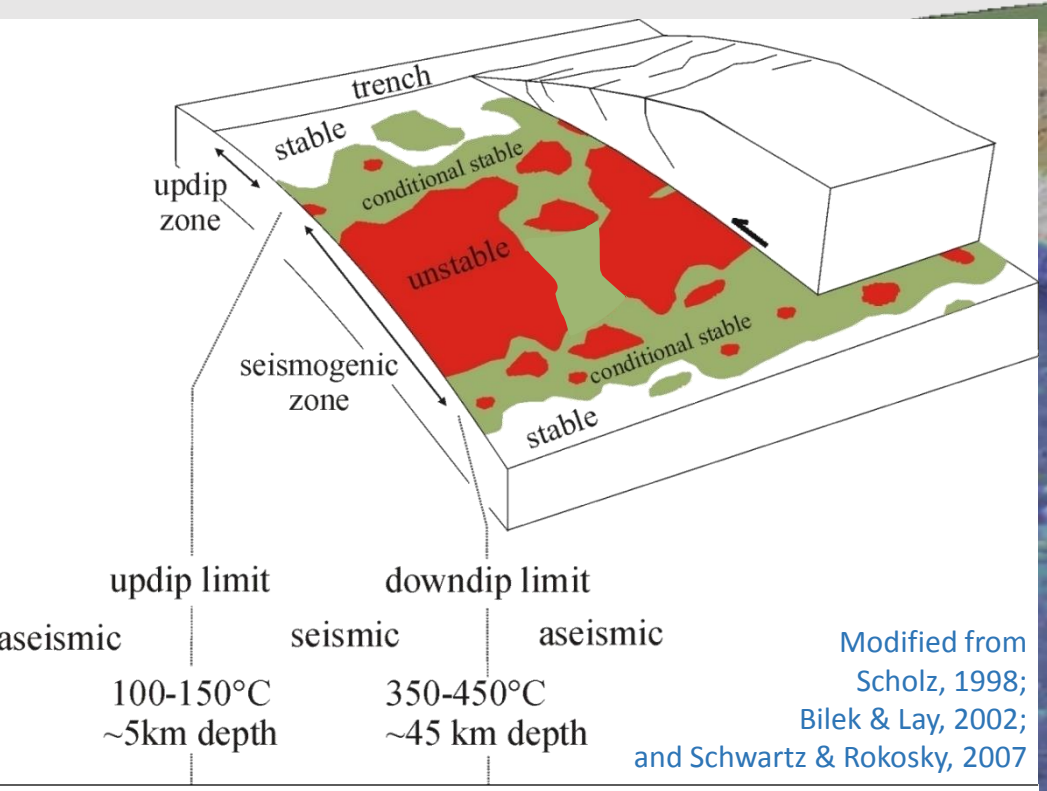
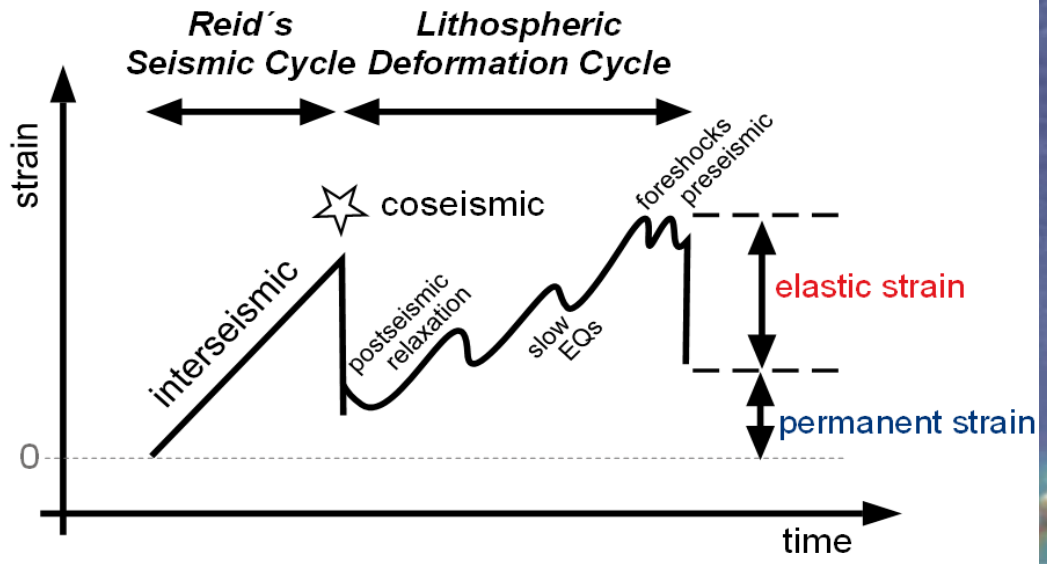


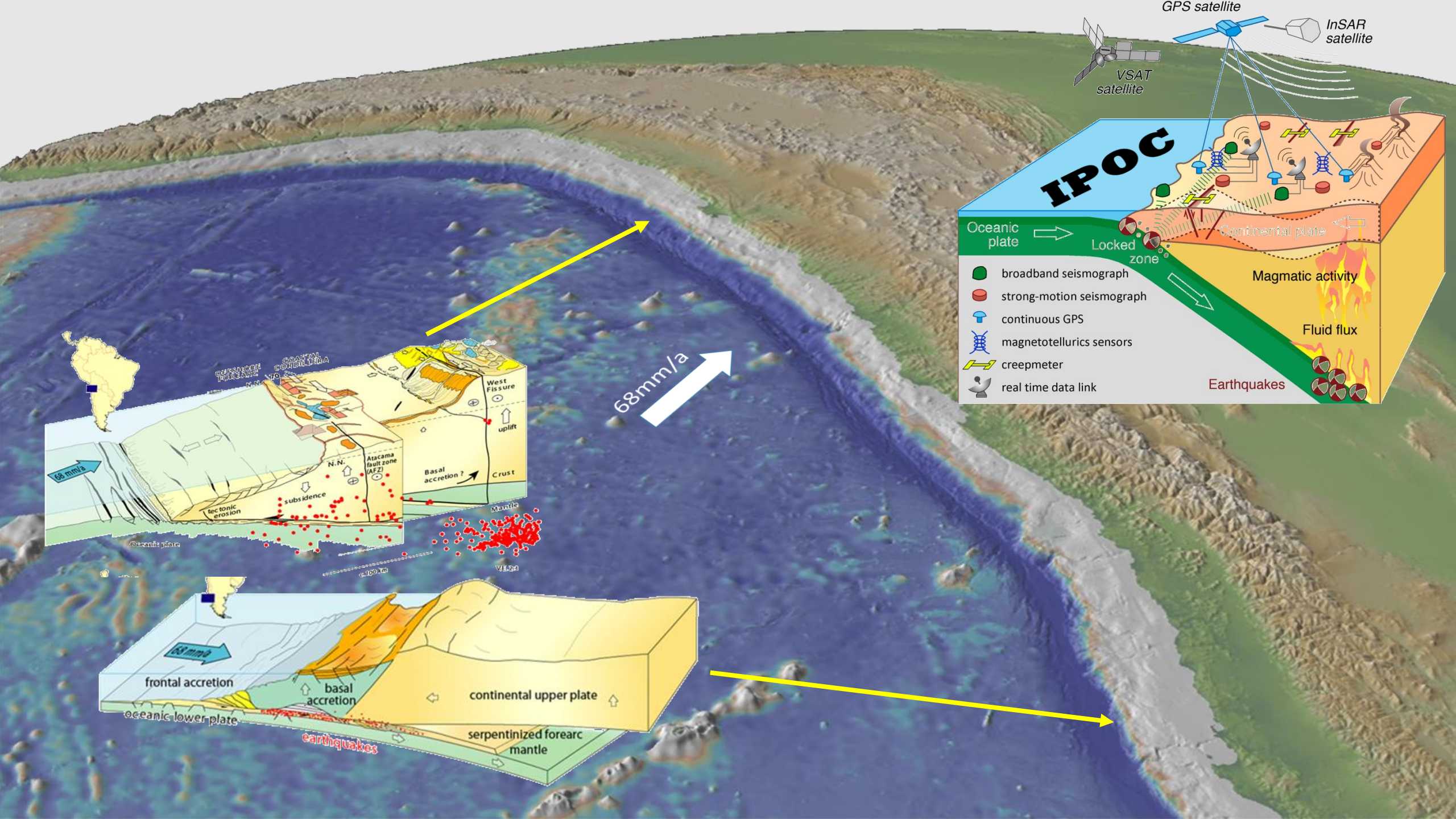
Modified from Scholz, 1998; Bilek & Lay, 2002; and Schwartz & Rokosky, 2007



Forearc deformation across time scales - a tale of fluids, locking and transients

