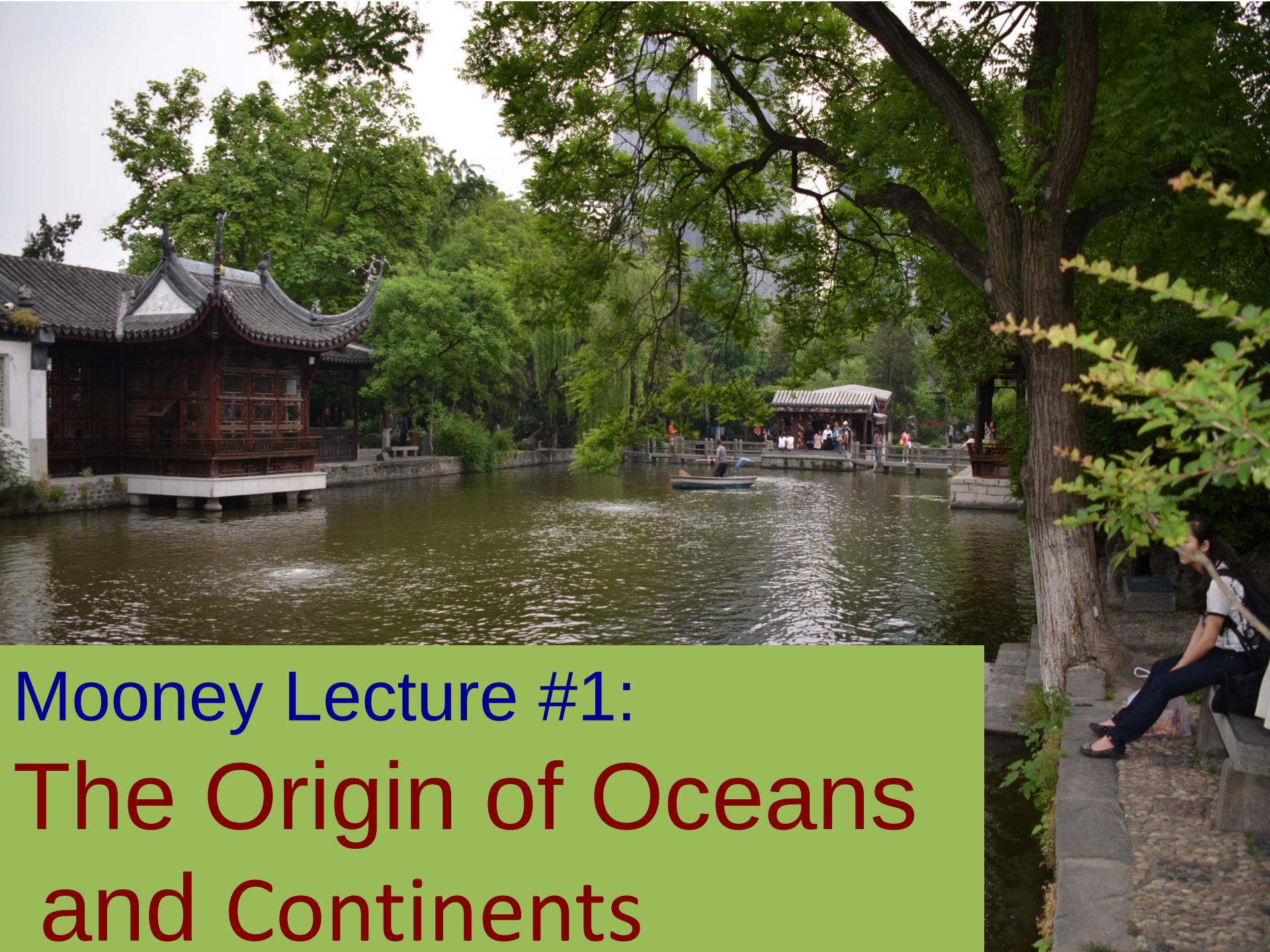
University of Trieste

October 2, 2019

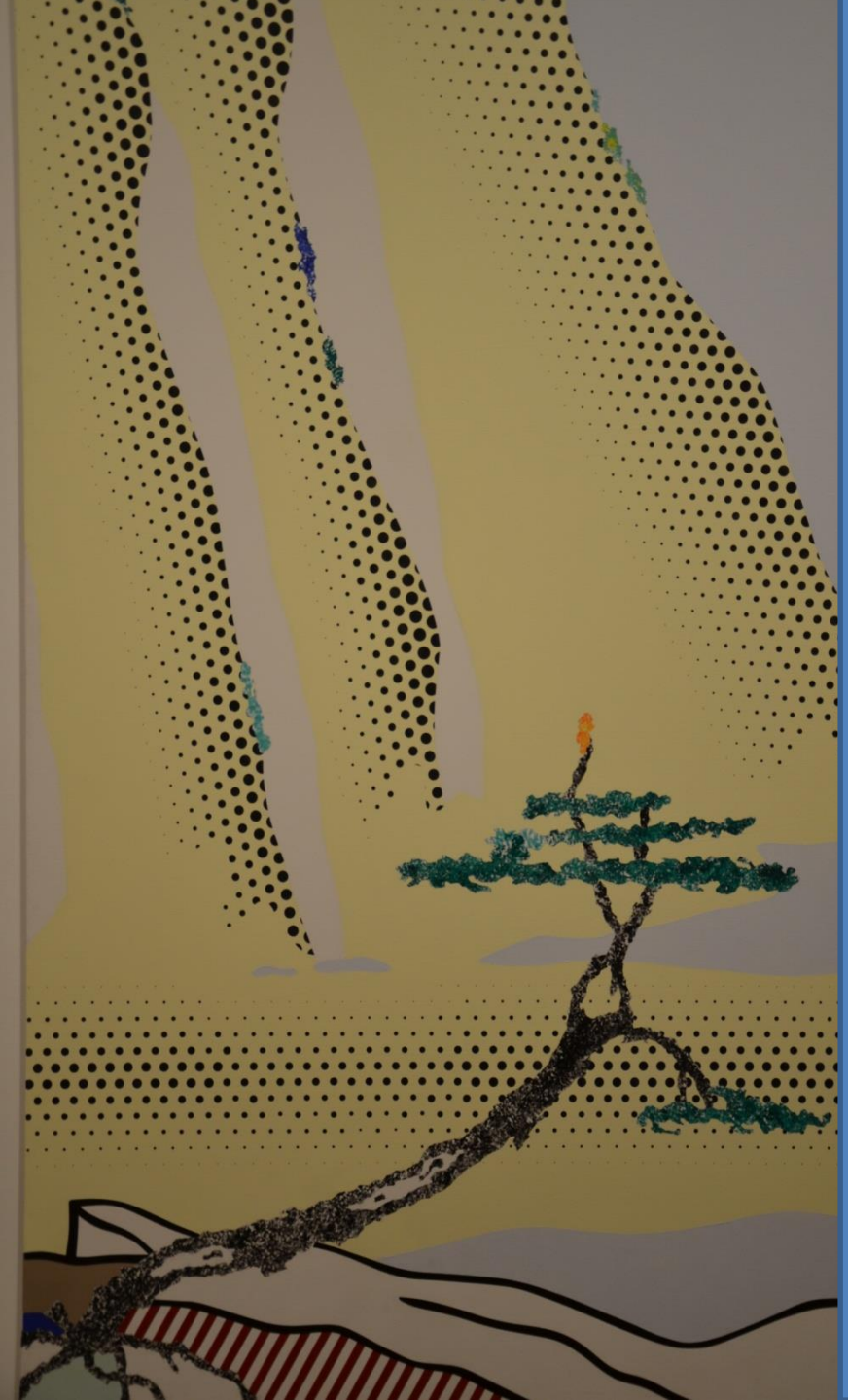
Prof. Walter D. Mooney
US Geological Survey
Menlo Park, California USA
mooney@usgs.gov

"The Origin Of Oceans And Continents"



Mooney Lecture #1:

The Origin of Oceans and Continents



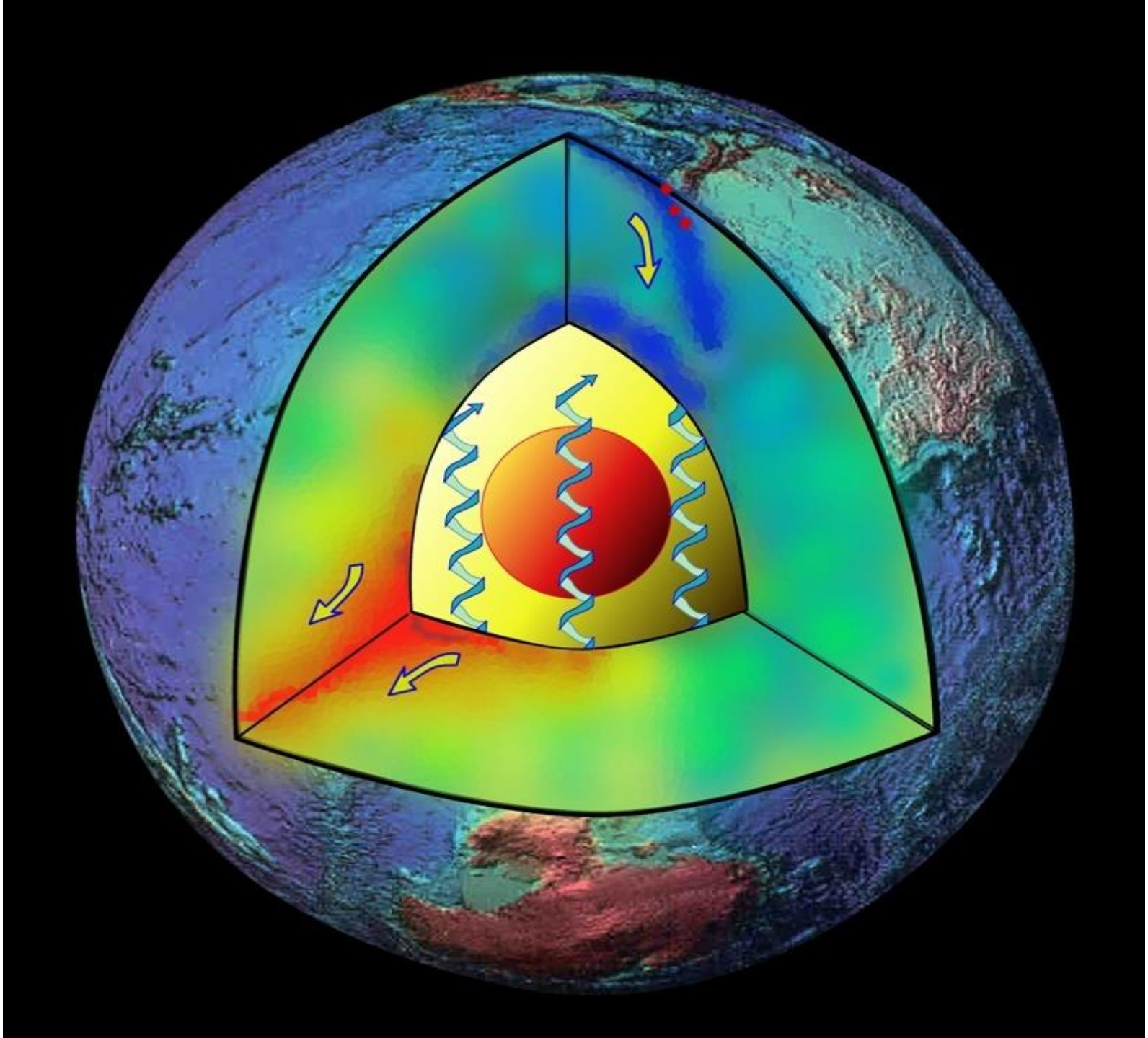
Thank you for this Invitation.

Magdala Tesauro

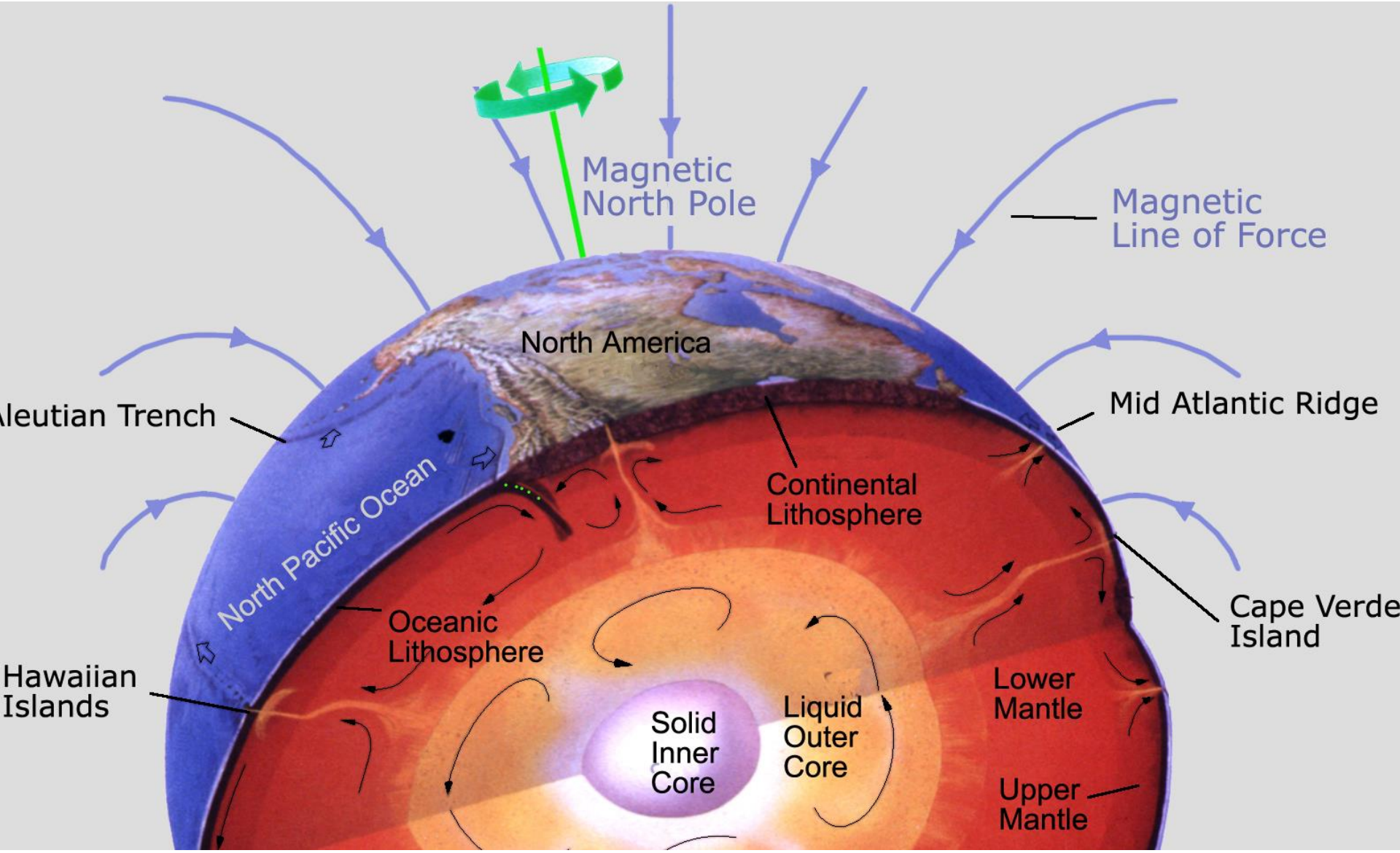
USGS Walter Mooney's Research Group

You are welcome to visit us at the USGS.

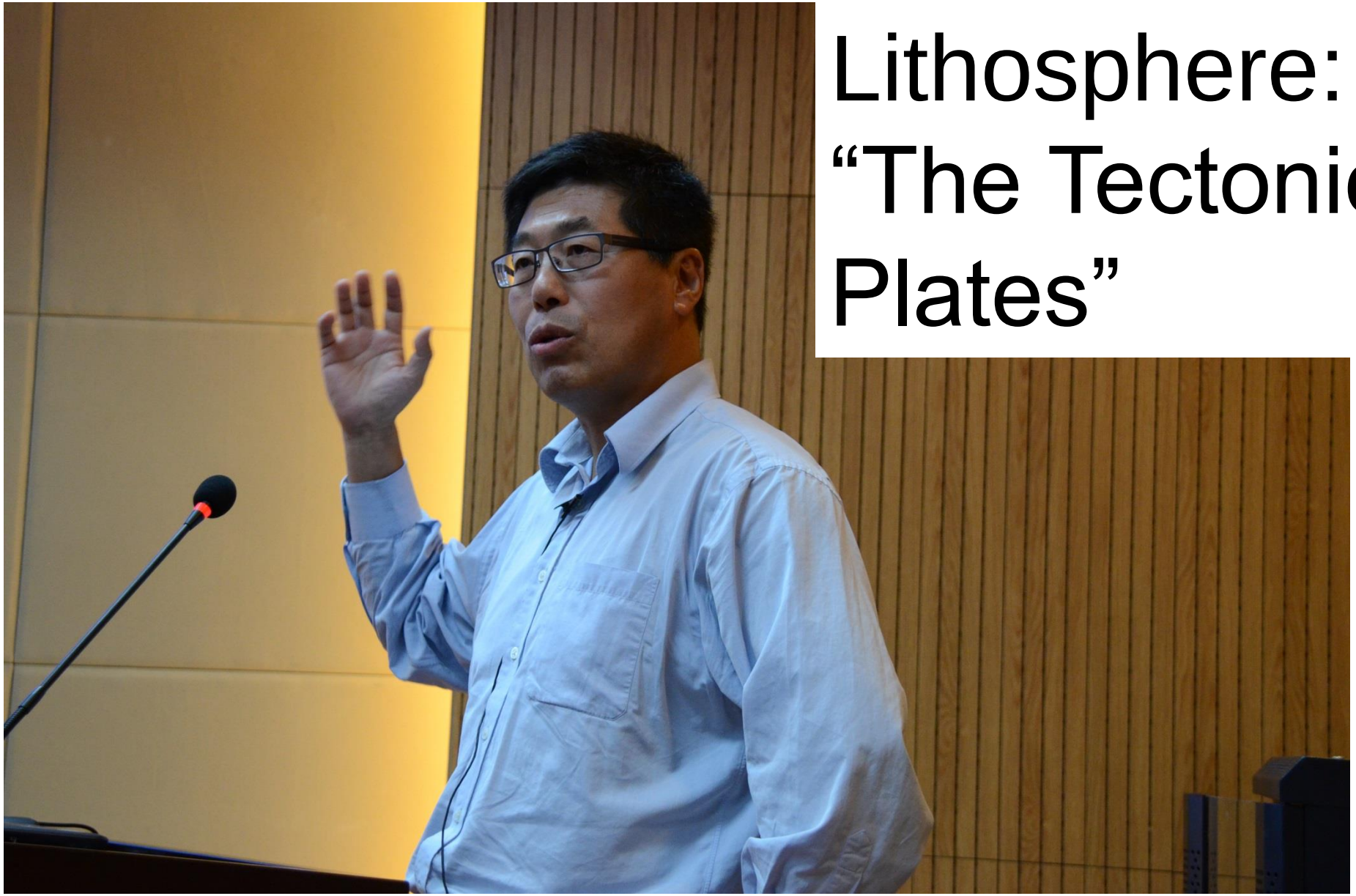

San
Francisco



Convection in the Earth



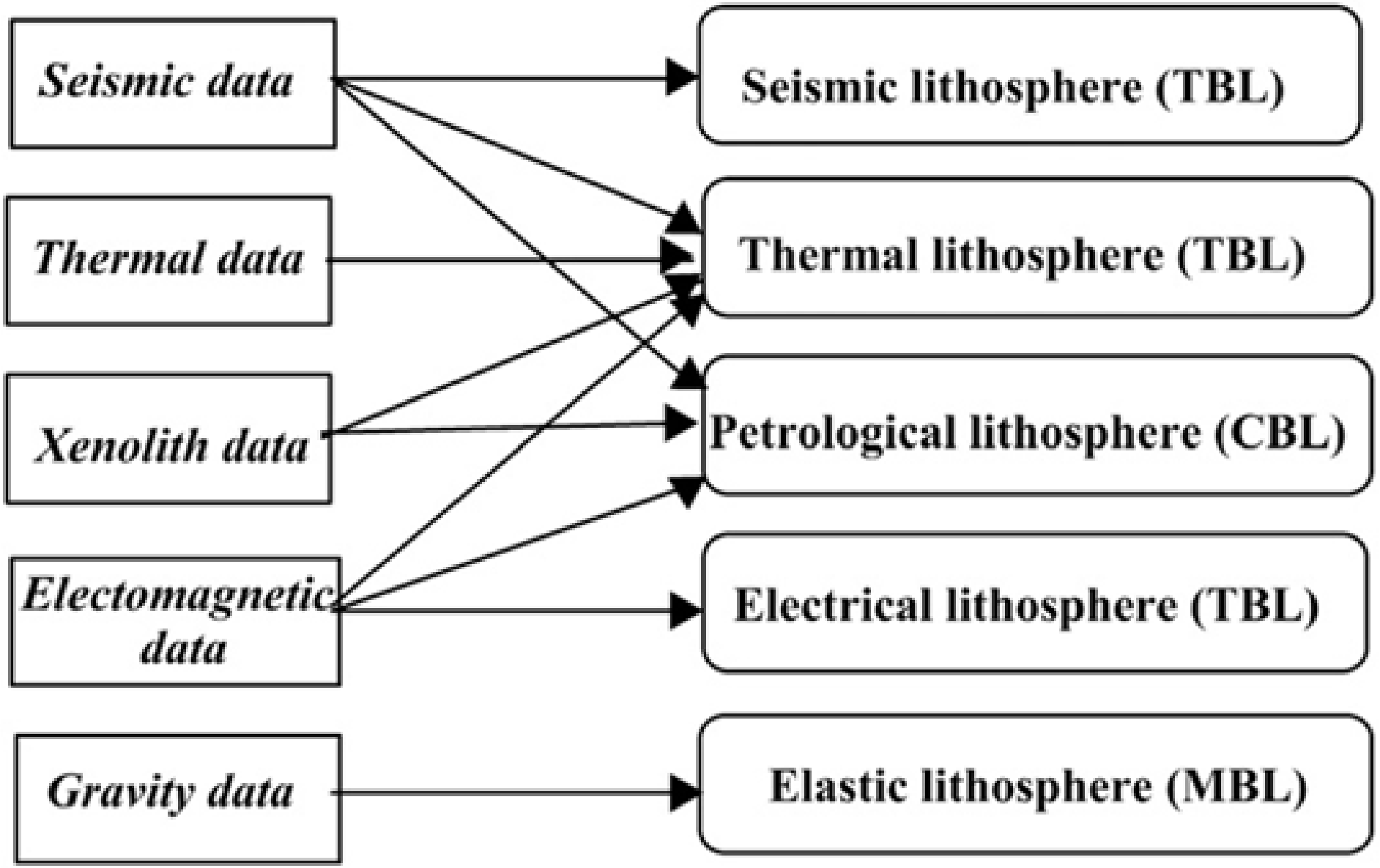

What is the
Lithosphere?



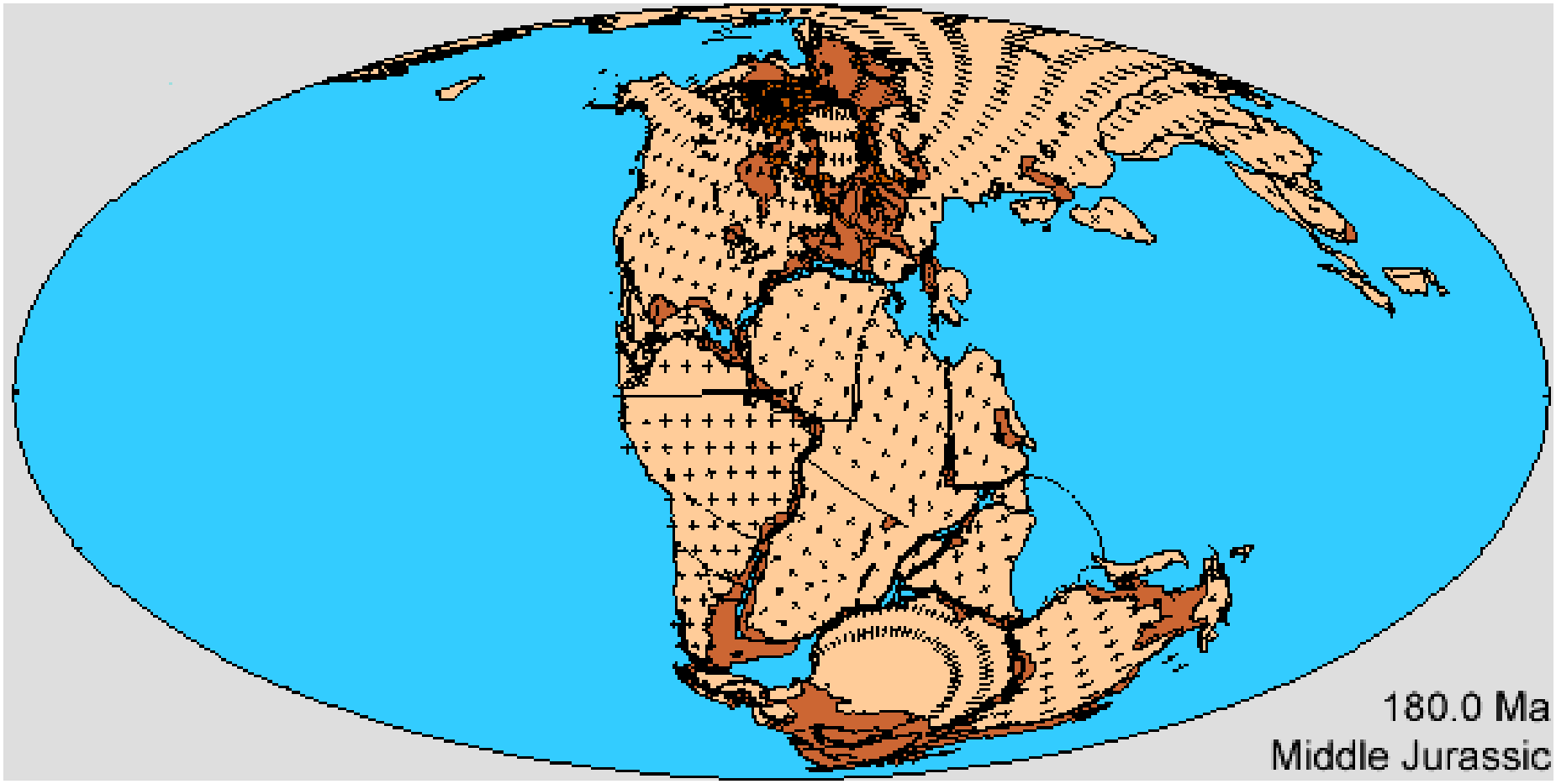
Lithosphere: “The Tectonic Plates”

Lithosphere:

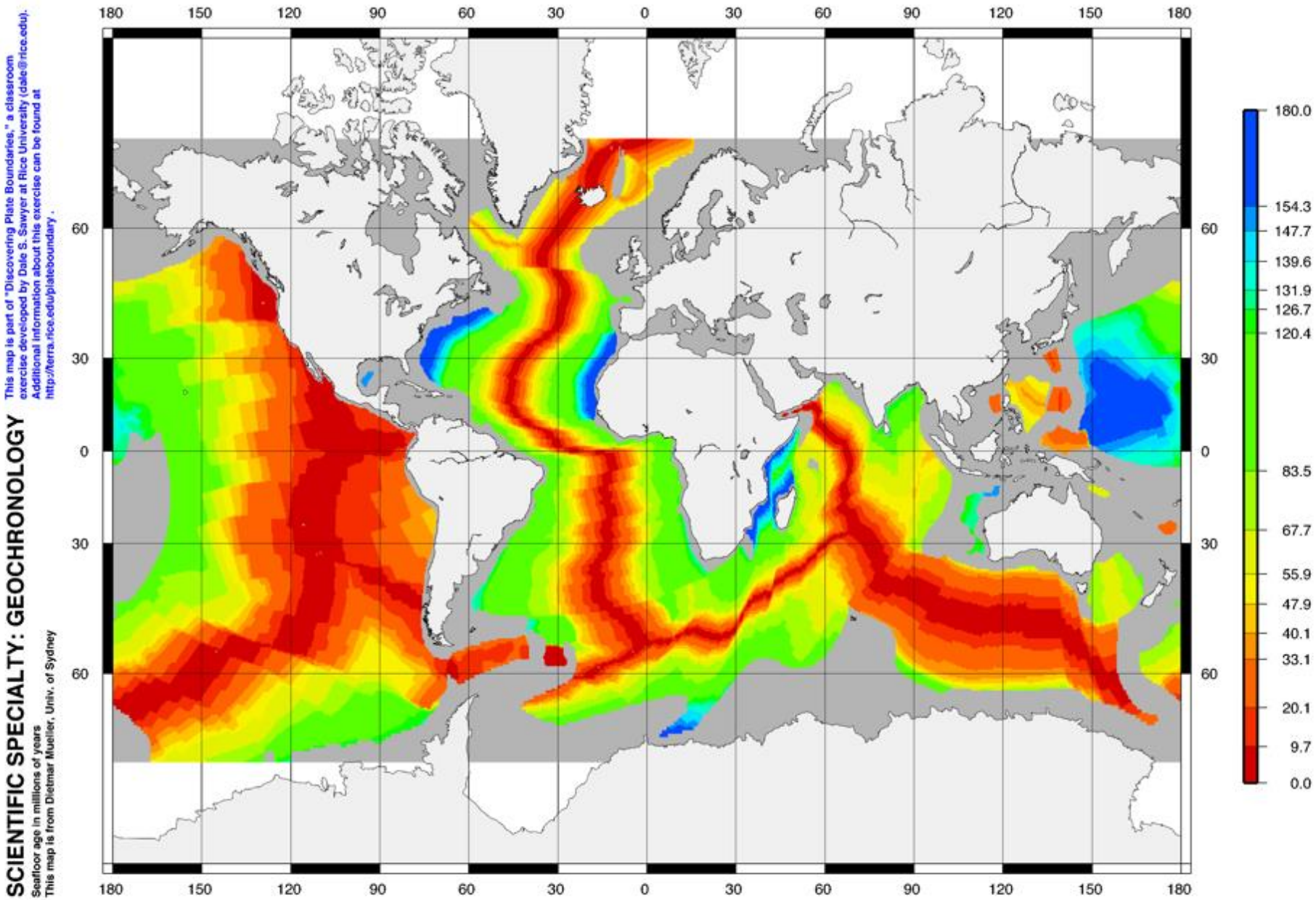
"Based on Seismology"


Seismic data
Thermal data
Xenolith data
Electomagnetic data
Gravity data
Seismic lithosphere (TBL)
Thermal lithosphere (TBL)
Petrological lithosphere (CBL)
Electrical lithosphere (TBL)
Elastic lithosphere (MBL)

Seafloor spreading

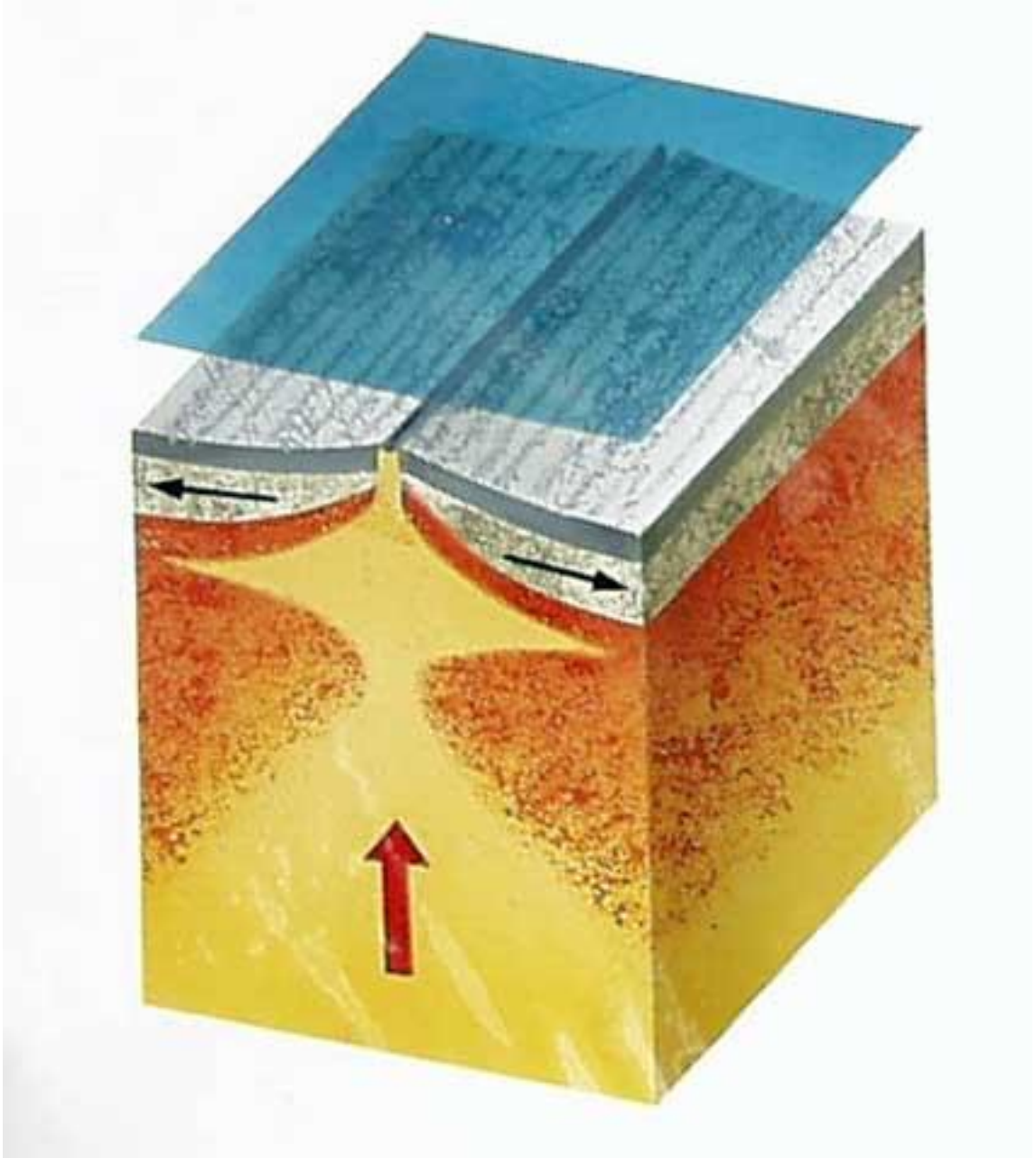


Source: Dietmar Muller,



http://terra.rice.edu/plateboundary/index.html

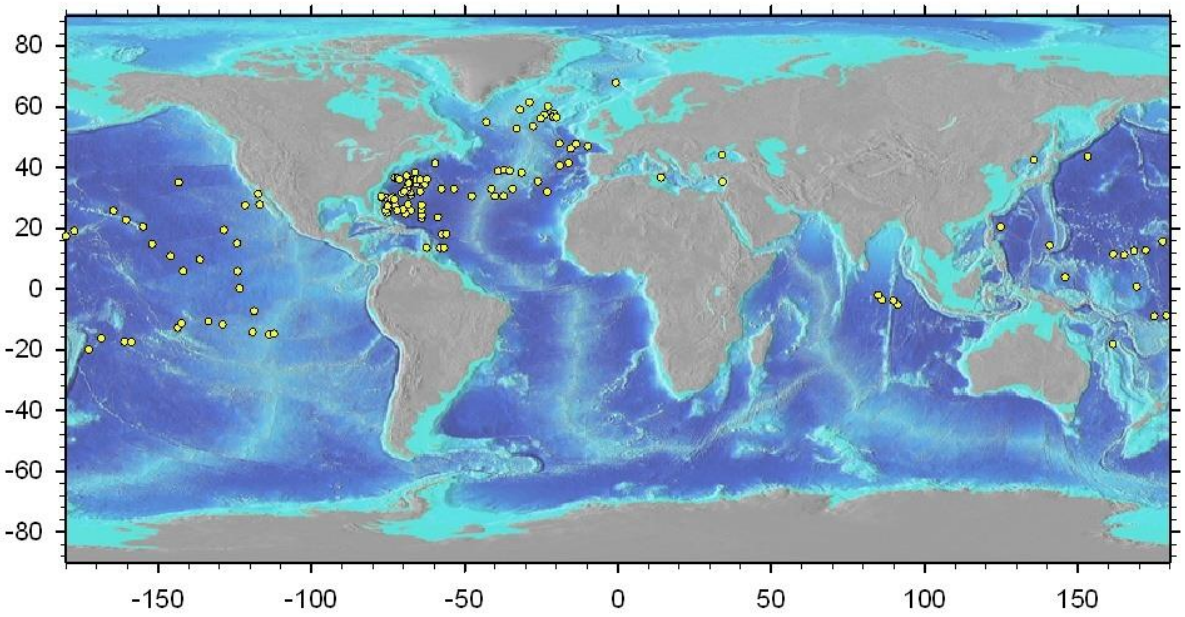
Mid-ocean ridge



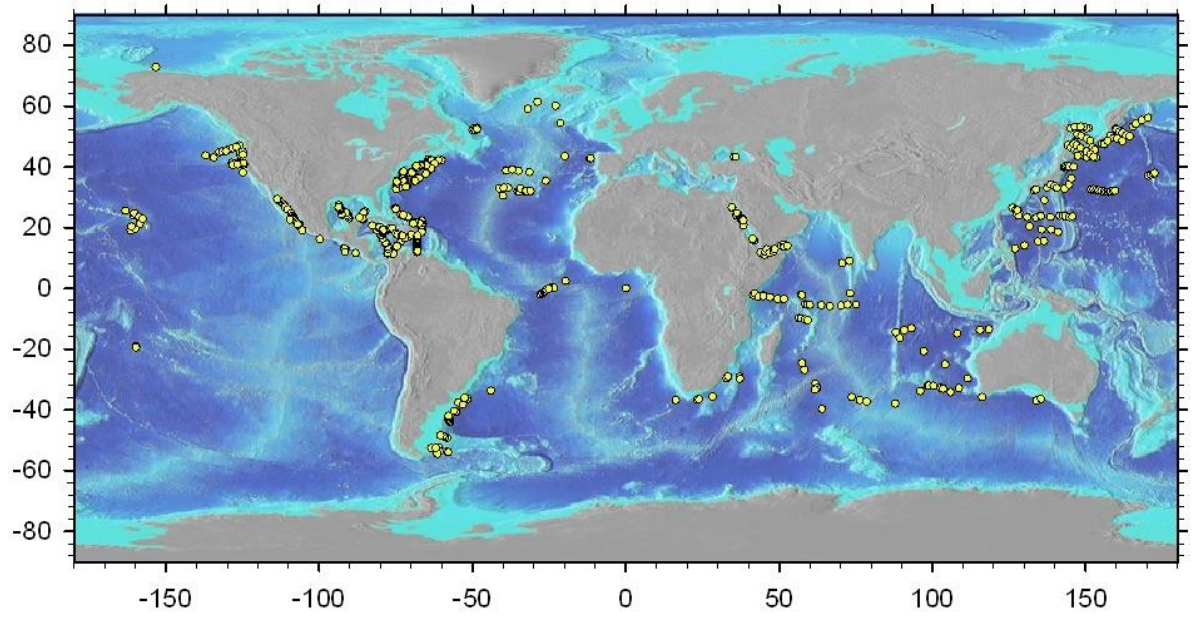
Marine Geophysicists in 1960's

George Shor, Maurice Ewing and Russell W. Raitt

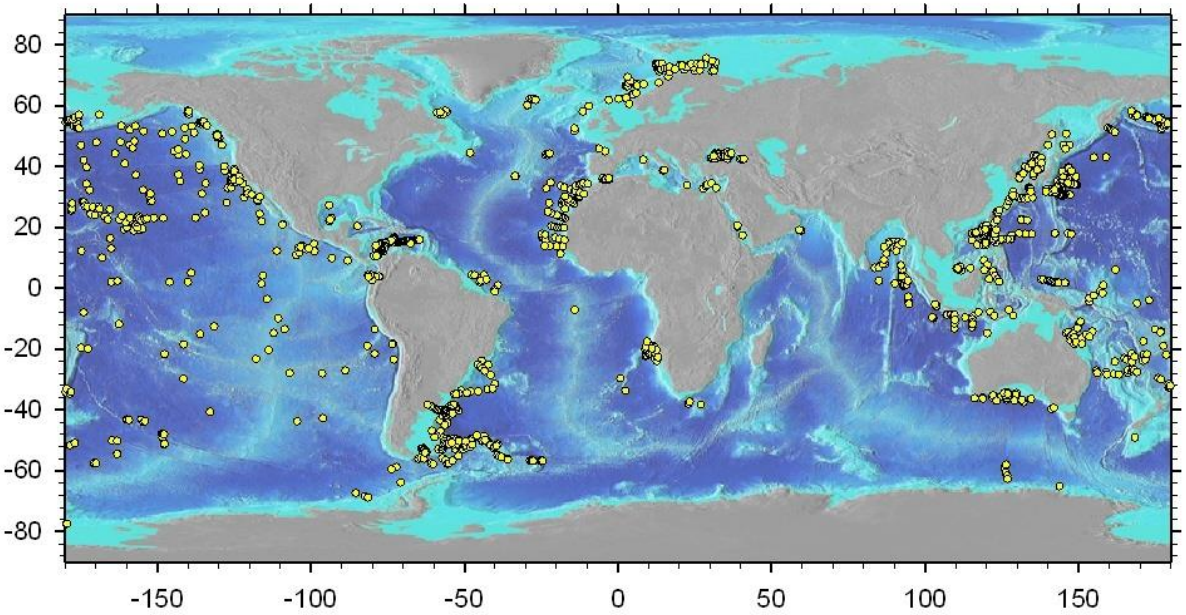
1950-1959: worldwide oceanic crust with bathymetry < - 250 m



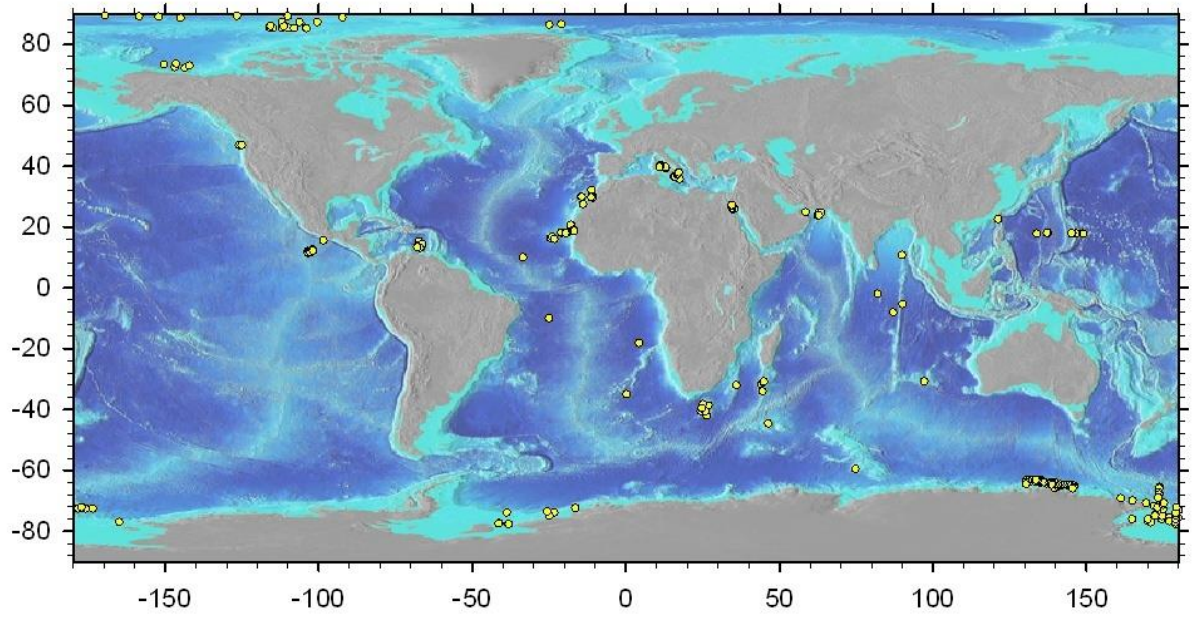
1960-1969: worldwide oceanic crust with bathymetry < - 250 m



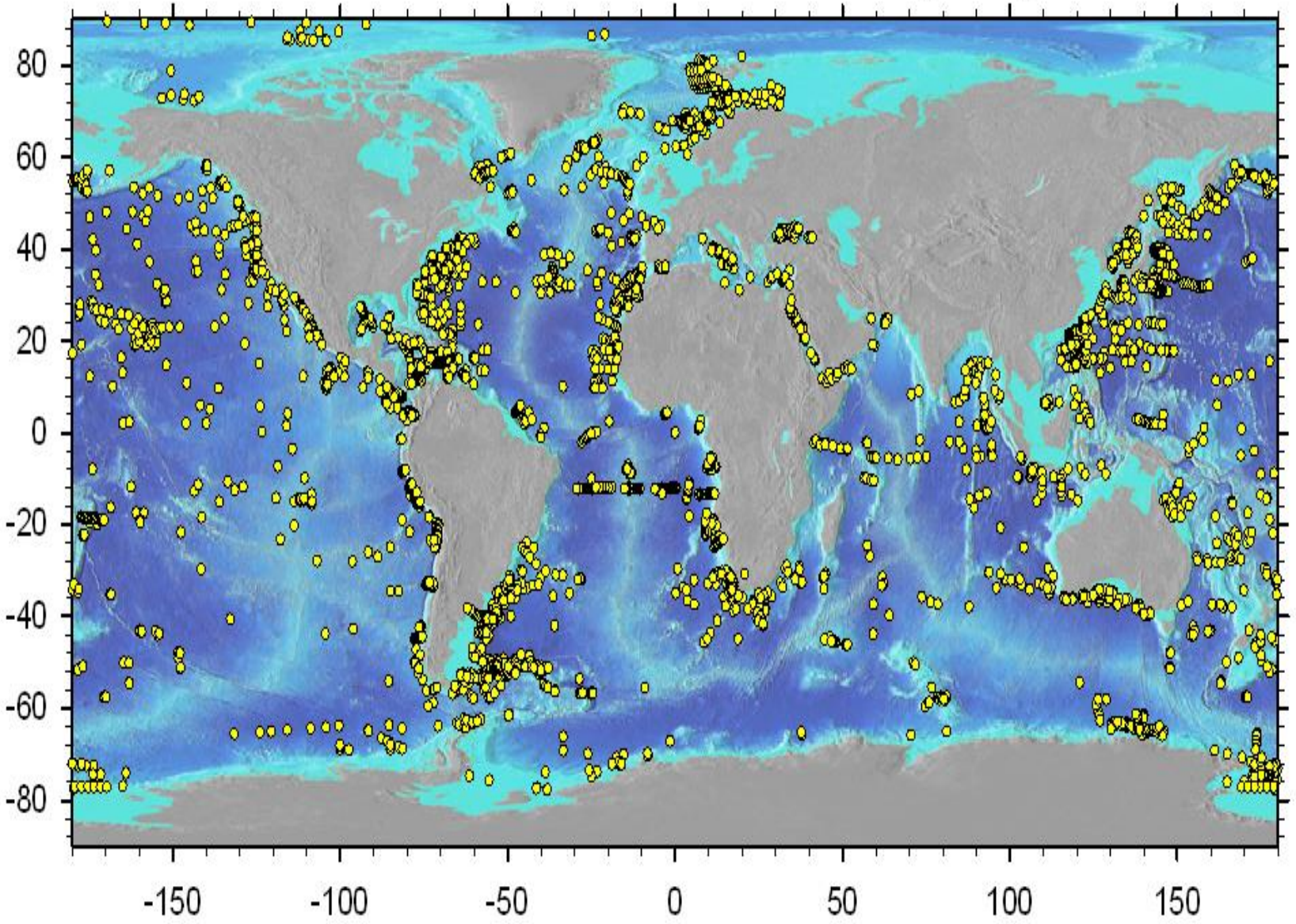
1970-1979: worldwide oceanic crust with bathymetry < - 250 m



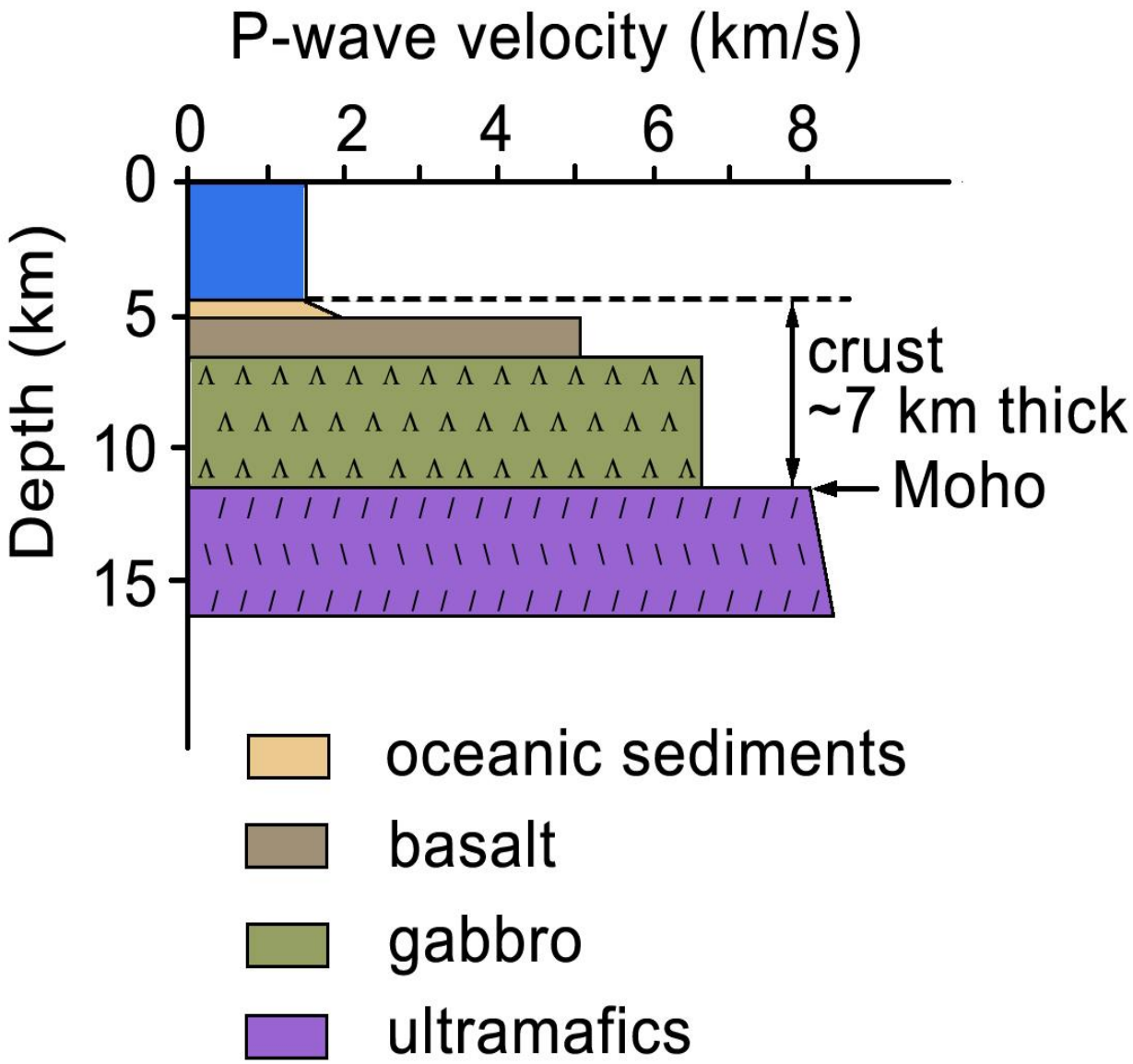
1980-1989: worldwide oceanic crust with bathymetry < - 250 m



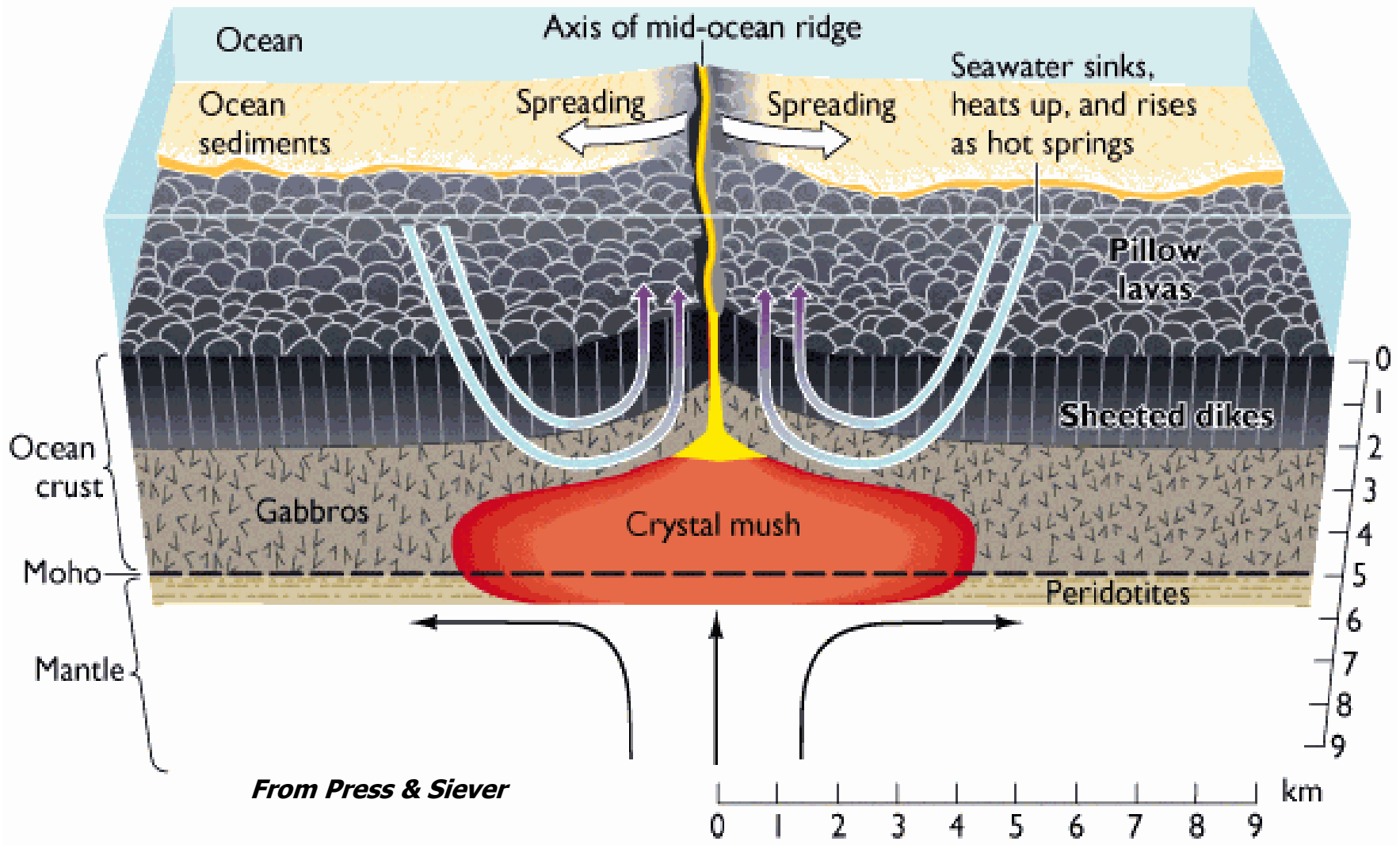
1950-2010: worldwide oceanic crust with bathymetry < - 250 m



