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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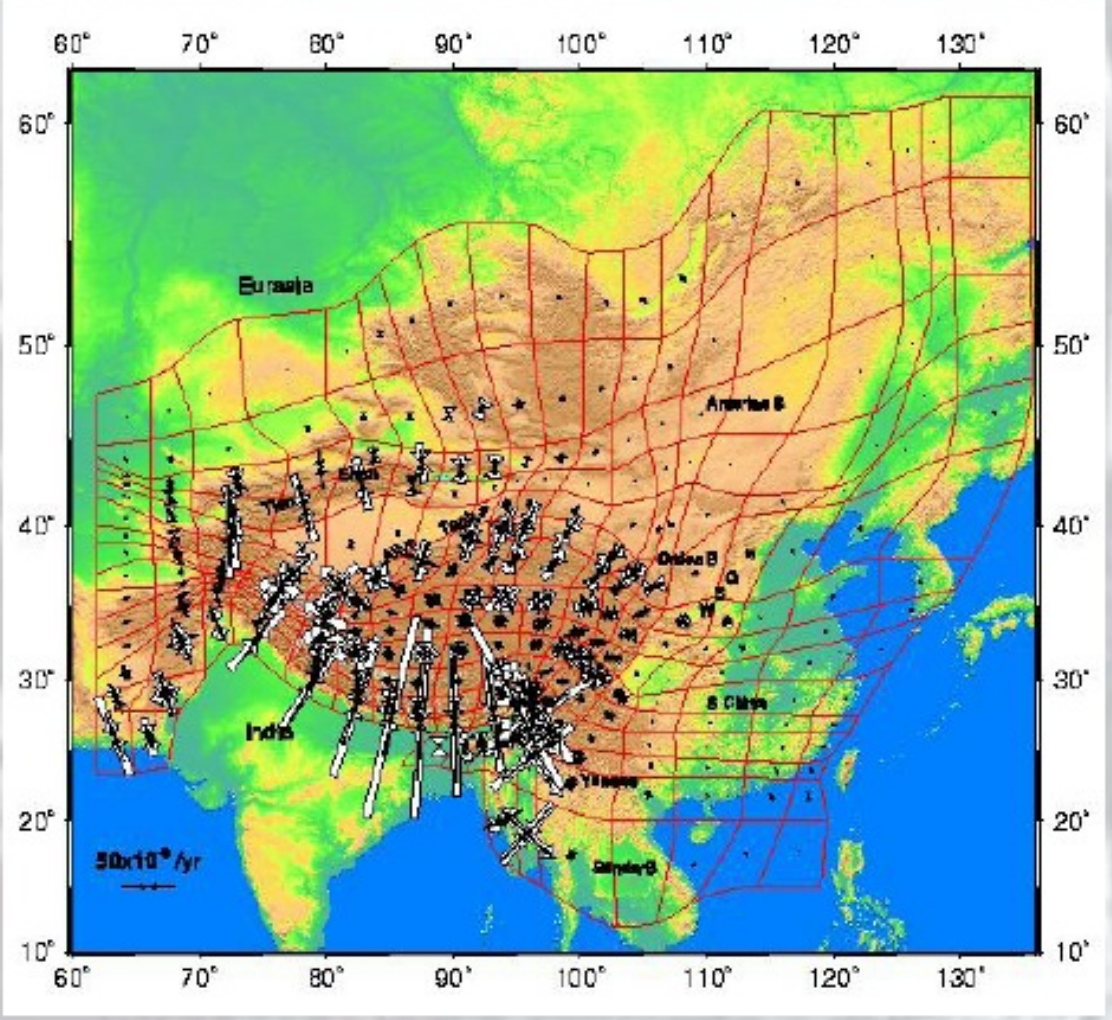
678-4929
Office Hours – Wed 14:00-16:00 or if I' m in my office.

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

Class 14

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.



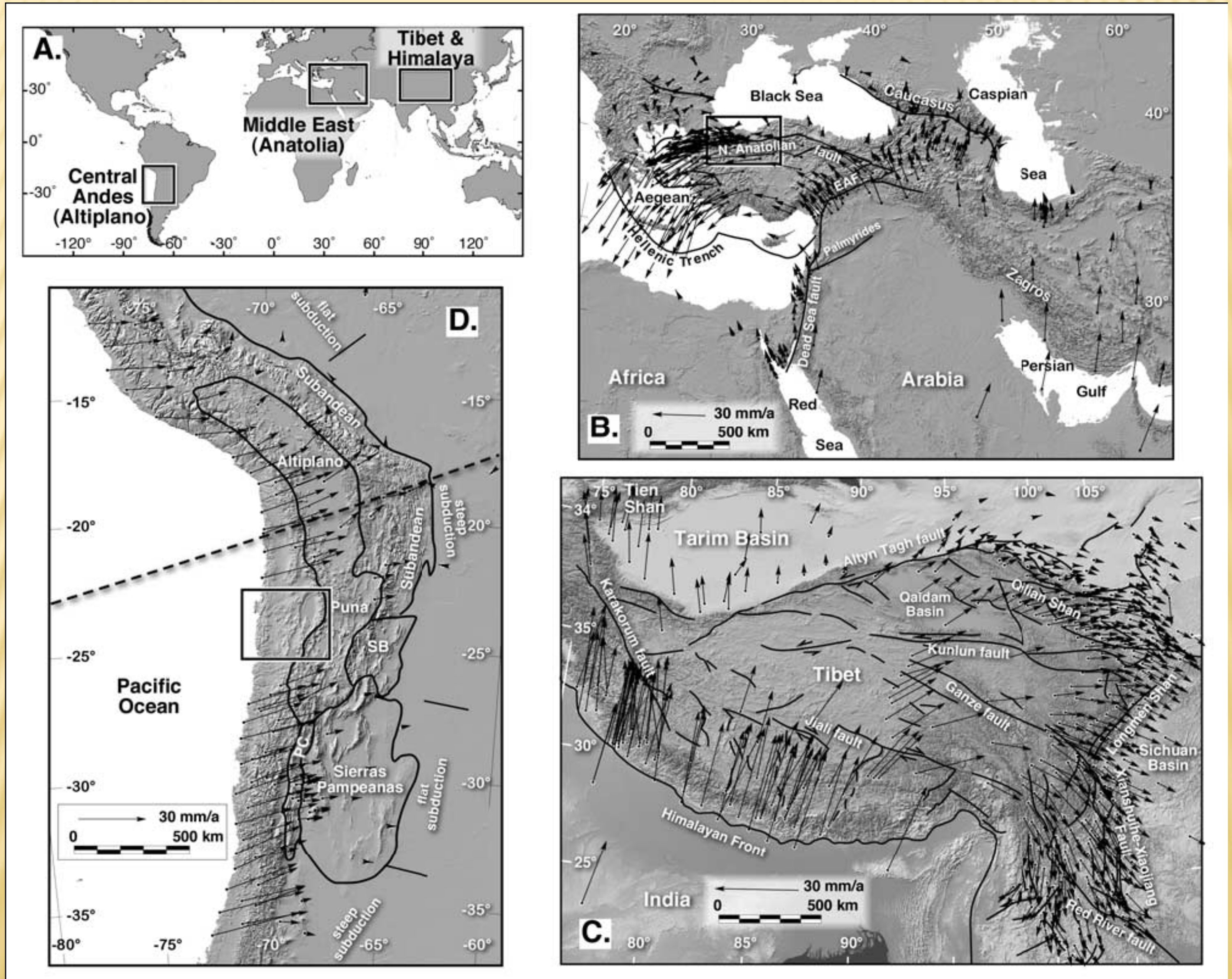
use

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

To solve for translation and deformation (strain + rotation)

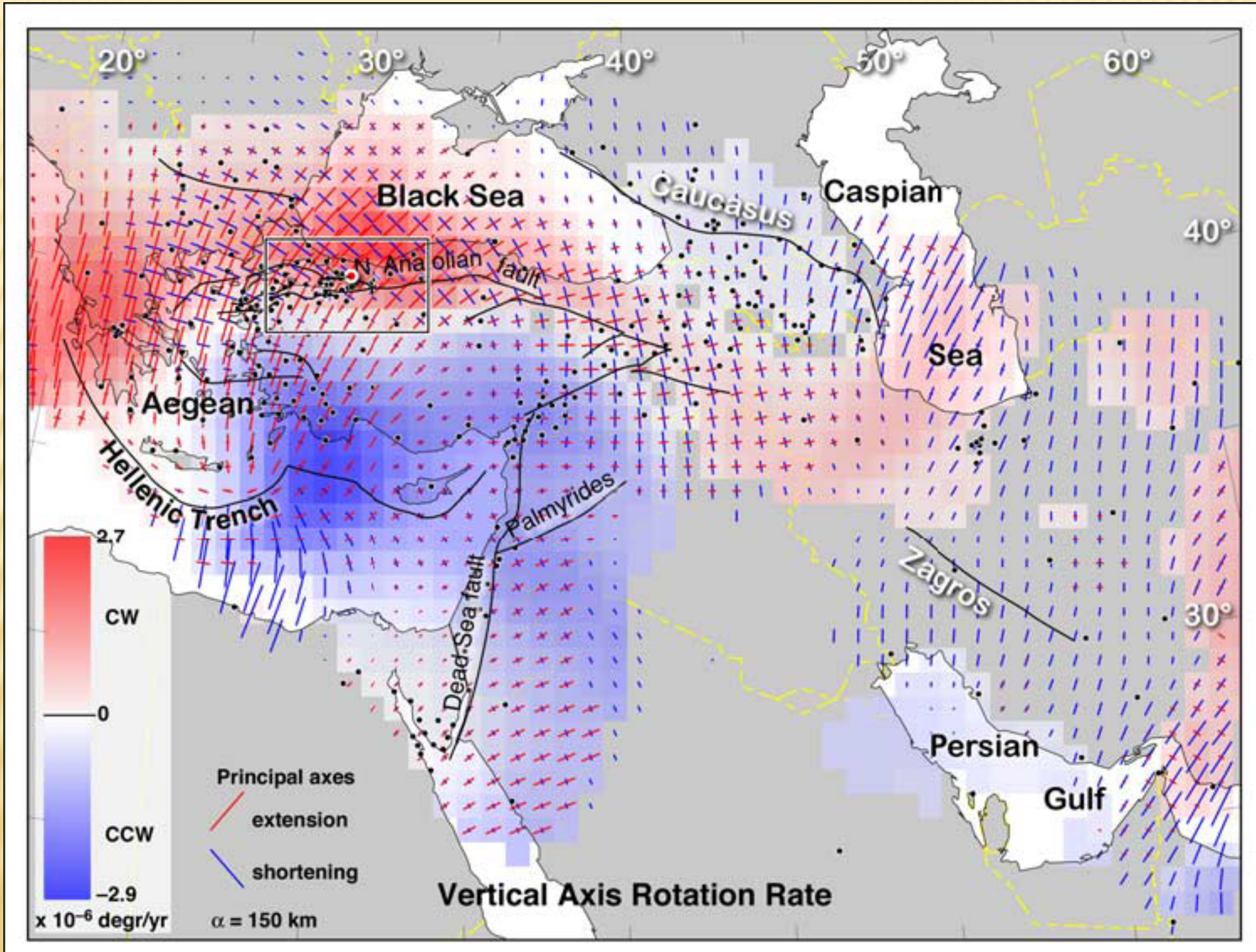
$(t_x, t_y, d_{xx}, d_{xy}, d_{yx}, d_{yy})$.

Start with velocities with respect to stable plates (deformations)

