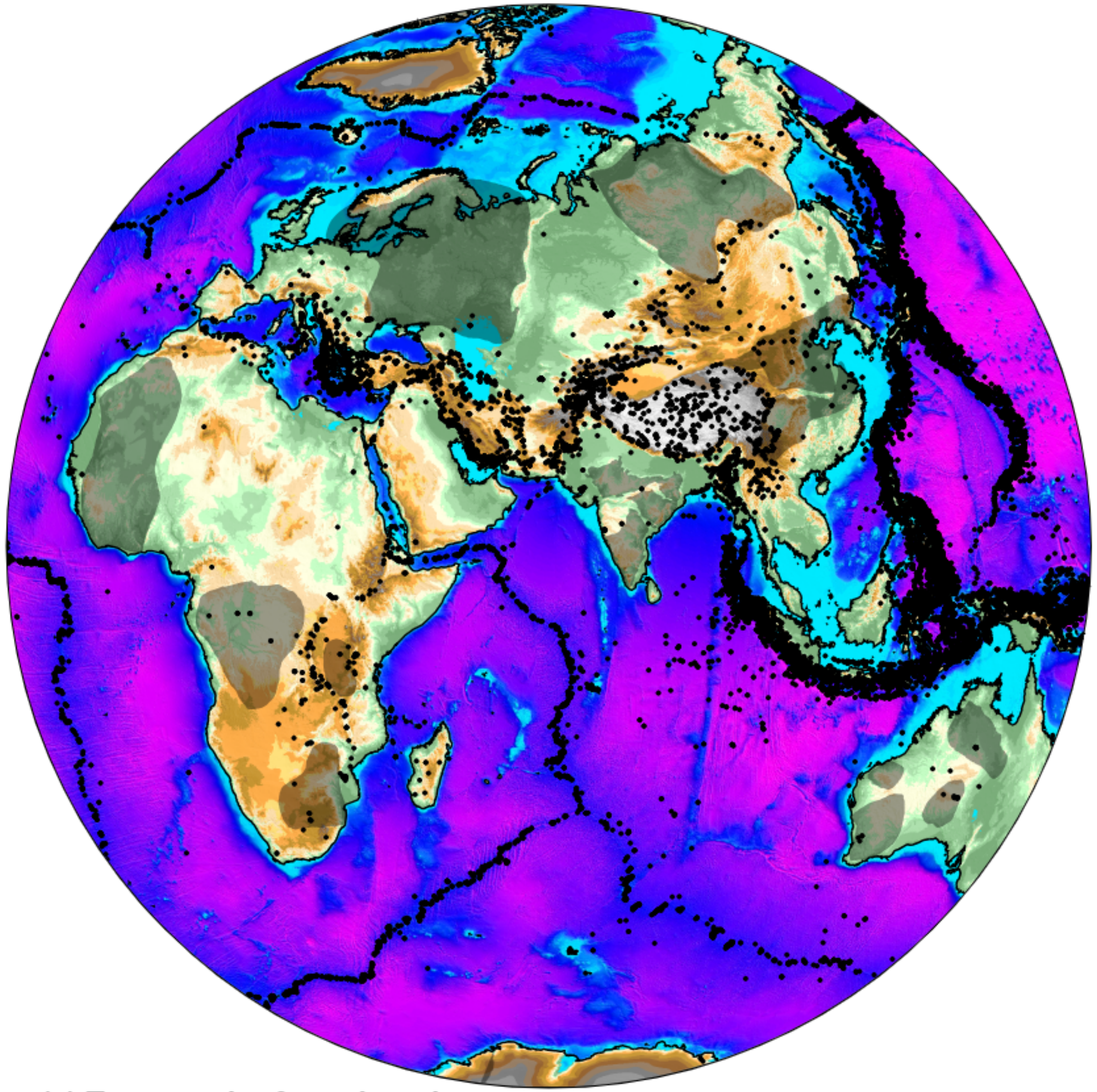
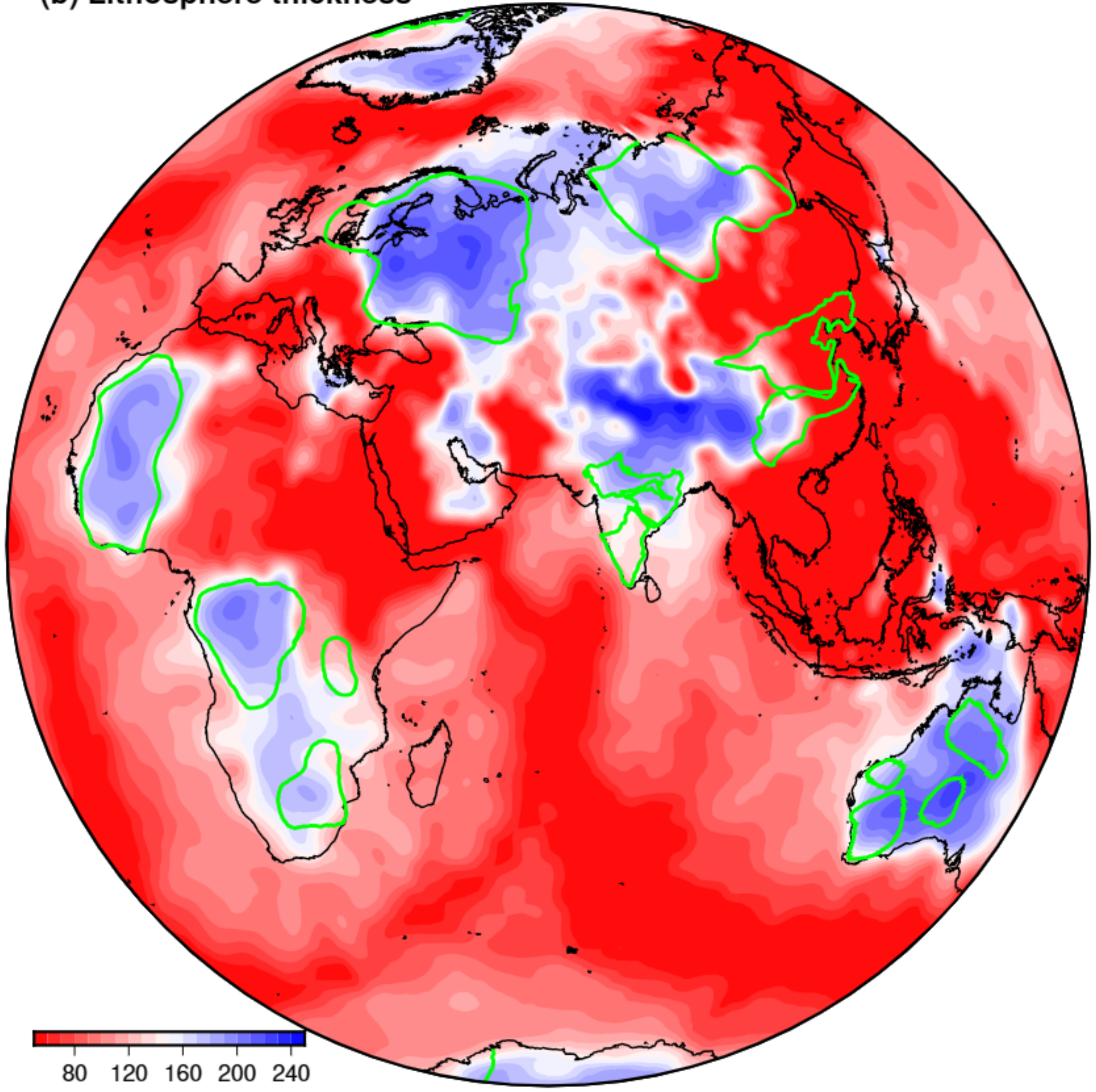
Lecture 1: Earthquake depths, lithosphere thickness, and strength

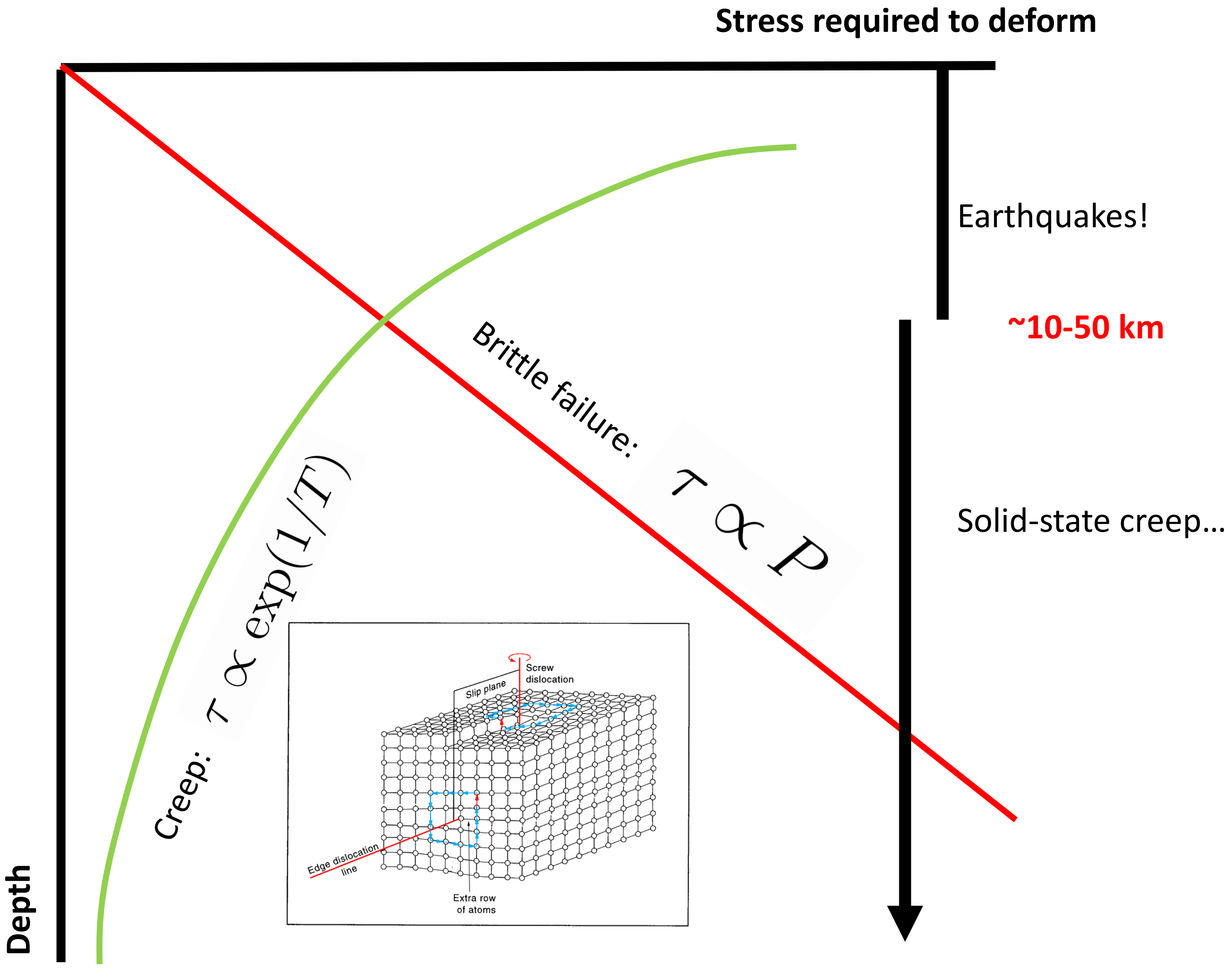


(a) Topography & earthquakes

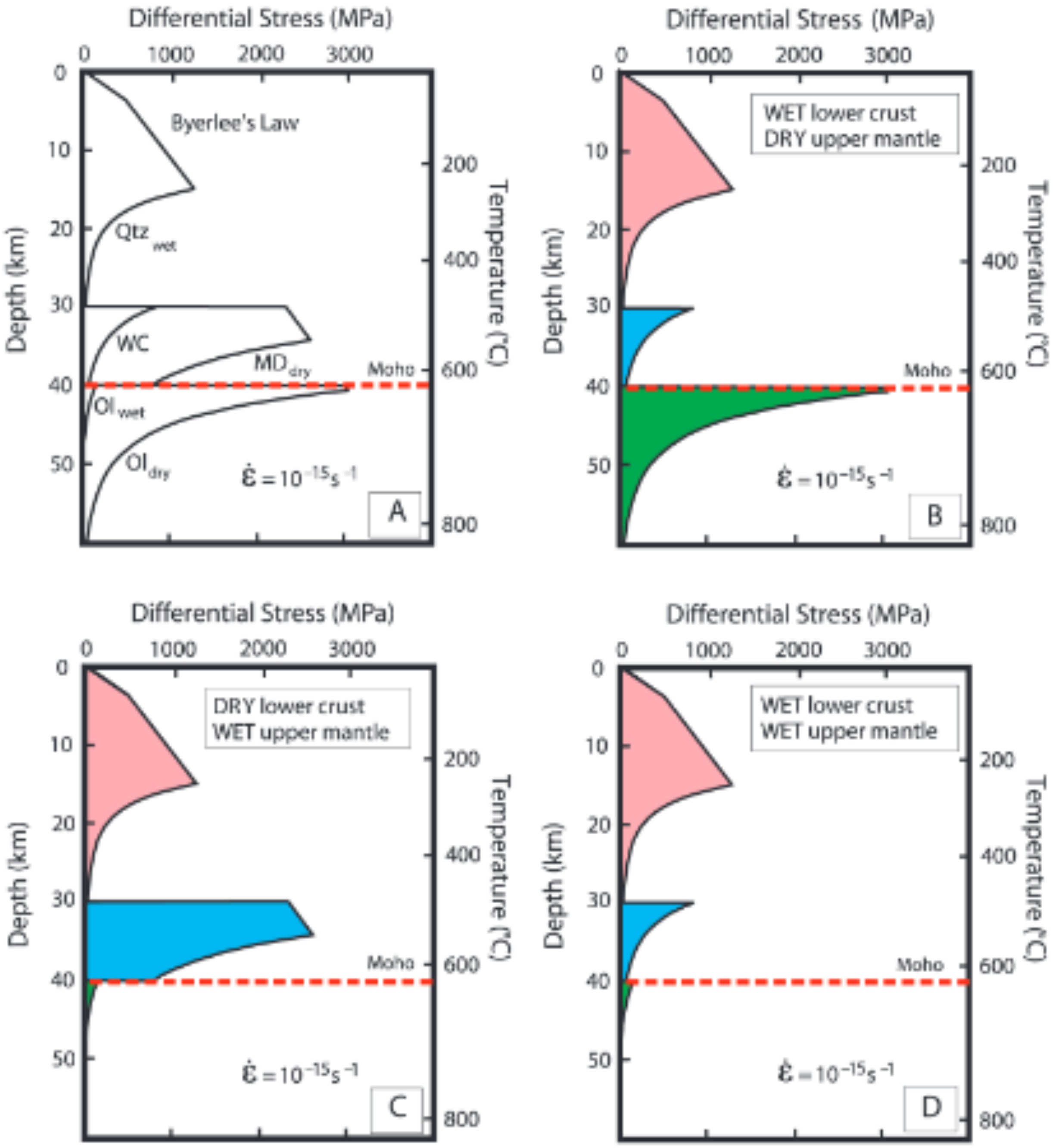
(b) Lithosphere thickness



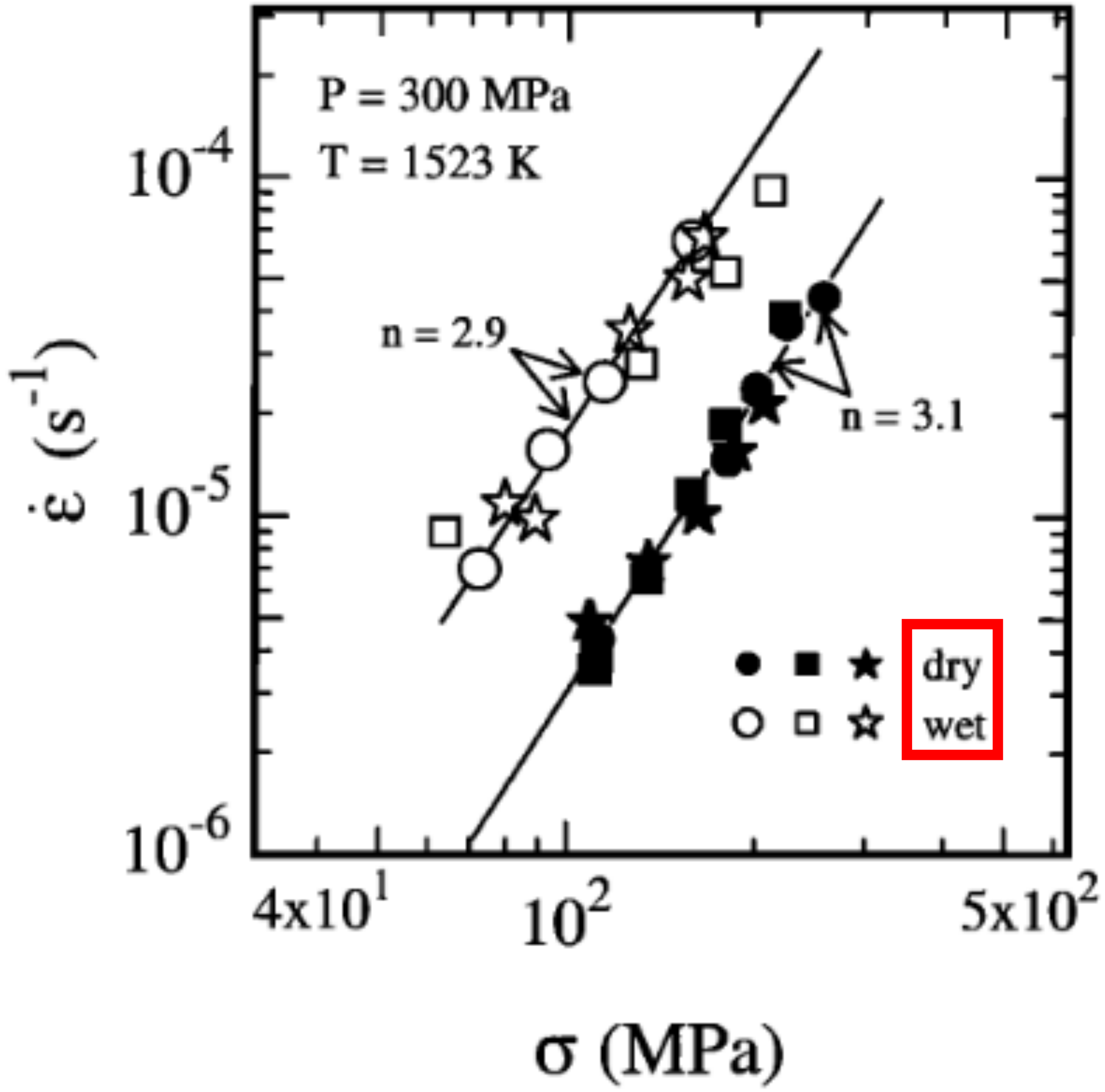
Deformation mechanism vs depth



Strength vs depth?



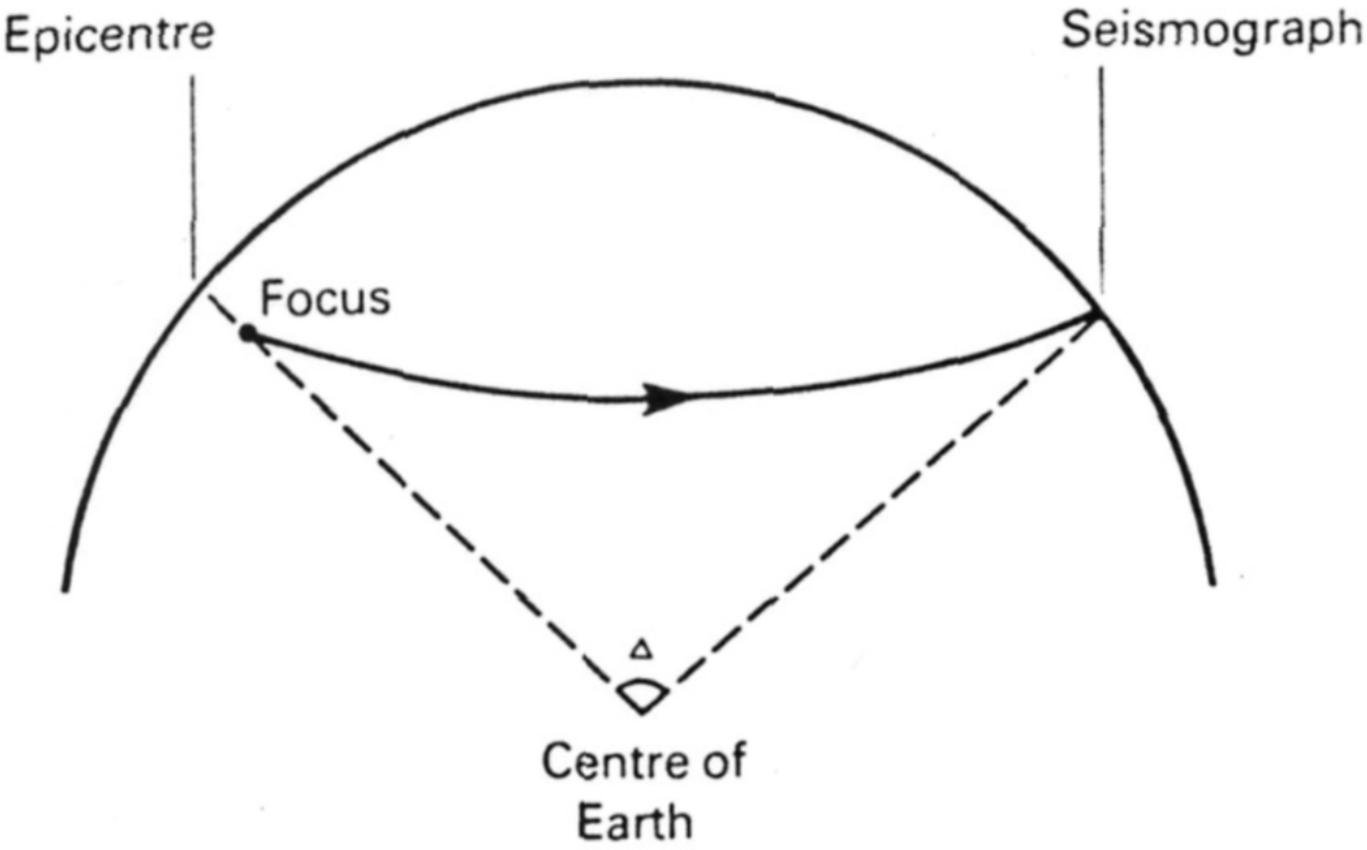
Laboratory measurements of creep strength (David Kohlstedt)

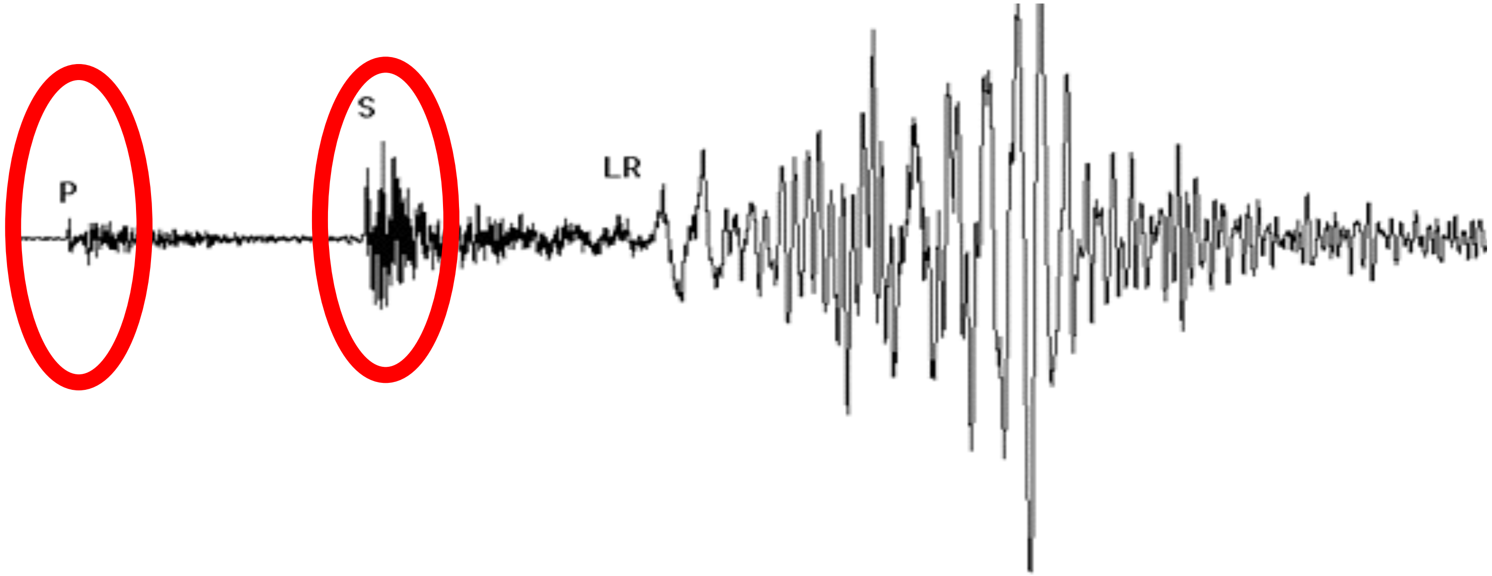


How do we distinguish between these models?

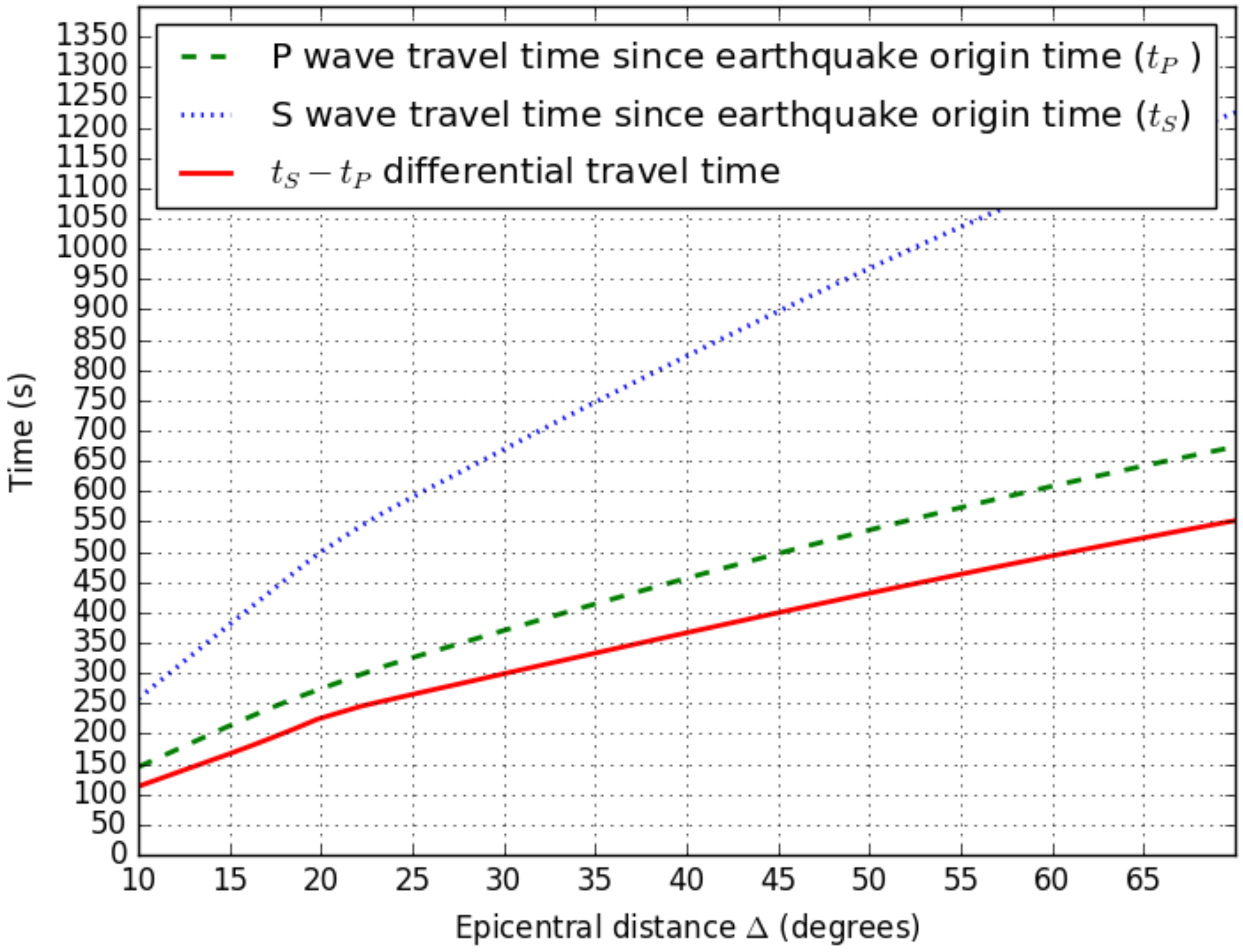
-> compare locations of earthquakes (easy)….

-> …with measures of strength (hard)


Epicentre
Seismograph
Focus
Δ
Centre of
Earth

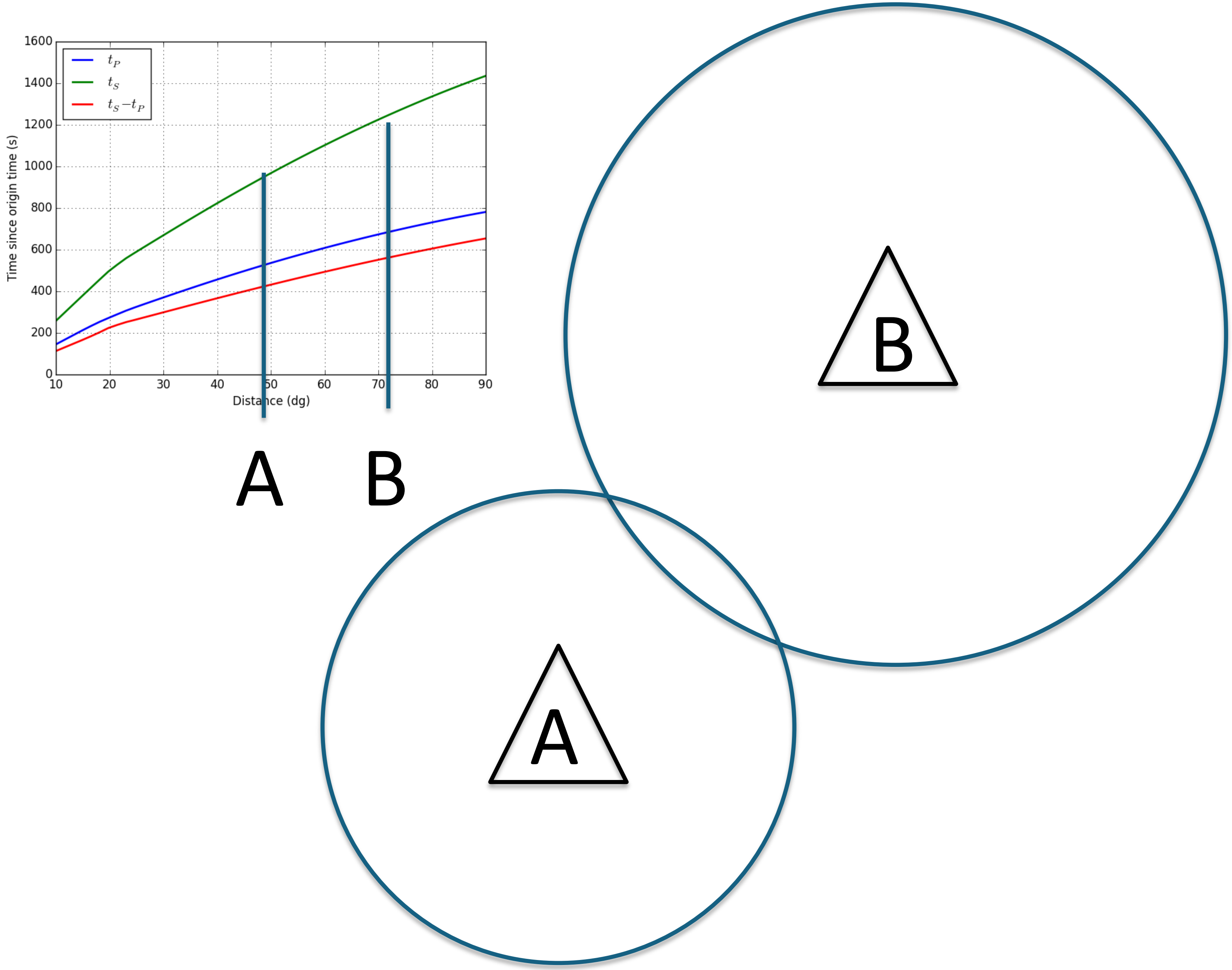

P
S
LR

Earthquake location. Travel times of P and S waves

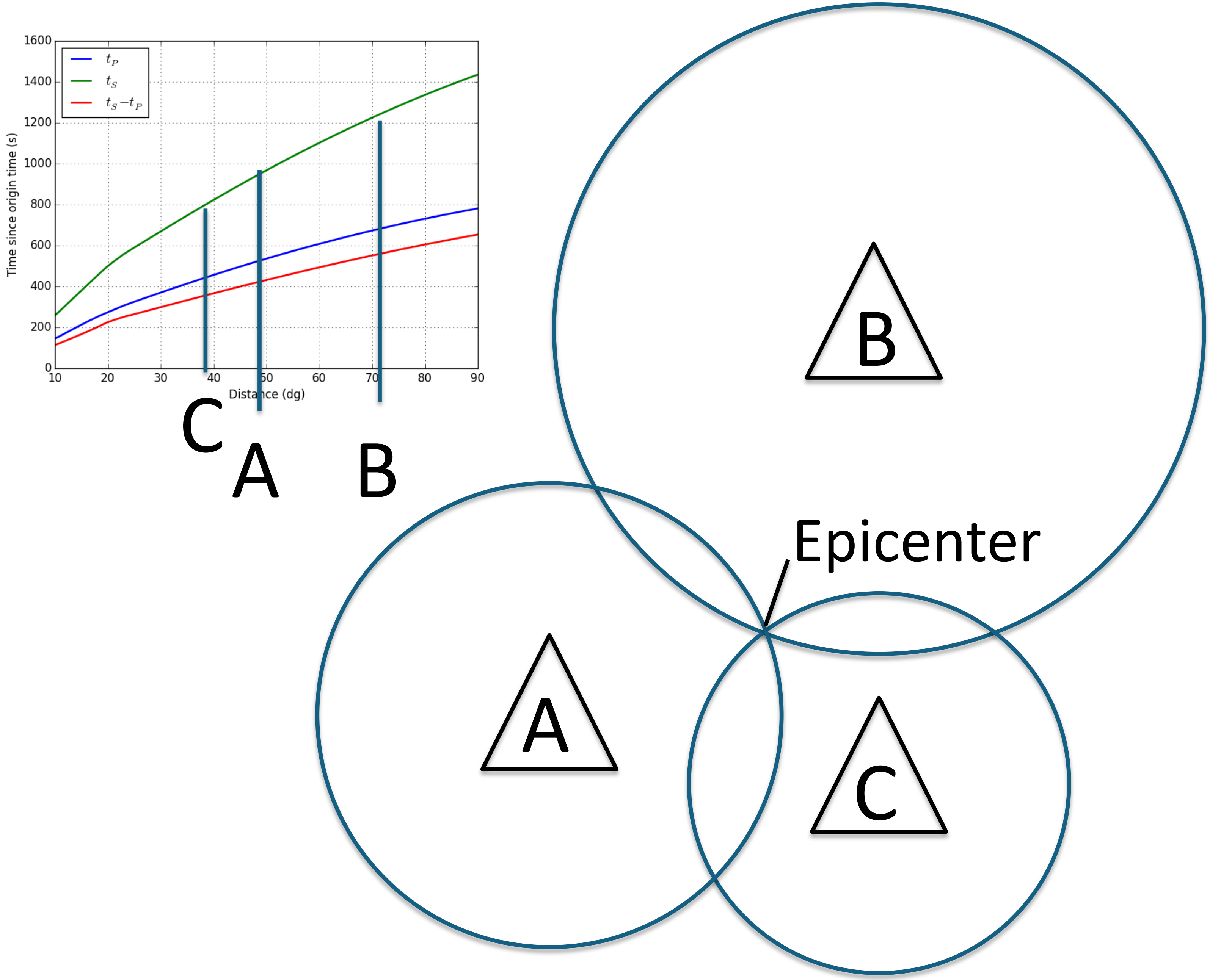


Difference in arrival time between the P and S wave gives the distance from the recording station to the earthquake.

