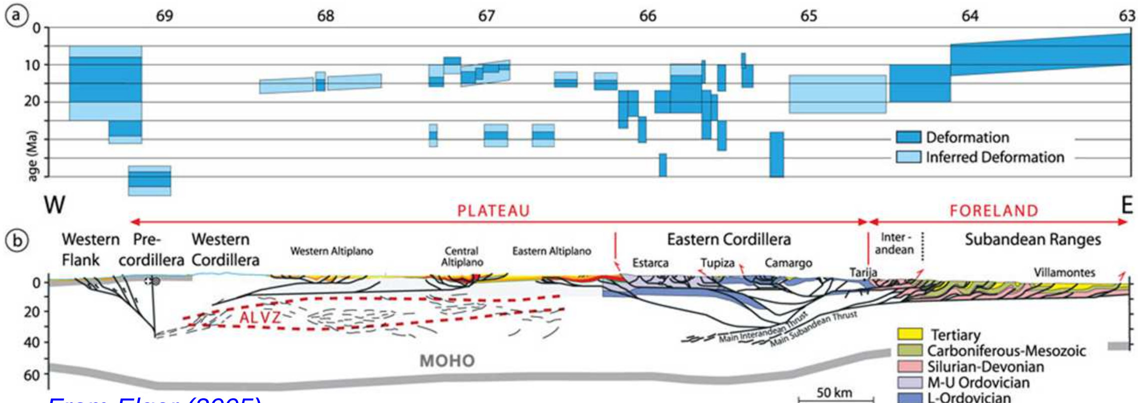
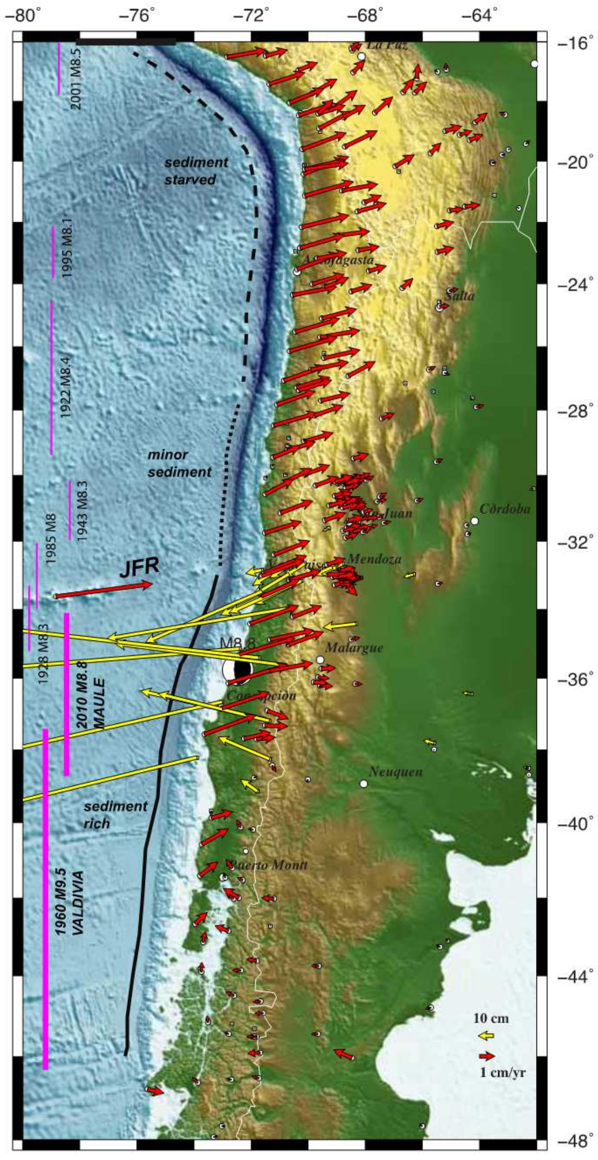
Mountain Belts and Earthquakes

Lessons from the Andes



From Elger (2005)



Michael Bevis

School of Earth Sciences

Ohio State University

Venzone, Italy, October 2011

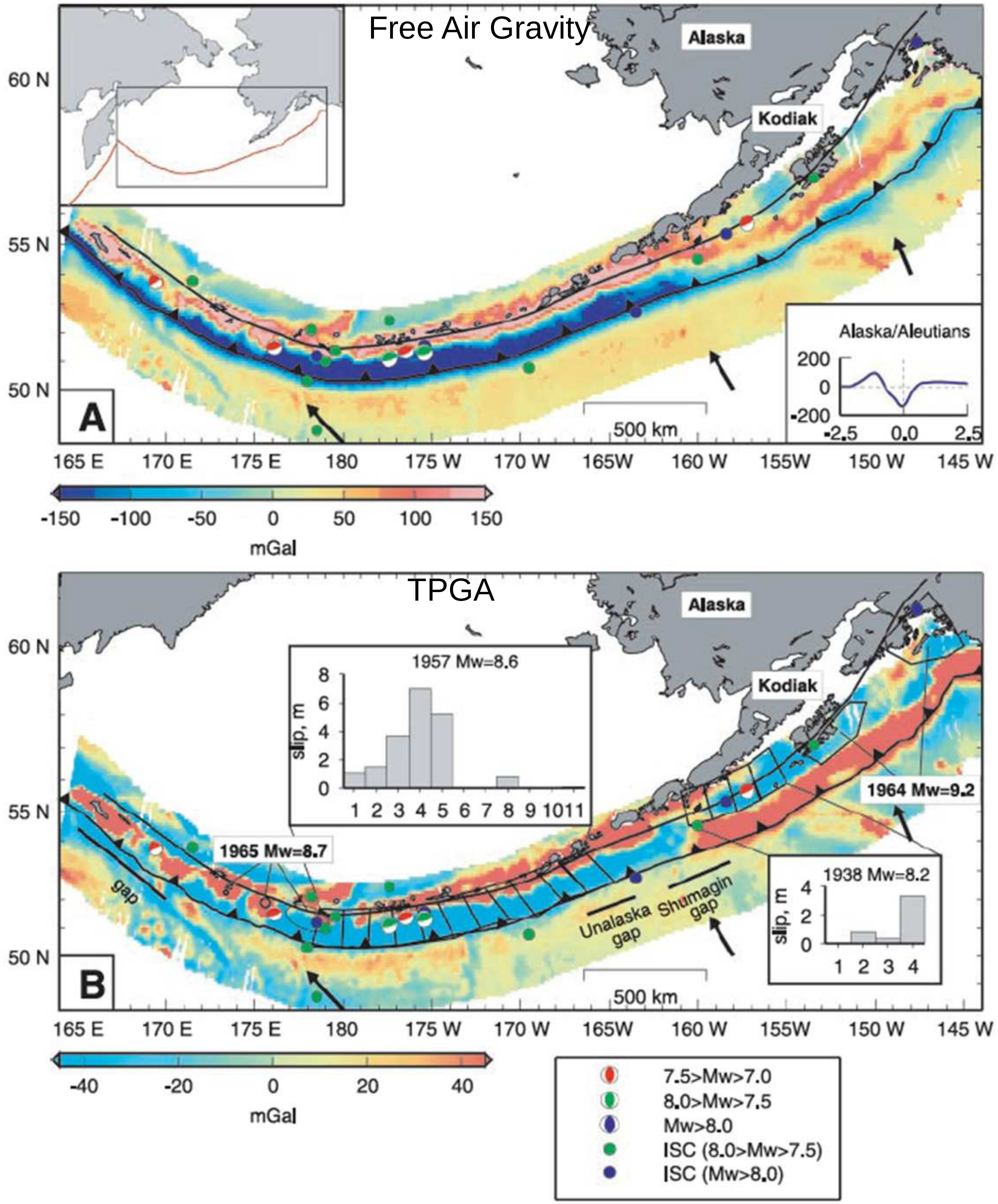
Two lessons from the Andes for Friuli

- Present-day geology controls aspects of seismogenesis as well as active tectonics

- 400 years of history in southern Bolivia probably misled us in the analysis of seismic risk – sometimes historically ‘aseismic’ areas can have very big earthquakes

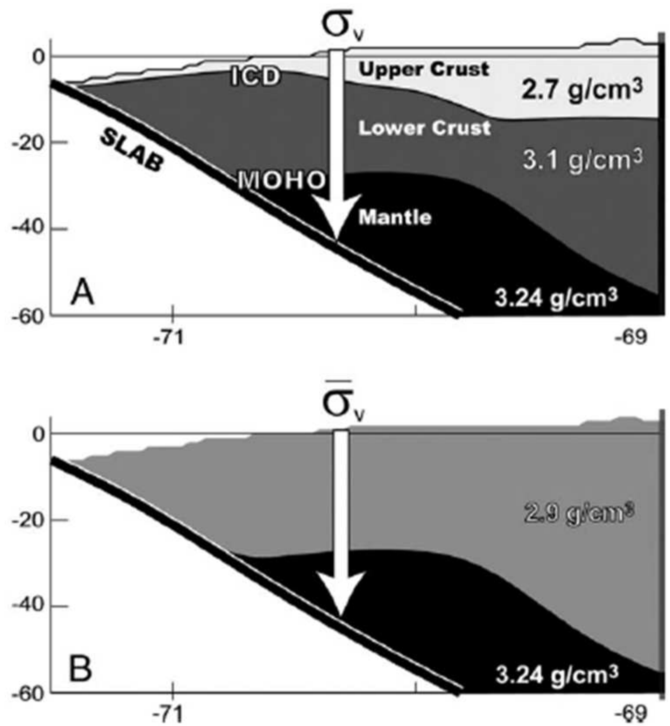
Song and Simons (2003)

Large earthquakes tend to occur in areas with strongly negative trench-parallel gravity anomalies



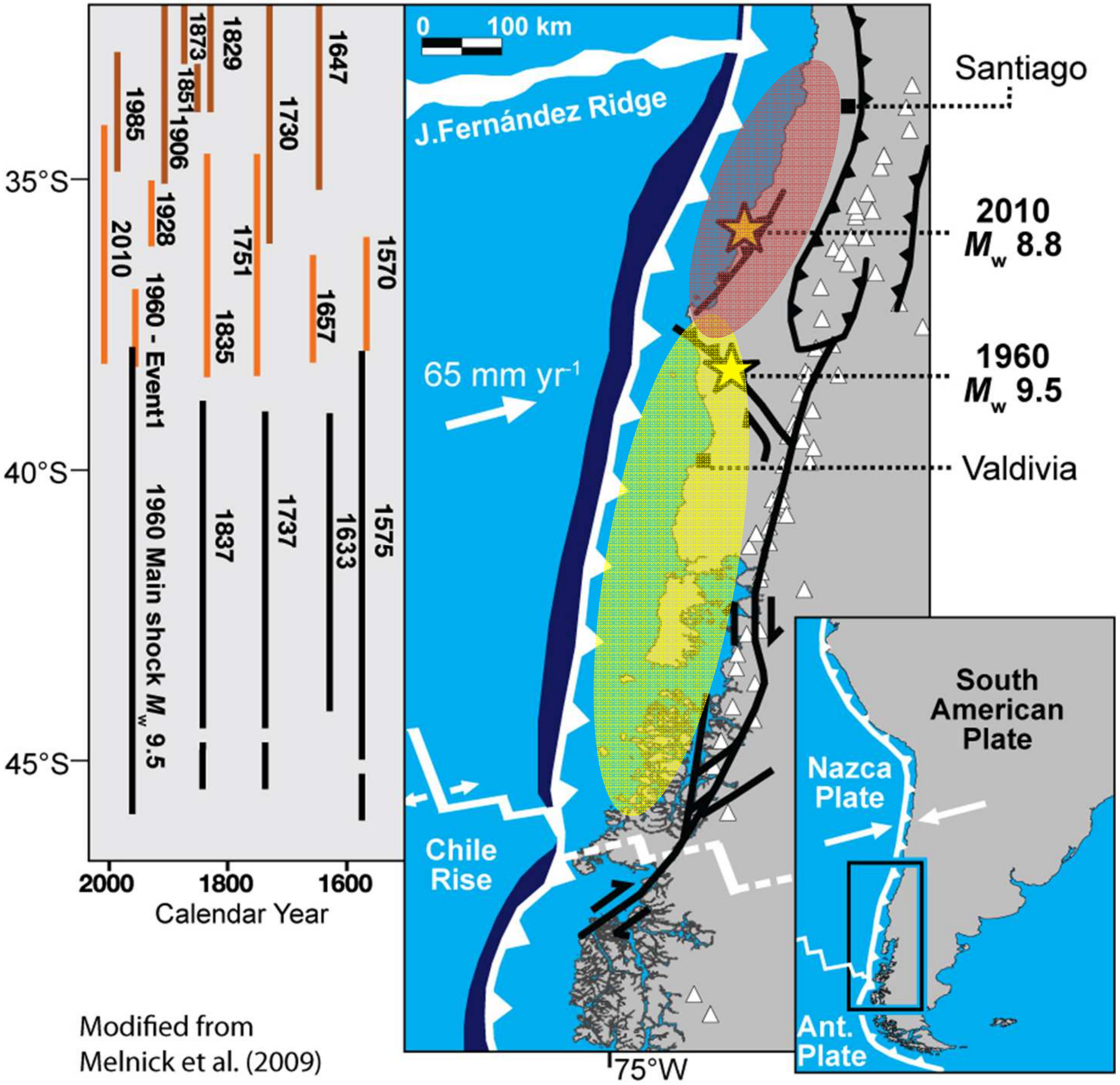
This finding suggests that seismogenic behavior is influenced by forearc structure. Song and Simons suggest that changes in frictional properties of the plate interface are the key control.

Tassara (2010) has estimated trench-parallel vertical stress anomalies (VSA) rather similar to the TPGA. They arise from variations in the density of the forearc.



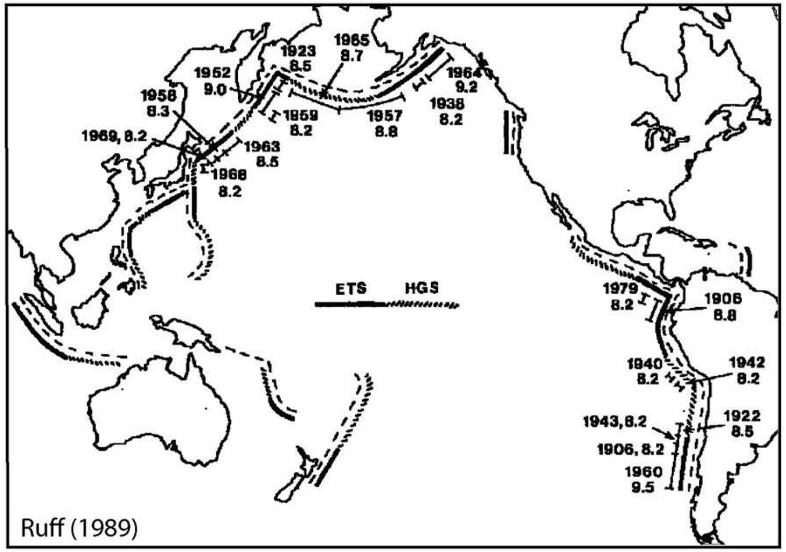
He claims normal stress influences megathrust shear strength and thus seismogenic behavior.

THE 2010 MAULE AND 1960 VALDIVIA EVENTS

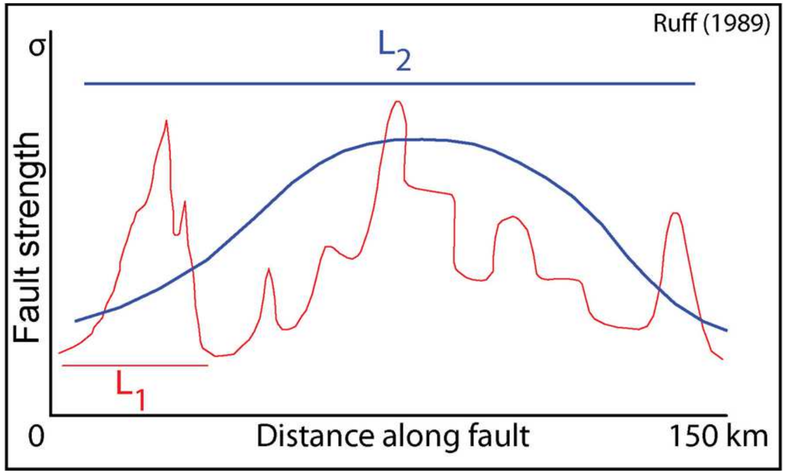


Modified from
Melnick et al. (2009)

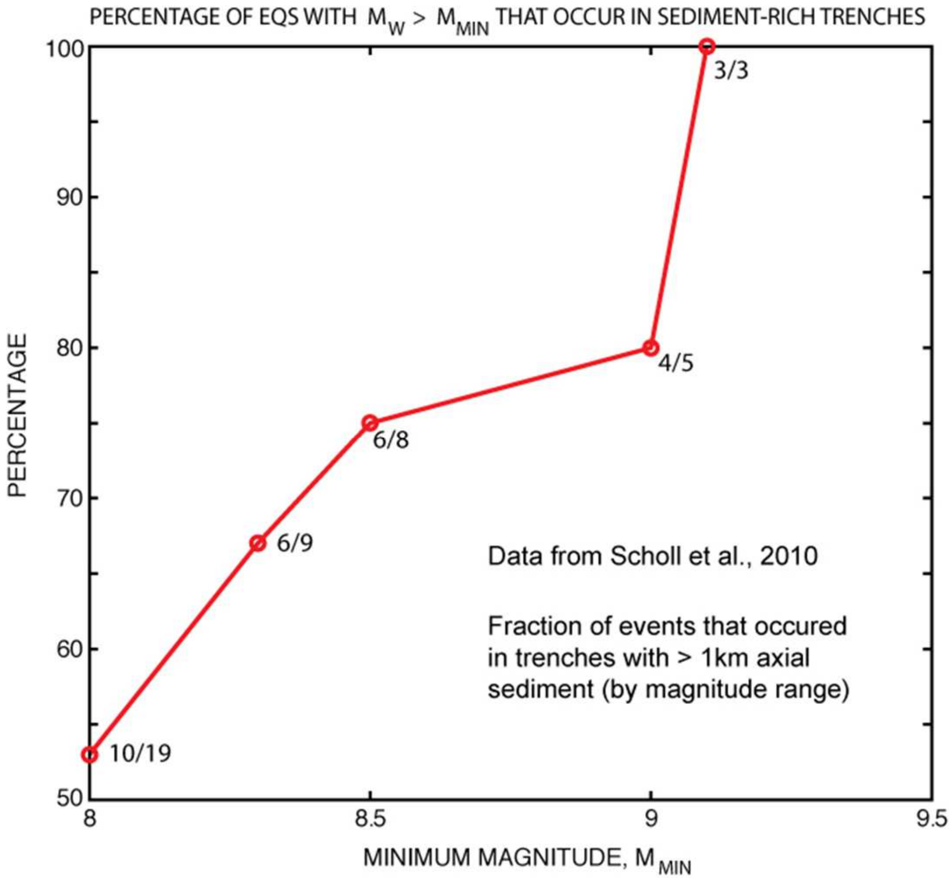
GEOLOGICAL CONTROLS



ETS= Excess Trench Sediments HGS = Horst & Graben Structure



Ruff (1989) noted a correlation between great earthquakes and trench sediments, and hypothesized that sediments promote a smoother strength profile that allows ruptures to grow to great size.

