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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678-4929
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 14

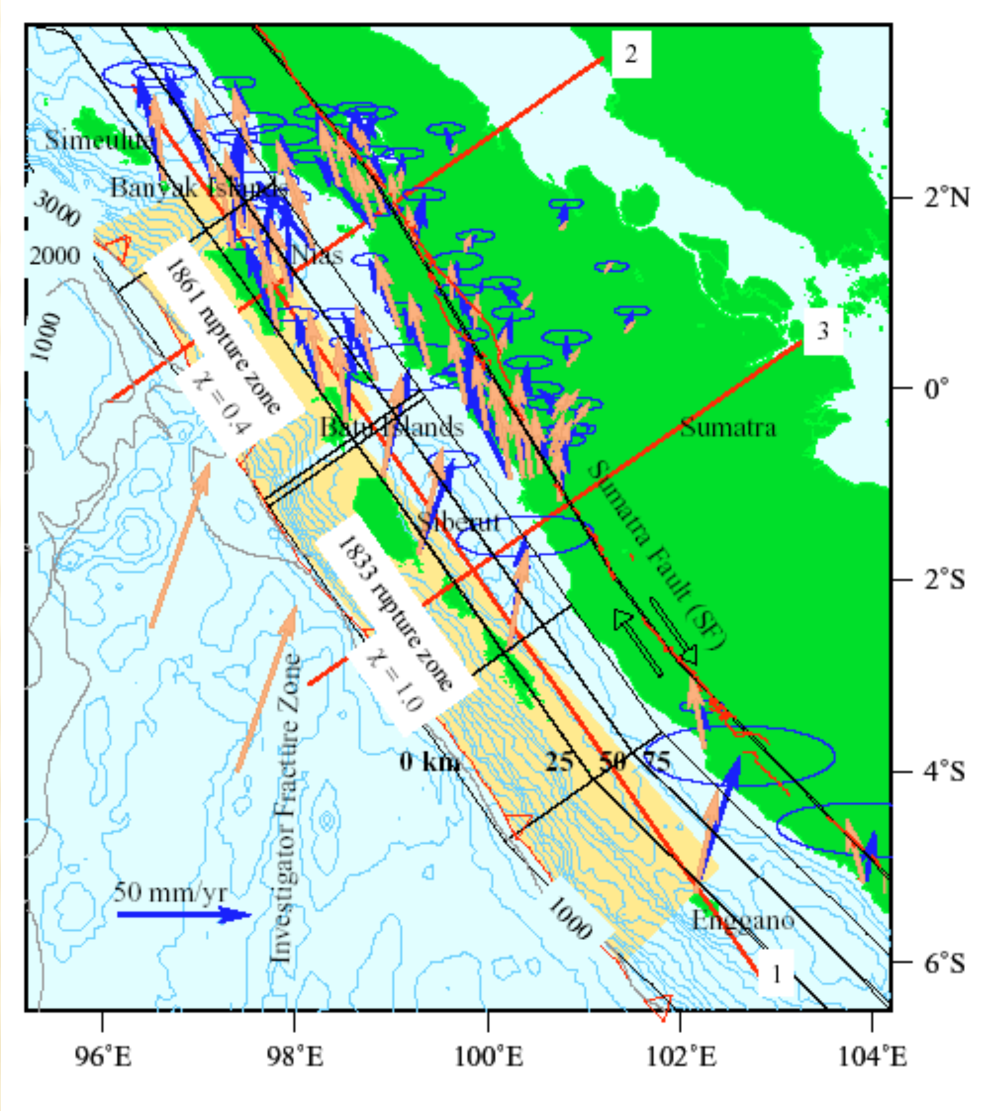
Strain and slip partitioning

Linear system

Can look at each "component" independently

Sum effects

- Downdip
- Strike-slip

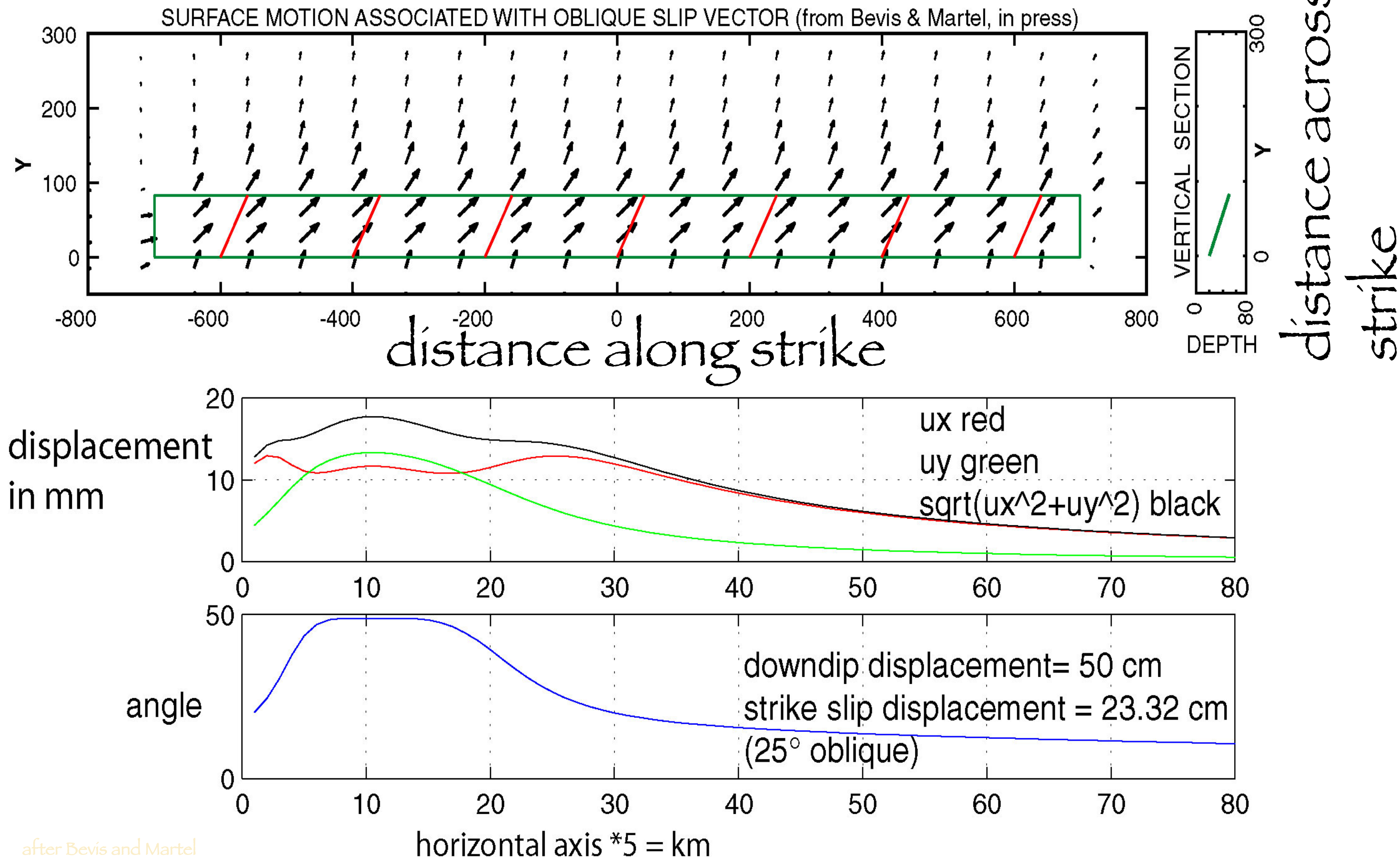


Oblique subduction in Sumatra

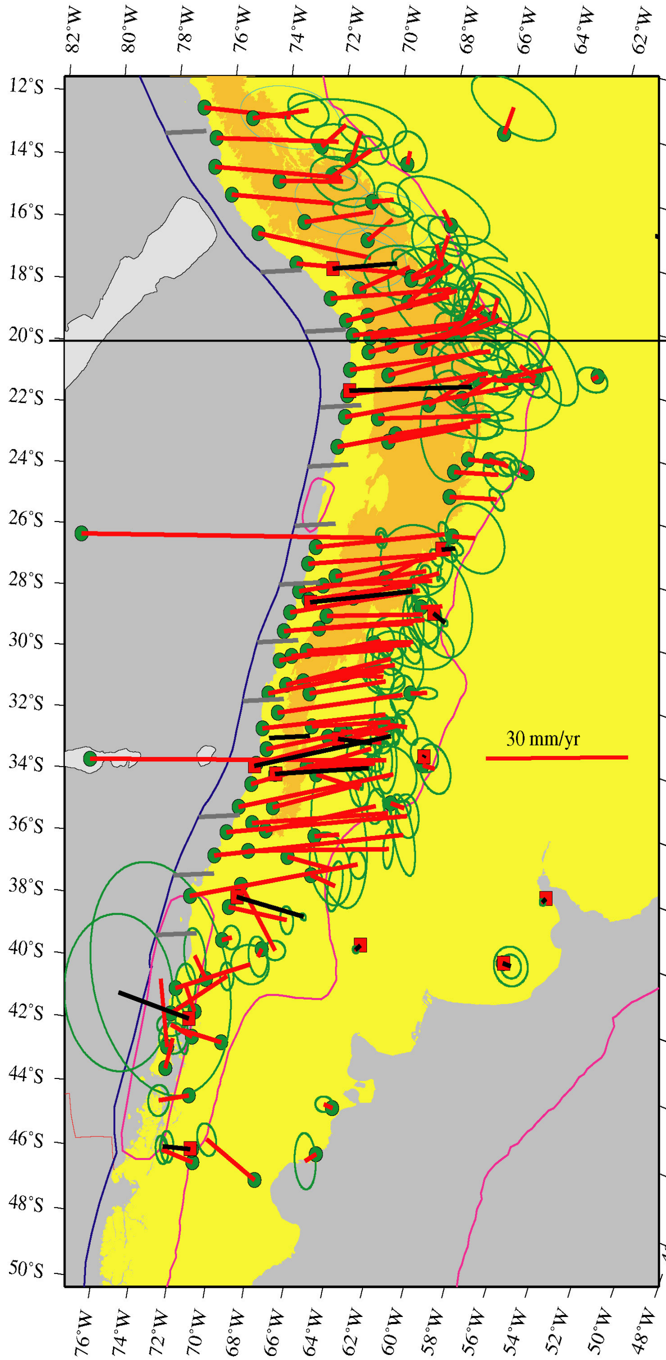
Strain partitioning poster child.

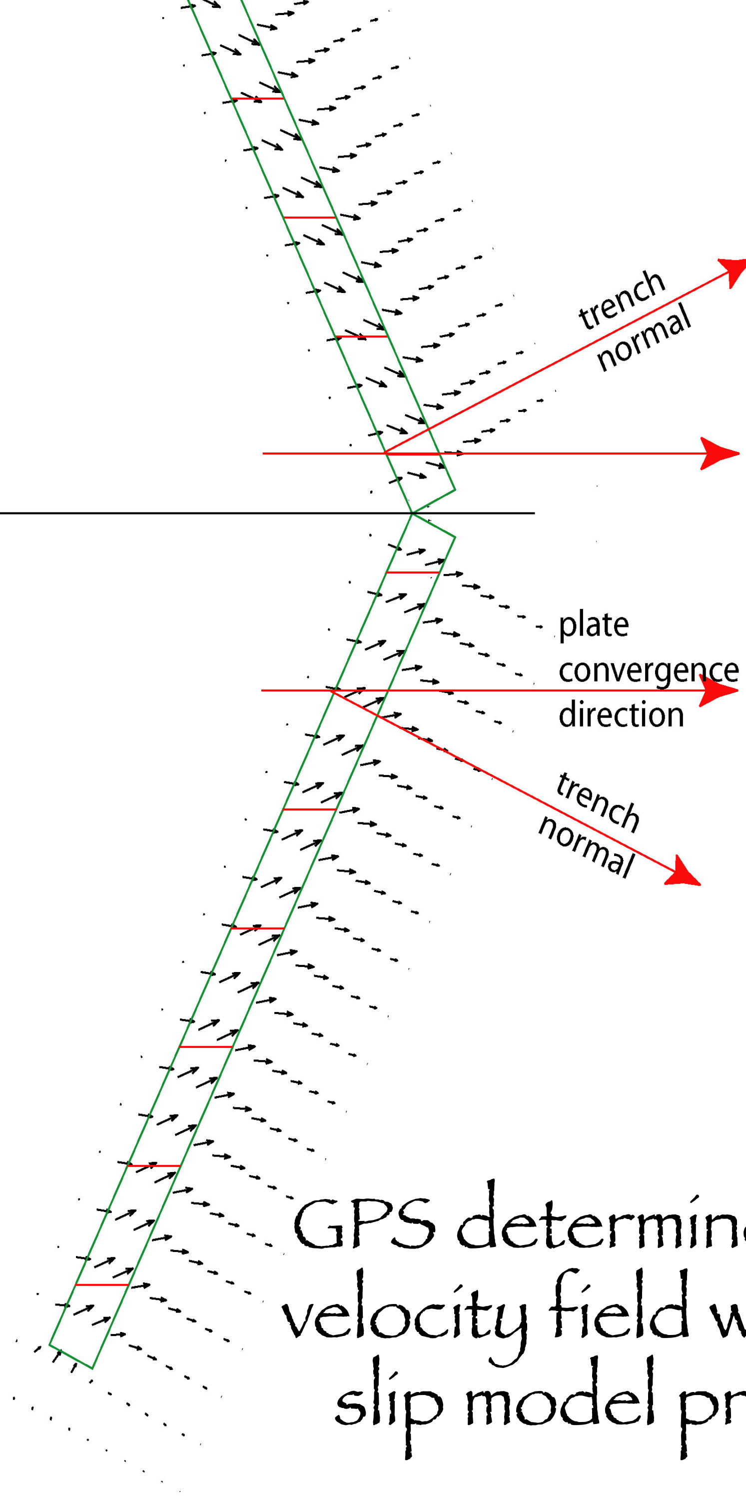
From McCaffrey, http://www.rpi.edu/~mccafr/sumatra04/

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



after Bevis and Martel





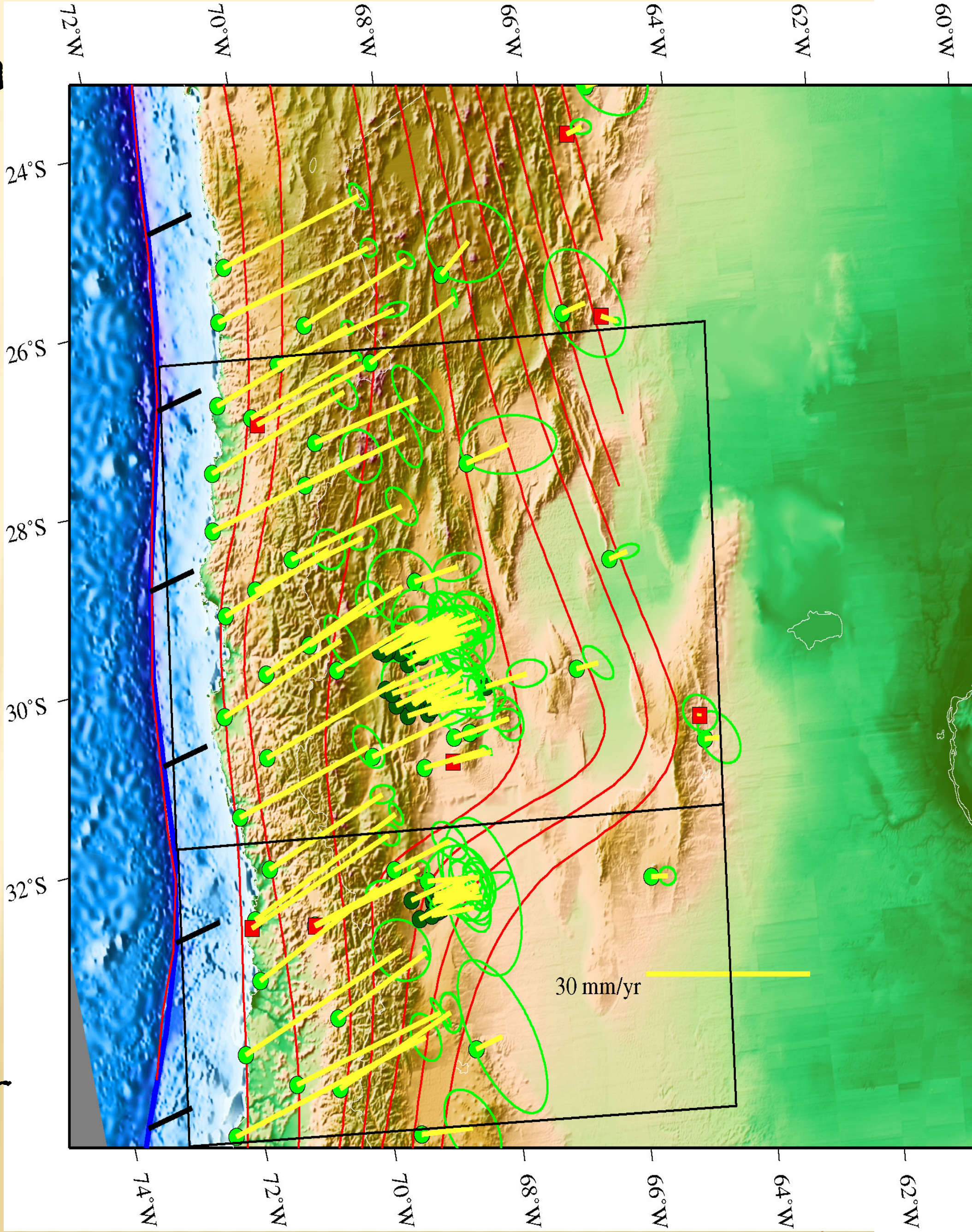
GPS determined surface velocity field with oblique slip model predictions.

Oblique Mercator projection in which coast lies along a meridian.

Shows crustal velocity field for CAP and MATE networks

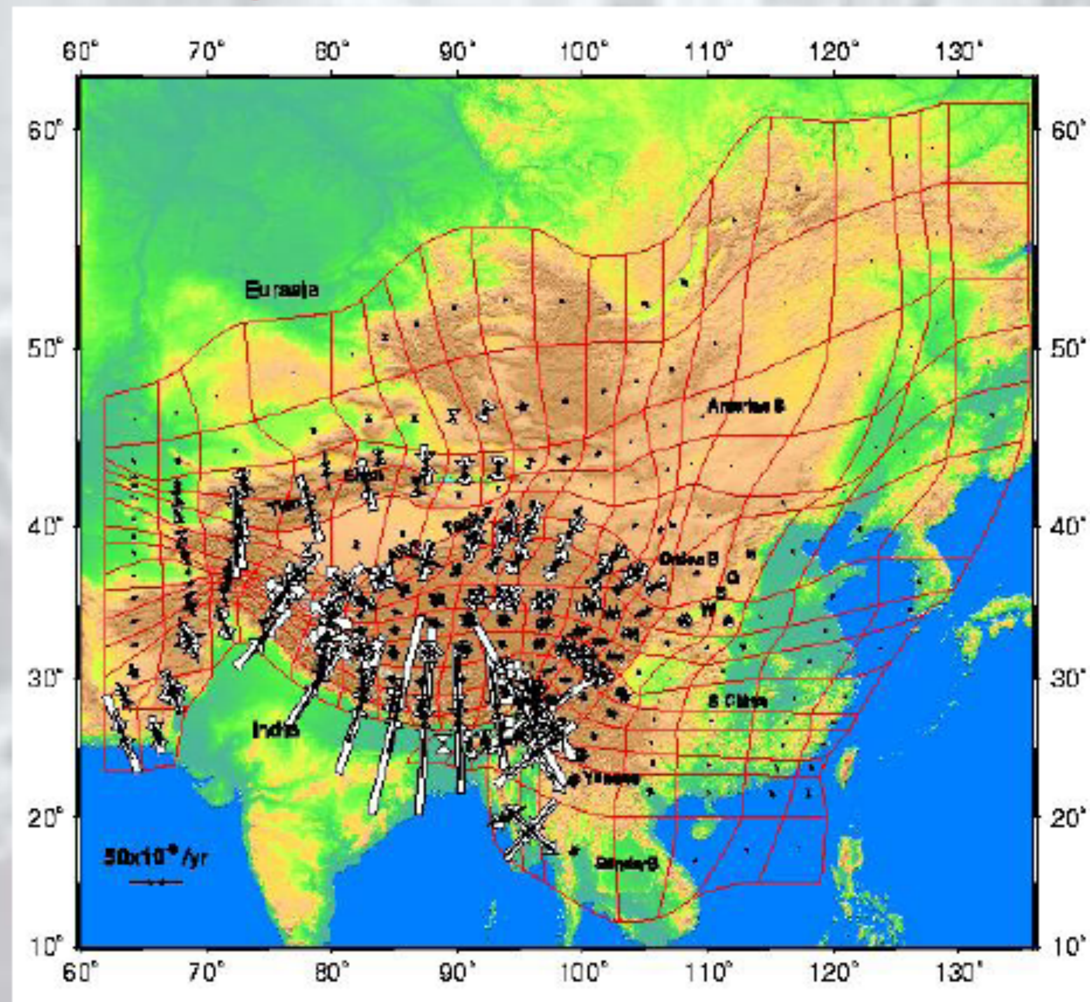
Note velocity gradient (deformation) across Andes

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



Deformation of tectonic plates

- Strain rates inferred from summation of Quaternary fault slip rates (white axes), and spatial averages of predicted strain rates (black axes) given by fitted velocities
- Fitted strain rate field is a self-consistent estimate in which both strain rates and GPS velocities are matched by model strain rates and velocity fields.



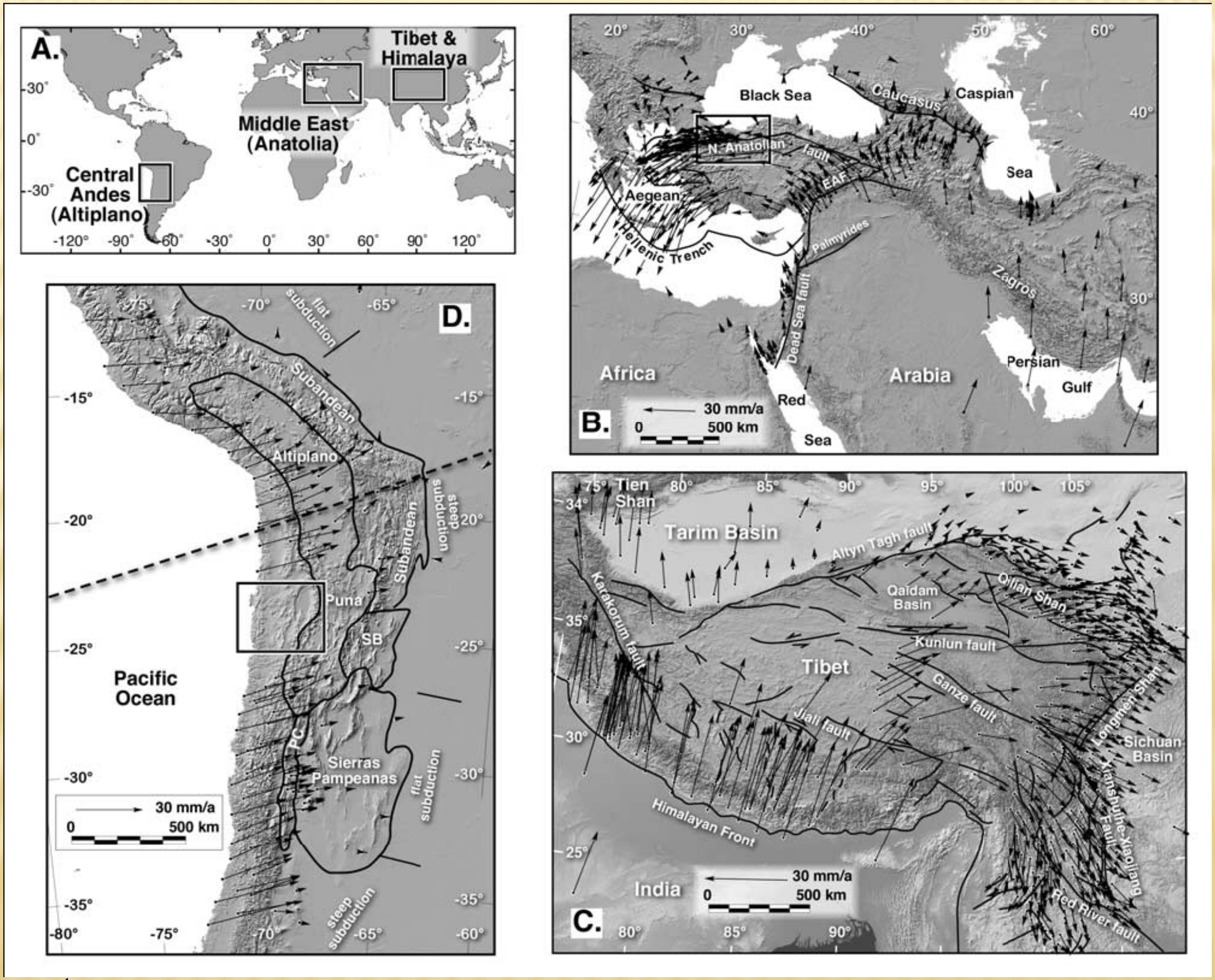
use

$$\begin{pmatrix} u_{x_1} \\ u_{y_1} \\ u_{x_2} \\ u_{y_2} \\ u_{x_3} \\ u_{y_3} \\ \vdots \\ u_{x_n} \\ u_{y_n} \end{pmatrix} = \begin{pmatrix} 1 & 0 & x_1 & y_1 & 0 & 0 \\ 0 & 1 & 0 & 0 & x_1 & y_1 \\ 1 & 0 & x_2 & y_2 & 0 & 0 \\ 0 & 1 & 0 & 0 & x_2 & y_2 \\ 1 & 0 & x_3 & y_3 & 0 & 0 \\ 0 & 1 & 0 & 0 & x_3 & y_3 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & x_n & y_n & 0 & 0 \\ 0 & 1 & 0 & 0 & x_n & y_n \end{pmatrix} \begin{pmatrix} t_x \\ t_y \\ d_{xx} \\ d_{xy} \\ d_{yx} \\ d_{yy} \end{pmatrix}$$

To solve for translation and deformation (strain + rotation)

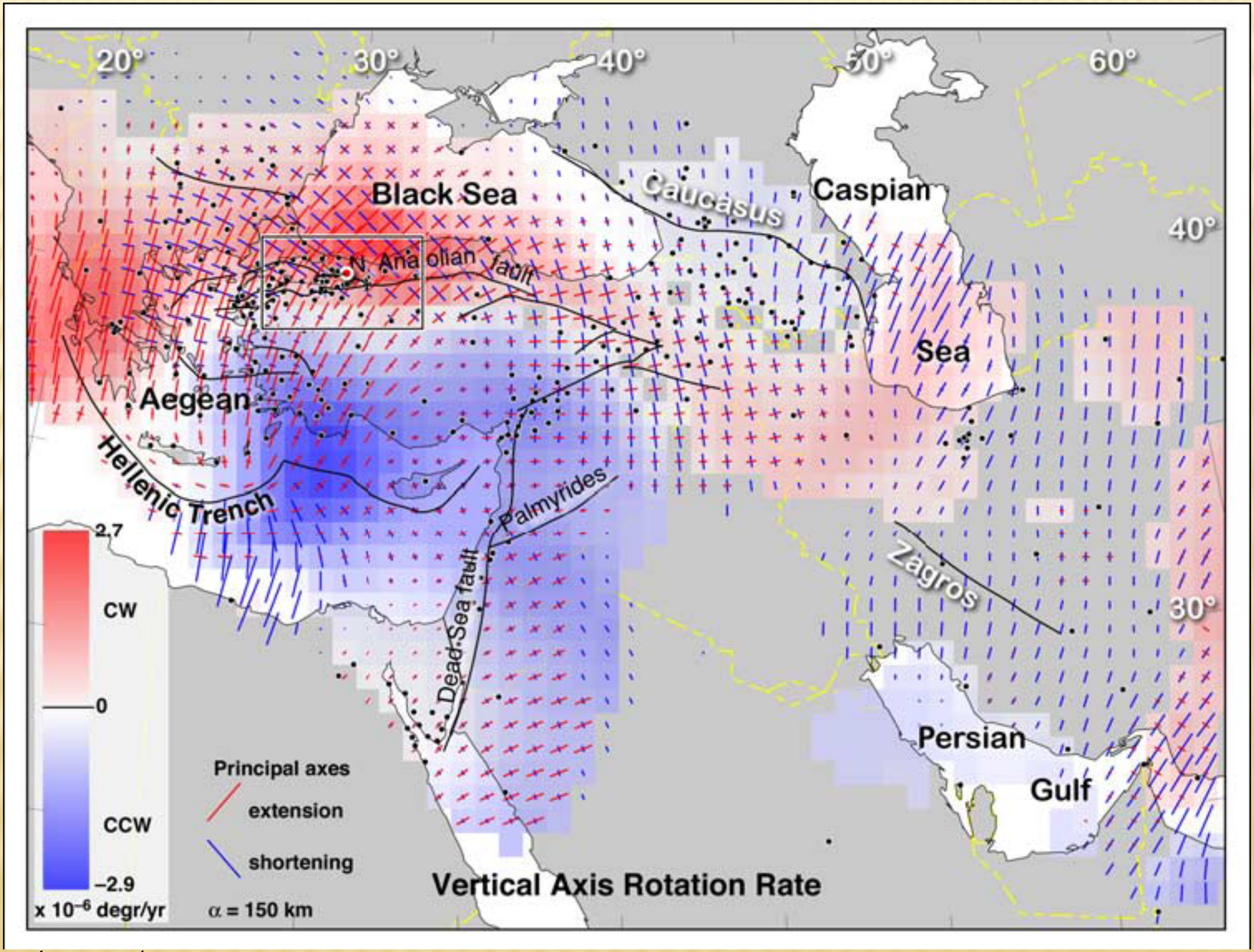
$(t_x, t_y, d_{xx}, d_{xy}, d_{yx}, d_{yy})$.