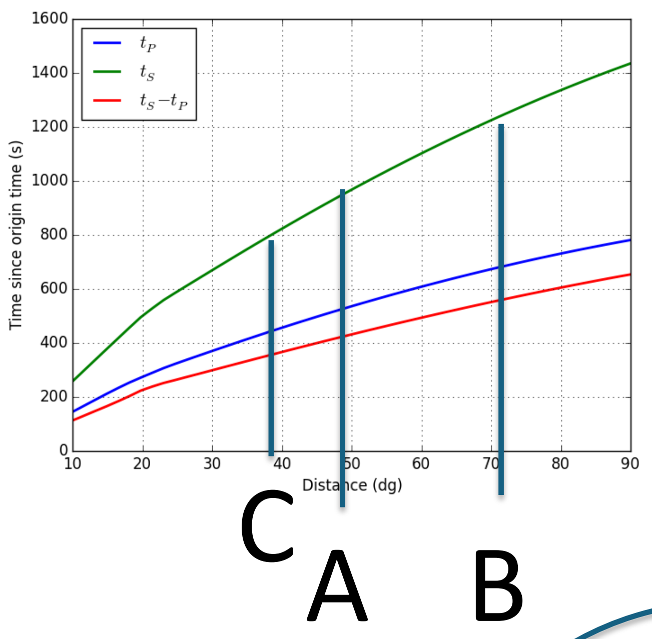
Earthquake location. Three station triangulation

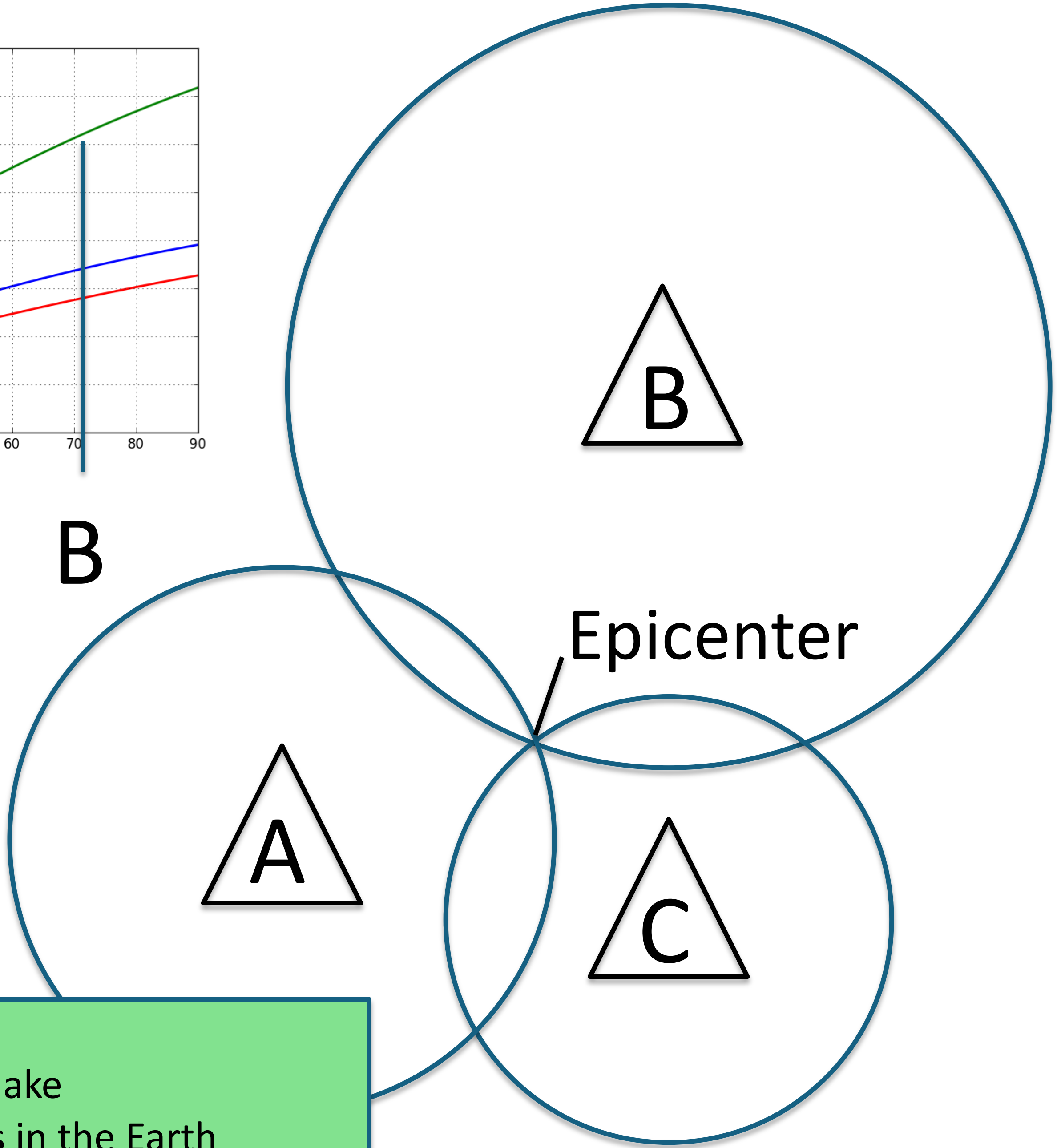


Earthquake location. Three station triangulation



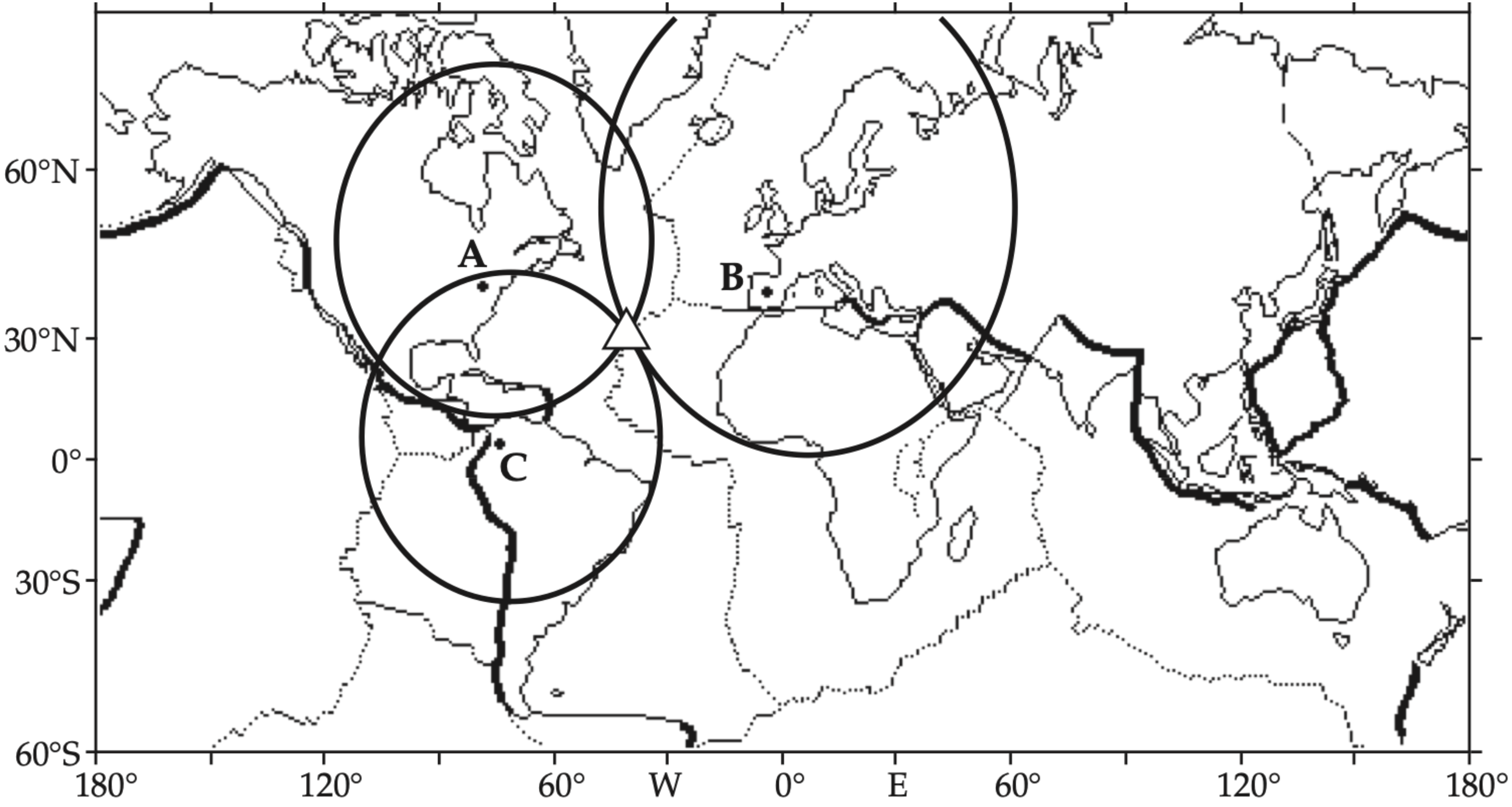
Earthquake location. Three station triangulation





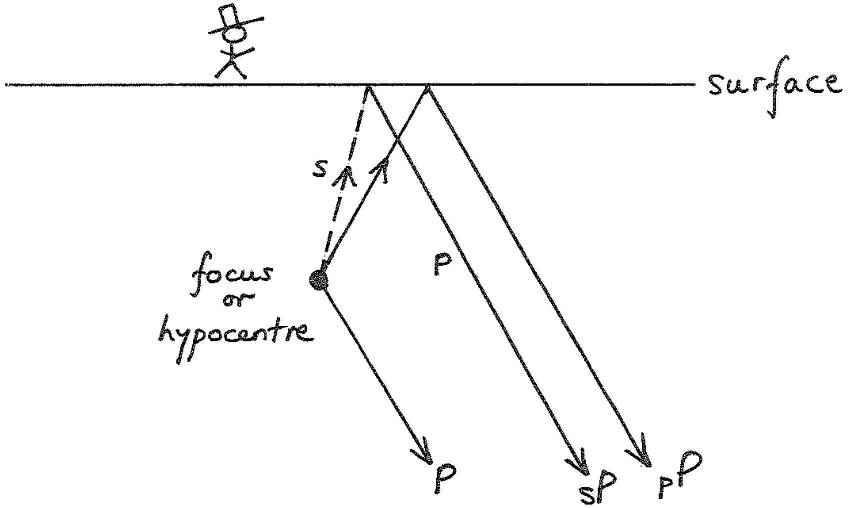
Complications:
Depth of the earthquake
3D velocity variations in the Earth

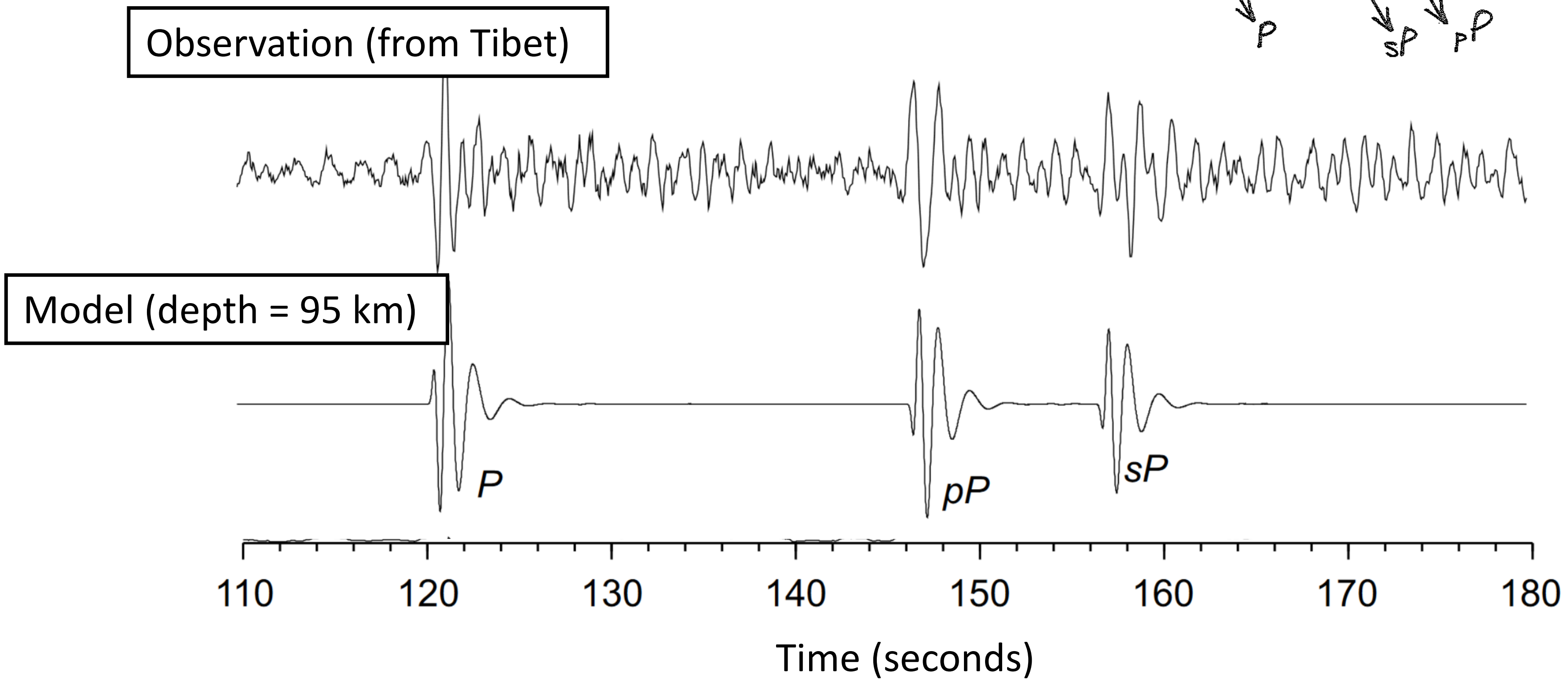
Earthquake location. On a spherical Earth



Earthquake depth

…is best determined using **depth phases.**

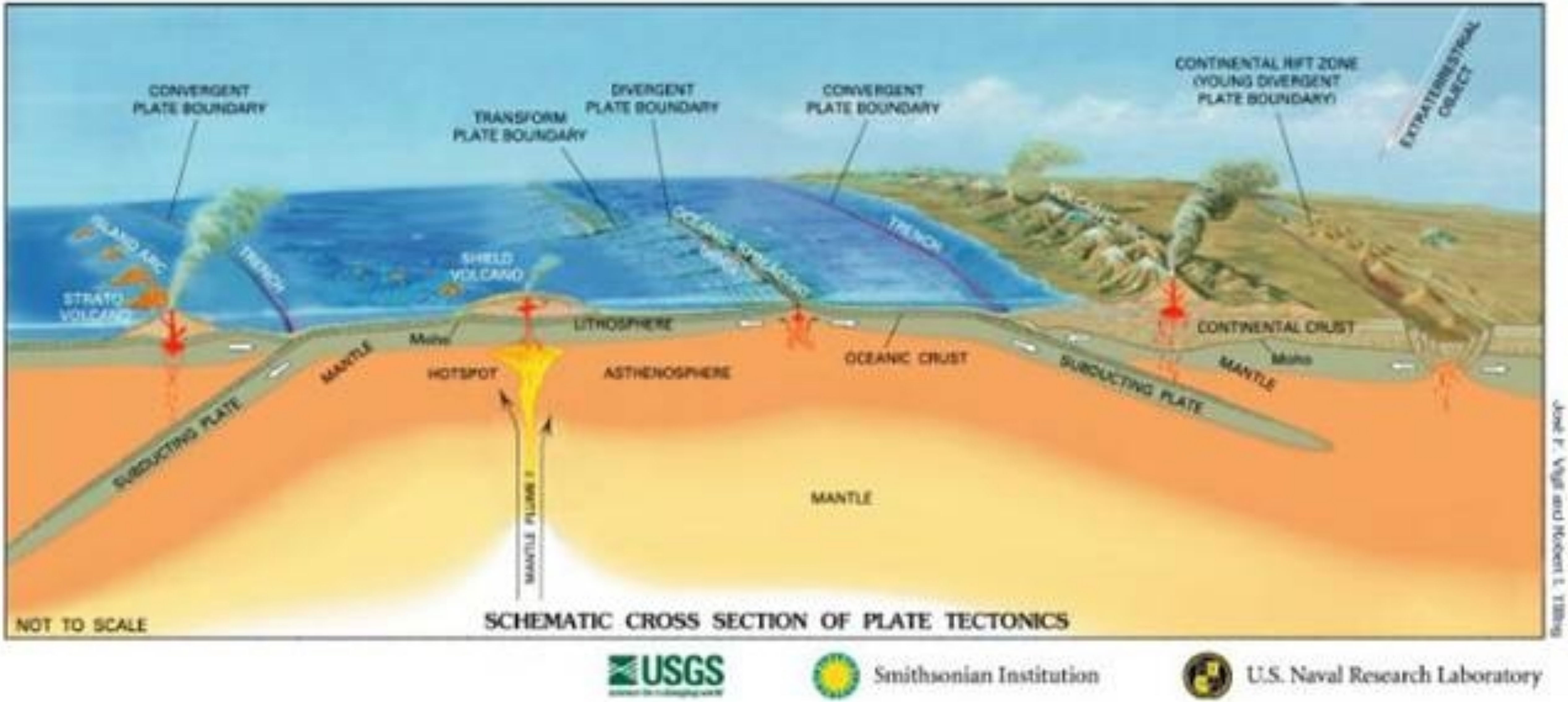




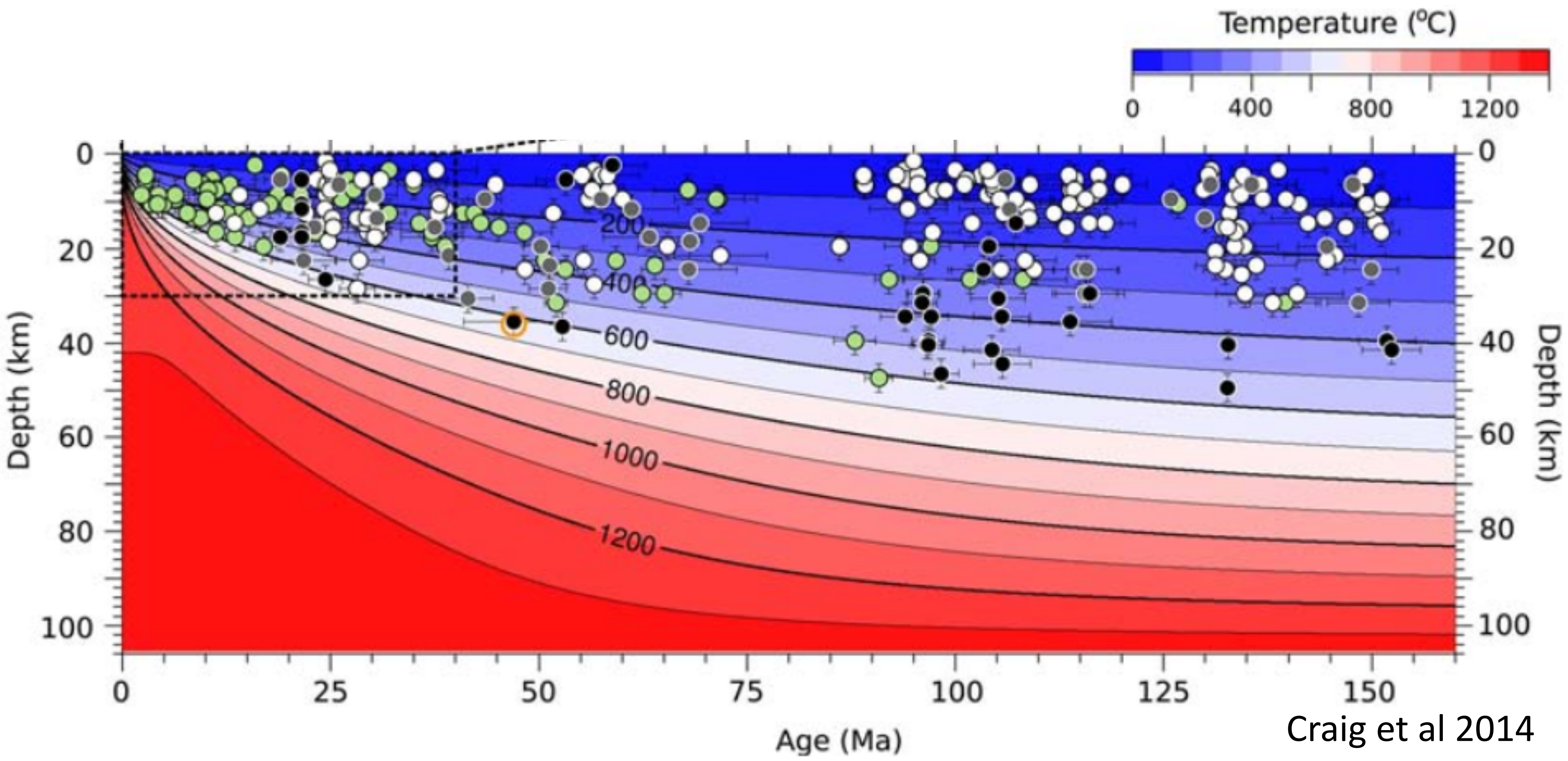
27 second delay from P-pP. So 13.5 seconds each way. Velocity of 6.5 km/s gives depth of ~90 km

(actual depth estimate slightly larger because of taking full geometry and velocity structure into account)

The Oceans… where life is simple…



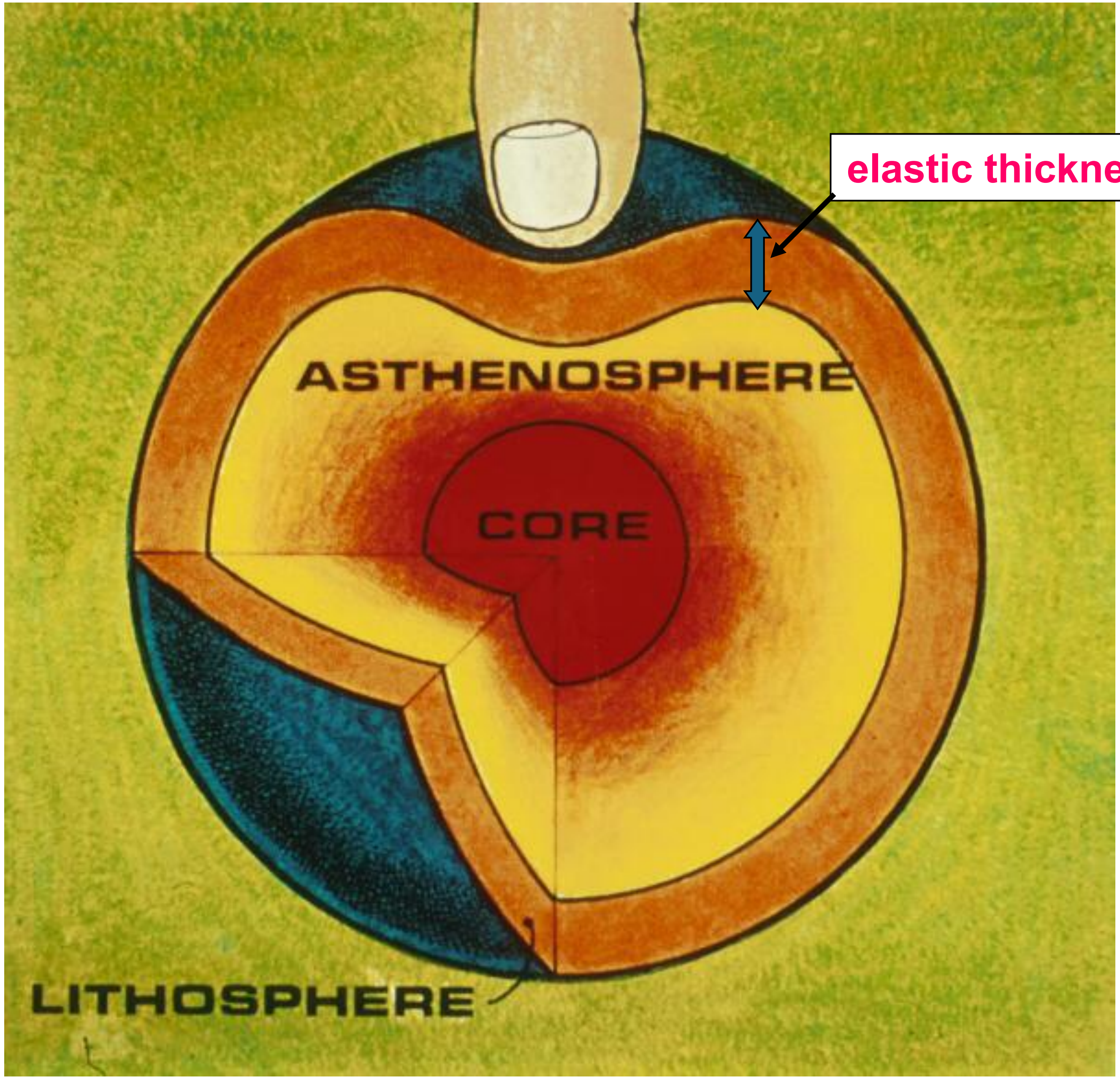
The Oceans… where life is simple…



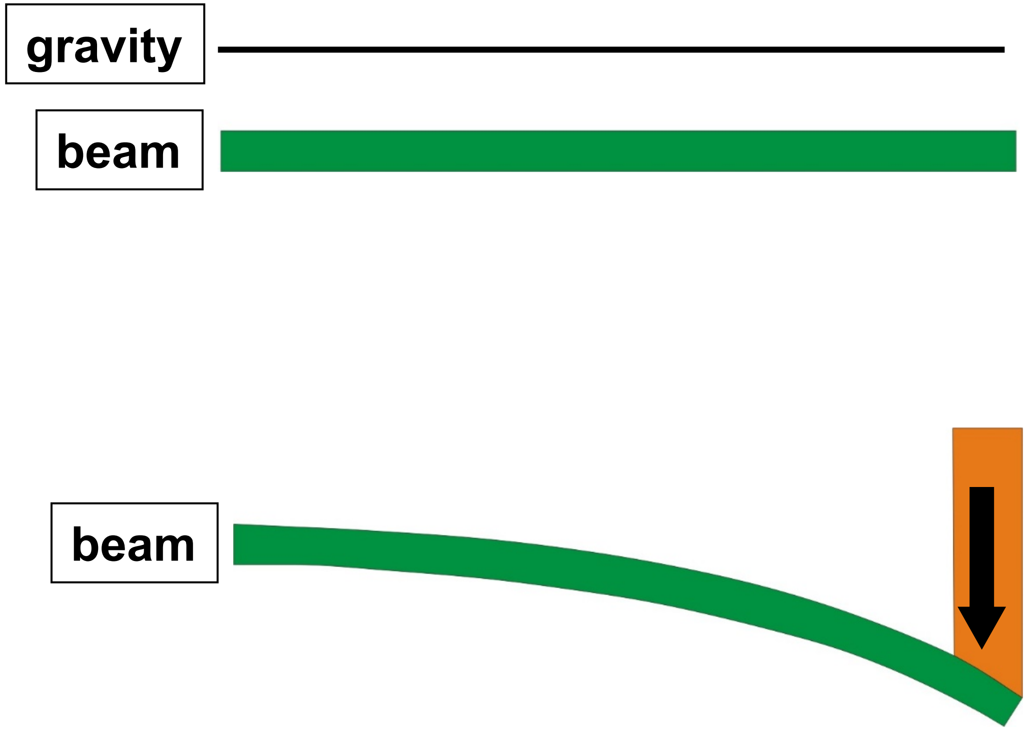
Craig et al 2014

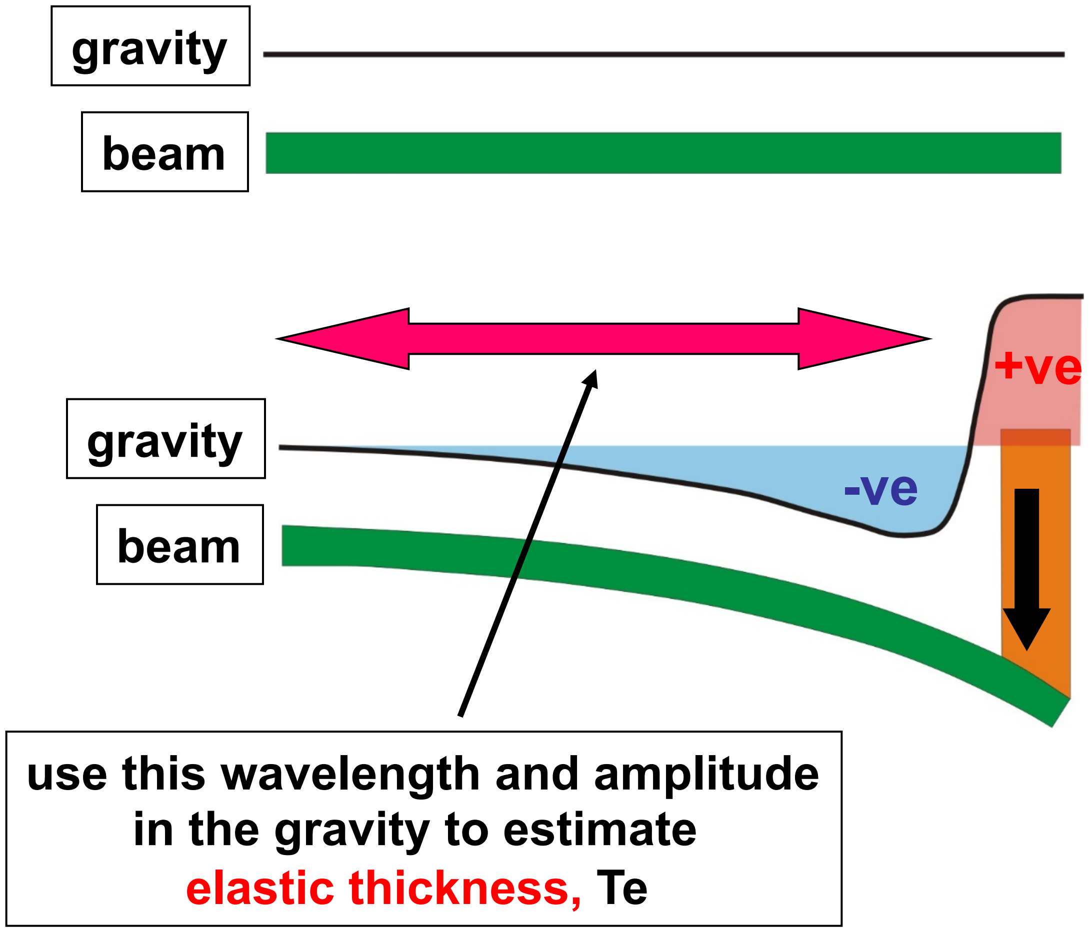
Earthquakes occur to temperatures of ~600 degrees.
Hotter material deforms by creep.

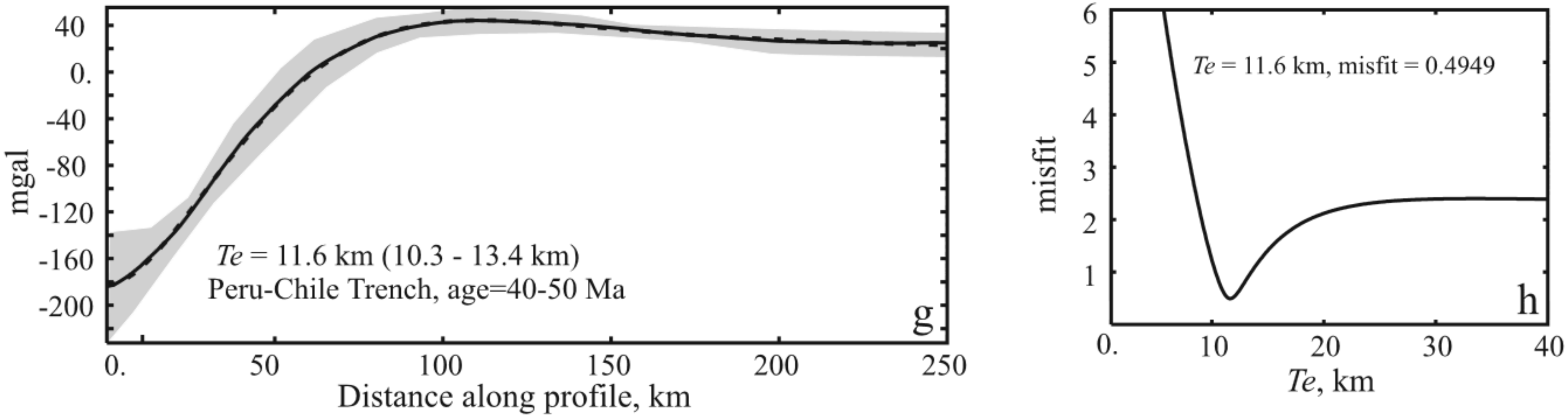
Measuring strength…



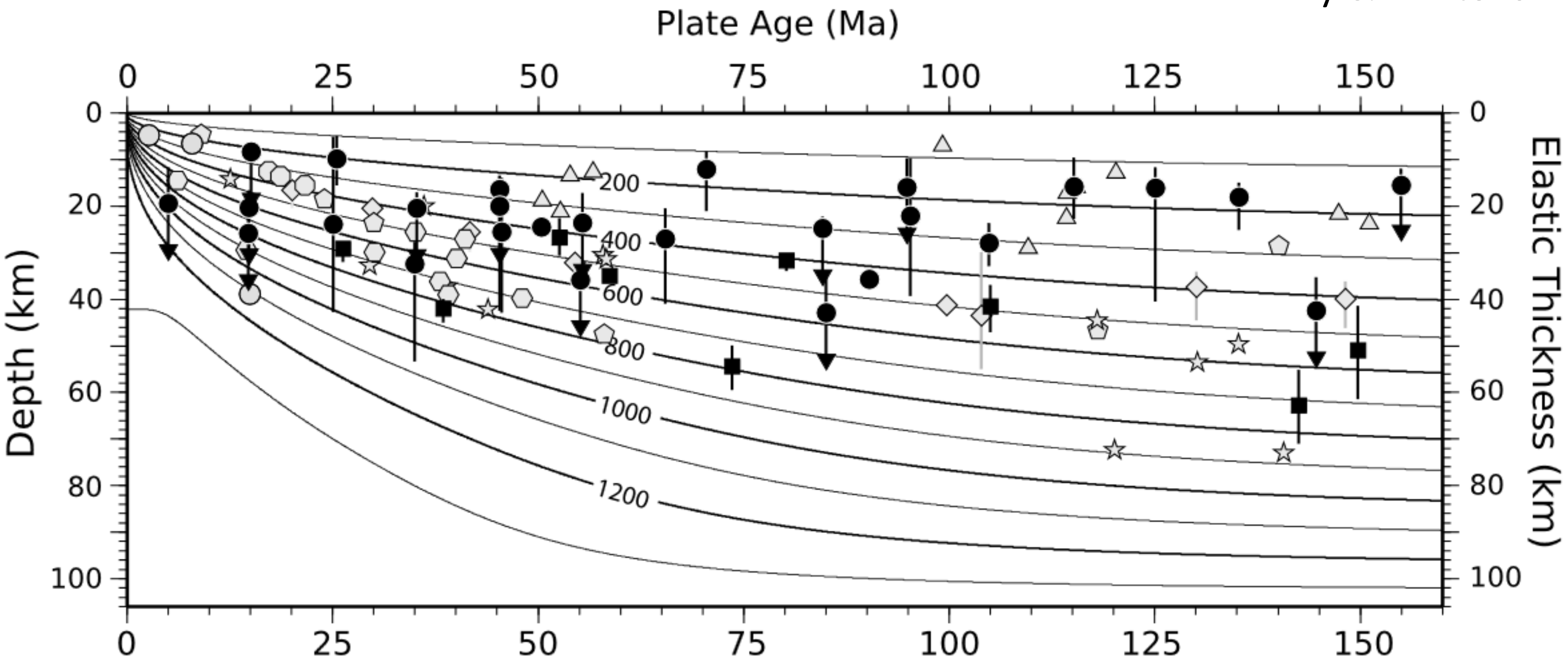
elastic thickness, Te


gravity
beam
beam


gravity
beam
+ve
gravity
-ve
beam
use this wavelength and amplitude
in the gravity to estimate
elastic thickness, Te



Bry & White '07

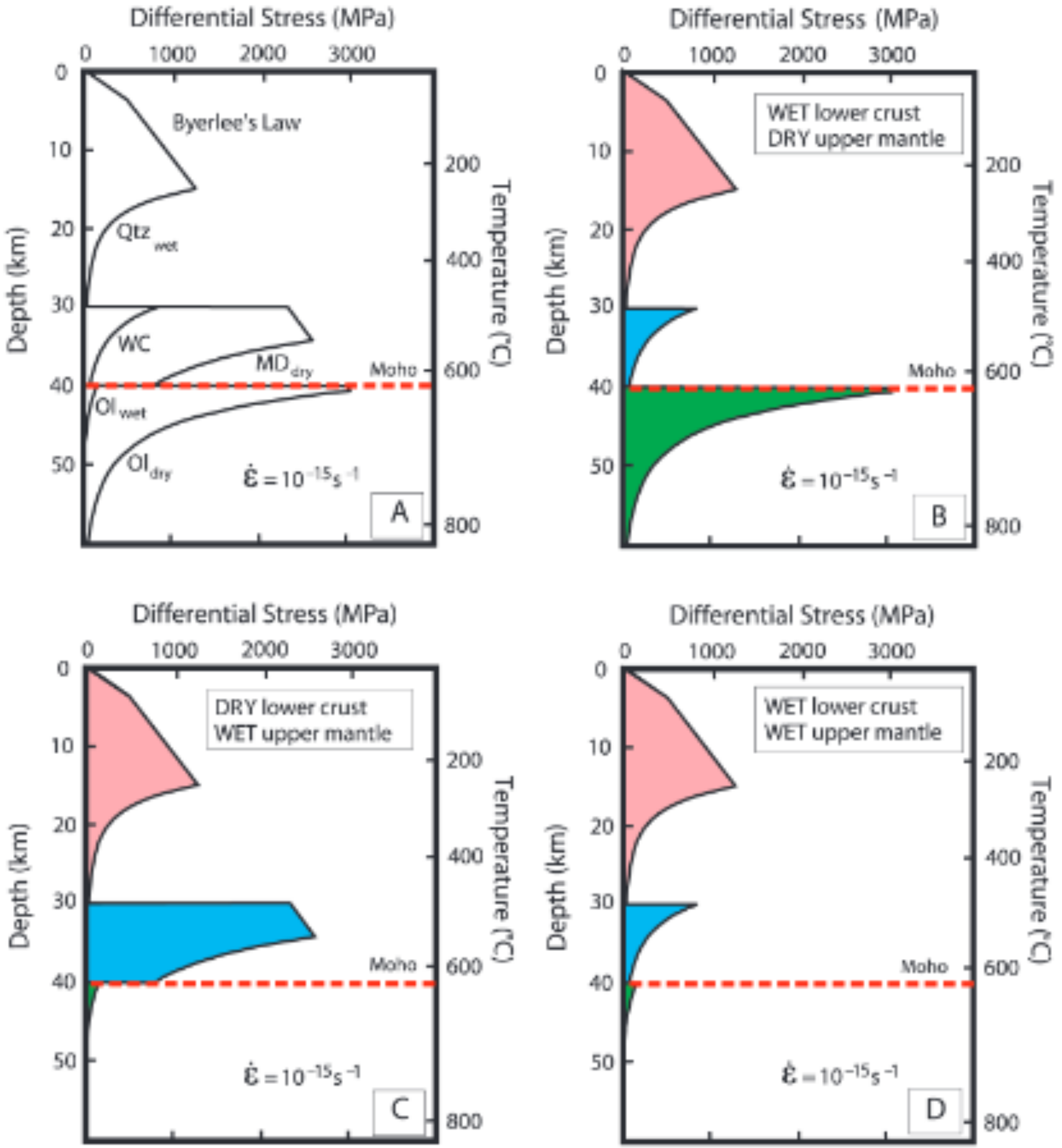


Craig & Copley '14

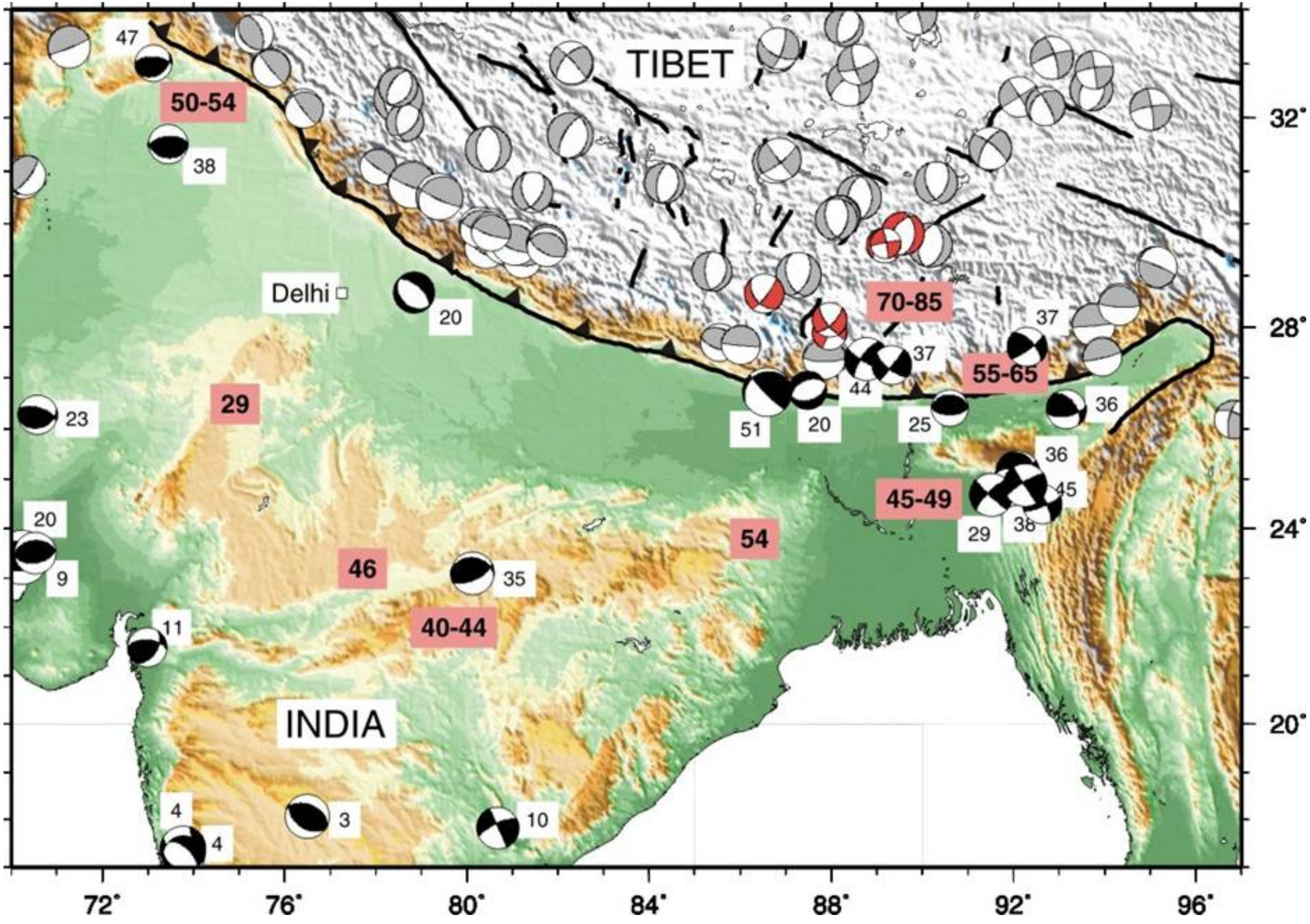
Oceanic Te ≤ Oceanic Ts

The strength is in the seismogenic layer (crust and mantle)

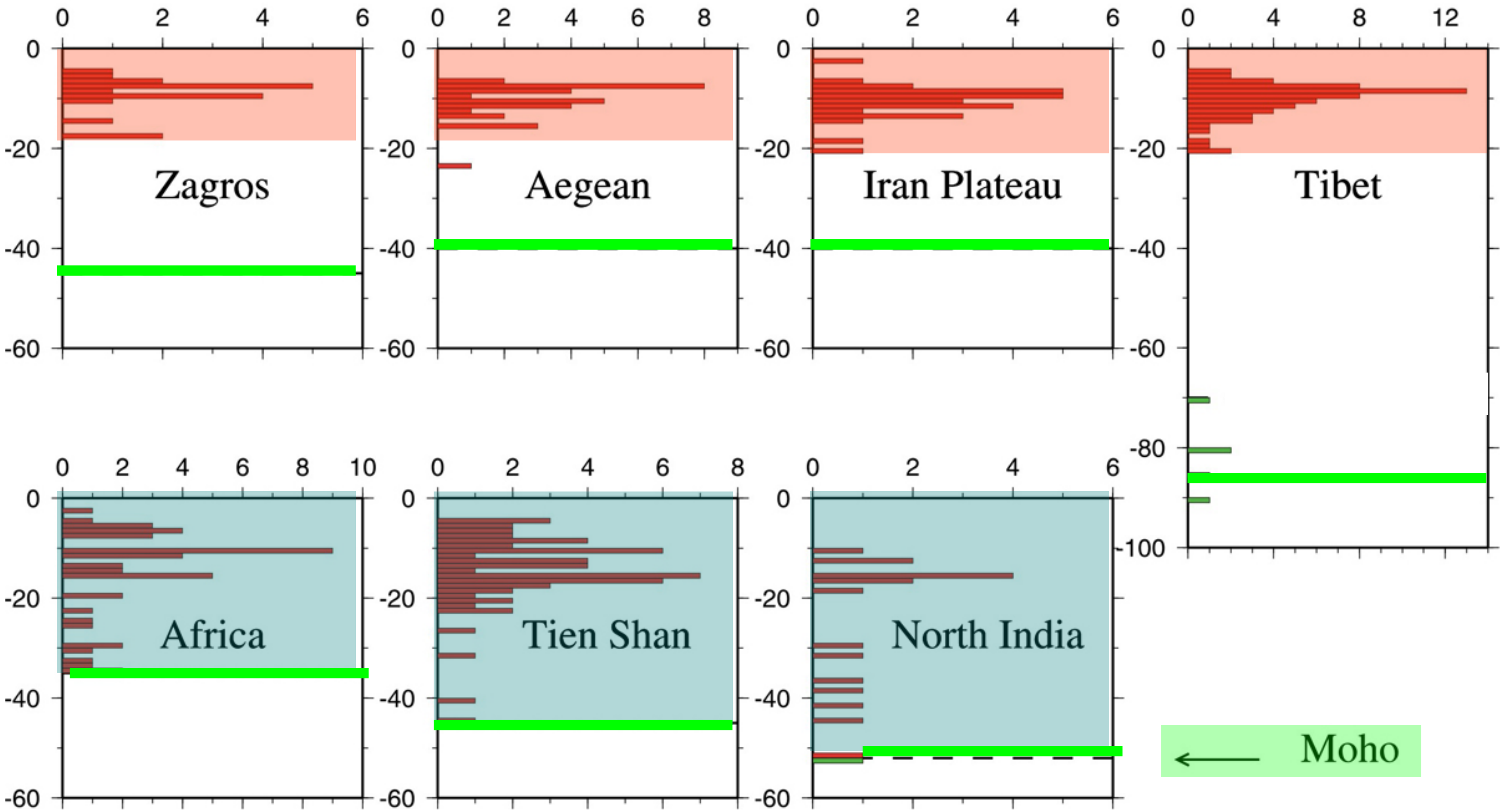
Earthquakes to 600 degrees -> implies the rocks are **anhydrous.**



To the continents….