Oceanic Crust



Generation of Earth's Oceanic Crust

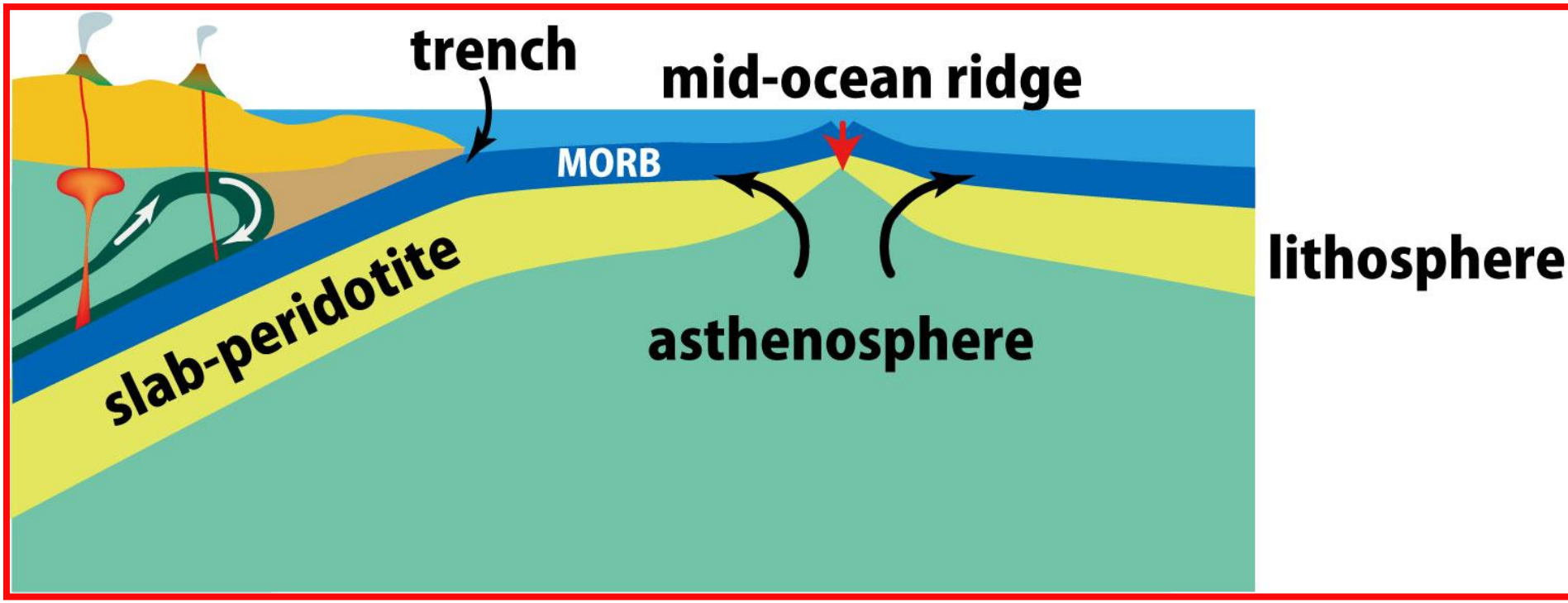


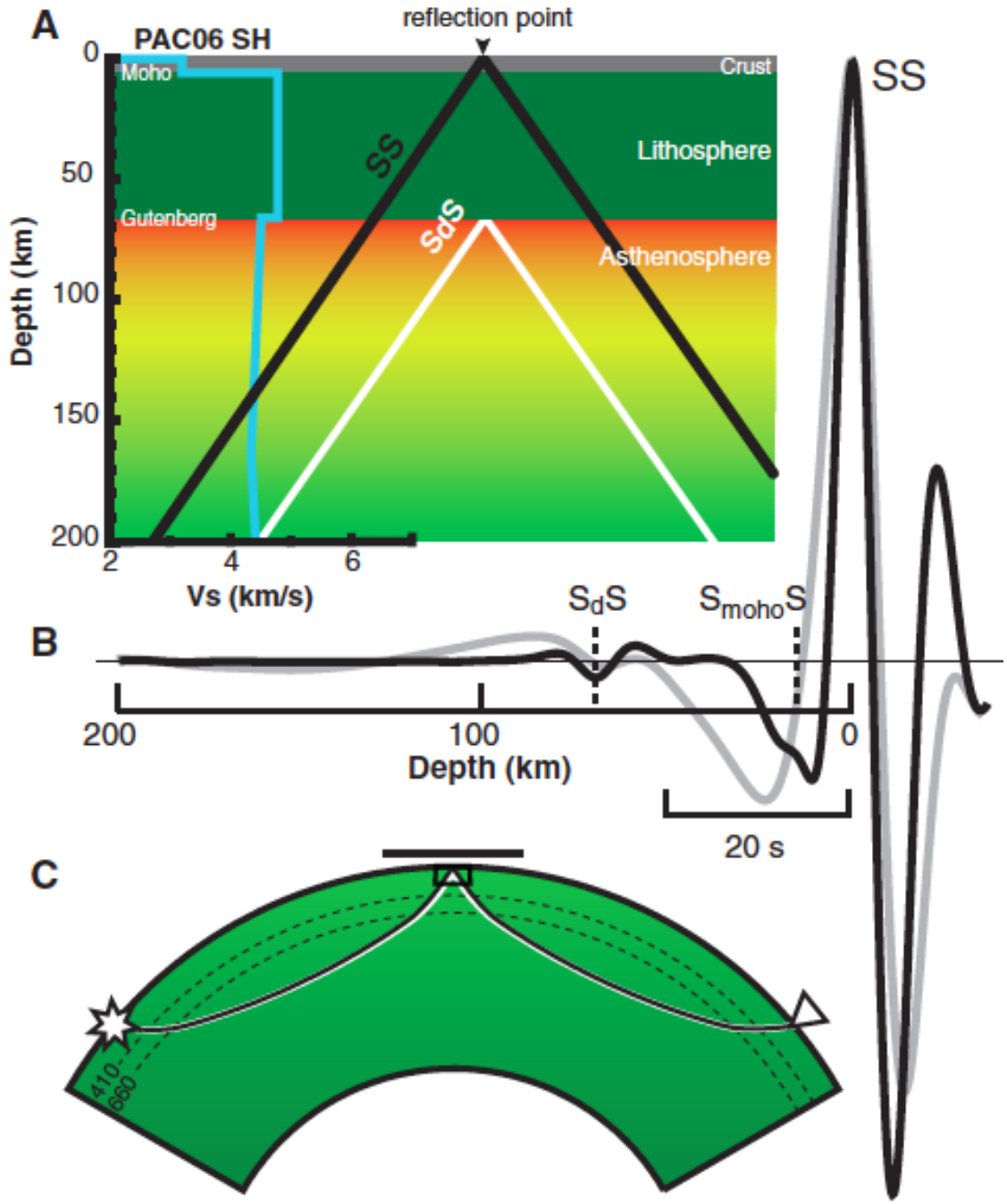
From Press & Siever

Columnar Basalt, Japan (2014)

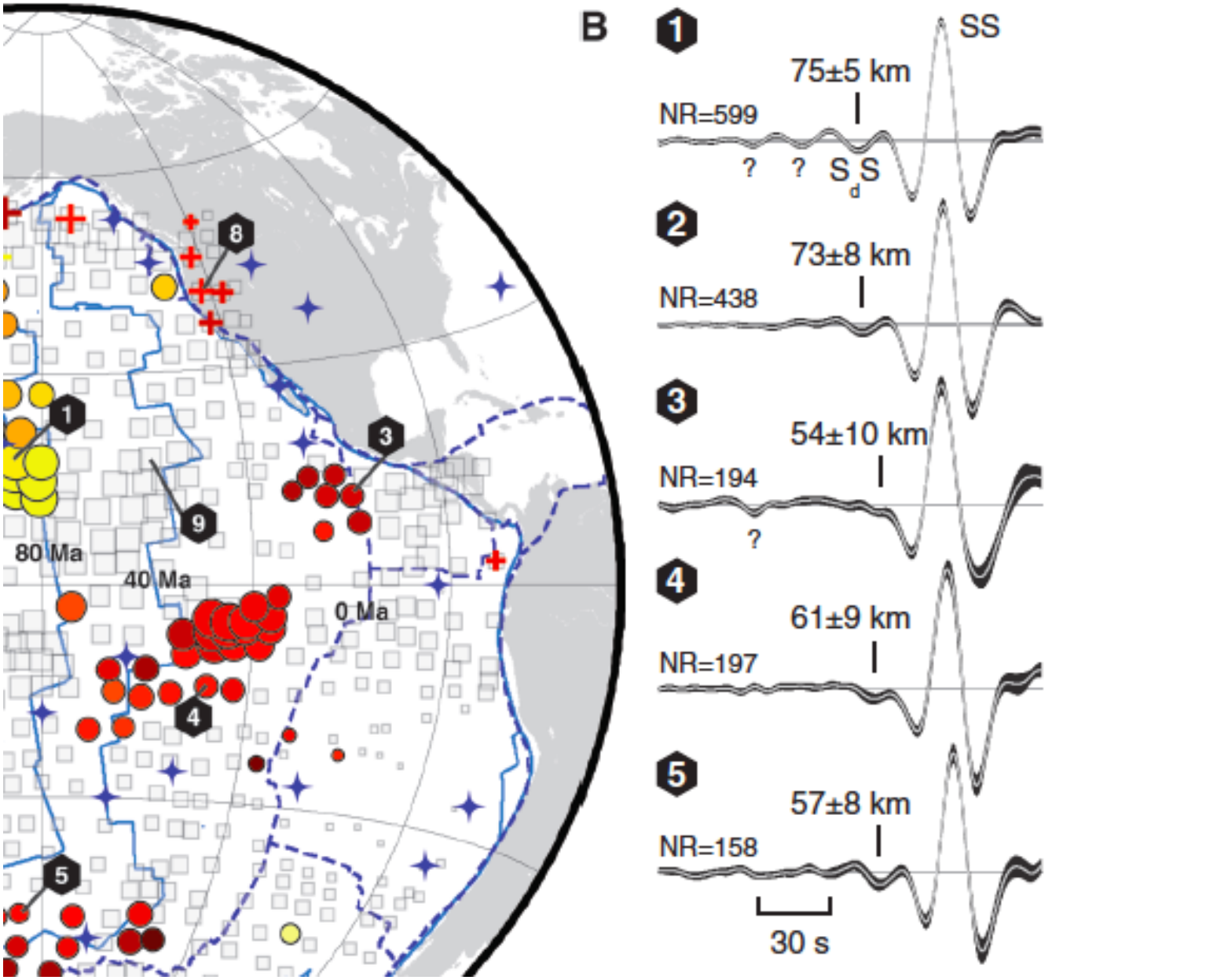

Hiroo Kanamori
Columnar Basalt, Japan (2014)

Oceans and Continents: Plate Tectonics

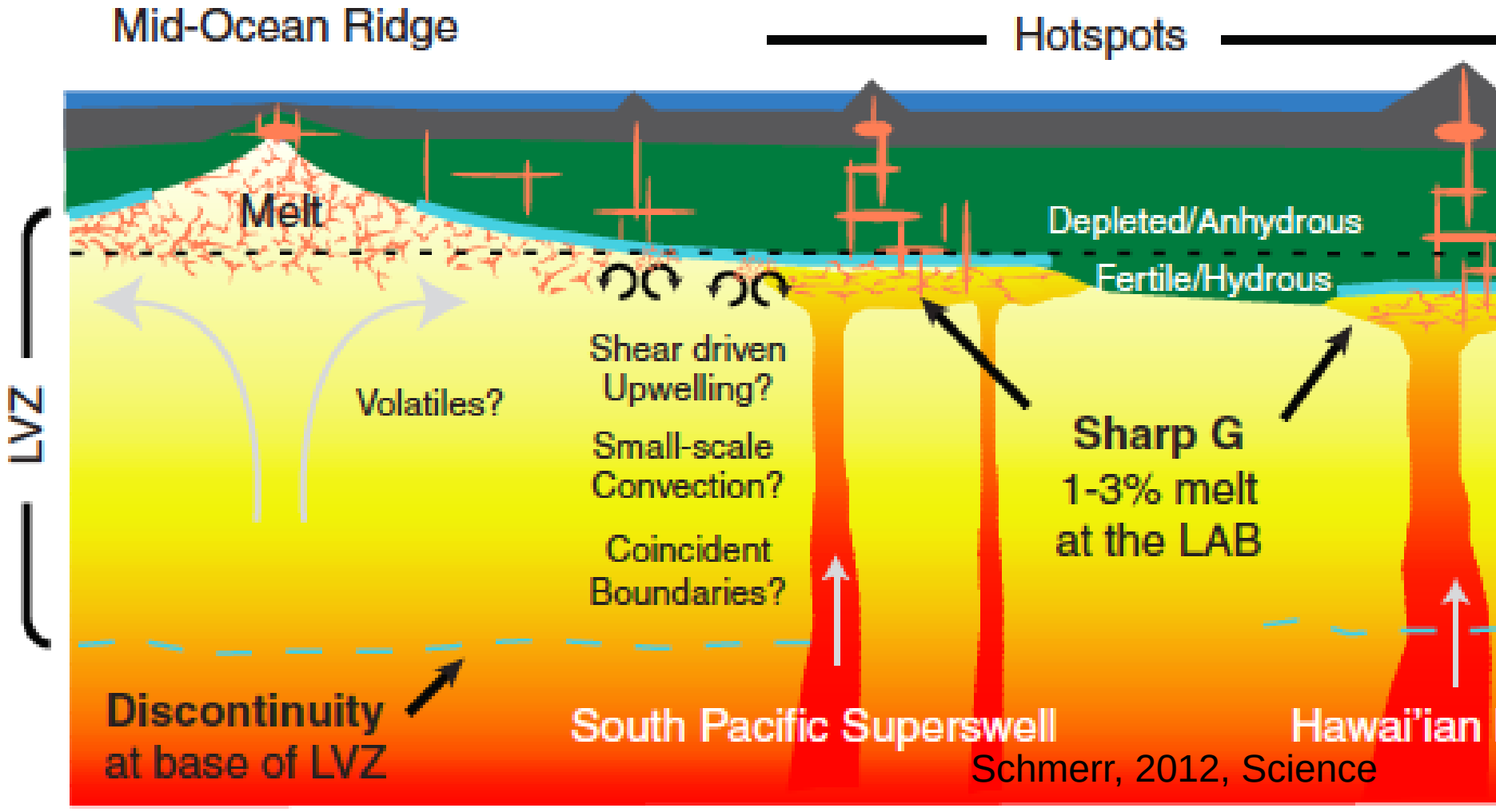




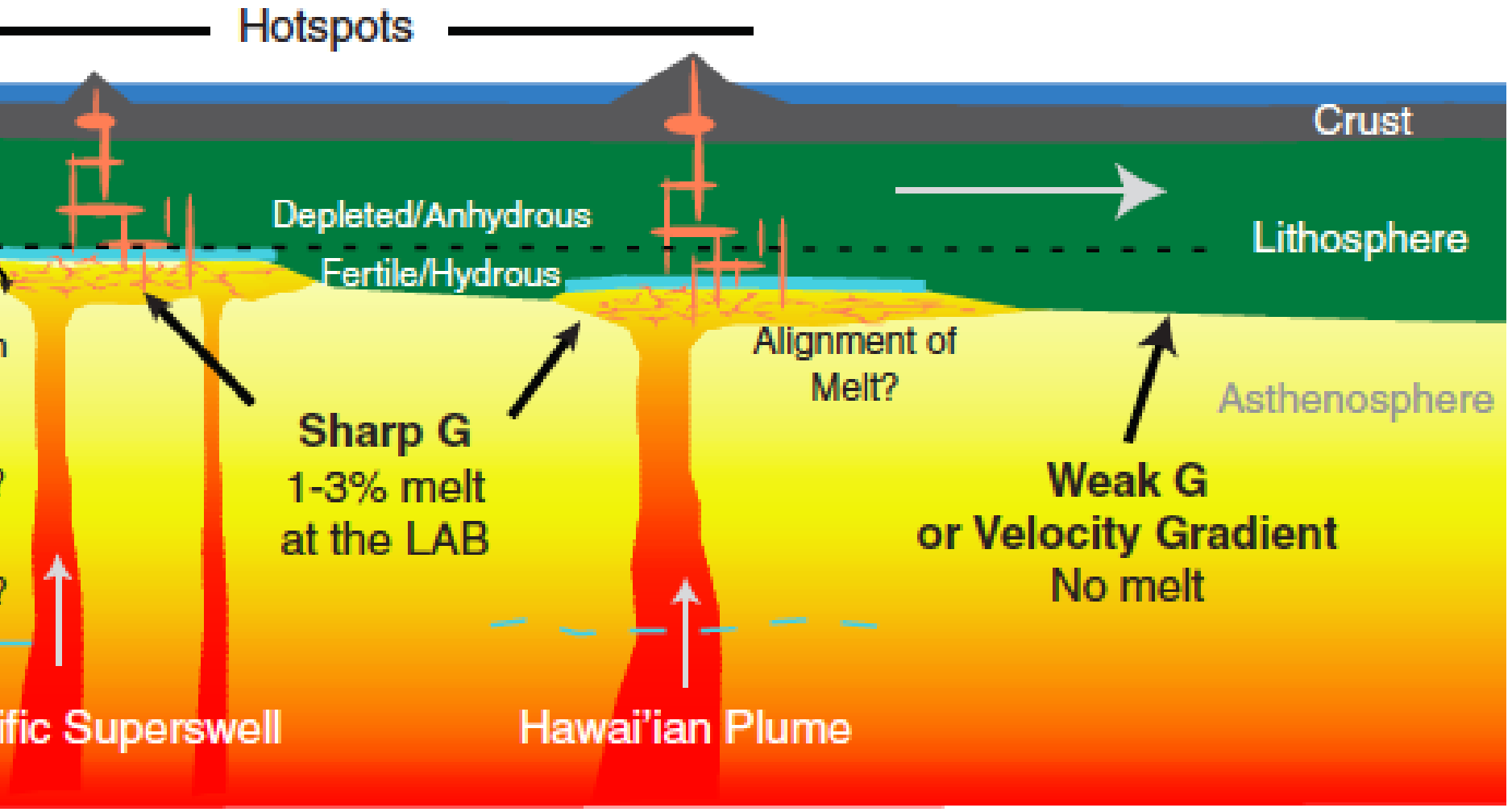
Probing Oceanic Lithosphere With Seismic Waves



Schmerr, 2012, Science

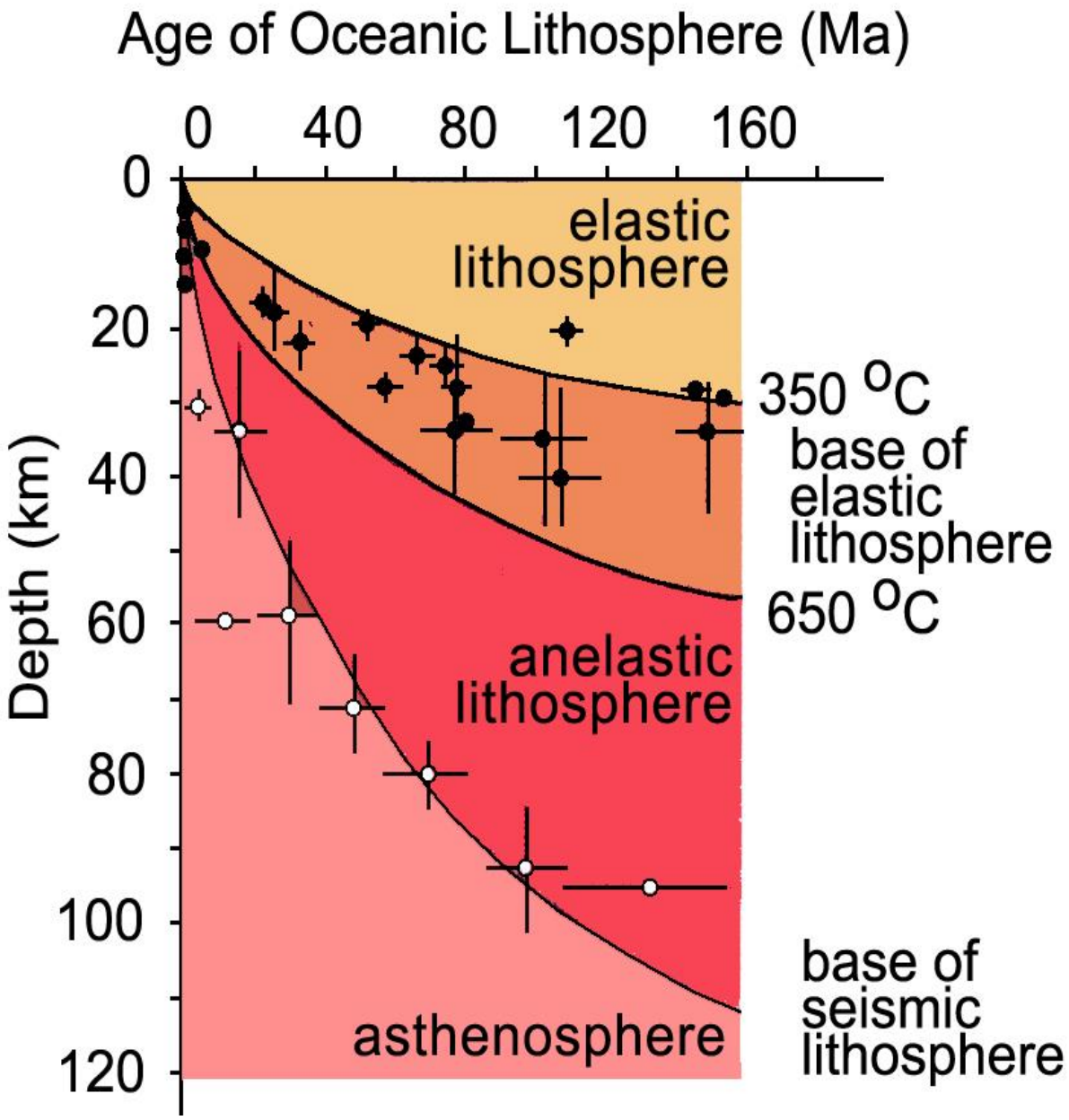


Schmerr, 2012, Science

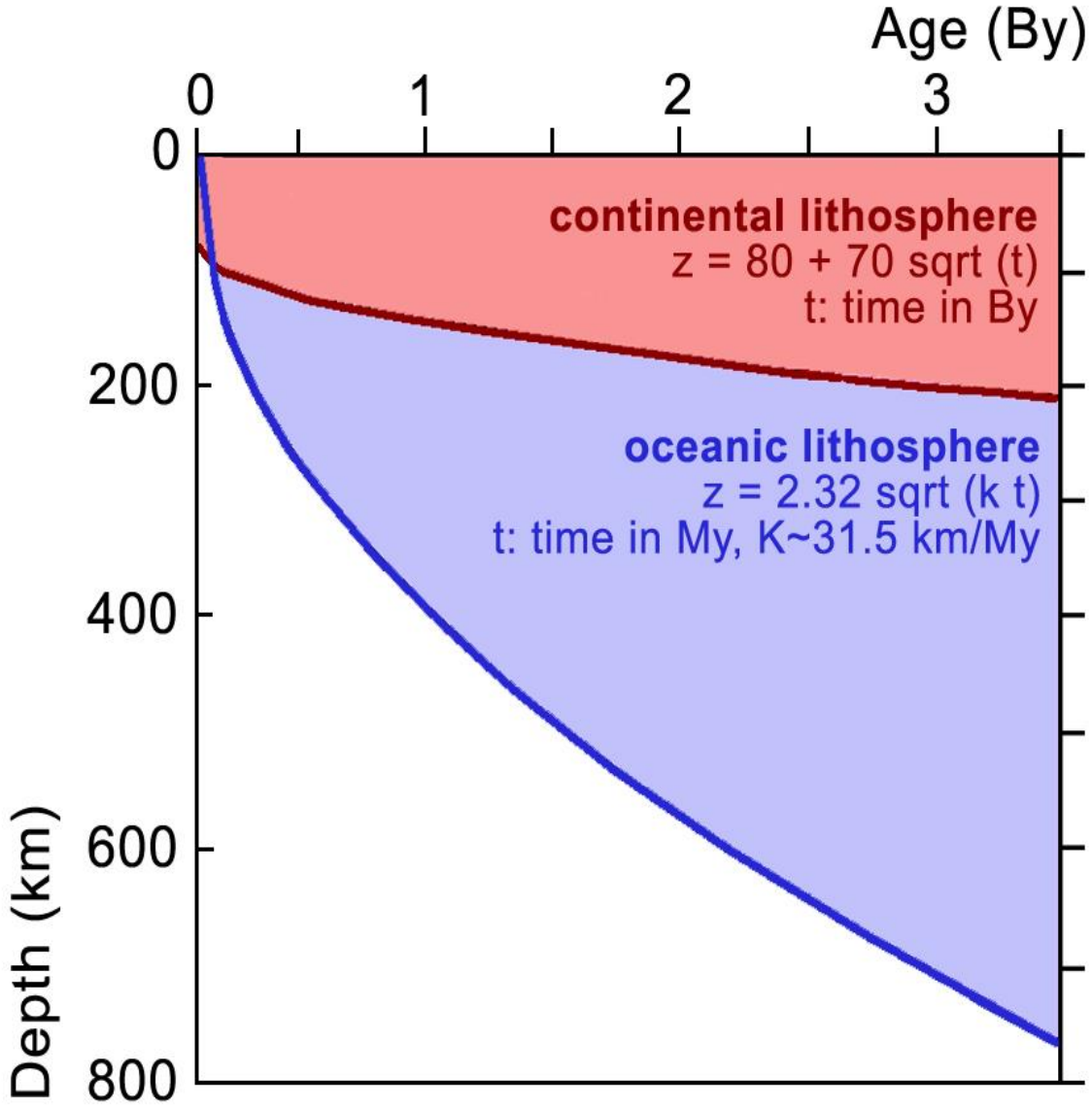


Schmerr, 2012, Science

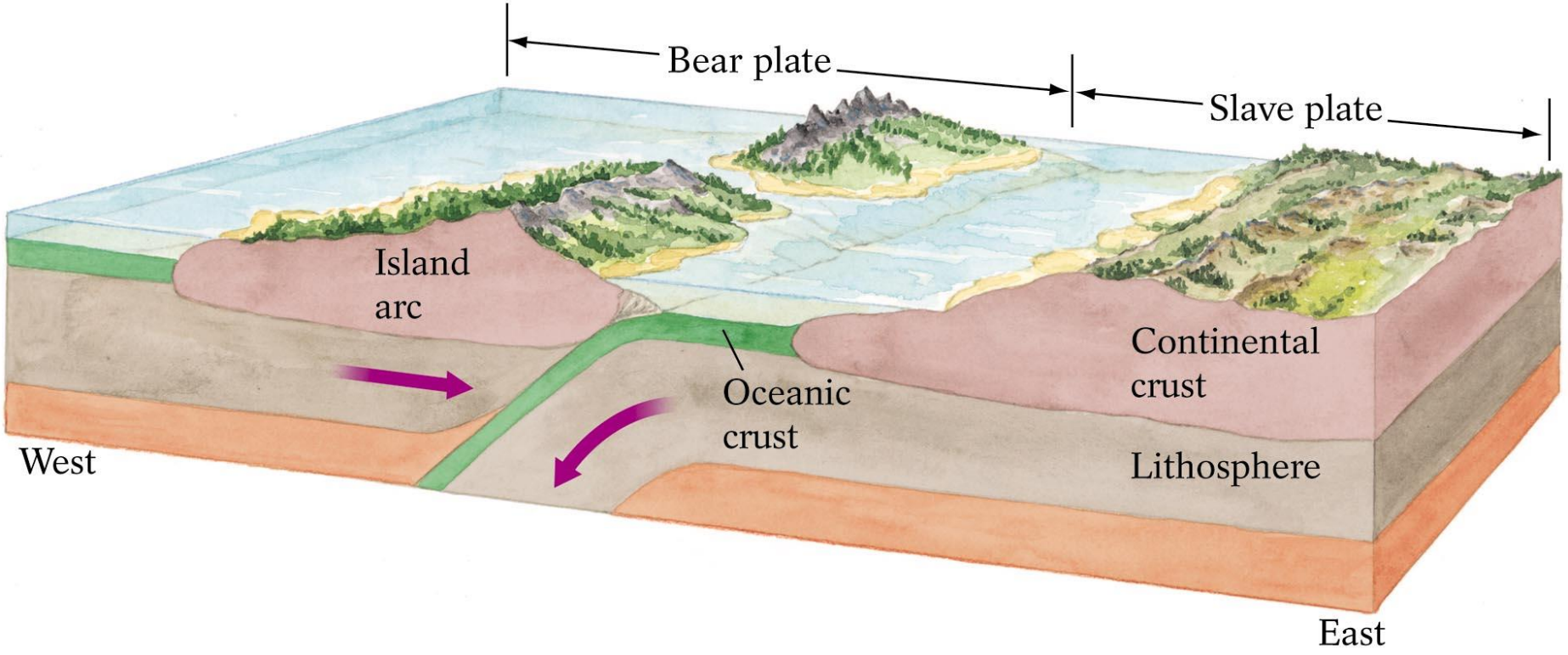
Oceanic Lithosphere Thickens by Cooling



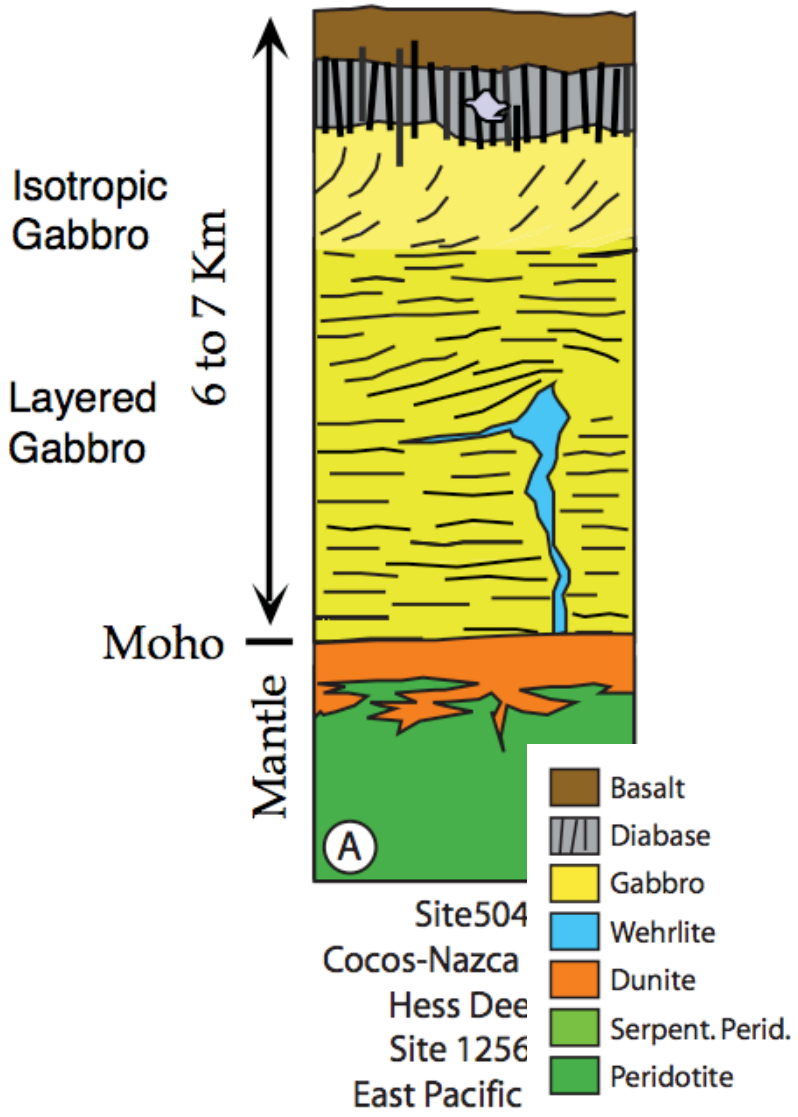
Comparing Oceanic vs. Continental Lithospheric Cooling



Accretion of Fragment of Oceanic Crust (Ophiolite)

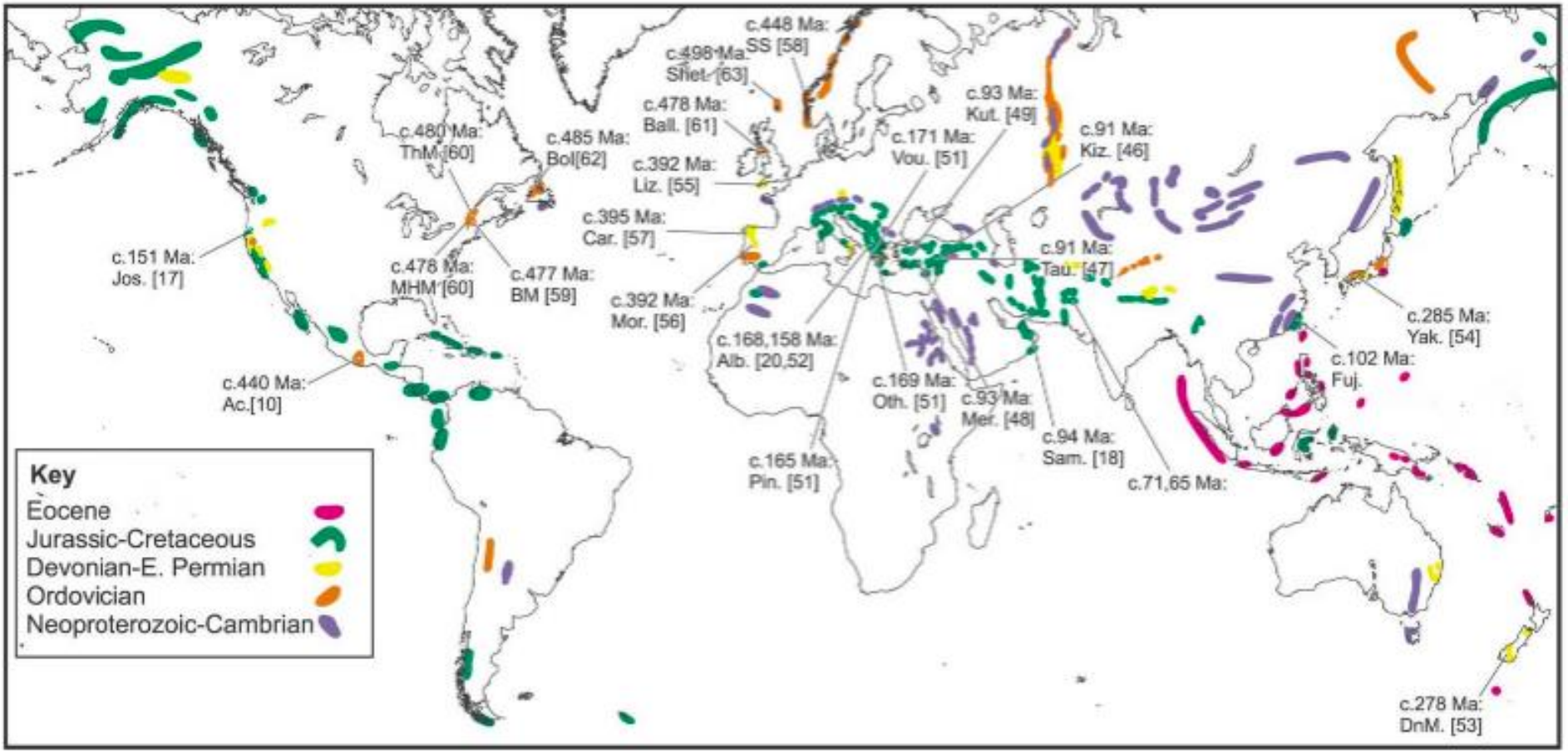


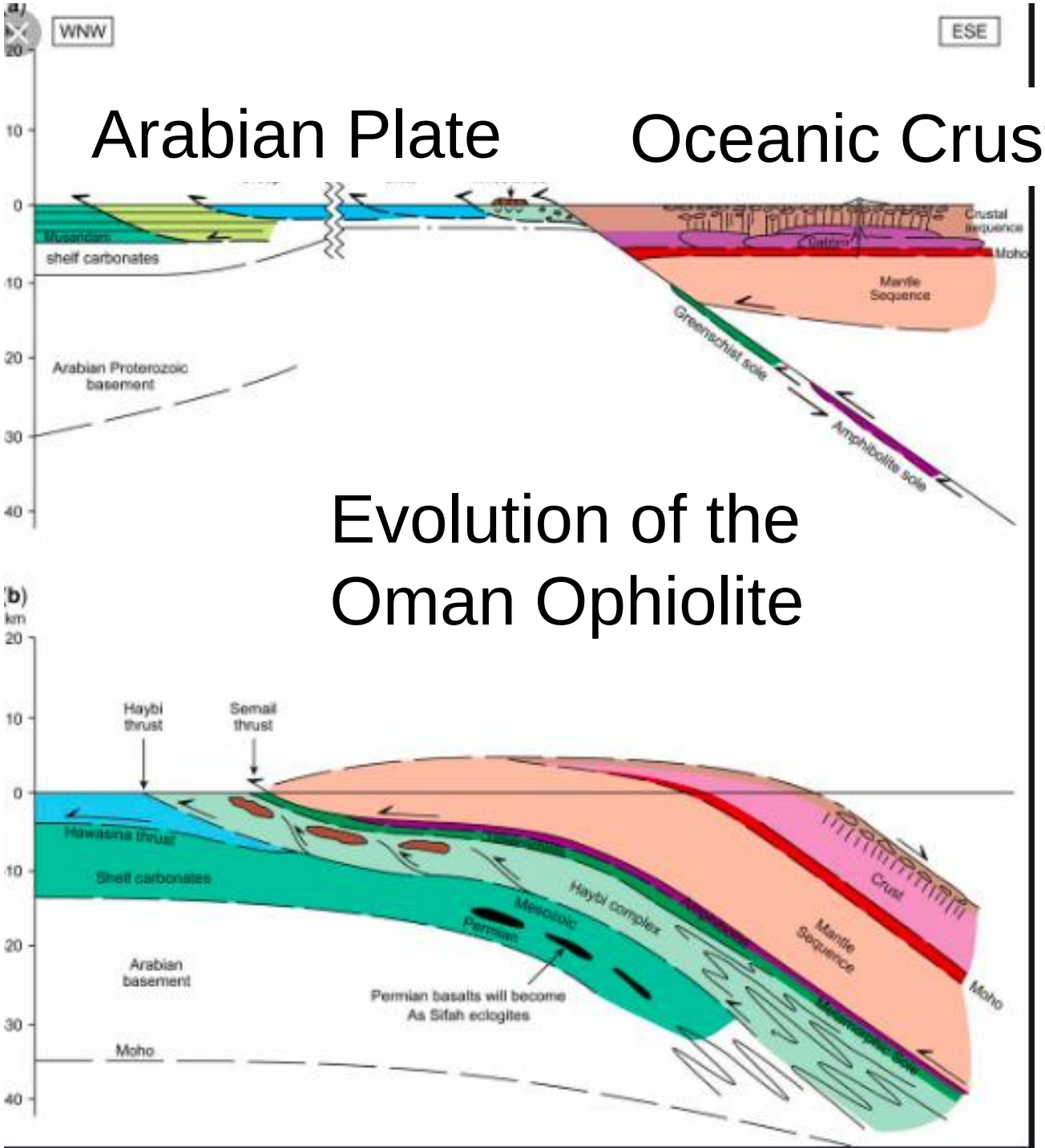
Penrose Ophiolite Model 1972

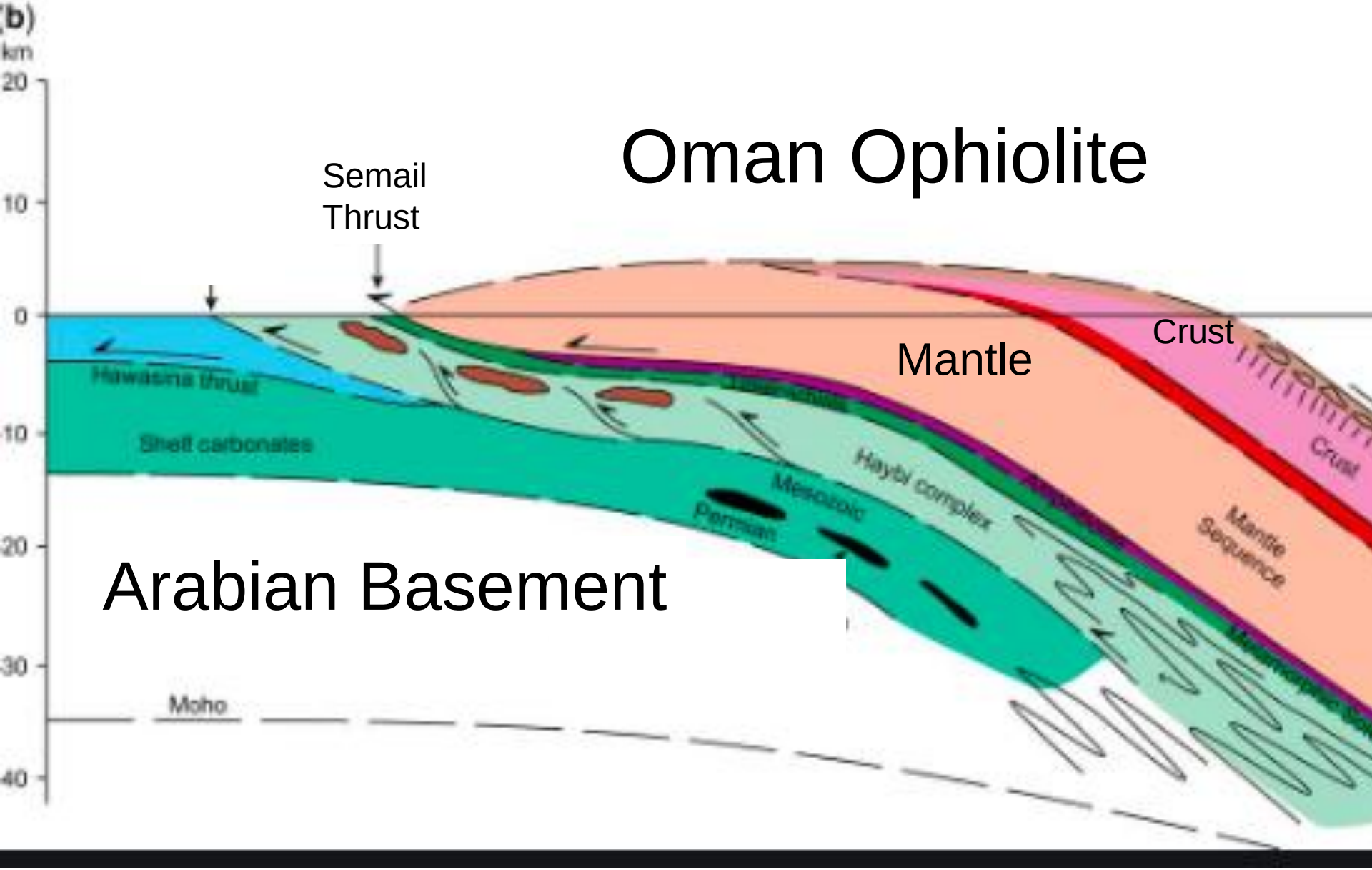


Dick, Natland and Ildefonse 2006

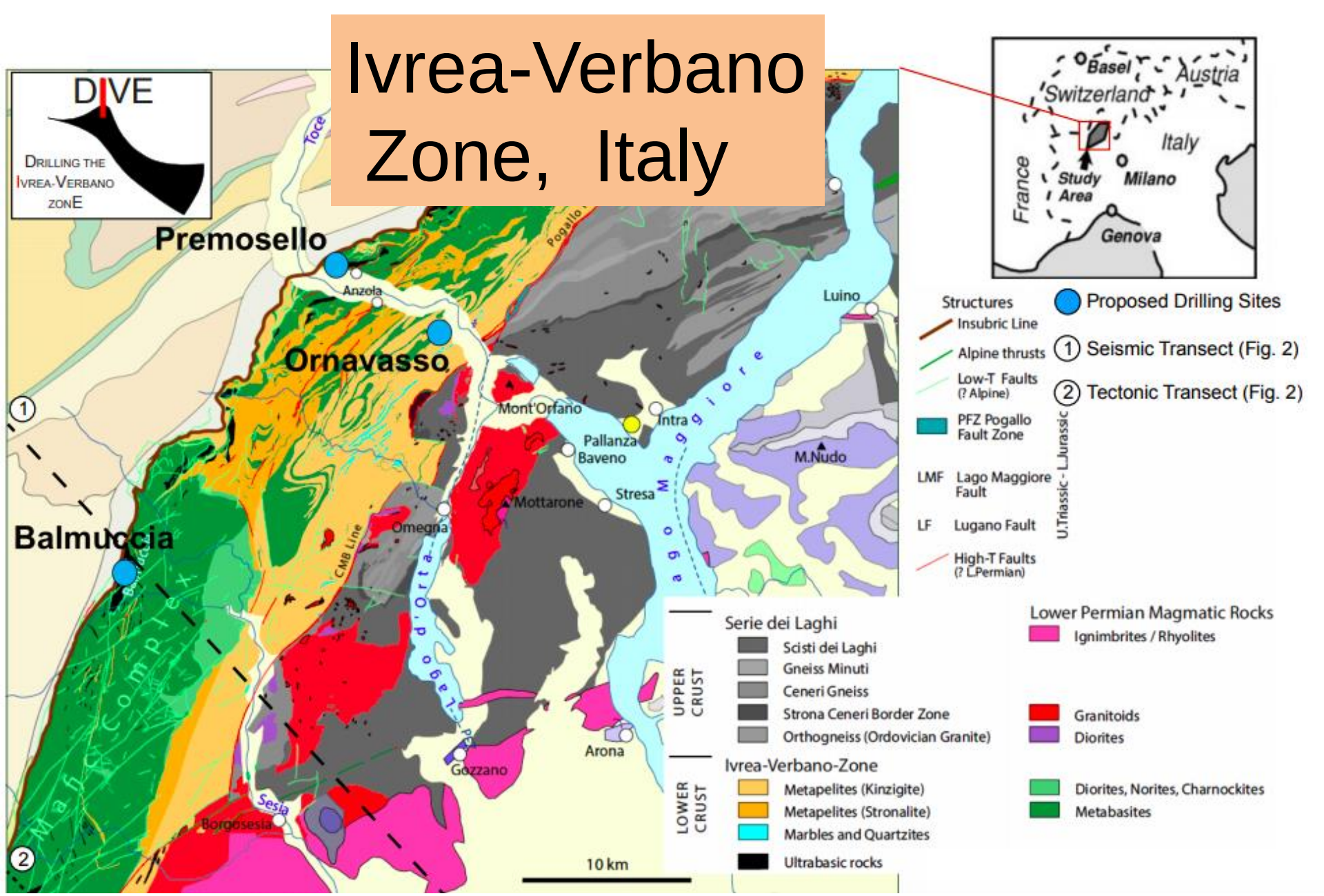
Global Ophiolite Distribution by Age



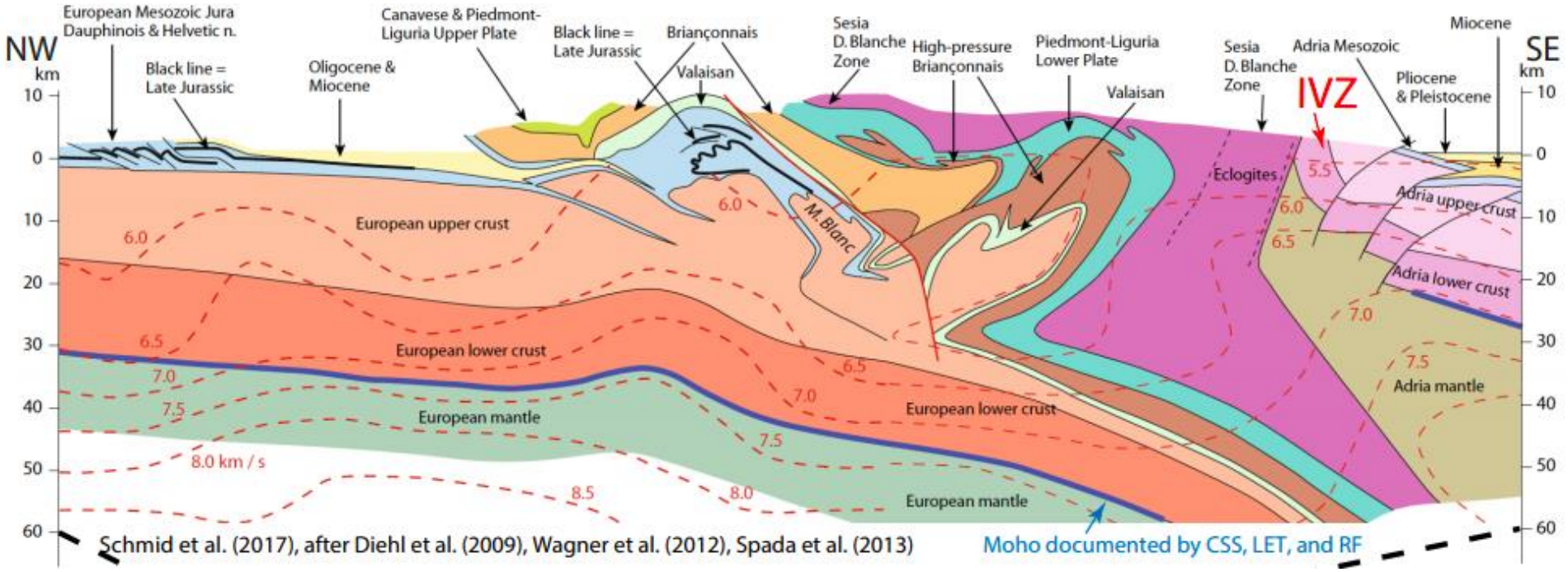

Arabian Plate
Oceanic Crust
WNW
ESE
Musandam
shelf carbonates
Arabian Proterozoic basement
Crustal sequence
Gabbro
Moho
Mantle Sequence
Greenschist sole
Amphibolite sole
Evolution of the Oman Ophiolite
(b)
km
Haybi thrust
Semail thrust
Hawasina thrust
Shelf carbonates
Haybi complex
Mesozoic
Permian
Arabian basement
Permian basalts will become As Sifah eclogites
Moho
Crust
Mantle Sequence
Moho

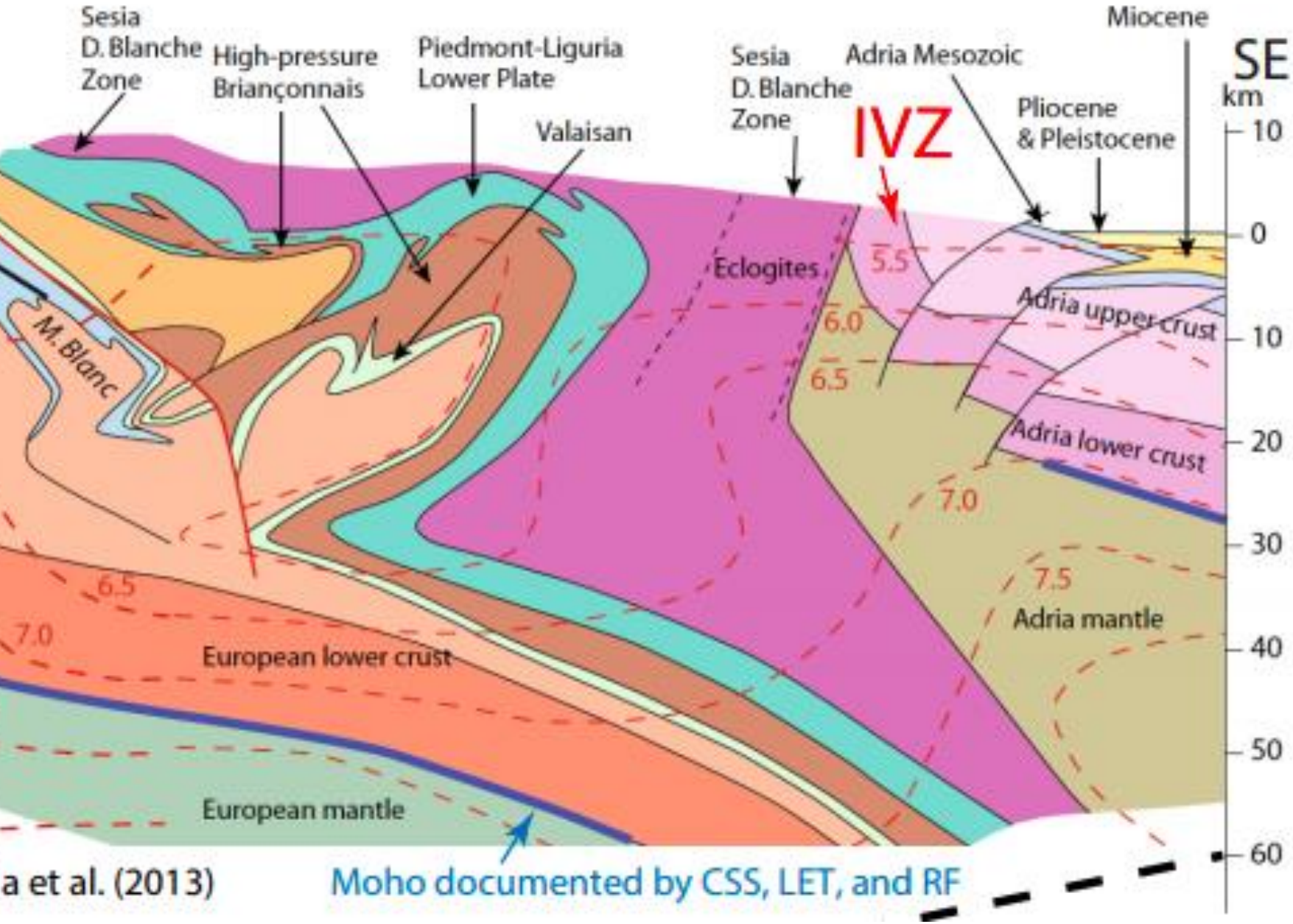

(b)
km
20
10
0
-10
-20
-30
-40
Semail
Thrust
Oman Ophiolite
Crust
Mantle
Arabian Basement
Hawasina thrust
Shelf carbonates
Haybi complex
Mesozoic
Permian
Crust
Mantle
Sequence
Moho