Start with velocities with respect to stable plates (deformations)

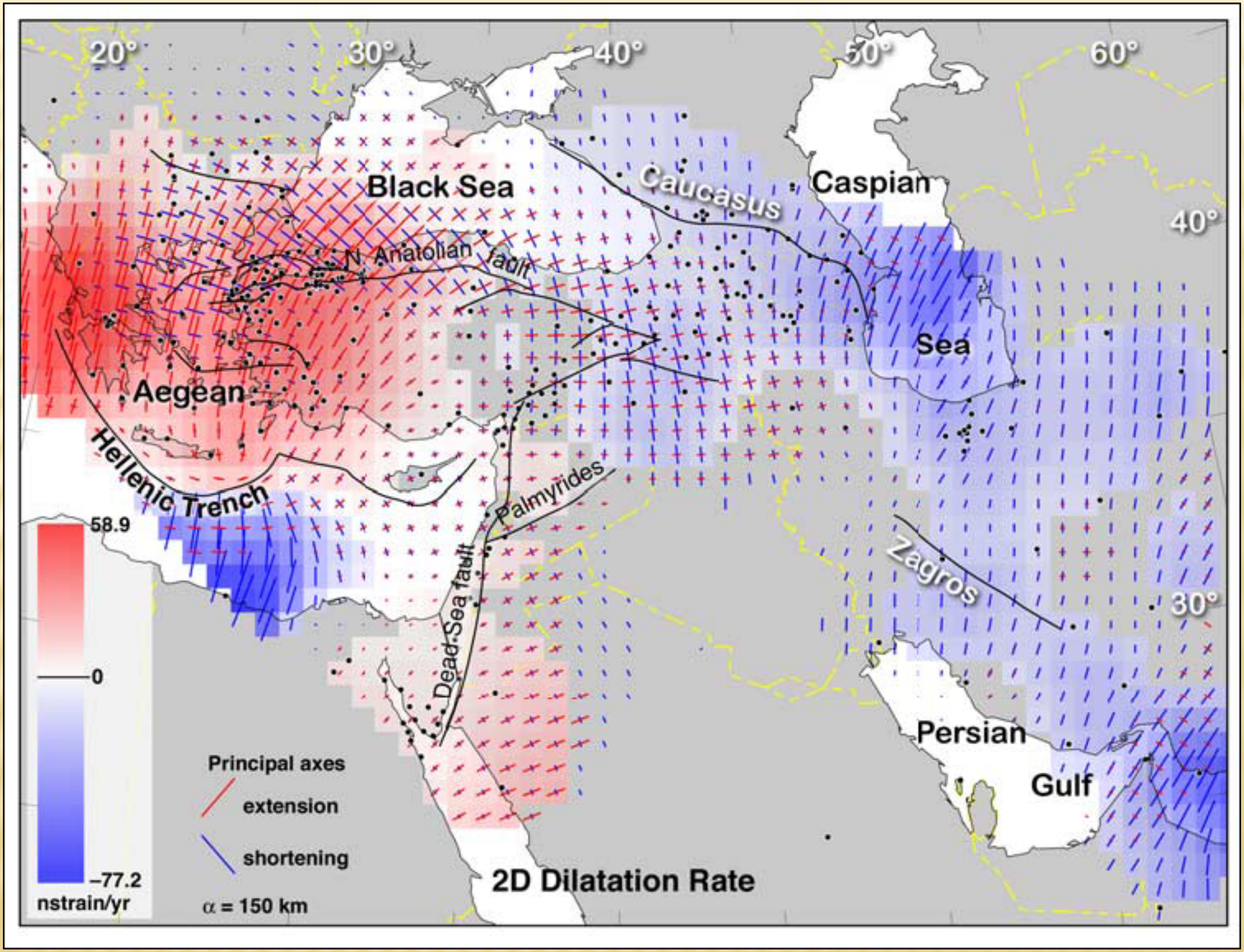


Allmendinger et al, 2007

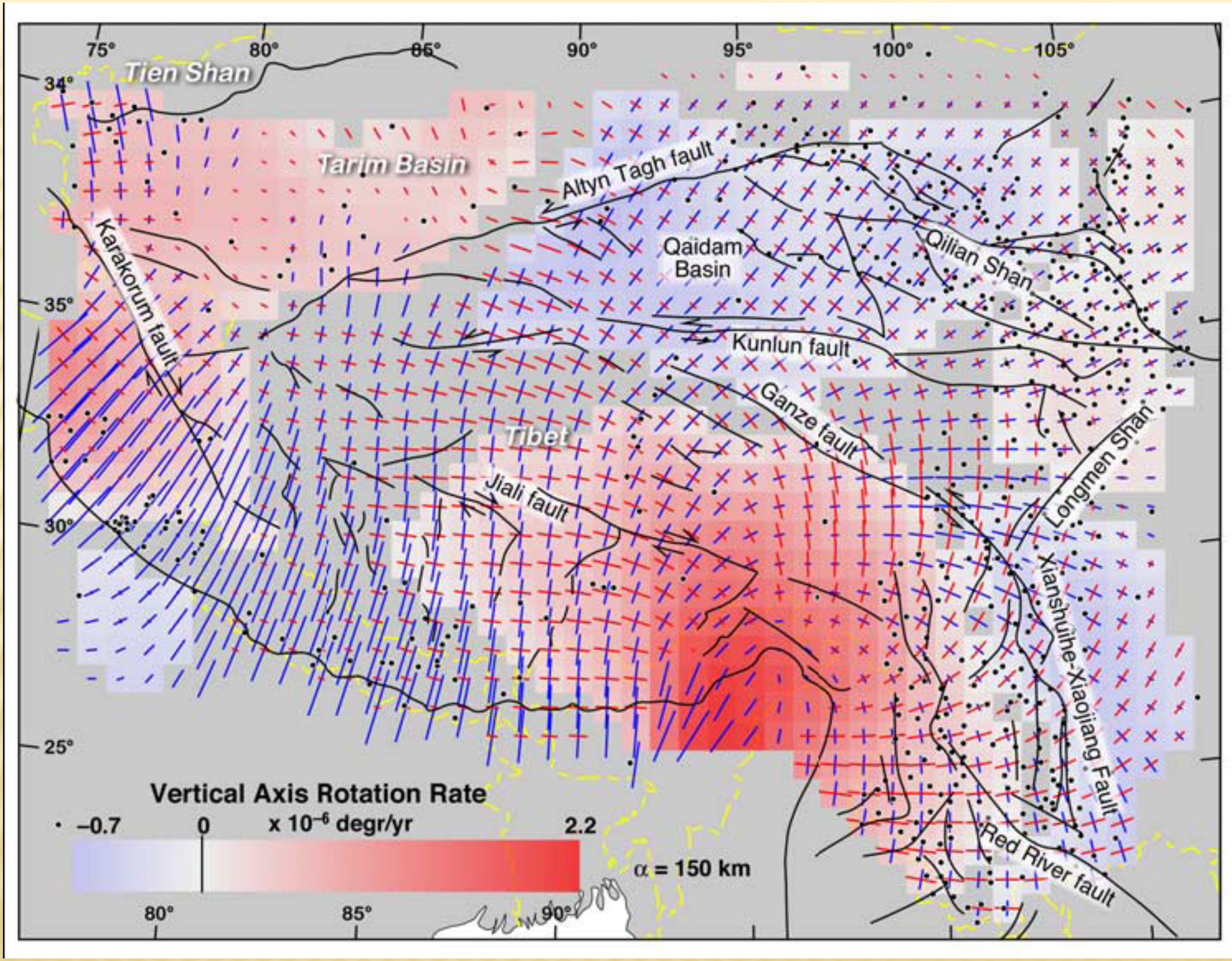
Calculate strains and rotations



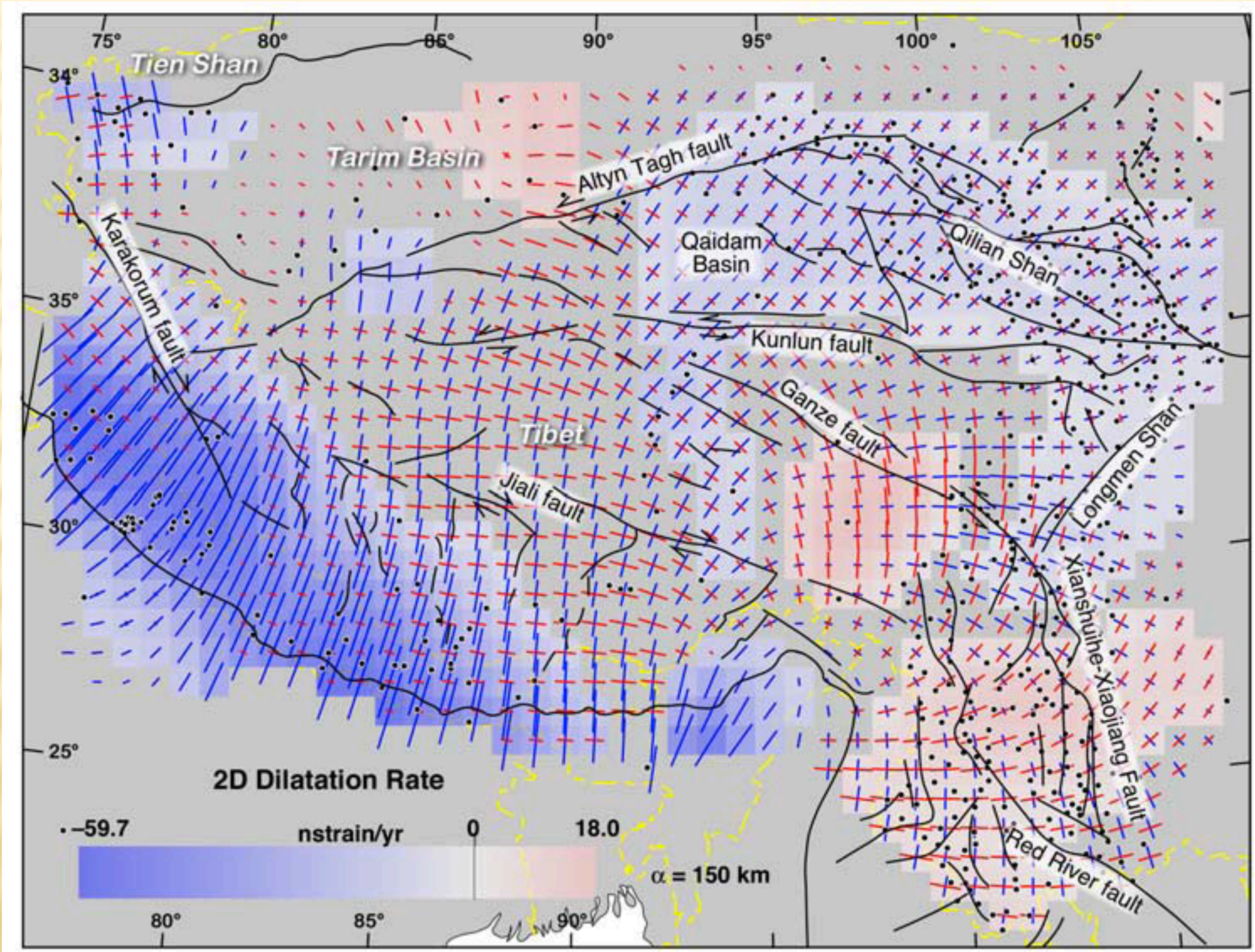
Allmendinger et al, 2007



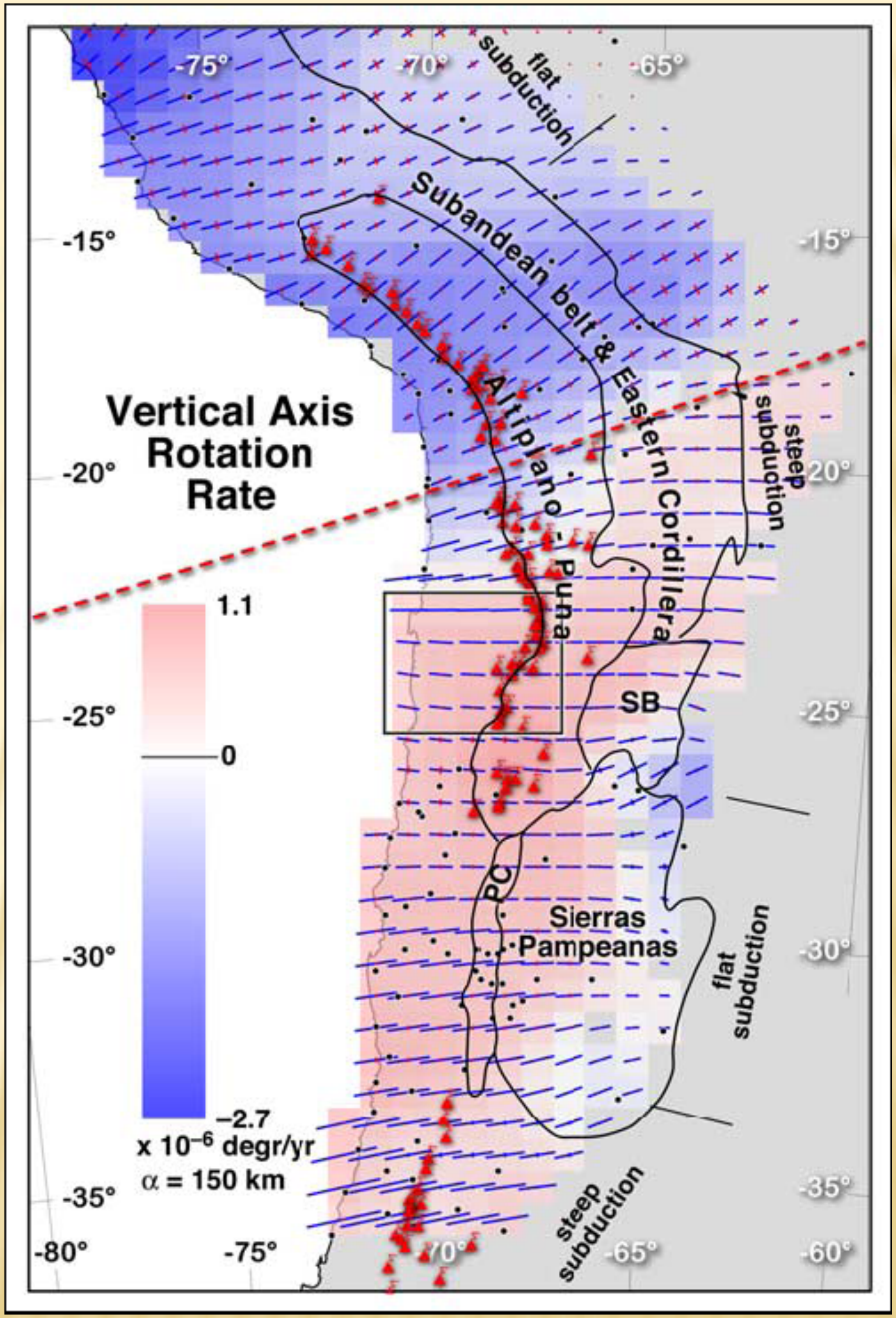
Allmendinger et al, 2007



Allmendinger et al, 2007

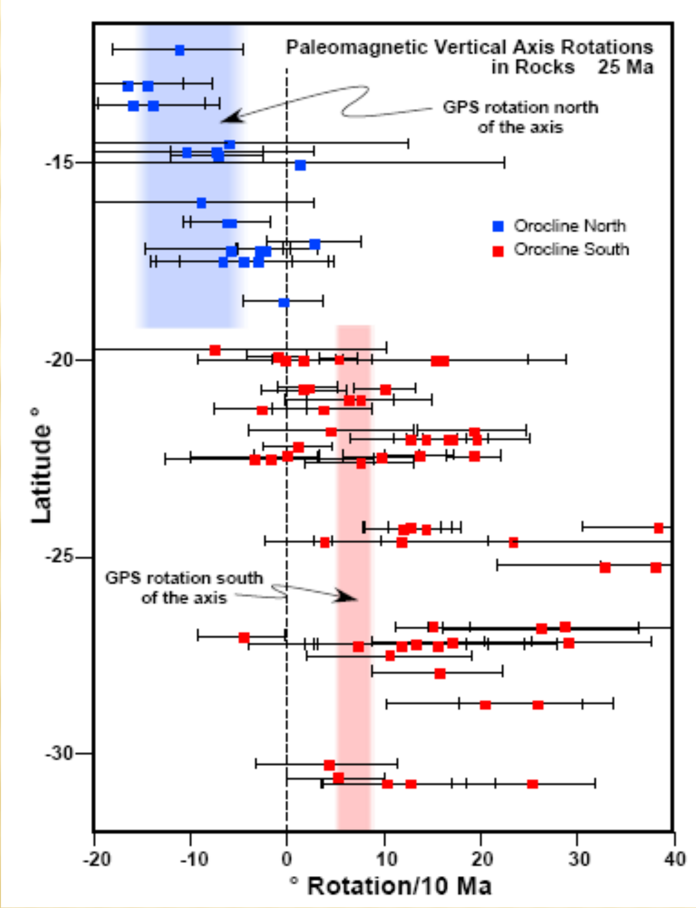


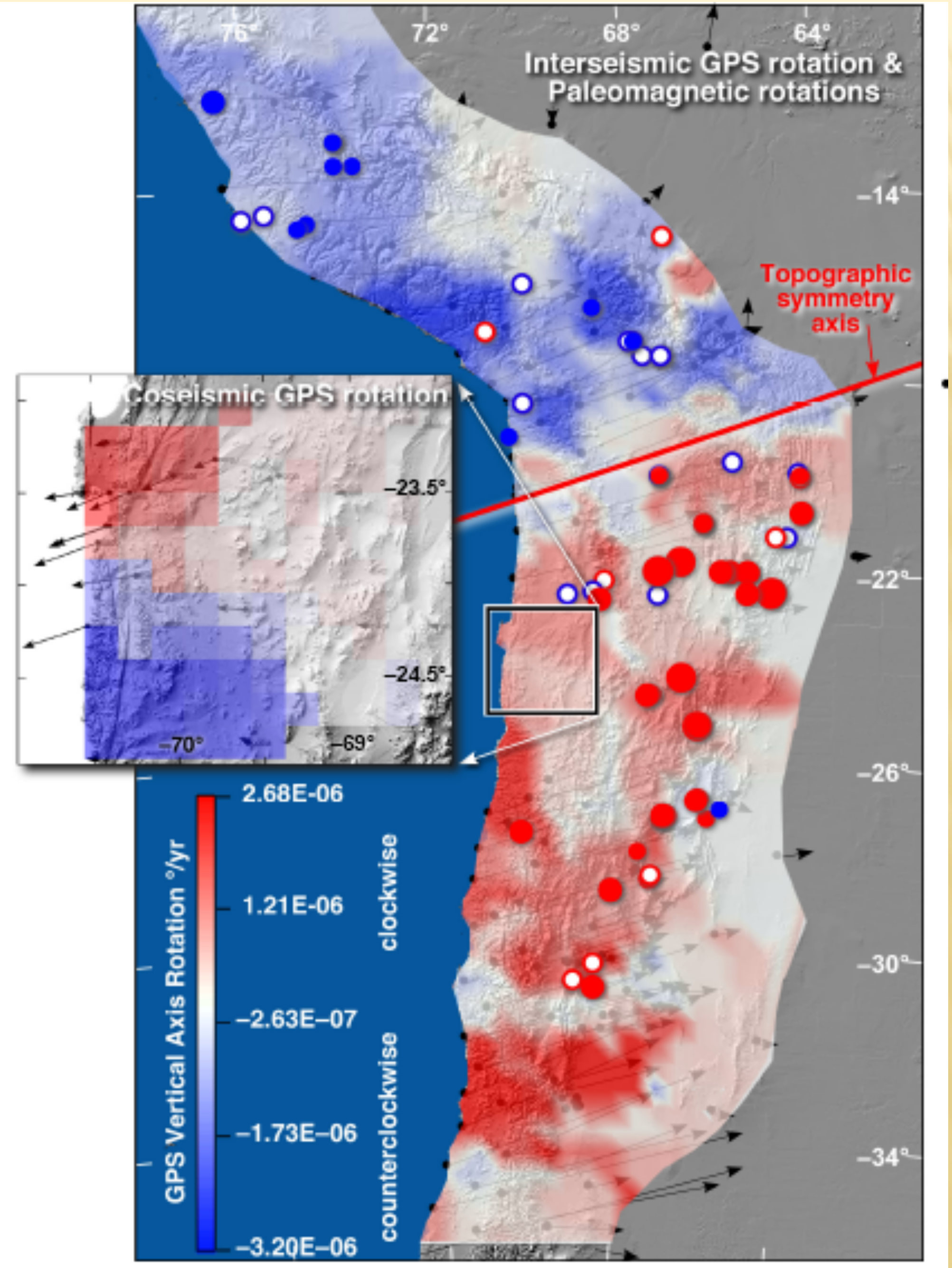
Allmendinger et al, 2007



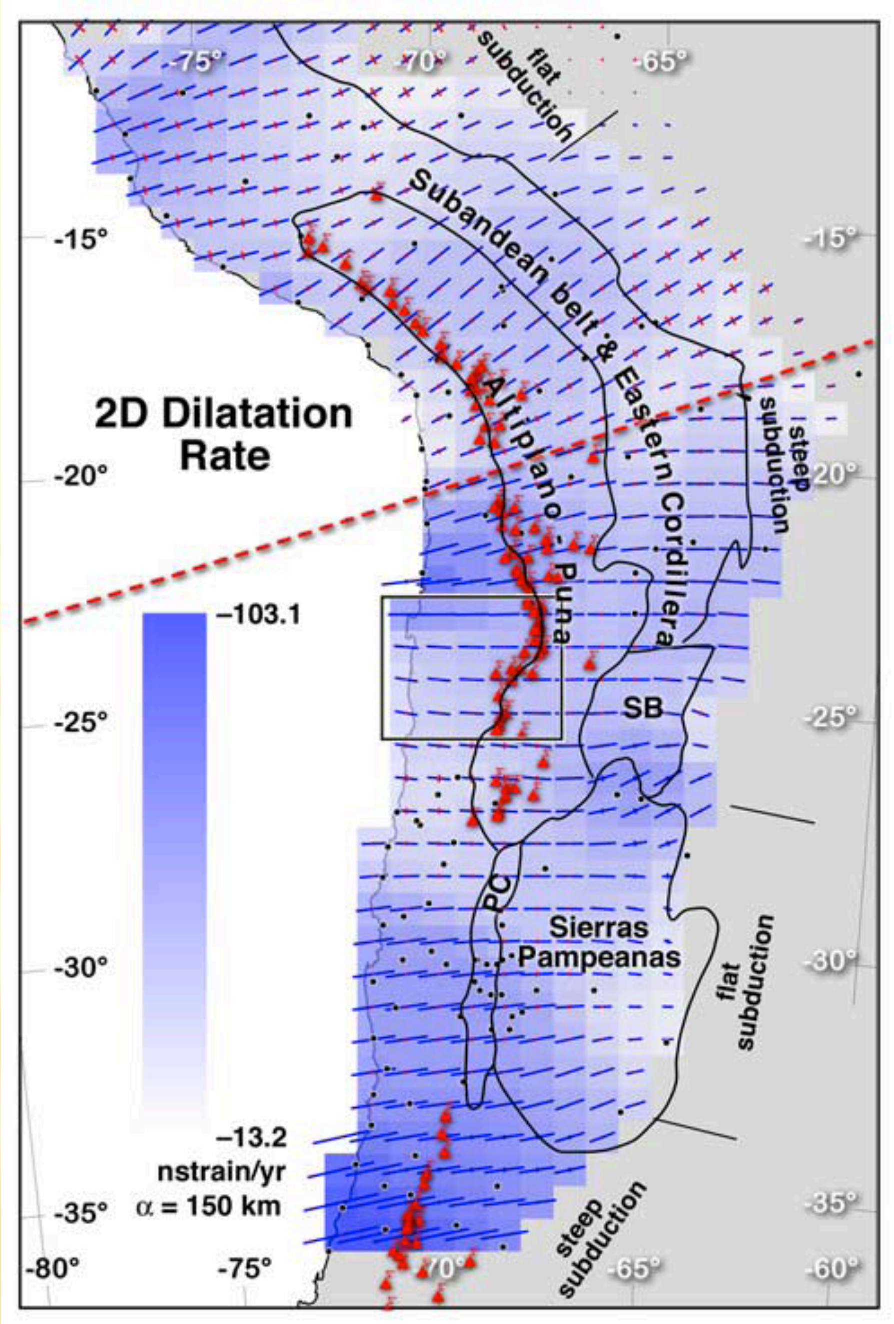
Allmendinger et al, 2007

Rotation rate tensor from GPS in central Andes – real time observation of oroclinal bending?