TIBET
INDIA
Delhi
50-54
29
46
40-44
54
70-85
55-65
45-49
47
38
20
23
20
9
11
35
3
4
4
10
51
20
44
37
37
25
36
36
45
29
38
32°
28°
24°
20°
72°
76°
80°
84°
88°
92°
96°

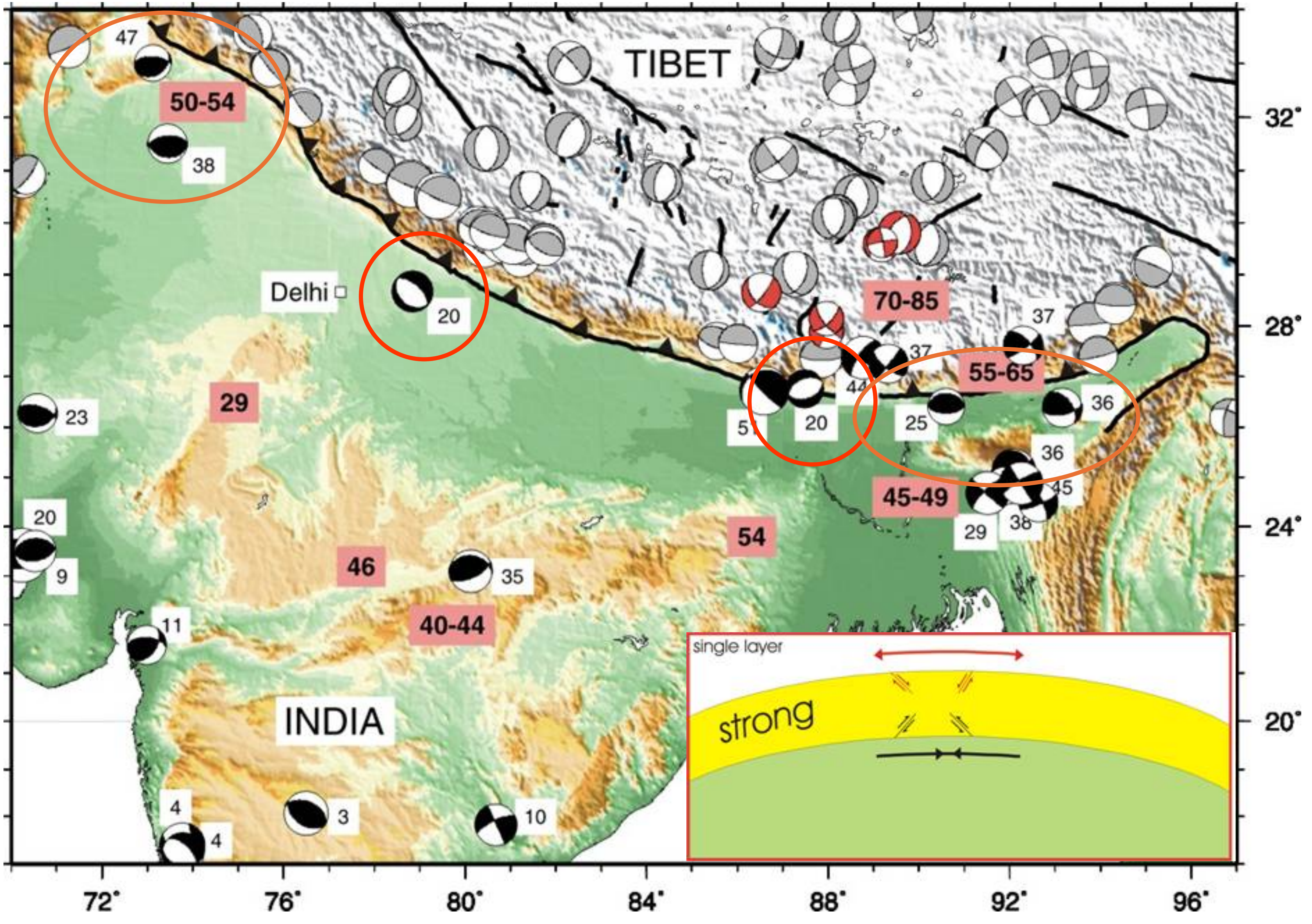
Focal Depth Distributions

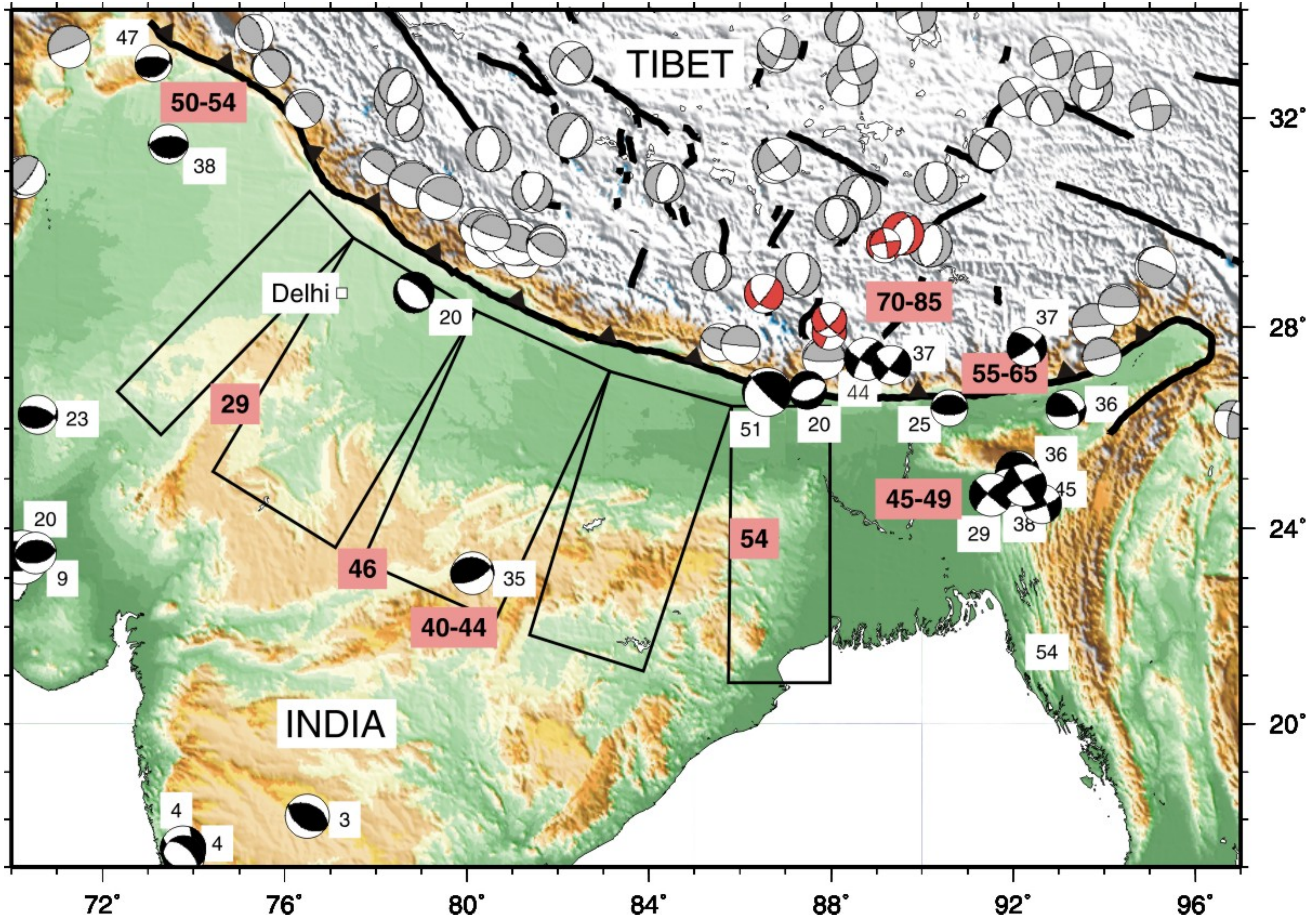


Earthquakes are in the CRUST
Contrast between YOUNG and OLD lithosphere

Maggi et al 2000

So what about the strength?


TIBET
50-54
47
38
Delhi
20
29
23
20
9
46
35
40-44
11
INDIA
4
4
3
10
70-85
37
37
55-65
44
51
20
25
36
36
45-49
45
29
38
54
single layer
strong
32°
28°
24°
20°
72°
76°
80°
84°
88°
92°
96°



TIBET
INDIA
Delhi
50-54
29
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70-85
55-65
45-49
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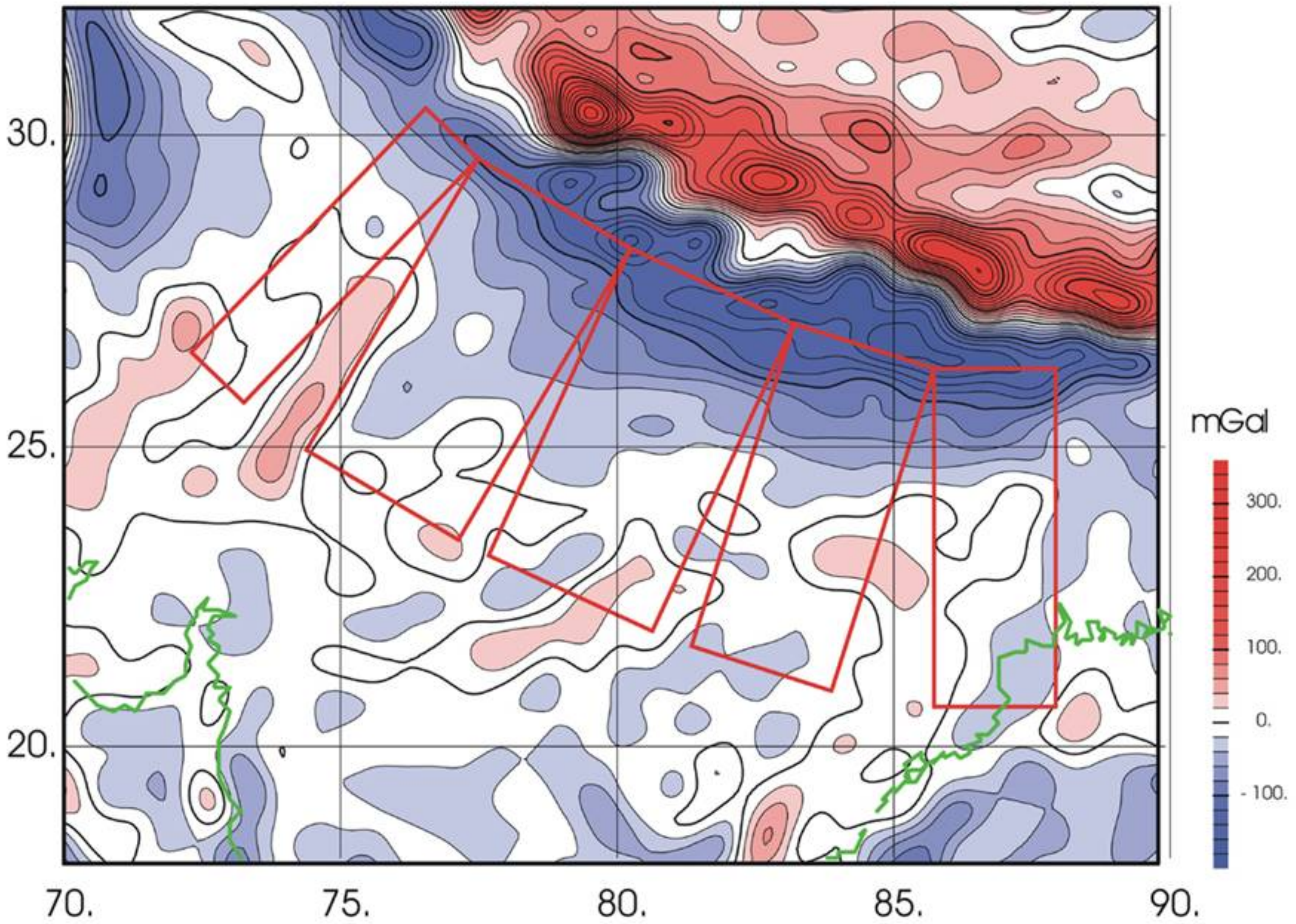
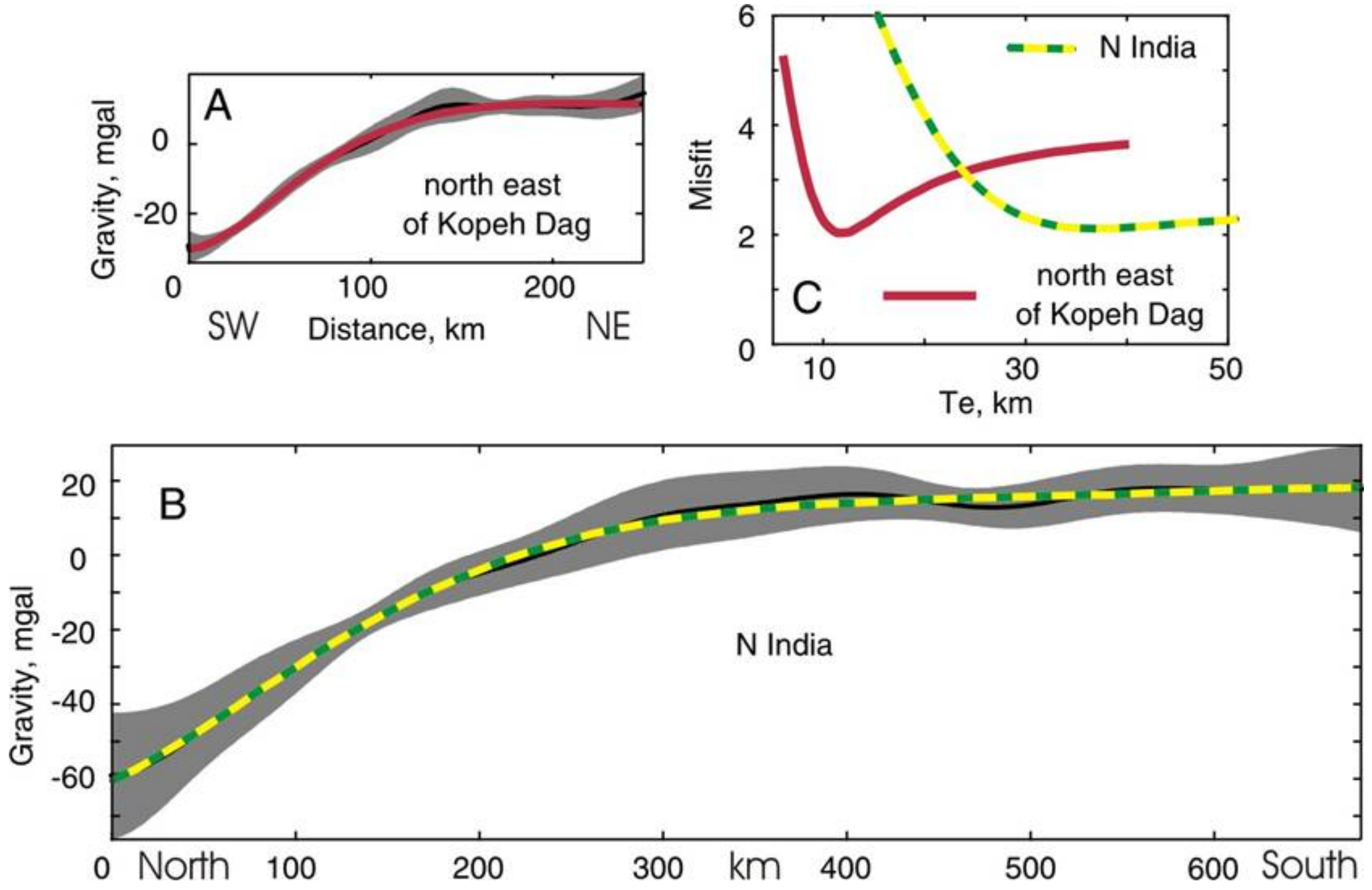
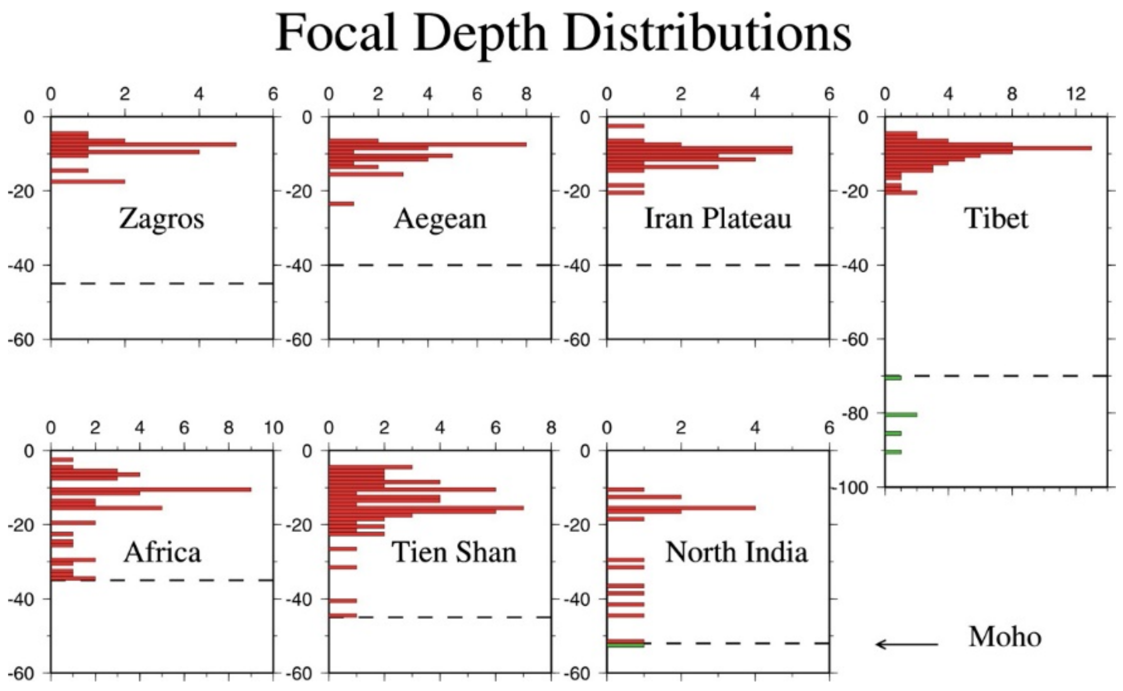
23
9
35
3
4
4
51
44
37
25
36
36
45
38
29
54
32°
28°
24°
20°
72°
76°
80°
84°
88°
92°
96°

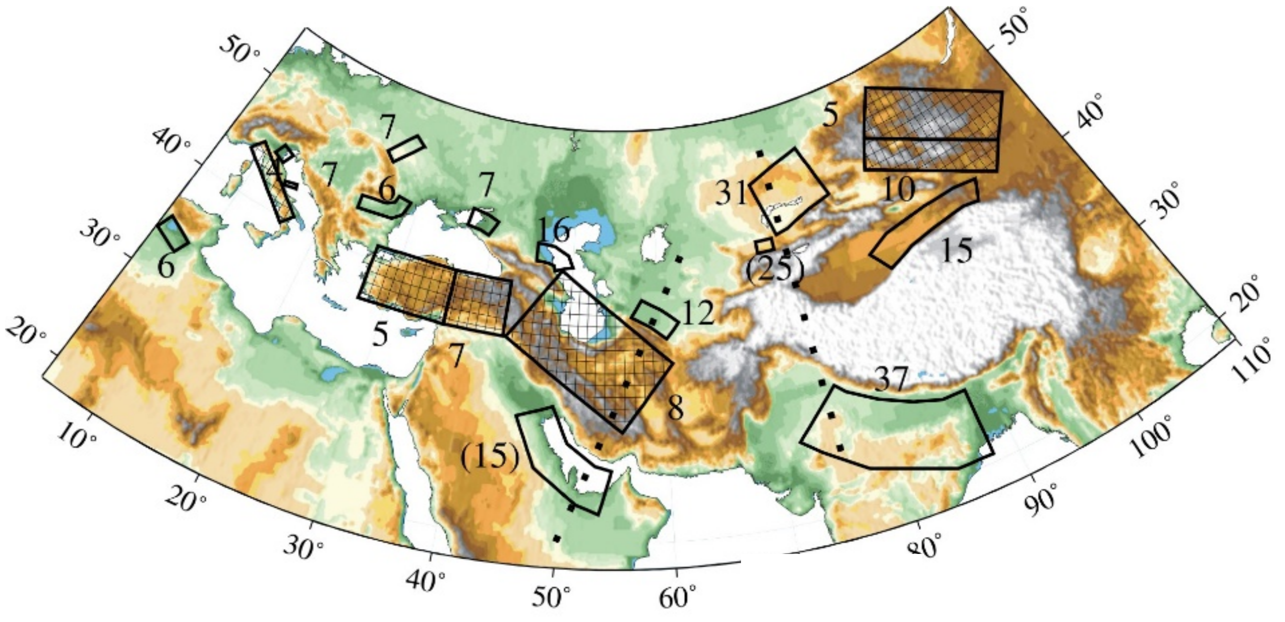
Northern India (from EGM96)




A
Gravity, mgal
0
-20
0
100
200
SW
Distance, km
NE
north east
of Kopeh Dag
6
4
2
0
Misfit
10
30
50
Te, km
N India
C
north east
of Kopeh Dag
B
20
0
-20
-40
-60
Gravity, mgal
N India
0
North
100
200
300
km
400
500
600
South

Te < Ts





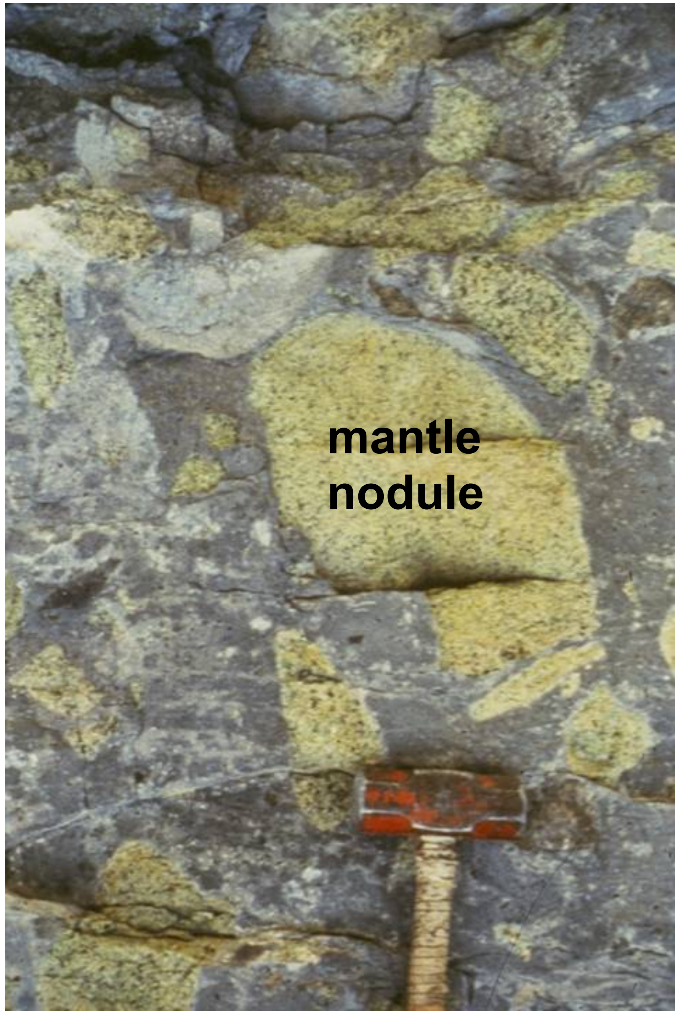
Maggi, Figure 2

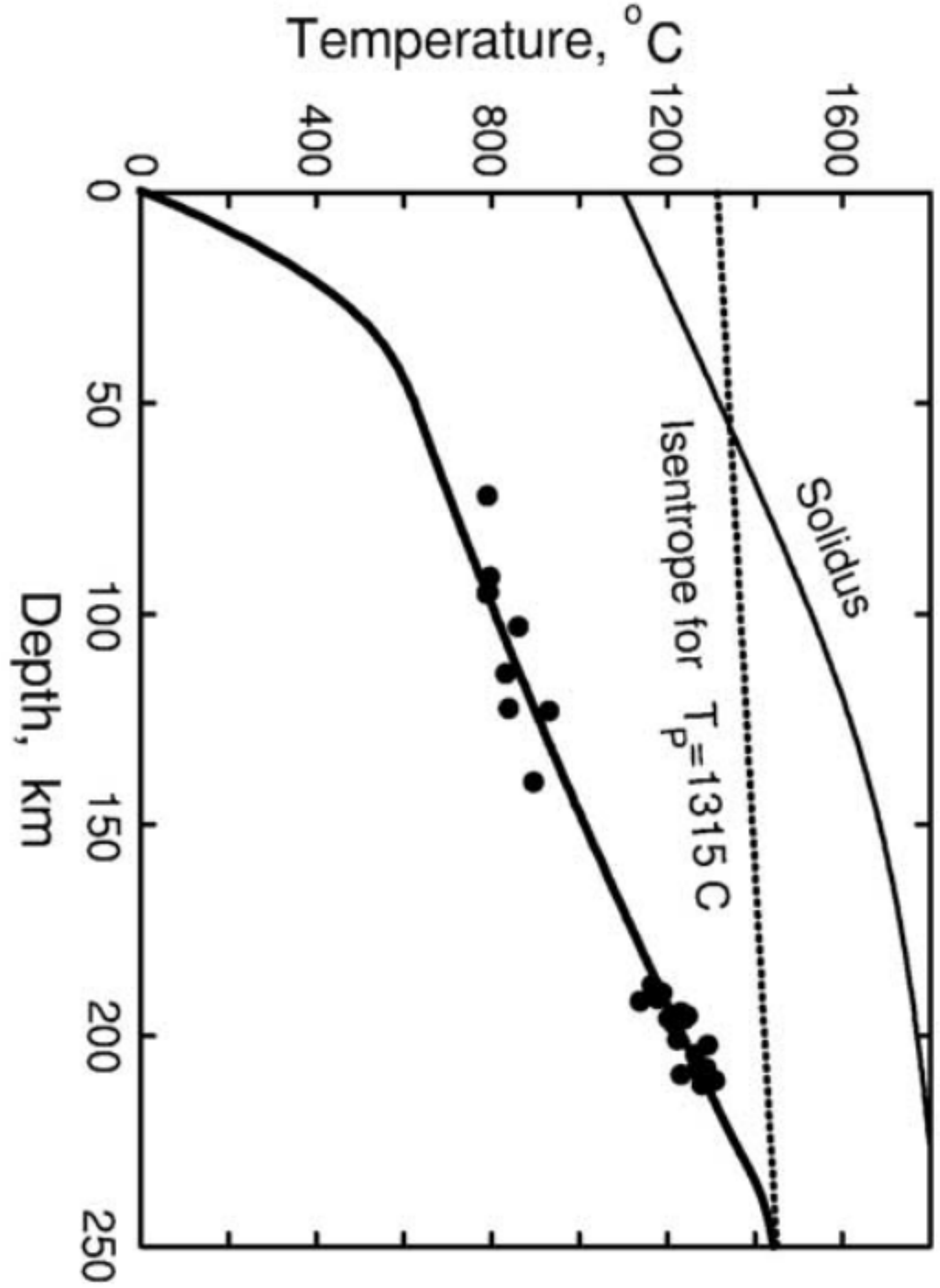
The strength is in the seismogenic layer

like the oceans

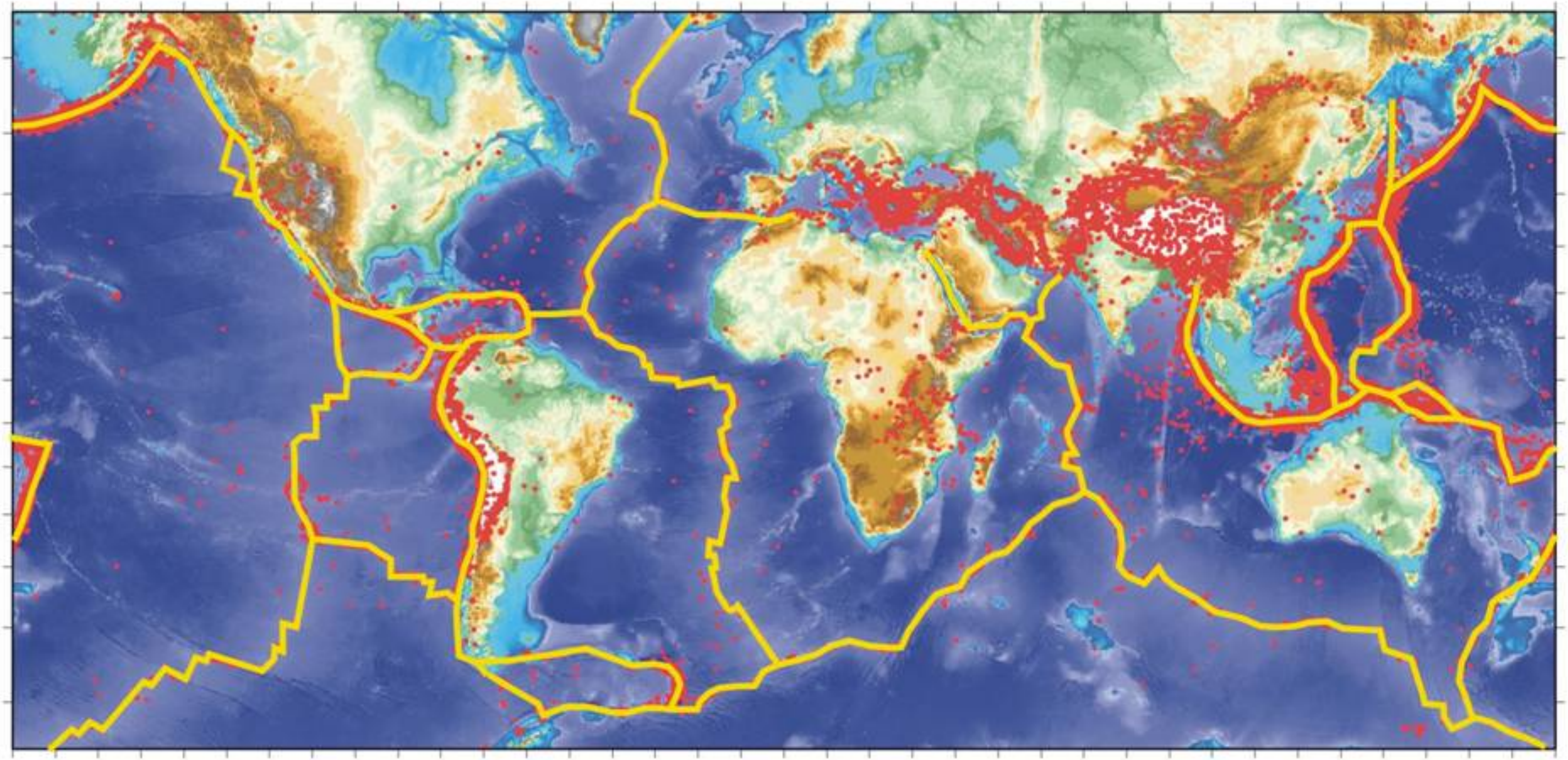
but unlike the oceans, only in the crust, not in the mantle

Flat, boring, cold Siberia:
Moho temperature 630 degrees.
Most places are hotter…

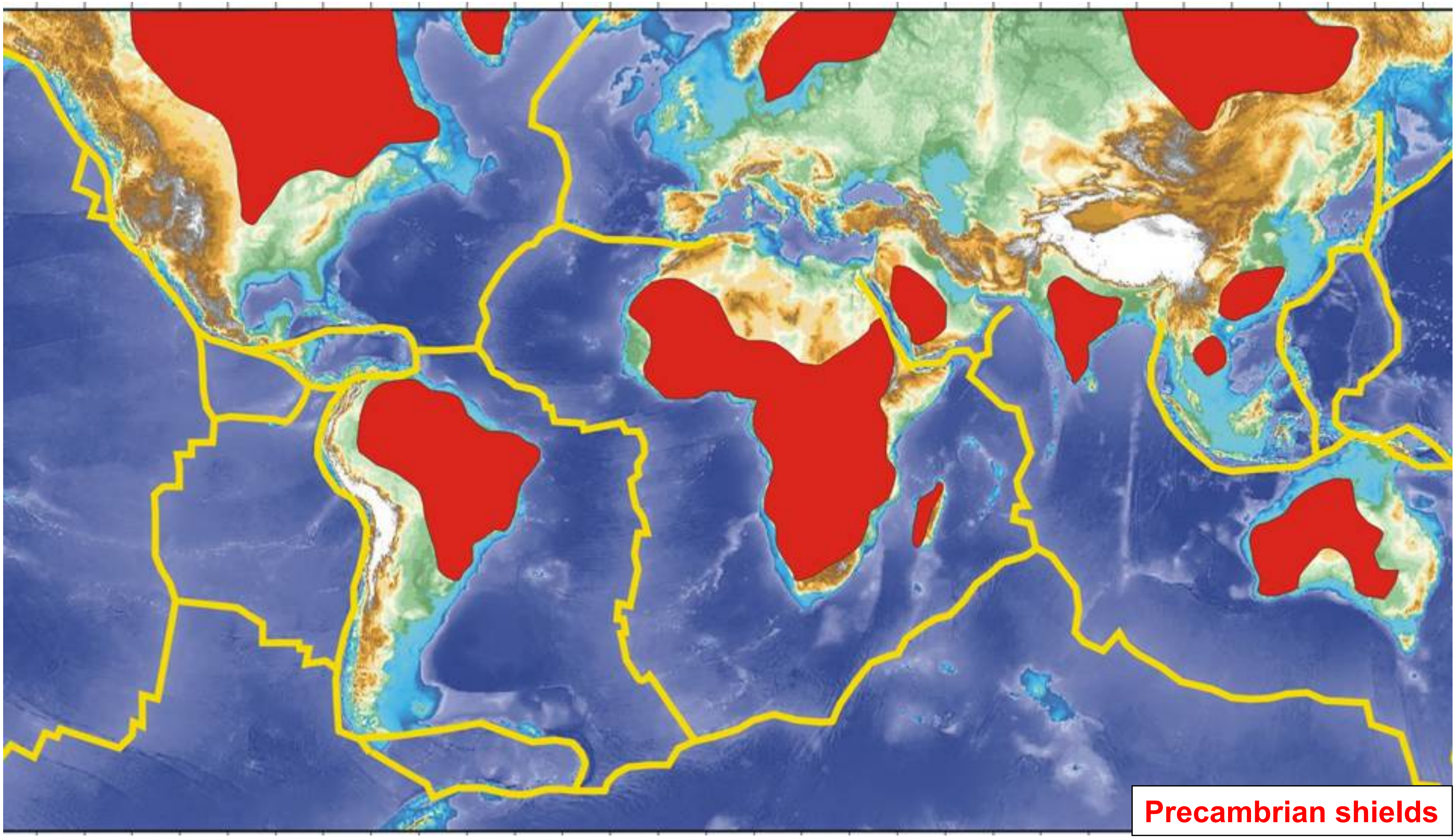




So why is the seismogenic thickness so laterally variable?



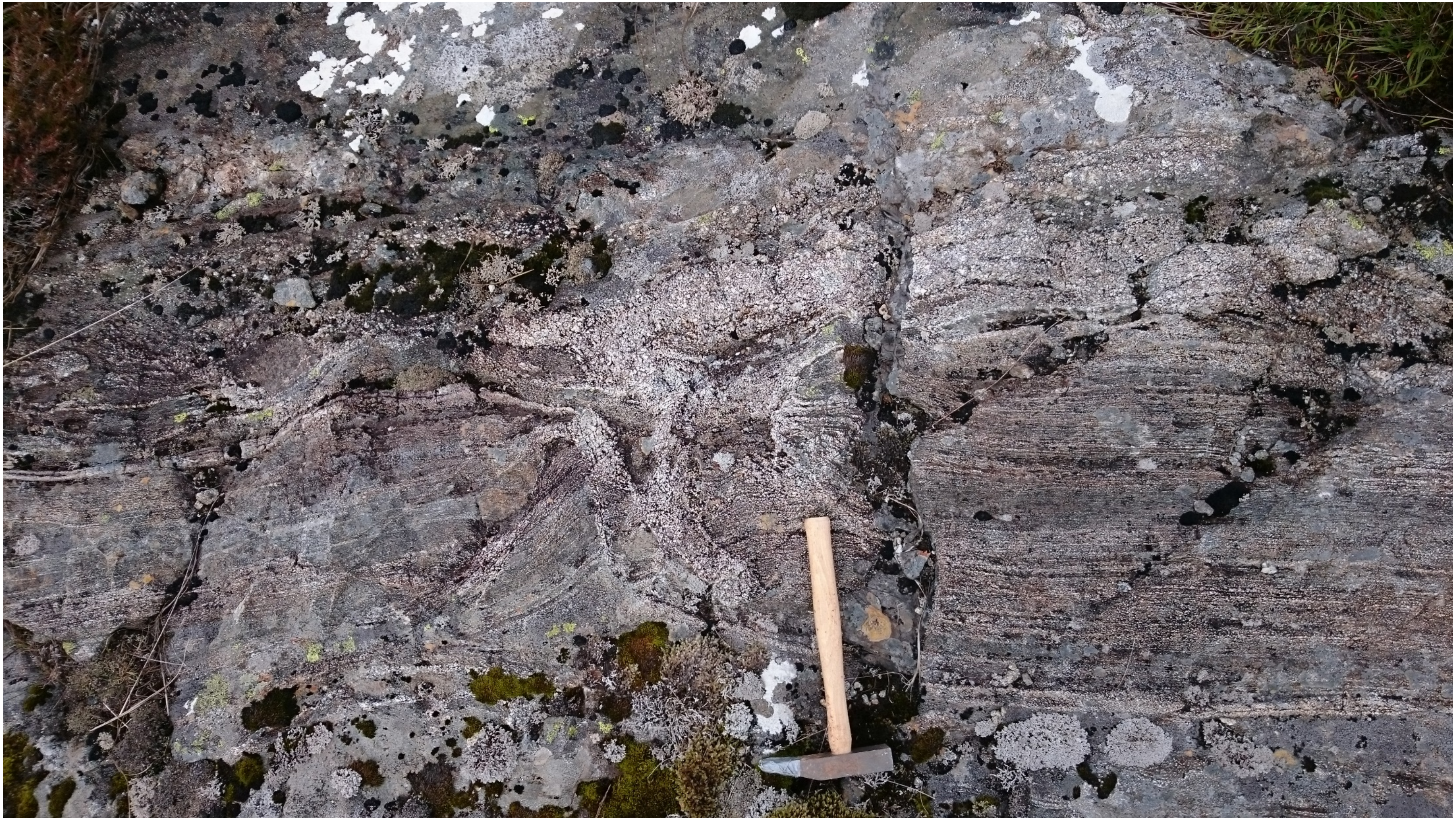
The continents. Lateral variability.


