Earth Science Applications of Space Based Geodesy

DES-7355

Tu-Th 9:40-11:05

Seminar Room in 3892 Central Ave. (Long building)

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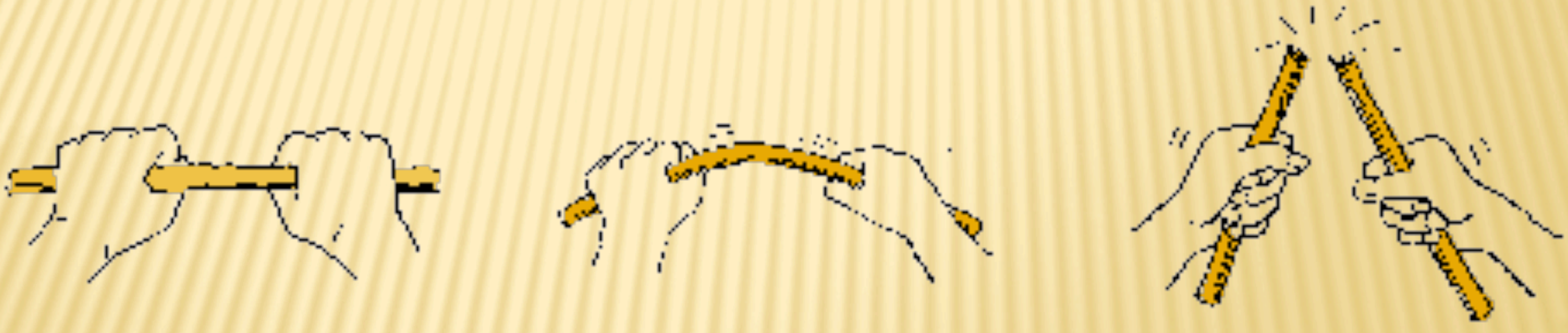
Office Hours – Wed 14:00-16:00 or if I' m in my office.

http://www.ceri.memphis.edu/people/smalley/ESCI7355/ESCI_7355_Applications_of_Space_Based_Geodesy.html

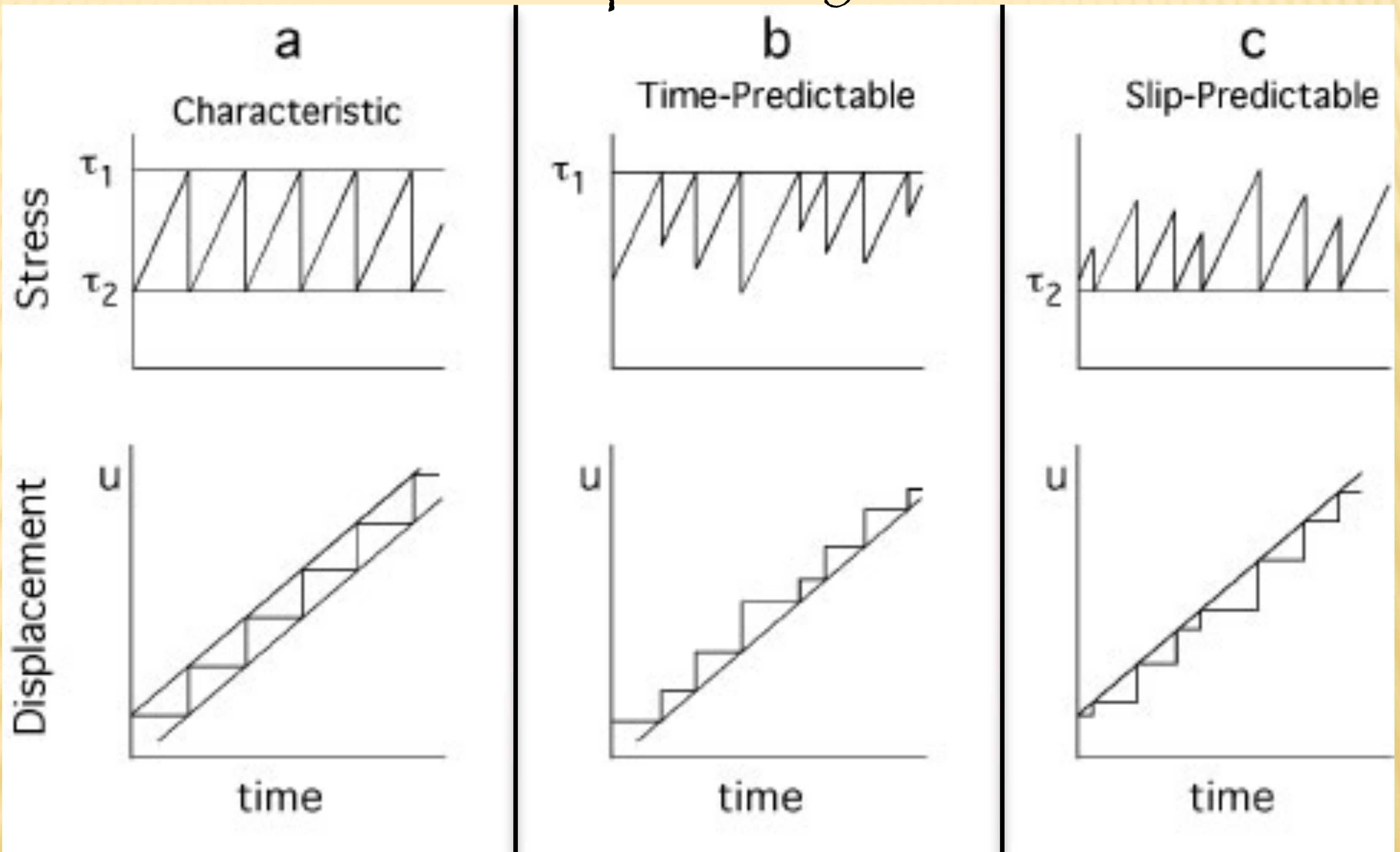
Class 13

Dynamics:
“Physics” of earthquakes



http://www.washington.edu/burkemuseum/earthquakes/bigone/waves.html

Earthquake "cycle"



Gives time and size of next earthquake. Seismic gap theory is application of this model.

Gives time, but not size of next earthquake.

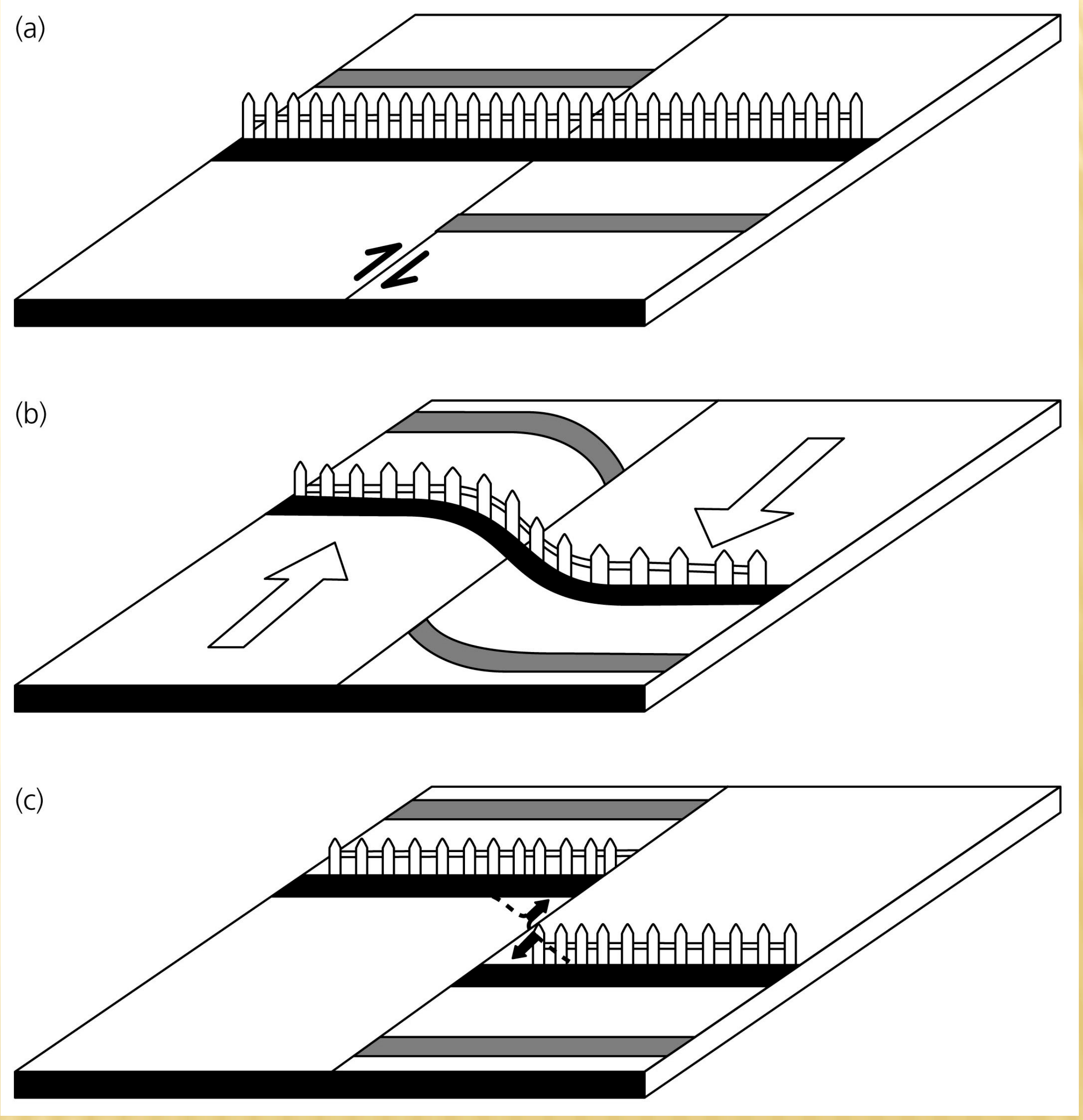
Gives size of next earthquake for any selected time in future.

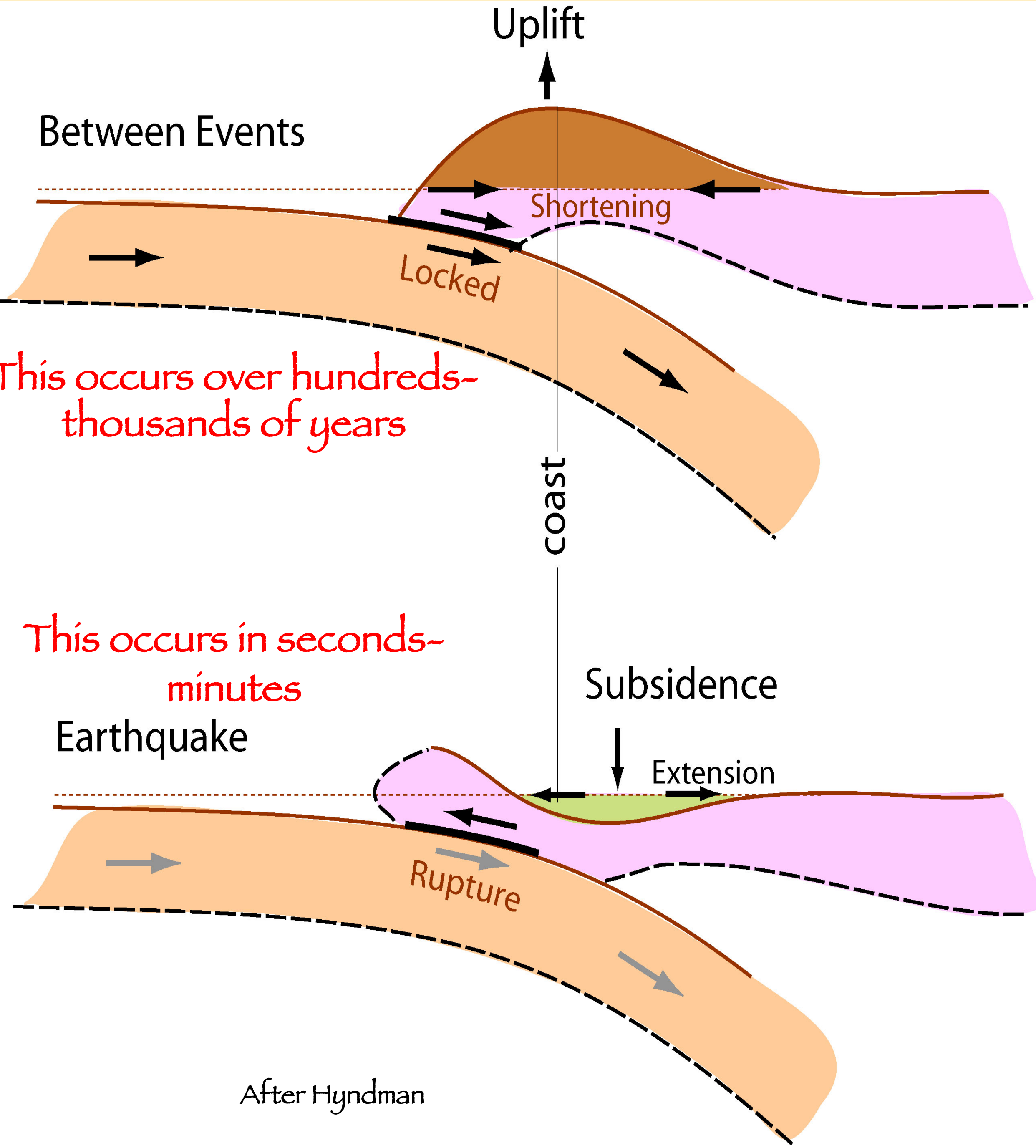
Reid's ELASTIC REBOUND OR SEISMIC CYCLE MODEL

Materials at distance on opposite sides of the fault move relative to each other, but friction on the fault "locks" it and prevents slip

Eventually strain accumulated is more than the rocks on the fault can withstand, and the fault slips in earthquake

Earthquake reflects regional deformation



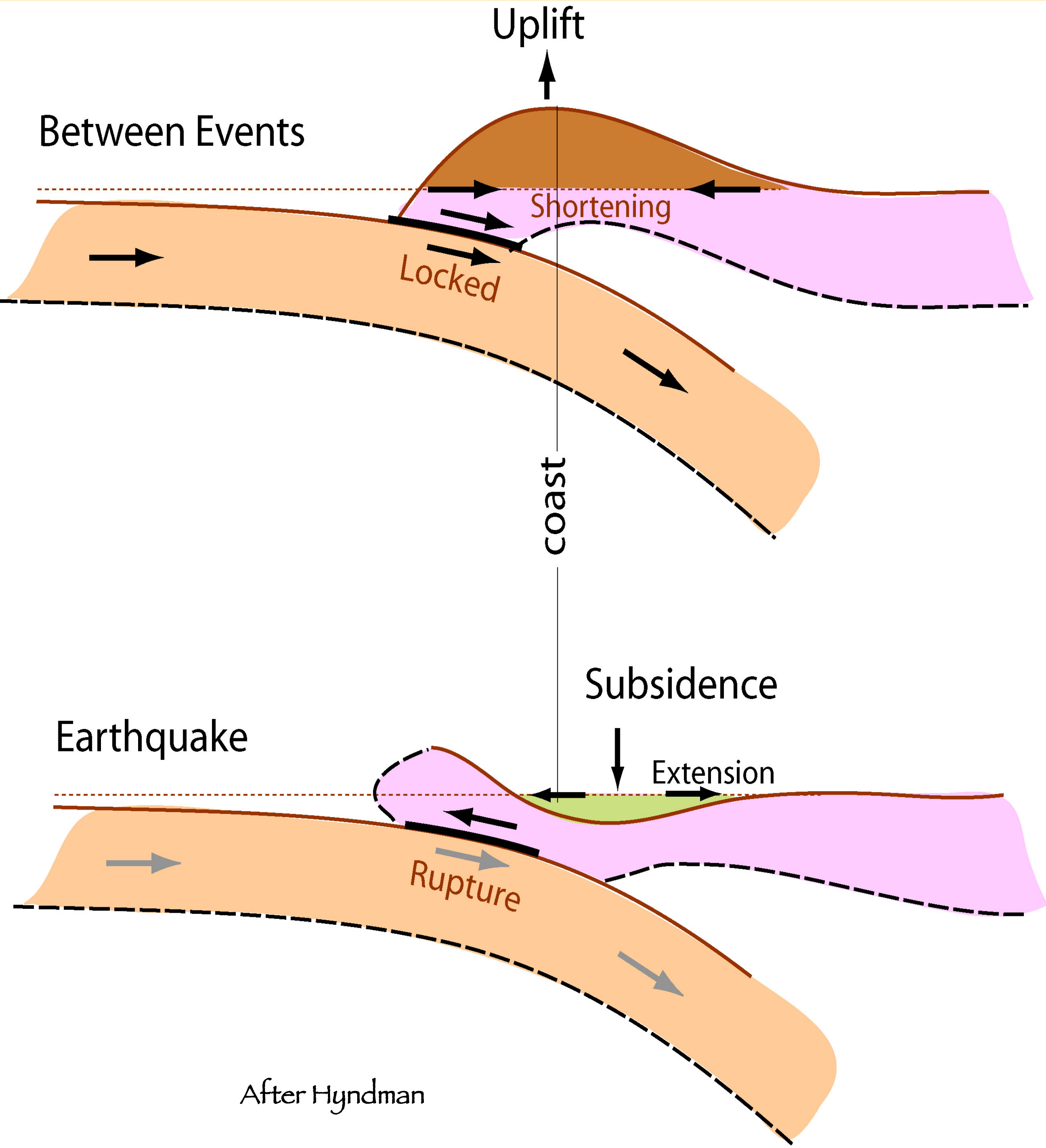


Subduction zone version of Elastic Rebound:

Cartoons for upper plate deformation during the interseismic (between earthquakes)

and seismic (earthquake)

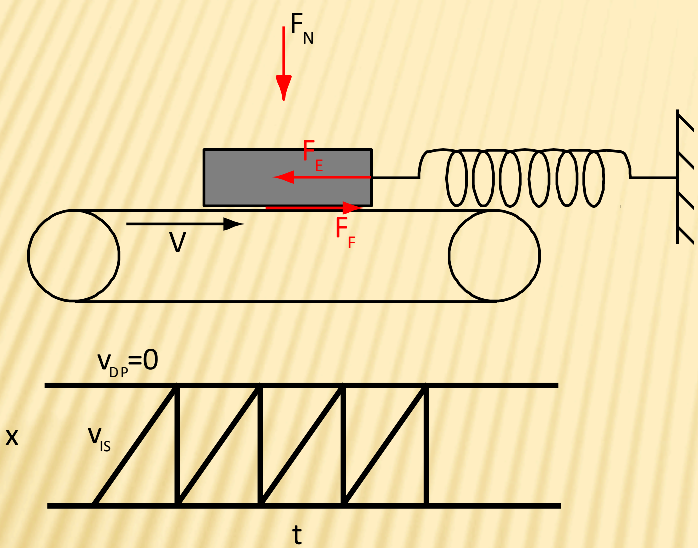
stages of the earthquake cycle.

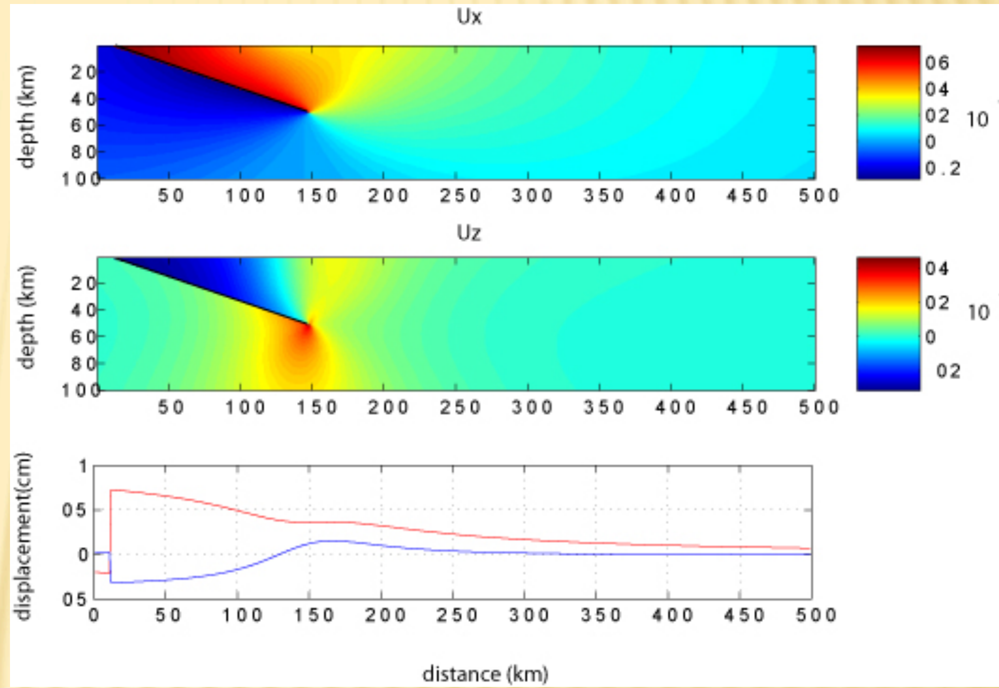


We will not look at each of the two parts individually.

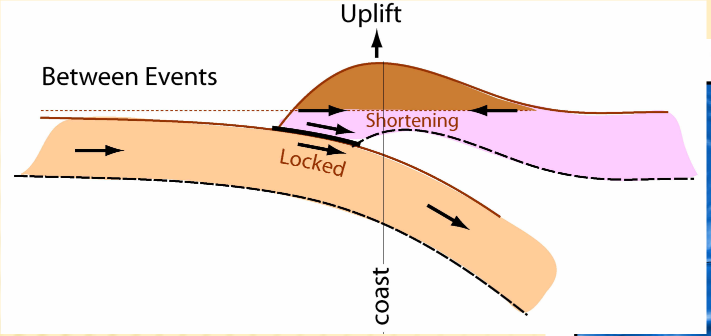
The earthquake first.

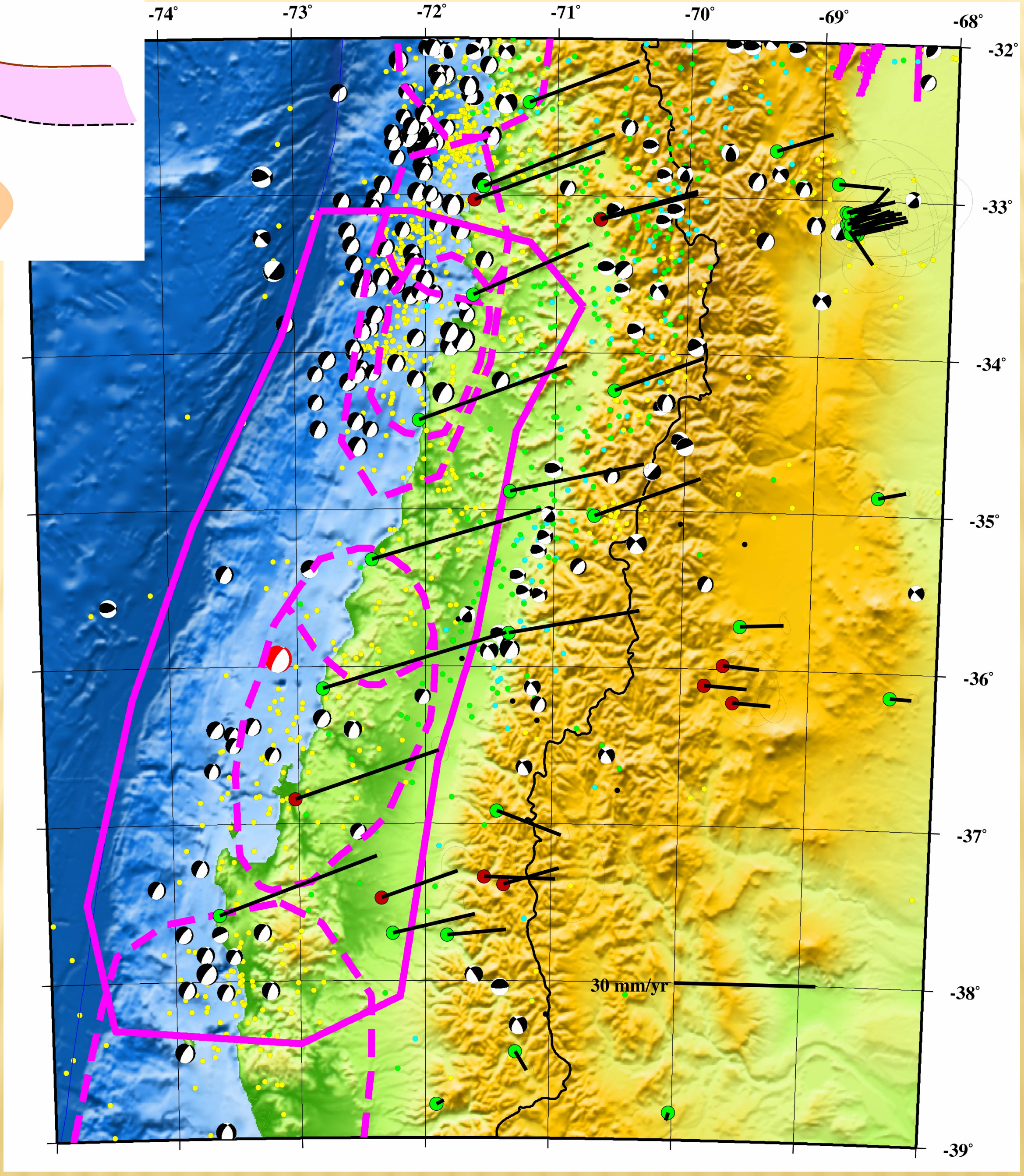
Elastic modeling of subduction process

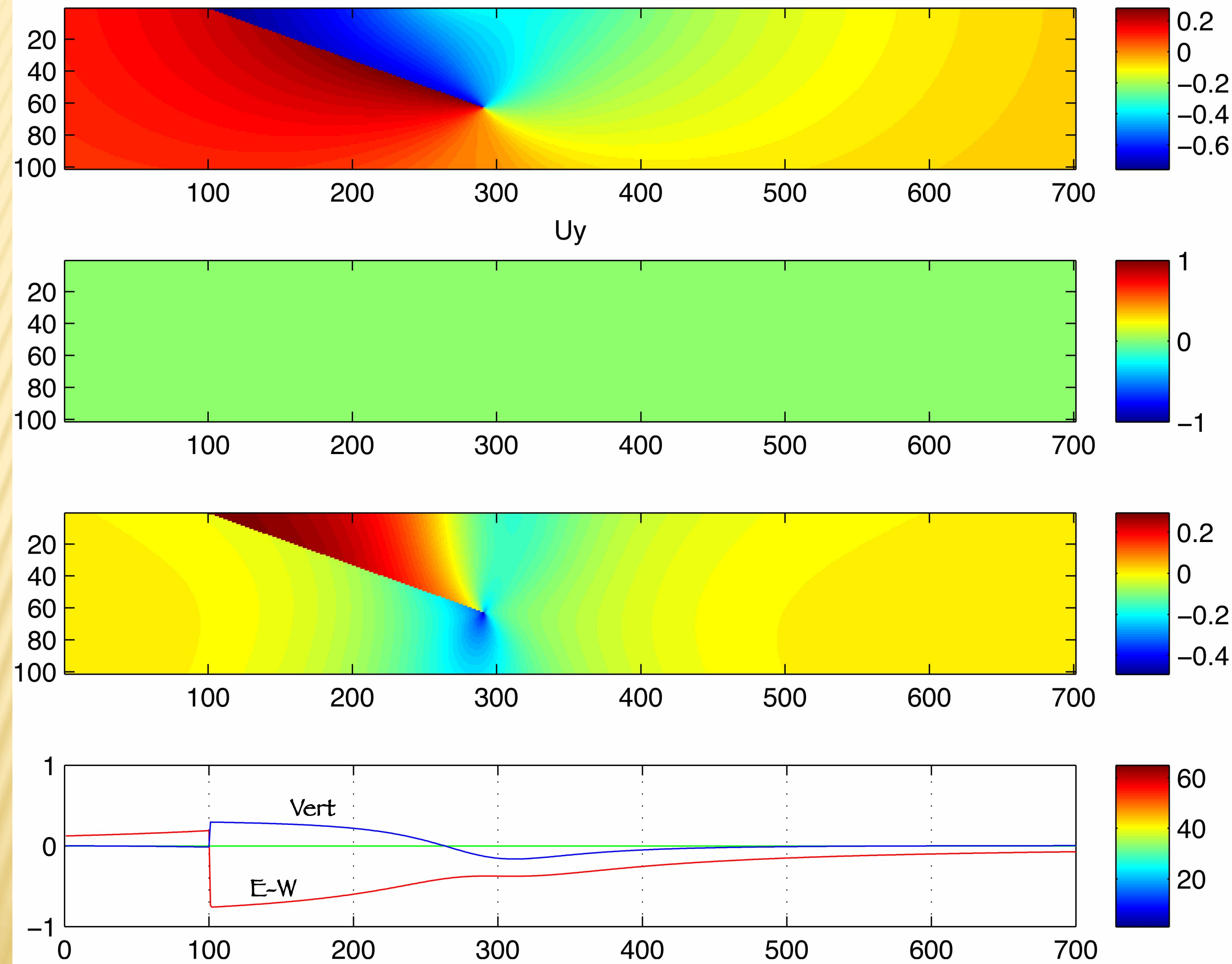




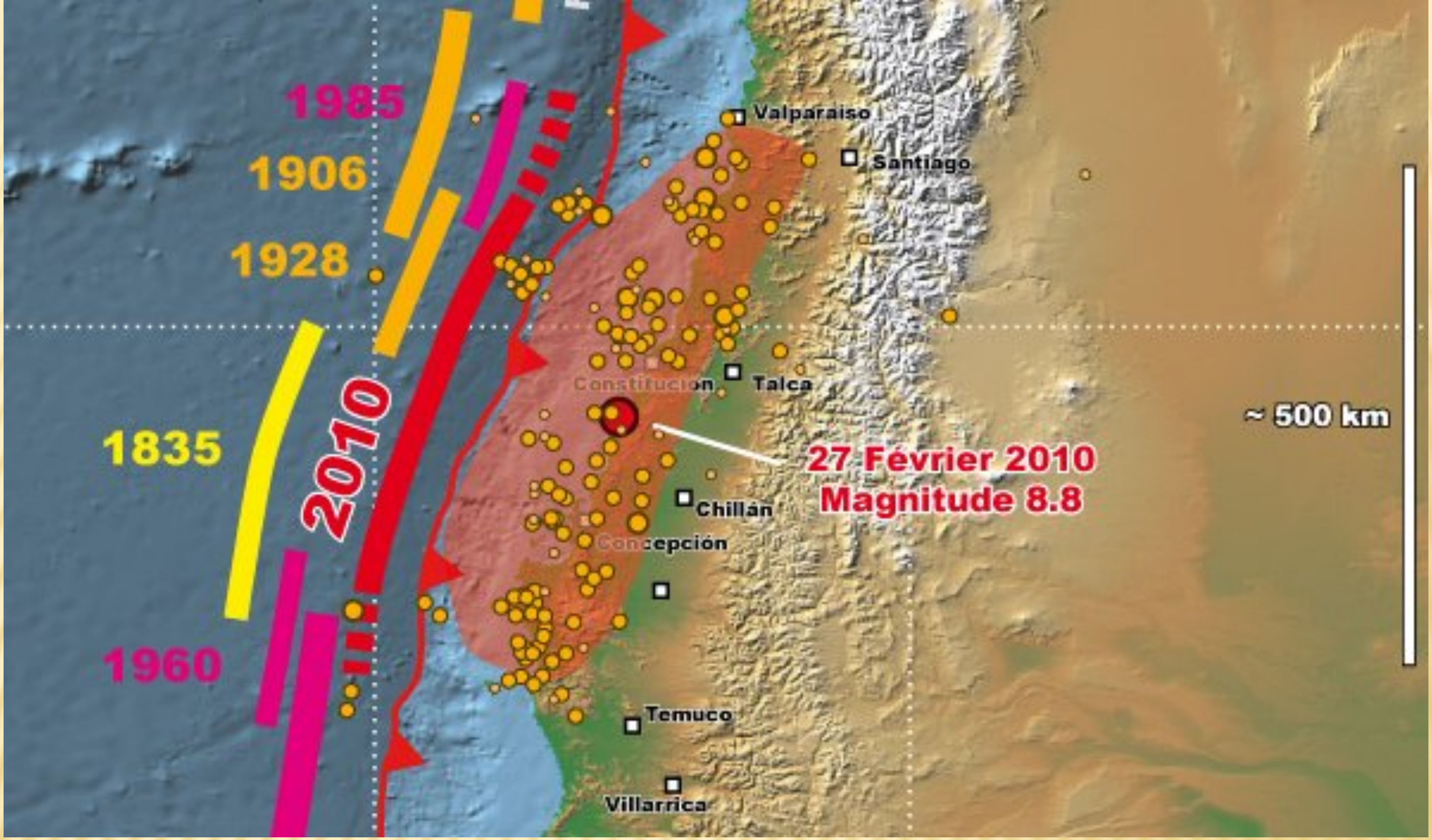
No permanent deformation (no mountains)


Uplift
Between Events
Shortening
Locked
coast


-74°
-73°
-72°
-71°
-70°
-69°
-68°
-32°
-33°
-34°
-35°
-36°
-37°
-38°
-39°
30 mm/yr



Elastic modeling of co-seismic deformation



Historical seismicity

Ruegg (2009) – no earthquake since 1835 => "mature seismic gap".

