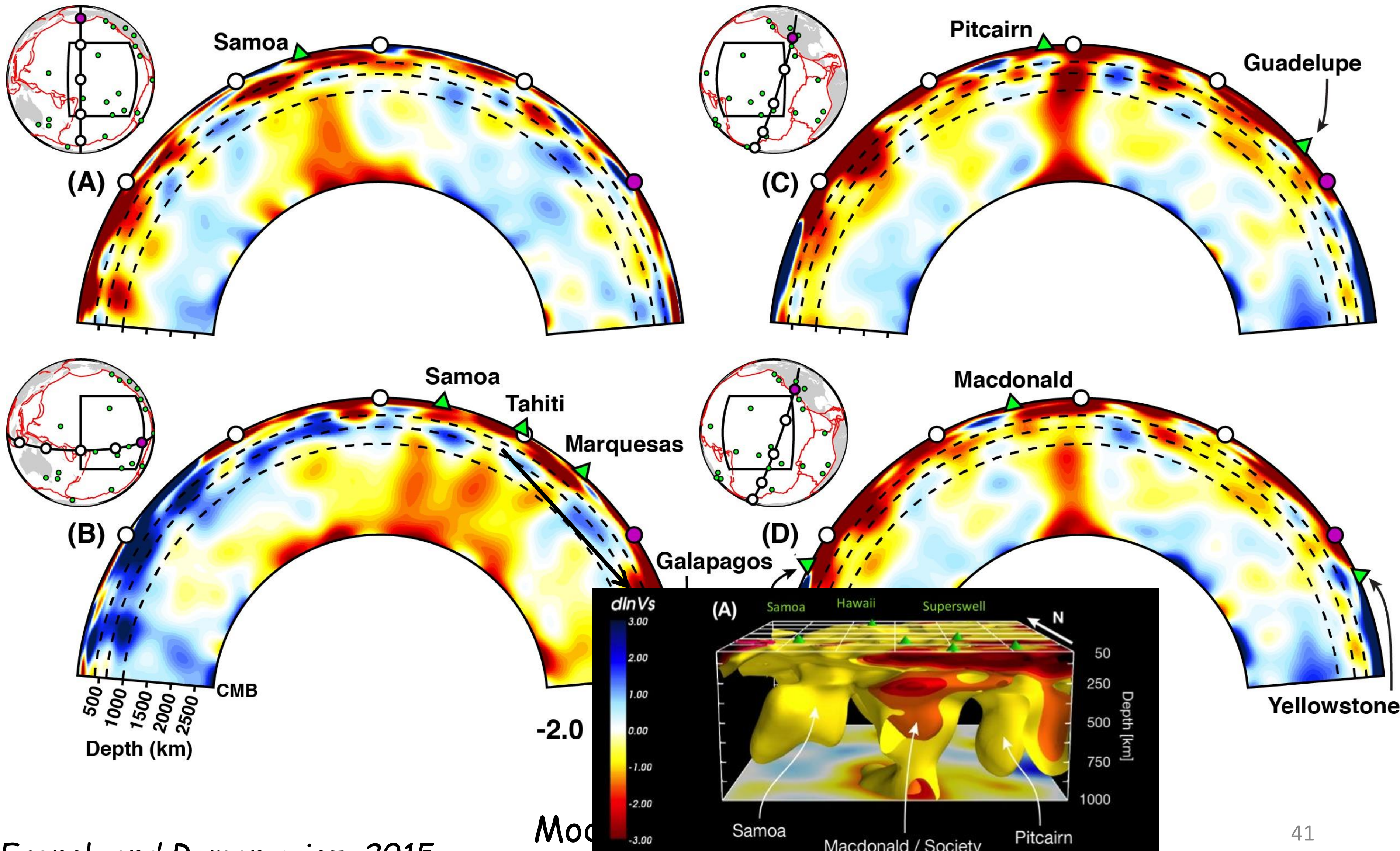

dlnVs
2.00
1.33
0.667
0.00
-0.667
-1.33
-2.00
Hawaii
Samoa
Depth:
1750 km
2000
2500
North


dlnVs
2.00
1.33
0.667
0.00
-0.667
-1.33
-2.00
Hawaii
Samoa
2500
Depth:
2000 km
North

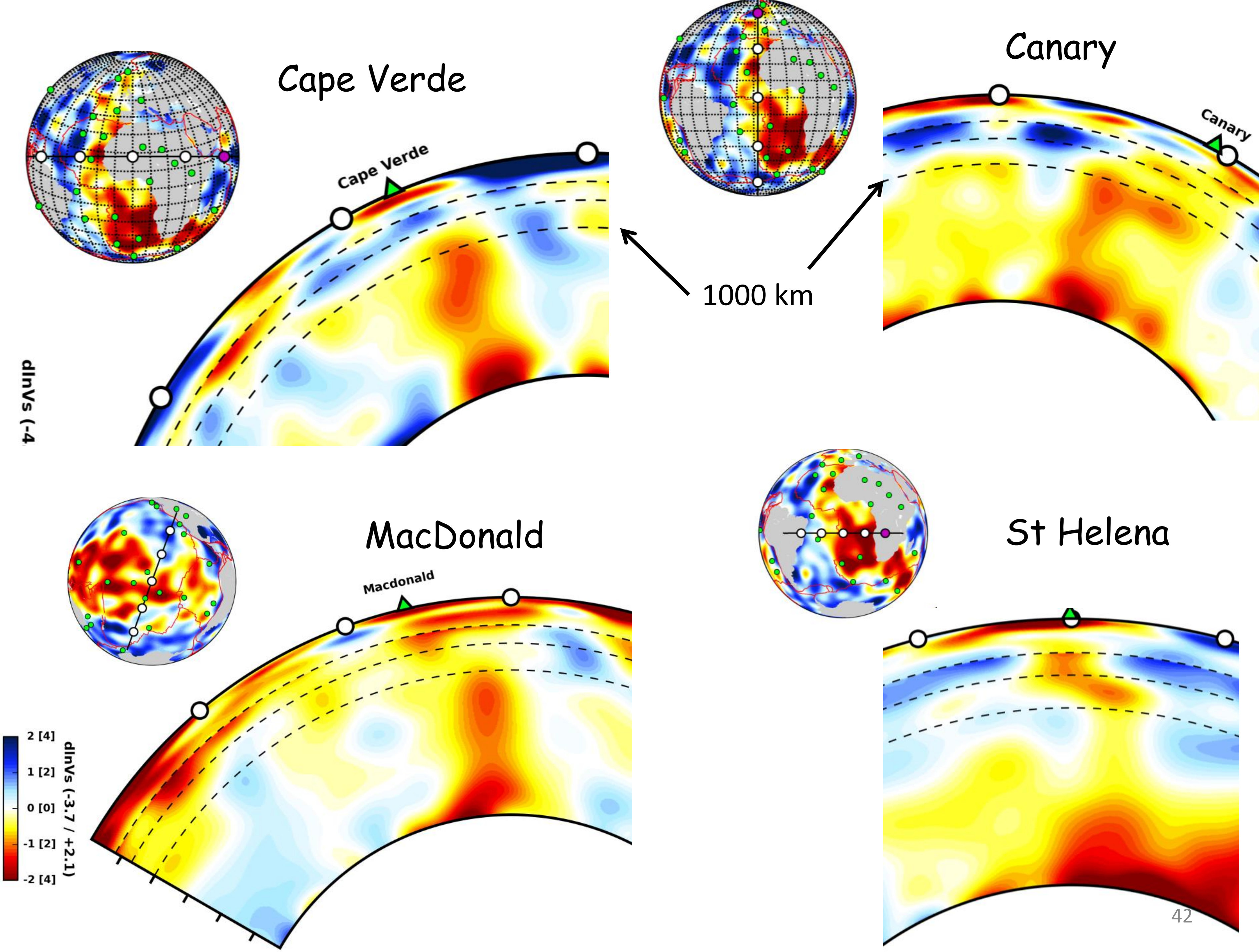

dlnVs
2.00
1.33
0.667
0.00
-0.667
-1.33
-2.00
Samoa
Hawaii
Depth:
2500 km
North


dlnVs
2.00
1.33
0.667
0.00
-0.667
-1.33
-2.00
Hawaii
Samoa
Depth:
2750 km
North

Pacific superswell region

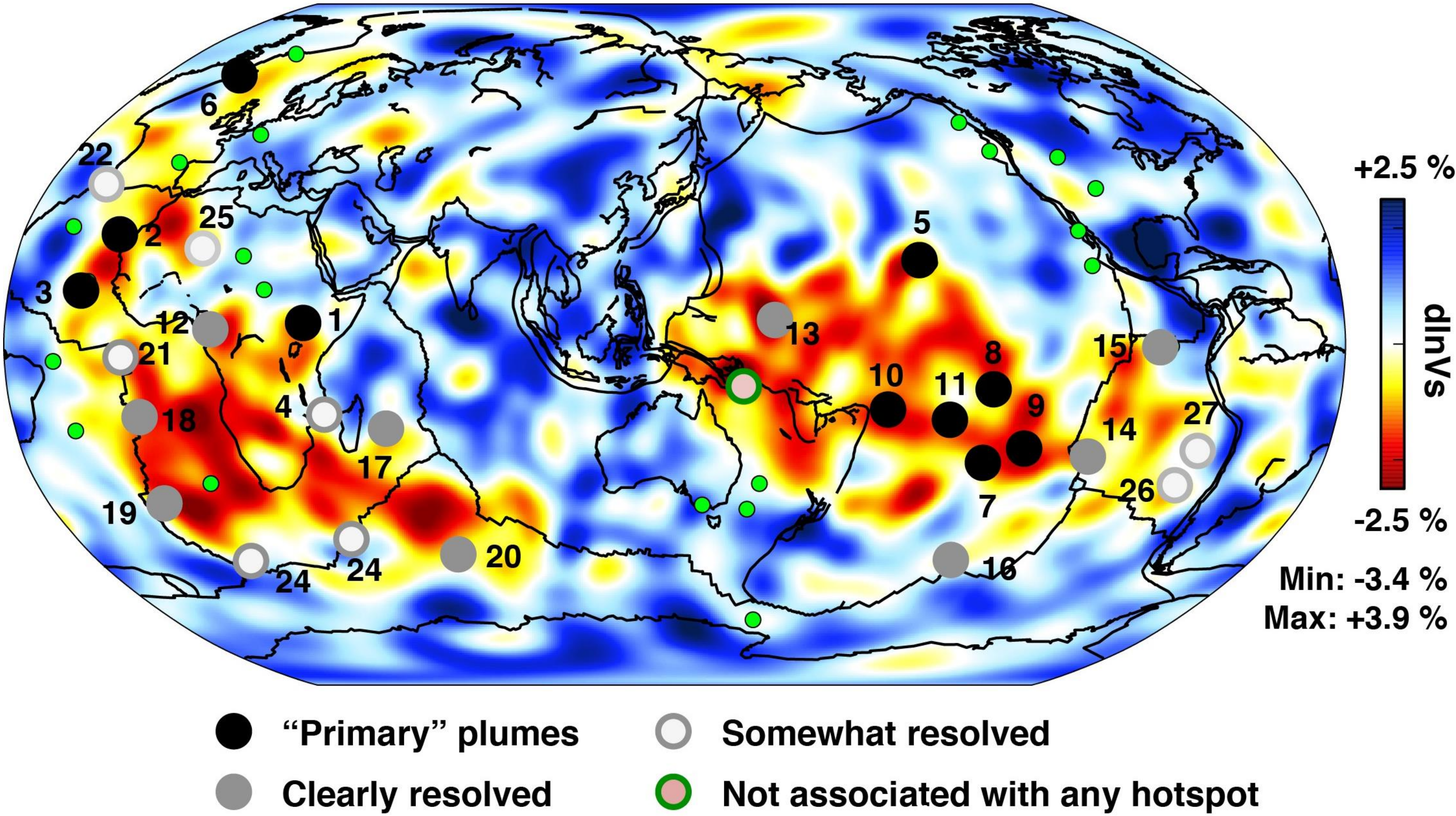


French and Romanowicz, 2015


Cape Verde
Canary
1000 km
MacDonald
St Helena
Cape Verde
Canary
Macdonald
dlnVs (-4.
2 [4]
1 [2]
0 [0]
-1 [2]
-2 [4]
dlnVs (-3.7 / +2.1)