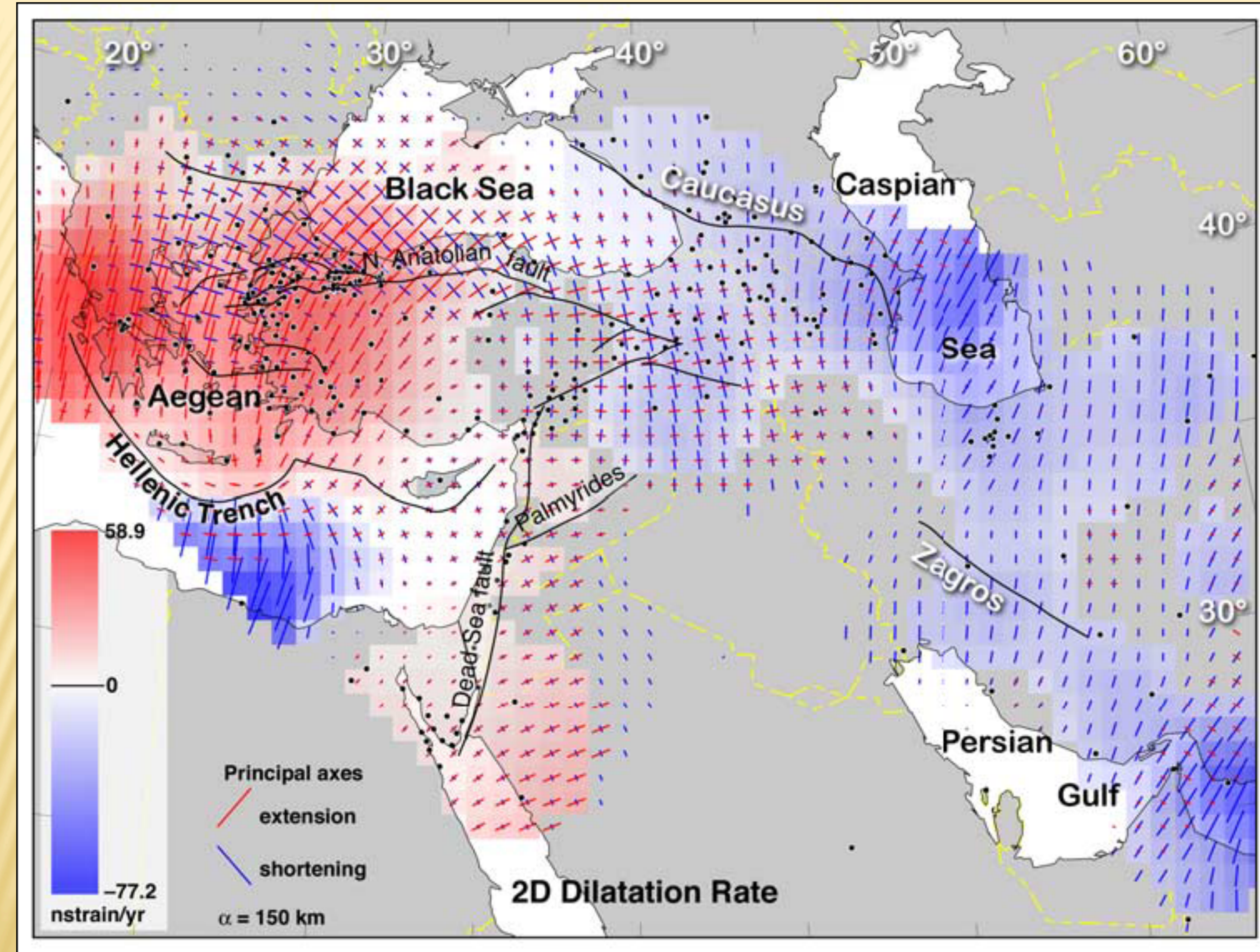


Allmendinger et al, 2007

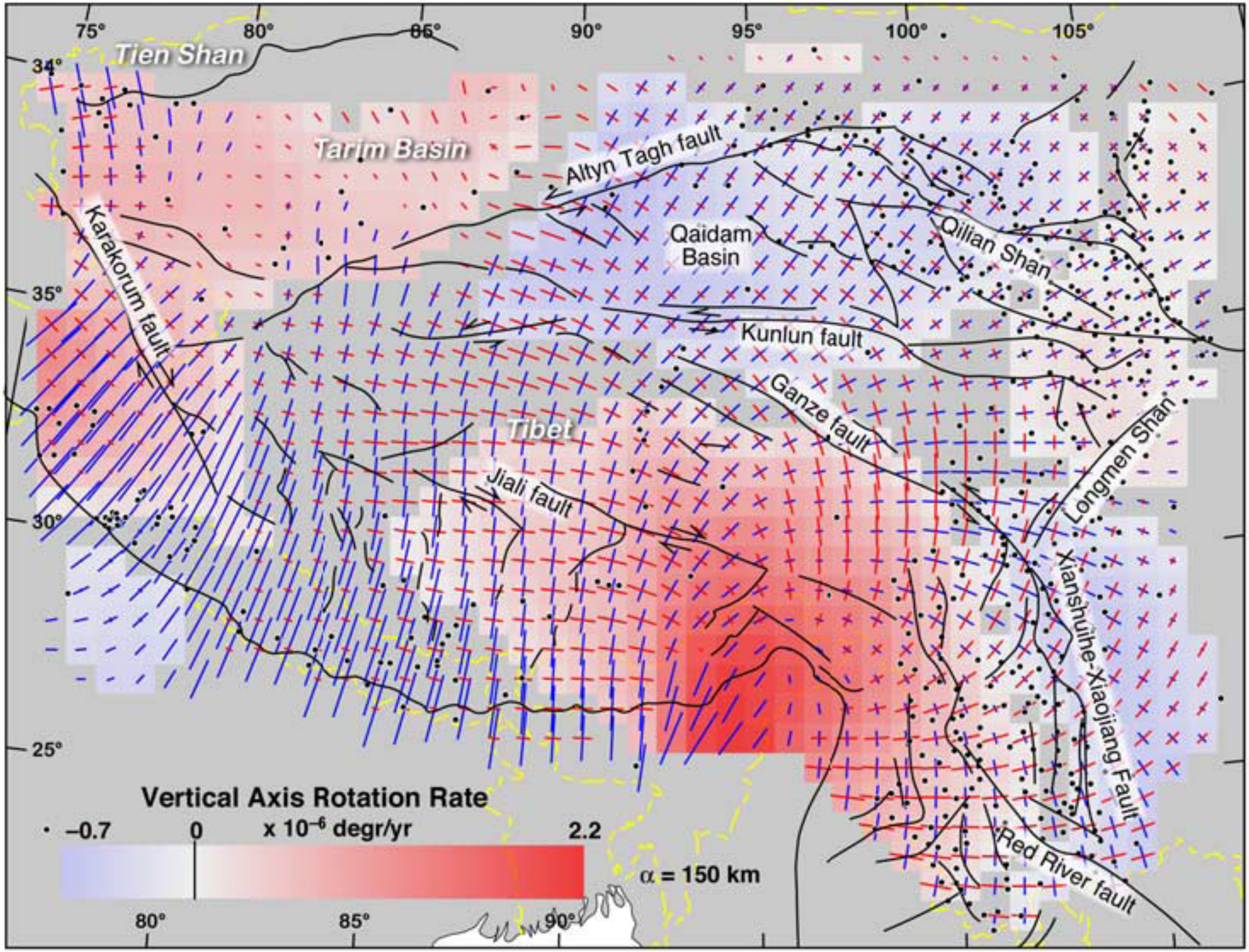
Calculate strains and rotations



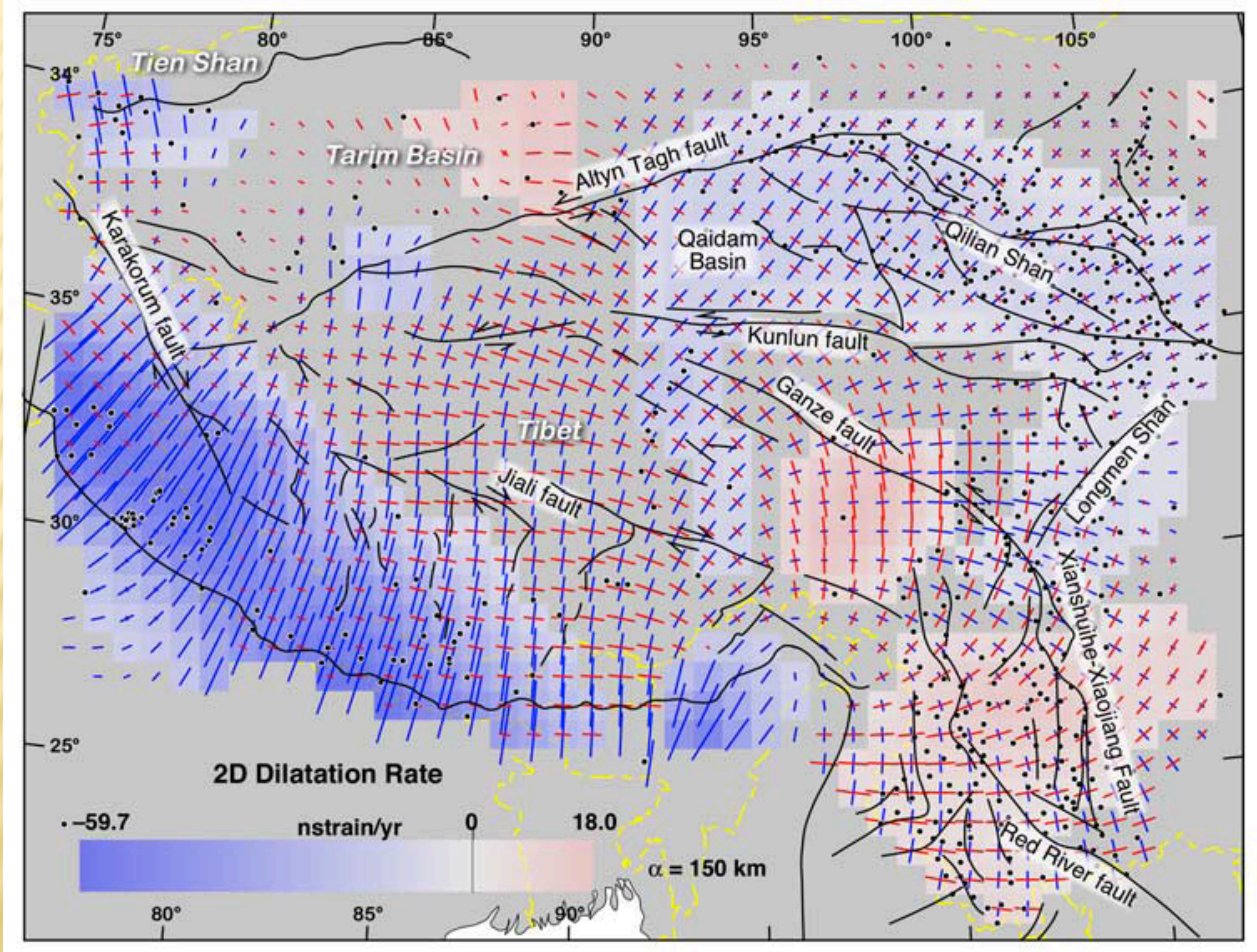
Allmendinger et al, 2007



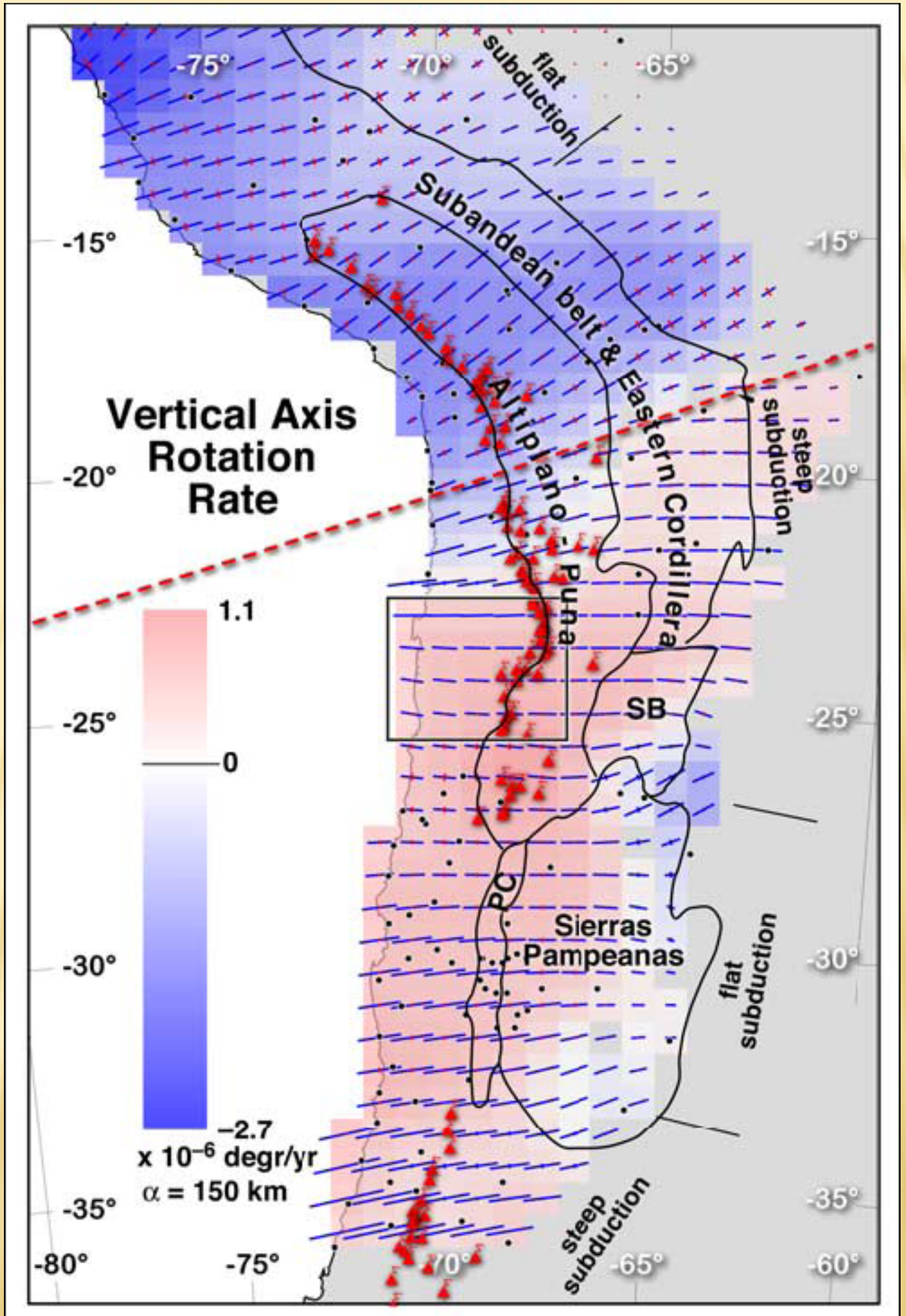
Allmendinger et al, 2007



Allmendinger et al, 2007

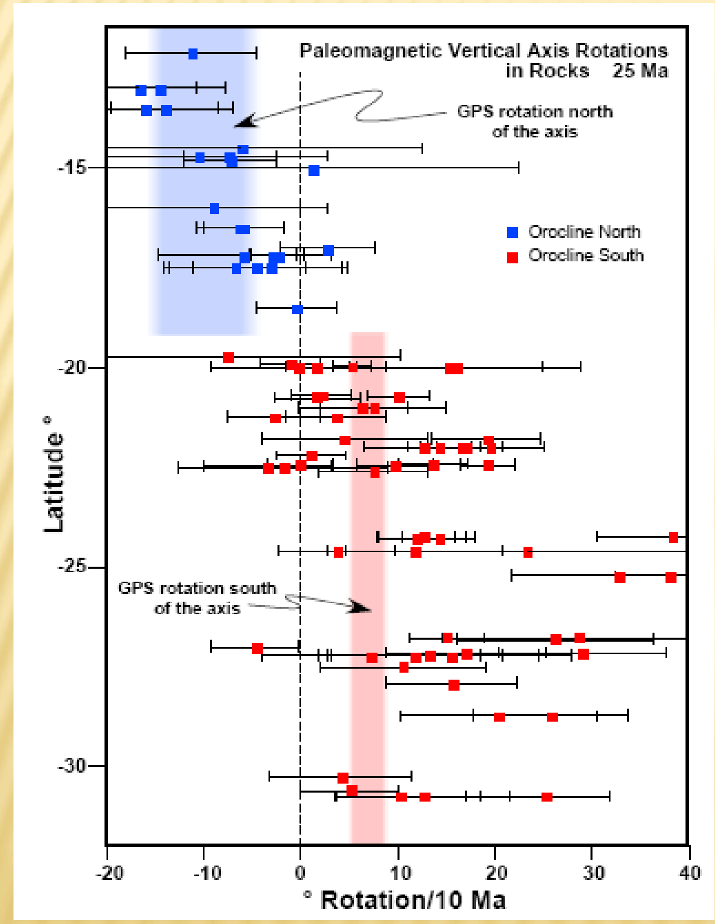


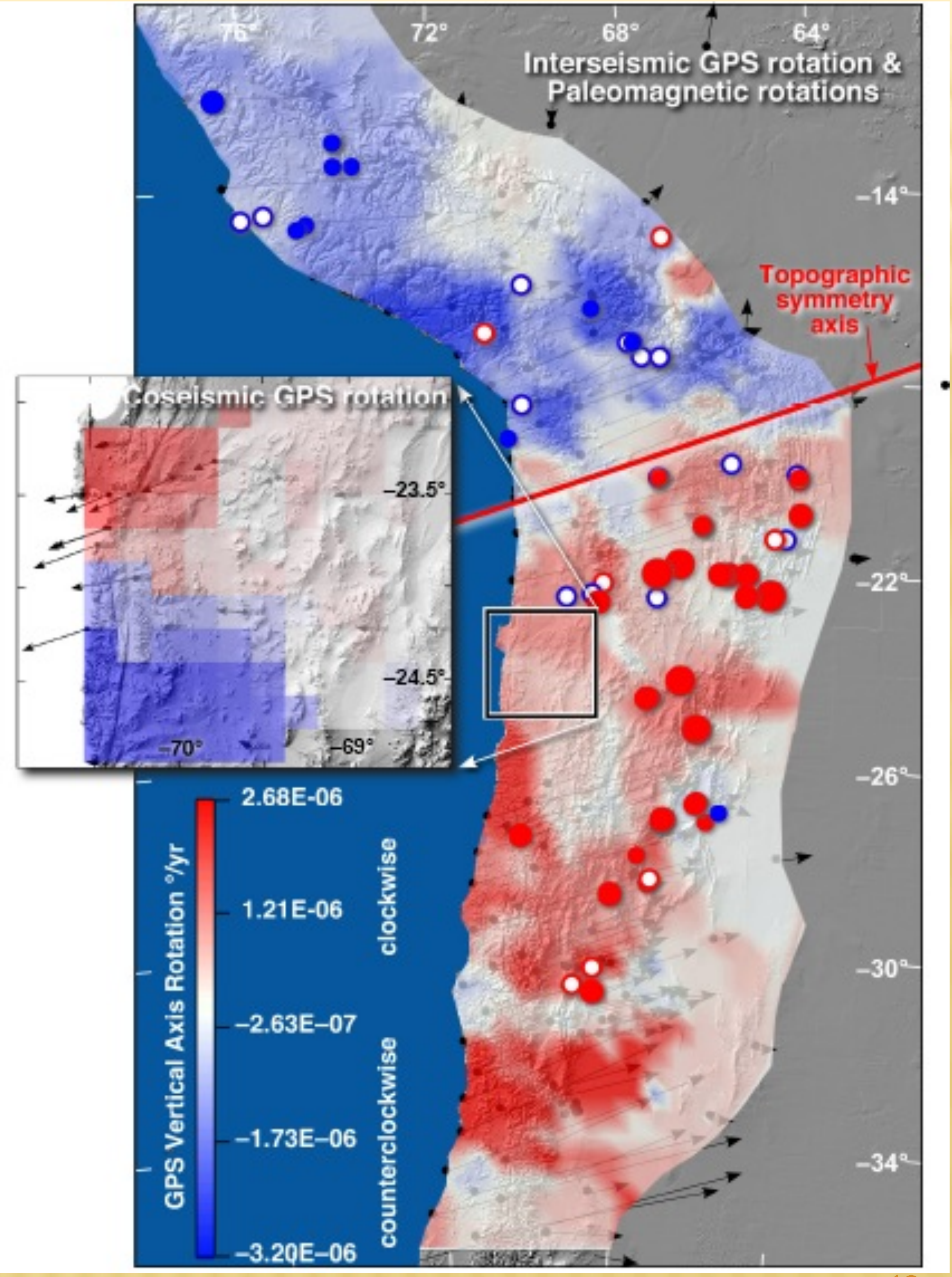
Allmendinger et al, 2007



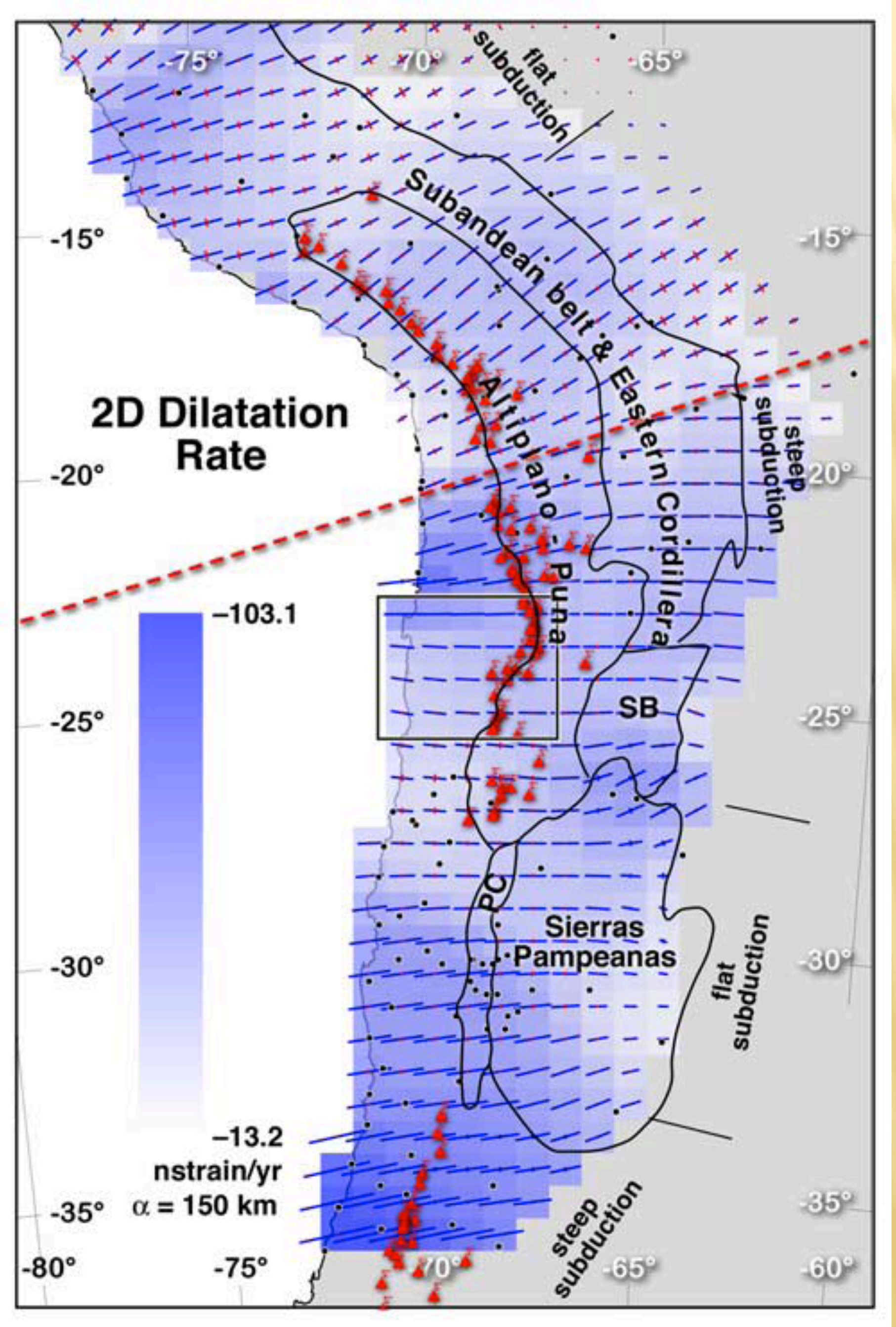
Allmendinger et al, 2007

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





From Allmendinger et al, 2005



Allmendinger et al, 2007

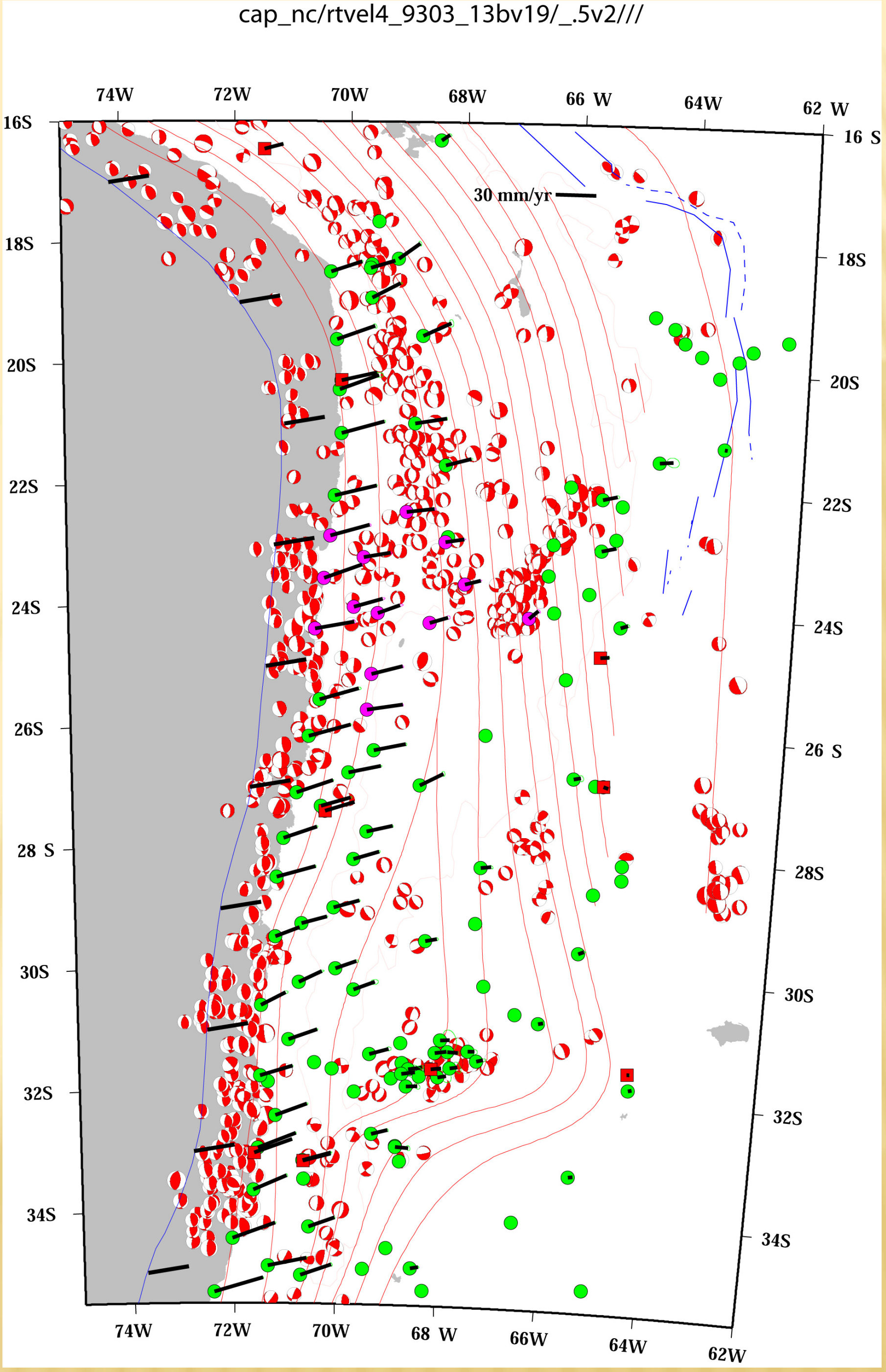
GPS plus focal mechanism data

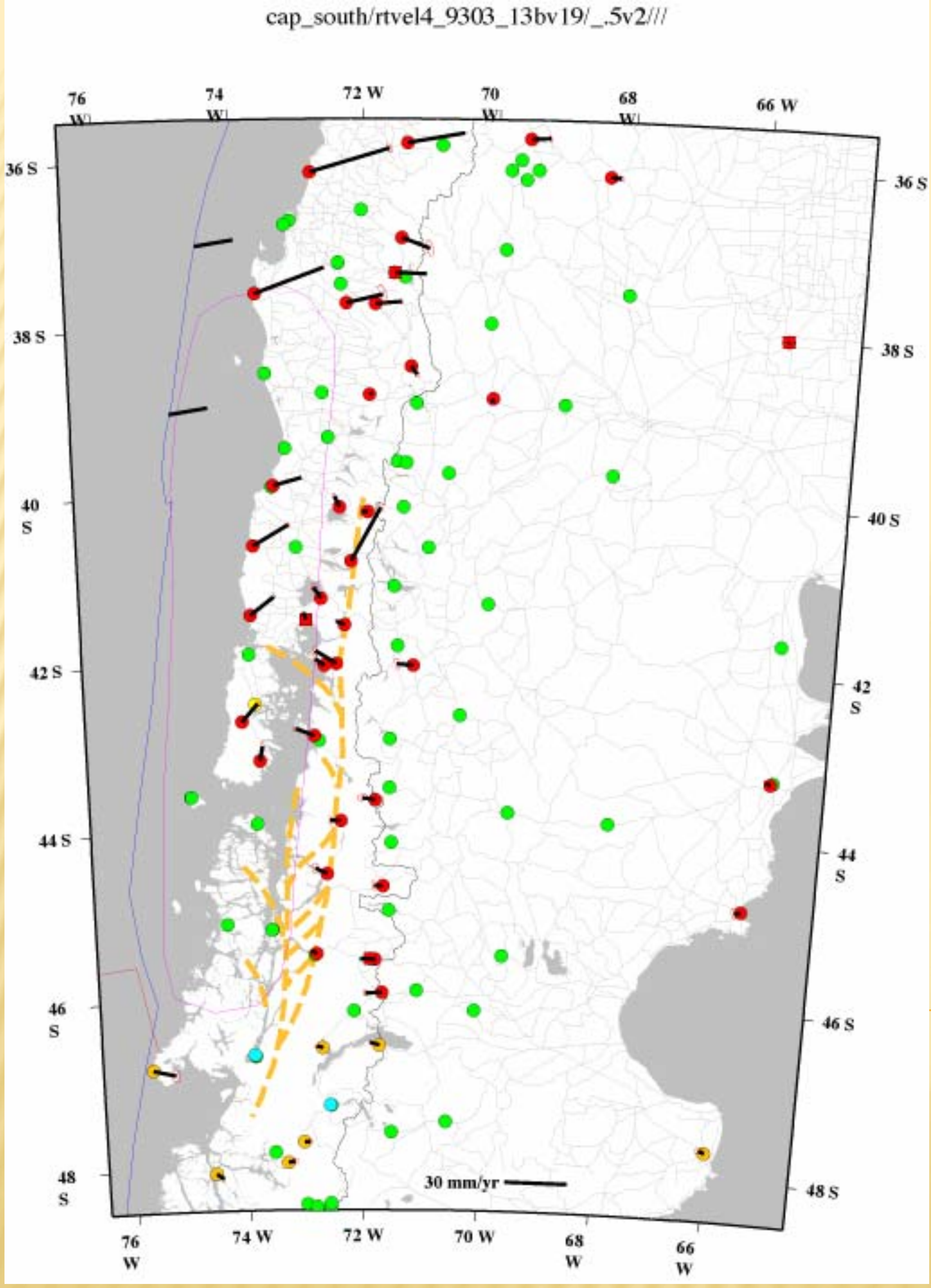
Downdip compression at bottom of wbz

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

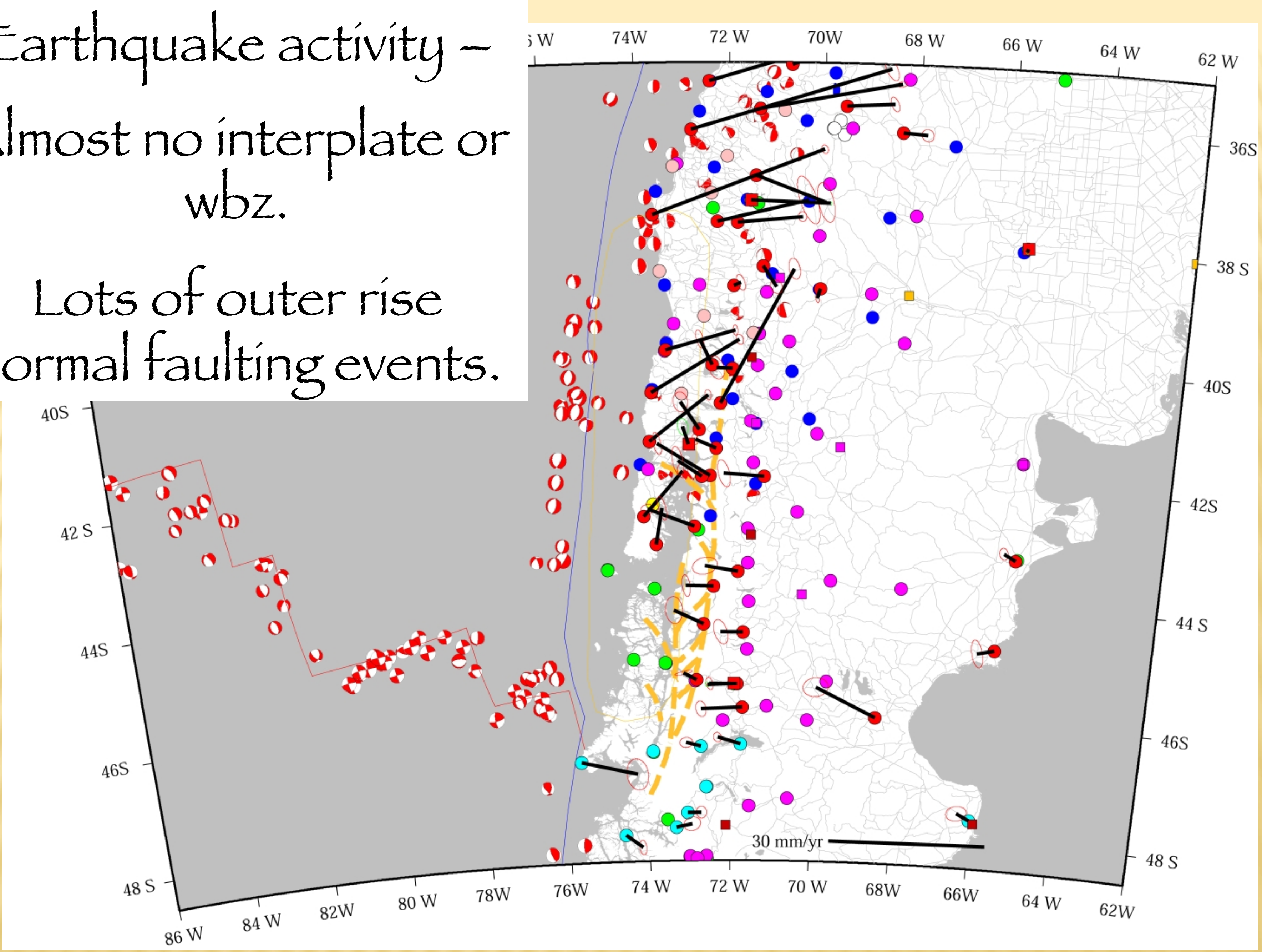
Along coast – vectors show convergence, but slower than to north

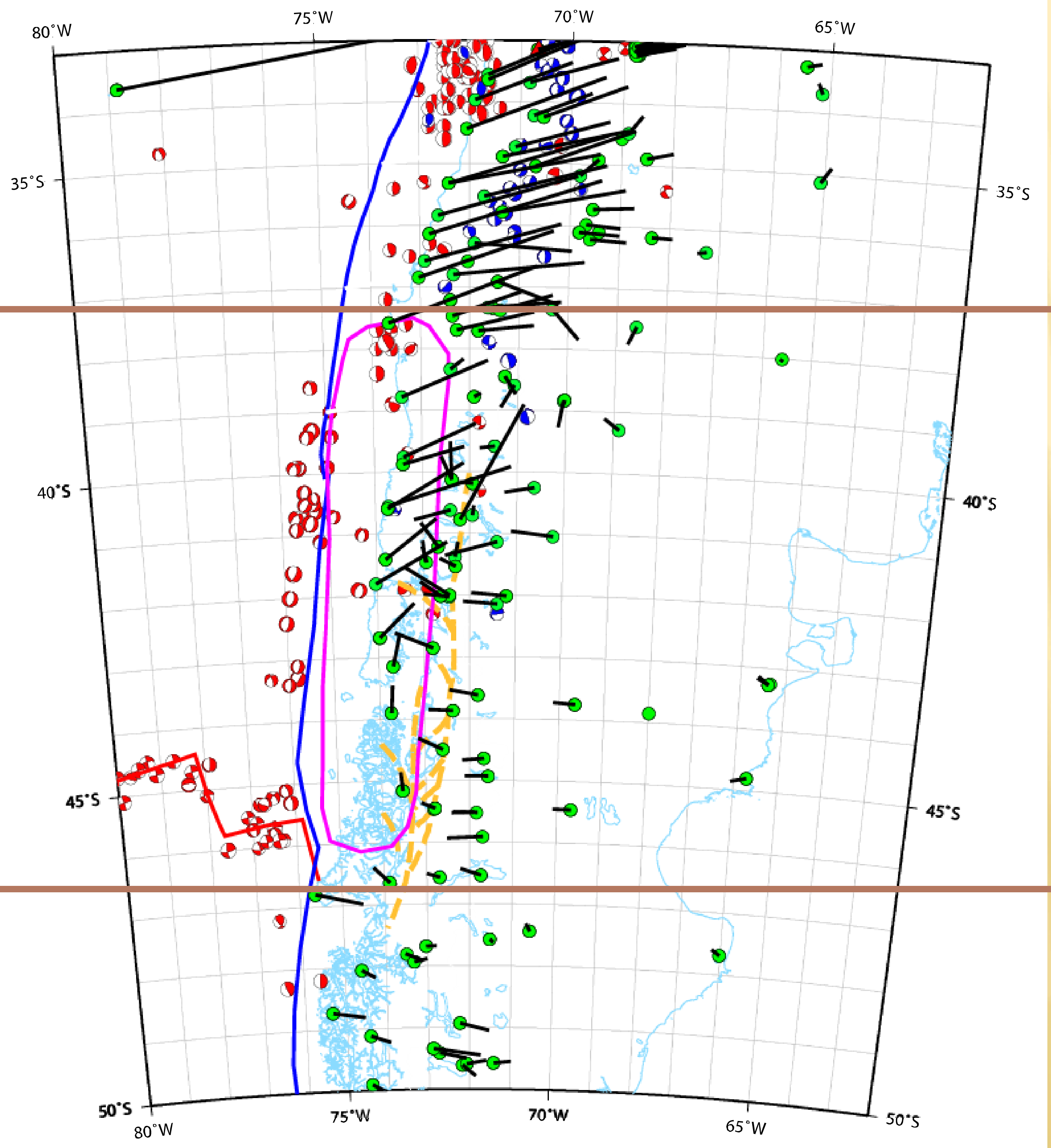
inland – vectors reverse

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

Earthquake activity – Almost no interplate or wbz.

Lots of outer rise normal faulting events.