From Allmendinger et al, 2005



Allmendinger et al, 2007

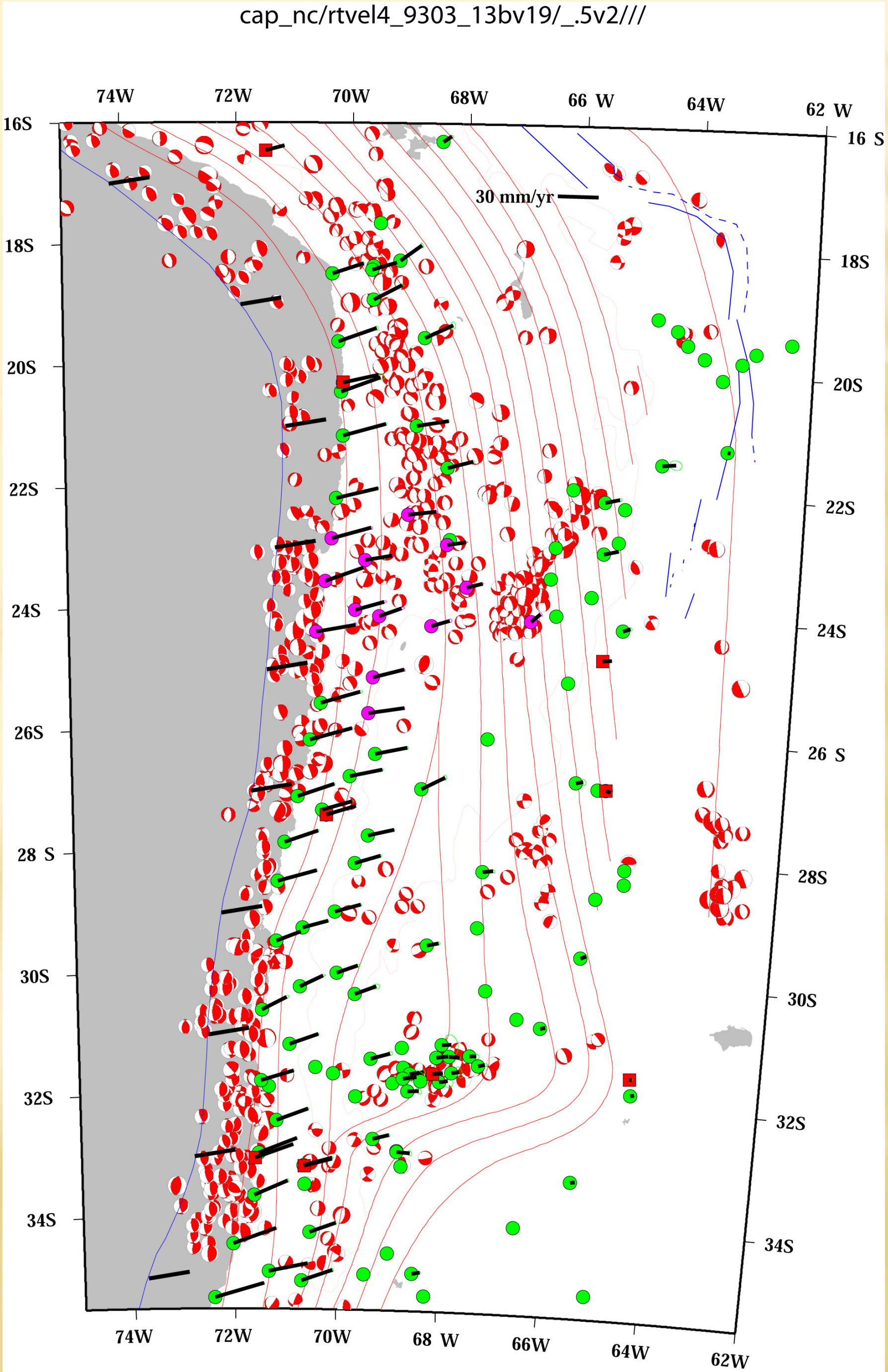
GPS plus focal mechanism data

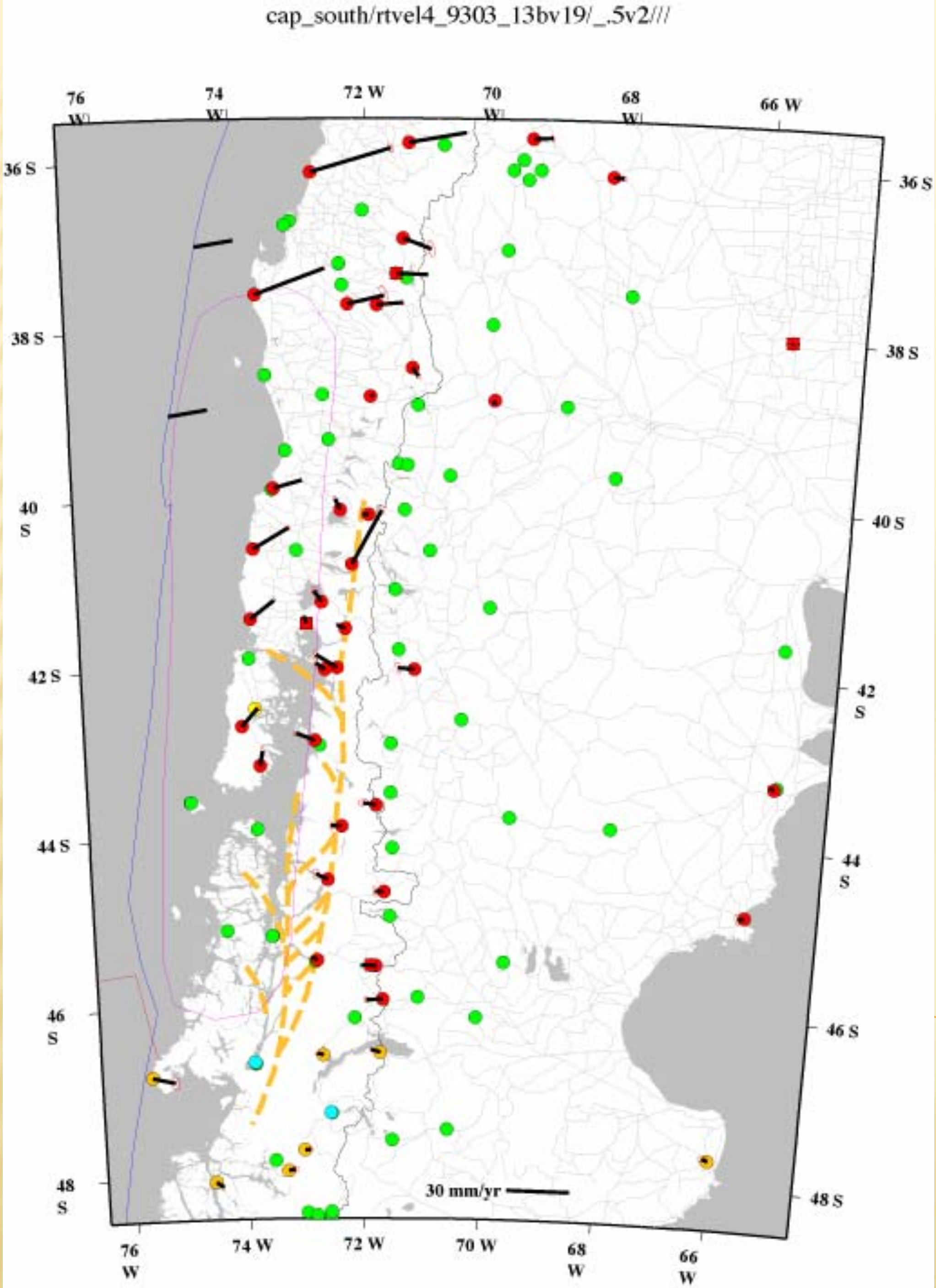
Downdip compression at bottom of wbz

Downdip extension at intermediate depths

Thrust mechanisms along interplate boundary

Normal faulting on outer rise (3 of em)?





Region of 1960 M9.5 earthquake.

Something funny going on

Along coast – vectors show convergence, but slower than to north

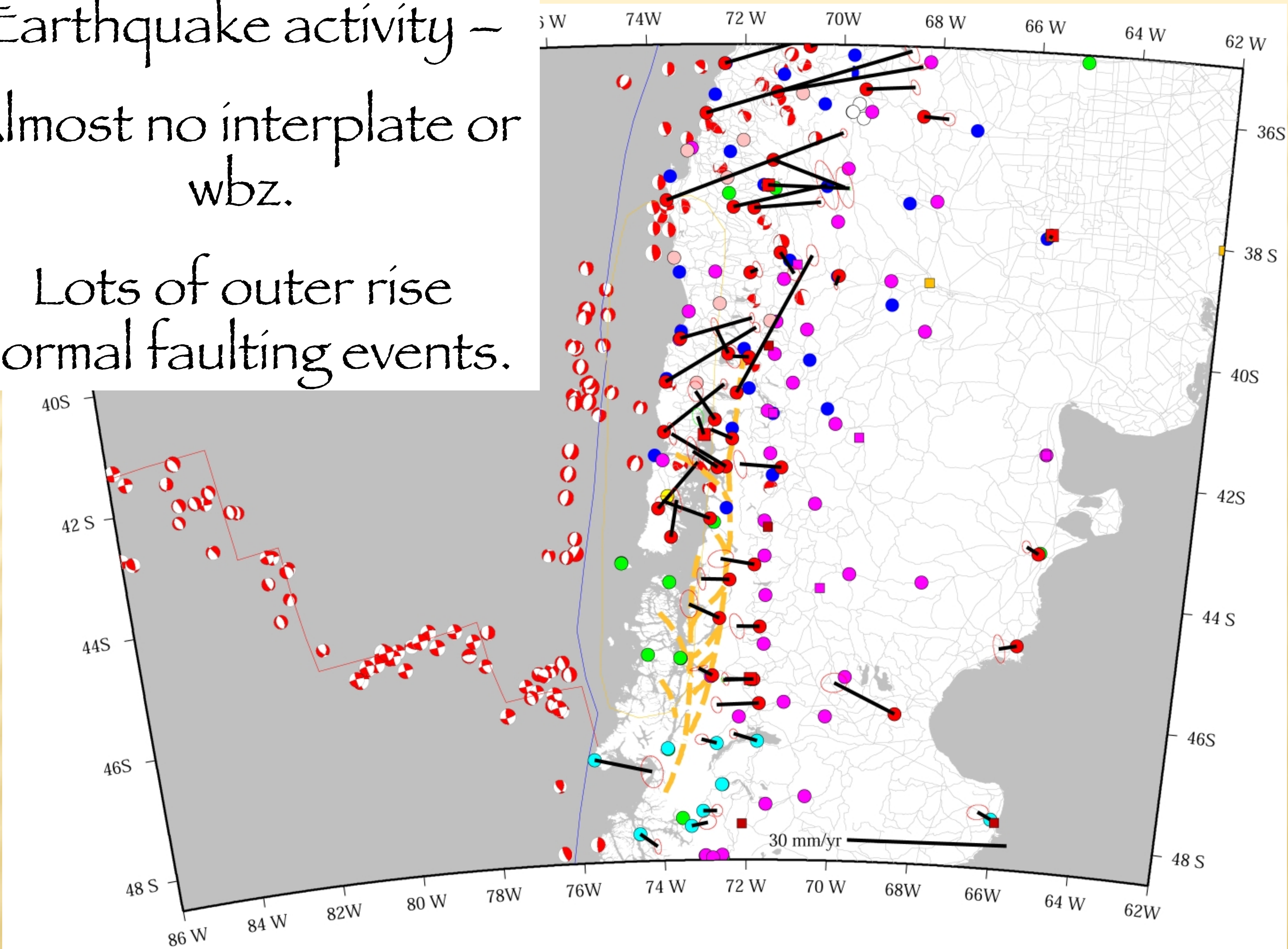
inland – vectors reverse

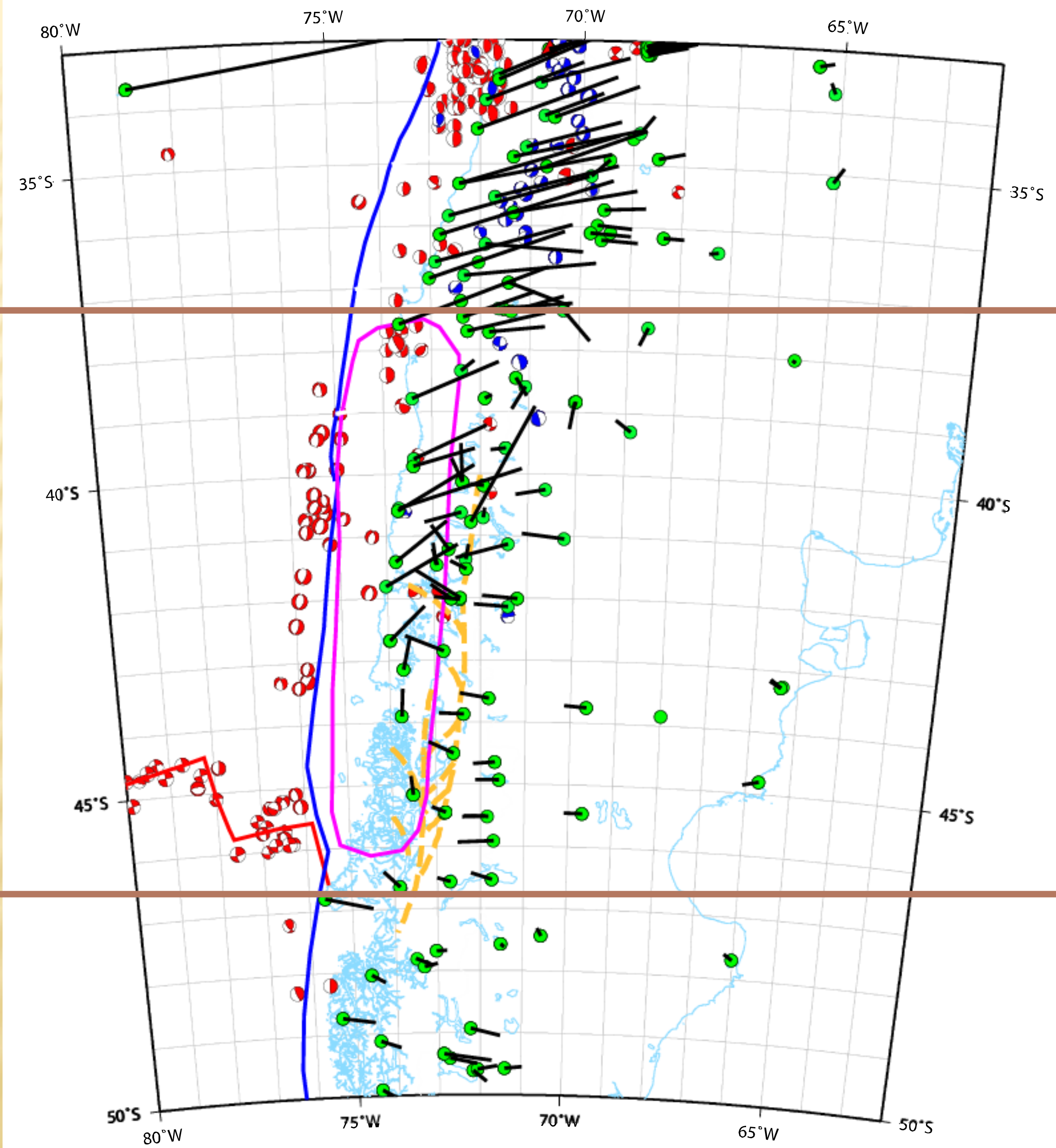
Also – strike slip faulting along Liquine-Ofqui fault system.

Earthquake activity –

Almost no interplate or wbz.

Lots of outer rise normal faulting events.

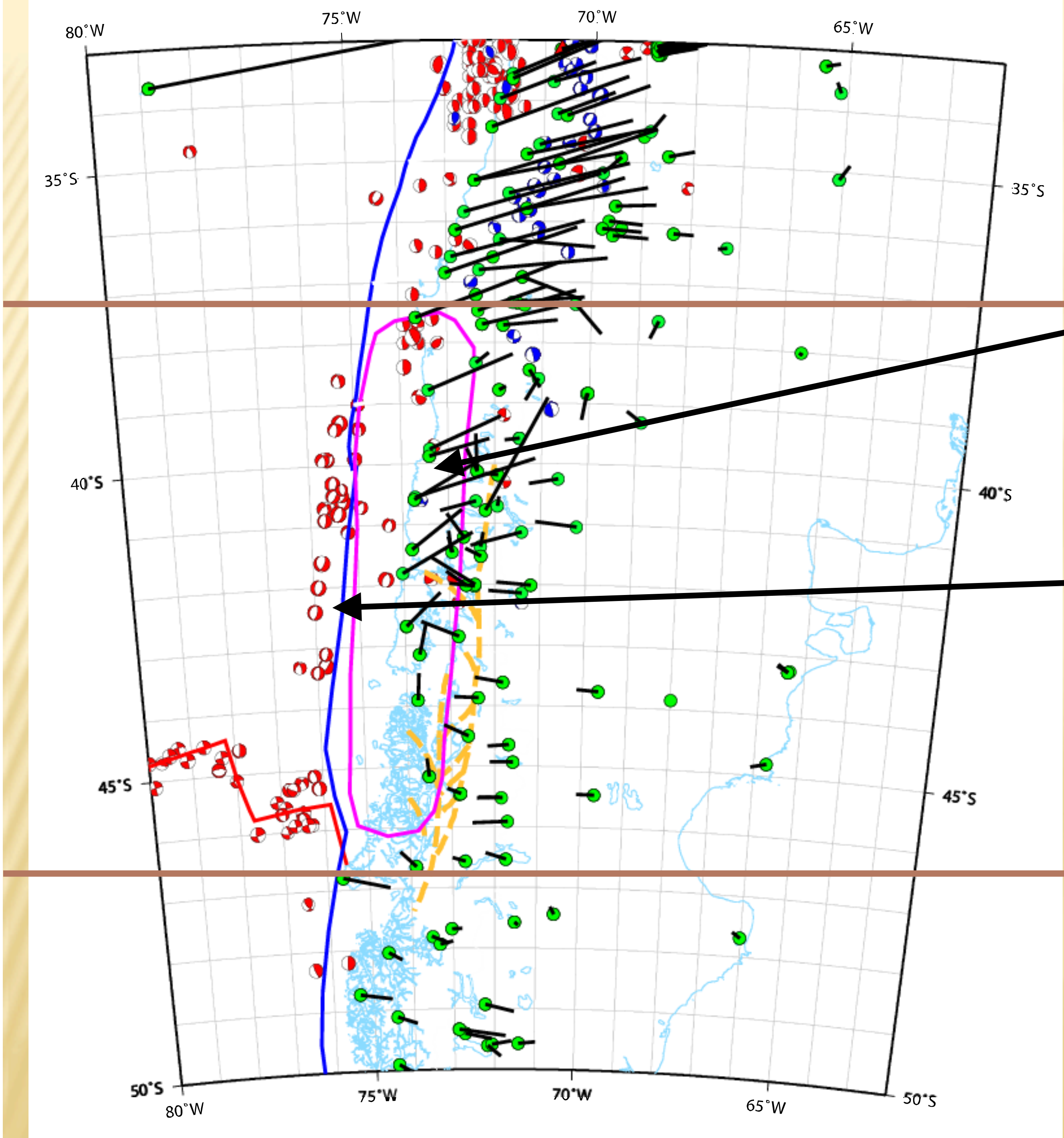




"normal"

1960 great Chilean earthquake

"normal"

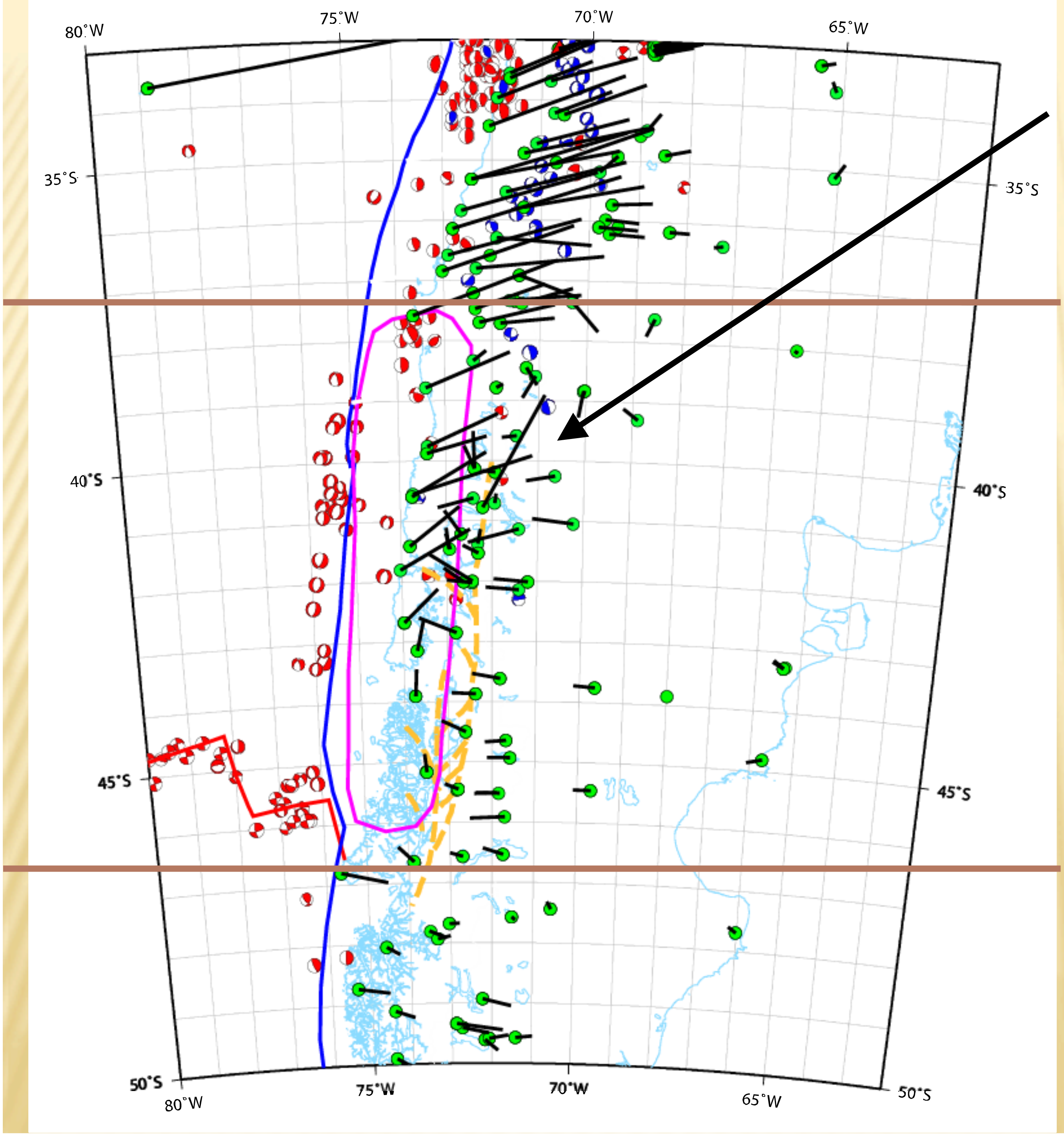


Postseismic

Earthquake activity –

Almost no interplate or wbz activity

Lots of outer rise normal faulting events



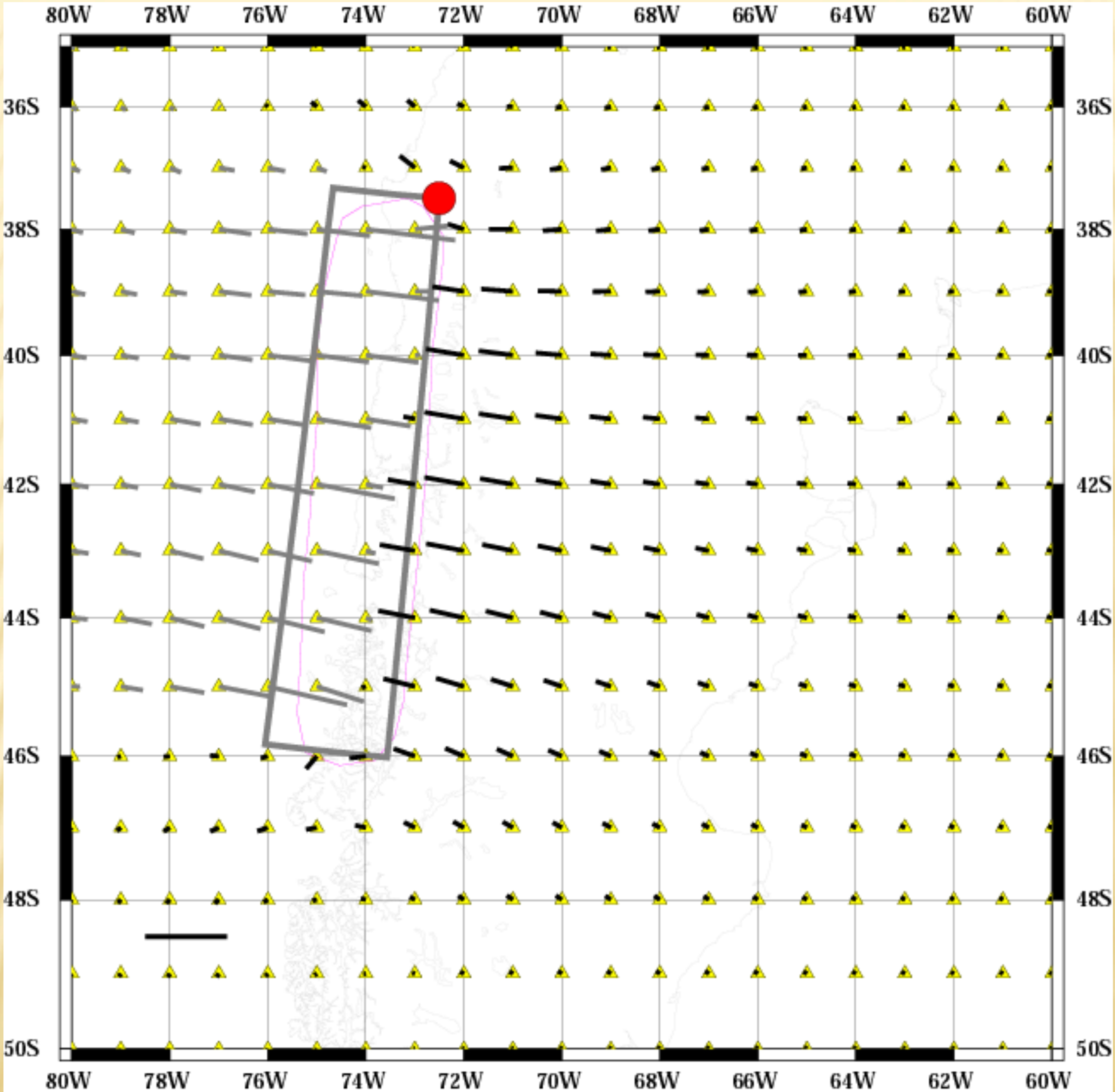
1960 rupture zone

-Reverses to east

-Liquiñe-Ofqui fault

-Subduction of ridge at triple juncion at south end

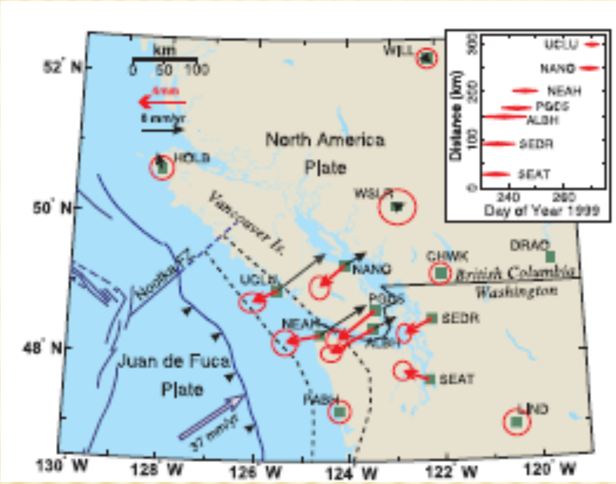
- Post-seismic viscoelatic relaxation – mantle.