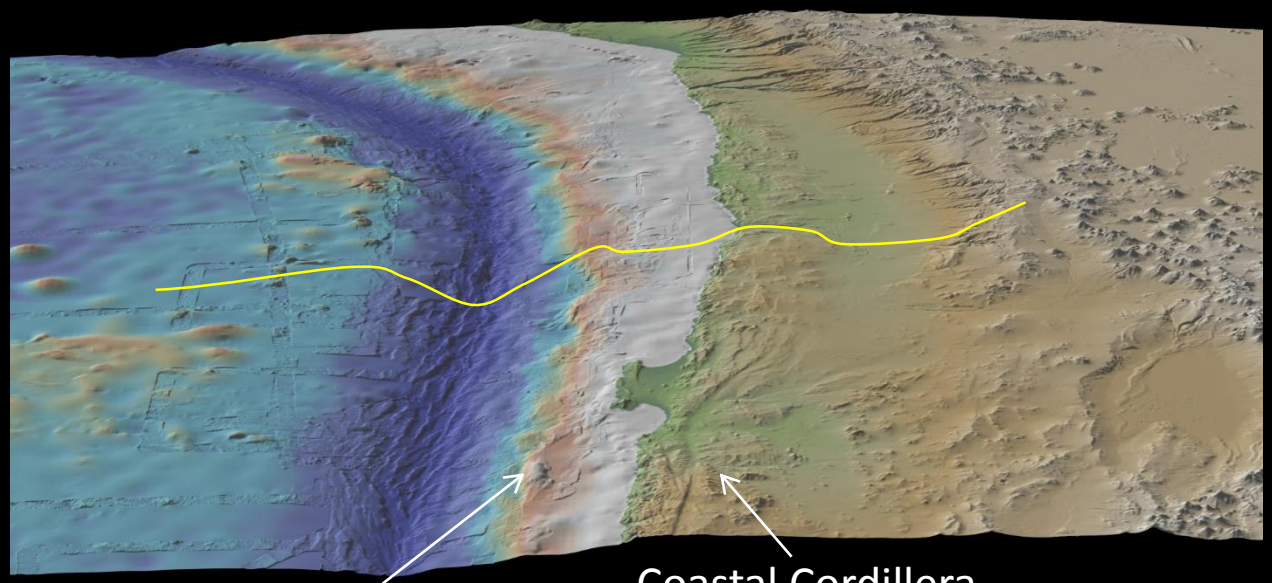
Onno Oncken, GFZ Potsdam

with M. Moreno, P. Victor, B. Schurr, I. Ioannidi, J. Bedford, V. Mouslopoulou, I. Urrutia, M. Rosenau, F. Hoffmann, S. Angiboust, S. Li … and many more


GPS satellite
InSAR satellite
VSAT satellite
IPOC
Oceanic plate
Continental plate
Locked zone
Magmatic activity
Fluid flux
Earthquakes
broadband seismograph
strong-motion seismograph
continuous GPS
magnetotellurics sensors
creepmeter
real time data link
68mm/a
West Fissure
uplift
Basal accretion ?
Crust
Mantle
N.N.
Atacama fault zone (AFZ)
subsidence
tectonic erosion
Oceanic plate
c.100 km
frontal accretion
basal accretion
continental upper plate
oceanic lower plate
earthquakes
serpentinized forearc mantle

Topographic architecture of the Chile plate margin

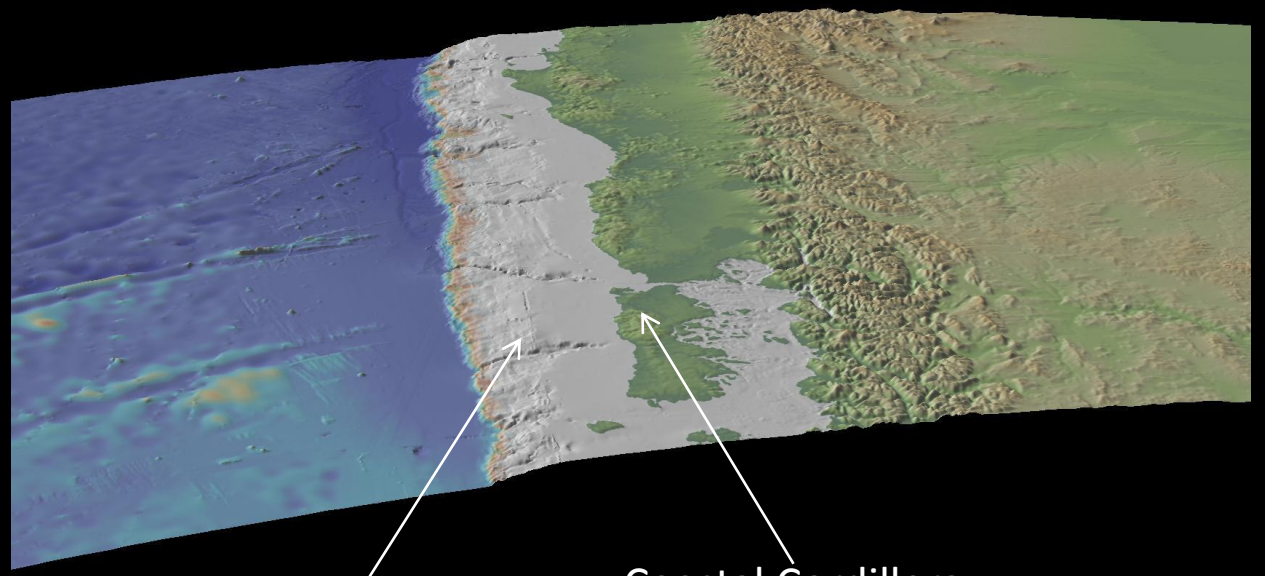
tectonically erosive north



external ridge

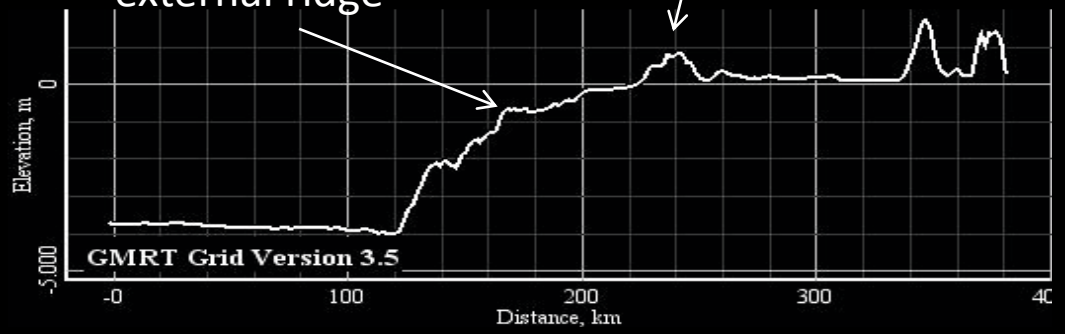
Coastal Cordillera

accretionary south

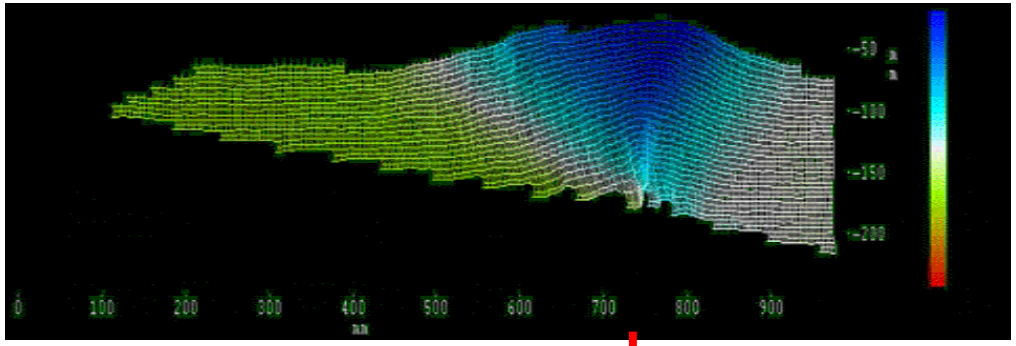


external ridge

Coastal Cordillera



Experimental seismotectonic deformation (10 – 10^5 years)