These broad plumes are found under major hotspots that lie over the LLSVPs

SEMUCB-WM1 at 2800 km depth

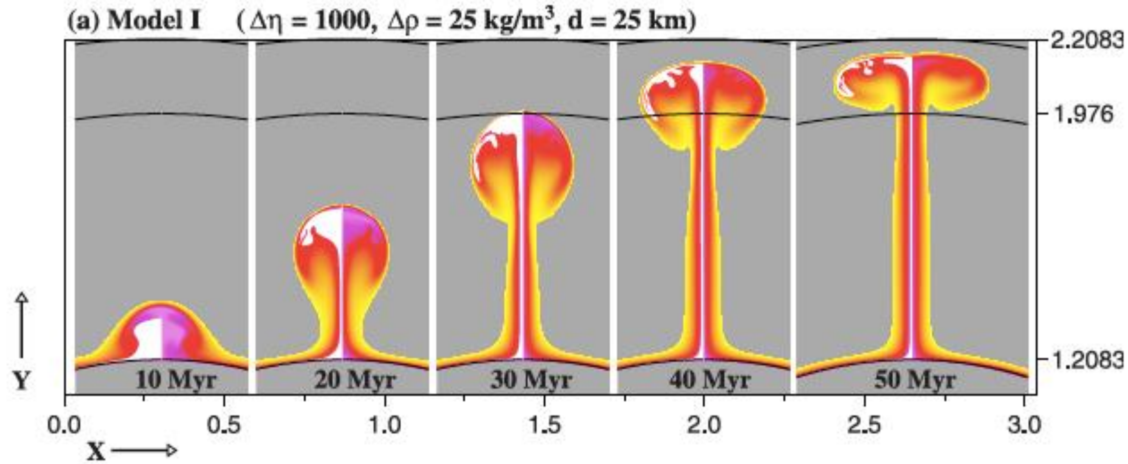


Other hotspots according to Steinberger (2000)