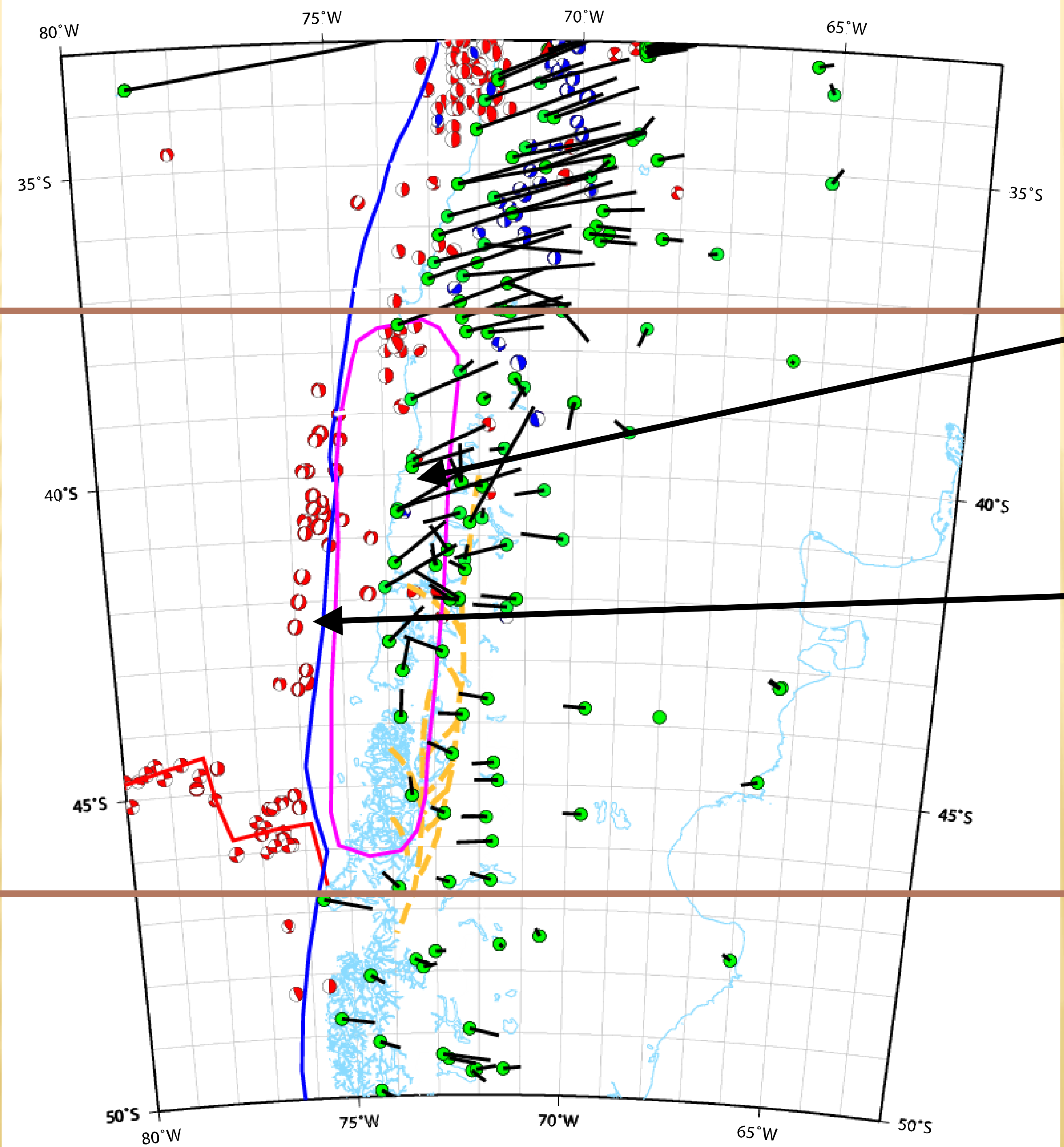




"normal"

1960 great Chilean earthquake

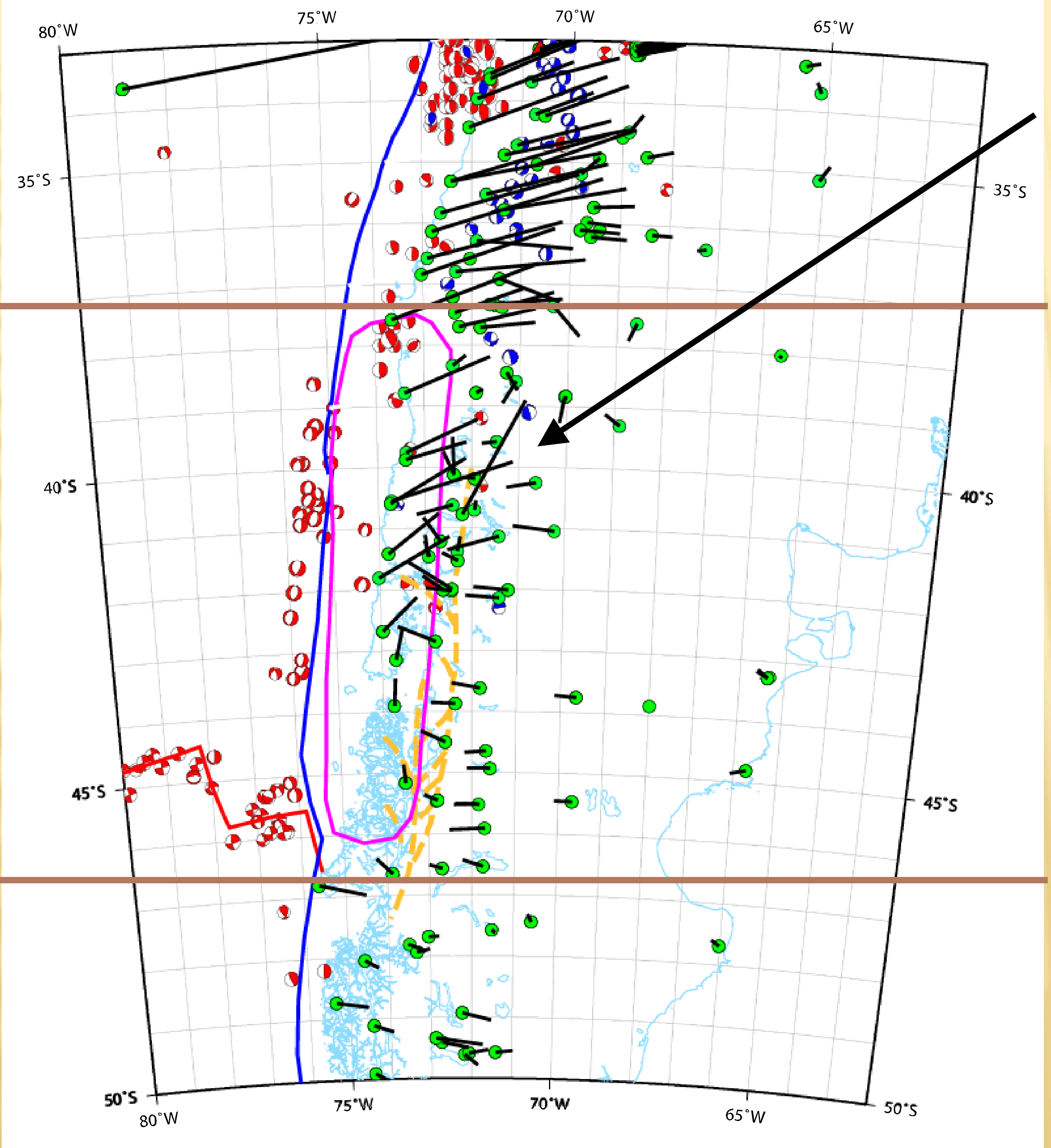
"normal"



Postseismic Earthquake activity –

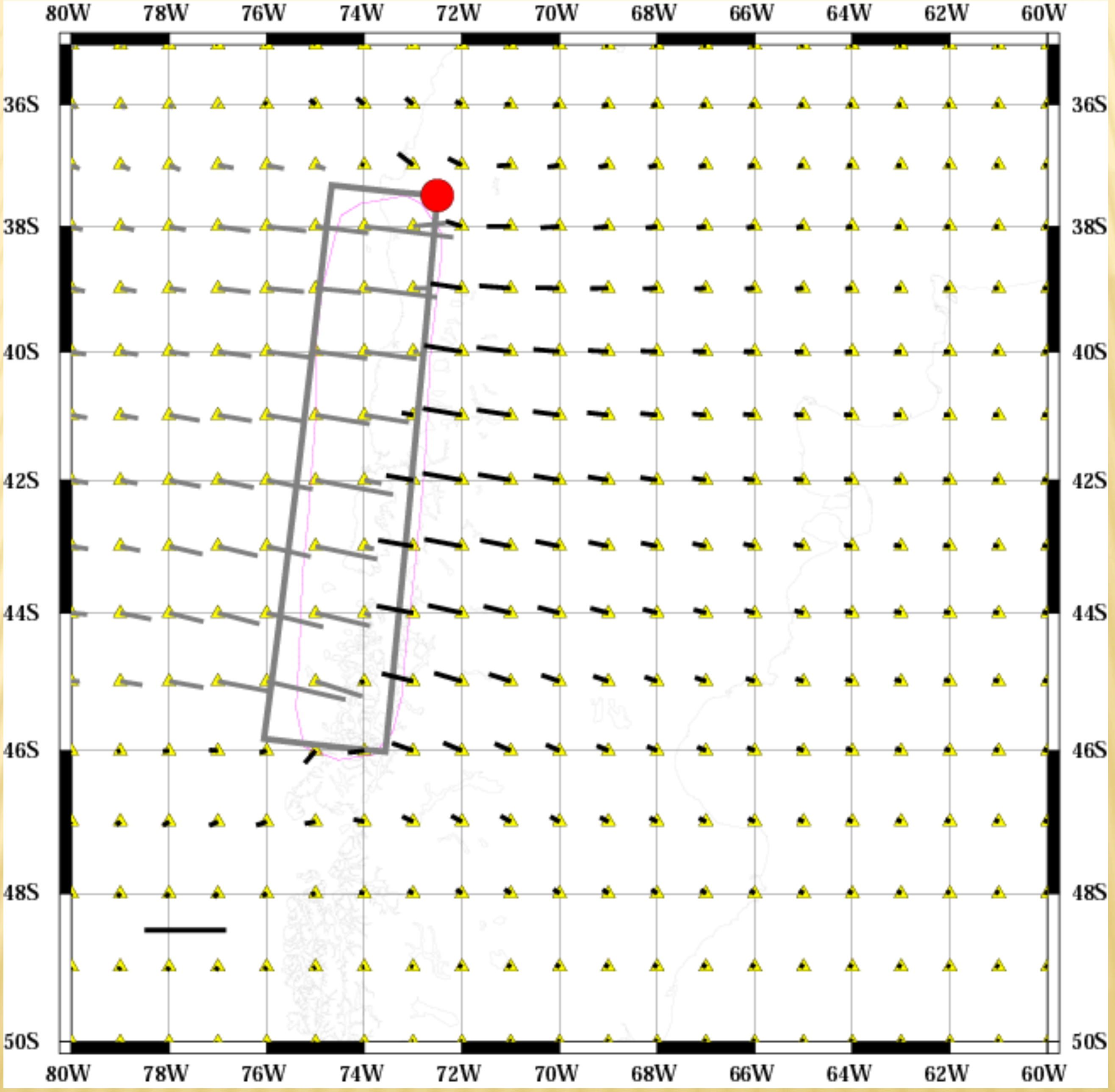
Almost no interplate or wbz activity

Lots of outer rise normal faulting events

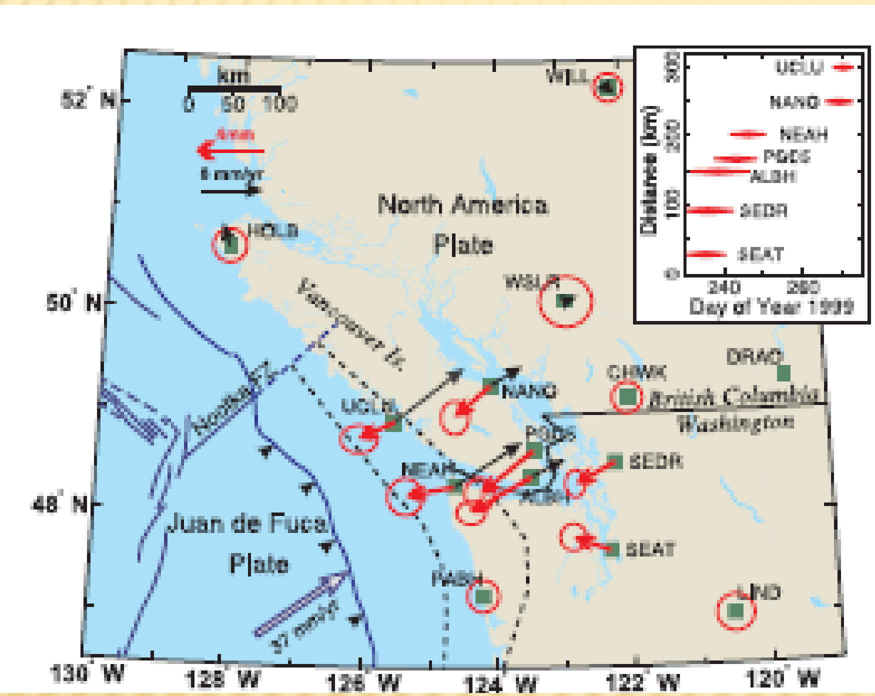


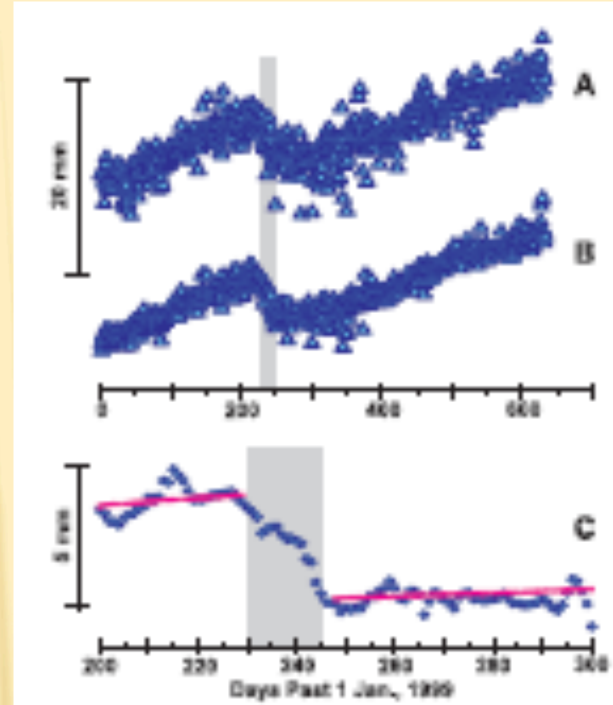
1960 rupture zone

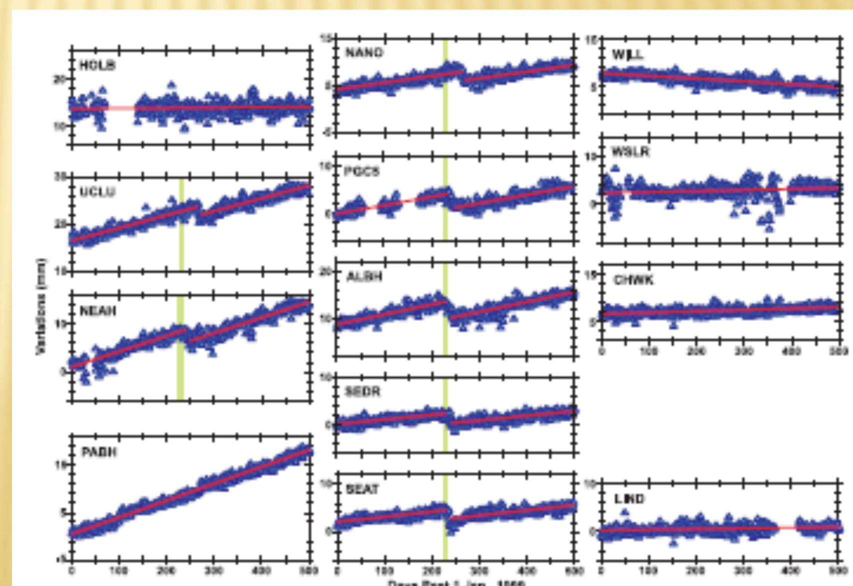
- Reverses to east
- Liquiñe-Ofqui fault
- Subduction of ridge at triple juncion at south end
- Post-seismic viscoelatic relaxation – mantle.


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





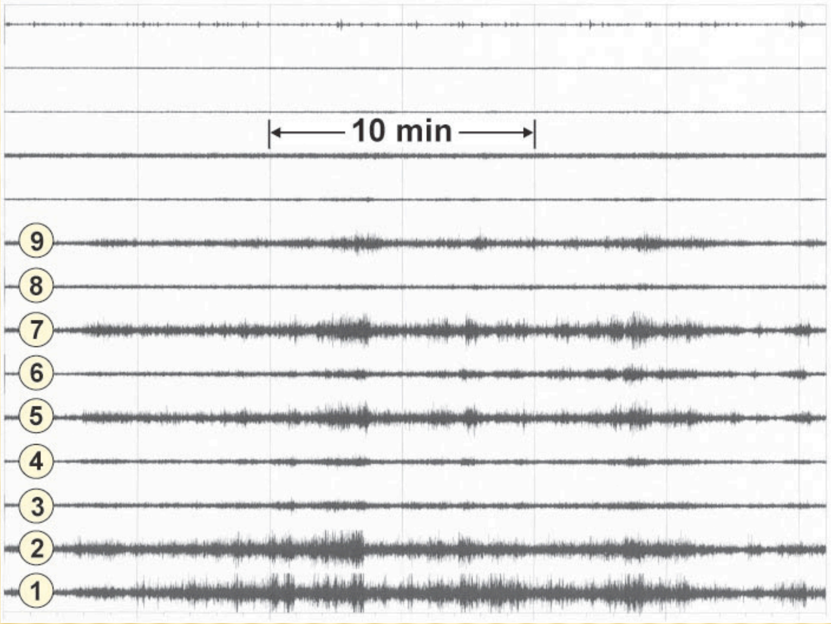


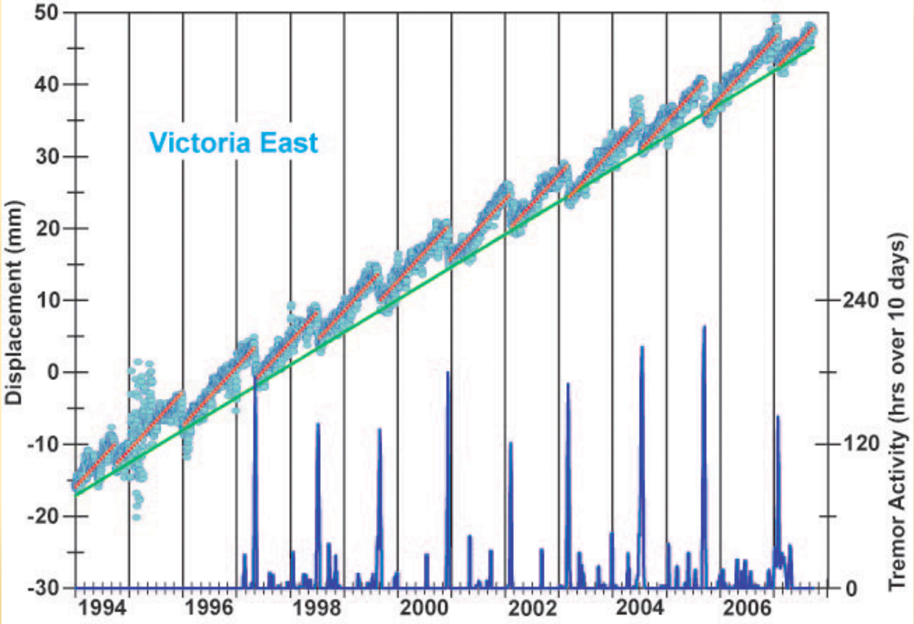
Dragert et al, 20013

Silent slip in subduction zones

Non-secular GPS displacements

Coupled with seismic tremor





Also observed (w/ different periods) in Mexico & Japan

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

http://www.nrcan.gc.ca/earth-sciences/energy-mineral/geology/geodynamics/earthquake-processes/7541

Postglacial rebound in Patagonia: An interaction of climate and tectonics.

G23B-06

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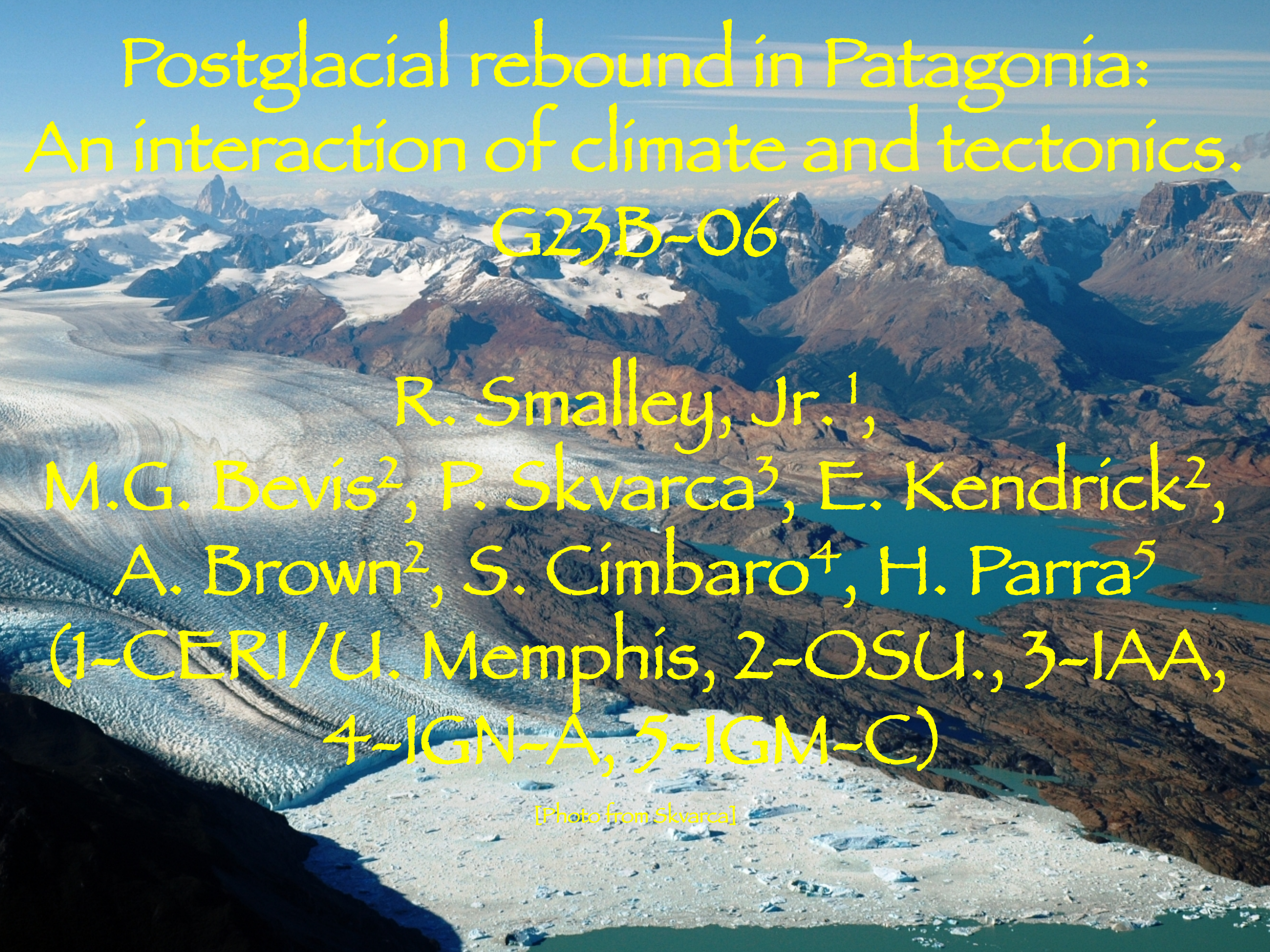
A. Brown[2], S. Cimbaro[4], H. Parra[5]
(1-CERI/U. Memphis, 2-OSU., 3-IAA,
4-IGN-A, 5-IGM-C)



[Photo from Skvarca]

GLACIAL ISOSTATIC ADJUSTMENT (GIA)

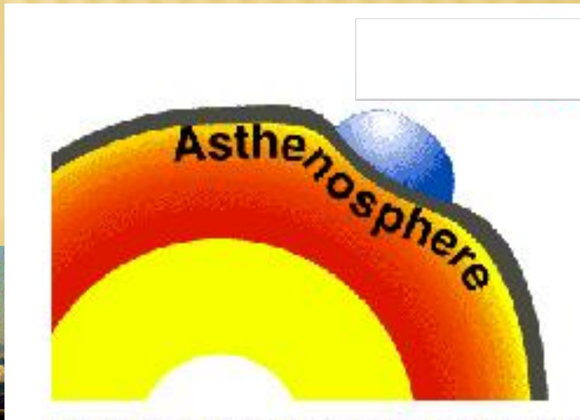
OLD - POST GLACIAL REBOUND (PGR)

An interplay between

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

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

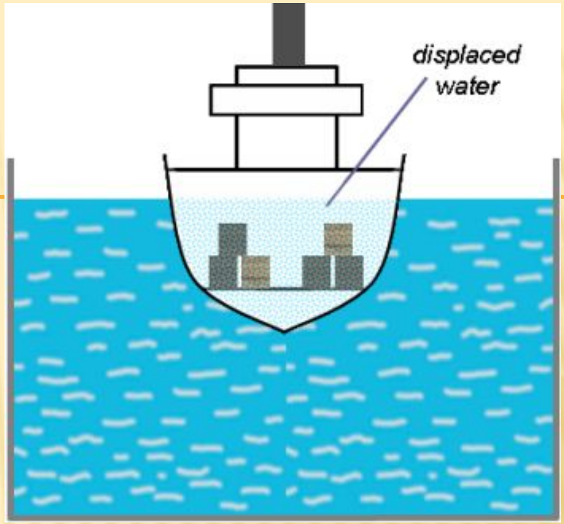
Geomechanical structure reflects tectonic setting!

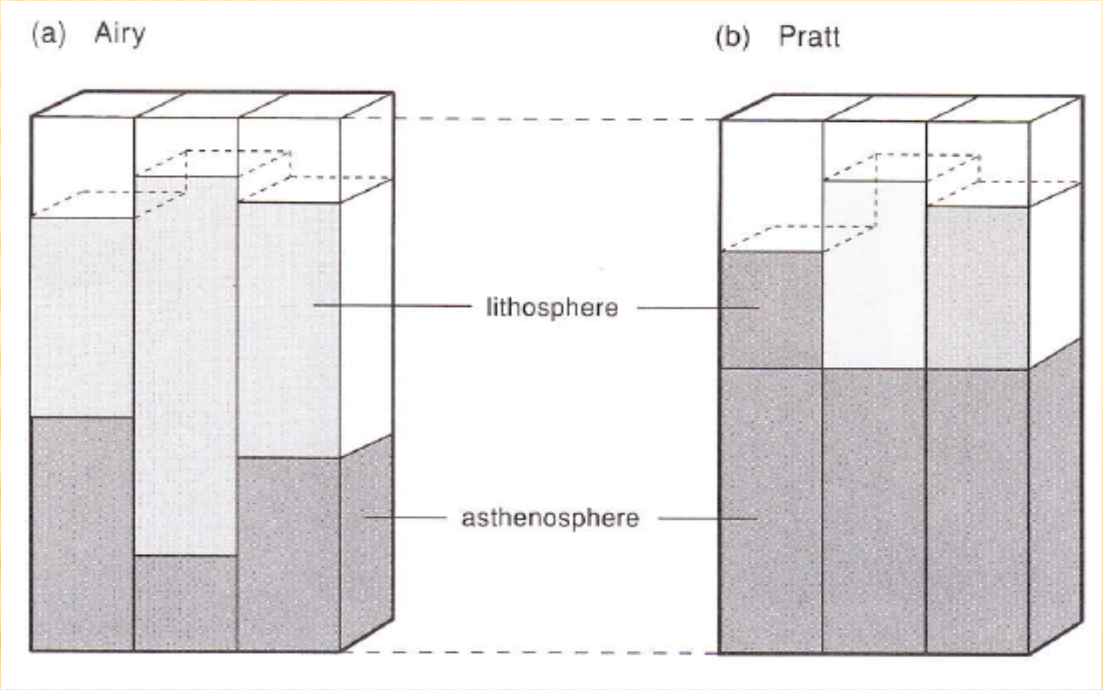


Raised beaches on Kongsøya, central-northern Barents Sea, where the highest marine limit on Svalbard occurs (110 m a.s.l.). The age of the marine limit is ca. 10,000 years. Photo: Ólafur Ingólfsson, 1991.

Buoyancy

In the earth we call it isostasy.