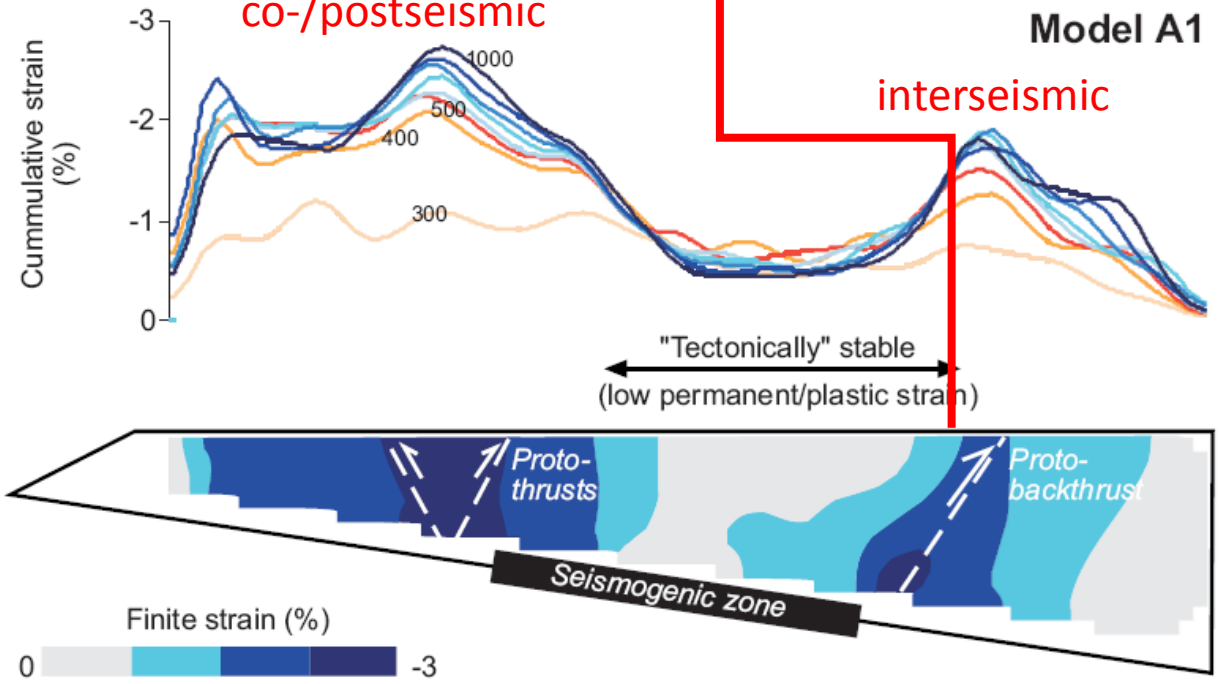


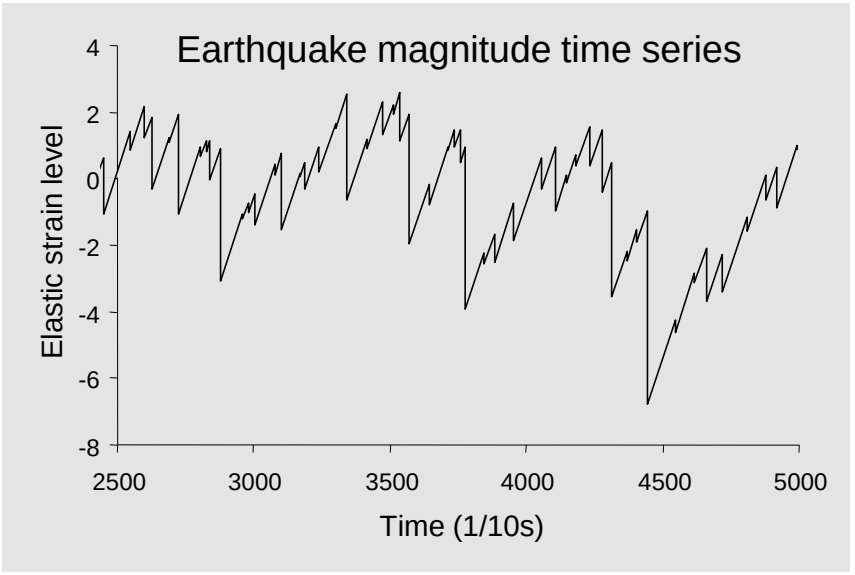
coastline

co-/postseismic

interseismic

Model A1





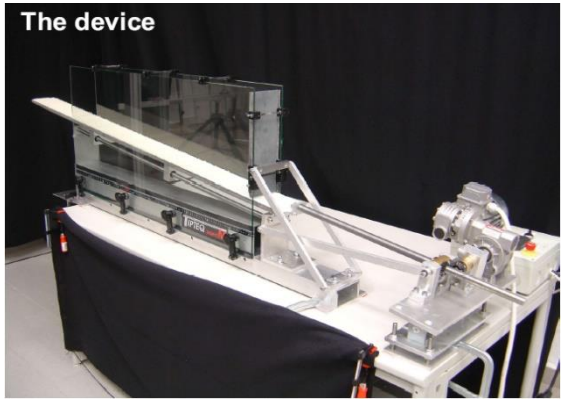
Simulation at large scale
(10^2 km, 10^3 years)

Monitoring at high resolution
(decimeter, minutes)

Nature scale

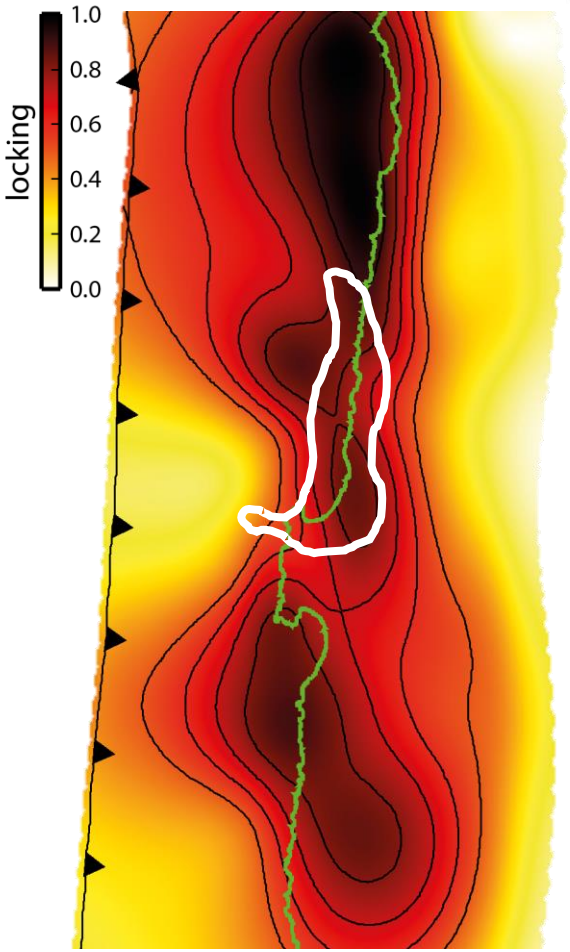
Dynamically scaled for:

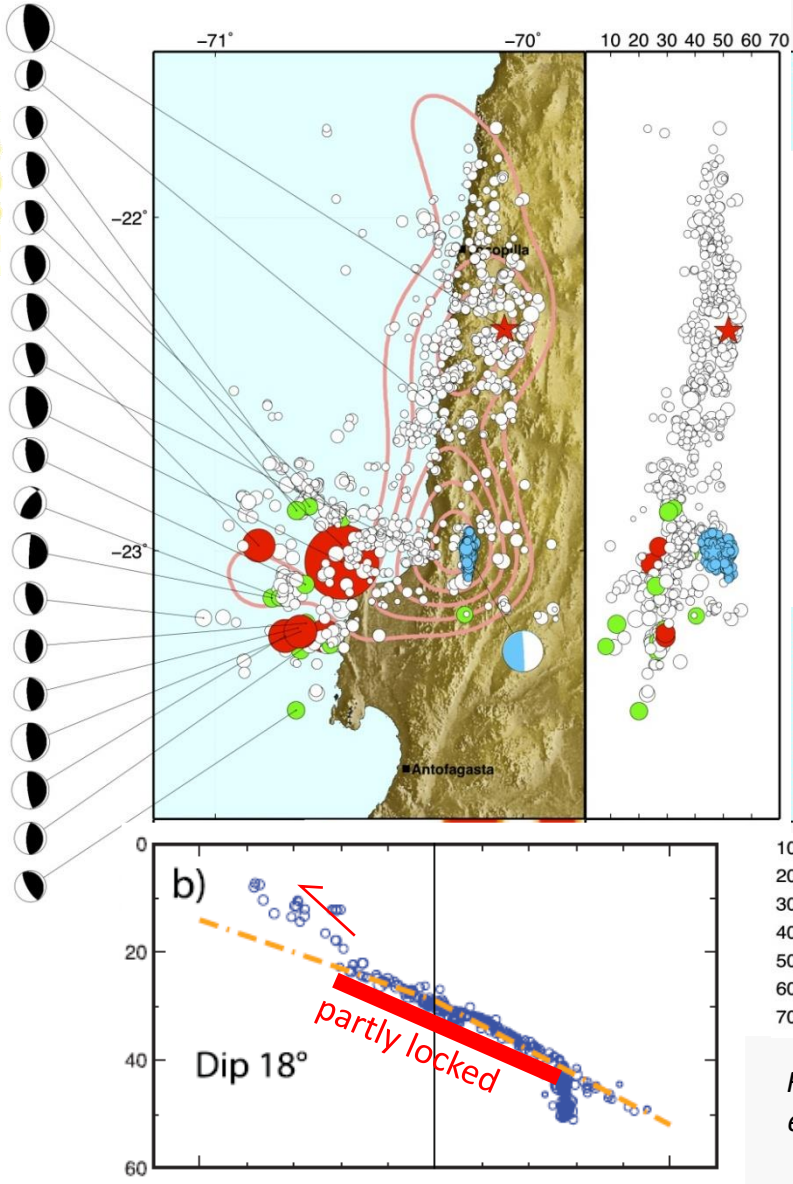
- Strength
- Elasticity
- Viscosity
- Inertia
- Gravitation

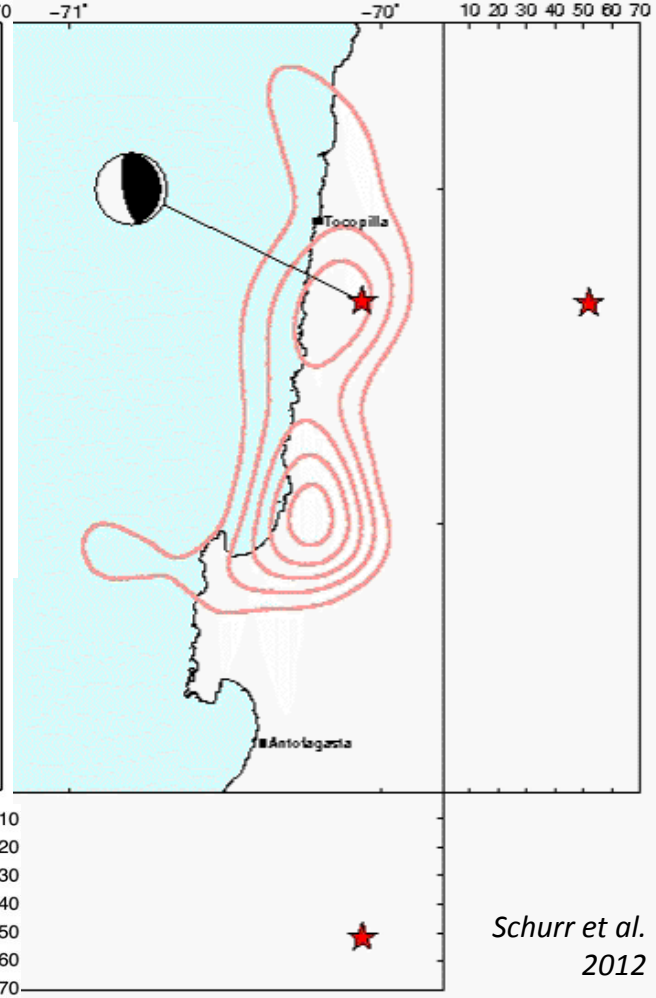


Rosenau & Oncken, JGR, 2009

The Mw = 7.8, Tocopilla earthquake, 2007
- aftershocks at updip end of locking drive uplift