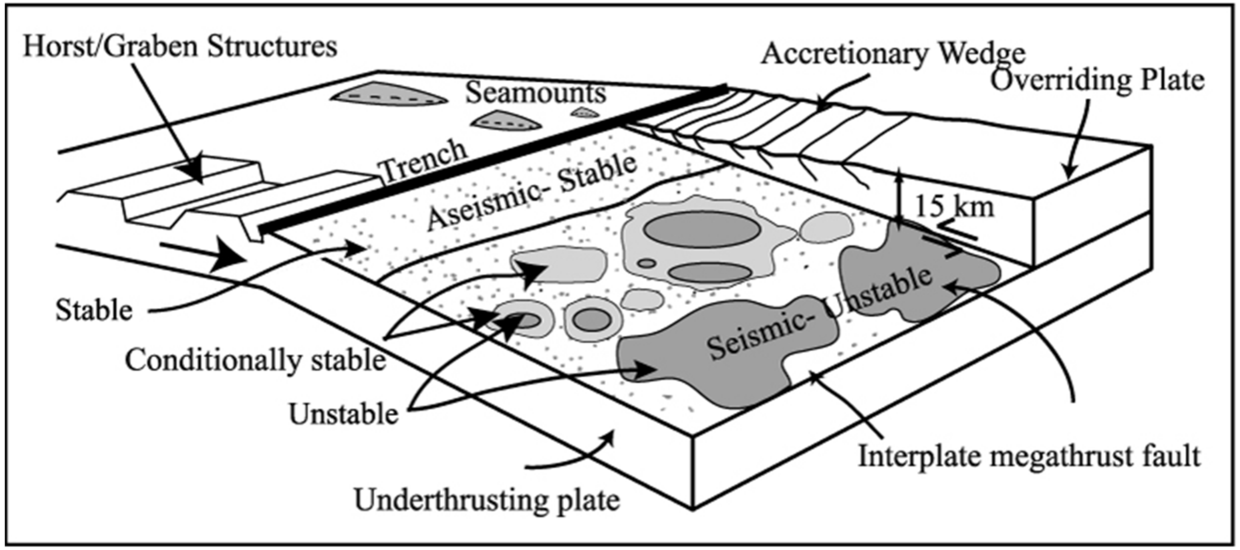


RATE & STATE FRICTION MODELS

There is a growing body of evidence suggesting that:

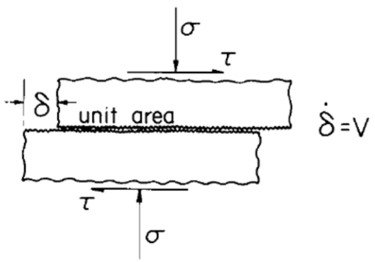
• afterslip following a great earthquake is largely confined to areas where little or no coseismic slip occurred

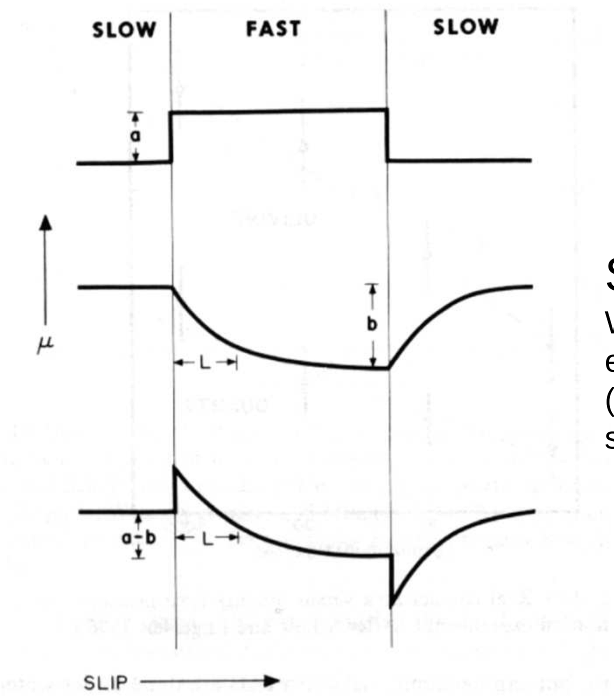
• this spatial segmentation of the megathrust is *persistent* at geological time scales, so it is probably related to geological structure or composition



A cartoon by Lay and Schwartz (2004) indicating how a megathrust is partitioned into stable, conditionally stable and unstable patches or domains. The unstable patches, associated with velocity weakening *friction, only slip seismically, whereas the stable patches, associated with* velocity strengthening *friction, move by creeping .*

Rate and State Friction Laws (Dieterich, 1979; 1981; Ruina, 1983)





Rate effect

When sliding velocity changes so does frictional resistance or shear strength

State effect

When sliding velocity changes frictional resistance evolves towards a new strength
(L or Dc, the critical slip distance, characterizes system 'memory')

Rate & State

state variable

Frictional shear stress equation

$$\tau = \sigma_n [\mu_0 + a \ln(V / V_0) + b \ln(V_0 \theta / D_c)]$$

'rate' effect *'state' effect*

normal stress

initial coefficient of friction

- Materials are 'velocity weakening' or 'velocity strengthening'
- Velocity stengthening materials engage in stable creeping behavior
- Velocity weakening materials can engage in unstable 'stick-slip' behavior (earthquakes), but also 'conditionally stable' behavior in which the fault is stable under static loading but instability can be trigged by dynamic stress changes

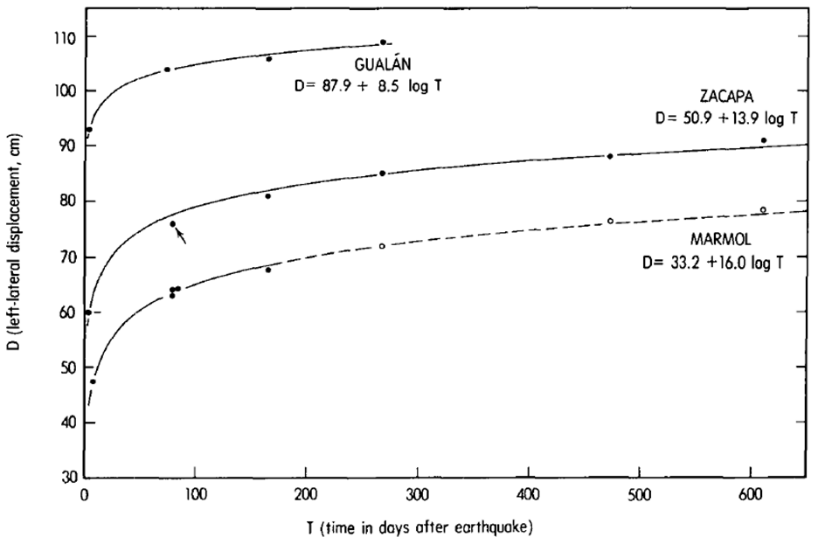
Dieterich: $\frac{d\theta}{dt} = 1 - \frac{V\theta}{D_c}$

Ruina: $\frac{d\theta}{dt} = -\frac{V\theta}{D_c} ln\left(\frac{V\theta}{D_c}\right)$

Afterslip (fault slip that occurs *after* an earthquake)

Bucknam et al., 1978 *Geology*

Afterslip following 1976 Guatamala EQ



Marone et al., 1991 *JGR*

Afterslip explained using rate and state friction models (Dieterich, 1979; 1981; Ruina, 1983)

$$d(t) = A \ln(1 + t / \tau)$$

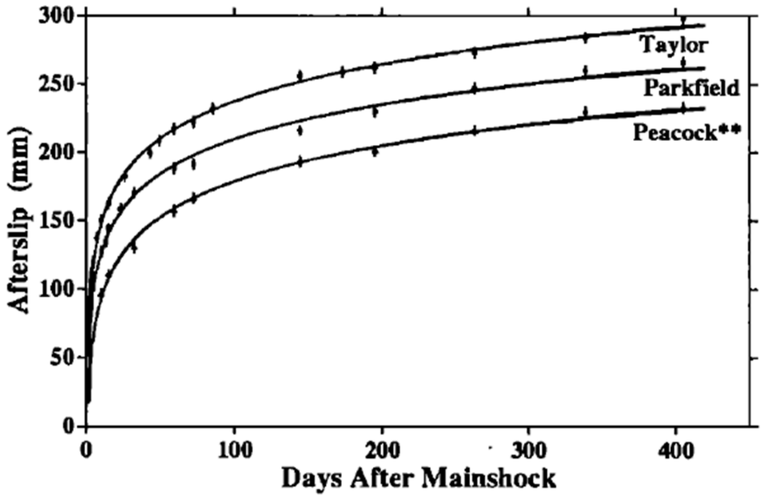
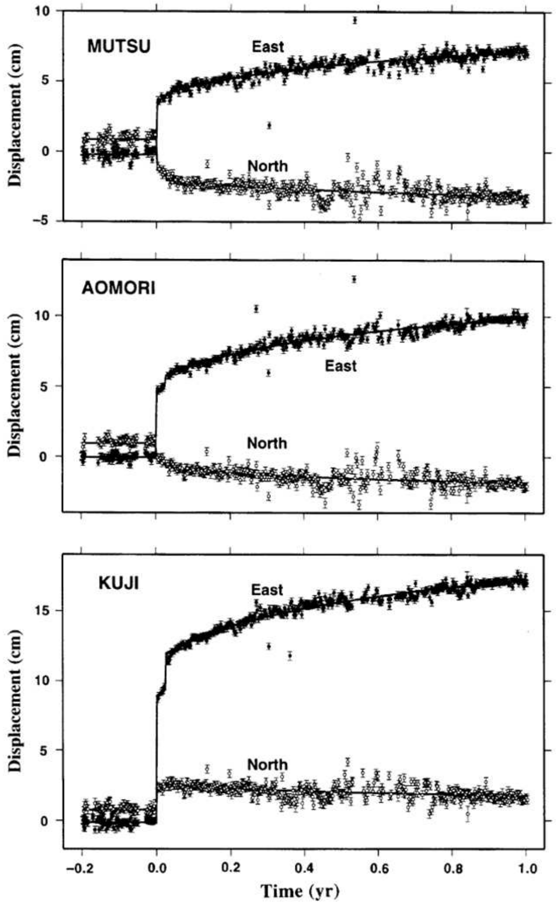


Fig. 8. Comparison of afterslip measurements with curves generated using equation (5) and the parameters given in Table 2. Error bars are ±4 mm. Data from *Smith and Wyss* [1968].



Silent fault slip following an interplate thrust earthquake at the Japan Trench

Kosuke Heki*, Shin'ichi Miyazaki† & Hiromichi Tsuji‡

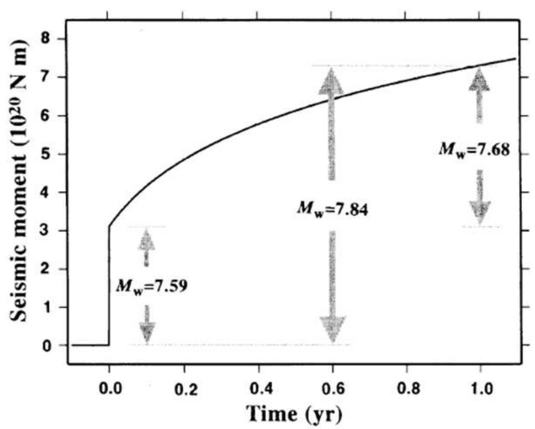
Heki et al., 1997
Sanriku-Haruka-Oki EQ sequence of Dec 1994

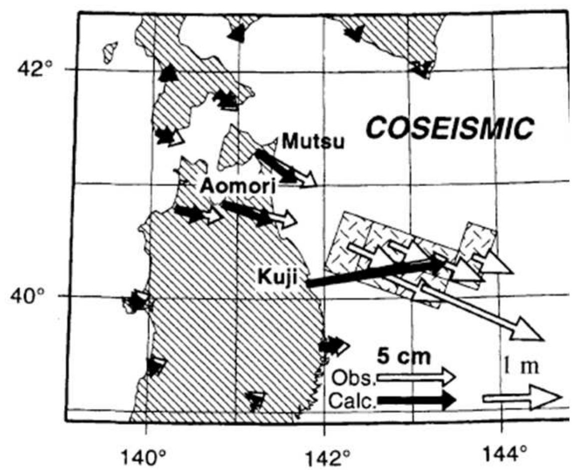
Japan's CGPS network detects widespread postseismic movements driven by afterslip.

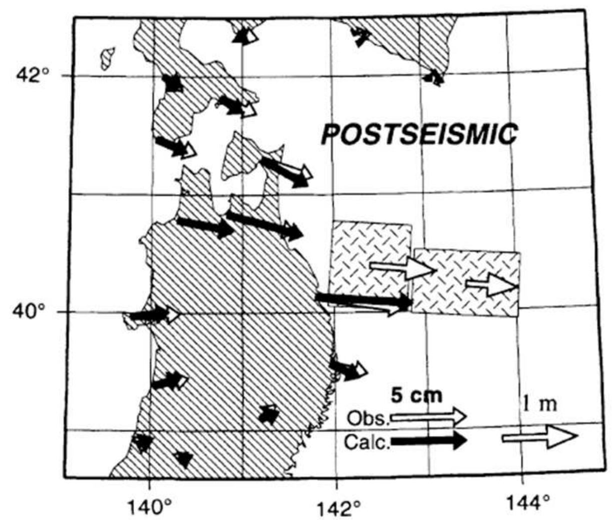
Time behavior of this displacement follows the prediction of rate and state friction theory, i.e. d = A ln(1 + t / τ)

The seismic moment (M=∫As) associated with afterslip can be comparable to that associated with the coseismic slip

Much if not most of the afterslip does not spatially overlap the coseismic slip.



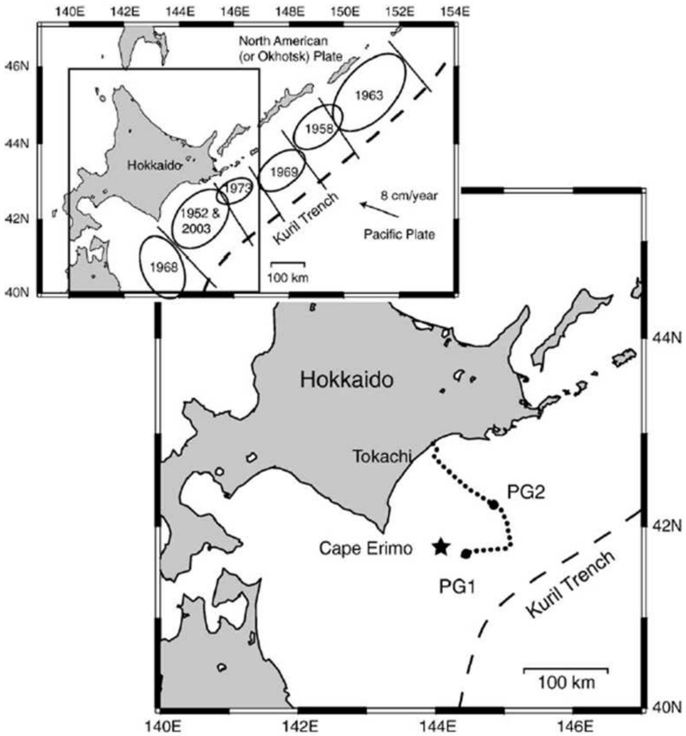




Coseismic Slip versus Afterslip Distributions

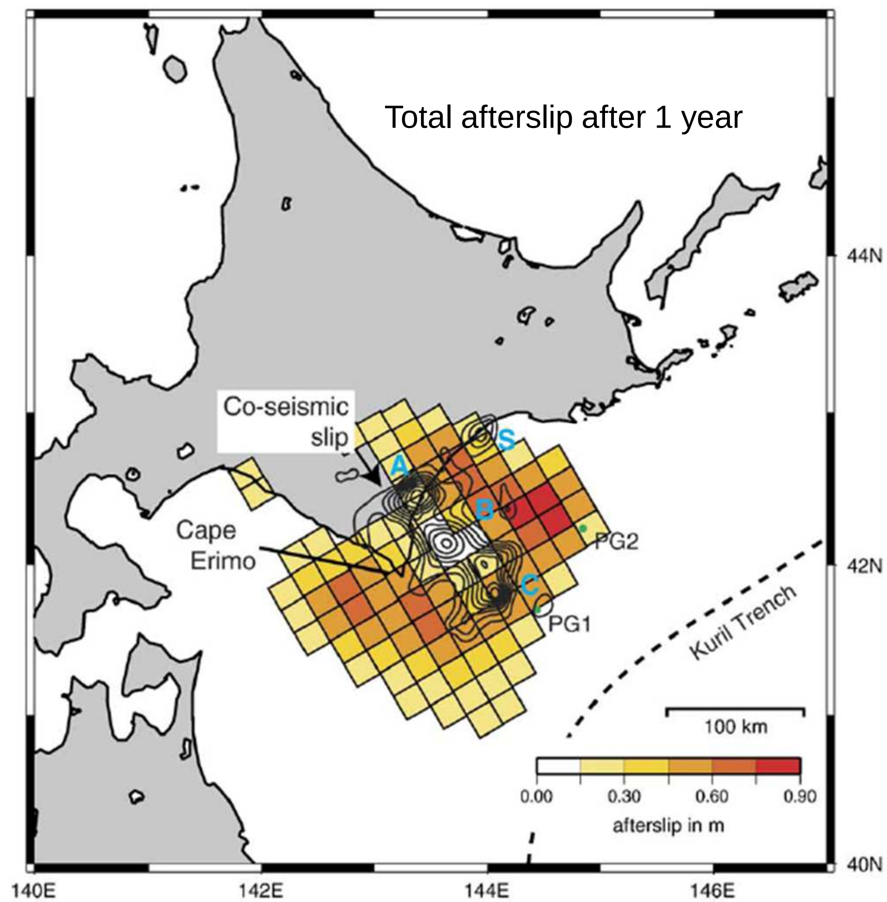
2003 (M 8.0) Tokachi-oki Earthquake

Baba et al. (2006)



Afterslip has a U-shaped pattern that 'surrounds' the zone of coseismic slip.

T. Baba et al. / Earth and Planetary Science Letters 241 (2006) 281–292



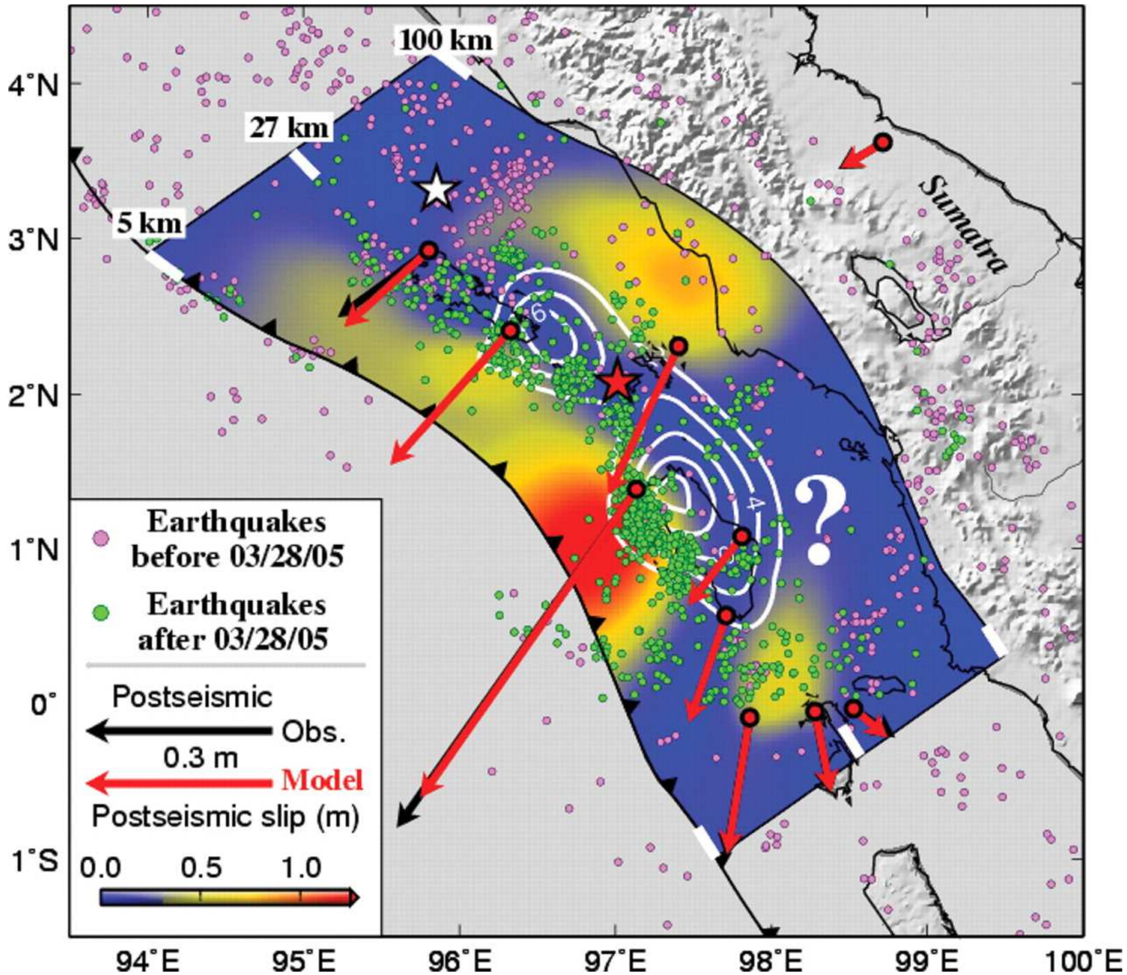
Coseismic slip vs afterslip is not controlled by P,T conditions which would imply strong zonation organized by depth. Perhaps the distinct slip domains are controlled by frictional properties of the megathrust. If material composition controls frictional properties, these patterns should be *persistent*.

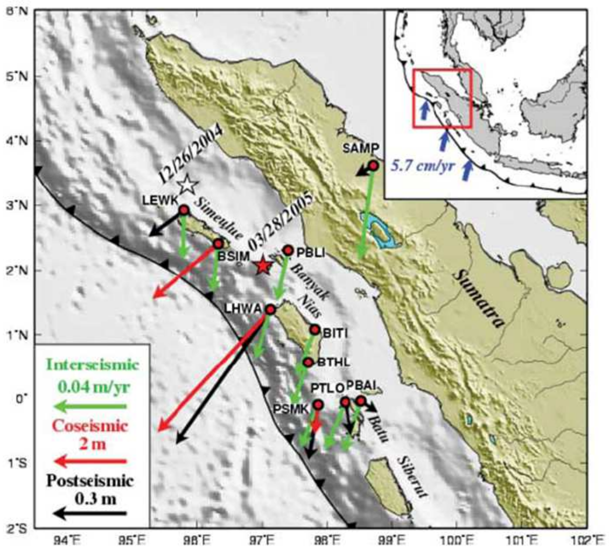
Coseismic Slip versus Afterslip Distributions

2005 Nias-Simeulue (M 8.7) Megathrust Event

Hsu et al. (2006)

White contours : coseismic slip (2 m intervals)





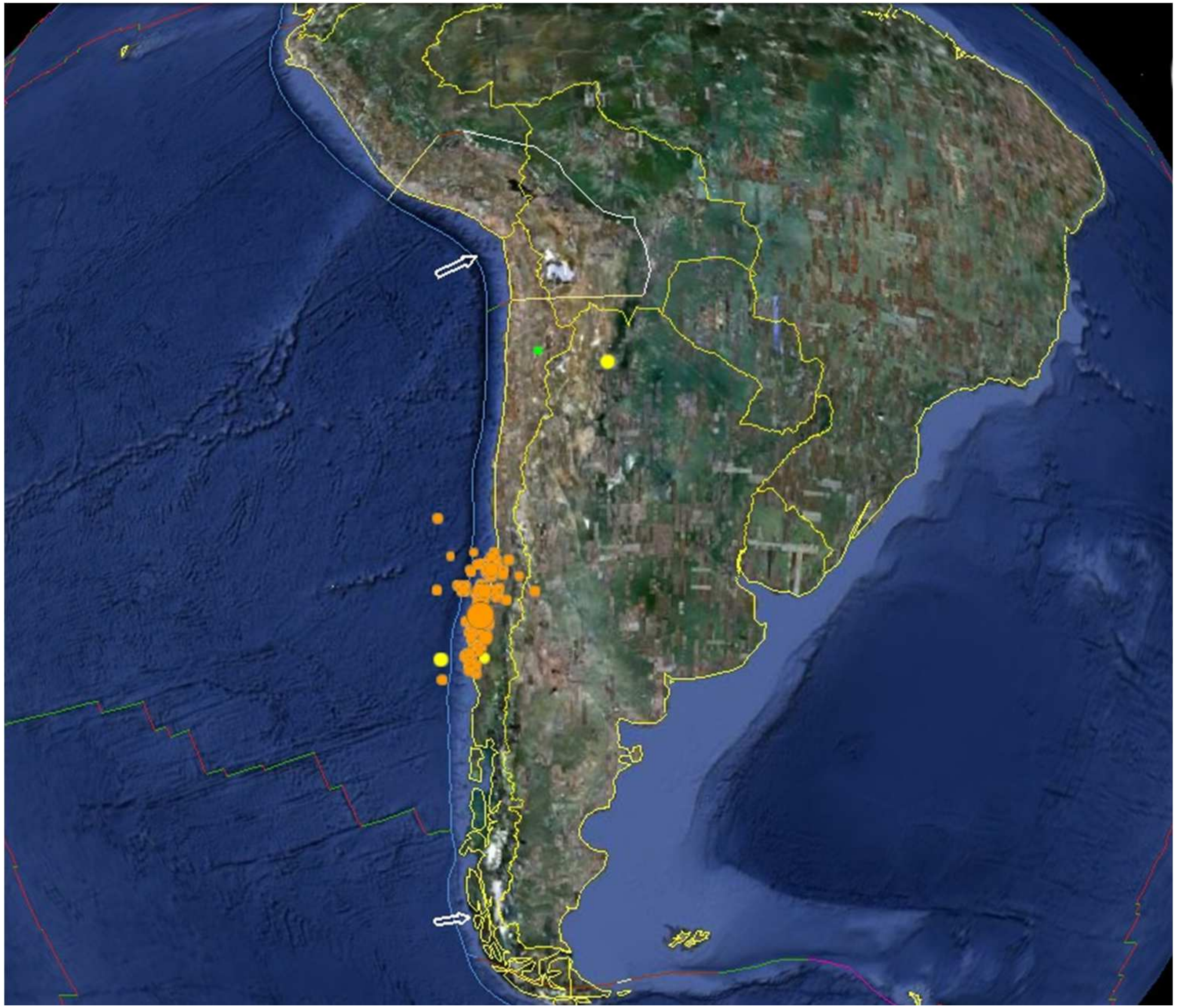
- Coseismic slip and afterslip seem to have *complementary* spatial distributions