Precambrian shields

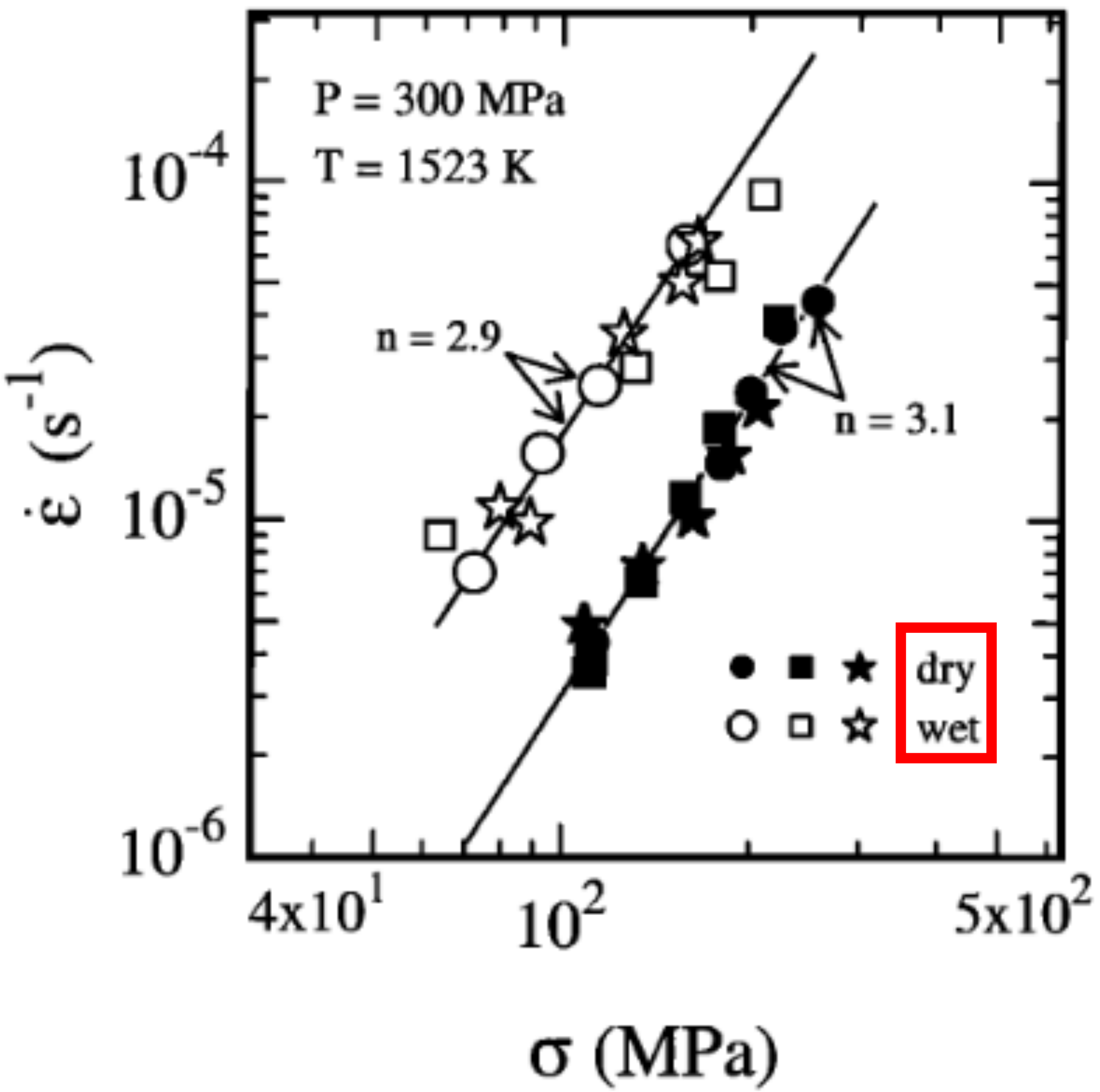

High-grade gneiss at the surface, ~40 km thick crust
800-900°C; 1.0 GPa; 945 Ma

Lewisian, Outer Hebrides. Very deformed, but nothing since the Precambrian.

Melt removal, loss of water and volatiles…

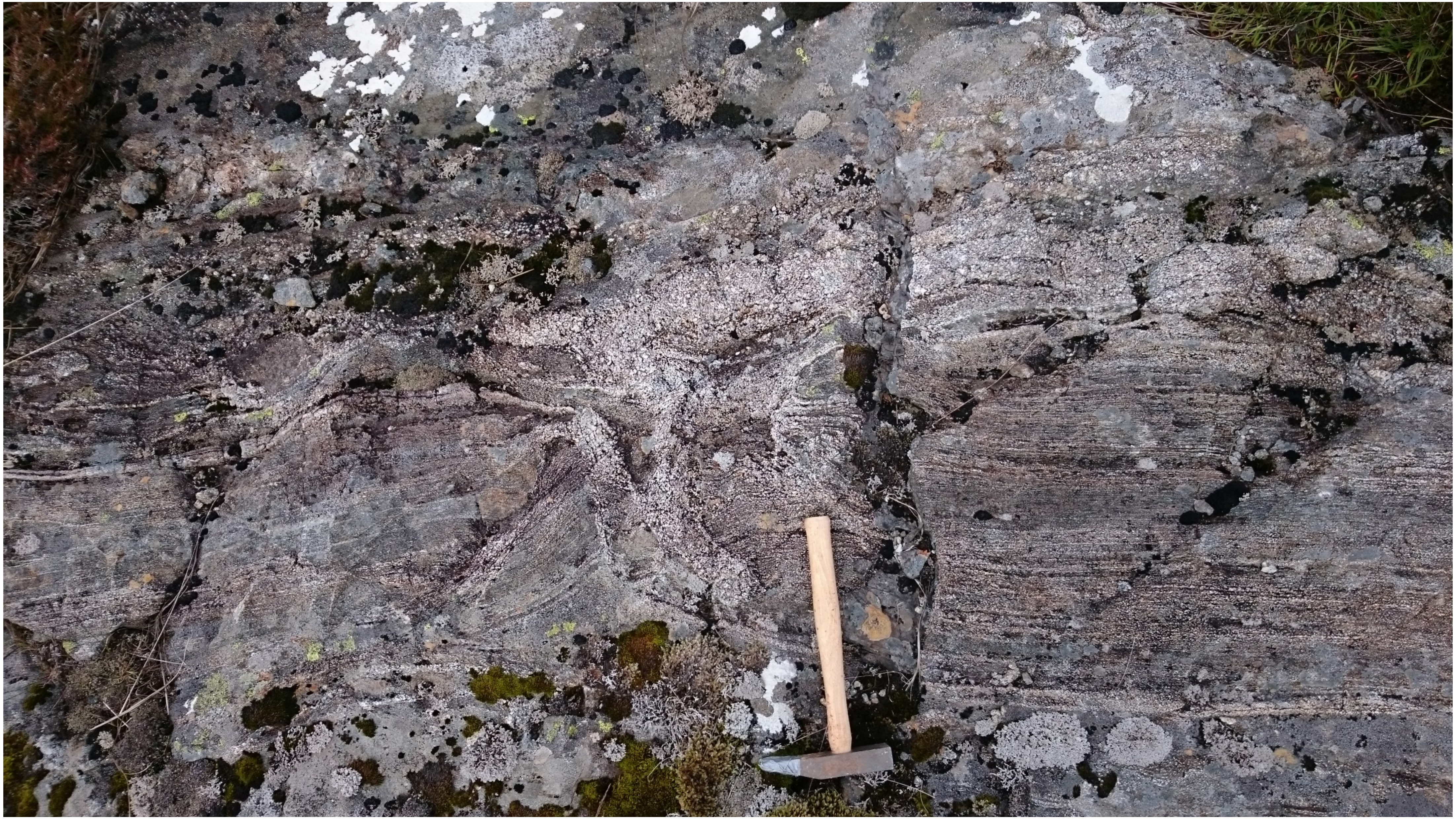


(Lewisian, Rum)



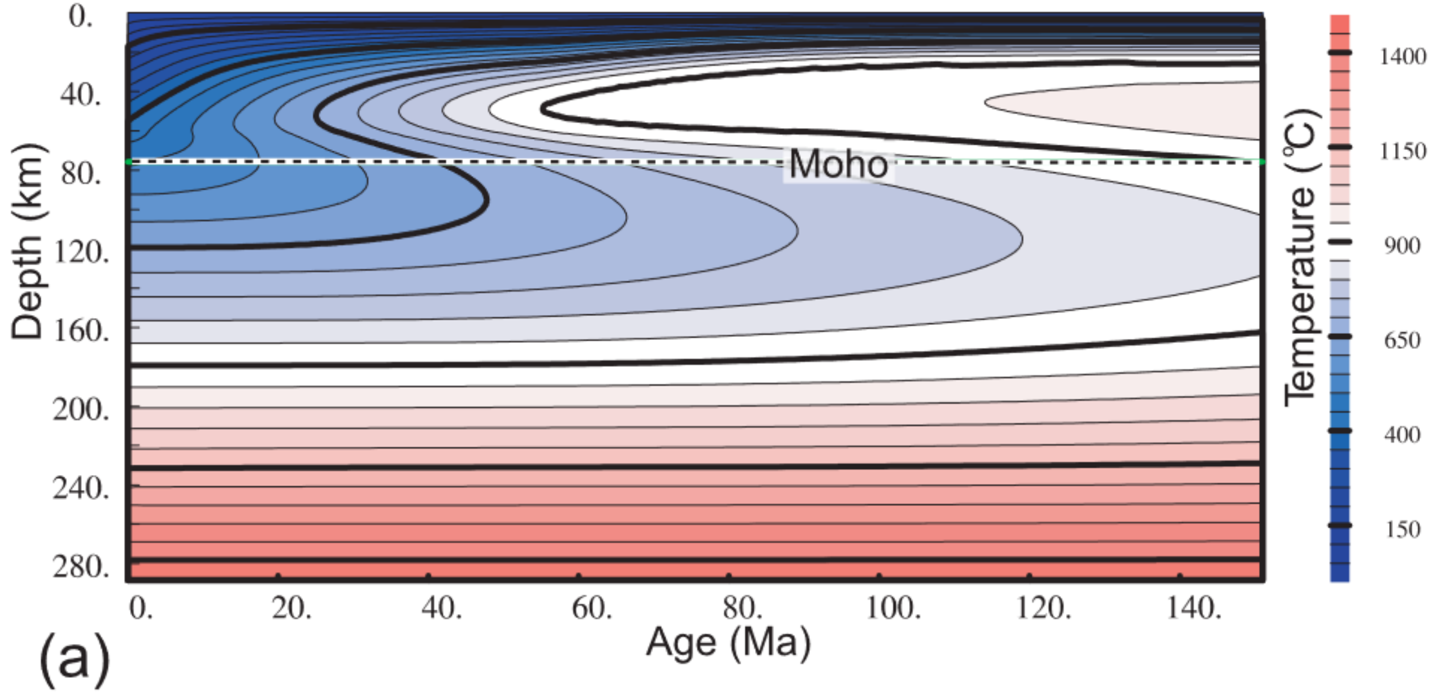
P = 300 MPa
T = 1523 K
n = 2.9
n = 3.1
dry
wet
10^{-4}
10^{-5}
10^{-6}
$\dot{\varepsilon}$ (s^{-1})
$4x10^1$
10^2
$5x10^2$
σ (MPa)

Melt removal, loss of water and volatiles…



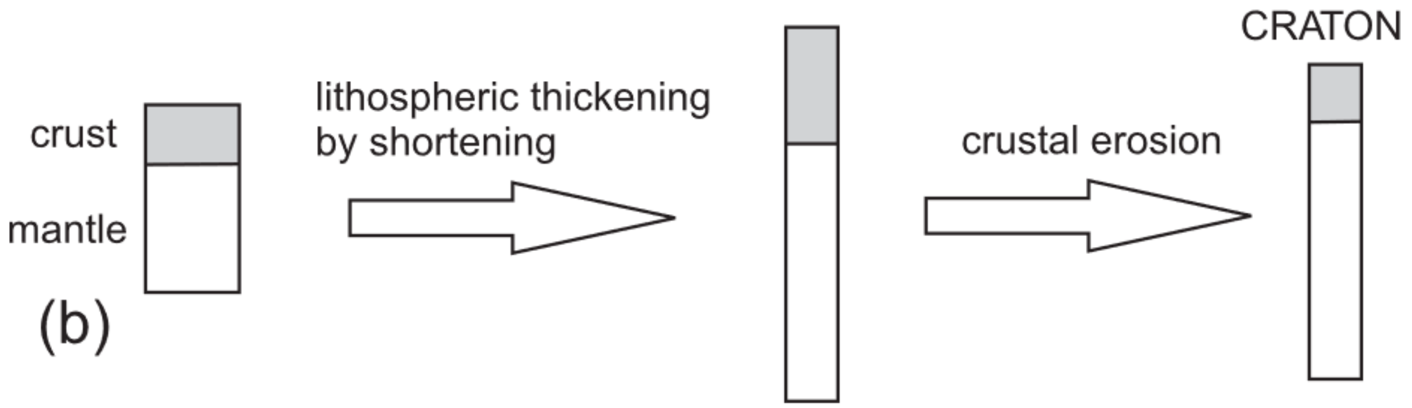
(Lewisian, Rum)

Metamorphic reactions without water (catalyst) are difficult -> metastability



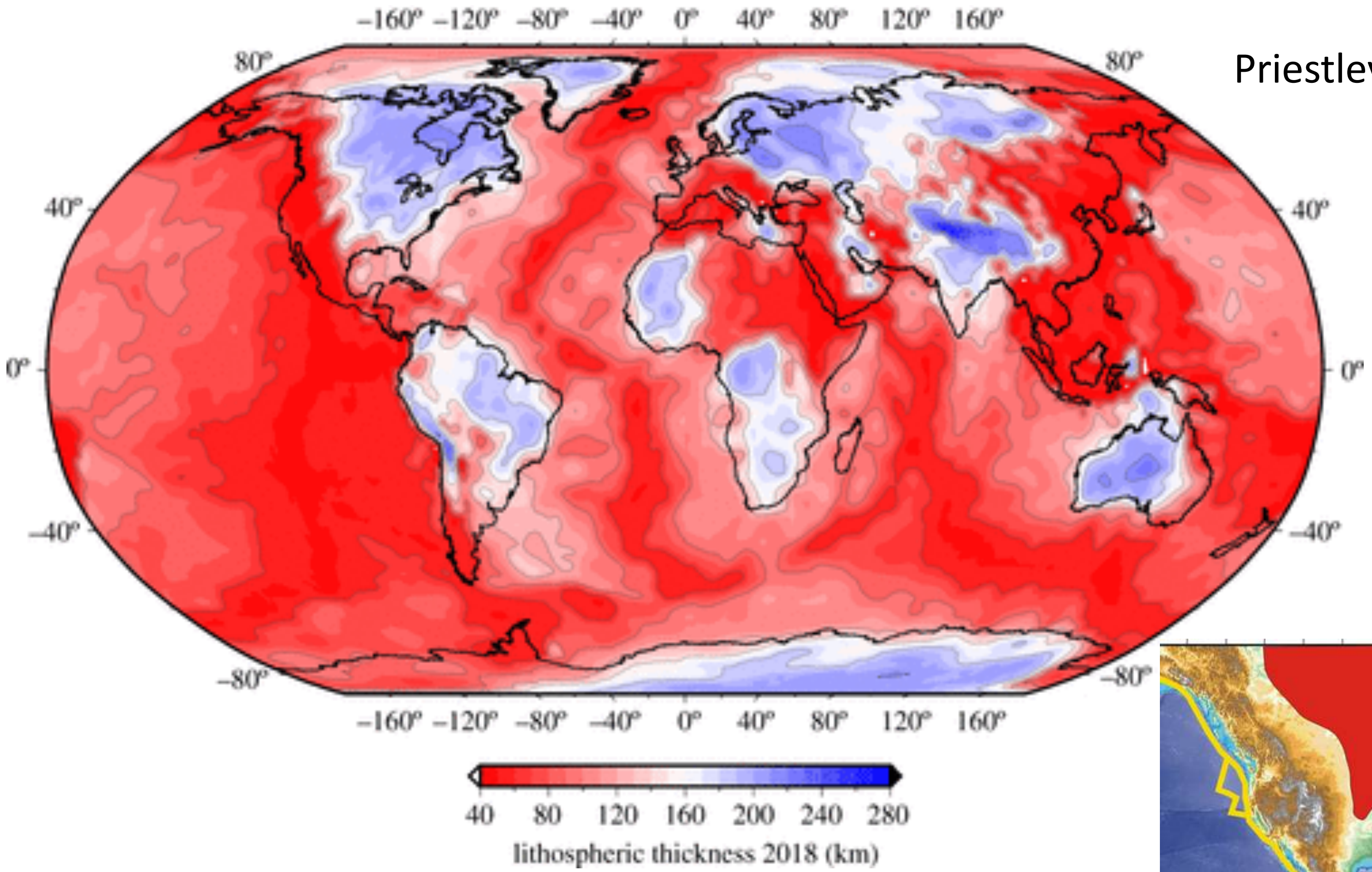
Continental crust – How to make it **strong**?

Jackson et al, Journal of the Geological Society, 2008

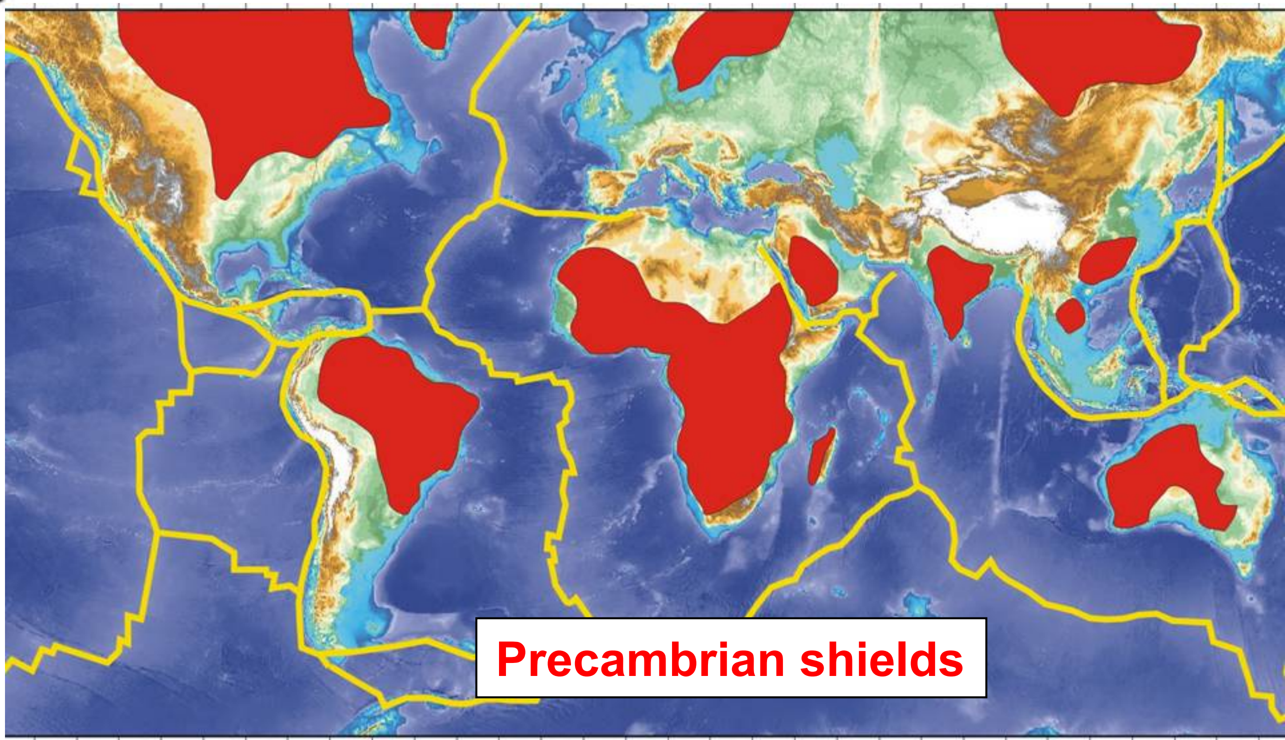


Thicken by mountain-building -> gets hot -> partial melting -> removal of volatiles (inc water) -> erode -> cool

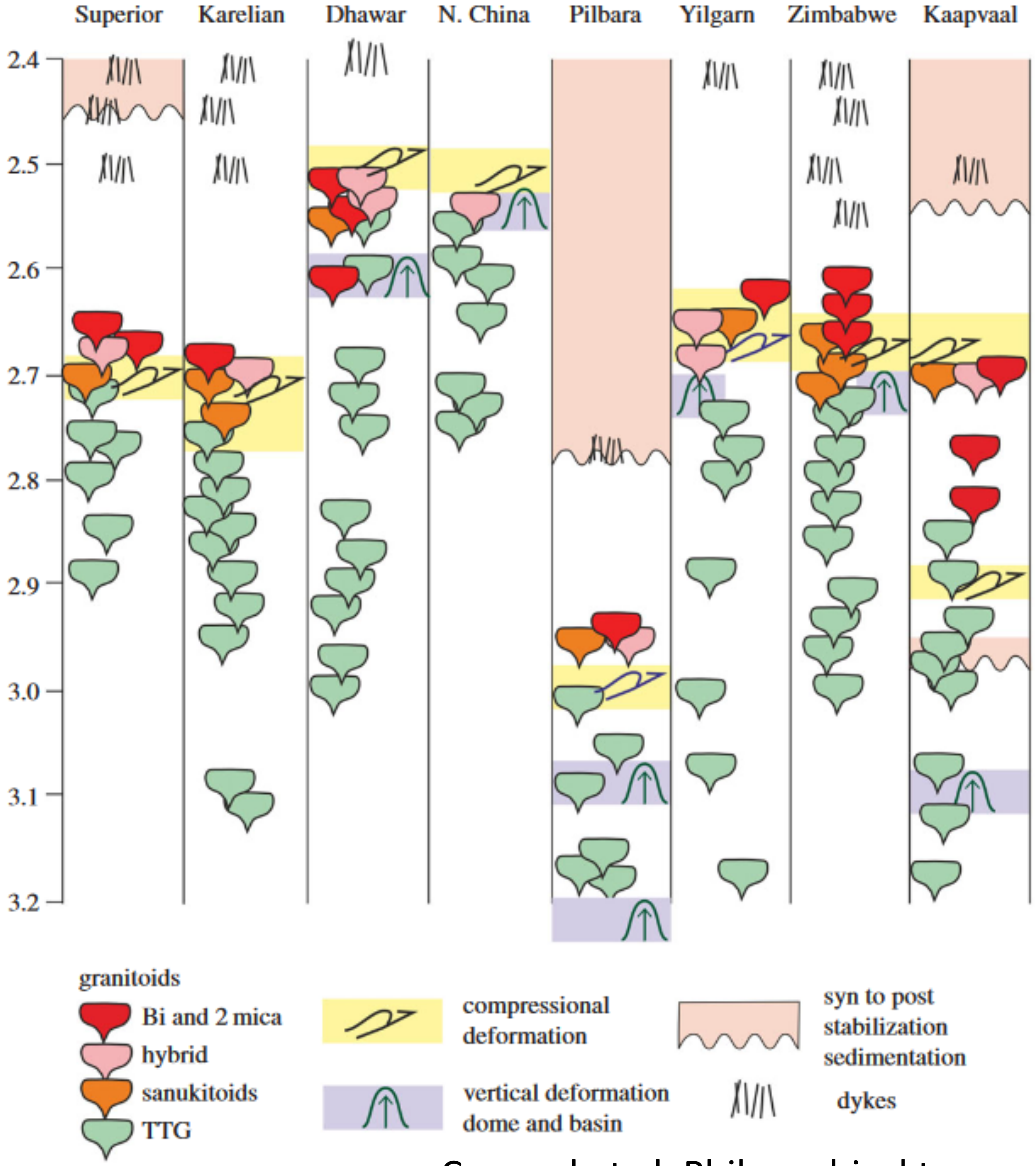
Result is thick lithosphere (so cold crust), with anhydrous crust, and is extremely strong.



Priestley et al 2019



The cratonic magmatic record



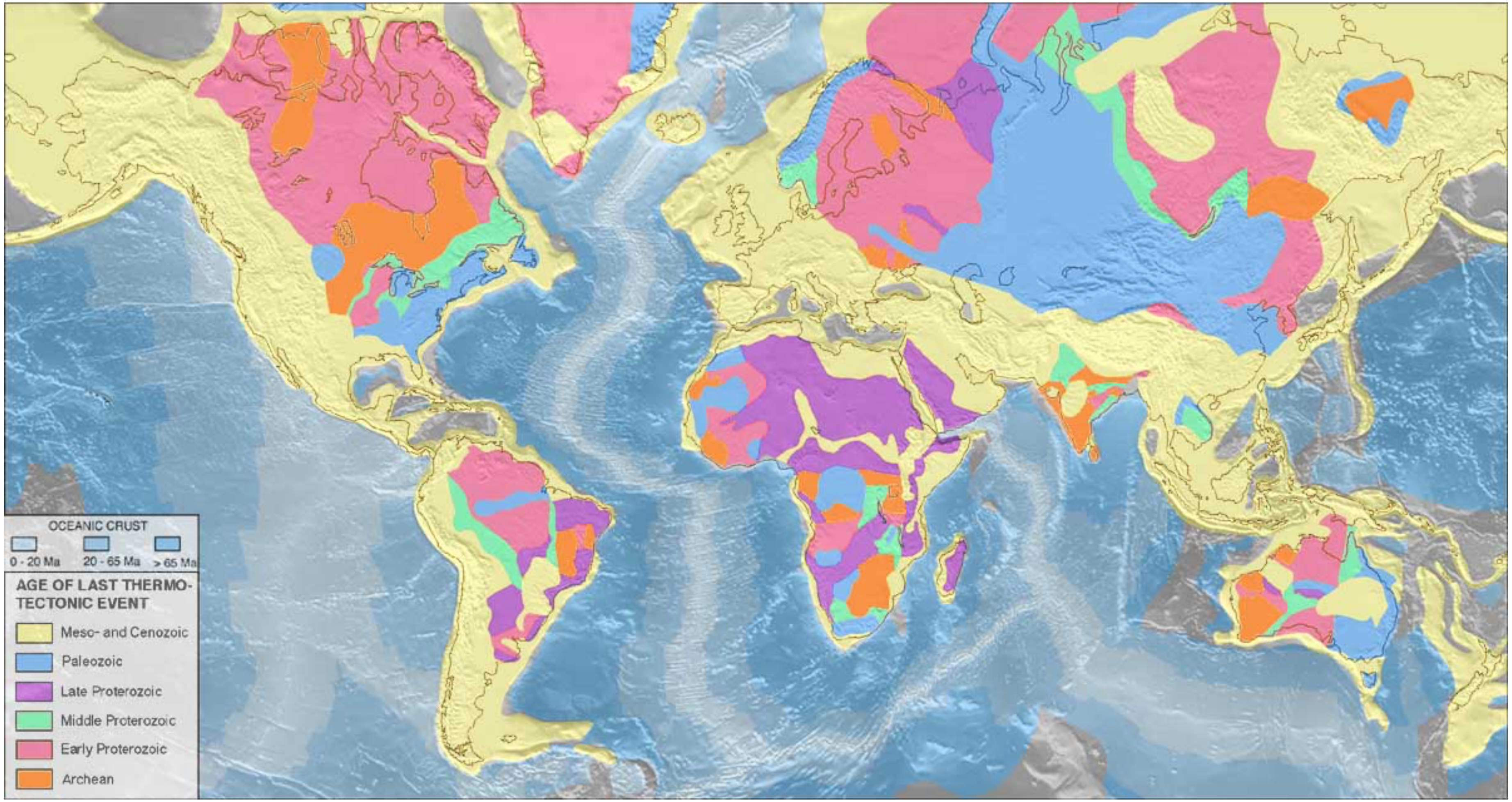
Green – forming the crust via plutonism

Red/yellow – re-melt the crust in mountain ranges, dehydrate, and make rigid.

Cawood et al, Philosophical transactions of the Royal Society A, 2018

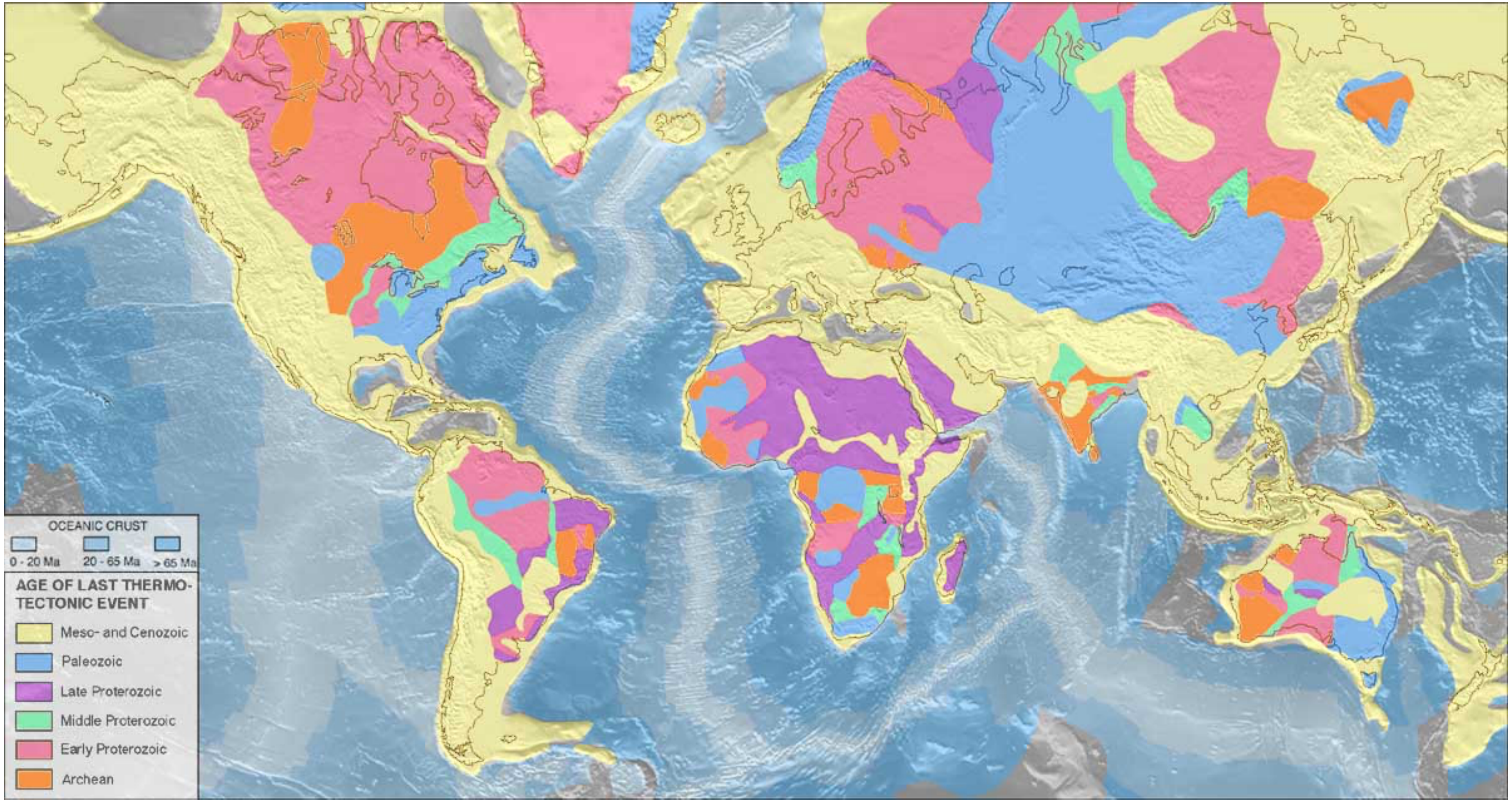
The continental ‘cores’/’cratons’/’shields’ -> the hard bits that are now flat and boring.

Mostly Precambrian.



The intervening wide deformation/mountain belts – mostly accreted arcs and sediments.

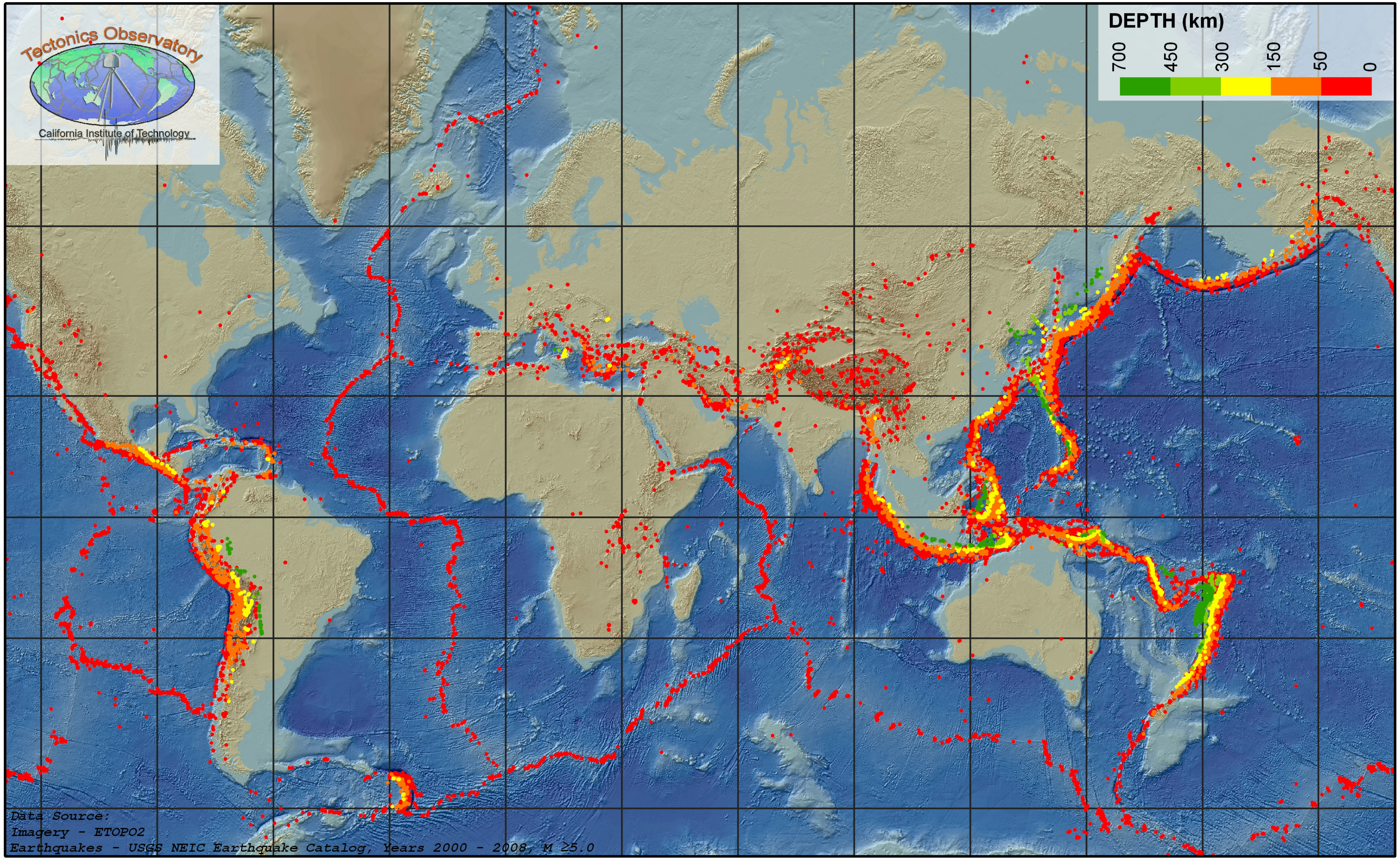
Understanding tectonics – think in terms of 3 kinds lithosphere



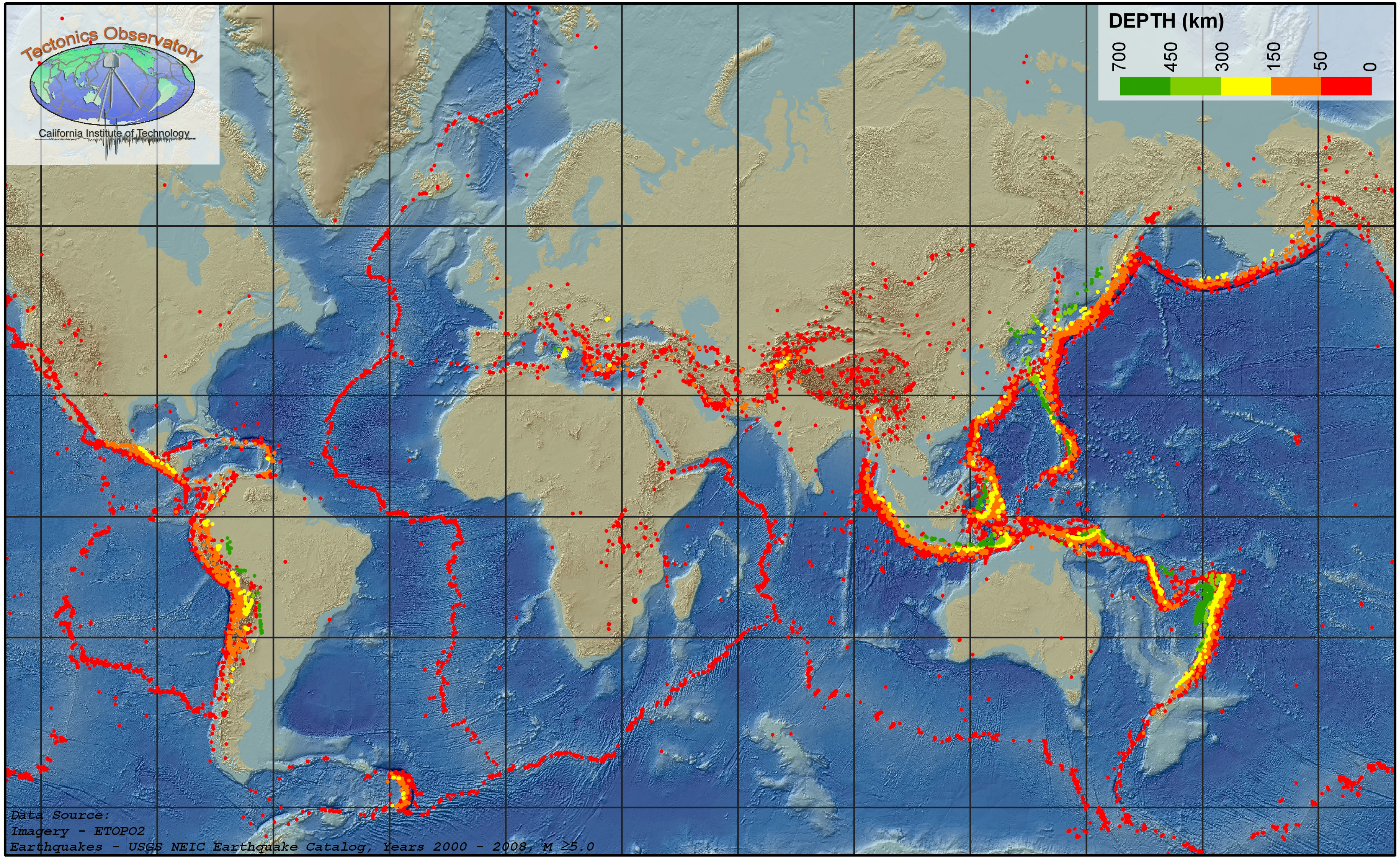
1. **Oceanic**
2. **Rigid Continental**
3. **Weak Continental**

Whether a piece of continent is in (2) or (3) depends on temperature and water content, and so geological history.

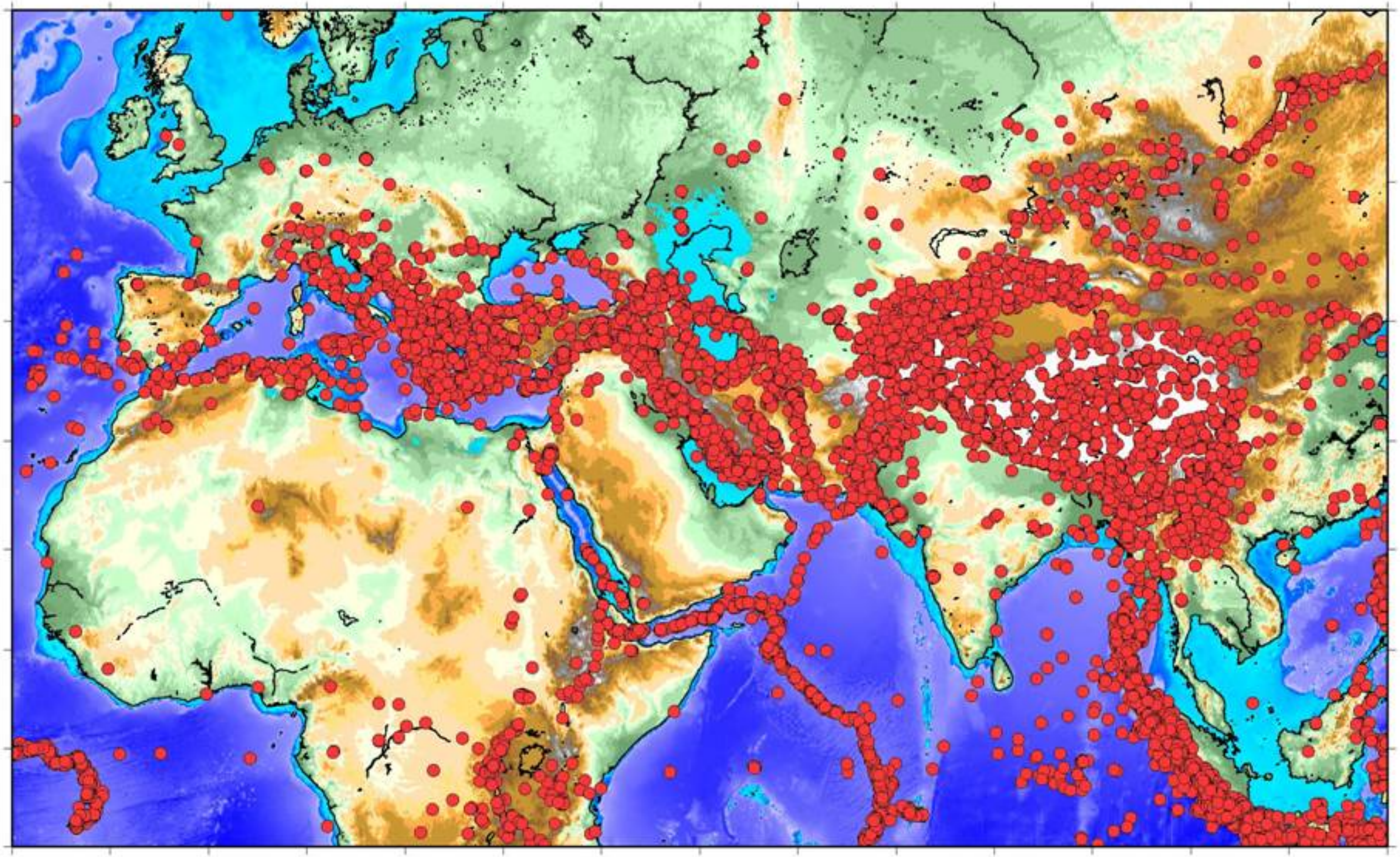
Deformation – oceanic lithosphere is mostly rigid, with deformation focussed on a few weak structures (e.g. mid-ocean ridges, transform faults) .