Estimated slip (rate x time) and max 8-8.5 from slip, but not rupture length.

Montessus de Ballore and Lacassin

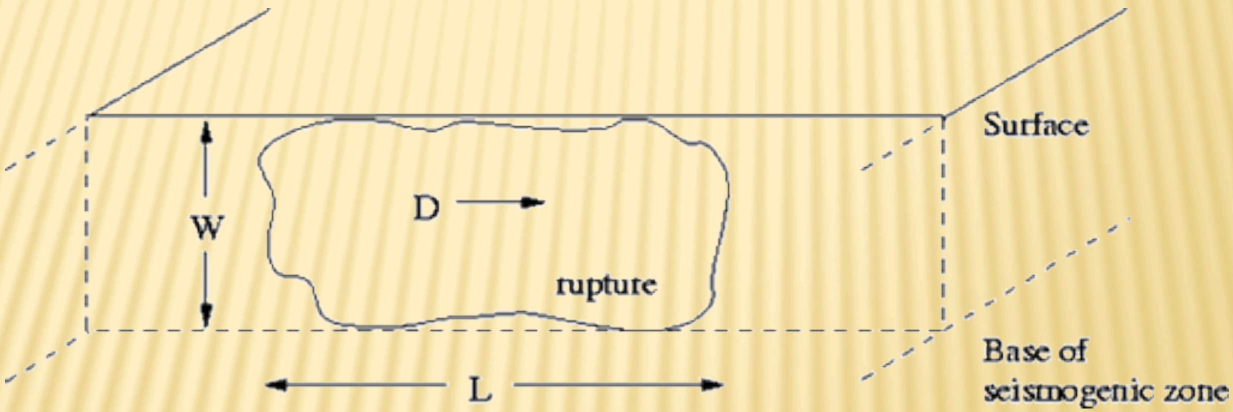
Tangent / aside

How "big" is a magnitude 5 earthquake?

(assume a square fault.
The answer will specify
1) the dimensions of the square and
2) the amount of slip.)

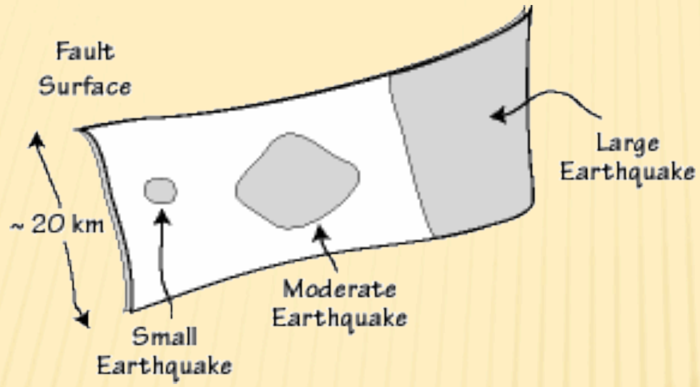
Earthquakes are caused by internal torques, from interactions of different blocks of the earth on opposite sides of faults.

After some rather complicated mathematics, it can be shown that the moment of an earthquake is simply expressed by:



$$M_0 = \mu AD$$

where μ is rigidity (units of stress = force/Area), A is fault area and D is average slip



The size of the area that slips, and the amount of slip that occurs during an earthquake both increase with earthquake size.

The shaded regions on the fault surface are the areas that rupture during different size events. The largest earthquakes generally rupture the entire depth of the fault

Notice that seismic moment does not saturate.

Also notice that it has the same units (dyne-cm = force times distance) as work and energy BUT it is NOT the same as work and energy (that's why we use dyne-cm or newton-m and not joules or ergs for seismic moment!).

Now we can (empirically) relate seismic moment, M_0, to the magnitude scales. We will do this by creating Moment Magnitude, M_W.

$$M_W = 2/3 \log M_0 - 10.73$$

$$\log M_0 = 3/2\, M_W + 16.1$$

And doing the same for the energy

$E = M_0/(2 \times 10^4)$ erg in terms of M_0, the seismic moment

Seismic moment is proportional to the product of the geologically reasonable and observable parameters – fault area that slipped and how much it slipped.

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So, how big are the fault areas and amounts of slip?

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So, how big are the fault areas and amounts of slip?

Are the fault area (or dimensions) and the amount of slip related?

Enter - Earthquake scaling relationships.

Earthquake scaling relationships.

Can we have 10 m of slip on a 1 m^2 fault?

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Obviously not (ridiculous example to make point).

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Obviously not (ridiculous example to make point).

We know rocks break when subjected to strains of between (small strain, weak rock) 10^{-5} and (larger strain, strong rock) 10^{-4}.

This means you can only store up so much strain energy in a given volume of rock.

So let's say a rock will break when it has been strained by 1 part in 20,000, and all the strain is released (by slip).

This means the rupture displacement in an earthquake will typically be about 1/20,000 of the rupture length.

For example, a 1 km long rupture would give a displacement of about 1km/20,000, or 0.05 meters.

A 100 km long rupture (more on this for non-symmetric faults a bit later) produces a displacement of a few meters.

Using this idea, scaling between fault size and slip, we can calculate typical rupture dimensions and slips for different moments and moment magnitudes.

Magnitude Mw	Fault area (km2)	Typical rupture dimensions (km x km)	Slip
4	1	1 x 1	5 cm
5	10	3 x 3	15 cm
6	100	10 x 10	.5 m
7	1000	30 x 30	1.5 m
8	10,000	50 x 200	2.5m,10m?

What happens with the last example? Which "size" do we use? Answer (probably) depends on direction of the slip.

km2cm	slipratio	rigidigy	moment	moment mag		
1.00E+05	1.00E-04	3.00E+11	1.00E+00	-1.07E+01		
perp dirn	slip dirn	slip	moment	moment mag	slip cm	
km	km	km				
1.00E+02	2.00E+01	2.00E-03	1.20E+27	7.35E+00	2.00E+02	
1.00E+01	1.00E+01	1.00E-03	3.00E+25	6.28E+00	1.00E+02	
2.00E+00	2.00E+00	2.00E-04	2.40E+23	4.89E+00	2.00E+01	
2.50E+00	2.50E+00	2.50E-04	4.69E+23	5.08E+00	2.50E+01	mag 5 size is 2.5 km x 2.5 km
3.00E+00	3.00E+00	3.00E-04	8.10E+23	5.24E+00	3.00E+01	
3.50E+00	3.50E+00	3.50E-04	1.29E+24	5.37E+00	3.50E+01	
8.00E+02	1.50E+01	1.50E-03	5.40E+27	7.79E+00	1.50E+02	1906 San Francisco
1.20E+03	2.00E+02	2.00E-02	1.44E+30	9.41E+00	2.00E+03	1960 Chile

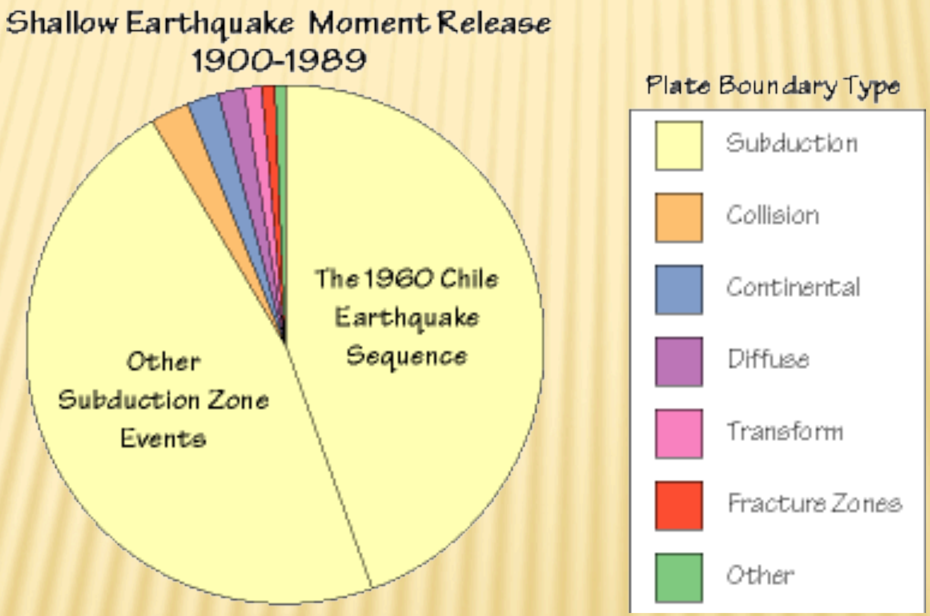
km2cm	slipratio	rigidigy	moment	moment mag		
1.00E+05	1.00E-04	3.00E+11	1.00E+00	-1.07E+01		
perp dirn	slip dirn	slip	moment	moment mag	slip cm	
km	km	km				
1.00E-03	1.00E-03	1.00E-07	3.00E+13	-1.72E+00	1.00E-02	
2.00E-03	2.00E-03	2.00E-07	2.40E+14	-1.11E+00	2.00E-02	
2.30E-03	2.30E-03	2.30E-07	3.65E+14	-9.92E-01	2.30E-02	mag -1 is 2.3 m x 2.3 m
3.00E-03	3.00E-03	3.00E-07	8.10E+14	-7.61E-01	3.00E-02	
4.00E-03	4.00E-03	4.00E-07	1.92E+15	-5.11E-01	4.00E-02	
5.00E-03	5.00E-03	5.00E-07	3.75E+15	-3.17E-01	5.00E-02	
6.00E-03	6.00E-03	6.00E-07	6.48E+15	-1.59E-01	6.00E-02	
7.00E-03	7.00E-03	7.00E-07	1.03E+16	-2.51E-02	7.00E-02	
8.00E-03	8.00E-03	8.00E-07	1.54E+16	9.09E-02	8.00E-02	mag 0 is 8 m x 8 m
9.00E-03	9.00E-03	9.00E-07	2.19E+16	1.93E-01	9.00E-02	
1.00E-02	1.00E-02	1.00E-06	3.00E+16	2.85E-01	1.00E-01	
2.00E-02	2.00E-02	2.00E-06	2.40E+17	8.87E-01	2.00E-01	
2.30E-02	2.30E-02	2.30E-06	3.65E+17	1.01E+00	2.30E-01	mag 1 is 23 m x 23 m

km2cm	slipratio	rigidigy	moment	moment mag		
1.00E+05	1.00E-04	3.00E+11	1.00E+00	-1.07E+01		
perp dirn	slip dirn	slip	moment	moment mag	slip cm	
km	km	km				
2.30E-02	2.30E-02	2.30E-06	3.65E+17	1.01E+00	2.30E-01	mag 1 is 23 m x 23 m
8.00E-02	8.00E-02	8.00E-06	1.54E+19	2.09E+00	8.00E-01	mag 2 is 80 m x 80 m
2.30E-01	2.30E-01	2.30E-05	3.65E+20	3.01E+00	2.30E+00	mag 3 is 230 m x 230 m
7.00E-01	7.00E-01	7.00E-05	1.03E+22	3.97E+00	7.00E+00	mag 4 is 700 m x 700 m
2.00E+00	2.00E+00	2.00E-04	2.40E+23	4.89E+00	2.00E+01	
3.00E+00	3.00E+00	3.00E-04	8.10E+23	5.24E+00	3.00E+01	
7.00E+00	7.00E+00	7.00E-04	1.03E+25	5.97E+00	7.00E+01	
8.00E+00	8.00E+00	8.00E-04	1.54E+25	6.09E+00	8.00E+01	
9.00E+00	9.00E+00	9.00E-04	2.19E+25	6.19E+00	9.00E+01	
2.00E+01	2.00E+01	2.00E-03	2.40E+26	6.89E+00	2.00E+02	
3.00E+01	3.00E+01	3.00E-03	8.10E+26	7.24E+00	3.00E+02	
7.00E+01	7.00E+01	7.00E-03	1.03E+28	7.97E+00	7.00E+02	
8.00E+01	8.00E+01	8.00E-03	1.54E+28	8.09E+00	8.00E+02	
3.00E+02	2.00E+02	2.00E-02	3.60E+29	9.00E+00	2.00E+03	
1.50E+03	2.00E+02	2.00E-02	1.80E+30	9.47E+00	2.00E+03	

The seismic moment and moment magnitude give us the tool we need to compare the size of the largest quakes.

We find that the "moment release" in shallow earthquakes throughout the entire 20th century is dominated by several large subduction zone earthquake sequences.

OUT OF DATE!!

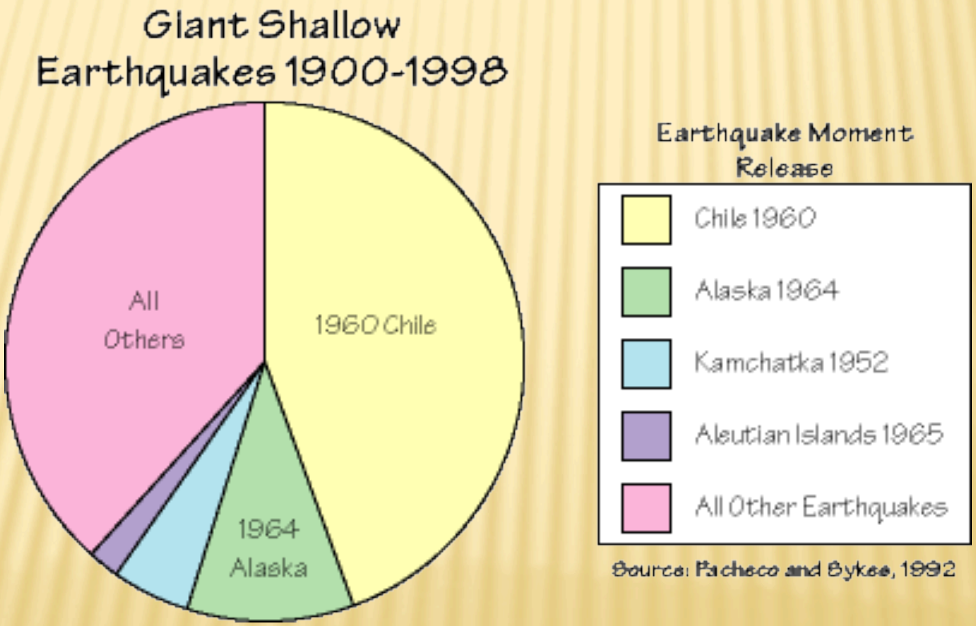


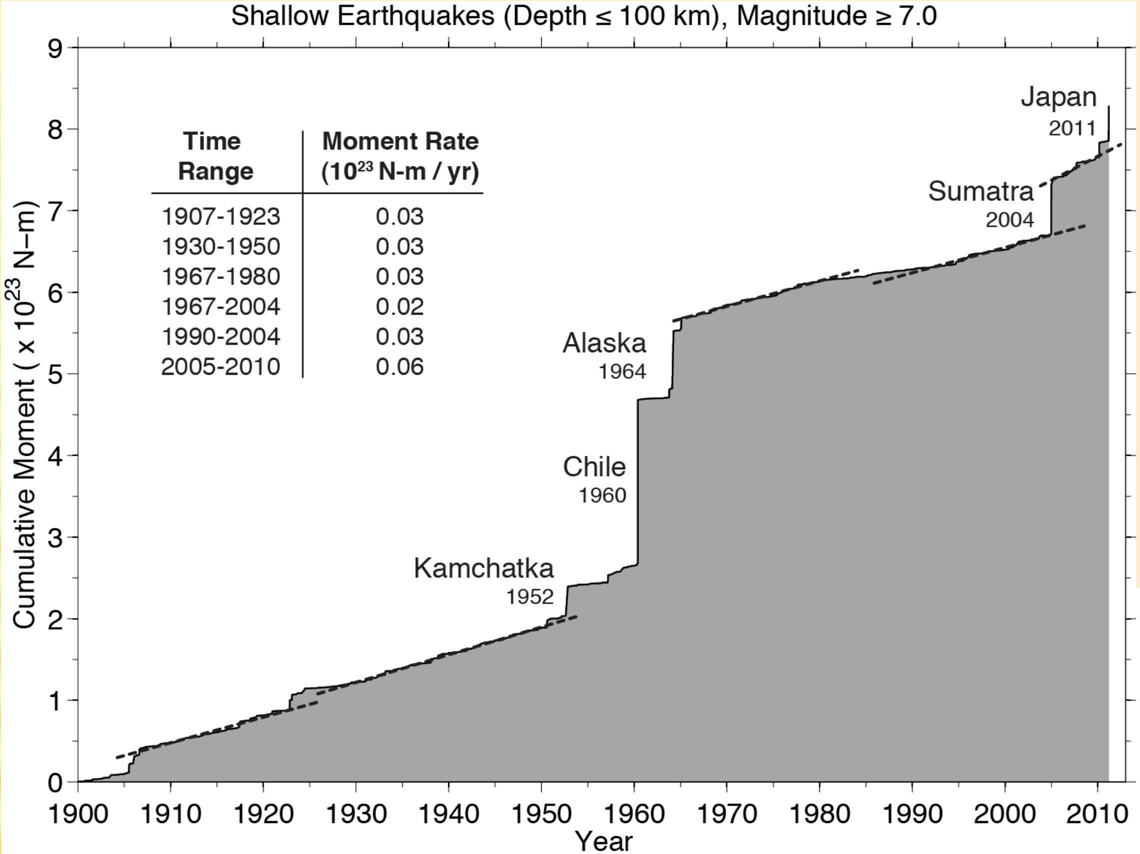
energy released in the different plate settings:

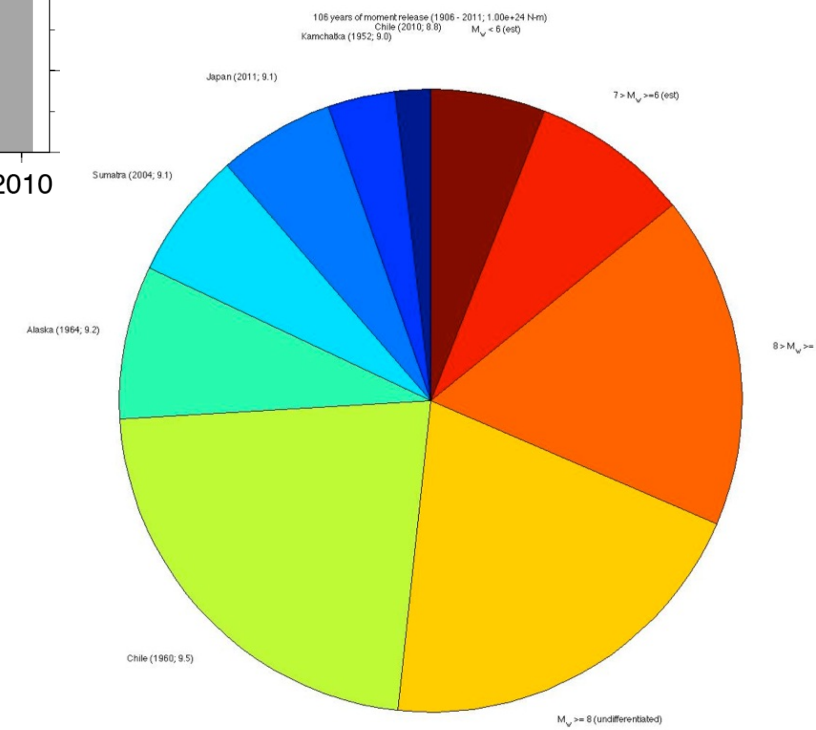
Energy released by largest four earthquakes (those with magnitudes greater than 9) and all the other shallow earthquakes

(needs updating for Sumatra 2004 and Maule 2010.)

OUT OF DATE!!





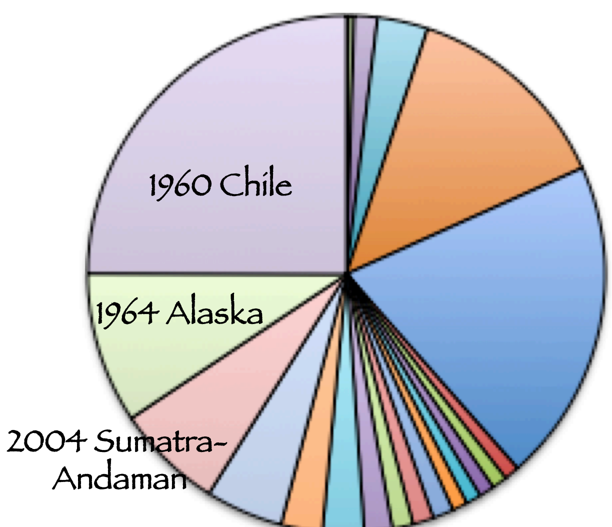


<u>update</u> for Sumatra 2004, Maule 2010 and Japan 2010.

Largest Earthquakes in the World Since 1900

	Location	Date UTC	Magnitude	Lat.	Long.	Reference
1.	Chile	1960 05 22	9.5	-38.29	-73.05	Kanamori, 1977
2.	Prince William Sound, Alaska	1964 03 28	9.2	61.02	-147.65	Kanamori, 1977
3.	Off the West Coast of Northern Sumatra	2004 12 26	9.1	3.30	95.78	Park et al., 2005
4.	Near the East Coast of Honshu, Japan	2011 03 11	9.0	38.322	142.369	PDE
5.	Kamchatka	1952 11 04	9.0	52.76	160.06	Kanamori, 1977
6.	Offshore Maule, Chile	2010 02 27	8.8	-35.846	-72.719	PDE
7.	Off the Coast of Ecuador	1906 01 31	8.8	1.0	-81.5	Kanamori, 1977
8.	Rat Islands, Alaska	1965 02 04	8.7	51.21	178.50	Kanamori, 1977
9.	Northern Sumatra, Indonesia	2005 03 28	8.6	2.08	97.01	PDE
10.	Assam – Tibet	1950 08 15	8.6	28.5	96.5	Kanamori, 1977
11.	Off the west coast of northern Sumatra	2012 04 11	8.6	2.311	93.063	PDE
12.	Andreanof Islands, Alaska	1957 03 09	8.6	51.56	-175.39	Johnson et al., 1994
13.	Southern Sumatra, Indonesia	2007 09 12	8.5	-4.438	101.367	PDE
14.	Banda Sea, Indonesia	1938 02 01	8.5	-5.05	131.62	Okal and Reymond, 2003
15.	Kamchatka	1923 02 03	8.5	54.0	161.0	Kanamori, 1988
16.	Chile-Argentina Border	1922 11 11	8.5	-28.55	-70.50	Kanamori, 1977
17.	Kuril Islands	1963 10 13	8.5	44.9	149.6	

km2cm	slipratio	rigidigy	moment	moment mag						
1.00E+05	1.00E-04	3.00E+11	1	-10.7						
perp dirn	slip dirn	slip	moment	moment mag	slip cm					
km	km	km				nrg	#/yr	nrg/100 yr	nrg/totnrg	
0.075	0.075	7.5E-06	1.2656E+19	2.0	0.75	2.35E+08	1000000	2.35E+16	0.00	1.00
0.23	0.23	0.000023	3.6501E+20	3.0	2.3	5.91E+09	100000	5.91E+16	0.00	1.00
0.75	0.75	0.000075	1.2656E+22	4.0	7.5	1.78E+11	10000	1.78E+17	0.00	1.00
2.4	2.4	0.00024	4.1472E+23	5.0	24	5.07E+12	1500	7.61E+17	0.01	1.00
7	7	0.0007	1.029E+25	6.0	70	1.11E+14	150	1.66E+18	0.03	0.98
24	24	0.0024	4.1472E+26	7.0	240	3.85E+15	18	6.92E+18	0.13	0.95
76	76	0.0076	1.3169E+28	8.0	760	1.06E+17	1	1.06E+19	0.20	0.82
130	130	0.013	6.591E+28	8.5	1300	4.99E+17		4.99E+17	0.01	0.61
130	130	0.013	6.591E+28	8.5	1300	4.99E+17		4.99E+17	0.01	0.61
130	130	0.013	6.591E+28	8.5	1300	4.99E+17		4.99E+17	0.01	0.60
130	130	0.013	6.591E+28	8.5	1300	4.99E+17		4.99E+17	0.01	0.59
130	130	0.013	6.591E+28	8.5	1300	4.99E+17		4.99E+17	0.01	0.58
145	145	0.0145	9.1459E+28	8.6	1450	6.84E+17		6.84E+17	0.01	0.57
145	145	0.0145	9.1459E+28	8.6	1450	6.84E+17		6.84E+17	0.01	0.55
145	145	0.0145	9.1459E+28	8.6	1450	6.84E+17		6.84E+17	0.01	0.54
161	161	0.0161	1.252E+29	8.7	1610	9.24E+17		9.24E+17	0.02	0.53
184	184	0.0184	1.8689E+29	8.8	1840	1.36E+18		1.36E+18	0.03	0.51
184	184	0.0184	1.8689E+29	8.8	1840	1.36E+18		1.36E+18	0.03	0.49
300	200	0.02	3.6E+29	9.0	2000	2.55E+18		2.55E+18	0.05	0.46
400	205	0.0205	5.043E+29	9.1	2050	3.52E+18		3.52E+18	0.07	0.41
600	200	0.02	7.2E+29	9.2	2000	4.95E+18		4.95E+18	0.09	0.34
1500	210	0.021	1.9845E+30	9.5	2100	1.31E+19		1.31E+19	0.25	0.25
								5.26E+19	1.00	



In last 100 years

1960 earthquake – 25% energy,

Six largest – 50% energy,

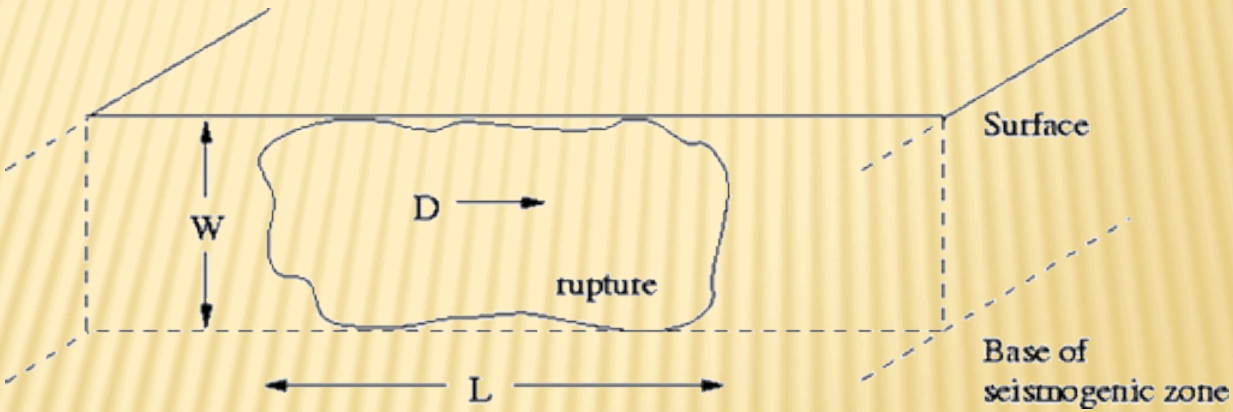
15 largest – 61% energy,

M>8 – >80% energy.