Ivrea-Verbano Zone, Italy



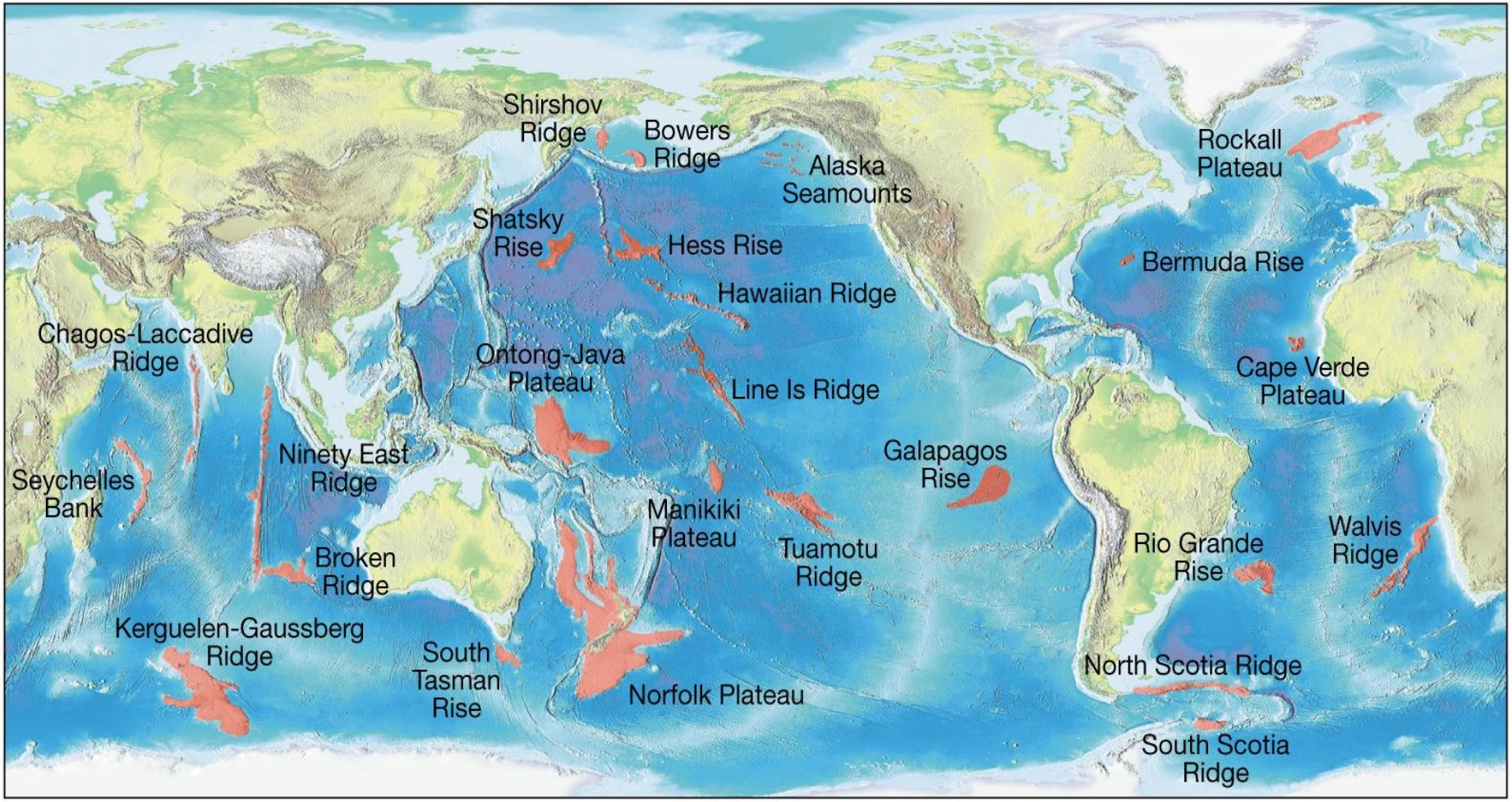
Lower Continental Crust and Upper Mantle at the Ivrea Verbano Zone (IVZ)

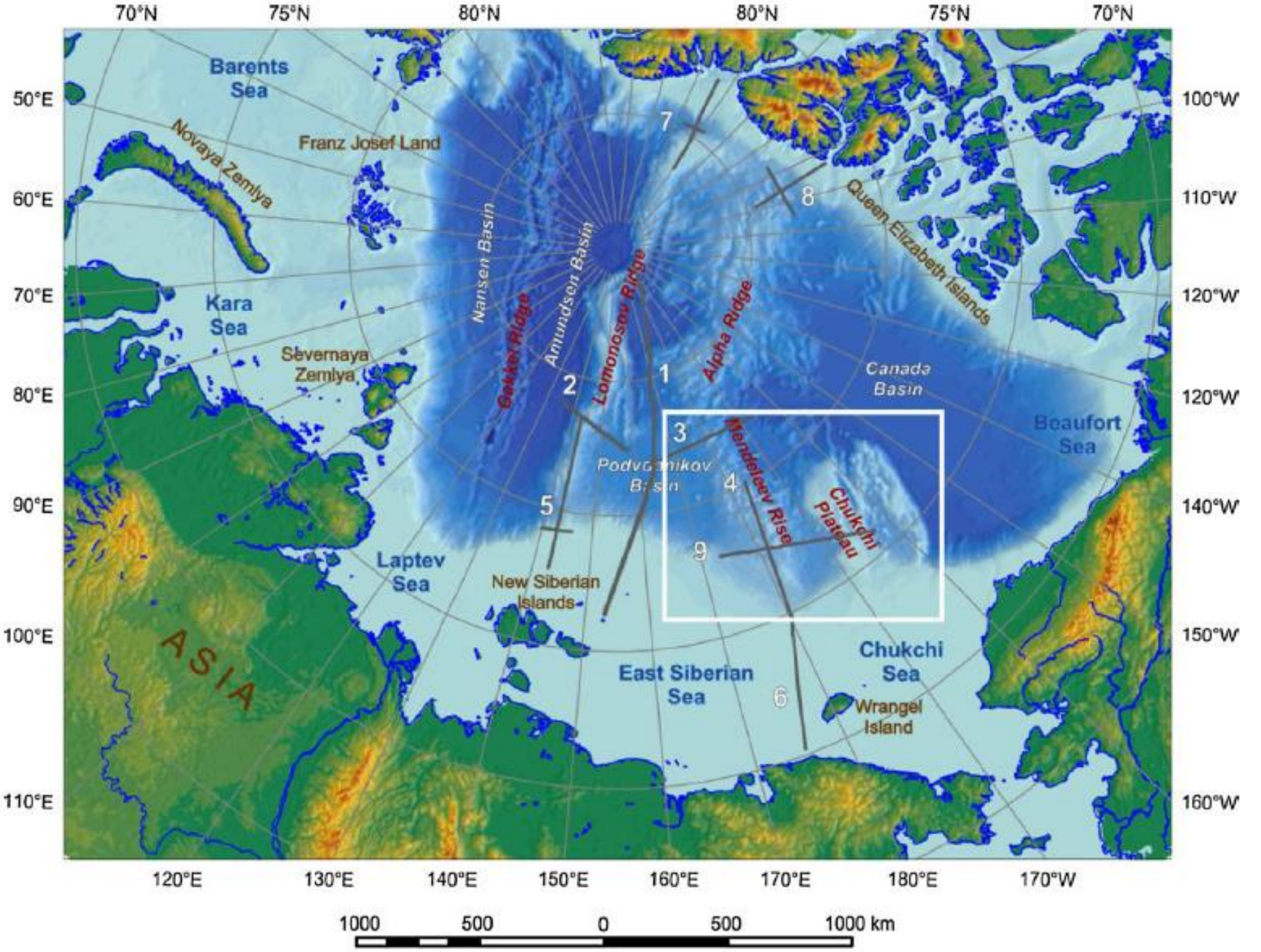


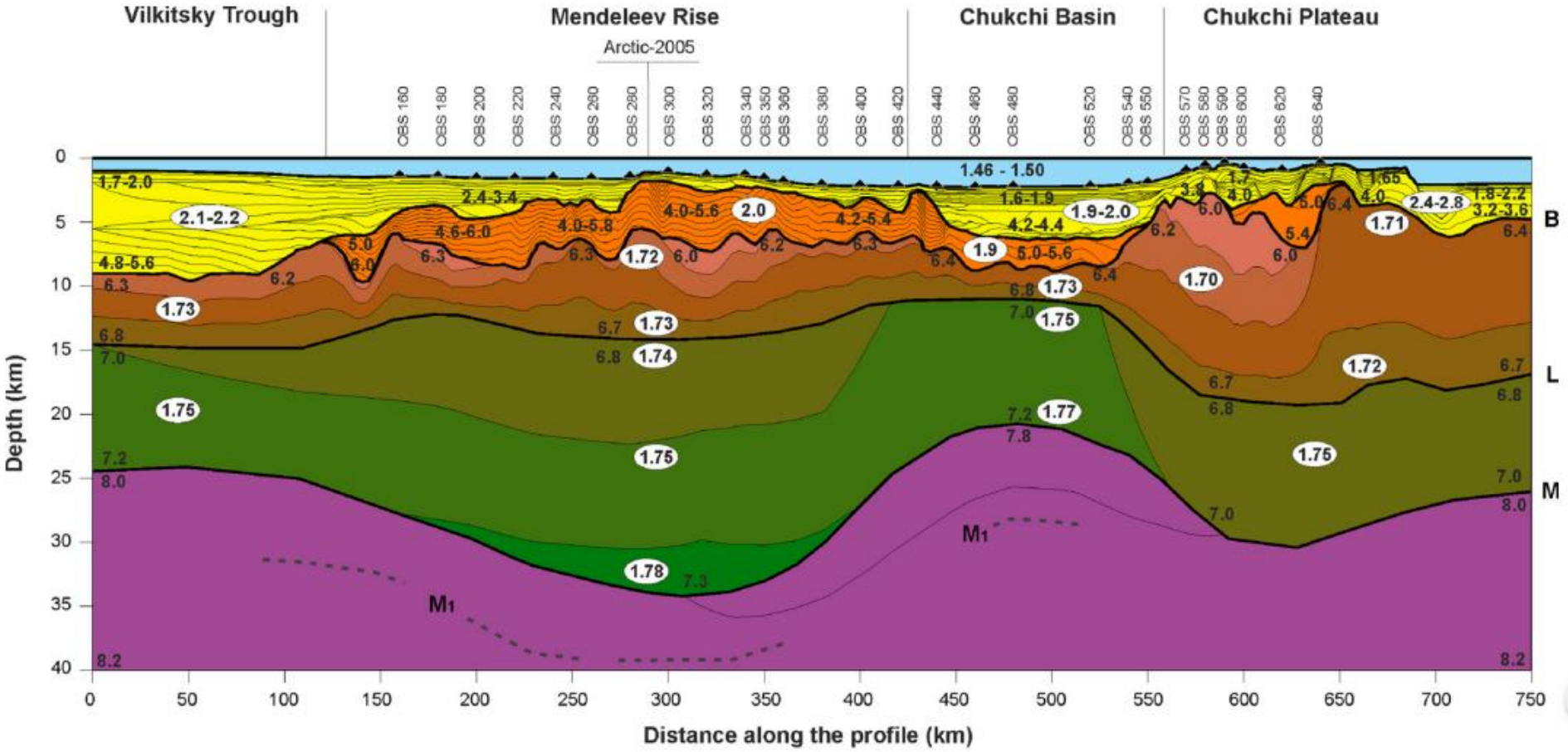

Sesia
D. Blanche
Zone
High-pressure
Briançonnais
Piedmont-Liguria
Lower Plate
Valaisan
Sesia
D. Blanche
Zone
IVZ
Adria Mesozoic
Miocene
Pliocene
& Pleistocene
SE
km
10
0
10
20
30
40
50
60
Eclogites
5.5
6.0
6.5
7.0
7.5
Adria upper crust
Adria lower crust
Adria mantle
M. Blanc
6.5
7.0
European lower crust
European mantle
Moho documented by CSS, LET, and RF

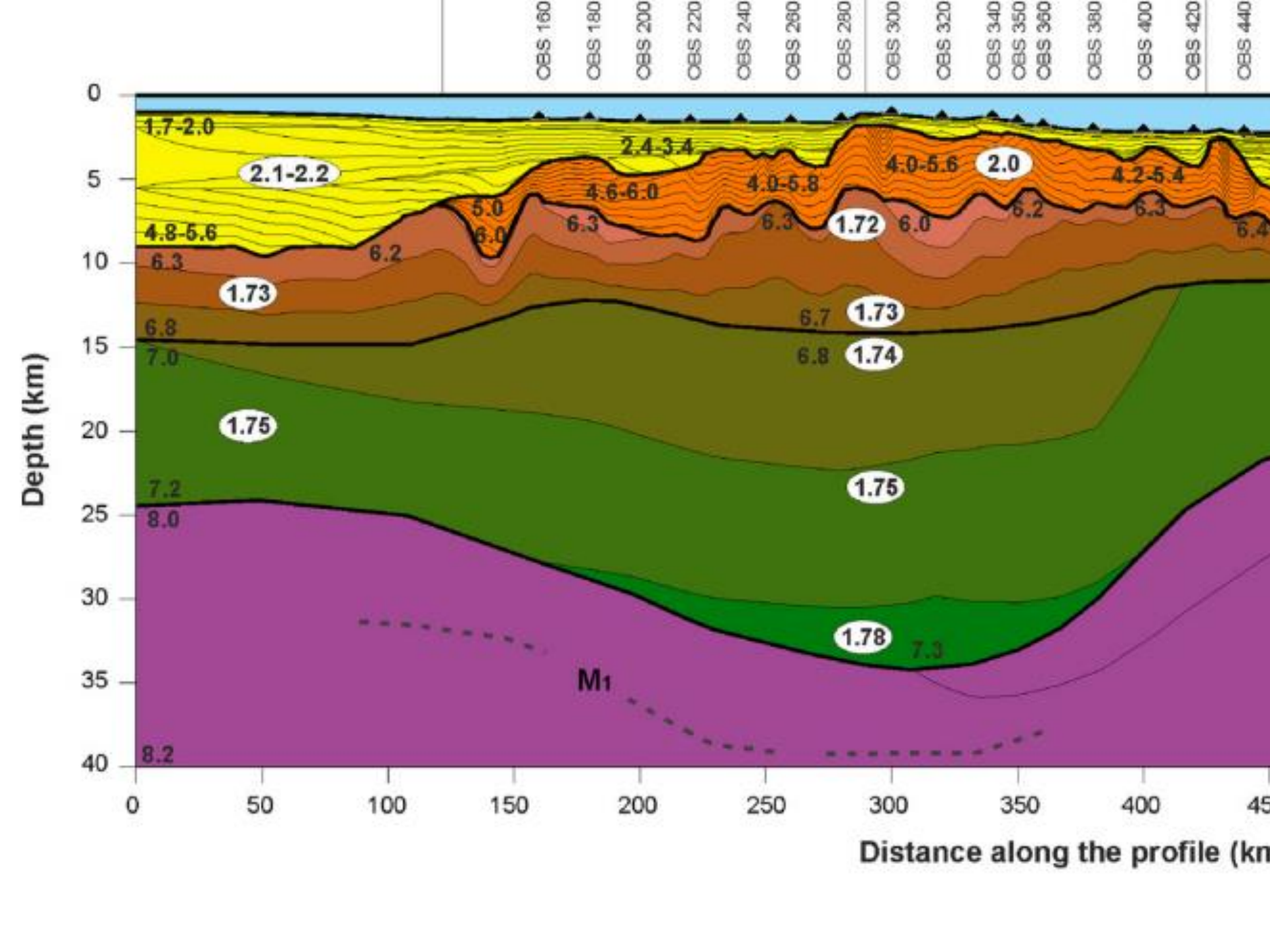
a et al. (2013)

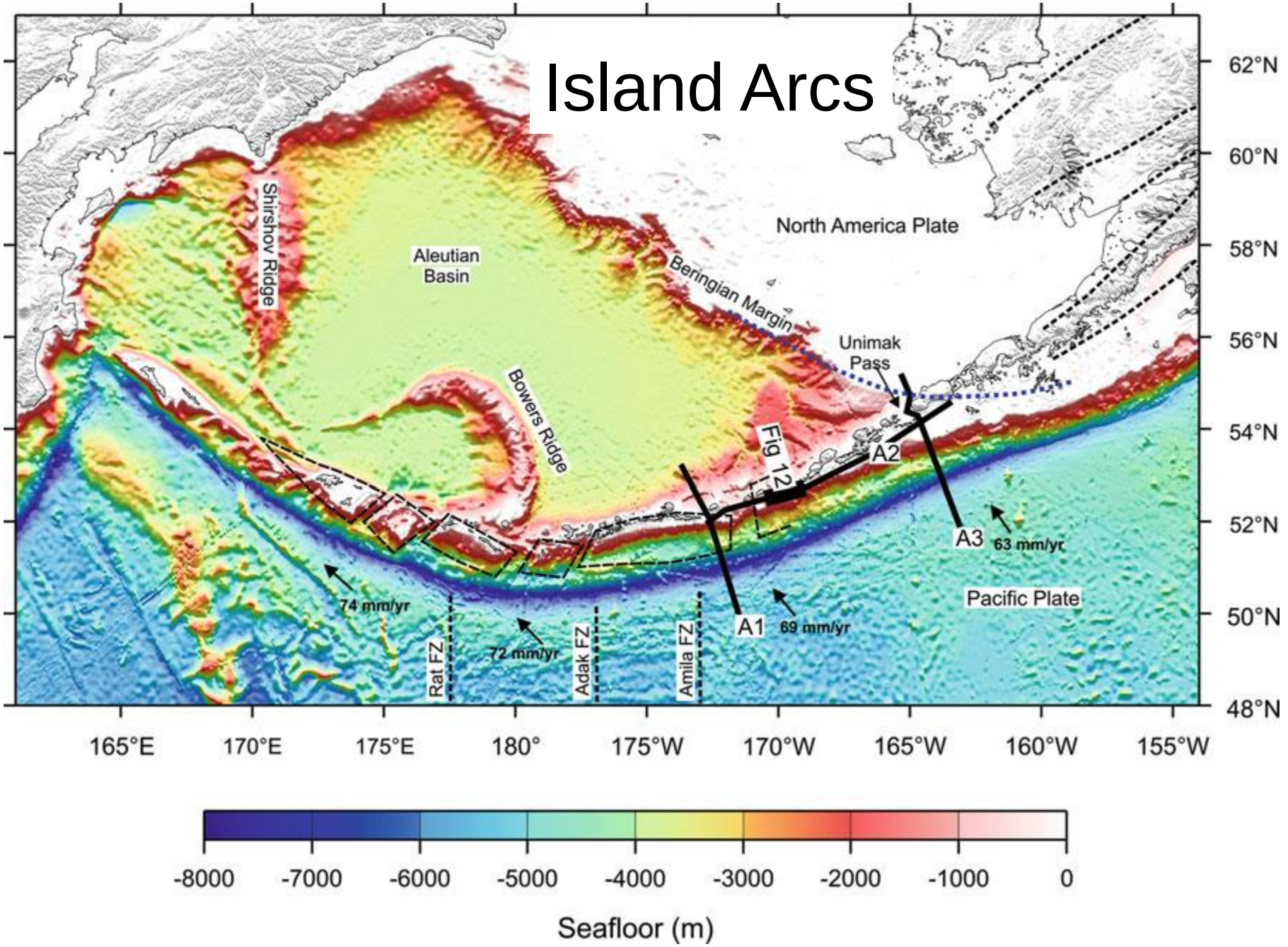
Oceanic Plateaus



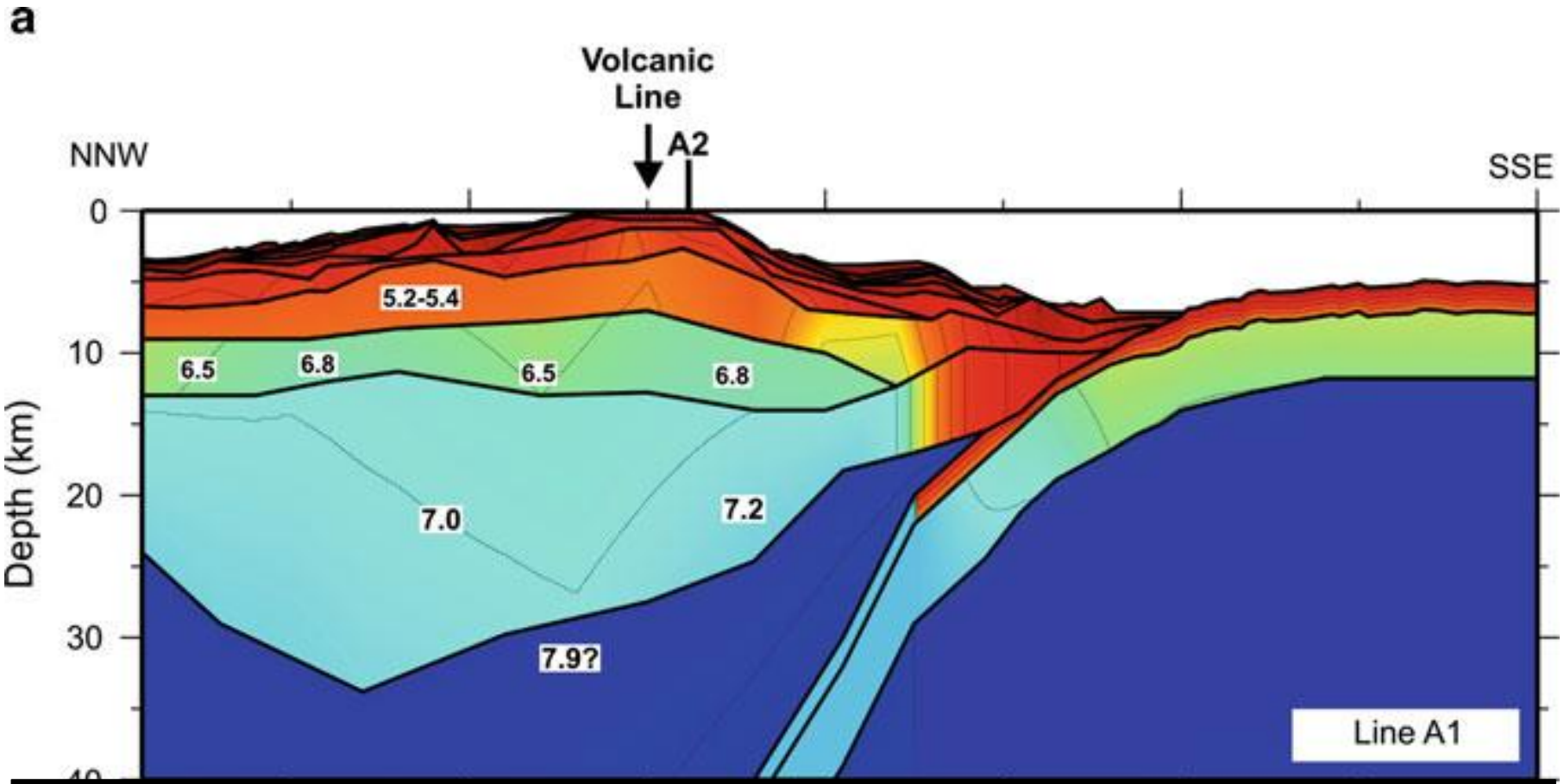

70°N
75°N
80°N
80°N
75°N
70°N
50°E
60°E
70°E
80°E
90°E
100°E
110°E
100°W
110°W
120°W
120°W
140°W
150°W
160°W
120°E
130°E
140°E
150°E
160°E
170°E
180°E
170°W
Barents Sea
Novaya Zemlya
Franz Josef Land
Kara Sea
Severnaya Zemlya
Nansen Basin
Amundsen Basin
Gakkel Ridge
Lomonosov Ridge
Alpha Ridge
Queen Elizabeth Islands
Canada Basin
Beaufort Sea
Podvodnikov Basin
Mendeleev Rise
Chukchi Plateau
Laptev Sea
New Siberian Islands
East Siberian Sea
Chukchi Sea
Wrangel Island
ASIA
1
2
3
4
5
6
7
8
9
1000
500
0
500
1000 km


Vilkitsky Trough
Mendeleev Rise
Chukchi Basin
Chukchi Plateau
Arctic-2005
OBS 160
OBS 180
OBS 200
OBS 220
OBS 240
OBS 260
OBS 280
OBS 300
OBS 320
OBS 340
OBS 350
OBS 360
OBS 380
OBS 400
OBS 420
OBS 440
OBS 460
OBS 480
OBS 520
OBS 540
OBS 550
OBS 570
OBS 580
OBS 590
OBS 600
OBS 620
OBS 640
1.46 - 1.50
1.7-2.0
2.1-2.2
2.4-3.4
4.6-6.0
4.0-5.8
4.0-5.6
2.0
4.2-5.4
1.6-1.9
1.9-2.0
4.2-4.4
1.9
5.0-5.6
1.65
2.4-2.8
1.8-2.2
3.2-3.6
1.71
1.70
1.72
4.8-5.6
1.73
1.74
1.75
1.77
1.78
1.76
M1
B
L
M
Depth (km)
Distance along the profile (km)

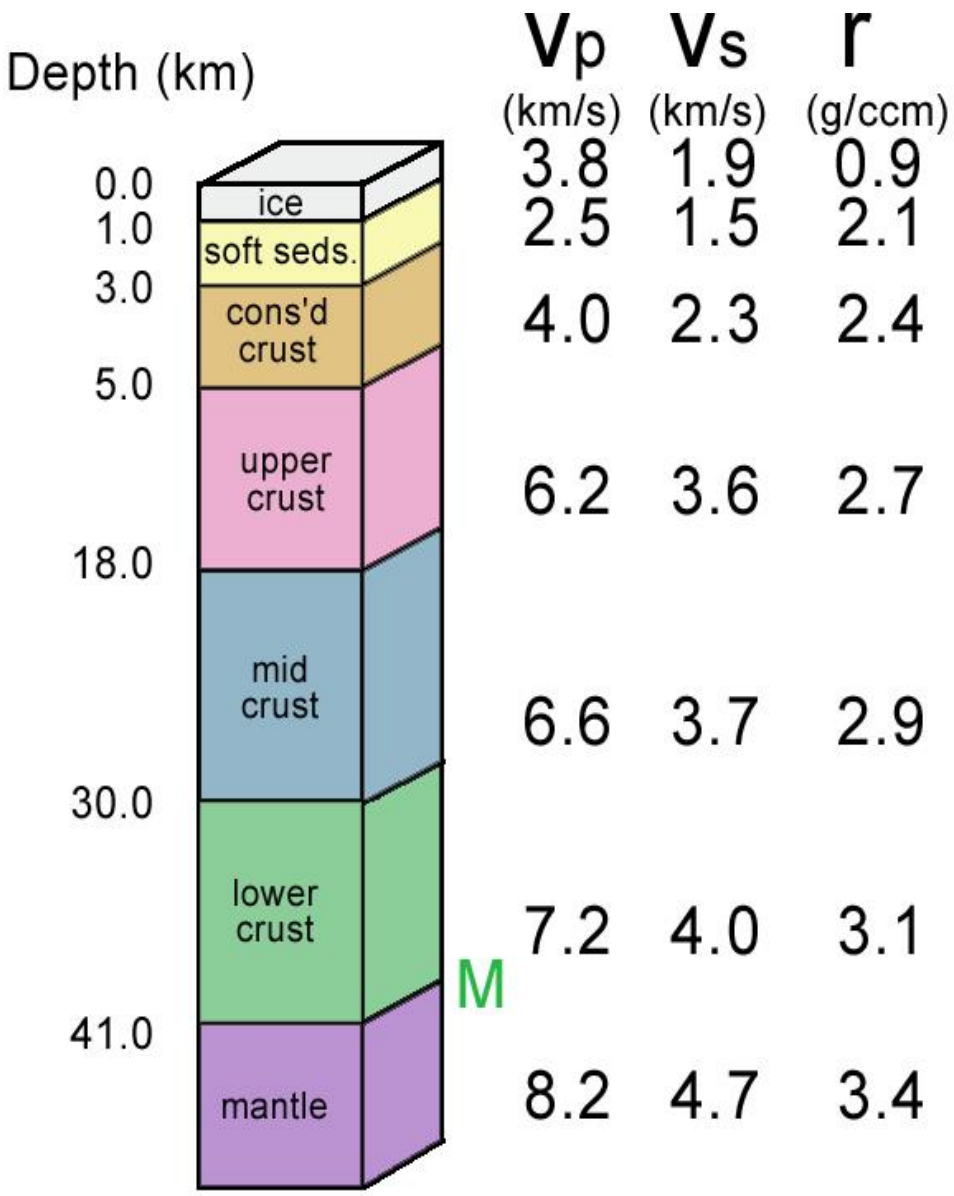

OBS 160
OBS 180
OBS 200
OBS 220
OBS 240
OBS 260
OBS 280
OBS 300
OBS 320
OBS 340
OBS 350
OBS 360
OBS 380
OBS 400
OBS 420
OBS 440
1.7-2.0
2.1-2.2
2.4-3.4
4.6-6.0
4.0-5.8
4.0-5.6
2.0
4.2-5.4
4.8-5.6
5.0
6.0
6.3
6.2
1.72
6.0
6.4
1.73
6.7
1.73
6.8
7.0
6.8
1.74
1.75
1.75
7.2
8.0
1.78
7.3
M1
8.2
Depth (km)
0
5
10
15
20
25
30
35
40
0
50
100
150
200
250
300
350
400
Distance along the profile (km


Island Arcs
Shirshov Ridge
Aleutian Basin
North America Plate
Beringian Margin
Unimak Pass
Bowers Ridge
Fig. 12
A1
A2
A3
63 mm/yr
69 mm/yr
74 mm/yr
72 mm/yr
Pacific Plate
Rat FZ
Adak FZ
Amila FZ
62°N
60°N
58°N
56°N
54°N
52°N
50°N
48°N
165°E
170°E
175°E
180°
175°W
170°W
165°W
160°W
155°W
-8000
-7000
-6000
-5000
-4000
-3000
-2000
-1000
0
Seafloor (m)

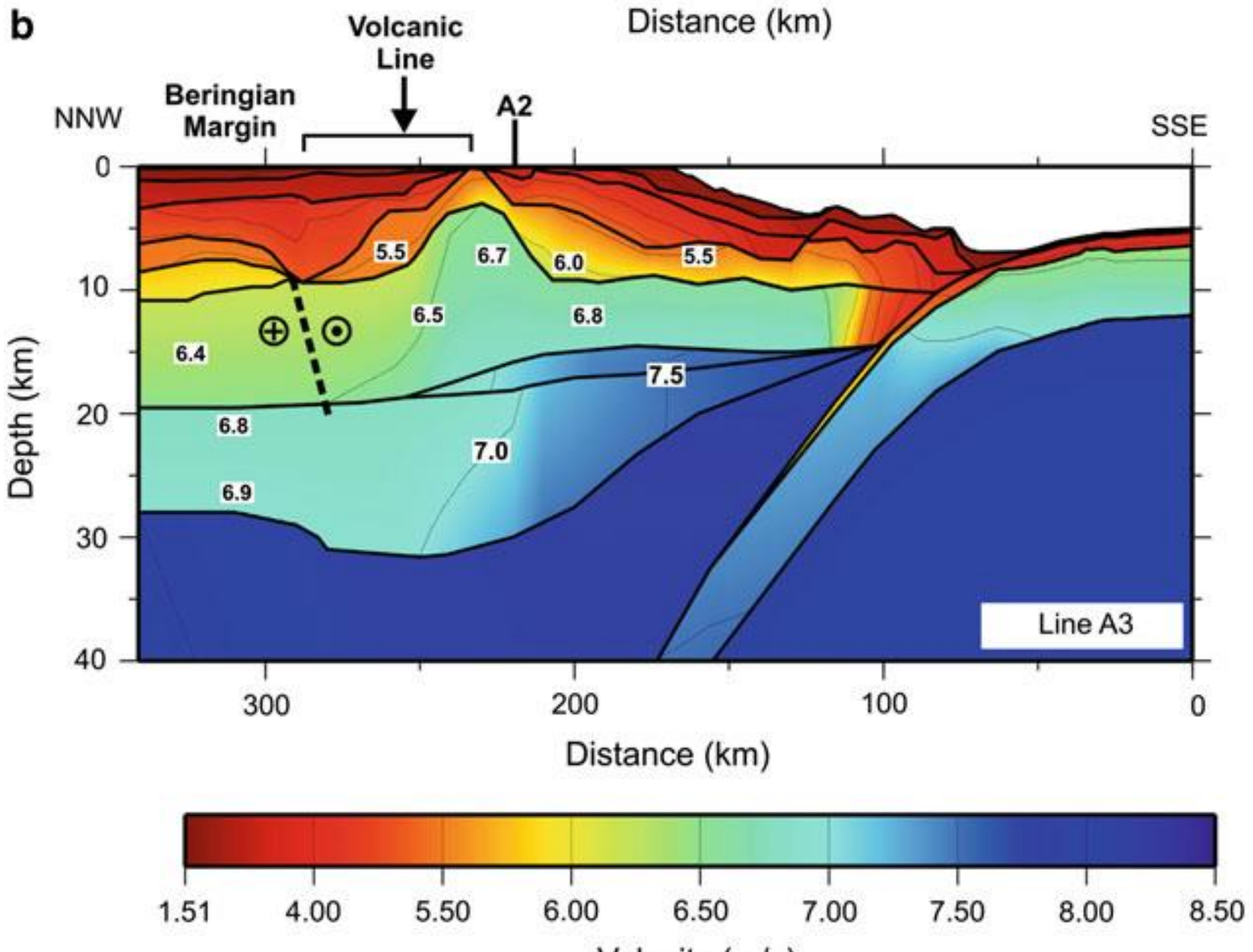
Island Arc: Mafic lower crust



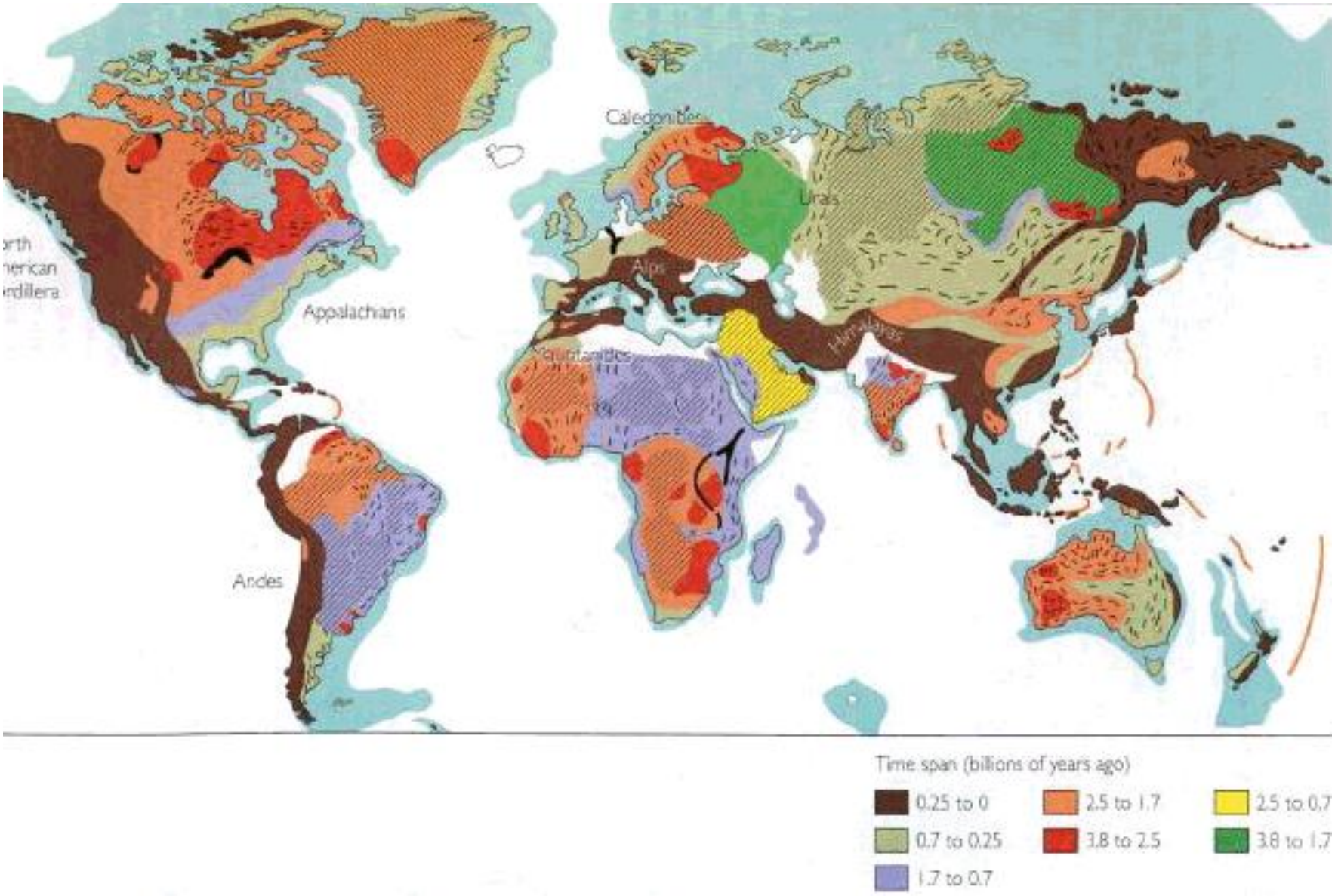
Typical Stable Continental Crust: Platform



Island Arc: Mafic lower crust

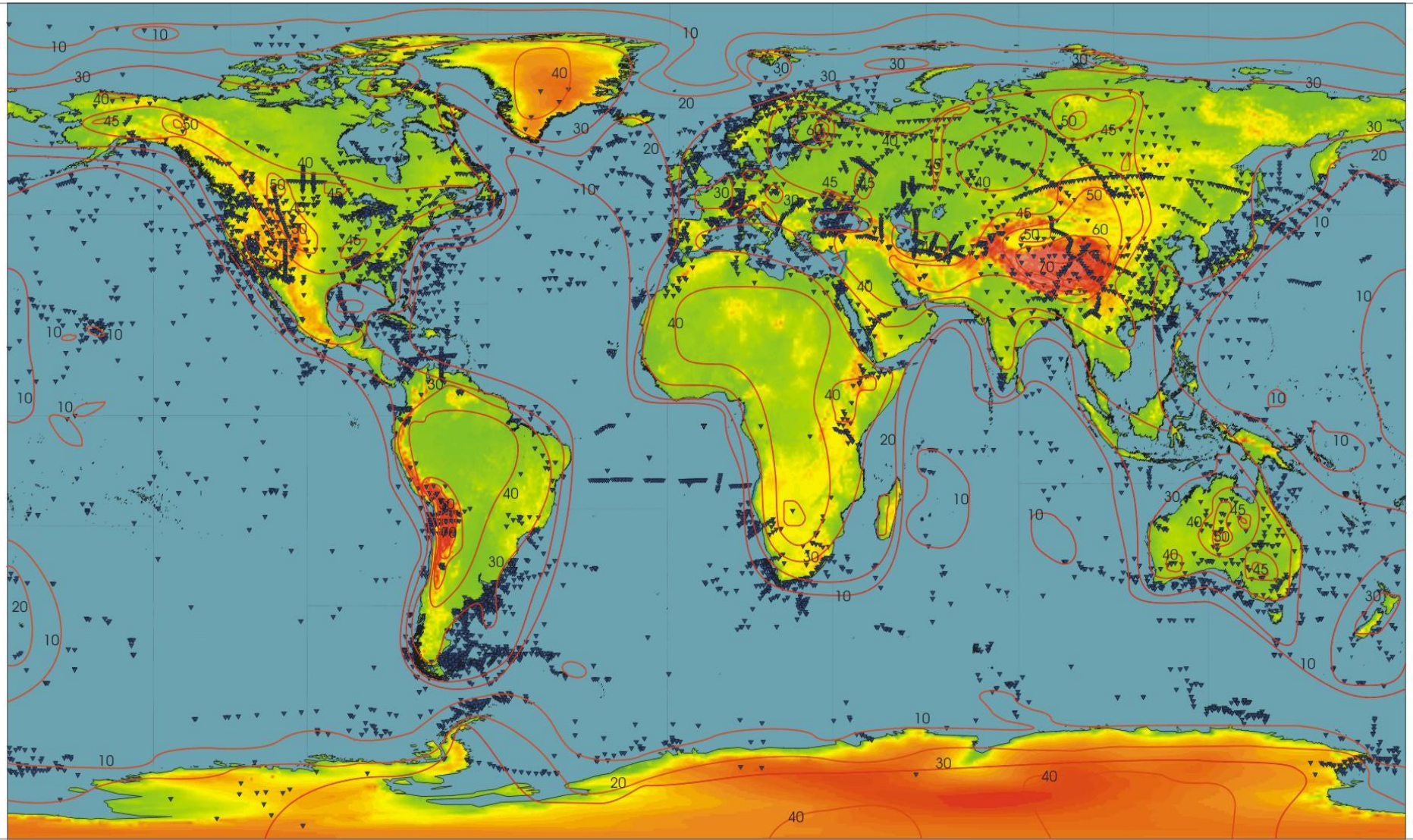


Precambrian Shields

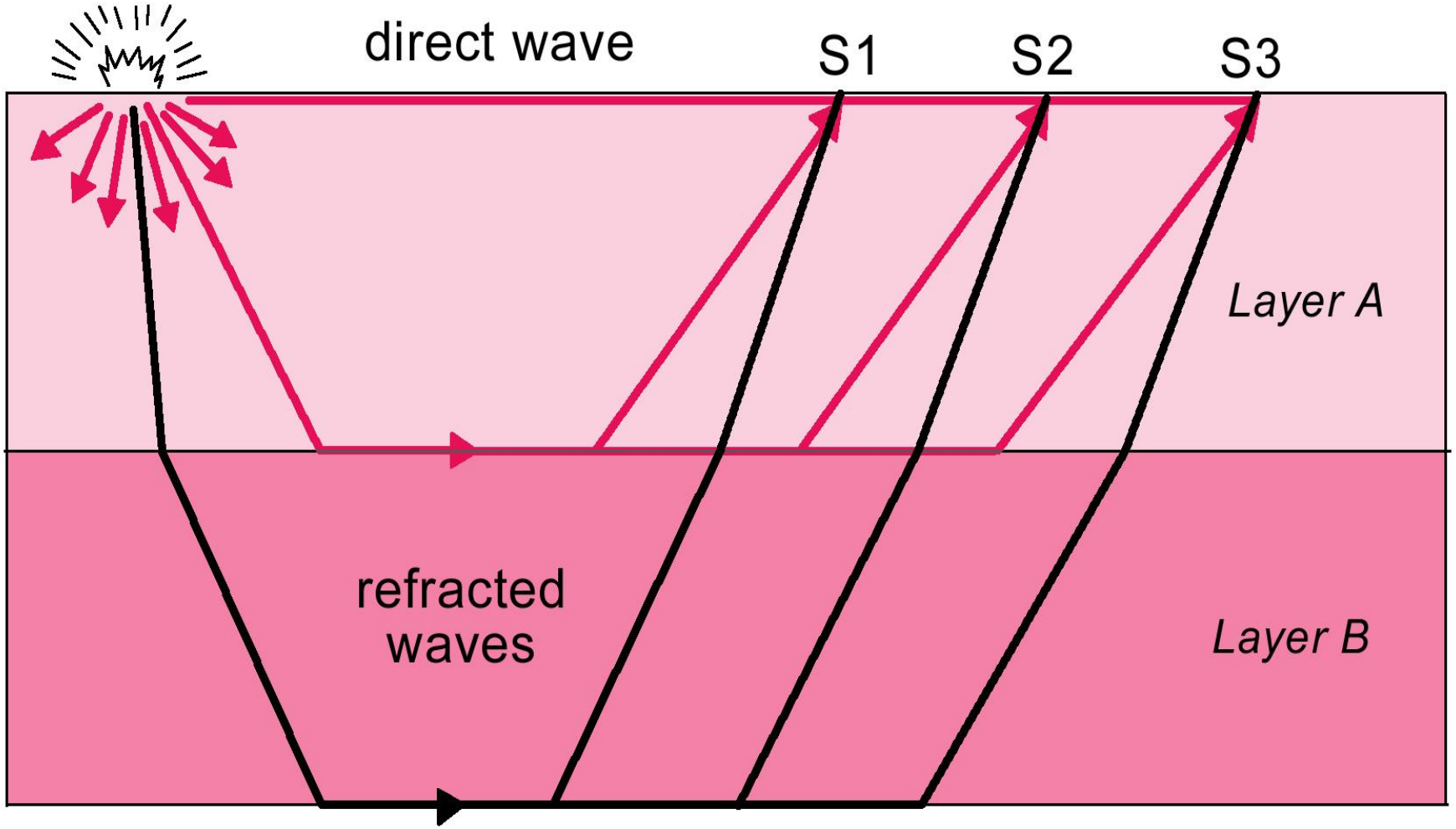


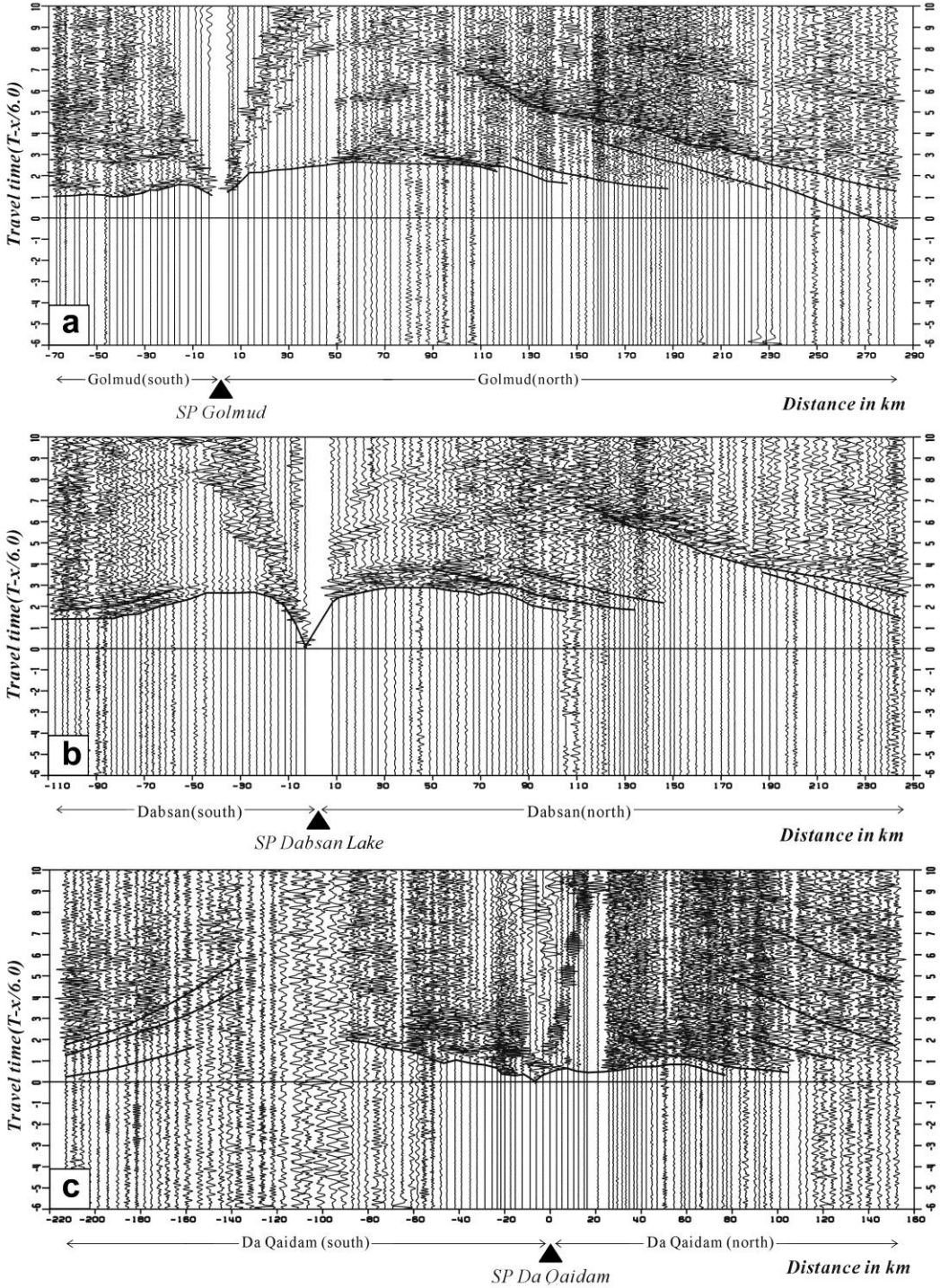
Global Seismic Refraction

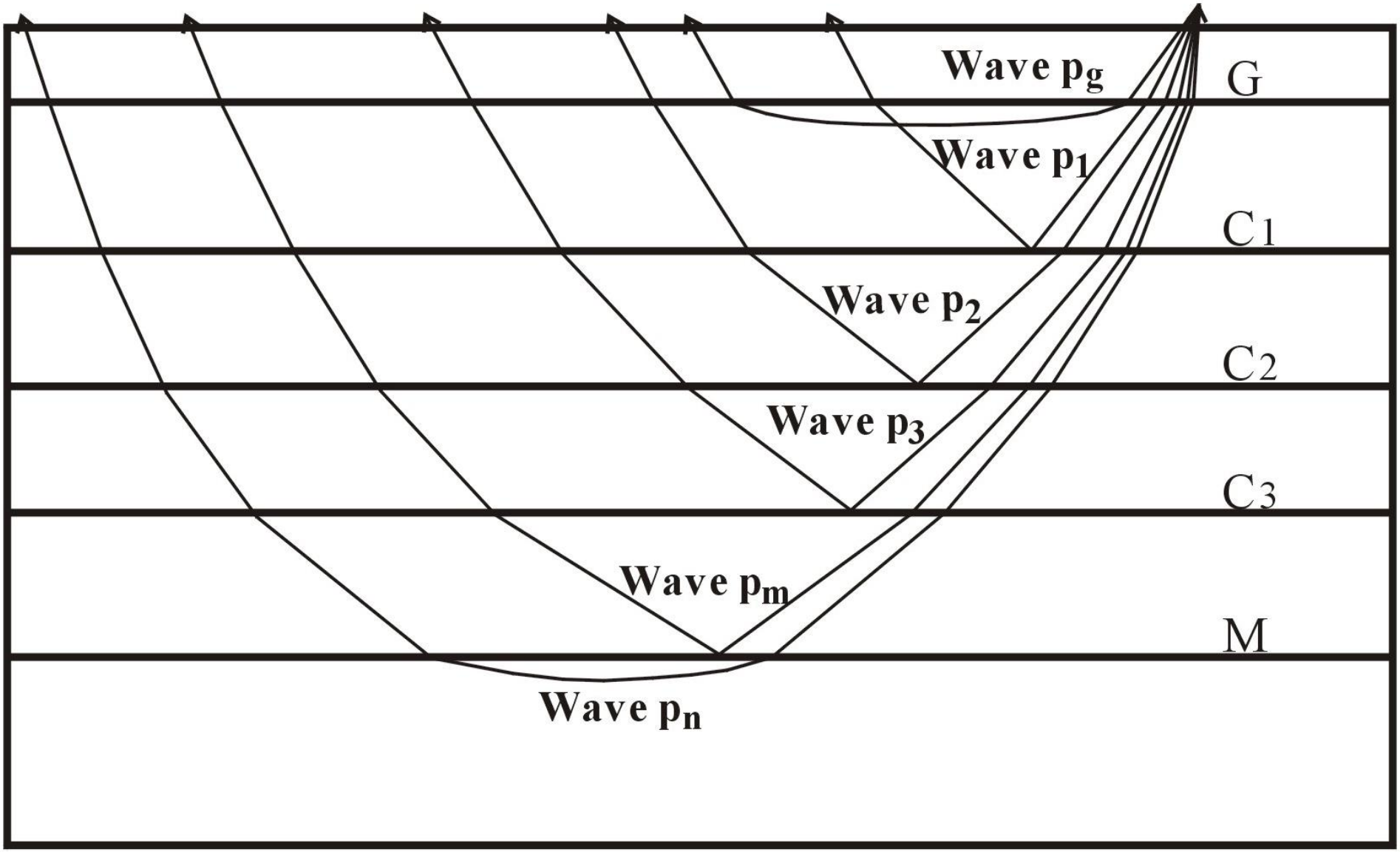
(Mooney, 2005, Treatise on Geophys. Prodehl and Mooney, 2012, GSA Memoir)