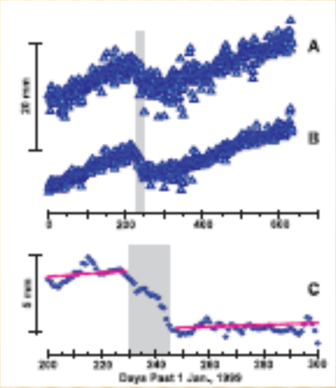

80W
78W
76W
74W
72W
70W
68W
66W
64W
62W
60W
36S
38S
40S
42S
44S
46S
48S
50S

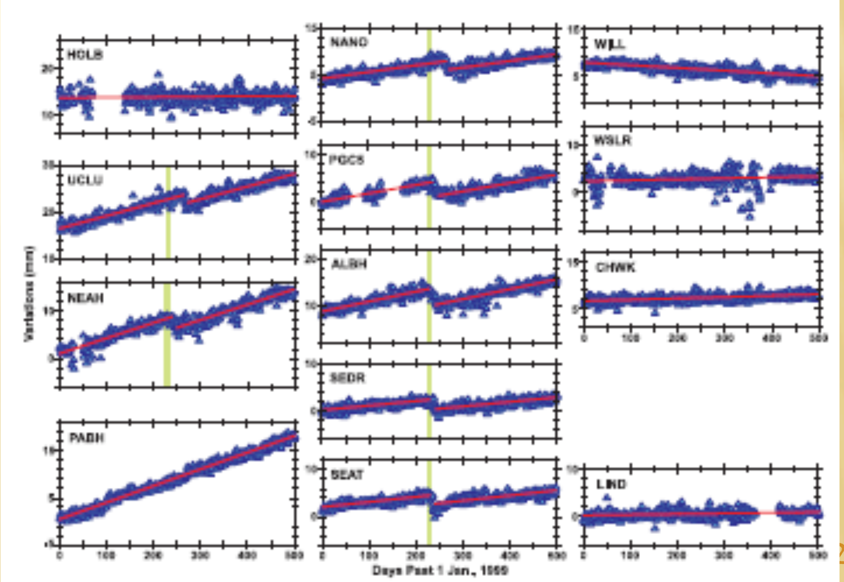
Silent slip in subduction zones

Non-secular GPS displacements

Coupled with seismic tremor







Dragert et al, 20013

Silent slip in subduction zones

Non-secular GPS displacements

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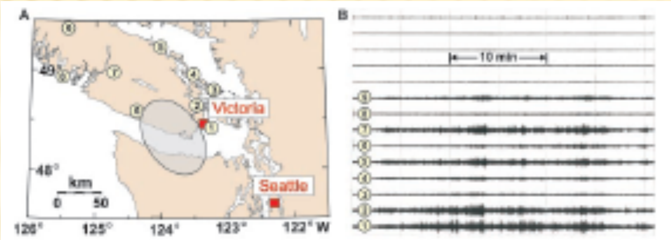
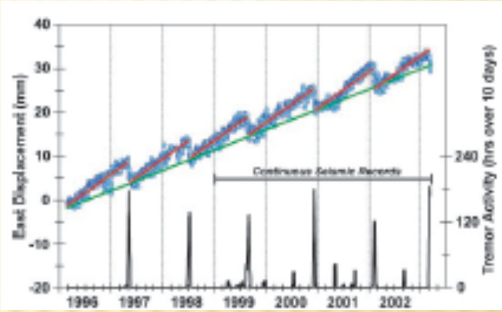




Also observed (with different periods) in Mexico and Japan

(seem to be ubiquitous – if have dense continuous GPS network and broadband seismic network in subduction zone you will find them)

Rogers and Dragert, 2003

GLACIAL ISOSTATIC ADJUSTMENT (GIA)

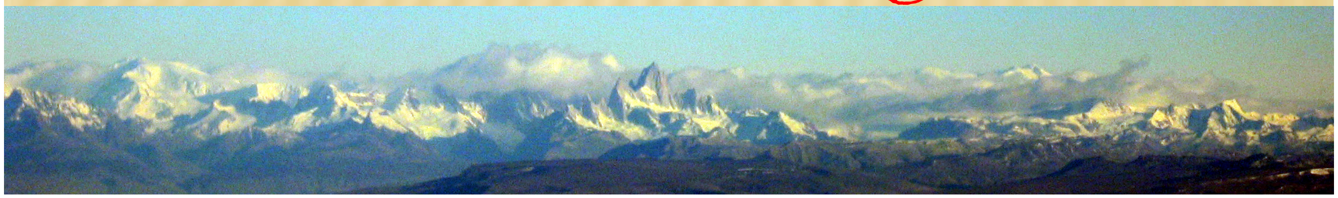
OLD - POST GLACIAL REBOUND (PGR)

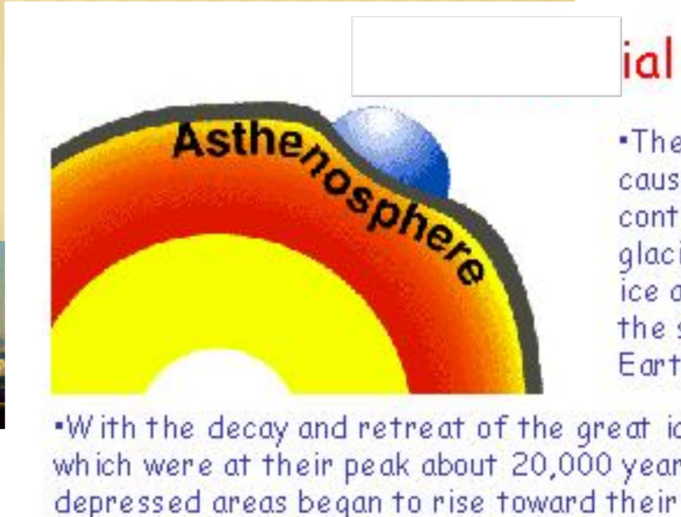
An interplay between

- Ice load history
- Geomechanical structure of region
  - Mantle viscosity profile
  - Lithosphere thickness

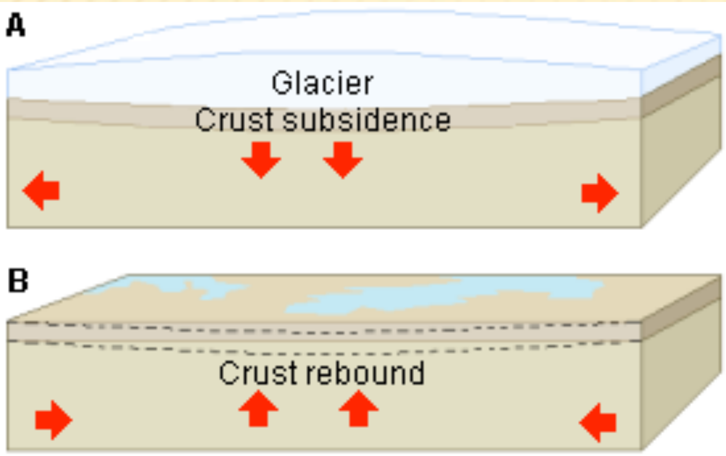
Ice load history reflects climate (and topography/tectonics?).

Geomechanical structure reflects tectonic setting!



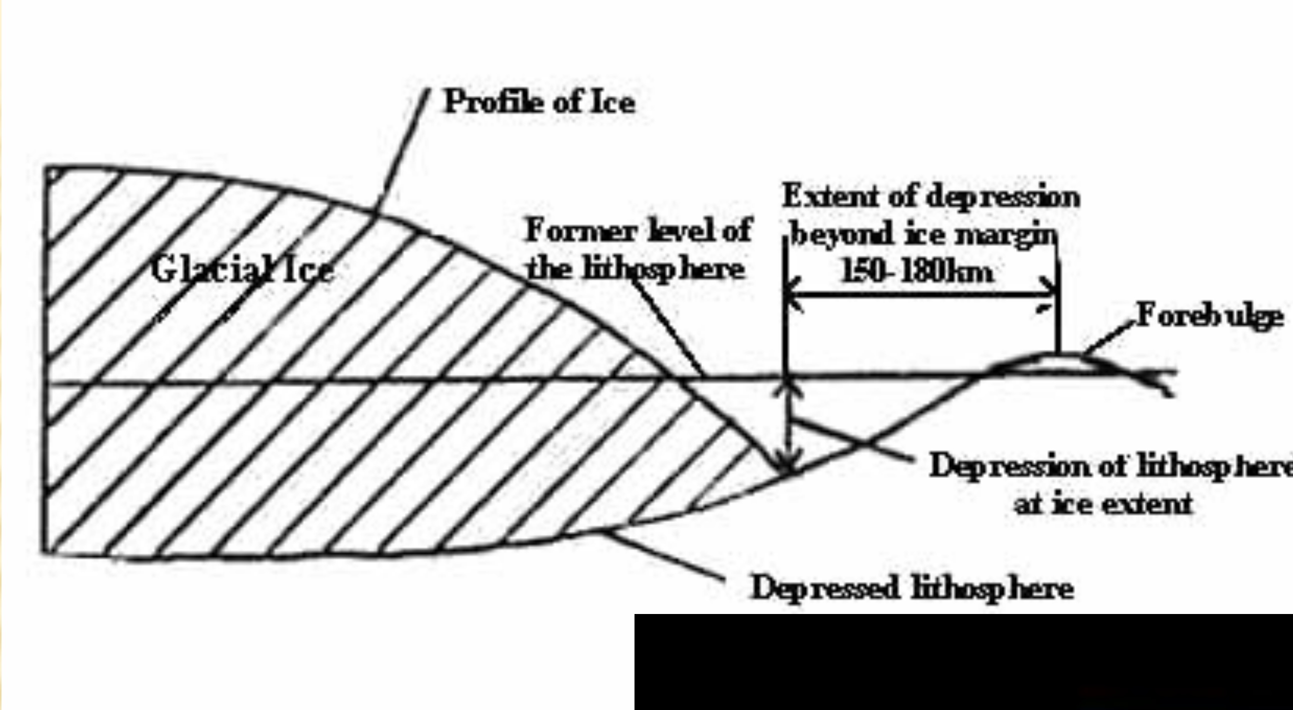


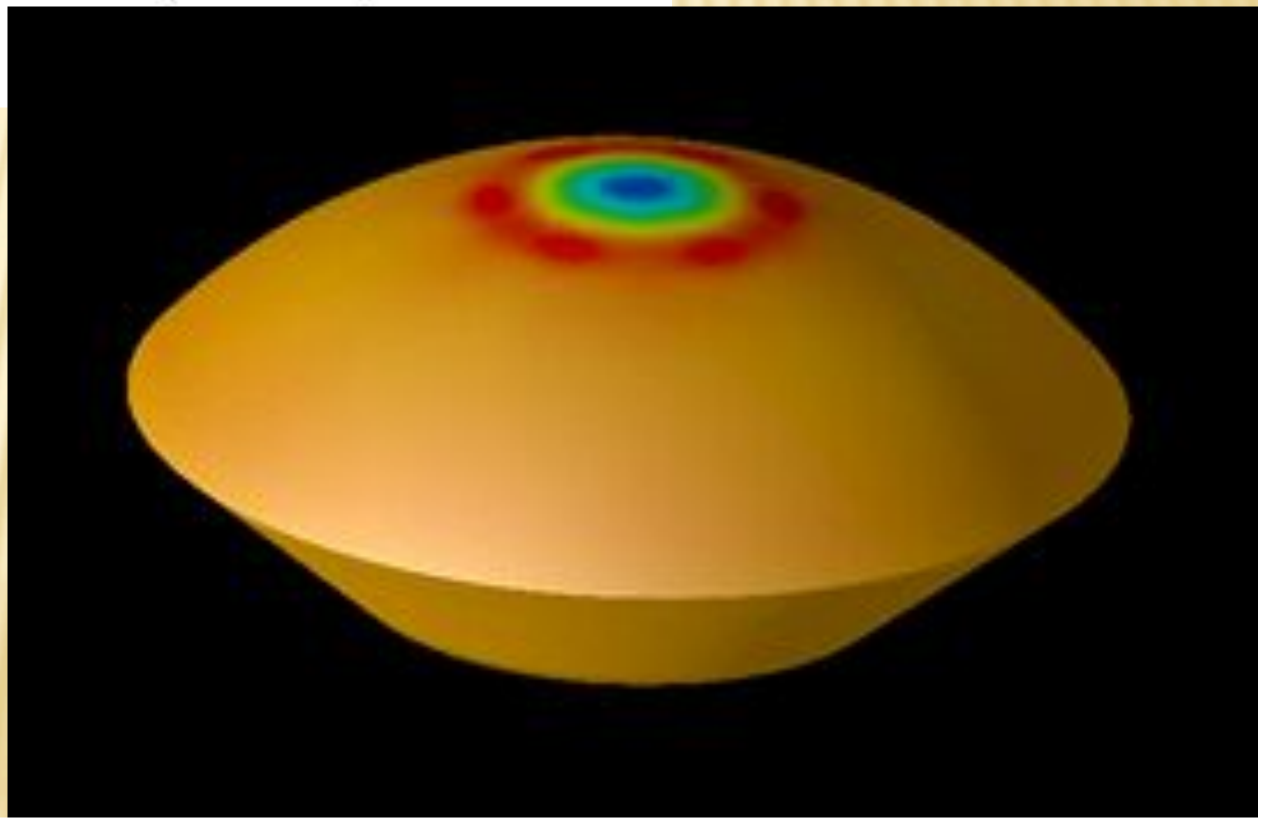
Raised beaches on Kongsøya, central-northern Barents Sea, where the highest marine limit on Svalbard occurs (110 m a.s.l.). The age of the marine limit is ca. 10,000 years. Photo: Ólafur Ingólfsson, 1991.

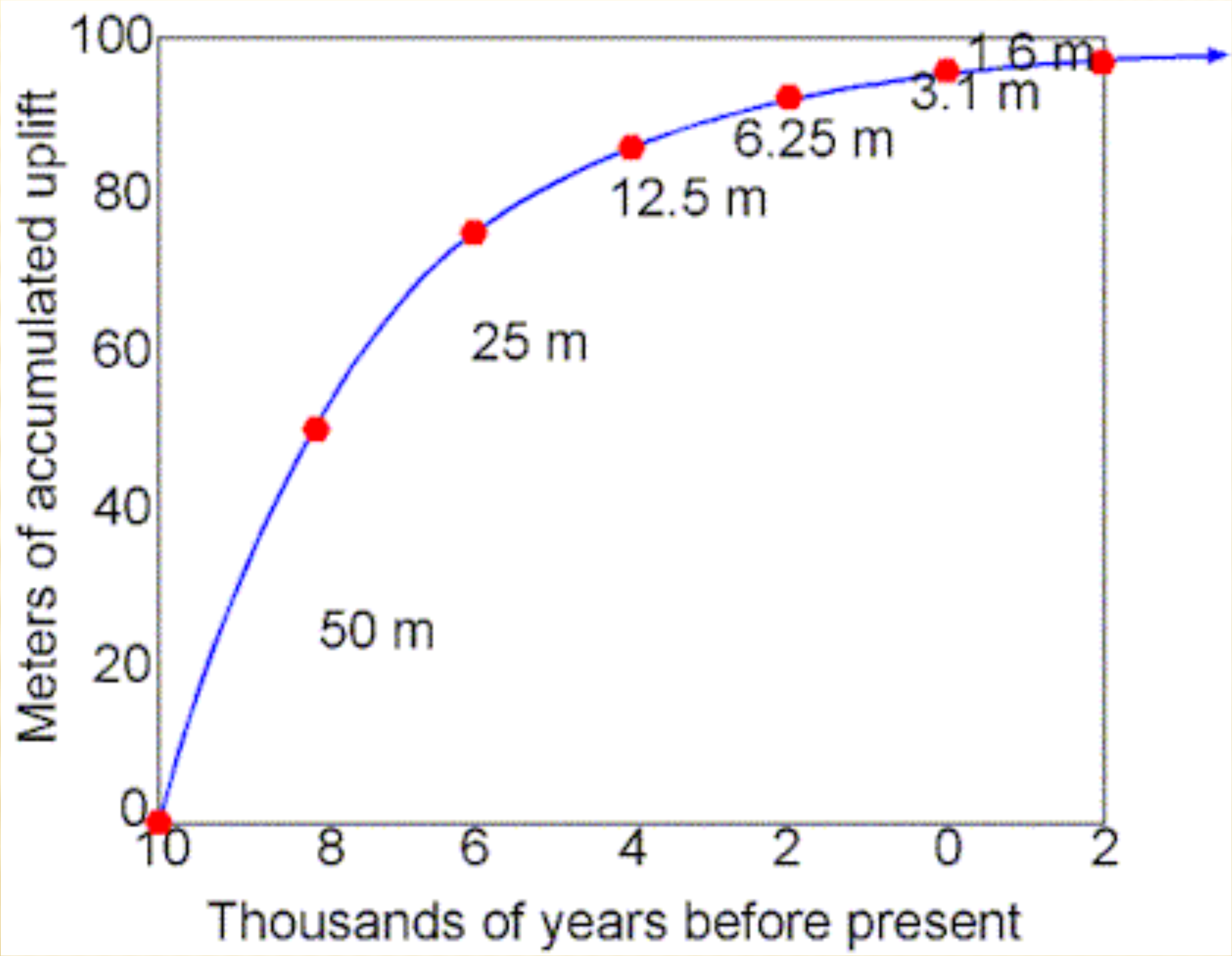


This simplified illustrations shows the crustal subsidence and subsequent rebound produced by variations of glaciers loads variations.

A: In Northern Canada and Scandinavia ice accumulated and bent the crust layer.
B: When ice started to melt down, the surface relocated back to its previous position.


Profile of Ice
Glacial Ice
Former level of the lithosphere
Extent of depression beyond ice margin 150-180km
Forebulge
Depression of lithosphere at ice extent
Depressed lithosphere





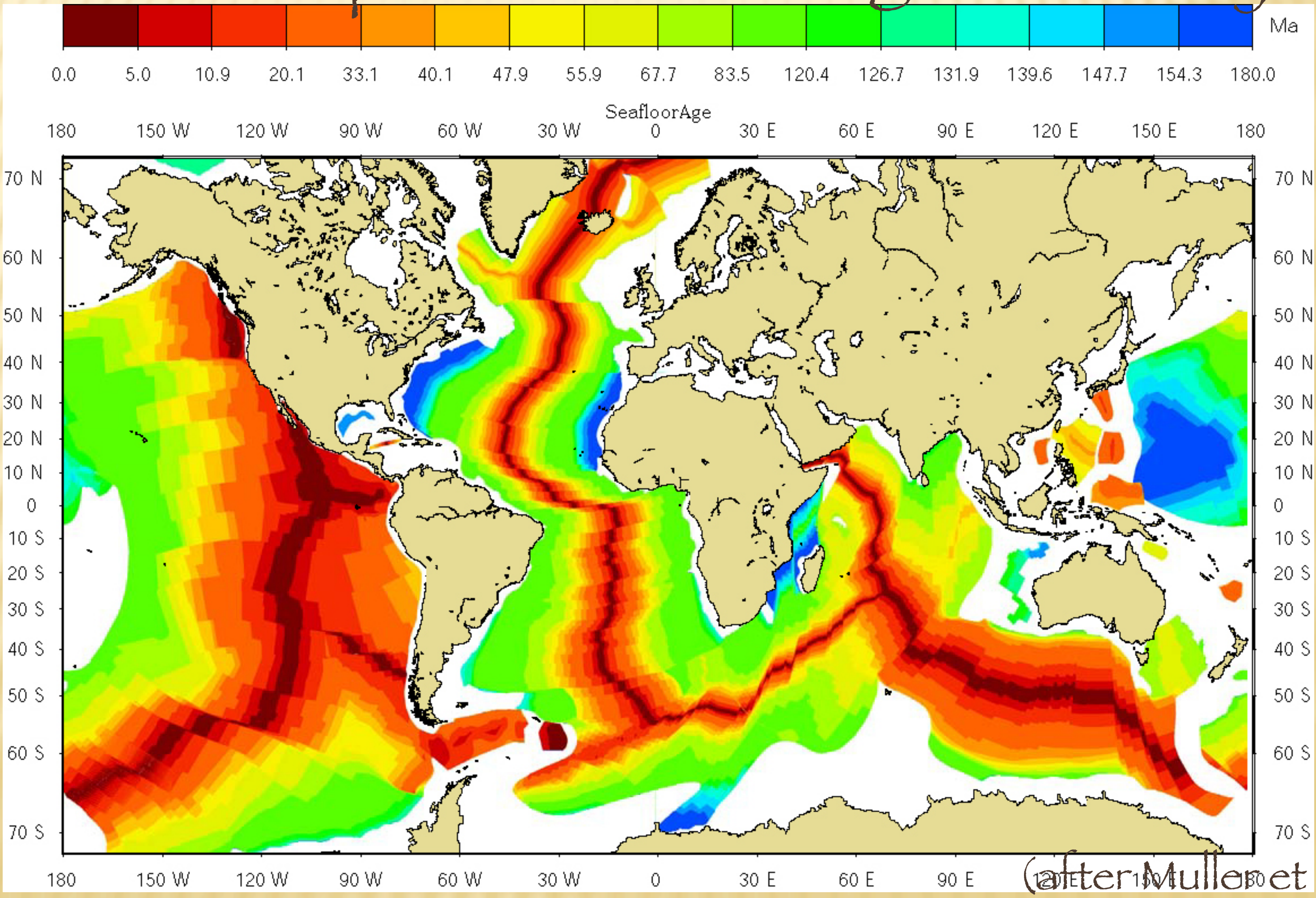
Meters of accumulated uplift
100
80
60
40
20
0
10
8
6
4
2
0
2
Thousands of years before present
50 m
25 m
12.5 m
6.25 m
3.1 m
1.6 m

Oceanic Geomechanical structure

varies simply with age of Seafloor

Young – thin lithosphere and hot, low viscosity mantle

Old – thick lithosphere and cold, higher viscosity mantle



(after Muller et al, 1997)

CONTINENTAL GEOMECHANICAL STRUCTURE

Varies between two global extremes:

Fennoscandian (Stable Craton)

Lithosphere thickness > 75 km

U Mantle viscosity $> 5 \times 10^{20}$ Pa s

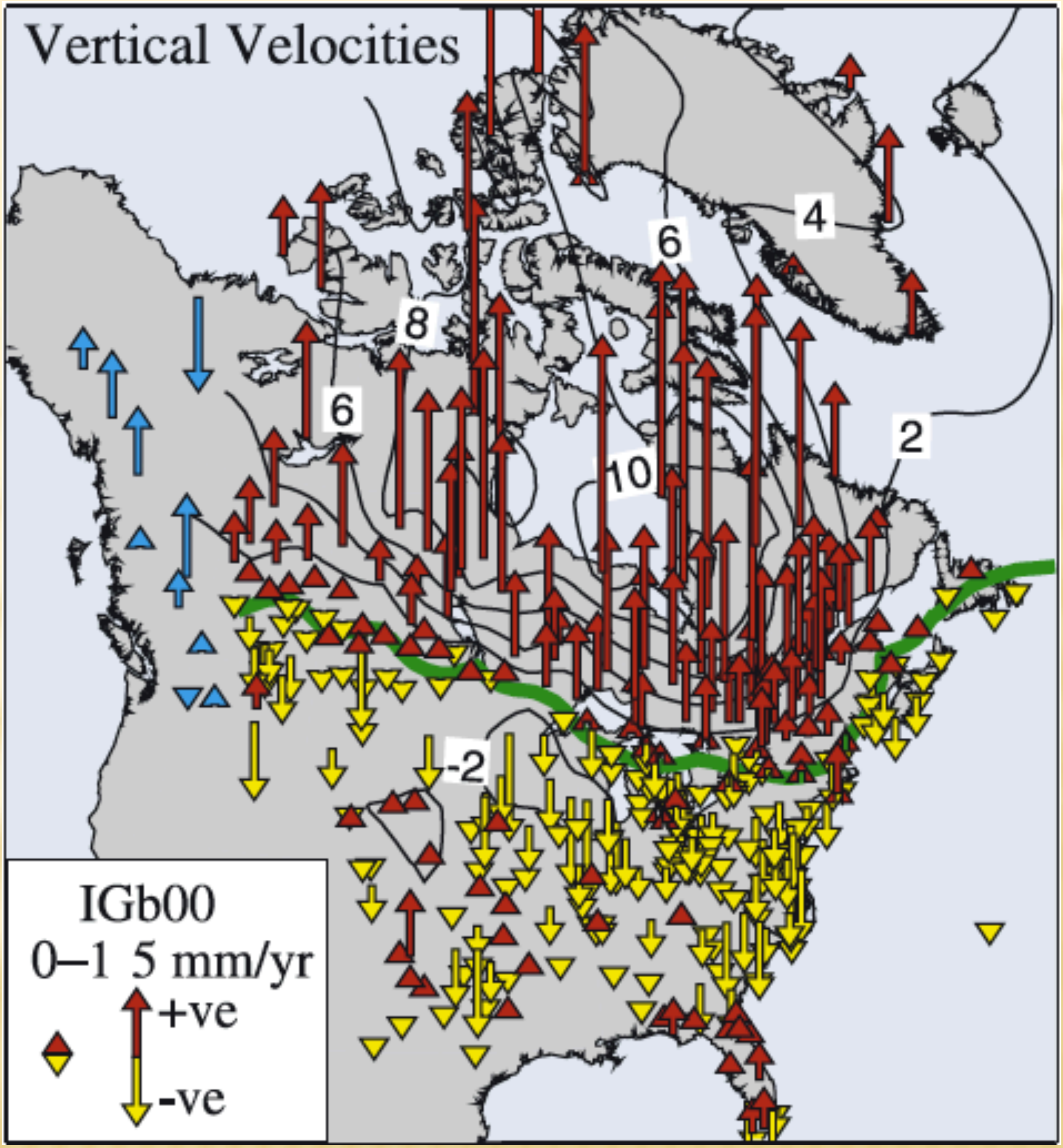
L Mantle viscosity $\sim 10^{22}$ Pa s

Basin and Range / Iceland/Other

Lithospheric thickness ~ 10 km

U Mantle viscosity $< 1 \times 10^{19}$ Pa s

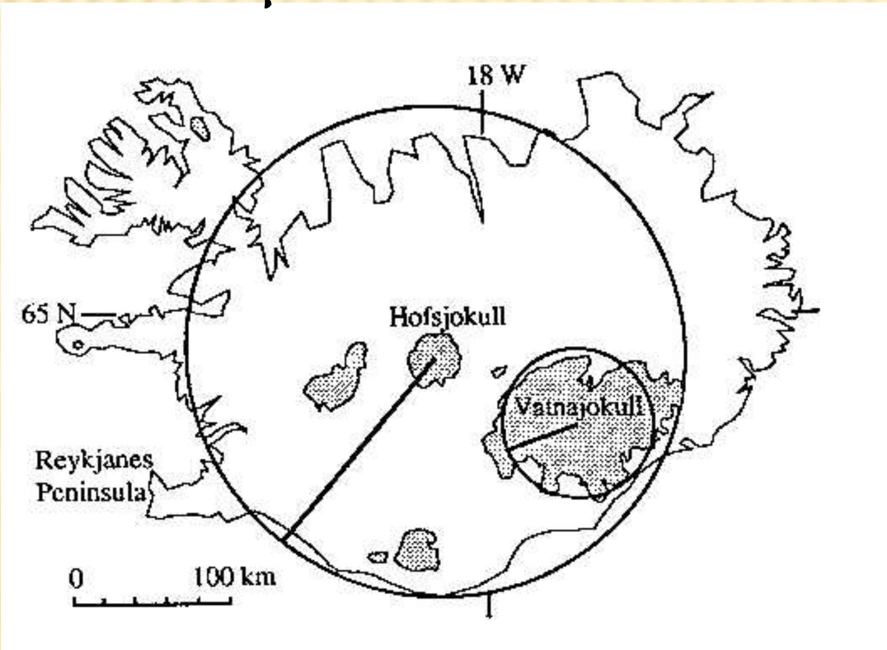
PGR North America

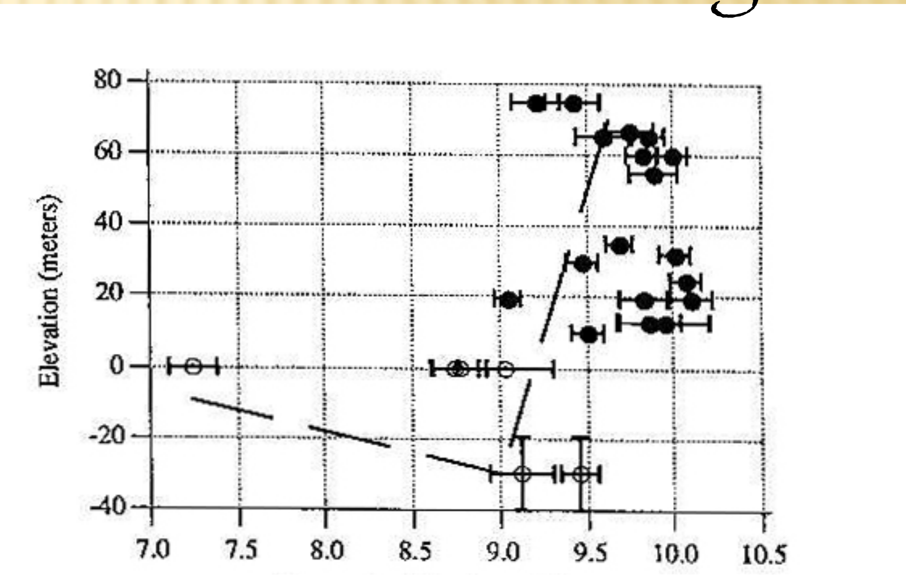


Sella et al., 2007

PGR in Iceland (young oceanic structure)

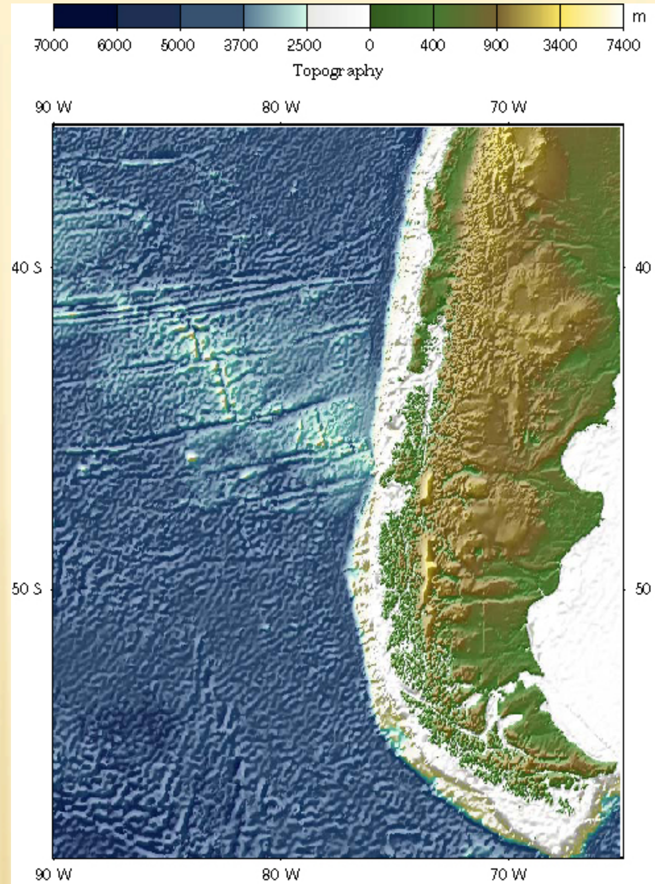
- Deglaciation following maximum at ~ 12000 yrsBP
  - PGR in Iceland was completed in 1000 yrs
    - U Mantle viscosity $< 1 \times 10^{19}$ Pa s
- Compare to Fennoscandia – PGR still occurring.