Another measure of Earthquake size

Seismic Potential

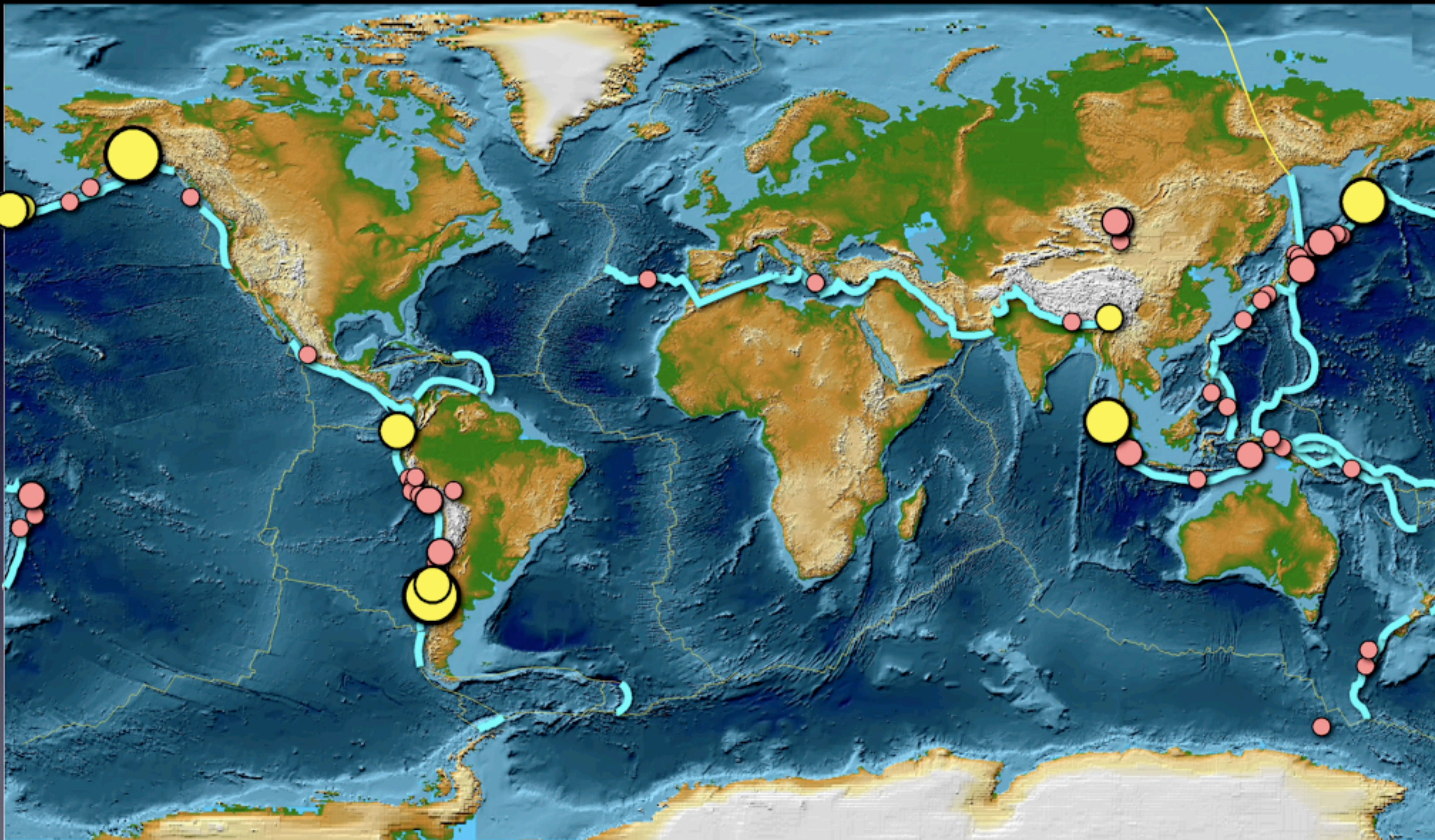
Removes the material properties (rigidity) and looks at the fault size and slip only – more direct comparison?



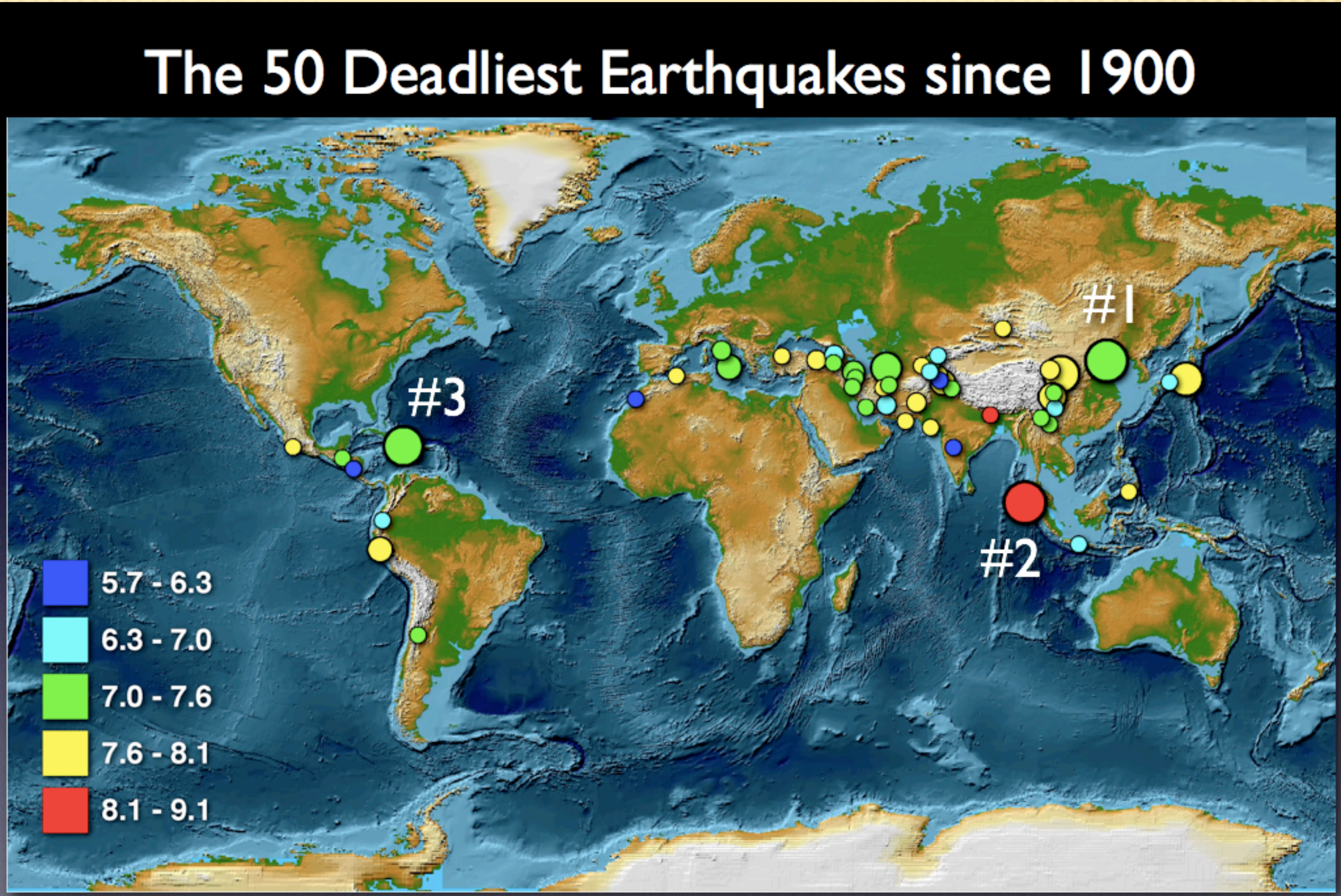
$$P=AD$$

A is fault area and D is average slip

Largest Earthquakes since 1900



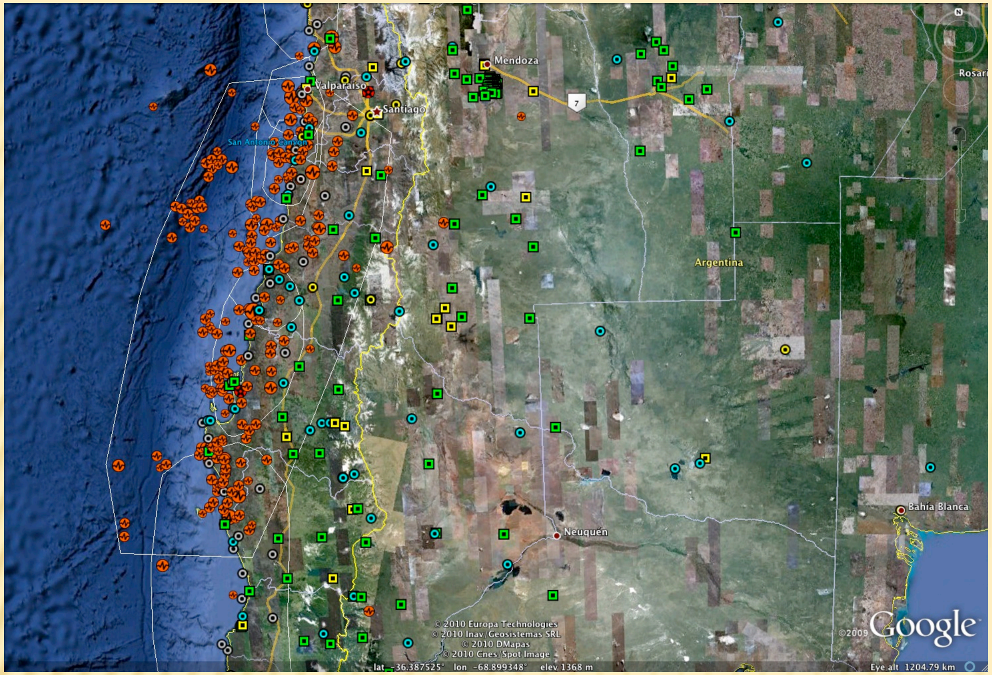
Magnitude often has little to do with number deaths.

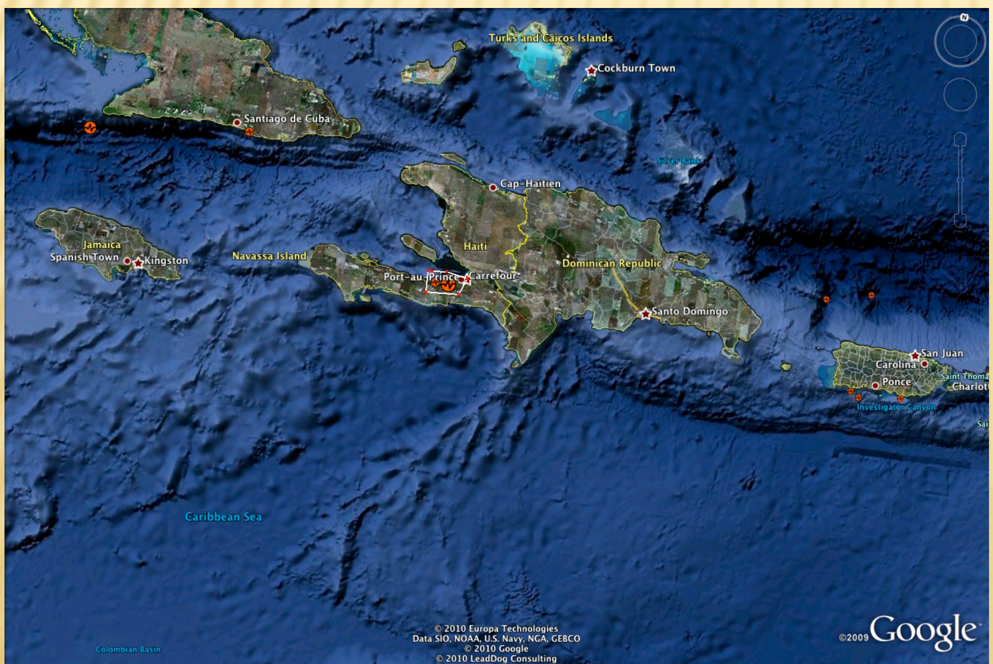


Ratio sizes 2010 Maule, Chile, earthquake and Hatian earthquake.

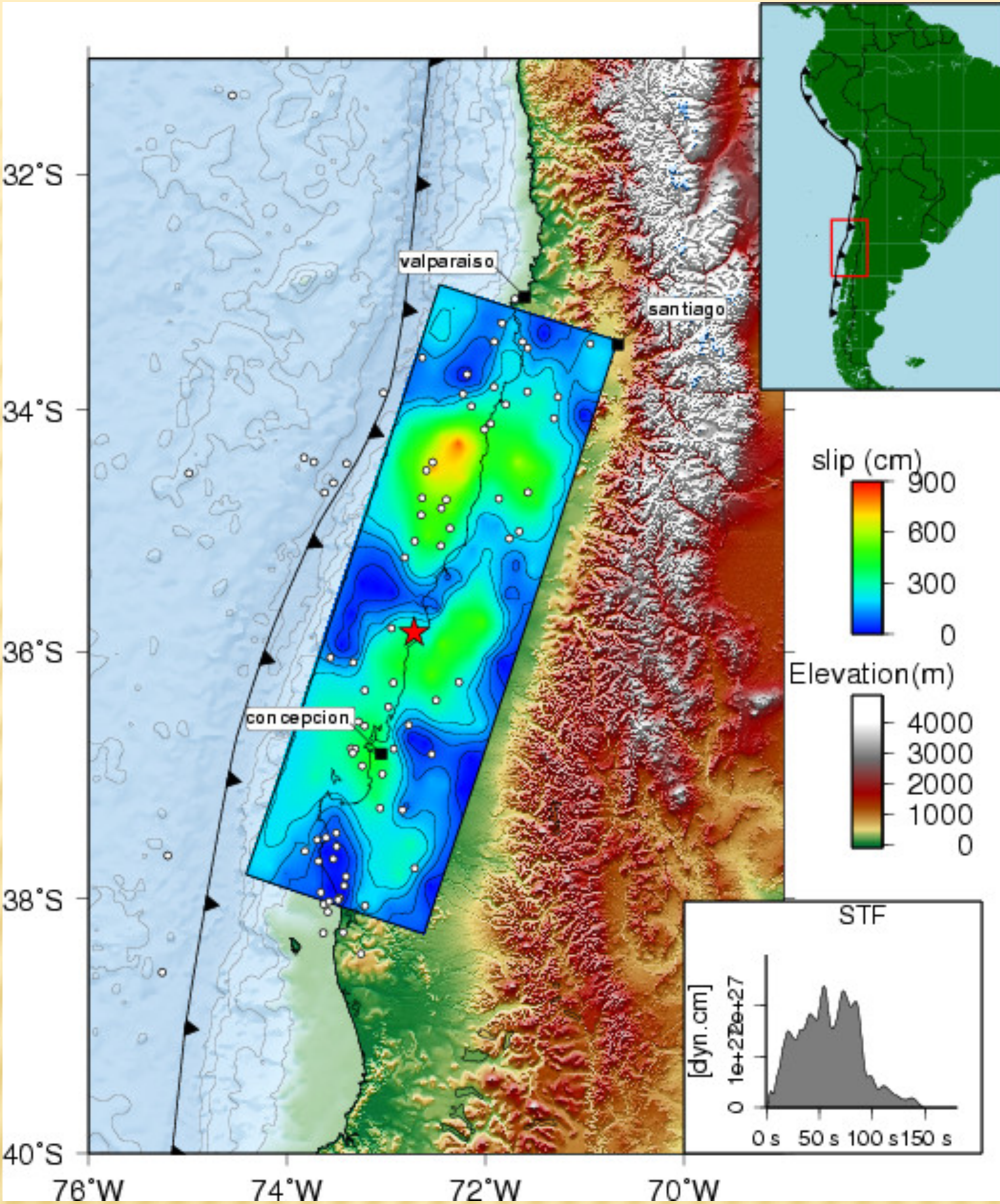
Chile 550 times bigger in energy (big hazard).

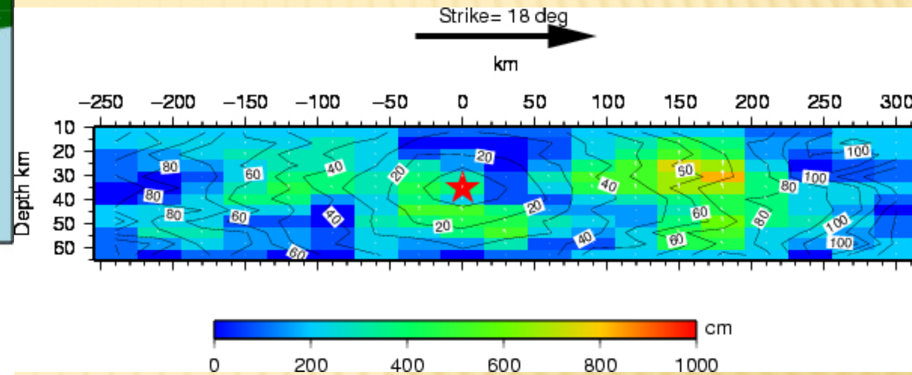
Haiti earthquake killed 550 times more people (big risk).

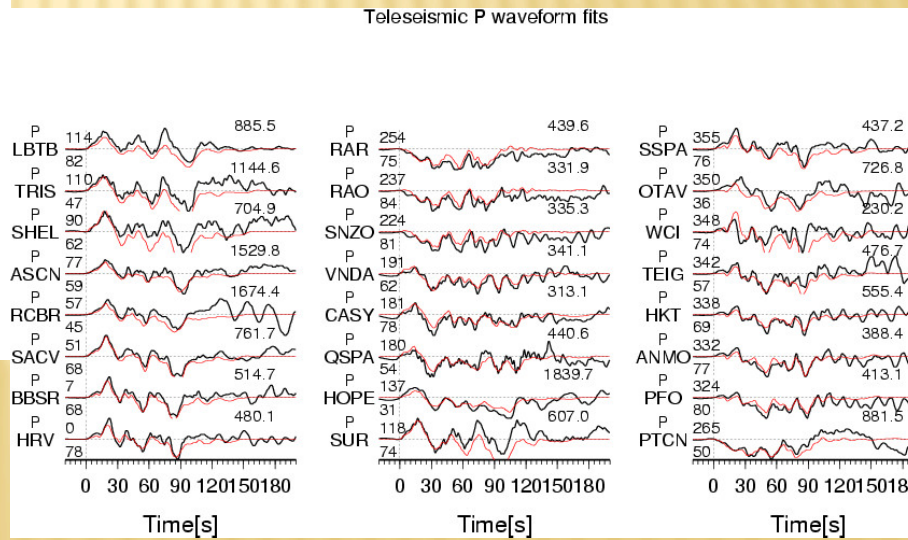




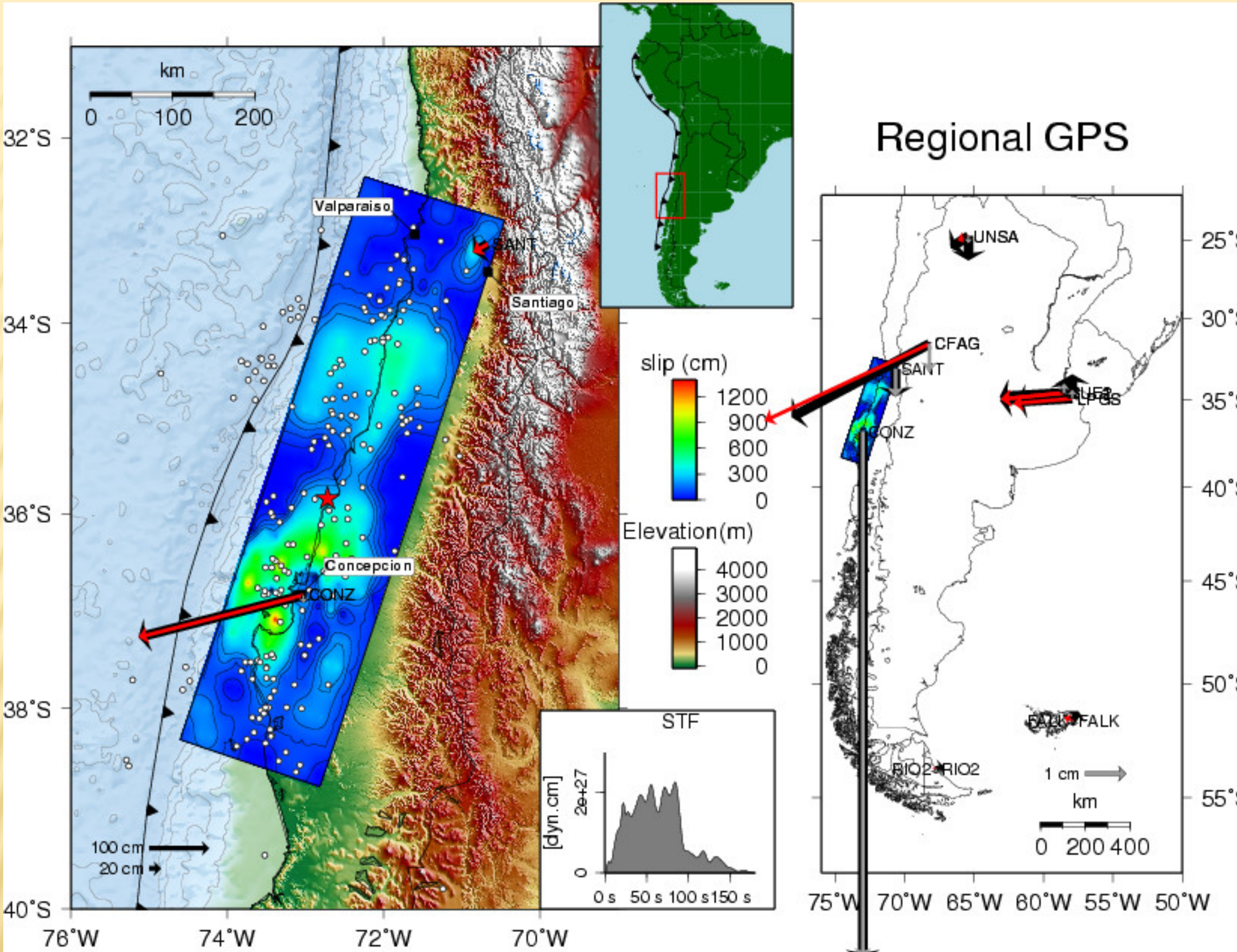
Comparison rupture areas from Maule and Haiti earthquakes (figures at same scale)



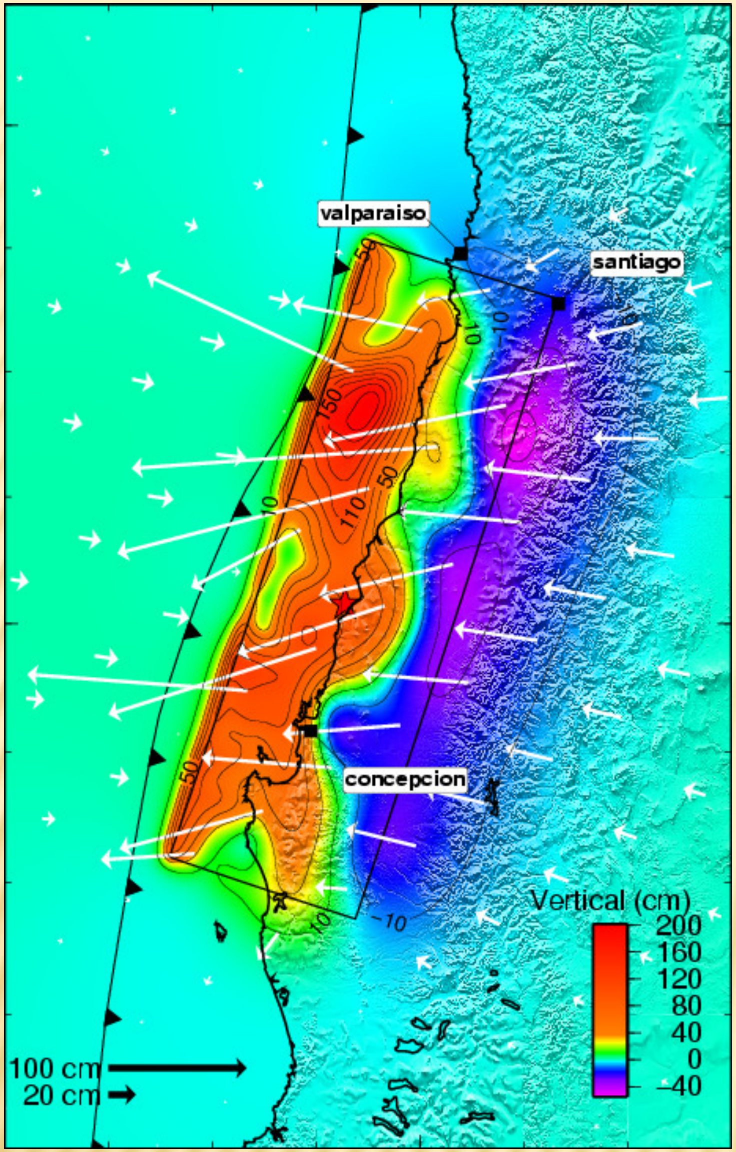


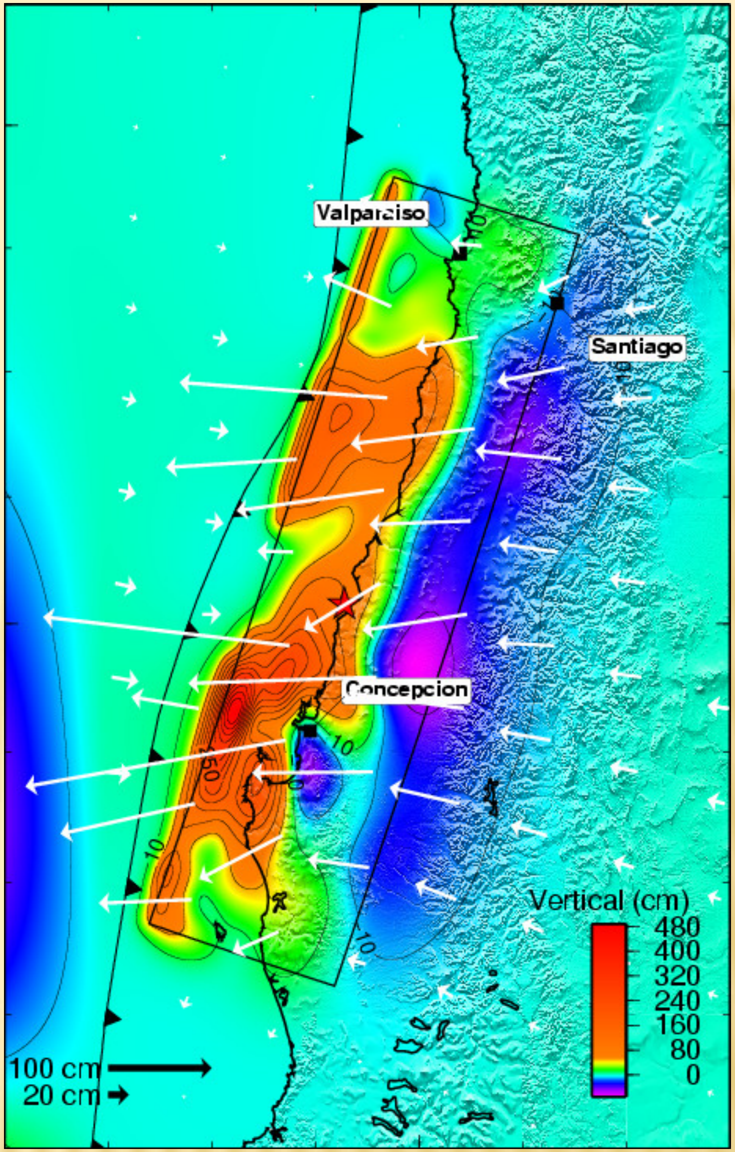


Finite Fault Model from seismic data
Preliminary Result of the Feb 27, 2010 Mw 8.8
Maule, Chile Earthquake
Anthony Sladen, CALTECH