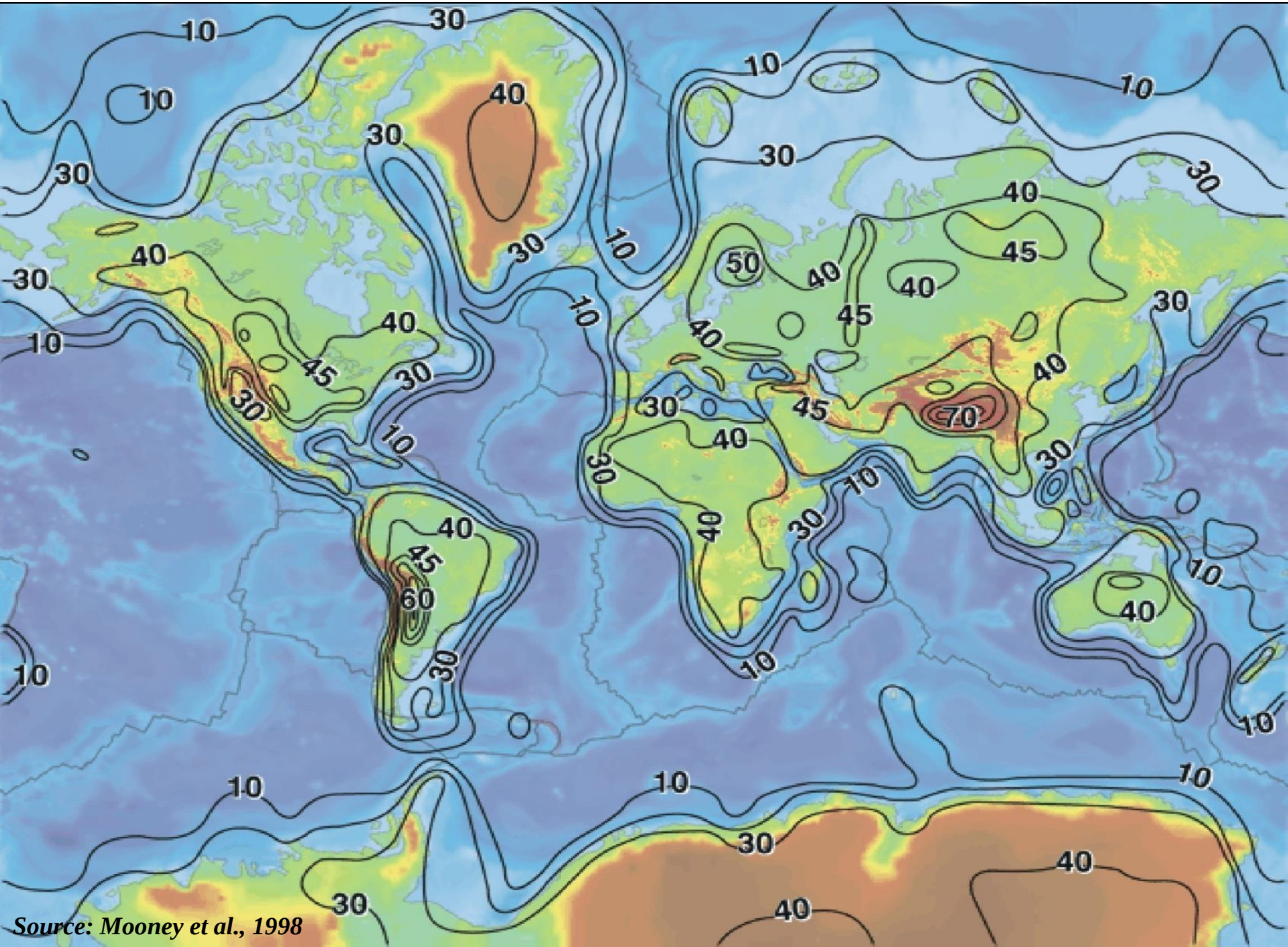


Measuring Crustal Velocities and Thickness



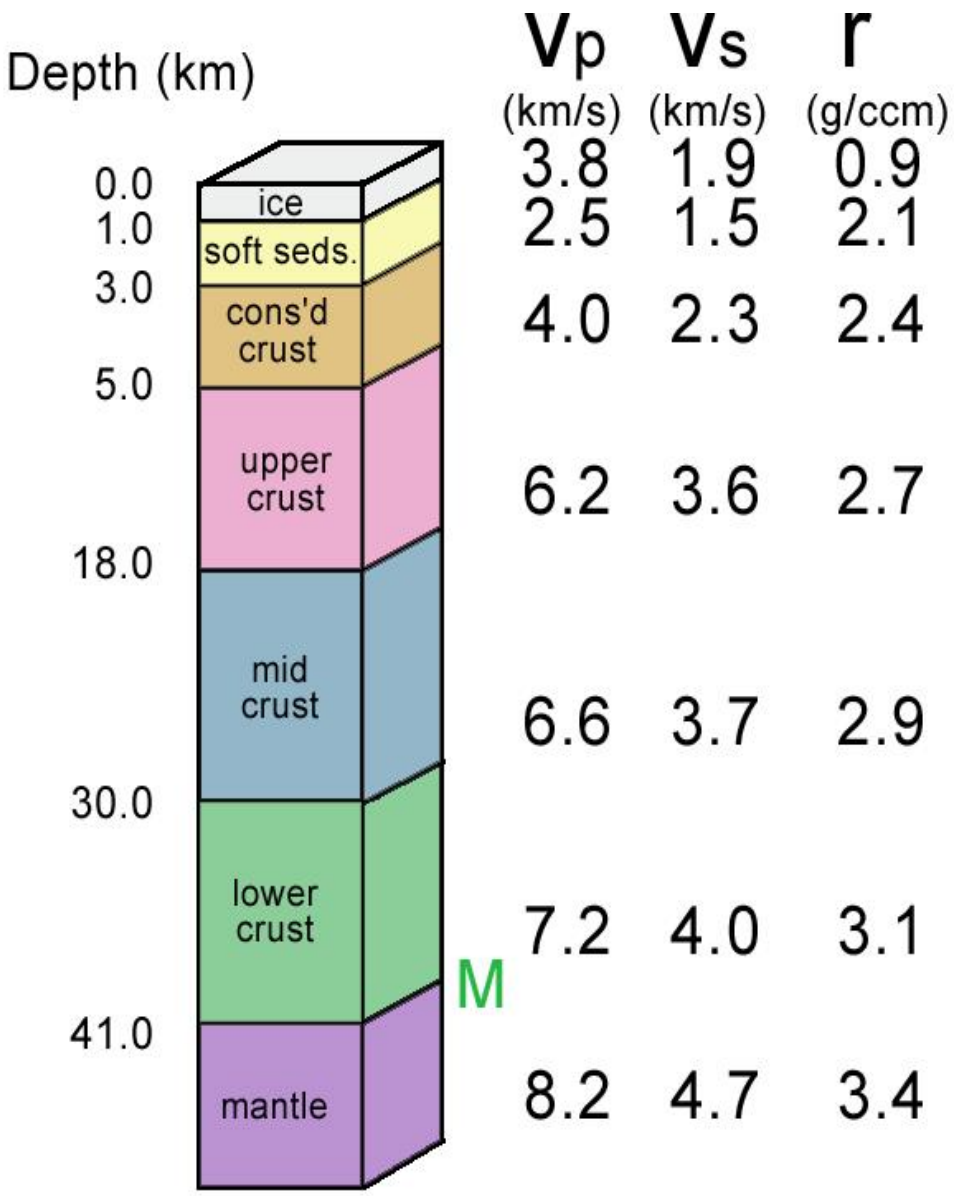

Travel time(T-x/6.0)
a
Golmud(south)
Golmud(north)
SP Golmud
Distance in km
Travel time(T-x/6.0)
b
Dabsan(south)
Dabsan(north)
SP Dabsan Lake
Distance in km
Travel time(T-x/6.0)
c
Da Qaidam (south)
Da Qaidam (north)
SP Da Qaidam
Distance in km


Wave p_g
G
Wave p_1
C_1
Wave p_2
C_2
Wave p_3
C_3
Wave p_m
M
Wave p_n

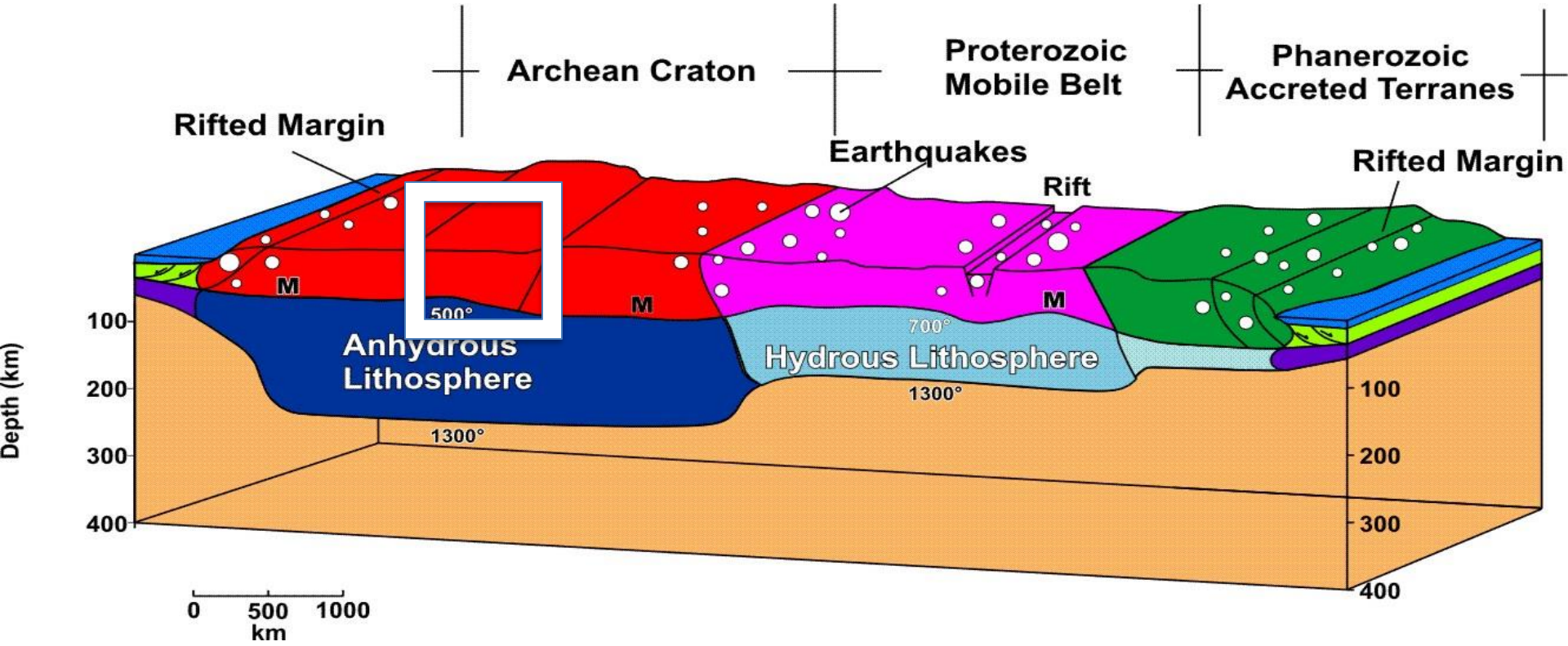


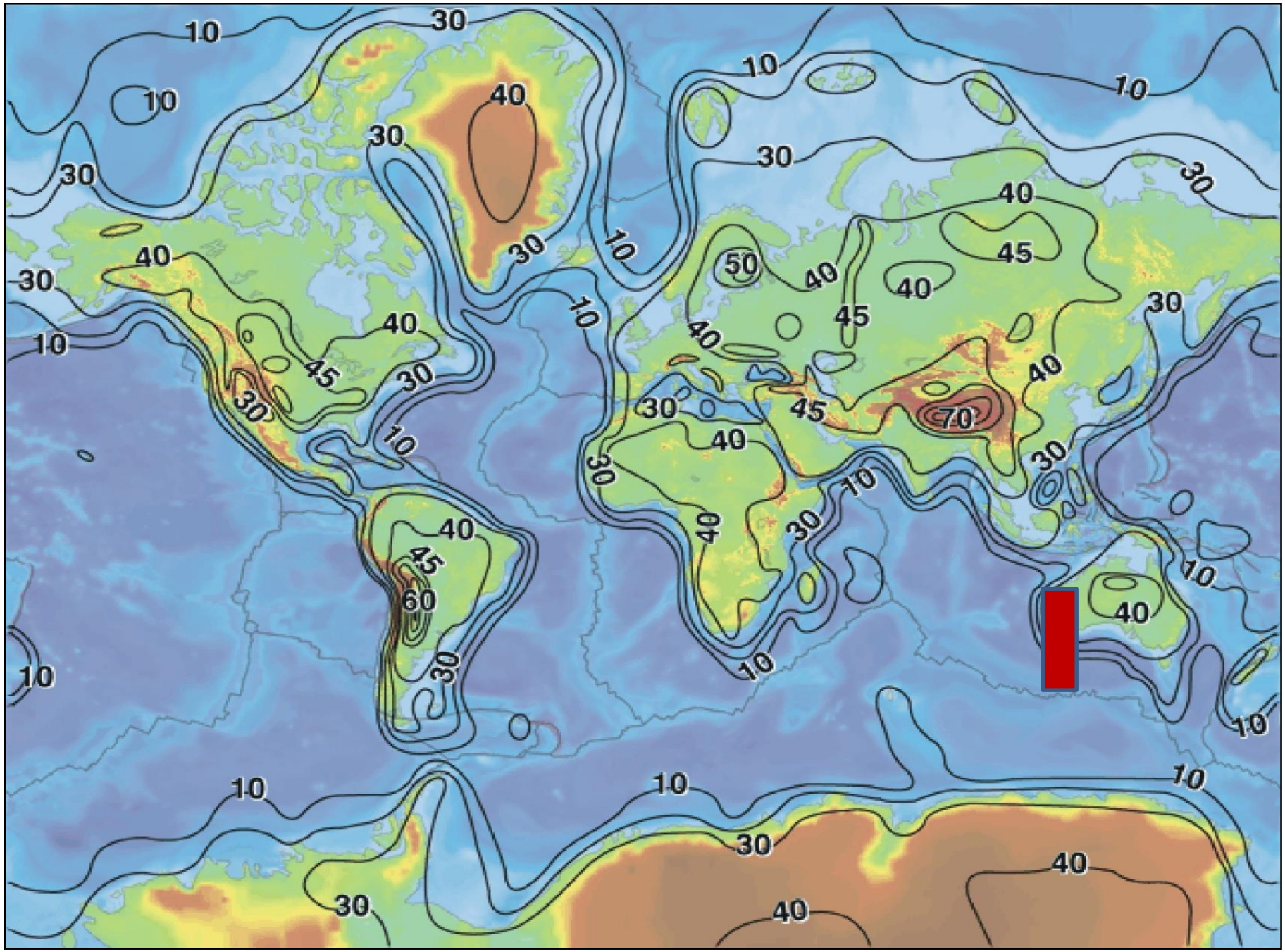
Source: Mooney et al., 1998

Typical Stable Continental Crust: Platform

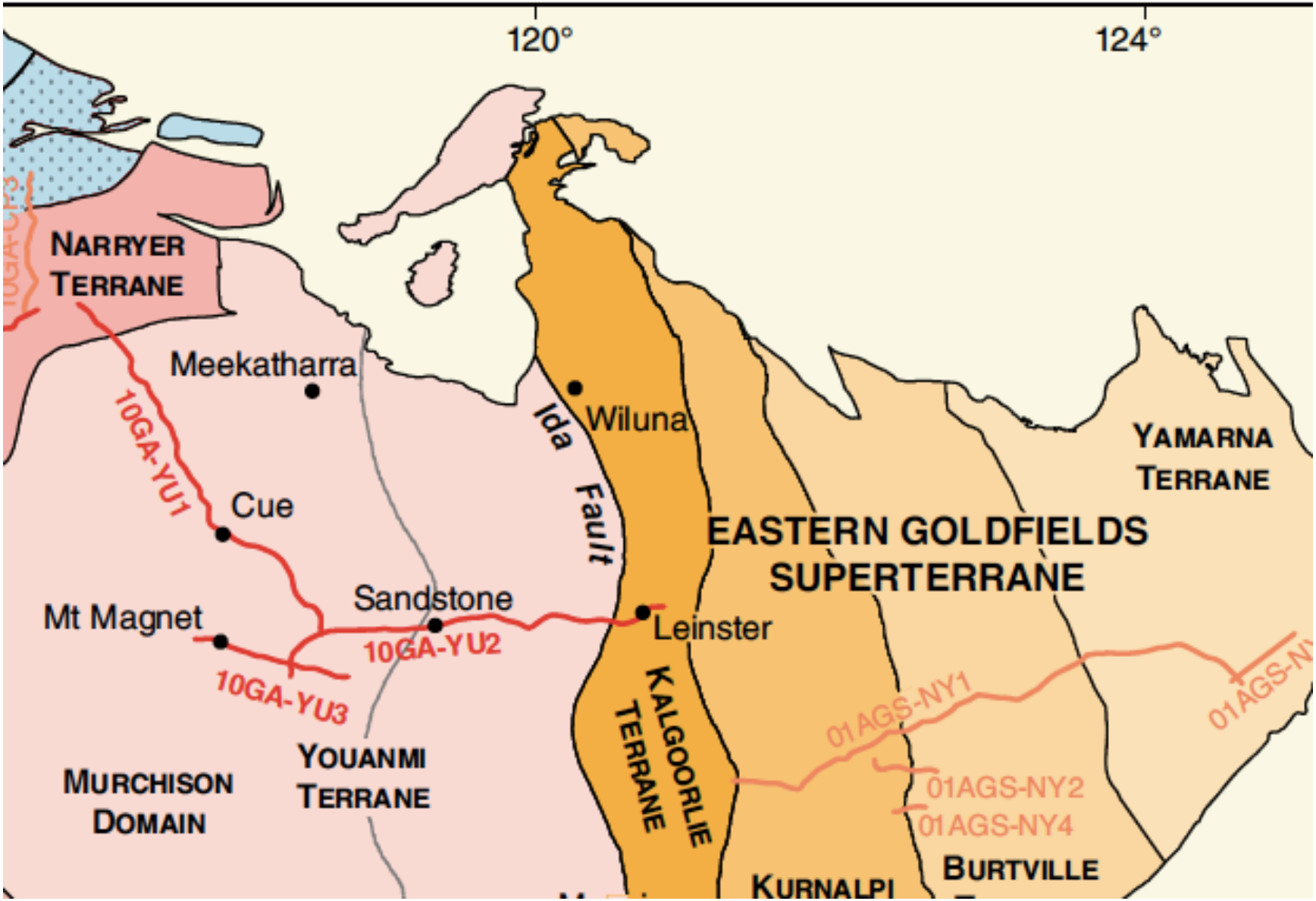


The Crust

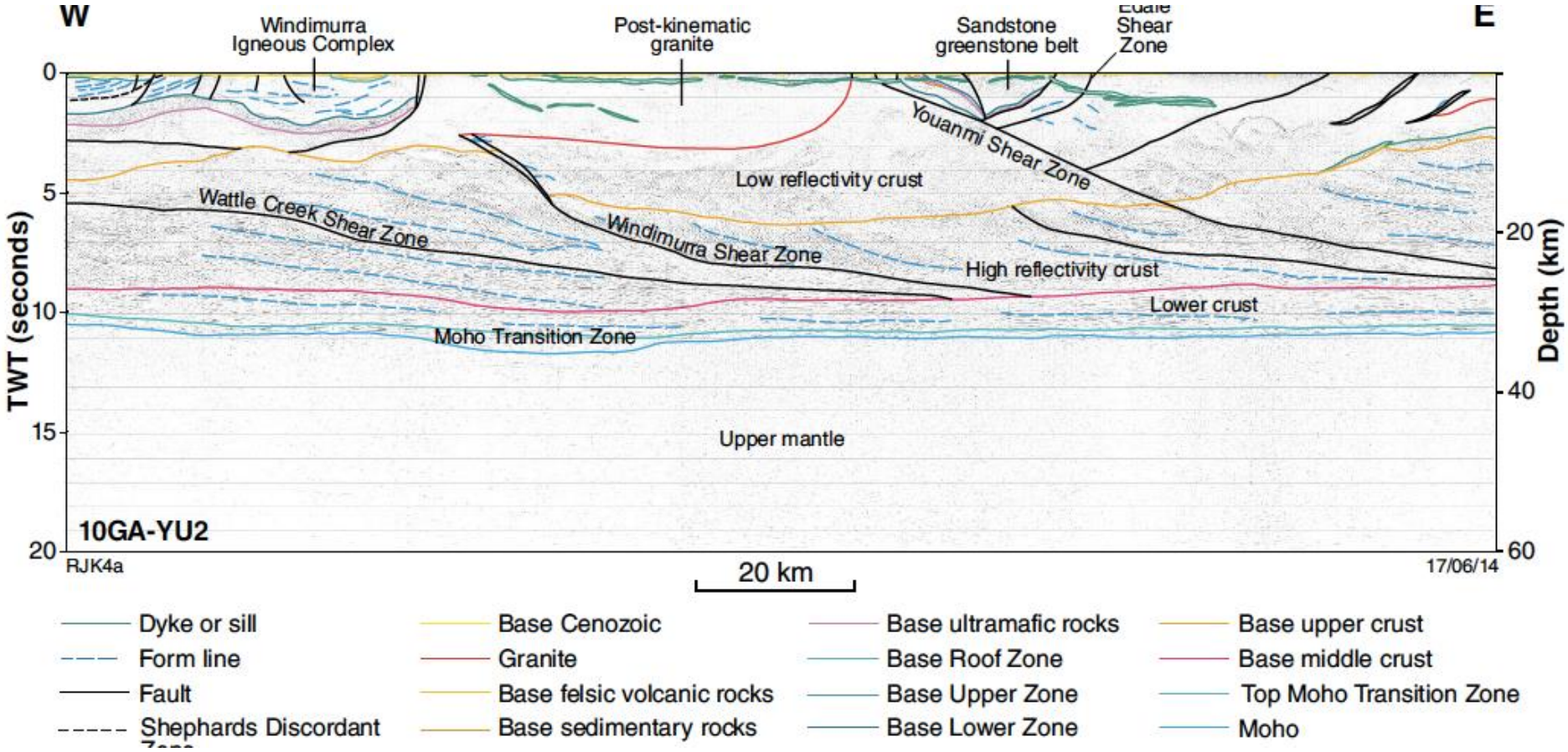

Archean Craton
Proterozoic Mobile Belt
Phanerozoic Accreted Terranes
Rifted Margin
Earthquakes
Rift
Rifted Margin
M
M
M
500°
700°
Anhydrous Lithosphere
Hydrous Lithosphere
1300°
1300°
Depth (km)
100
200
300
400
100
200
300
400
0
500
1000
km



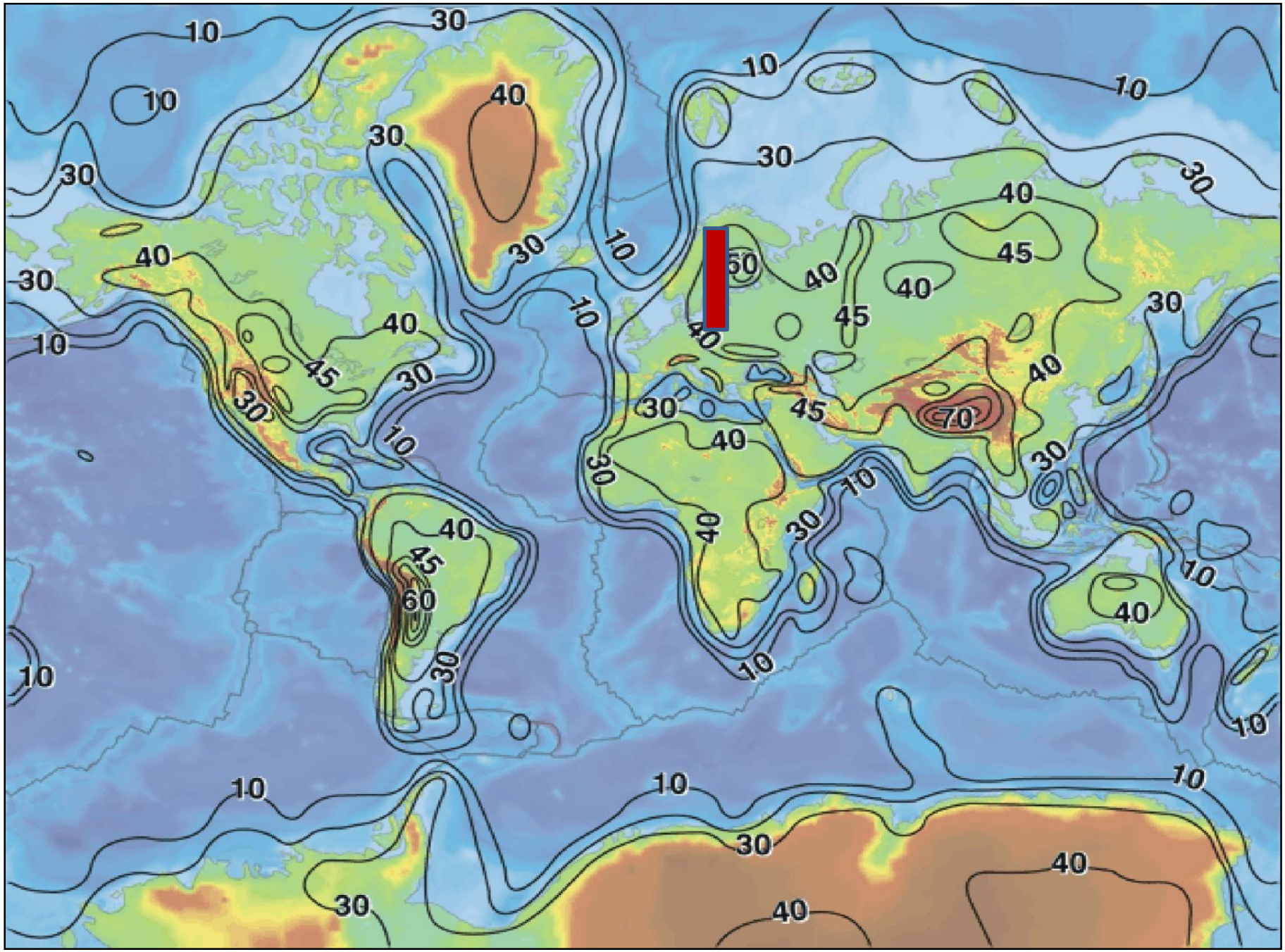
Source: Mooney et al., 1998


120°
124°
NARRYER TERRANE
Meekatharra
10GA-YU1
Cue
Mt Magnet
Sandstone
10GA-YU2
10GA-YU3
Wiluna
Ida Fault
Leinster
KALGOORLIE TERRANE
EASTERN GOLDFIELDS SUPERTERRANE
YAMARNA TERRANE
01AGS-NY1
01AGS-NY2
01AGS-NY4
BURTVILLE
KURNALPI
YOUANMI TERRANE
MURCHISON DOMAIN

Seismic Reflection
3.0 Ga Crust: Yilgarn, 10GA-YU3

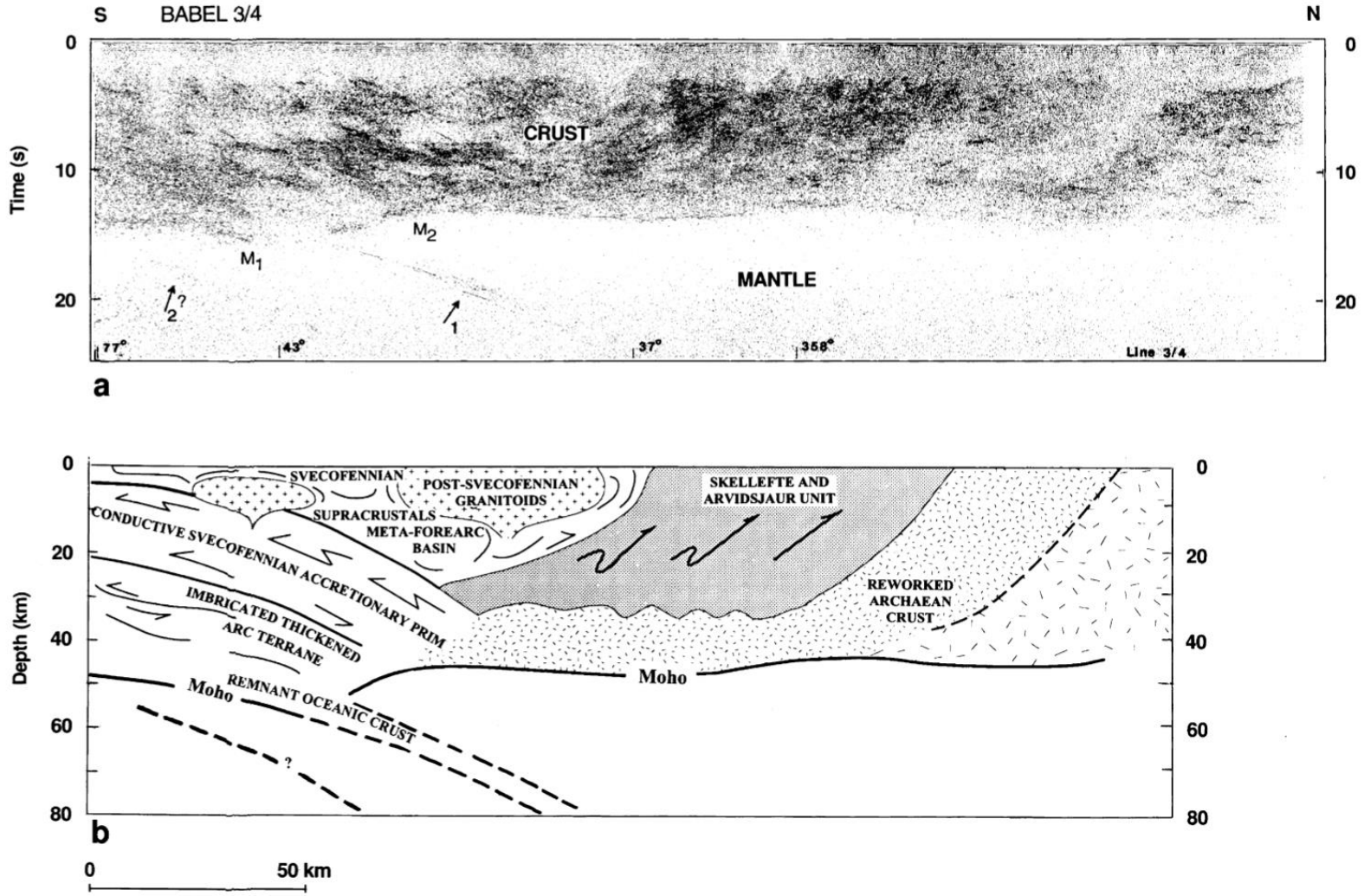


Zibra et al., GSWA Record 2013/6, pp. 87-95



Source: Mooney et al., 1998

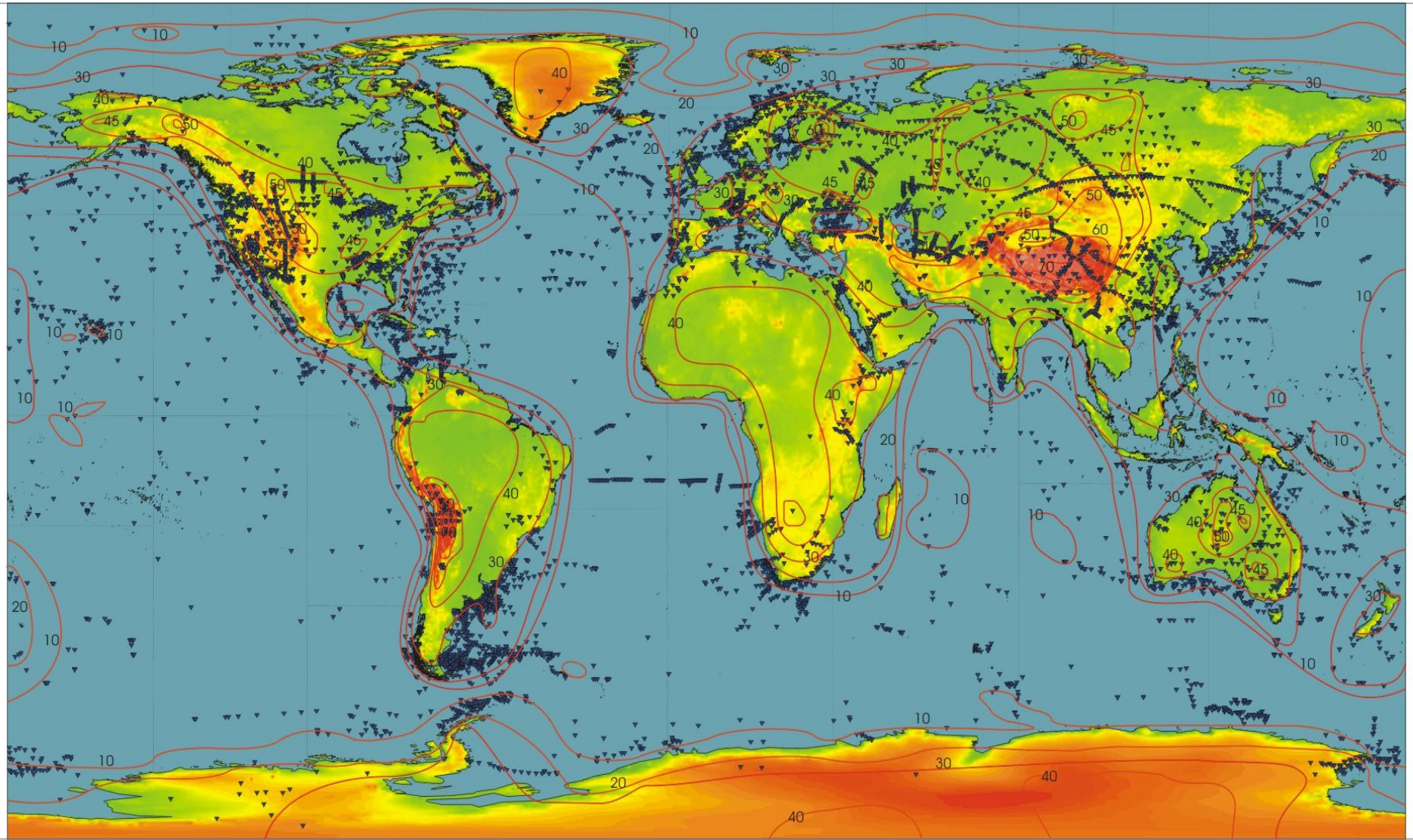
northern Gulf of Bothnia

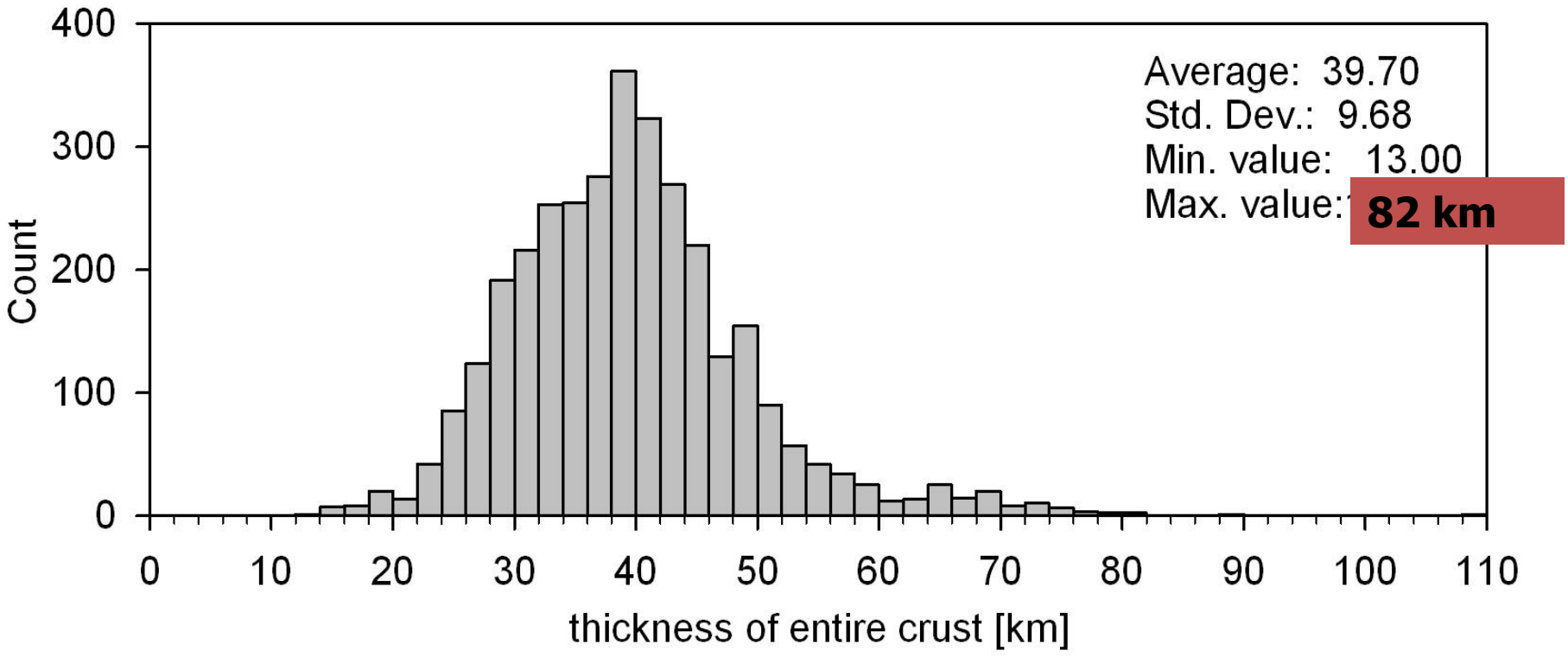


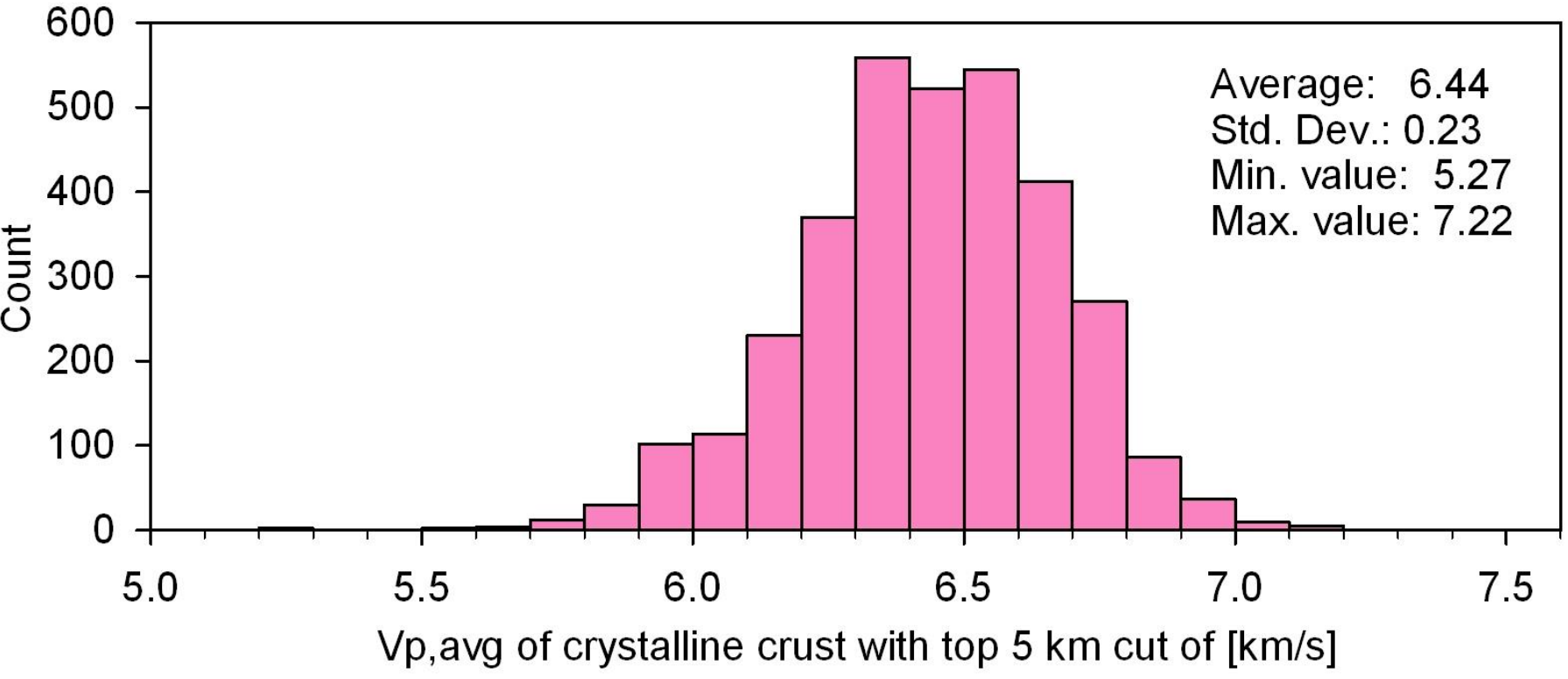
Balling 2000

Global Seismic Refraction

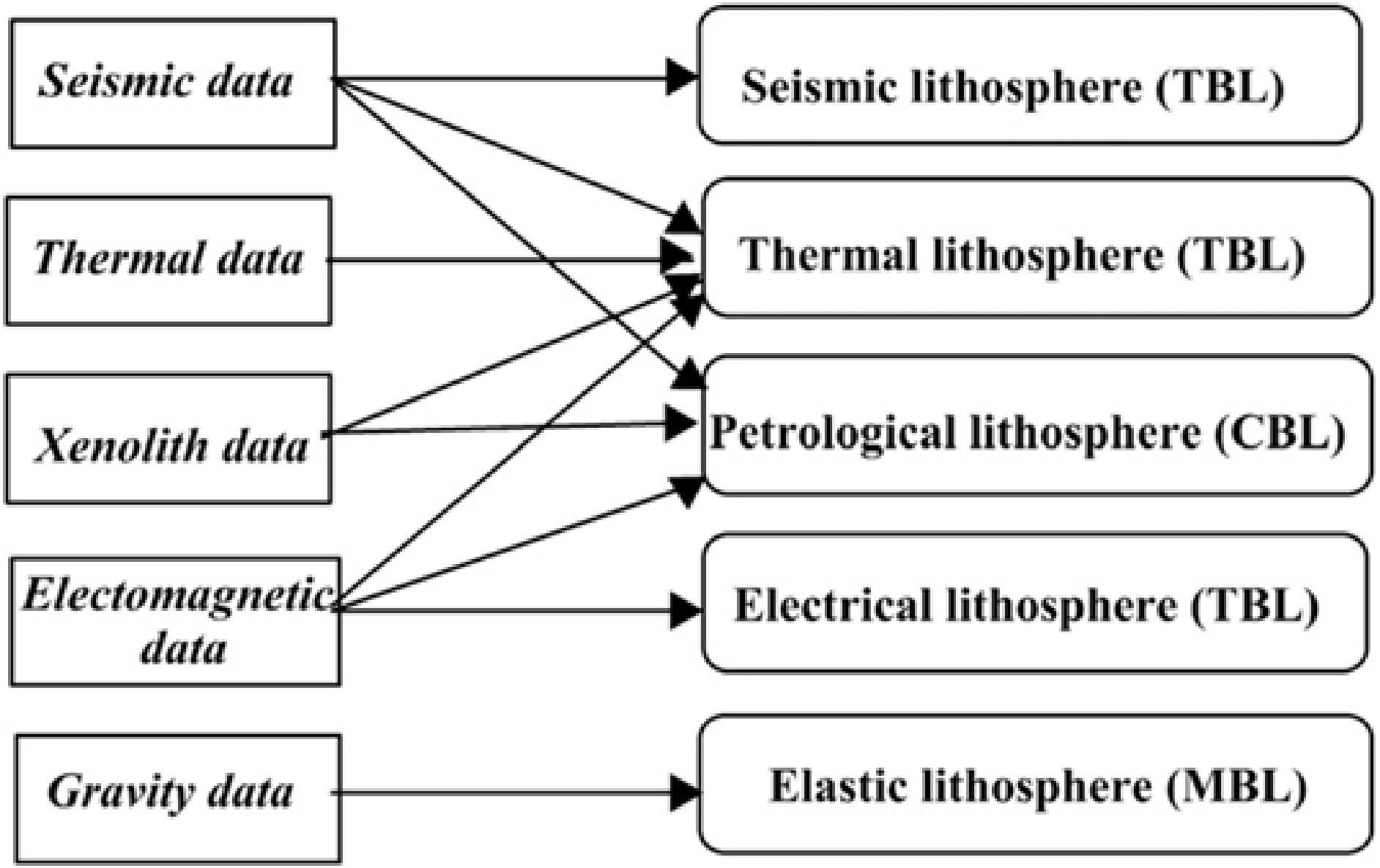
(Mooney, 2005, Treatise on Geophys. Prodehl and Mooney, 2012, GSA Memoir)

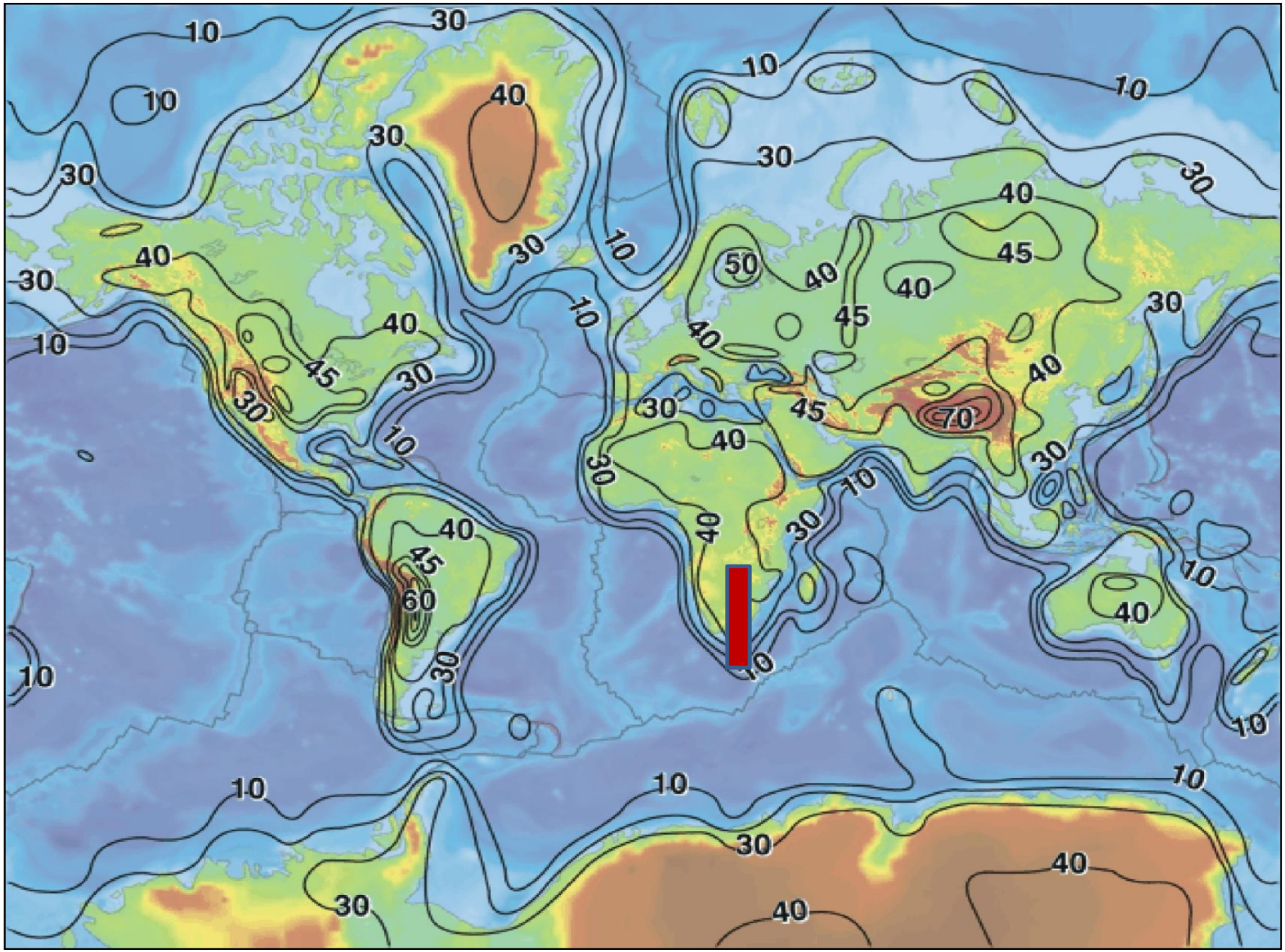



Average: 39.70
Std. Dev.: 9.68
Min. value: 13.00
Max. value:
82 km
Count
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
100
110
thickness of entire crust [km]


600
500
400
300
200
100
0
Count
5.0
5.5
6.0
6.5
7.0
7.5
Vp,avg of crystalline crust with top 5 km cut of [km/s]
Average: 6.44
Std. Dev.: 0.23
Min. value: 5.27
Max. value: 7.22

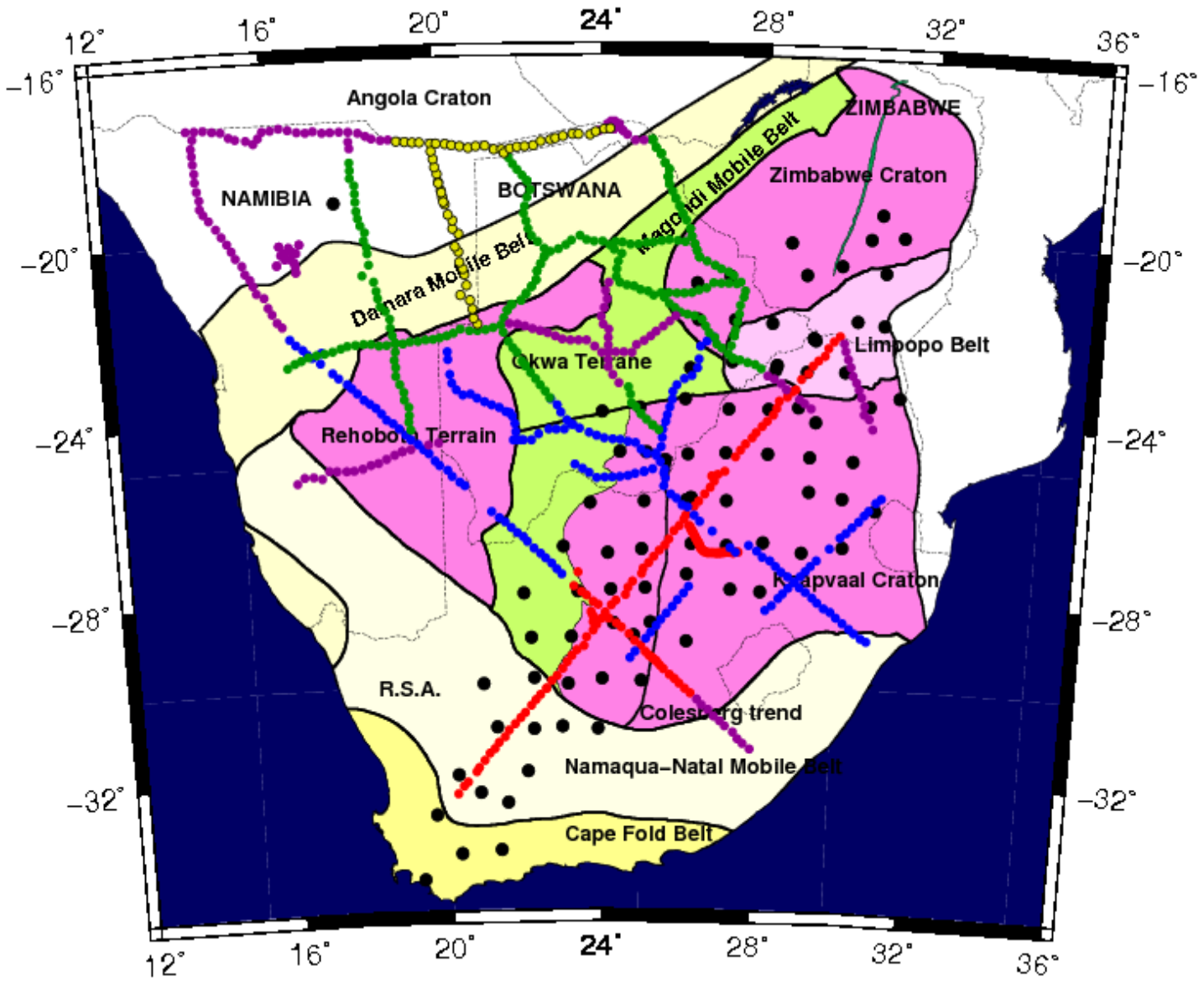
- The Electrical Lithosphere


Seismic data
Thermal data
Xenolith data
Electomagnetic data
Gravity data
Seismic lithosphere (TBL)
Thermal lithosphere (TBL)
Petrological lithosphere (CBL)
Electrical lithosphere (TBL)
Elastic lithosphere (MBL)