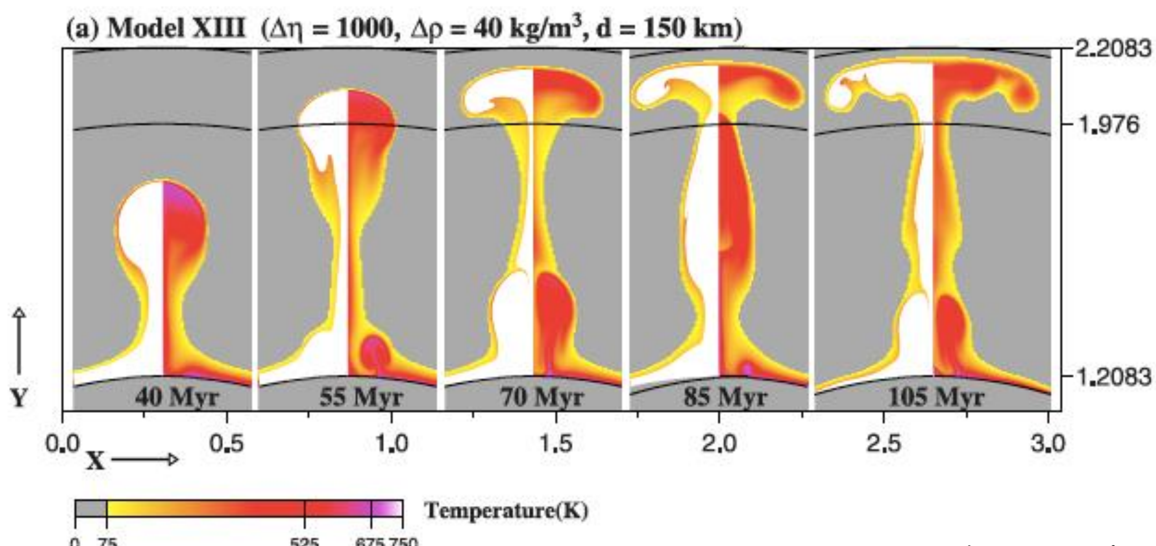
French and Romanowicz, 2015

Panaches Thermochimiques

Cas 1: Panache thermique



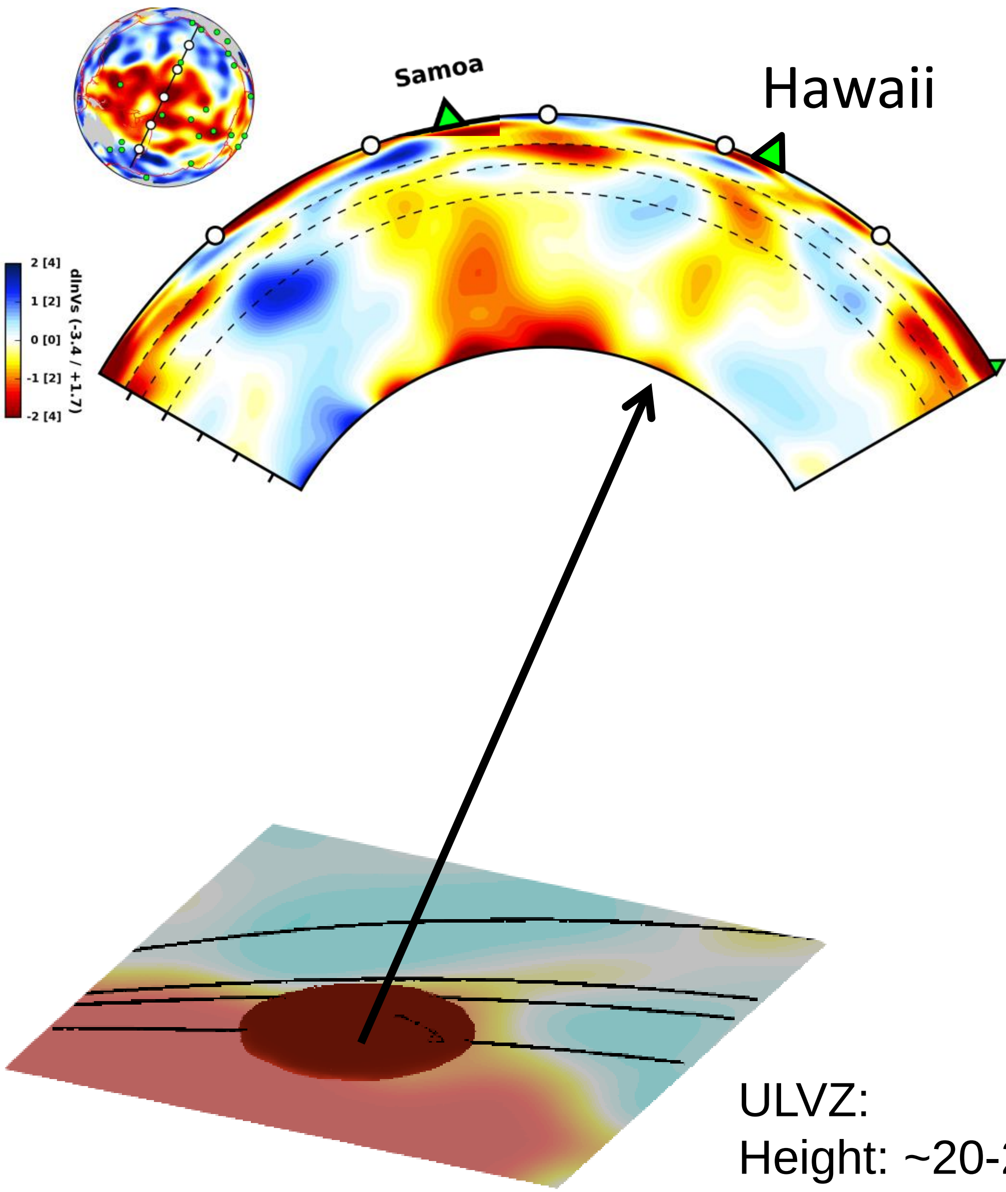
Cas 3: Panache thermochimique



blanc = matière plus dense

Lin and VanKeken, 2006

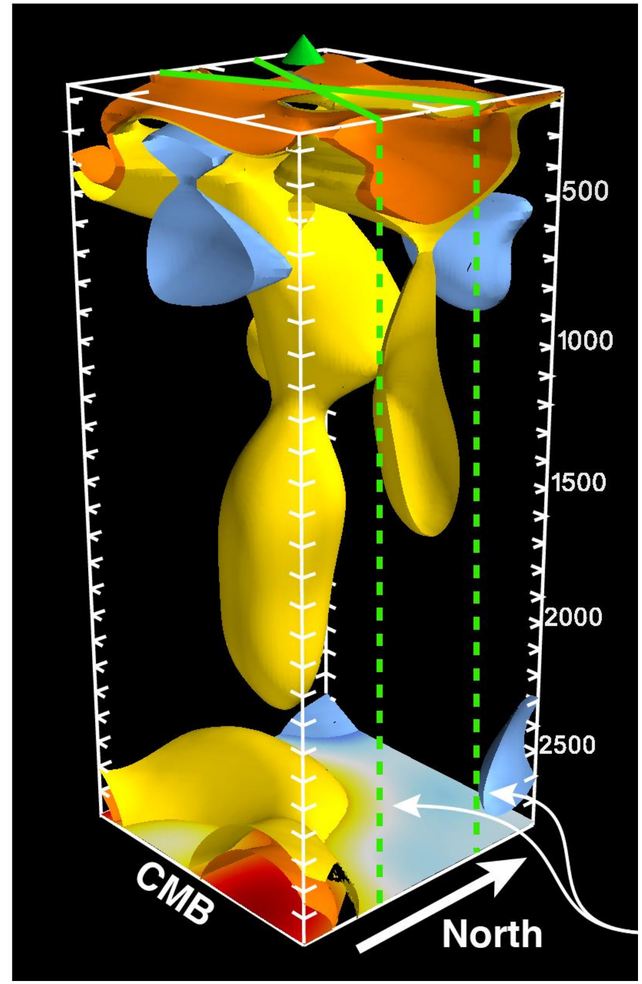
SEMUCB_WM1
Depth = 2800 km



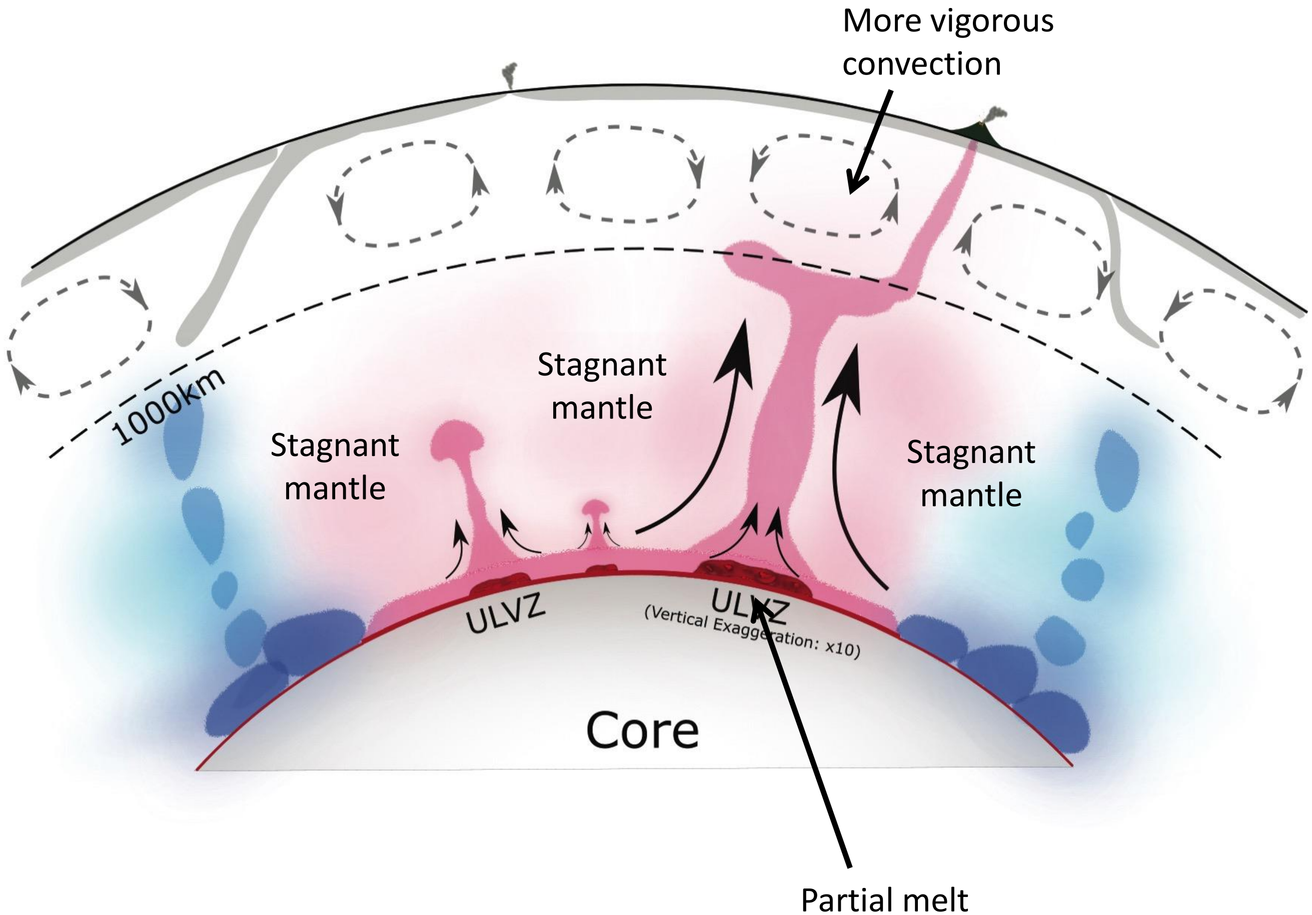
Cottaar and Romanowicz, 2012

ULVZ:
Height: ~20-25km
Diameter:~910 km
Velocity reduction:~20%

Hawaiian plume viewed from South East



forward modelling of Sdiff


More vigorous convection
1000km
Stagnant mantle
Stagnant mantle
Stagnant mantle
ULVZ
ULVZ
(Vertical Exaggeration: x10)
Core
Partial melt

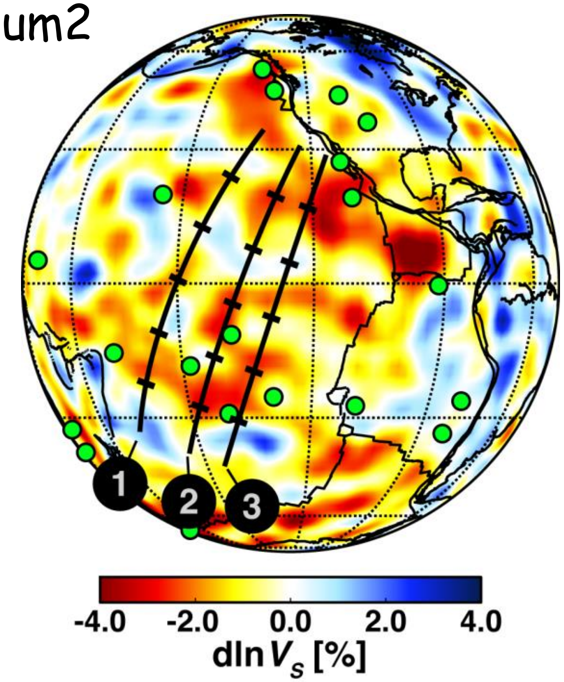
The 1-D Reference Earth

Les années 1980…

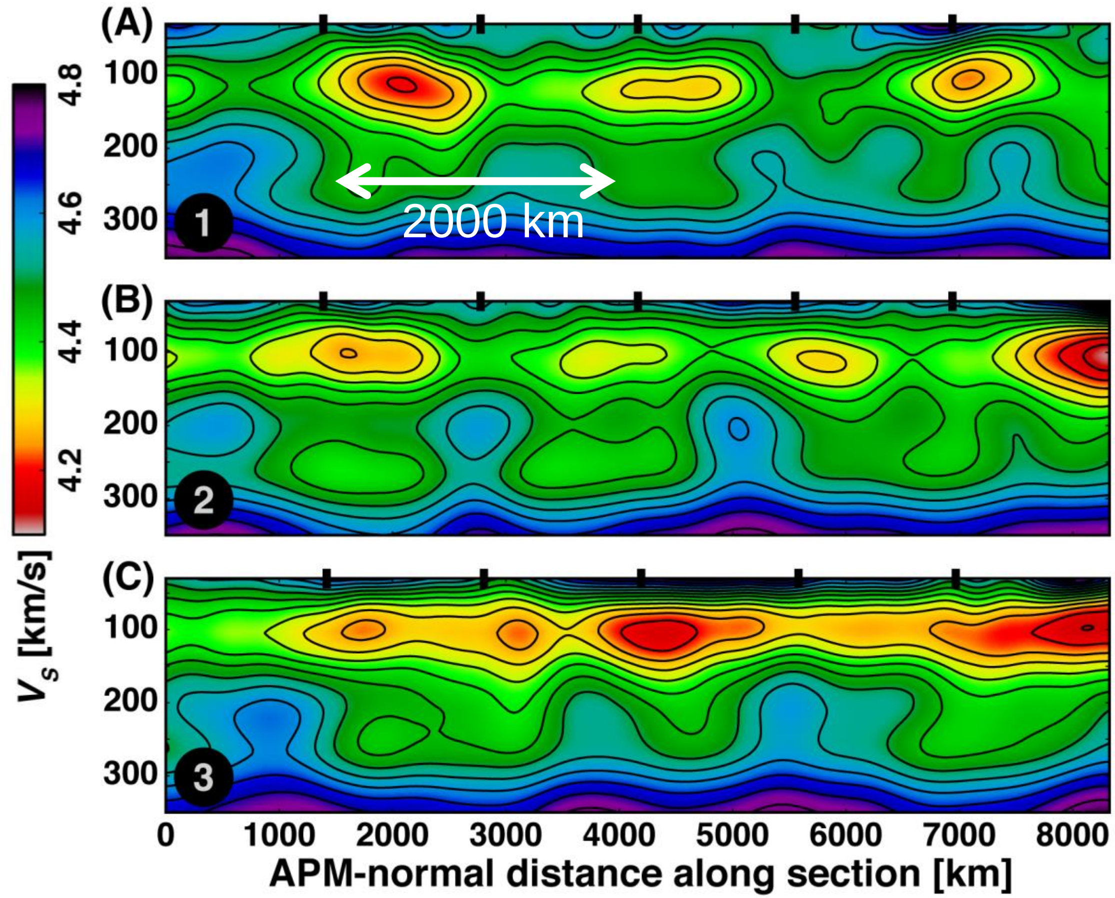
La vision actuelle

Le futur?