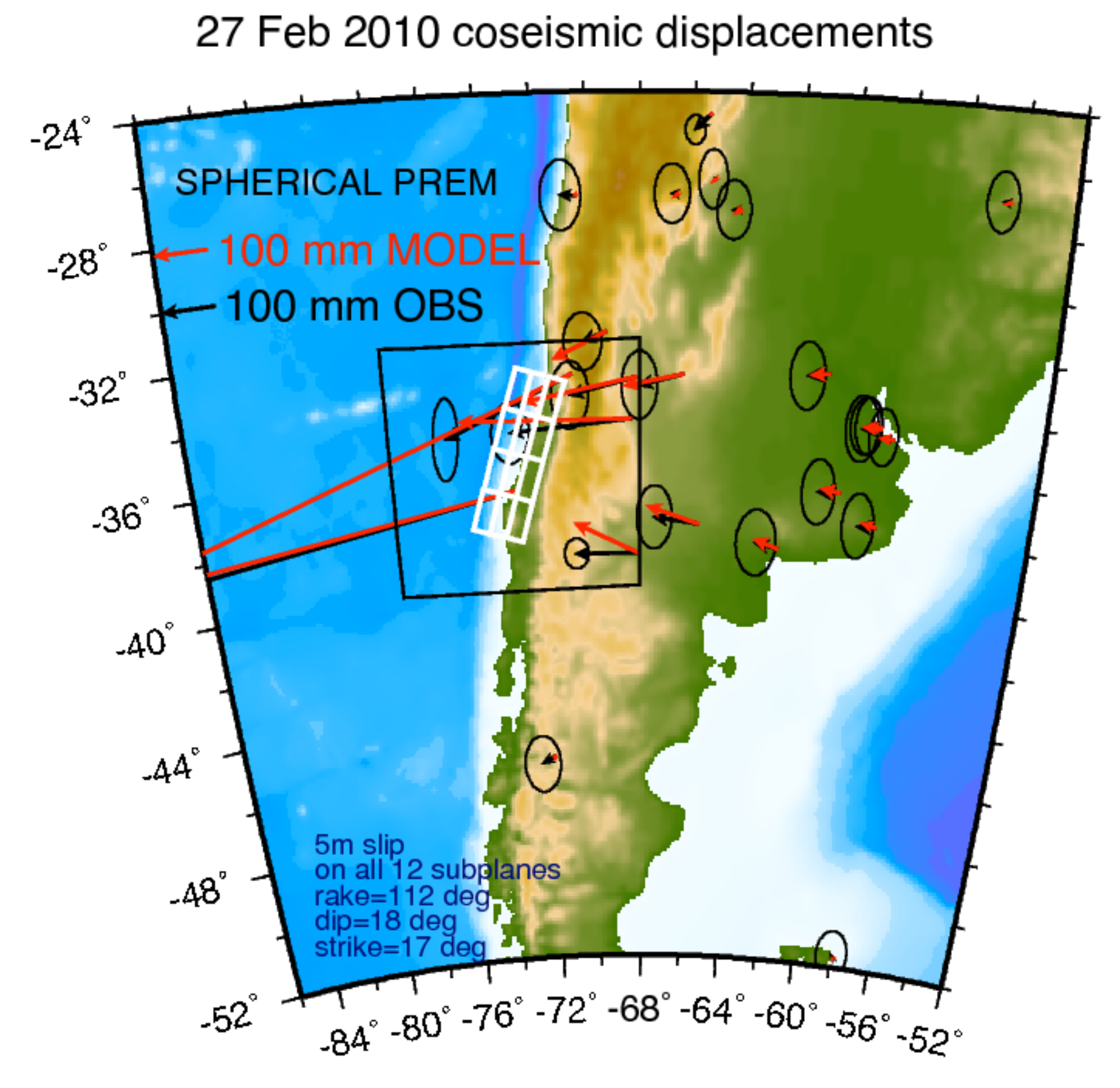


Finite Fault Model from seismic and GPS (static) data
Preliminary Result of the Feb 27, 2010 Mw 8.8 Maule, Chile Earthquake
Anthony Sladen and Susan Owen, CALTECH



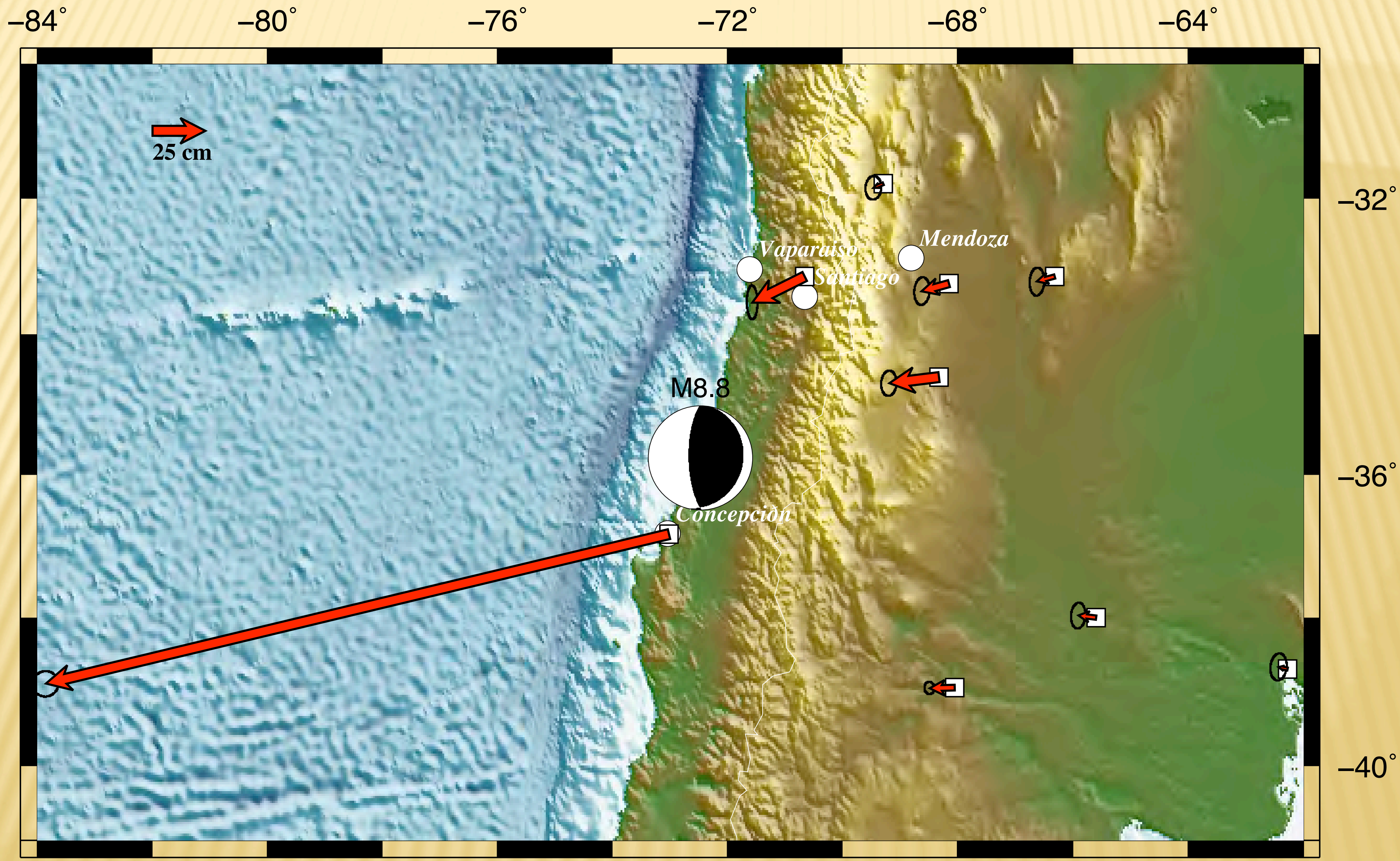


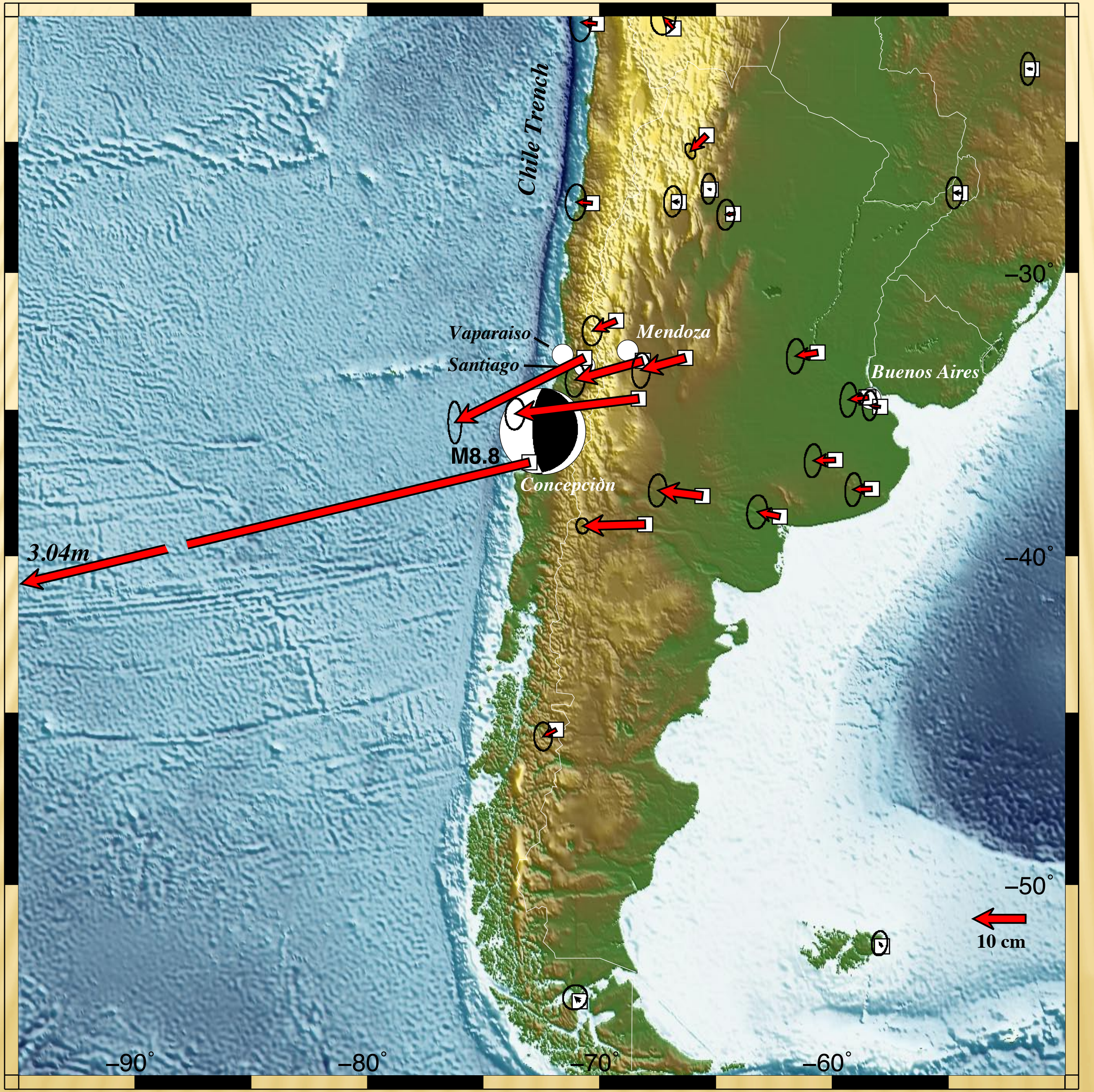
Static displacements from seismic only (left) and combined seismic and GPS (right)
Preliminary Result of the Feb 27, 2010 Mw 8.8 Maule, Chile Earthquake
Anthony Sladen and Susan Owen, CALTECH



Fred Pollitz: USGS

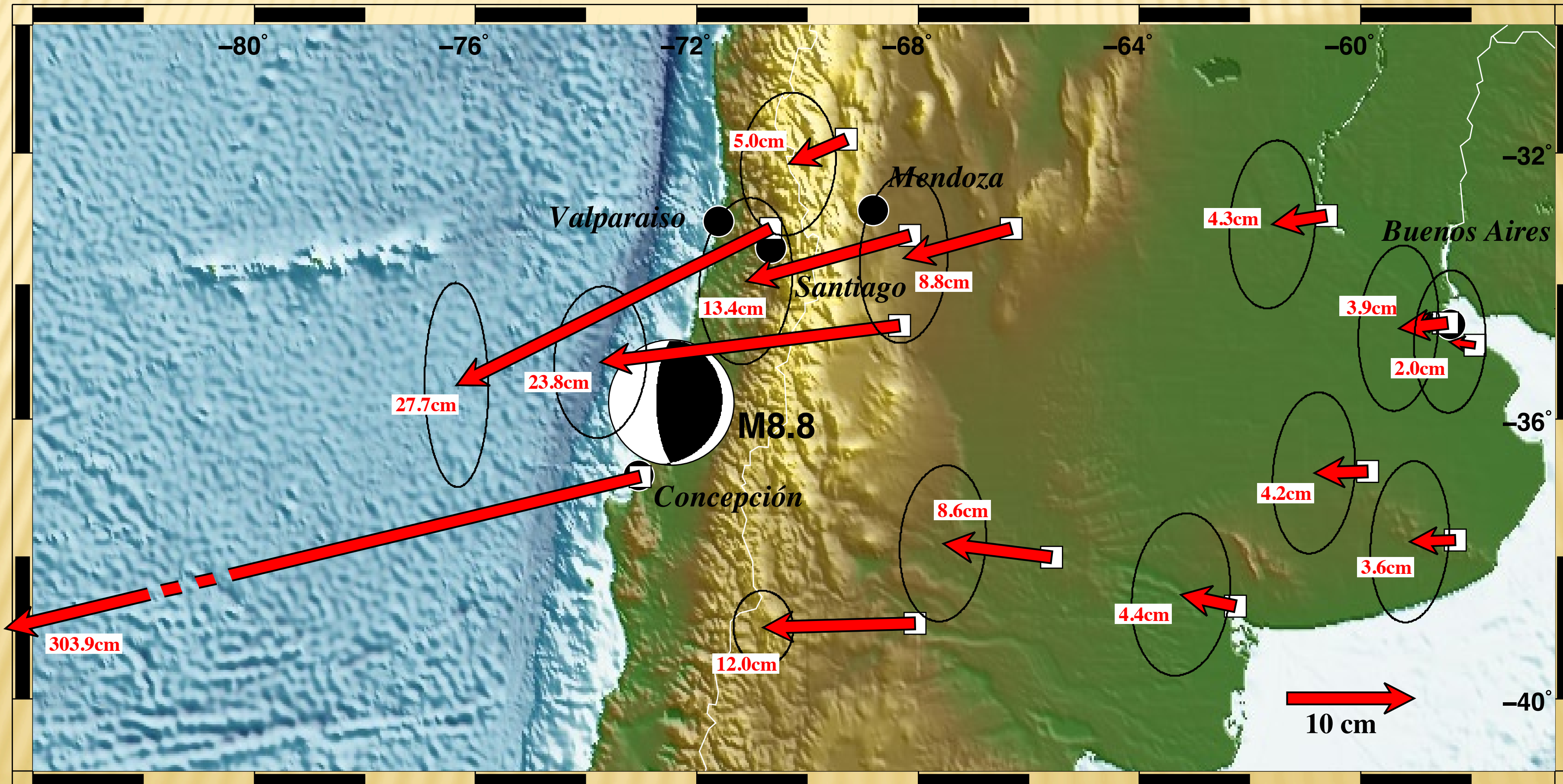
Co-seismic static deformation (all at same scale).



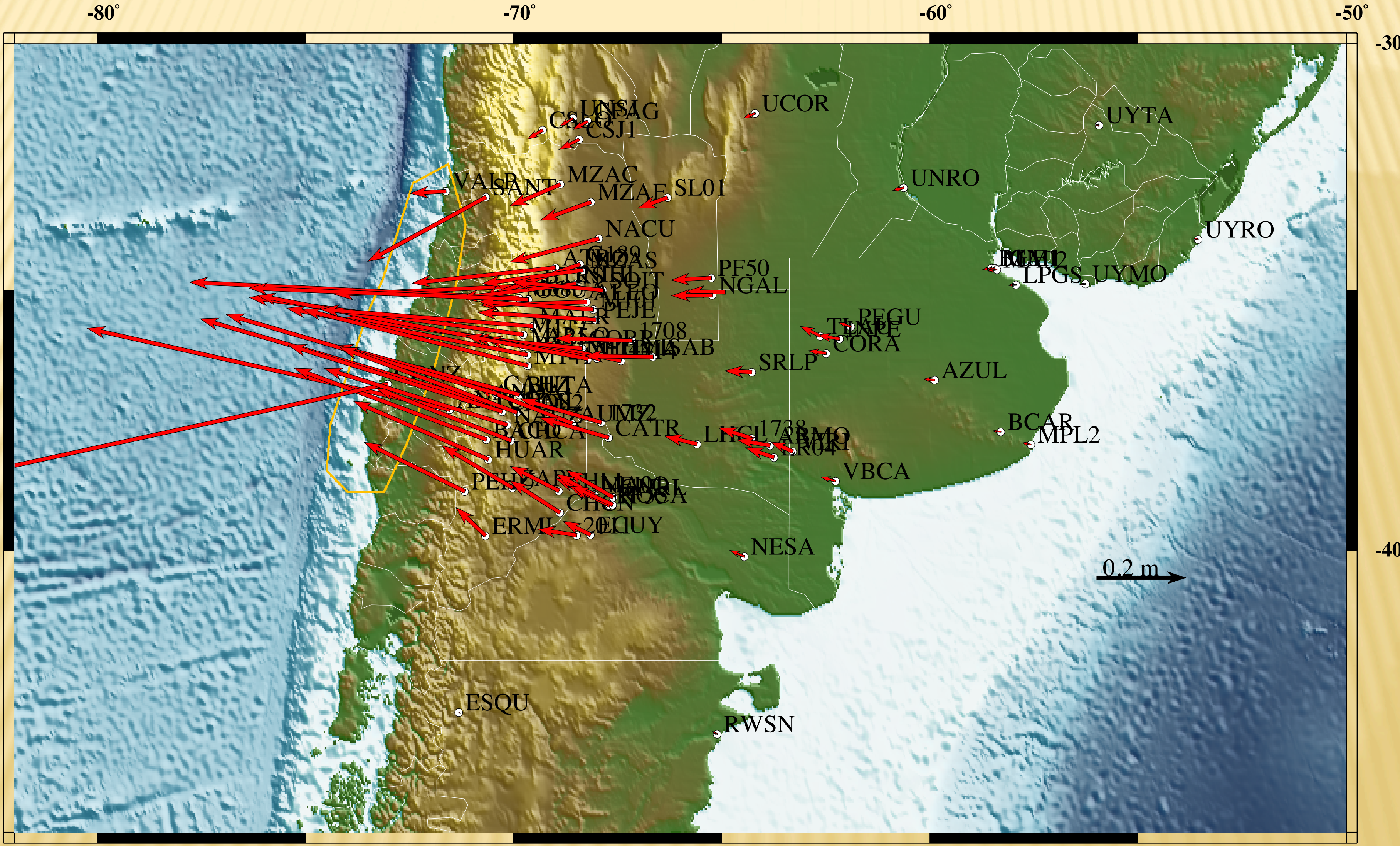


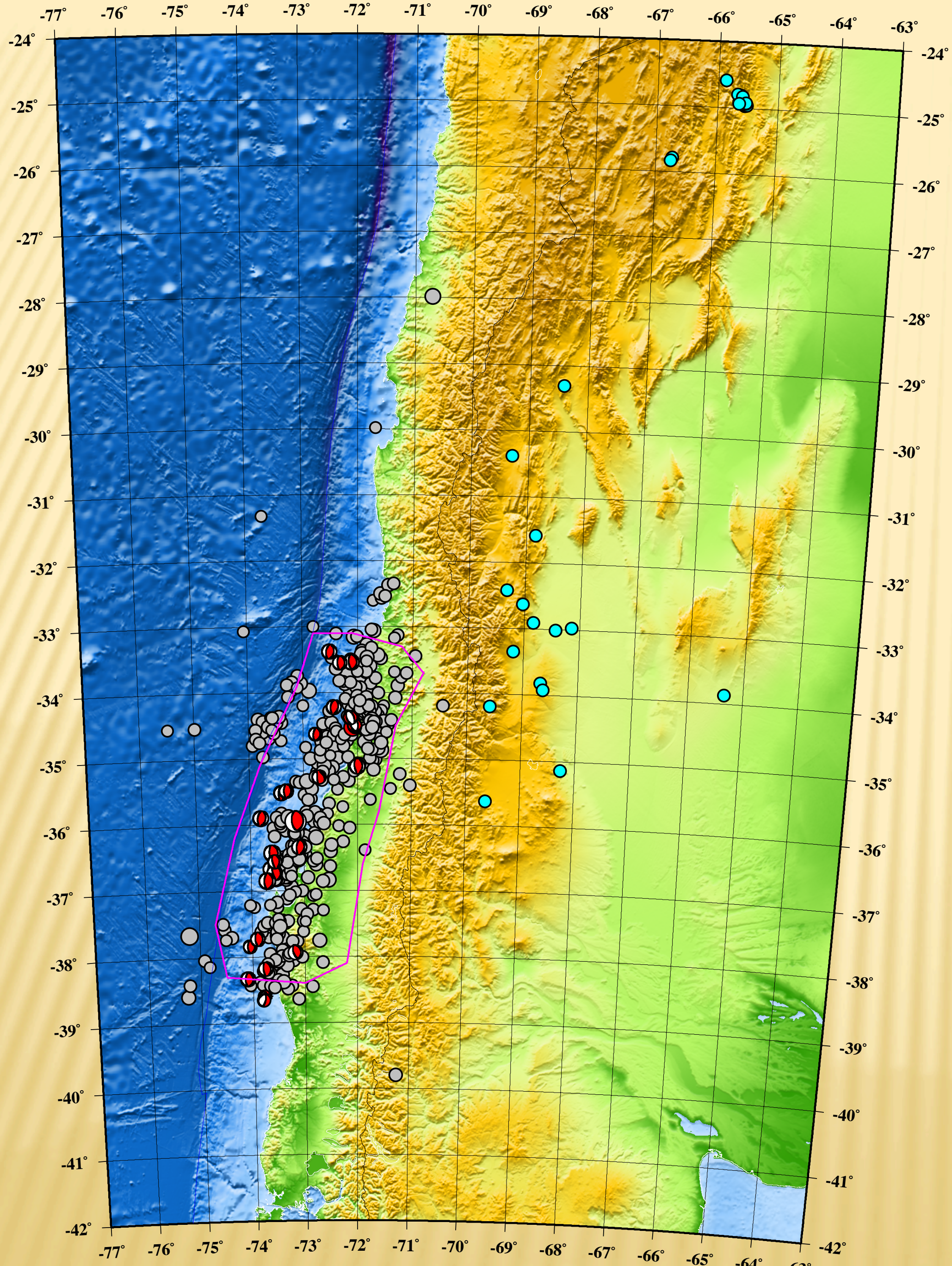
Co-seismic static deformation (Concepción not to scale).

Co-seismic static deformation – zoom on far field (Concepción not to scale).



sismoignzoom//Users/robertsmalley/unixside/geolfigs/Gamit_Coord-GMT.txt





Aftershocks

"Triggered" seismicity in trench and back-arc in Argentina.

(grey – ANSS, cyan – INPRES)

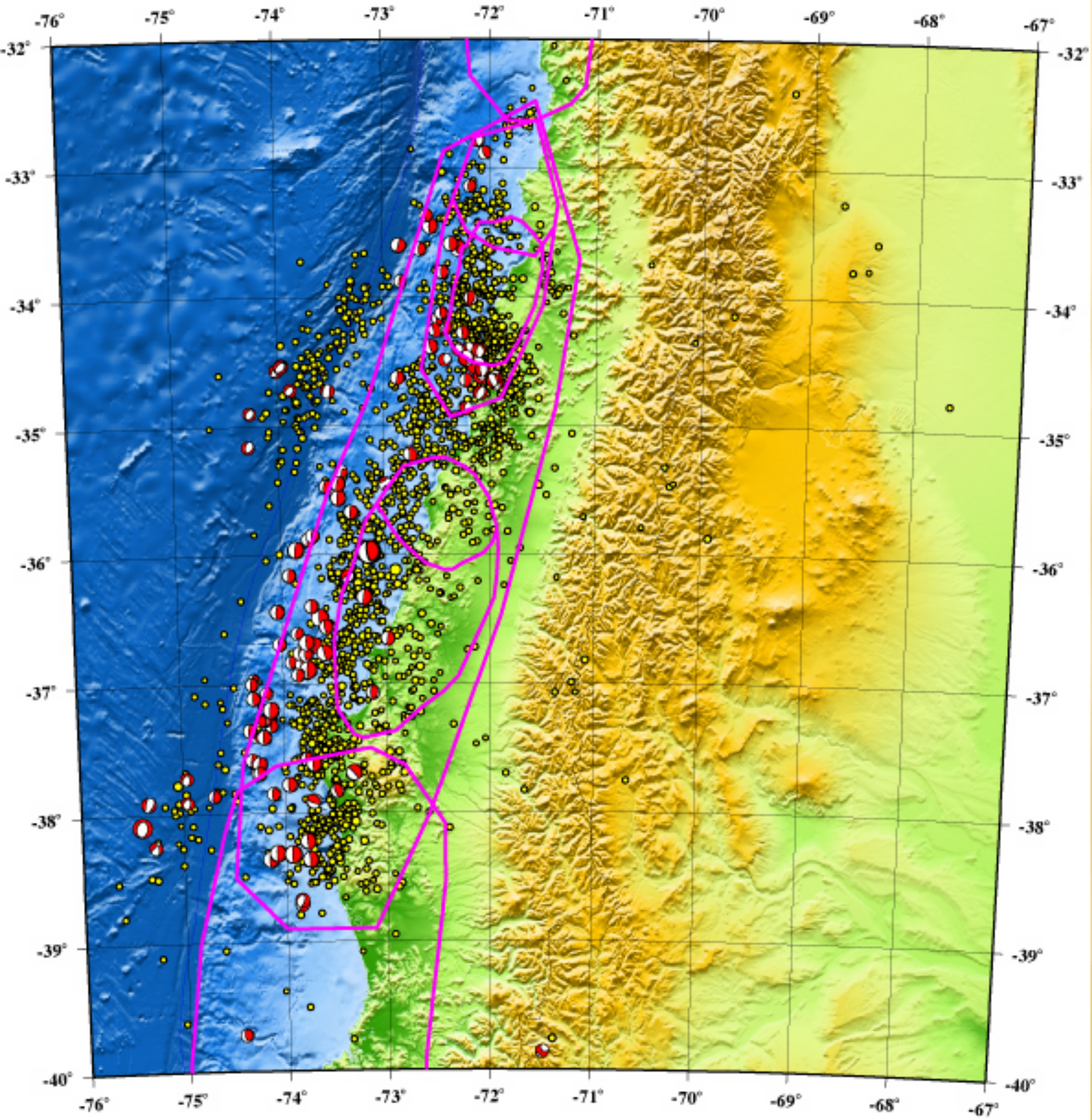
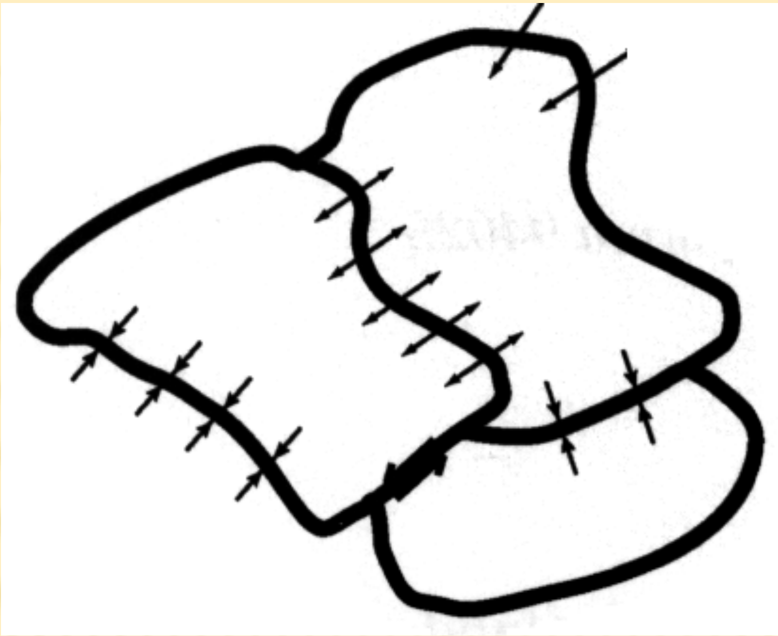
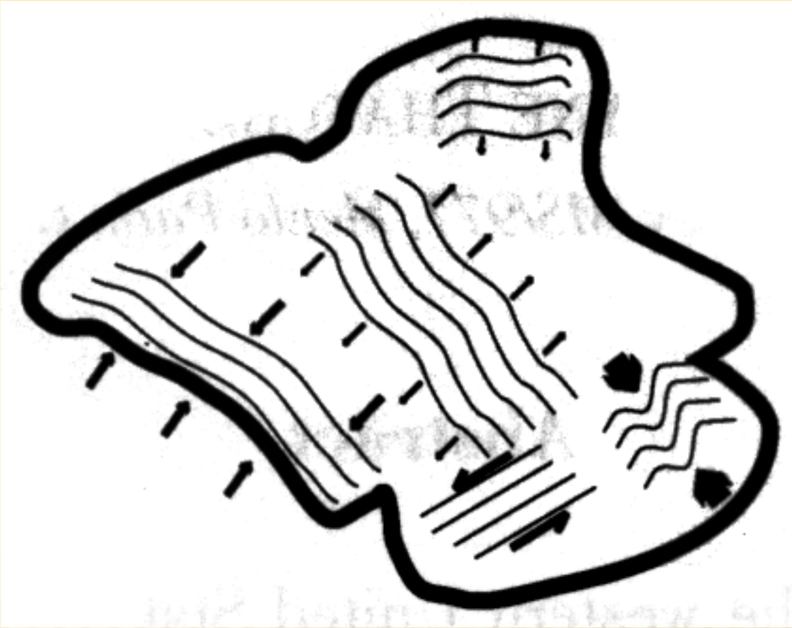


Plate bending events – normal faulting focal mechanisms - in subducting plate on west side of trench.
(not "regular" aftershocks).