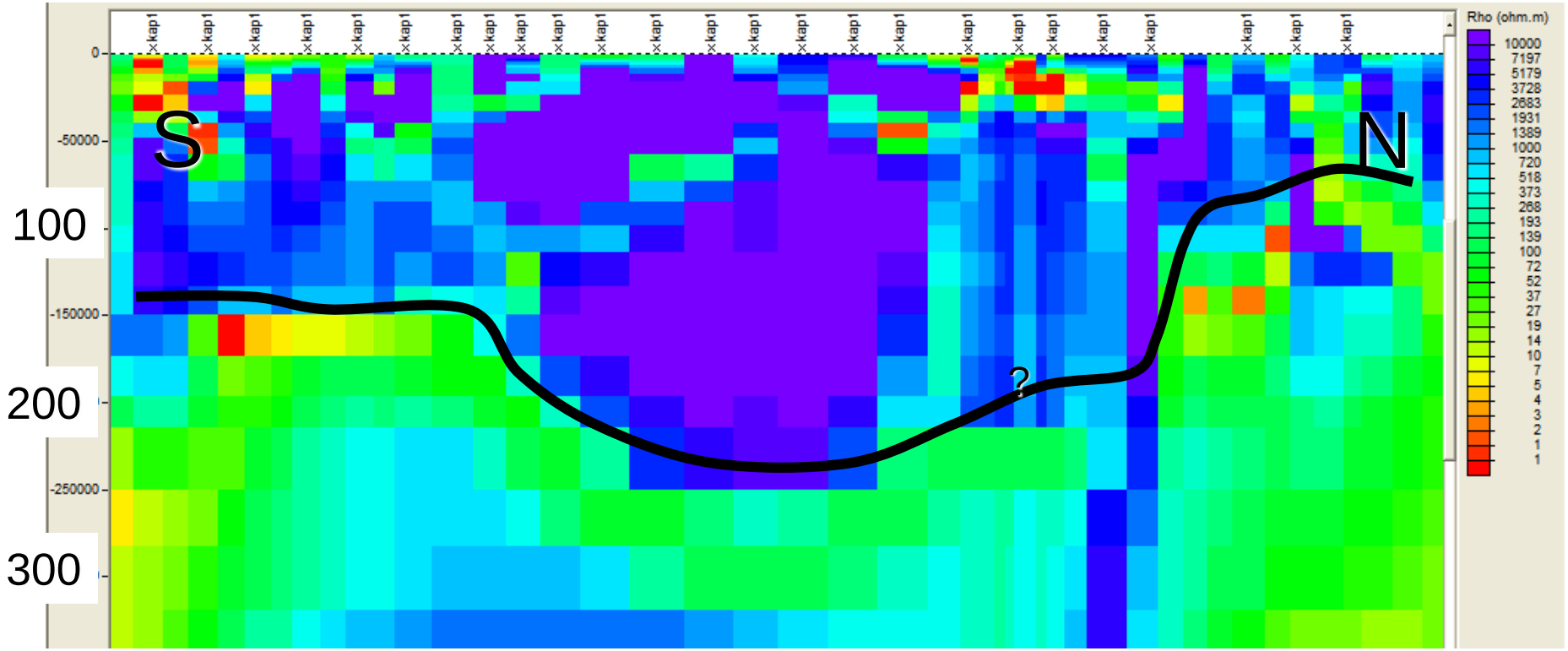


Source: Mooney et al., 1998

Geo-electrical and Seismic Data

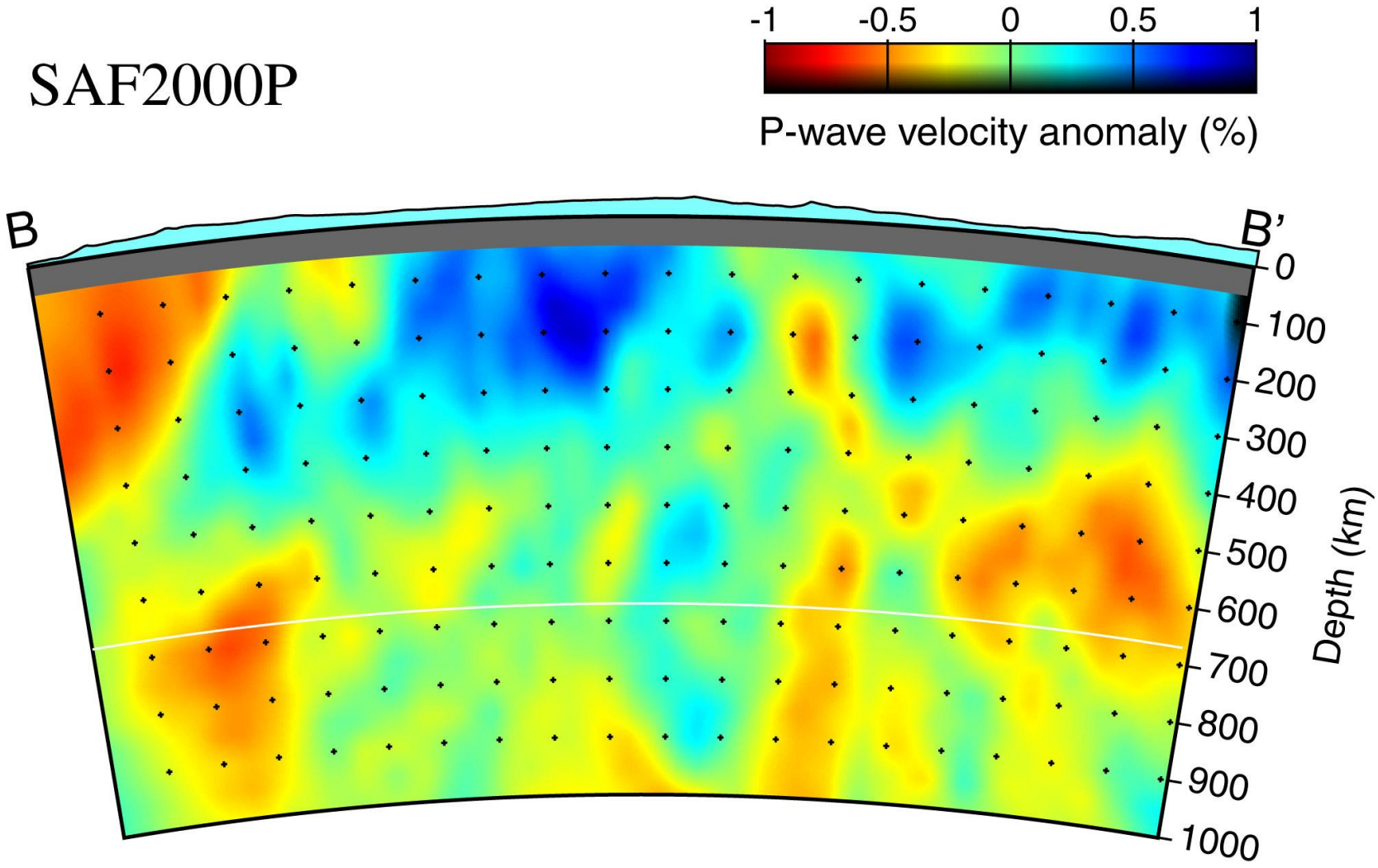


2-D model: Main result – variation in LAB



Lithospheric thickness varies along the profile, with the thickest part from just south of Kimberley -> north of Pretoria

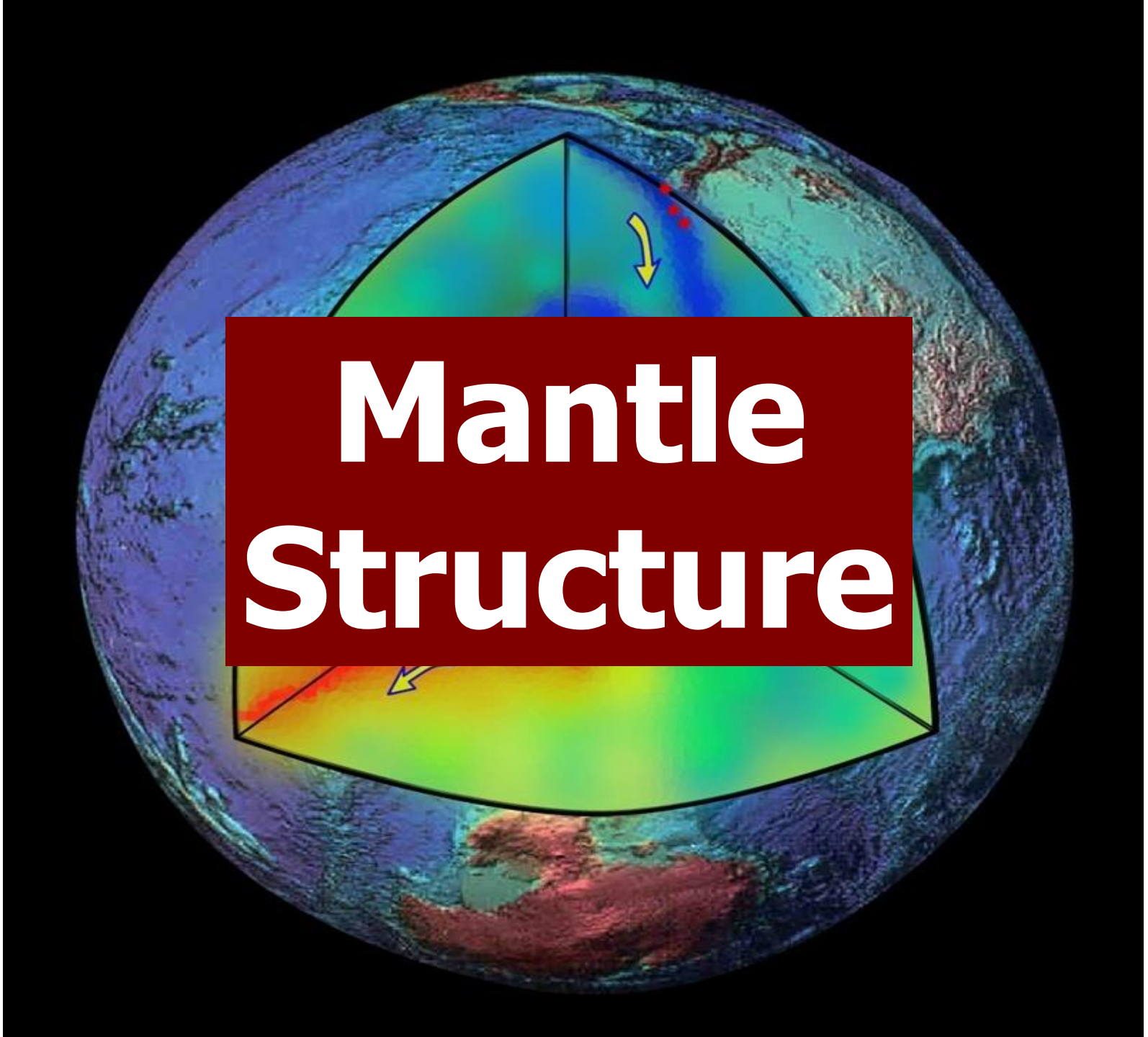
SAF2000P



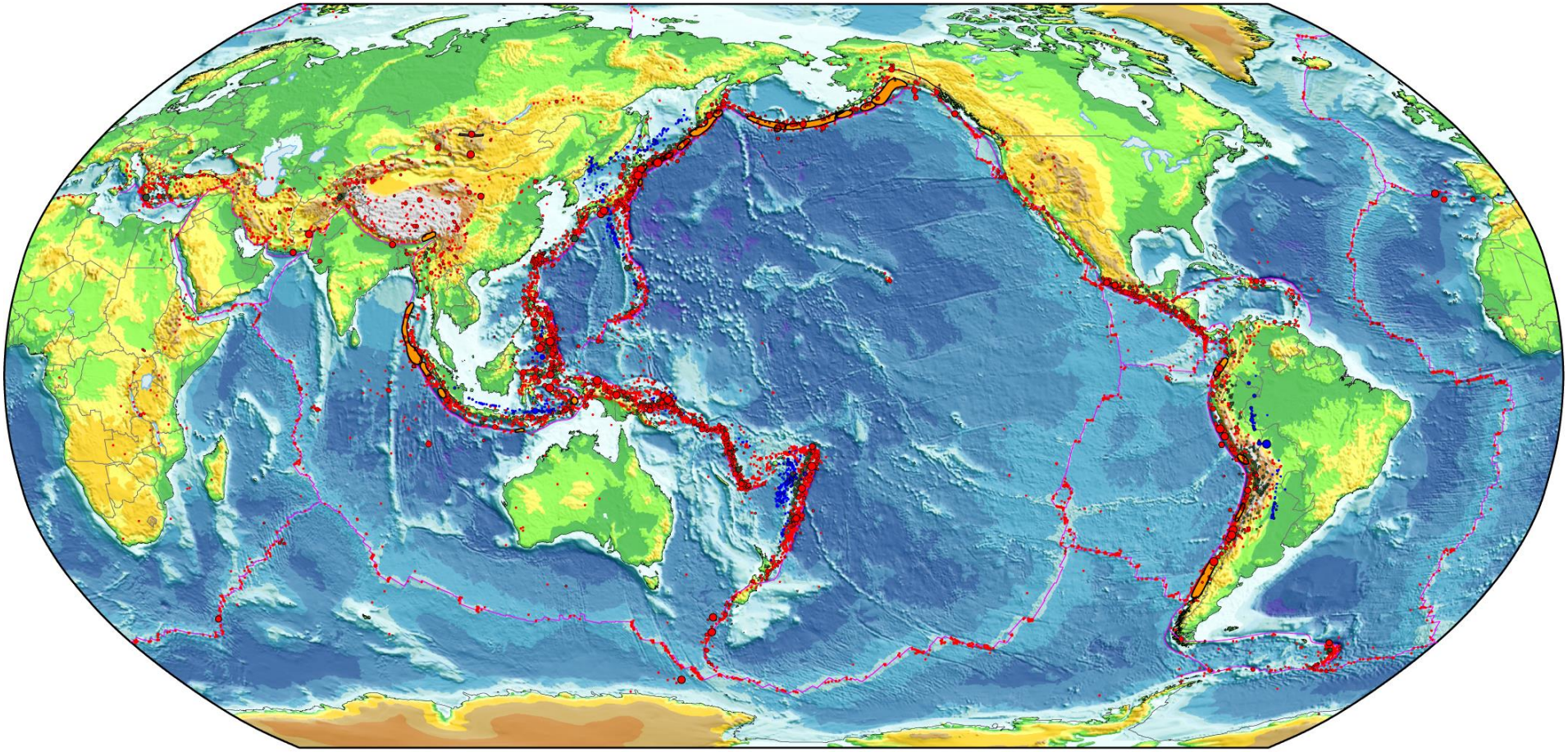
B: (34.25S, 19.25E)

B’: (18.50S, 31.50E)

- The Seismological Lithosphere


Mantle
Structure

Seismicity of the Earth (1900-2007)

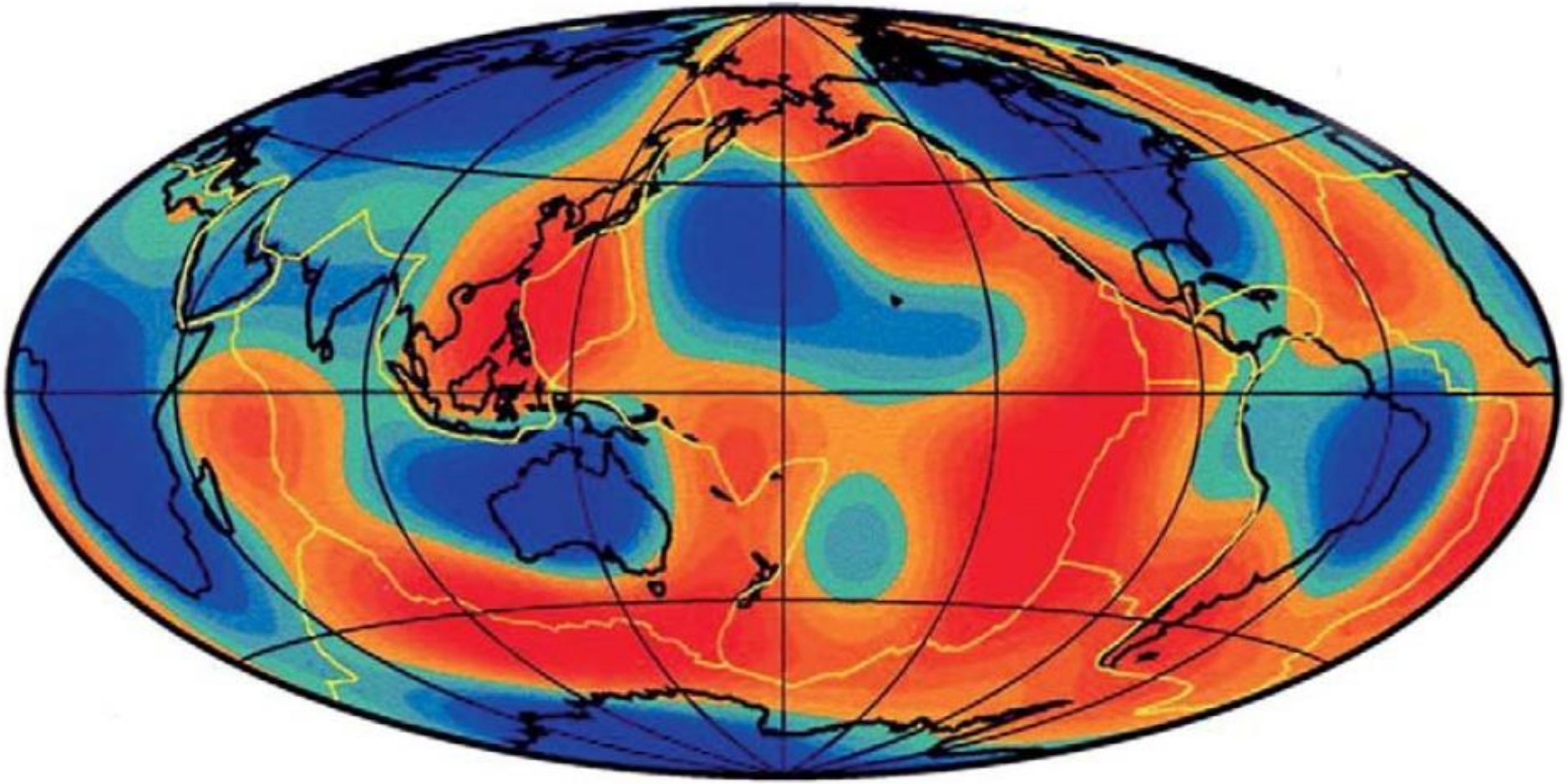


Villaseñor, Benz and Engdahl (Fall AGU, 2007)

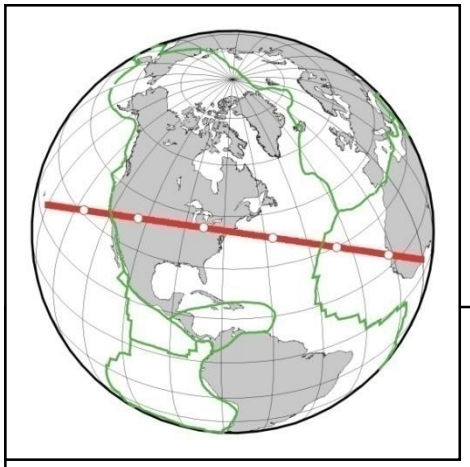
Adam Dwiewonski, Harvard University, 1936 - 2016

Woodhouse and Dziewonski, 1984

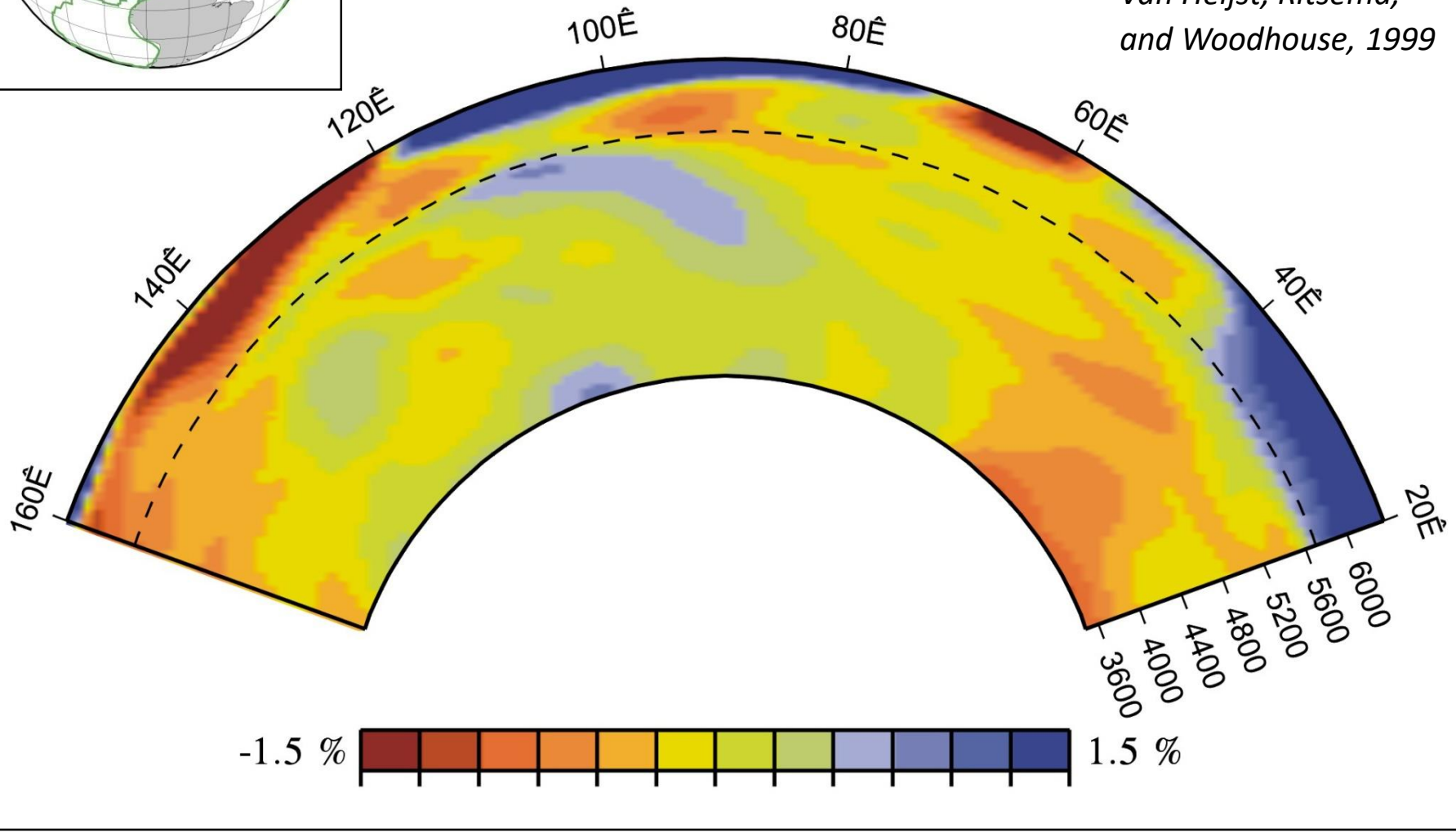
Vs at 100 km; blue is positive, red is negative



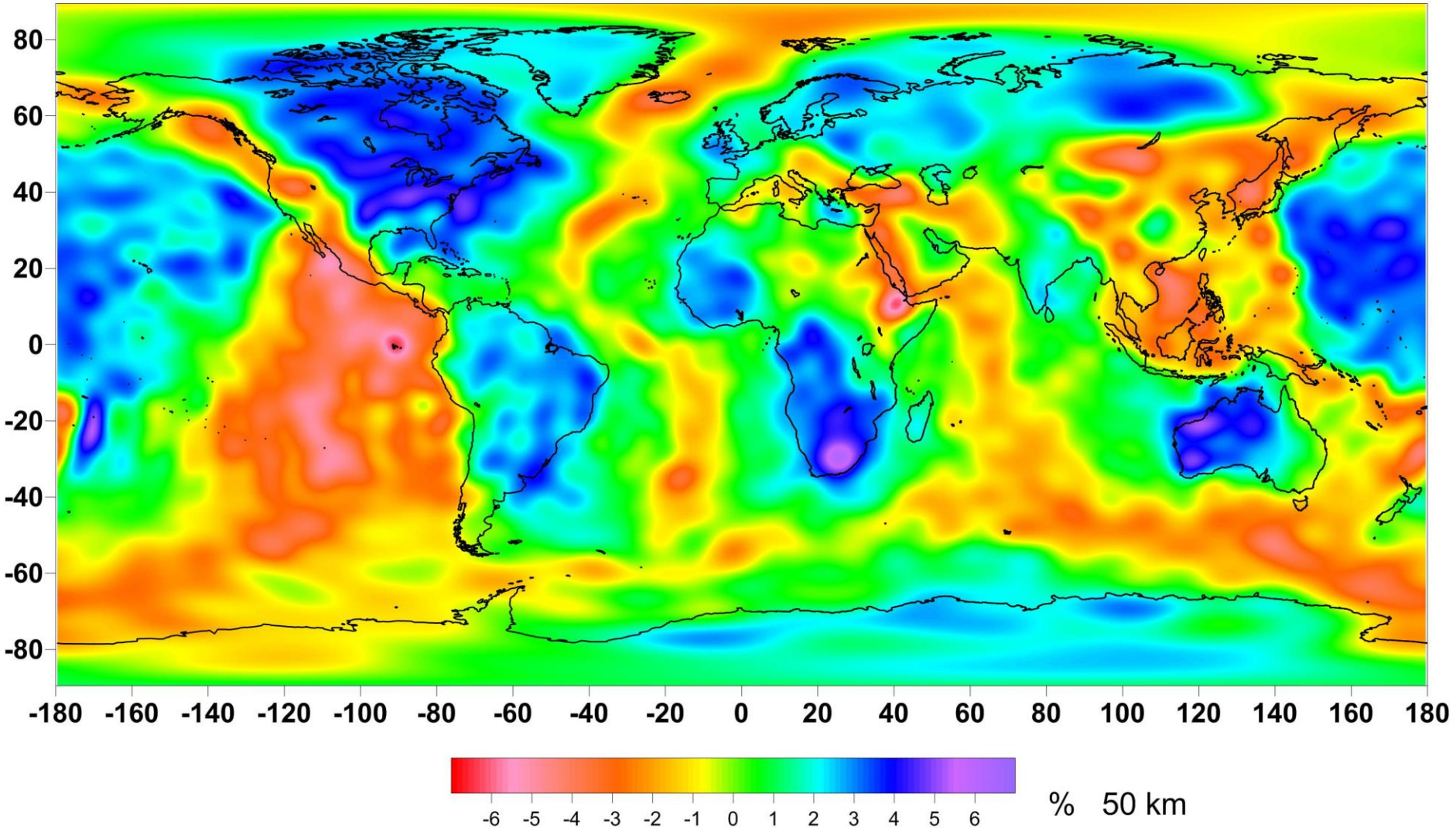
Tomographic Model



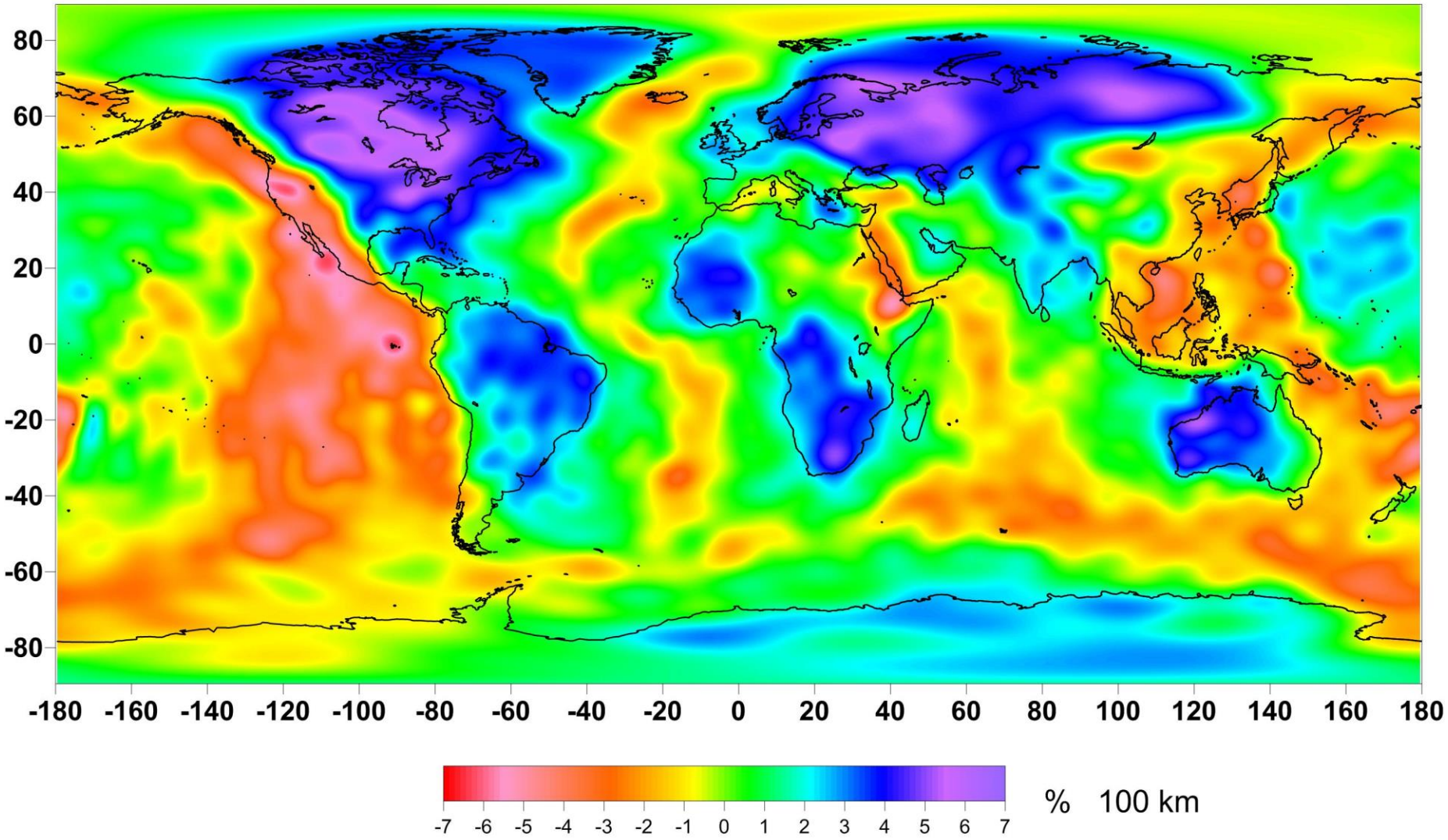
Van Heijst, Ritsema, and Woodhouse, 1999



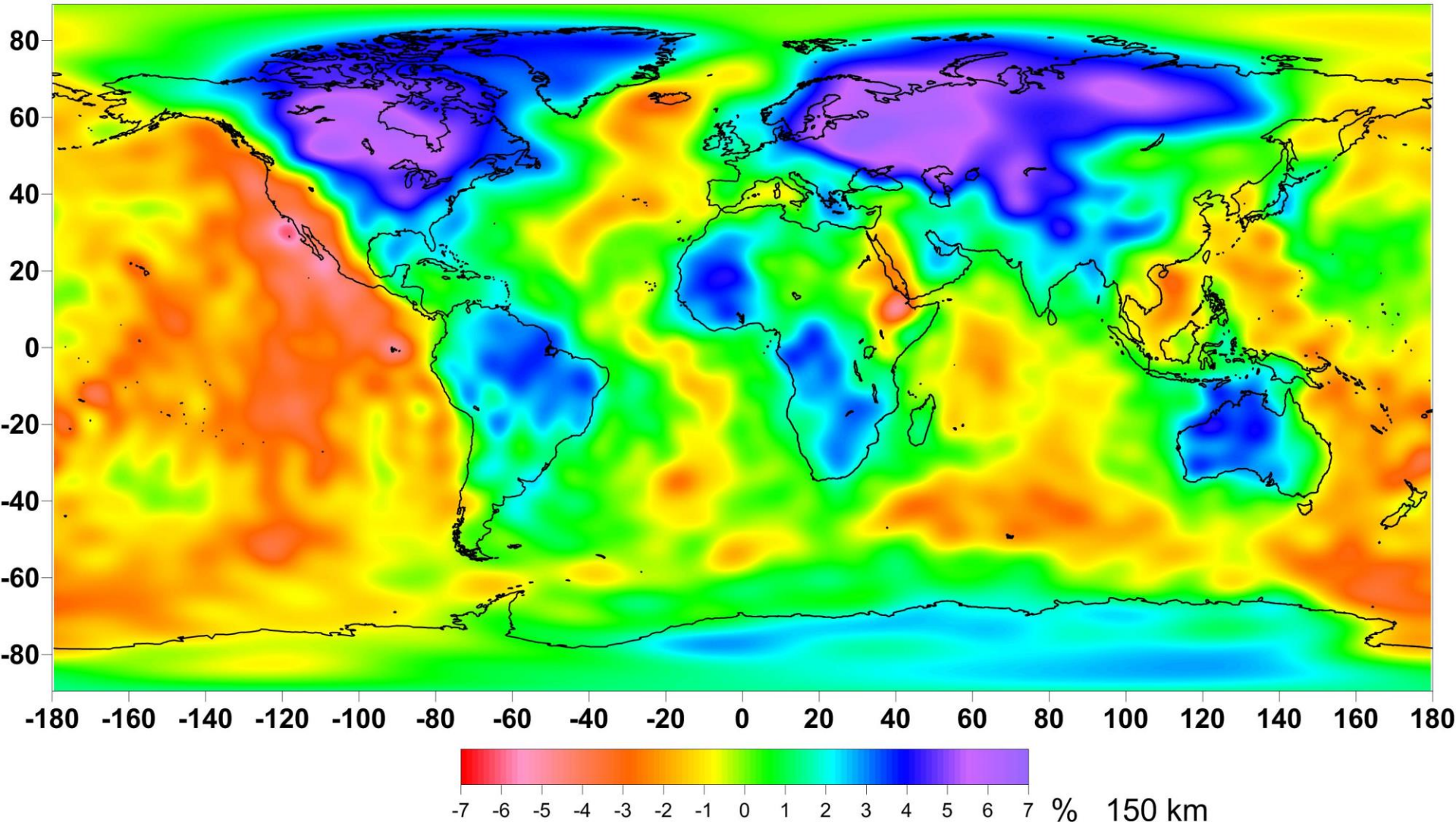
S-wave Anomaly 50 Km



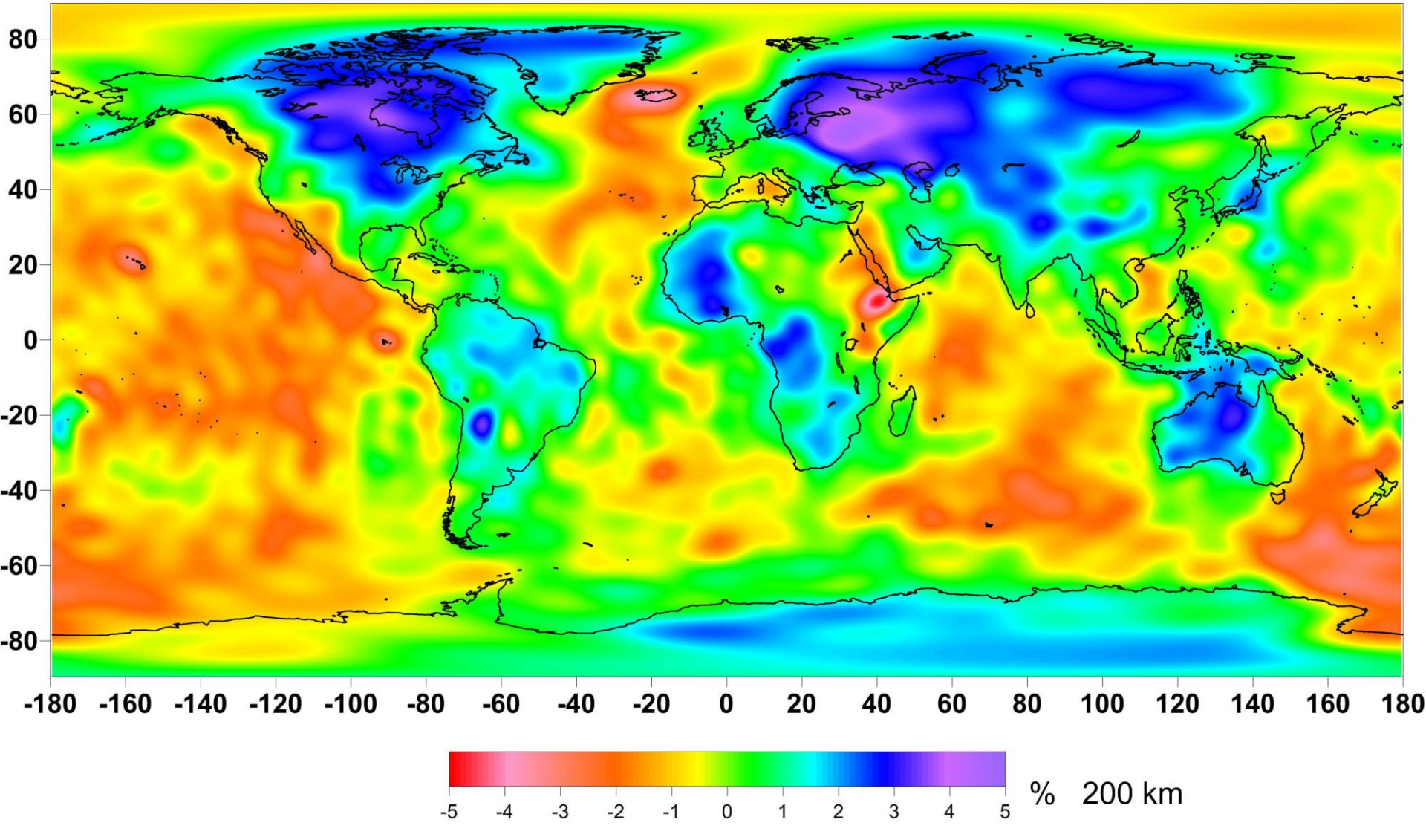
S-wave Anomaly 100 km



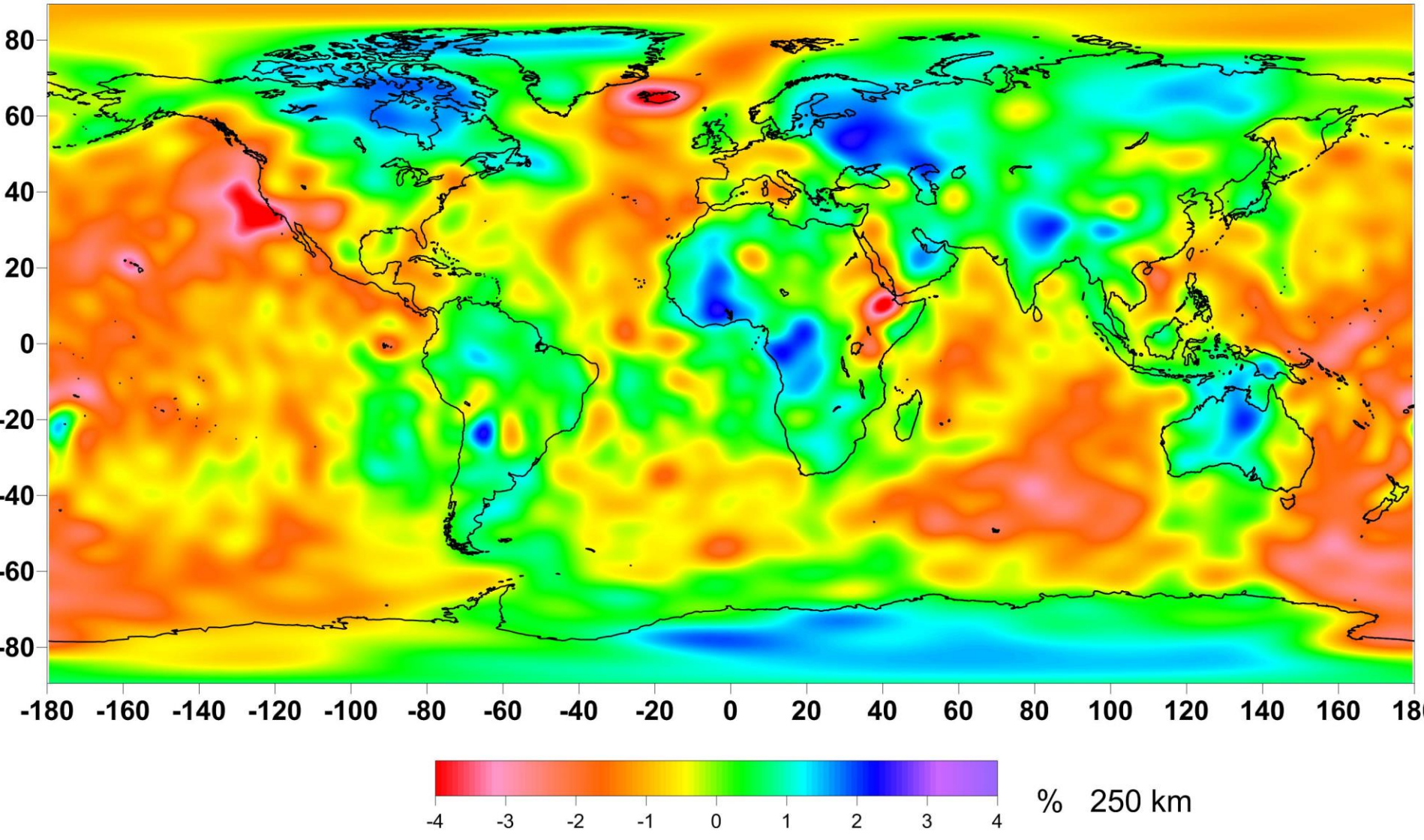
S-wave Anomaly, 150 km



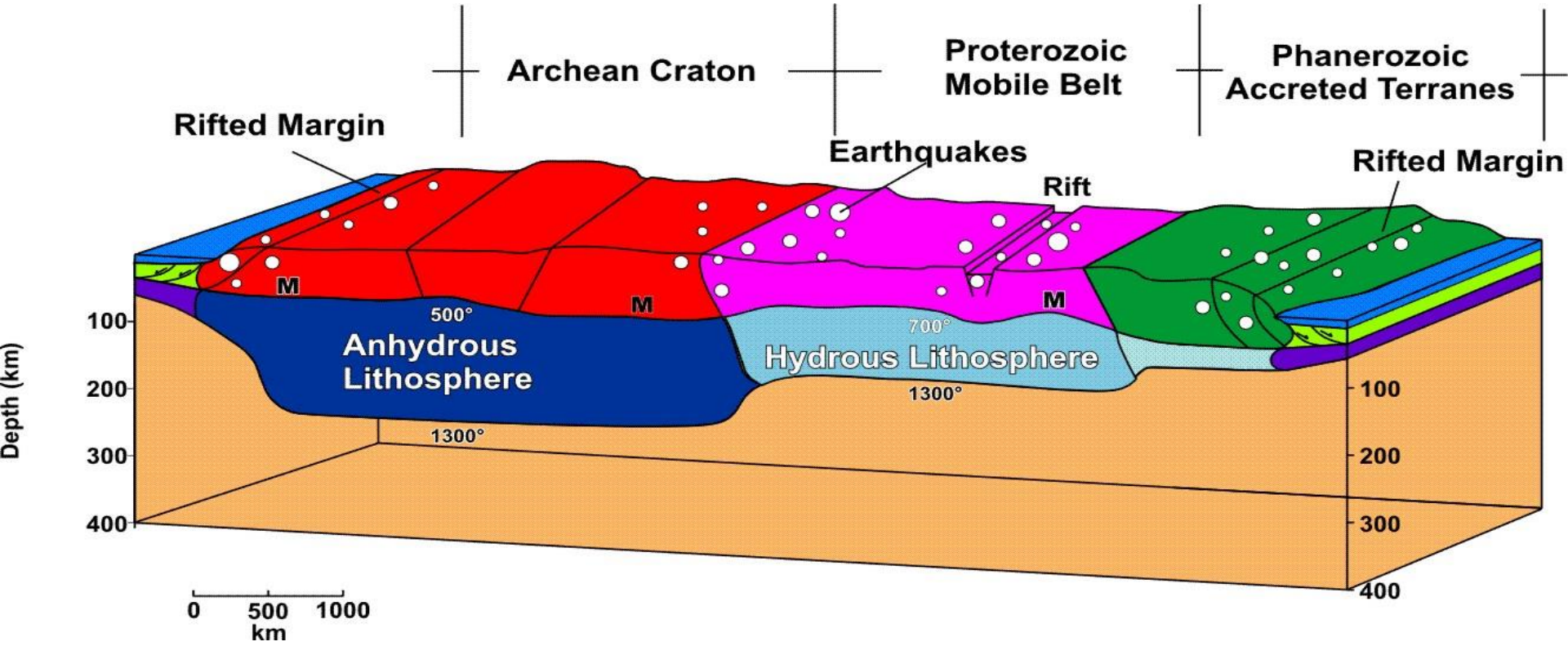
S-wave Anomaly 200 km



S-wave Anomaly 250 km

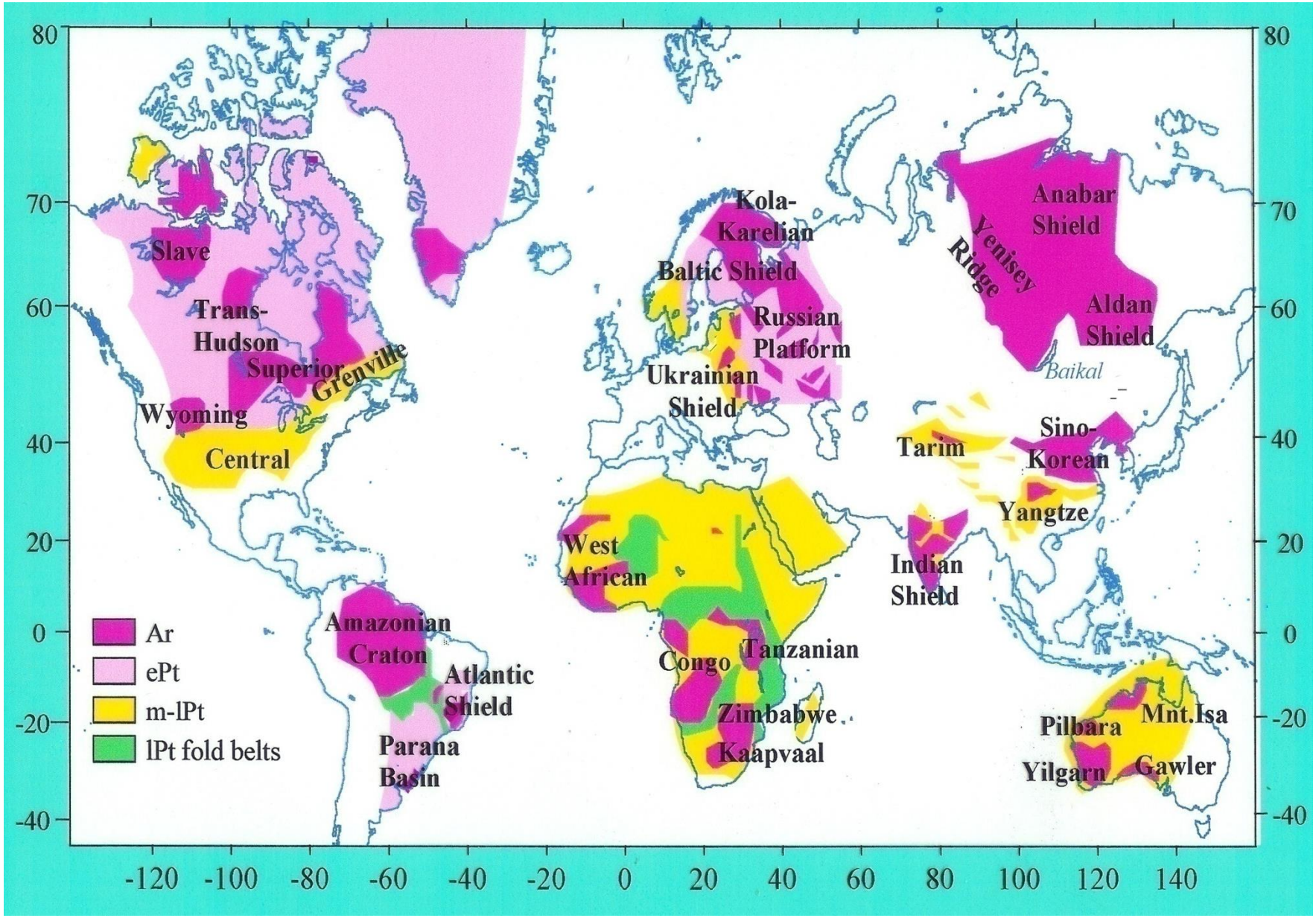


The Lithosphere



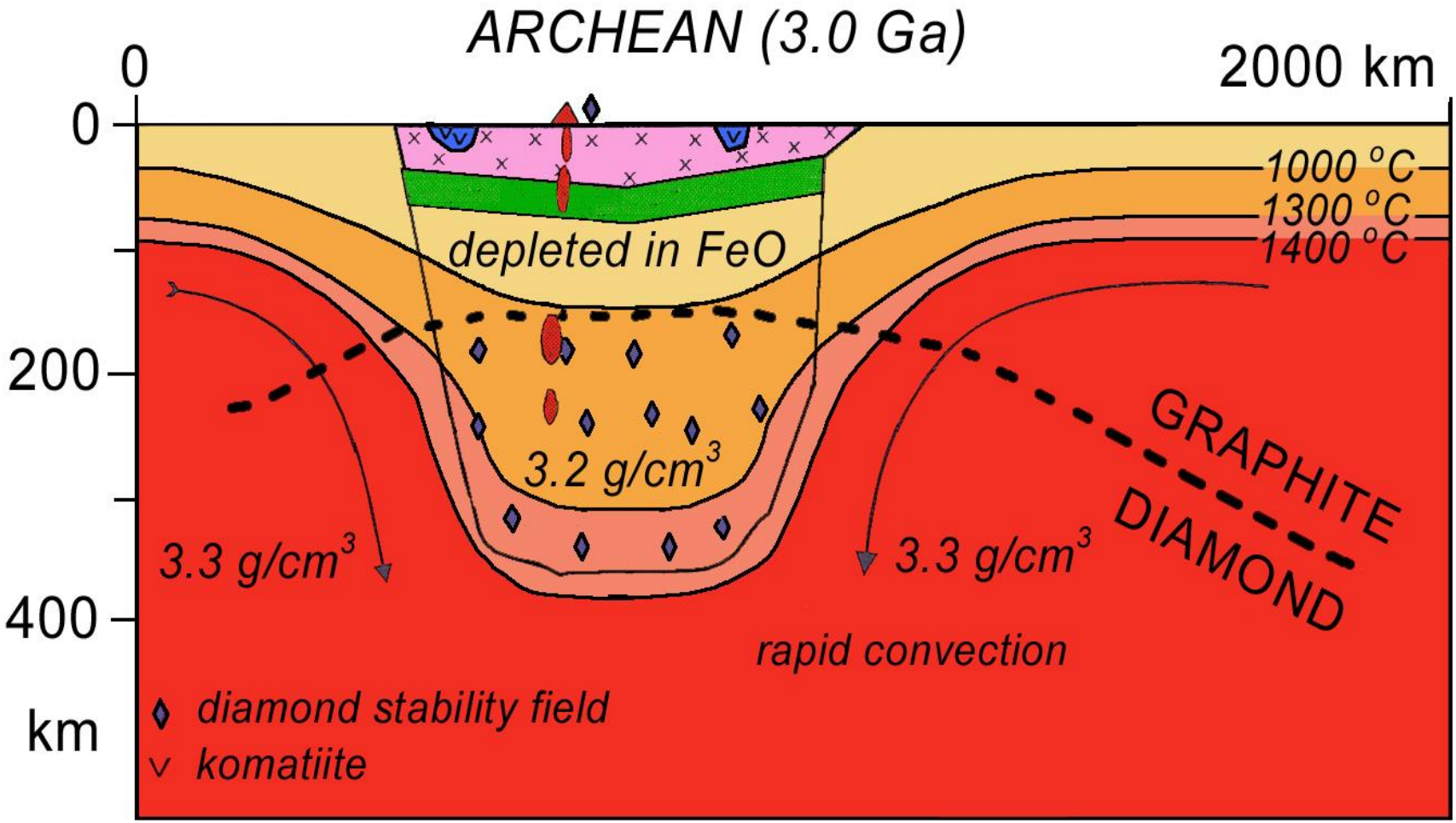
- Petrologic Constraints on Lithospheric Roots beneath Continents