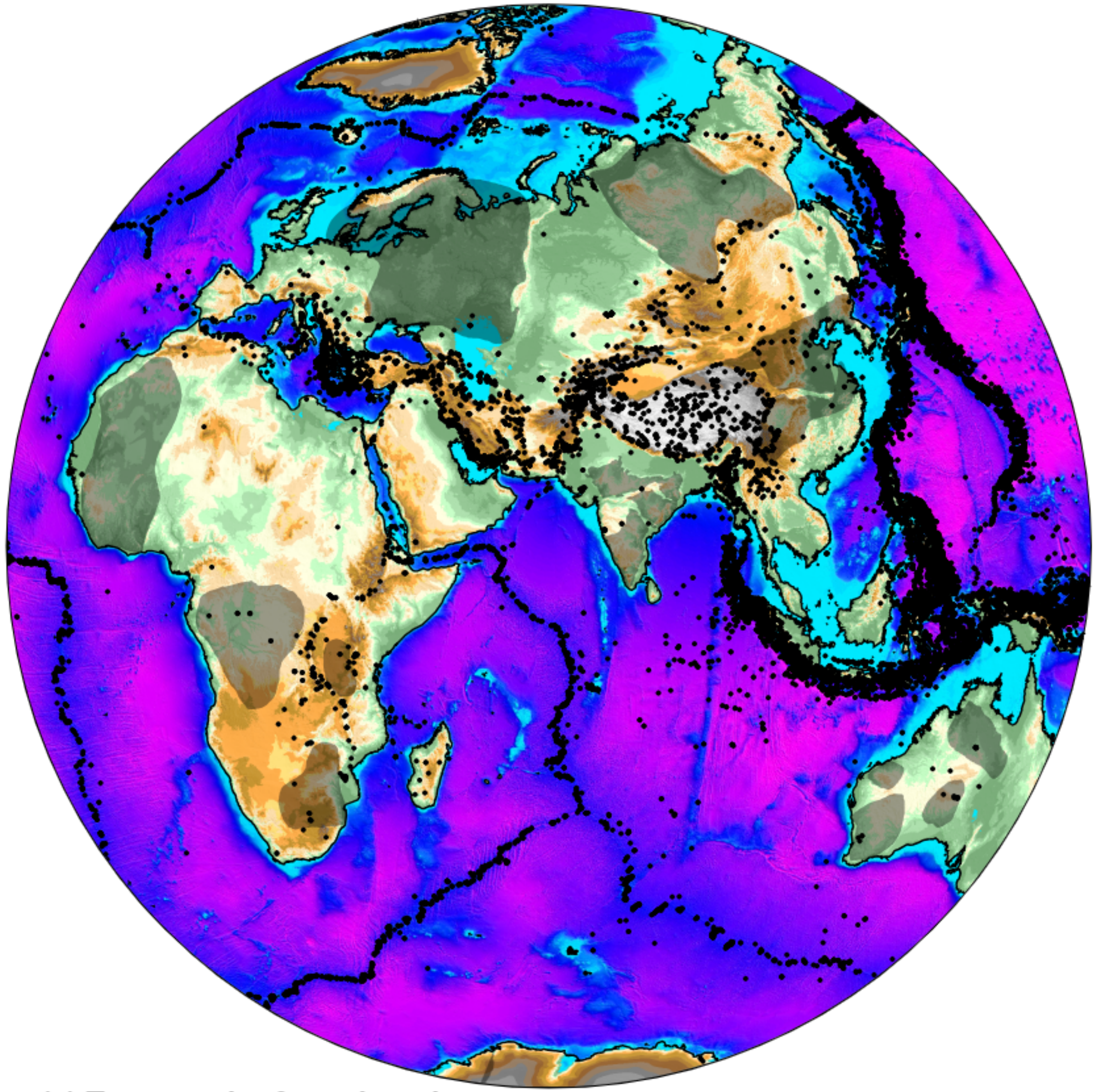
Deformation – cold/anhydrous continent - rigid



Deformation – hot/hydrous continental - distributed

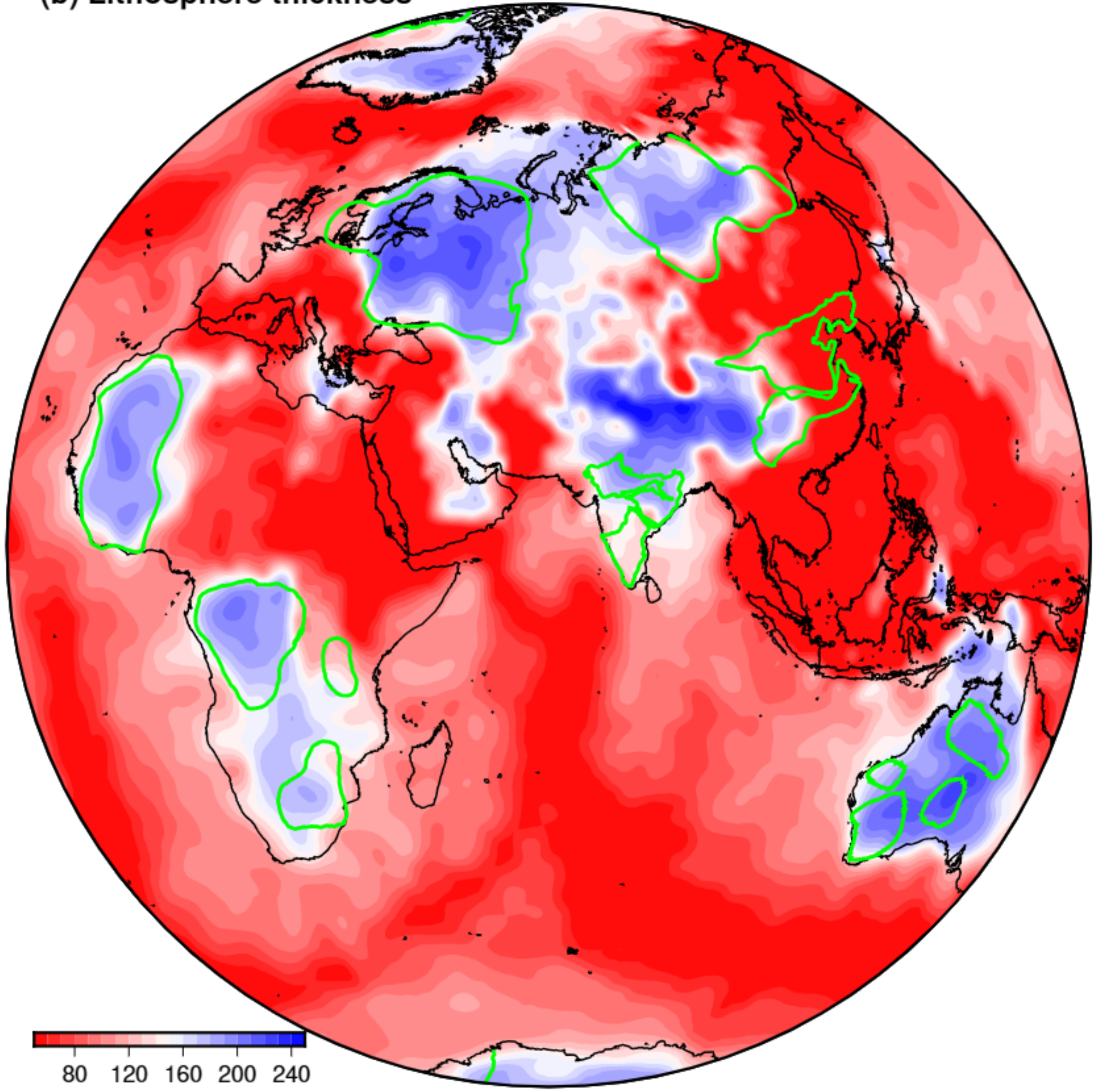


No single 'plate boundary' – faulting distributed over thousands of kilometres.



(a) Topography & earthquakes

(b) Lithosphere thickness



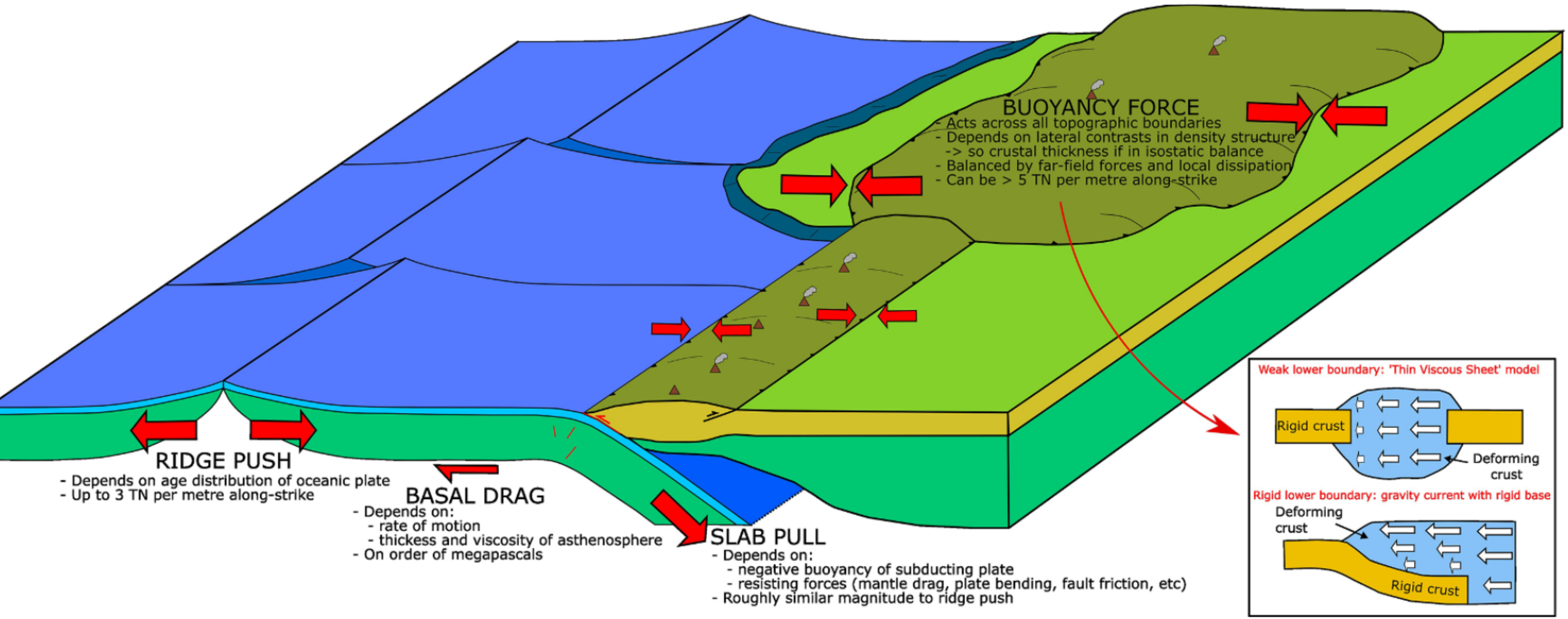
Summary

- Contrasts in earthquake depth distributions are controlled by variations in temperature and composition, and are a proxy for strength

- Large lateral variations reflect the geological history of the continents

- Next lecture: what influence do these variations have on the tectonic behaviour of the continents?

Lecture 2: Lithosphere-scale controls on continental dynamics



What forces move and deform the lithosphere?

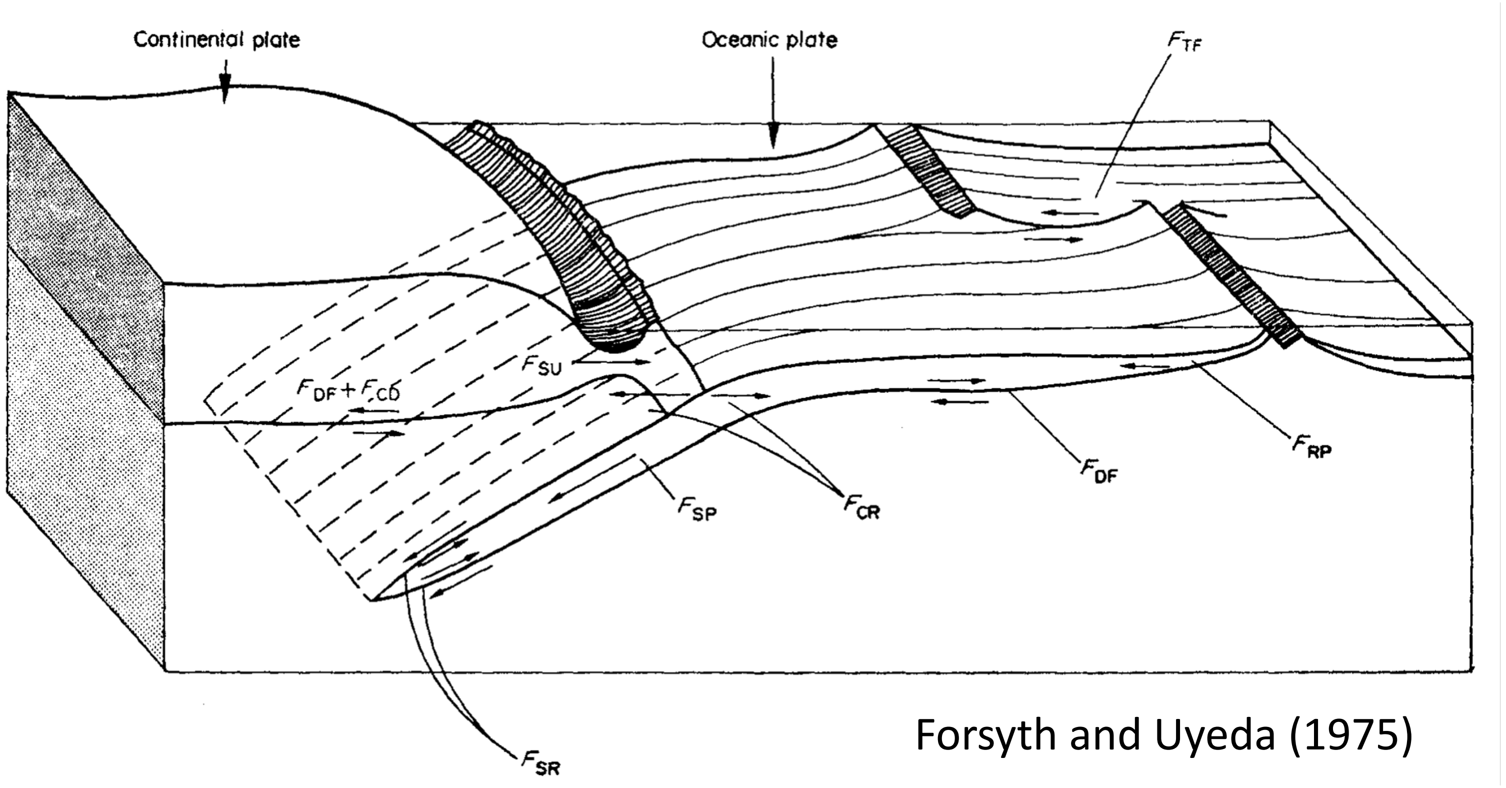
The four most important ones are:

- ridge push
- slab pull

Driving forces, roughly equal in importance

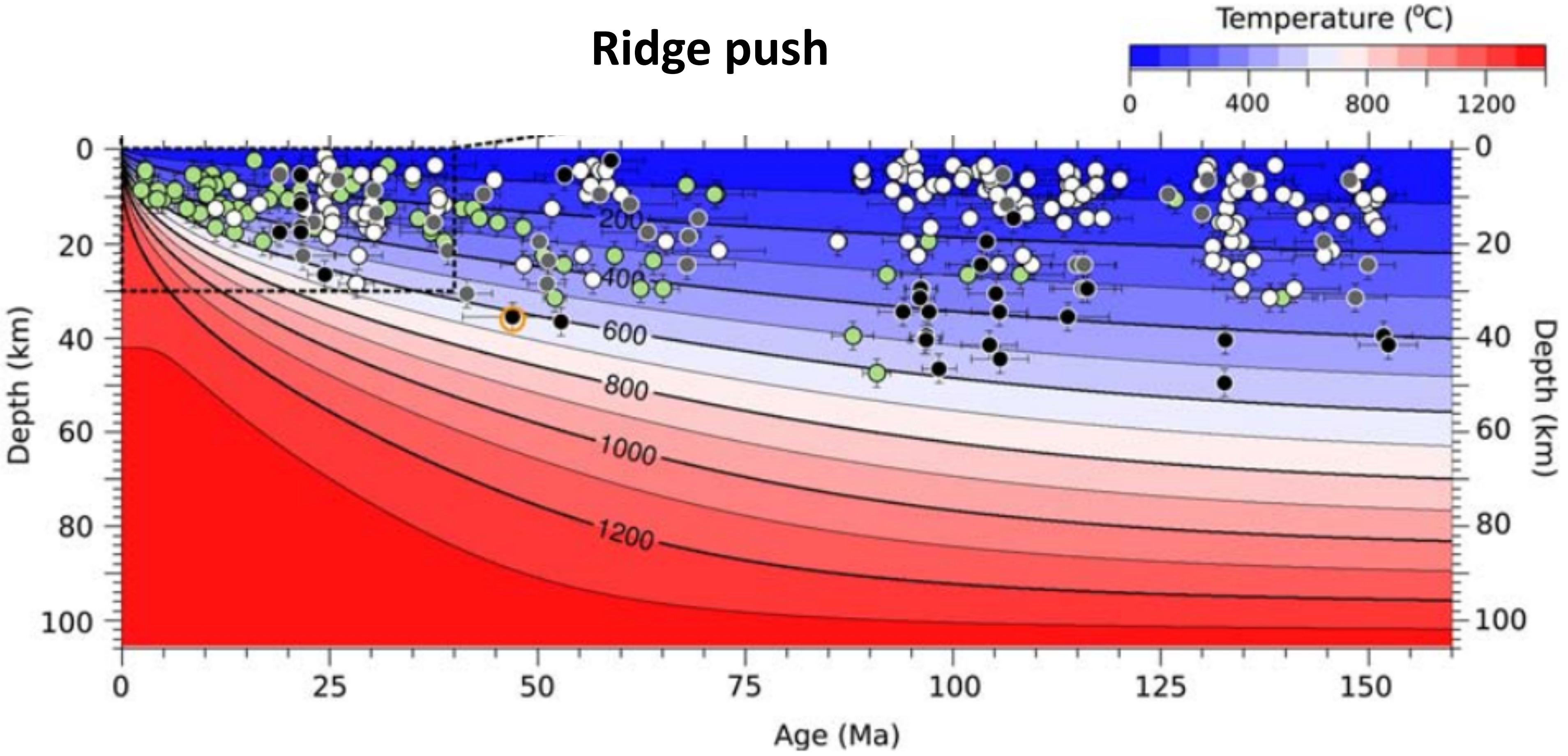
- Mountain range buoyancy
- Basal drag

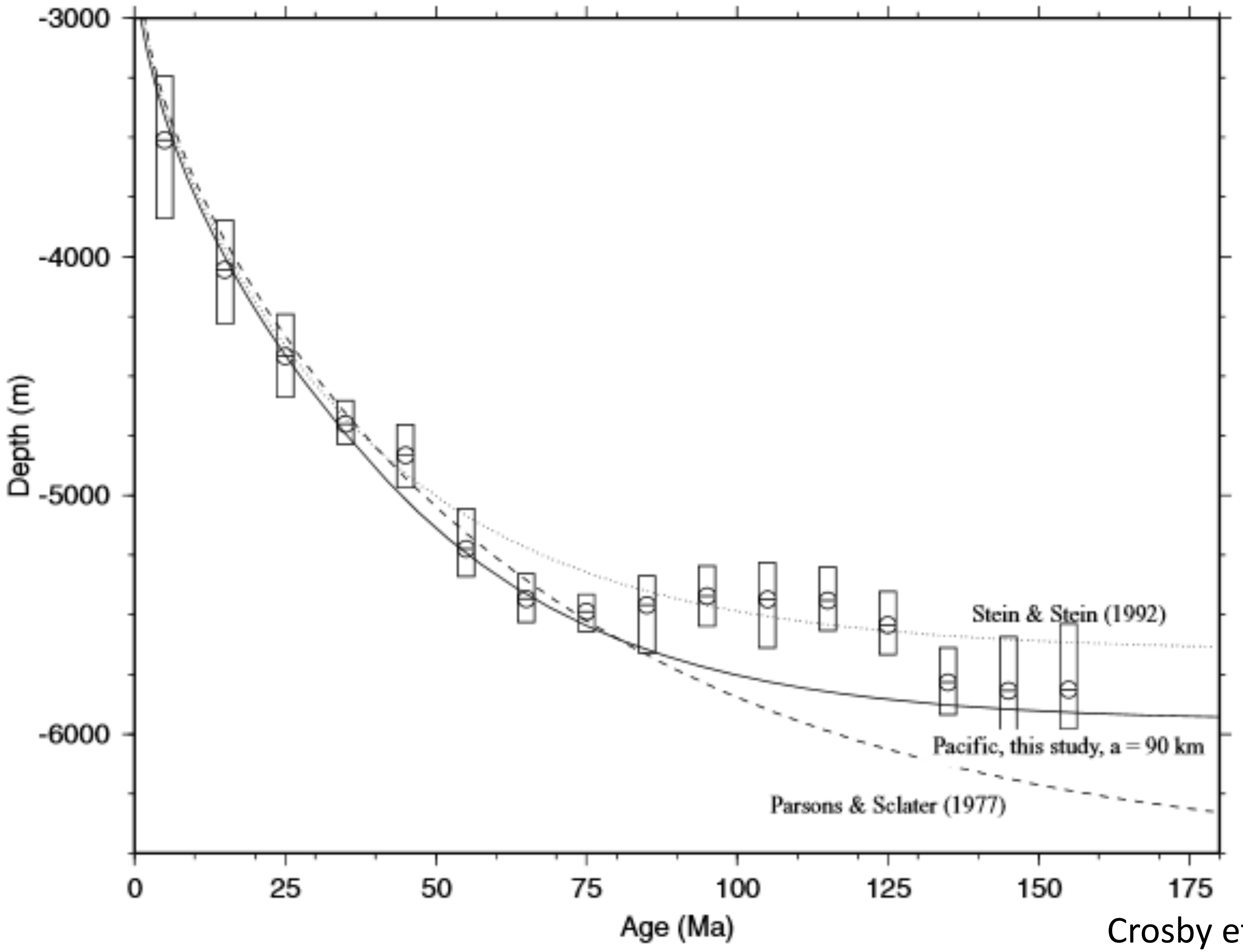
Resisting forces, magnitude varies



Forsyth and Uyeda (1975)

Ridge push

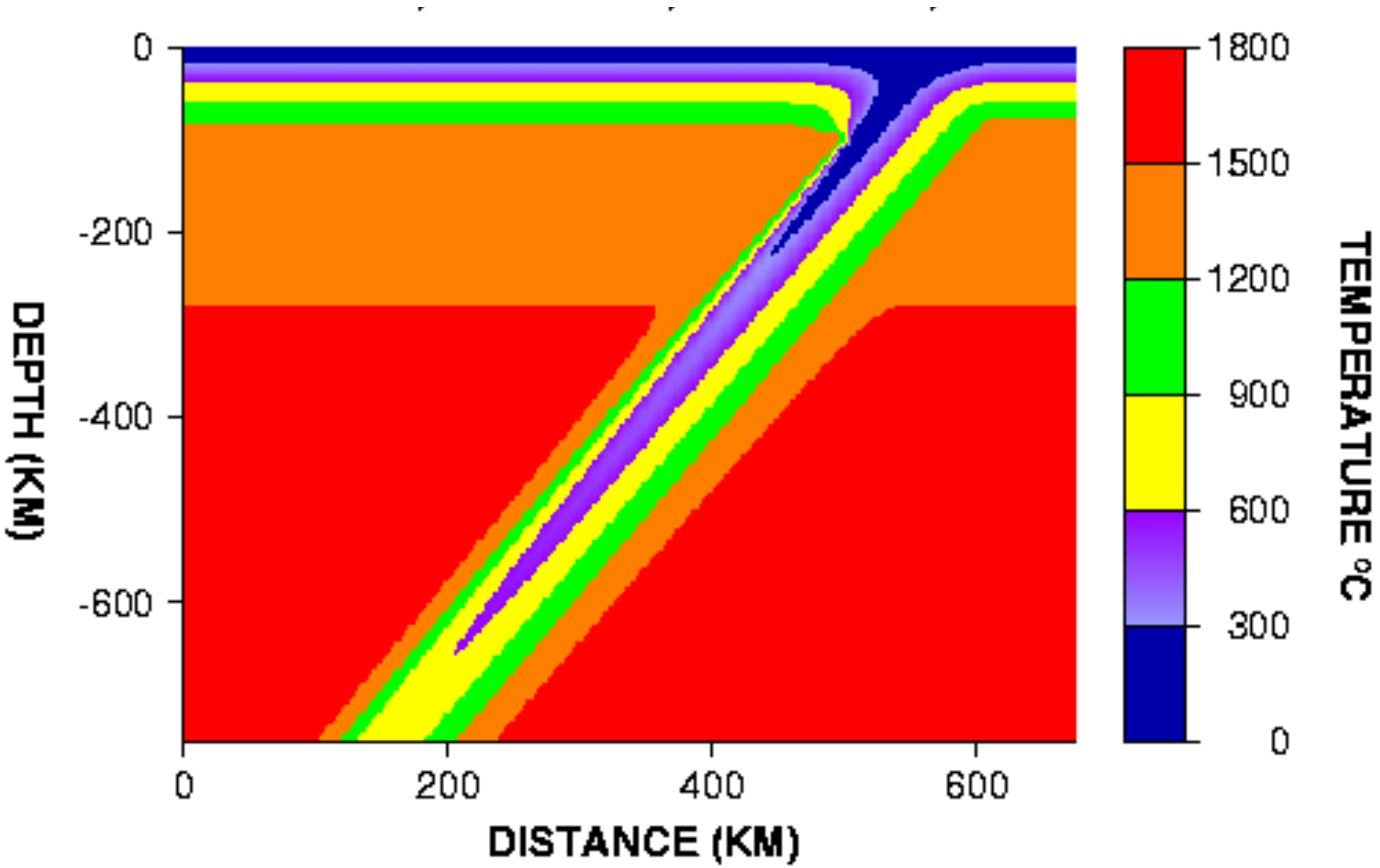

Temperature (°C)
0
400
800
1200
200
400
600
800
1000
1200
Depth (km)
0
20
40
60
80
100
Age (Ma)
0
25
50
75
100
125
150



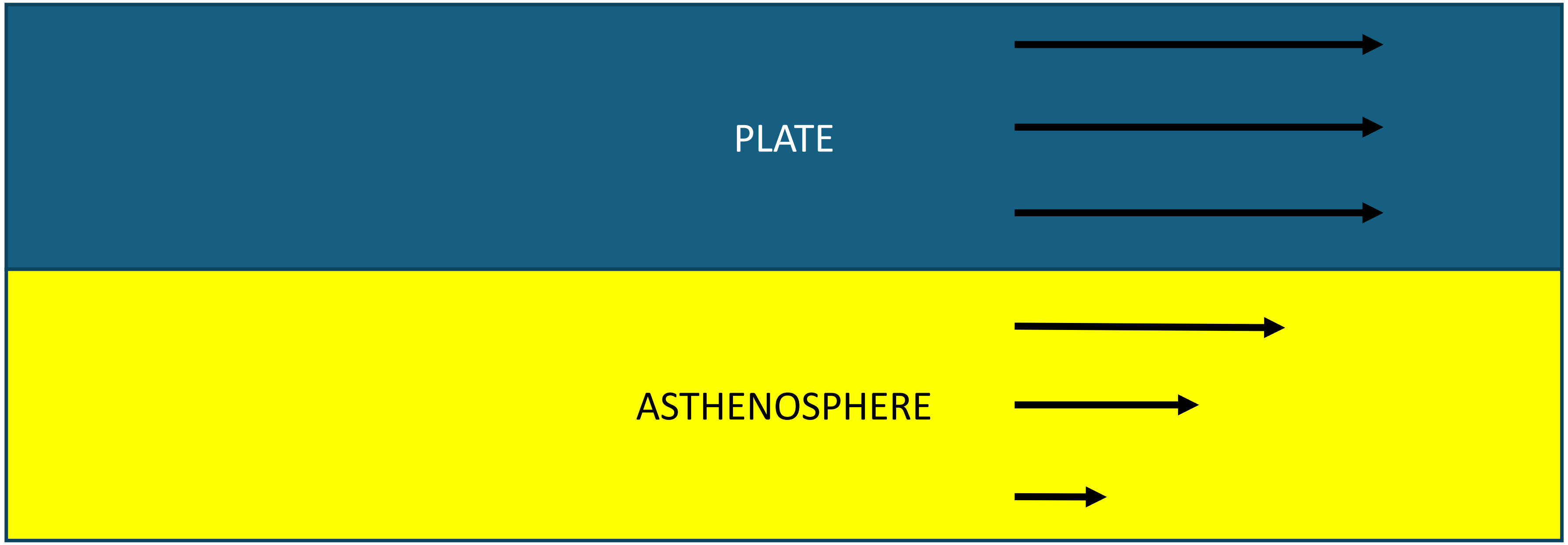
Crosby et al 2006

Elevated mid-ocean ridges exert a horizontal force on the surrounding older lithosphere

Slab pull – cool and dense slabs sinking into the mantle, dragging the plate with them



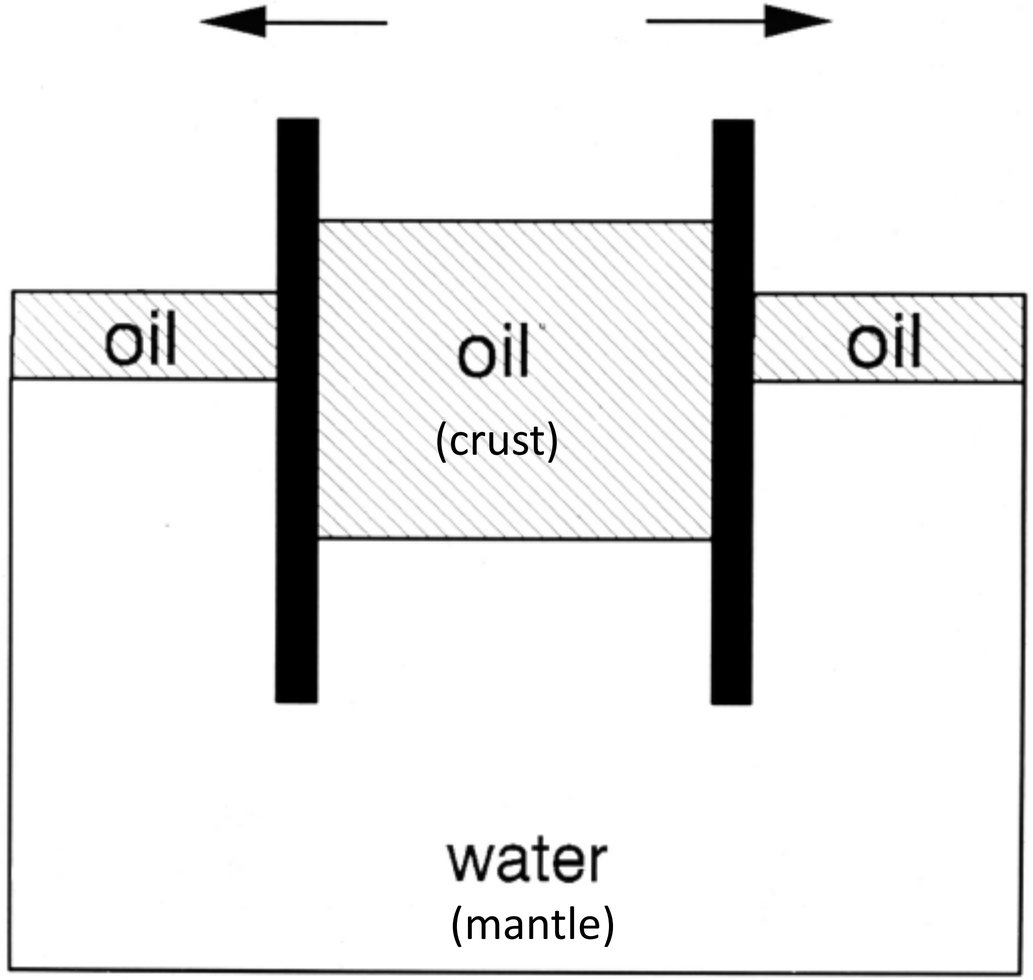
Basal drag



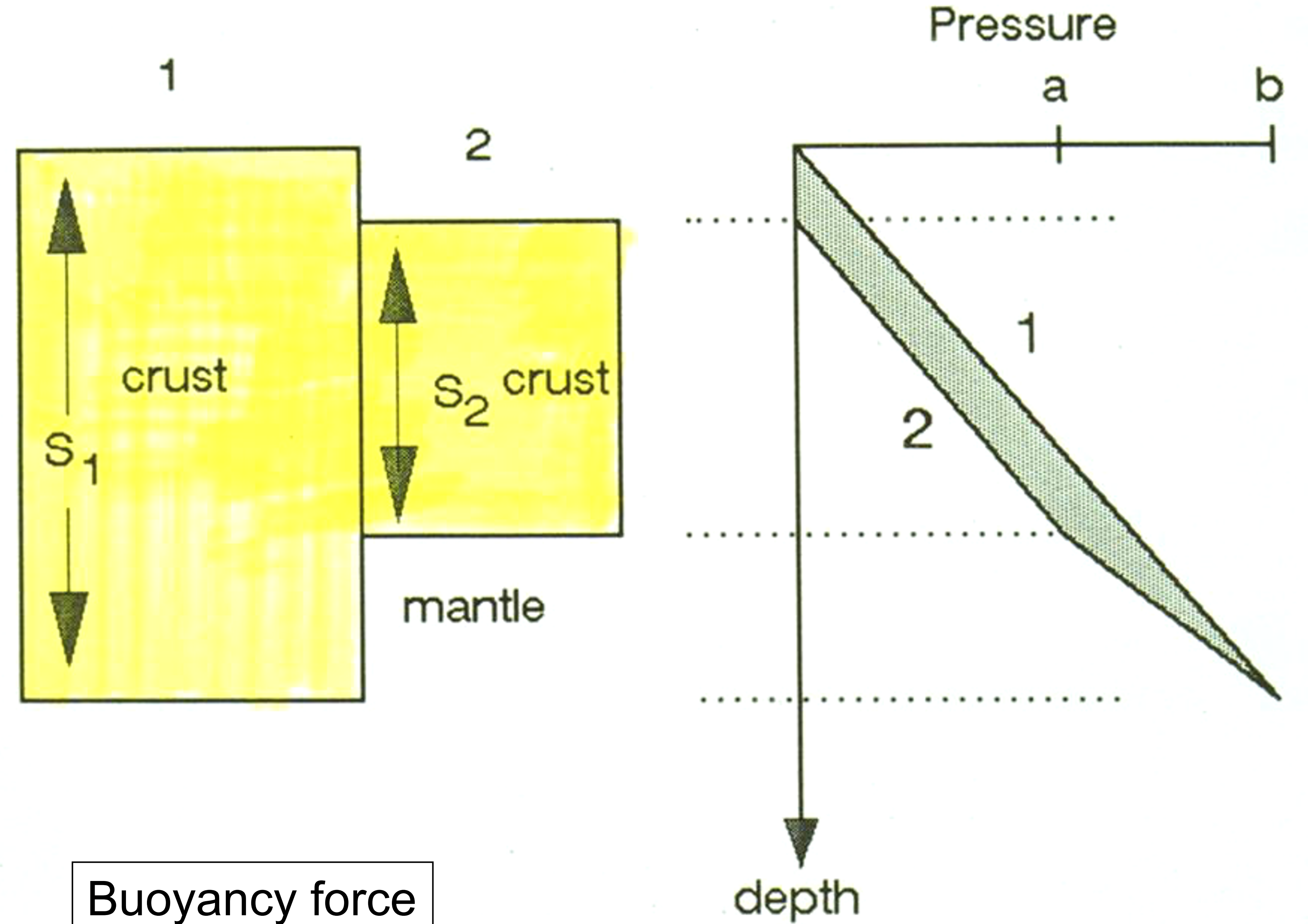
Convecting mantle

Mountain range 'buoyancy force'

An analogy….



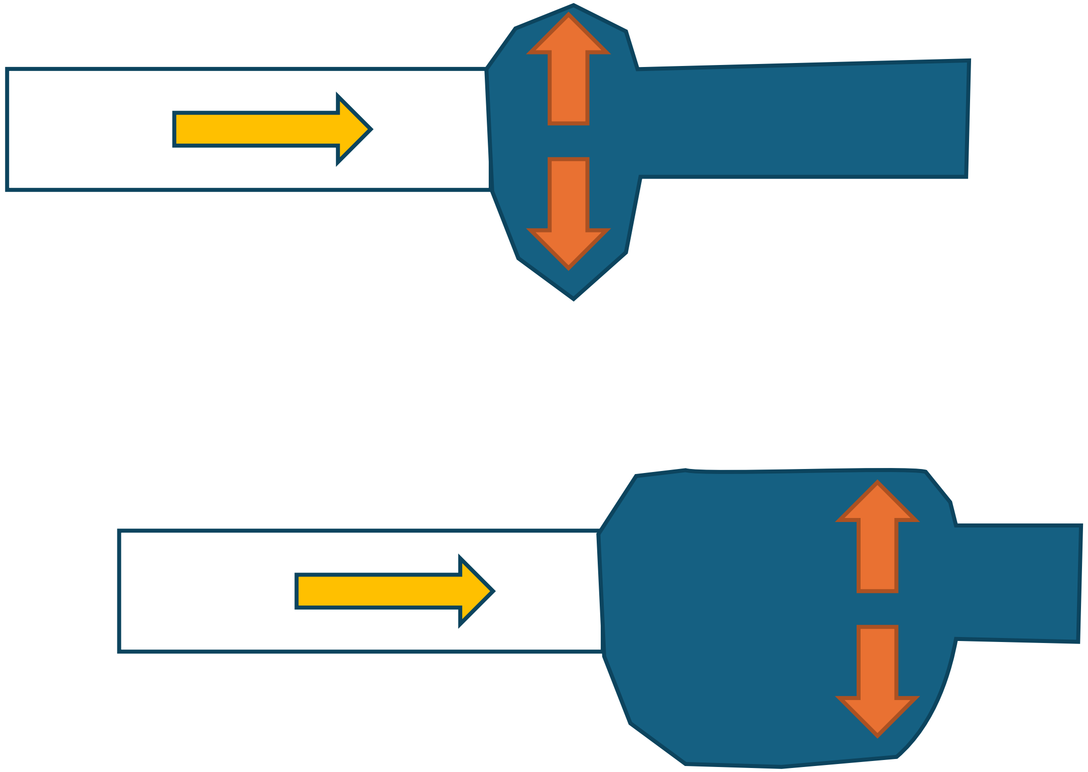
- There is a limit to how high mountain ranges can get (they need a force to hold them up).