Large deformation field associated with Maule earthquake – in accord with elastic rebound.

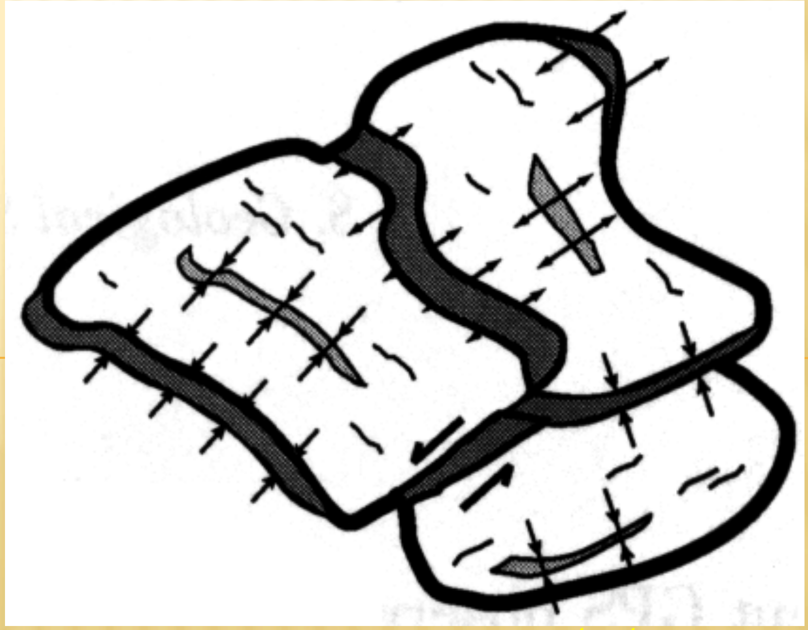
Start of measurements of post-seismic deformation. GPS displacement seismograms (later).



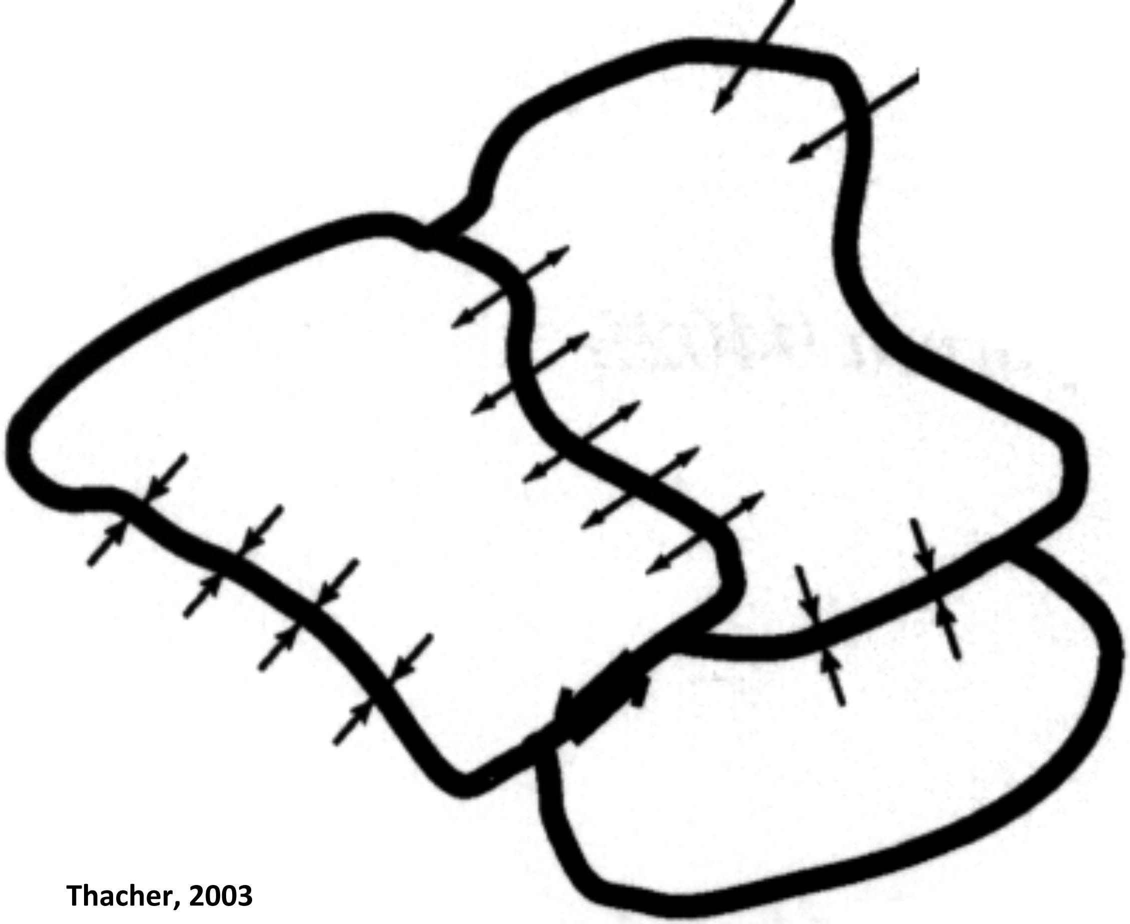


How might plates deform?

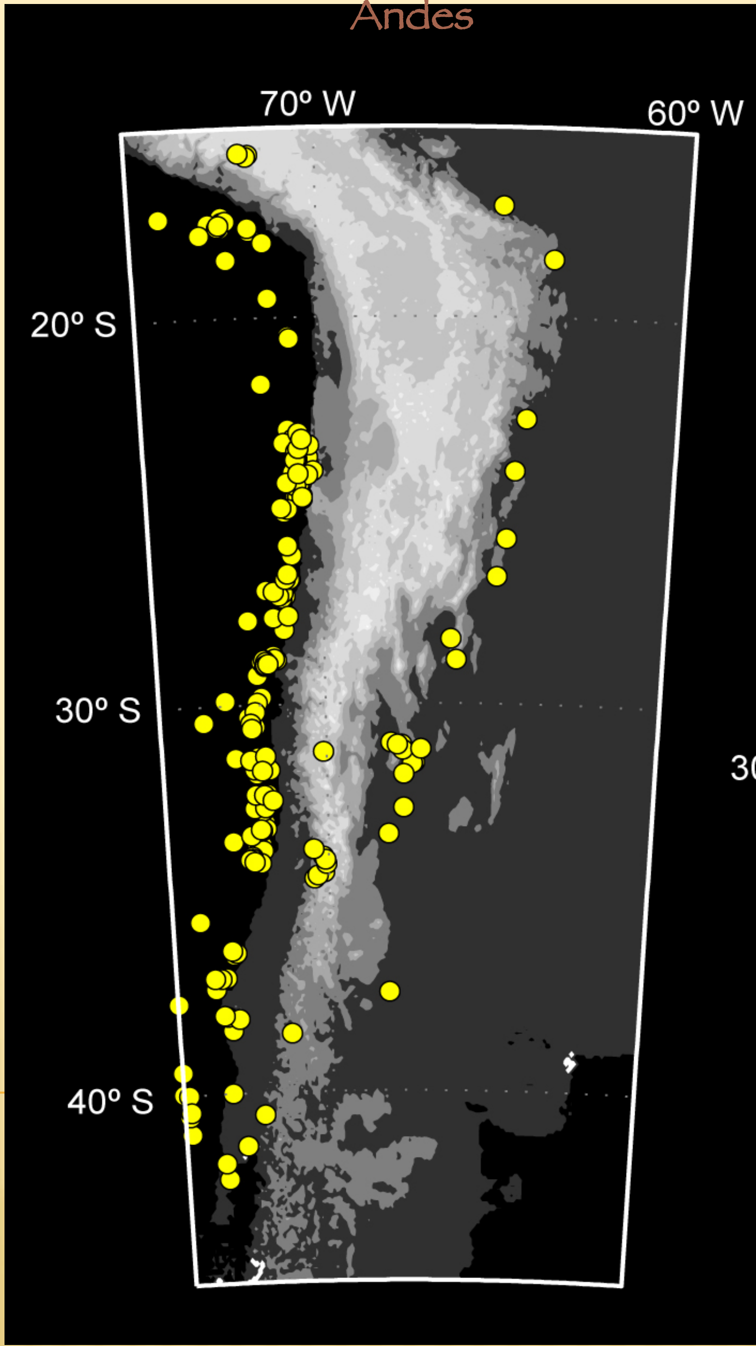
Continuum, block, etc.?



Thacher, 2003



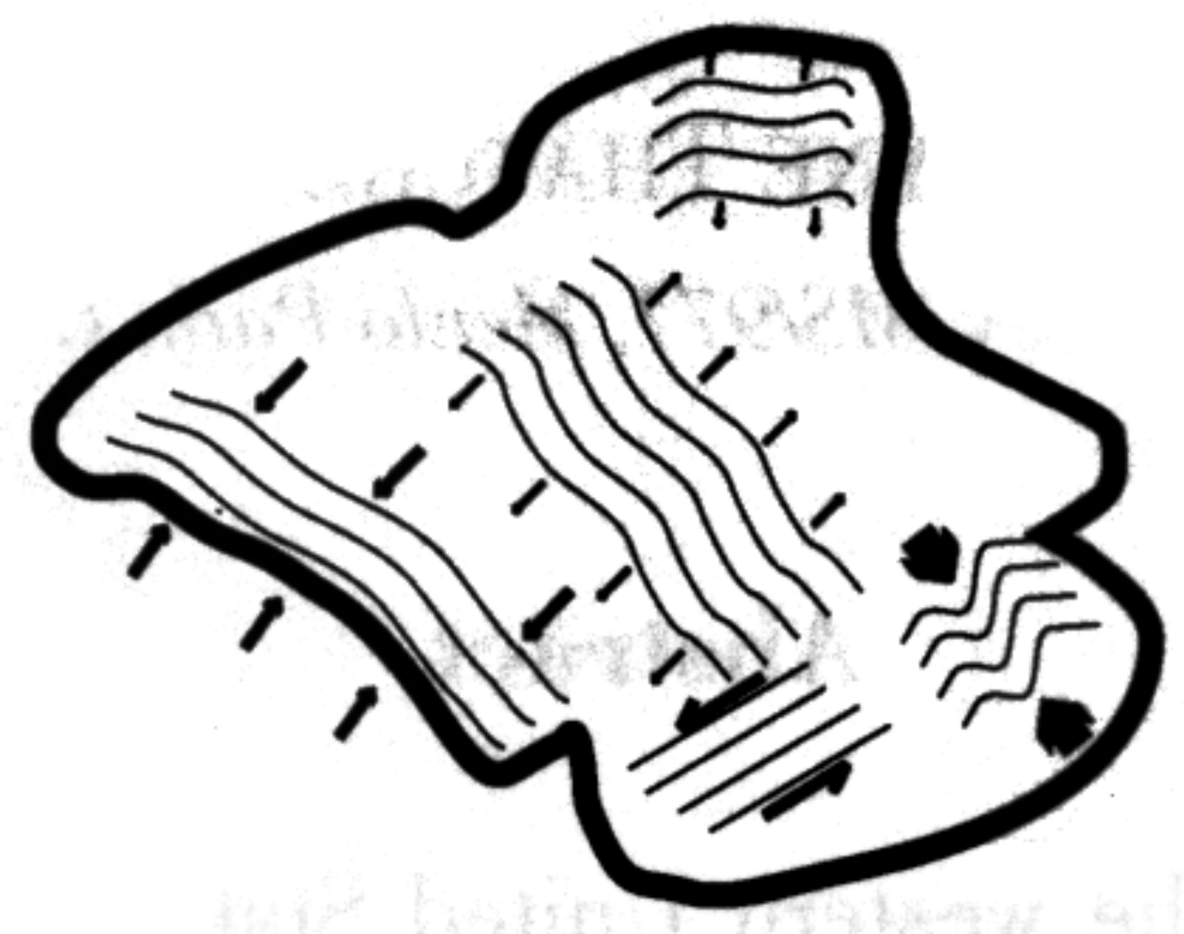
Thacher, 2003

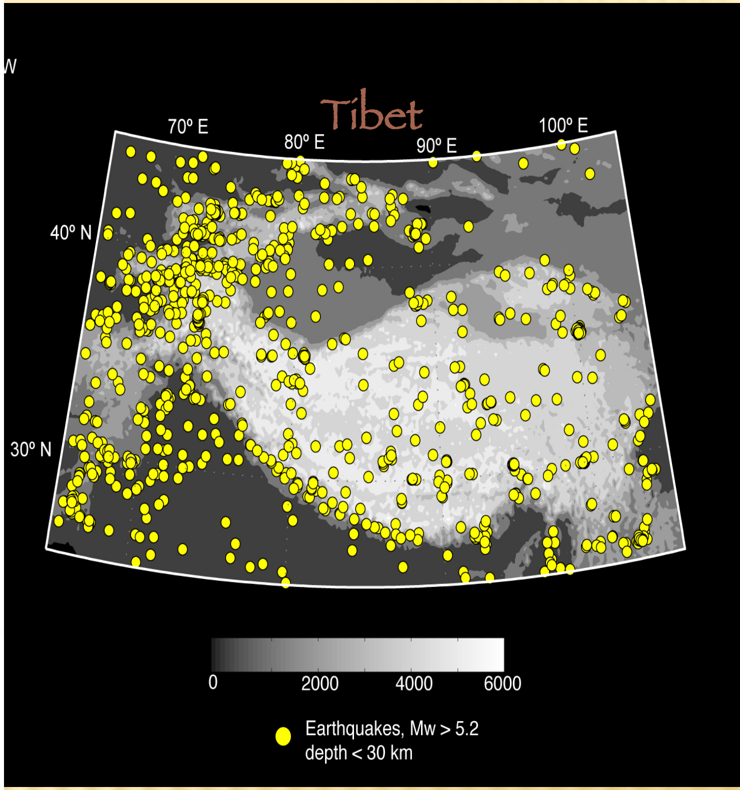


Andes

Thacher, 2003

Rigid blocks.
Sort of mini-version of plate tectonics.
"Easy" to see with GPS.



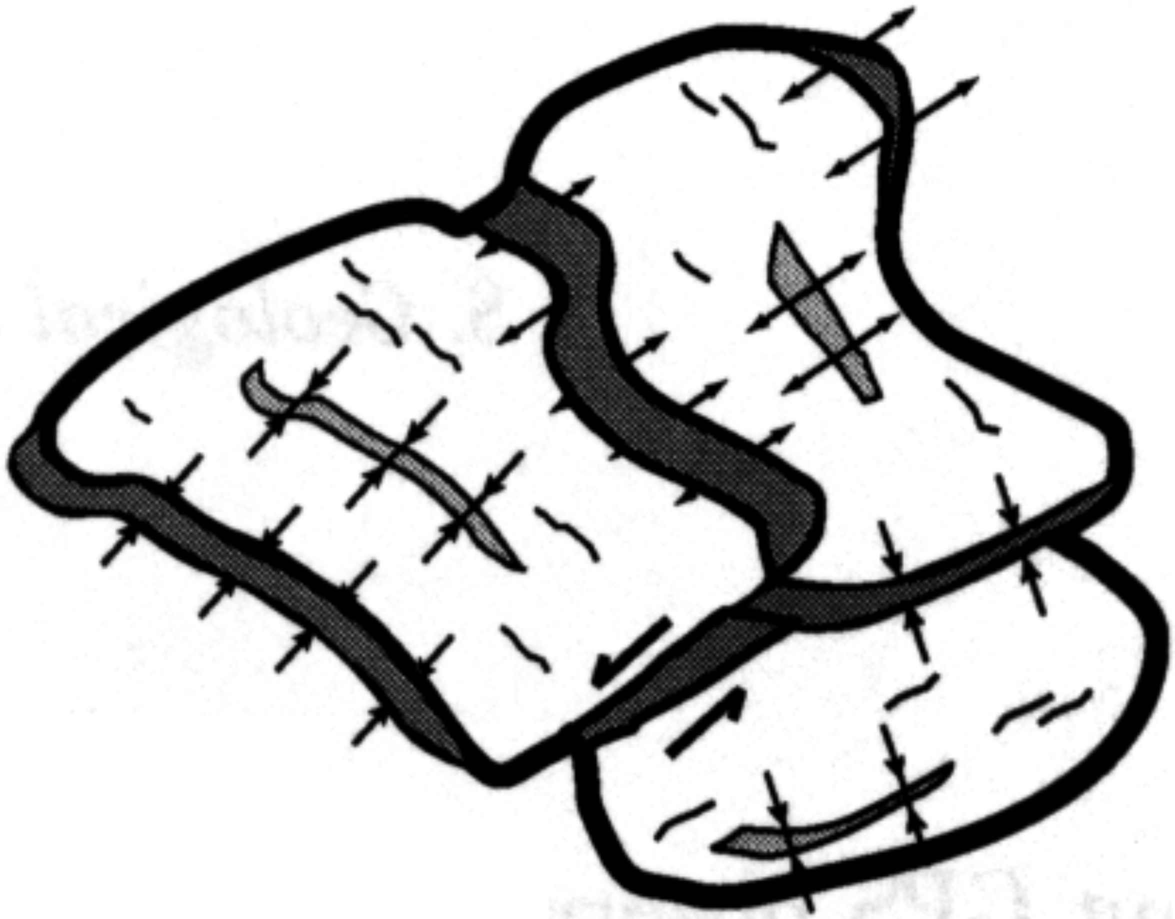


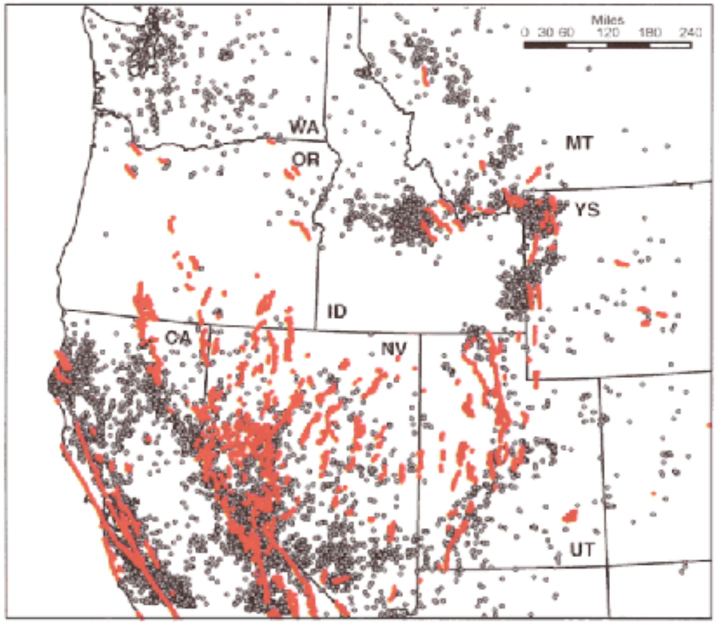
Quasi-continuous deformation. Pervasive internal deformation (but not fast enough to invalidate plate tectonics) .

Continuum sea.

"Harder" to see with GPS.

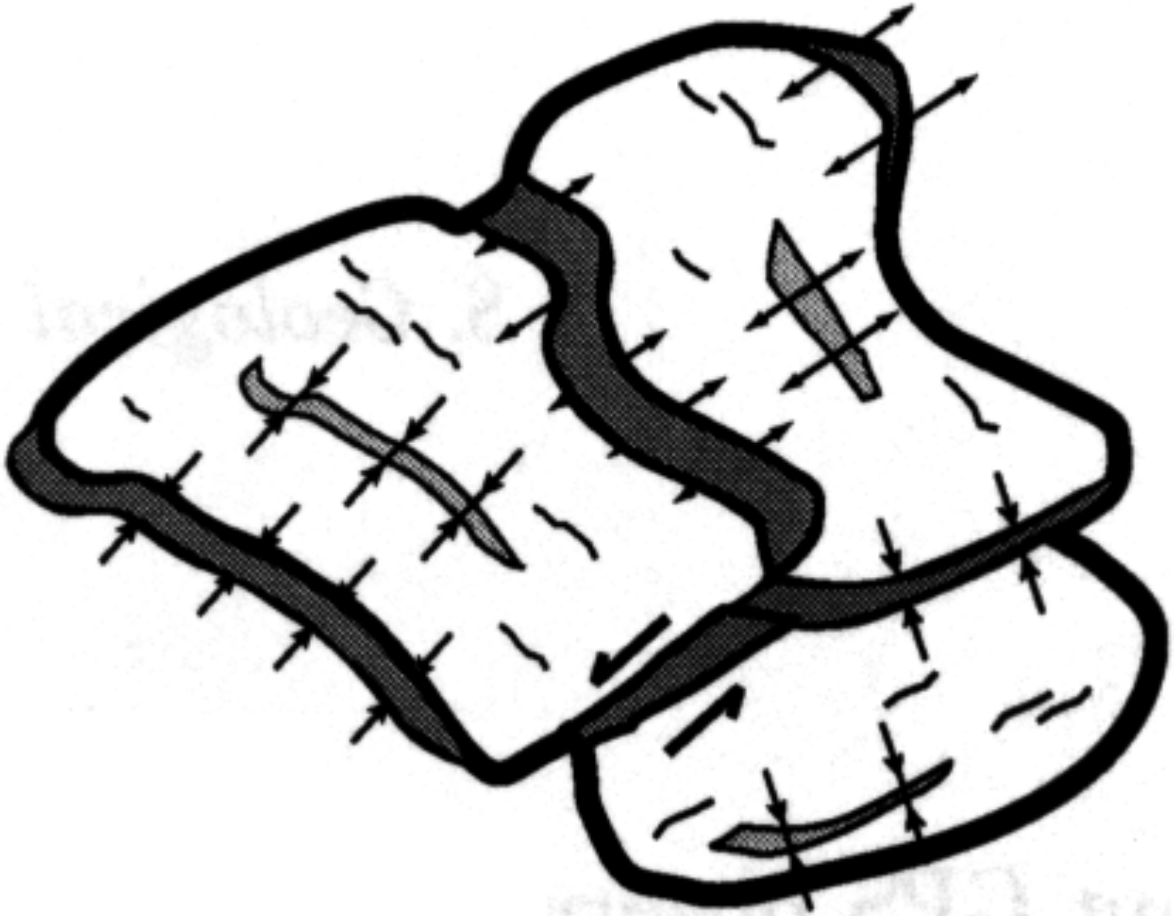
Thacher, 2003

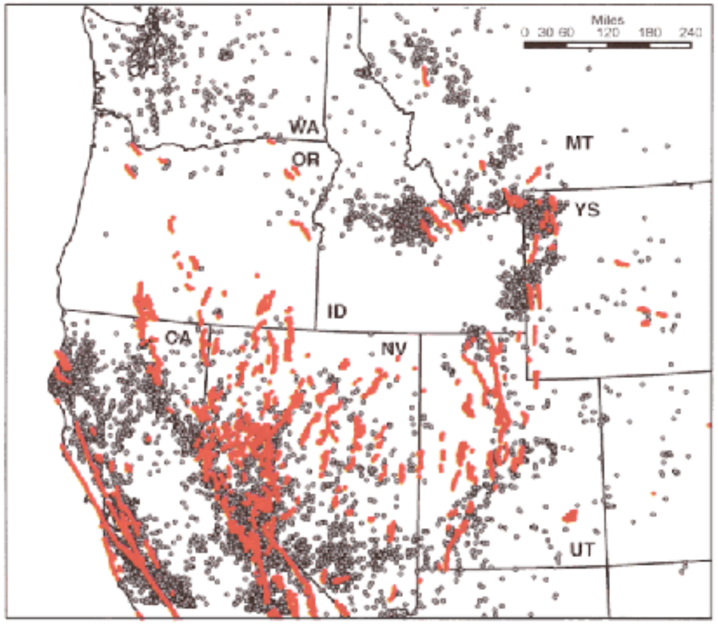




Narrow deformation zones.
Concentrated zones of deformation within inactive regions.
"Challenging" to see with GPS.

Thacher, 2003





More faults with evidence of active deformation than actively deforming zones.

May jump around (on human or geologic scale).

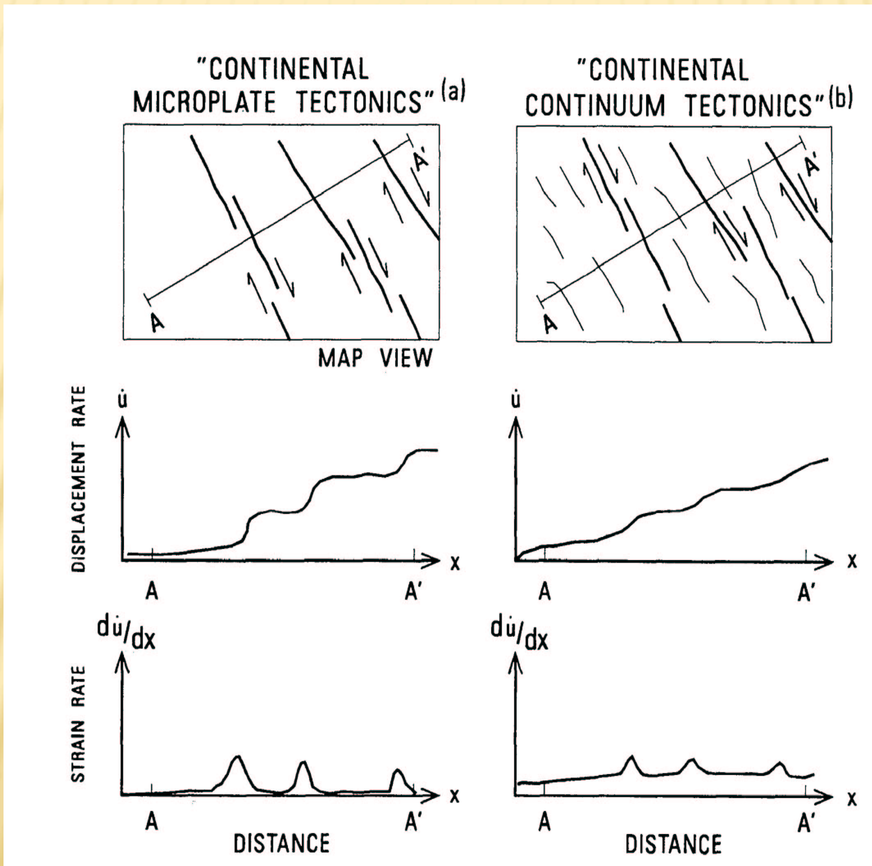
“Challenging” to see with GPS.