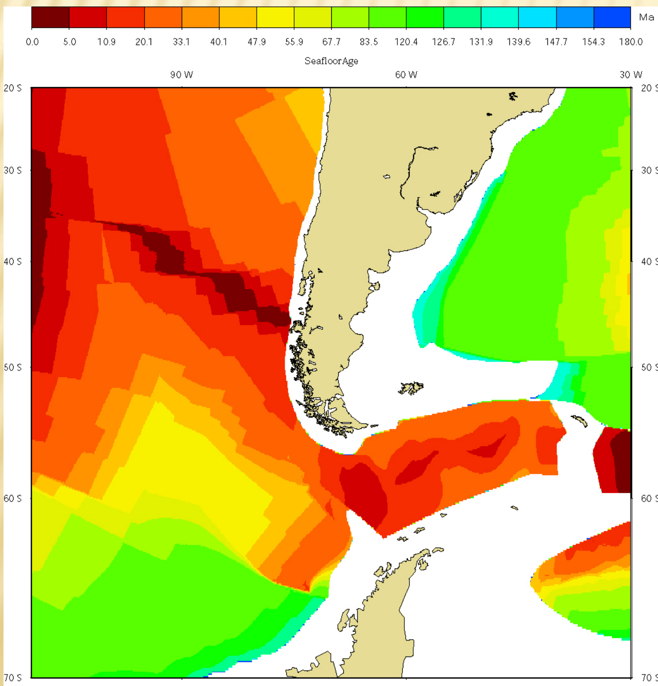


Sigmundsson (1991)

Geomechanical structure in Patagonia

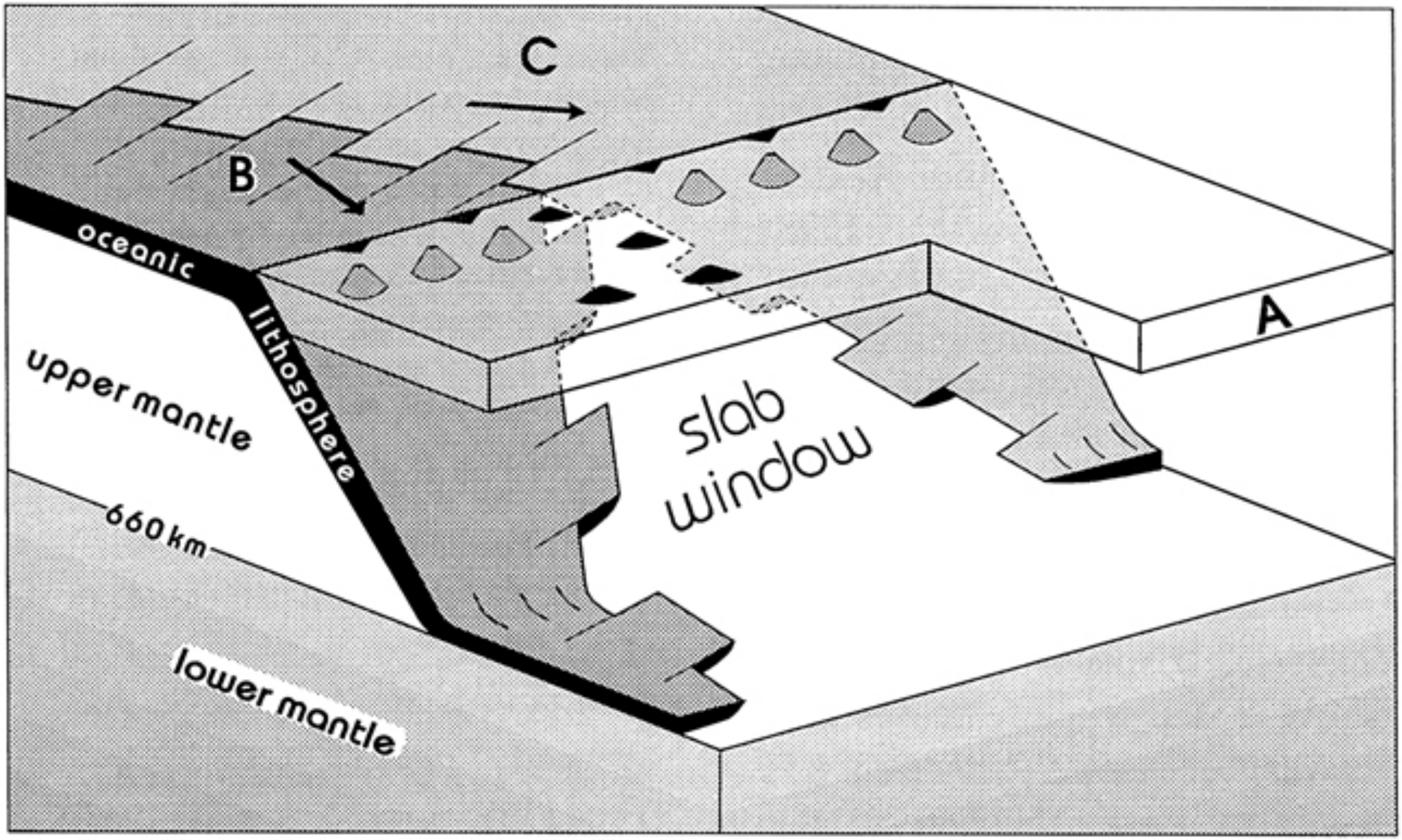


-Taitao Triple Junction
- Ridge subduction



PGR in Patagonia?
Continental, but not Fennoscandia.
More like Basin and Range?

Formation of a slab window



FROM THORKELSON (1996)

Crustal response to loads – ice

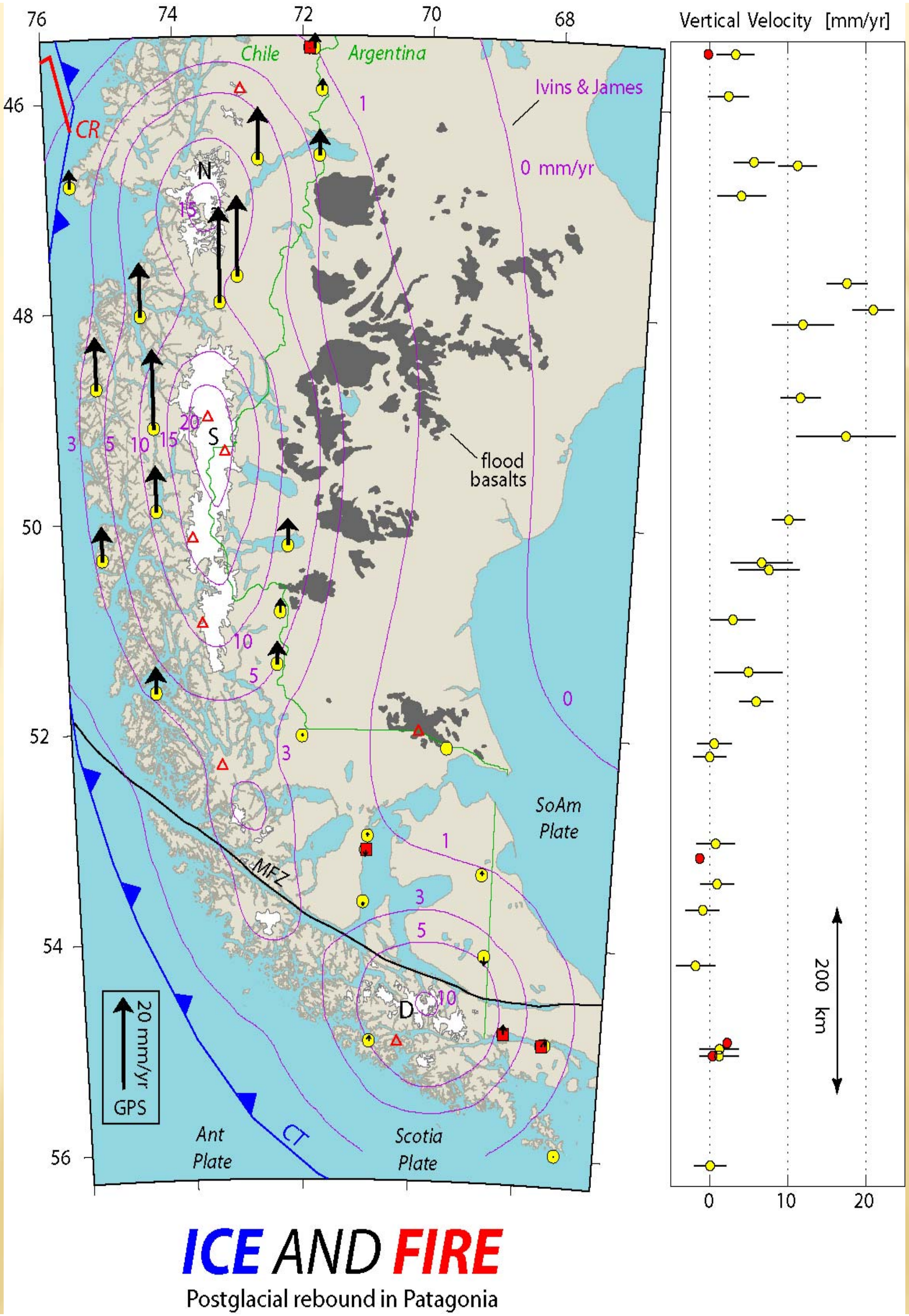
GPS Results

Uplift signal related to changes in ice mass in the Patagonian ice fields

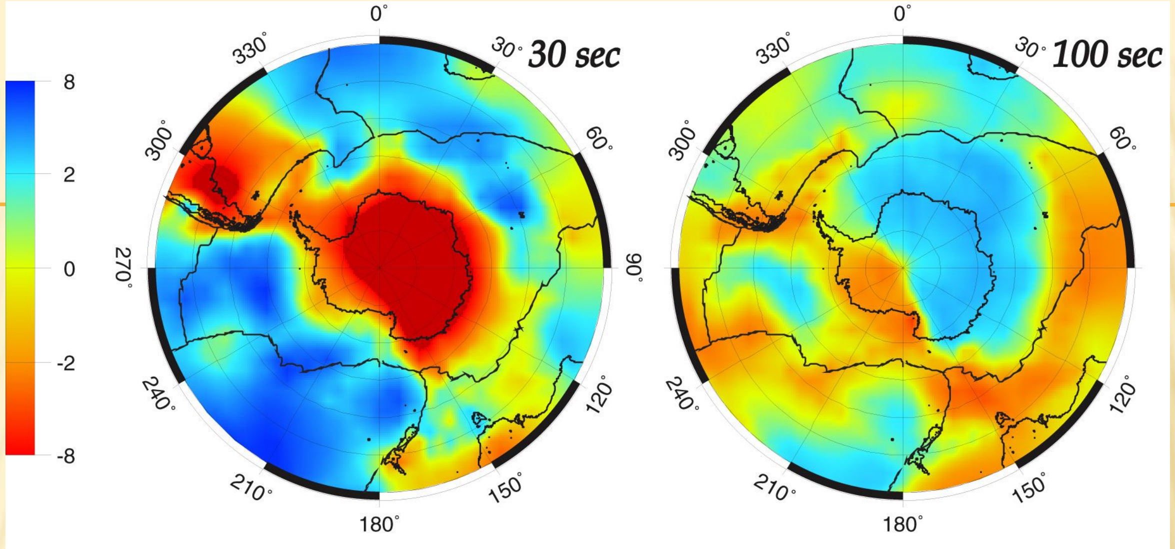
2 components –

Post glacial rebound amplified by upper mantle modified by subduction of ridge.

Elastic compression of crust.



Rayleigh Wave velocity



Geomechanical Structure of Antarctica: Part I

Rayleigh wave velocity

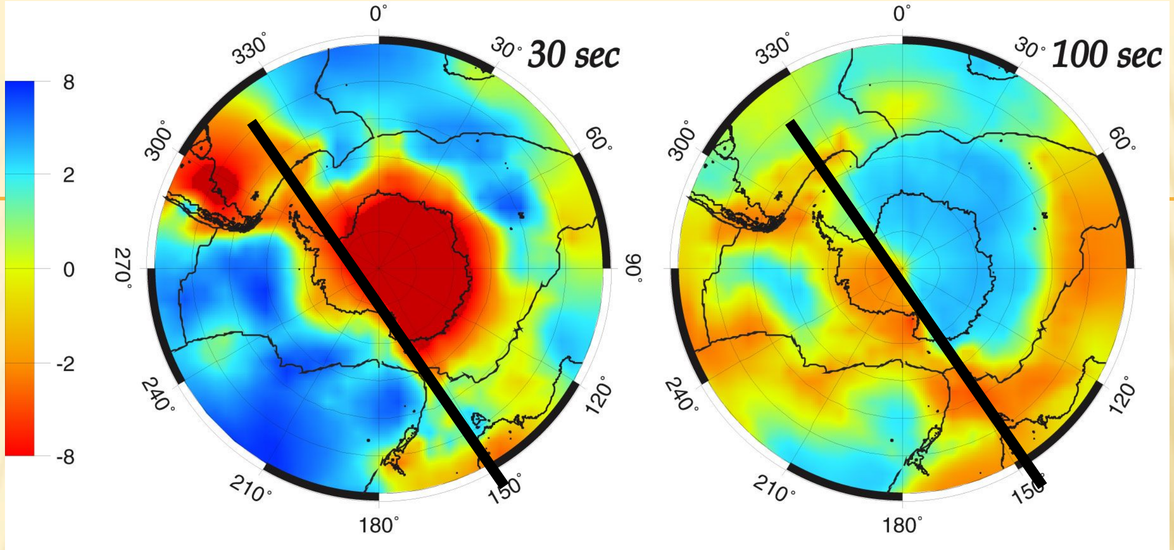
•proxy for lithospheric thickness

- thin is "weak"

Determines wavelength and amplitude of isostatic response

Danesi & Morelli, 2001

Rayleigh Wave velocity



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Danesi & Morelli, 2001

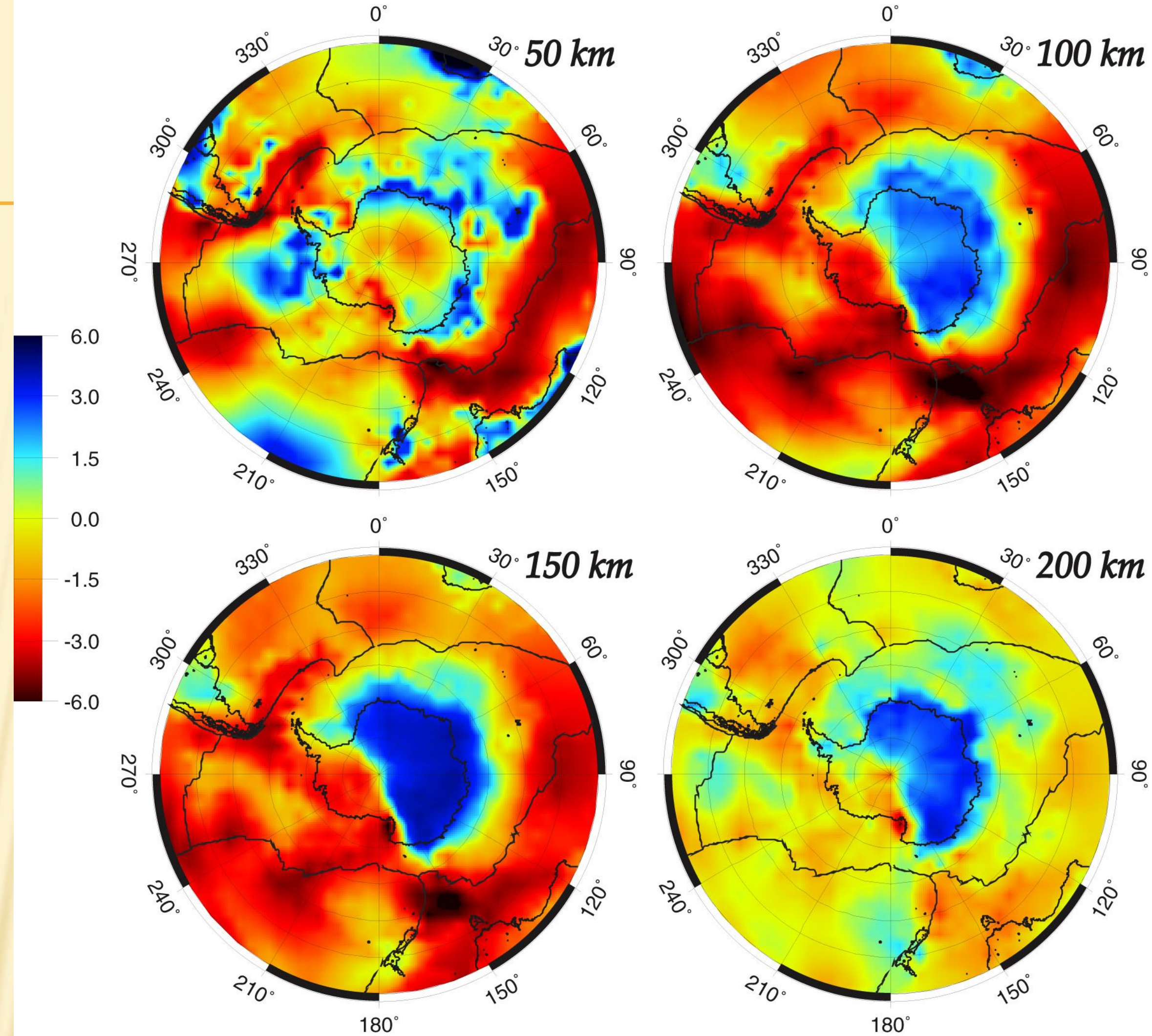
Result -- West Antarctica thin

Geomechanical Structure of Antarctica: Part II

Sv velocity

•proxy for temperature

- hot is lower viscosity (runny).



Determines speed of isostatic response.

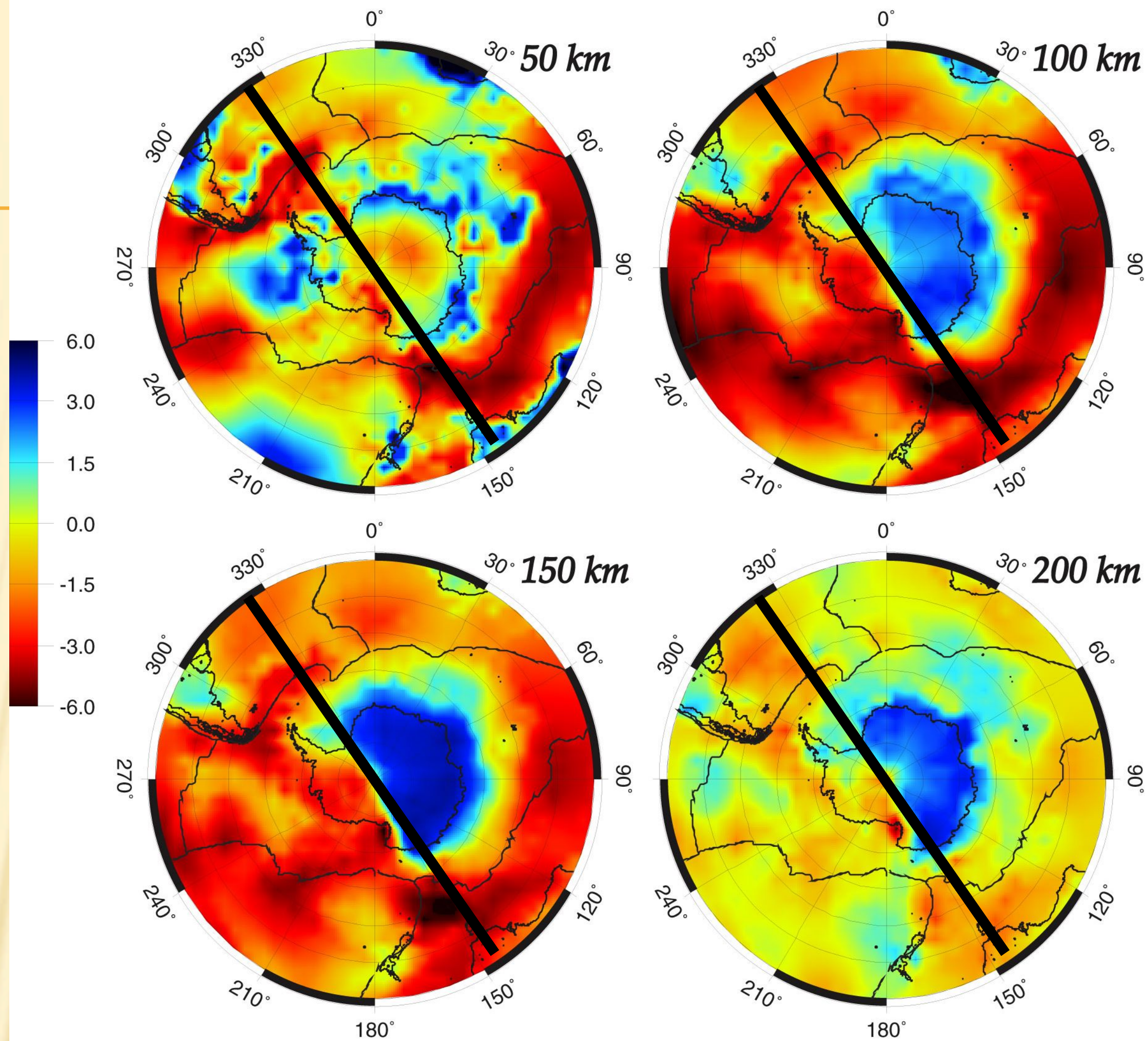
Danesi & Morelli, 2001

Geomechanical Structure of Antarctica: Part II

Sv velocity

•proxy for temperature

- hot is lower viscosity (runny).

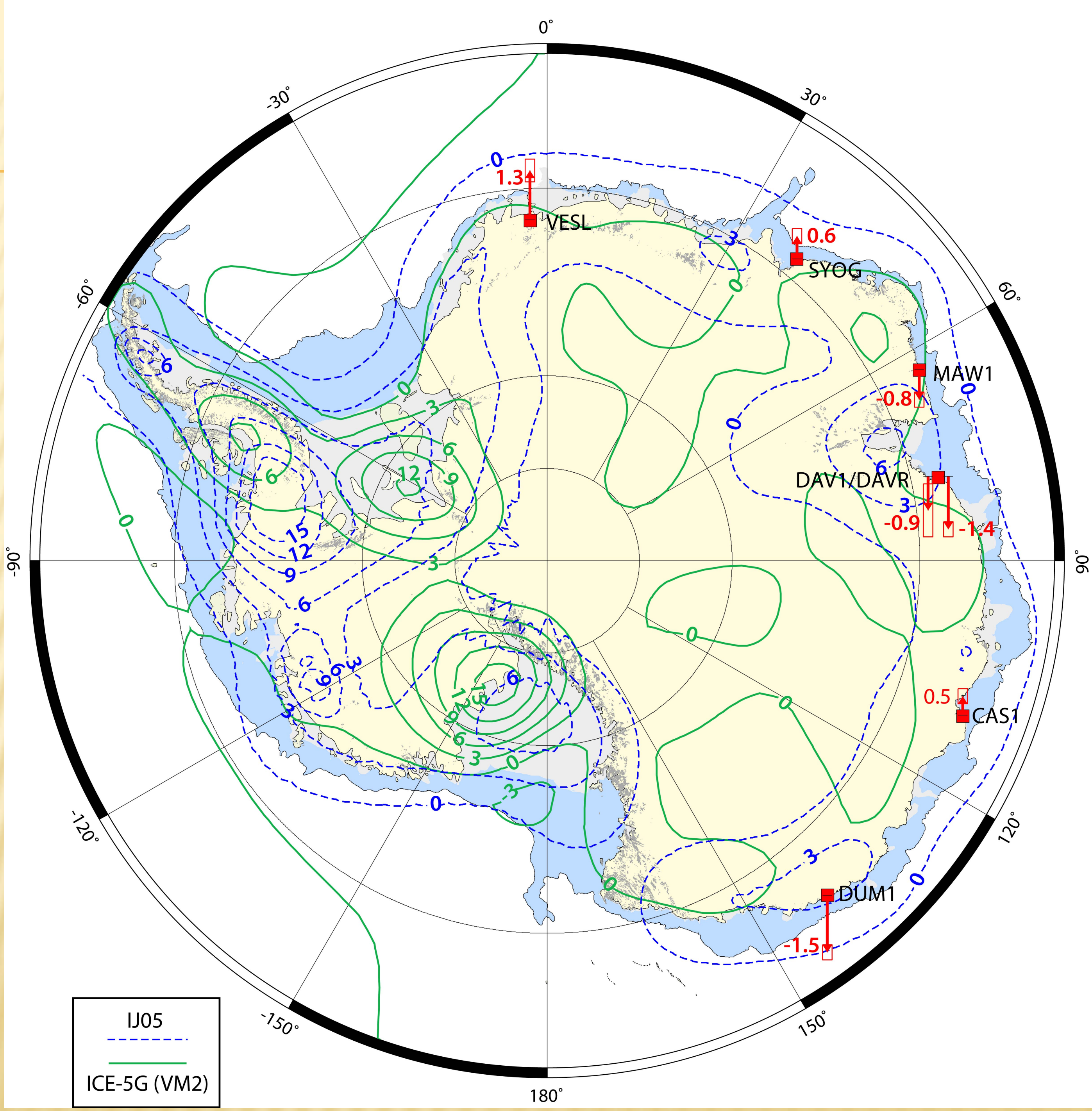


Determines speed of isostatic response.