Buoyancy force

ISOSTATIC balance DOESN'T mean there is no HORIZONTAL FORCE

Therefore, would expect a range to grow VERTICALLY, then LATERALLY once the lowlands have reached their breaking point



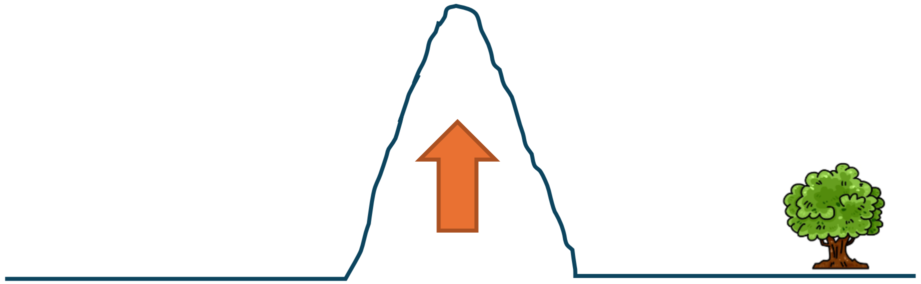
Mountain ranges as a ‘pressure gauge’

Two forces dominate mountain building

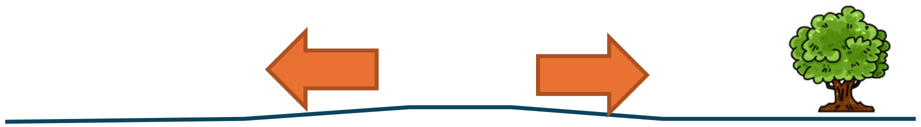
1. The forces relating to the convergence of the two plates

2. Gravity acting on elevation contrasts

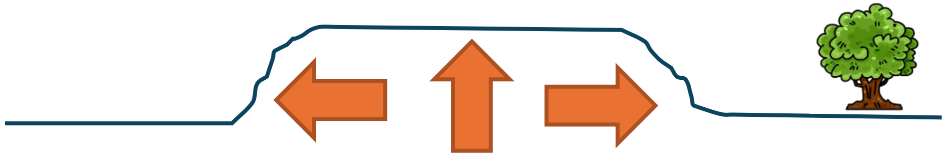
If $F_{plate} >> F_{gravity}$



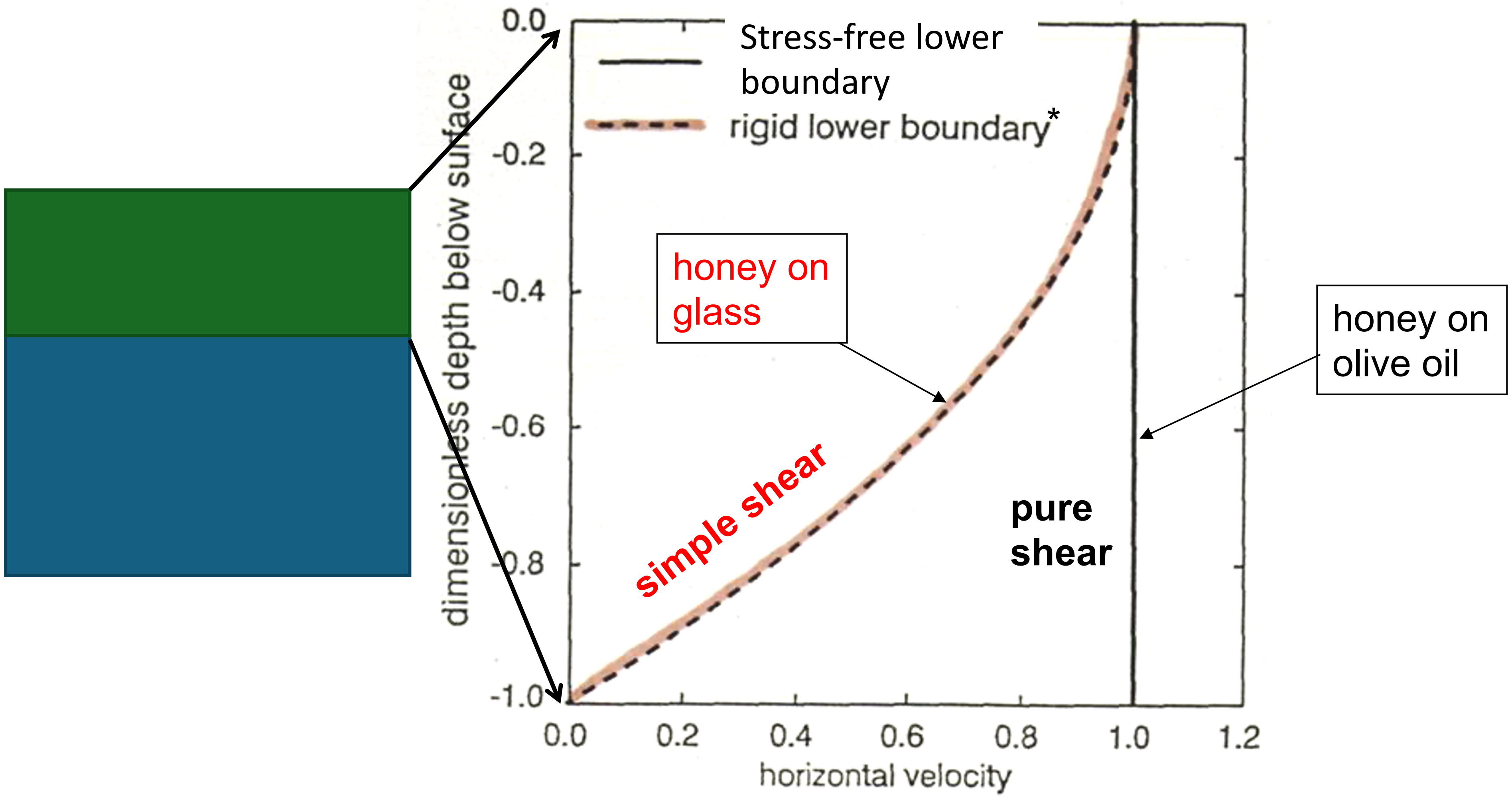
If $F_{plate} << F_{gravity}$



If $F_{plate} \approx F_{gravity}$



Viscous Gravity Currents

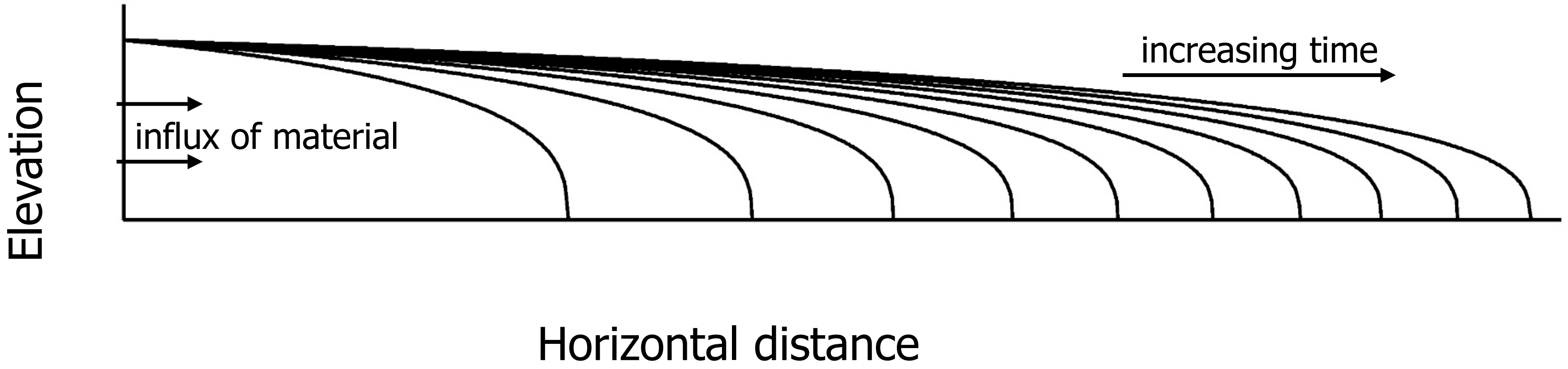


Importance of the boundary condition:
(need rigid boundary or viscosity contrast for simple shear)

McKenzie et al (2000)

Flow in a thin layer with a rigid base

produces distinctive topography – a gently sloping top and a steep front (Huppert 1982)

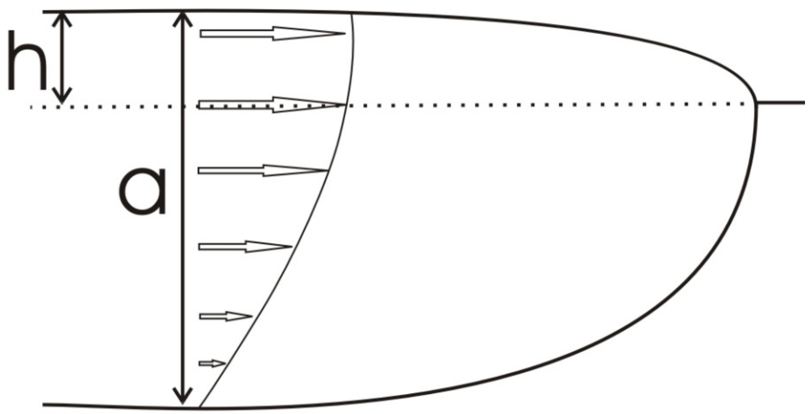


Surface velocity depends on viscosity, surface slope, and flow thickness:

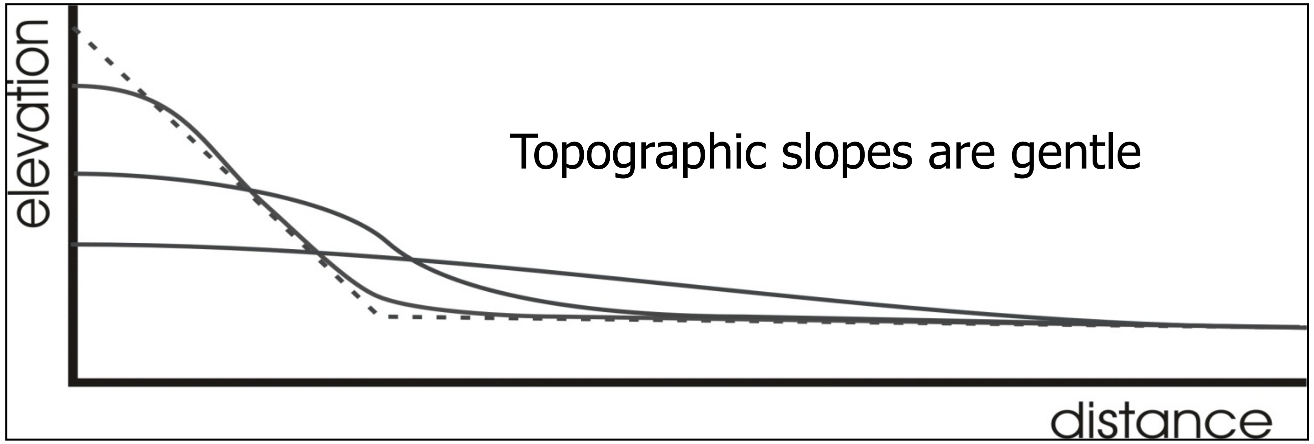
$$u = -\frac{\rho g (f+1)^2}{2\eta} h^2 \nabla h$$

(McKenzie et al 2000)

Vertical planes deform by simple shear above the rigid base:

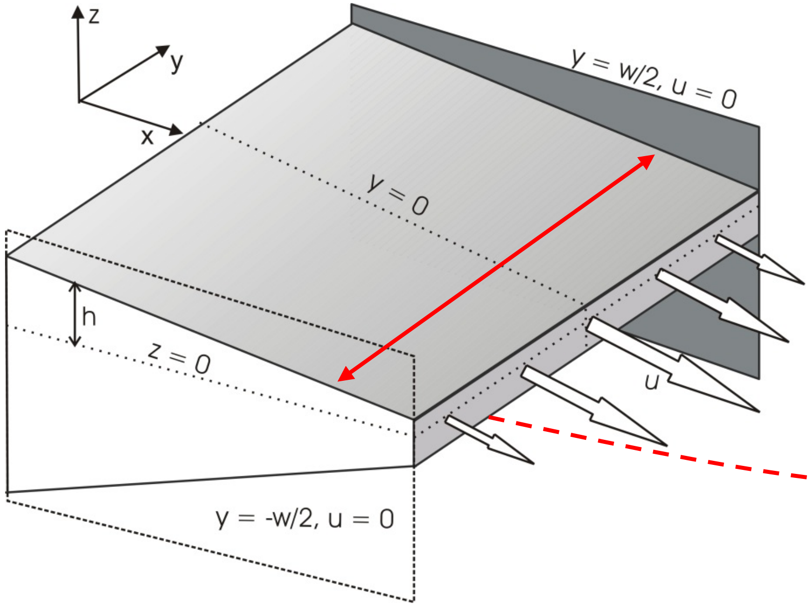


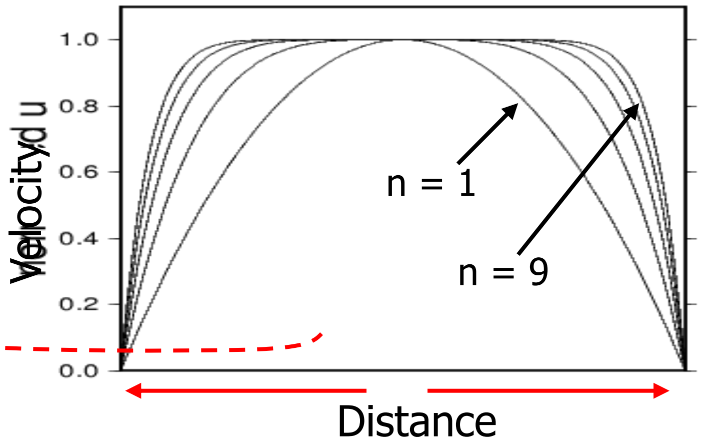
Flow in a thin layer with zero shear stress on the base



Velocity depends on viscosity, surface slope, and distance to the lateral boundaries:

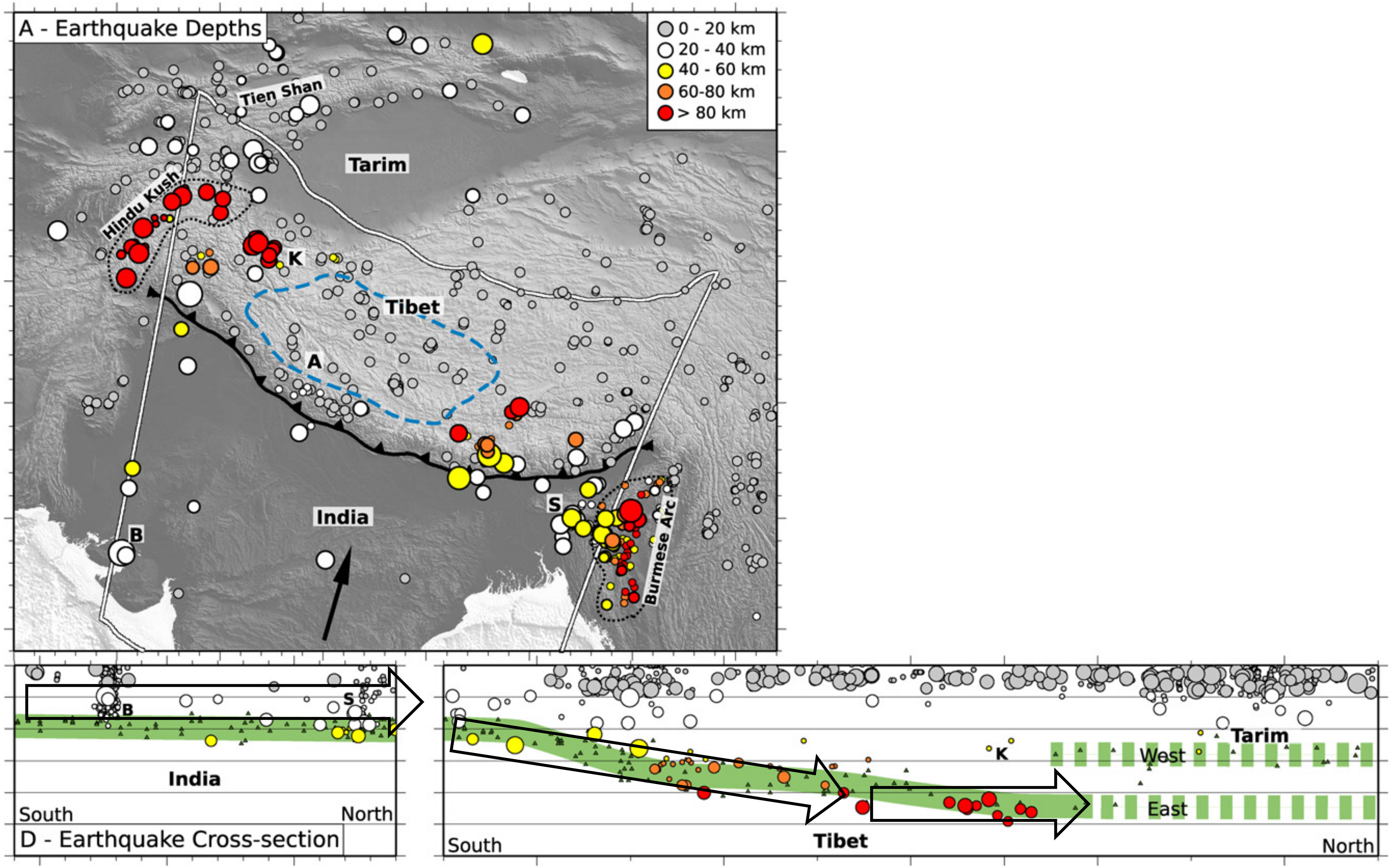
$$u = \left(\frac{\sqrt{2}^{1/n-1}}{B} \frac{\partial P}{\partial x} \right)^n \left(\frac{y^{n+1} - (w/2)^{n+1}}{n+1} \right)$$



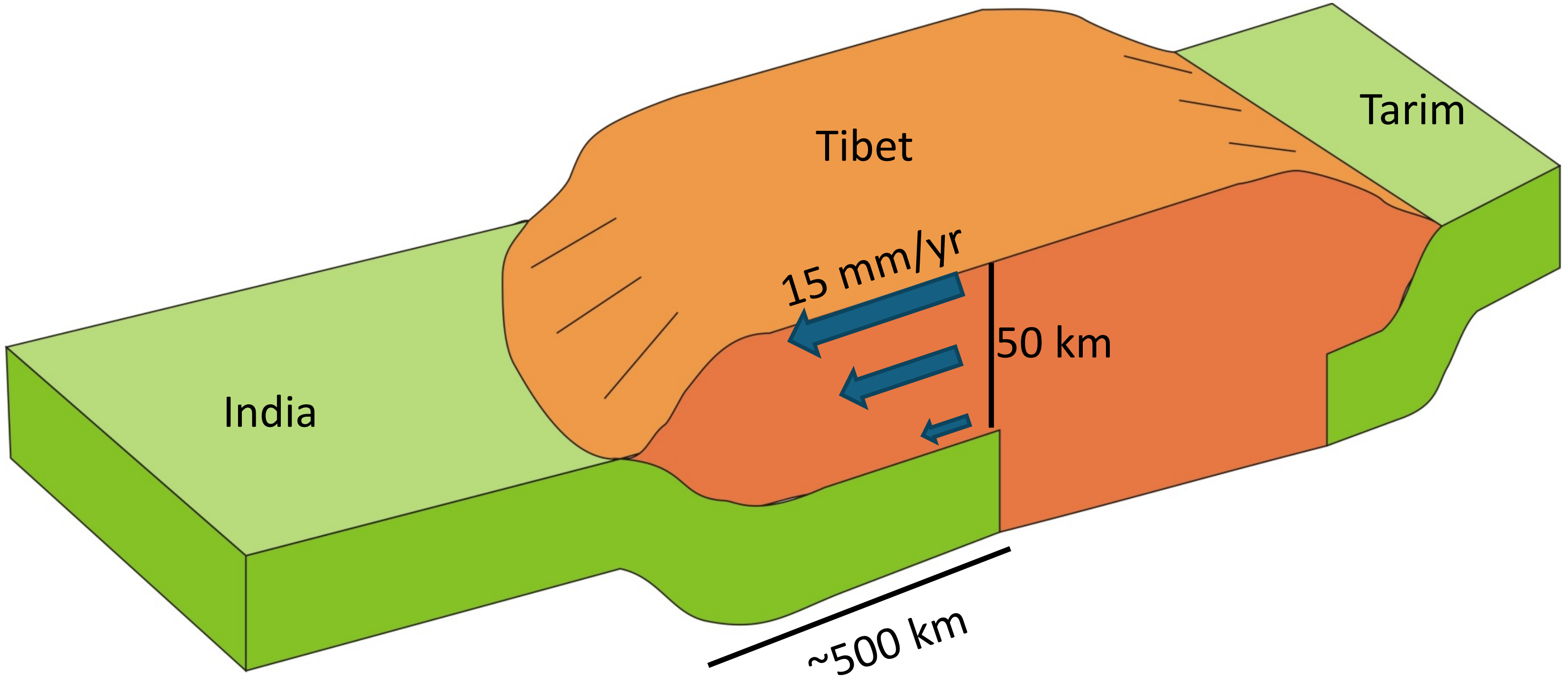


Tibetan seismicity

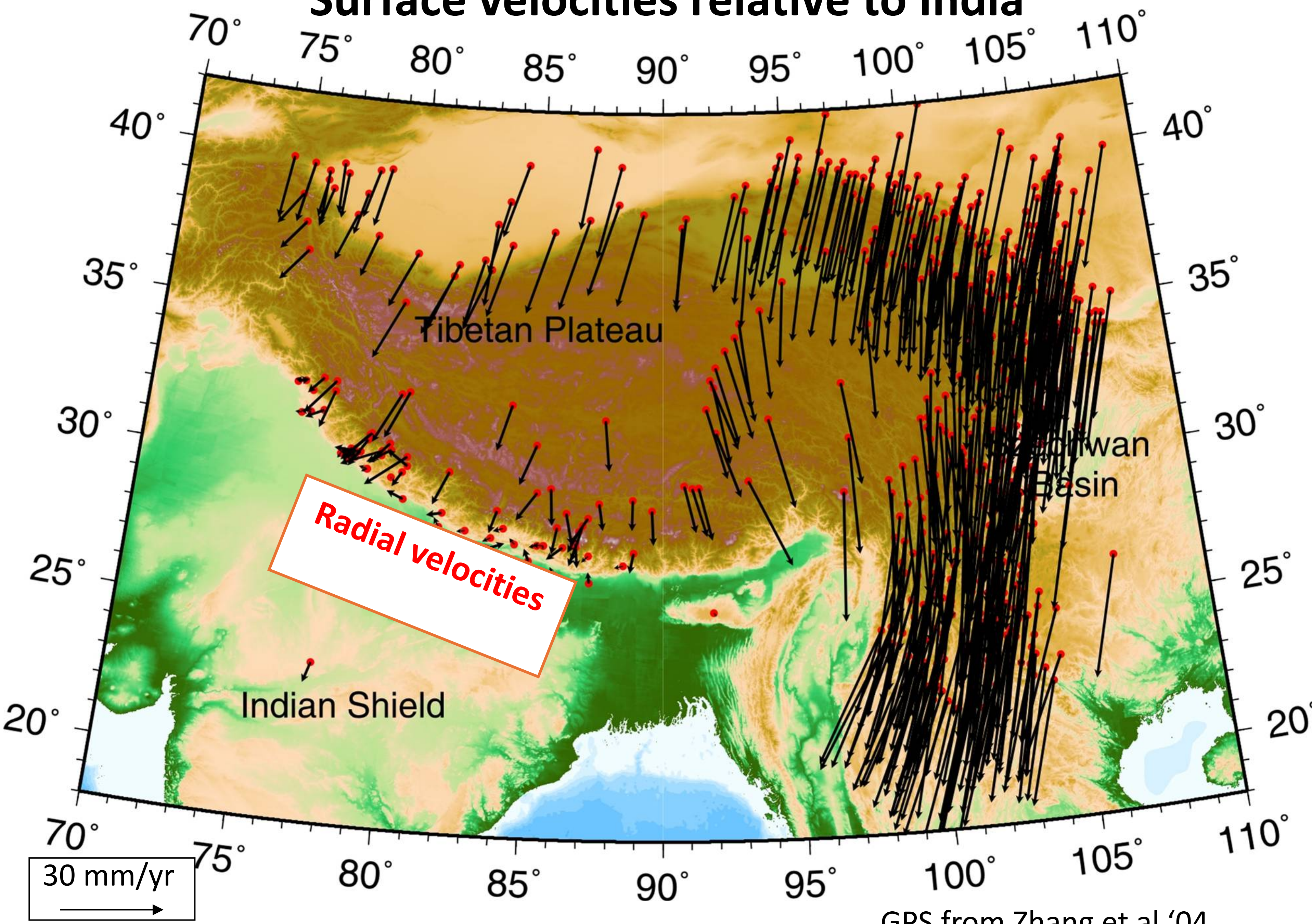
(Craig et al 2012)



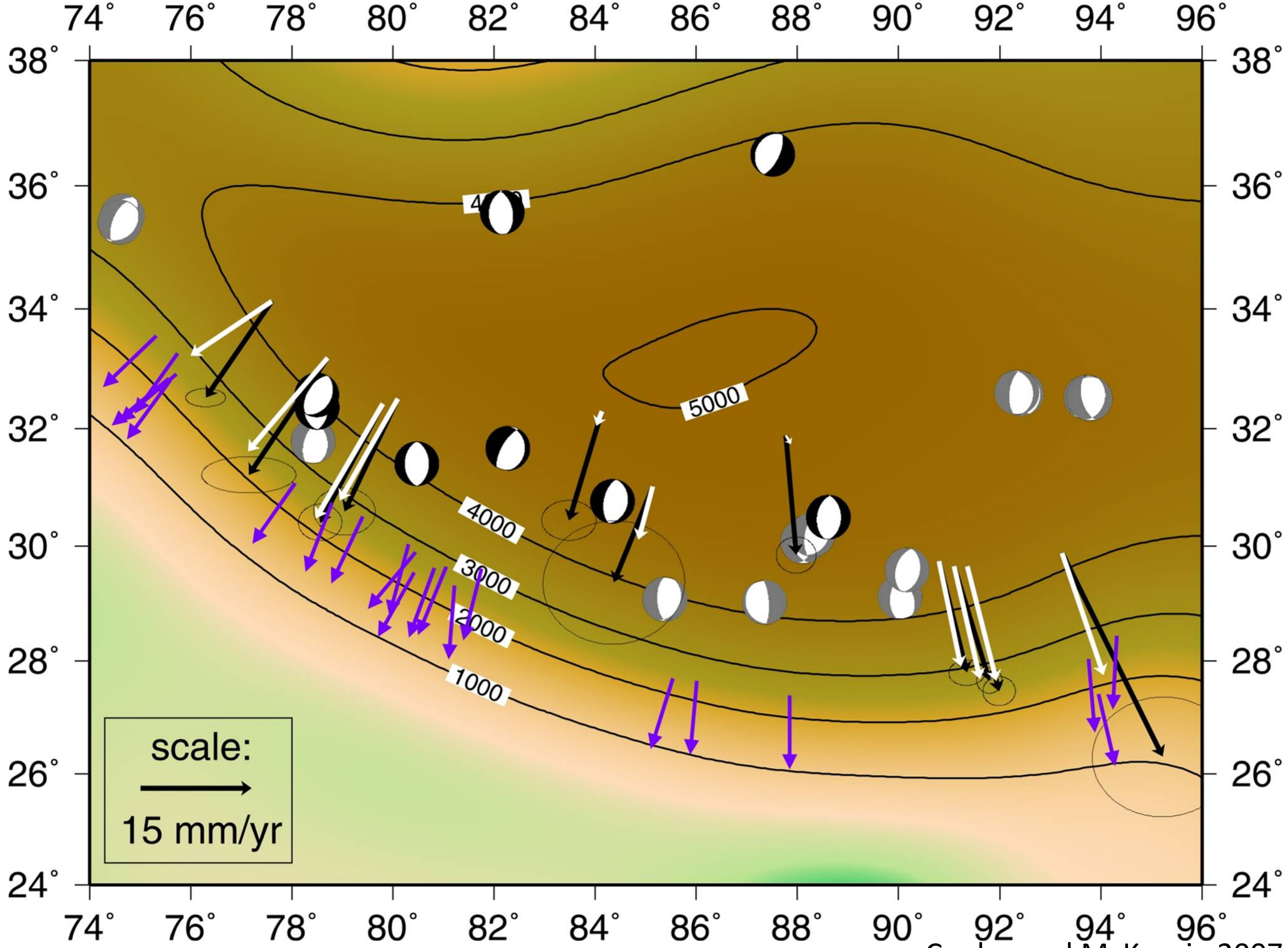
Schematic cross-section through Tibet



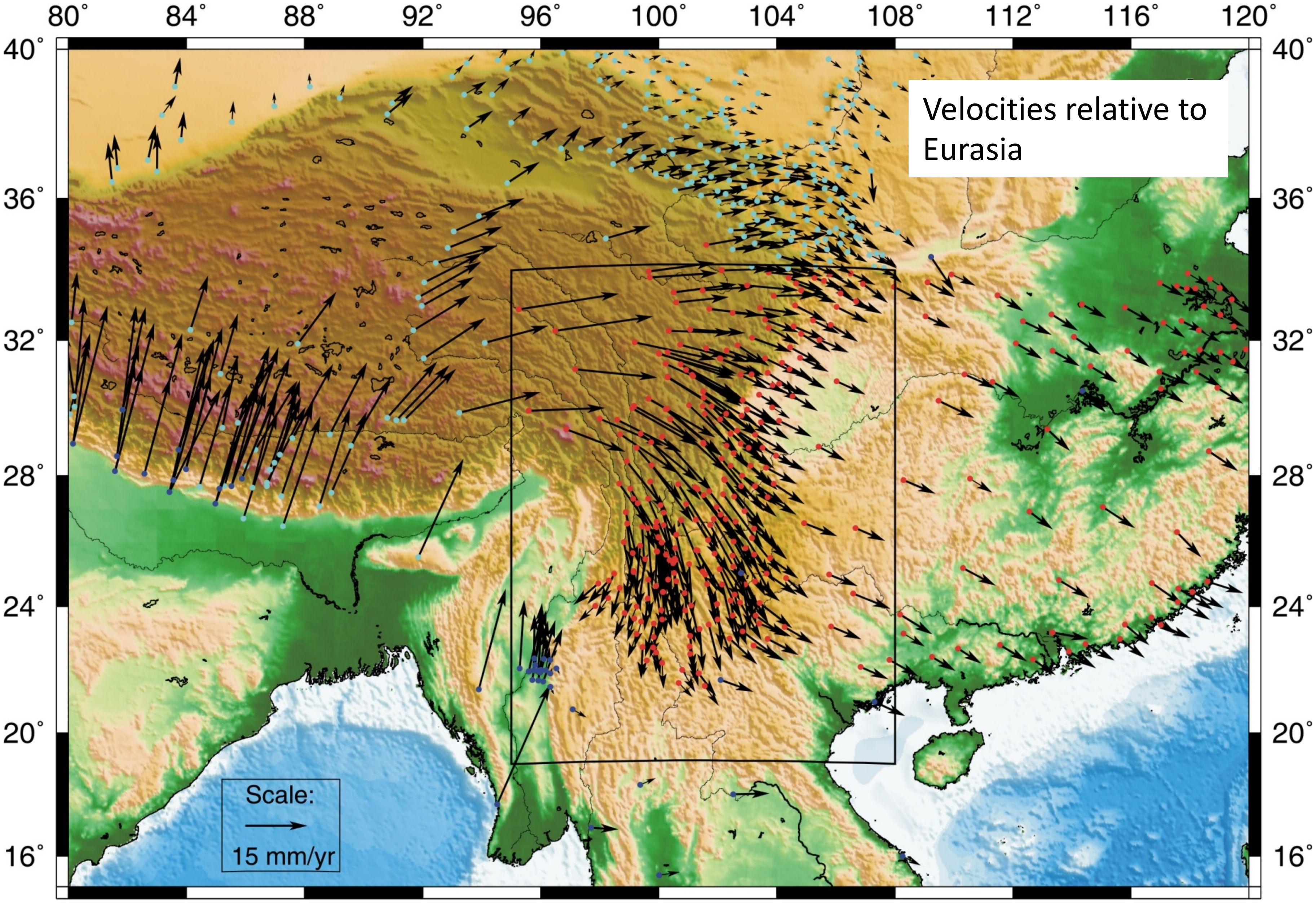
Surface velocities relative to India



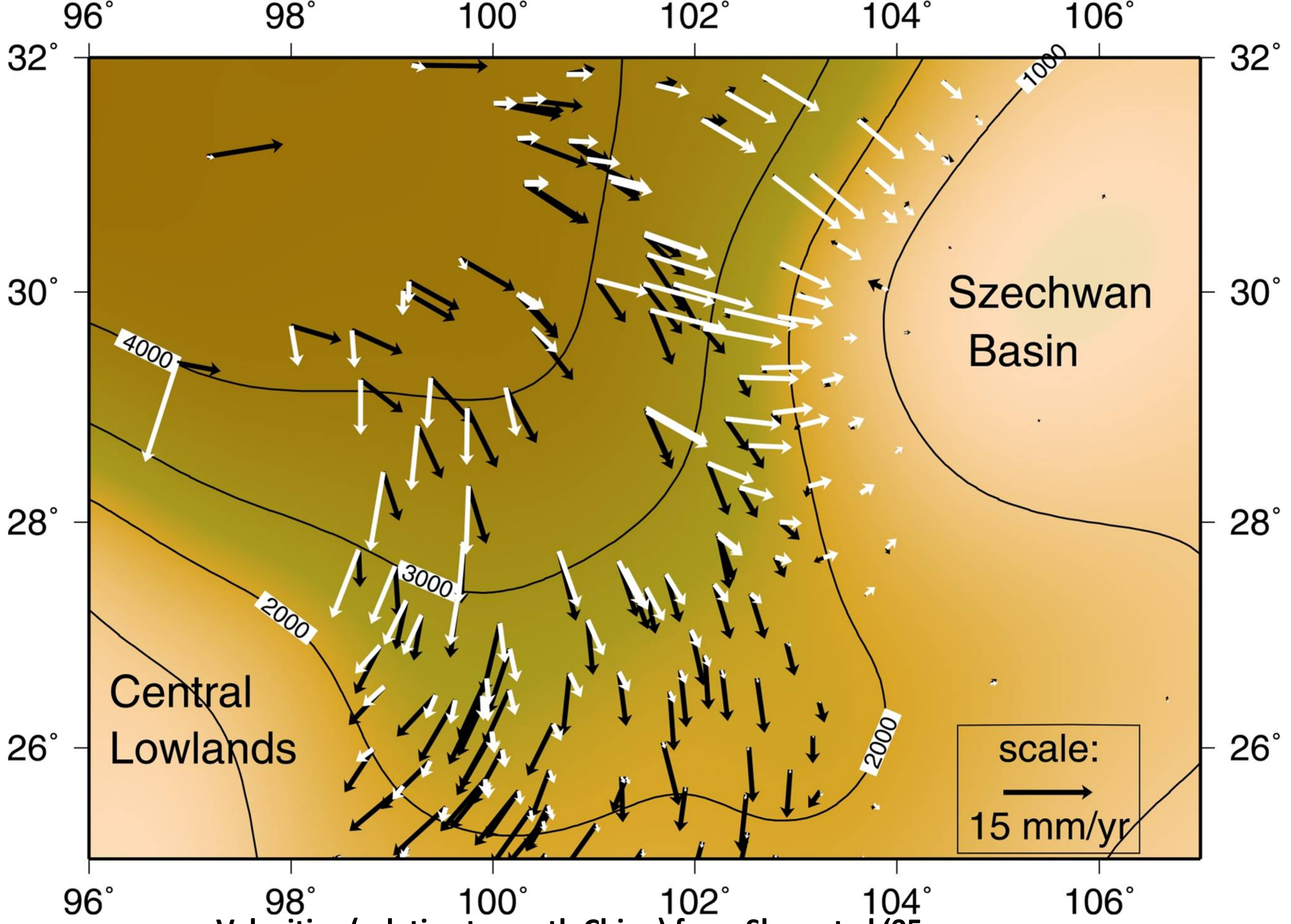
GPS from Zhang et al ‘04



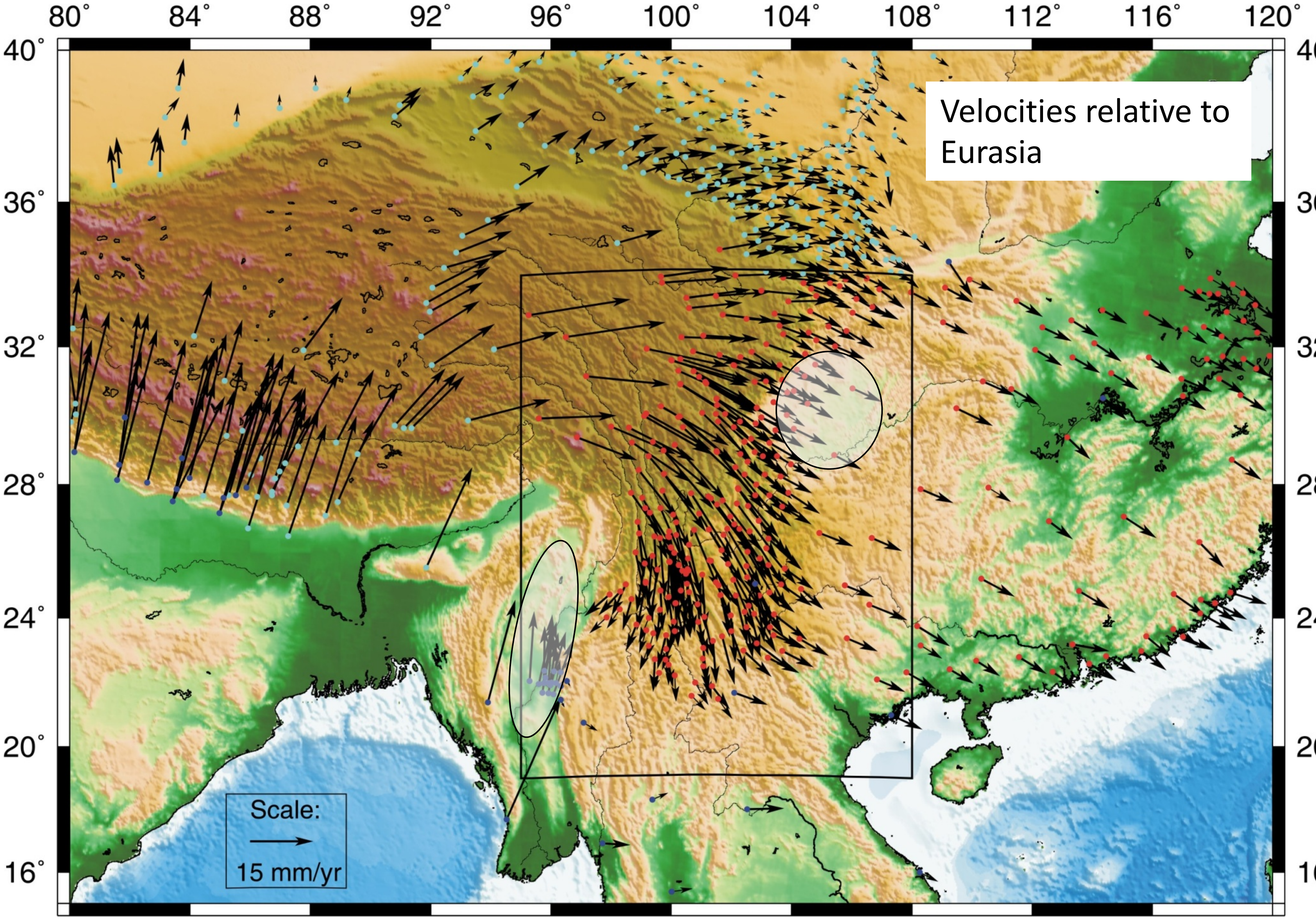
Copley and McKenzie 2007



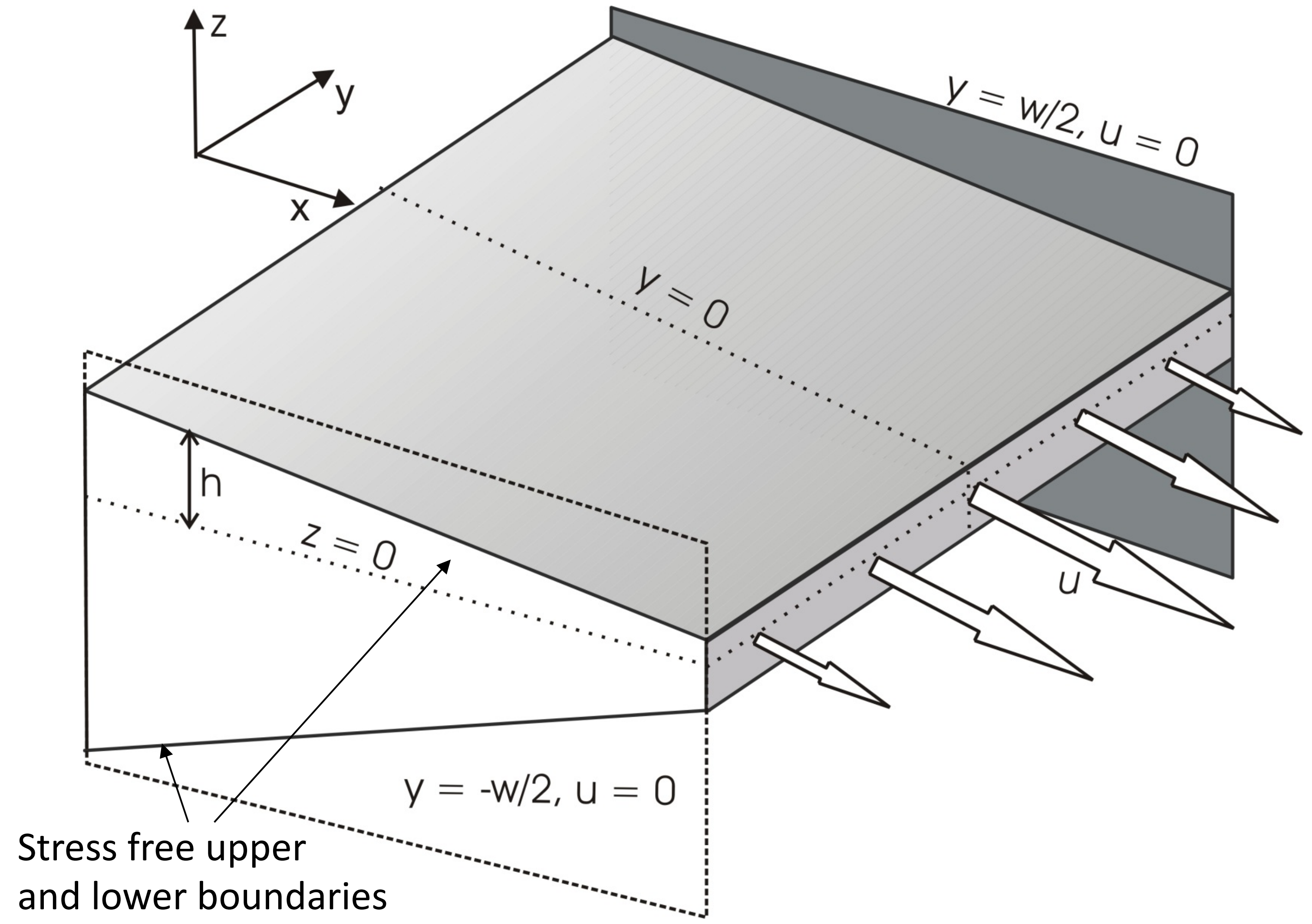
Pale blue bases = Zhang et al '04, red = Shen et al '05, dark blue = Socquet et al '06