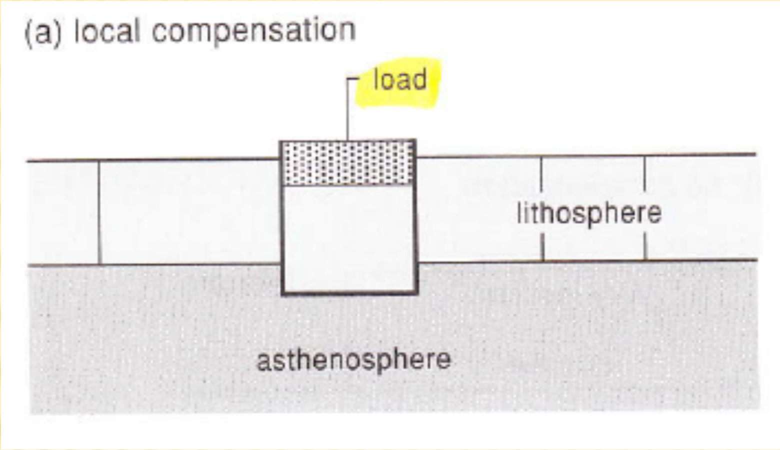




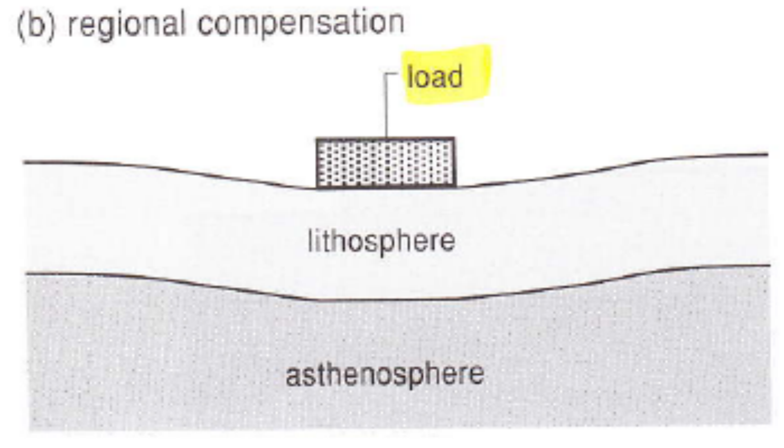
Two end members for floating equilibrium.

A) uniform density, topography and "root".
B) varying density, topography with uniform depth to "base"

Now add "strong", elastic lithosphere

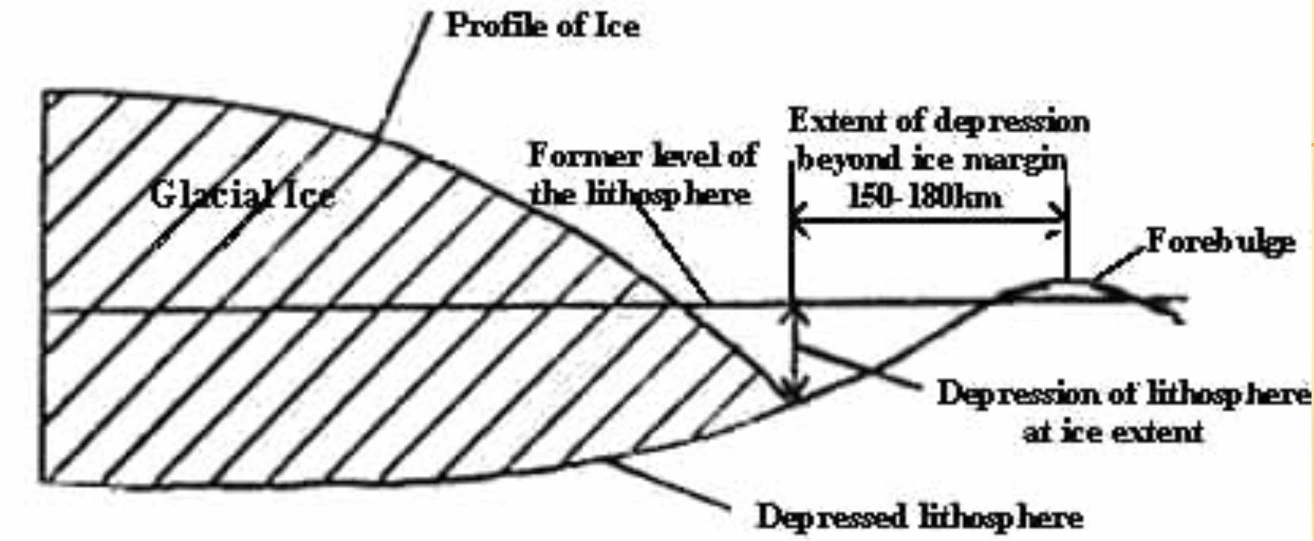


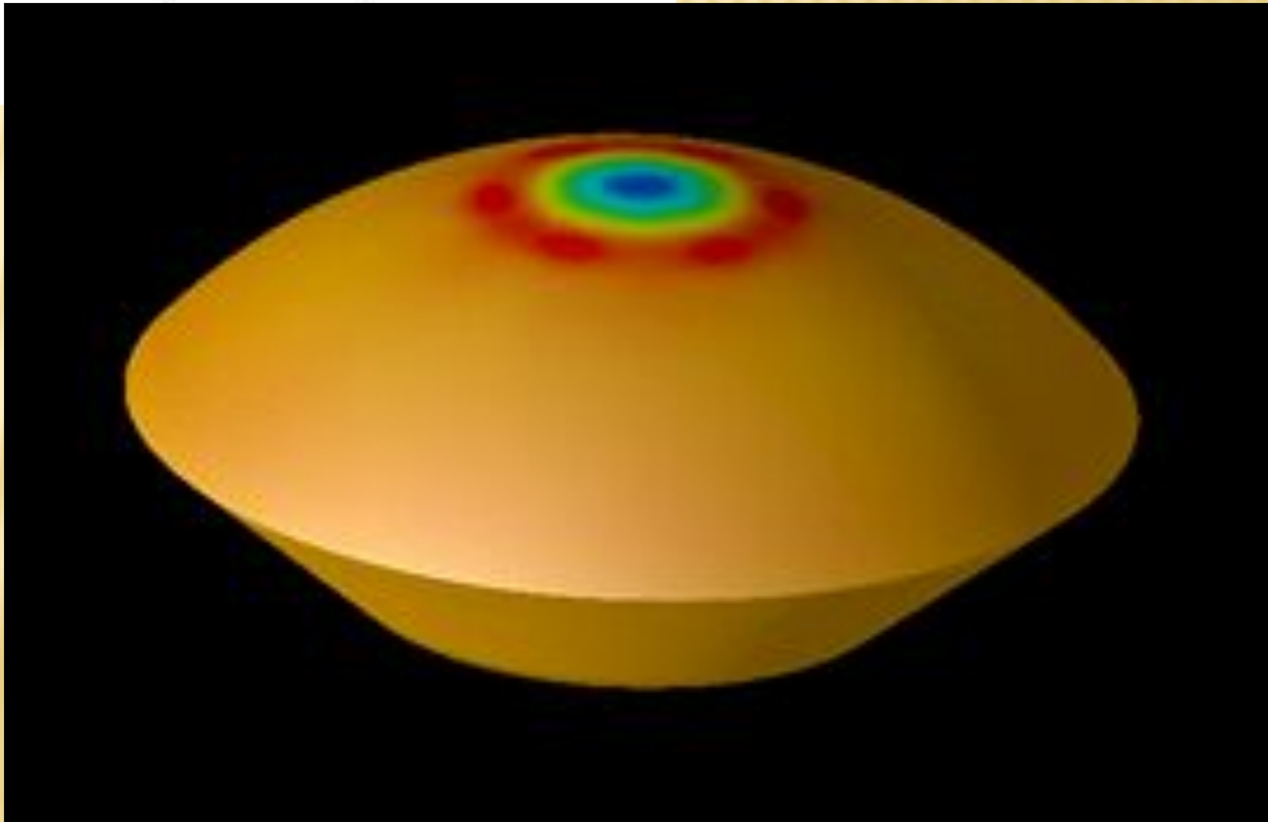
Lithosphere NOT strong enough to support load (weight) of mountain.

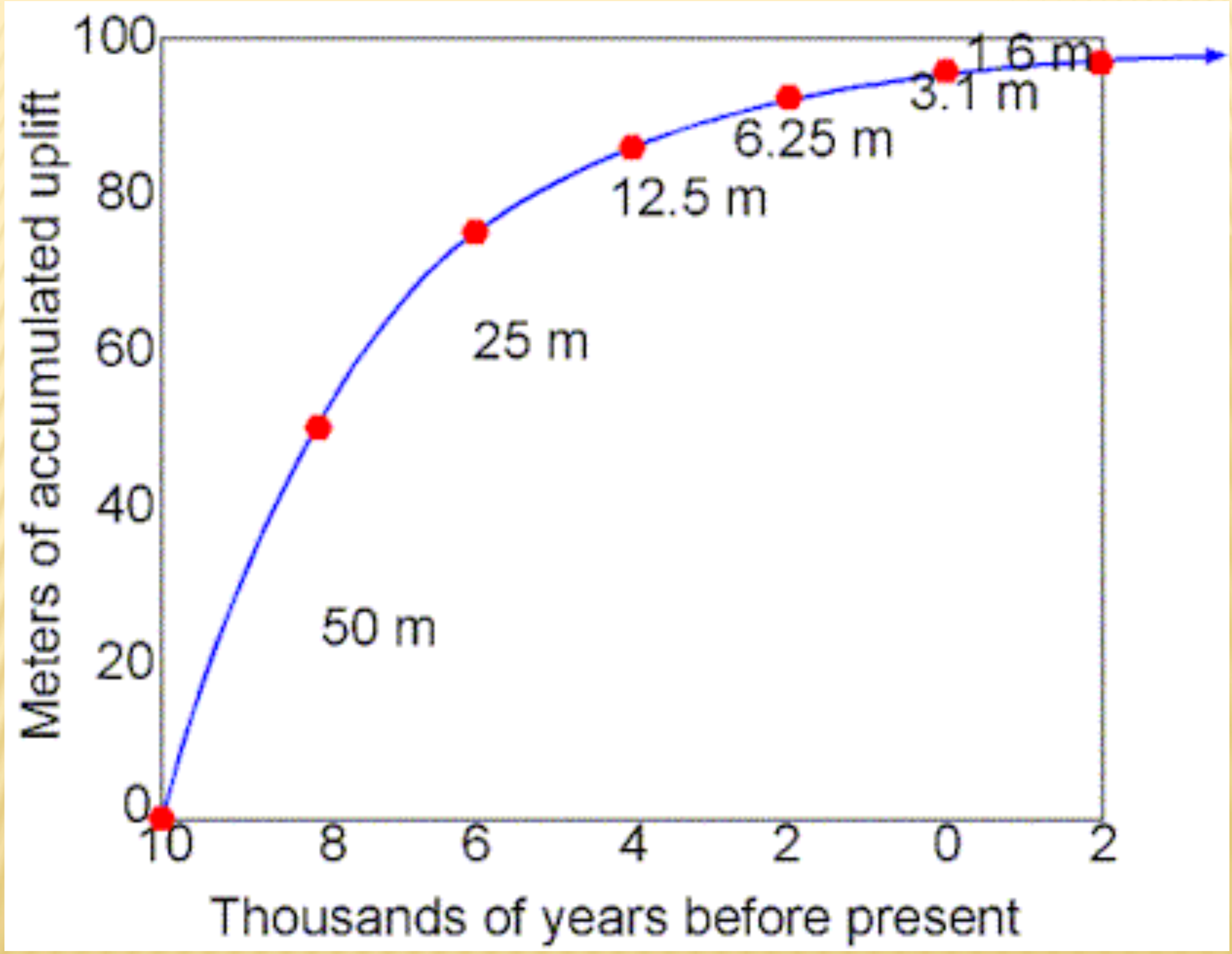


Lithosphere is strong enough to "support" load (weight) of mountain.

So far we are considering equilibrium states.


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



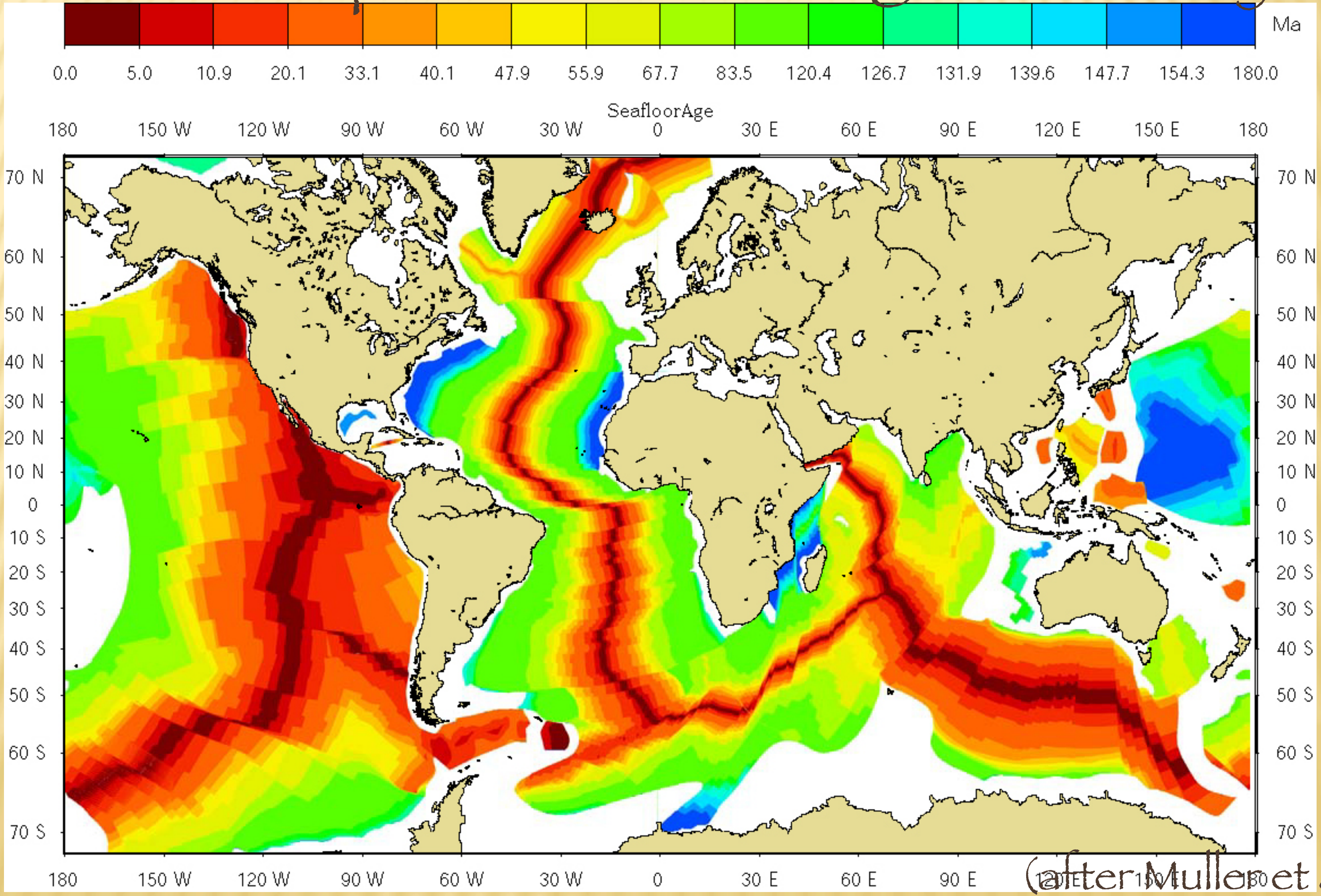


Meters of accumulated uplift
100
80
60
40
20
0
10
8
6
4
2
0
2
Thousands of years before present
50 m
25 m
12.5 m
6.25 m
3.1 m
1.6 m

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 > 5×10^{20} Pa s

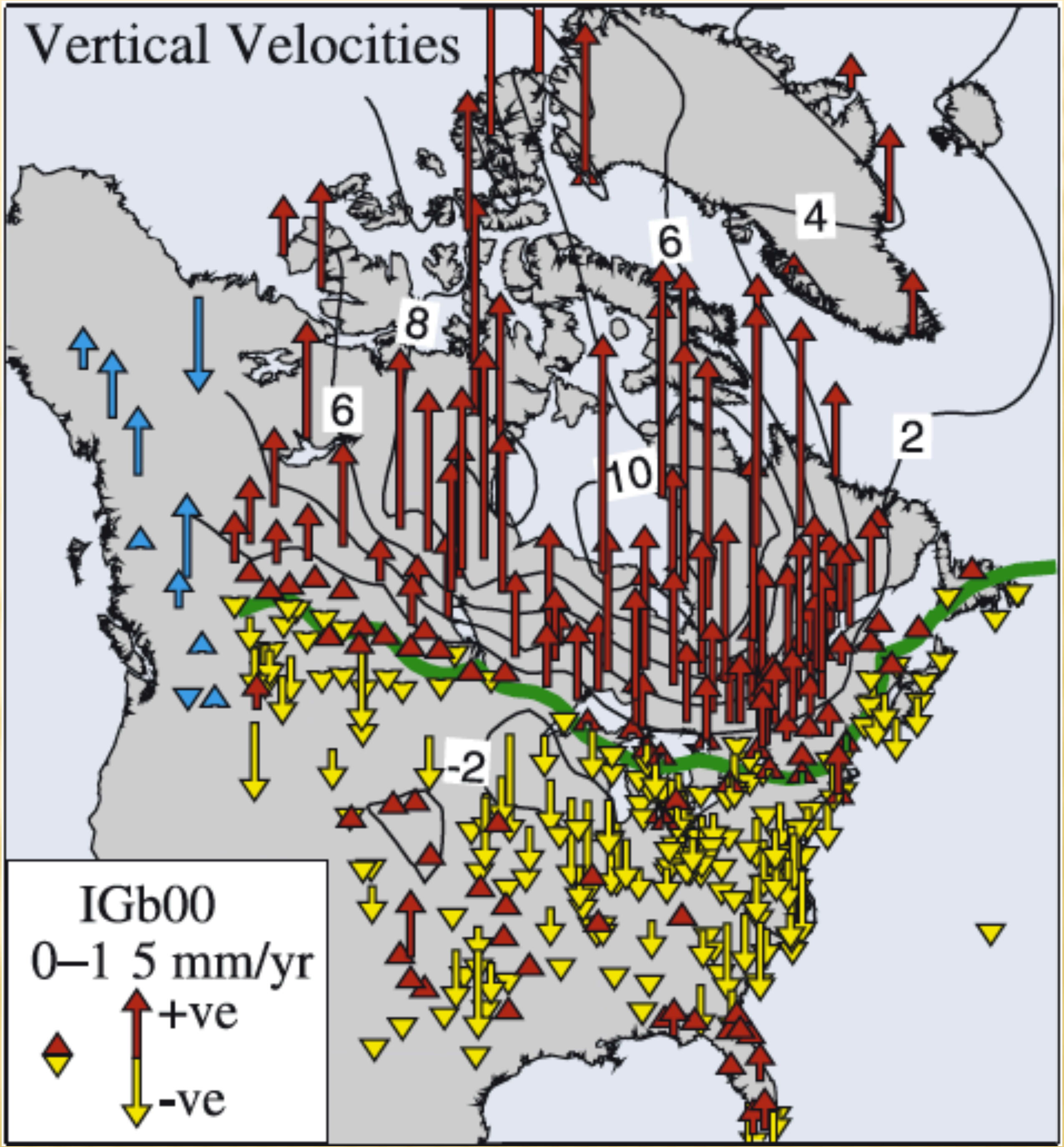
L Mantle viscosity ~ 10^{22} Pa s

Basin and Range / Iceland/Other

Lithospheric thickness ~ 10 km

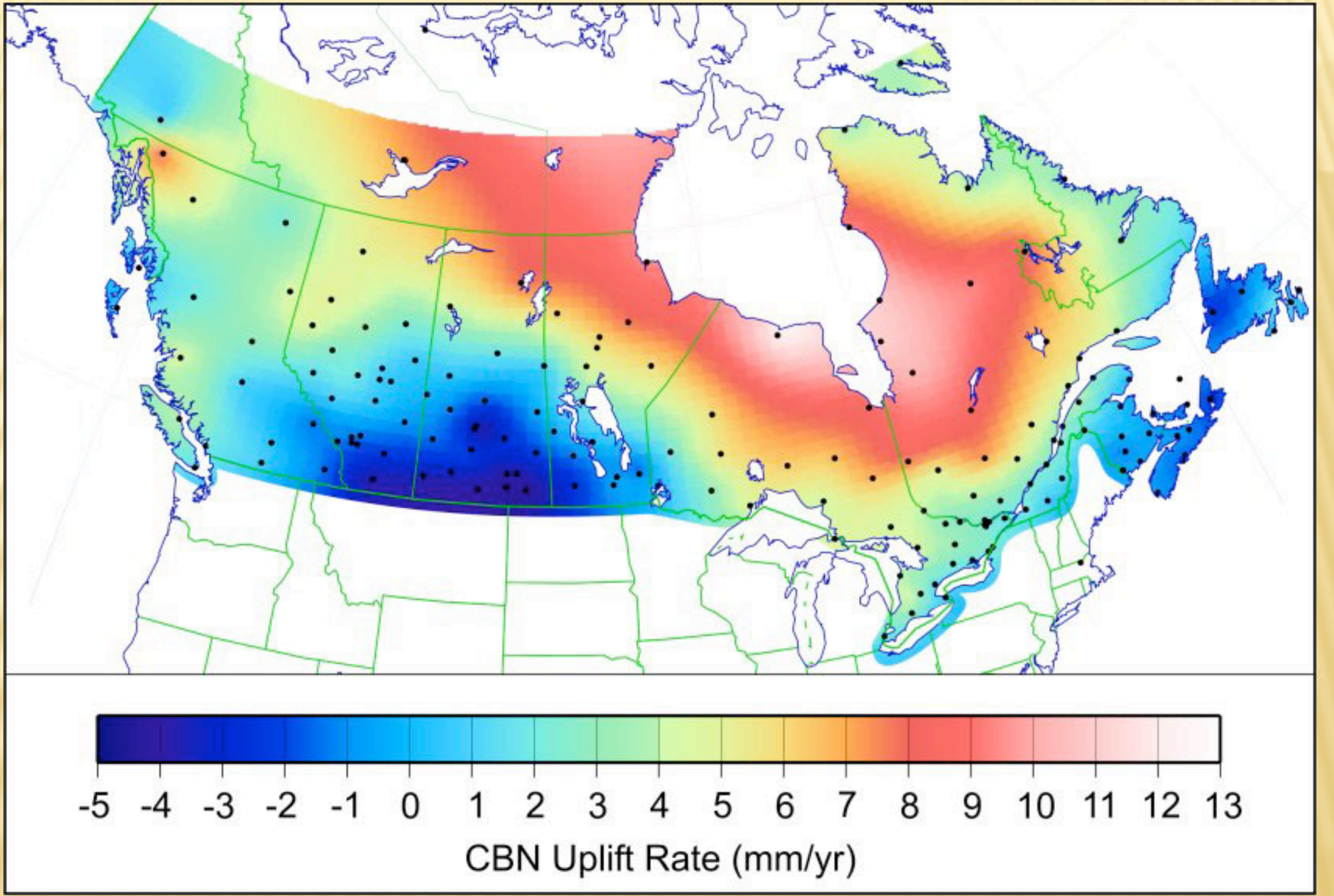
U Mantle viscosity < 1×10^{19} Pa s

PGR North America



Sella et al., 2007

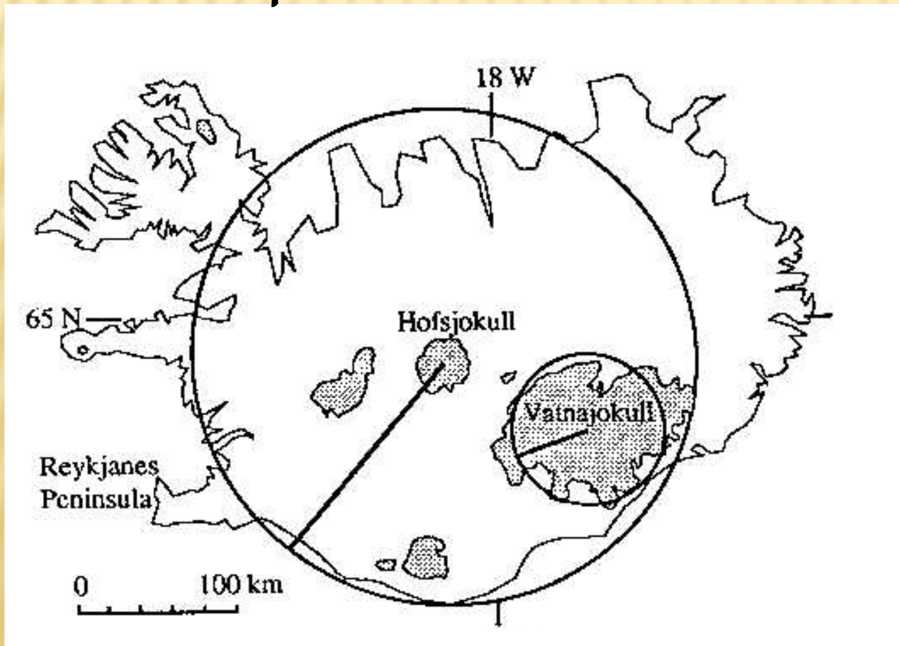
PGR North America

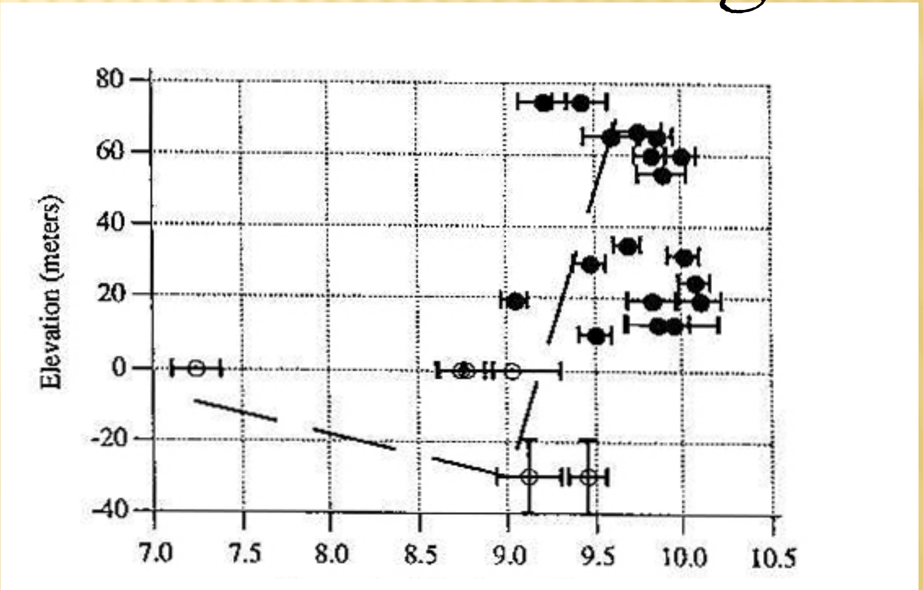


Henton et al., 2006

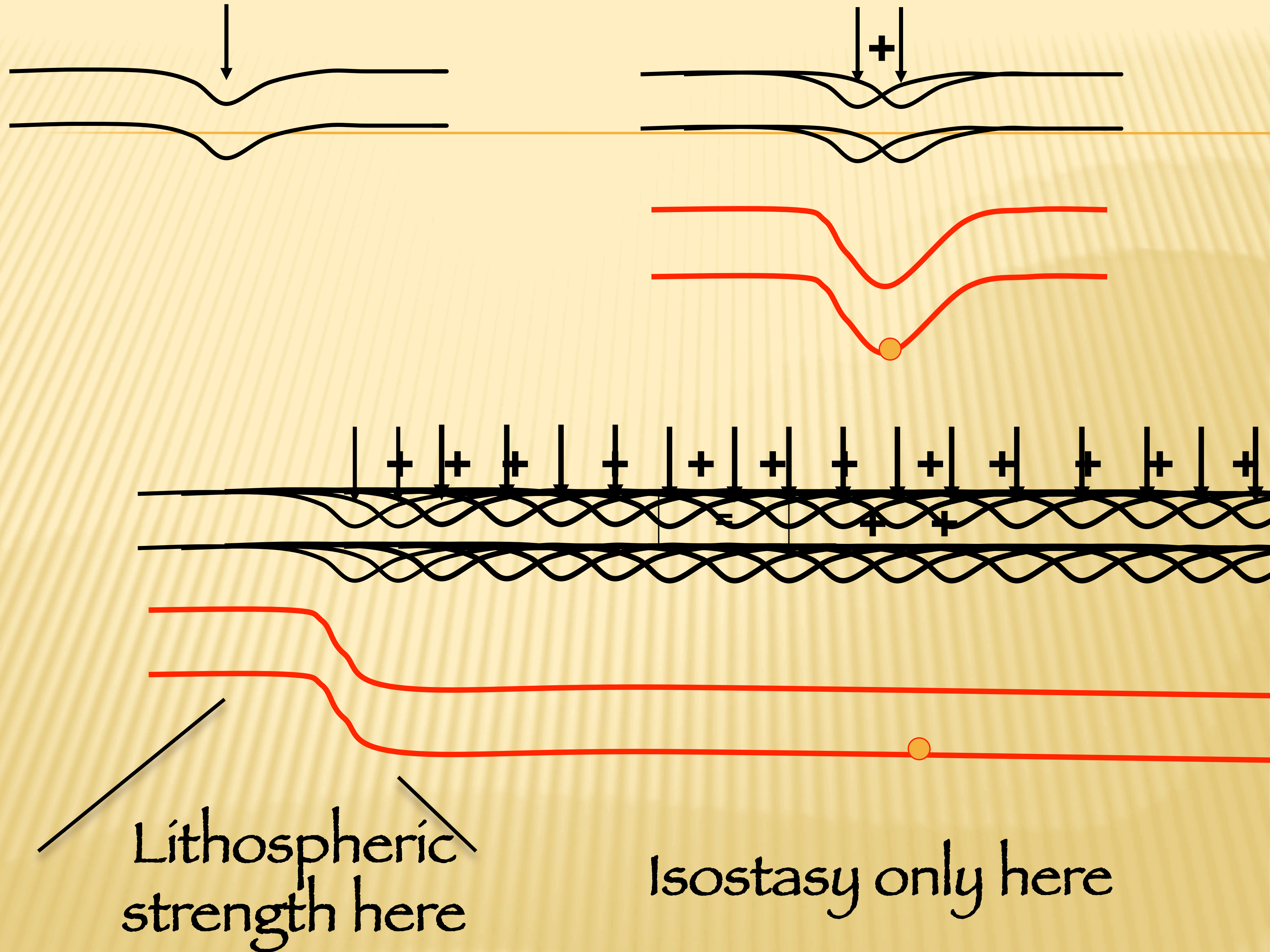
PGR in Iceland (young oceanic structure)