- A similar finding was made for the 2007 (M 8.0) Pisco earthquake in Southern Peru by Perfettini et al. (2010)

- There are *many* more GPS stations in the Maule region (and better InSAR coverage too), so we will better resolve the coseismic and afterslip distributions and provide a far stronger test of the hypothesis of complementarity

Mw 8.8 MAULE, CHILE

Saturday, February 27, 2010 at 06:34:17 UTC



The Maule Earthquake

Saturday, February 27, 2010
3:34 AM (local time)

Moment magnitude 8.8

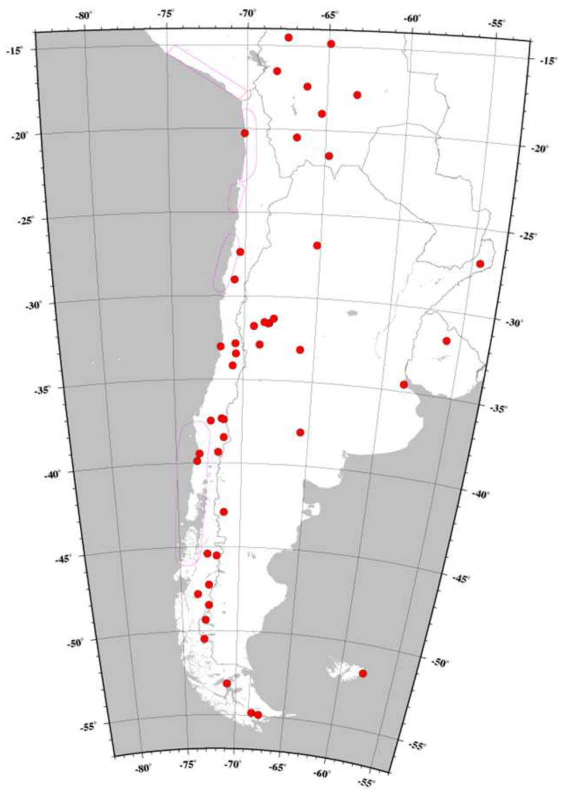
460 aftershocks in next 30 days

Fatalities ~ 400
Economic damage ~ US$ 30 billion

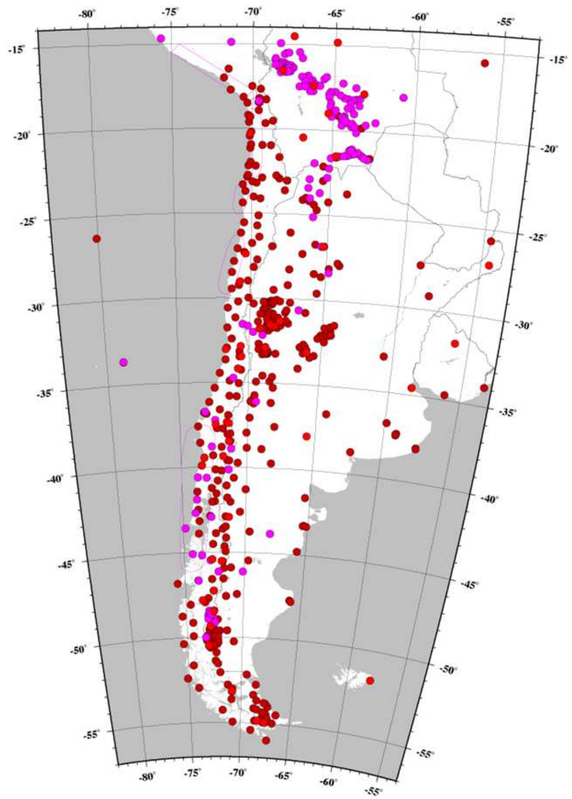
Scientific value ~ priceless

CAP = <u>C</u>entral and Southern <u>A</u>ndes GPS <u>P</u>roject

CAP began operations in 1993 and has functioned continuously since then. It has been funded by NSF and NASA, and using university funds. It has constructed a dual use GPS network. The CAP network supports a variety of scientific research agendas but also constitutes a large fraction of the spatial reference system of its host countries.



Continuous GPS or CORS stations (2009)



Survey or campaign GPS stations (2009)

CAP Partner Institutions

USA:
Ohio State University
University of Memphis
University of Hawaii

Chile:
Instituto Geográfico Militar
Universidad de Concepción
Centro de Estudios Científicos
Universidad de Magallanes
Universidad de Talca

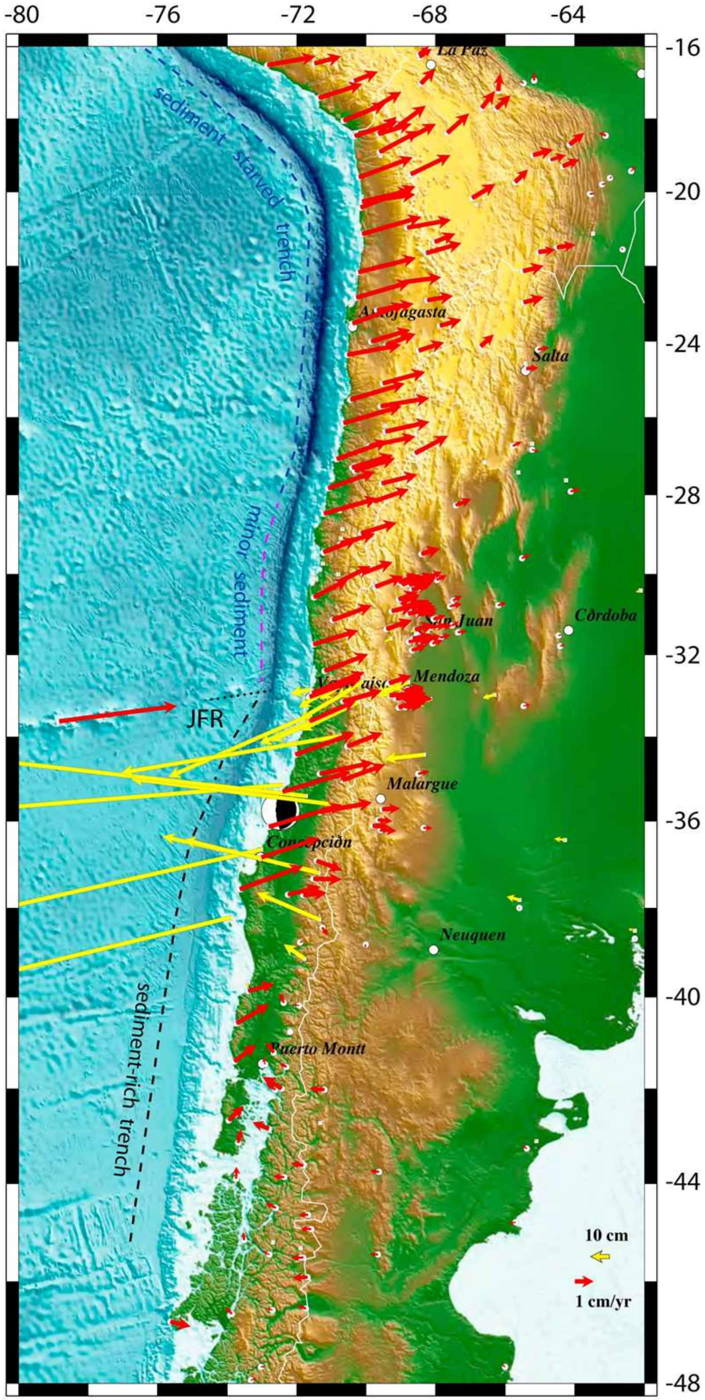
Argentina:
Instituto Geográfico Nacional
Universidad Nacional de Cuyo
Universidad de Tucumán
Instituto Nacional de Prevención Sísmica
Universidad de Buenos Aires
Administración Nacional de Parques

Bolivia:
Instituto Geográfico Militar
Observatorio San Calixto

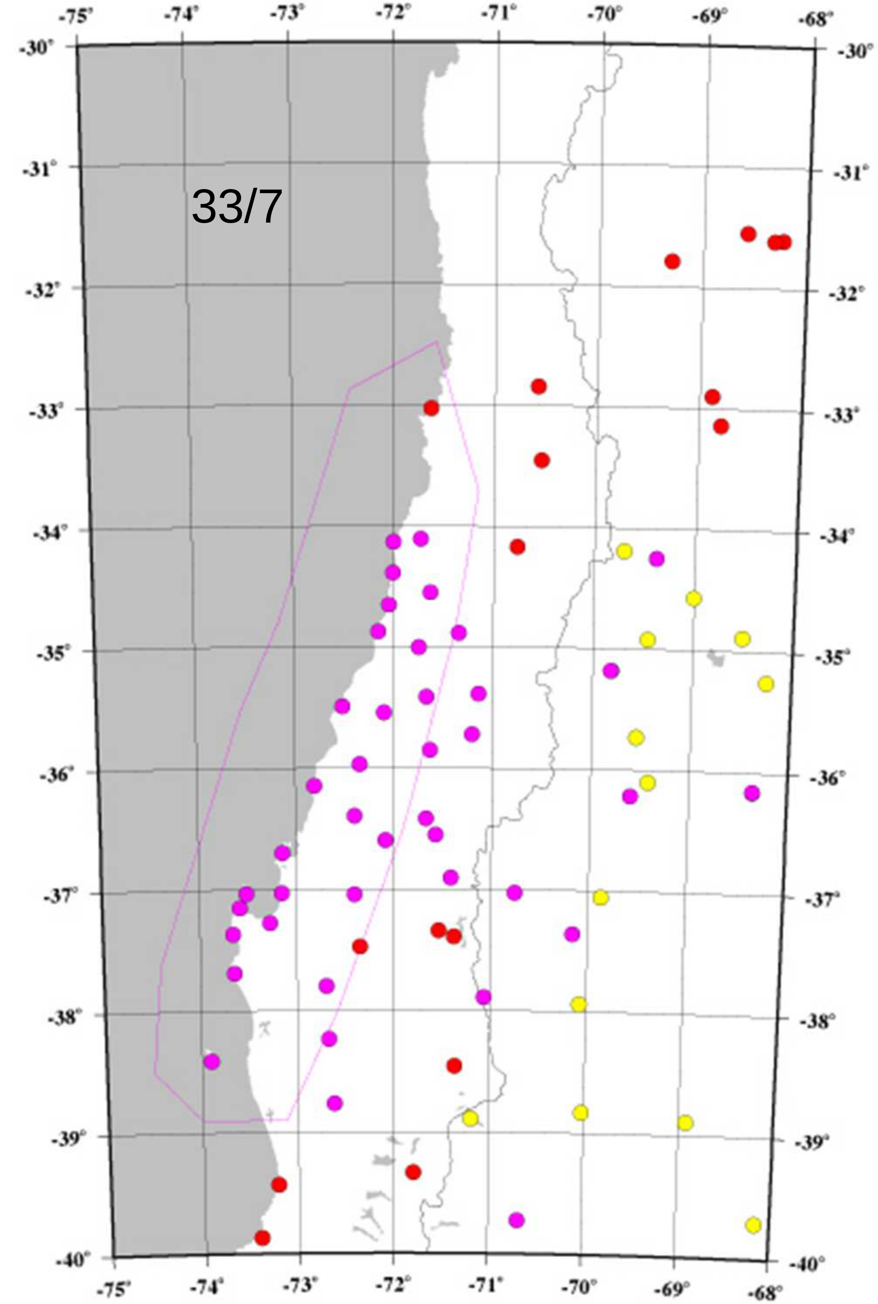
Post Maule EQ

CAP joins forces with
Caltech **GFZ**
UNAVCO **University of Potsdam**
University of Liverpool

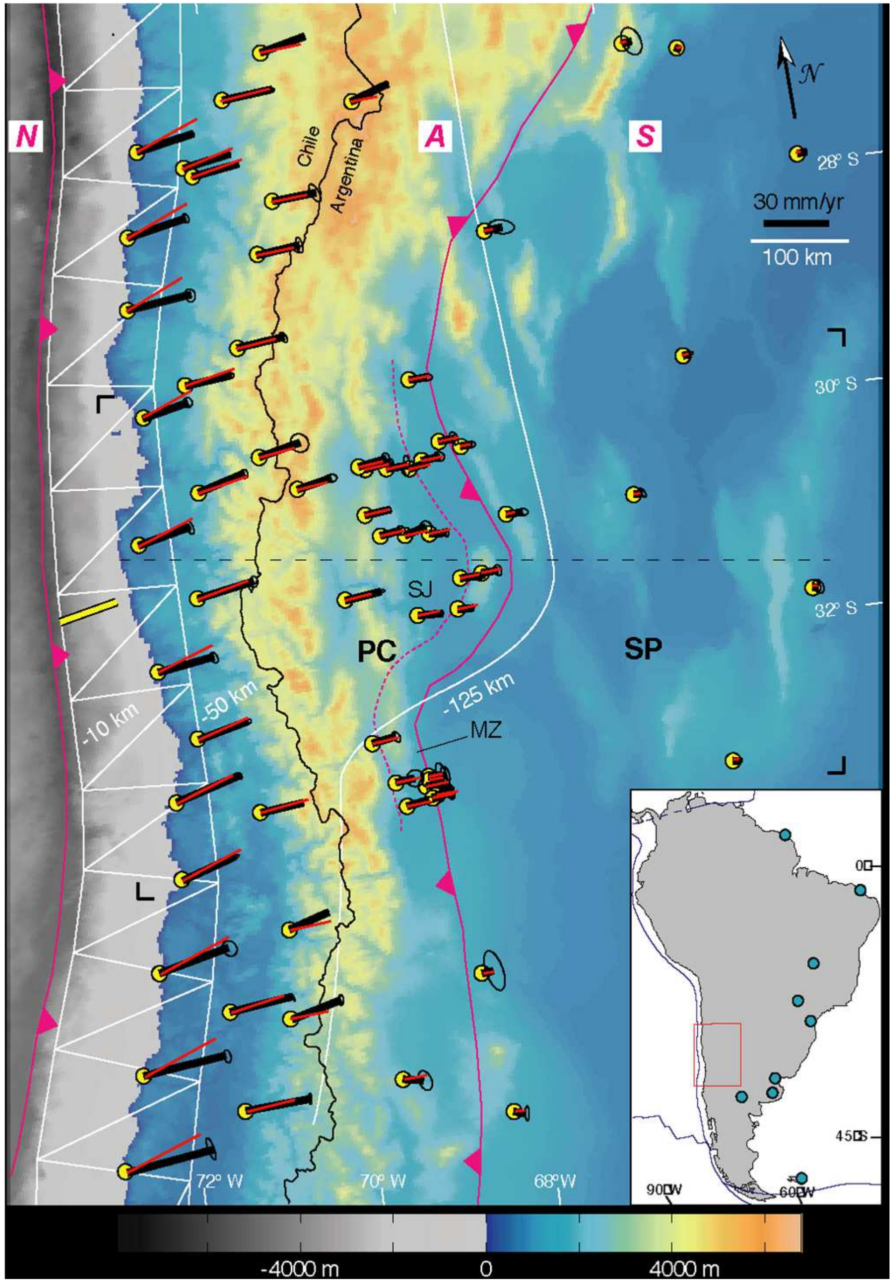
EMERGENCY GEODETIC RESPONSE USING NSF *RAPID* FUNDING



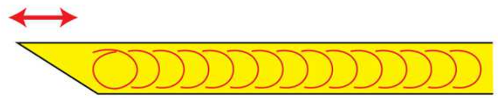
Red - pre-existing CAP (Central Andes GPS Project) continuous GPS stations.
Yellow - pre-existing CAP campaign GPS stations remeasured after Maule earthquake.
Purple - new continuous GPS stations installed after Maule earthquake.



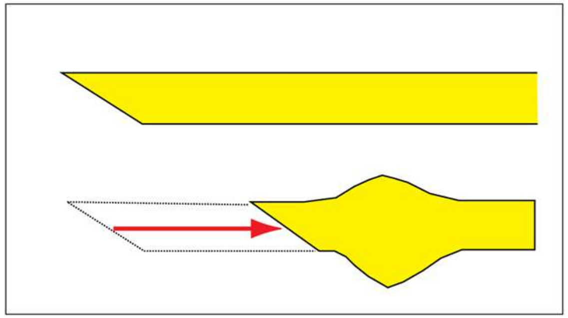
Interseismic Deformation

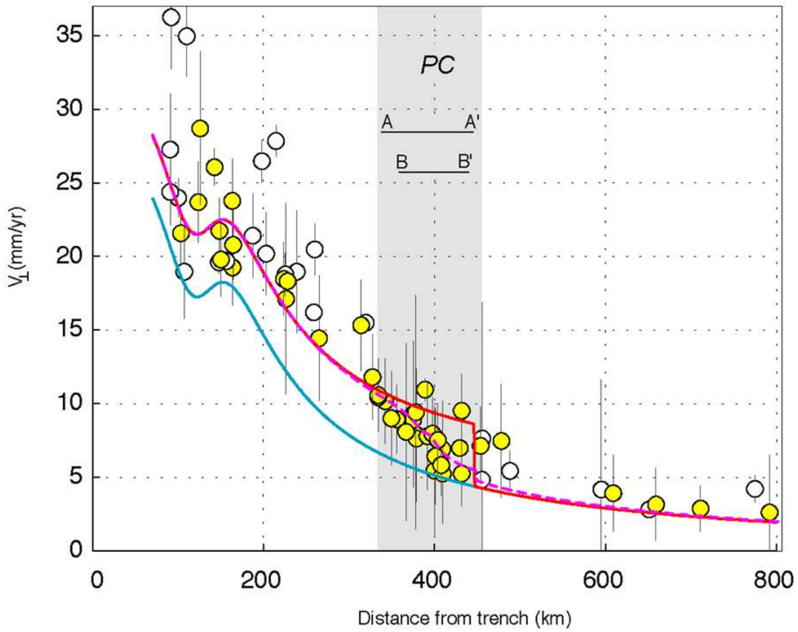


EQ deformation cycle (elastic)

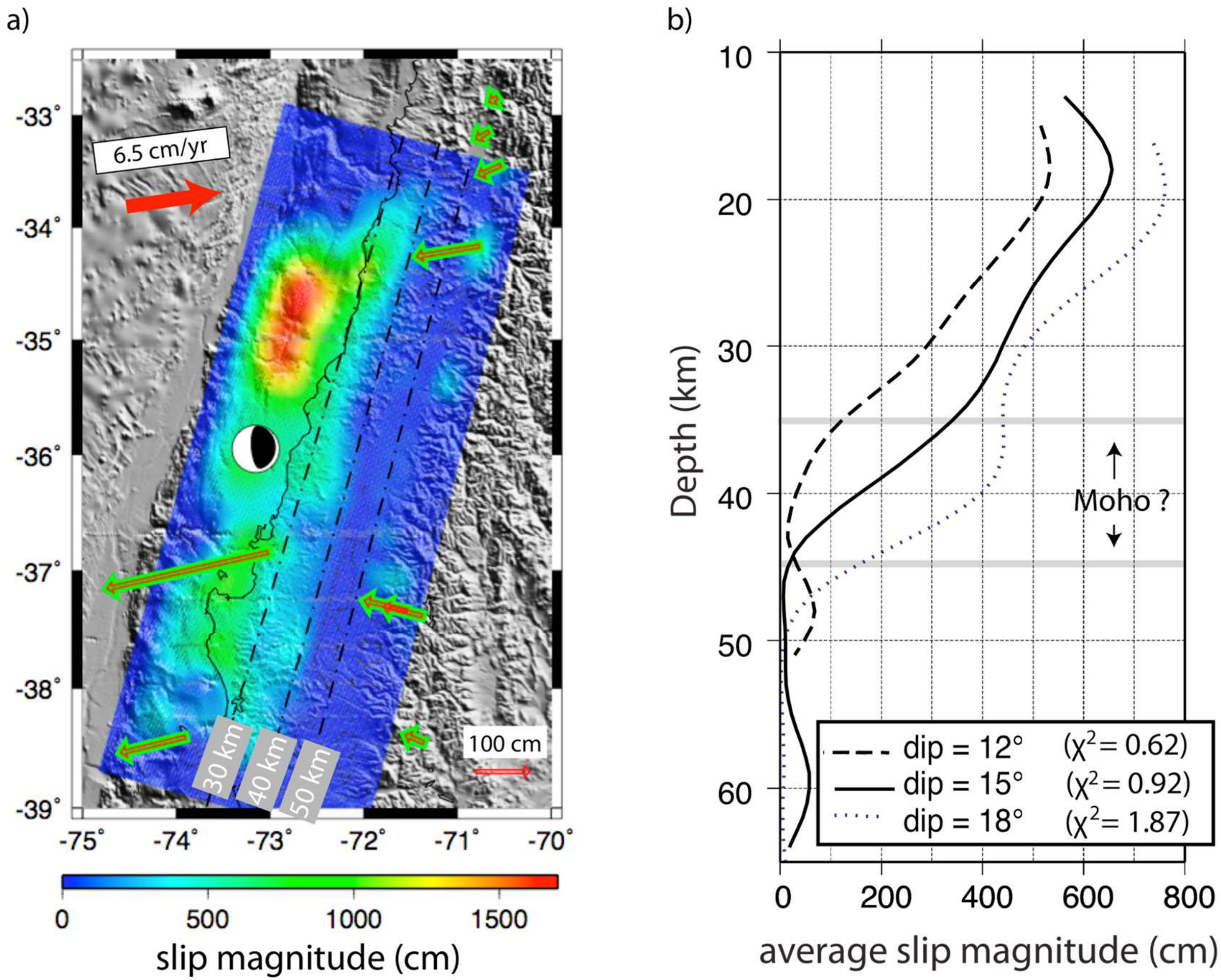


Orogenic deformation (plastic)