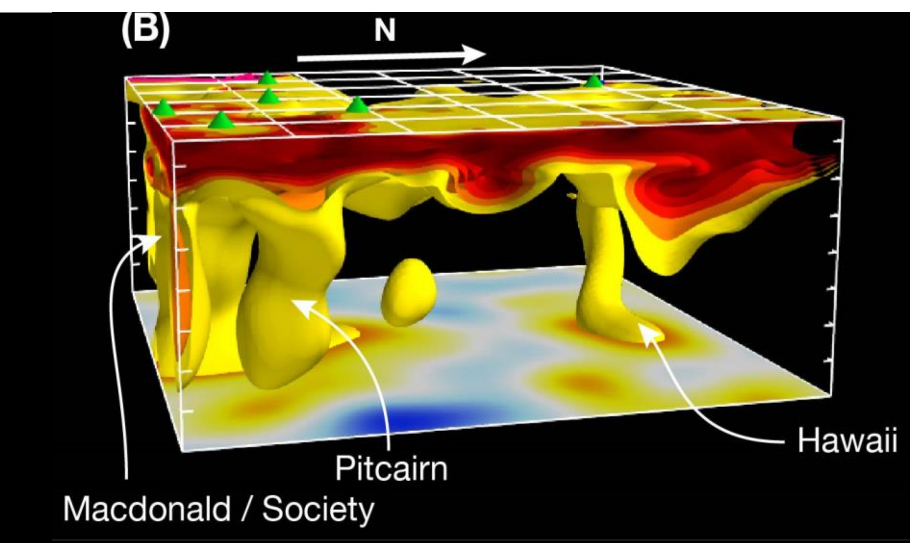
SEMum2

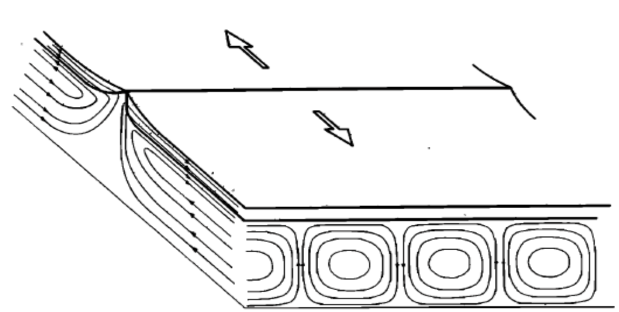


Vs perturbation
from the mean at 250 km depth



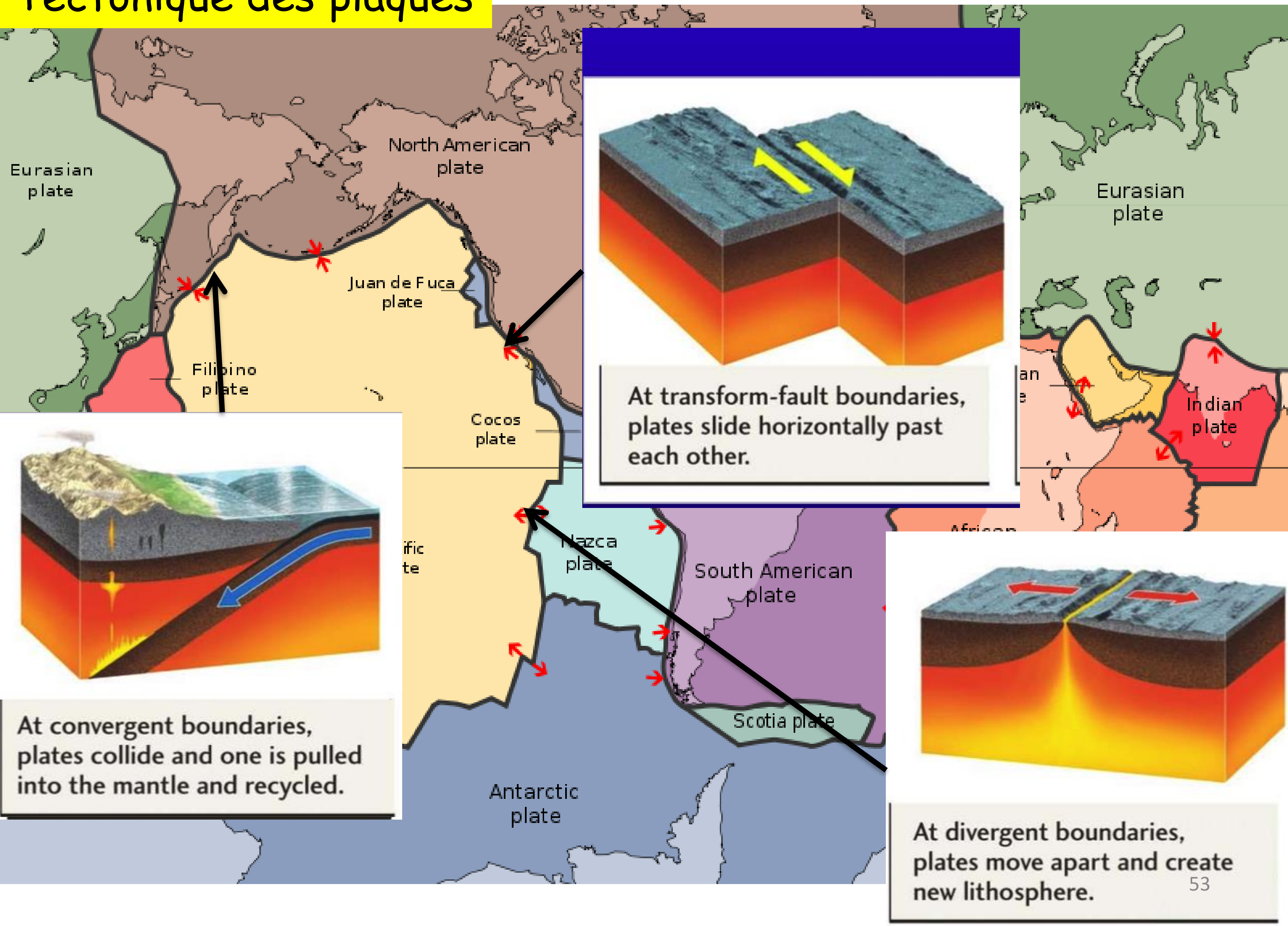
Absolute velocity

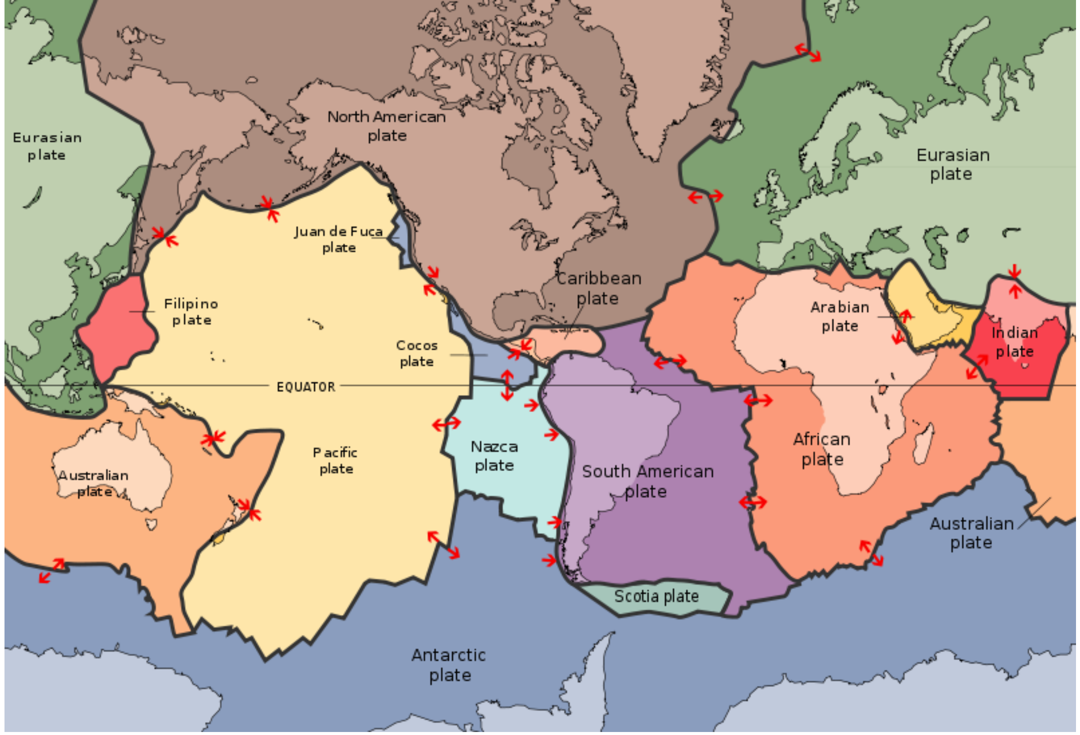


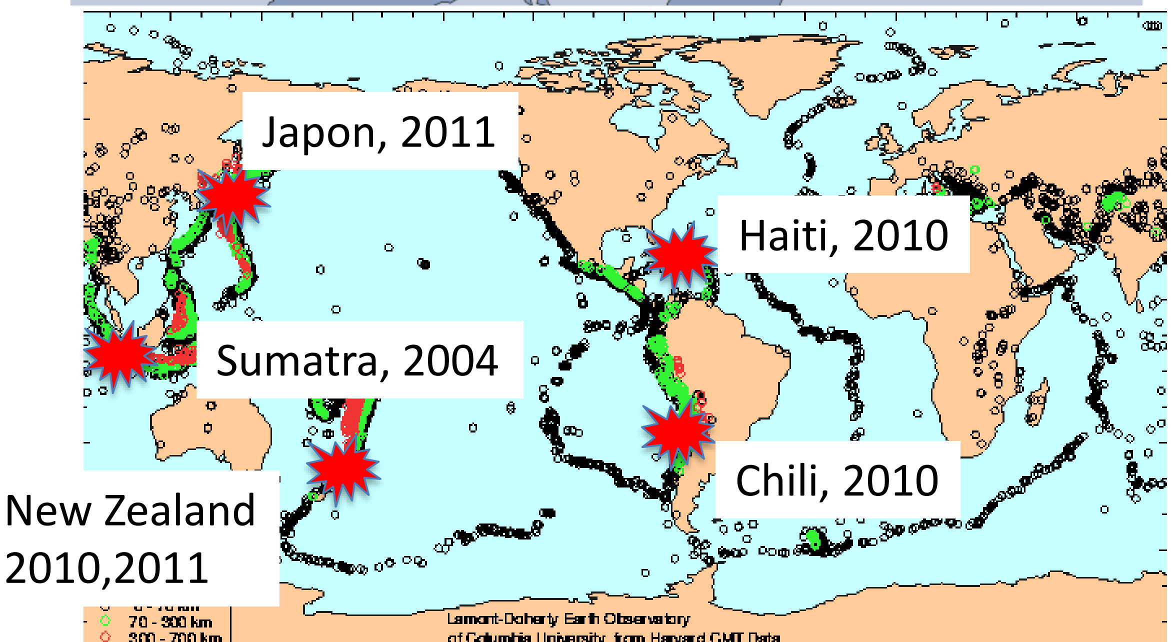


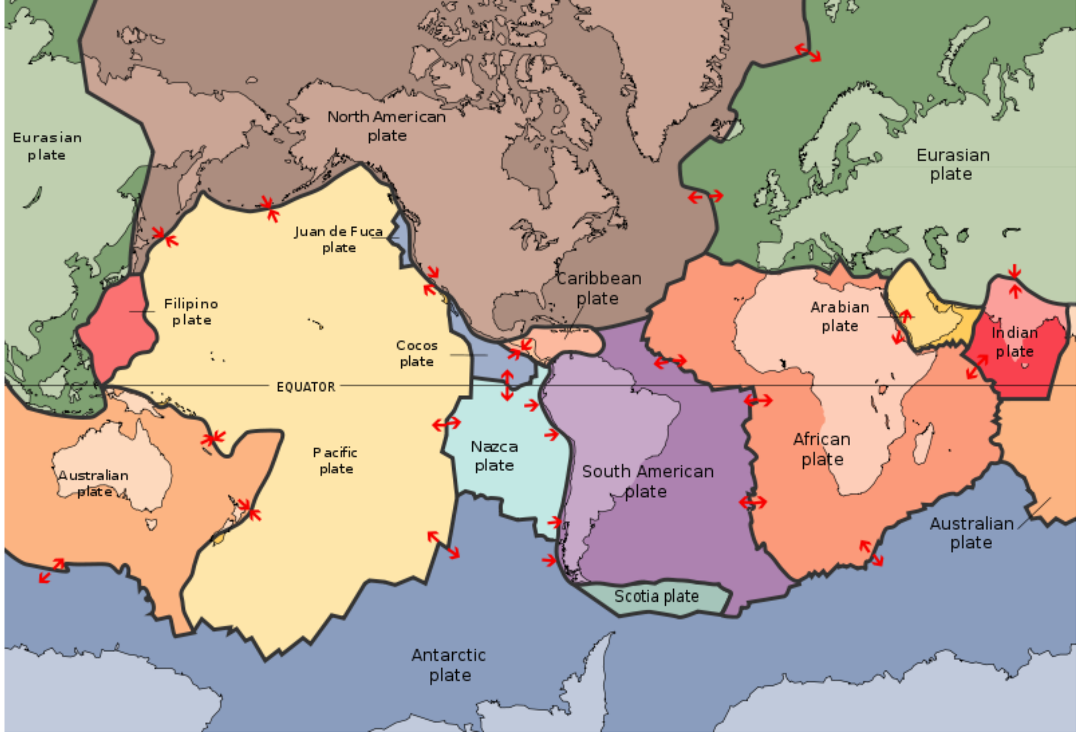
French et al., Science 2013

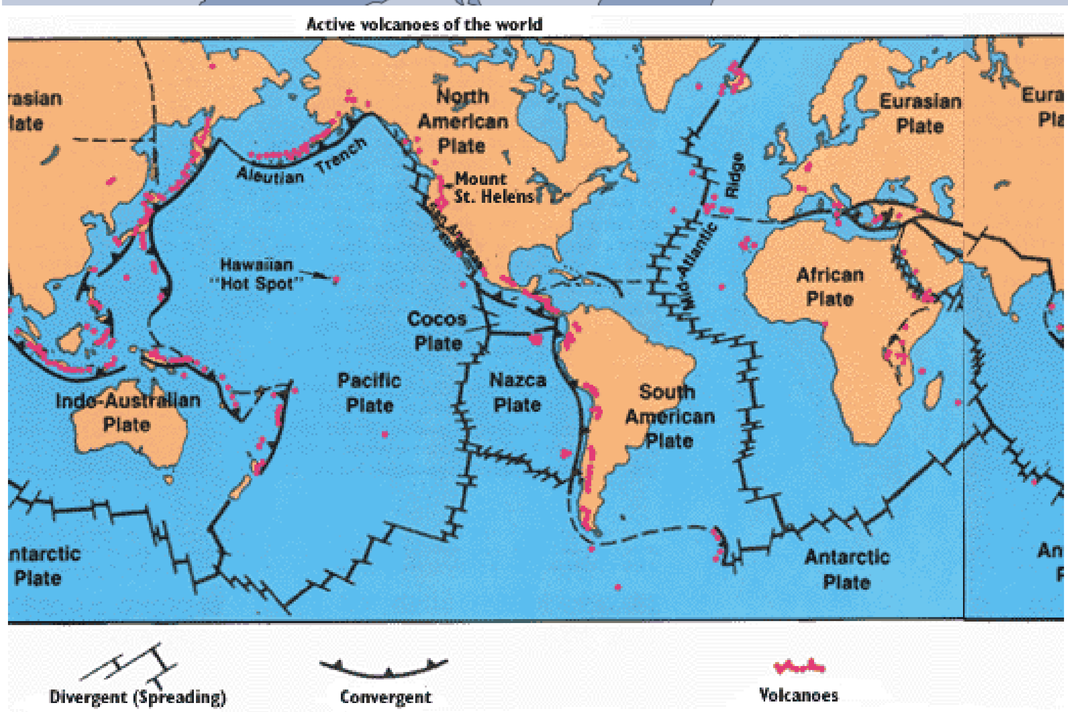
Tectonique des plaques

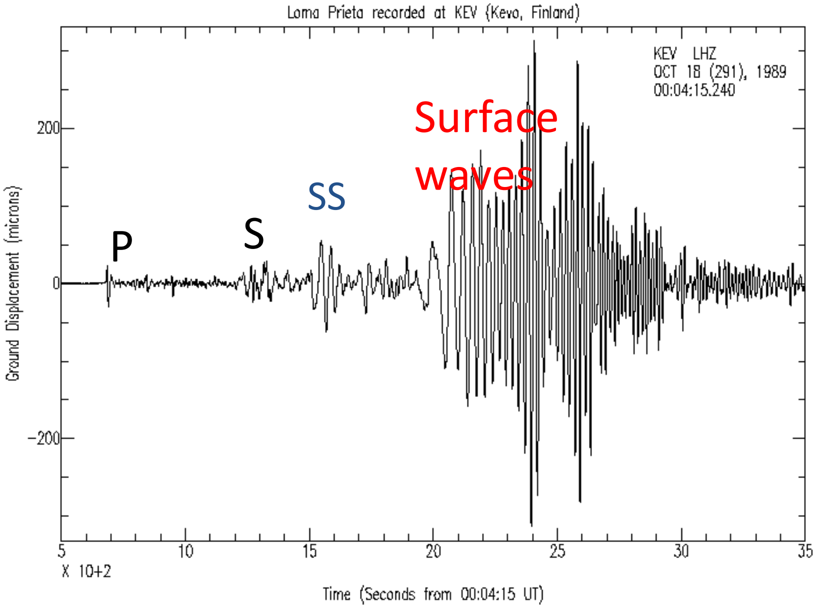



Eurasian plate
North American plate
Eurasian plate
Juan de Fuca plate
Filipino plate
Caribbean plate
Arabian plate
Indian plate
Cocos plate
EQUATOR
Nazca plate
Pacific plate
African plate
South American plate
Australian plate
Australian plate
Scotia plate
Antarctic plate

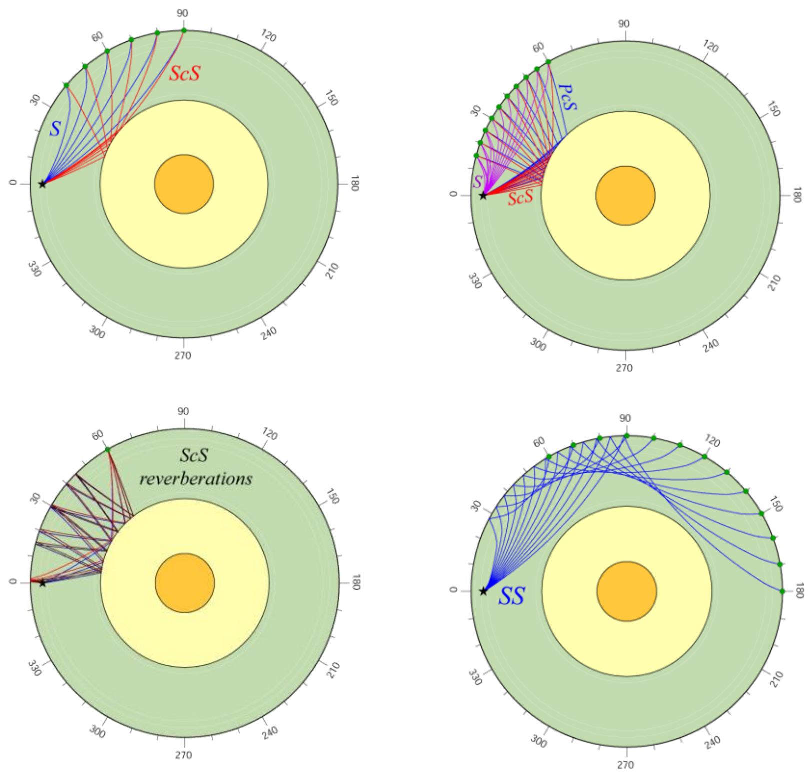

Japon, 2011
Haiti, 2010
Sumatra, 2004
Chili, 2010
New Zealand 2010,2011
70 - 300 km
300 - 700 km