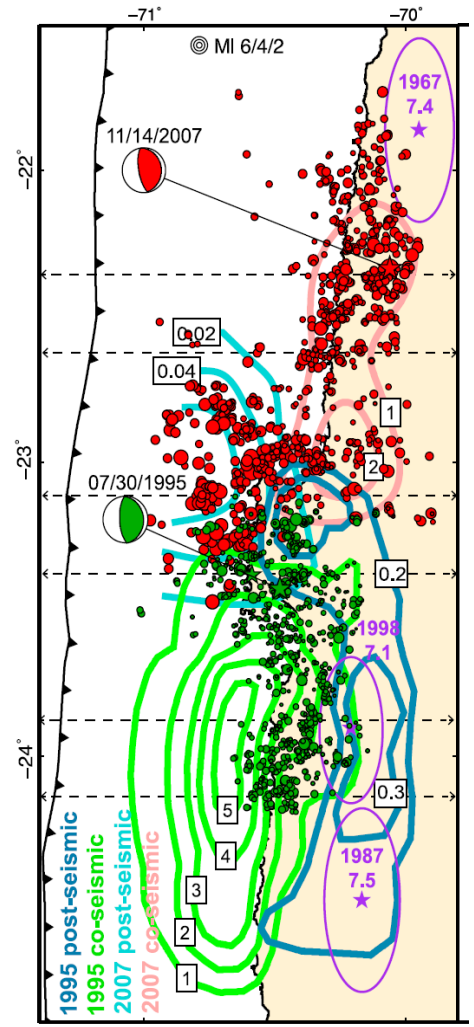




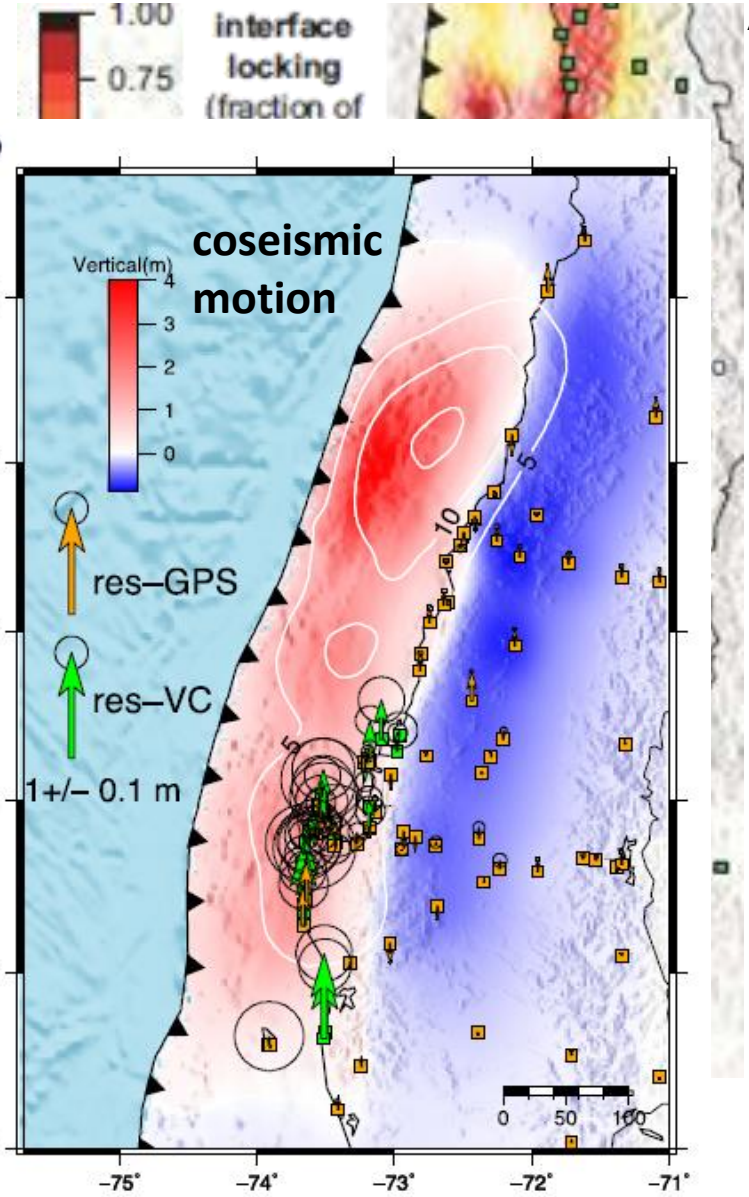


Schurr et al. 2012

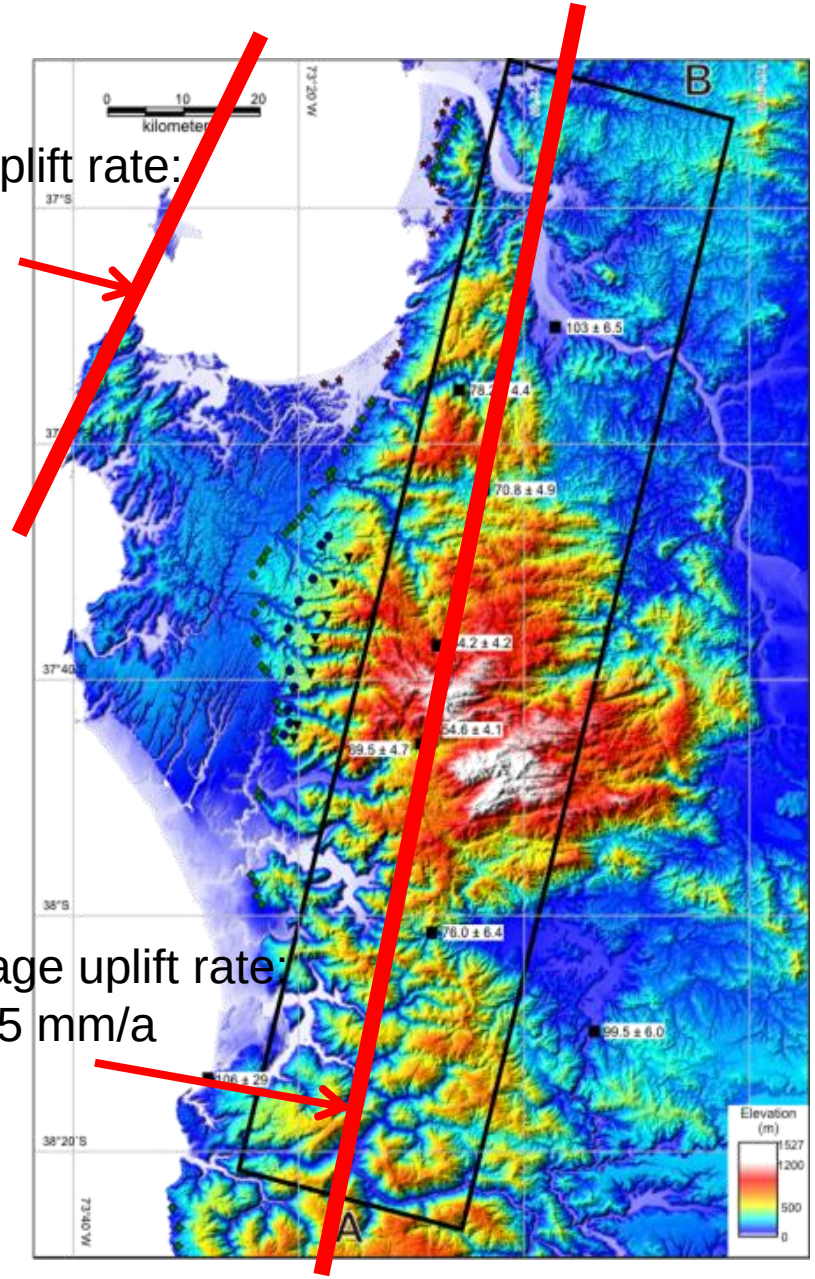
Fuenzalida et al. 2012



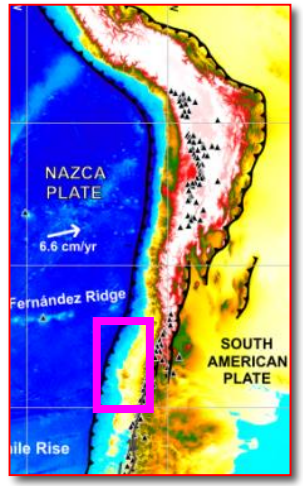
Arauco peninsula - Kinematics since c.3 Ma