Thacher, 2003

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. B3, PAGES 3885–3894, MARCH 10, 1995

Microplate versus continuum descriptions of active tectonic deformation

Wayne Thatcher
U.S. Geological Survey, Menlo Park, California

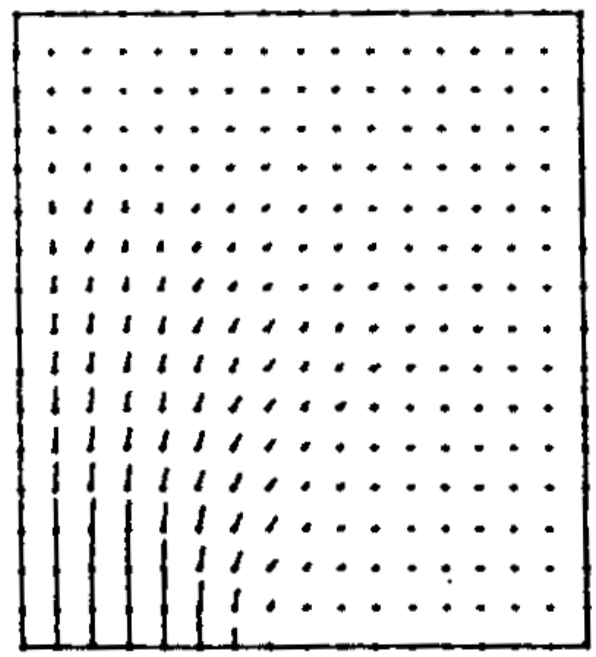


Geophys. J. R. astr. Soc. (1982) 70, 295–321

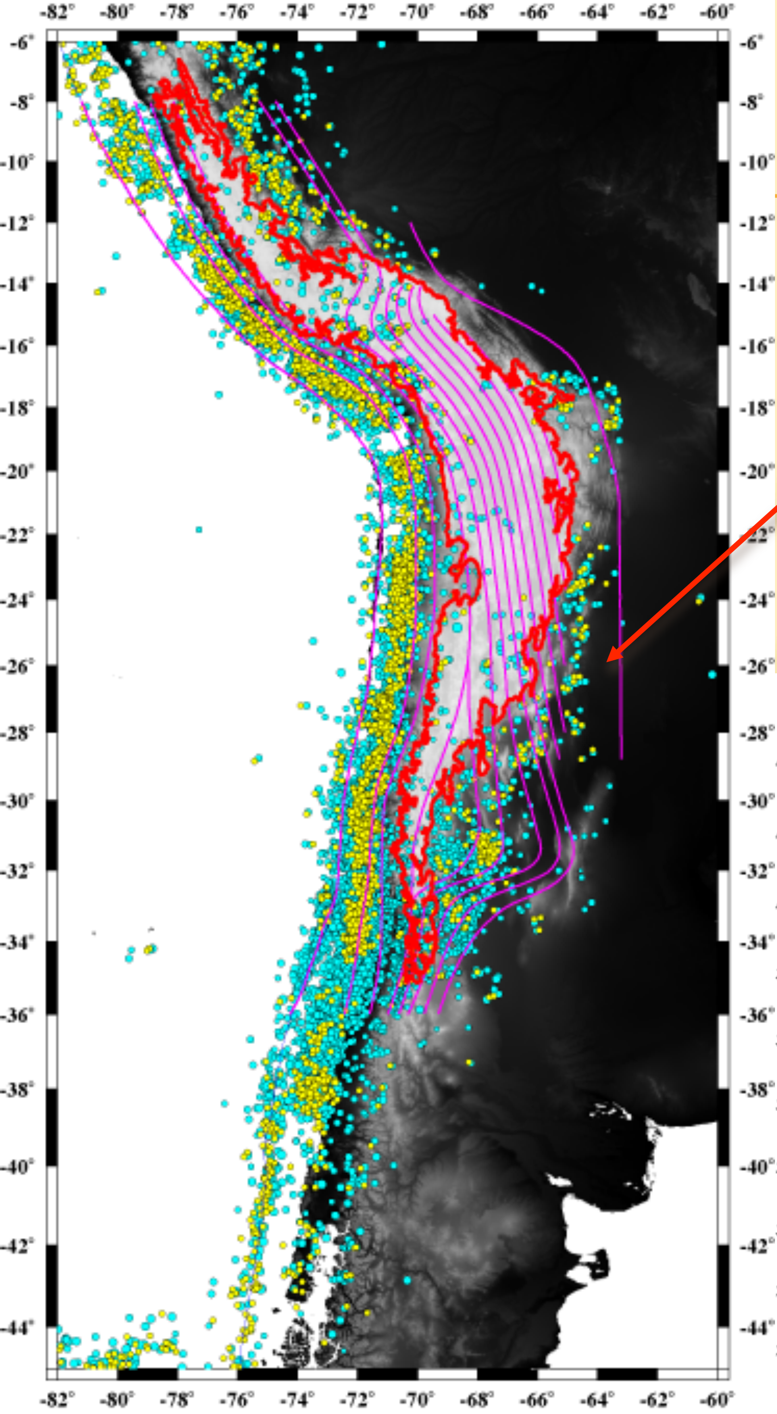
A thin viscous sheet model for continental deformation

Philip England* and Dan McKenzie *Department of Earth Sciences, University of Cambridge, Bullard Laboratories, Madingley Rise, Madingley Road, Cambridge CB3 0EZ*

The TVS 'test':
'If the orientation of buoyancy stresses
(calculated from maps of crustal thickness)
and tectonic stresses (from velocity field
and TVS formulation) are the same,
then the region is essentially behaving as a fluid' (England and Molnar, '97)



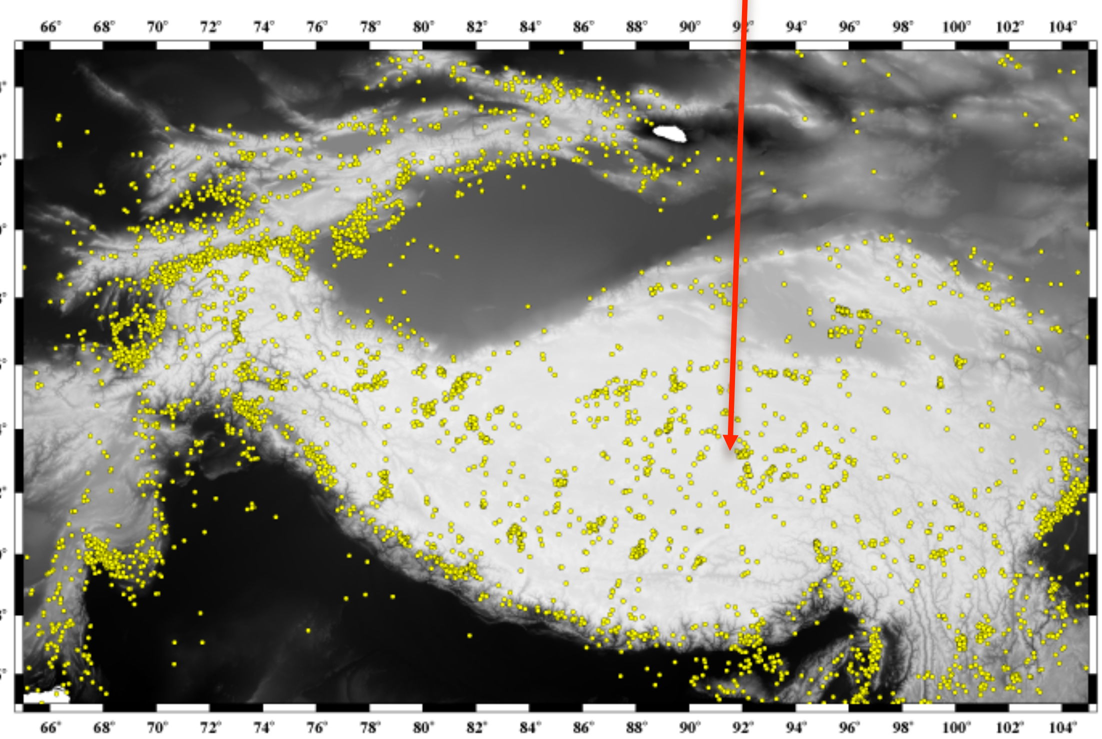
Compare seismicity of Himalaya and Andes



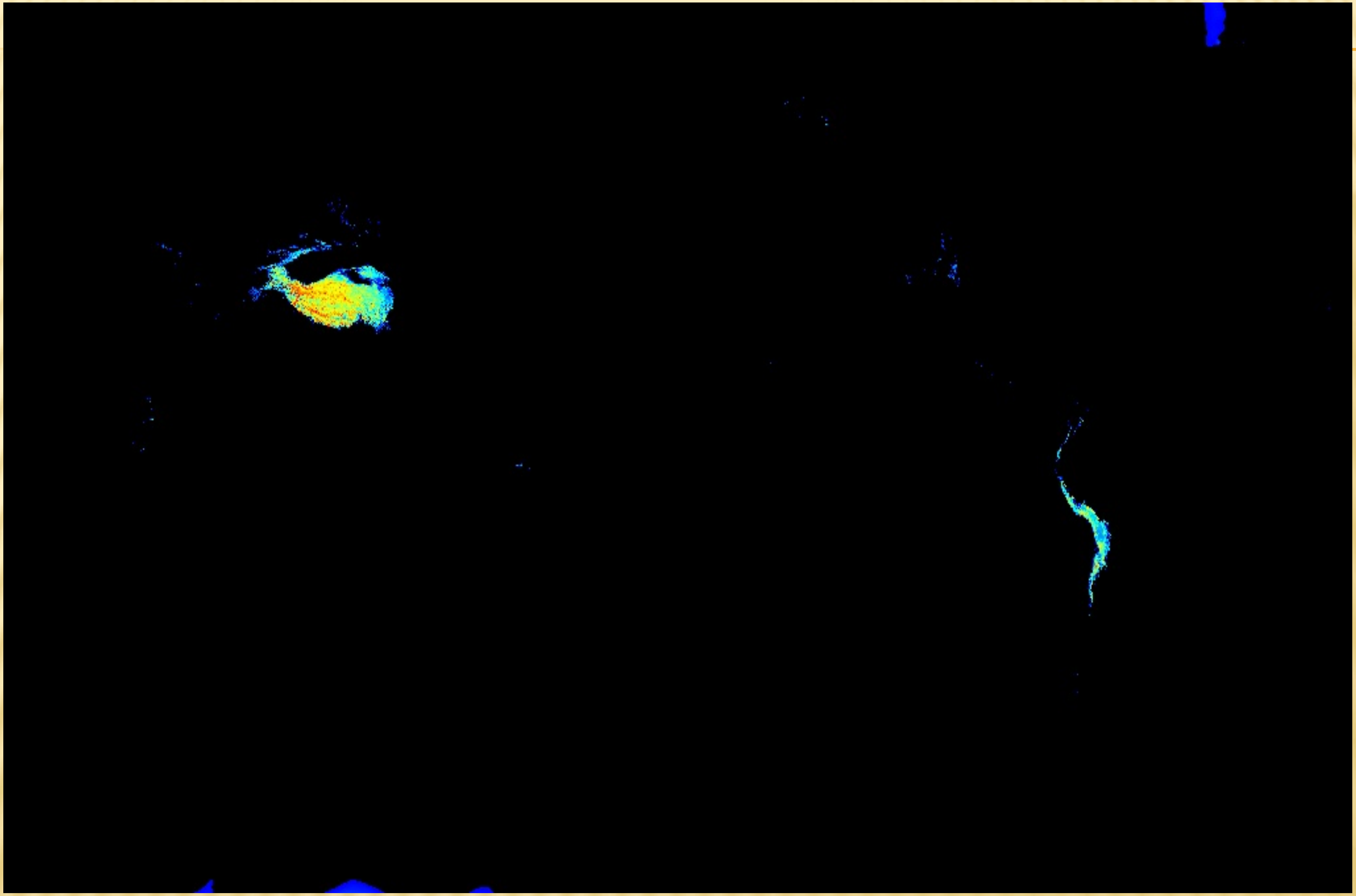
Around edges

After Brooks et al, 2003

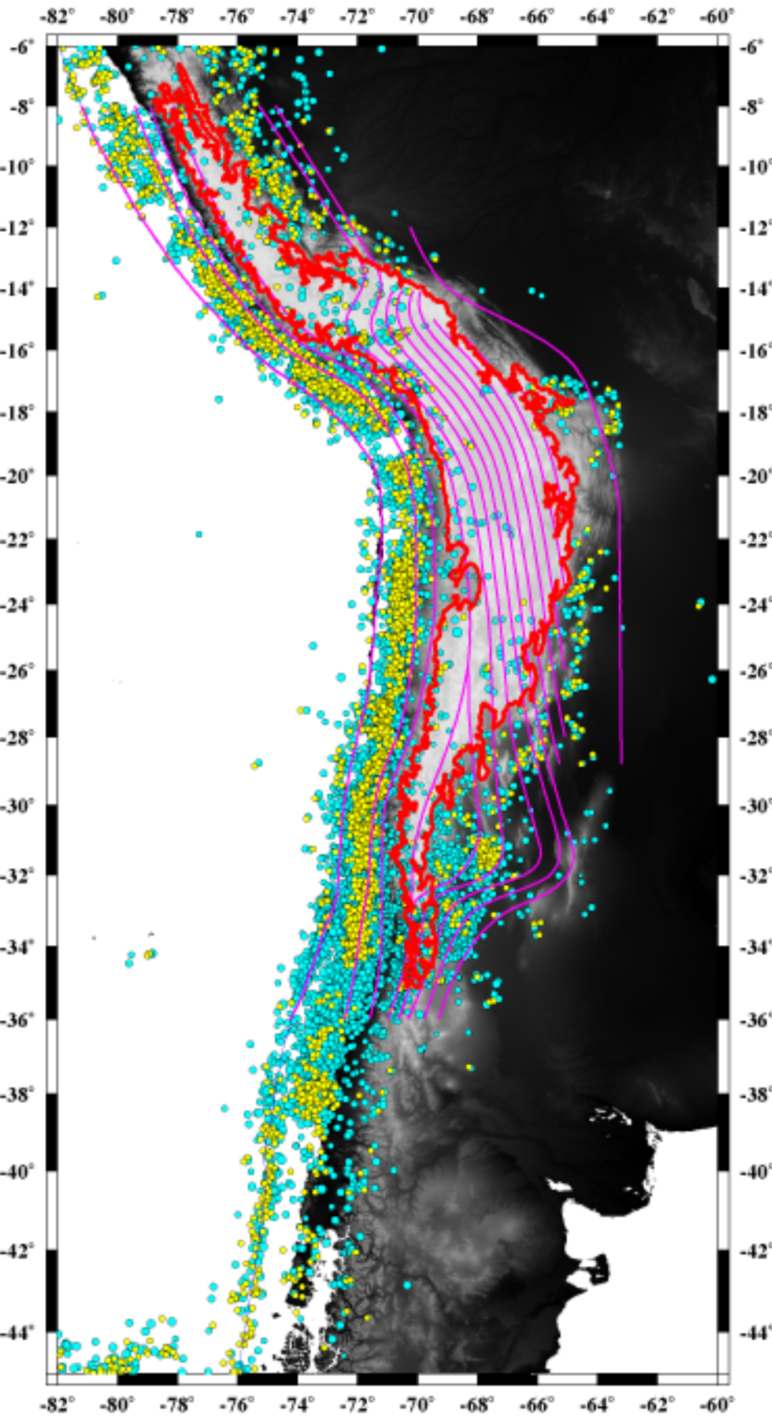
Distributed



Map of topography higher than 3 km.



Himalaya and Andes

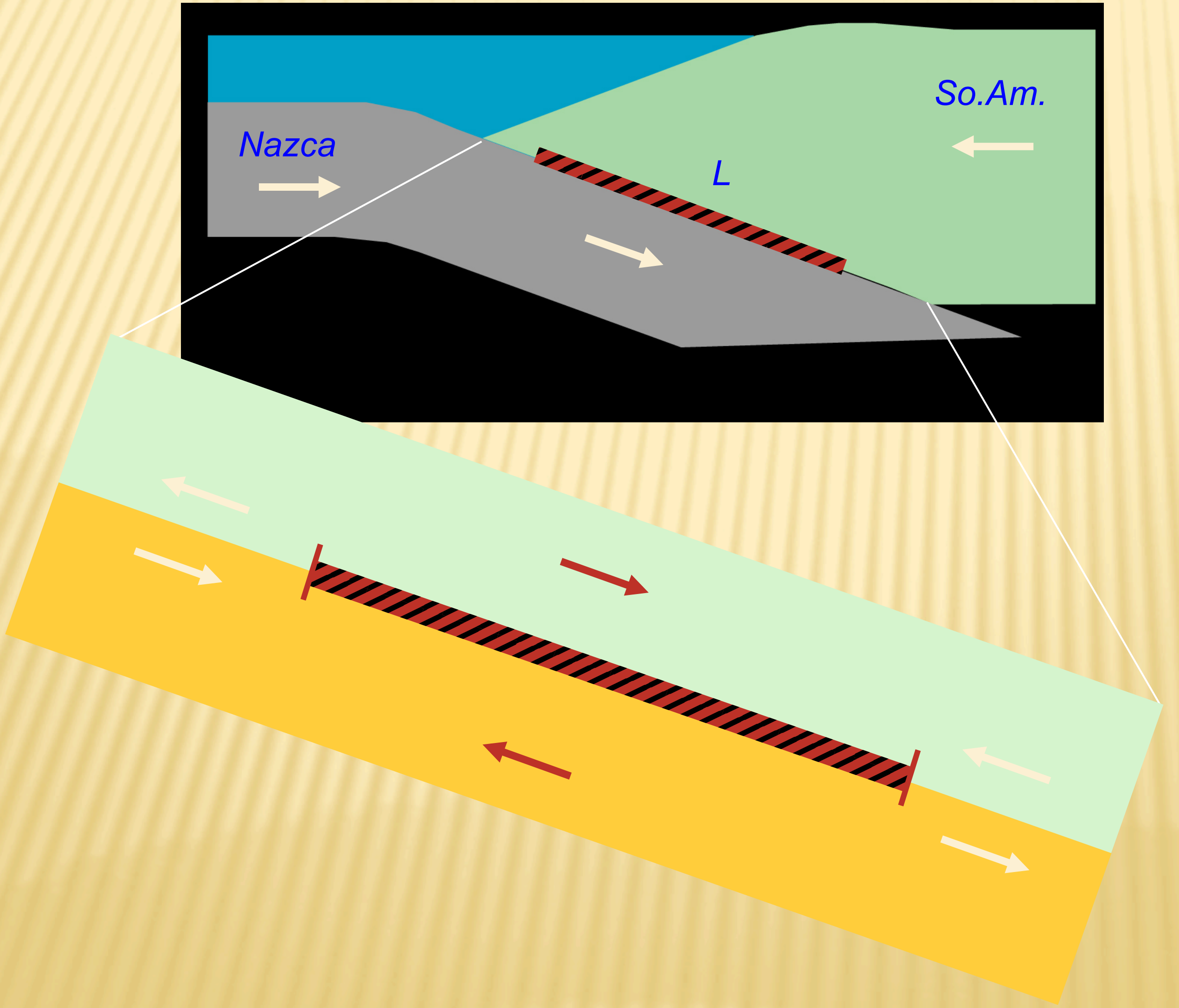


Andean seismicity:

- Plate boundary
- Crust is "aseismic" in high elevations
- Active crustal seismicity between eastern 3 Km elevation contour and eastern limit (surface projection) of Wadati-Benioff seismicity.

MODELING INTERSEISMIC STRAIN: 'BACKSLIP'

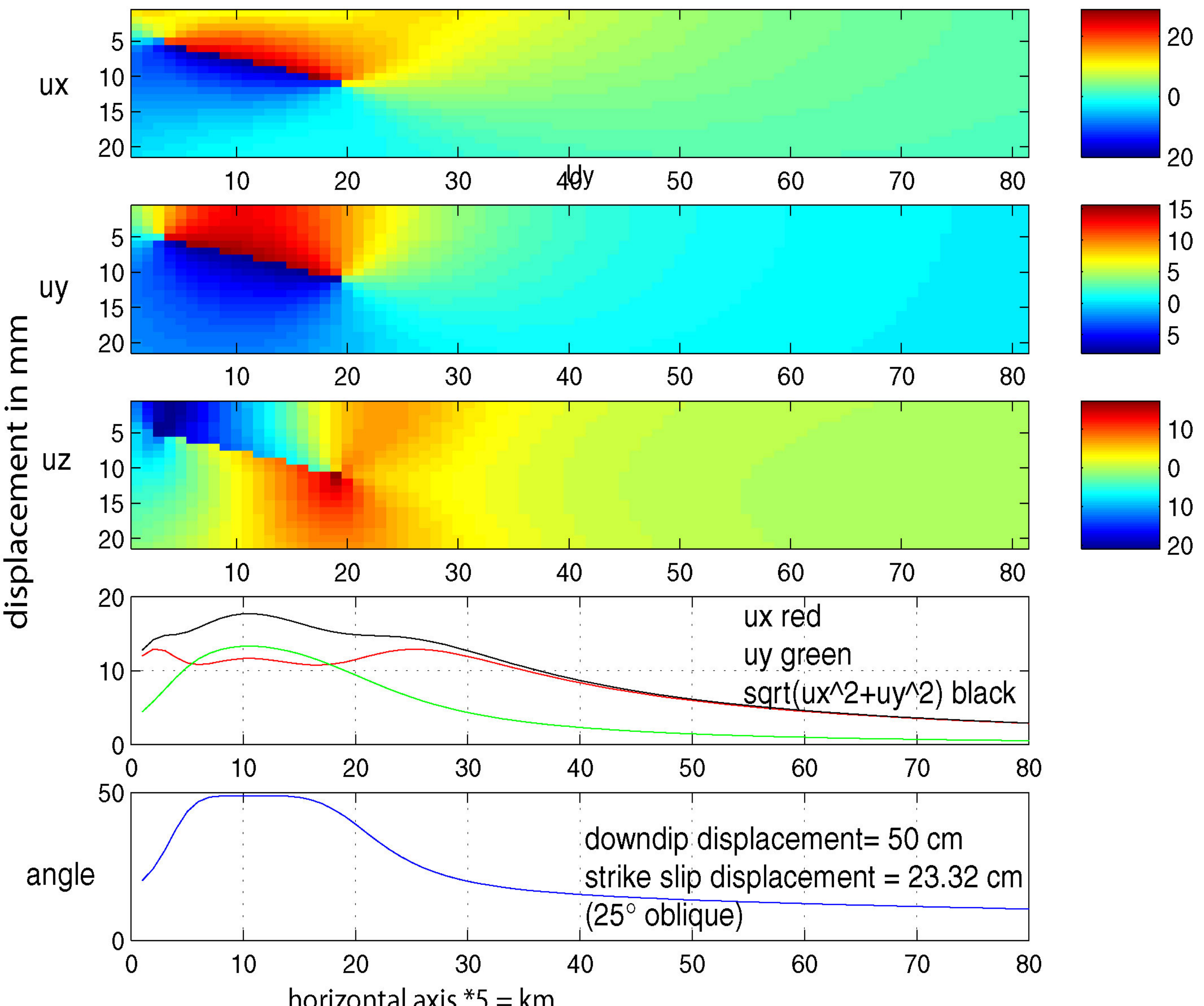
(after Savage, '83; Bevis & Martel, '01)



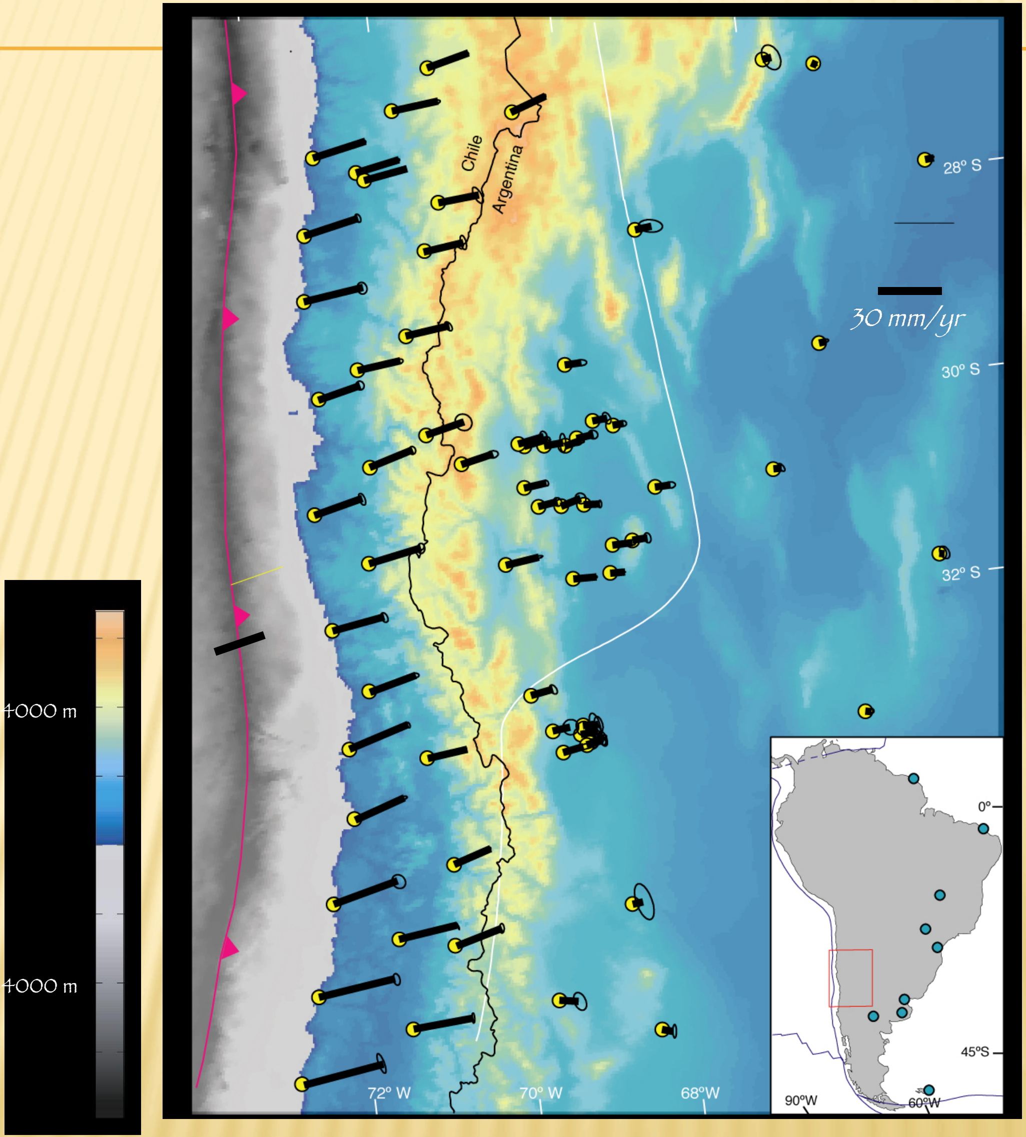
Savage backslip approach.

Run an earthquake "backwards" on the fault.