Precambrian Cratons

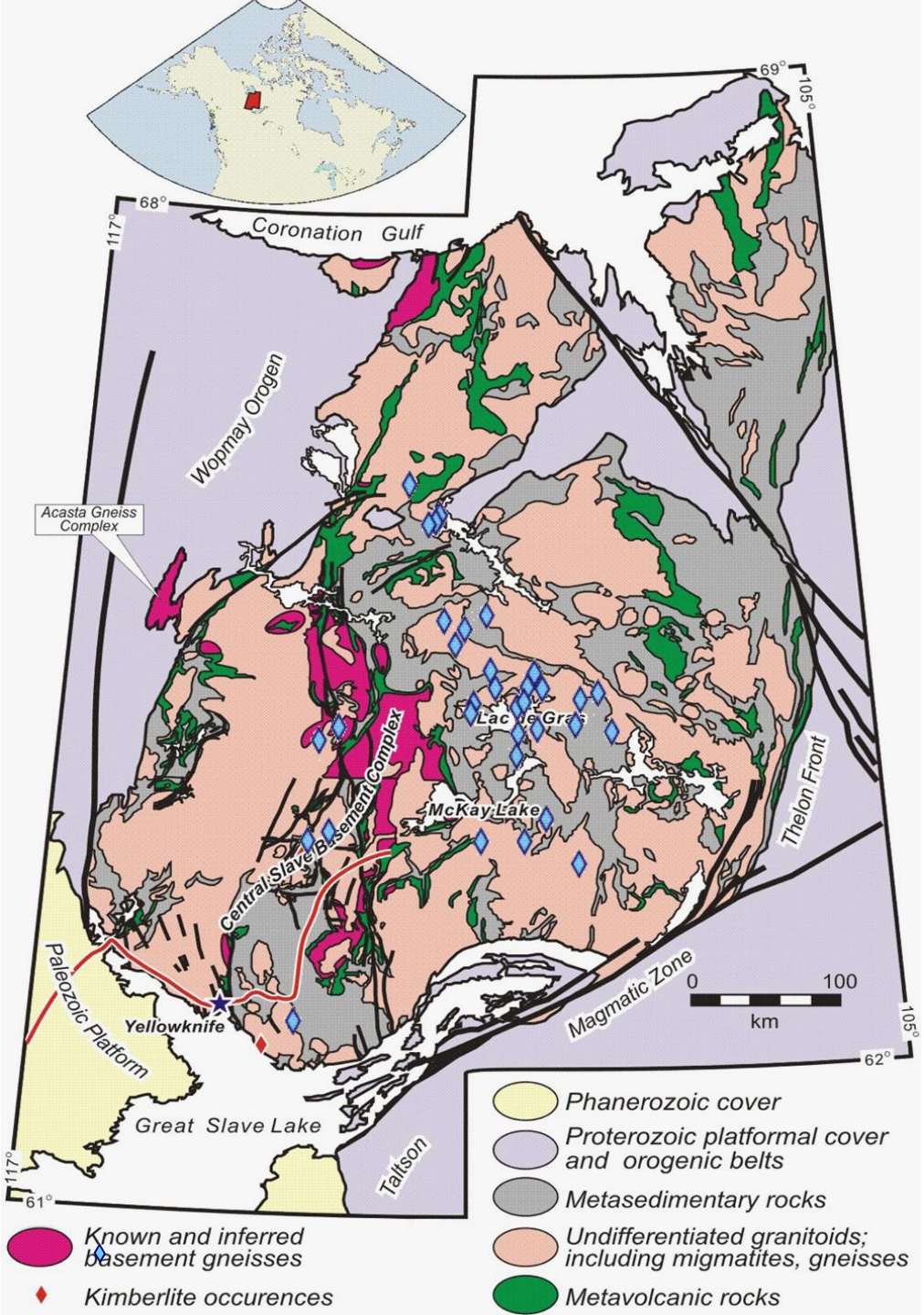


Source: Artemieva and Mooney, 2000

Model for Archean Lithospheric Evolution



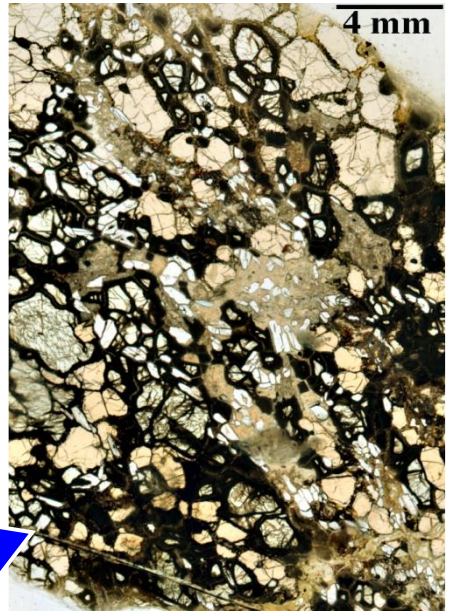
Slave Province

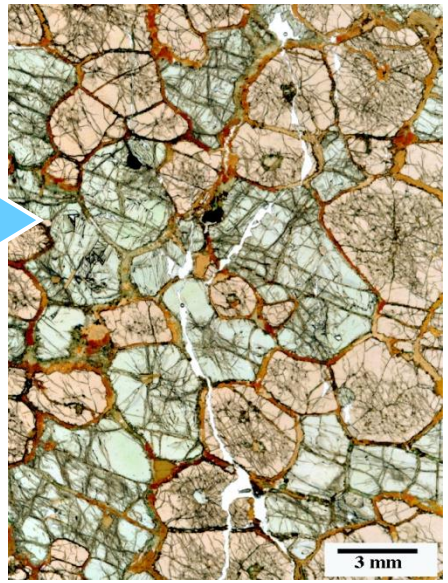


Kimberlite Discoveries

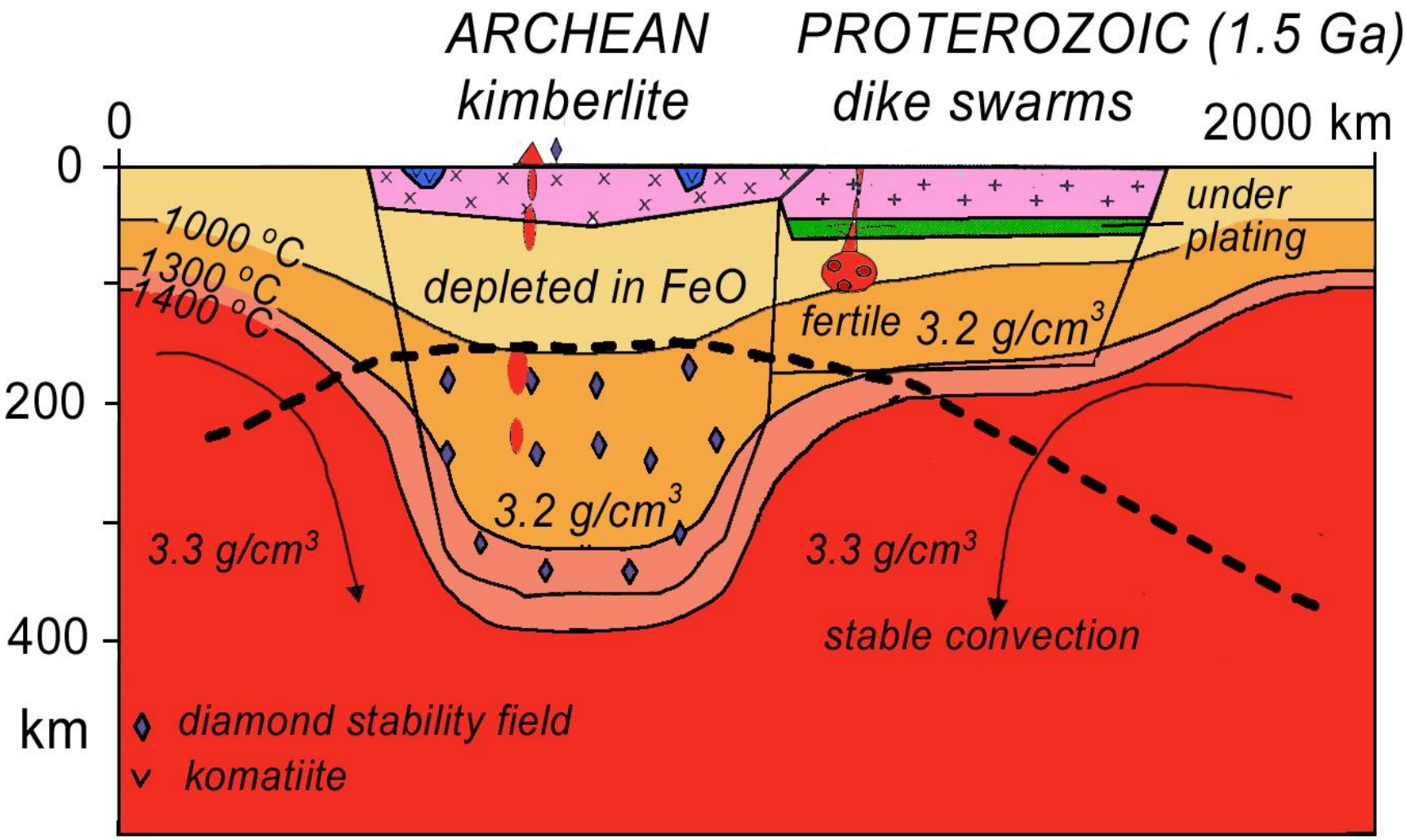
Bleeker and Davis, CJES, 1999

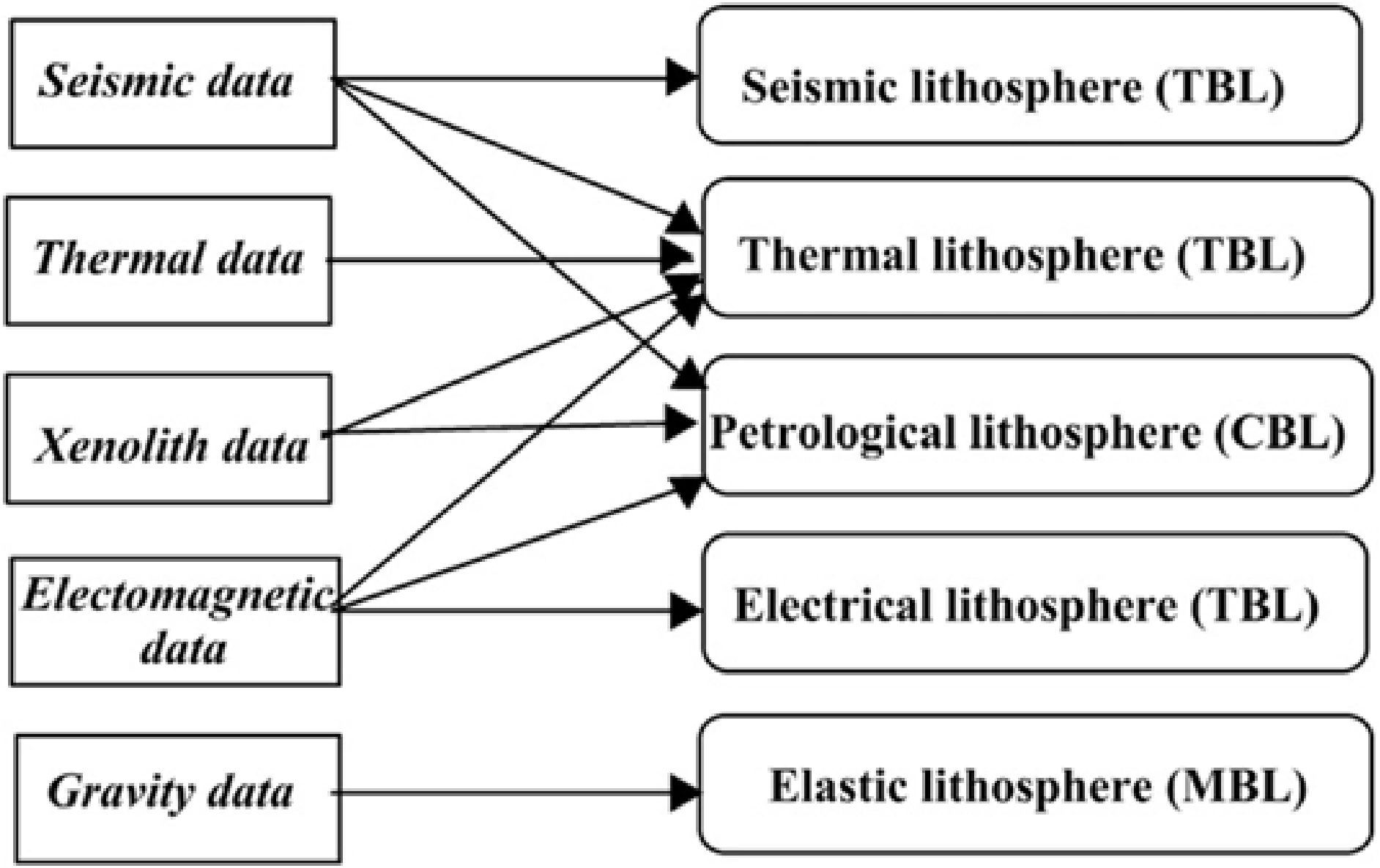
Mantle petrological studies of composition.



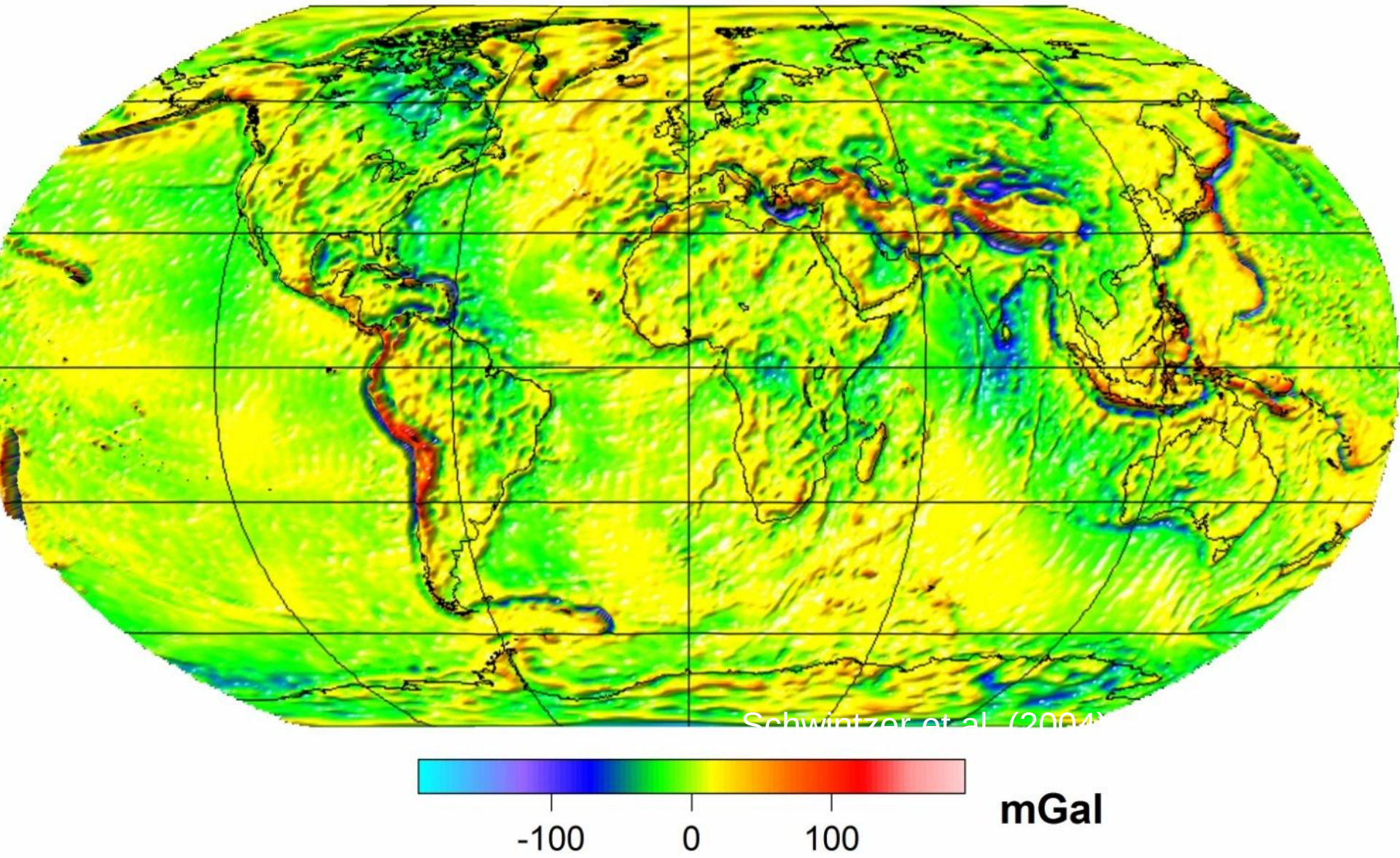


Model for Proterozoic Lithospheric Evolution

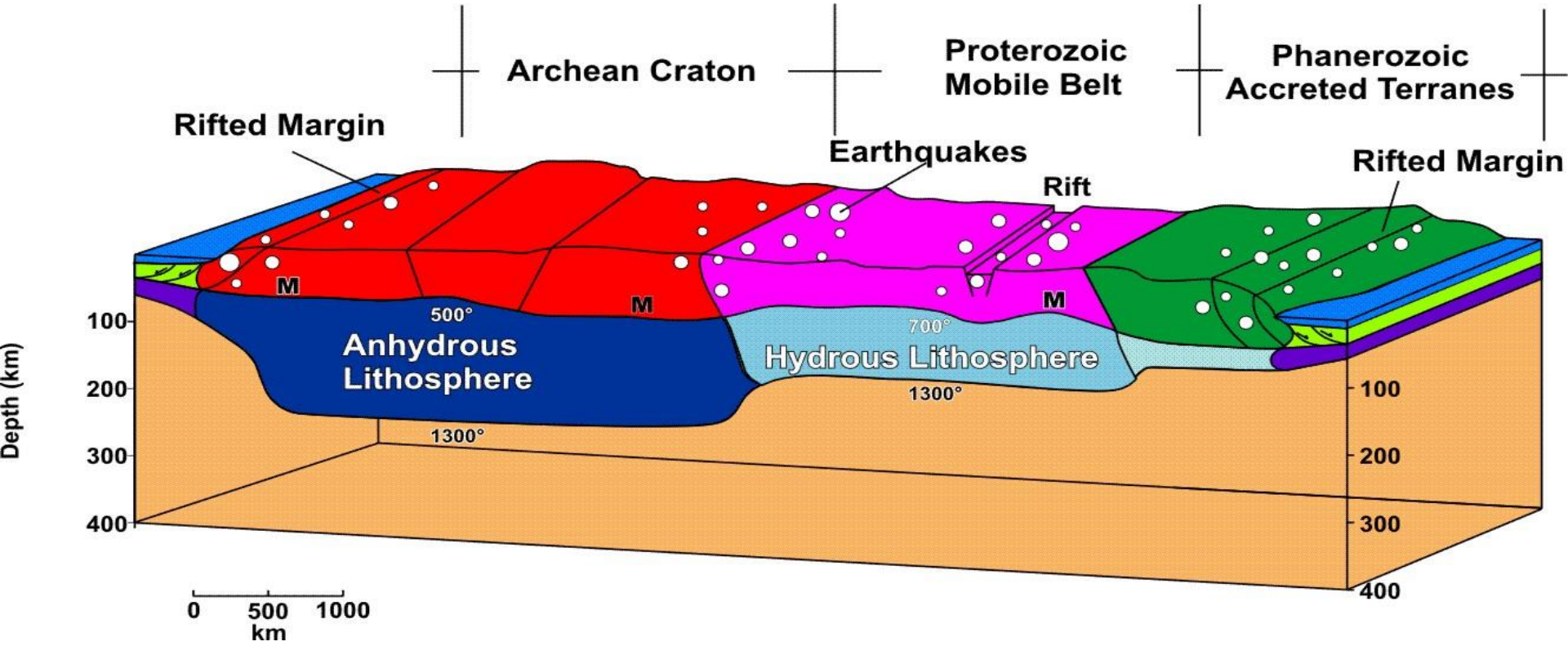



Seismic data
Thermal data
Xenolith data
Electomagnetic data
Gravity data
Seismic lithosphere (TBL)
Thermal lithosphere (TBL)
Petrological lithosphere (CBL)
Electrical lithosphere (TBL)
Elastic lithosphere (MBL)

New Model of the Gravity Field (CHAMP, & GRACE)(

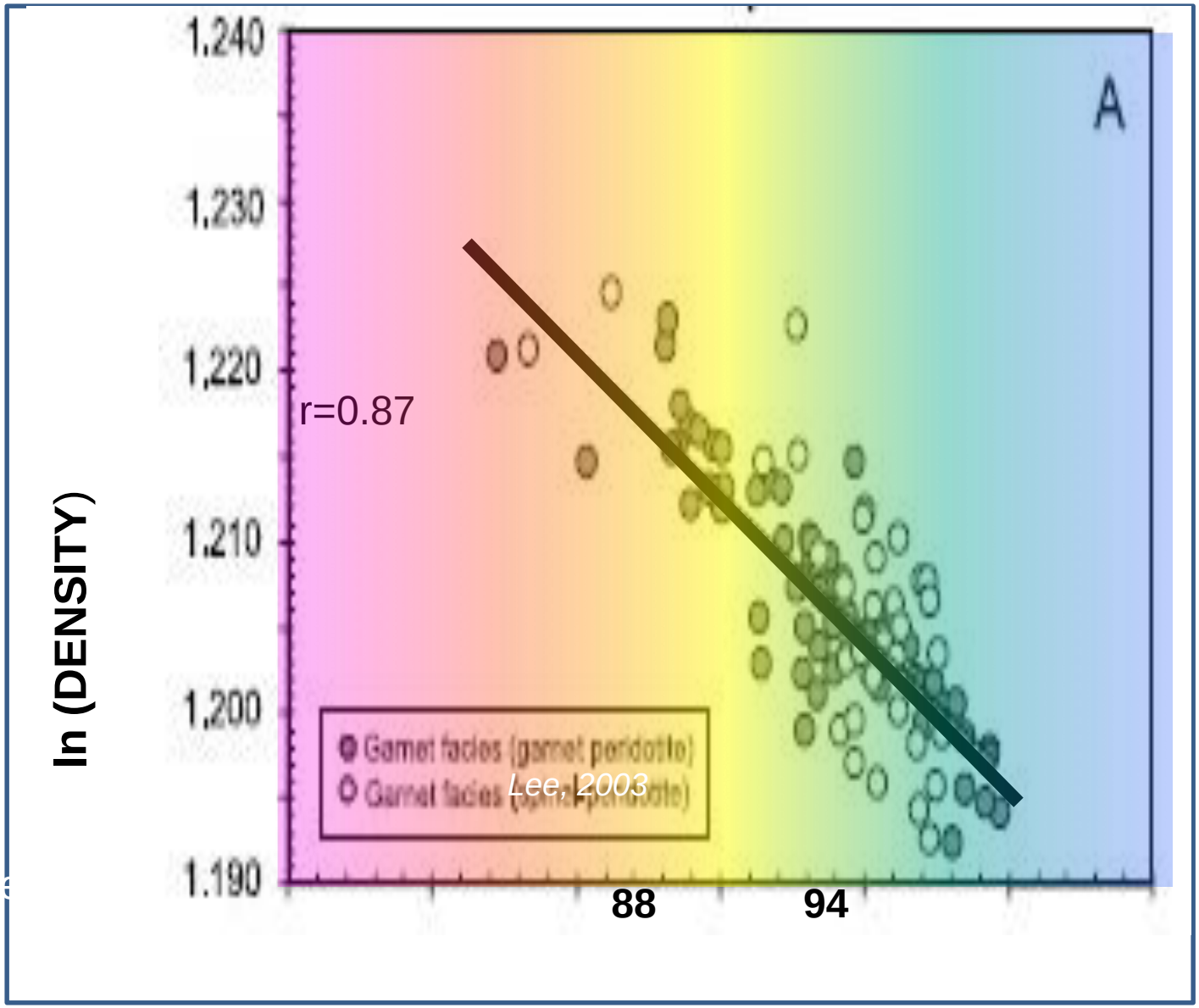


The Lithosphere



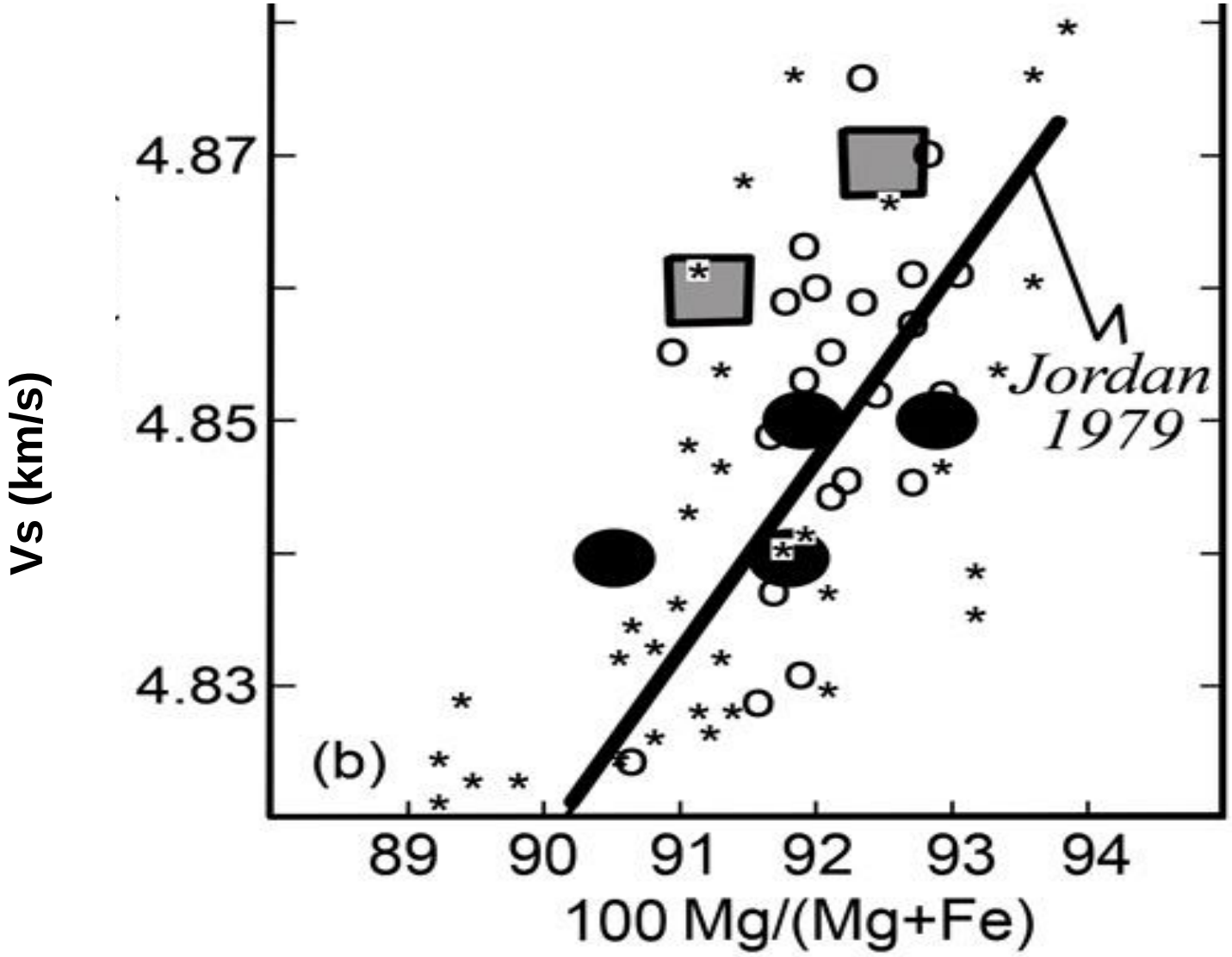
Thank You!

- EXTRA SLIDES

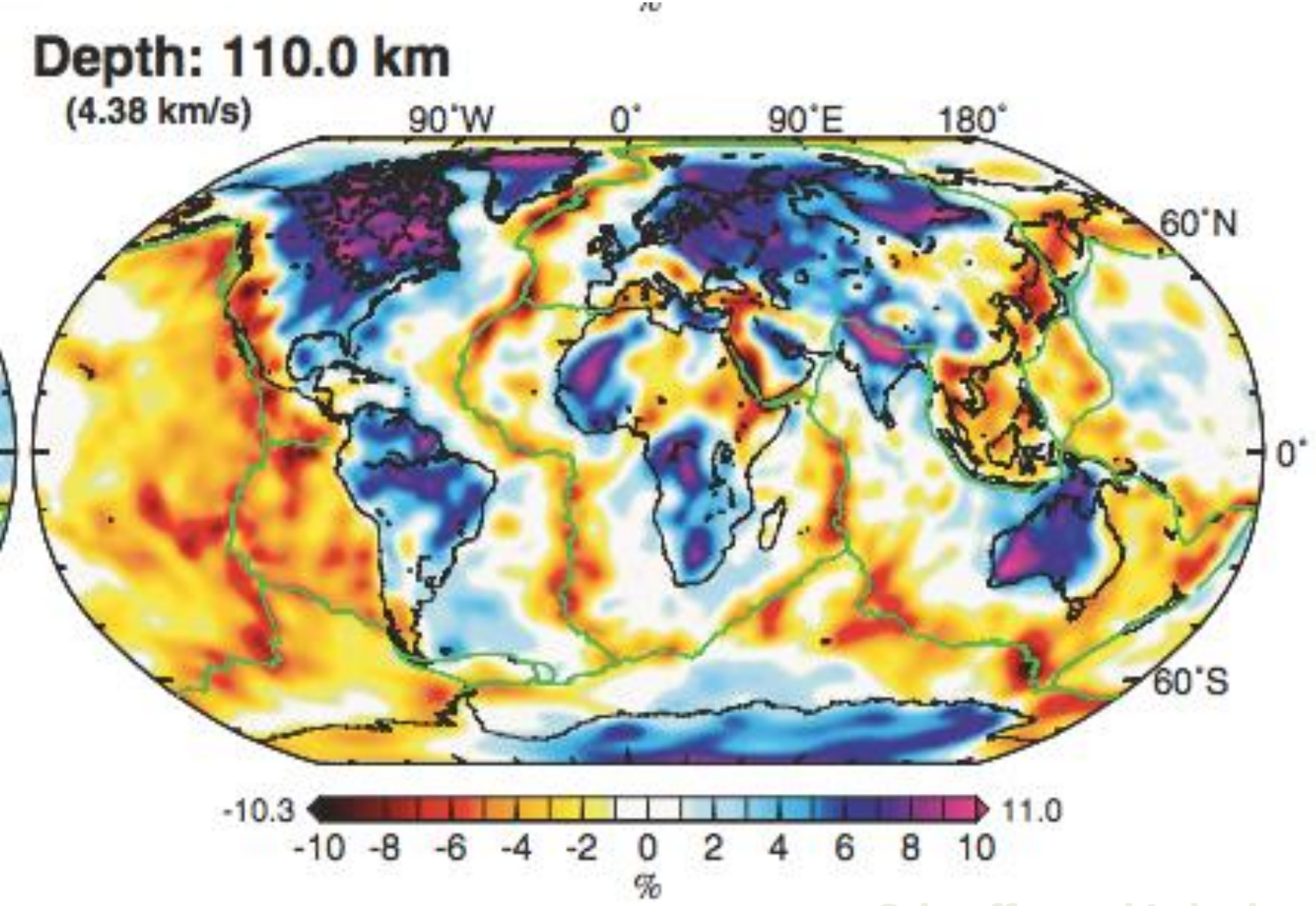


Lower density With higher chemical depletion

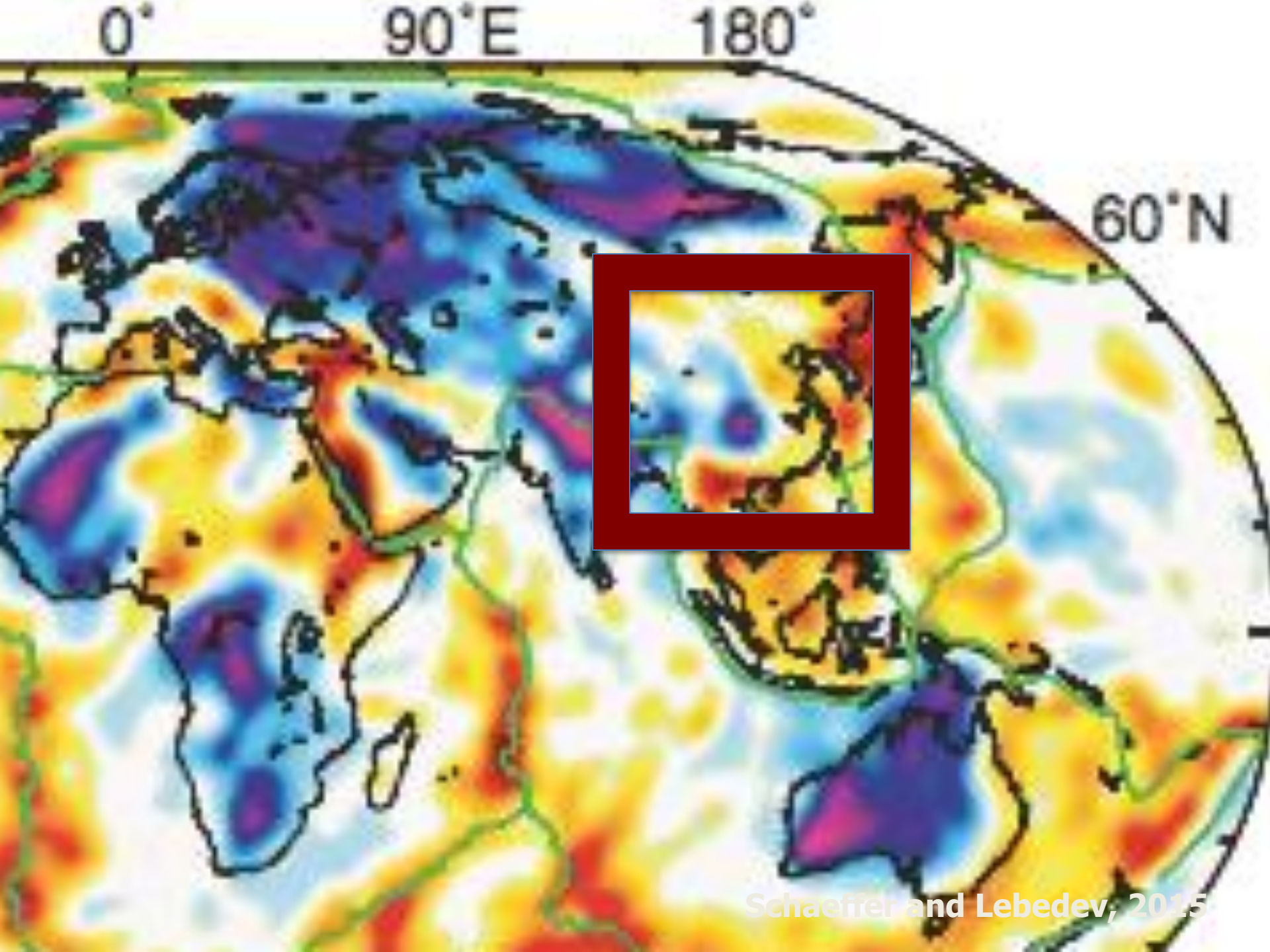
Mg Number



Higher Vs With Chemical depletion

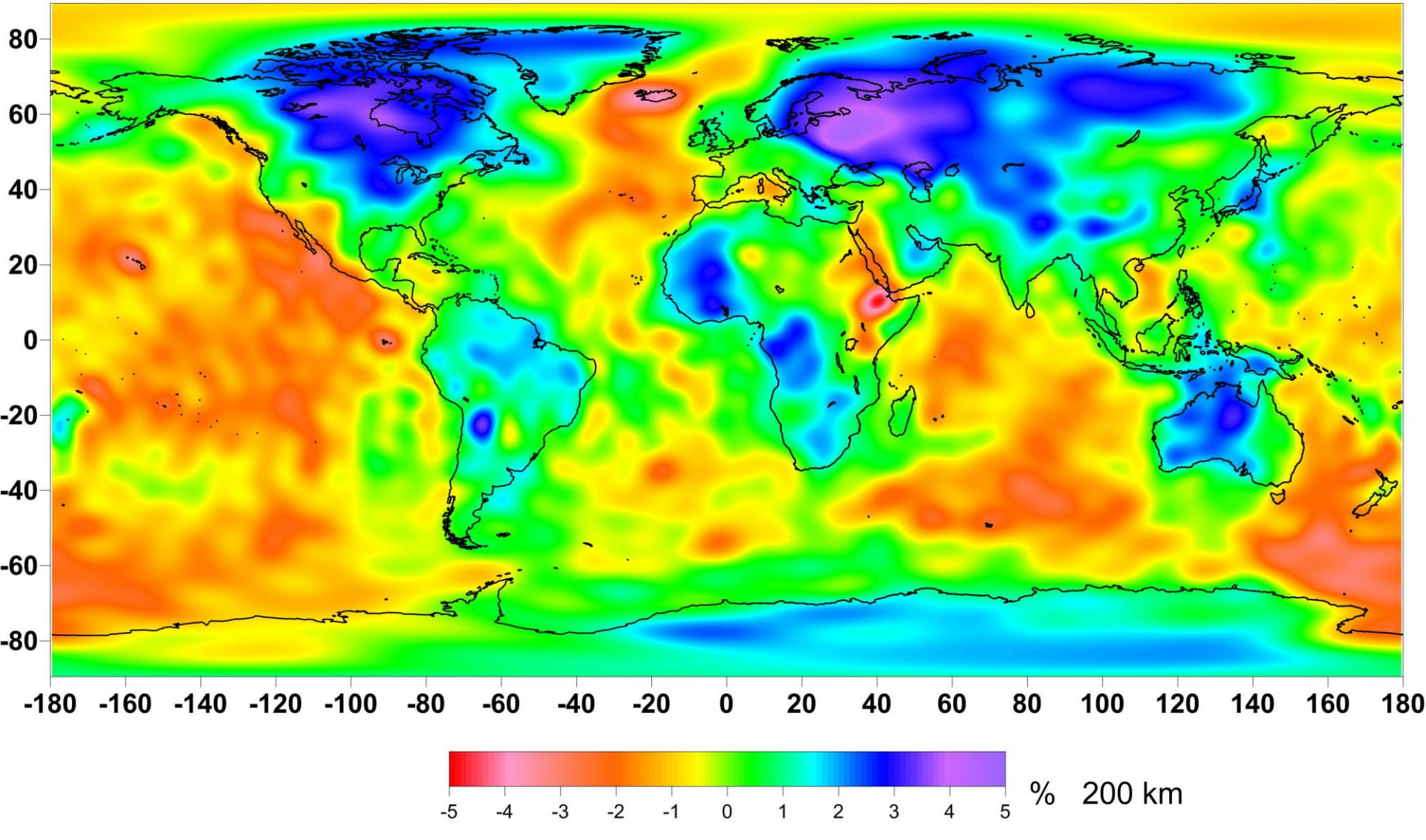


Schaeffer and Lebedev, 2015

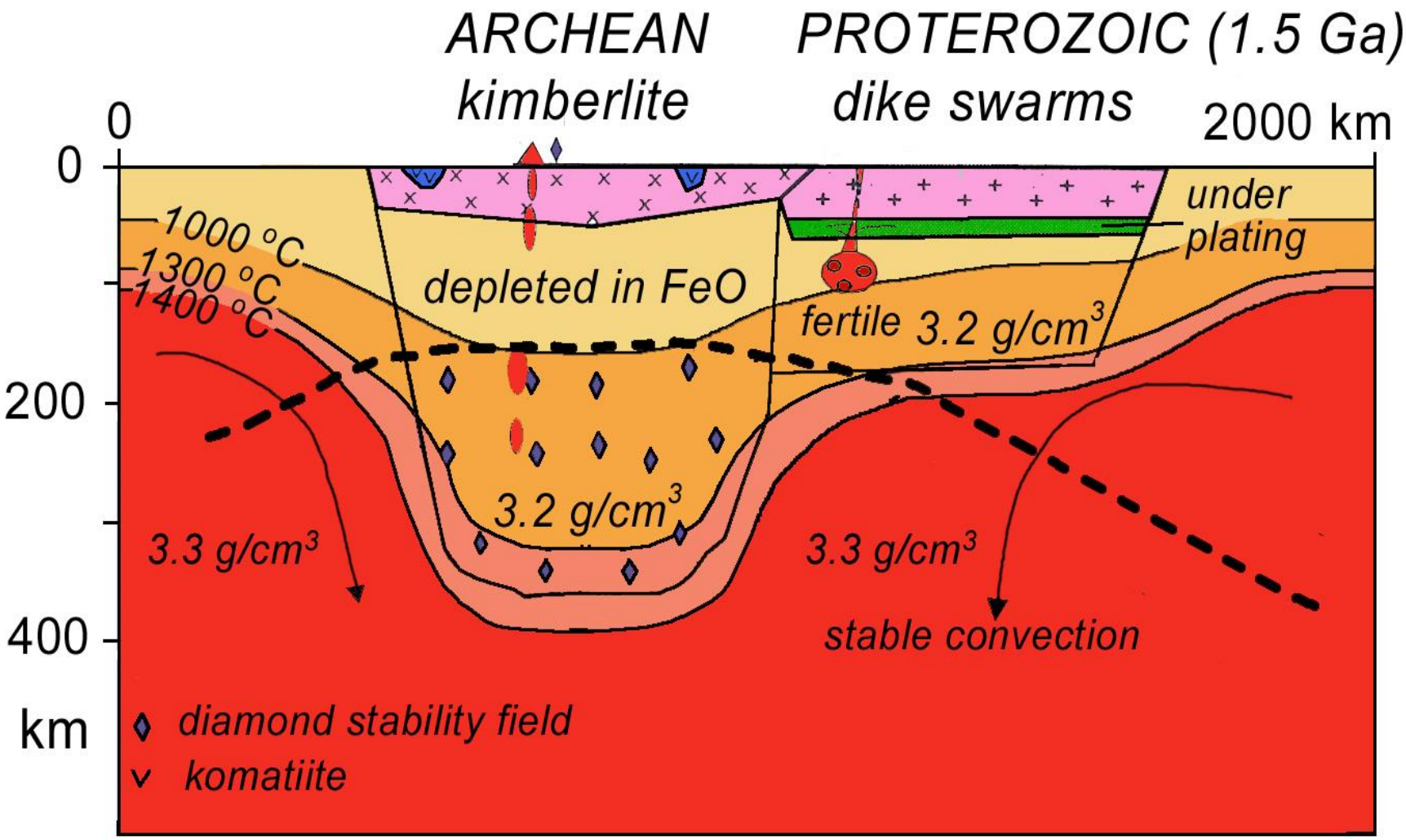


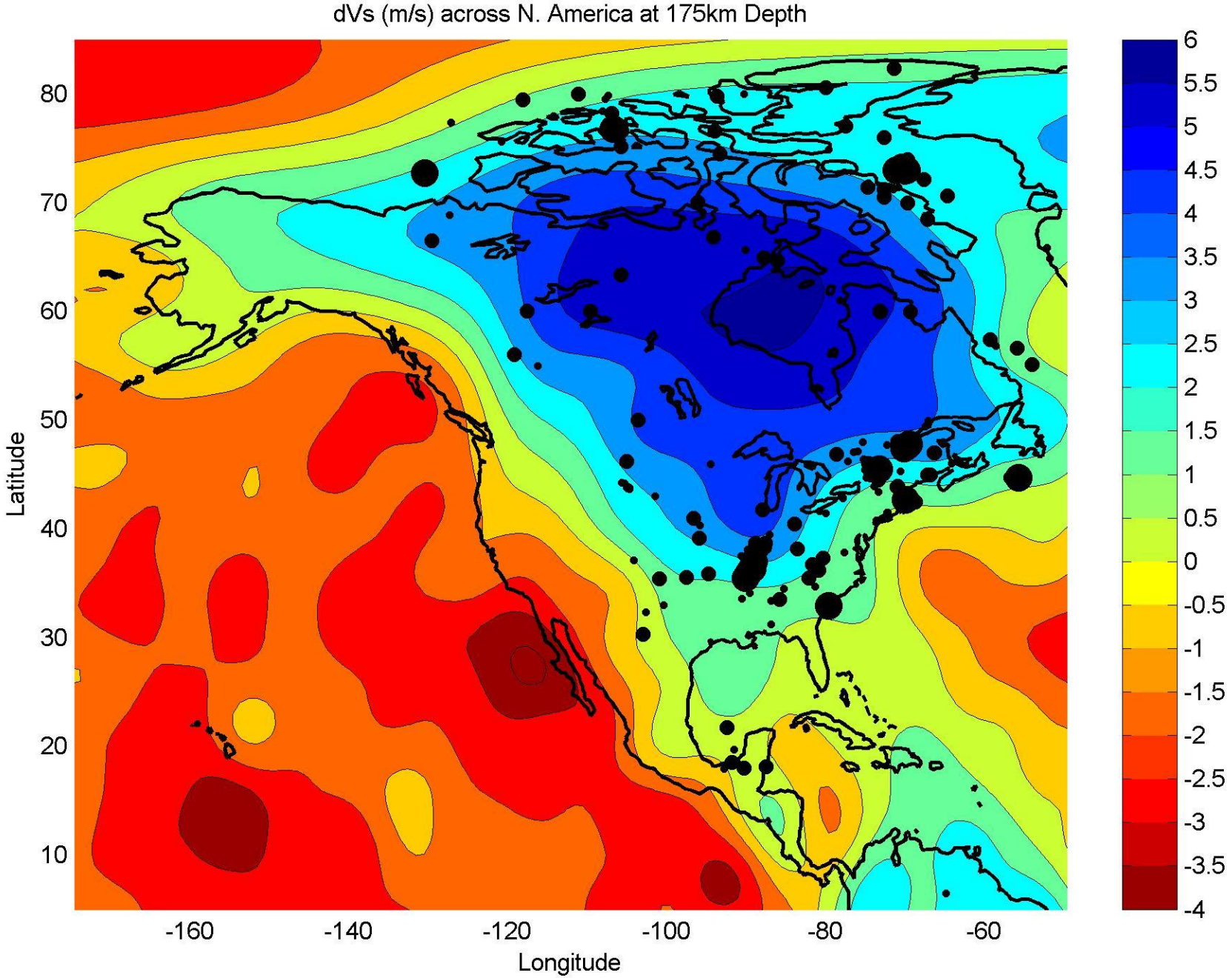
Schaeffer and Lebedev, 2015

S-wave Anomaly 200 km

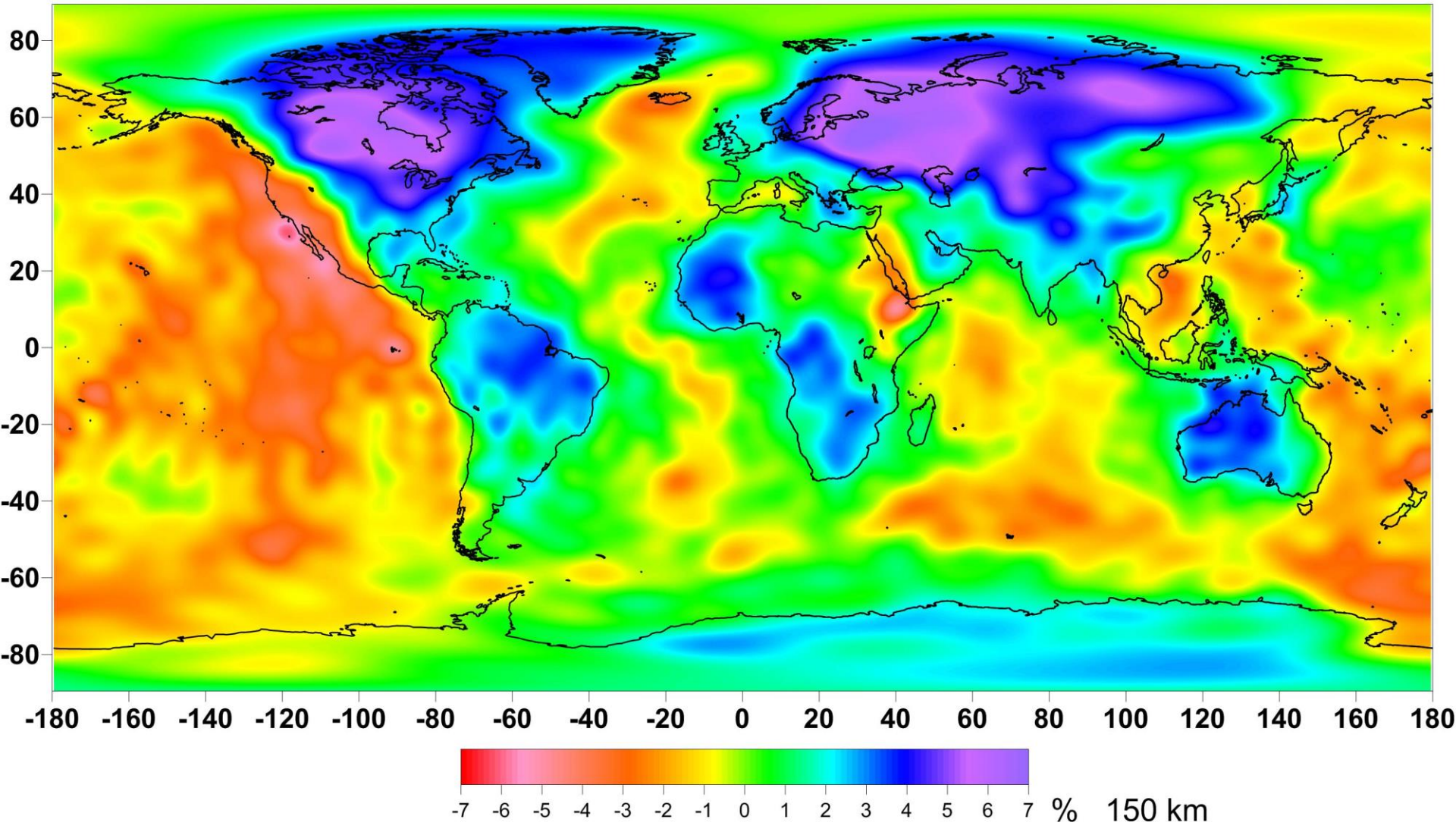


Model for Proterozoic Lithospheric Evolution

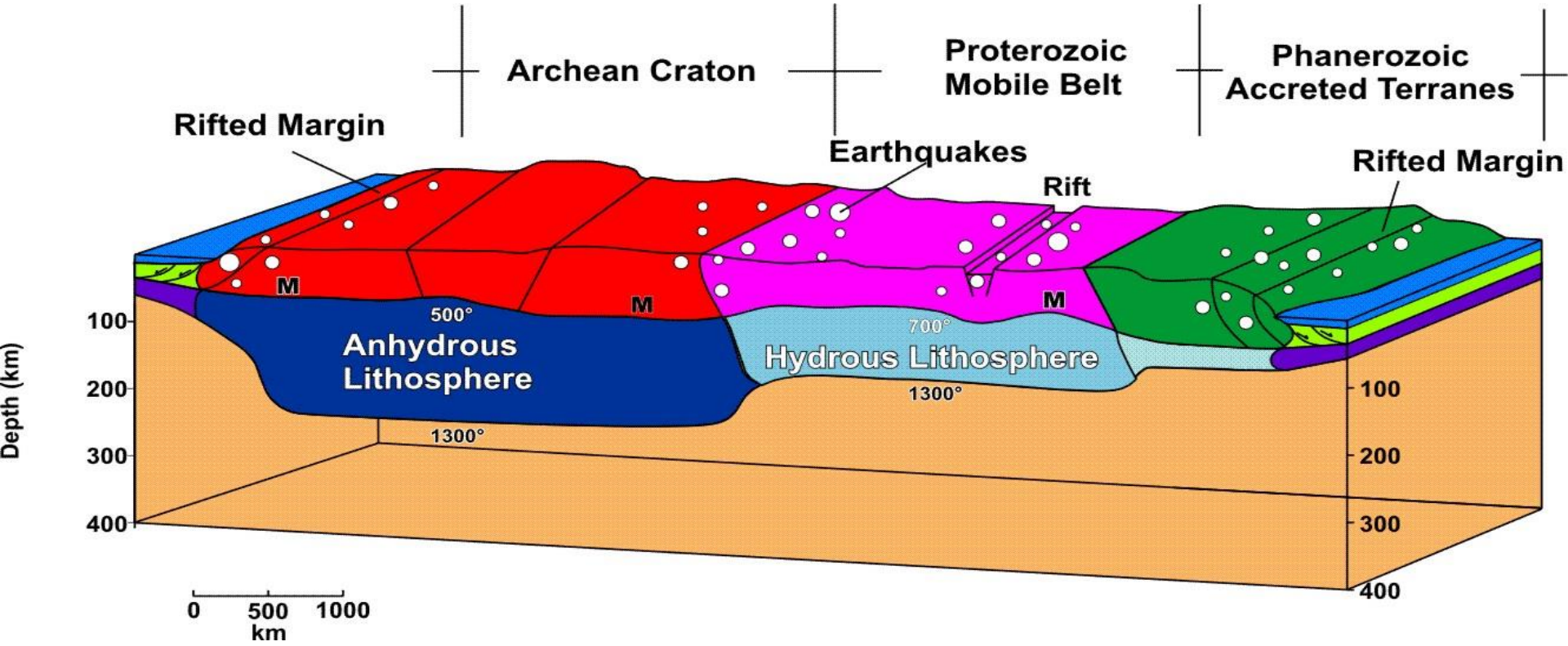



dVs (m/s) across N. America at 175km Depth
Latitude
80
70
60
50
40
30
20
10
-160
-140
-120
-100
-80
-60
Longitude
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4