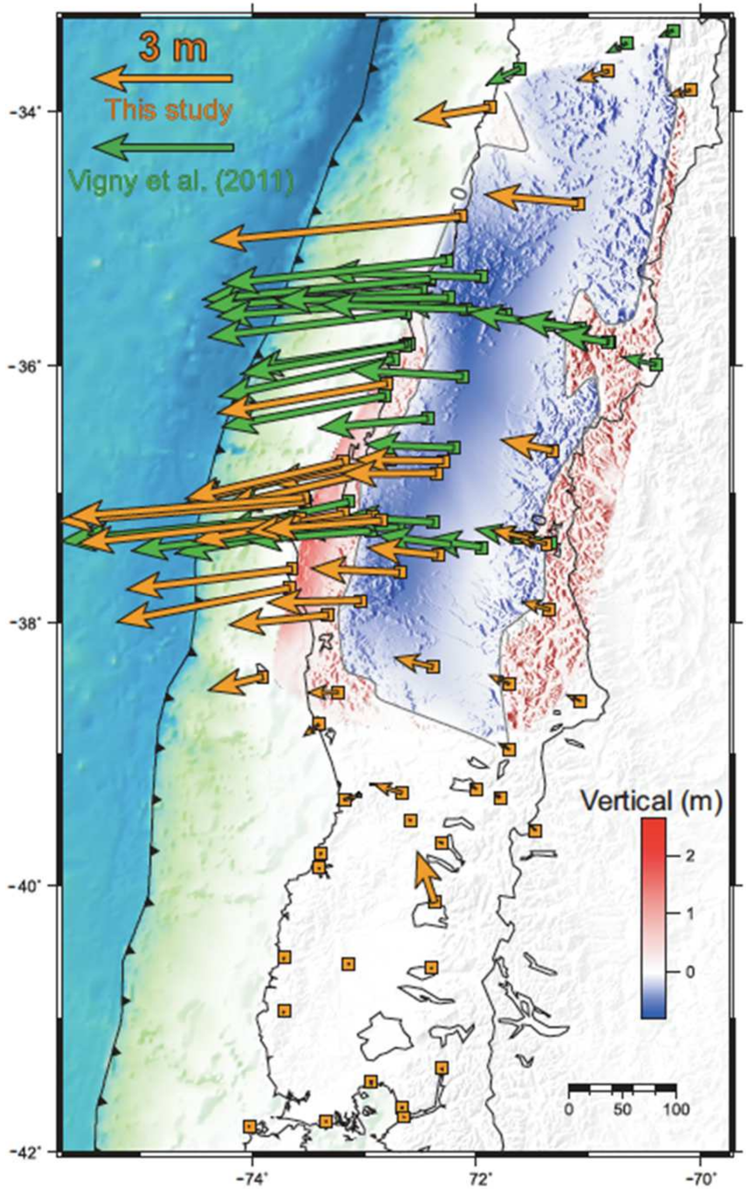


Coseismic slip distribution and composition of the hanging wall

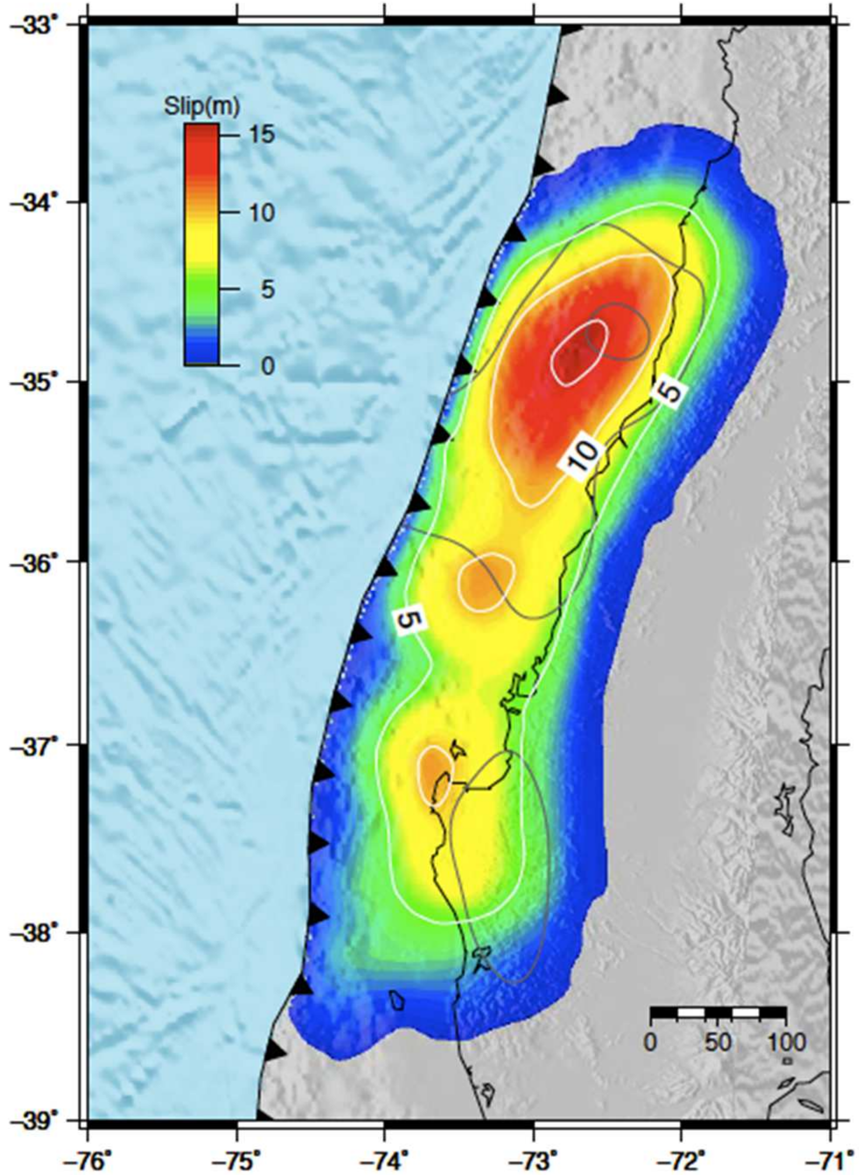


From Tong et al., 2011, GRL

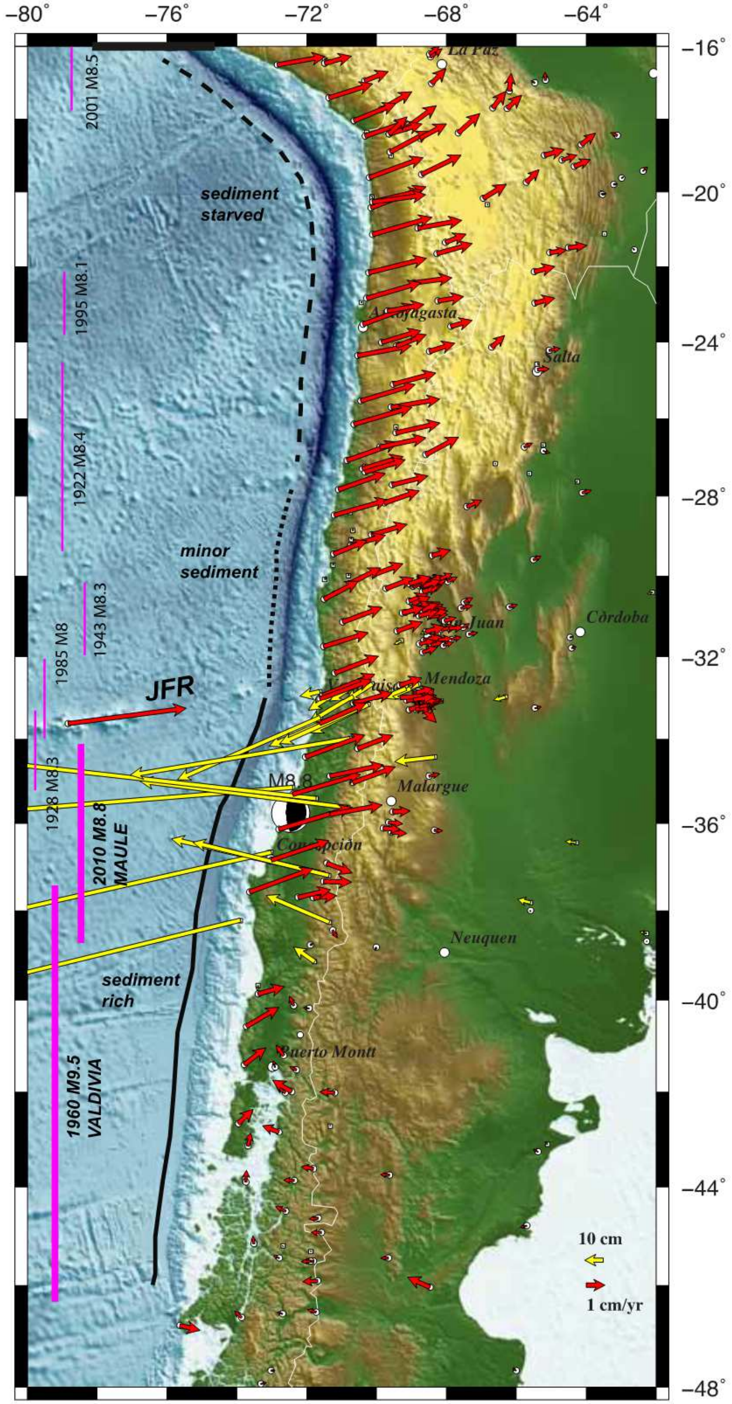
Moreno et al. (in review, 2011)



Coseismic Displacements (GPS)

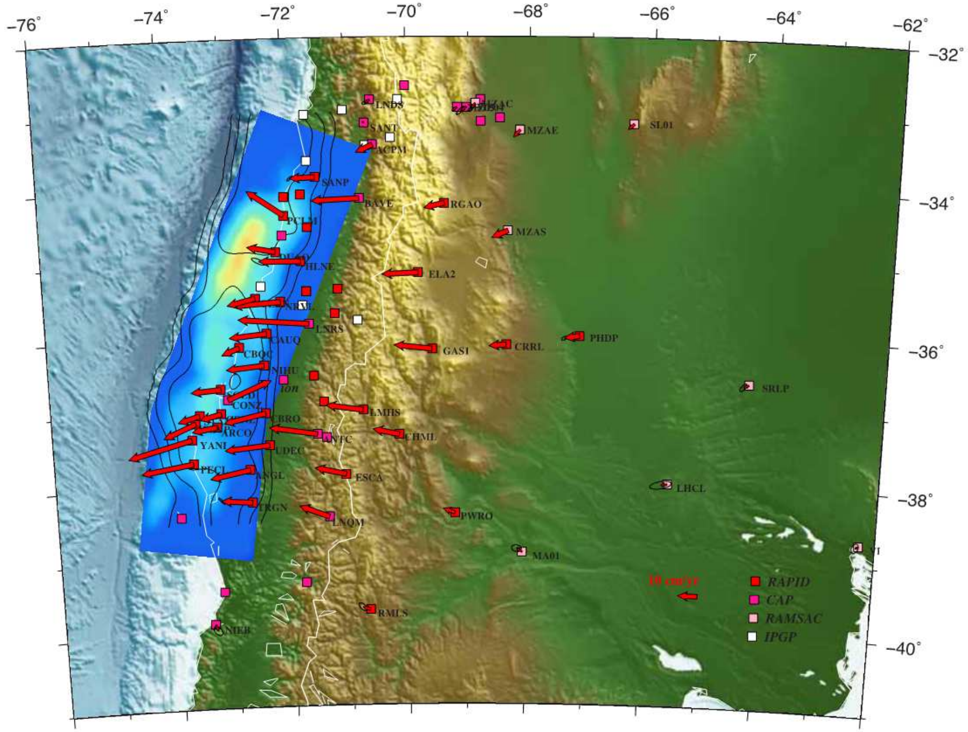


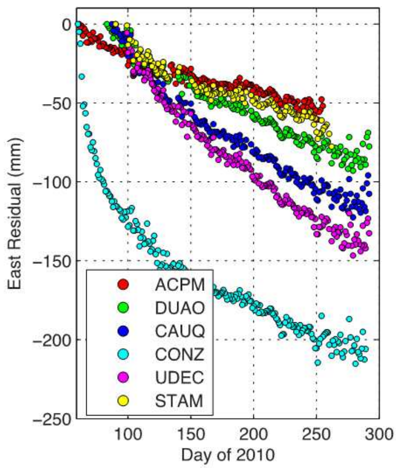
Coseismic Slip Distribution from InSAR, GPS & Coastal Uplift

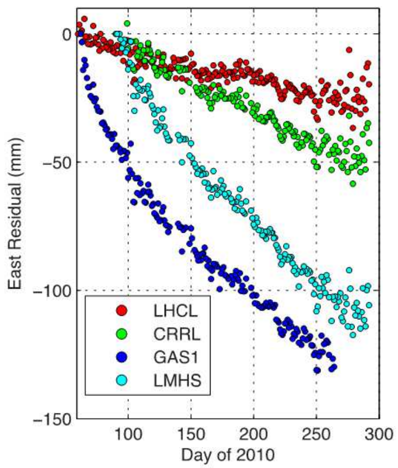


Postseismic motion following Maule EQ

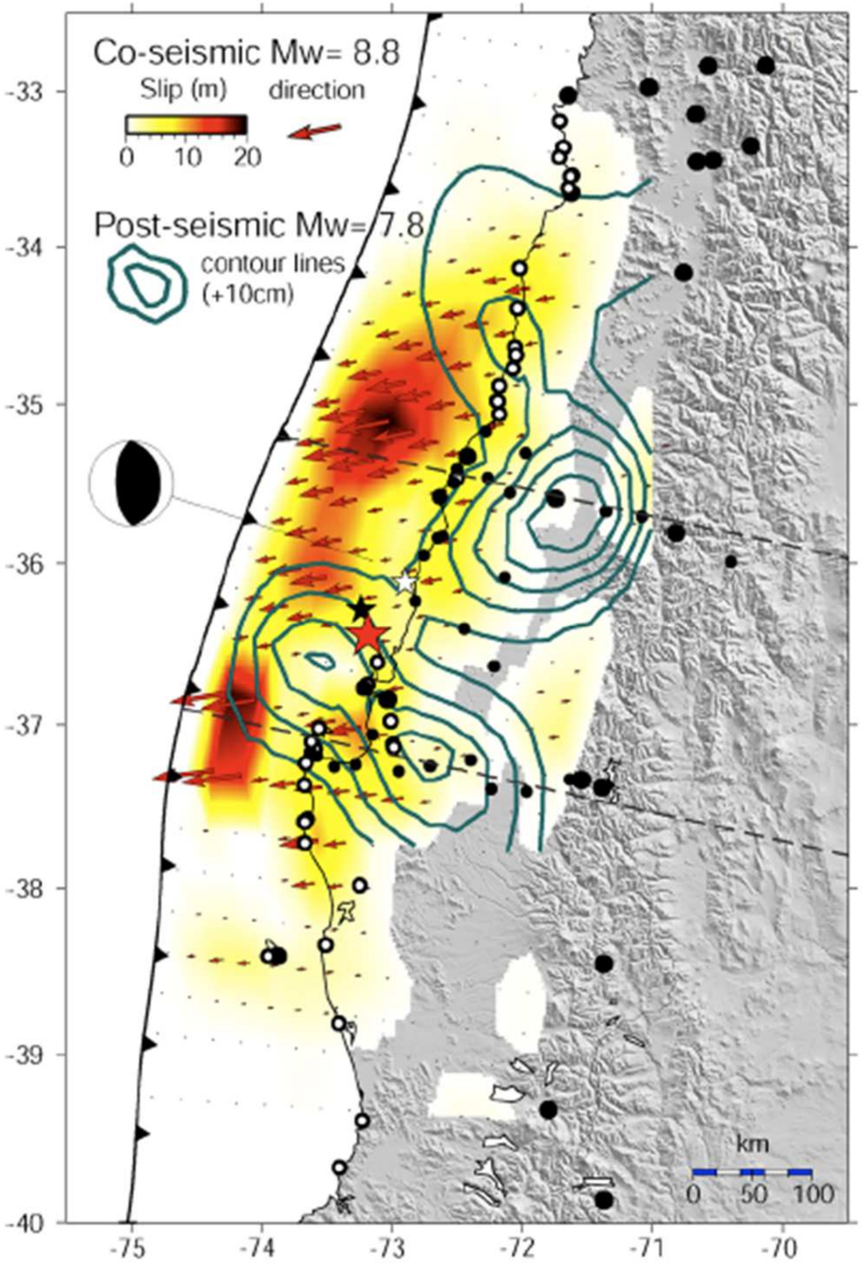
Average postseismic velocities for DOY 150-275. Coseismic slip distribution inverted from GPS and InSAR by Anthony Sladen (Caltech)







Post-seismic deformation



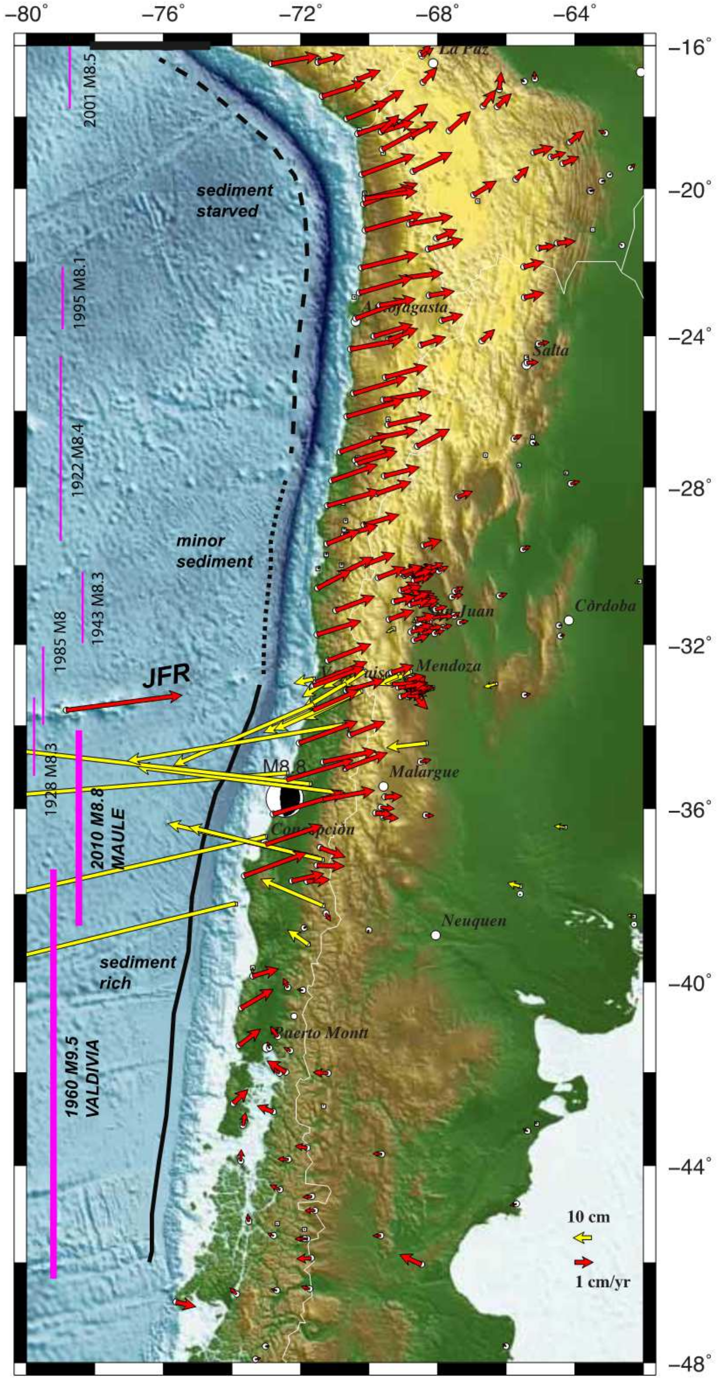
Vigny et al. (2011) Science

Interpreted postseismic surface motions in the first 12 days after the Maule event as arising from afterslip on the megathrust

Inverting the posteismic movements using a dislocation model implies

• afterslip complemented coseismic slip in terms of its spatial distribution, and

• these 12 days of ‘silent’ slip were (in sum) equivalent to a M 7.8 earthquake in terms of moment release



SEISMIC COUPLING vs TECTONIC COUPLING

The Andean Plateau is the 2nd biggest active orogenic plateau on earth (after the Tibetan plateau).

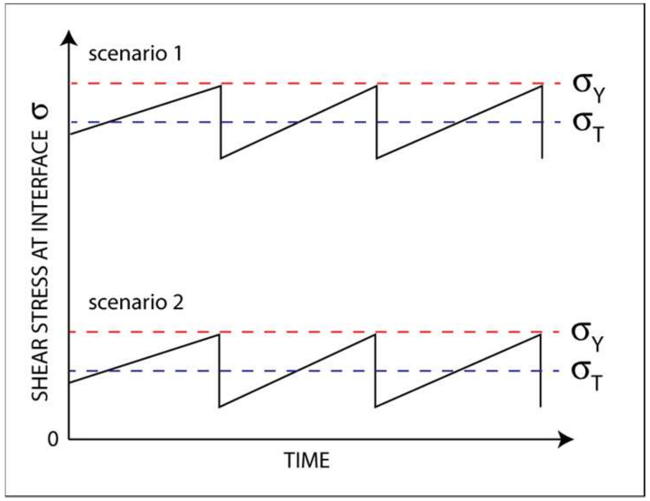
So the Central Andes serve as the type example of subduction induced orogeny (Dewey and Bird, 1970). This is explained in terms of strong ‘tectonic coupling’ between the plates.

This subduction zone is also the world’s most seismogenic plate boundary. It has the highest ‘seismic coupling’ on earth.

However, the Andes are far lower and narrower to the north or the south of the Central Andes. So, why aren’t the Central Andes more seismogenic than the southern Andes?