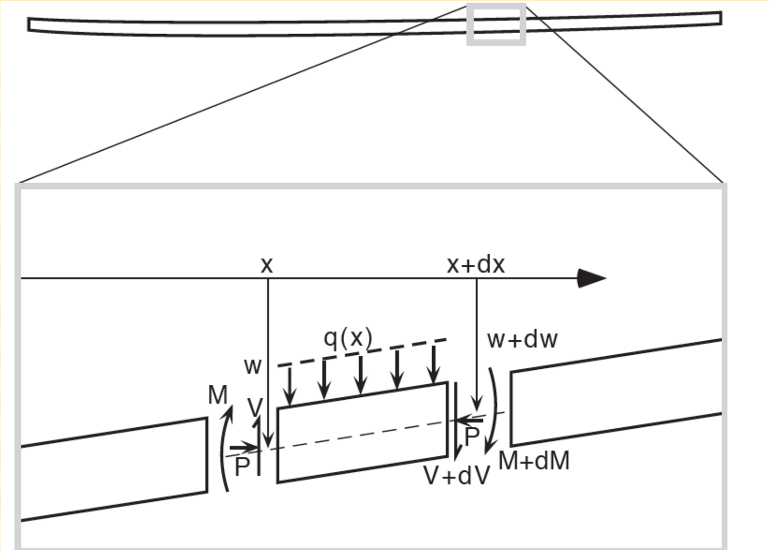
- Deglaciation following maximum at ~ 12000 yrsBP
- PGR in Iceland was completed in 1000 yrs
  - U Mantle viscosity $< 1 \times 10^{19}$ Pa s
- Compare to Fennoscandia – PGR still occurring.

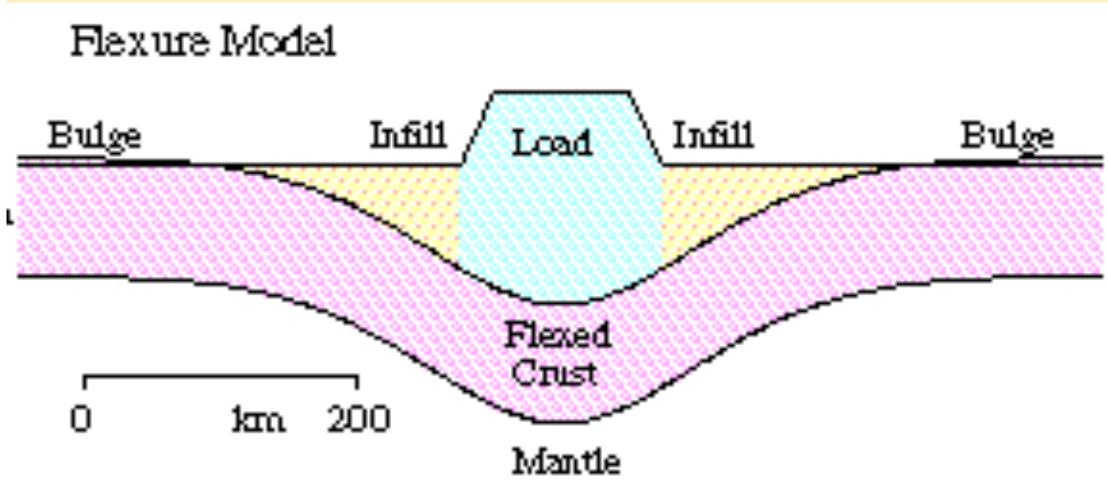




Sigmundsson (1991)


Lithospheric strength here
Isostasy only here





Full story of lithospheric flexure takes bending moments into account, get "bulge" outboard.

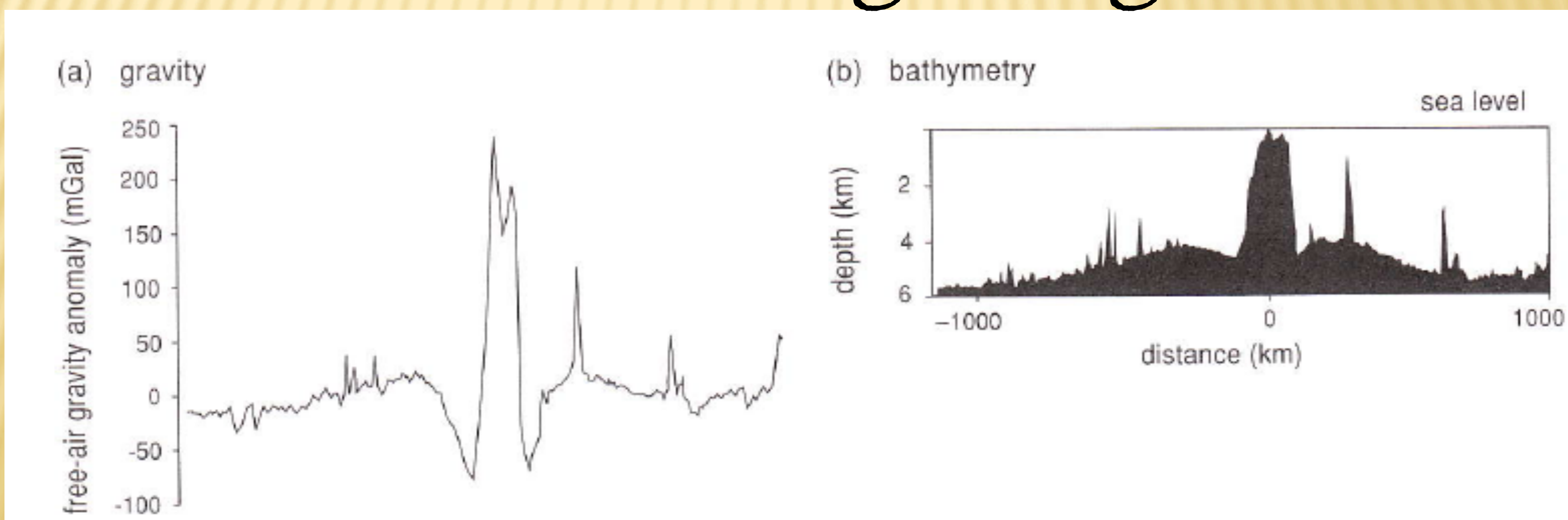
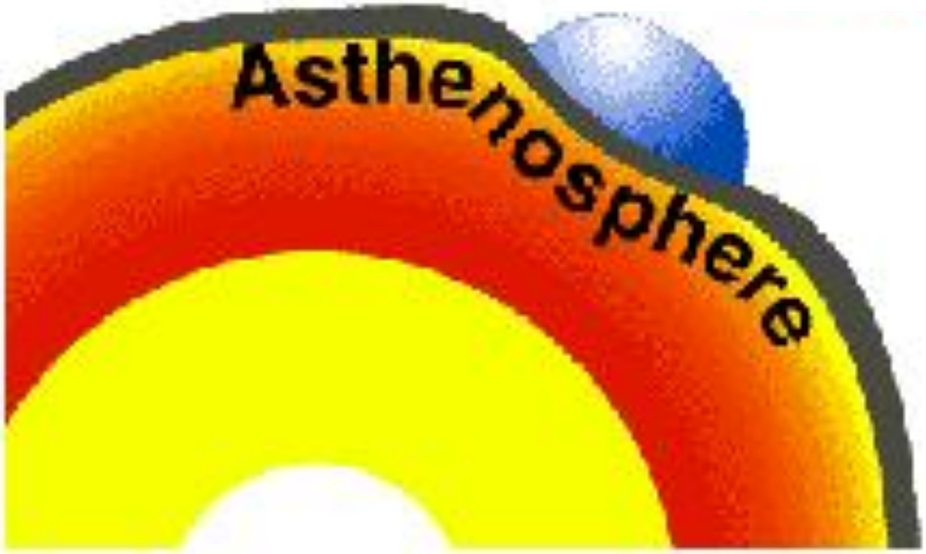


Figure 9.12 Bathymetry and gravity anomaly across Hawaiian Islands.

Glacial Isostatic Adjustment (GIA)

[used to be known as Post Glacial Rebound (PGR)]

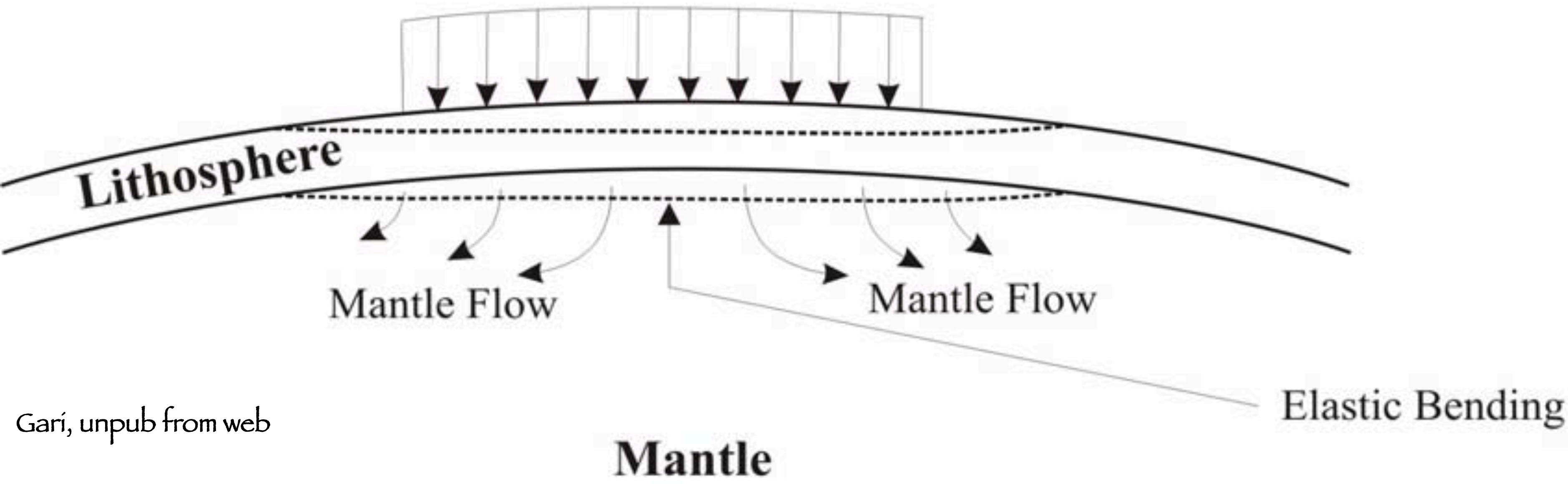
An interplay between



- Ice load history
- Geomechanical structure of region
  - Mantle viscosity profile
  - Lithosphere thickness, elastic (flexure) properties

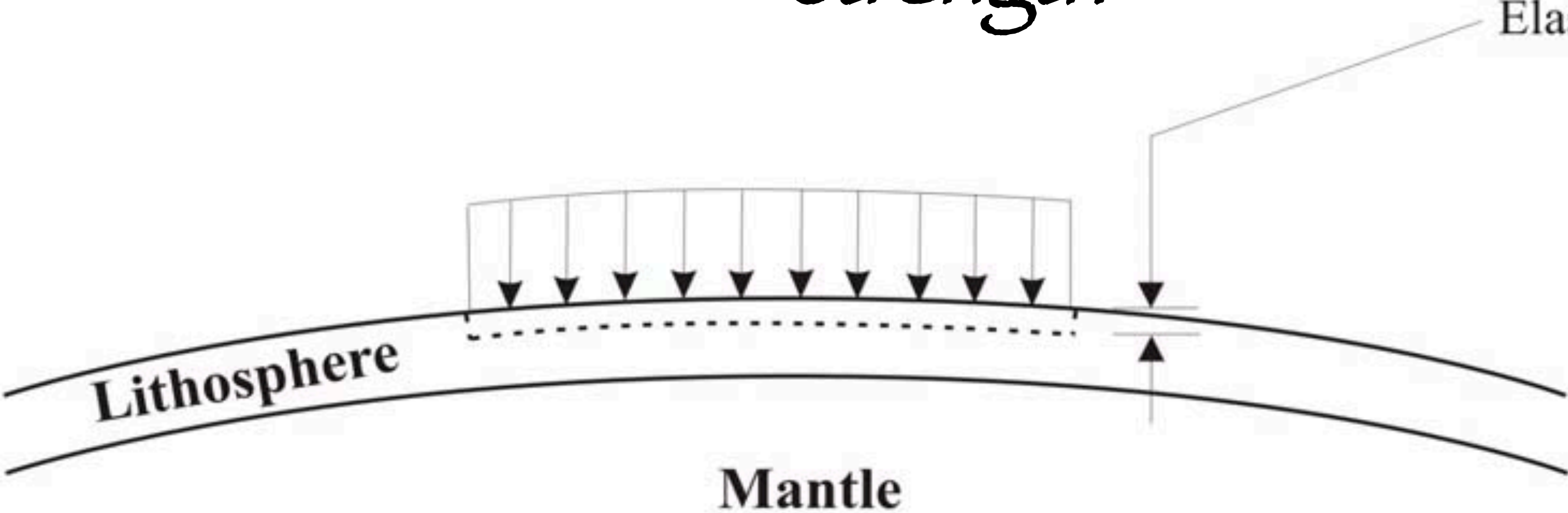
- Ice load history reflects climate (and topography/tectonics?).
- Geomechanical structure reflects tectonic setting.

How the earth supports loads – Part I - Isostacy

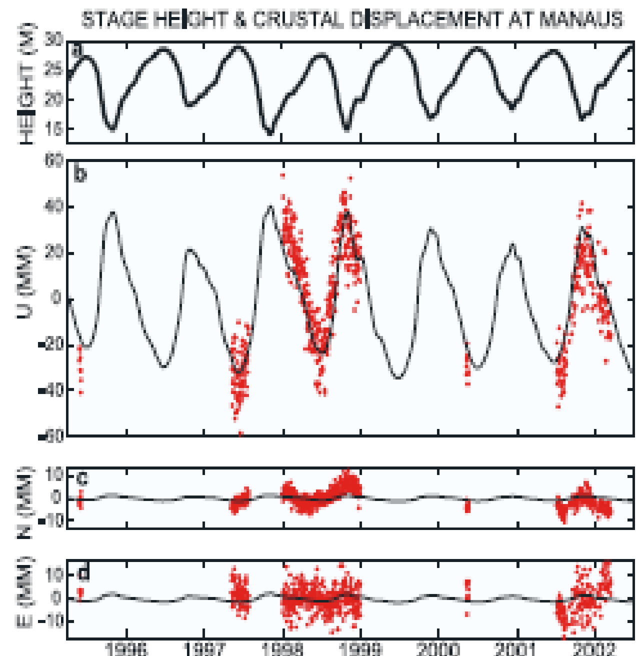


Gari, unpub from web

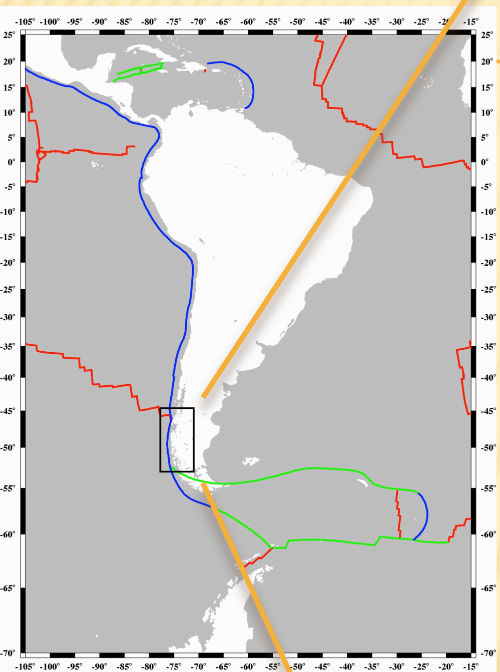
How the earth supports loads – Part 2 – Elastic strength

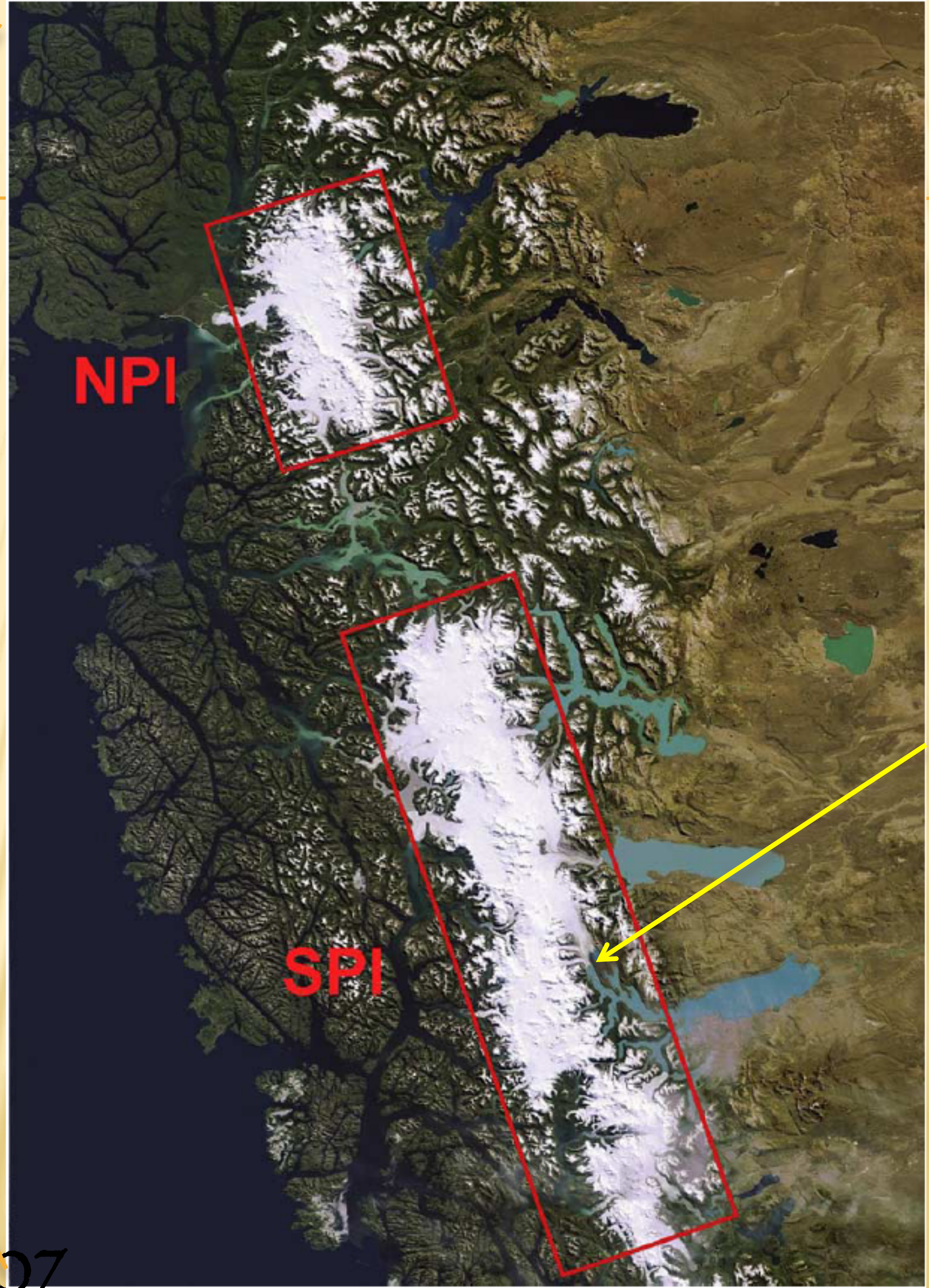


Gari, unpub from web



Bevis et al., 2005



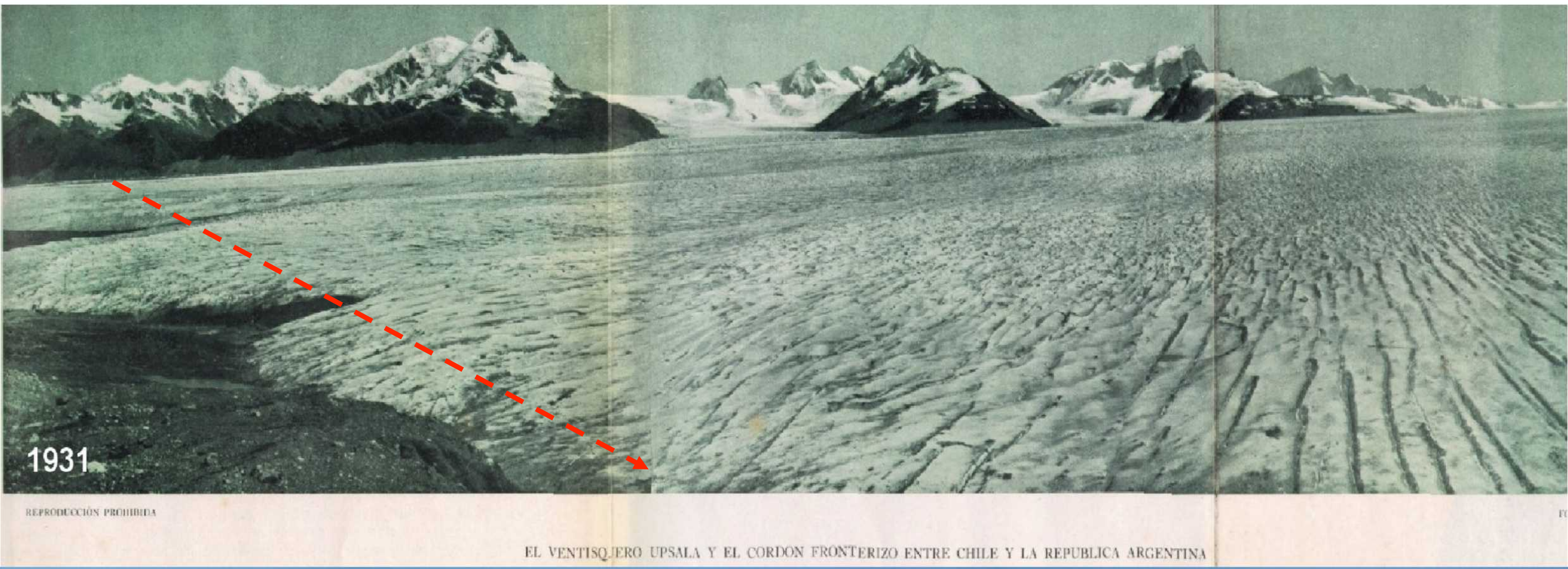


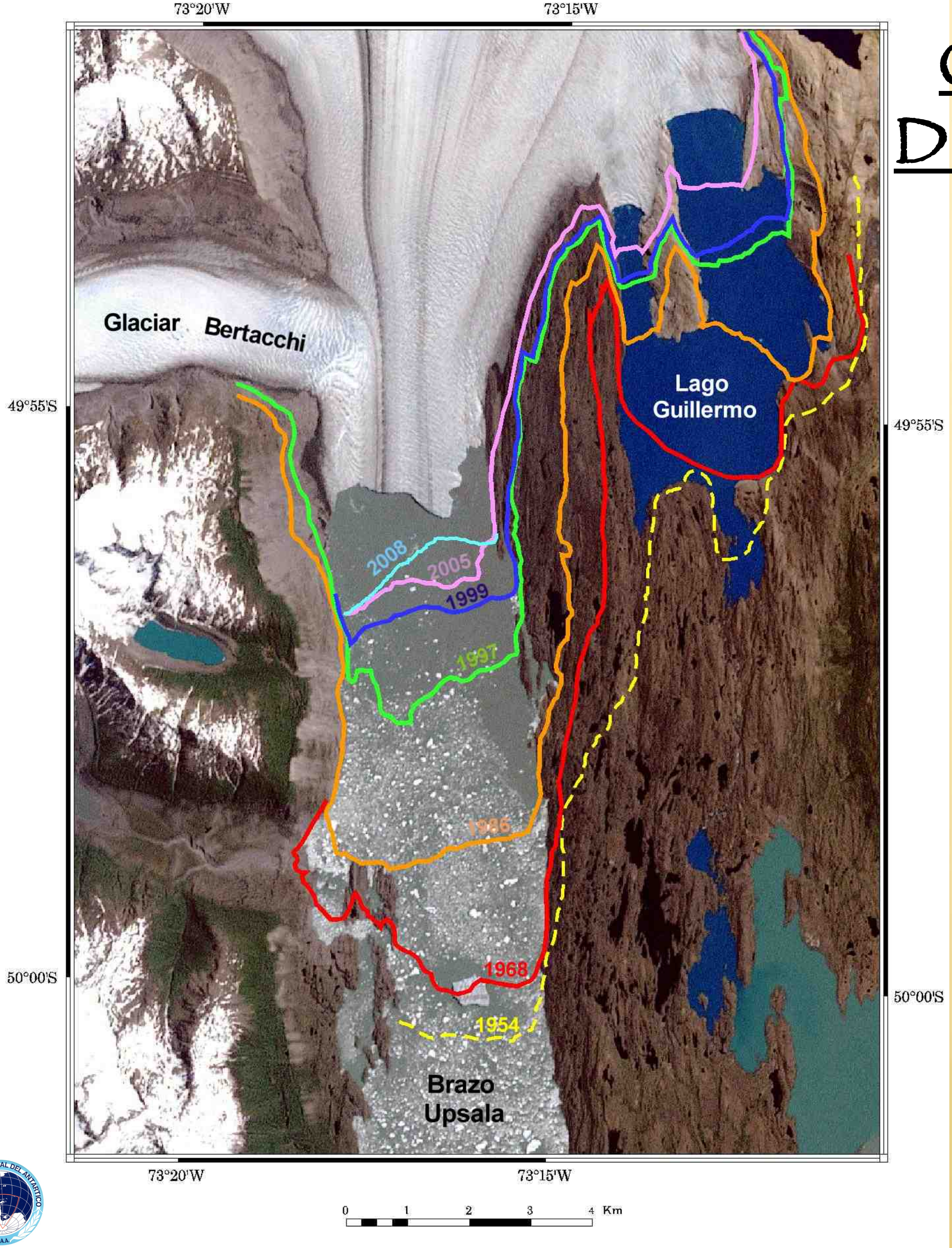
Upsala Glacier

Chen et al. 2007

The red doted line shows Skvarca's 1967 traverse, which is now a large lake (Lago Guillermo).