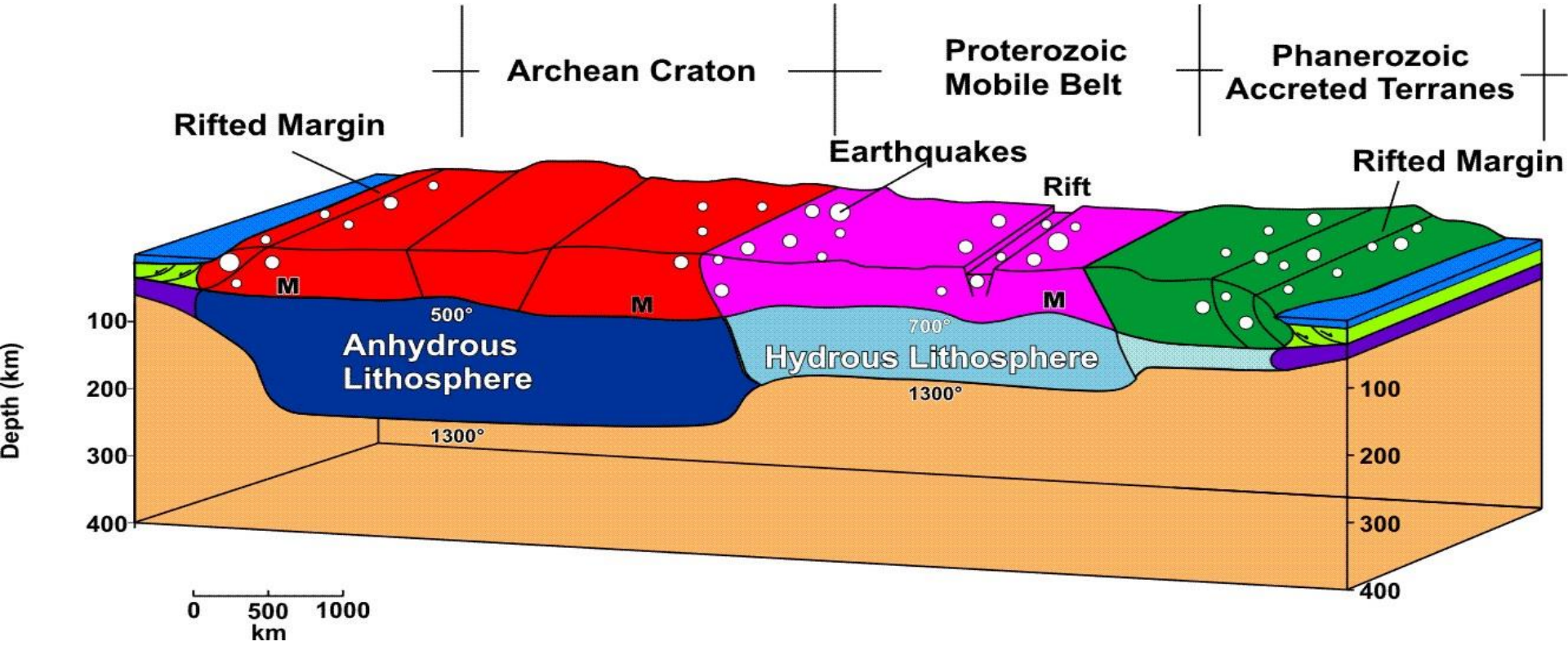
S-wave Anomaly, 150 km



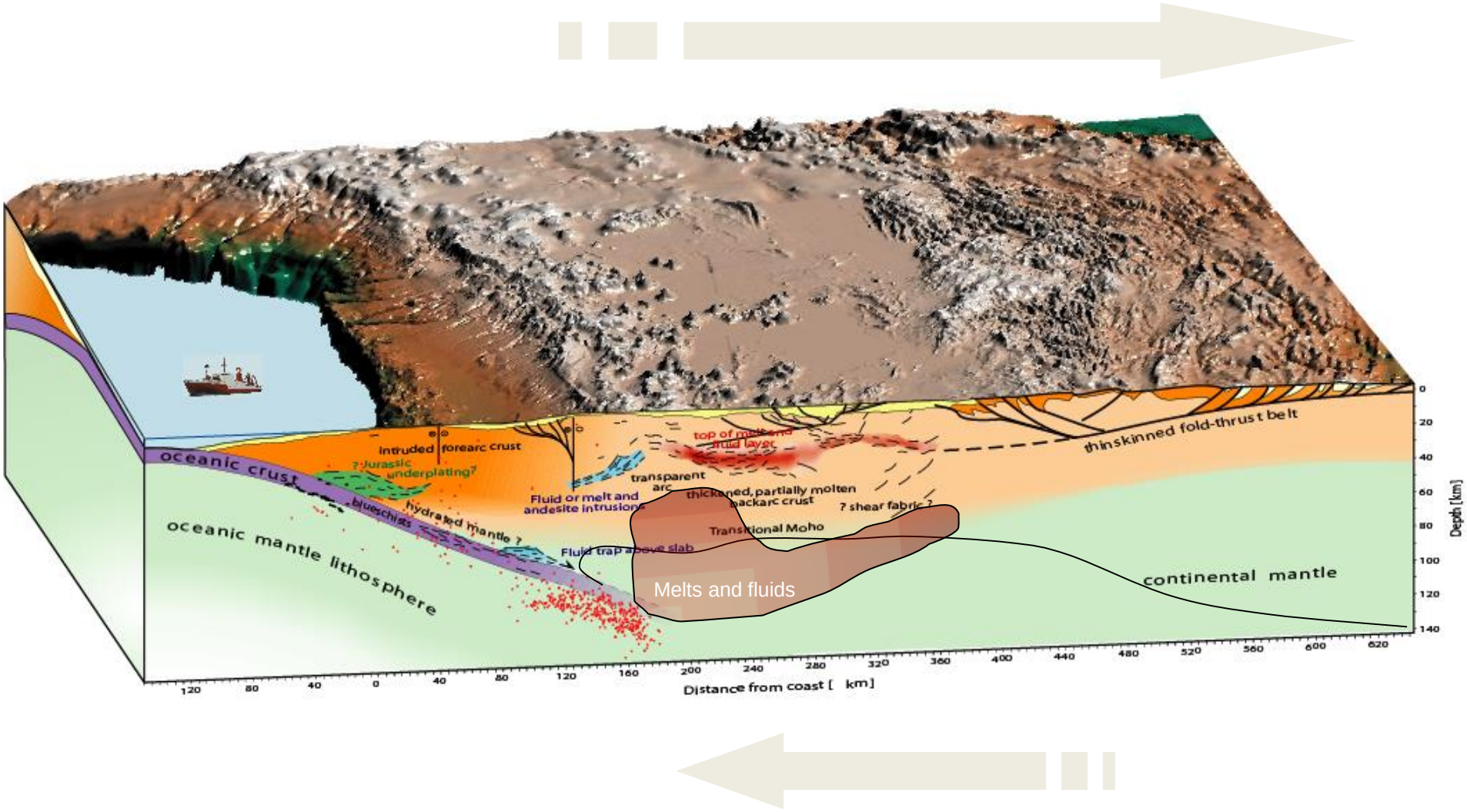
Intraplate EQ and the Lithosphere



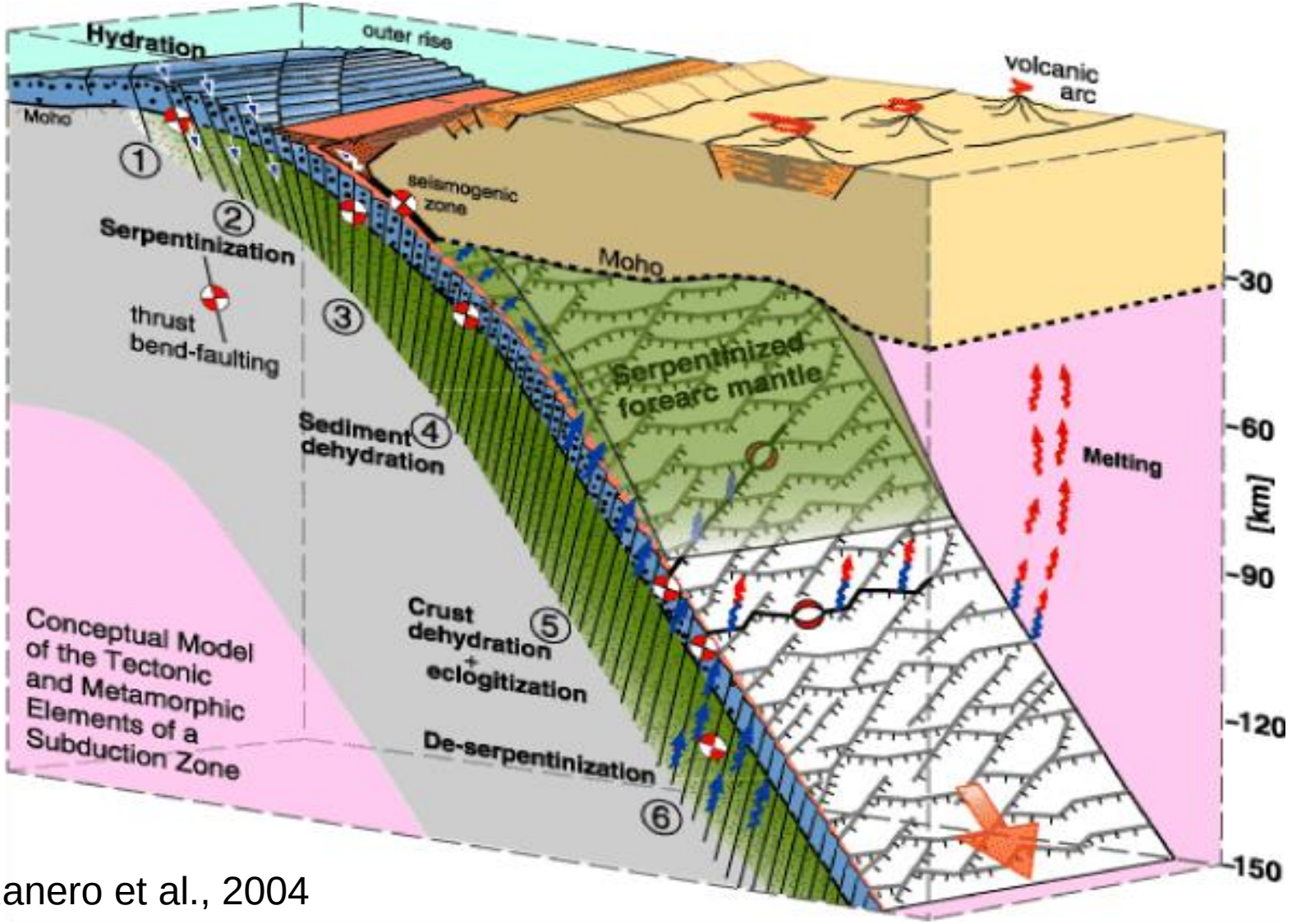
The Lithosphere



The Central Andes (Oncken, 2006)

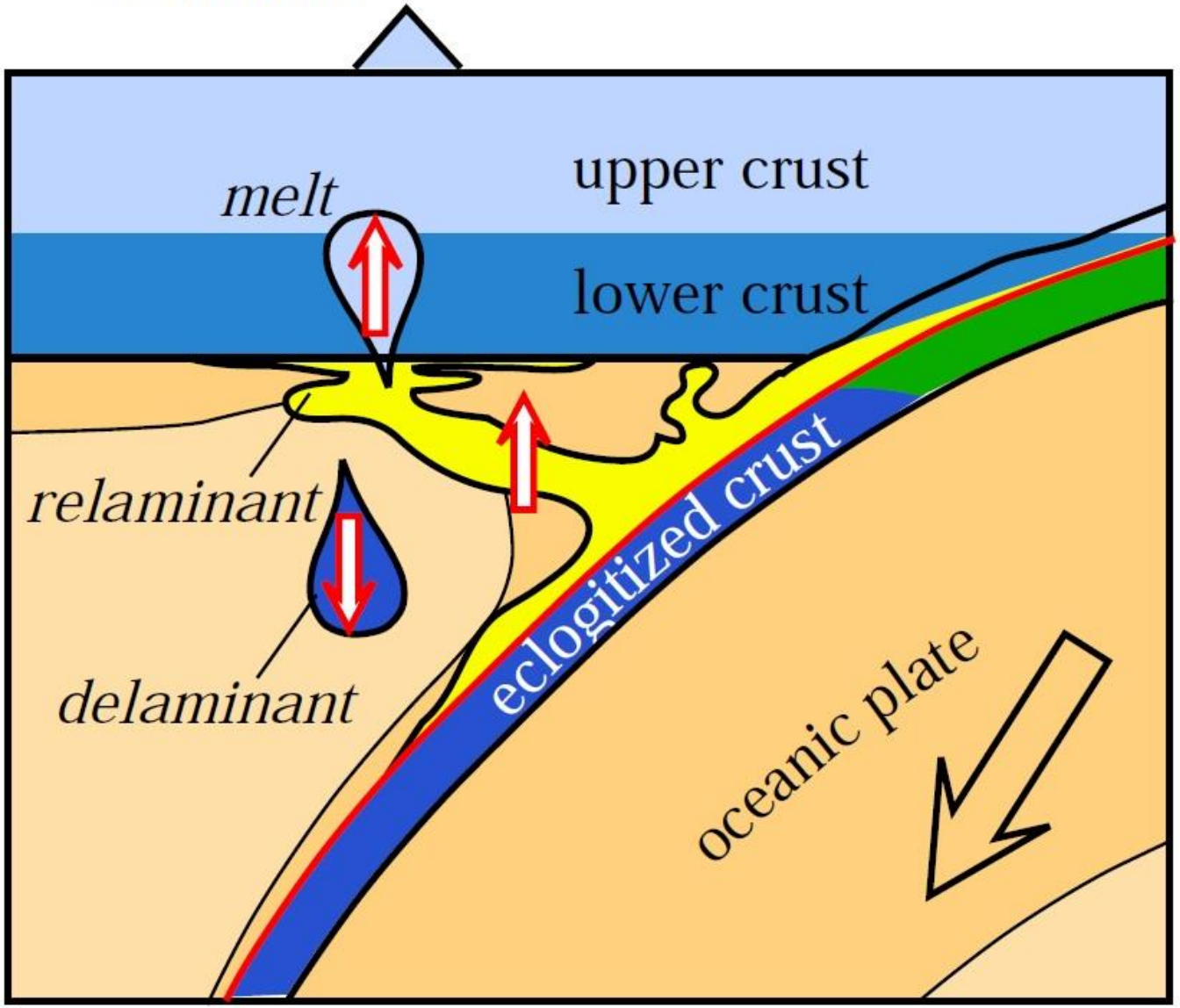


Dehydration reactions in subduction zone



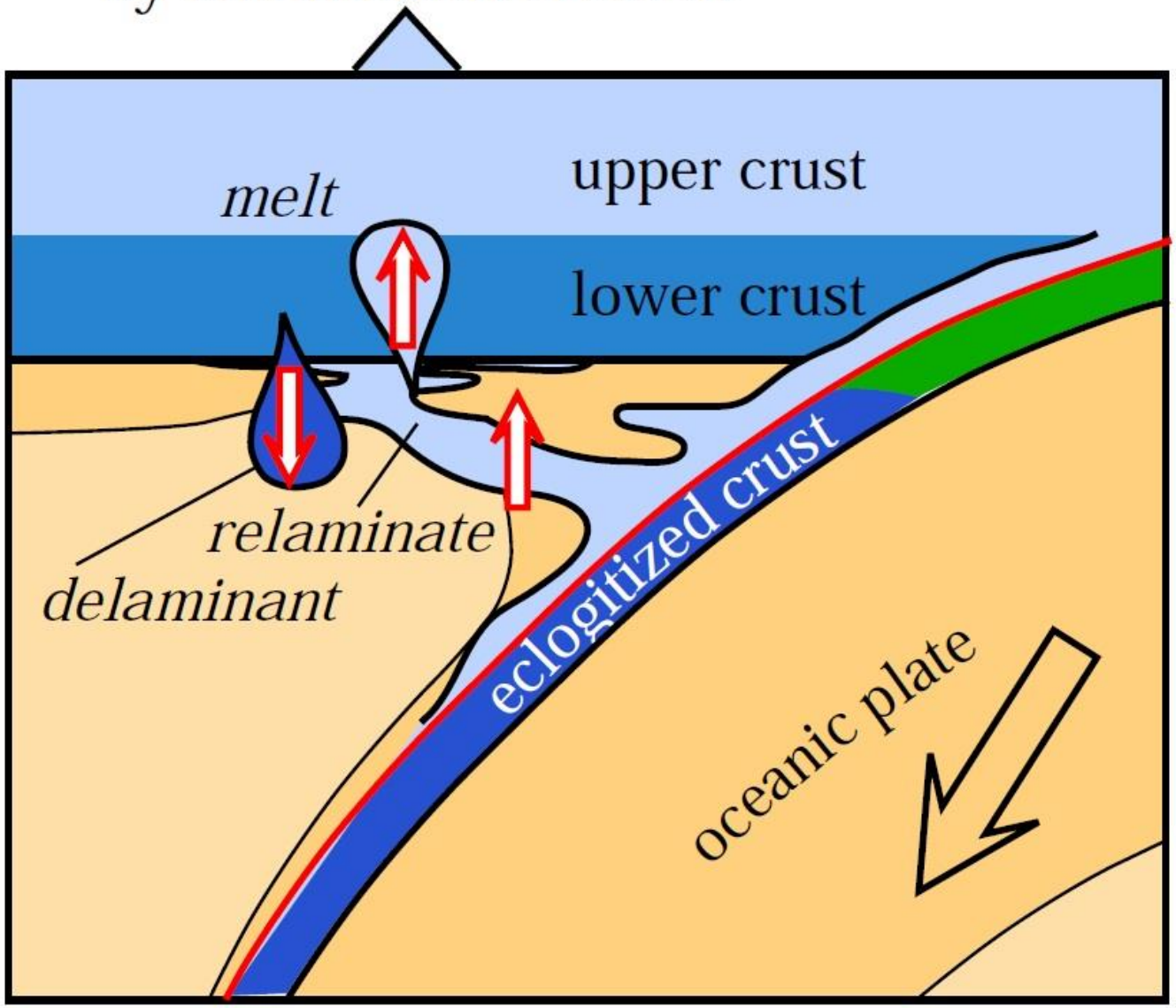
Ranero et al., 2004

A) relamination of subducted sediment



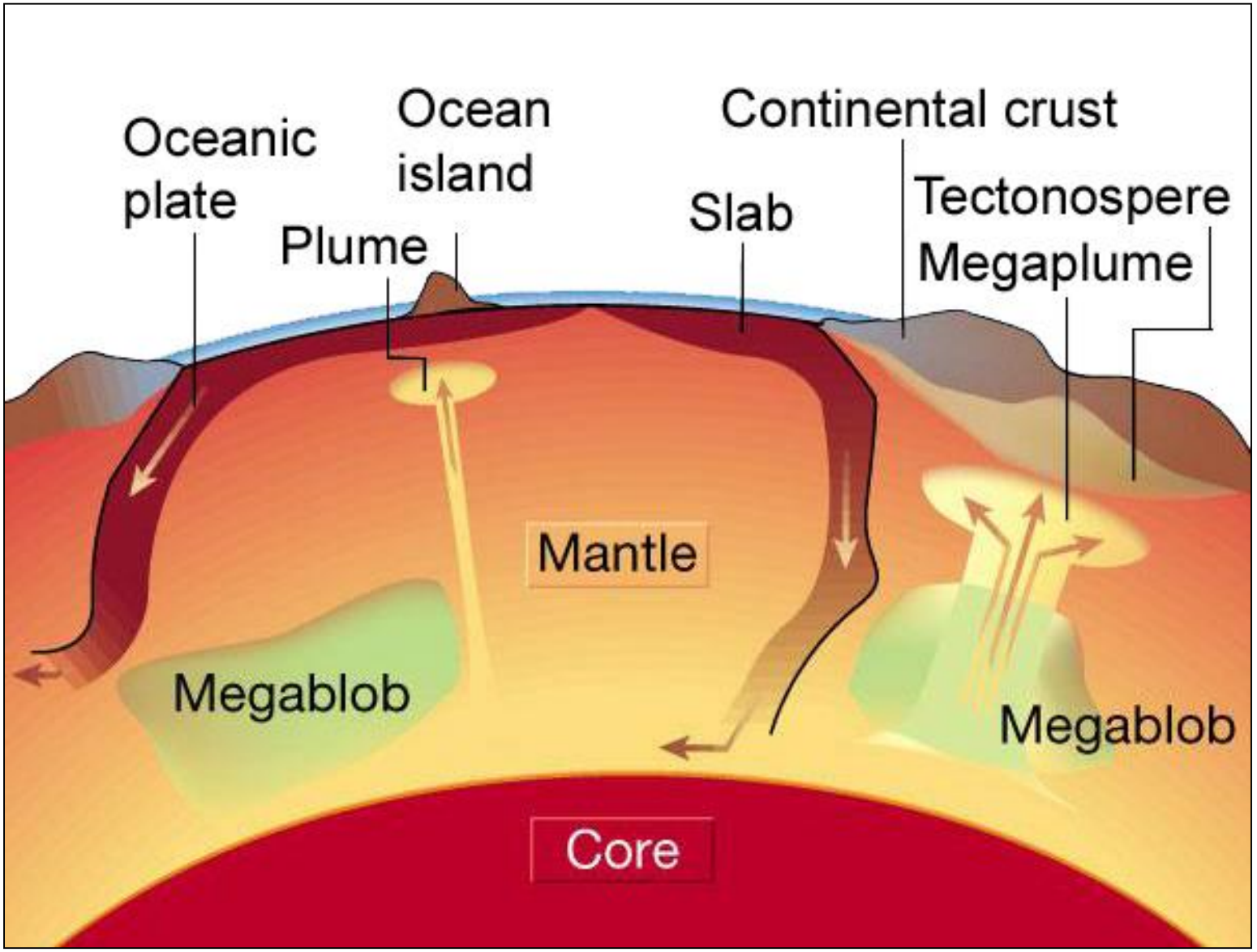
Hacker et al., 2011

C) relamination of crust removed by subduction erosion



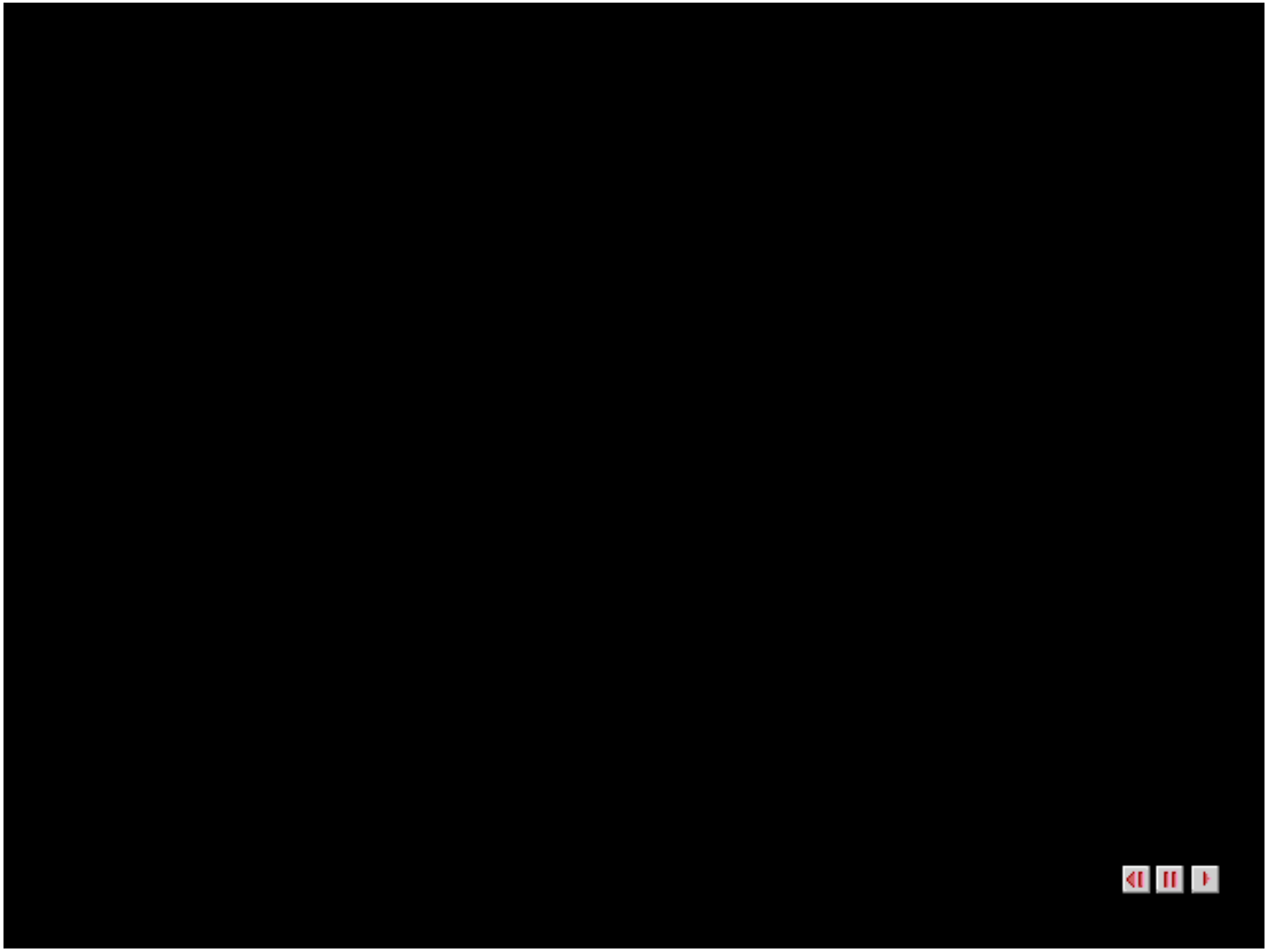
Hacker et al., 2011

Mantle Structure



Source: Forte and Mitrovica (2001)

Propagation of Seismic Waves Through the Earth's Interior



Fishwick's 2009 regional models

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1) fundamental + first four higher models: period range 50-120 seconds

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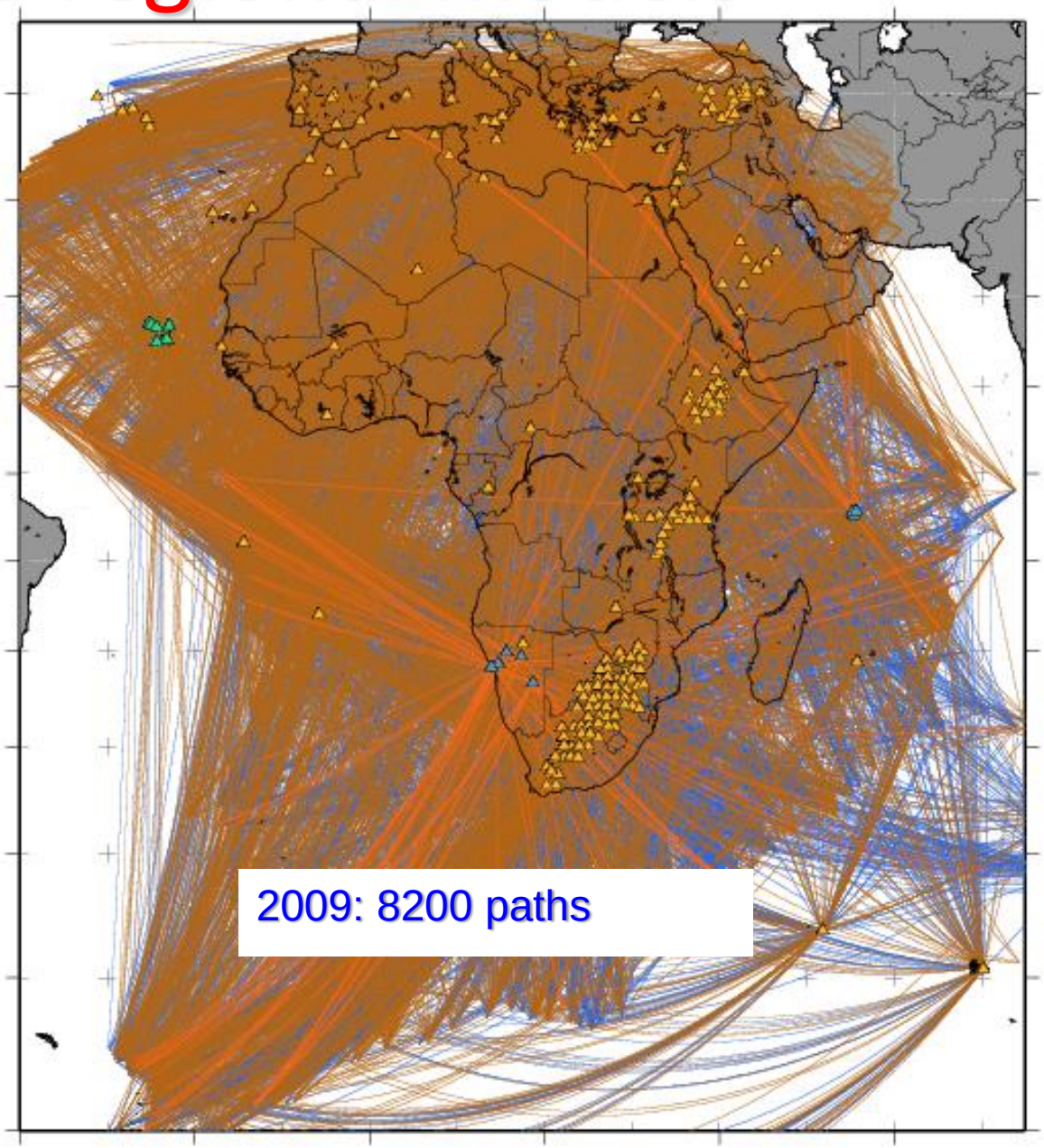
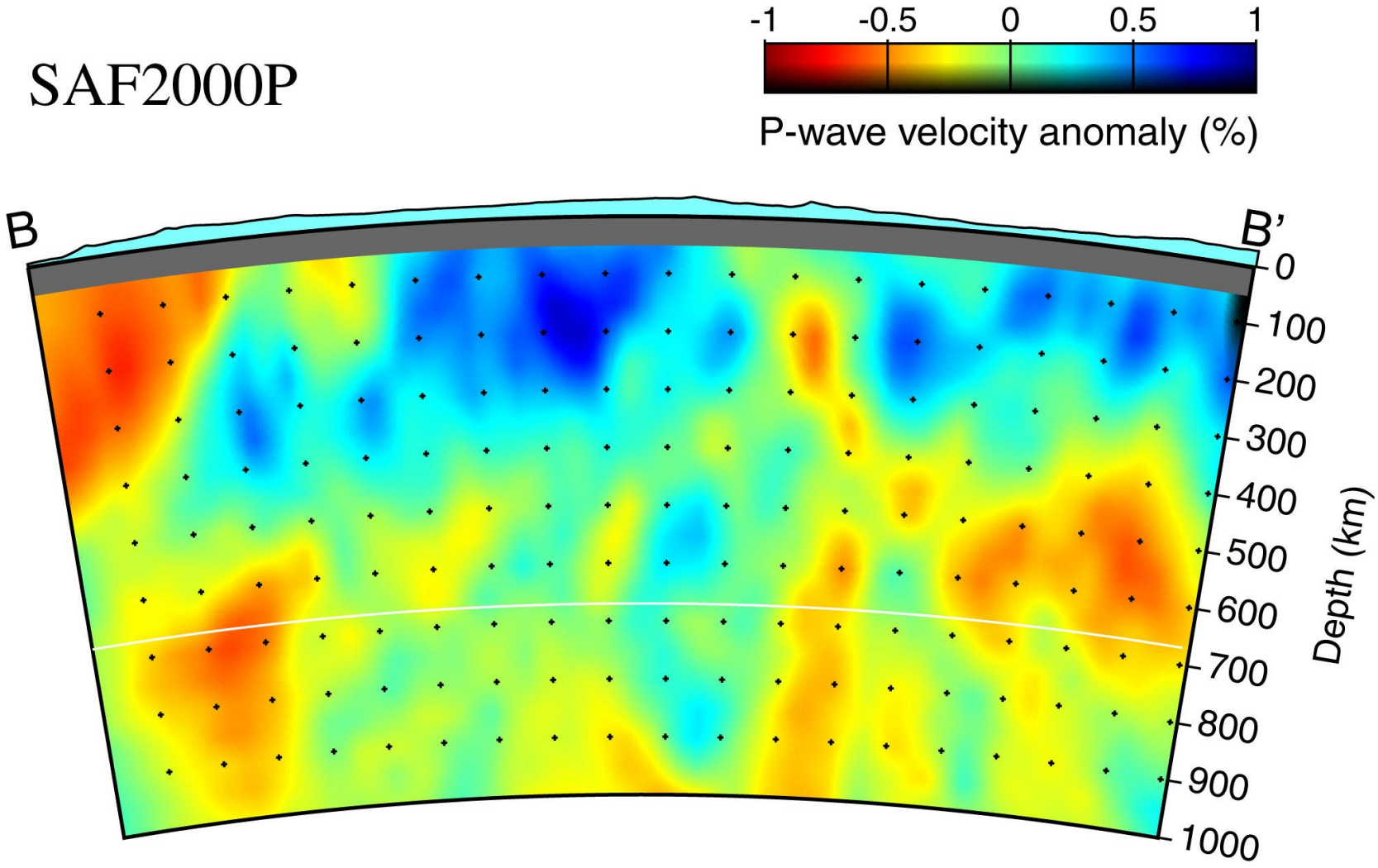
Includes data from GFZ stations in NW Namibia



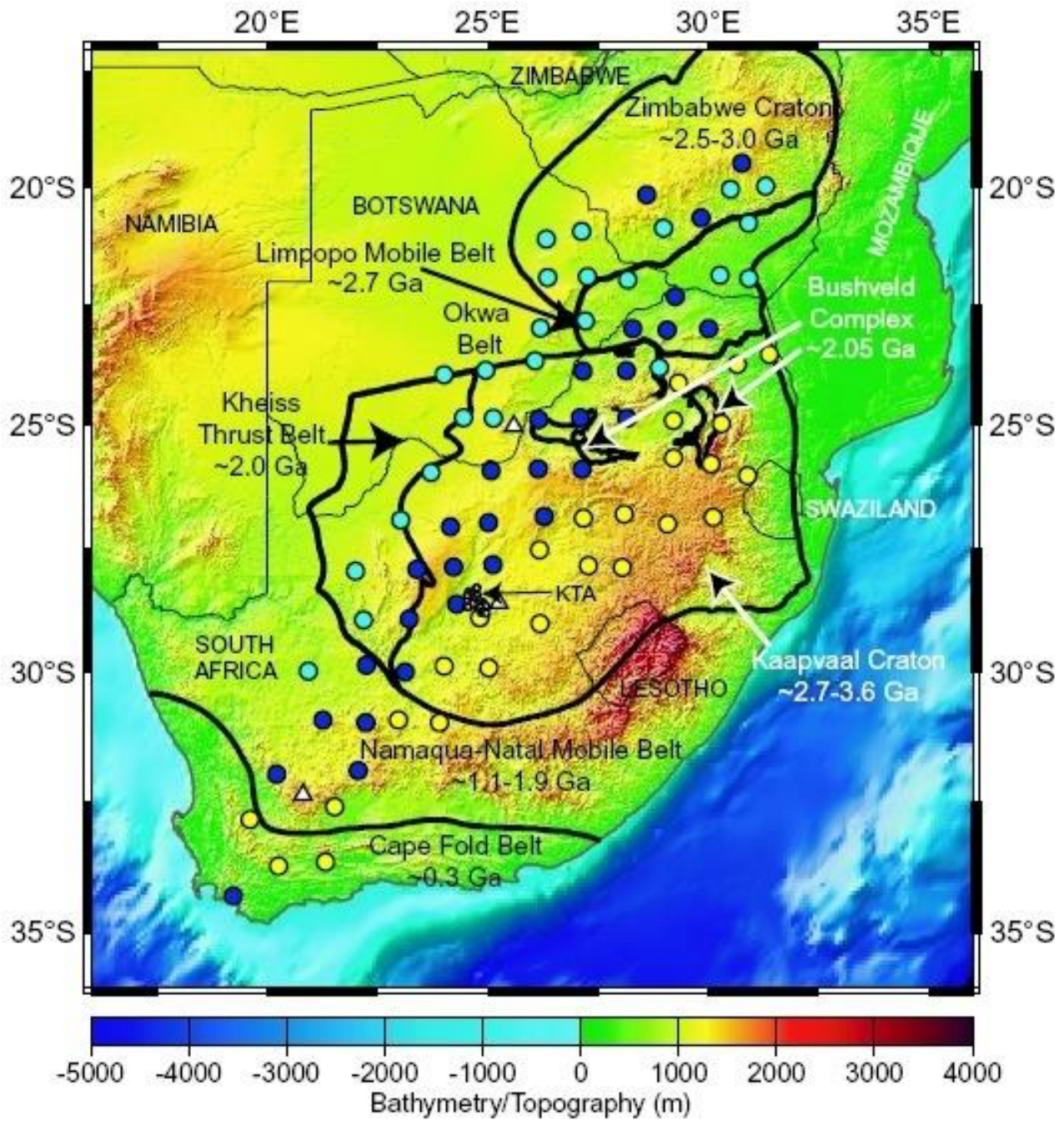
SAF2000P



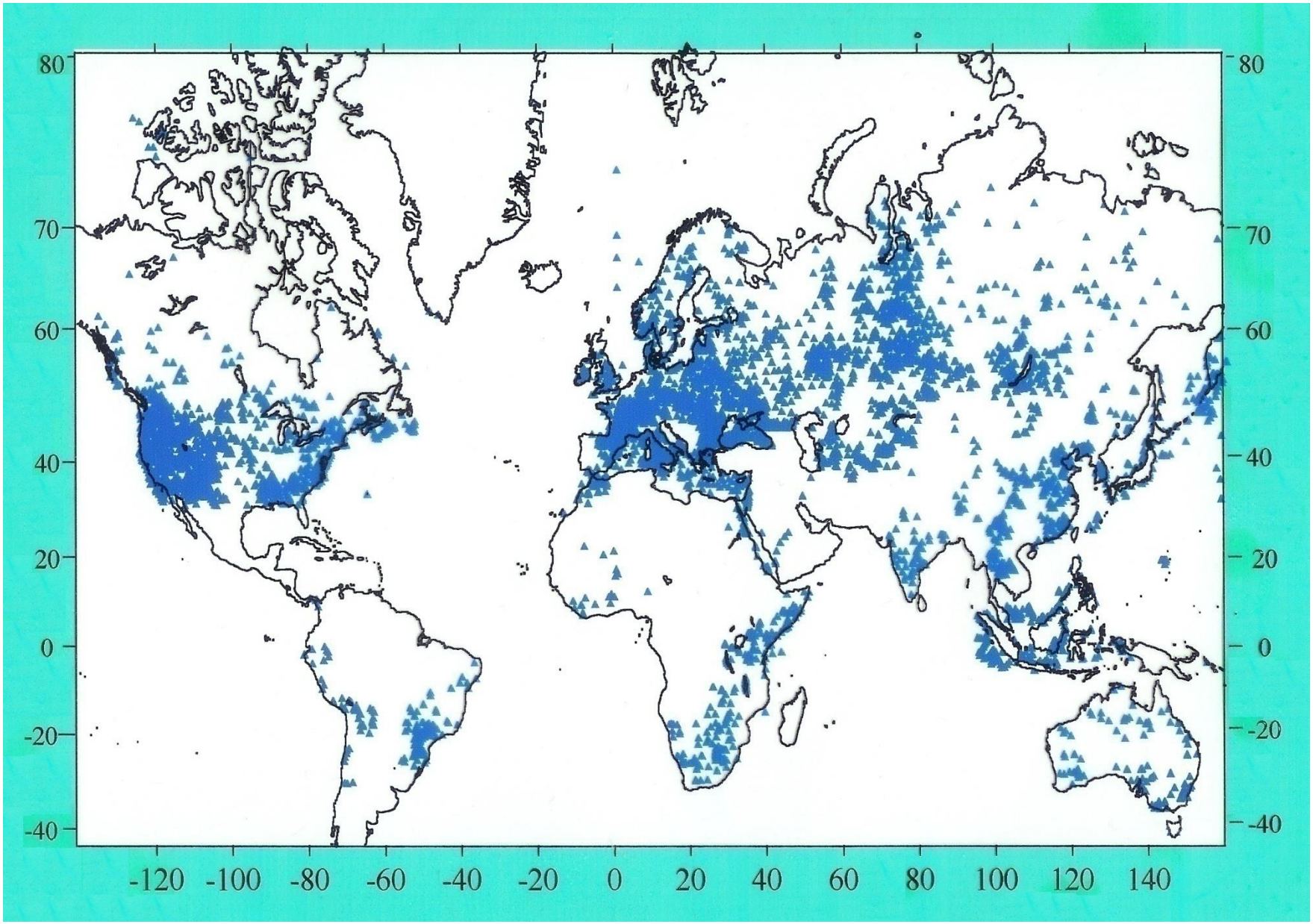
B: (34.25S, 19.25E)

B’: (18.50S, 31.50E)

Southern African (or Kaapvaal) Seismic Experiment

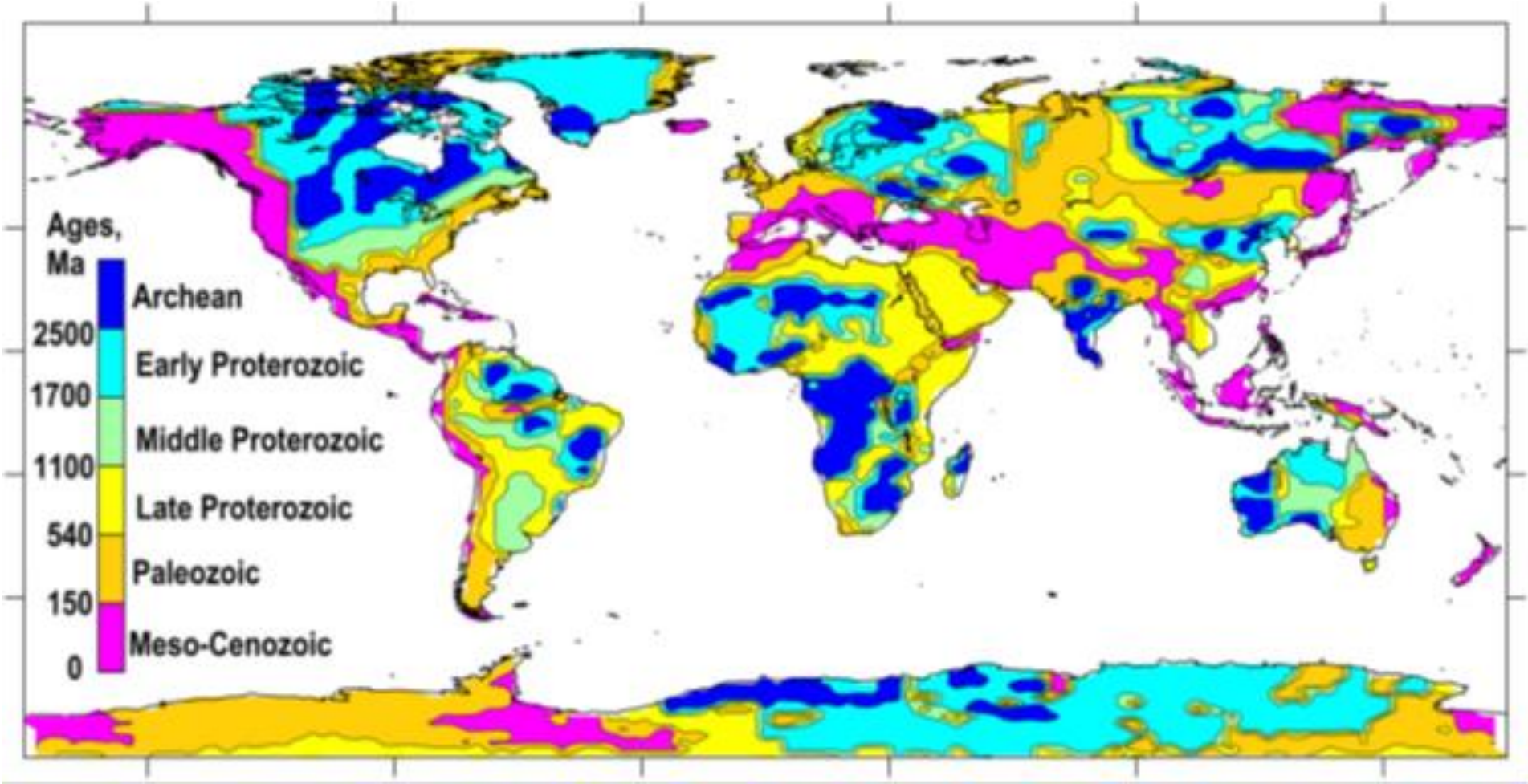


Heat Flow Data for Continents

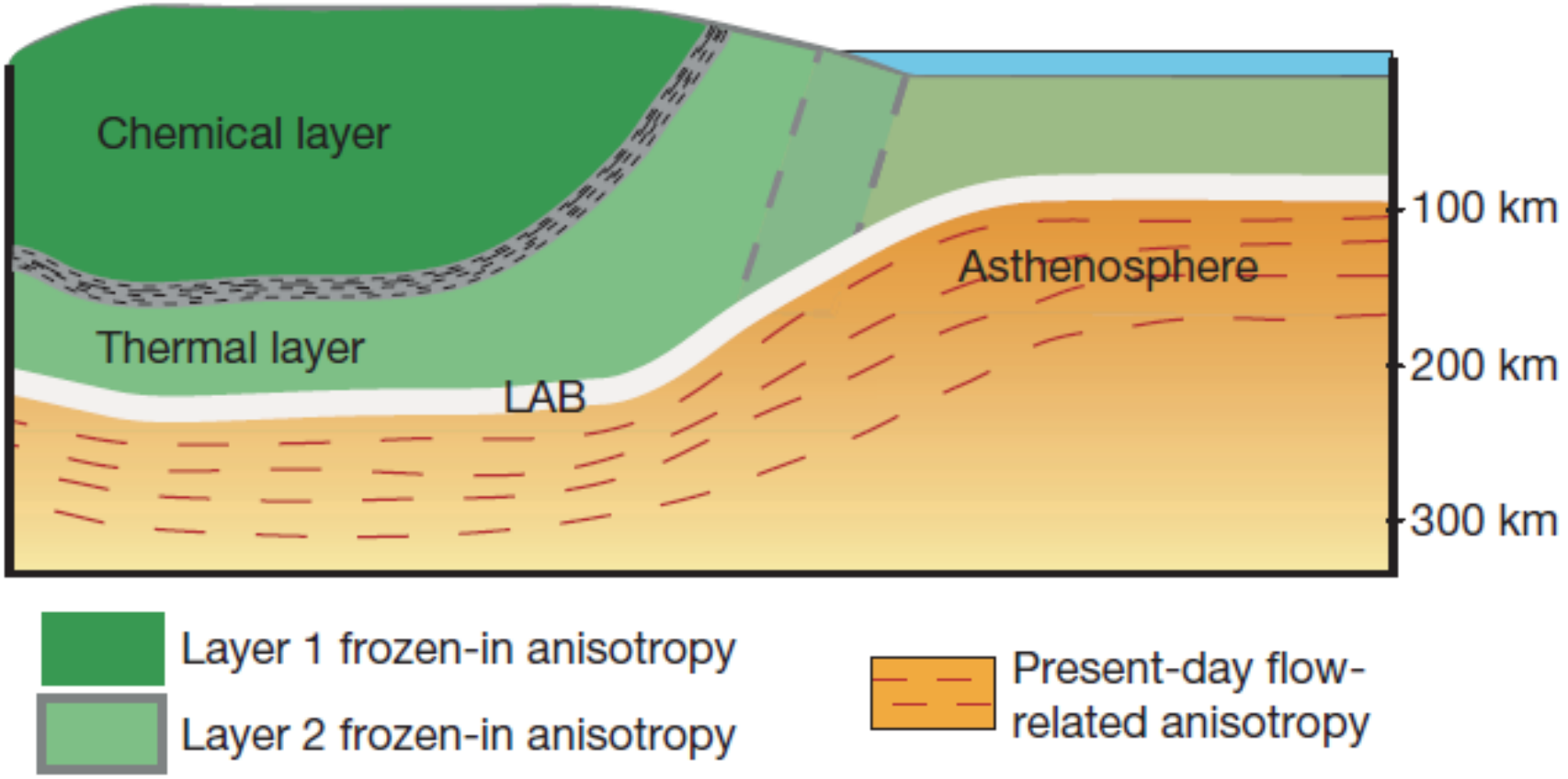


Source: Artemieva and Mooney, 2000

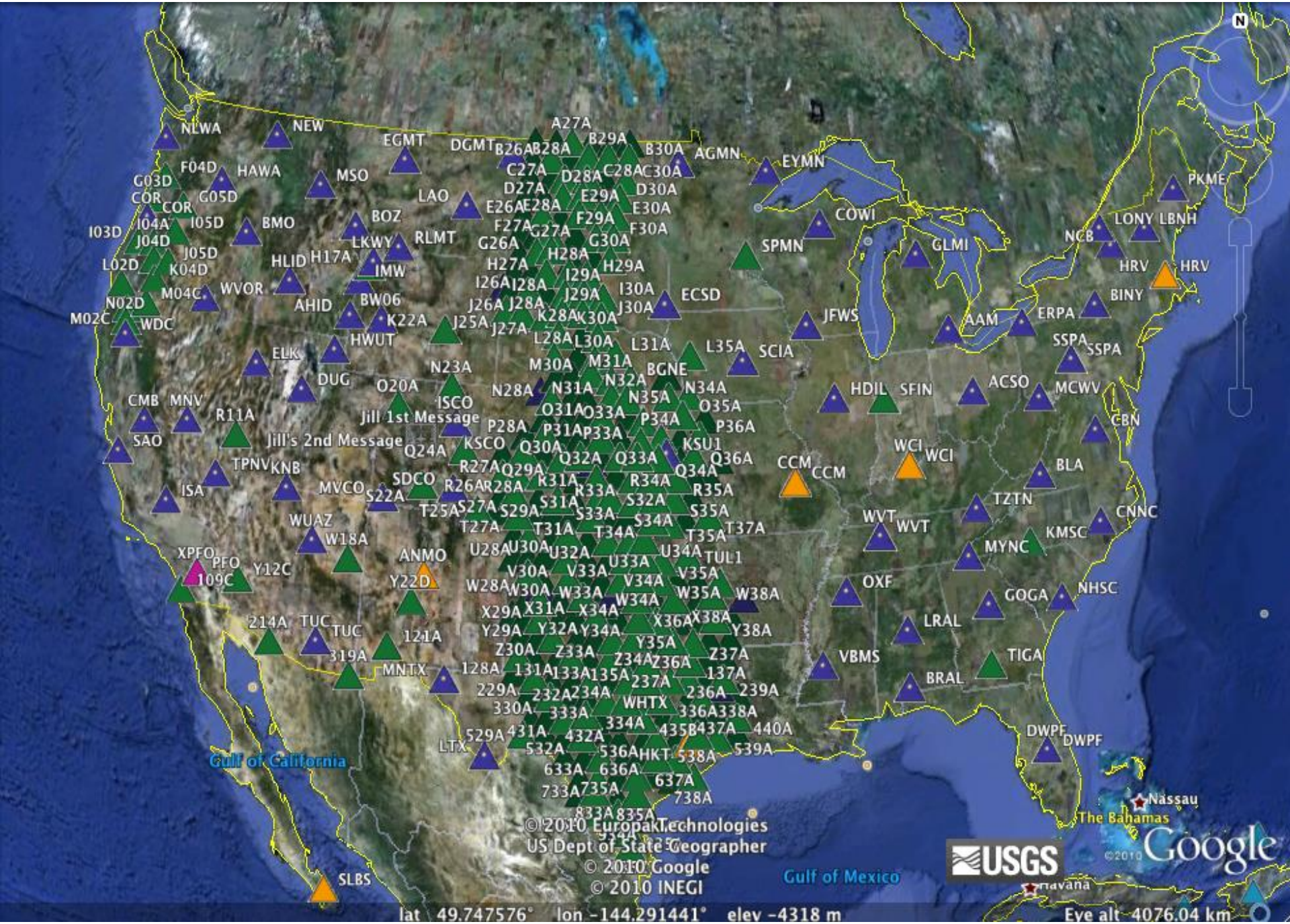
Age of Continents



Lithospheric Structure: Seismic Anisotropy



Yuan and Romanowicz, *Nature,* 466, 1063-1068, 2010


NLWA
NEW
EGMT
DGMT
A27A
B26A
B28A
B29A
B30A
AGMN
EYMN
F04D
HAWA
MSO
G03D
COR
G05D
LAO
C27A
D28A
C28A
C30A
D27A
D30A
E26A
E28A
E29A
E30A
F27A
F29A
F30A
G27A
G30A
G26A
H27A
H28A
H29A
I26A
I28A
I29A
I30A
J26A
J28A
J29A
J30A
K28A
K30A
J25A
J27A
L28A
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L31A
L35A
M30A
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Q32A
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Q34A
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U34A
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431A
432A
LTX
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536A
HKT
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636A
637A
733A
735A
738A
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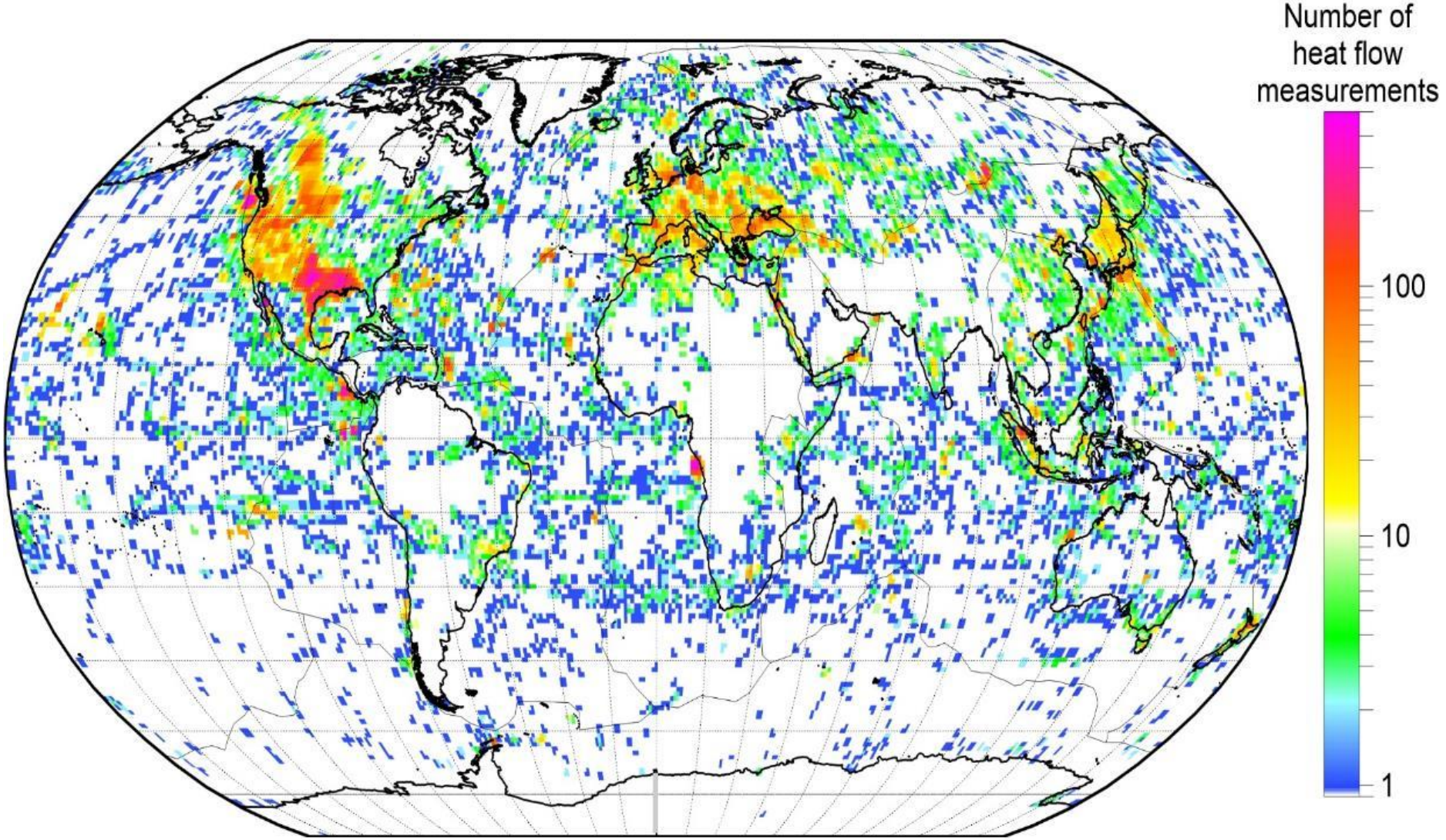
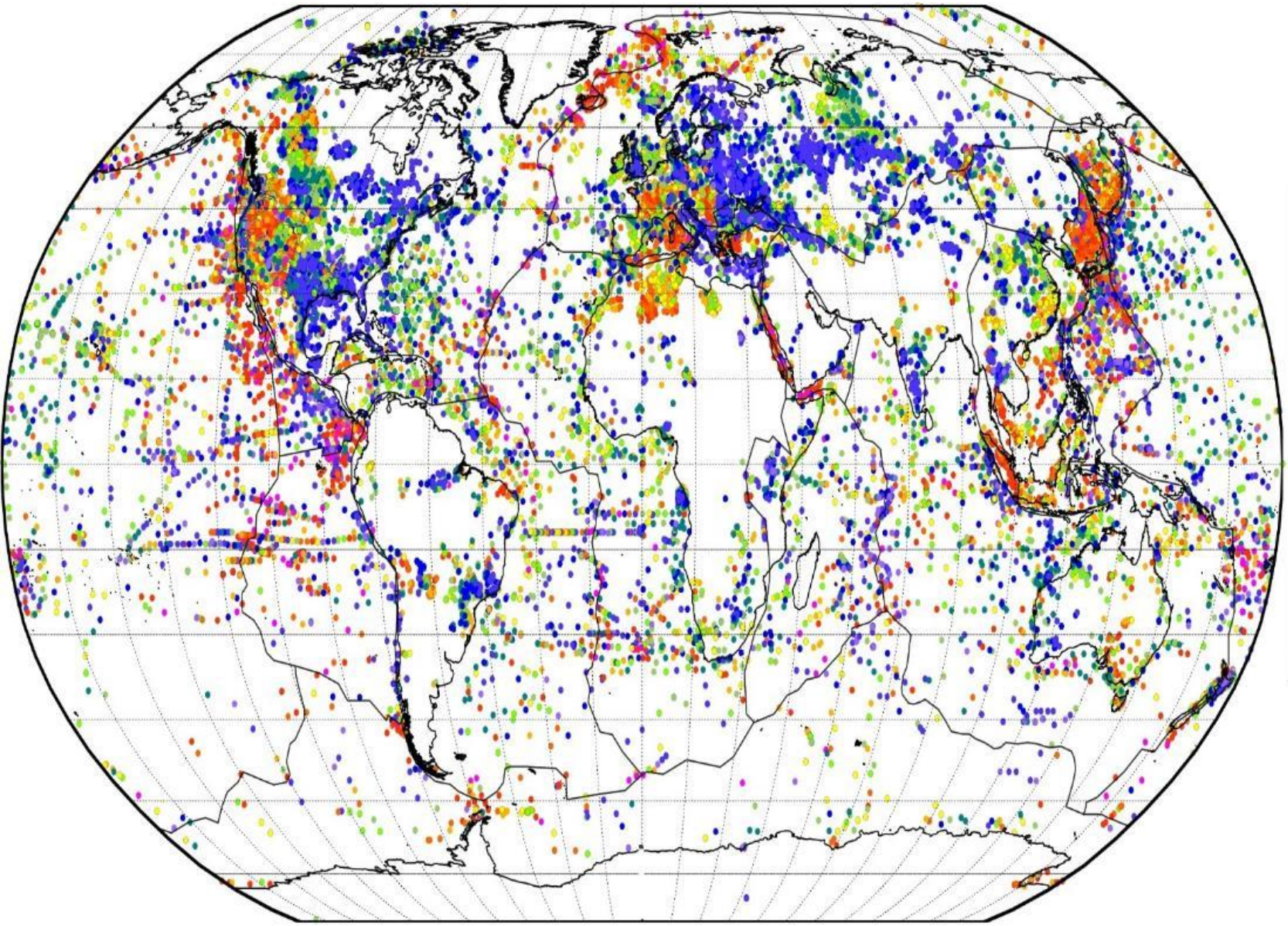
835A
BMO
BOZ
LKWY
RLMT
I03D
I04A
I05D
J04D
J05D
L02D
K04D
HLID
H17A
IMW
M04C
WVOR
N02D
M02C
WDC
AHID
BW06
K22A
HWUT
ELK
DUG
O20A
N23A
ISCO
Jill 1st Message
Jill's 2nd Message
CMB
MNV
R11A
SAO
TPNV
KNB
ISA
MVCO
SDCO
S22A
KSCO
KSU1
WUAZ
W18A
XPFO
PFO
109C
Y12C
ANMO
Y22D
214A
TUC
121A
319A
MNTX
SLBS
Gulf of California
ECSD
SPMN
COWI
JFWS
SCIA
BGNE
HDIL
SFIN
ACSO
MCWV
WCI
CCM
BLA
TZTN
CNNC
WVT
KMSC
MYNC
OXF
GOGA
NHSC
LRAL
TIGA
VBMS
BRAL
DWPF
Nassau
The Bahamas
Havana
Gulf of Mexico
PKME
LONY
LBNH
NCB
GLMI
HRV
BINY
ERPA
AAM
SSPA
CBN
© 2010 EuropaTechnologies
US Dept of State Geographer
© 2010 Google
© 2010 INEGI
USGS
Google
©2010
lat 49.747576° lon -144.291441° elev -4318 m
Eye alt 4076.04 km