Lamont-Doherty Earth Observatory of Columbia University, from Harvard CMT Data


Eurasian plate
North American plate
Eurasian plate
Juan de Fuca plate
Caribbean plate
Arabian plate
Filipino plate
Cocos plate
Indian plate
EQUATOR
Nazca plate
African plate
Pacific plate
Australian plate
South American plate
Australian plate
Scotia plate
Antarctic plate

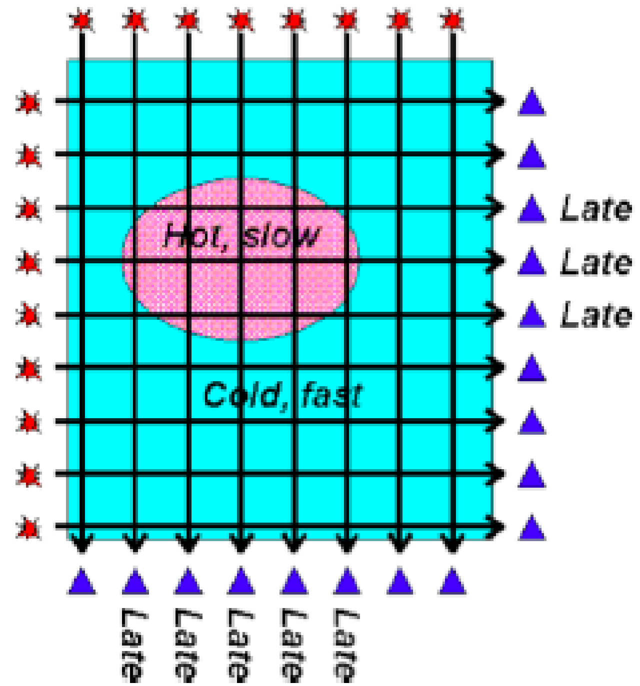

Active volcanoes of the world
North American Plate
Eurasian Plate
Aleutian Trench
Mount St. Helens
Mid-Atlantic Ridge
Hawaiian "Hot Spot"
African Plate
Cocos Plate
Pacific Plate
Nazca Plate
South American Plate
Indo-Australian Plate
Antarctic Plate
Divergent (Spreading)
Convergent
Volcanoes



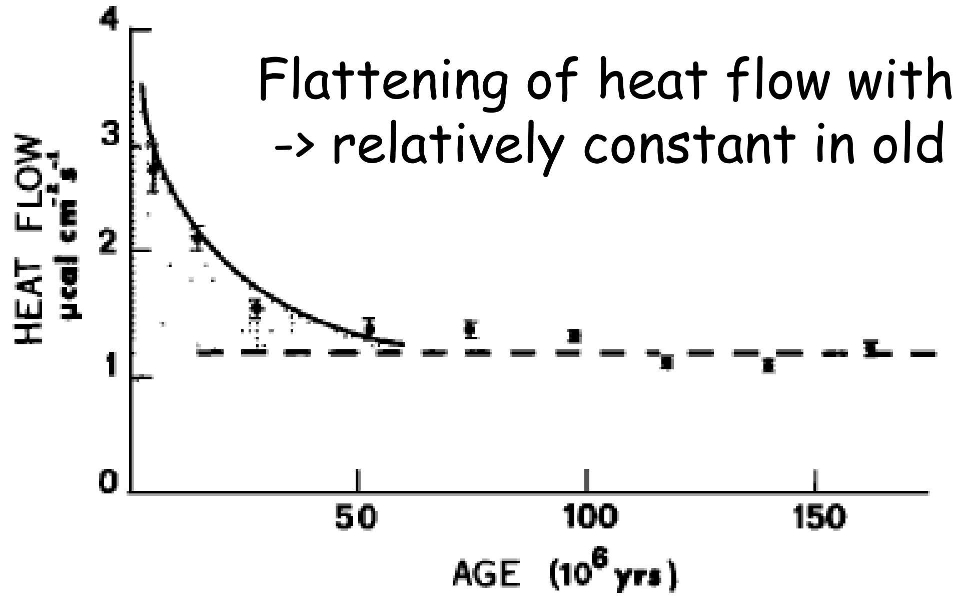
Loma Prieta recorded at KEV (Kevo, Finland)
KEV LHZ
OCT 18 (291), 1989
00:04:15.240
Surface waves
SS
S
P
Ground Displacement (microns)
Time (Seconds from 00:04:15 UT)
X 10+2