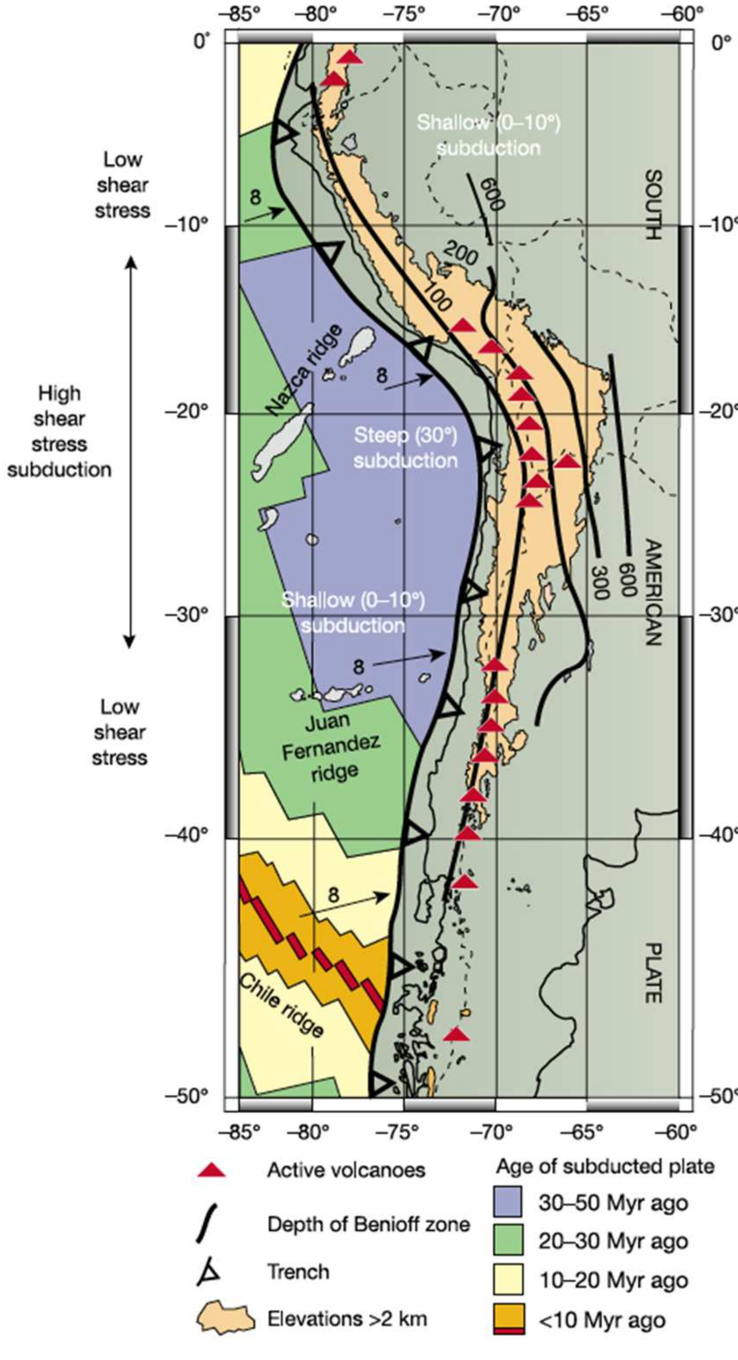
INFERENCE: SEISMIC COUPLING AND TECTONIC COUPLING ARE NOT THE SAME THING!

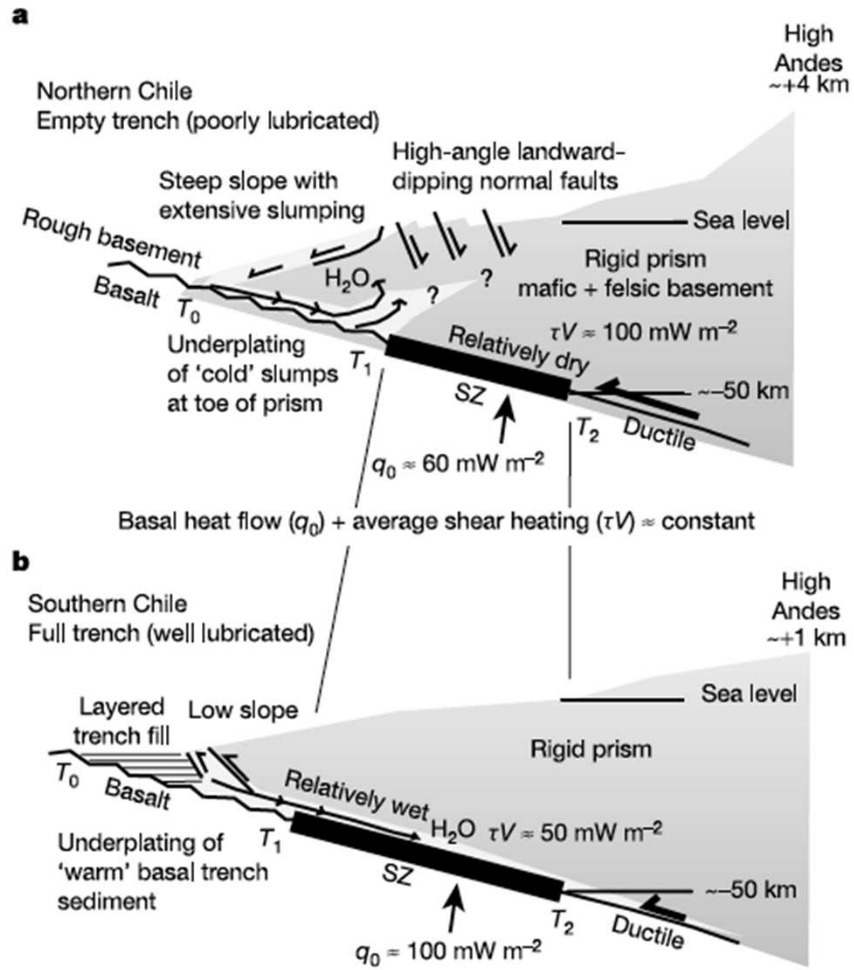
Giant earthquakes require very large stress *drops* On the megathrust, but do not require nor imply high yield (or tectonic) stresses.

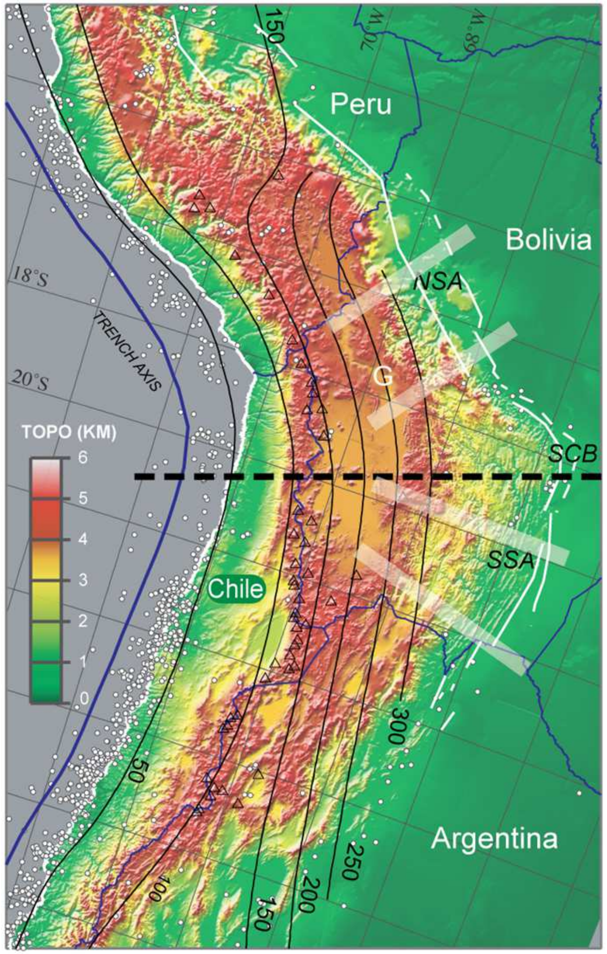


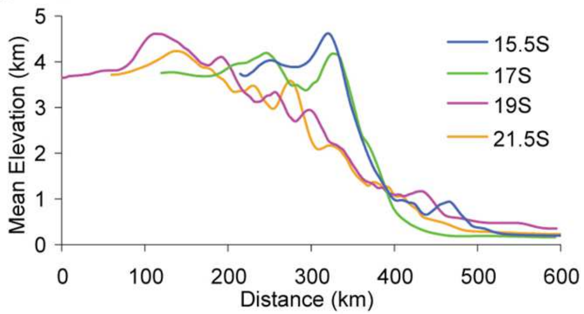
GEOLOGICAL CONTROLS

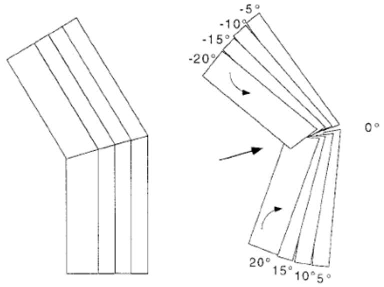
Lamb and Davis (2003) suggested that a lack of sediments in the trench of the Central Andes increased the frictional strength of the plate interface, and thus drove the development of the orogenic plateau.





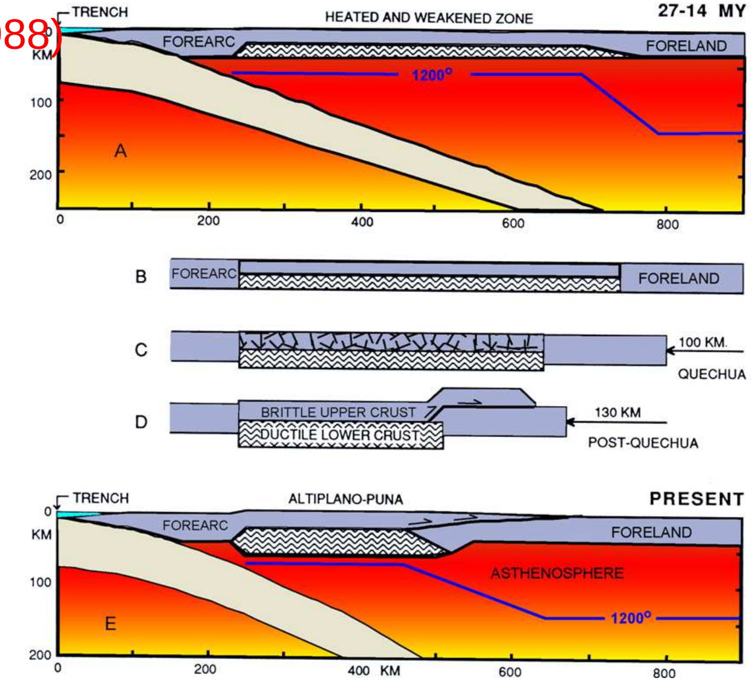


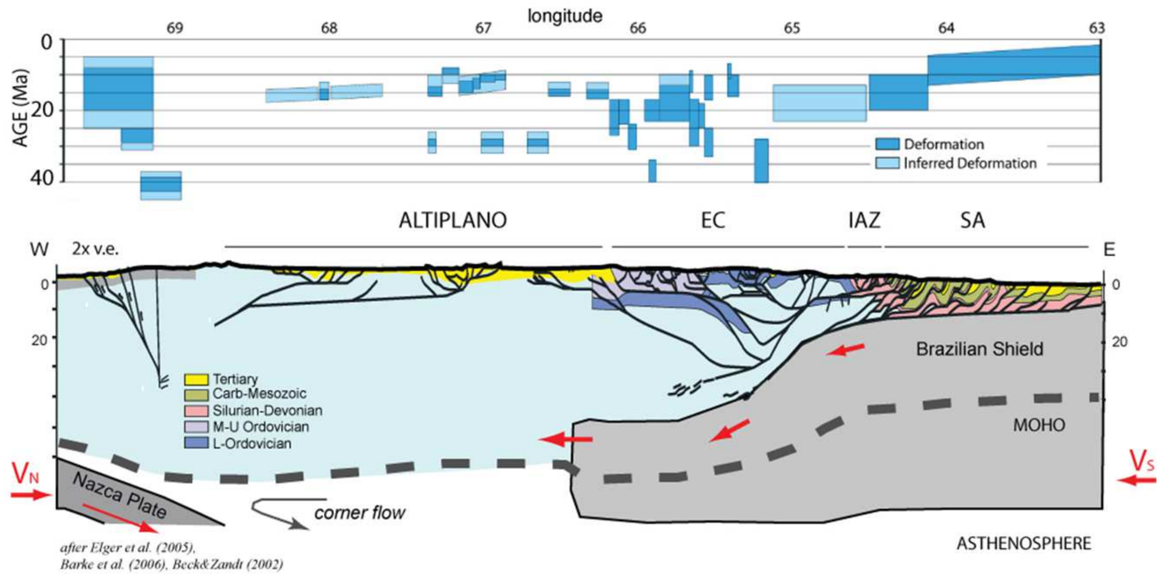


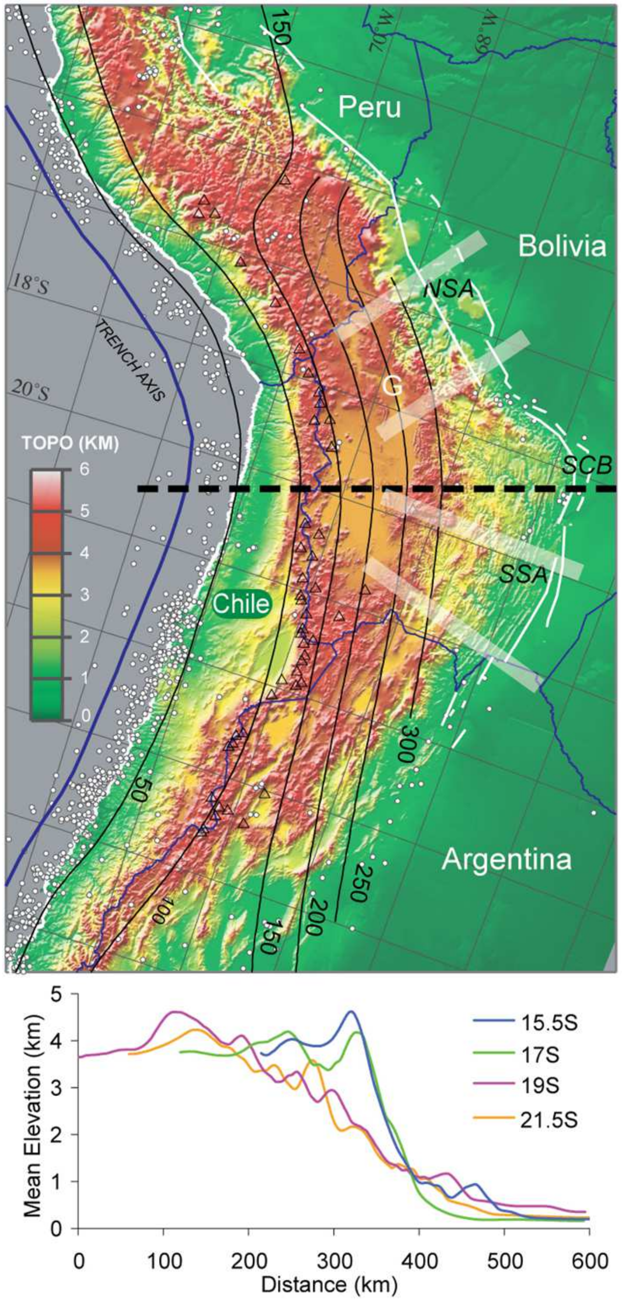


Kley (1999)

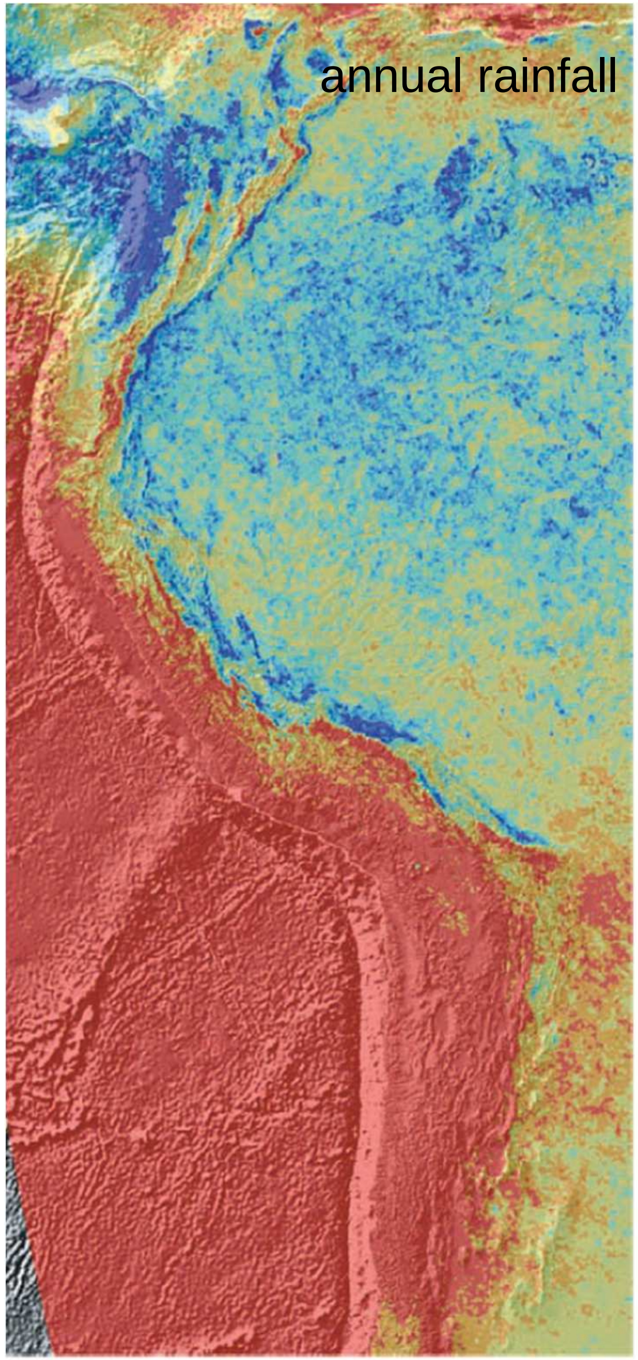
Isacks (1988)







Peru
Bolivia
NSA
G
SCB
SSA
Chile
Argentina
18°S
20°S
TRENCH AXIS
TOPO (KM)
6
5
4
3
2
1
0
150
300
50
100
150
200
250
Mean Elevation (km)
Distance (km)
15.5S
17S
19S
21.5S



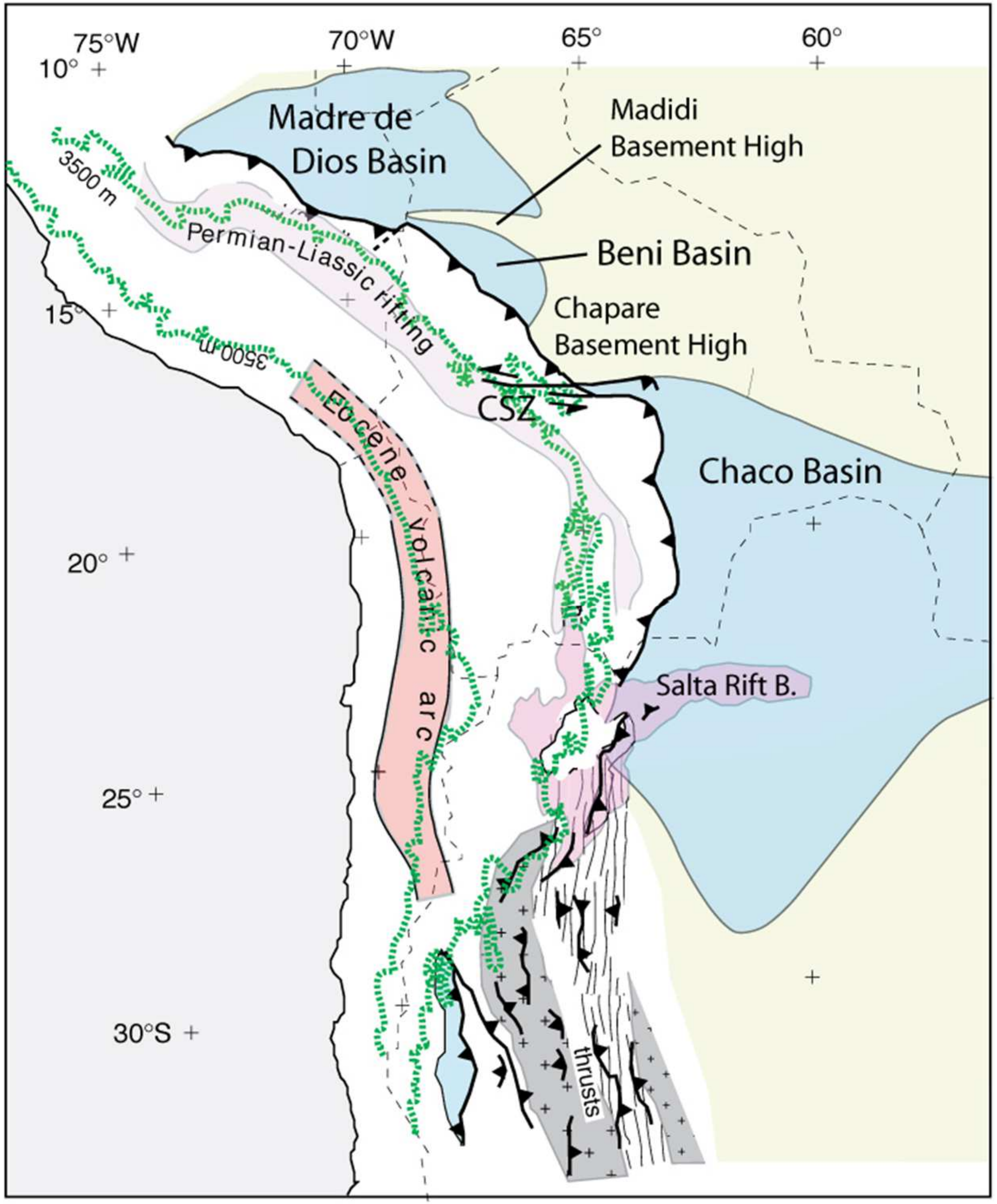
annual rainfall

Paleozoic shales provide the majority of the detachment horizons within the Beni and Chaco segments of the Subandes (*Baby et al., 1989; Herail et al., 1990; Roeder & Chamberlain, 1995; Dunn, 1995)*