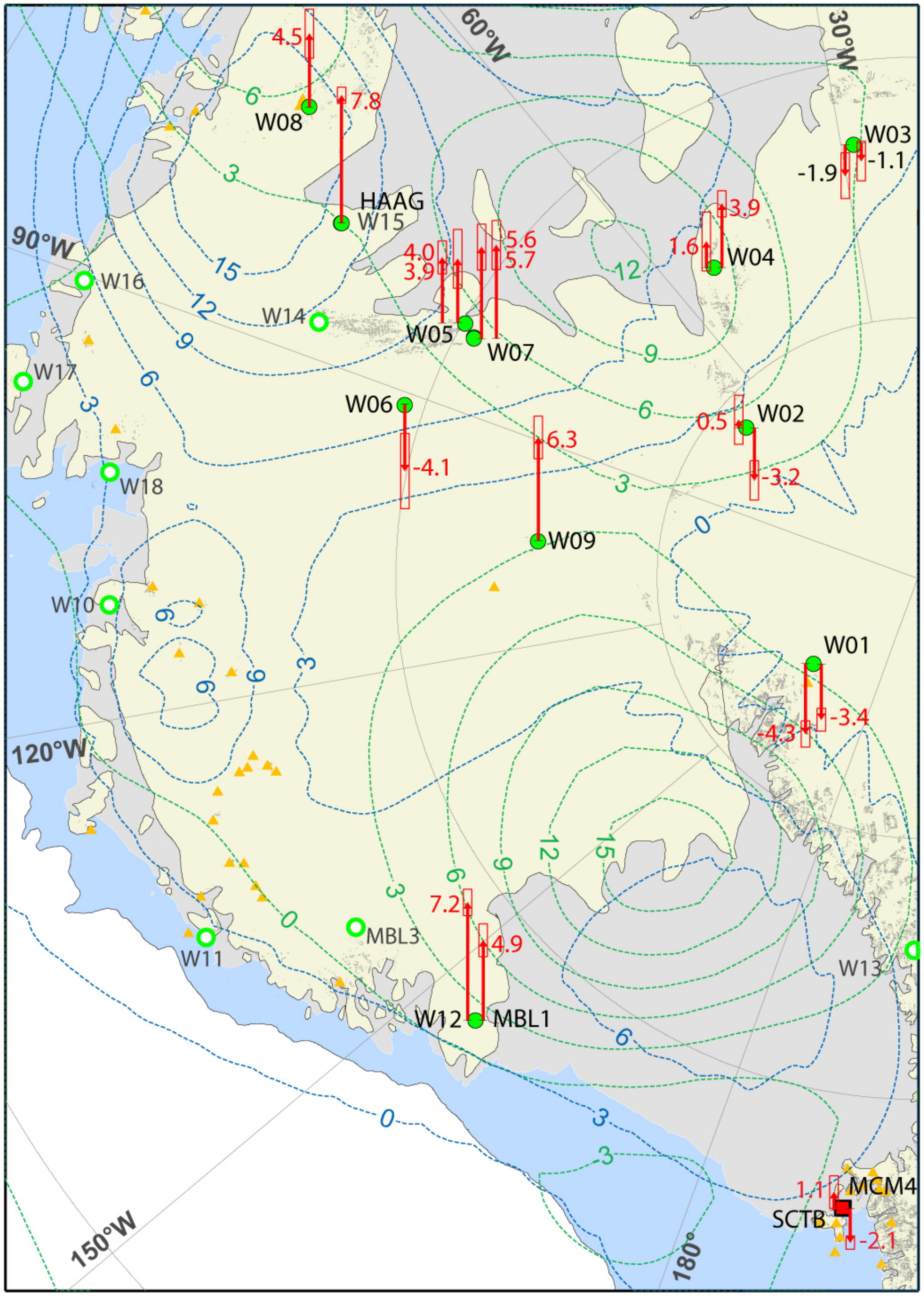
Result -- West Antarctica hot

Danesi & Morelli, 2001

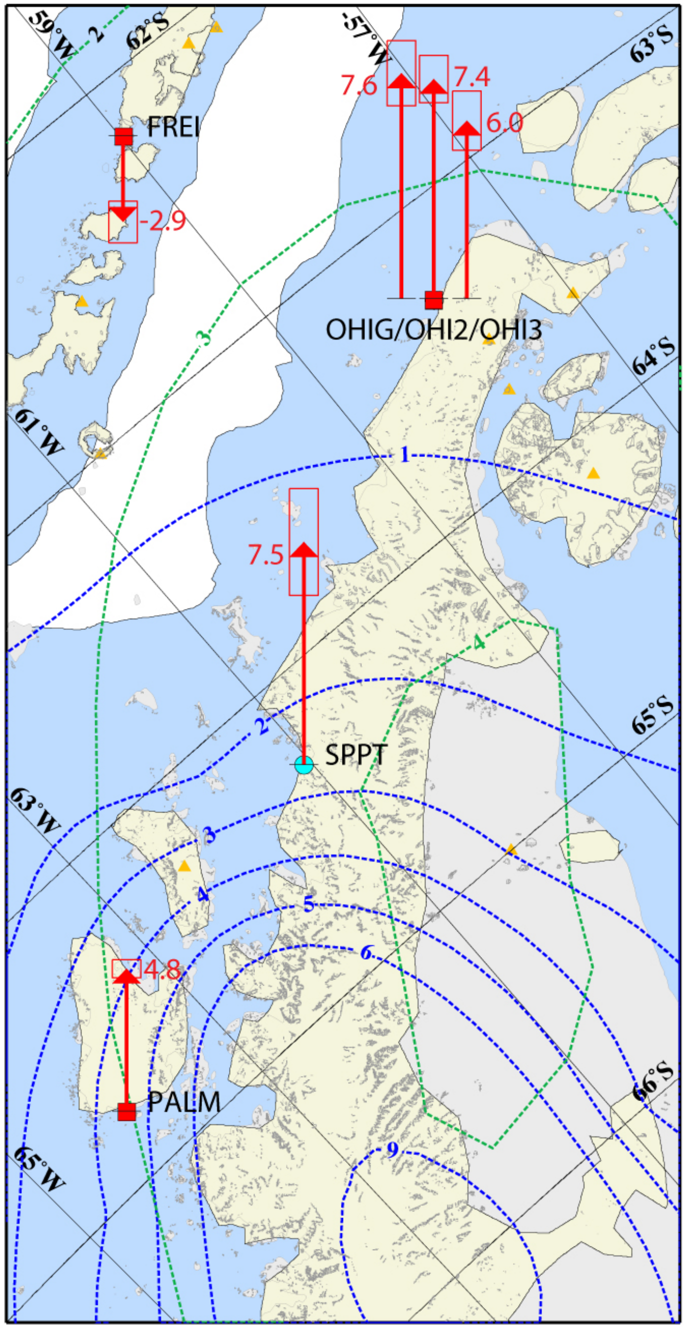

AP
TI
EWM
EA
MBL



0°
30°
60°
90°
120°
150°
180°
-150°
-120°
-90°
-60°
-30°
VESL
1.3
SYOG
0.6
MAW1
-0.8
DAV1/DAVR
-0.9
-1.4
CAS1
0.5
DUM1
-1.5
IJ05
ICE-5G (VM2)

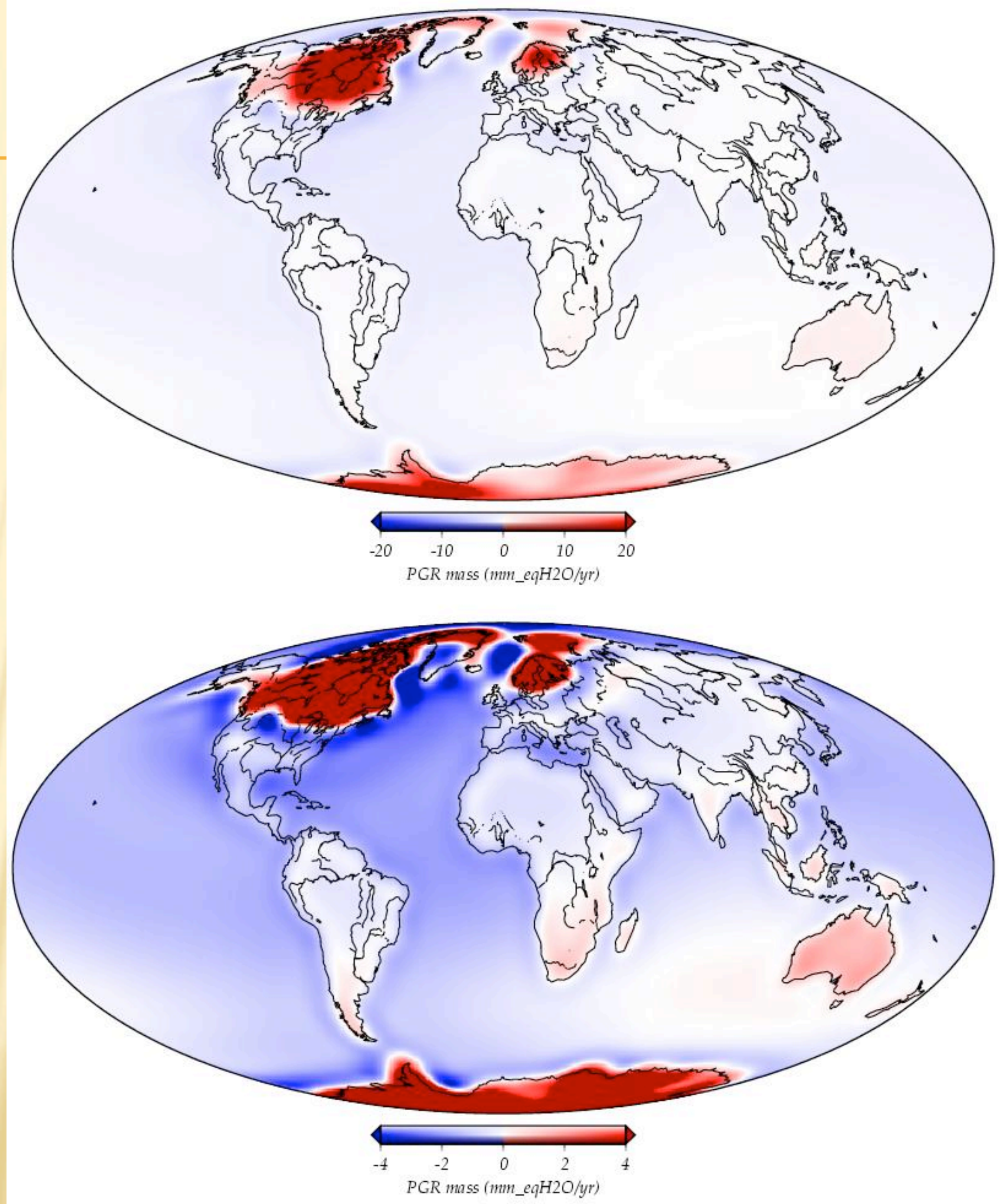


60°W
30°W
90°W
120°W
150°W
180°
W08
4.5
7.8
HAAG
W15
W16
W14
W05
W07
4.0
3.9
5.6
5.7
W03
-1.9
-1.1
W04
1.6
3.9
W17
W06
-4.1
6.3
W02
0.5
-3.2
W18
W09
W10
W01
-3.4
-4.3
W11
MBL3
7.2
4.9
W12
MBL1
W13
MCM4
SCTB
1.1
-2.1



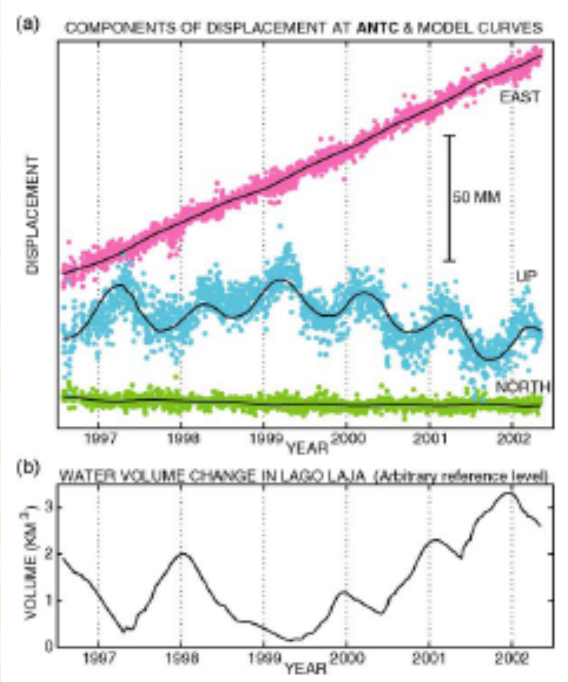
59°W
62°S
57°W
63°S
64°S
65°S
66°S
61°W
63°W
65°W
FREI
-2.9
7.6
7.4
6.0
OHIG/OHI2/OHI3
7.5
SPPT
4.8
PALM

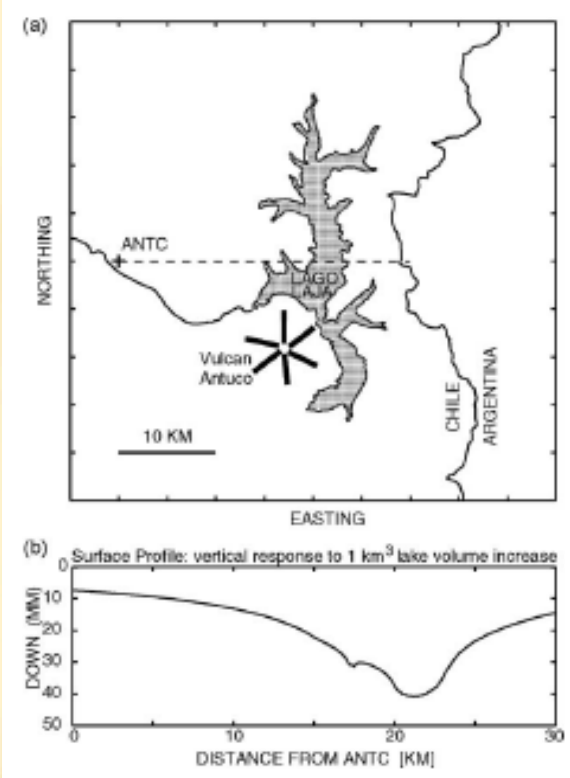
Model of present-day surface elevation change due to PGR and reloading of ocean basins with seawater. Red areas rising due to removal of ice sheets. Blue areas falling due to re-filling of ocean basins when ice sheets melted and because of collapse forebulges around the ice sheets.

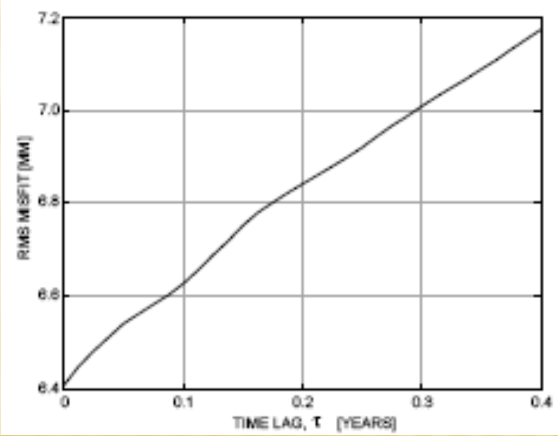


Paulson, A., http://grace.jpl.nasa.gov/data/pgr

Crustal response to loads
Annual lake loading

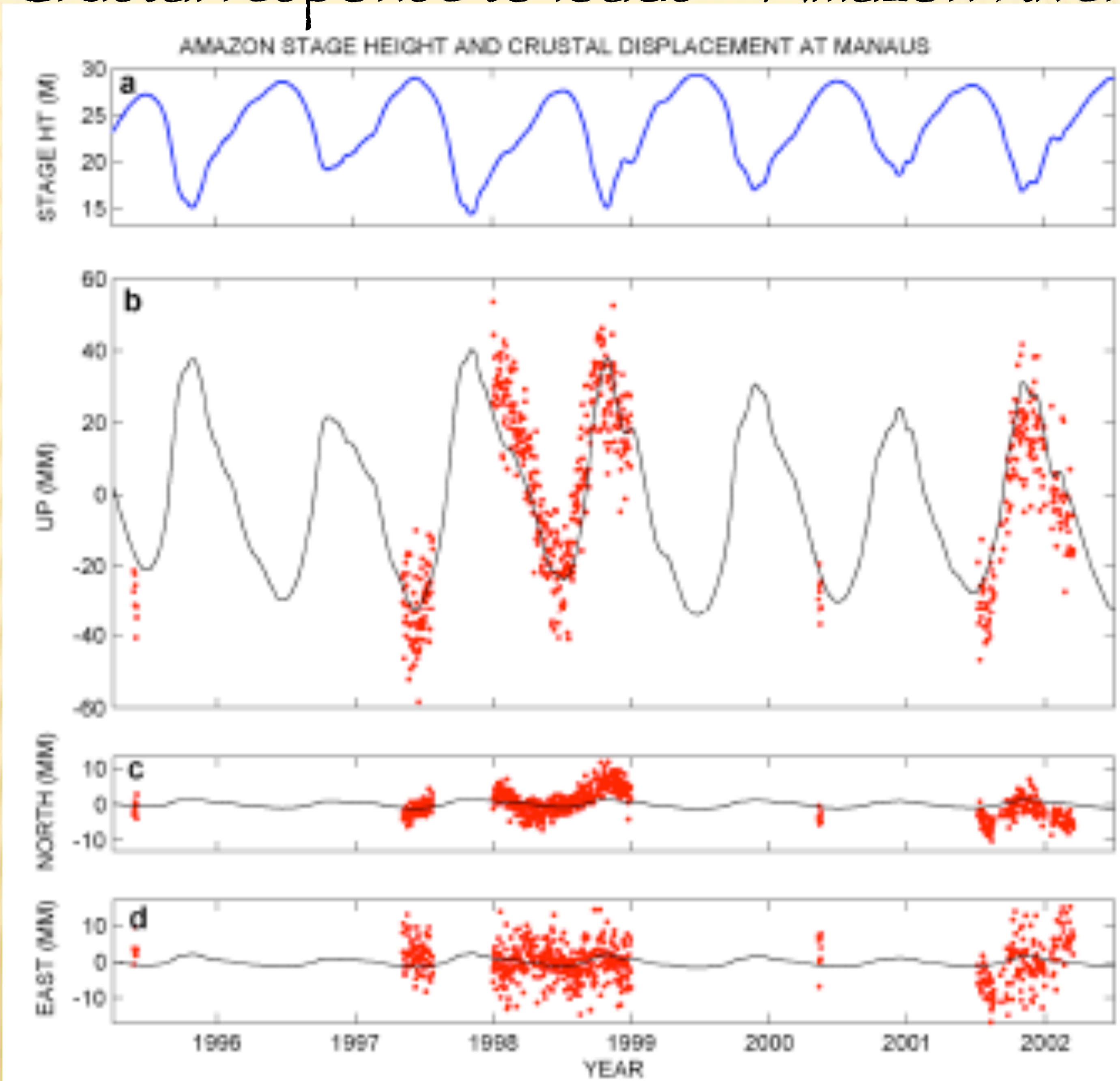






Check for anelasticity – no time lag/phase shift -> elastic.

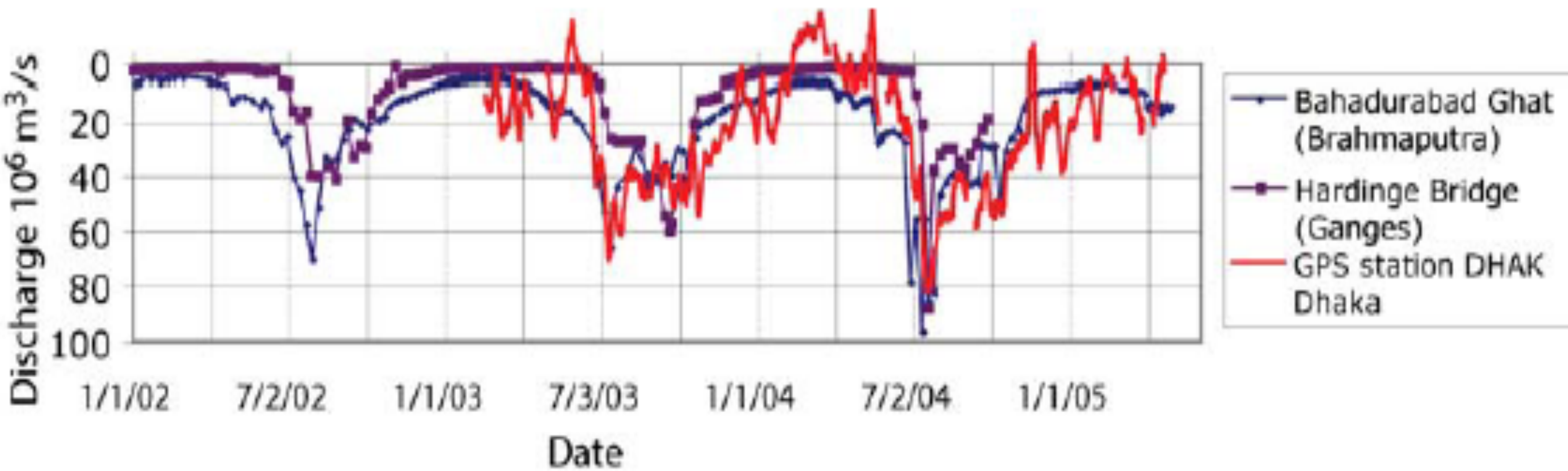
Crustal response to loads – Amazon River



Bevis et al, 2005

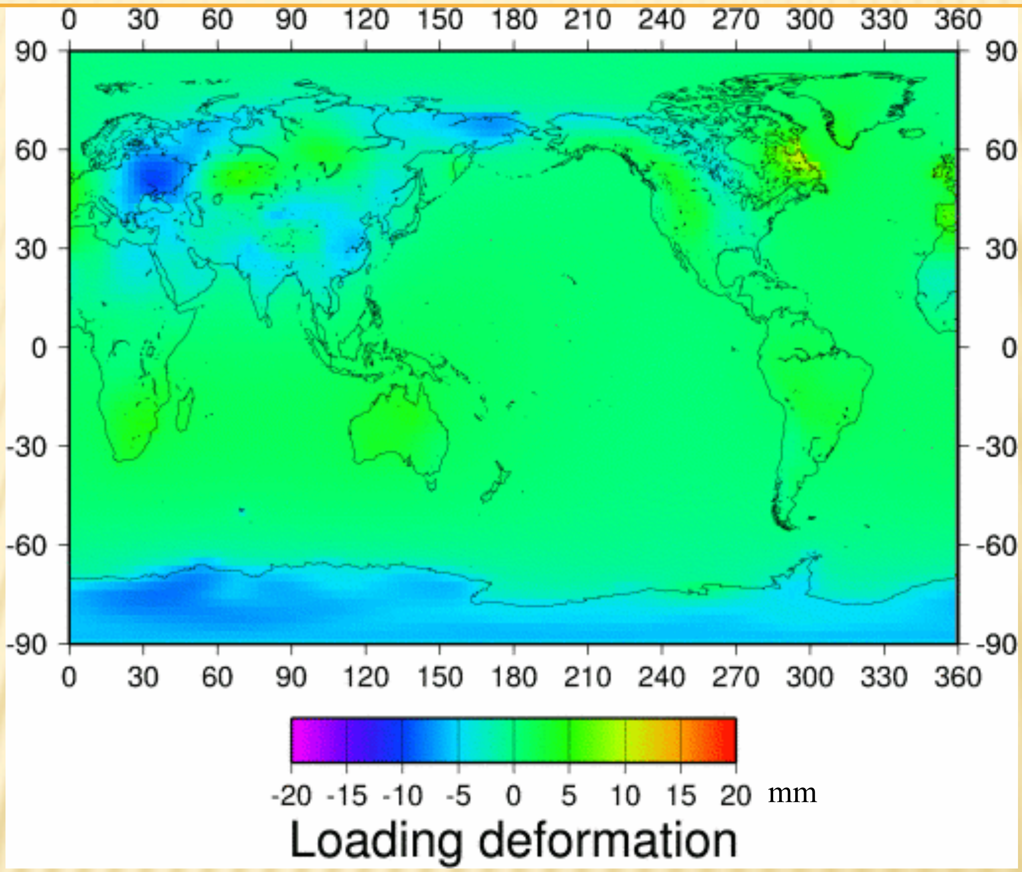
Response of crust to loading from Brahmaputra and Gandes

Requires continuous GPS to observe non-secular (in this case annual) signals.



www.unavco.org/pubs_reports/proposals/2007/facility2007/section3/UNV-GRID-SPREAD-TP_41.pdf

Elastic deformation in vertical from loading – complication or another interesting signal?



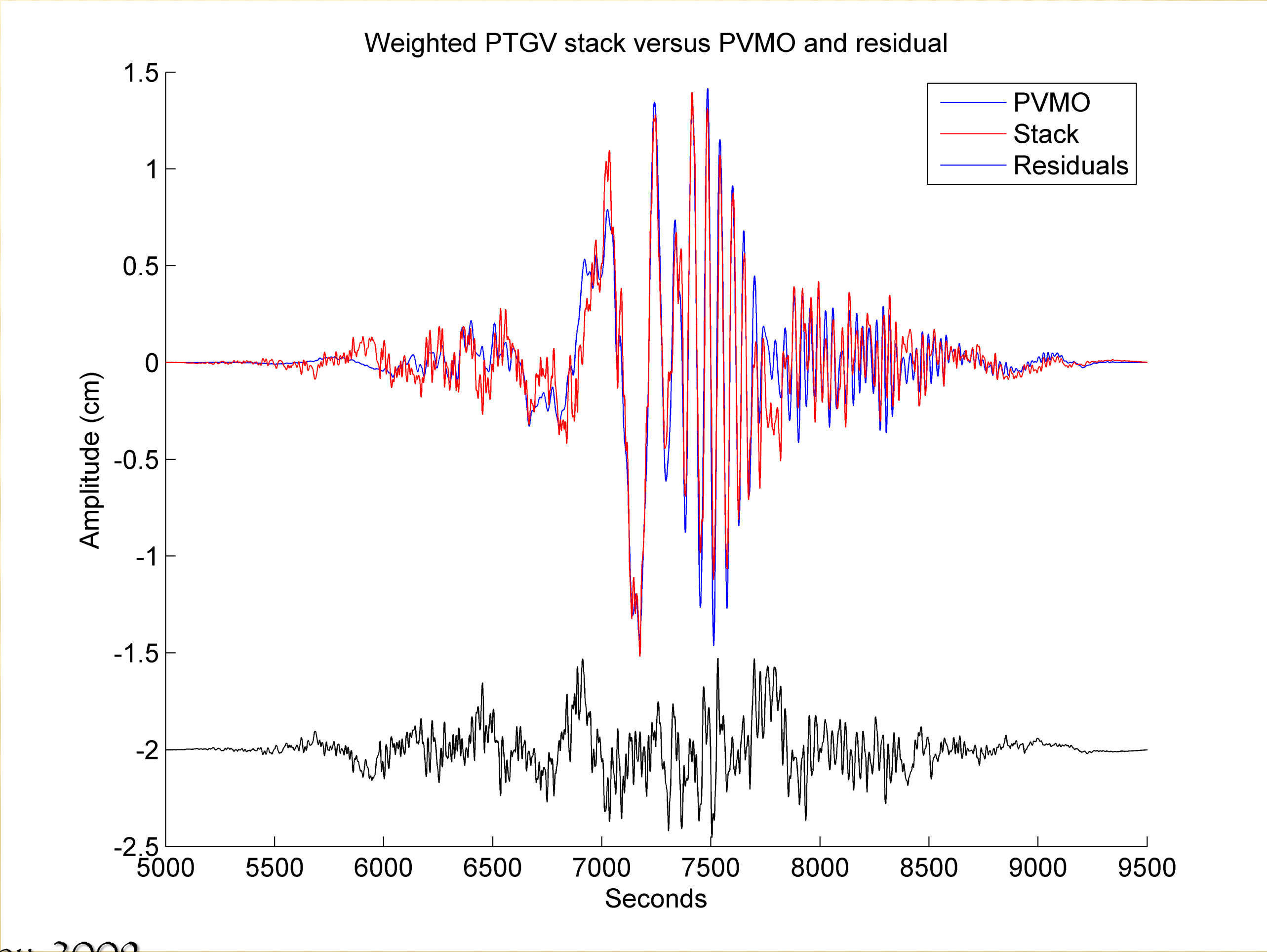
Weather systems:

Aerial extent – thousands of square km.