Between 1990-93 Skvarca measured a drastic thinning rate at Glaciar Upsala of 11 m/yr.





GLACIAR UPSALA: DRAMATIC RETREAT

Area loss 1986-2010: ~ 48.5 km^2
Retreat 1986 - 2010: ~7 KM

The retreat rate increased from 260 m/yr in 1978-2008 to 740 m/yr in 2008-2009.

The major part of large thinning rate is due to stretching, caused by the release of backstress.

From Pedro Skvarca

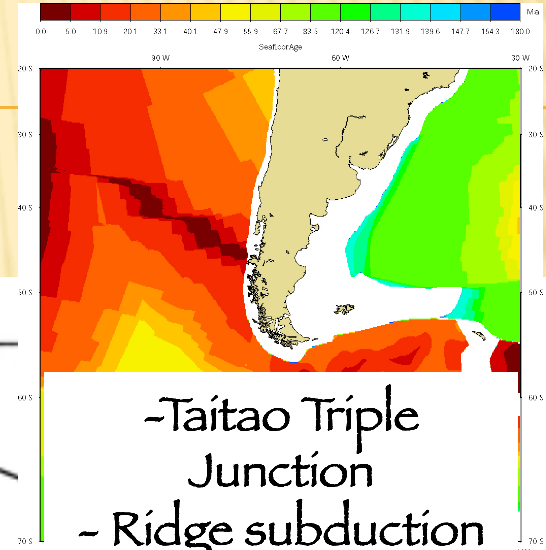
Use GPS as a scale. Measure response of earth (principally vertical) to load changes.

What affects geomechanical structure in Patagonia

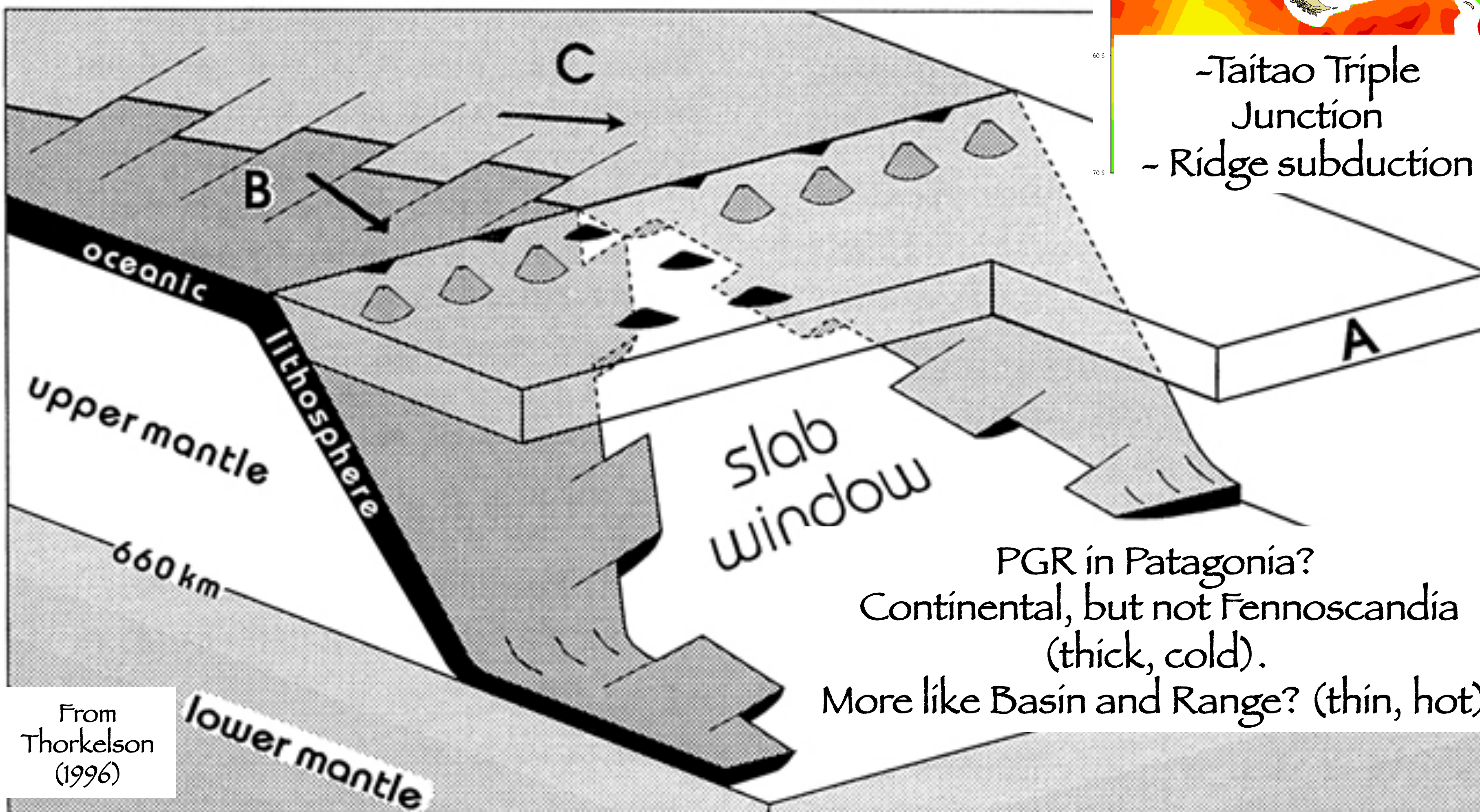
Ridge subduction -- Formation of a slab window

Modifies the geodynamic properties

– hotter upper mantle/asthenosphere, thinner lithosphere
– reminiscent of Basin and Range structure.



-Taitao Triple Junction
- Ridge subduction



PGR in Patagonia?
Continental, but not Fennoscandia (thick, cold).
More like Basin and Range? (thin, hot)

From Thorkelson (1996)

Ivins and James (1999)

Examined parameter space for PGR models of Patagonia:

- If Patagonia has Fennoscandian or intermediate mechanical structure

  PGR should be <u>≤ 1 mm/yr</u>.

- If Patagonia has Basin and Range like structure

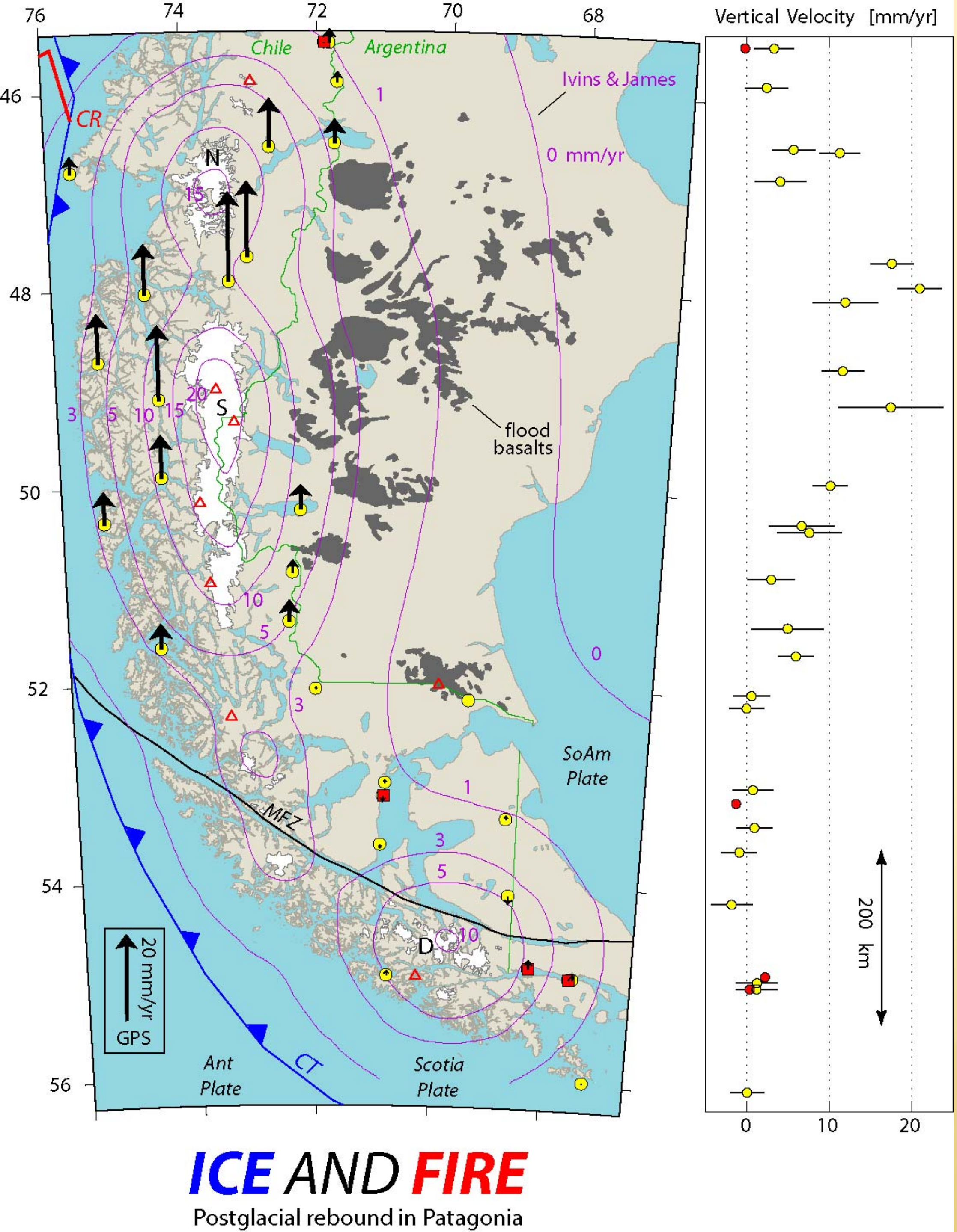
  PGR should be <u>~ 10 mm/yr</u>

  and PGR will be dominated by recent changes in ice load, NOT LGM

  (short term isostatic memory)

And noted:

B&R structure likely on tectonic grounds

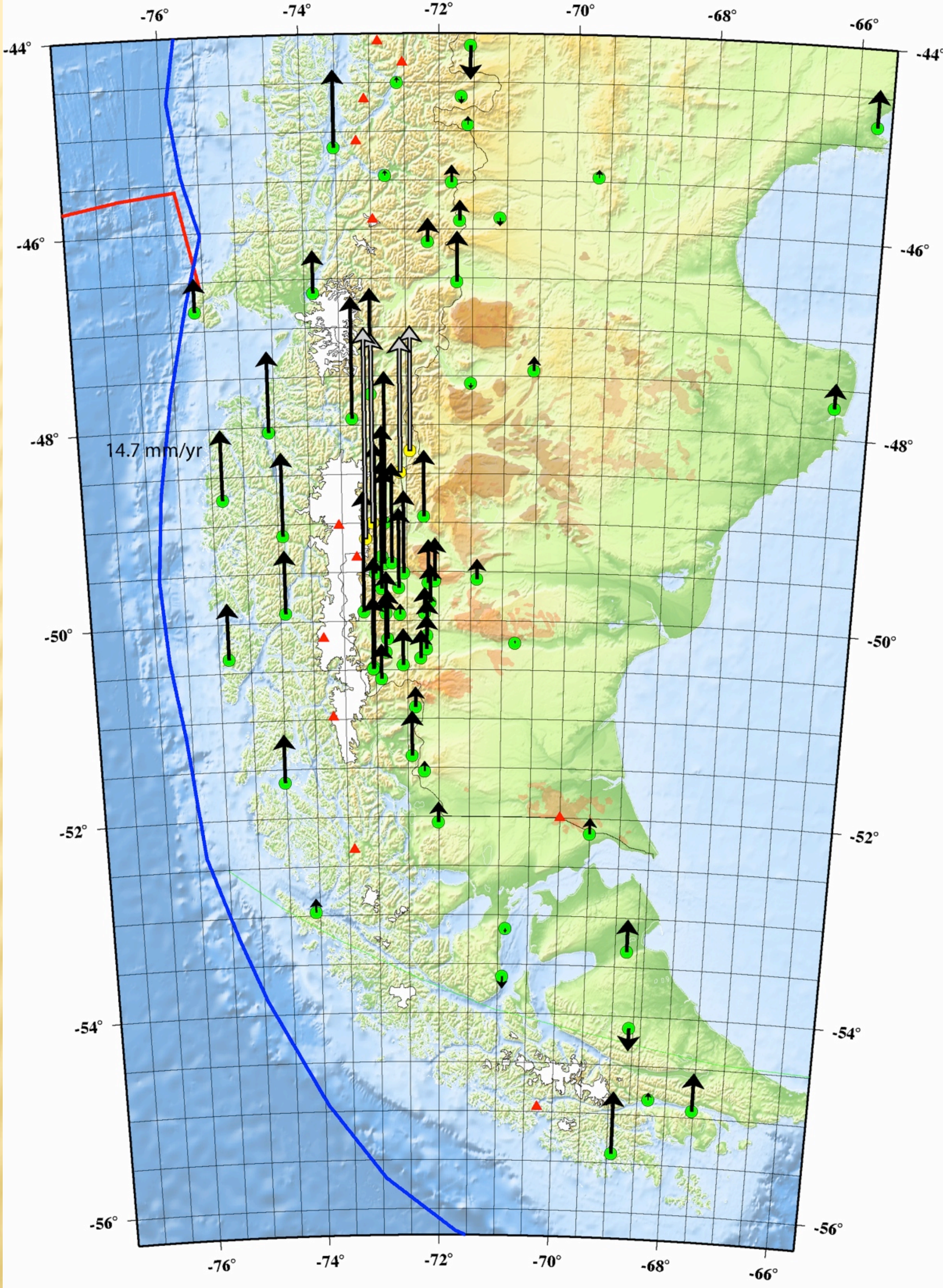


GPS and I&J (2004 results, Kendrick Ph.D. thesis)

-Clear coherent vertical signal observed in the region of Patagonian Ice Fields.

-Rates too fast and spatially incompatible to be continuing recovery from LGM.

What is it recovering

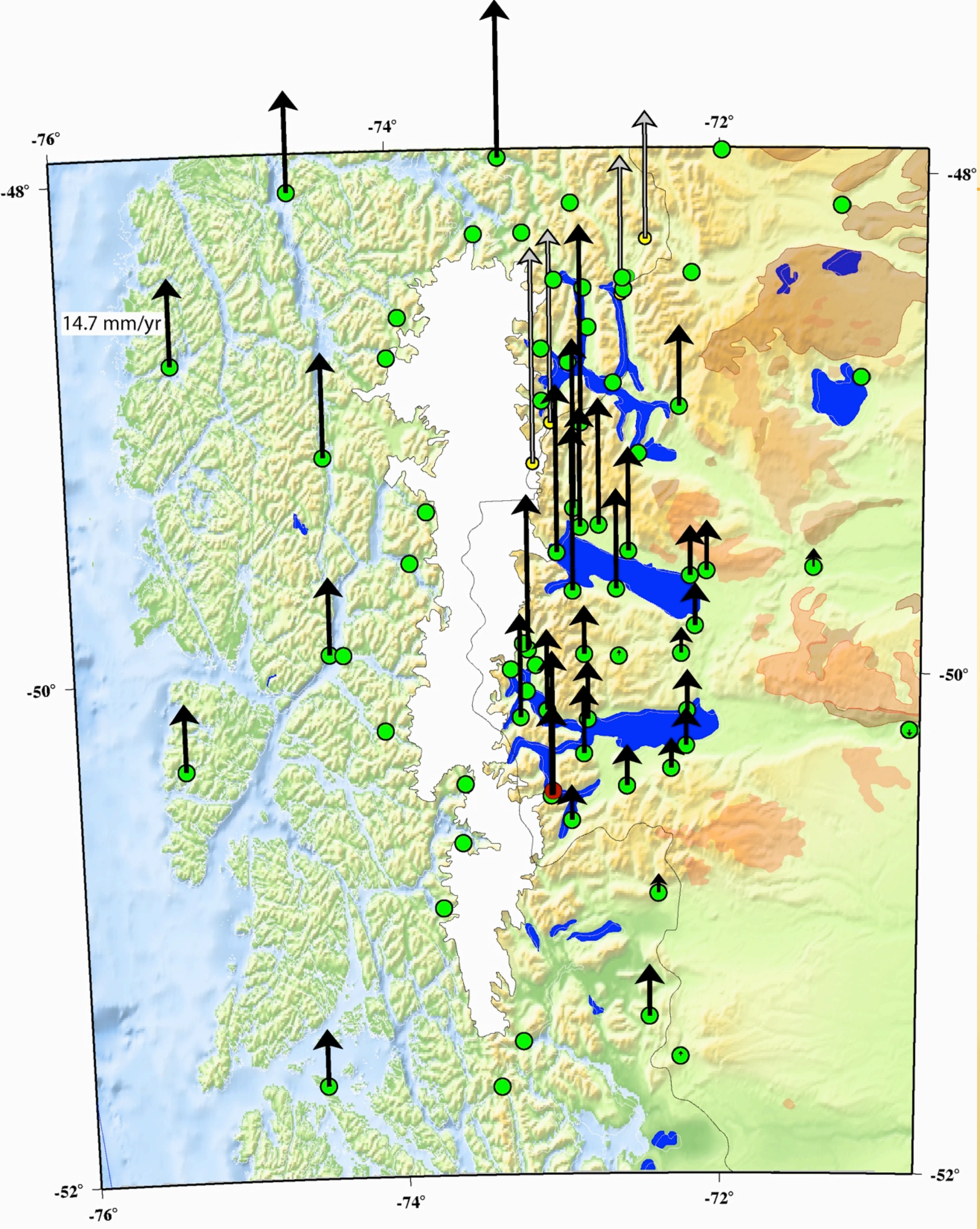


- Since 2004, we have built a new geodetic network focused on GIA.

- Provides increased spatial resolution of GIA signal.

- Provides longer time series.

- Introduces continuous GPS



Focus on Southern Patagonian Ice Fields

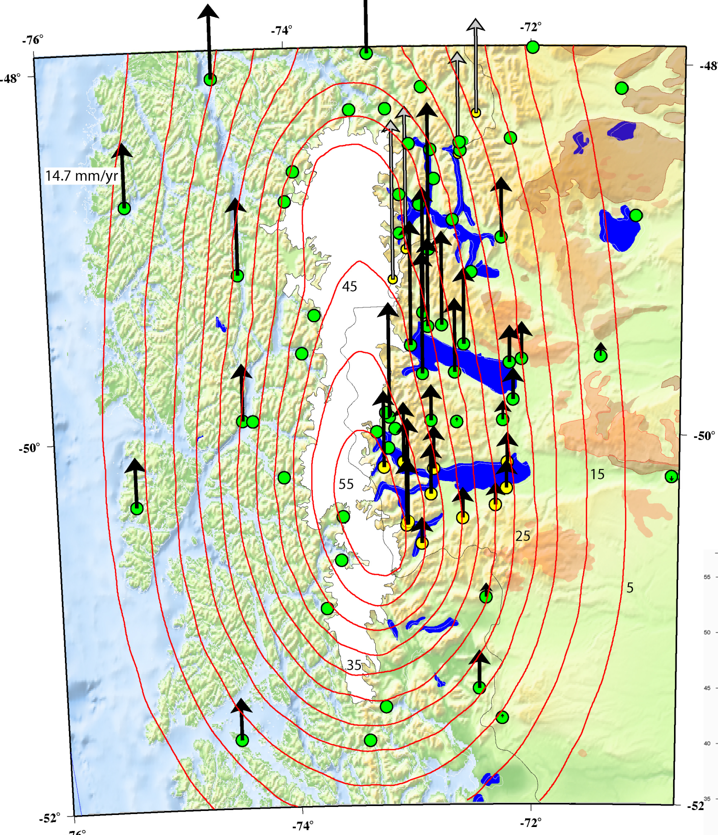
Black – new results

Grey – 4 vectors from Dietrich et. al. (2009)

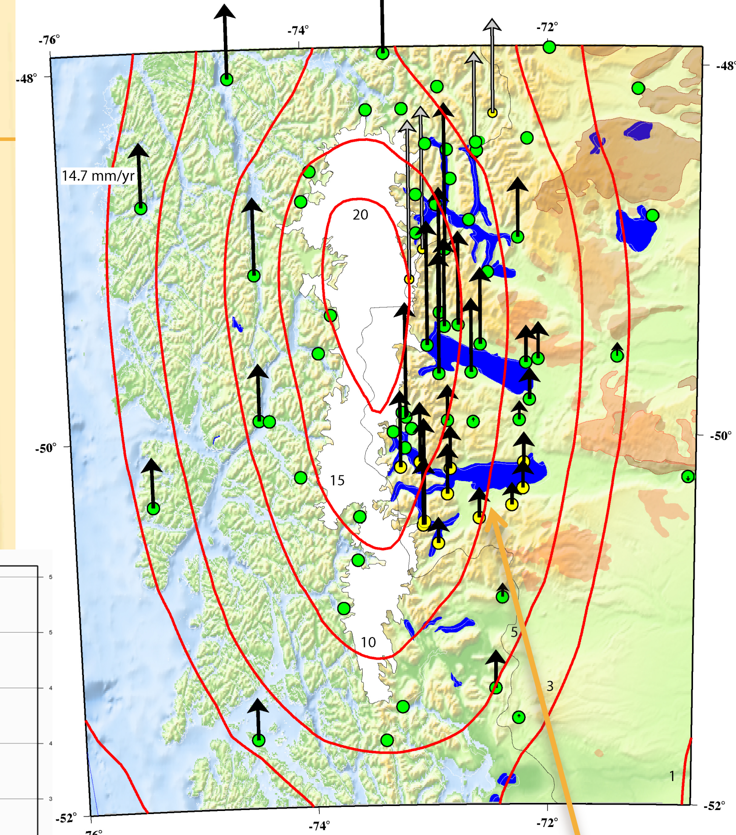
Points with no vectors have either <4 measurements or <6 year span (stay tuned).

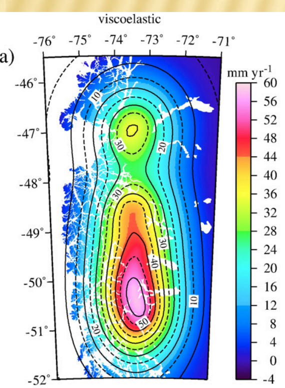
Compare GPS results for vertical velocity to models

Contours from Dietrich et al, 2009

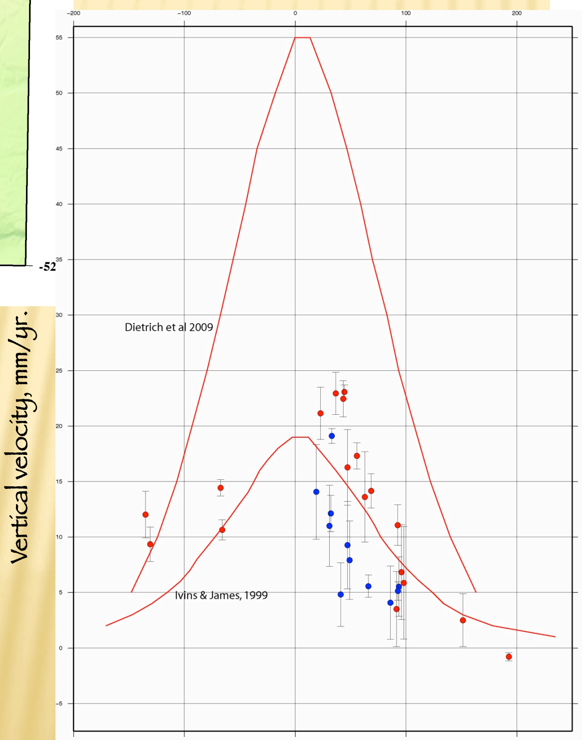


Contours from I&J (1999), Kendrick, (2004)





Need better sampling, but suggestion of shallower gradient on west, possible change in geodyamic structure due to subducted Antarctic plate.