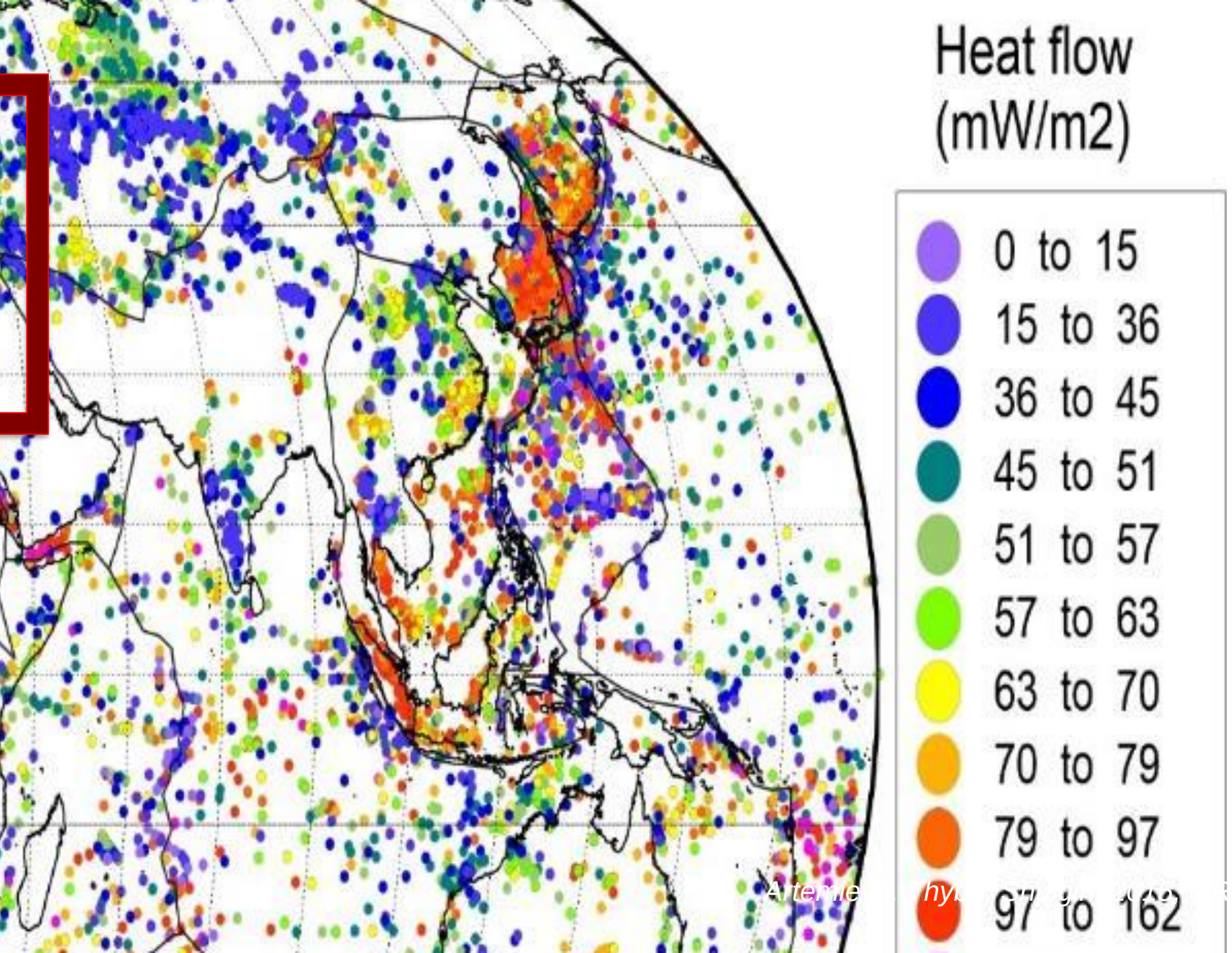
Global Heat Flow Data



Global heat flow data:

Paleoclimate corrections can be 30-40%.


Heat flow
(mW/m2)
0 to 15
15 to 36
36 to 45
45 to 51
51 to 57
57 to 63
63 to 70
70 to 79
79 to 97
97 to 162
162 to 500


Heat flow
(mW/m2)
0 to 15
15 to 36
36 to 45
45 to 51
51 to 57
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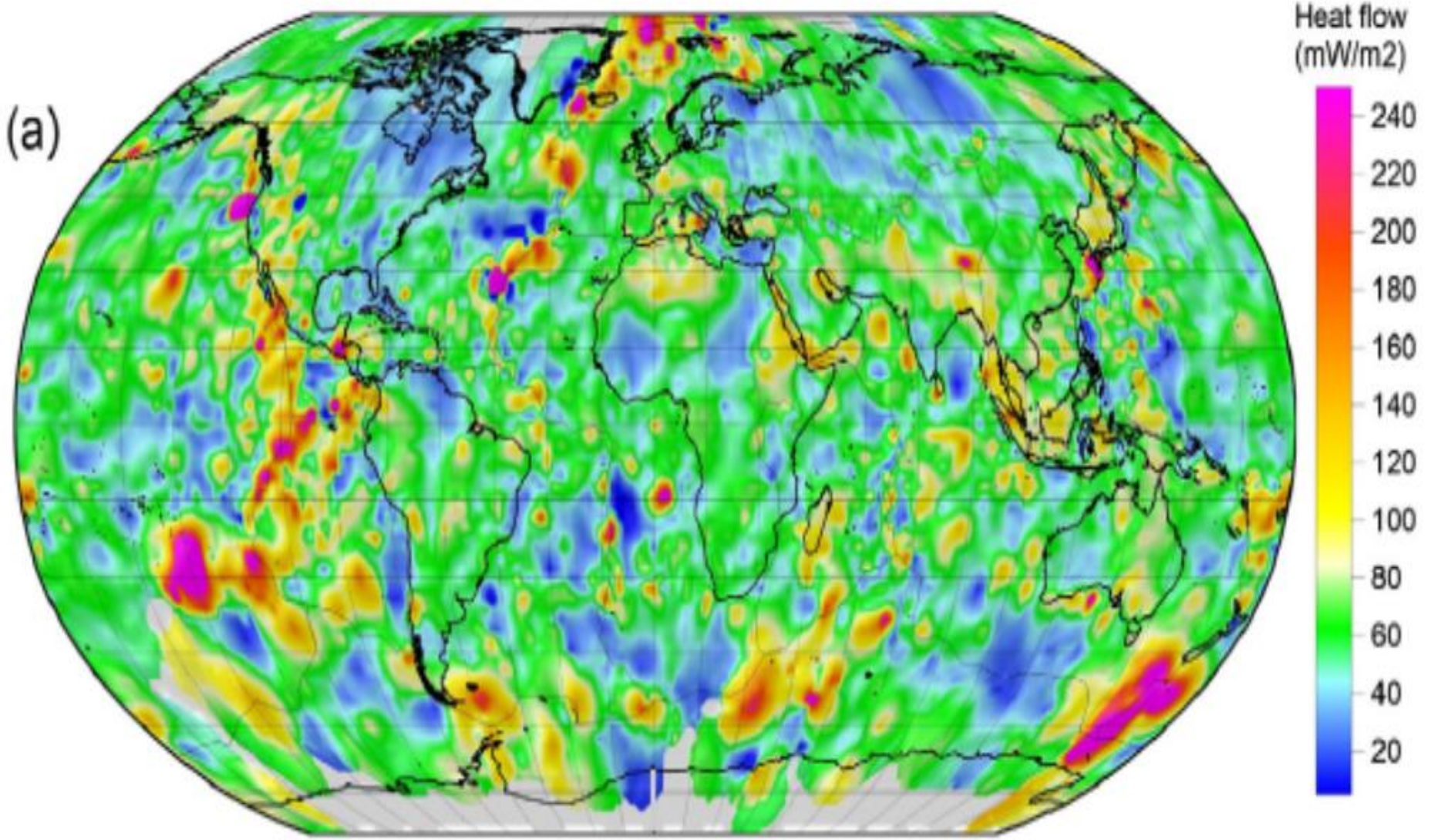
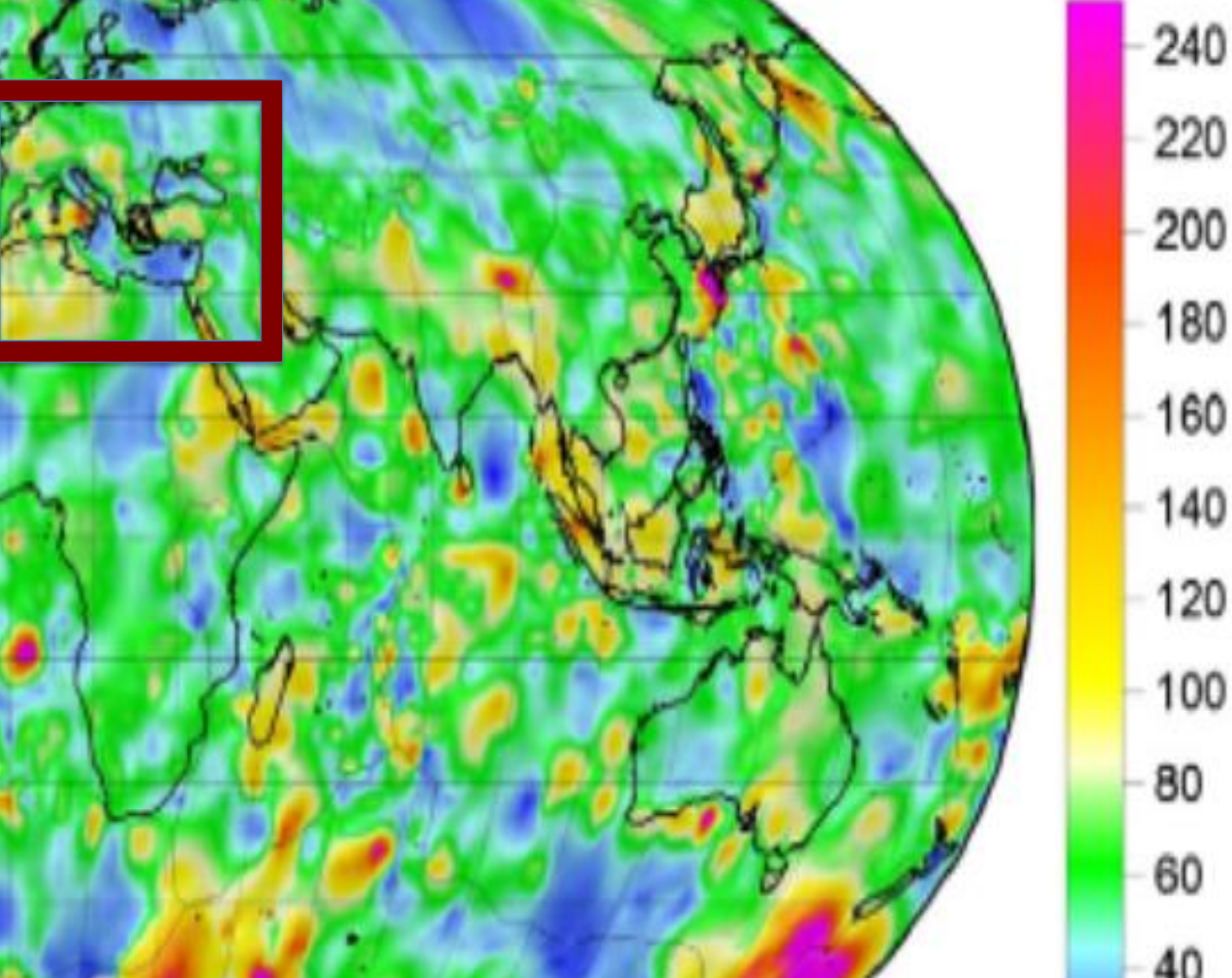
79 to 97
97 to 162


(a)
Heat flow
(mW/m2)
240
220
200
180
160
140
120
100
80
60
40
20


240
220
200
180
160
140
120
100
80
60
40

Lithospheric Thermal Thickness

Steady State Thermal Conductivity

$$\partial^2 T / \partial z^2 = - A / k$$

at $z = 0$: $T = 0$

$$Q_0 = - k \cdot \partial T / \partial z$$

+ Assumption

$$A(z) = A_0 \cdot \exp(-z / D)$$

$$Q_0 = q + A_0 \cdot D$$

A_0 – surface radioactivity

Q_0 - surface heat flow

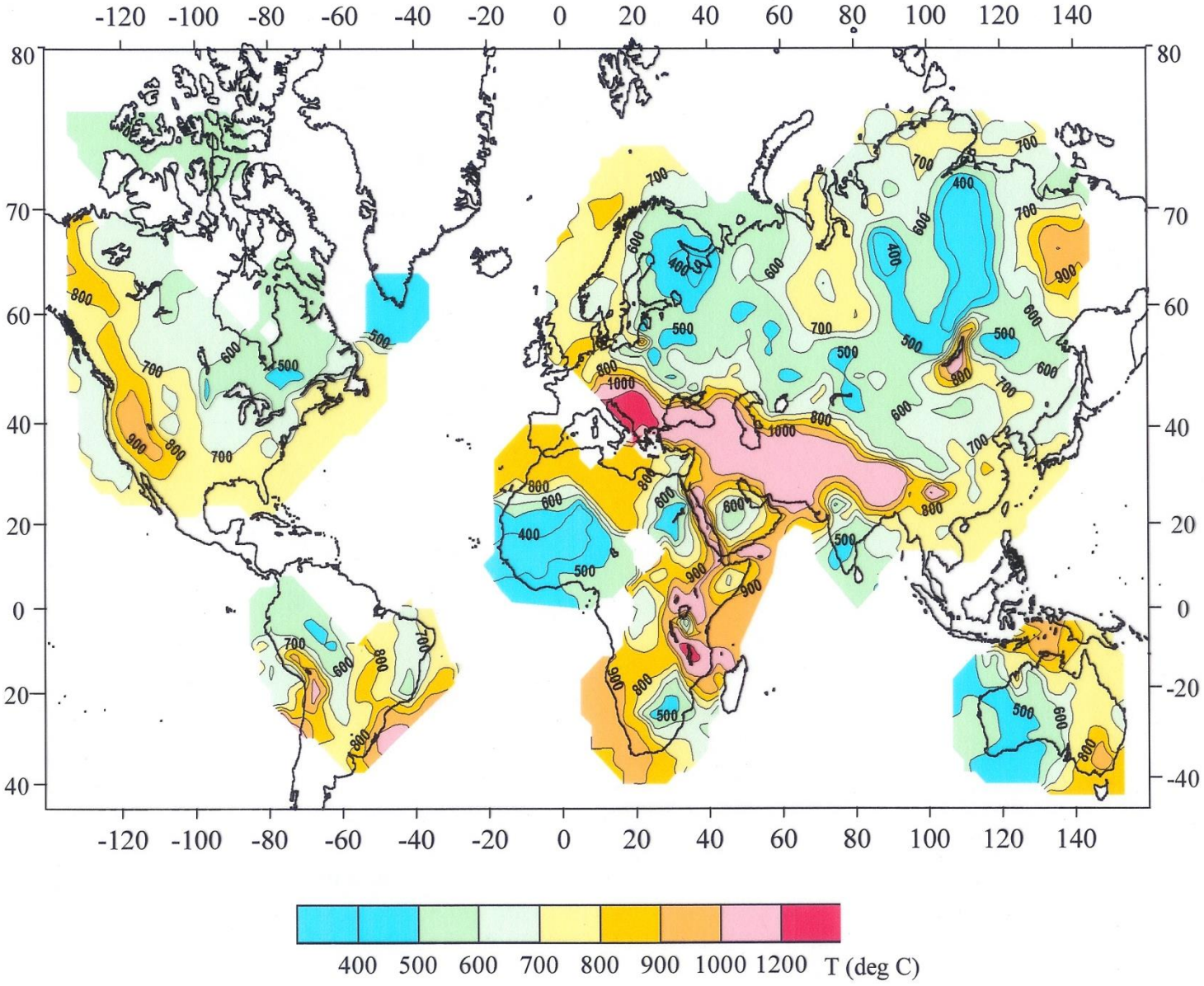
q - reduced (mantle)heat flow

k- thermal conductivity

T- temperature

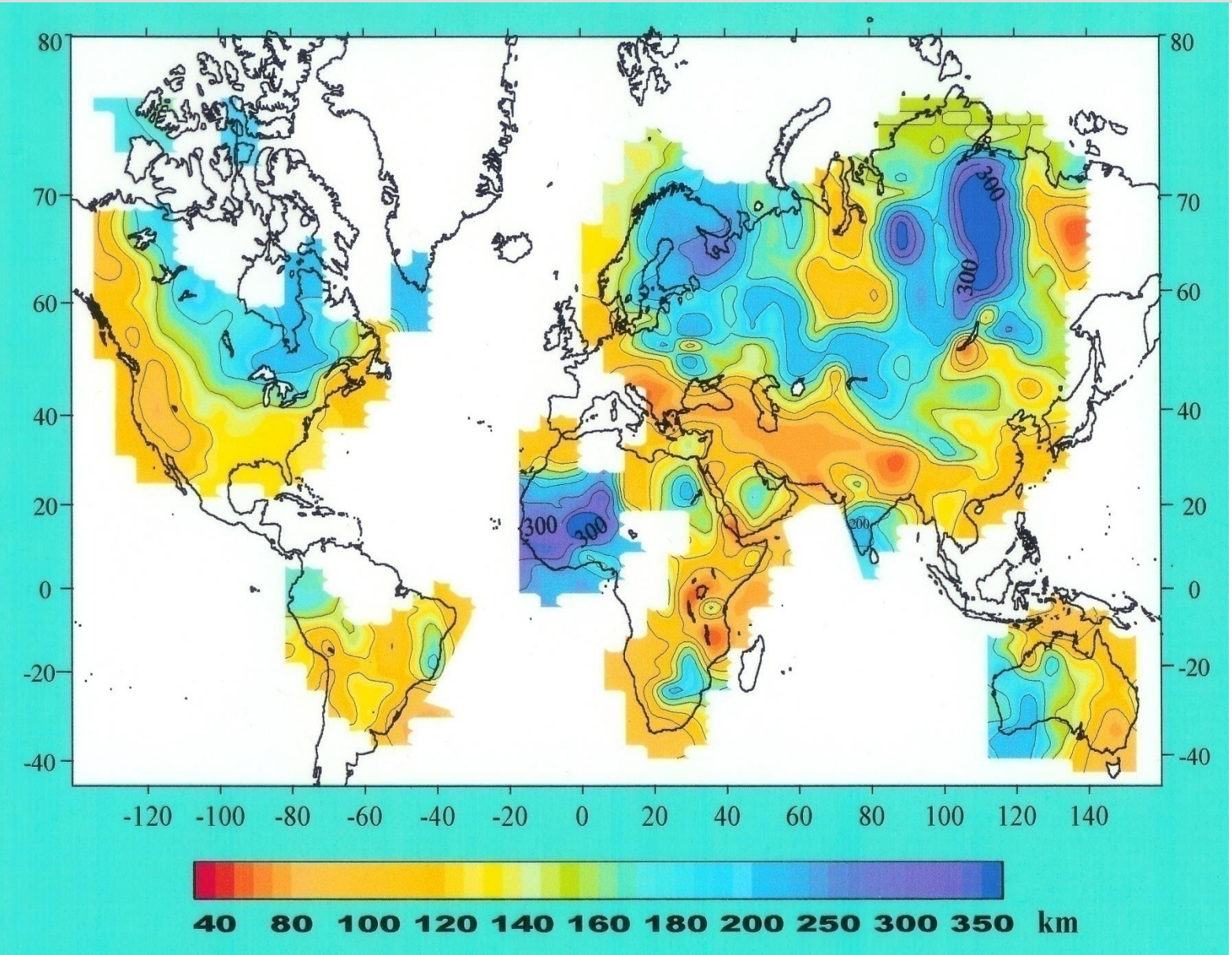
D – characteristic depth

Estimated Temperature at 50 km Depth



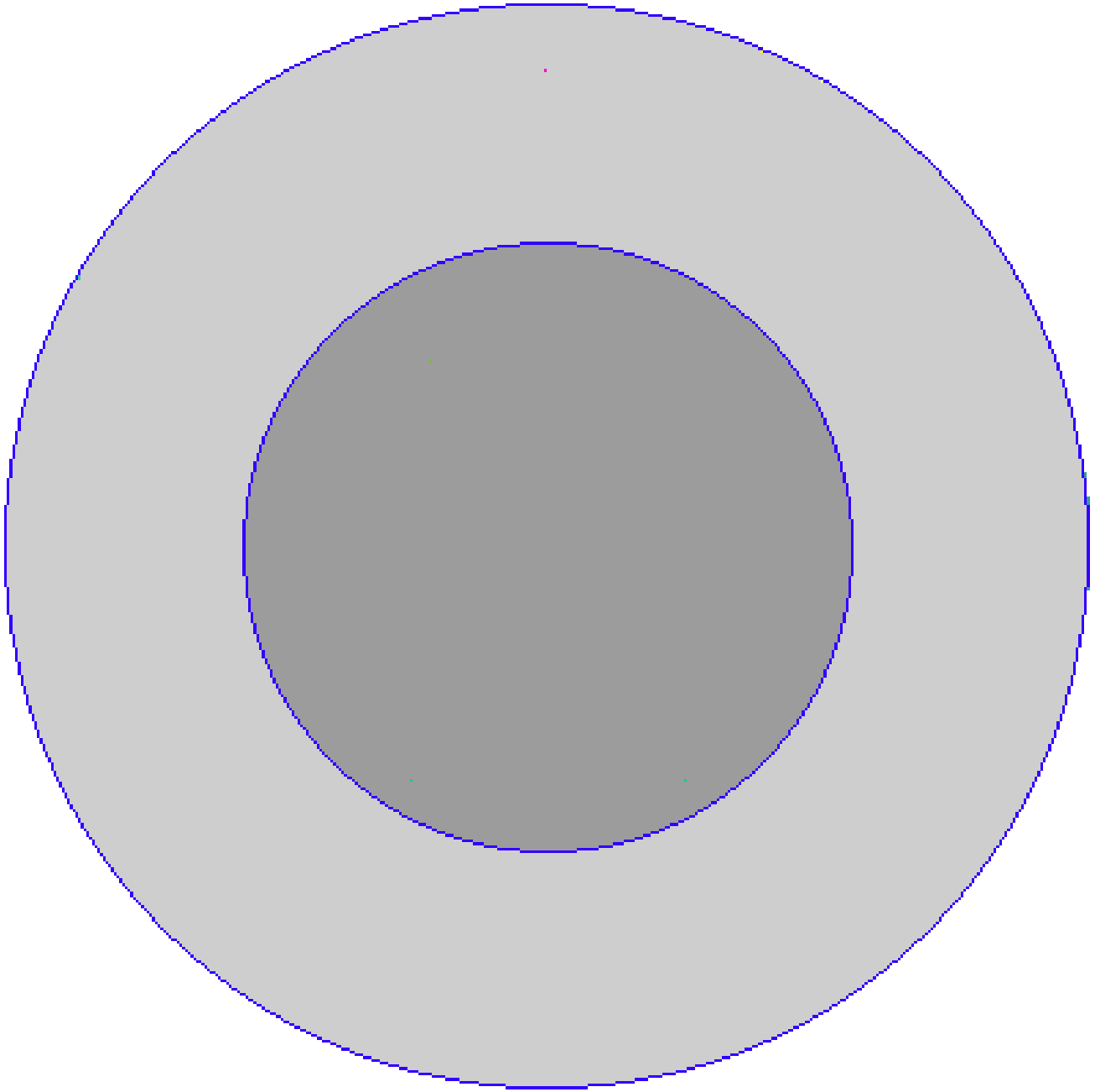
Source: Artemieva and Mooney, 2000

Lithosphere Thermal Thickness as the Depth to 1300 ° C



Source: Artemieva and Mooney, 2000


Thank You!



Seismic Waves

Source: Steven Dutch, University of

“Standard Model” of the Earth

Sir Harold Jeffreys
(1891 – 1989)

Keith Edward Bullen
(1906 - 1976)

Fishwick's 2009 regional models

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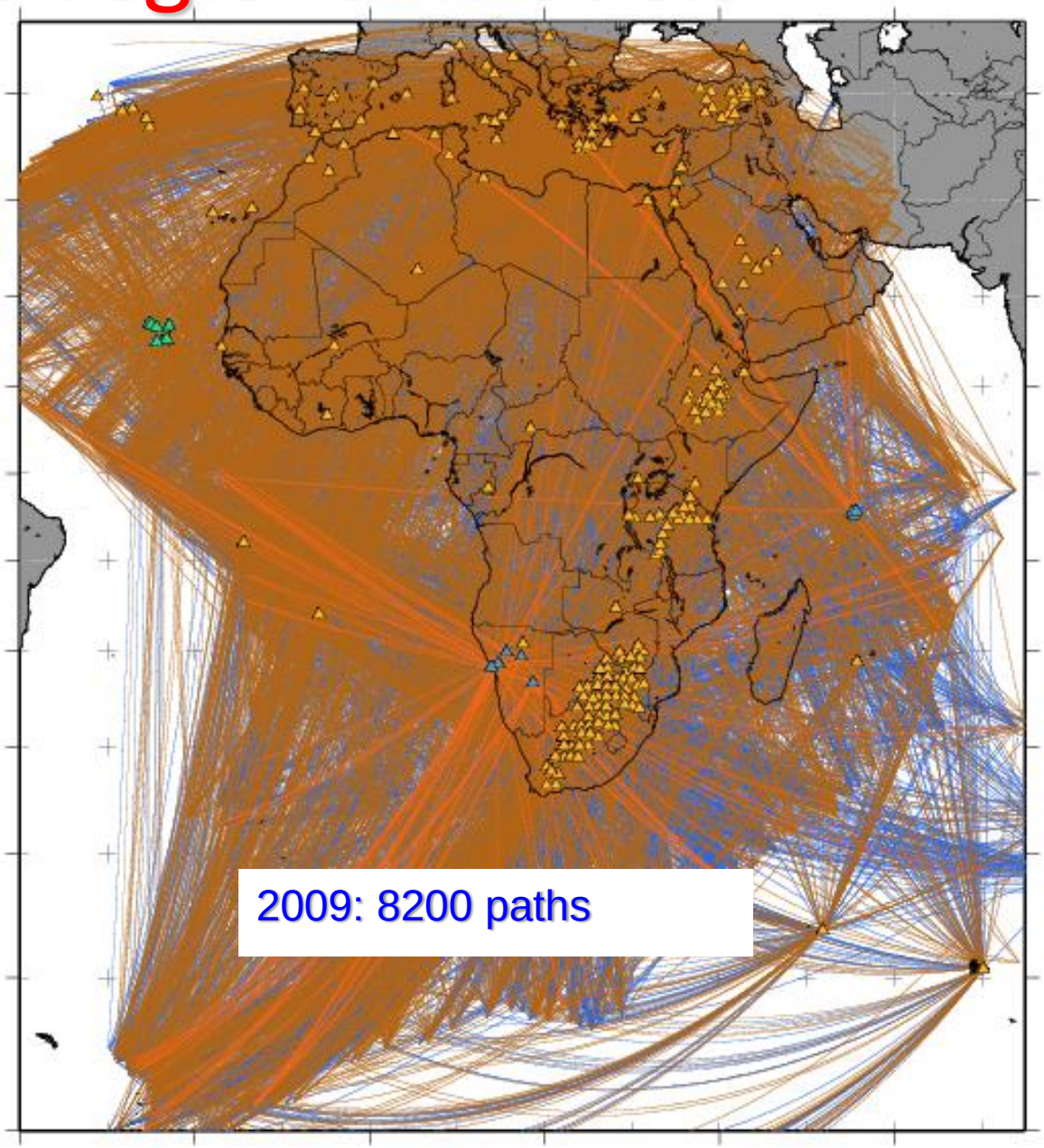
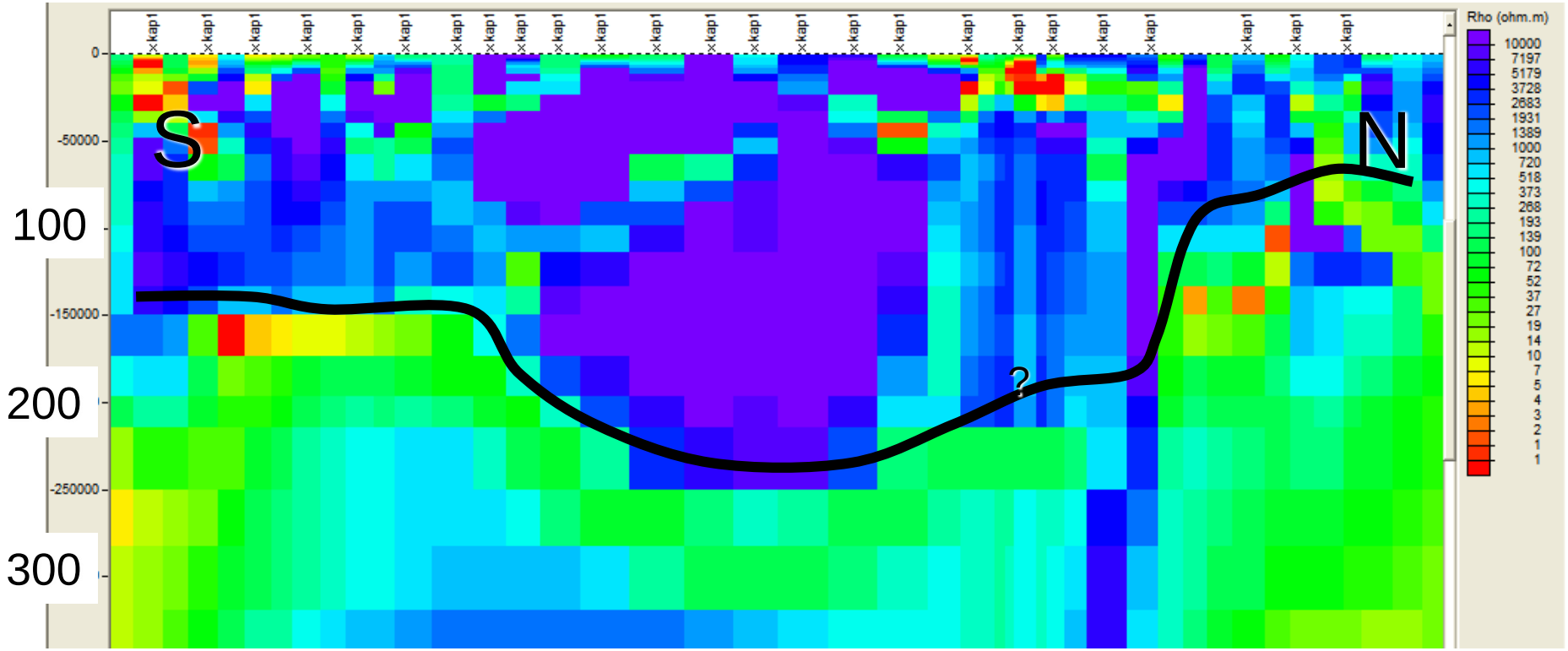
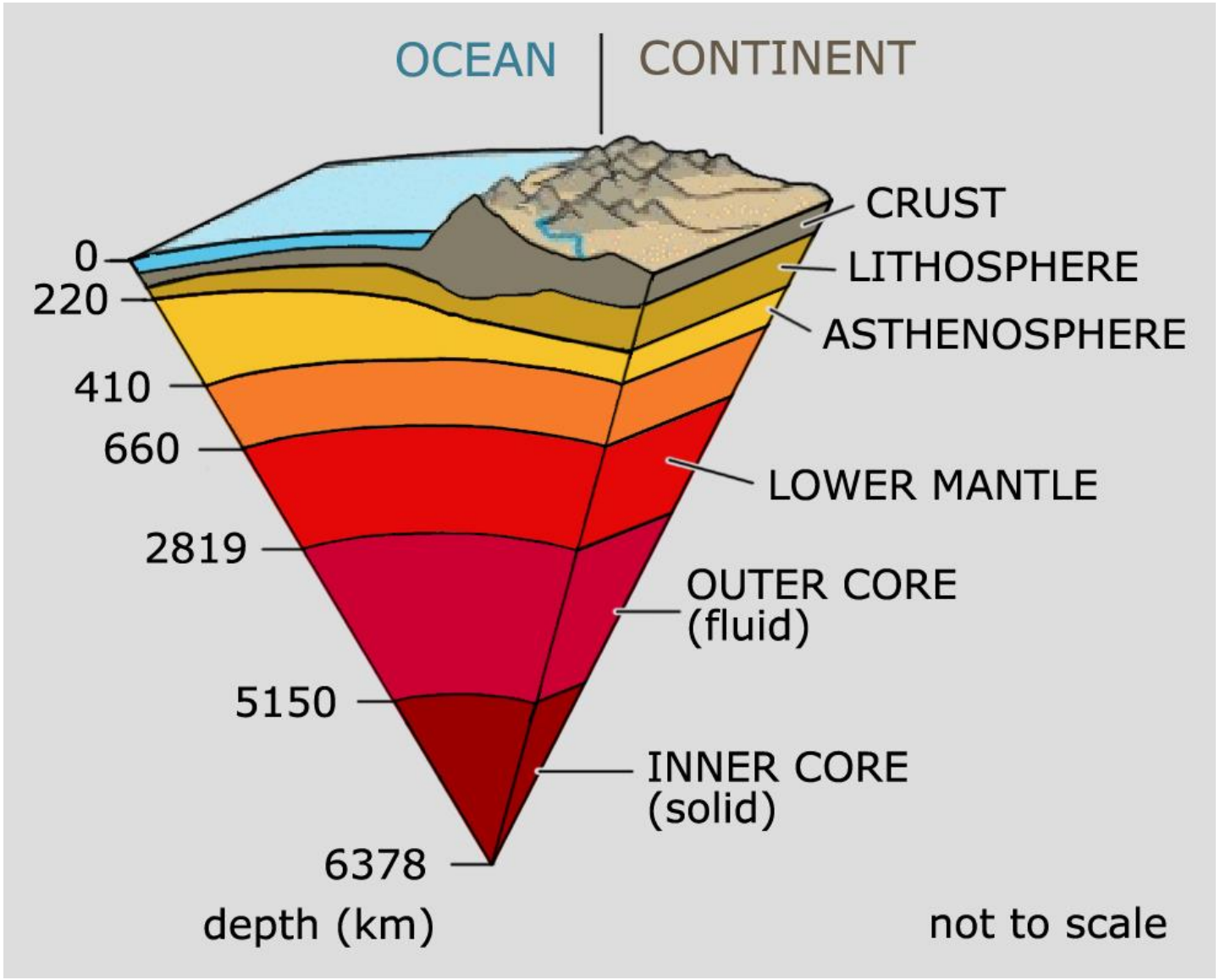


2-D model: Main result – variation in LAB

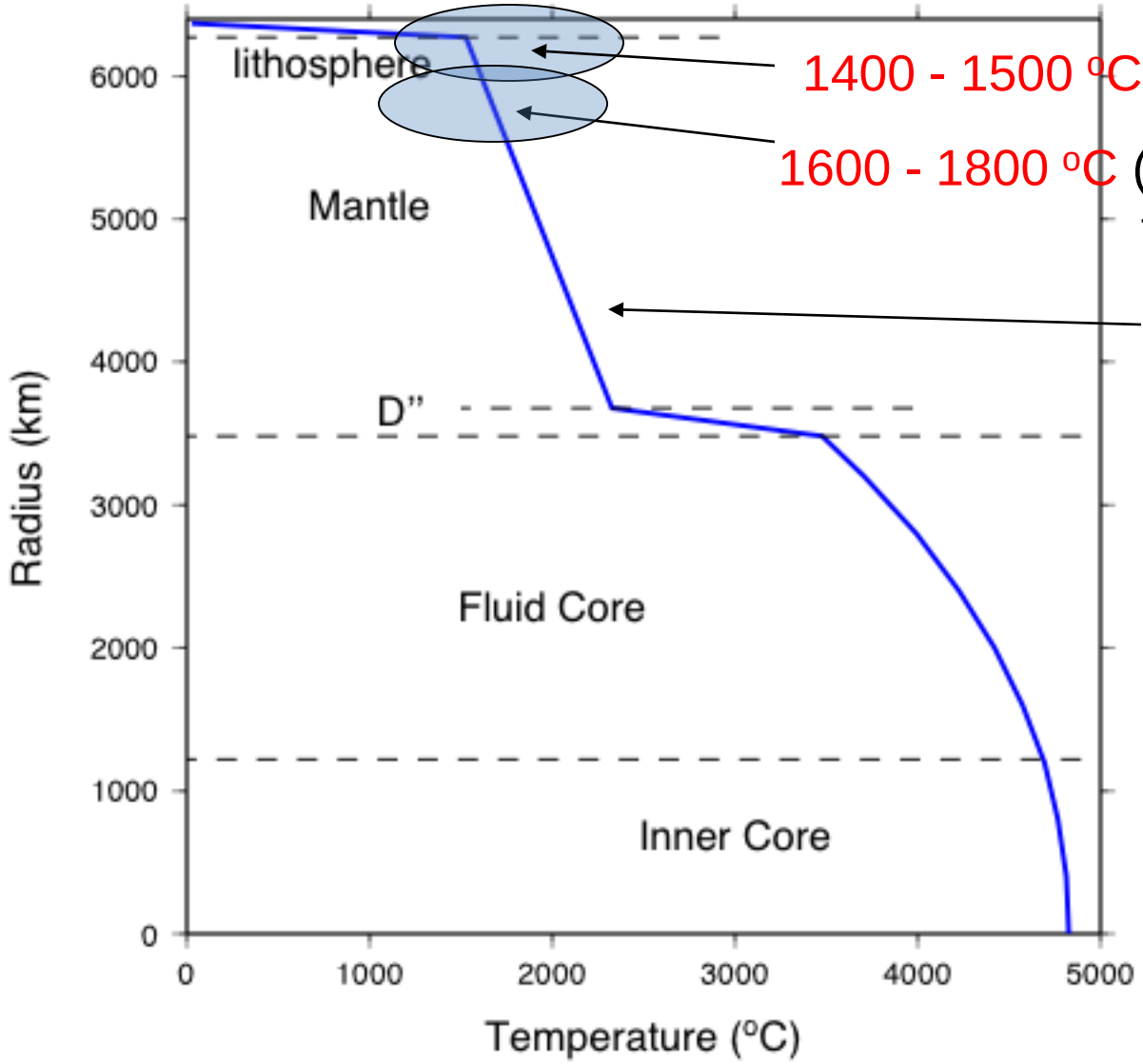


Lithospheric thickness varies along the profile, with the thickest part from just south of Kimberley -> north of Pretoria

“Standard Model” of the Earth



Temperature profile inside Earth

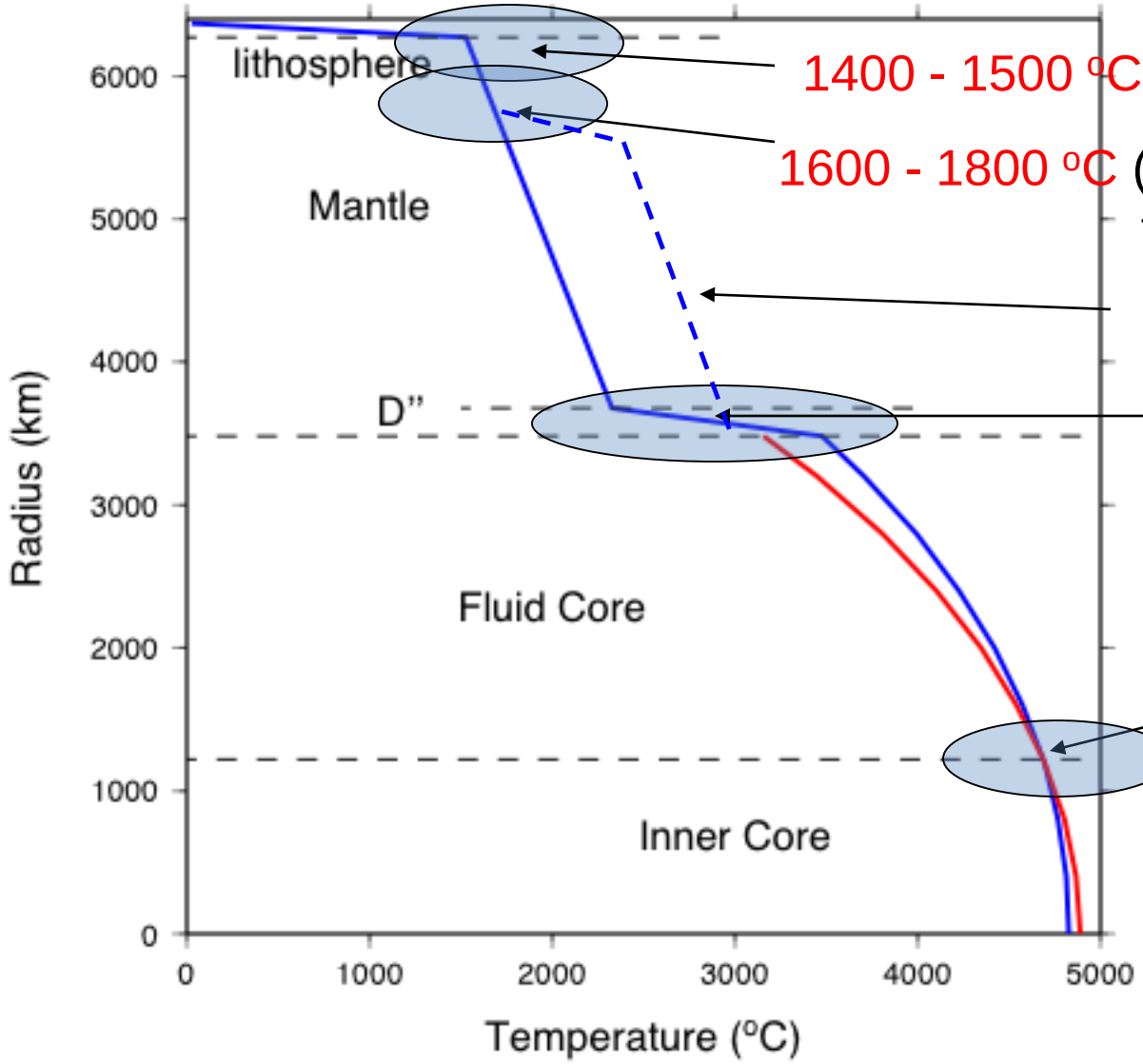


1400 - 1500 °C (cooling of lithosphere)

1600 - 1800 °C (phase transition temp. from mineral physics)

Mantle adiabatic gradient

Temperature profile inside Earth



1400 - 1500 °C (cooling of lithosphere)

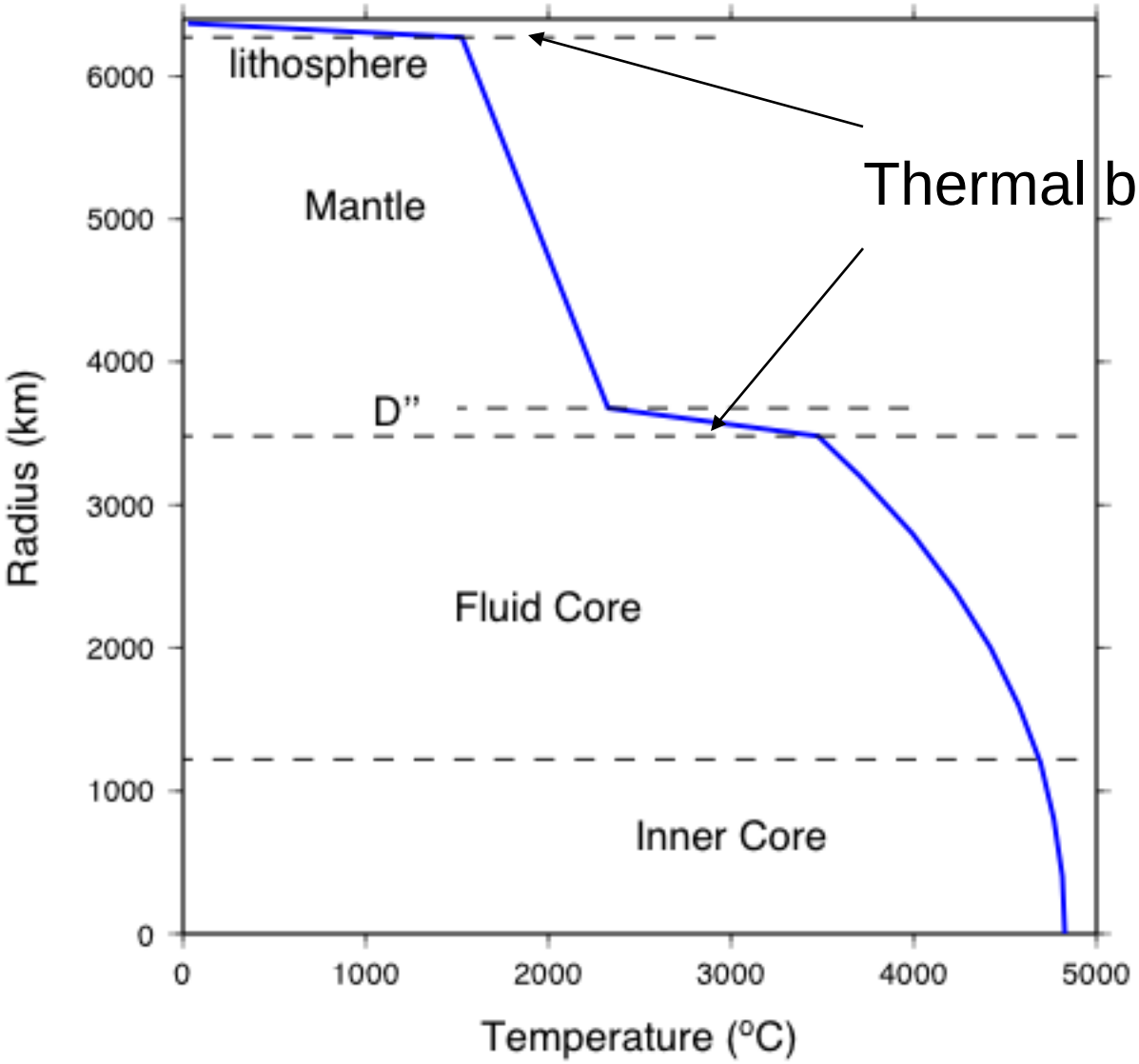
1600 - 1800 °C (phase transition temp. from mineral physics)

Layered convection

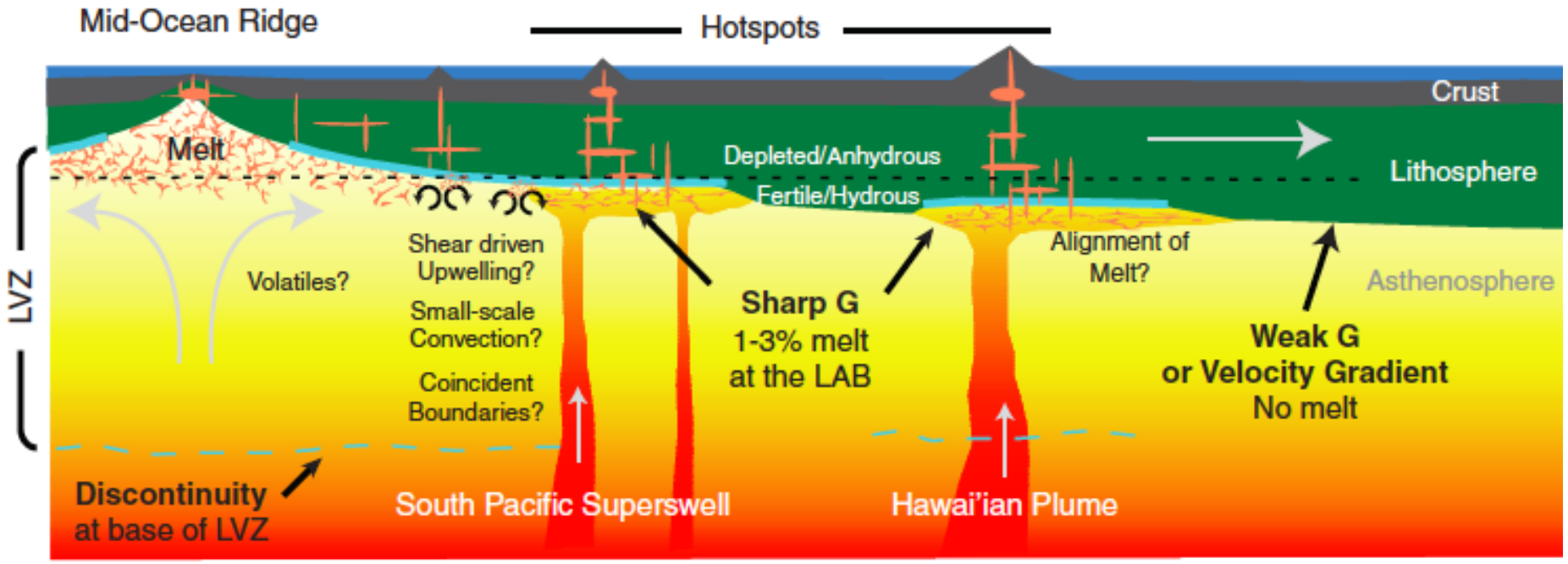
dT ~ 800 - 1800 °C

5000 - 5300 °C (mineral physics)

Temperature profile inside Earth



Thermal boundary layers



Schmerr, 2012, Science