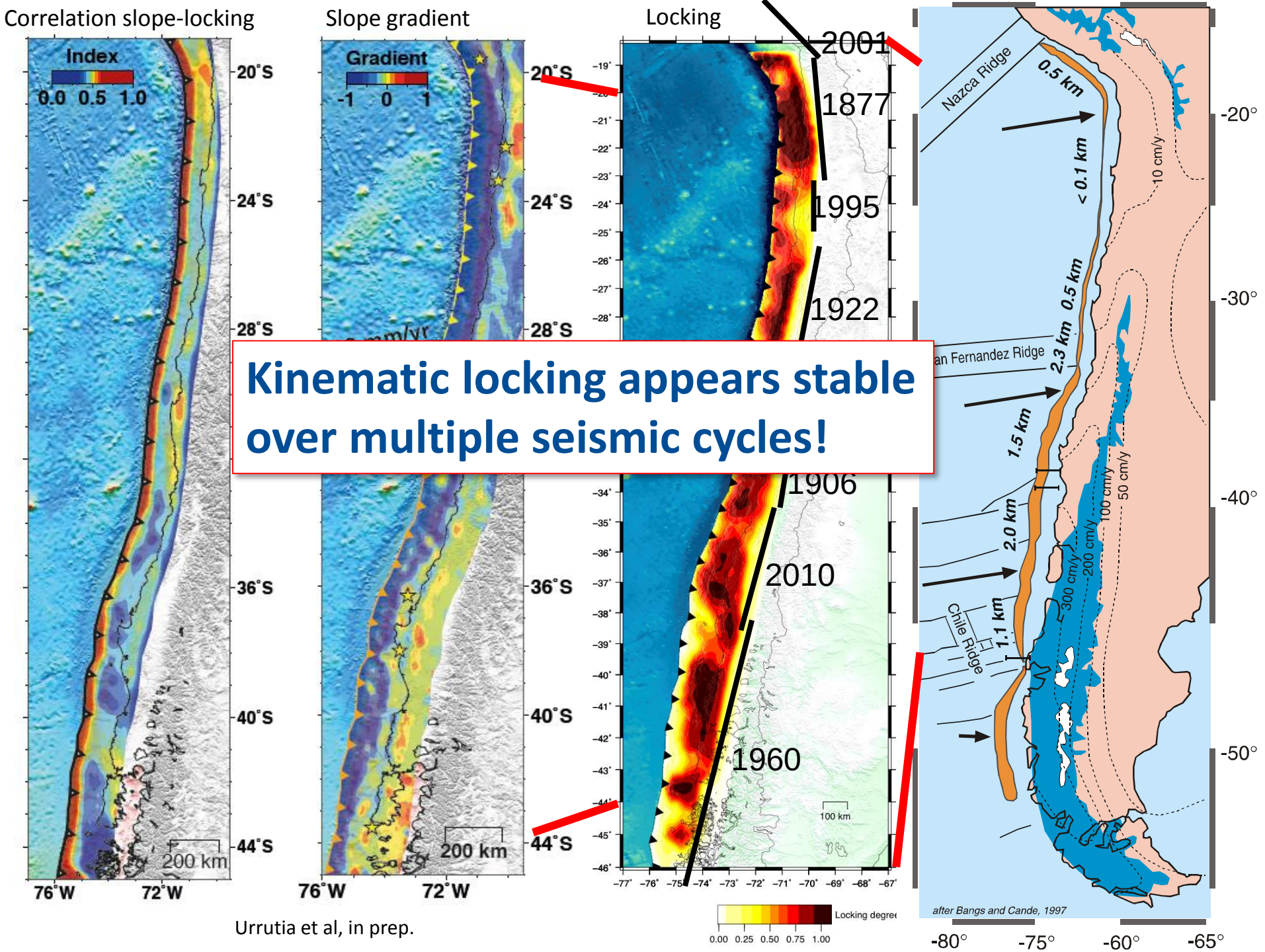
Average uplift rate:
2.3 mm/a



Average uplift rate:
1 - 1.5 mm/a



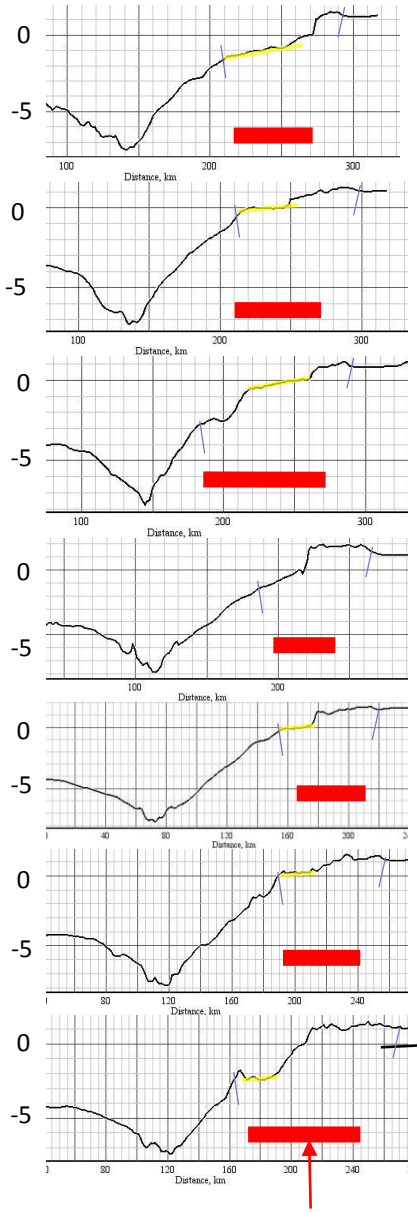
Bookhagen et al., Melnick et al, 2006, 2009

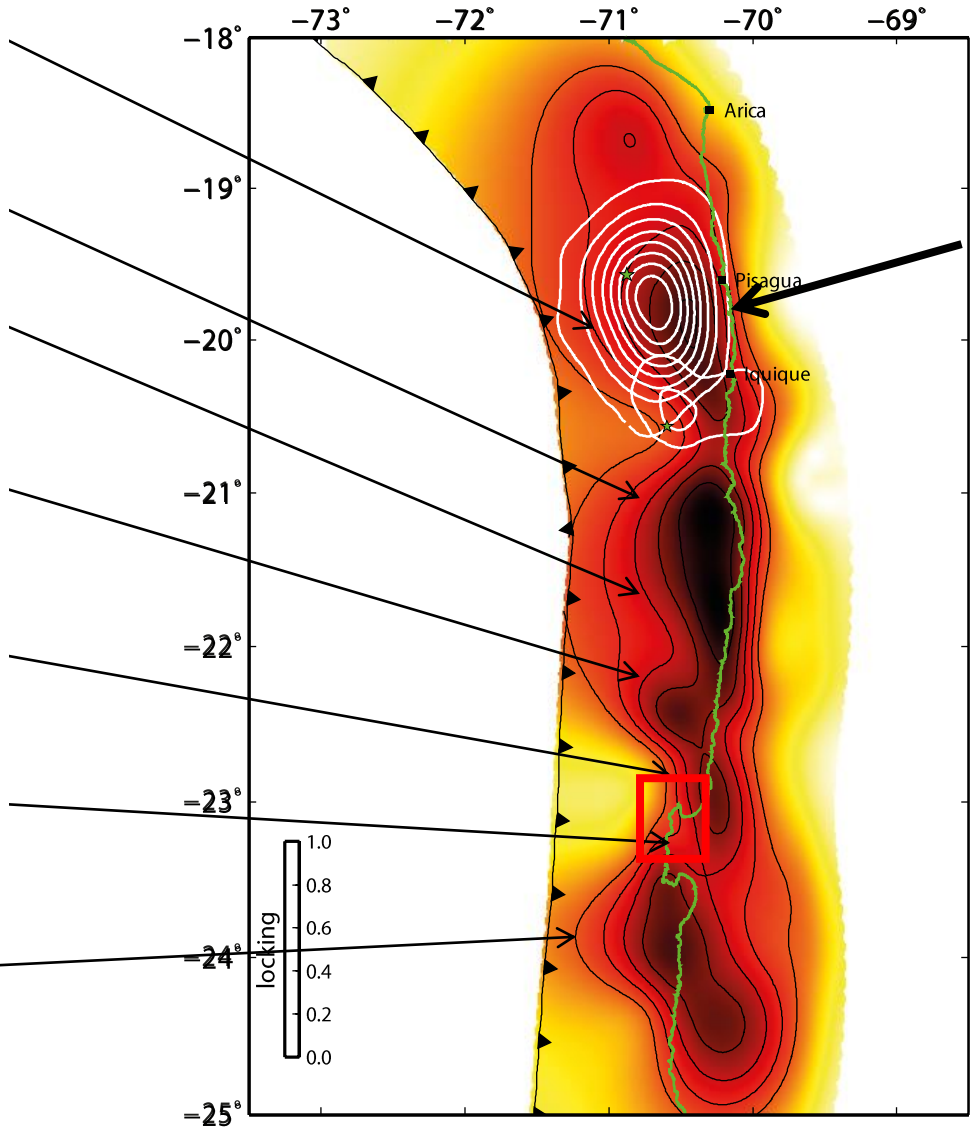


Kinematic locking appears stable over multiple seismic cycles!

Urrutia et al, in prep.

Are locked patches stable over 10^5-10^7 years? And through what mechanism?