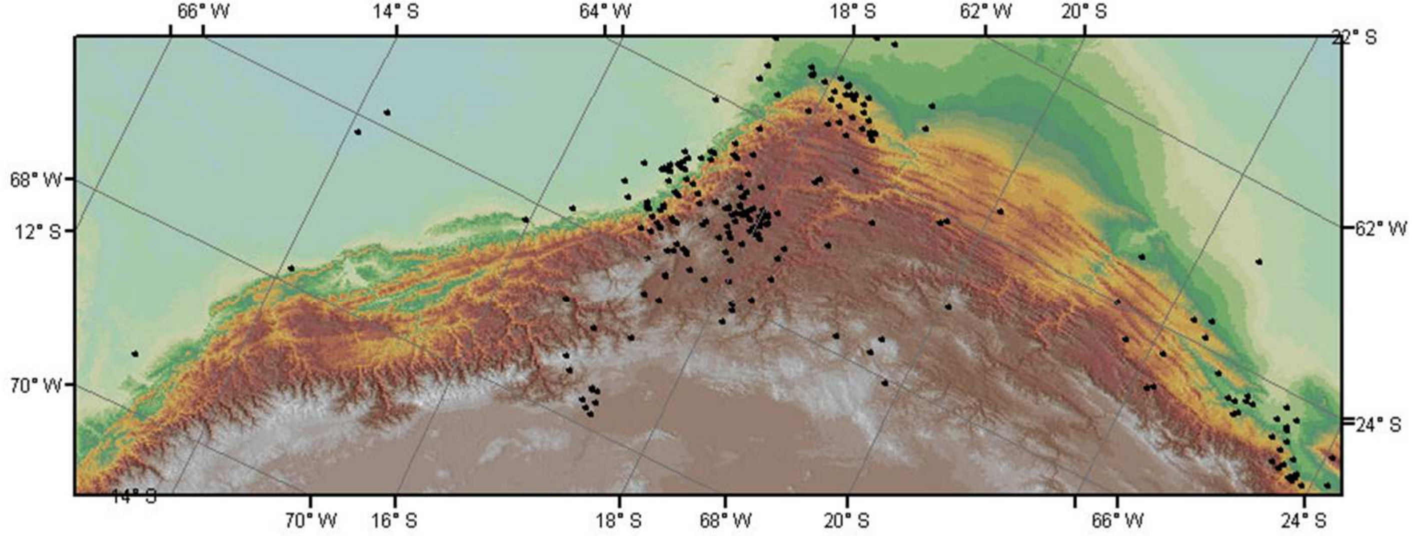
The southern termination of the Subandes in NW Argentina roughly coincides with the southwards pinching out of these sediments (*Allmendinger and Gubbels, 1996*)

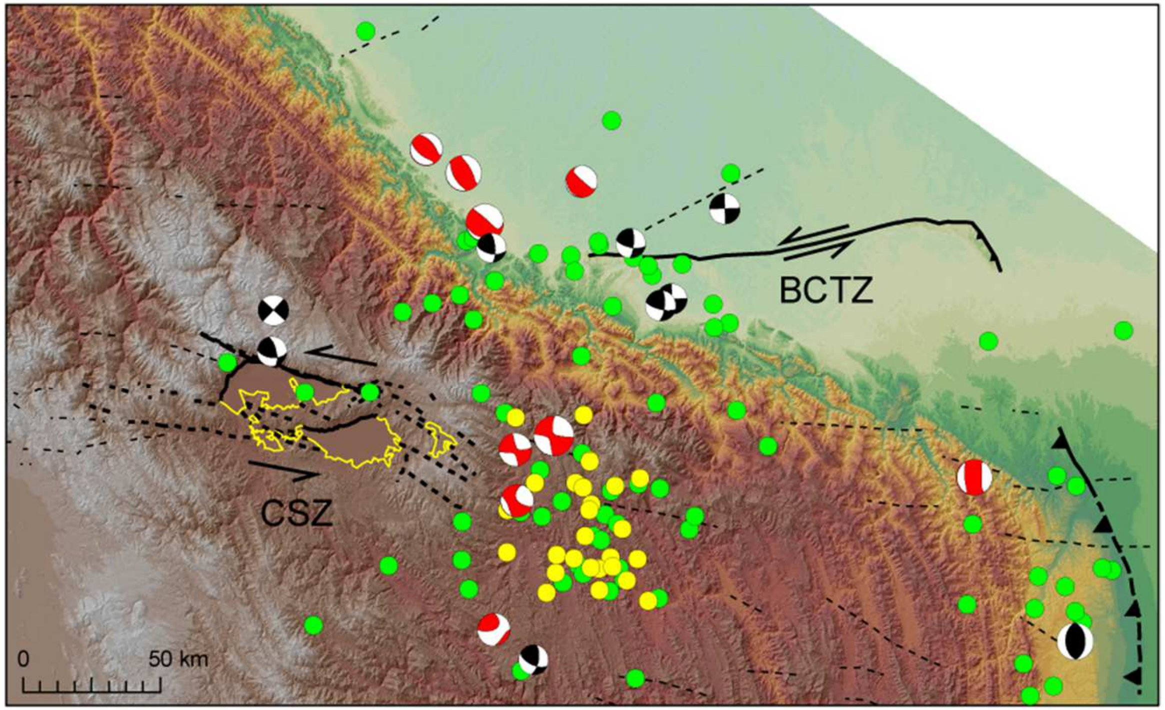
The CBTZ and the Cochabamba Shear Zone (CSZ) align with the northern border of the Paleozoic basin which coincides with the southern edge of the Chapare Basement High (Sheffels, 1995)]

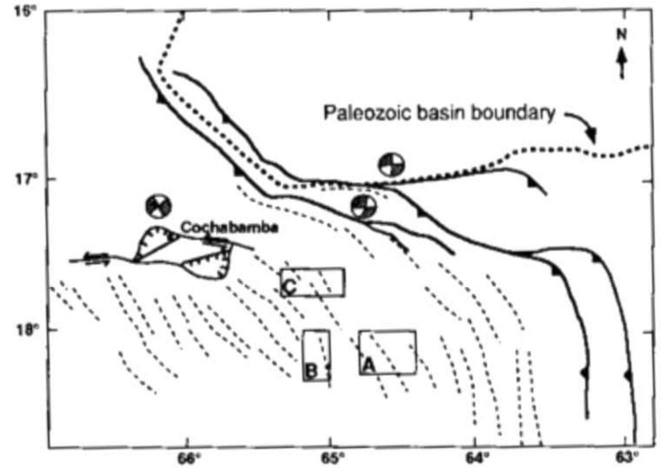
The map view setting of the Andean Plateau as a whole closely corresponds to the along-strike distribution of the three Paleozoic basins (Oncken et al., 2007)



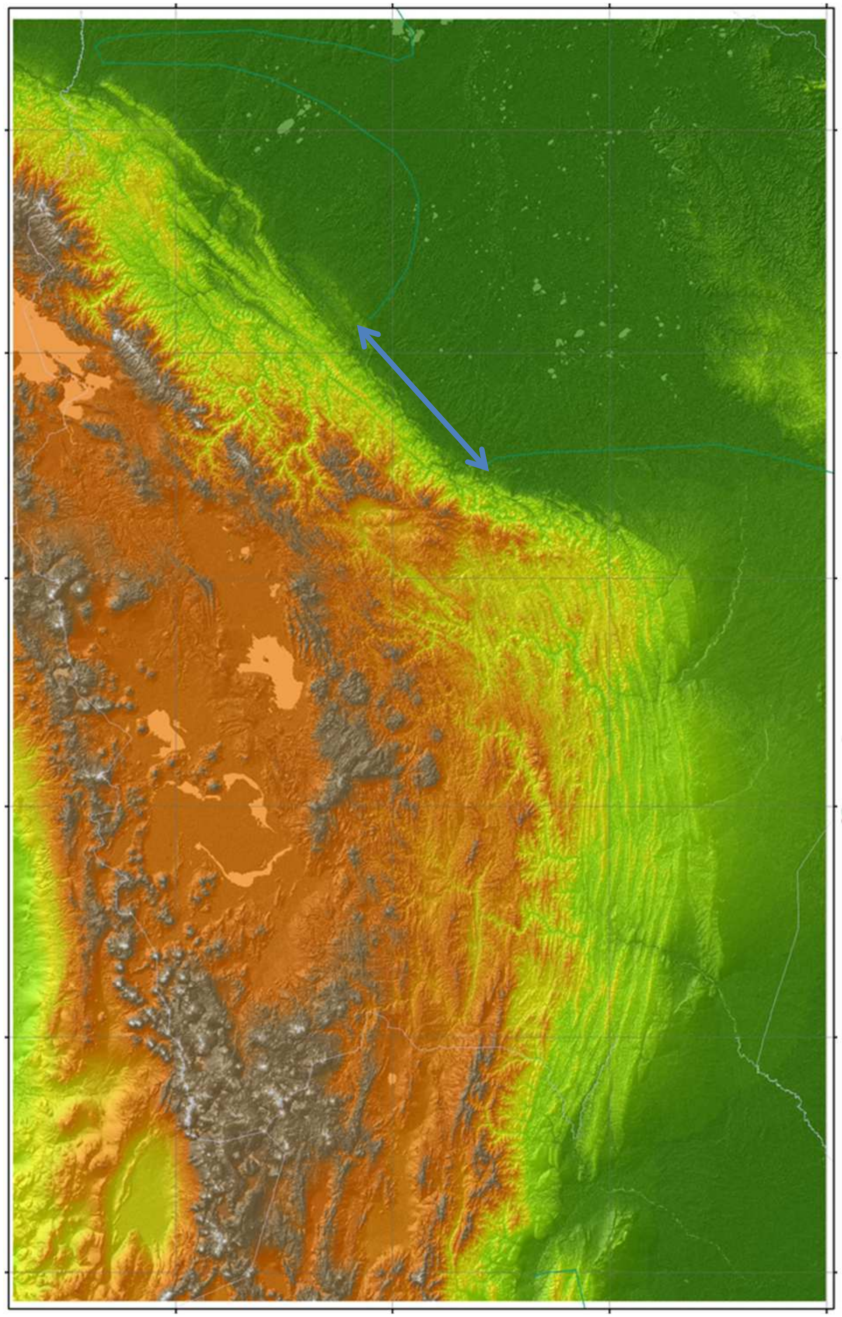
From Oncken et al, 2007

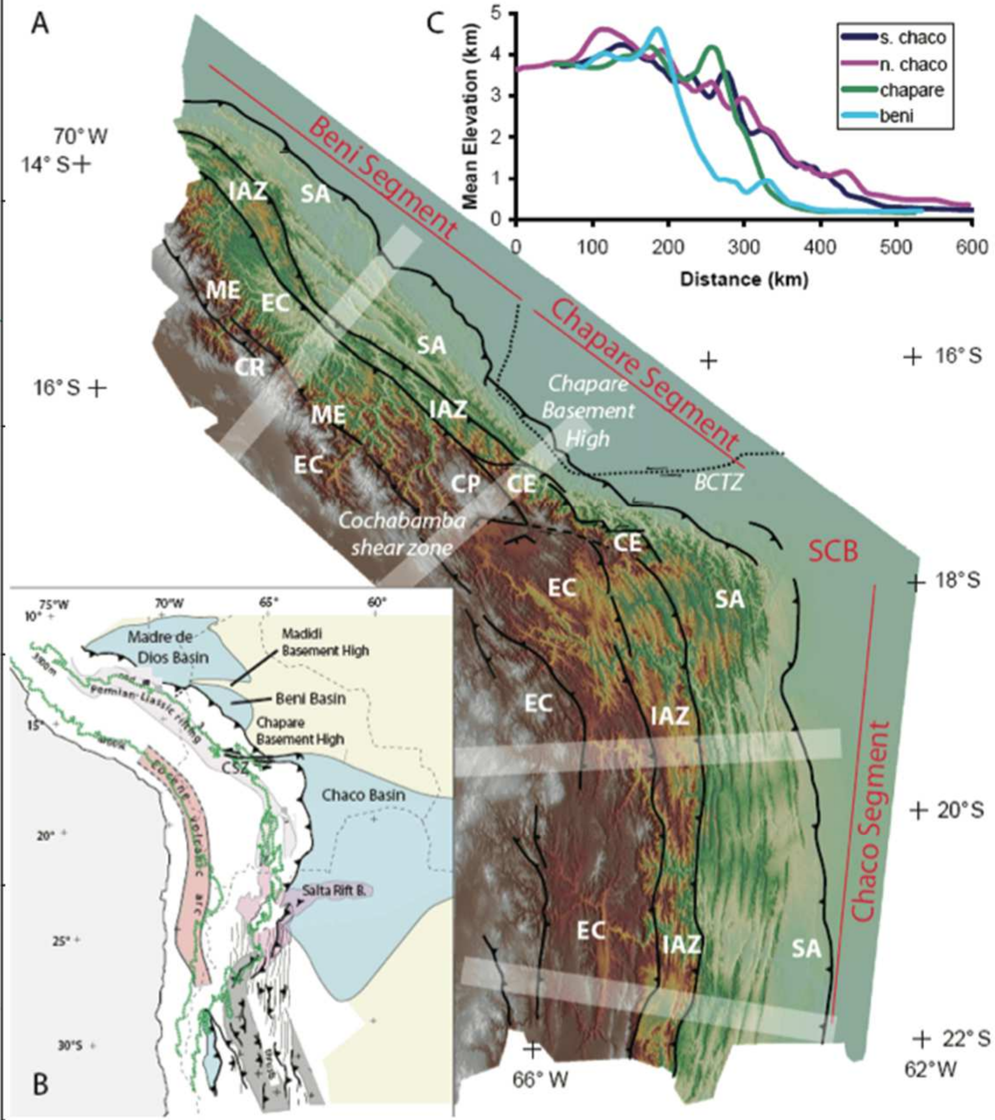




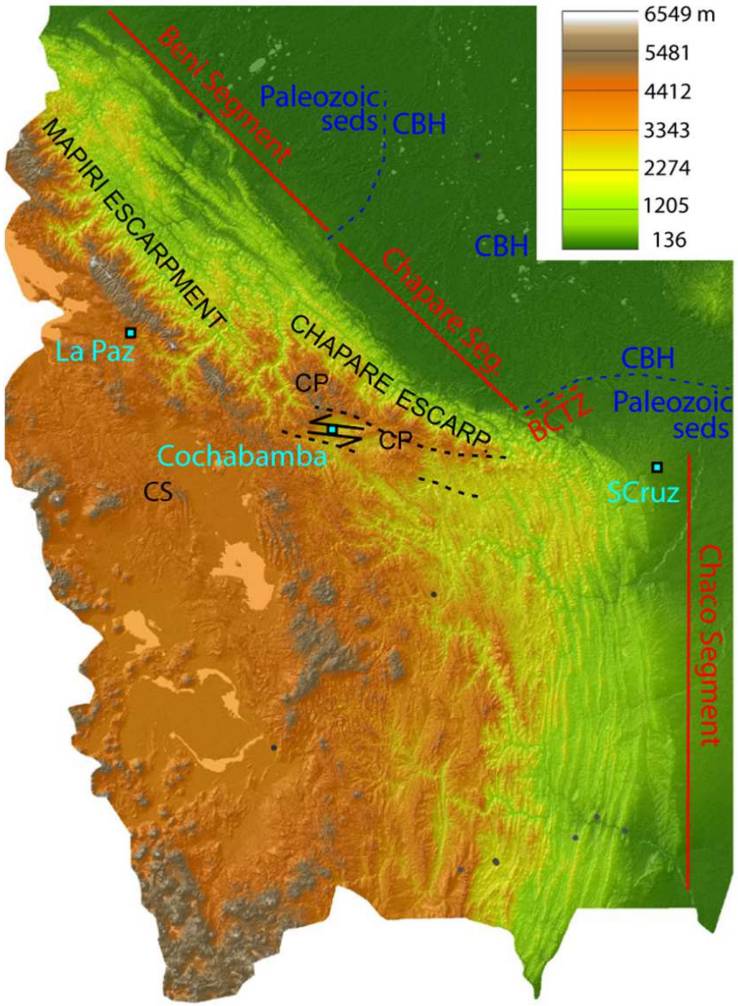


Sheffels, 1995
AAPG Bulletin

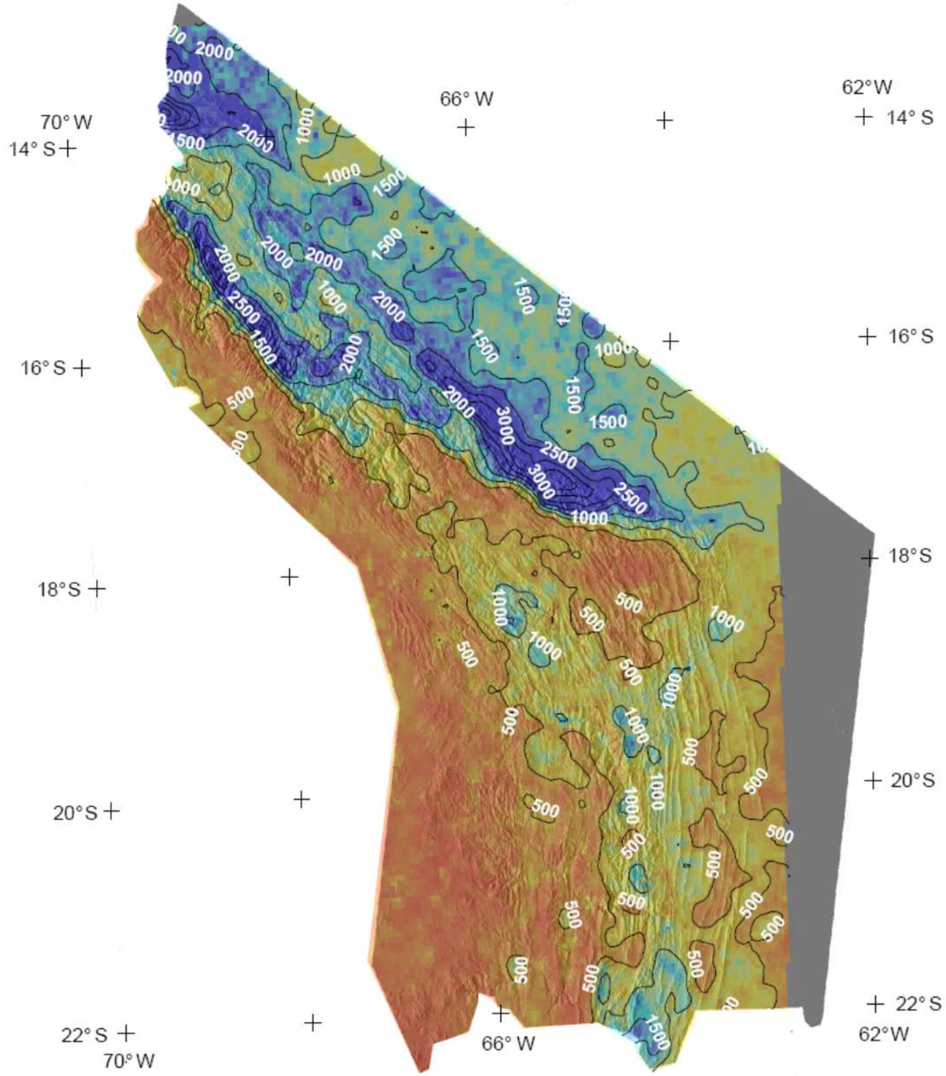




A
B
C
Beni Segment
Chapare Segment
Chaco Segment
SCB
IAZ
SA
ME
EC
CR
CP
CE
Chapare Basement High
BCTZ
Cochabamba shear zone
70° W
14° S
16° S
18° S
20° S
22° S
66° W
62° W
Mean Elevation (km)
Distance (km)
s. chaco
n. chaco
chapare
beni
0
1
2
3
4
5
100
200
300
400
500
600
75°W
70°W
65°
60°
10°
15°
20°
25°
30°S
Madre de Dios Basin
Madidi Basement High
Beni Basin
Chapare Basement High
CSZ
Chaco Basin
Salta Rift B.