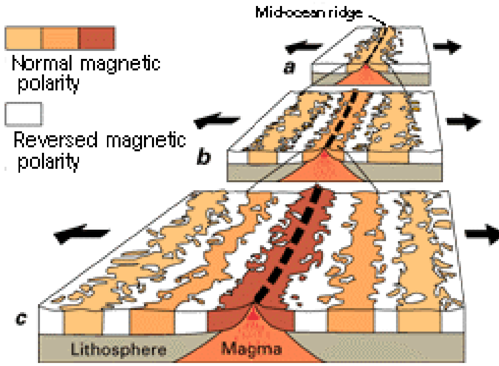
ScS
S
PcS
ScS reverberations
SS



Late
Late
Late
Hot, slow
Cold, fast
Late
Late
Late
Late
Late

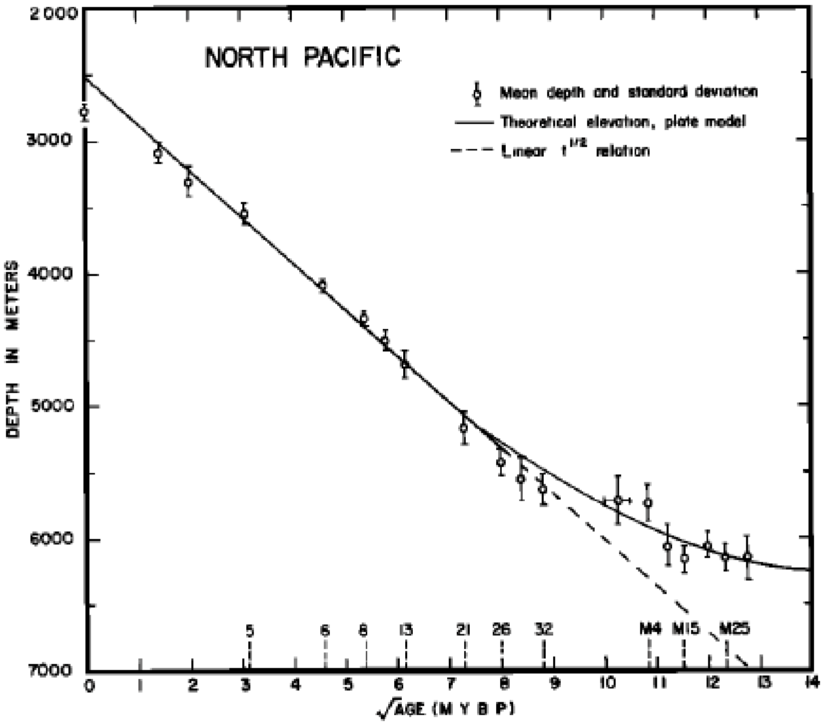


Flattening of heat flow with age
-> relatively constant in old ocean basins



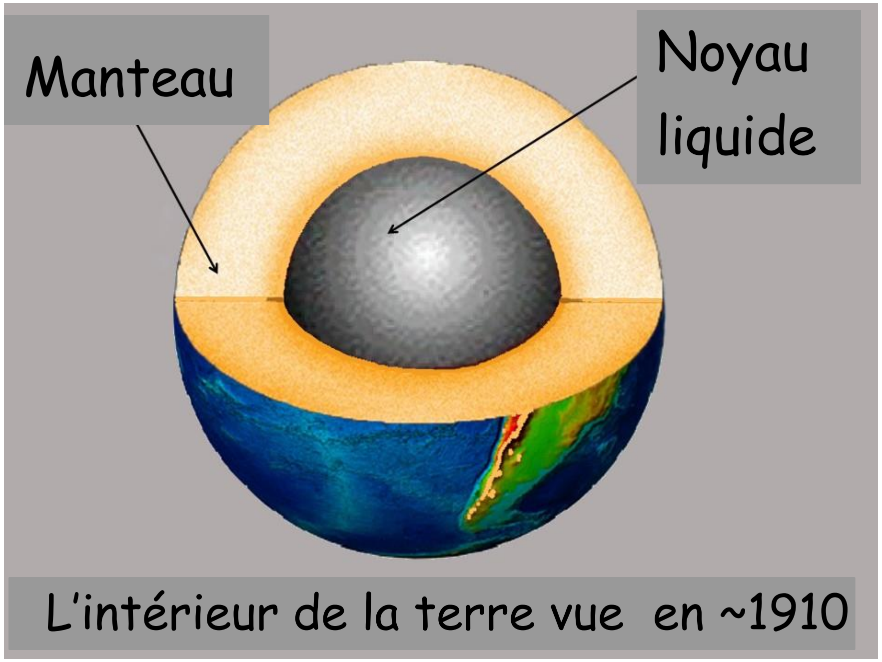
Sclater and Francheteau, 1970

Bathymetry departs from square root of age law at ages > 40 Ma



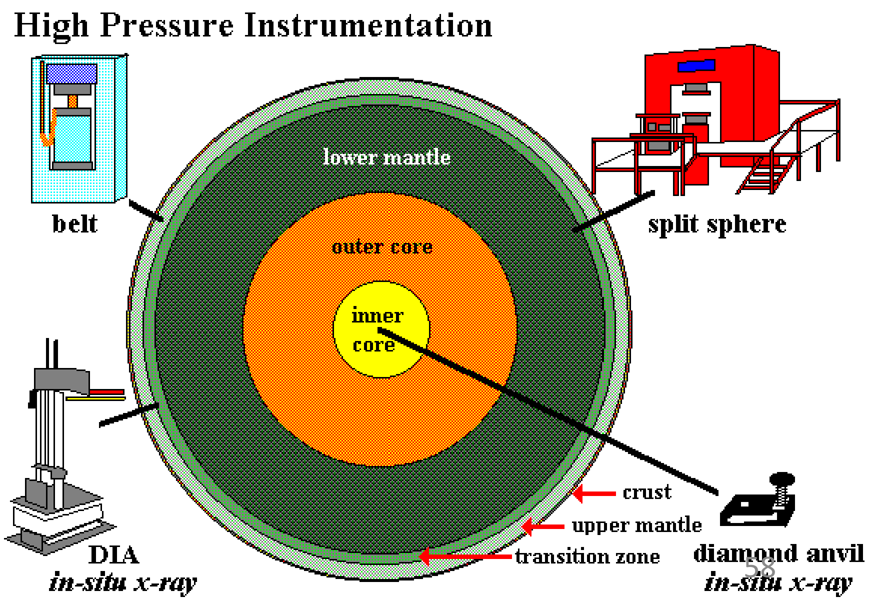
=> Plate model ~ constant supply of heat from below (McKenzie, 1967)

Parsons and Sclater, 1977

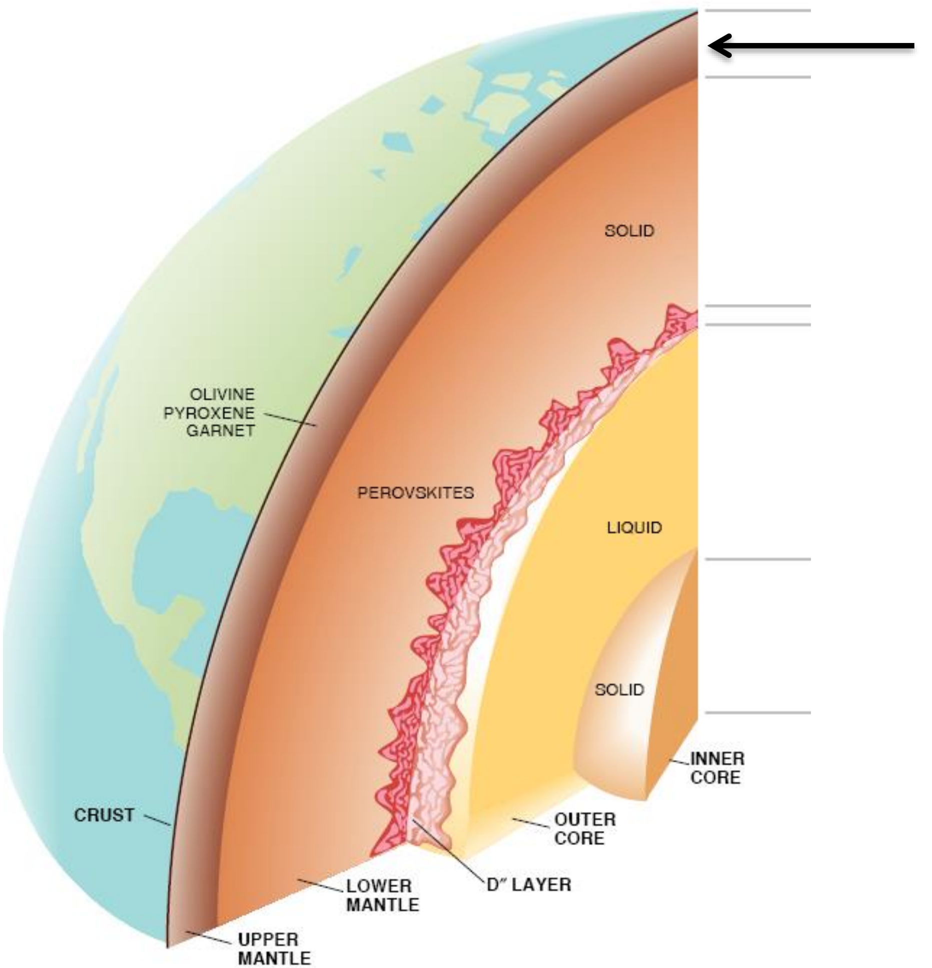


Densité moyenne de la terre:
ρ = 5515 kg/m^3
Densité des roches en surface:
~ 2600 kg/m^3 (granite)

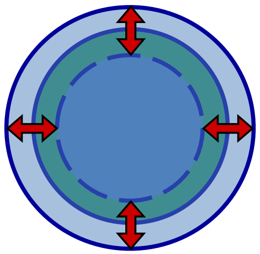
..et en 1970:

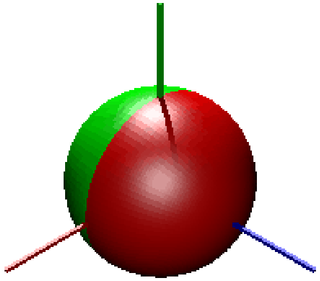


- Dans le manteau supérieur
  …… à 100-300 km de profondeur



Spheroidal normal modes: examples:



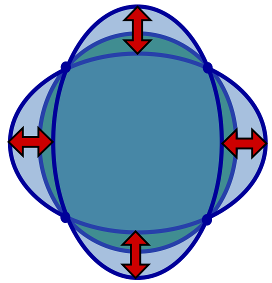


${}_0S_0$: « balloon » or

« breathing » :

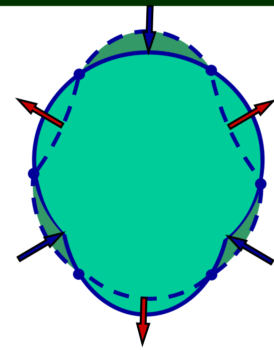
radial only

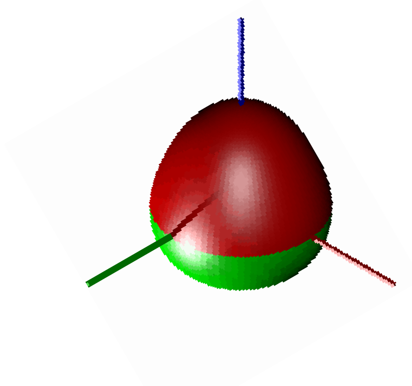
(20.5 minutes)



${}_0S_2$: « football » mode

(Fundamental, 53.9 minutes)

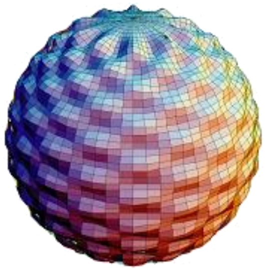




${}_0S_3$:

(25.7 minutes)

…



…

${}_0S_{29}$:

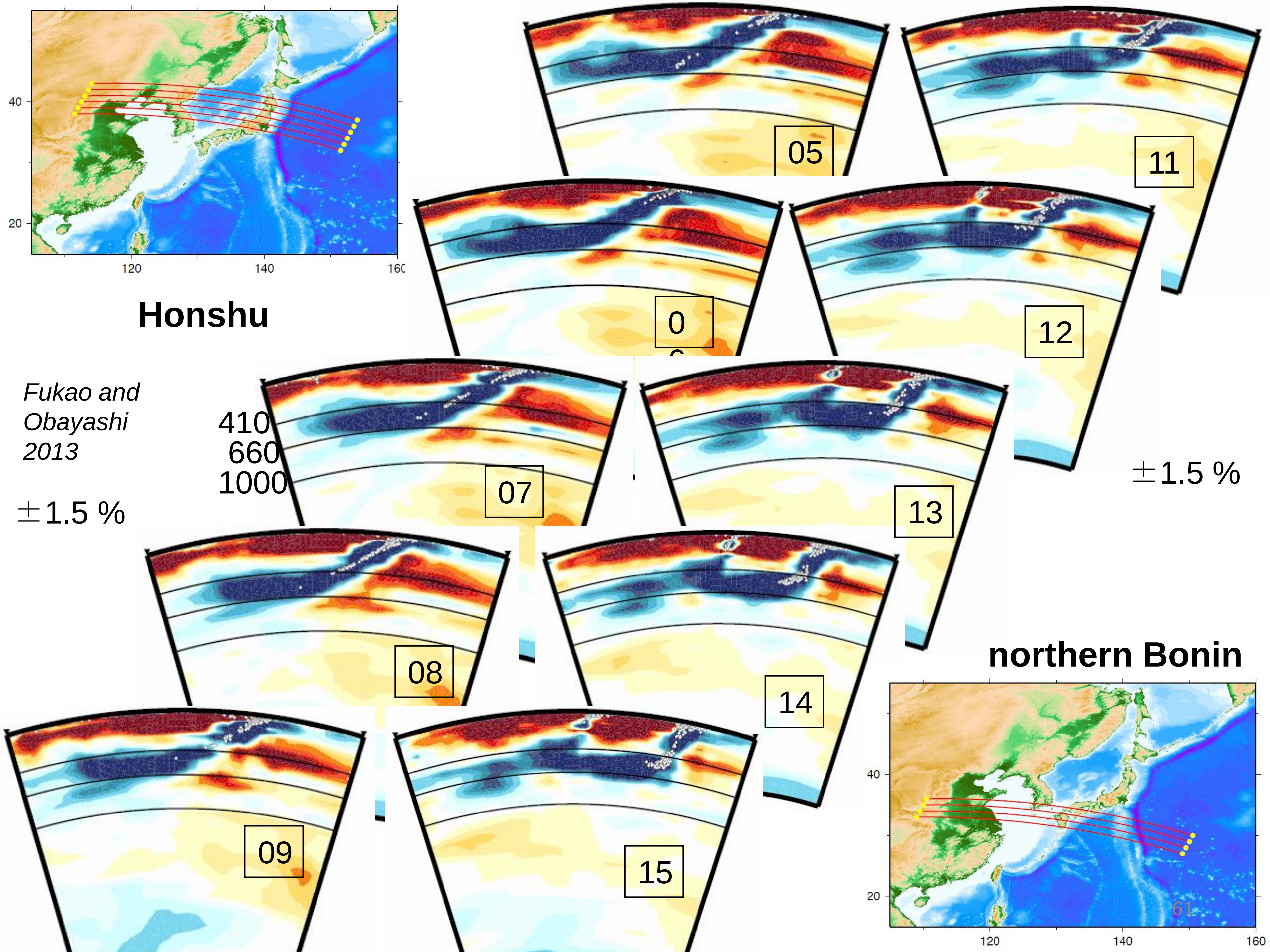
(4.5 minutes)

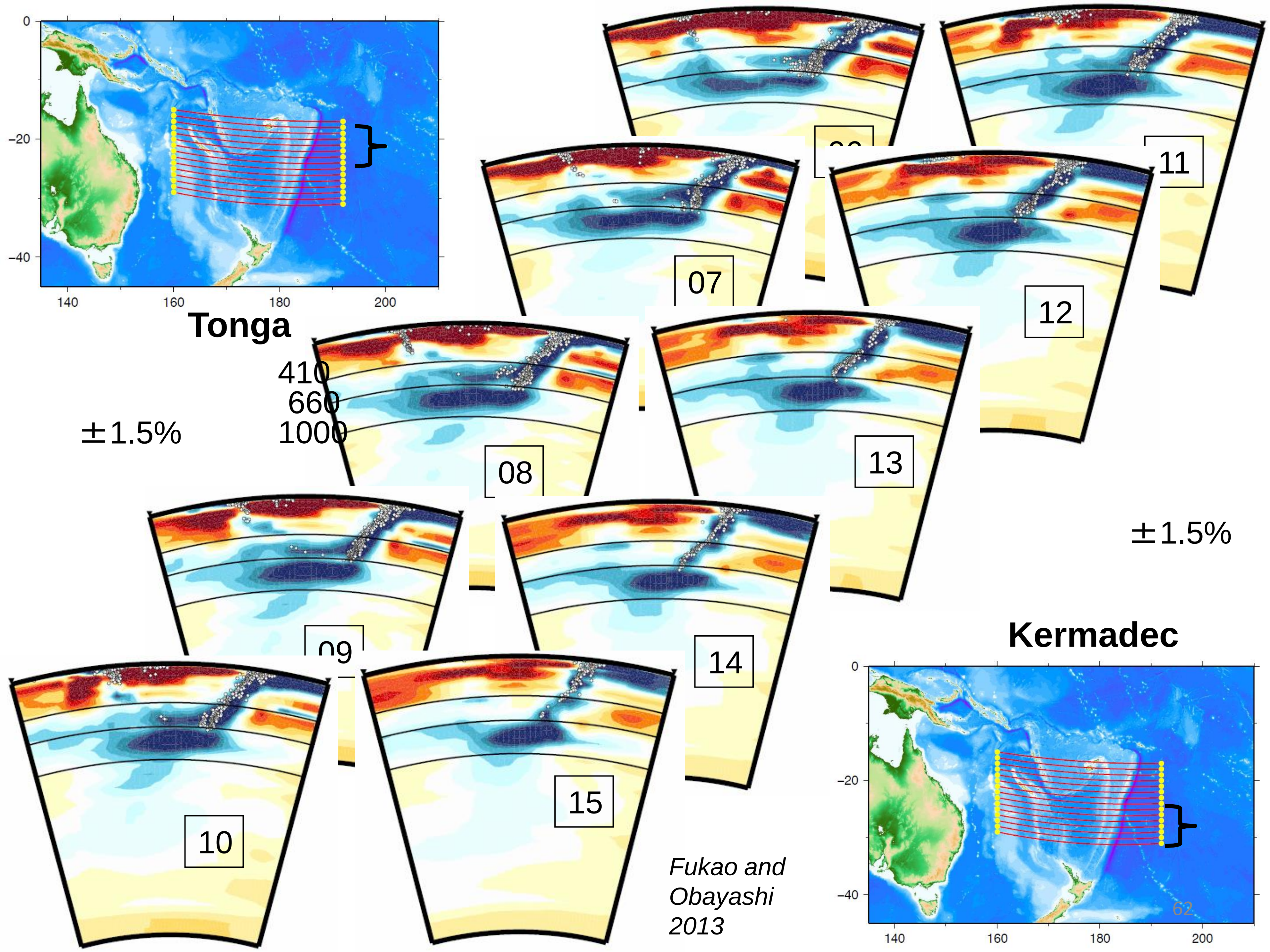
Rem: ${}_0S_1$= translatio

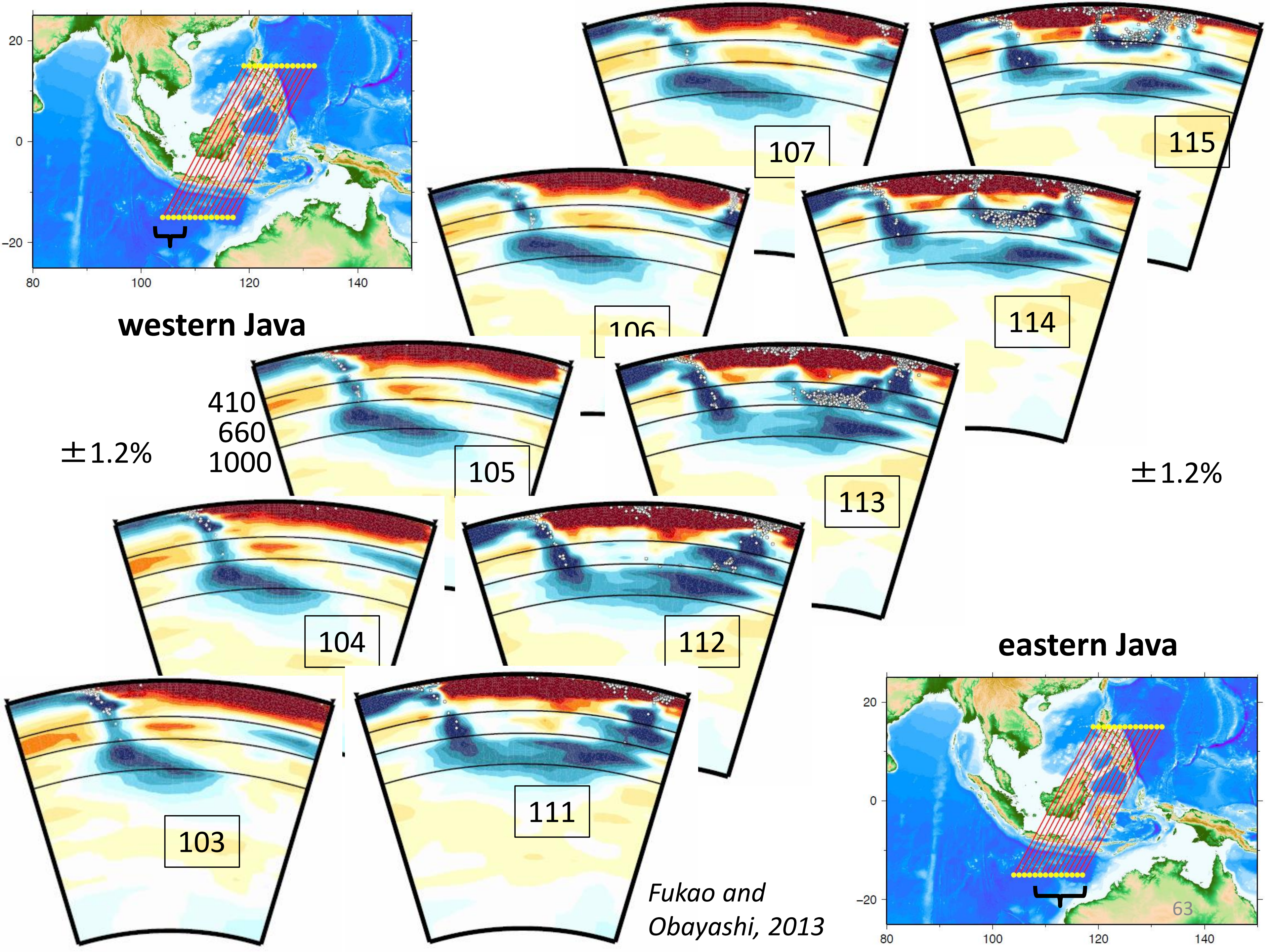
Animation ${}_0S_{0/3}$ from Lucien Saviot
http://www.u-bourgogne.fr/REACTIVITE/manapi/saviot/deform/

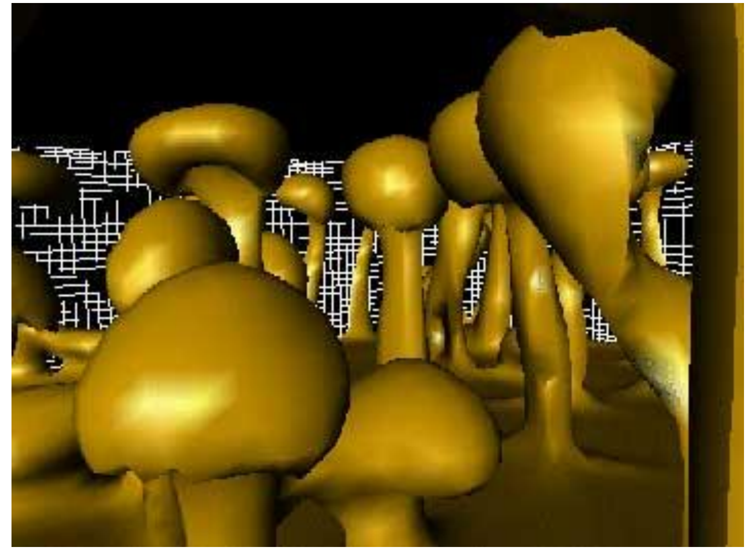
Animation ${}_0S_2$ from Hein Haak
http://www.knmi.nl/kenniscentrum/eigentrillingen-sumatra.html