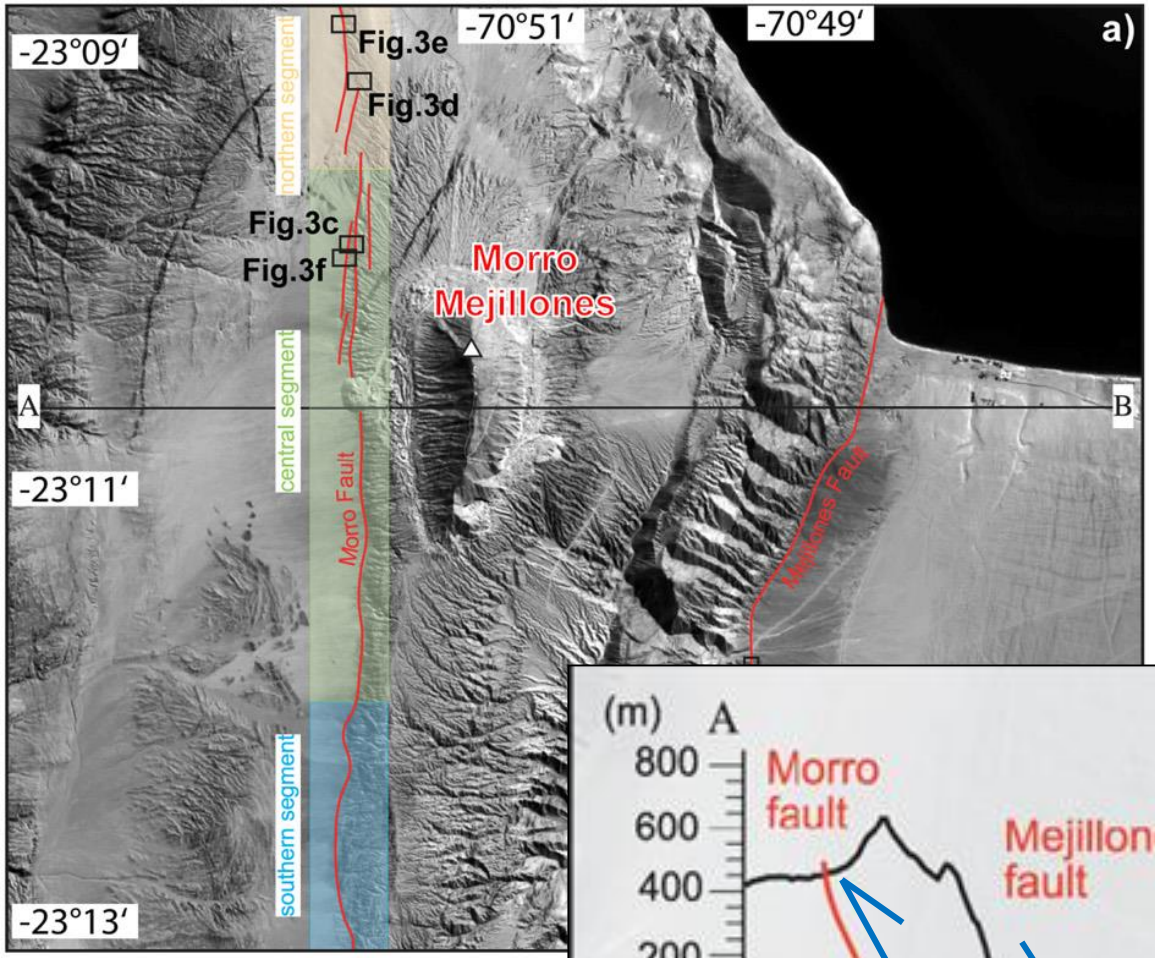


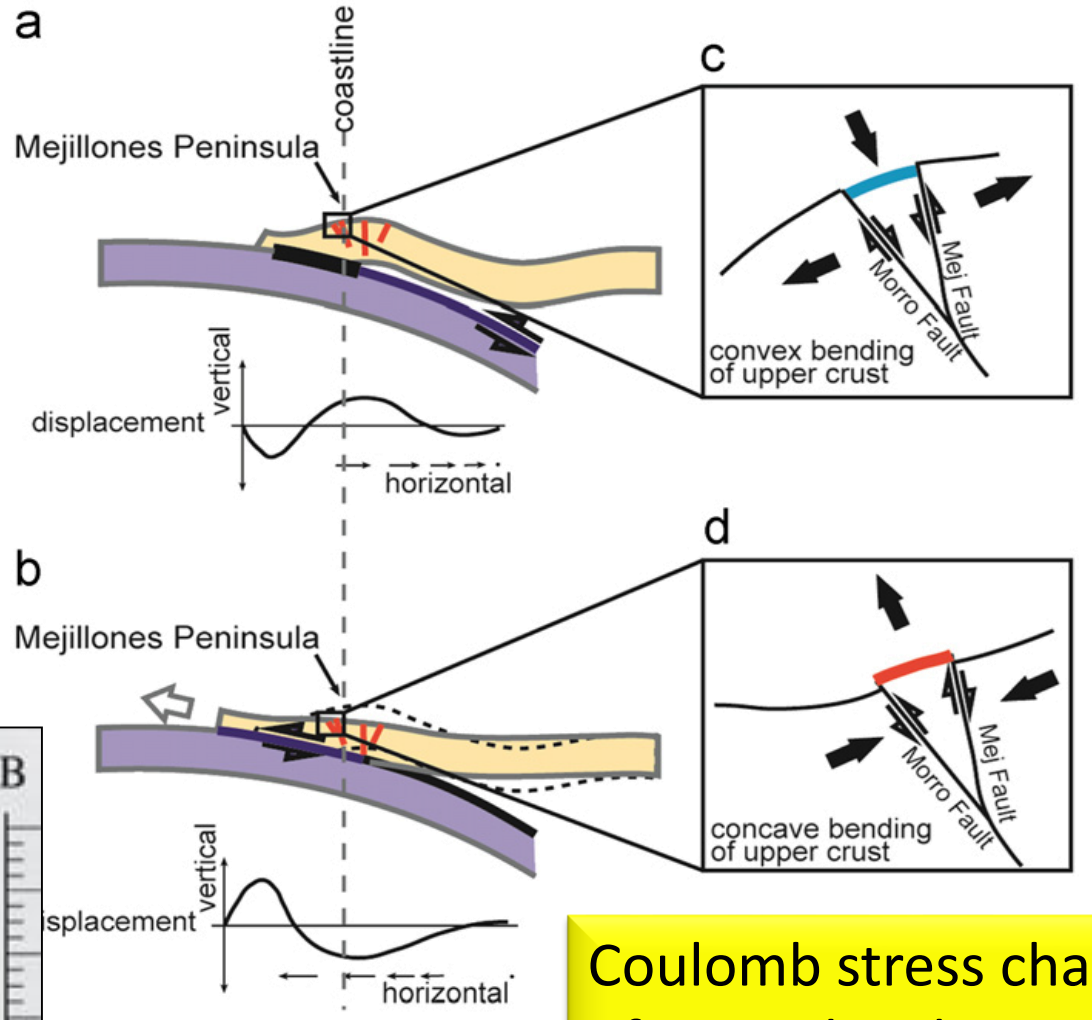


Mw8.1 Iquique earthquake, 4-1-2014

Schurr et al., Nature, 2014

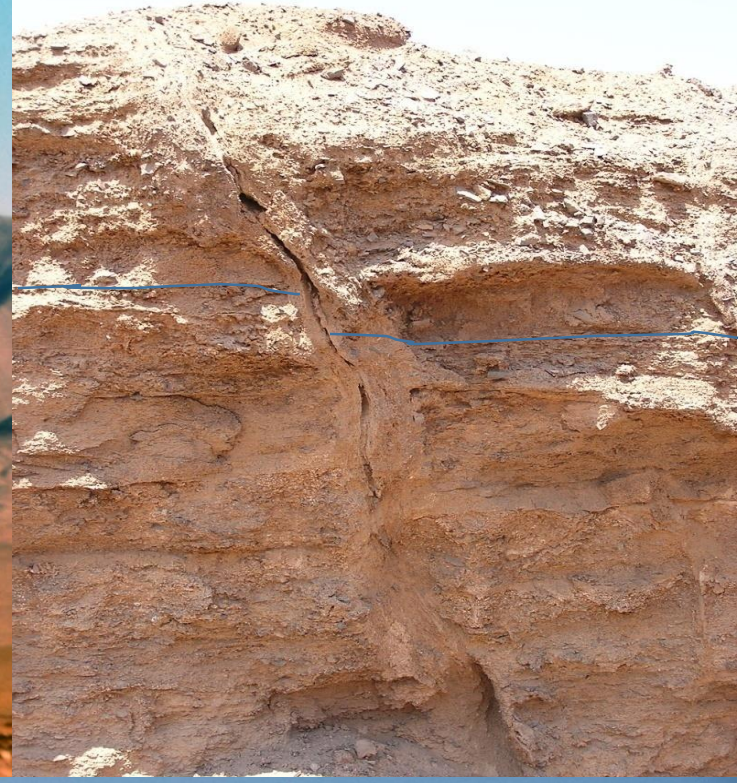
Slip reversal on upper plate faults during megathrust seismic cycle ?