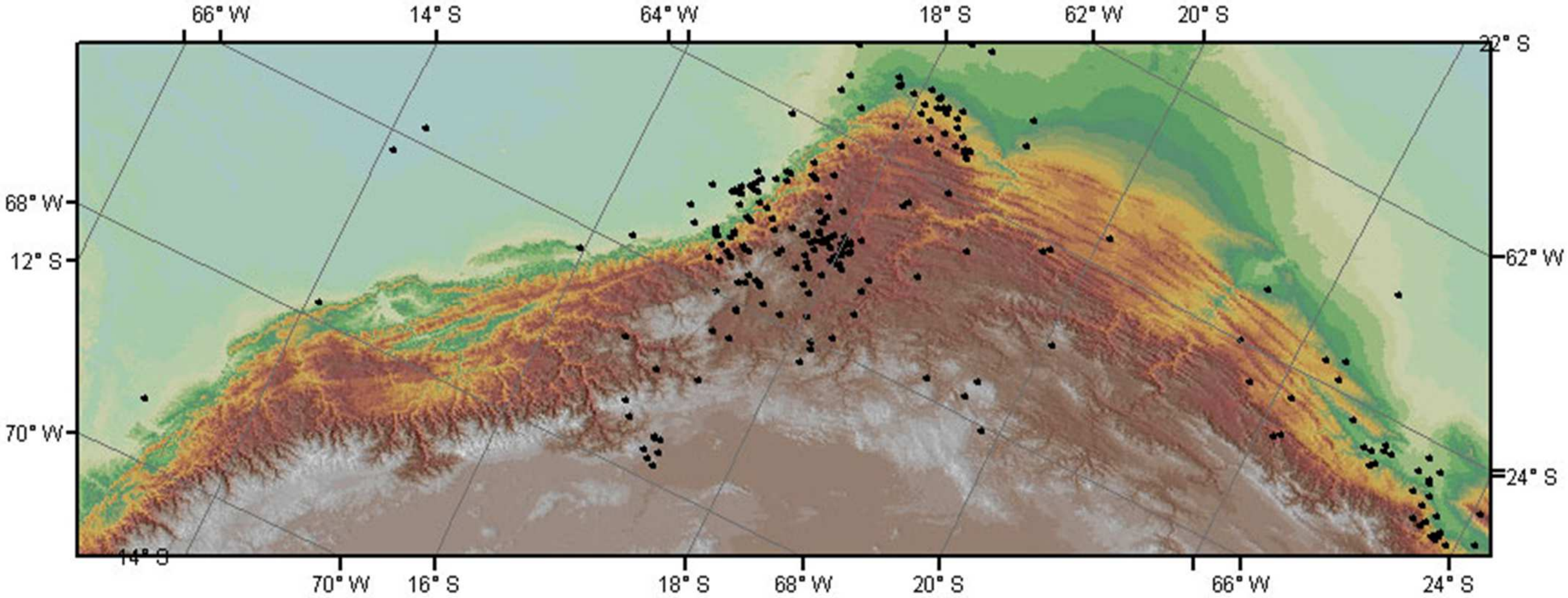
TRRM rainfall - annual

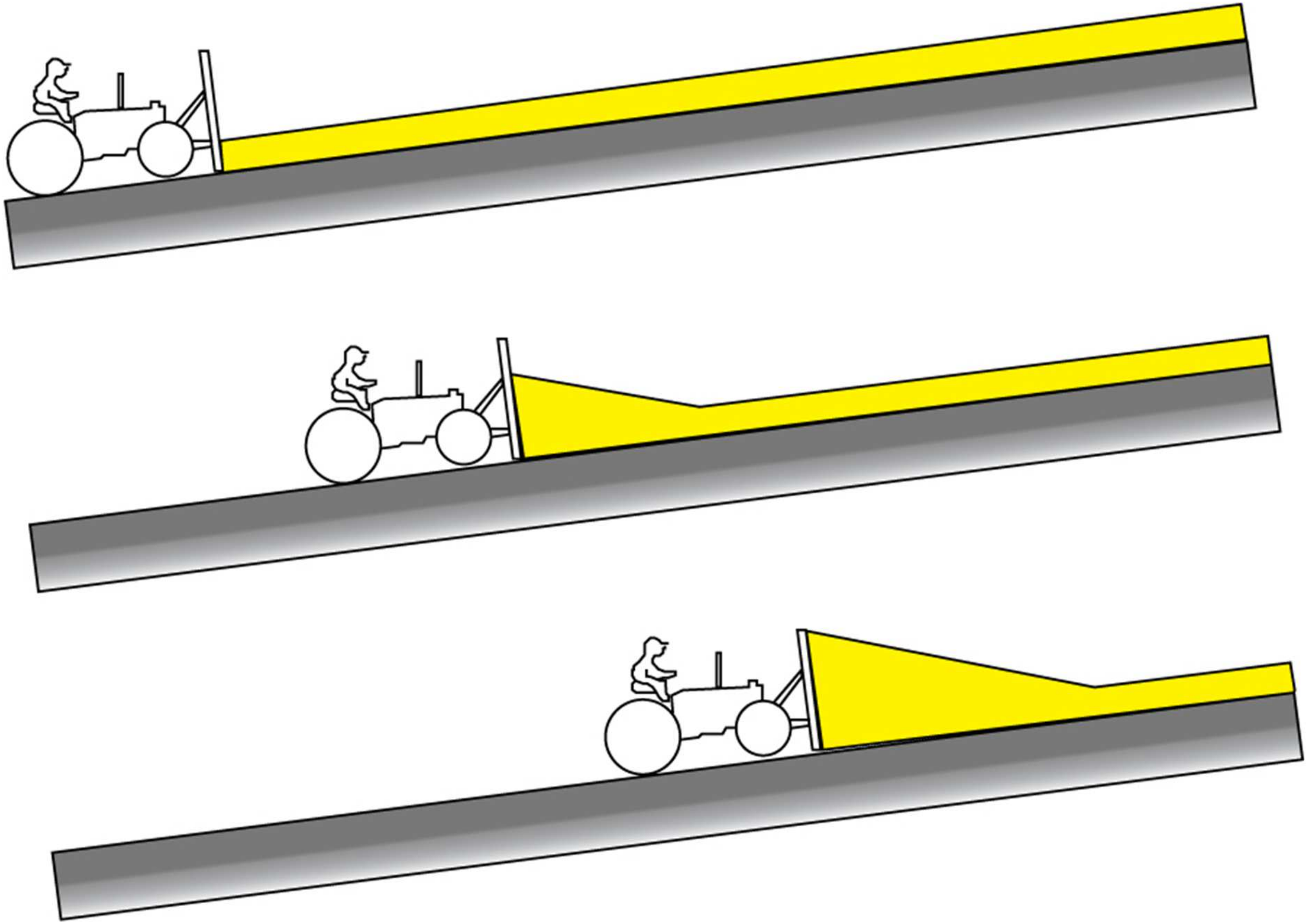


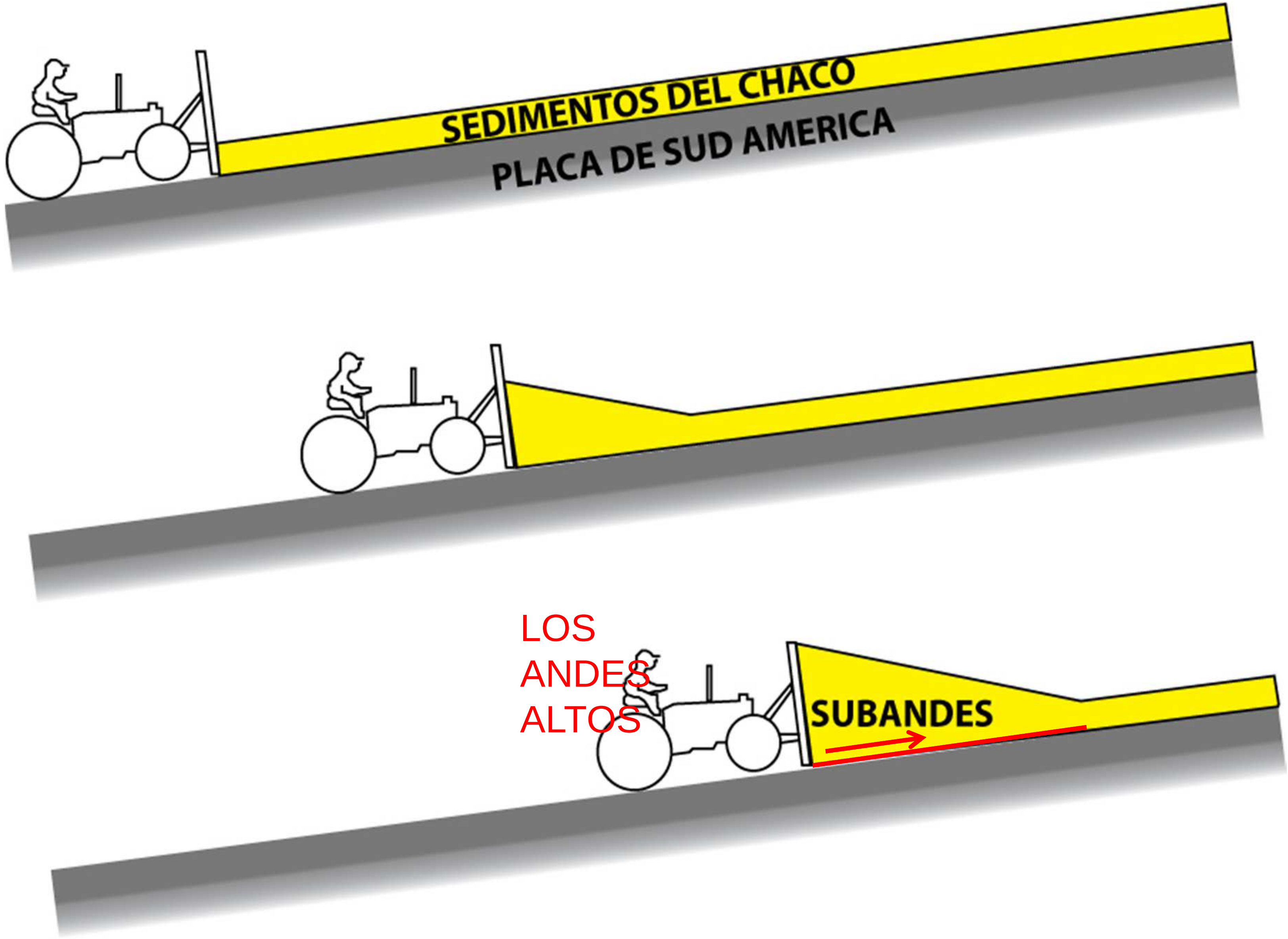
Nesbitt and Anders, 2009

LESSON 2 FROM THE SOUTHERN SUBANDES OF BOLIVIA

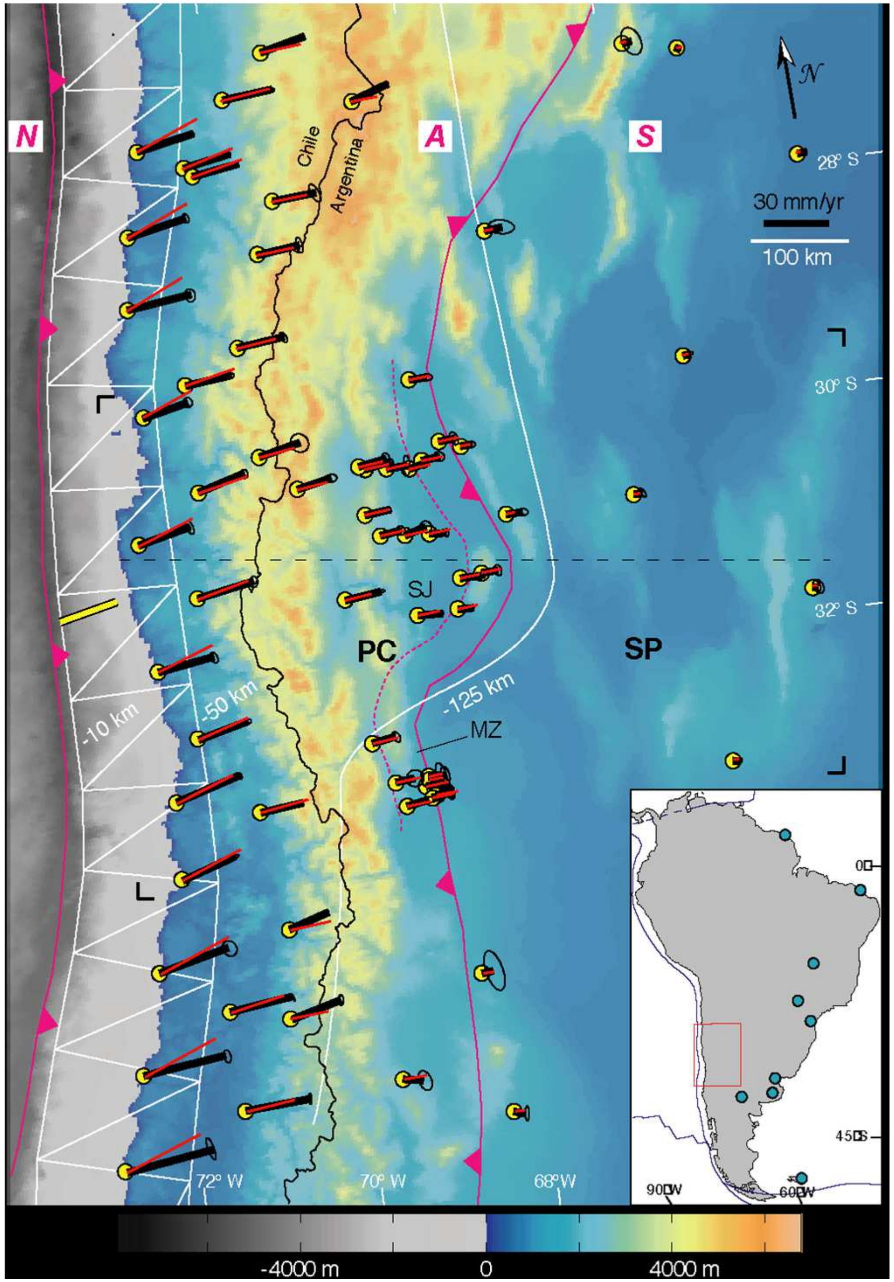
Making inferences from interseismic deformation observed in a tectonic wedge without a history of great earthquakes



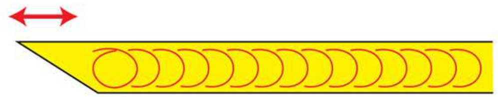



SEDIMENTOS DEL CHACO
PLACA DE SUD AMERICA
LOS
ANDES
ALTOS
SUBANDES

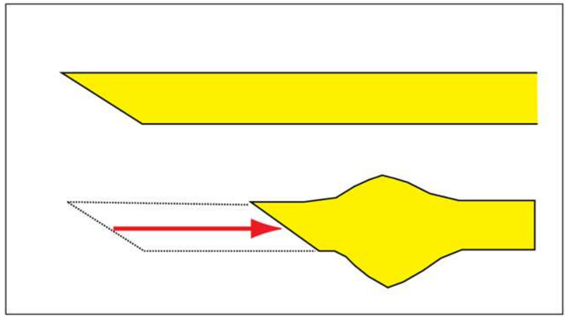
Interseismic Deformation

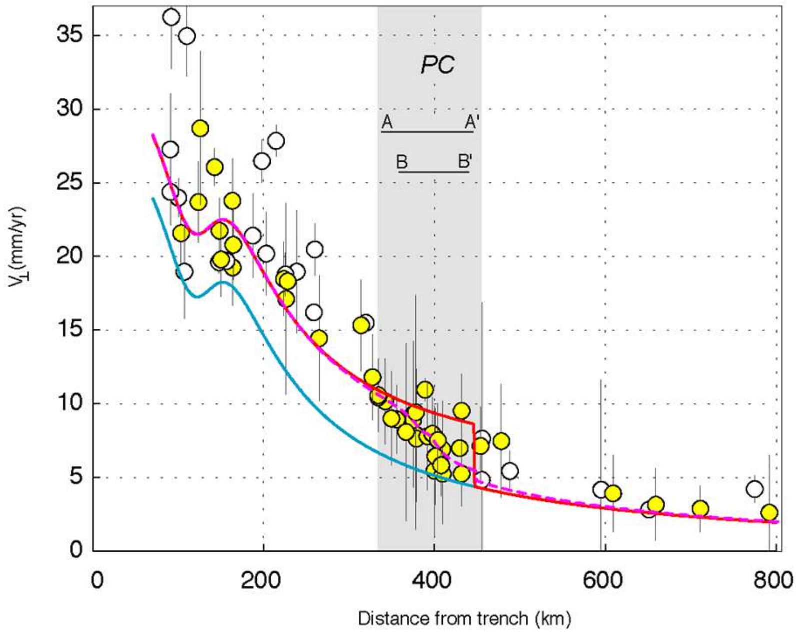


EQ deformation cycle (elastic)

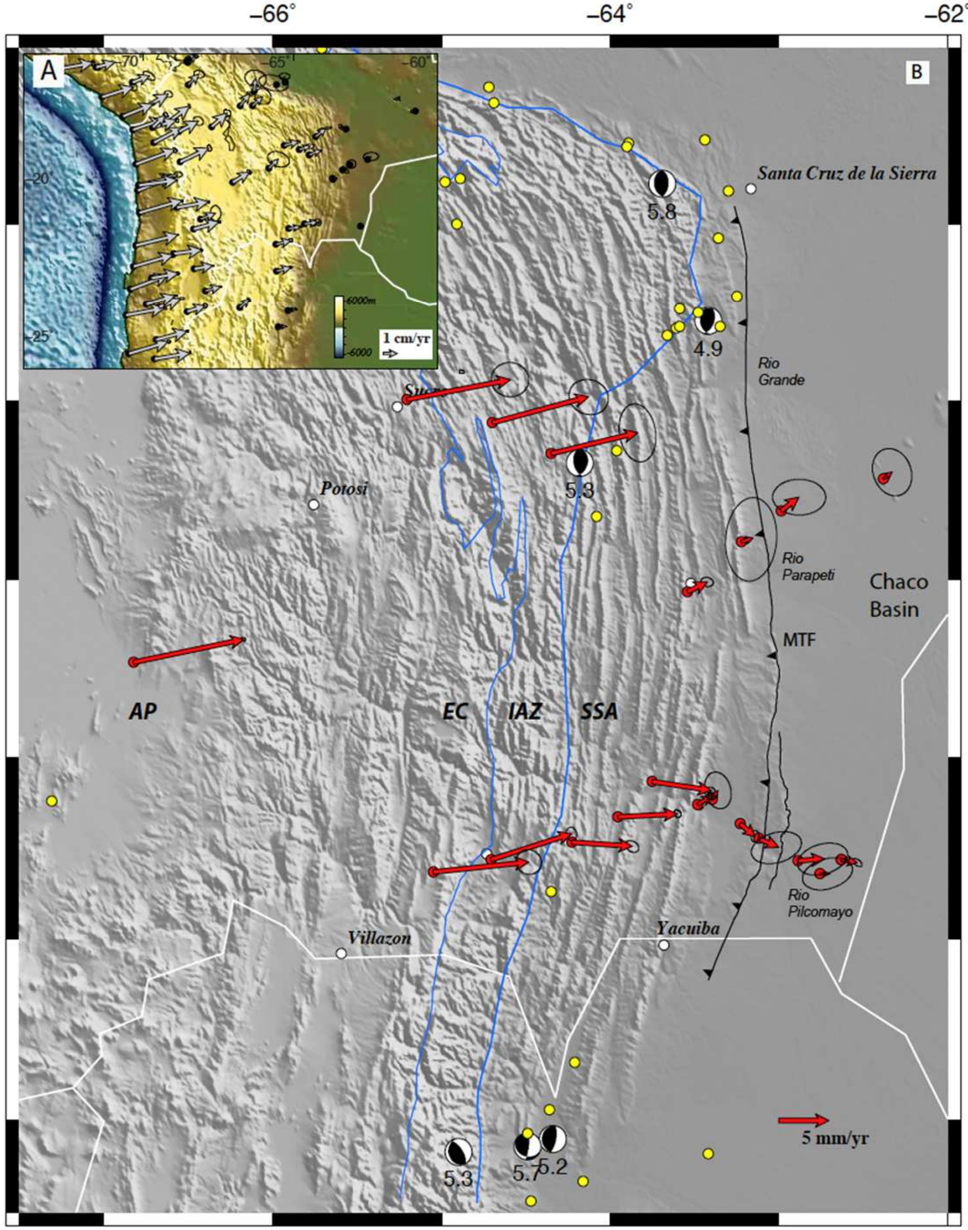


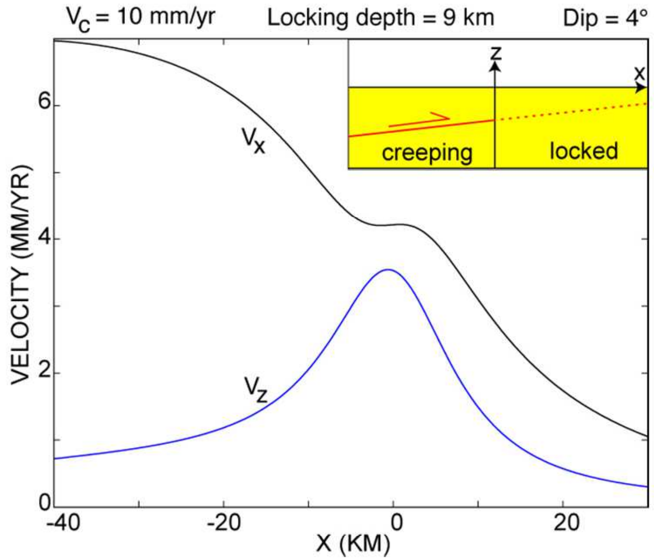
Orogenic deformation (plastic)

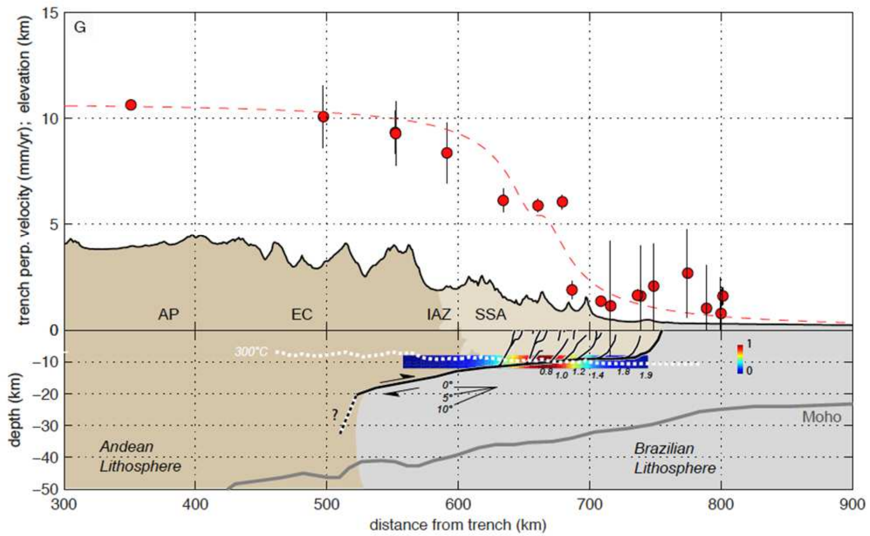




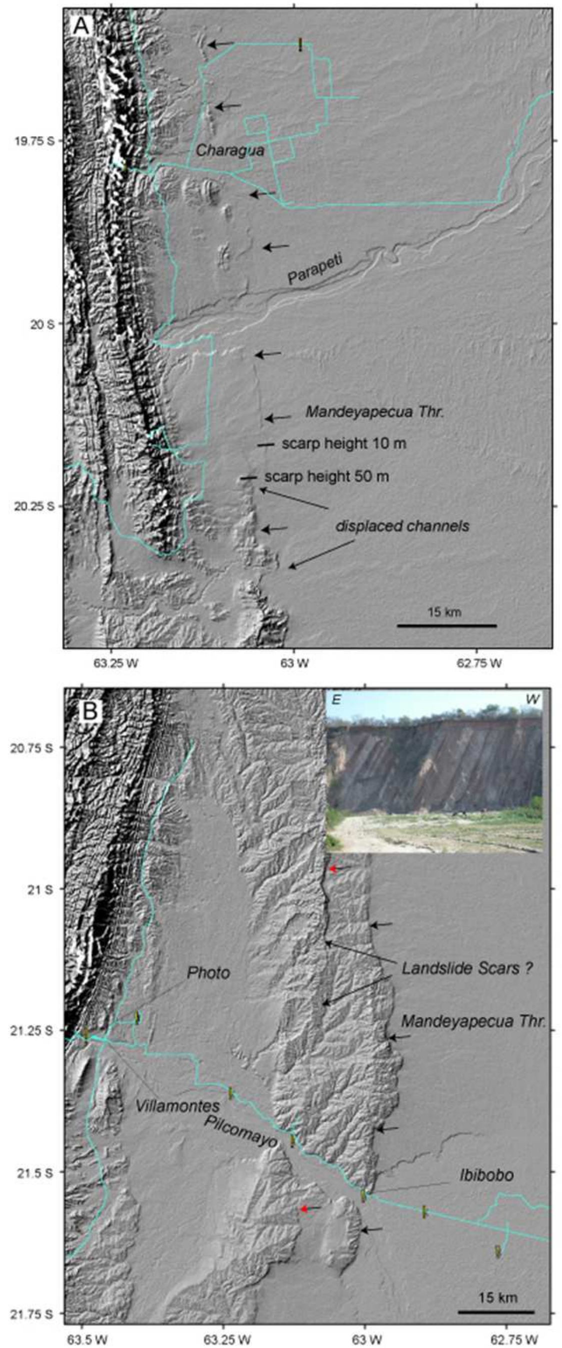
Elastic modeling of a locked decollement