Elastic modeling – interseismic

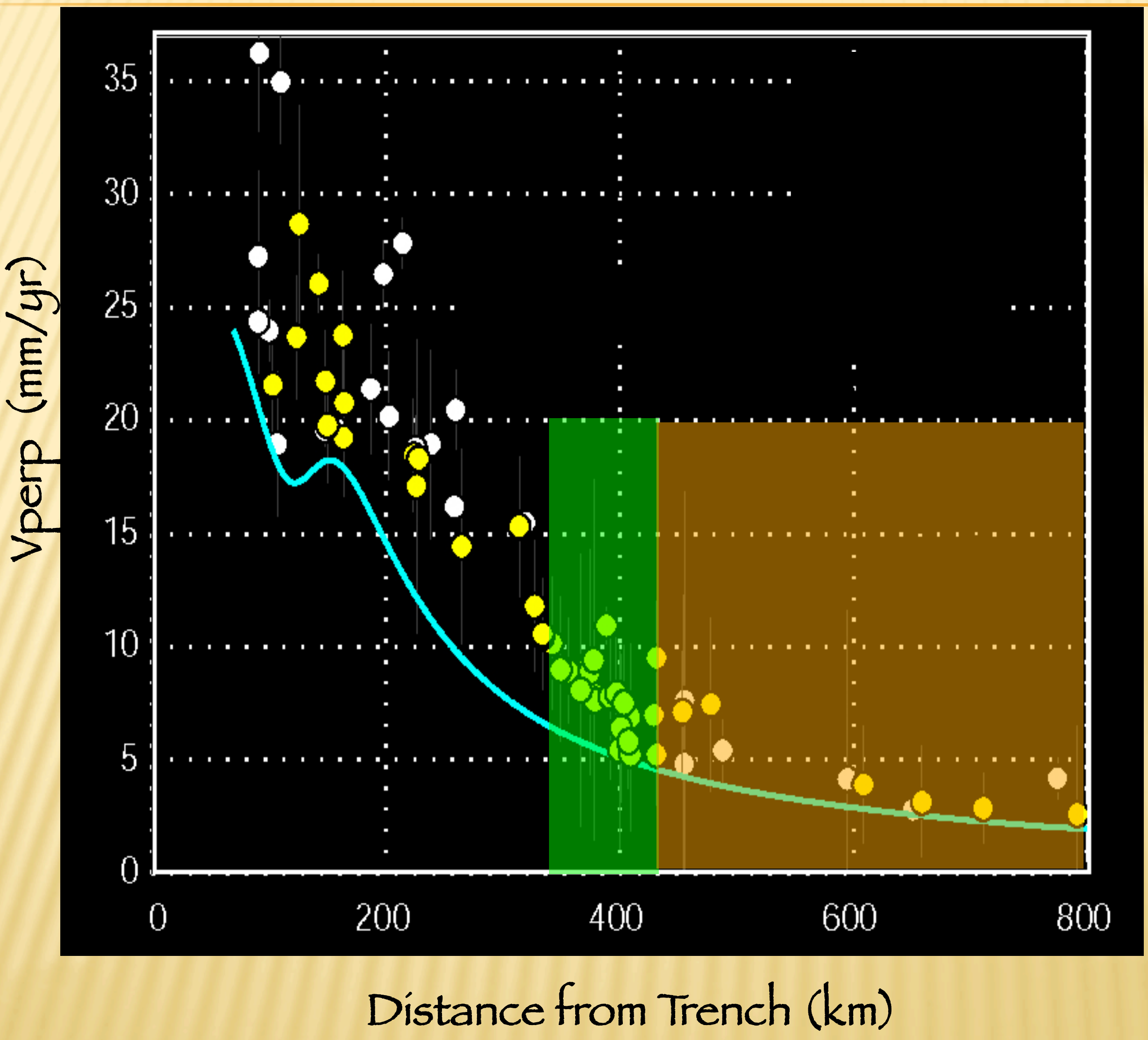


GPS velocity field, south central Andes



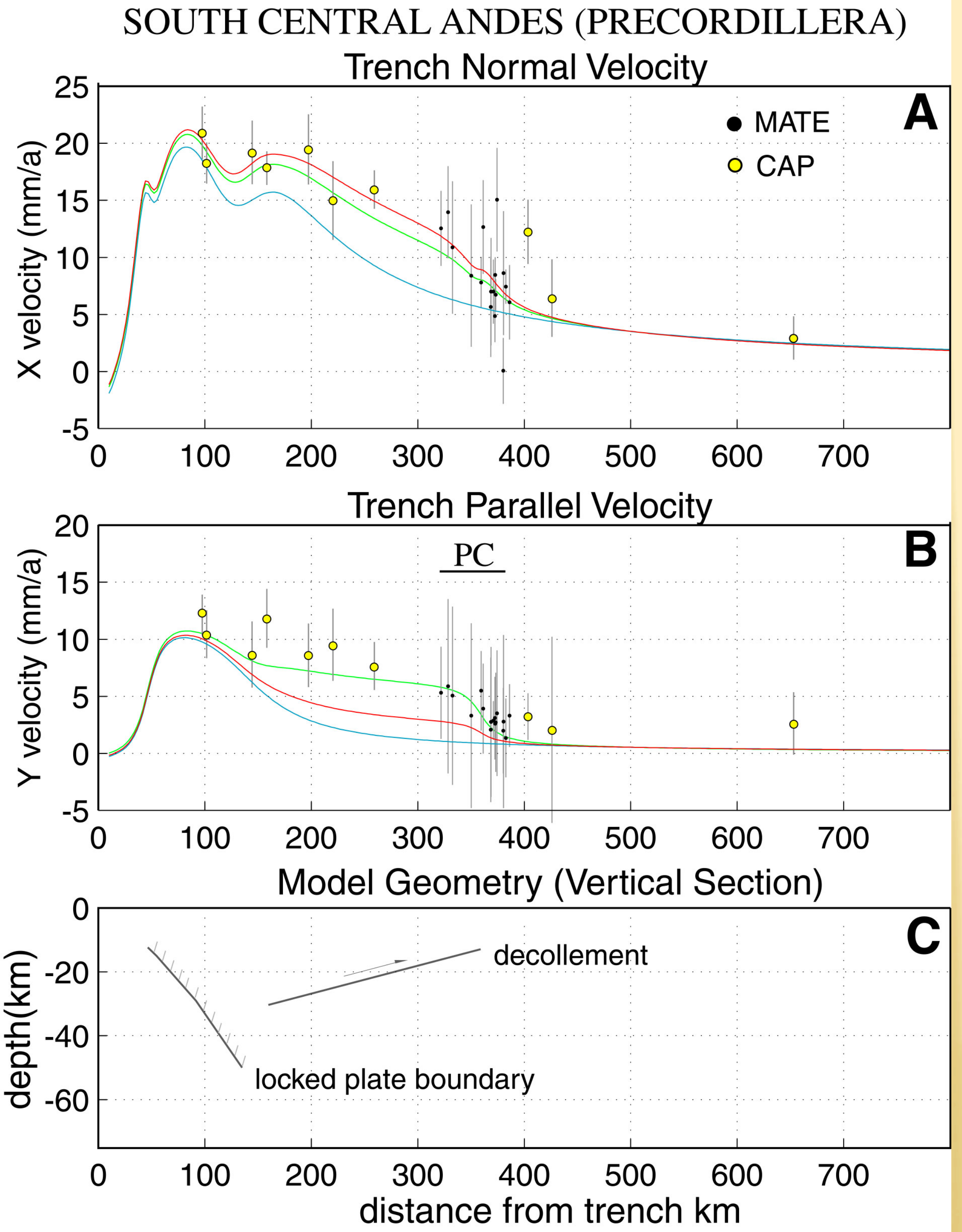
From Brooks et al, 2003

Horizontal velocity profile: back slip model (blue) vs data



100% locked

From Brooks et al, 2003

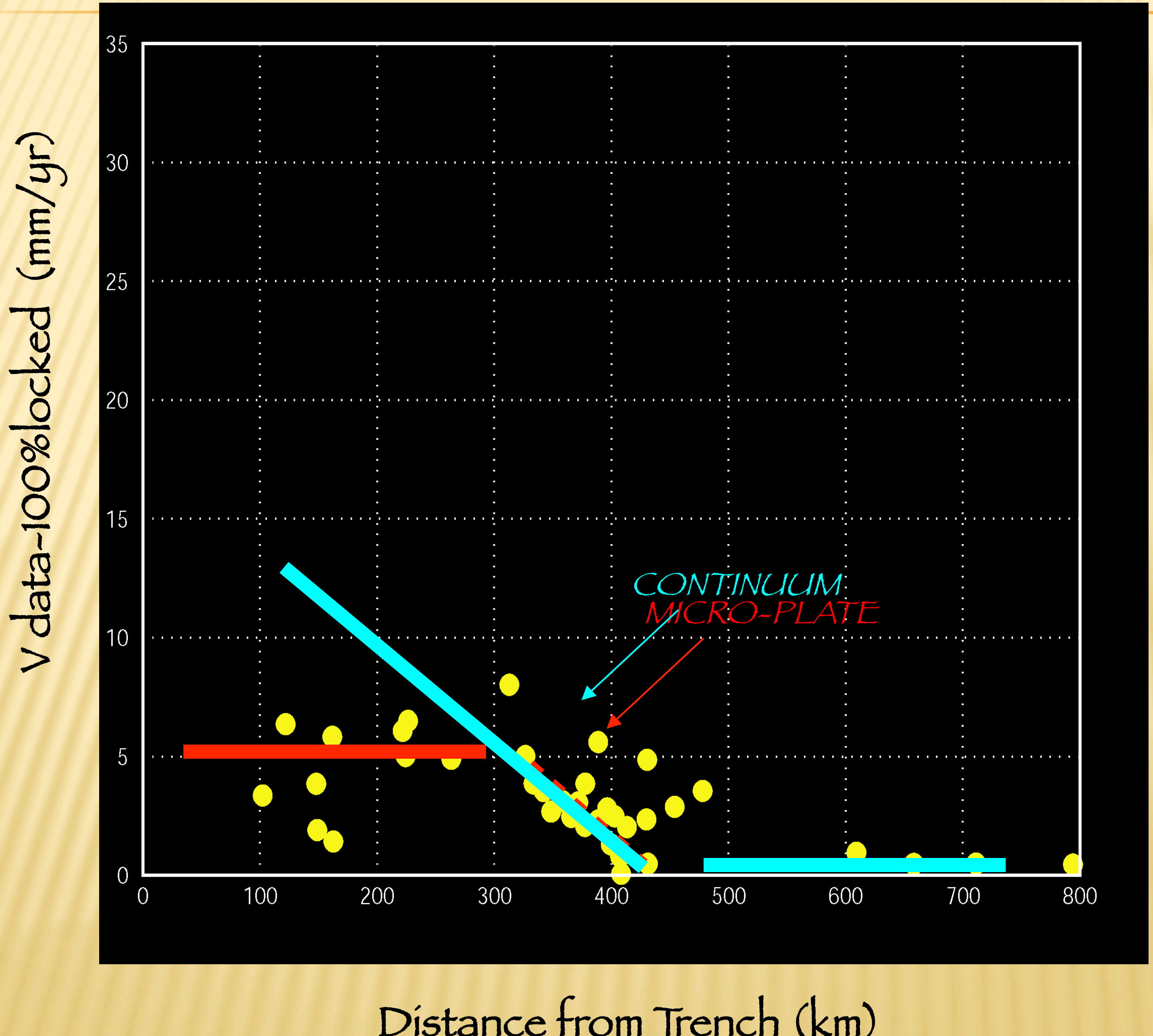


Cross section of horizontal velocity across south central Andes.

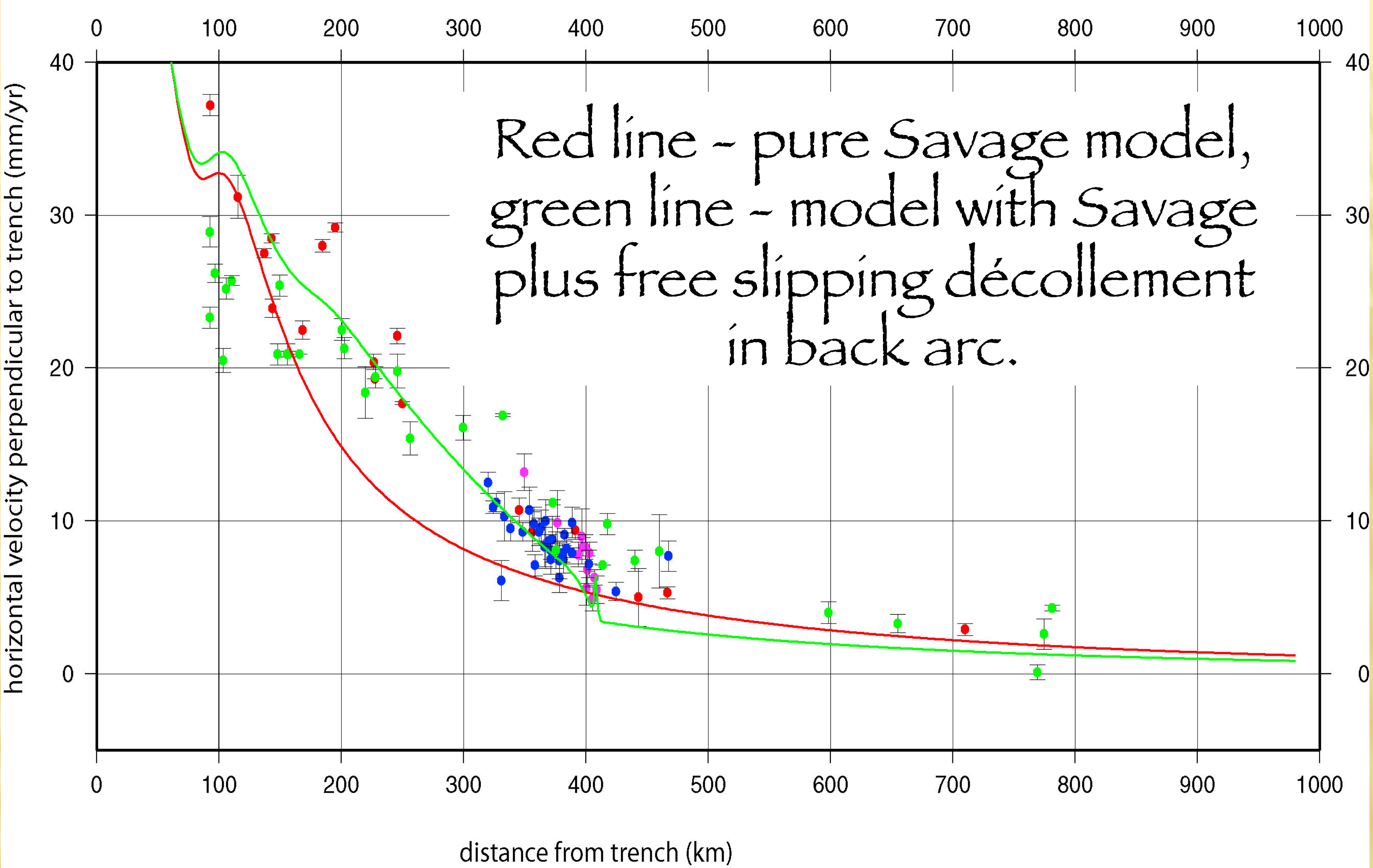
Strike is perpendicular to plate boundary.

From Brooks et al, 2003

Residual (*data-100% locked model*) velocity profile



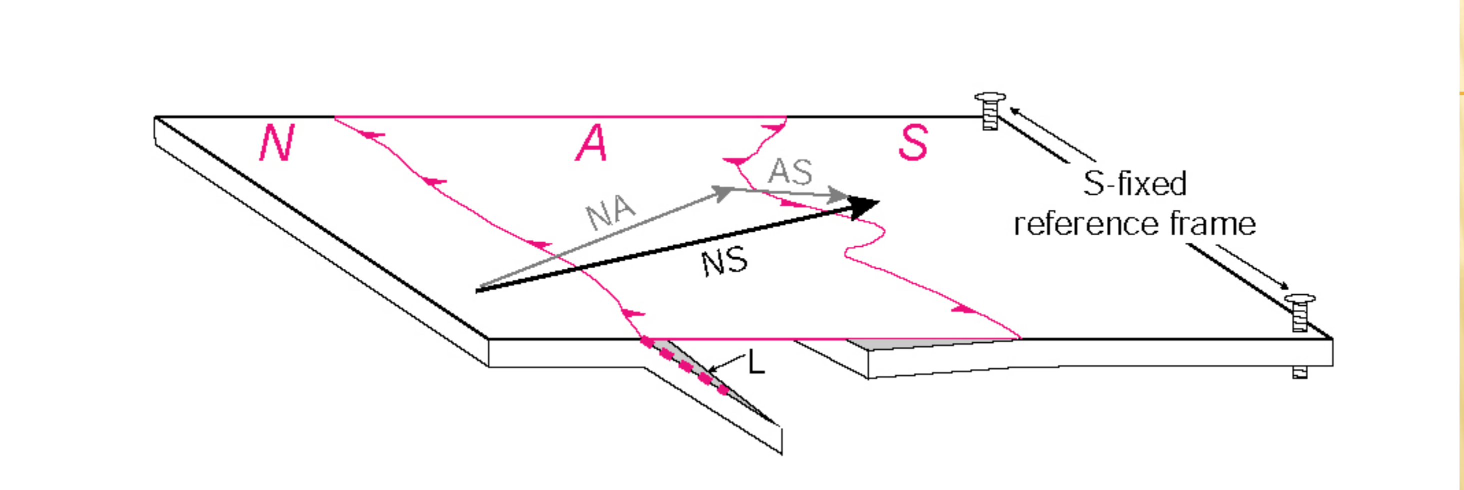
From Brooks et al, 2003



Cross section of horizontal velocity across south central Andes.
Strike is perpendicular to plate boundary.

From Brooks et al, 2003

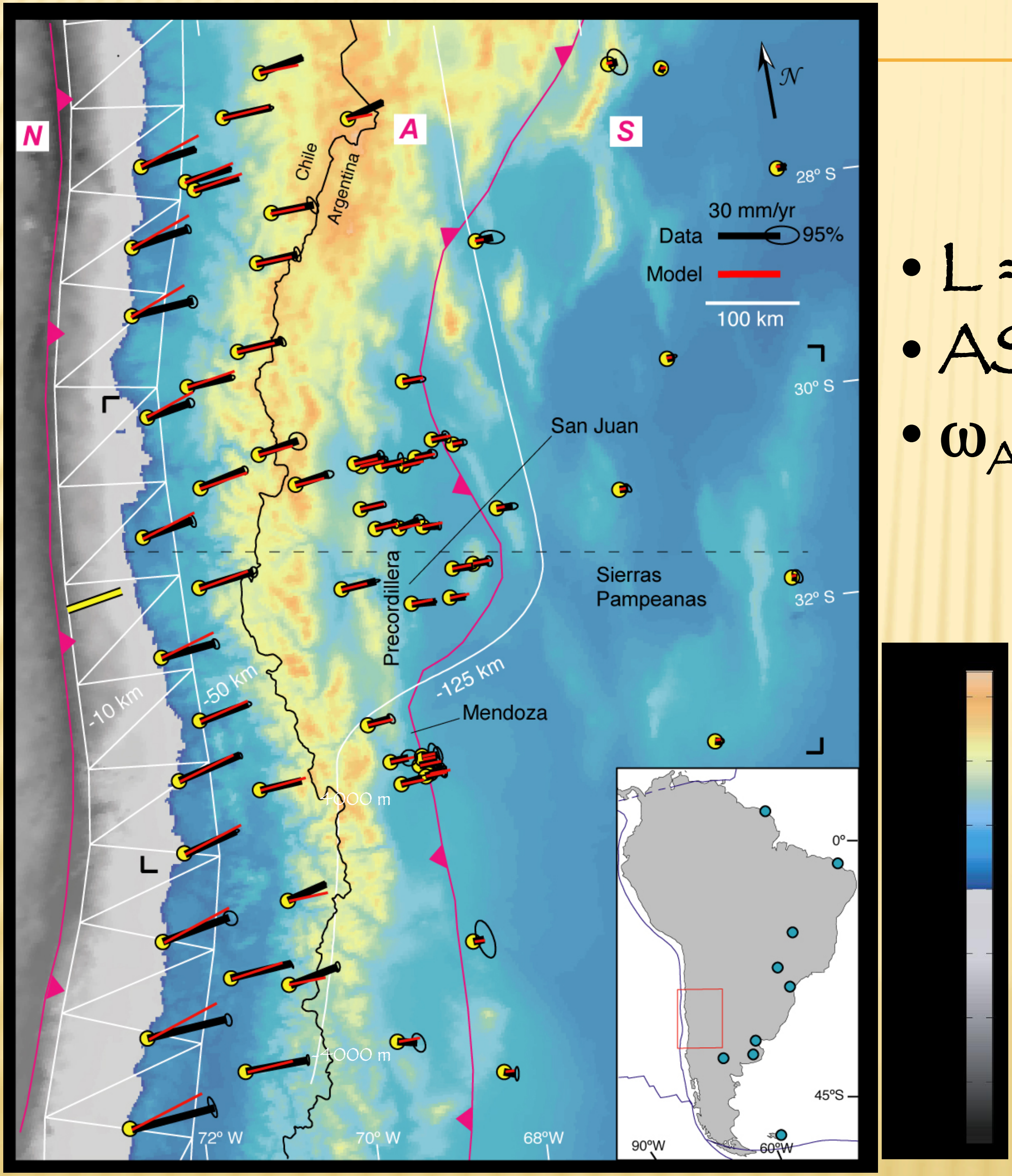
3-D, 3 "plate" model



- $U_{total} = U_{elastic} + U_{plate}$
- Inversion for 4 parameters:
  - L
  - AS_{lat}
  - AS_{lon}
  - AS_{w}
- (n.b. L is a free parameter doesn't have to be 100%)

From Brooks et al, 2003

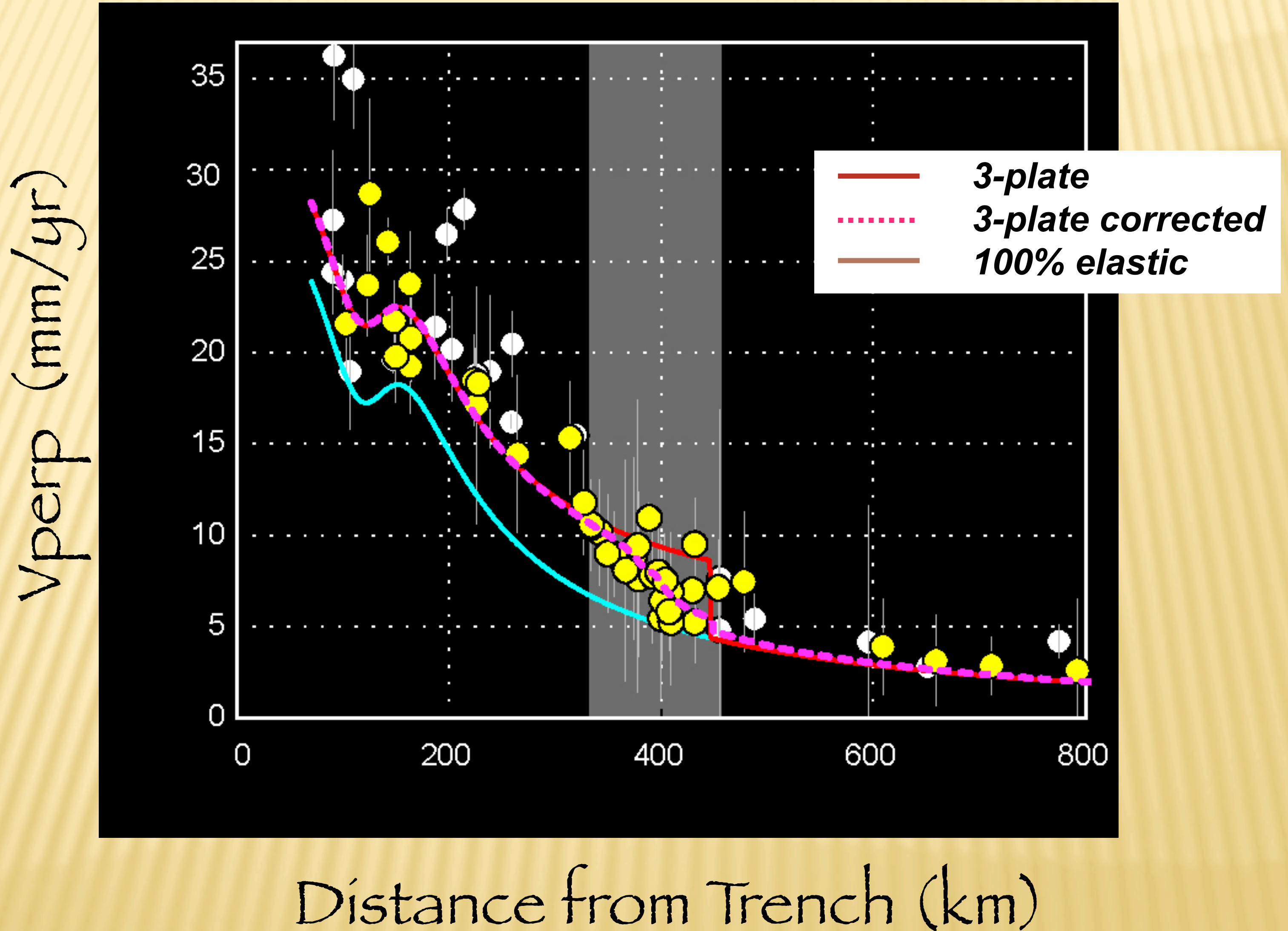
Modeled vs measured velocity field



- L = 1
- AS velocity ~ 4.5 mm/yr
- ω_{AS} in Canada

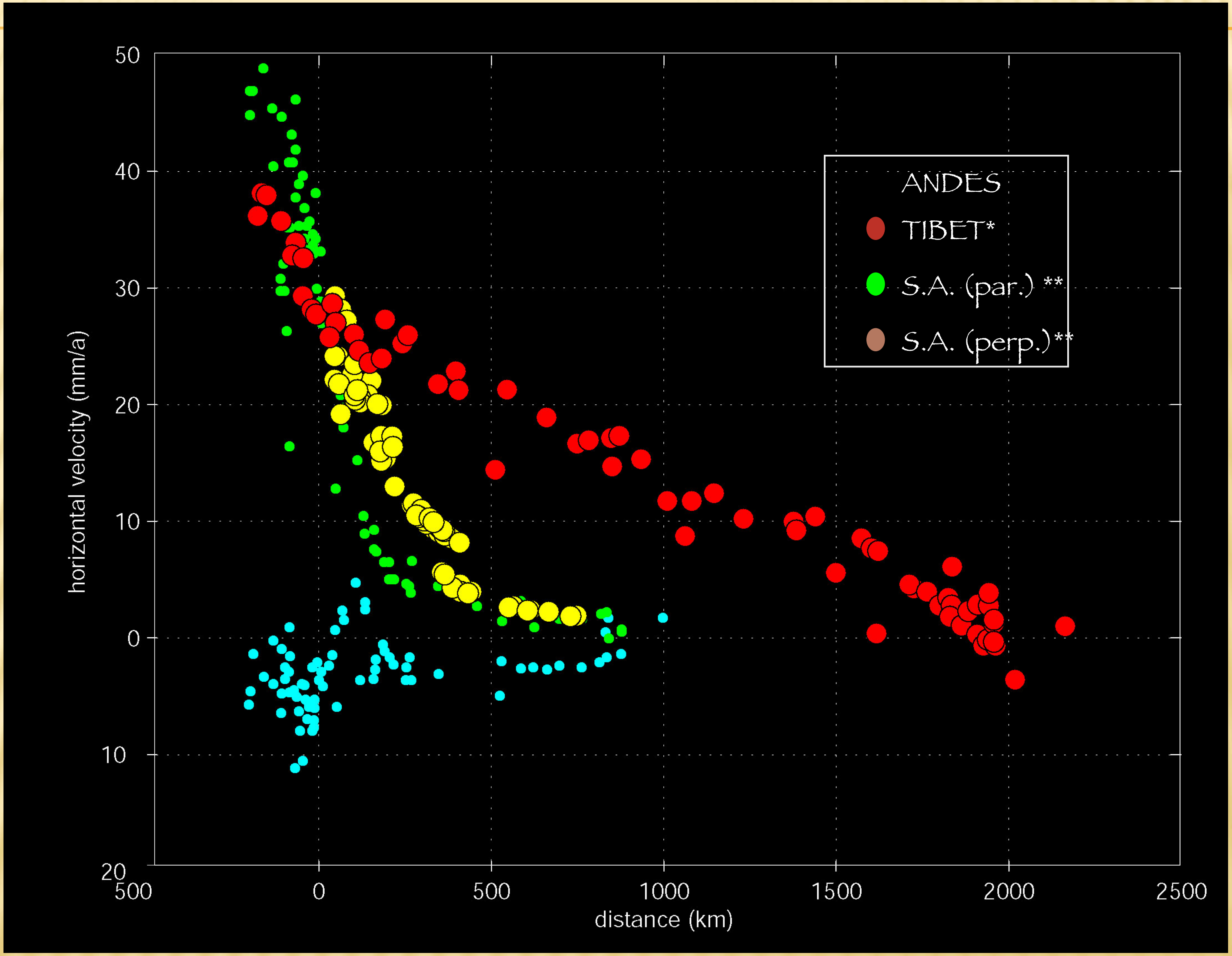
From Brooks et al, 2003

Horizontal, plate normal, velocity profile



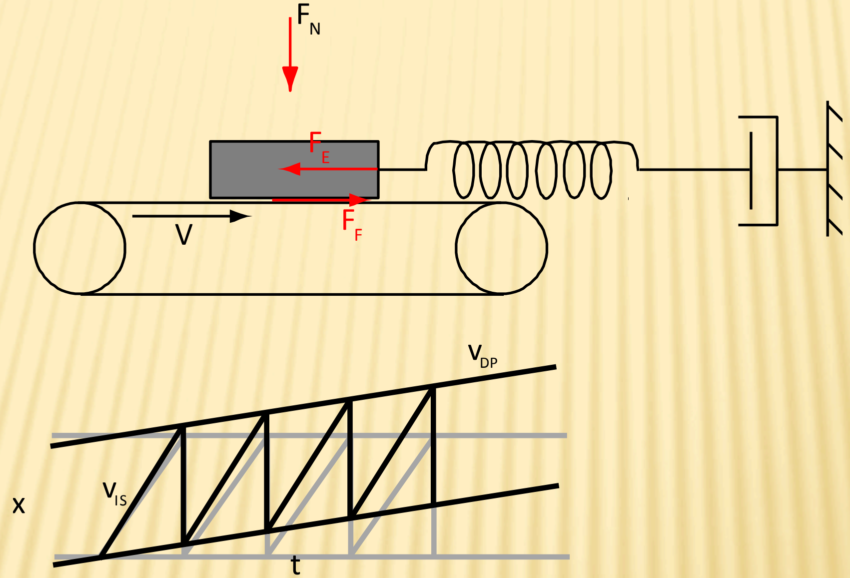
From Brooks et al, 2003

Comparative velocity profiles



(* Wang et. al, 2001; ** Bennett et. Al, 1999)

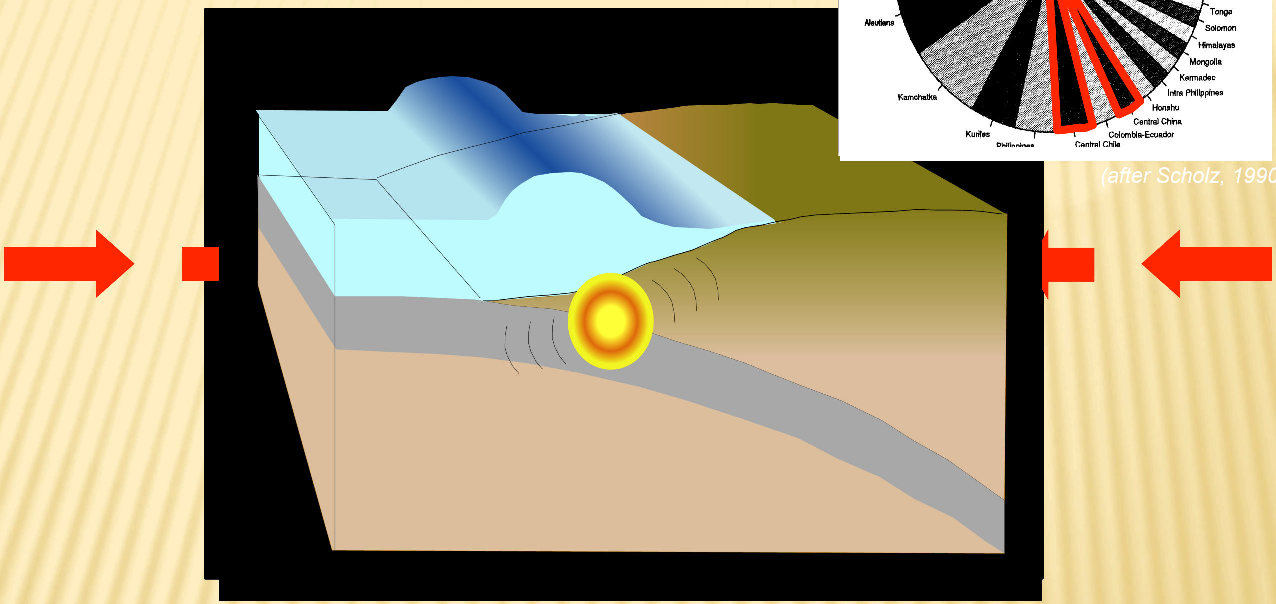
Simple visco-elastic modeling of subduction process