Period – weeks.

Kinematic GPS

GPS absolute displacement seismograms – Love wave of 2004 M9.0, Sumatra-Andaman earthquake in Portageville, AR.

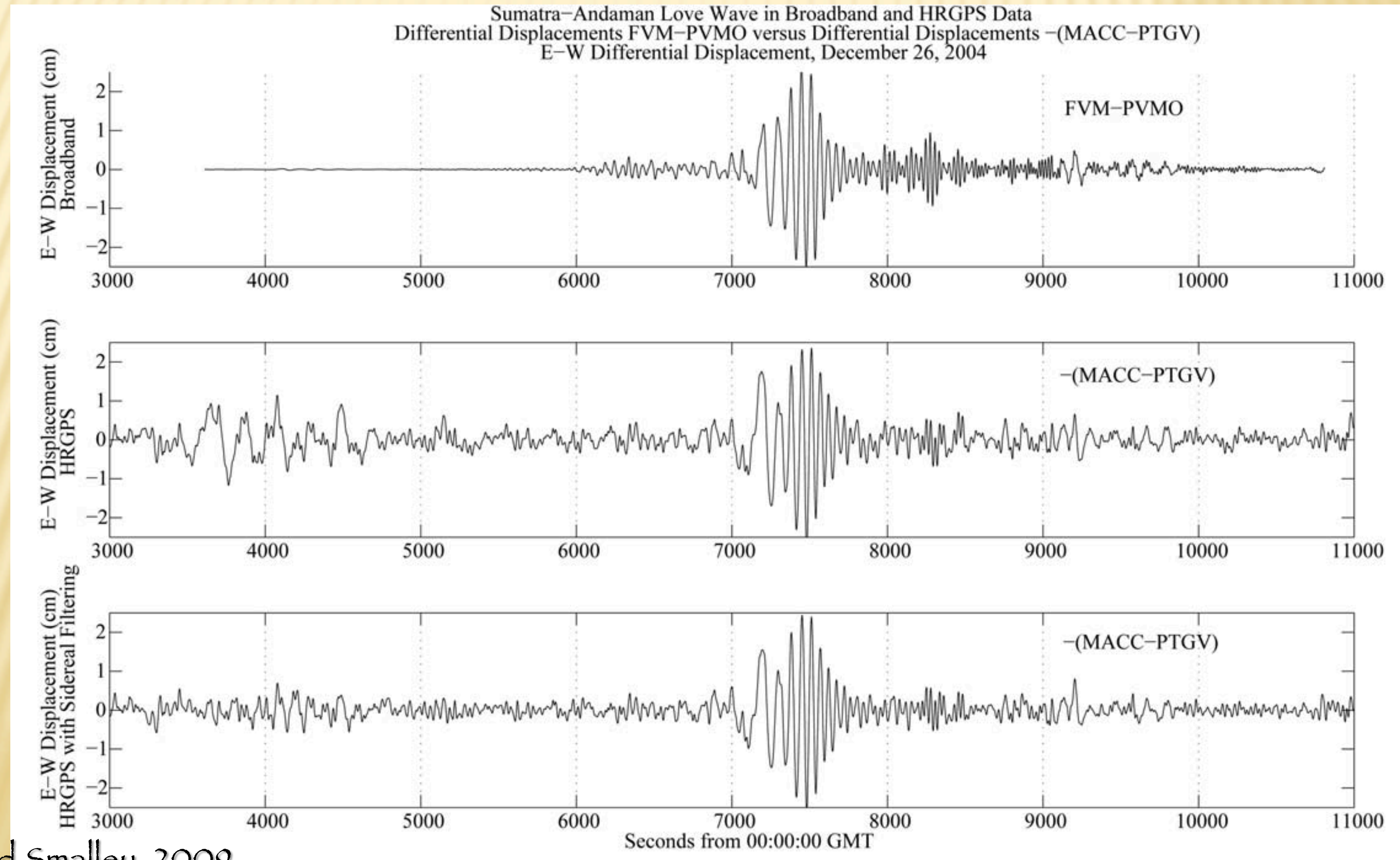


Davis and Smalley, 2009

Kinematic GPS

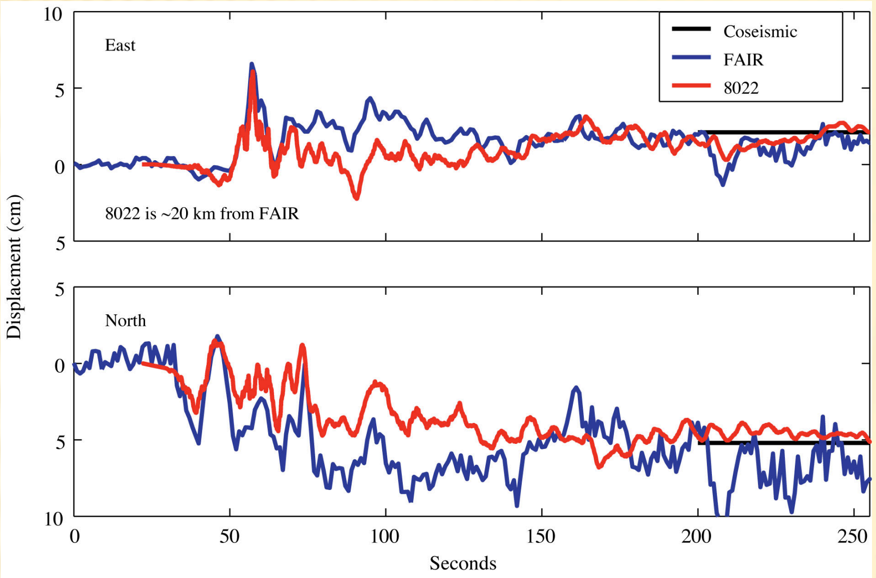
Differential – difference in position between two GPS antennas, one assumed "fixed". (PPP methods also exist, but are less precise)

$$D_{differential} = D_{kinematic} - D_{fixed}$$

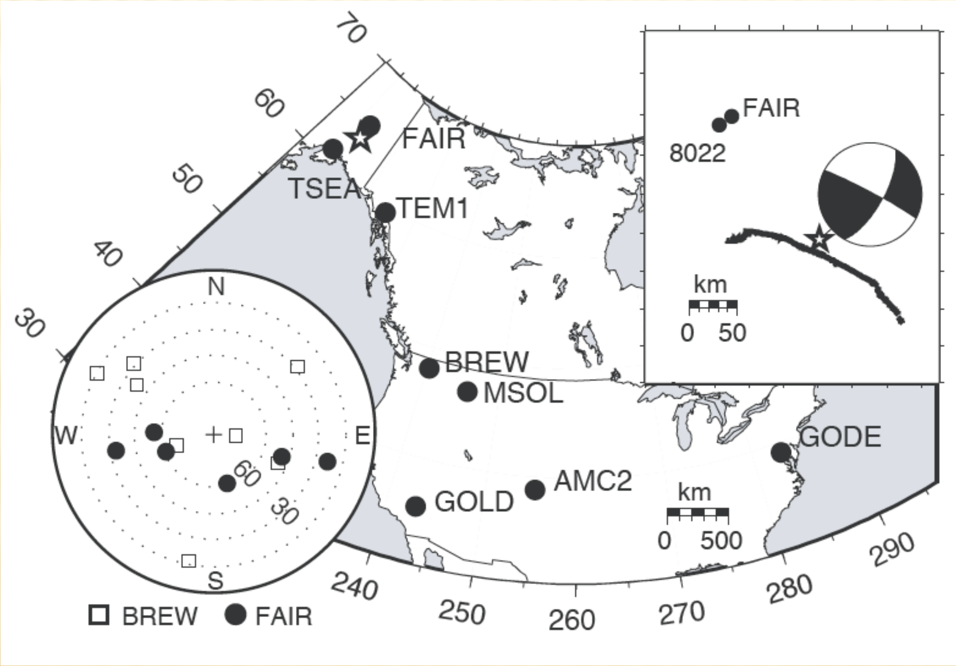


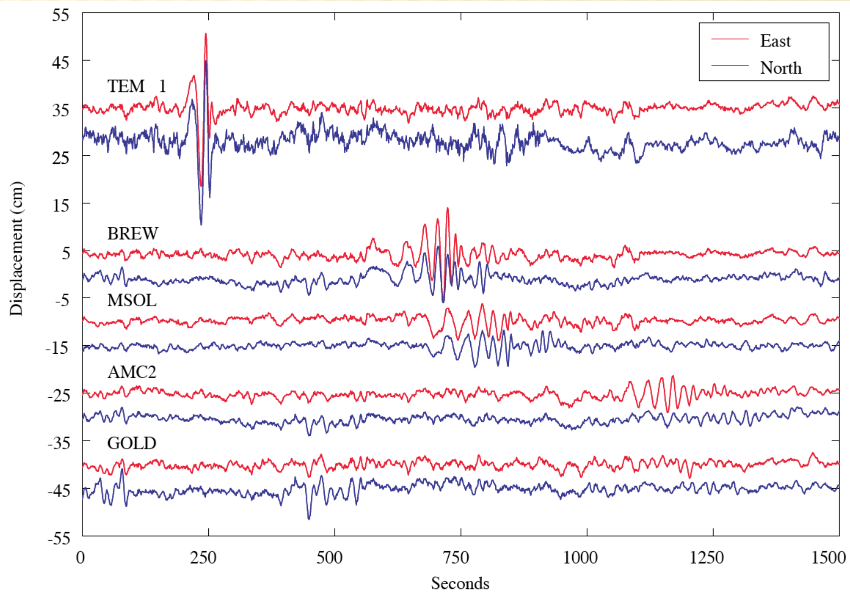
Davis and Smalley, 2009

How to get absolute displacements?



Most popular way to have one of the two sites outside the region with displacements (site is "fixed") – discovered GPS recorded surface waves at few thousand km.





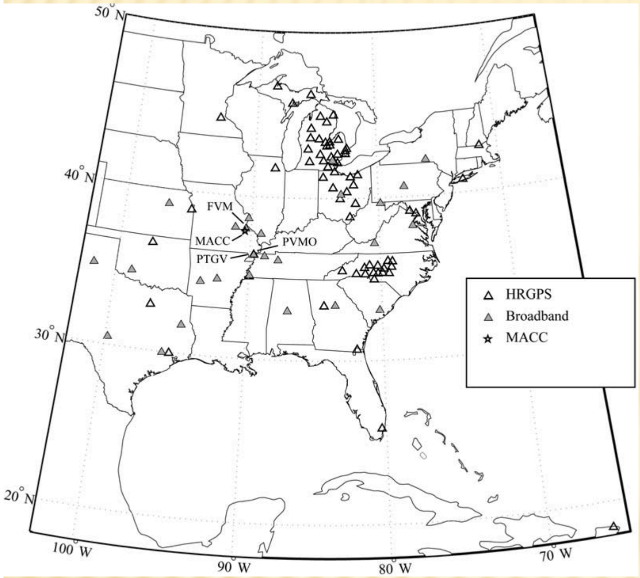
Larson et al, 2003

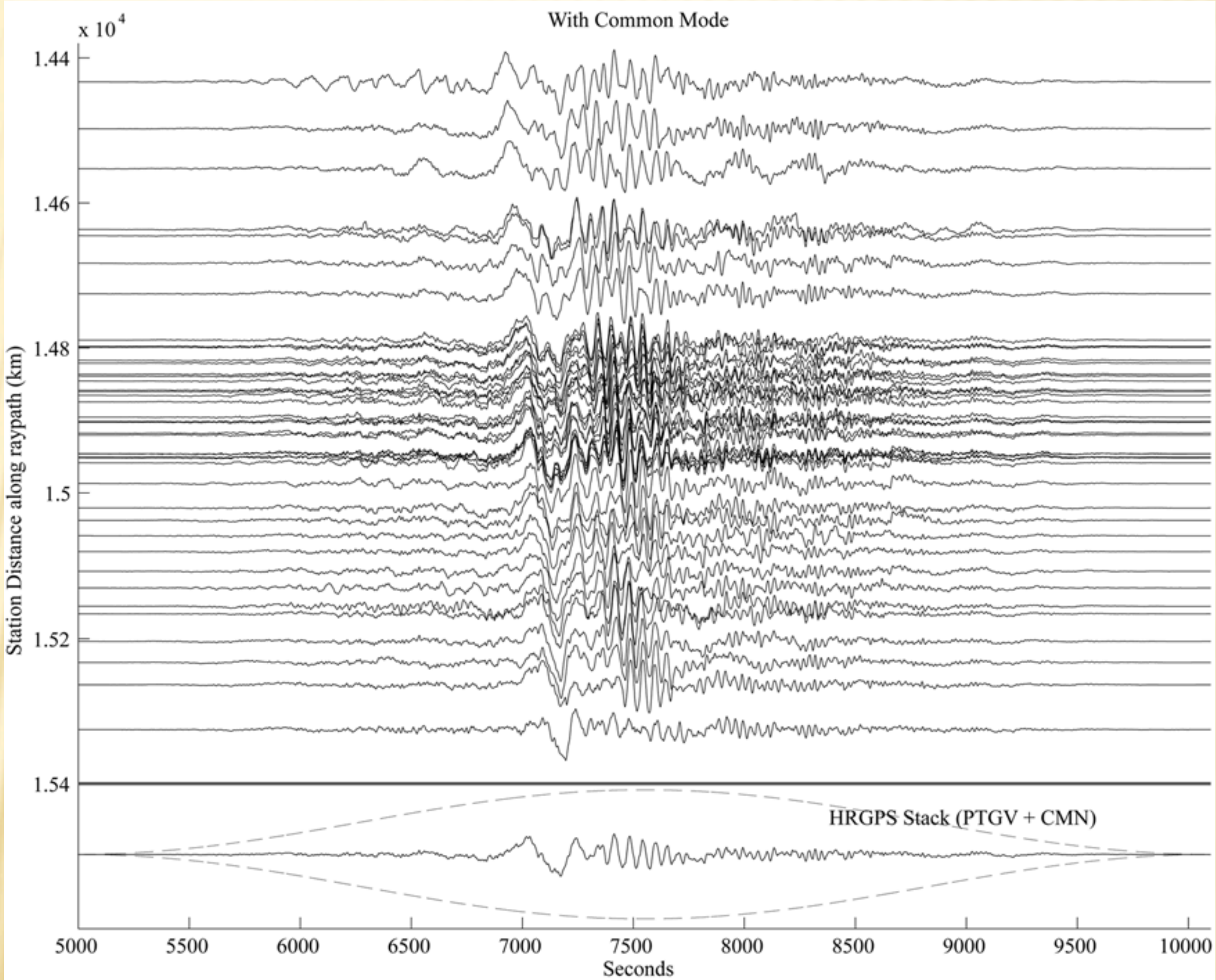
Does not work for surface waves from really big earthquakes with long duration surface wave trains

can't find "fixed" site.

(Fixed site has to be able to see common set satellites with kinematic site – since is differential.
The longer the baseline the fewer satellites are in common and the worse the overall location geometry.
The signal may be of longer duration than the time it takes for the waves to travel from the kinematic to the fixed site.)

Calculate differential displacement seismograms for large number sites in central North America – using "fixed" site in central North America.





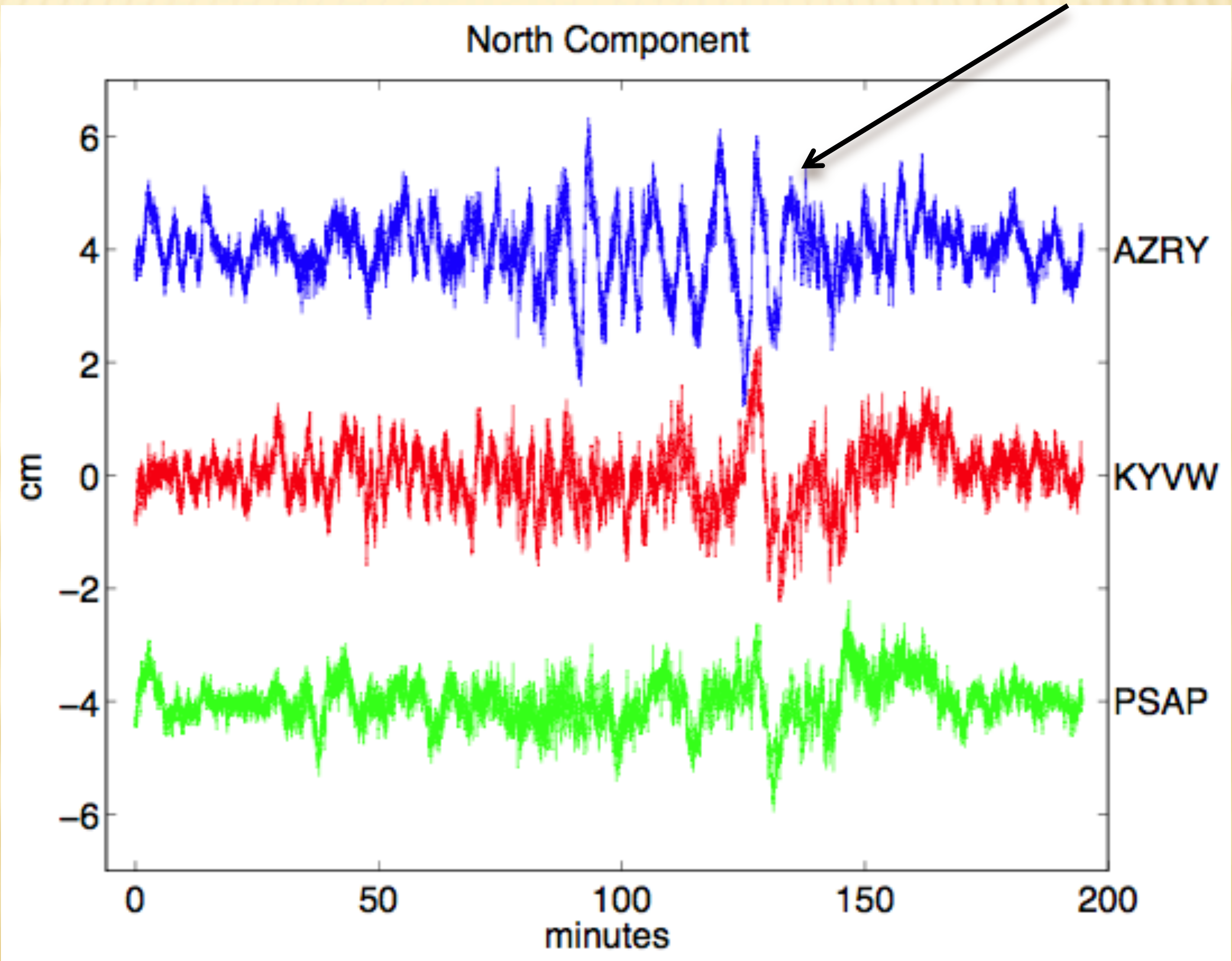
Difficult to tell are not absolute seismograms.

(Bottom trace is sum.)

Davis and Smalley, 2009

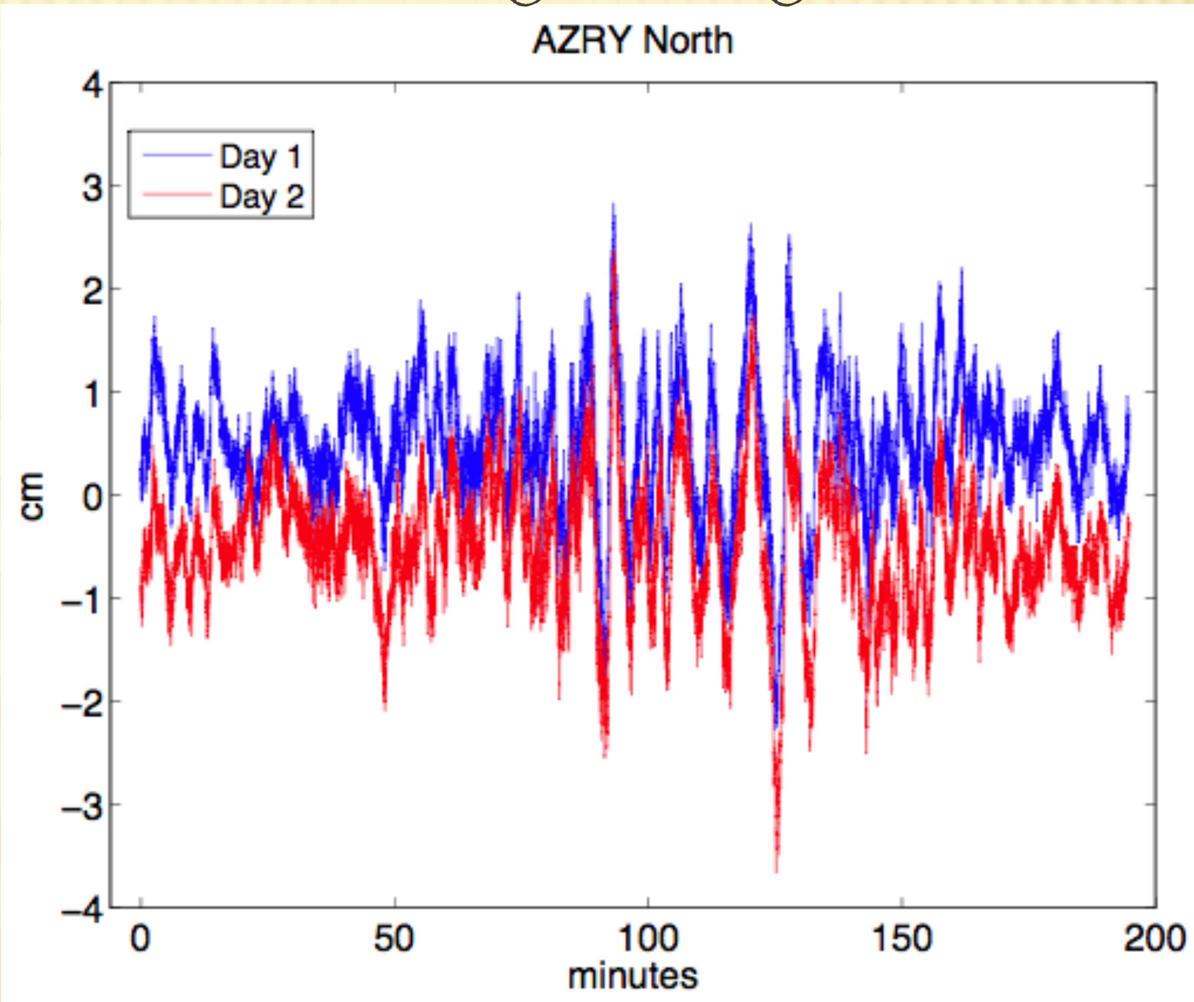
Sidetrack – Multipath

Multipath (reflected signals) is important (and doesn't difference out). Looks like earthquake?



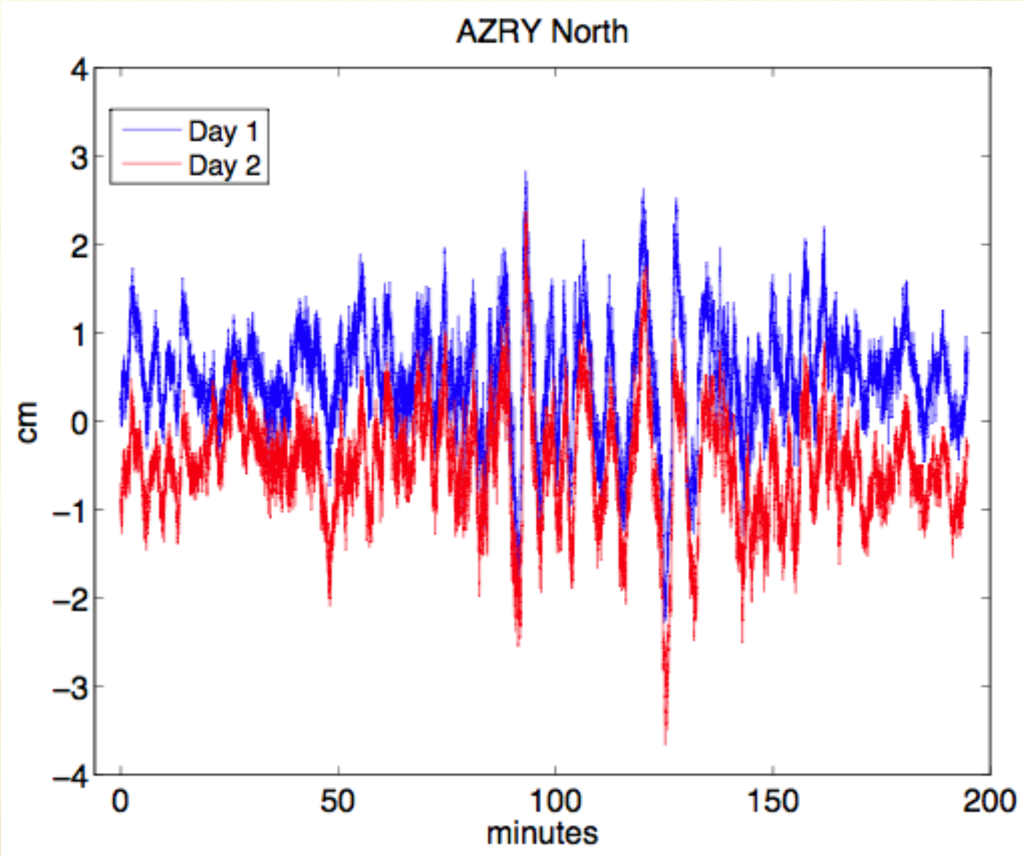
From Larson

But look at day before or after – looks the same. Multipath looks same from day to day – due to orbits repeating, generating same reflections, day to day.



From Larson

So the trick is to calculate the GPS displacement time series from the day before or after and subtract from the day with the earthquake. Have to shift by the ~4 minutes due to the "almost" part of the 2x/day GPS orbit.



From Larson

This is called Sidereal Filtering and it removes much of the multipath.

But it depends on the reflection environment remaining the same (no rain, snow, movement of nearby objects such as parked vehicles, etc.)