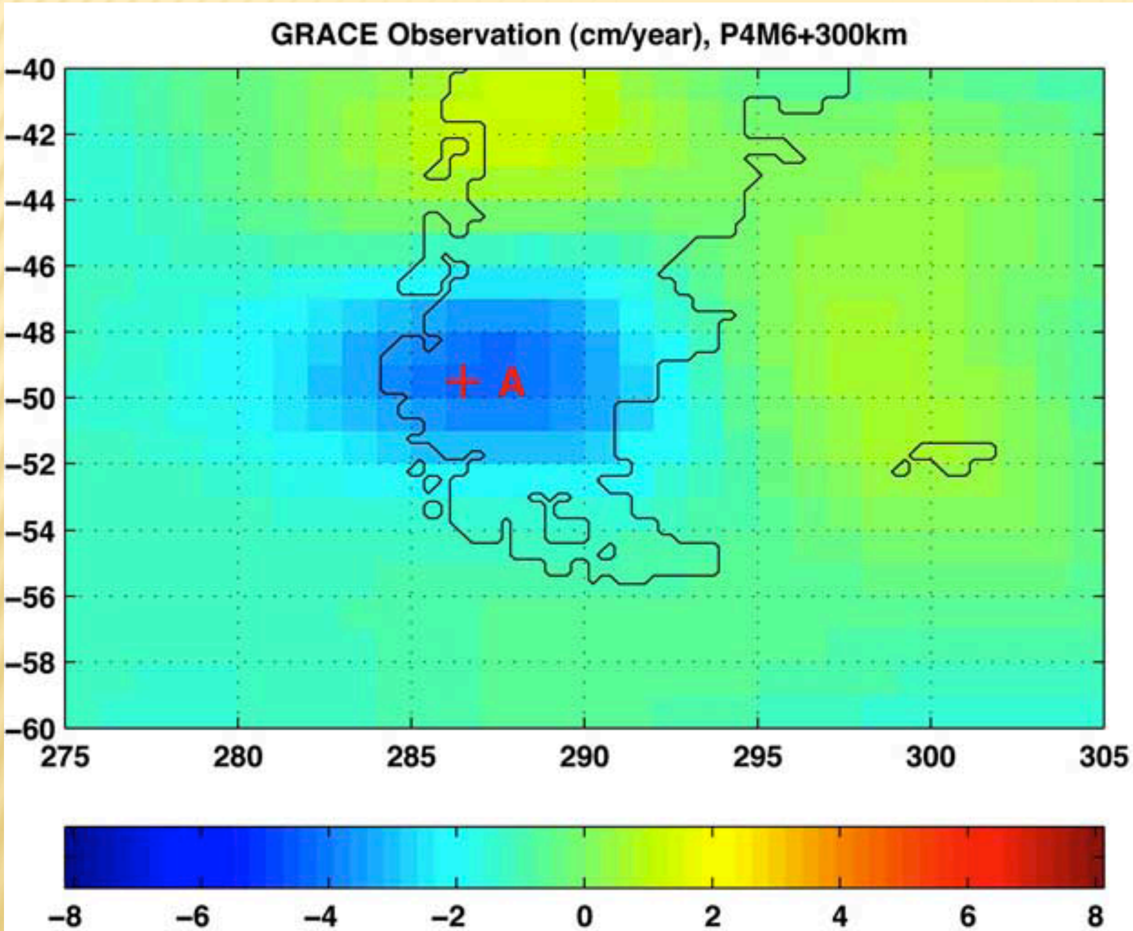


Km from -73.5
East-West cross section of vertical velocities.

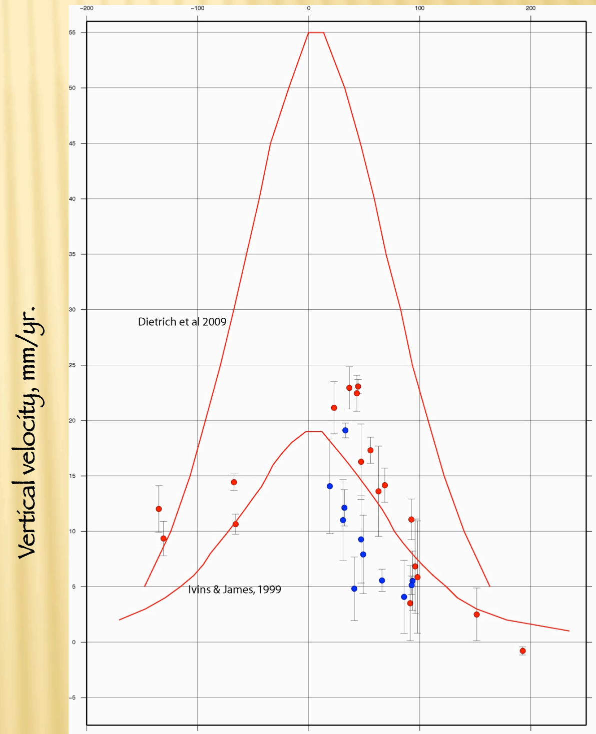
Steep gradient in vertical velocities on east.
(contours at 20, 15, 10, 5, 3, 1 mm/yr)

Sites around Lago Argentino are slower than those to north.

GIA also provides important "correction" when using gravity to measure changes in ice mass.



Chen et al, 2007



Km from -73.5
East-West cross section of vertical velocities.

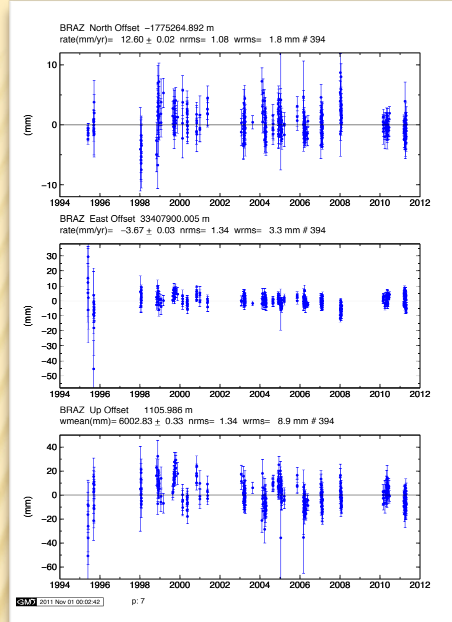
Upsala Glacier/Lago Guillermo

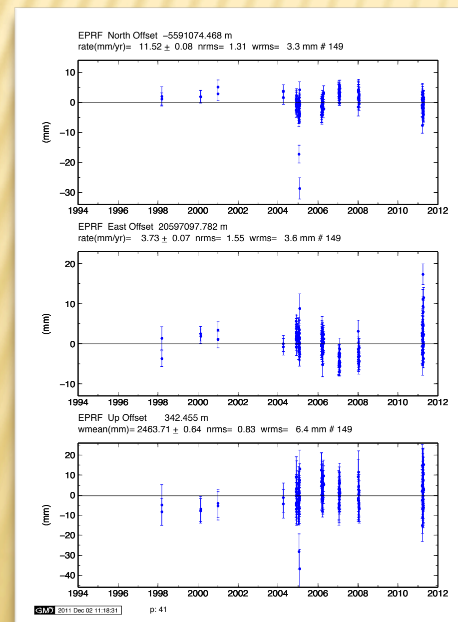
Viedma Glacier

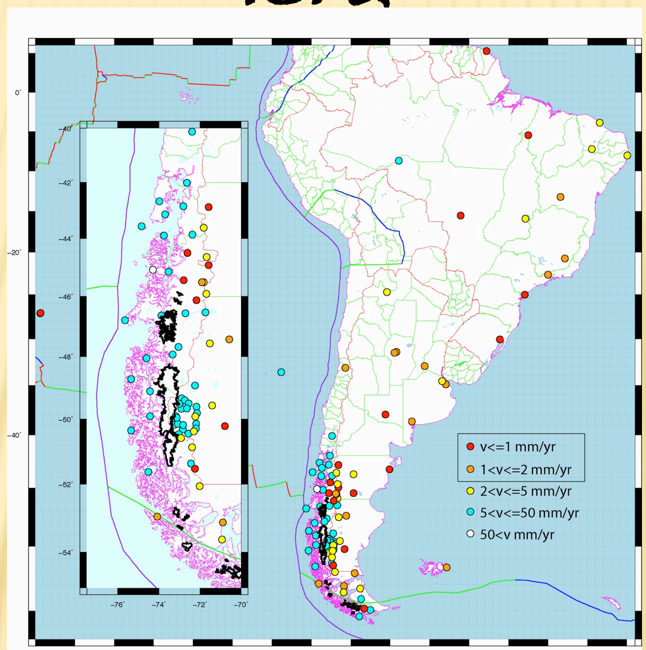
Estancia Porfiada – reference

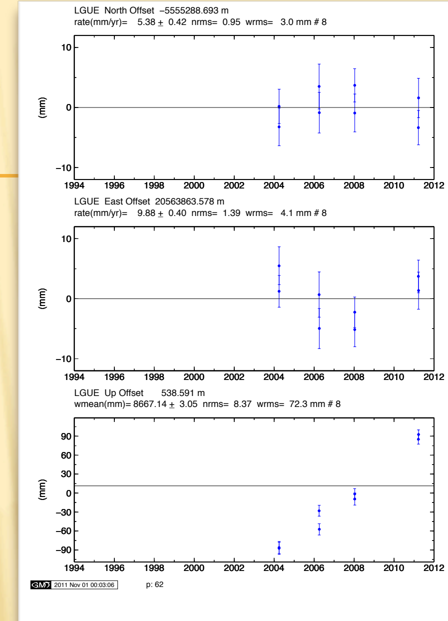
Time series –

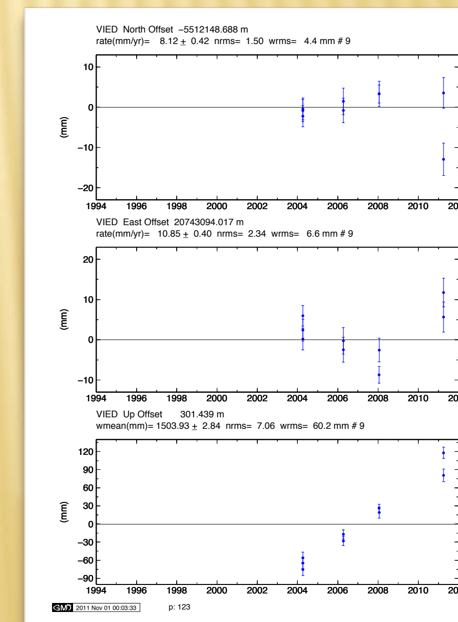
reference stations (map below) TS on left,











campaign stations TS on right.

Conclusions

- Clear coherent vertical signal observed in the region of Patagonian Ice Fields.

- Uplift rates and steep gradient to the east support interpretation of weak geomechanical structure and response to recent load changes (little ice age).

- Need better geodynamic models and ice/load history to explain along and across strike variation.

- Still need to quantify elastic response?

- GIA/PGR results will provide important non-ice mass changes for gravity/altimetry missions.

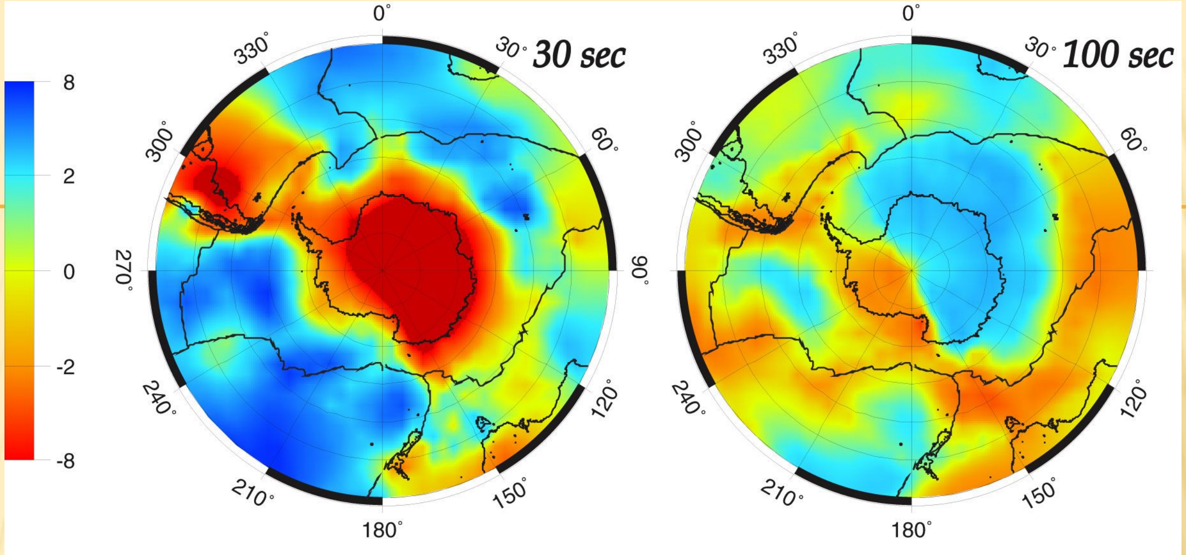
Similar effects and tectonic questions in Antarctica

Projects –

WAGN
TAMDEF

POLENET

Rayleigh Wave velocity



Geomechanical Structure of Antarctica: Part I

Rayleigh wave velocity

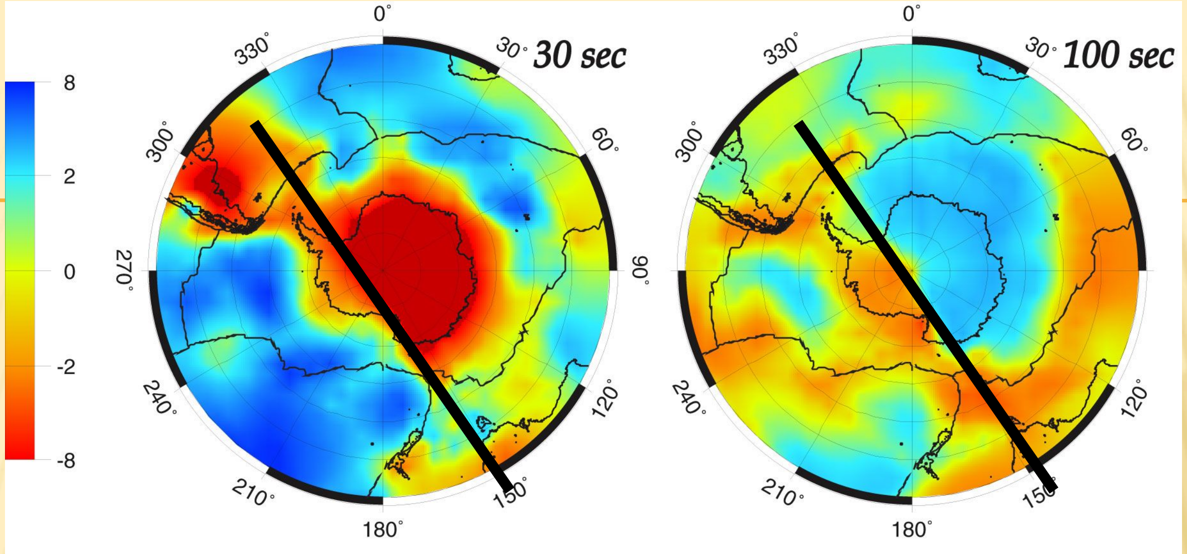
•proxy for lithospheric thickness

- thin is "weak"

Determines wavelength and amplitude of isostatic response

Danesi & Morelli, 2001

Rayleigh Wave velocity



Geomechanical Structure of Antarctica: Part I

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Determines wavelength and amplitude of isostatic response

Danesi & Morelli, 2001

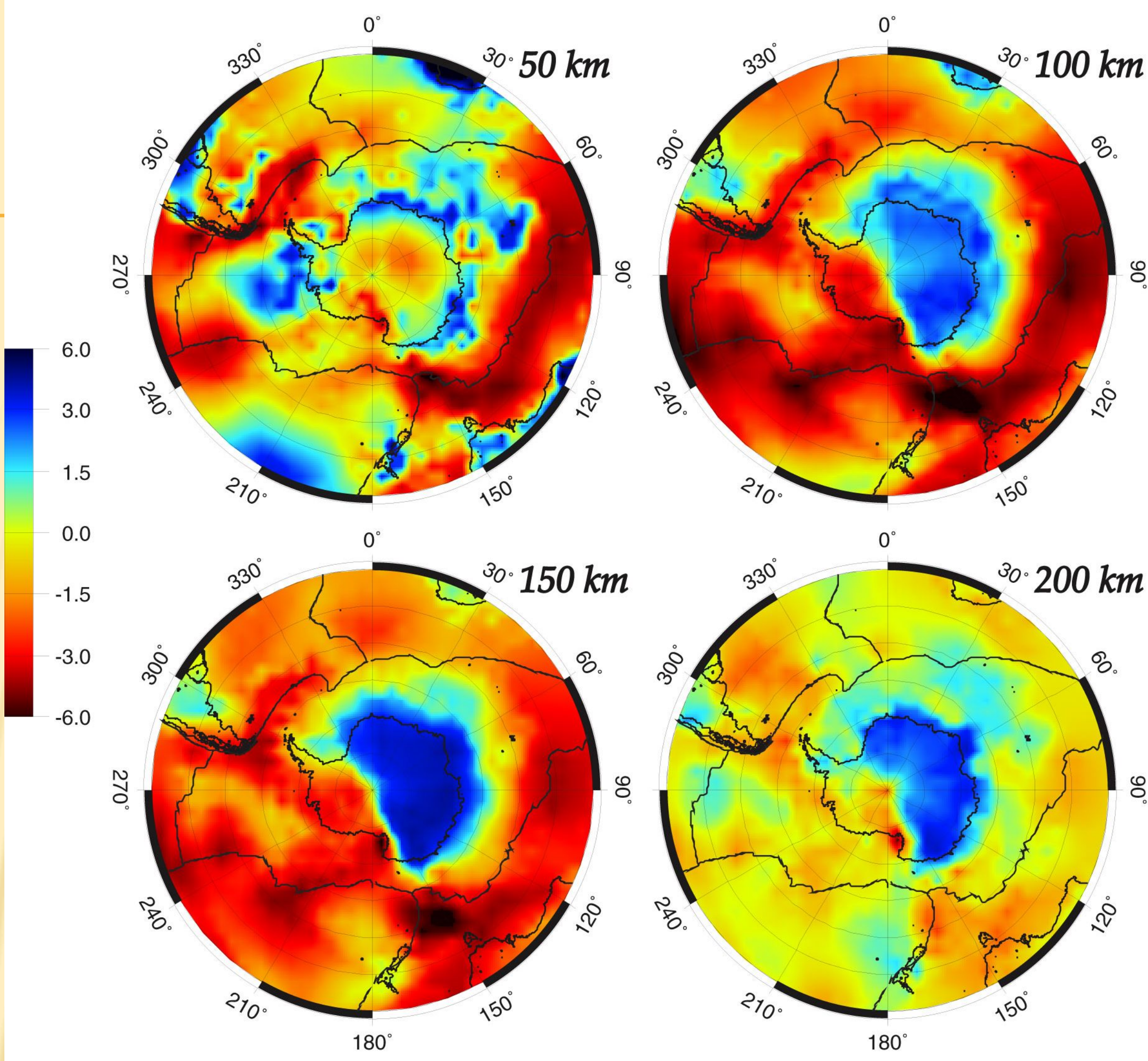
Result -- West Antarctica thin

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

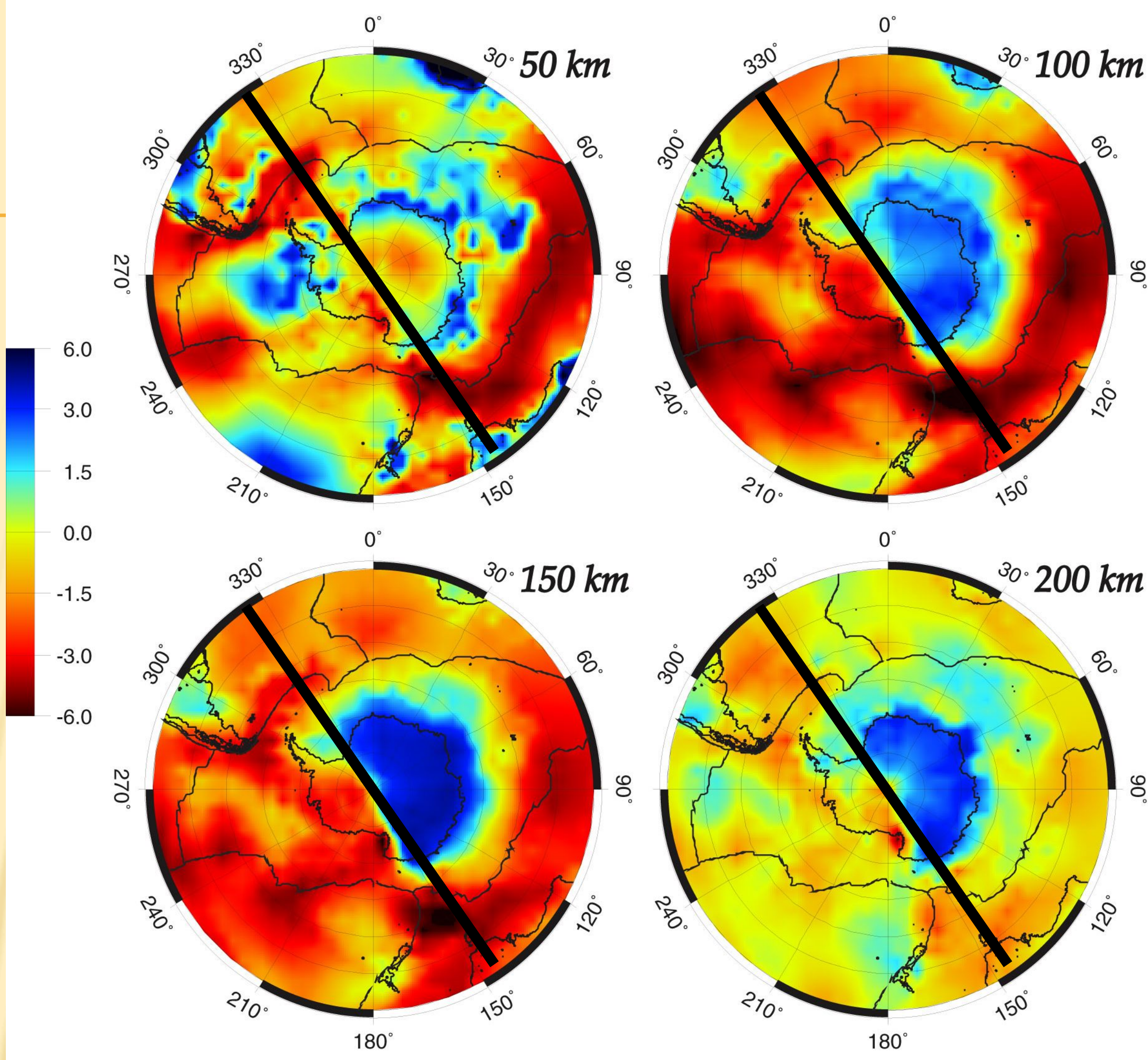
Sv velocity

•proxy for temperature

- hot is lower viscosity (runny).

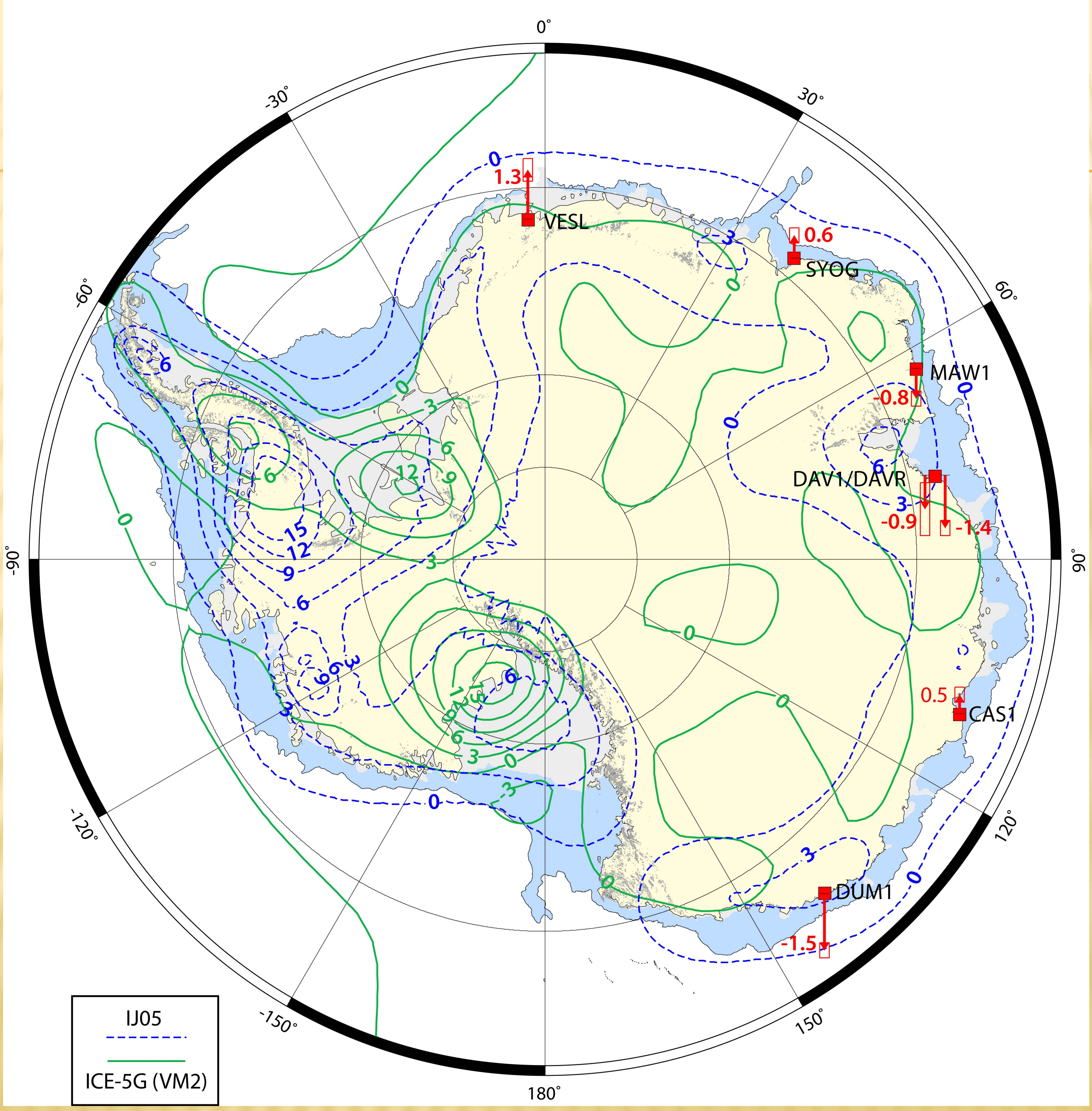
Determines speed of isostatic response.