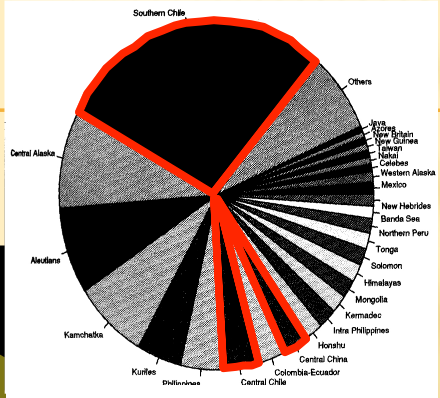


Permanent deformation (Mountains/Andes)

Mod from Hindle et al

Andean Crustal Deformation – Short Term



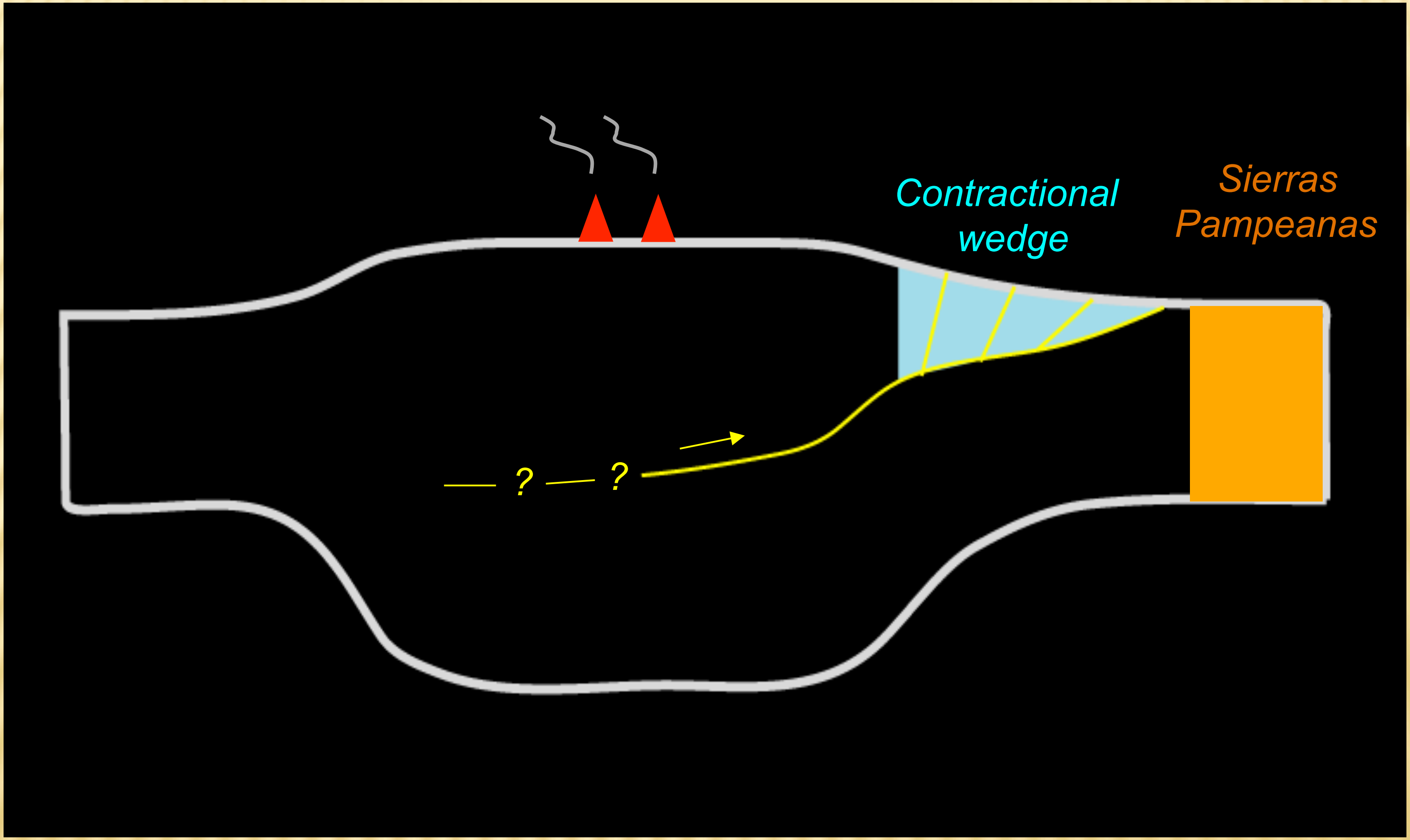


(after Scholz, 1990)

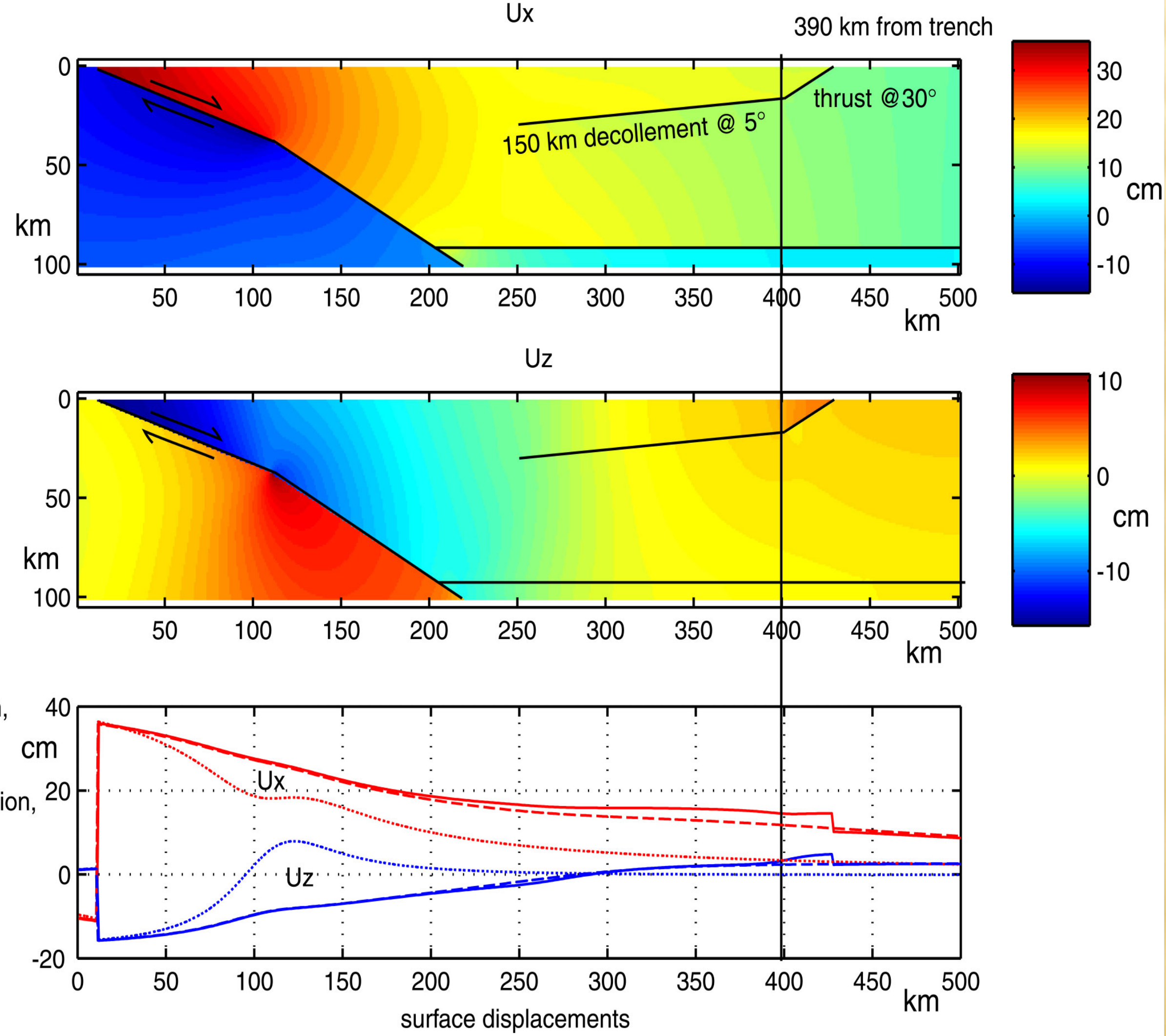
Along entire boundary: M ≥ 8 somewhere every ~10 yrs.
Each "traditional" segment: M ≥ 8 every ~100 years.

4-5 "newly recognized?" segments (800-1000+ km long)
M≥9 every ~400 years.

Boundary conditions for Andean orogeny.



locked plate boundary 20° to 50 km depth, with imposed back slip to represent interseismic strain buildup, then free slipping at 30° (no opening/closing), free slipping base to upper plate lithosphere at 90 km depth (no opening/closing)

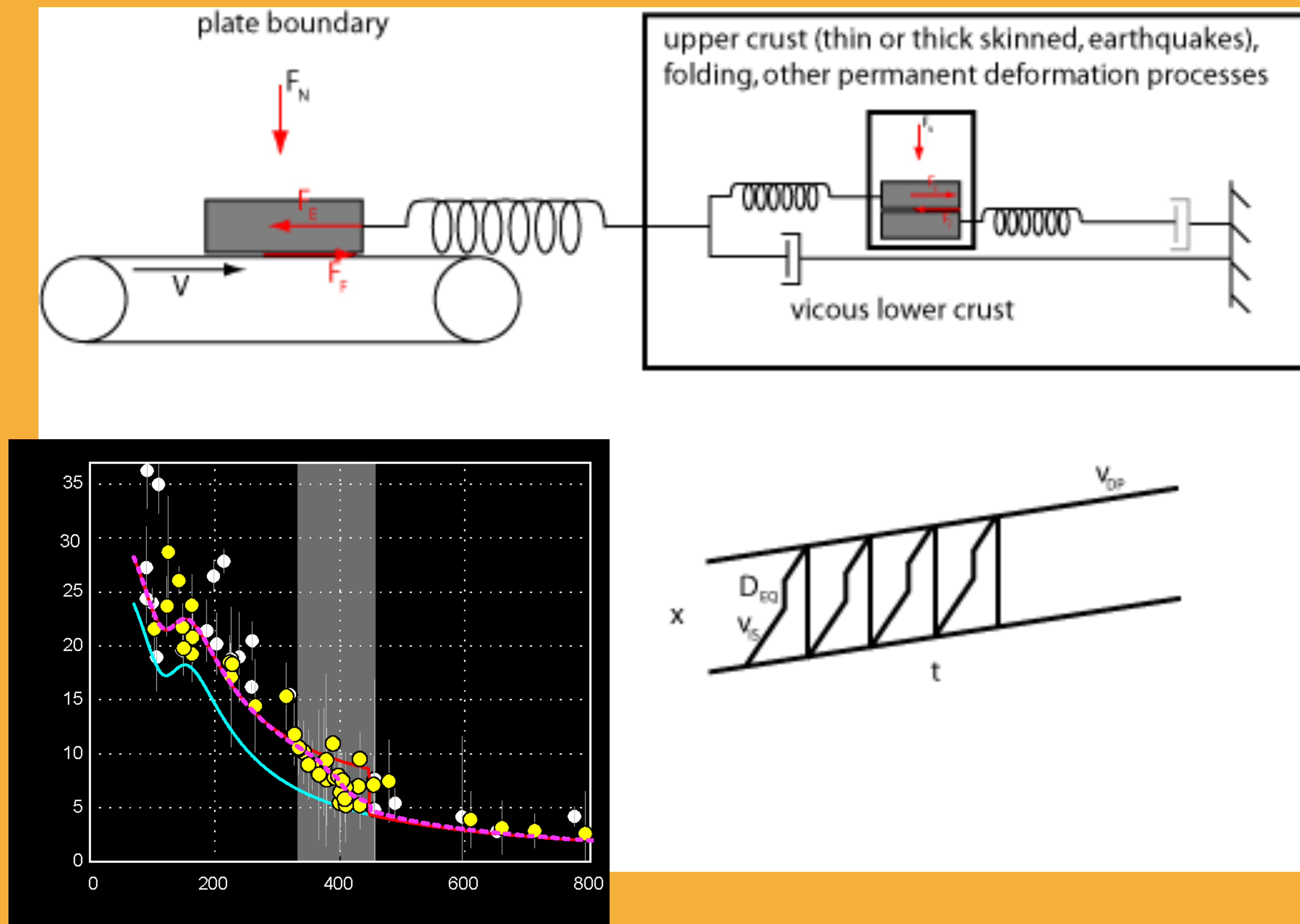


solid - 2 segment subduction, free slipping back arc

dashed - 2 segment subduction, no back arc sturctures

dotted - single segment subduction, no back arc structures

Simple visco-elastic modeling of subduction plus Andes block



Permanent deformation (Andes + foreland deformation)

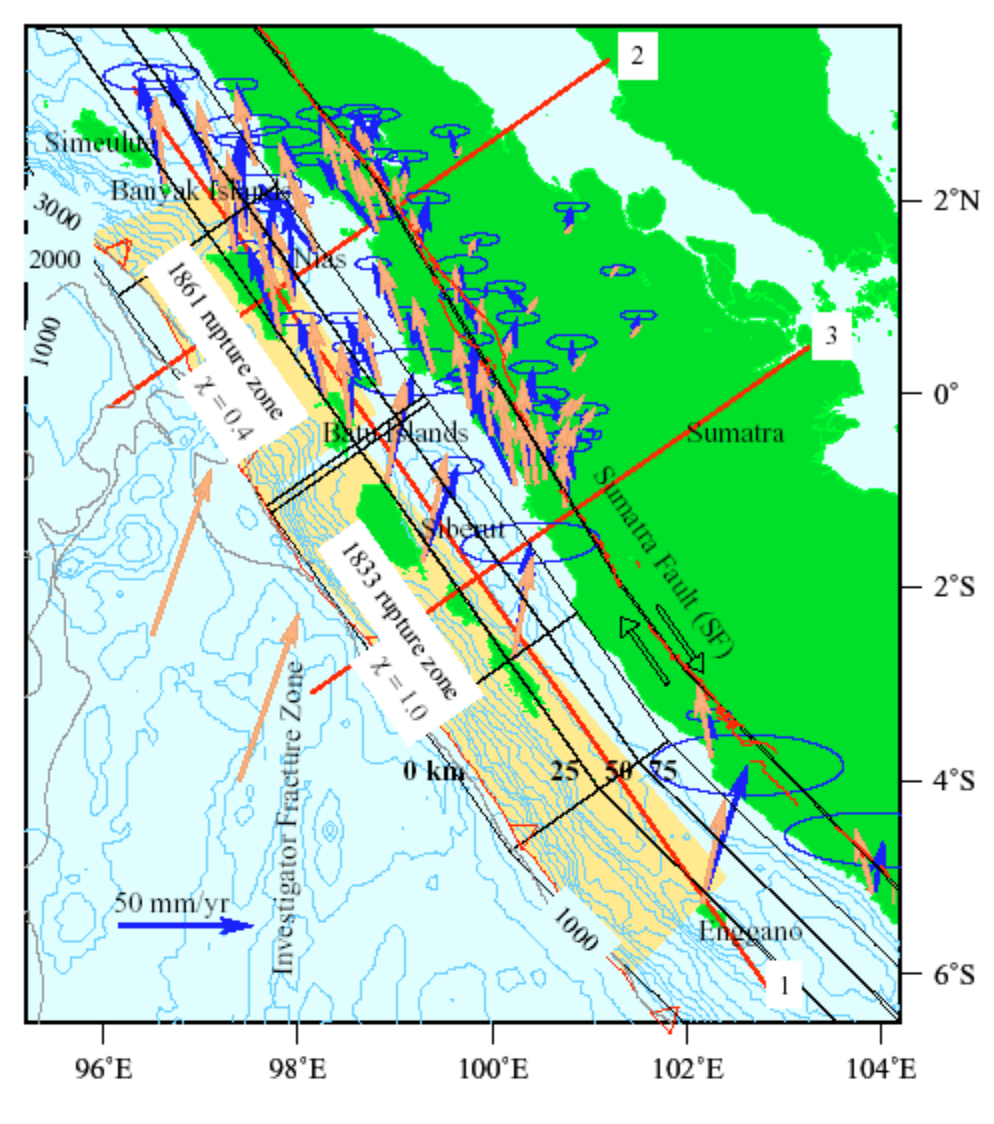
Strain and slip partitioning

Linear system

Can look at each “component” independently

Sum effects

- Downdip
- Strike-slip

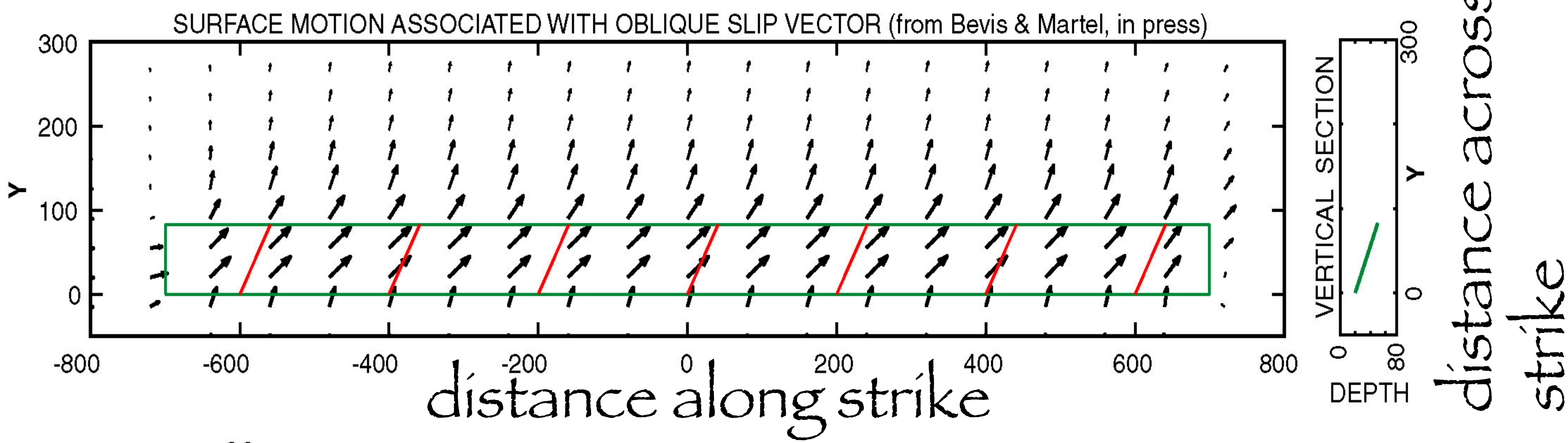


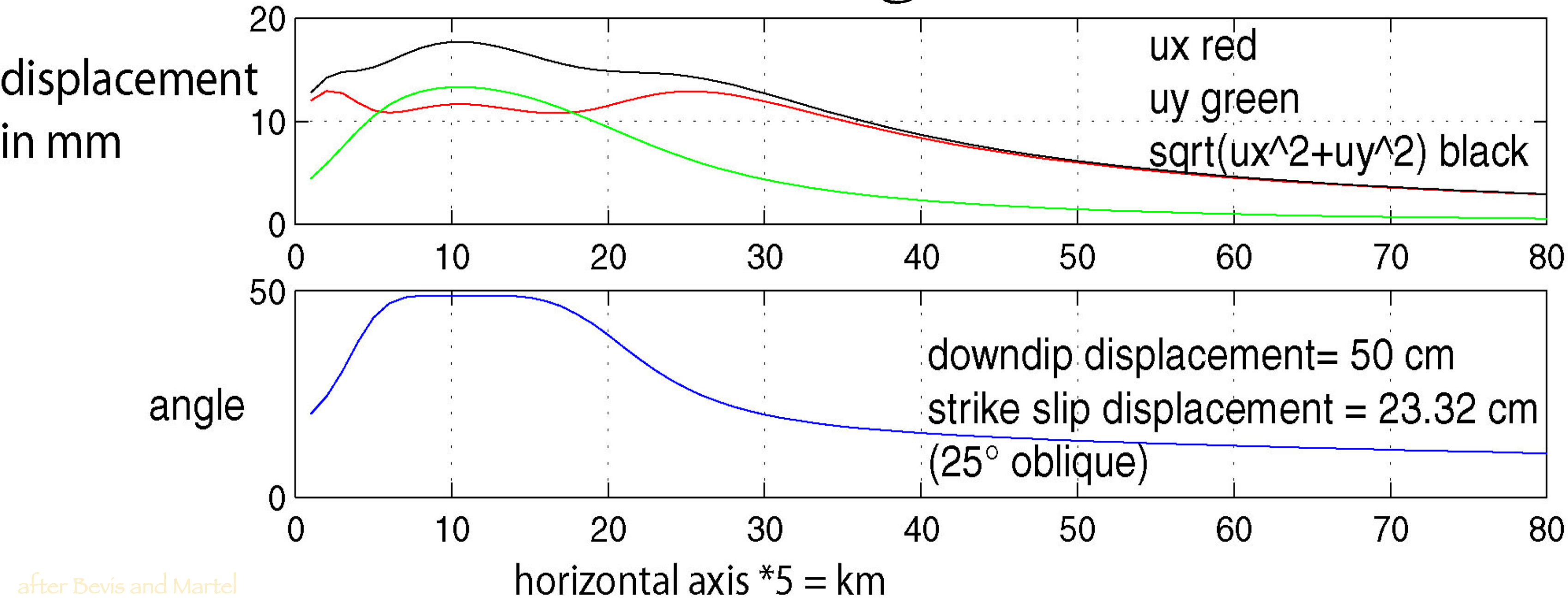
Oblique subduction in Sumatra

Strain partitioning poster child.

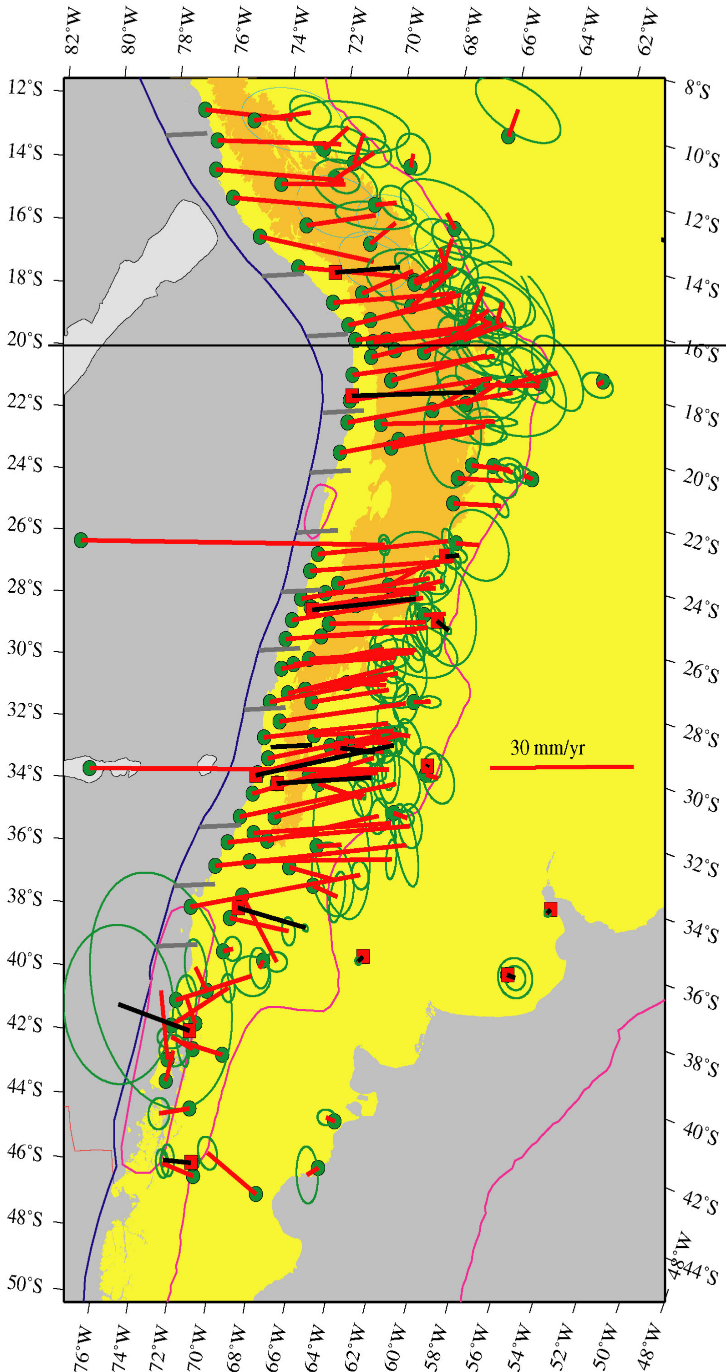
From McCaffrey, http://www.rpi.edu/~mccafr/sumatra04/

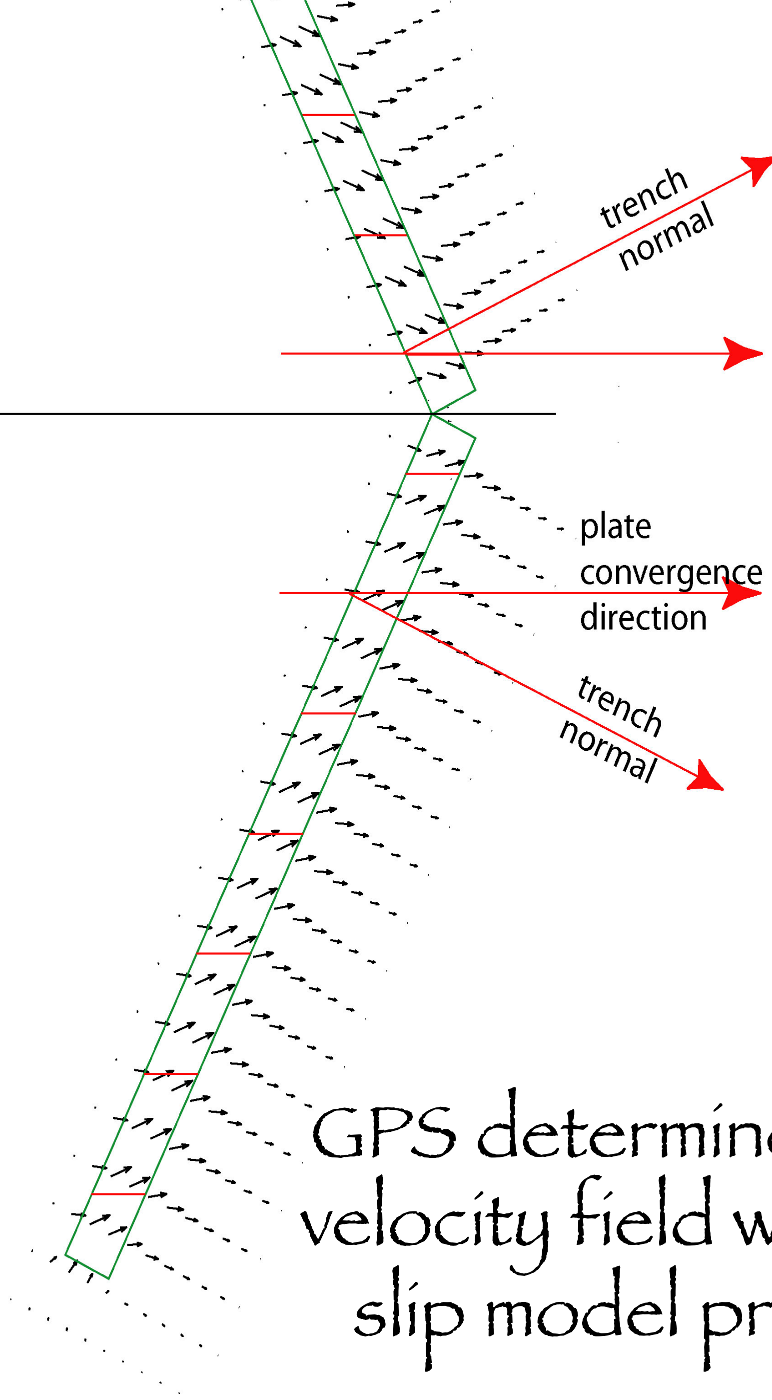
Oblique slip model - geometry of shortening controlled by trench orientation, not convergence direction.





after Bevis and Martel





GPS determined surface velocity field with oblique slip model predictions.

Oblique Mercator projection in which coast lies along a meridian.

Shows crustal velocity field for CAP and MATE networks

Note velocity gradient (deformation) across Andes

Note variation of obliquity from greater than plate convergence direction to approximately perpendicular to coast/plate boundary.