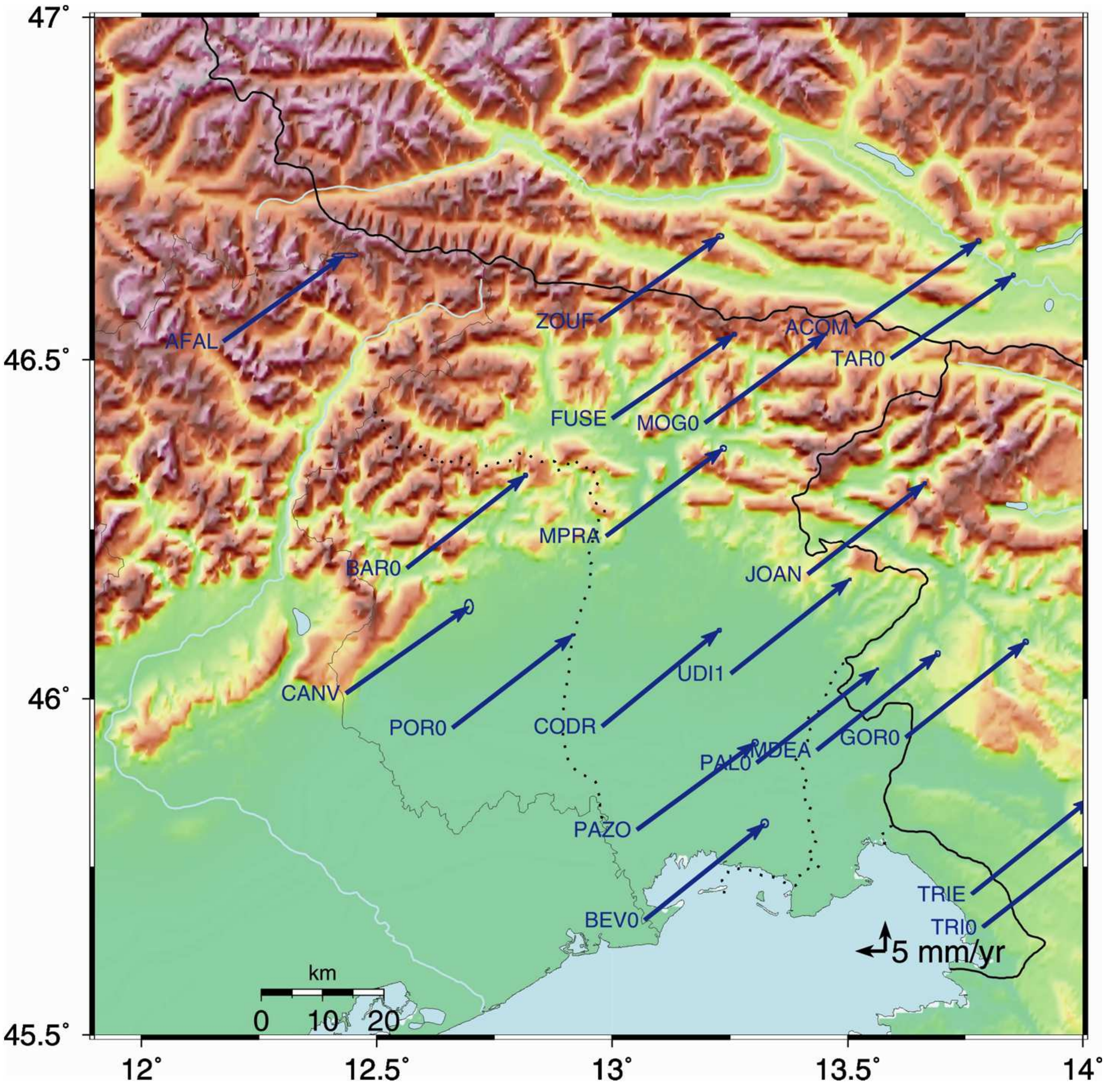


from Brooks et al. (2011, Nature Geoscience)



A
Charagua
Parapeti
Mandeyapecua Thr.
scarp height 10 m
scarp height 50 m
displaced channels
15 km
19.75 S
20 S
20.25 S
63.25 W
63 W
62.75 W
B
E
W
Photo
Landslide Scars ?
Mandeyapecua Thr.
Villamontes
Pilcomayo
Ibibobo
15 km
20.75 S
21 S
21.25 S
21.5 S
21.75 S
63.5 W
63.25 W
63 W
62.75 W

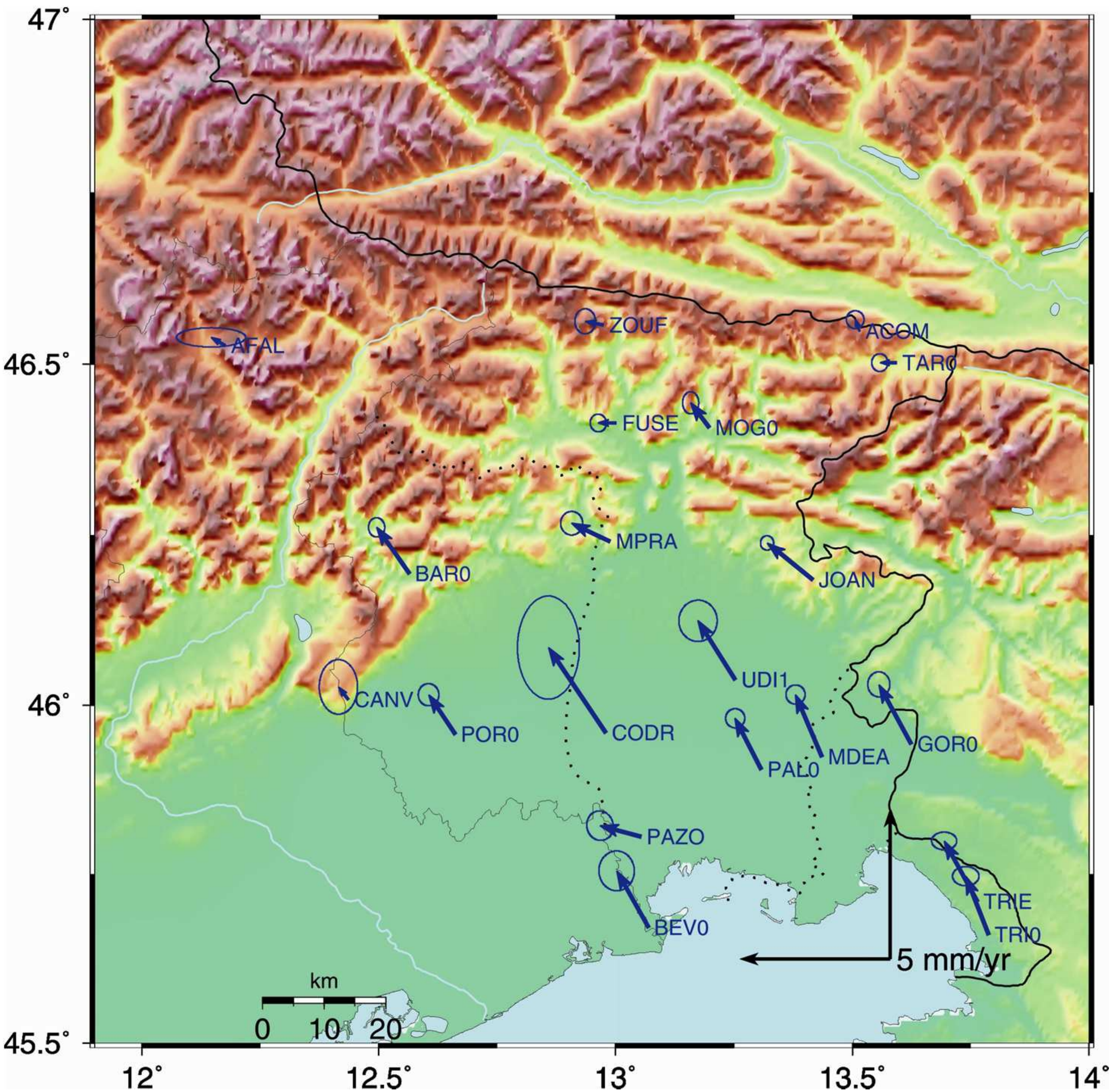
Intersiesmic velocity in Friuli



Relative to

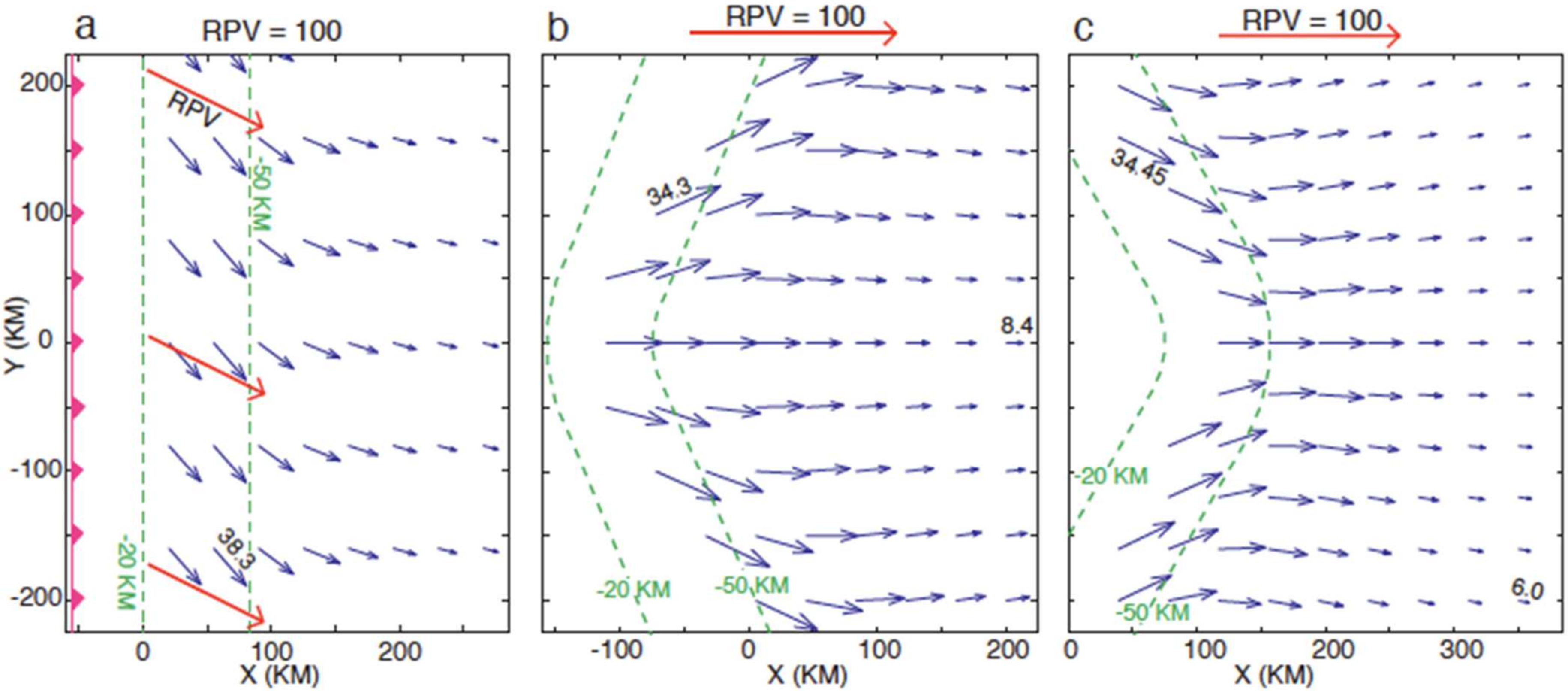
ITRF

Intersiesmic velocity in Friuli

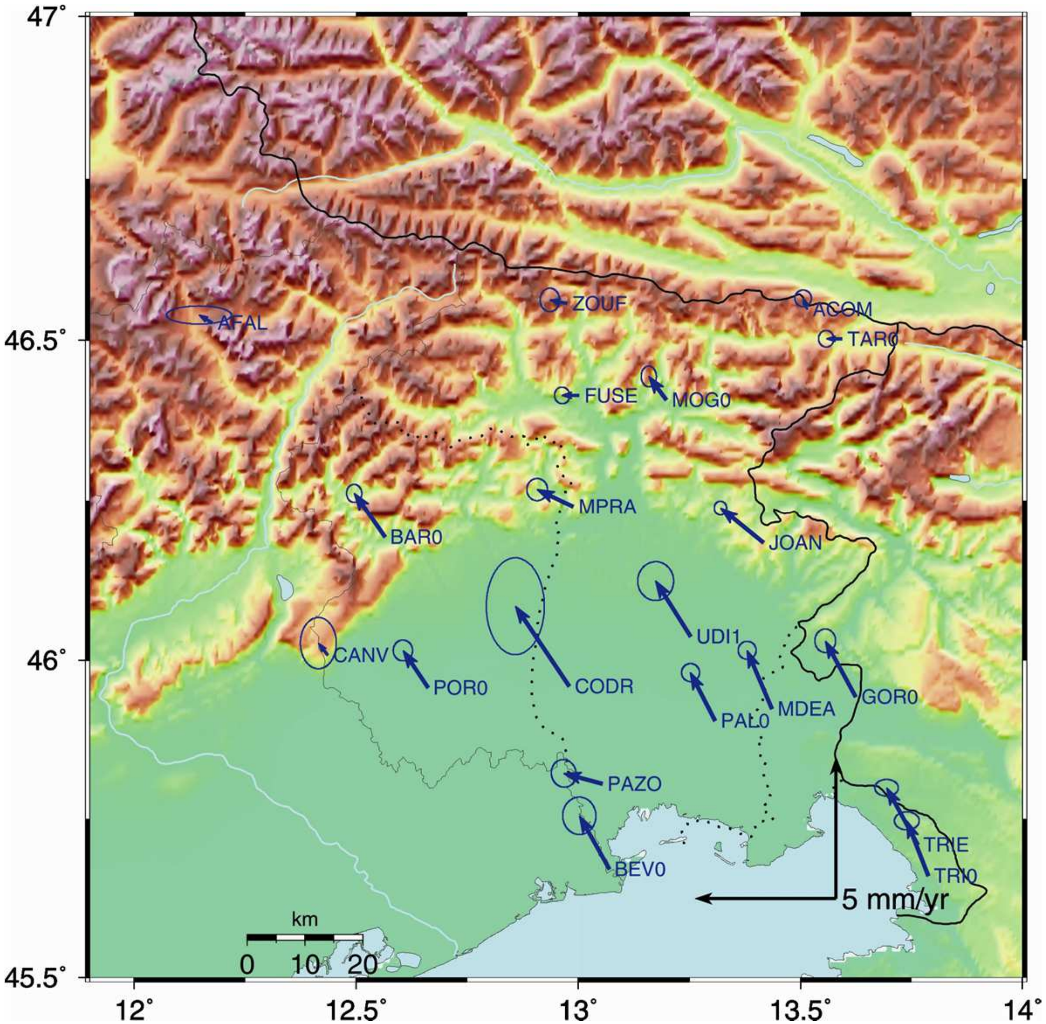


Relative to the European RF of McClusky

Locking of a plate boundary associated with oblique convergence, and locking of boundaries which are curved in map view, leads to complicated and ‘rotating’ velocities fields



Bevis et al. (2001) G-cubed, see also Bevis and Martel (2001) G-cubed



To interpret this interseismic velocity field carefully, we need to know more about the geometry of faulting. If there is a decollement beneath the Friuli plan?, what is

• its location (including its map view curvature)?

• its dip?

We must also consider the outer neotectonic framework. The motion of 'stable' Italy relative to stable (northern) Europe

It would be useful to see the velocity field east and west of Friuli, and add more GPS stations within Friuli.

The most cost effective geological tool for seeking buried faults (blind thrusts, etc) within the plain is probably airborne LIDAR.

Reprocessing of all available seismic sections (acquired by oil companies) would be very useful too.

THANKS FOR YOUR ATTENTION!

'*The Road of Death'*

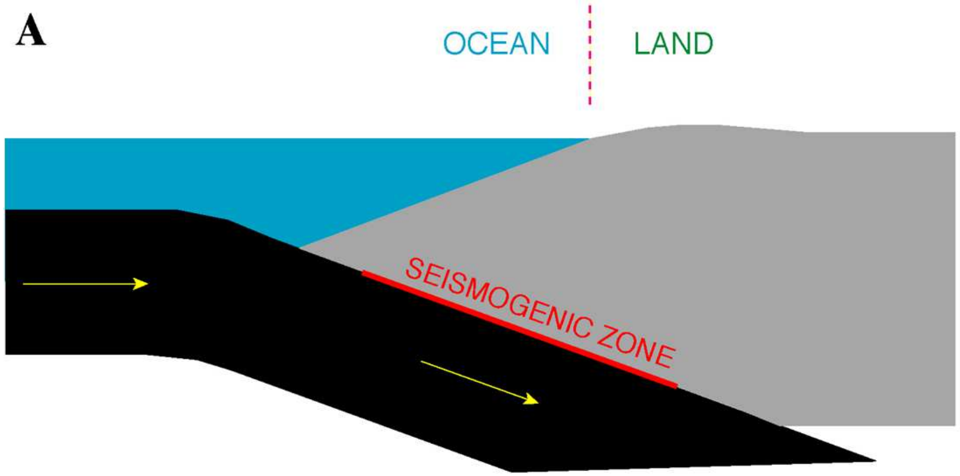
Deep incision of the Northeast Flank of the Andean Plateau (Bolivia)

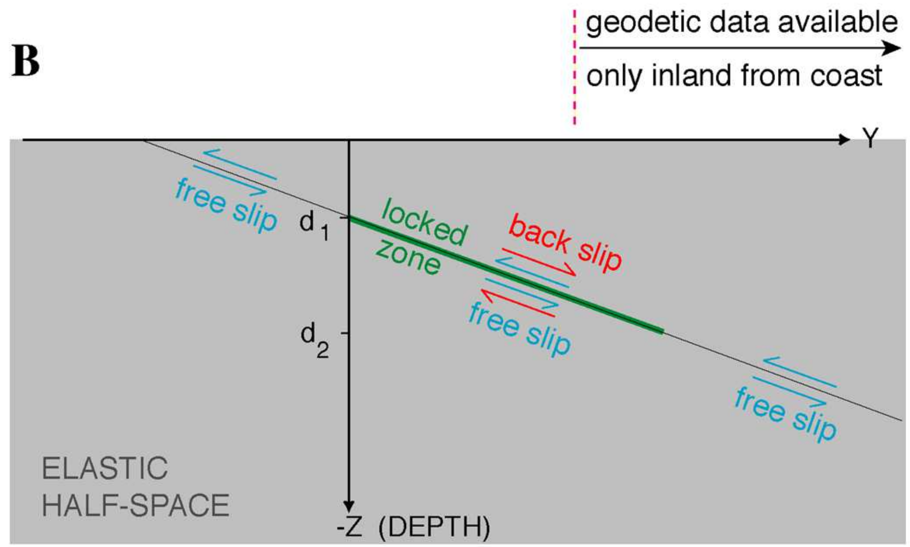
Interseismic straining

Savage's (1983)

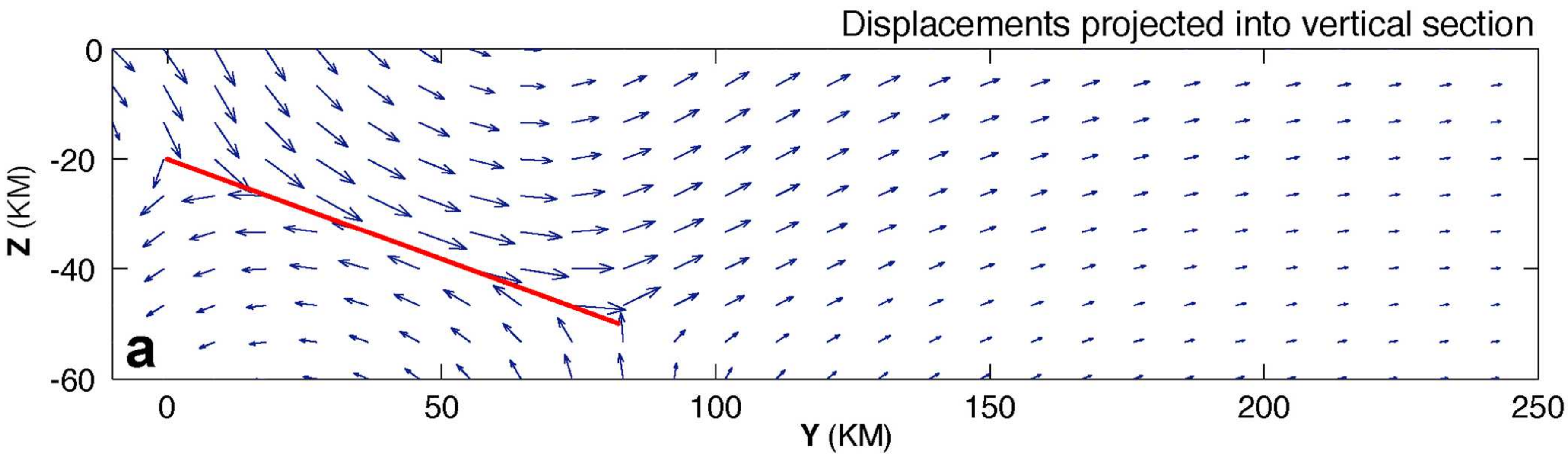
backslip model

An convenient way to model (approximately) the elastic deformation driven by locking of the main plate boundary





Interseismic straining



Backslip model implemented in an elastic halfspace (using Okada)