Result -- West Antarctica hot

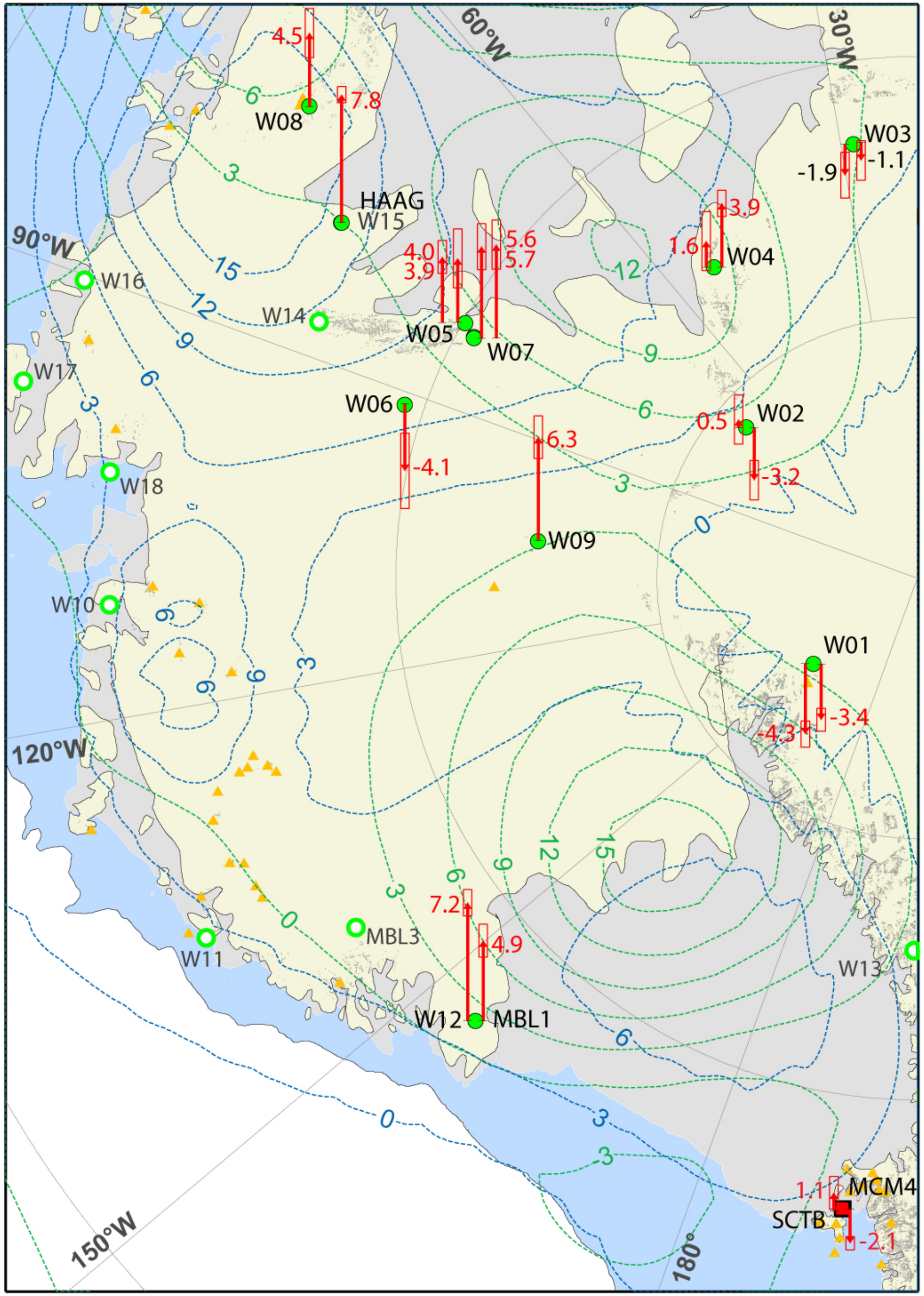


Danesi & Morelli, 2001

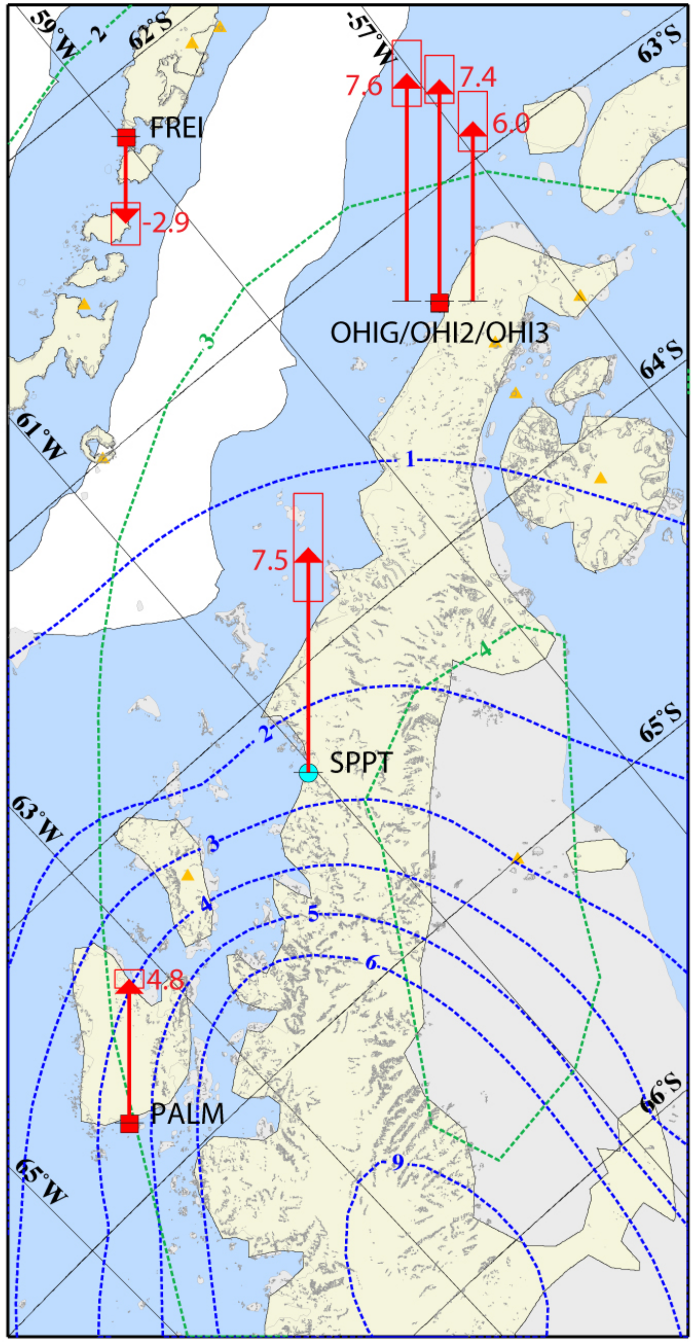

AP
TI
EWM
EA
MBL



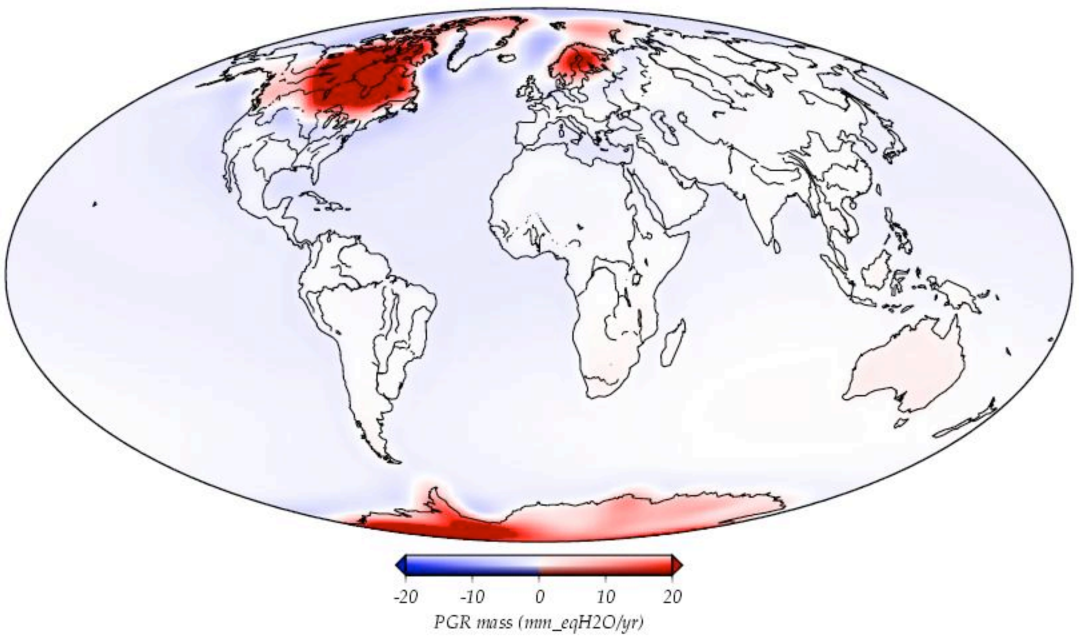
0°
30°
60°
90°
120°
150°
180°
-150°
-120°
-90°
-60°
-30°
VESL
1.3
SYOG
0.6
MAW1
-0.8
DAV1/DAVR
-0.9
-1.4
CAS1
0.5
DUM1
-1.5
IJ05
ICE-5G (VM2)

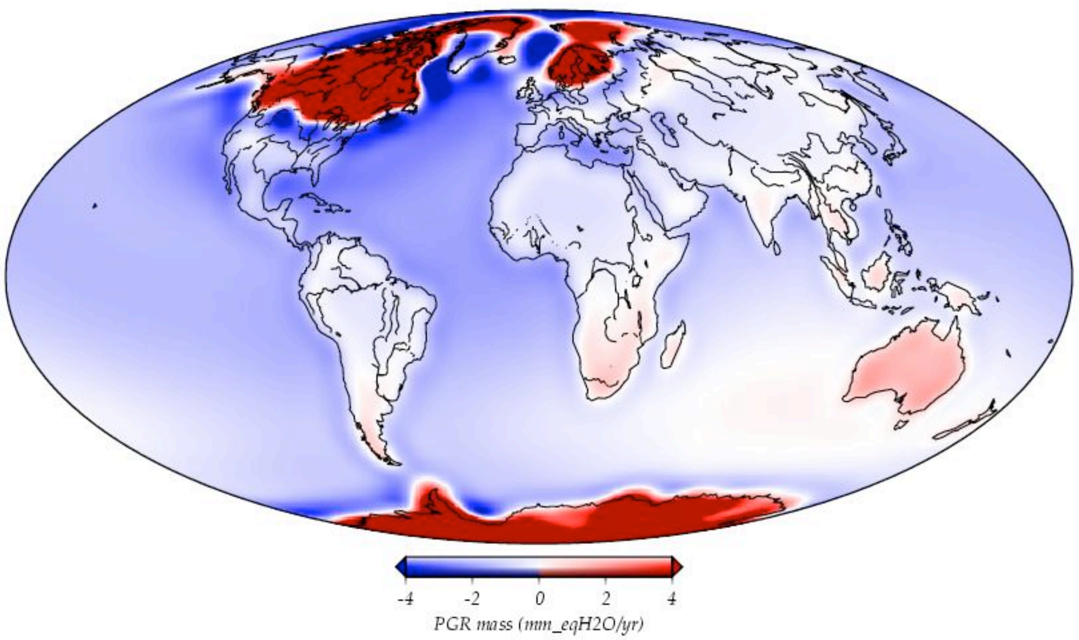


60°W
30°W
90°W
120°W
150°W
180°
W08
HAAG
W15
W16
W14
W05
W07
W17
W06
W18
W09
W10
W04
W03
W02
W01
W11
MBL3
W12
MBL1
W13
MCM4
SCTB
4.5
7.8
4.0
3.9
5.6
5.7
1.6
3.9
-1.9
-1.1
0.5
-3.2
-4.1
6.3
-4.3
-3.4
7.2
4.9
1.1
-2.1


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
1
2
3
4
5
6
9

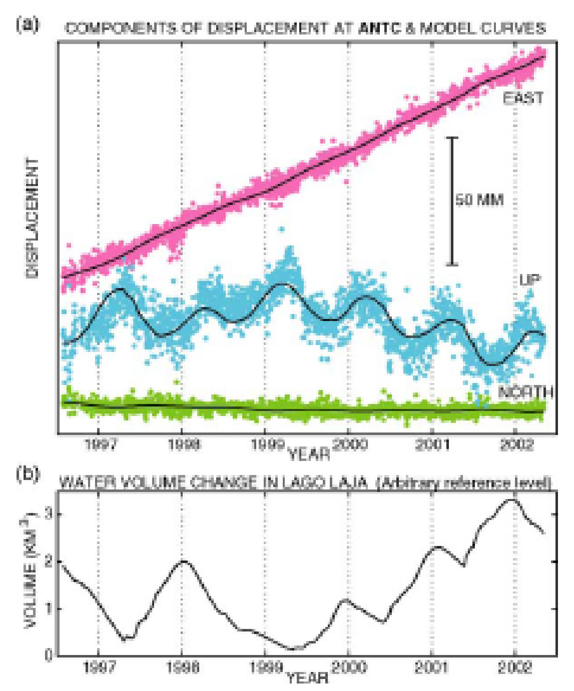
Model of present-day surface elevation change due to PGR and reloading of ocean basins with seawater. Red areas rising due to removal of ice sheets. Blue areas falling due to re-filling of ocean basins when ice sheets melted and because of collapse forebulges around the ice sheets.

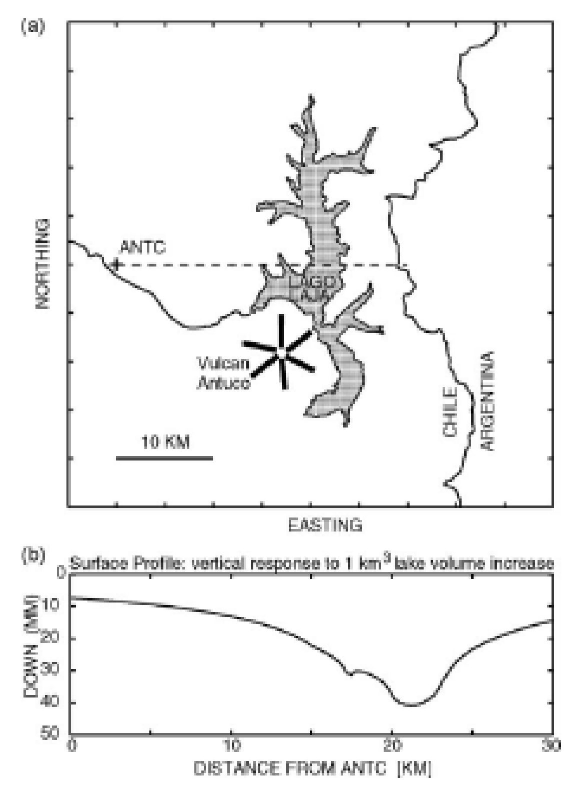


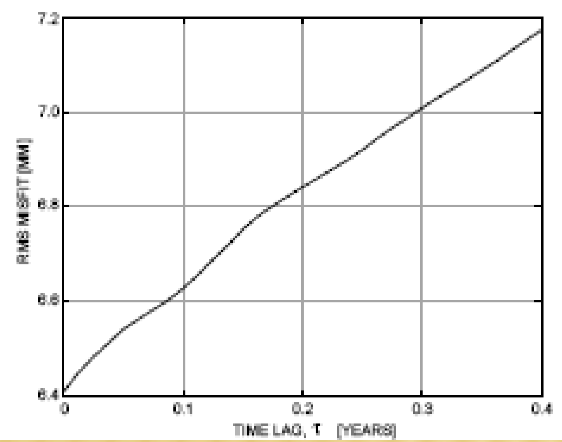


Paulson, A., http://grace.jpl.nasa.gov/data/pgr

Crustal response to loads
Annual lake loading

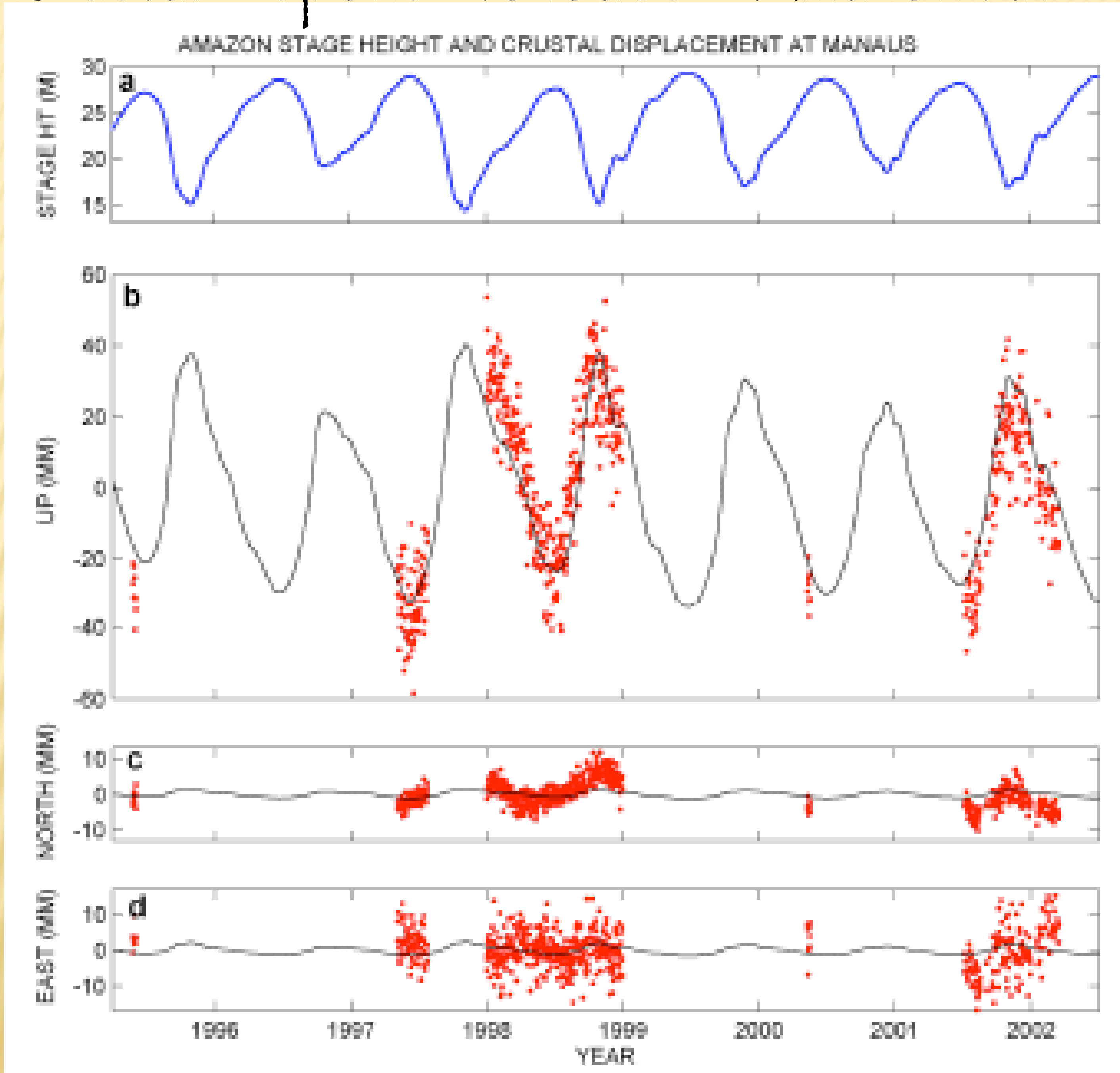






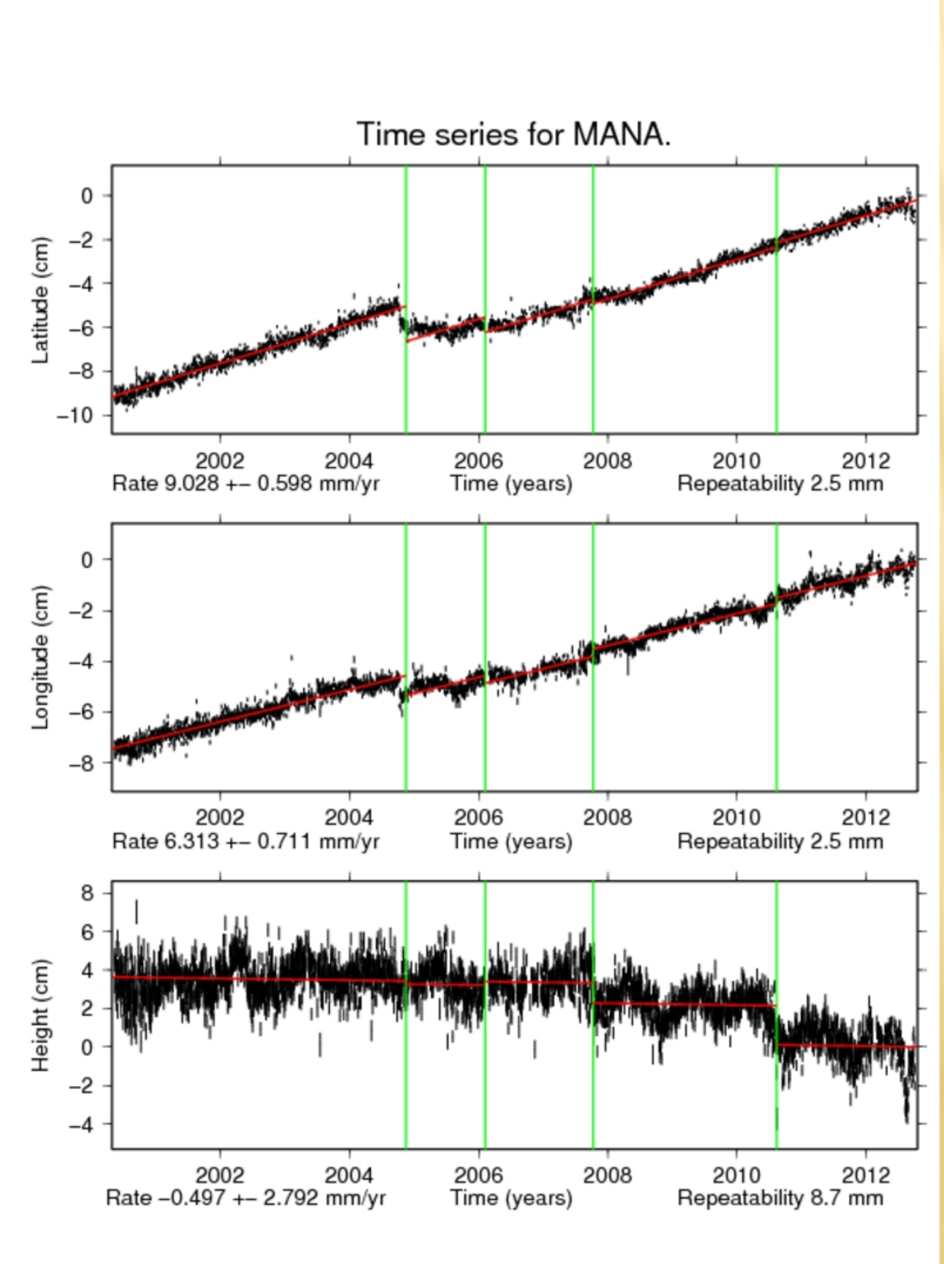
Check for anelasticity – no time lag/phase shift -> elastic.

Crustal response to loads – Amazon River



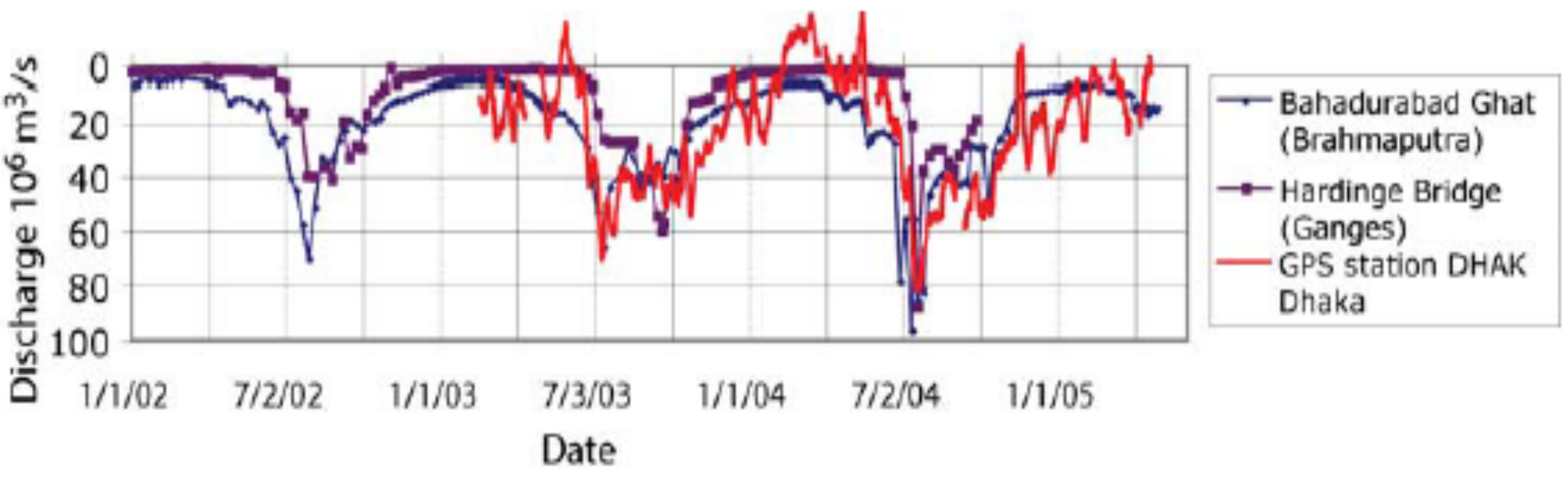
Bevis et al, 2005

Crustal response to loads – Amazon River



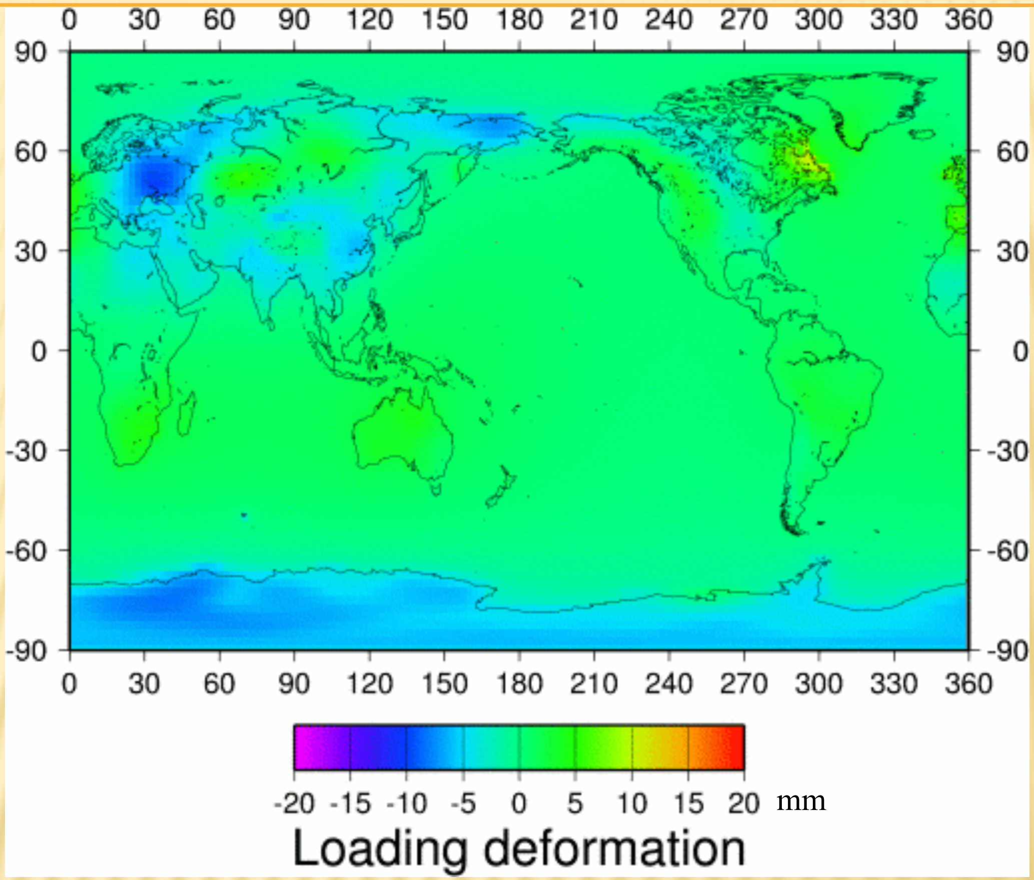
Response of crust to loading from Brahmaputra and Gandes

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.