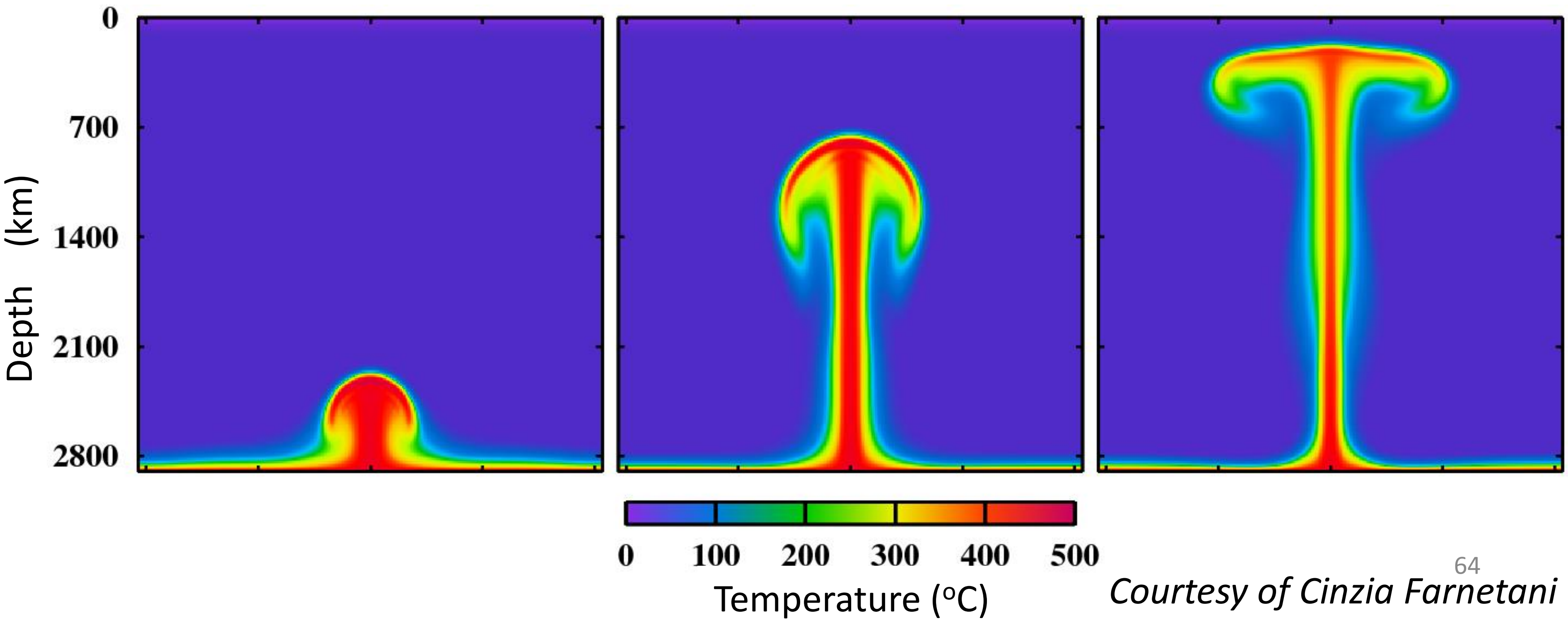
${}_0S_{29}$ from:
http://wwwsoc.nii.ac.jp/geod-soc/web-text/part3/nawa/nawa-1_files/Fig1.jpg


Honshu
Fukao and Obayashi 2013
410
660
1000
±1.5 %
05
11
0
12
07
13
08
14
09
15
±1.5 %
northern Bonin
40
20
120
140
160

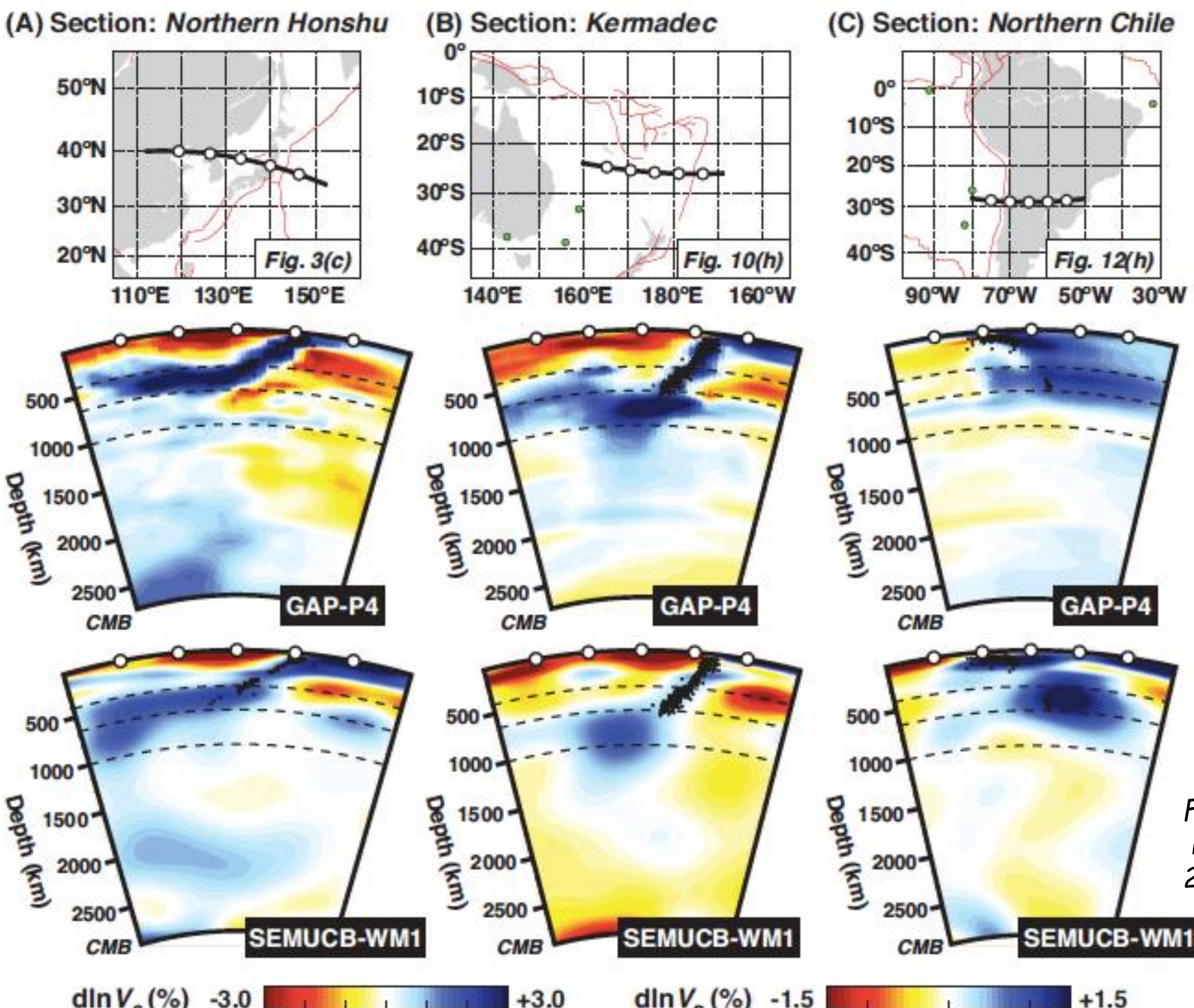

Tonga
410
660
1000
±1.5%
07
08
09
10
11
12
13
14
15
±1.5%
Kermadec
0
−20
−40
140
160
180
200
Fukao and Obayashi 2013
62


western Java
eastern Java
410
660
1000
±1.2%
±1.2%
103
104
105
106
107
111
112
113
114
115
20
0
−20
80
100
120
140
Fukao and Obayashi, 2013



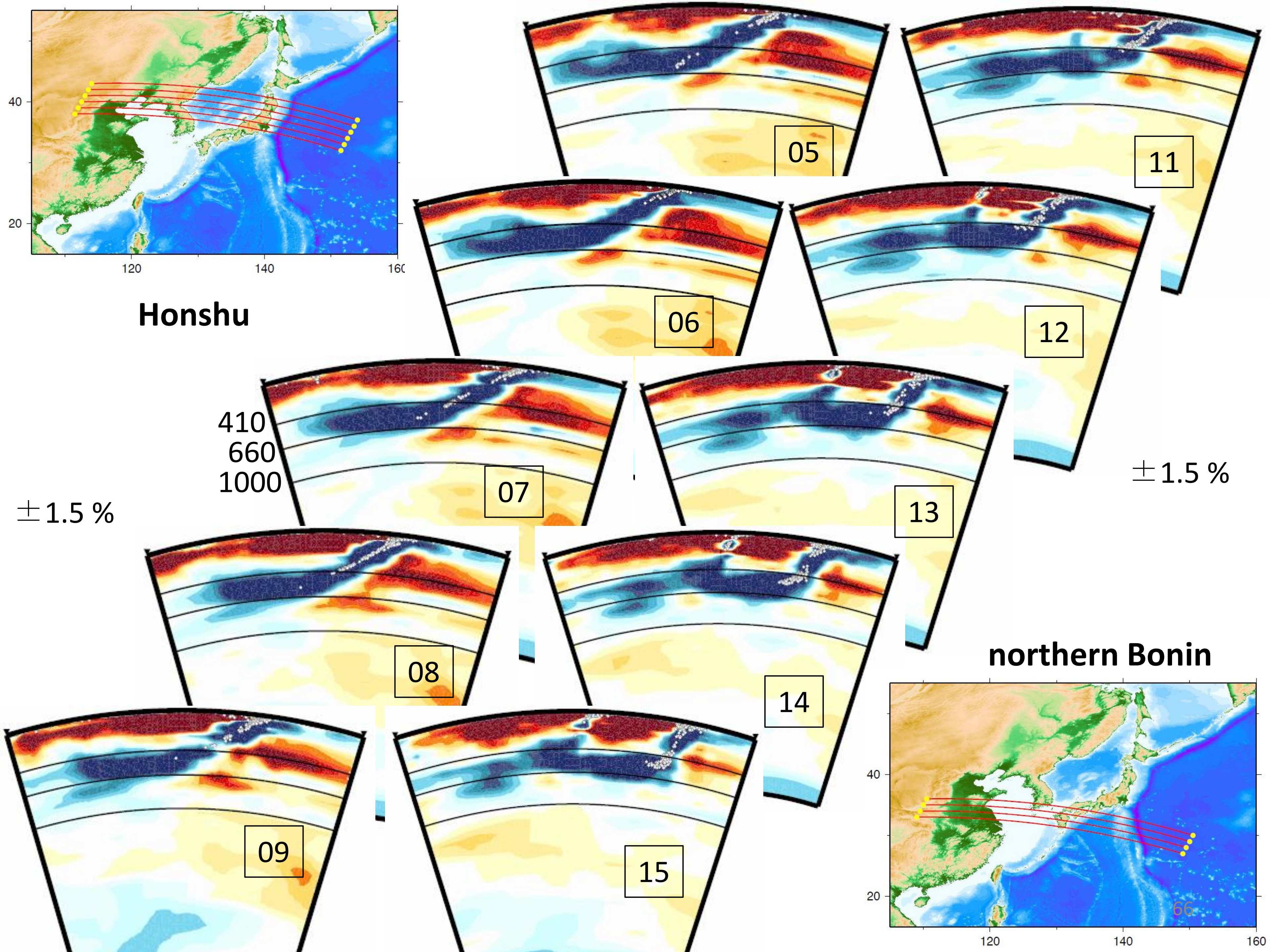


Courtesy of Cinzia Farnetani



Fukao and Obayashi, 2013

French and Romanowicz, 2014



40
20
120
140
Honshu
05
11
06
12
410
660
1000
07
13
±1.5 %
±1.5 %
08
14
northern Bonin
09
15
40
20
120
140
160