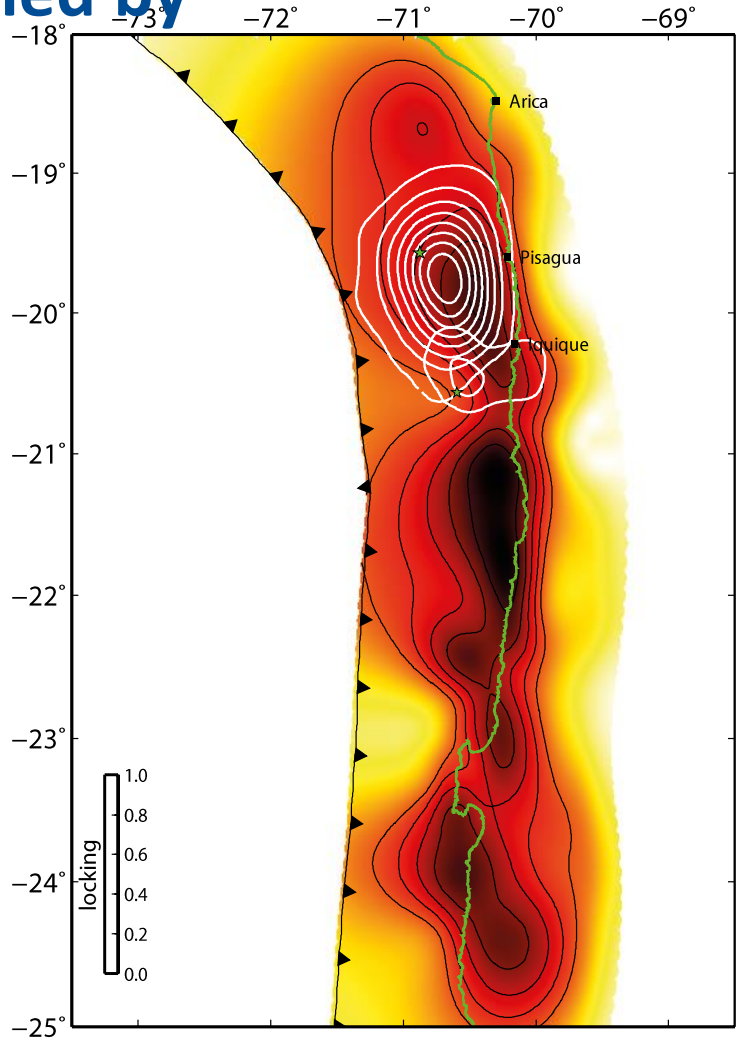
Coulomb stress change of several 10 kPa only!!

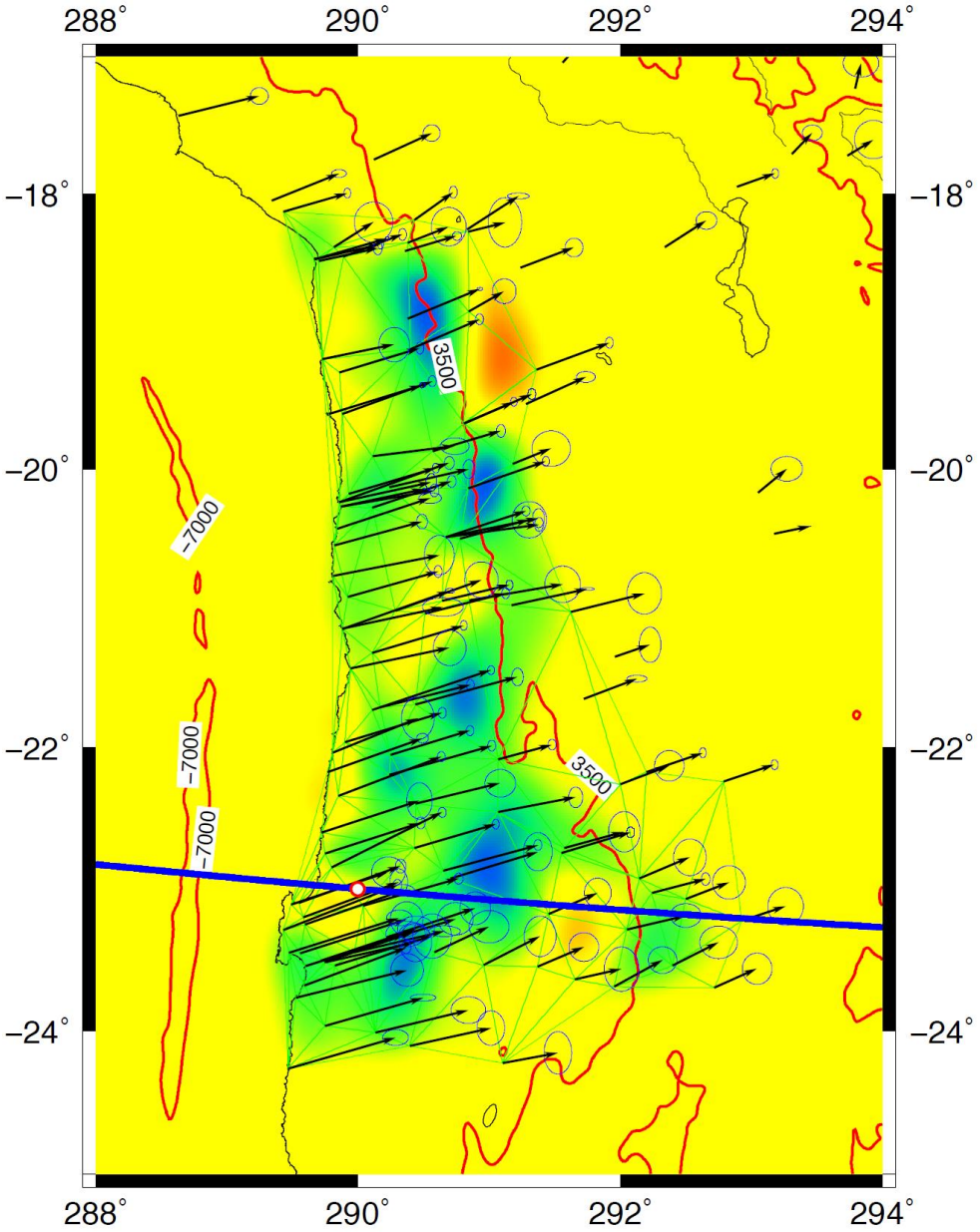
Shirzaei et al., GRL, 2012



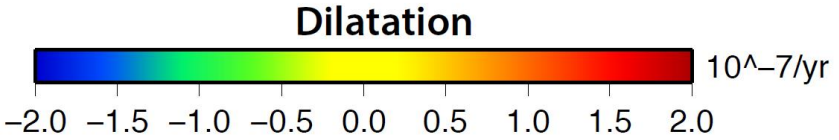
extension during postseismic relaxation and afterslip, shortening interseis-mically?

Late interseismic kinematic mode indeed governed by compression landward of the locked zone