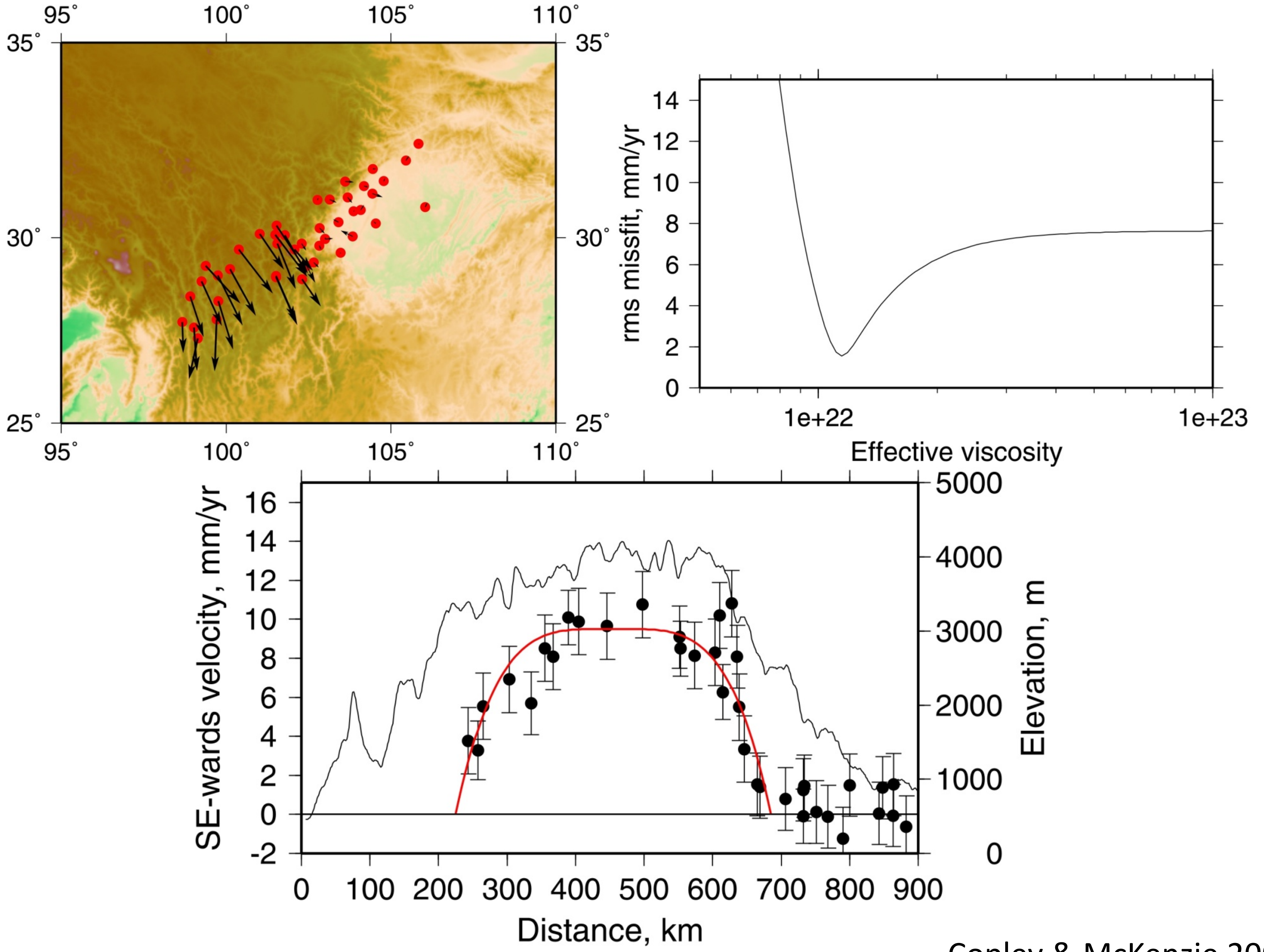


Velocities (relative to south China) from Shen et al '05

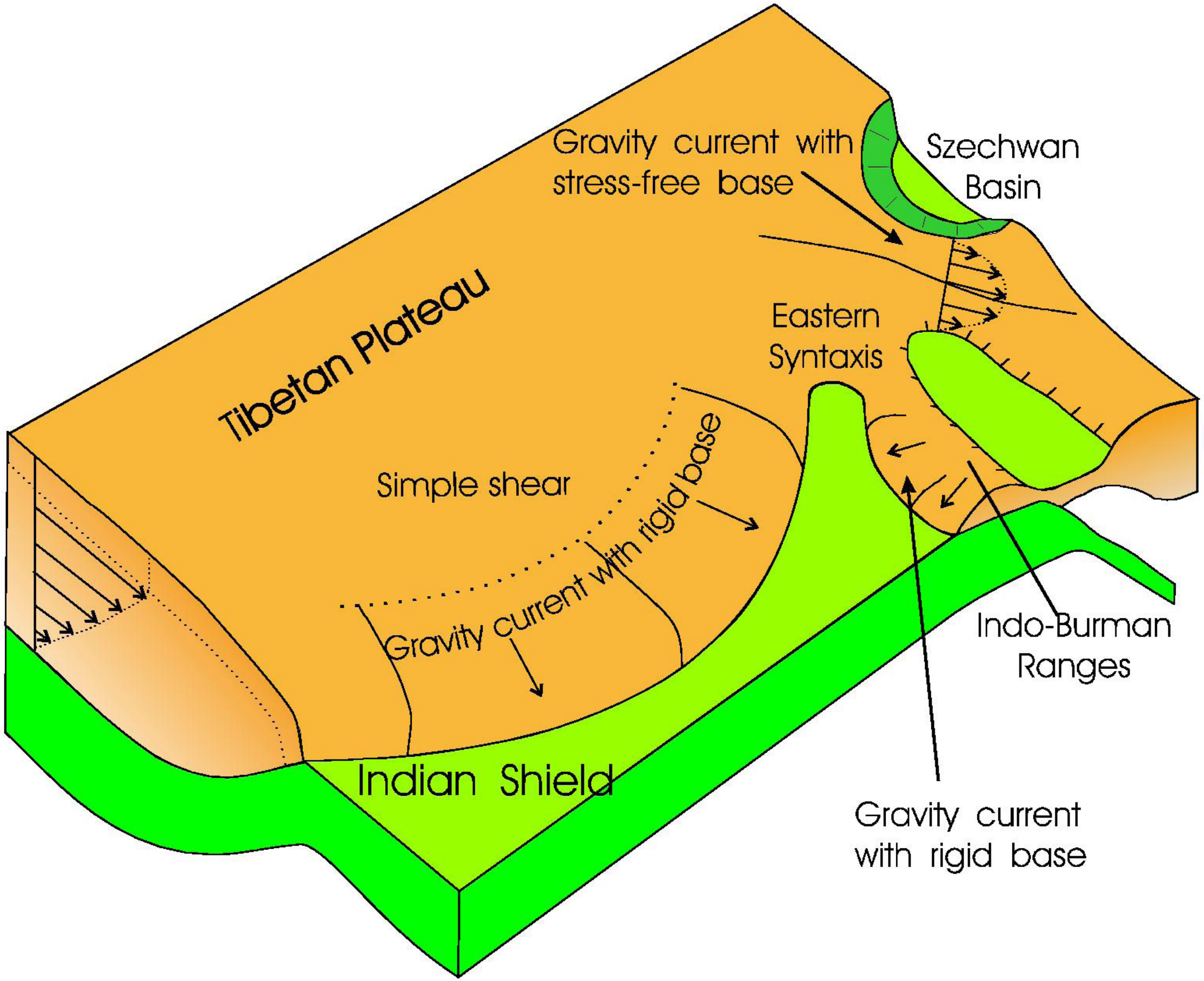


Pale blue bases = Zhang et al ‘04, red = Shen et al ’05, dark blue = Socquet et al ‘06 du/dy is now the dominant velocity gradient

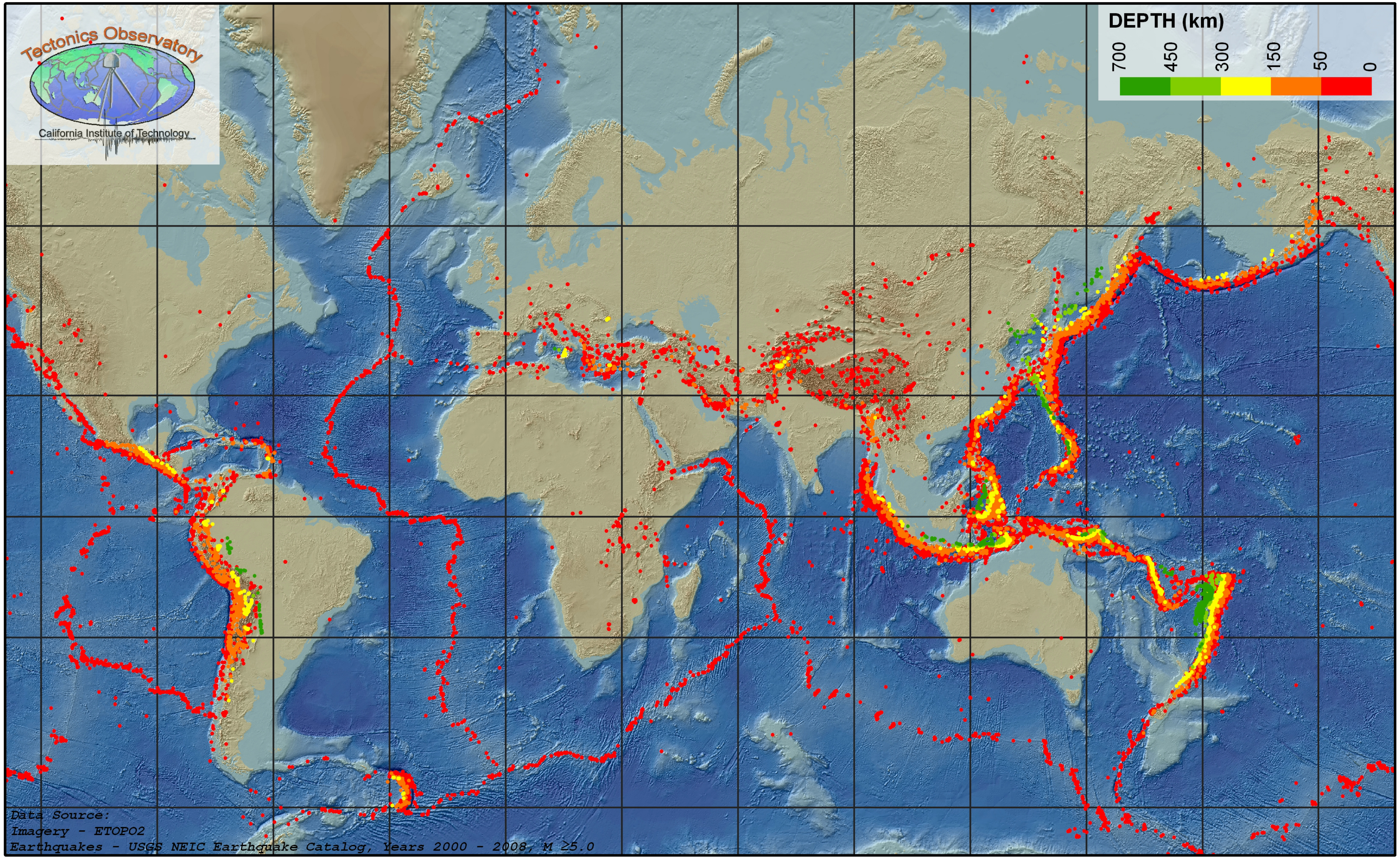


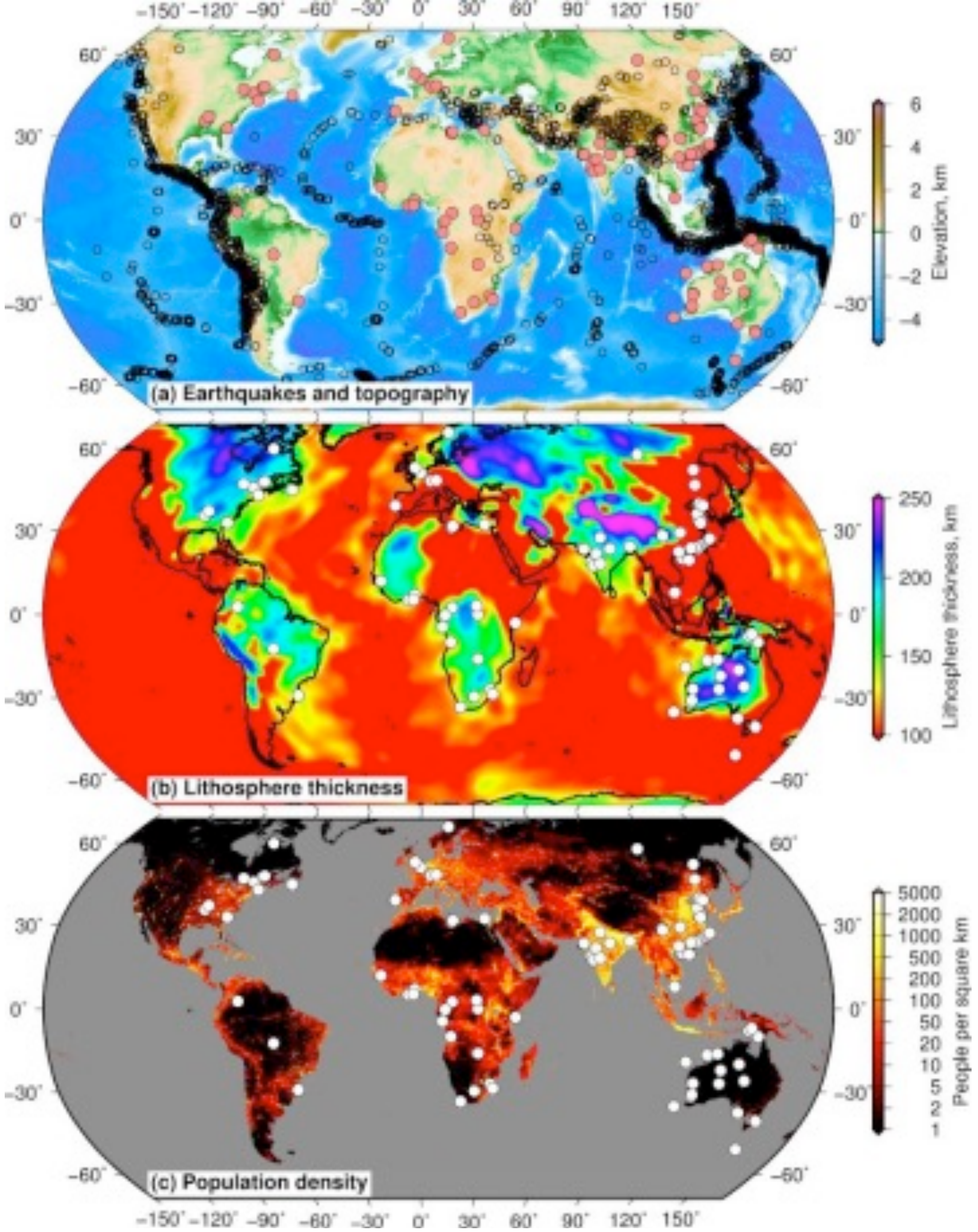


Copley & McKenzie 2007



Copley & McKenzie 2007


Tectonics Observatory
California Institute of Technology
DEPTH (km)
700
450
300
150
50
0
Data Source:
Imagery - ETOPO2
Earthquakes - USGS NEIC Earthquake Catalog, Years 2000 - 2008, M ≥5.0

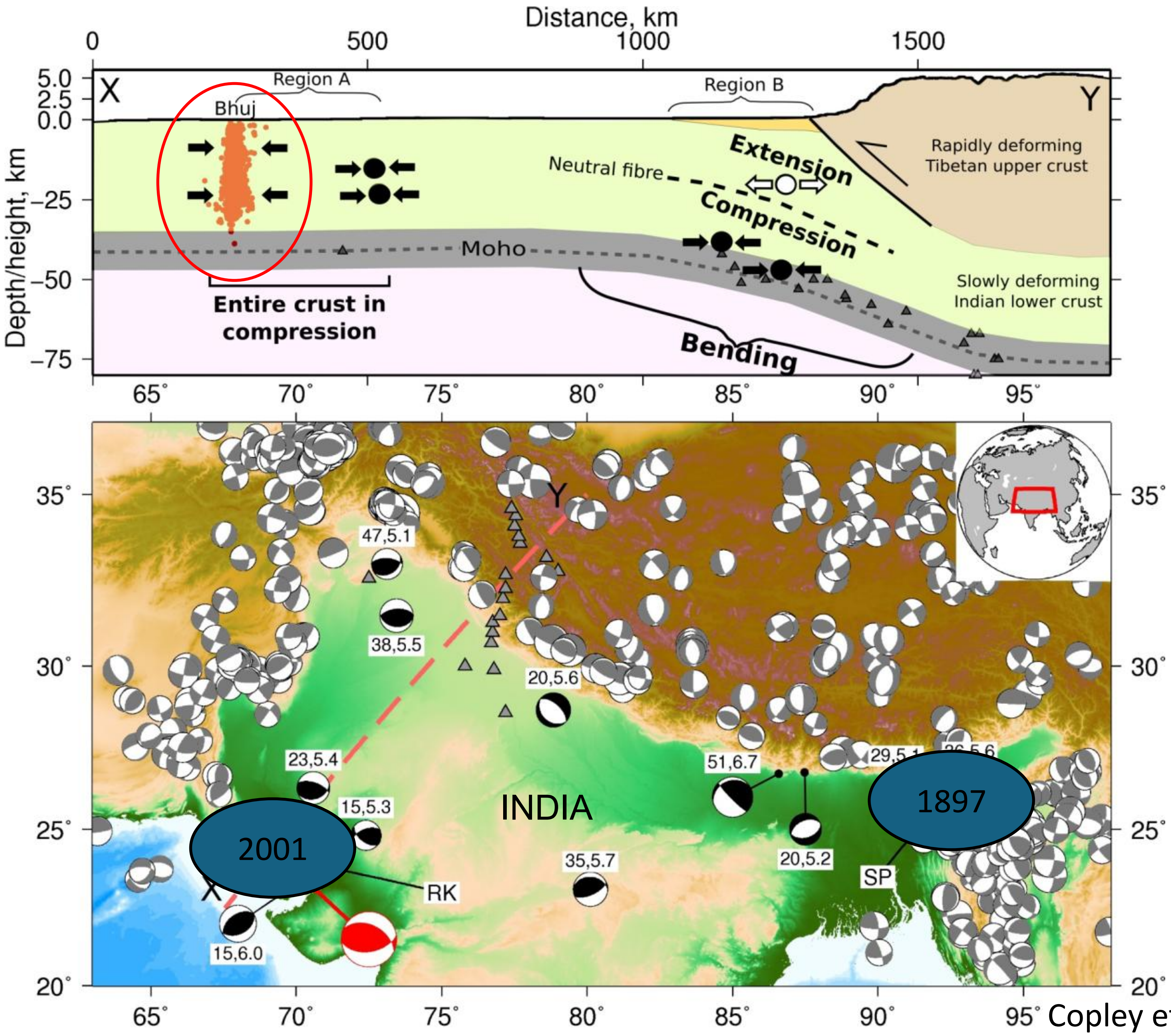


‘Stable continental region’ earthquakes

Rare (low strain rates because of strength), but can be huge.

- Hazard often not known in advance. Most recent event often prehistoric.

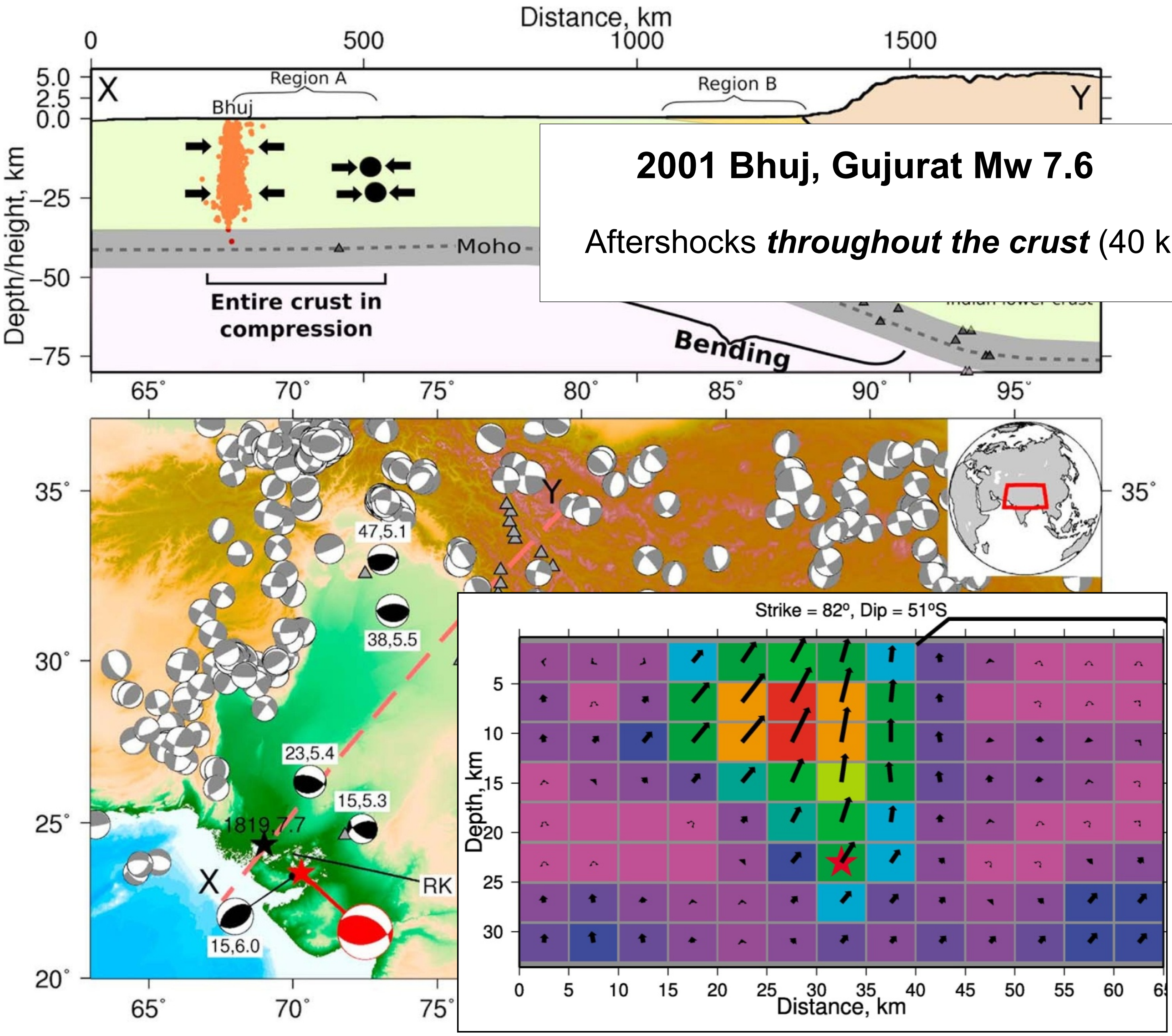
- Can be larger magnitude than a country is used to thinking about.

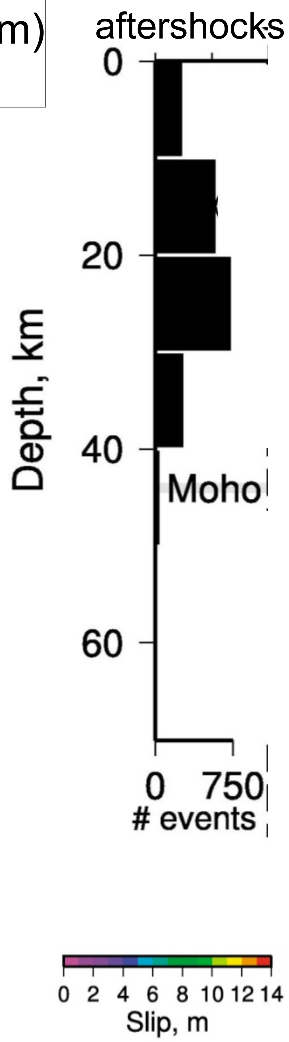


Copley et al (2011)

2001 Bhuj, Gujurat Mw 7.6

Aftershocks ***throughout the crust*** (40 km)

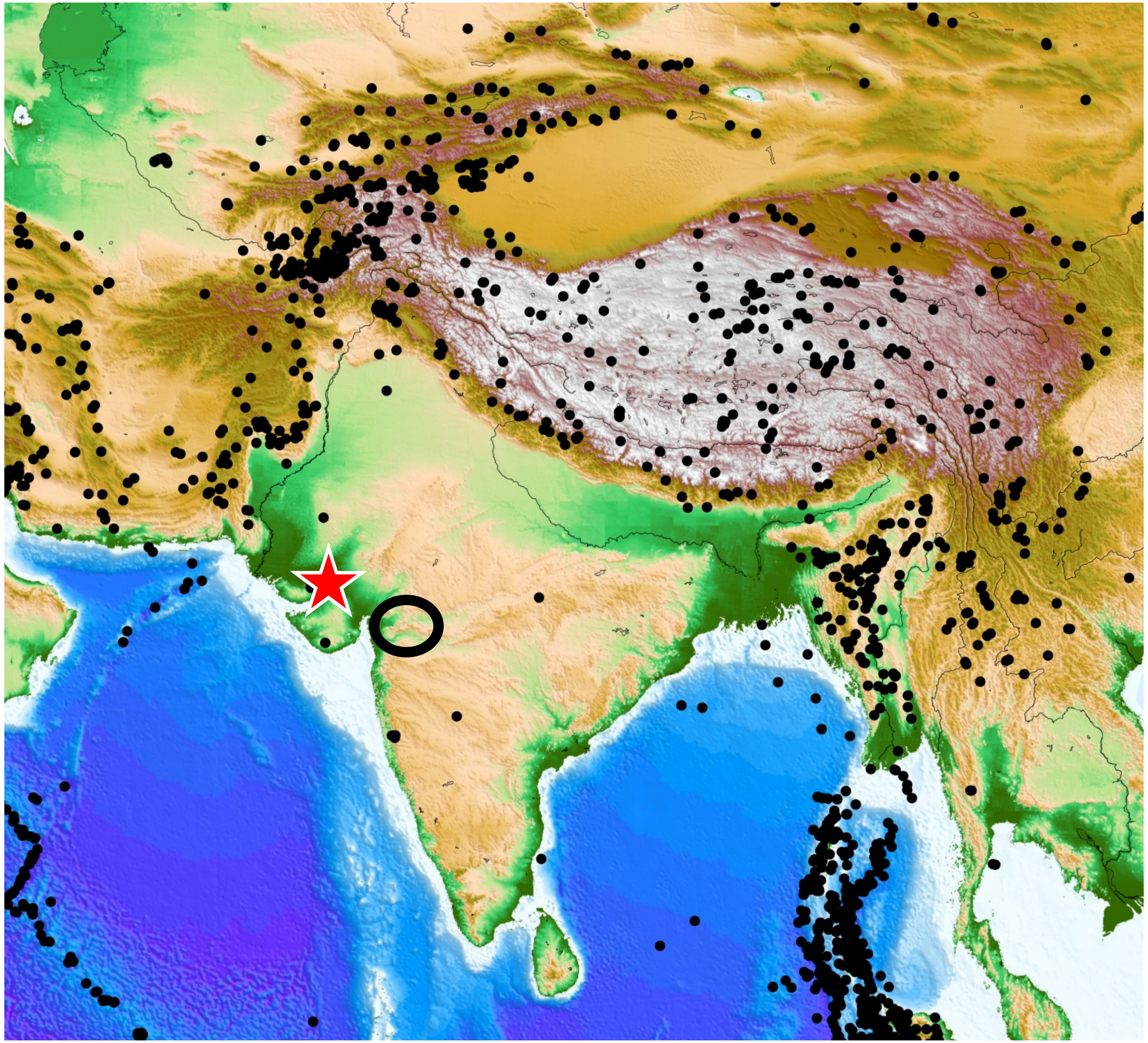




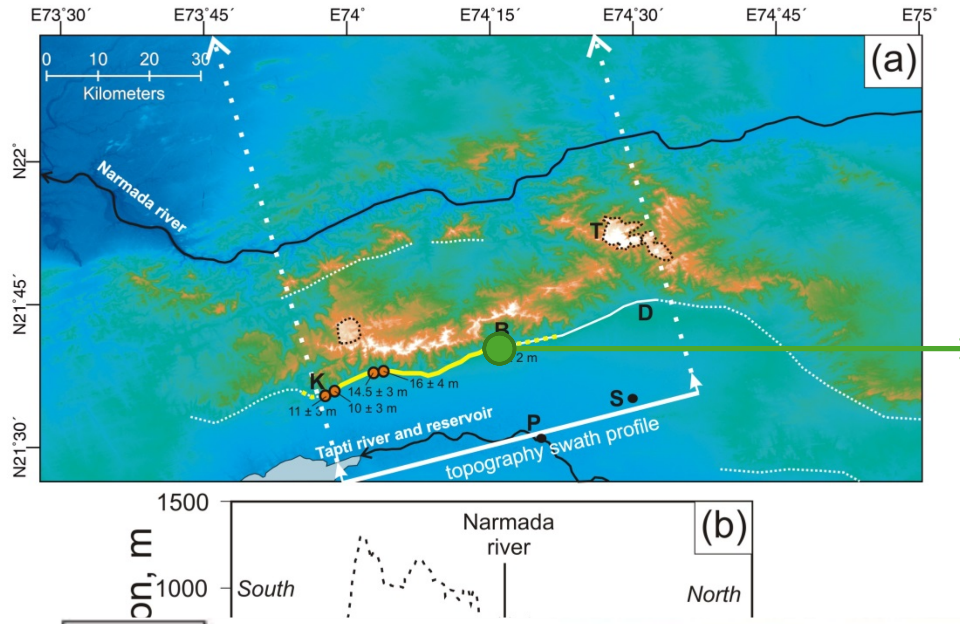
Copley et all, JGR, 2011

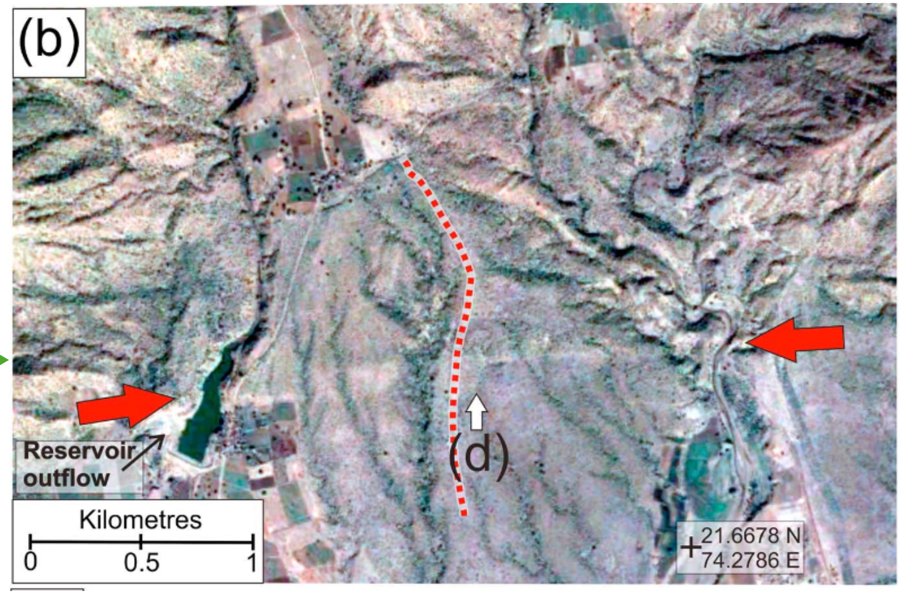
Copley et al (2011)

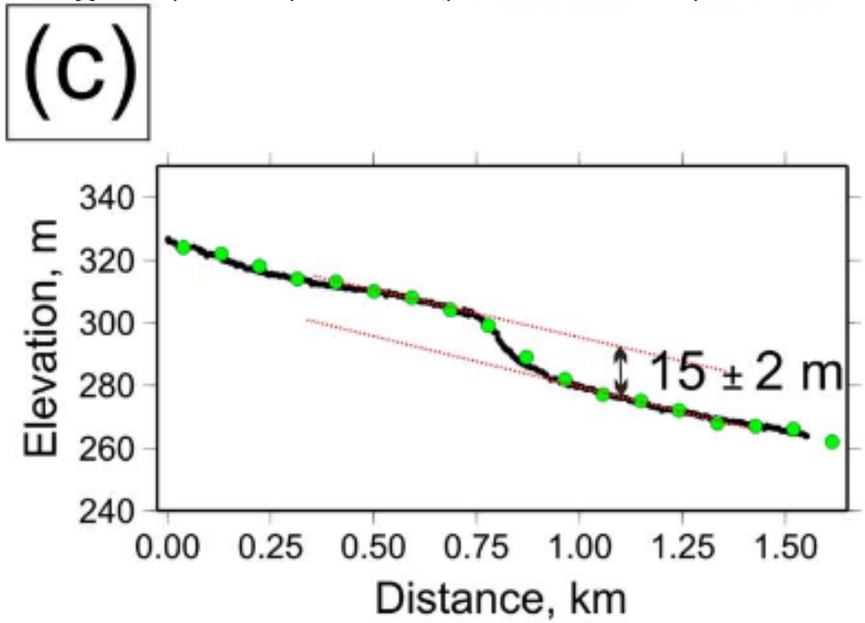
Is Bhuj unique?