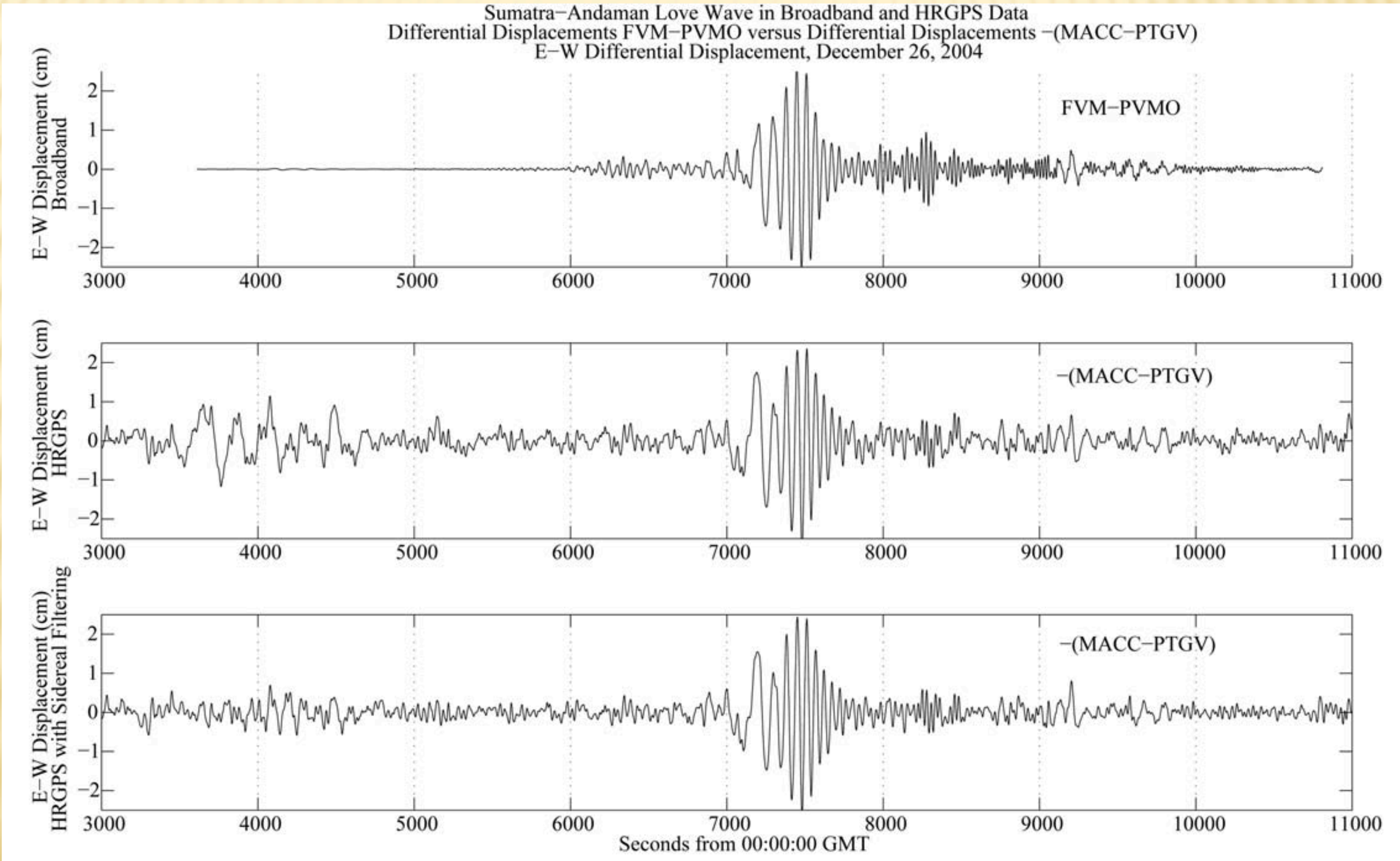
It also depends on getting the time shift right. Modification is to cross correlate between the two days to get a better time shift (each satellite's orbit is nominally 4 minutes short – but they vary individually, which effects the locations, etc.).
This is called "modified sidereal filtering"

Sometimes done with average of a few days, but this low pass filters the sidereal filter time series.

Advantage – don't need signal – can estimate multipath.

Multipath (approximately) stationary for a few days (when reflection environment stays same).

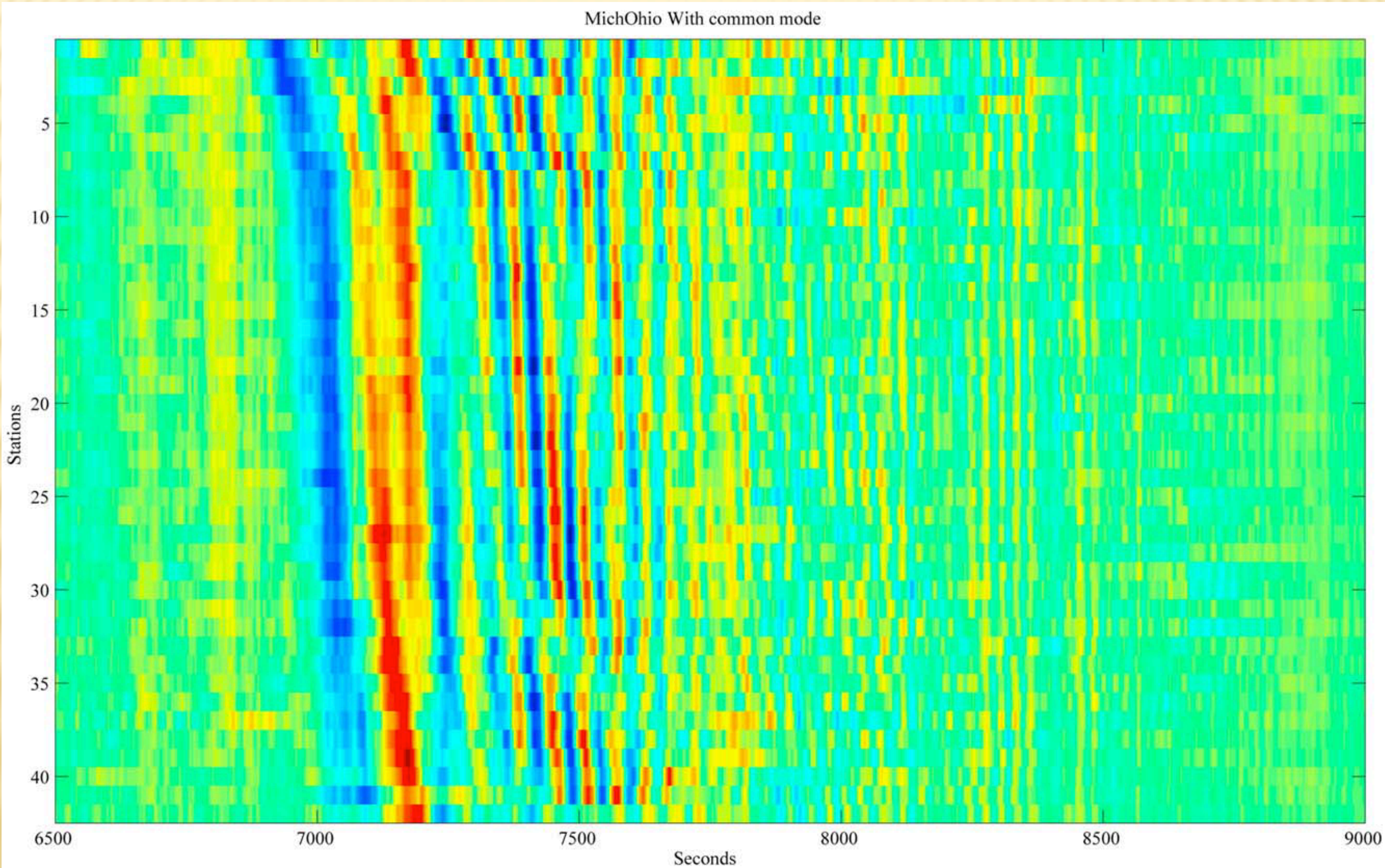
Note difference between middle and bottom traces – the bottom one has been sidereally filtered.



Davis and Smalley, 2009

Differential seismograms plotted as surface.

Now is does not quite look "right" (eg. - vertical lines, no "move-out")

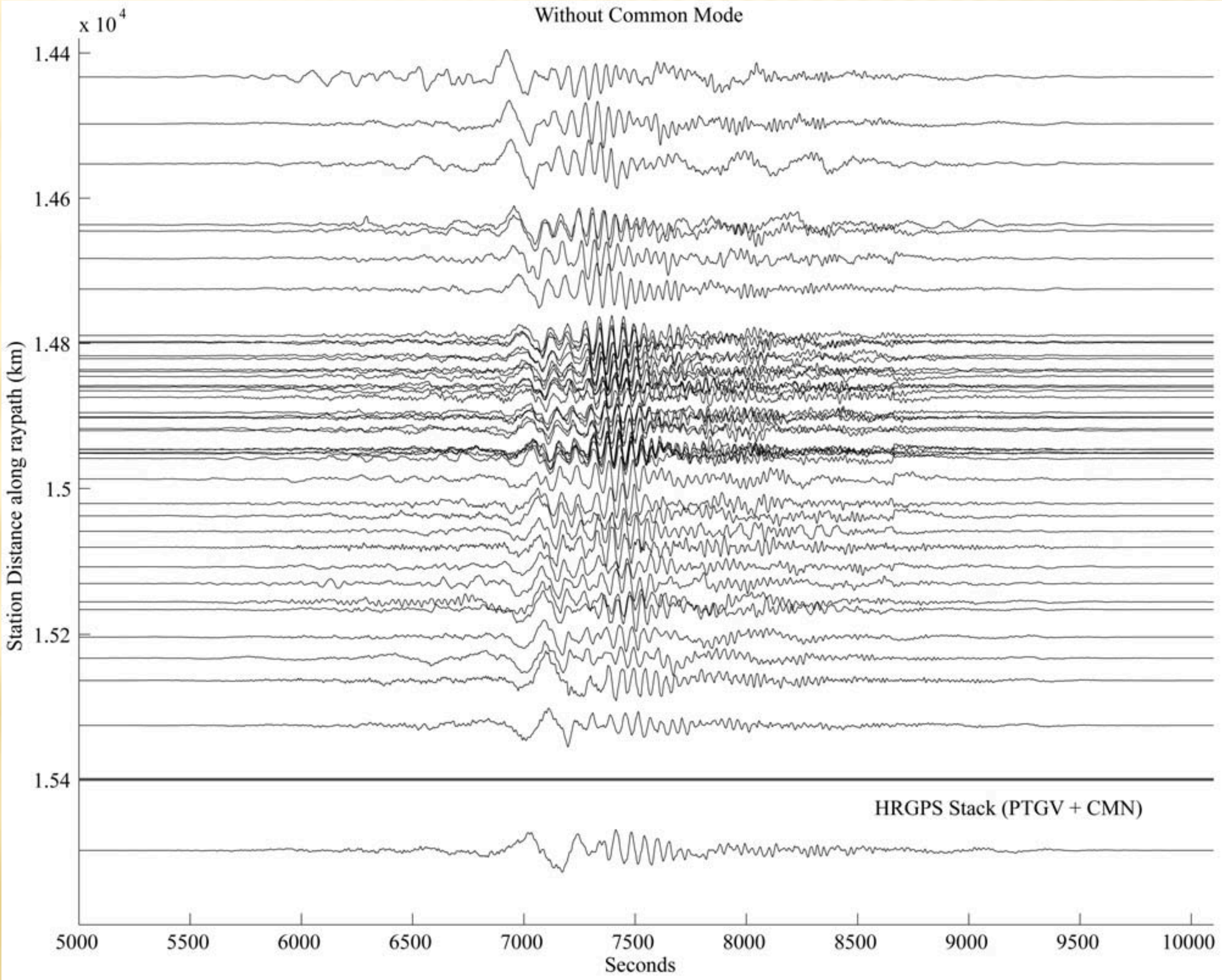


Davis and Smalley, 2009

Bottom trace is sum of differential seismograms (fixed-kinematic). This is an estimate of the absolute displacement of the "fixed" site – the kinematic sites "cancel" out.

$$\left\langle D_{fixed} \right\rangle = \sum_{n=1}^{m} \left(D_n - D_{fixed} \right)$$

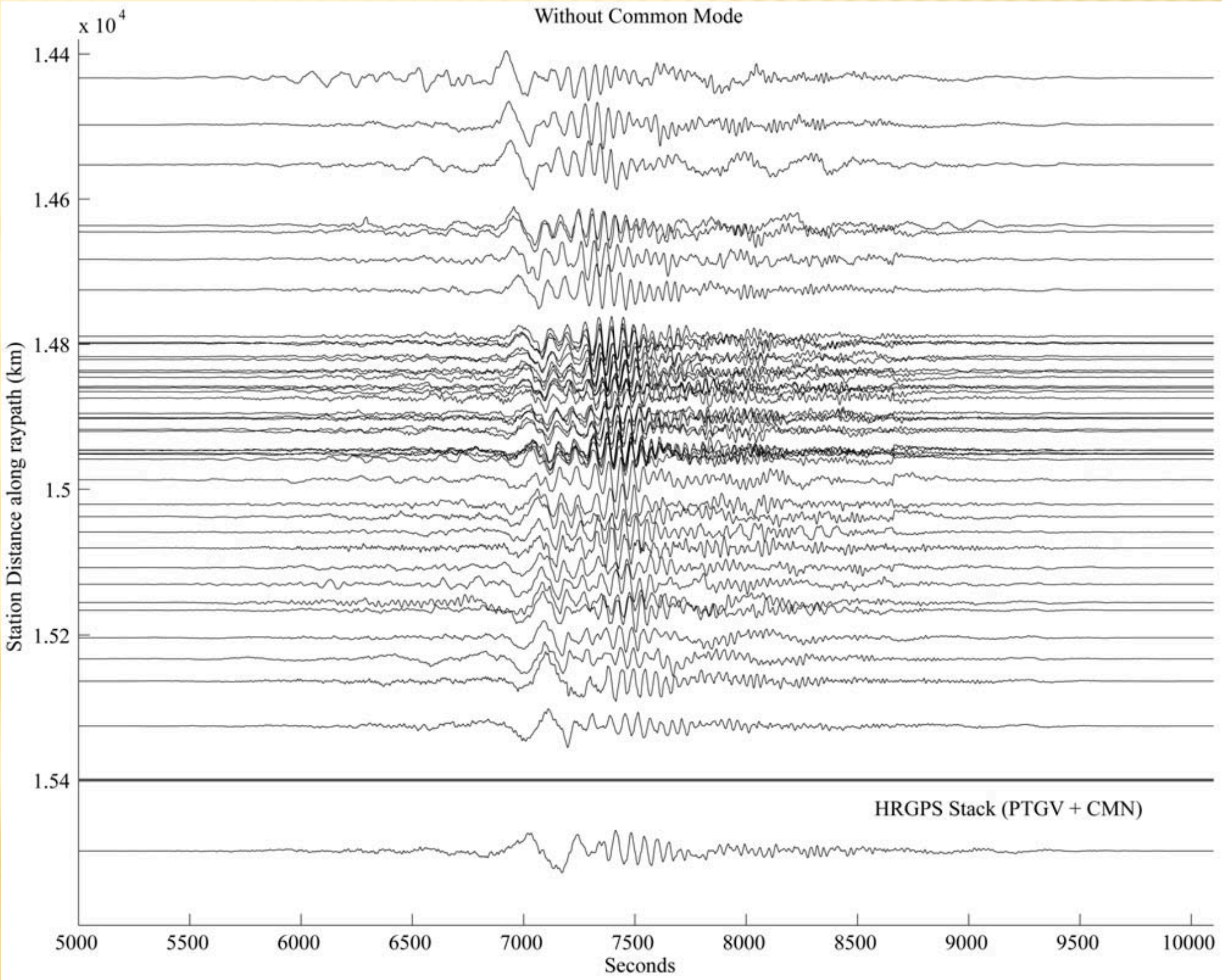
(Assume kinematic sites random with respect to one another)



Davis and Smalley, 2009

Subtracting the estimate of the absolute displacement time series of the fixed site (bottom trace) from the kinematic sites differential traces results in absolute displacement time series for the kinematic sites.

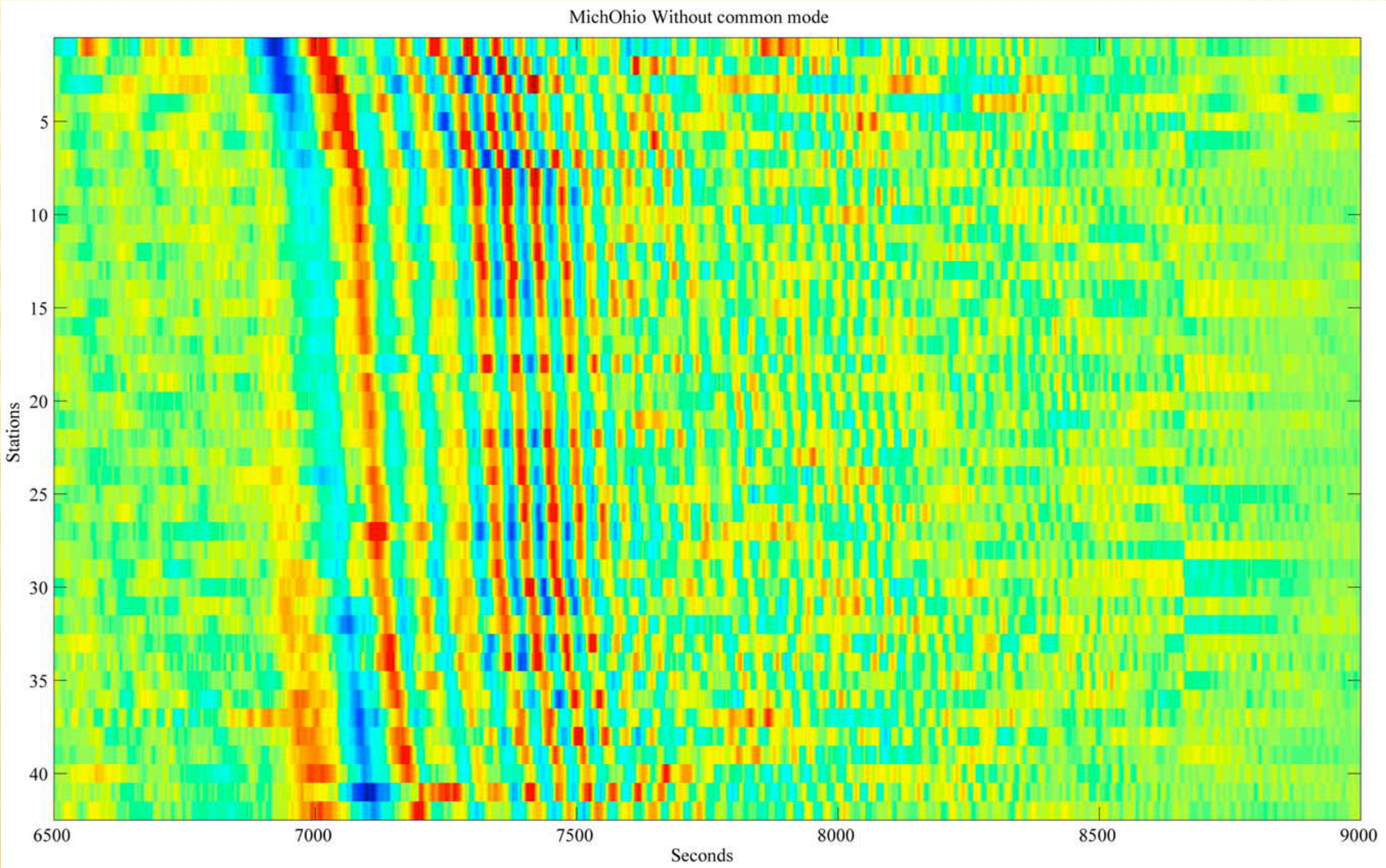
$$D_{kinematic} - D_{fixed} + \langle D_{fixed} \rangle$$



Davis and Smalley, 2009

Absolute seismograms plotted as surface.

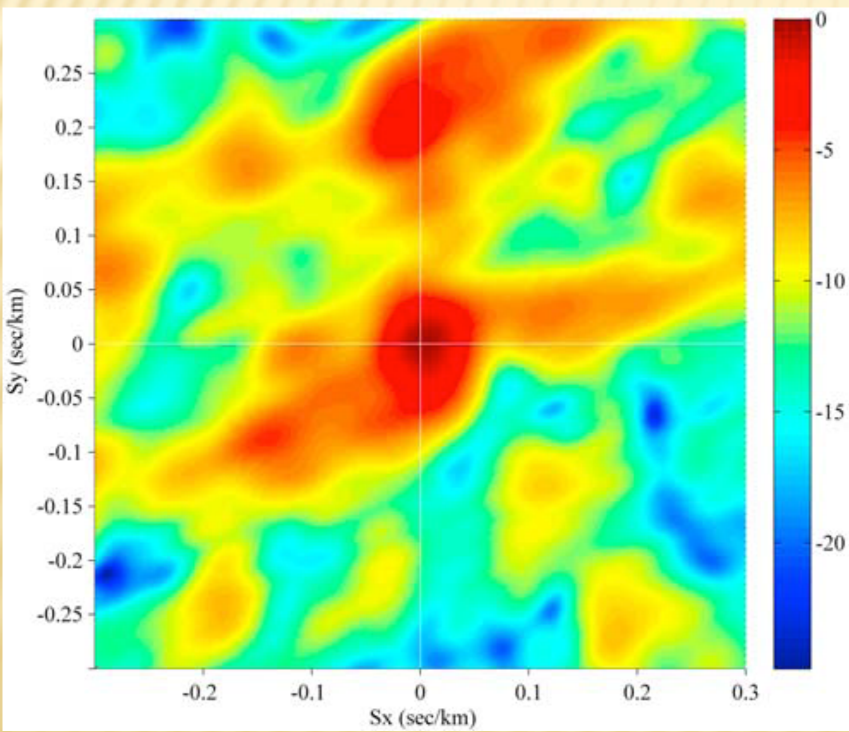
Now looks "right" ("move-out")

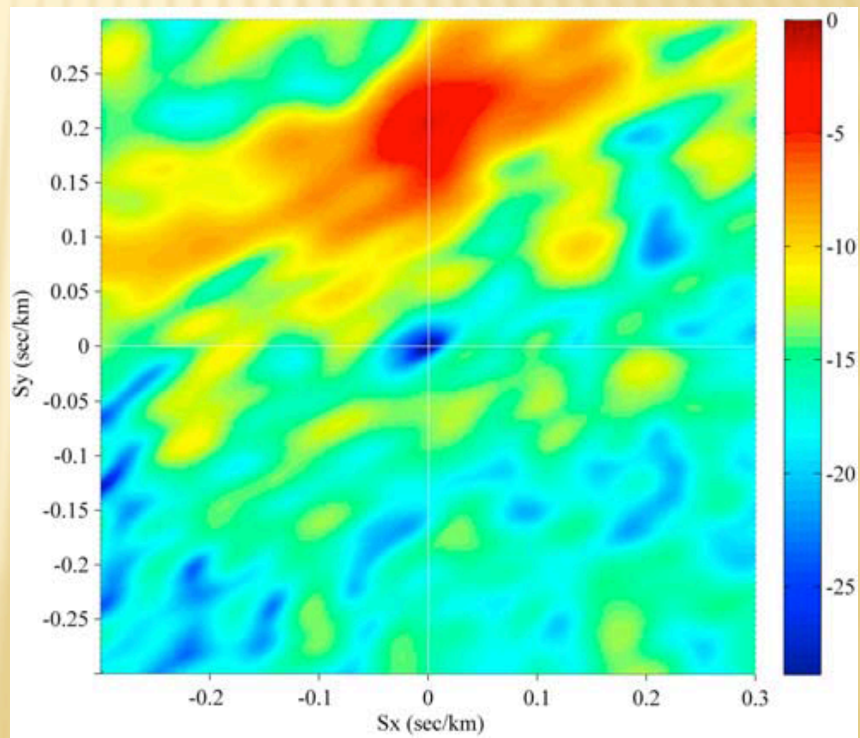


Davis and Smalley, 2009

Can also see by array processing (beam steering). Peaks show azimuth and slowness of plane waves crossing array. Peak in center (left) is infinite apparent velocity plane wave (everyone doing same thing at same time – the "fixed site"), the other peak is the surface wave.

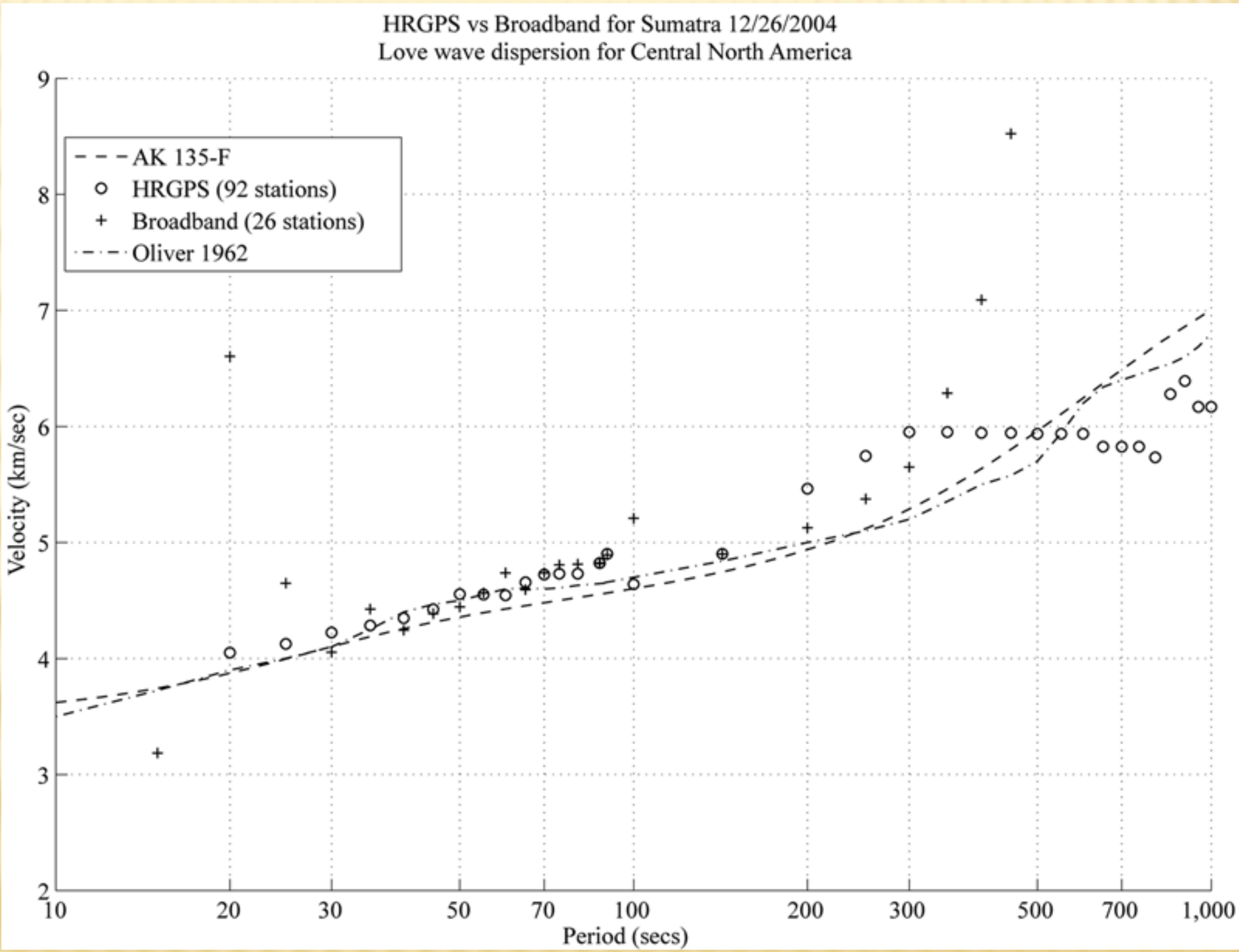
After removing fixed site can see just the surface wave.





Davis and Smalley, 2009

Now use beam steering to measure slowness at different periods and determine dispersion curve.



Davis and Smalley, 2009

James is working on this for his thesis.

Further improvements to estimating HRGPS time series.
Additional applications (gradiometry).

Intro to GPS processing with GAMIT/GLOBK

"people who have trouble with typing commands should not be using a computer."

(Response of the Unix community to criticism that Unix ignored the needs of the unsophisticated user.)

If you thought UNIX was user-hostile, you have not seen anything yet!

Homework for Thursday, Oct 28.

In your account on capybara, copy the "example" folder from /Users/ceri-gps/gamit to your directory, and name it "scal"

At the same level as the "scal" directory, make a soft link to /Users/ceri-gps/gg/tables.

Go into scal and follow the instructions in the README. (the tables directory they refer to in the README is the one in scal, not the one you did the soft link to above)

This should establish that everything is working. Come see me, James, Wale, or John when it does not work!