Topography of the Tapti Fault

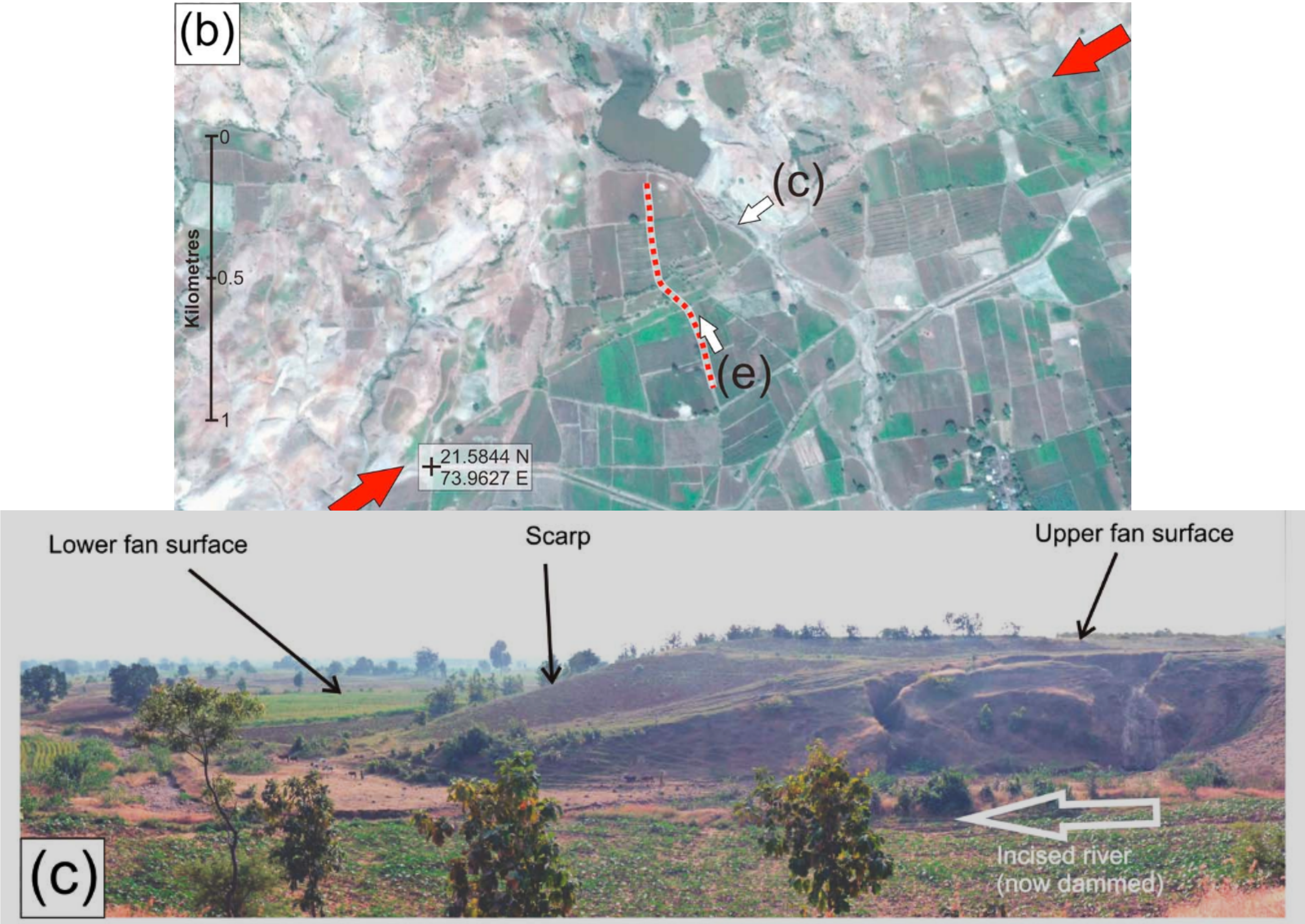






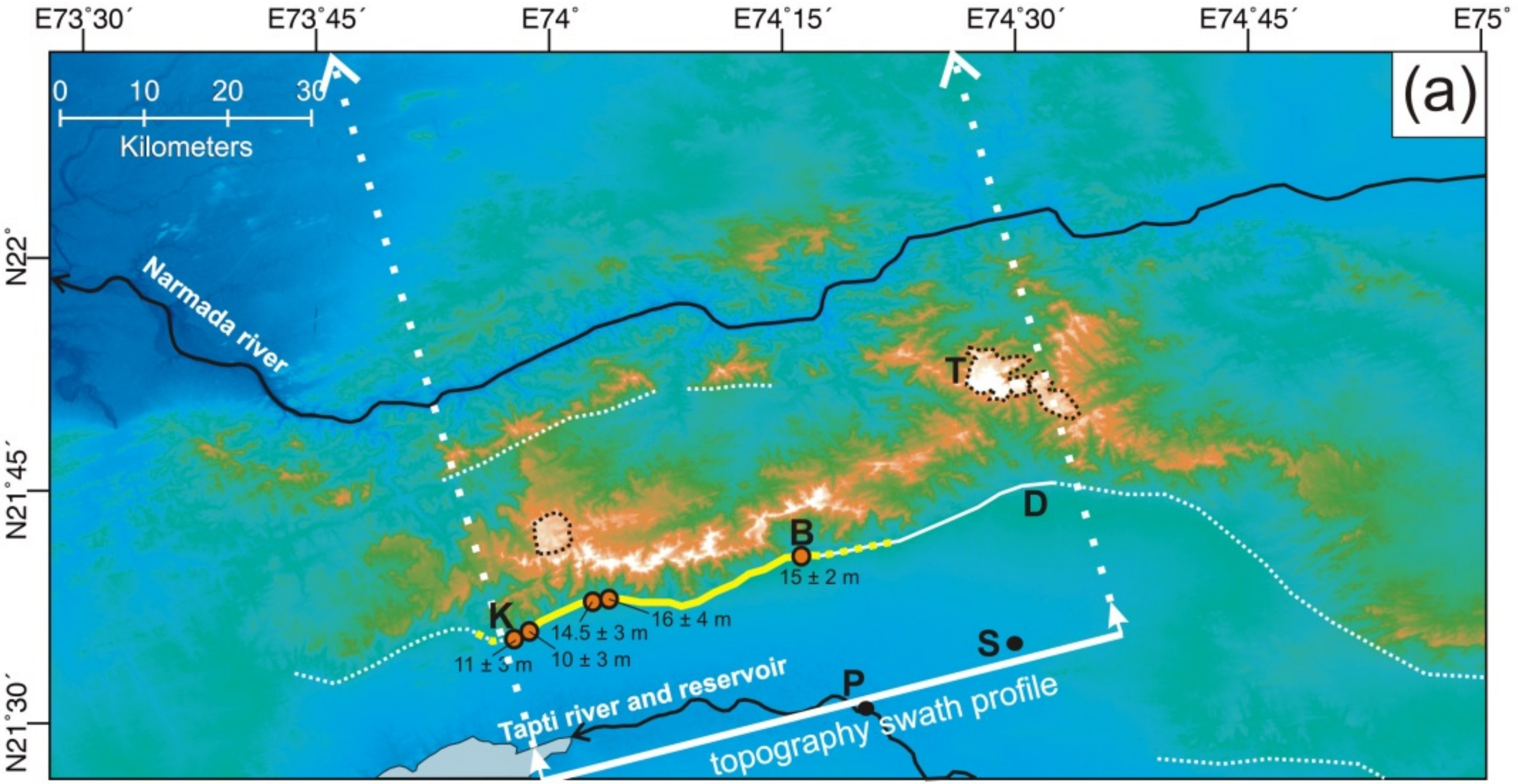
Copley et al (2014)

Alluvial fan offsets



Copley et al (2014)

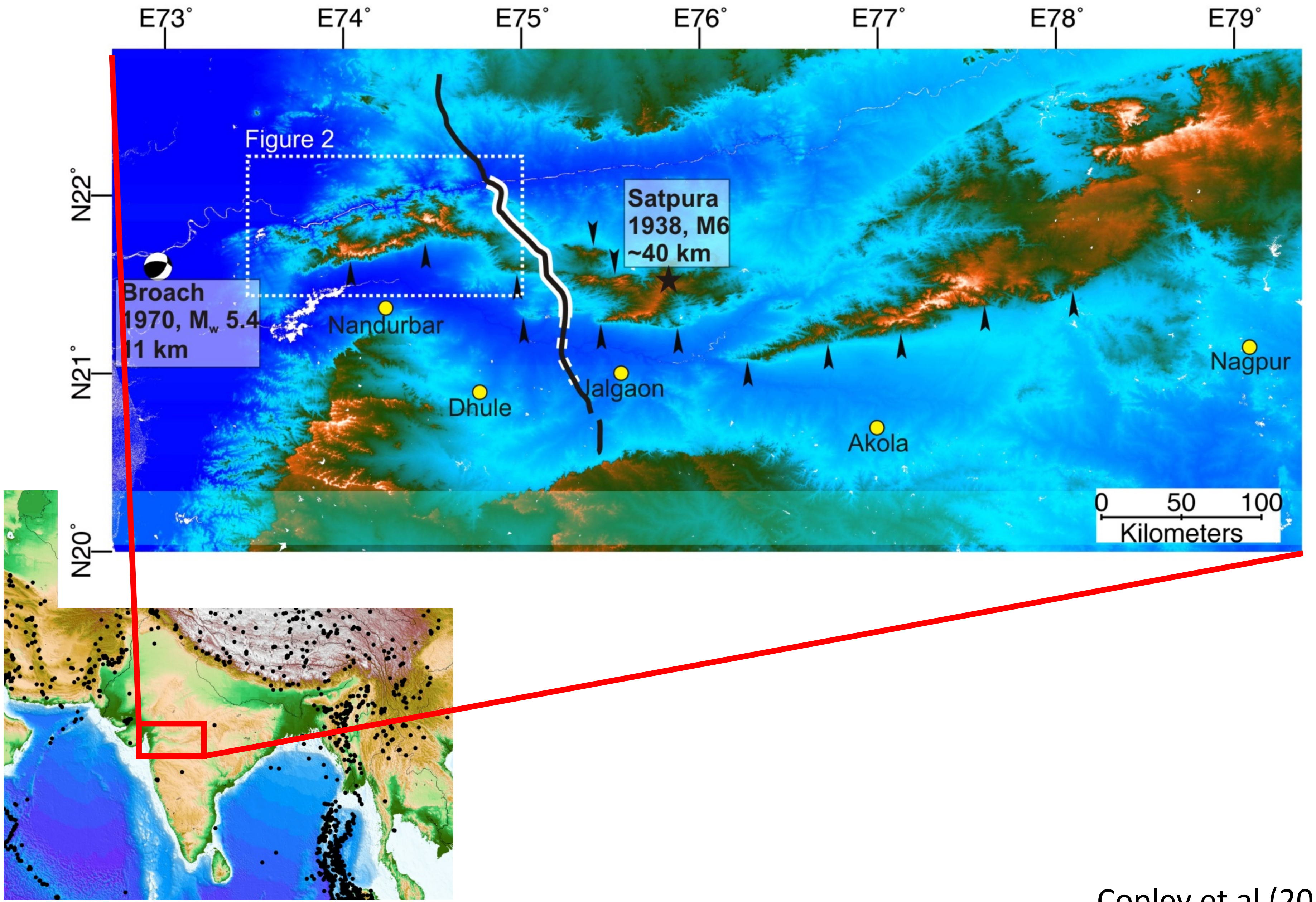
Alluvial fan offsets



Ancient Tapti Fault earthquake: mag. 7.8 – 8.4
Stress drop approx. same as Bhuj

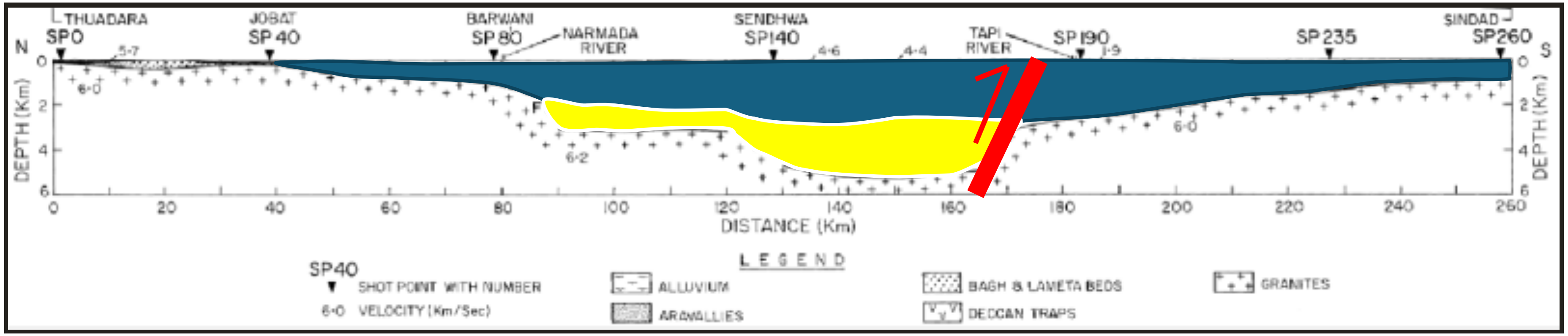
Copley et al (2014)

Active faults in central India

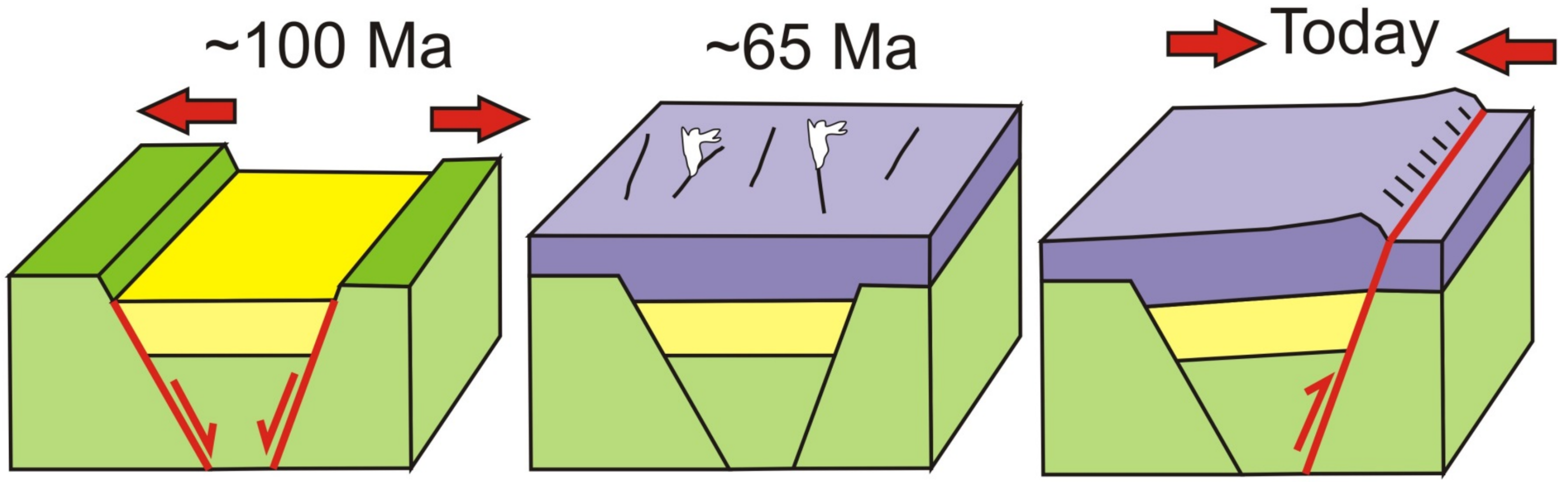


Copley et al (2014)

What controls the location of the faulting?



Sridhar and Tewari 2001

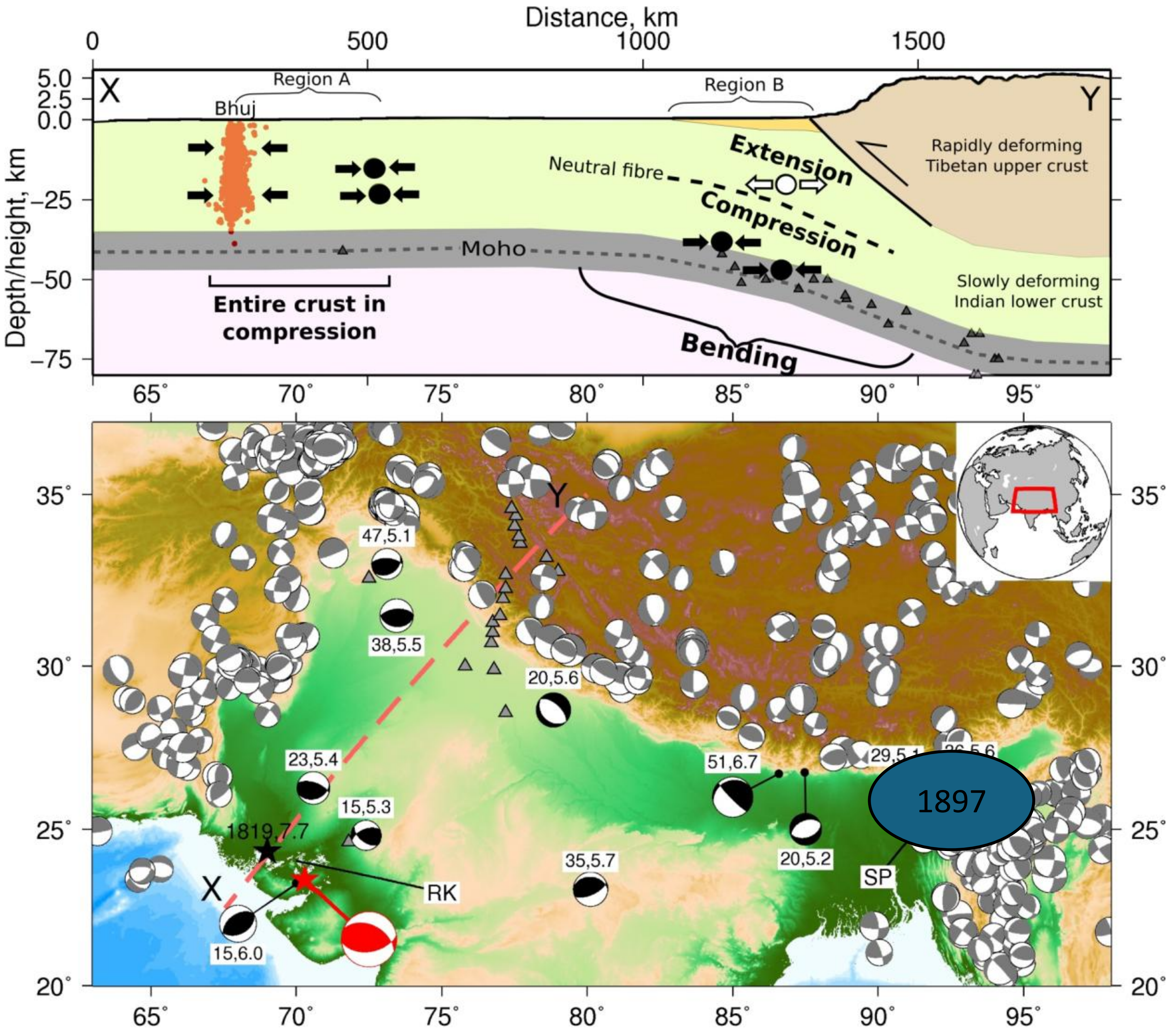


Extensional faulting
Rift filled with sediments

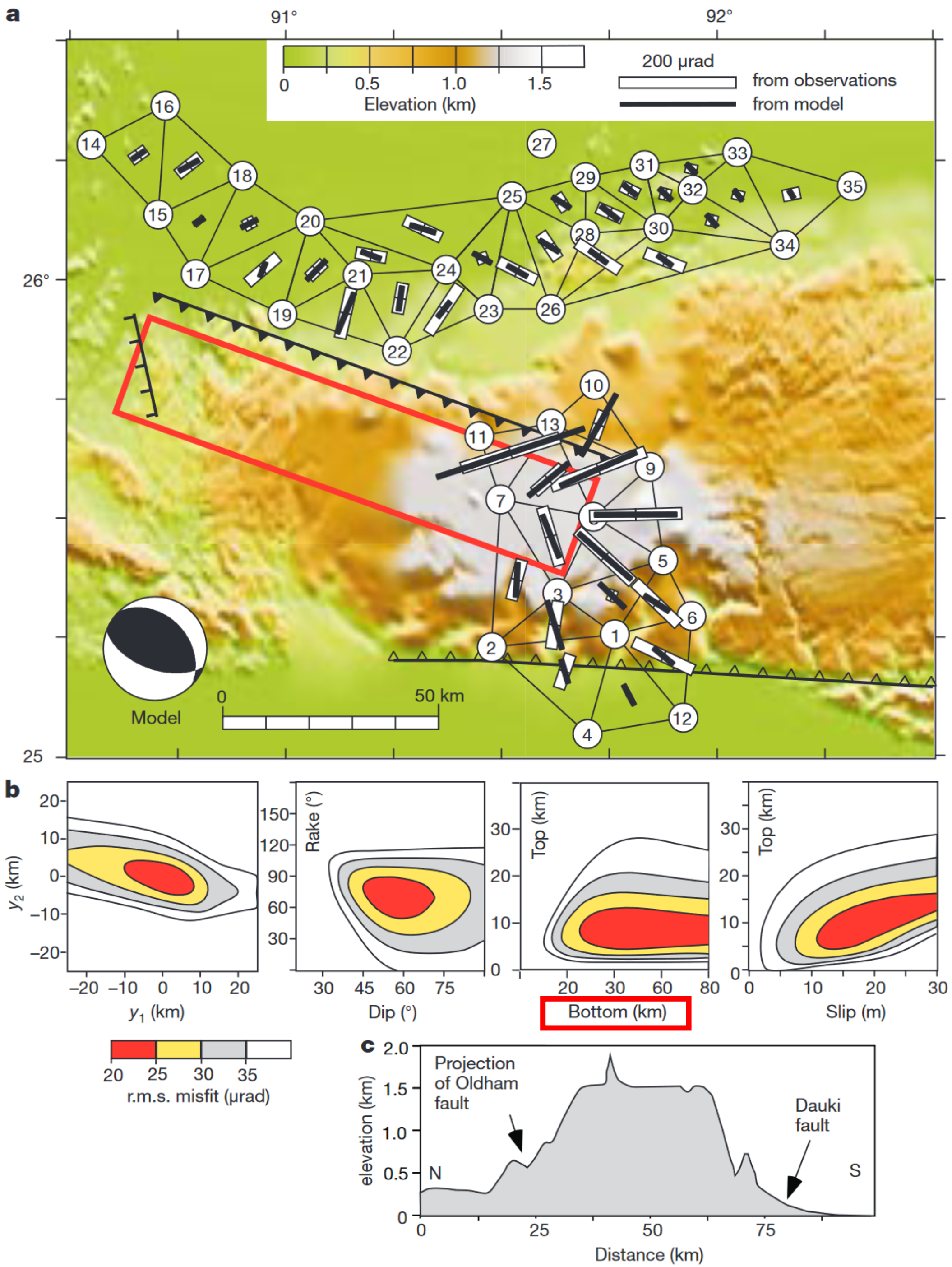
Eruption of Deccan volcanics

Thrust faulting on old normal faults

Copley et al (2014)



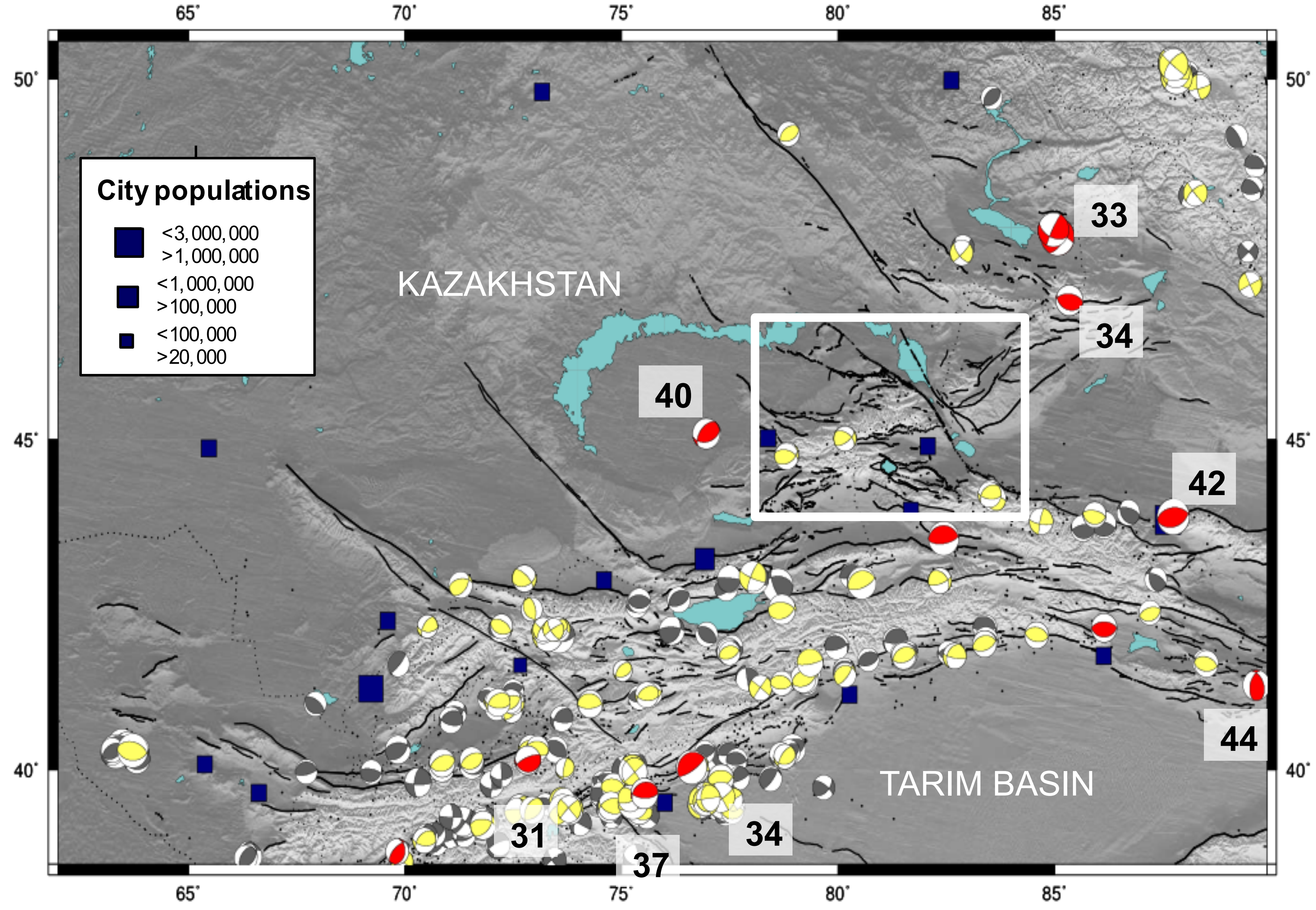
Distance, km
0
500
1000
1500
5.0
2.5
0.0
−25
−50
−75
Depth/height, km
X
Y
Region A
Region B
Bhuj
Extension
Neutral fibre
Compression
Rapidly deforming
Tibetan upper crust
Moho
Slowly deforming
Indian lower crust
Entire crust in
compression
Bending
65°
70°
75°
80°
85°
90°
95°
35°
30°
25°
20°
47,5.1
38,5.5
20,5.6
23,5.4
15,5.3
1819,7.7
35,5.7
51,6.7
20,5.2
29,5.1
26,5.6
1897
SP
RK
15,6.0



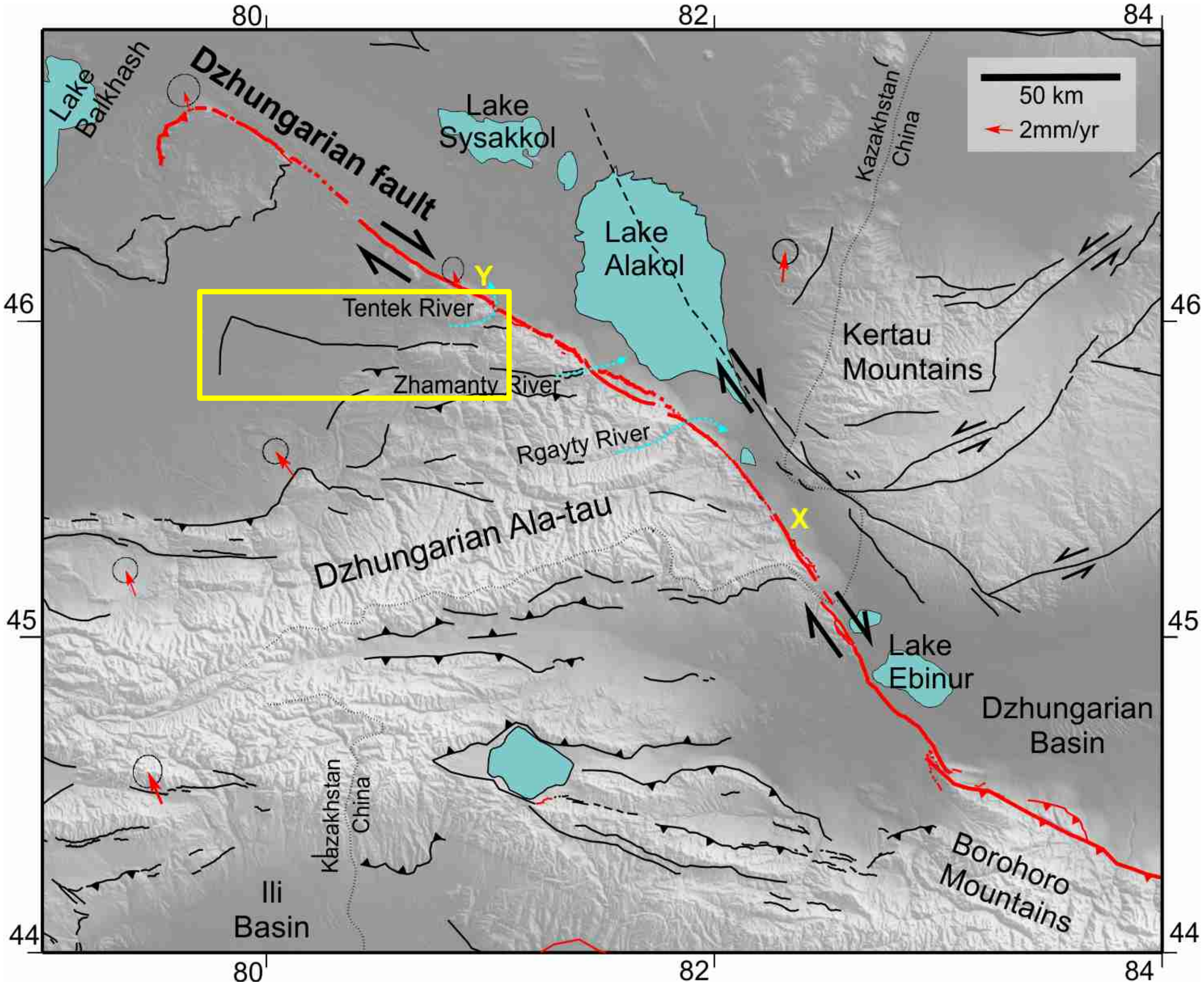
Thrust faulting

Magnitude ~ 8

Bilham and England (2001)

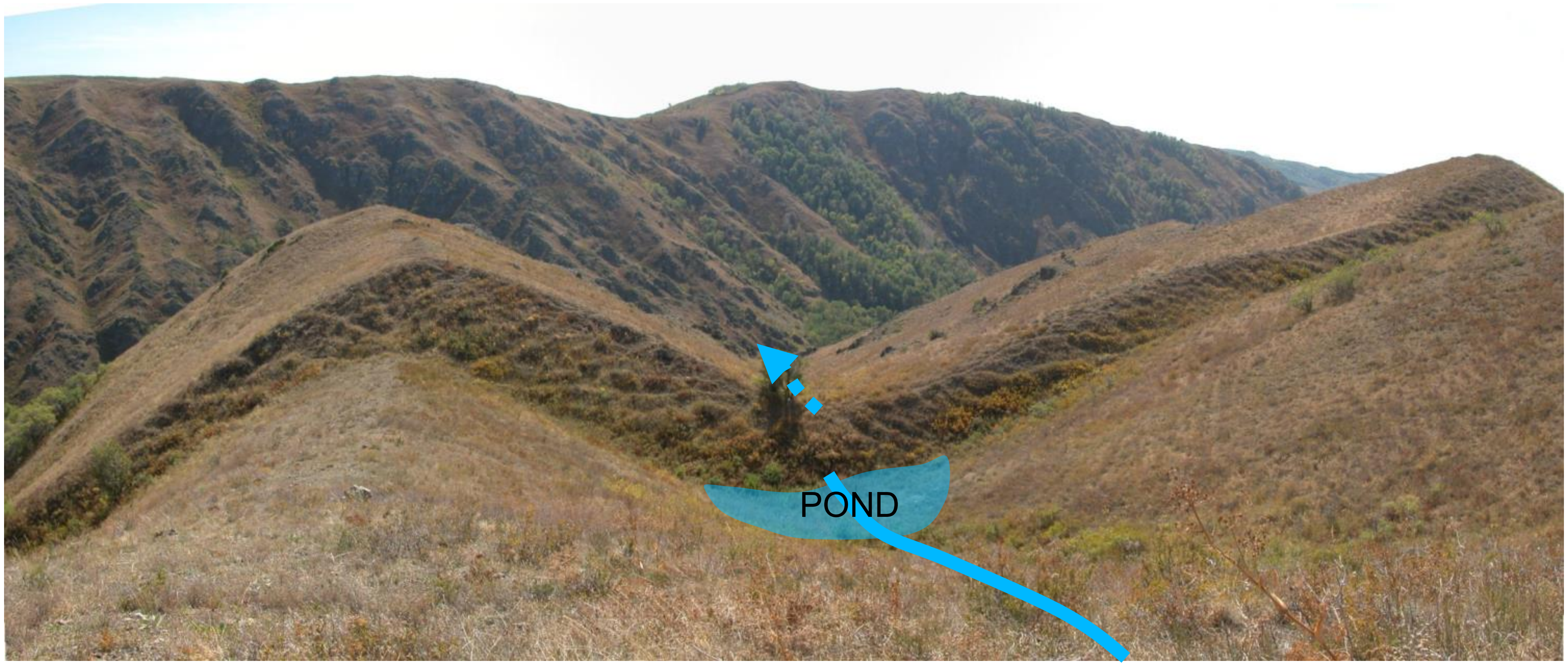


Campbell et al, 2013



Campbell et al, 2013

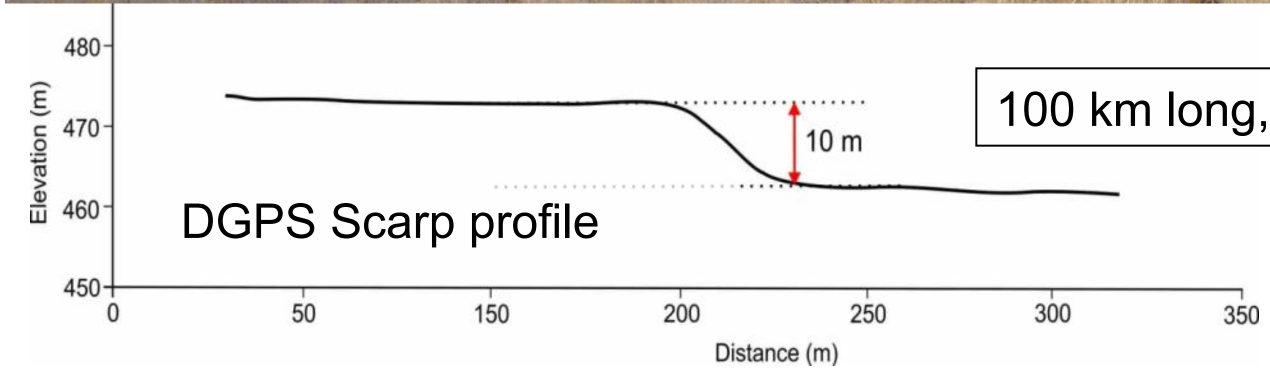
Lepsy Fault, east end: Dzungar Alatau



Campbell et al, 2013

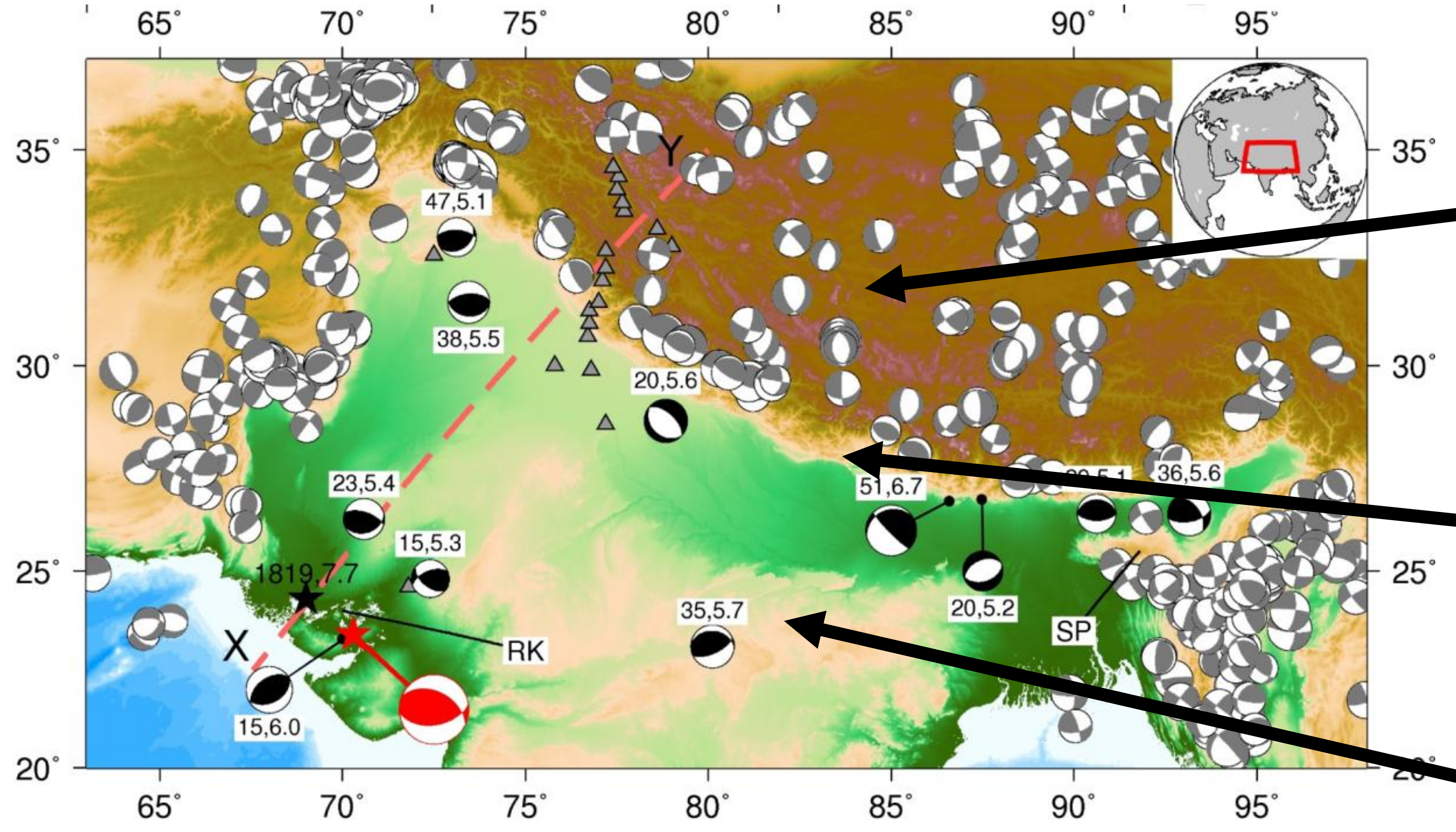

Lepsy Fault, Dzungar Alatau
10 metres

Lepsy Fault, Kazakhstan



100 km long, 10m slip …. Magnitude ~8

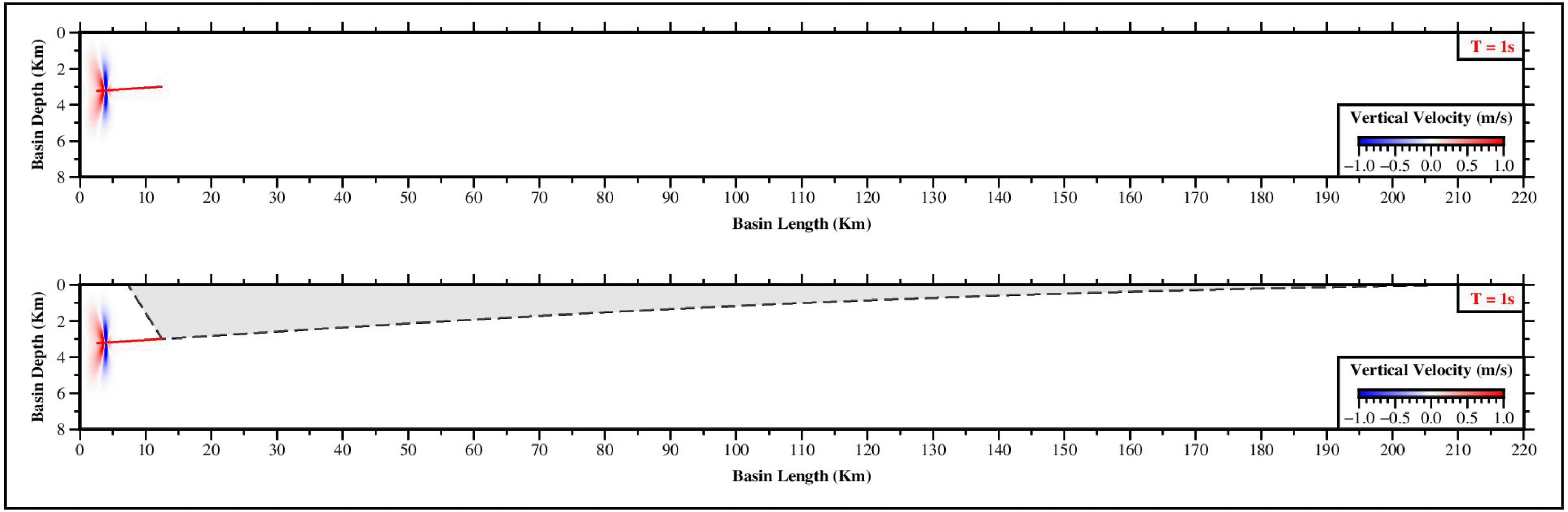
Campbell et al, 2013



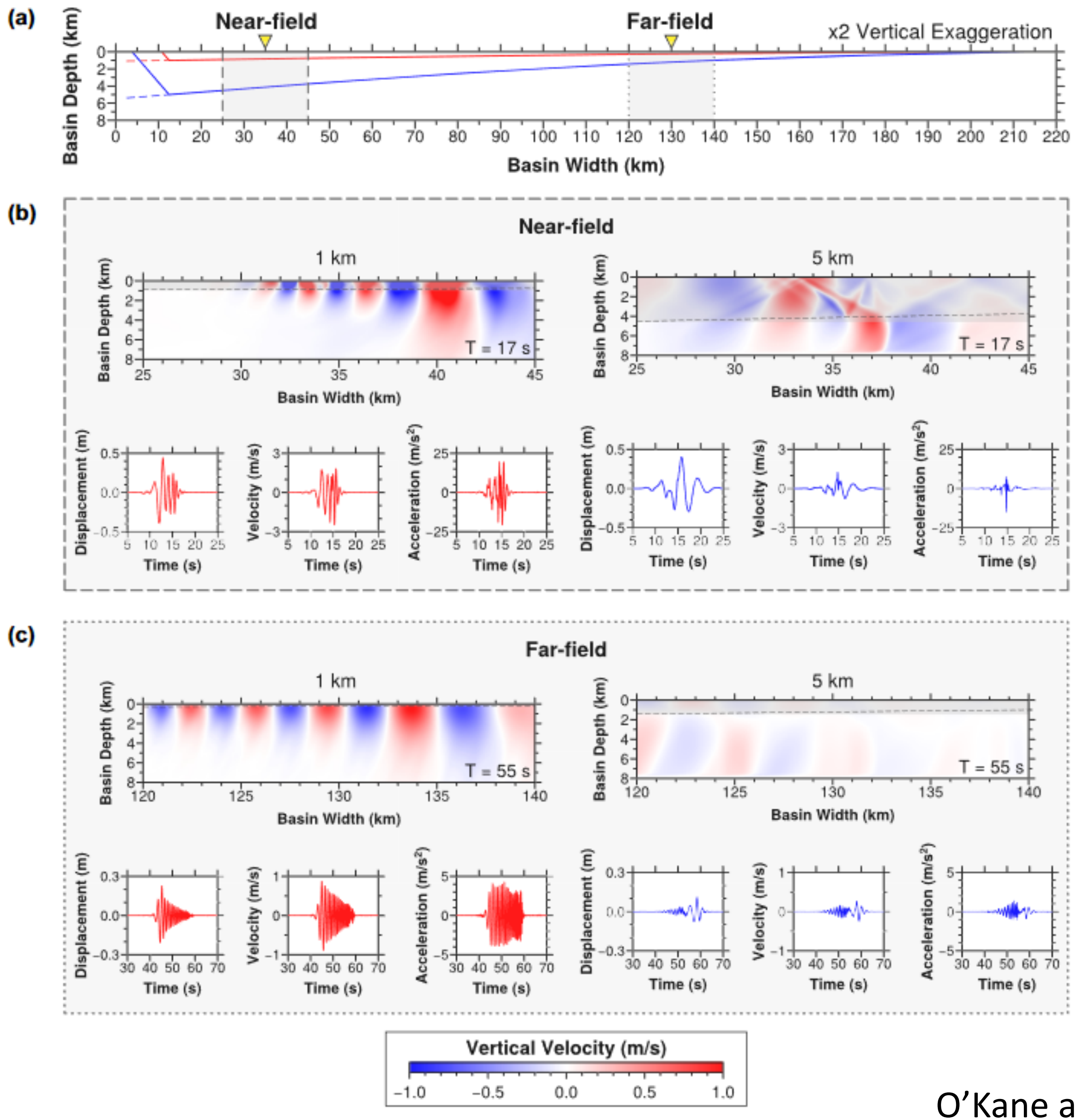
Weak crust
Thin seismogenic layer
Regular earthquakes
Mostly mag 6 (in range interior)

On the strength contrast
Regular earthquakes
Can be mag 7 to 8

Strong crust
Thick seismogenic layer
Rare earthquakes
Can be mag 7 to 8



O’Kane and Copley (2021)



O'Kane and Copley (2021)

Summary

- The forces driving lithosphere deformation

- The importance of strength contrasts in governing the behaviour

- The link between lithosphere structure/strength and earthquake locations and characteristics