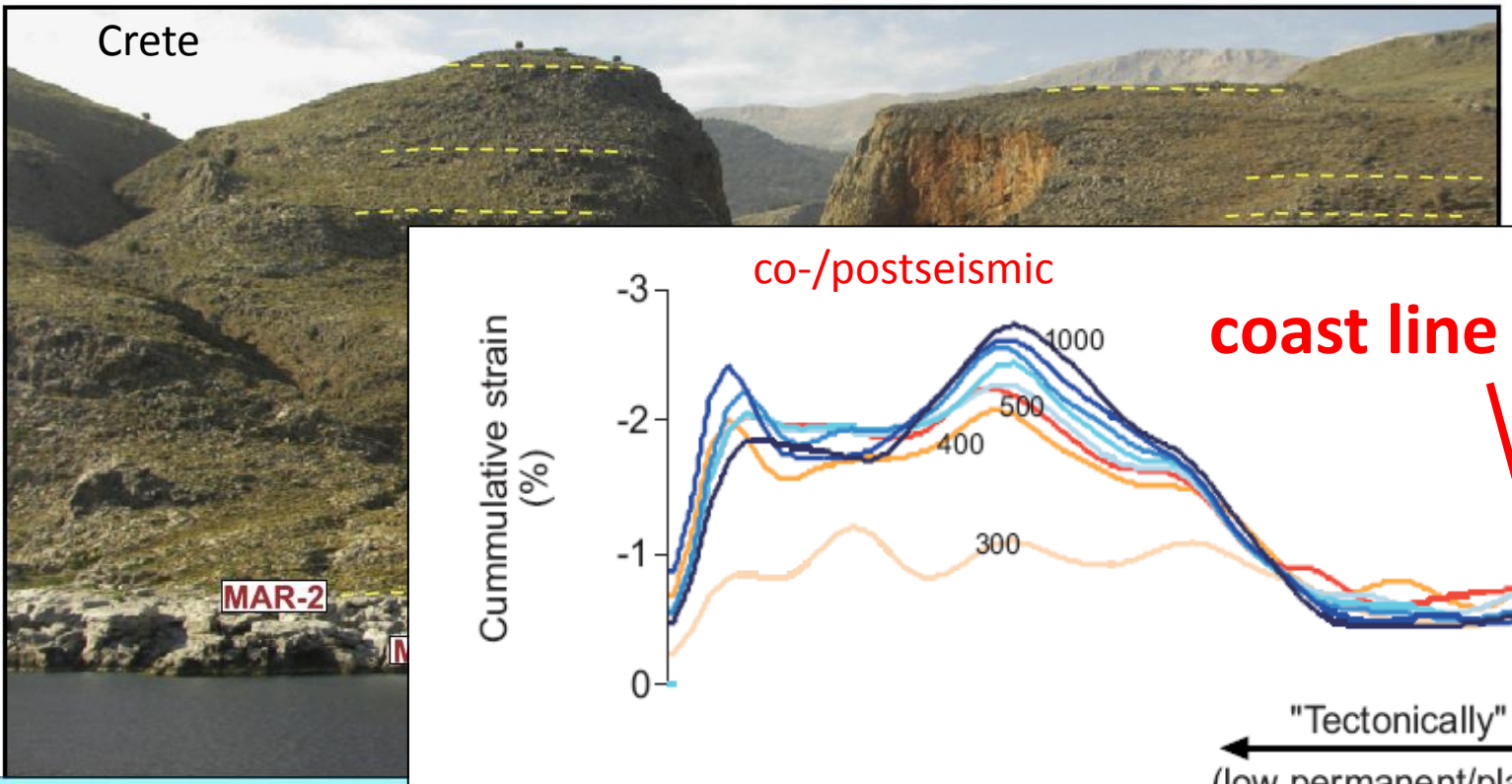


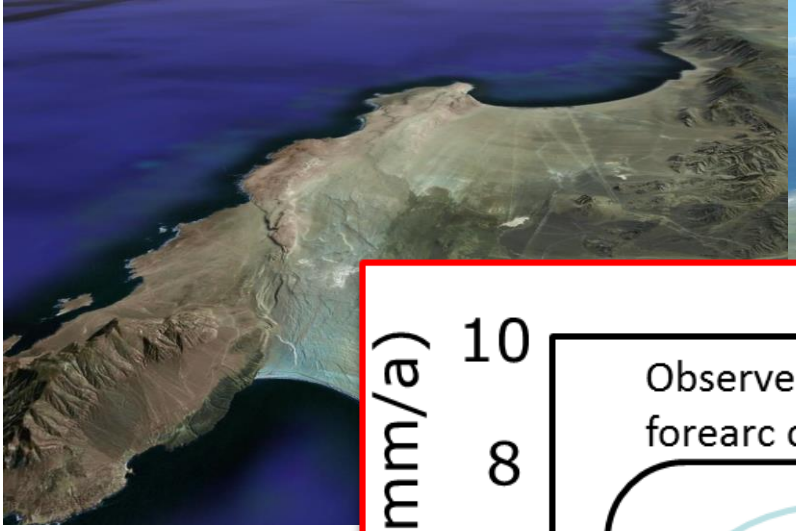


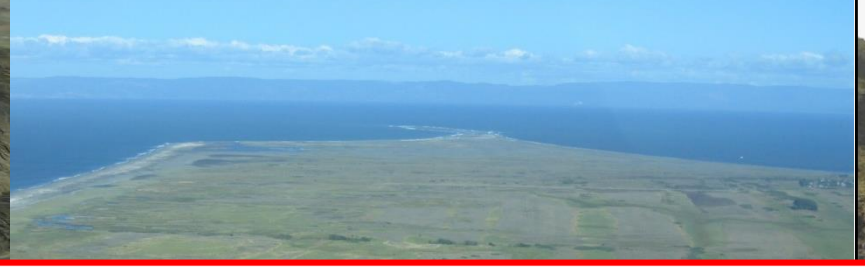
data in Hoffmann et al., 2018;
strain calculation courtesy of S. Lamb

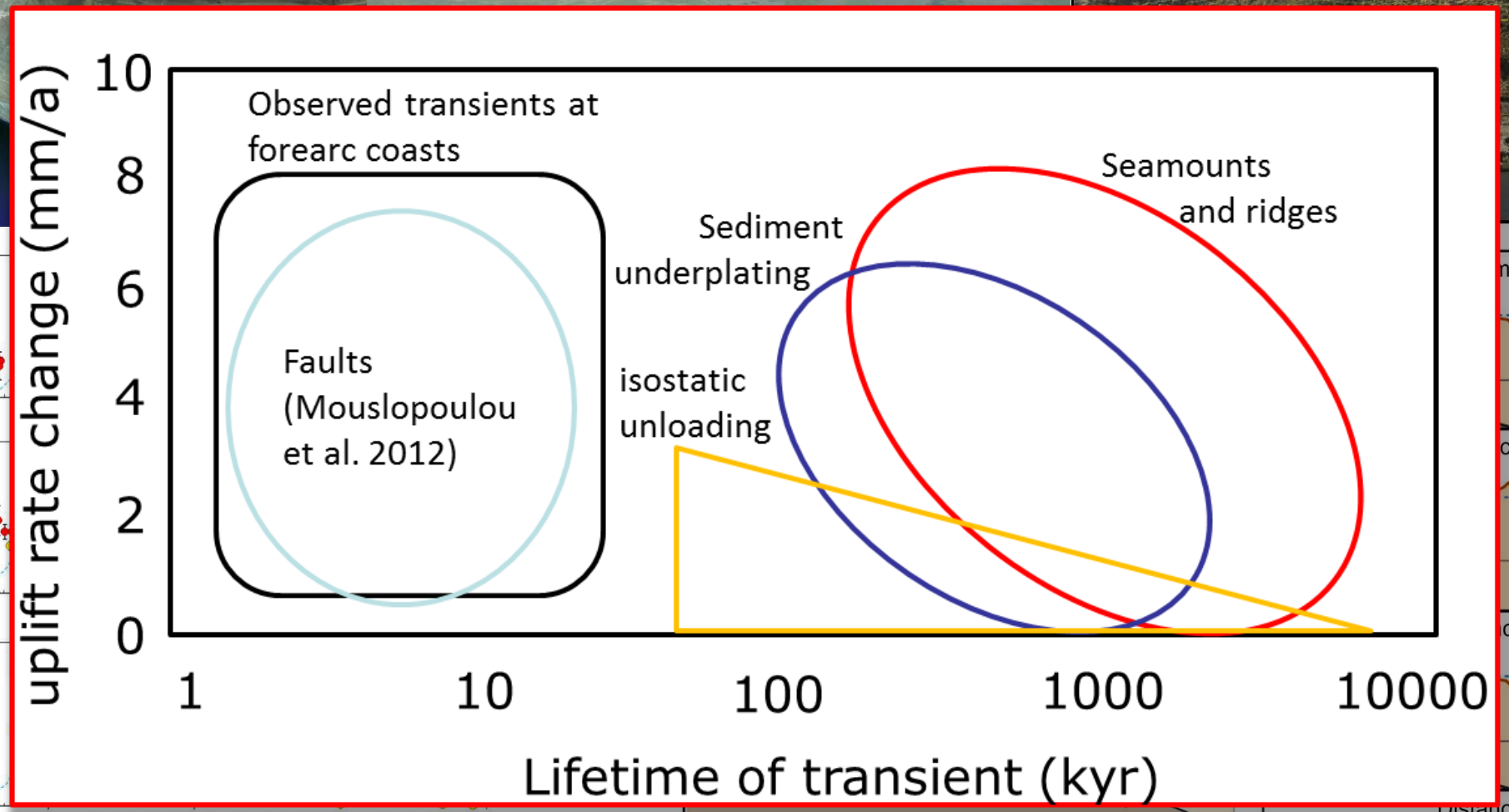


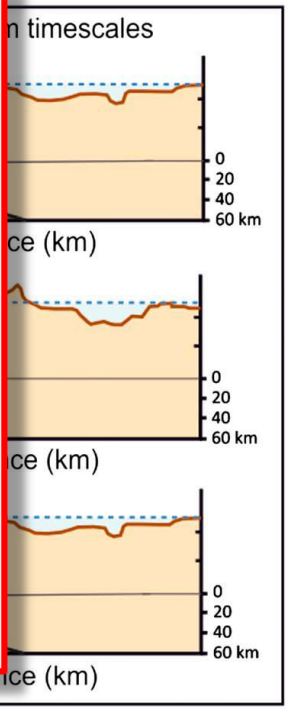
Strandlines mark sea level – and past earthquakes









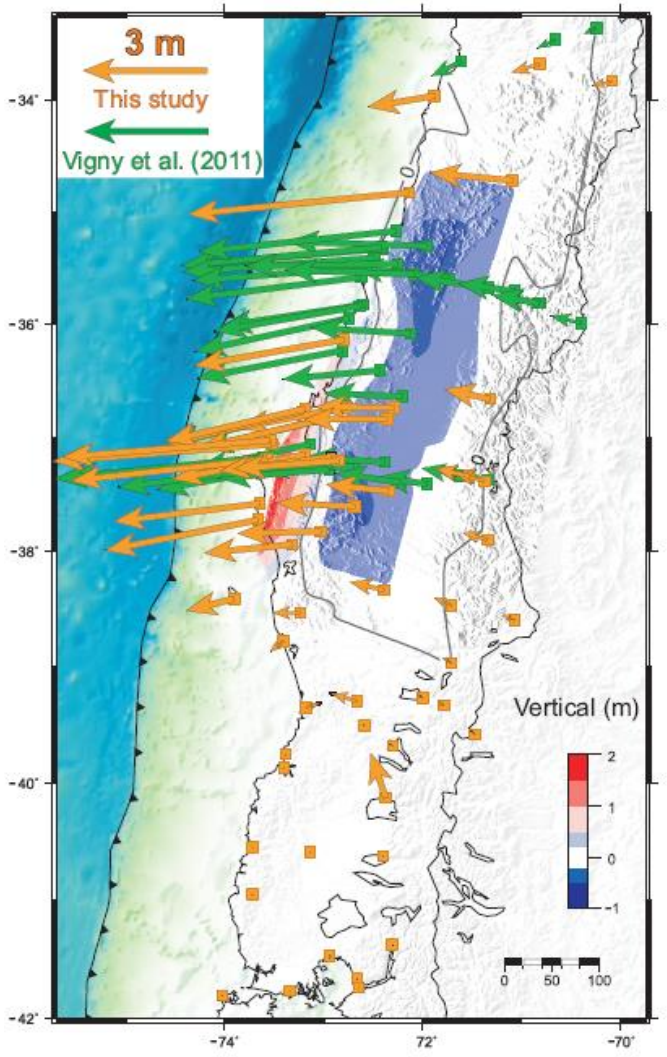


Mouslopoulou et al., 2015, 2016

Long-term uplift transients in forearcs from earthquake clustering

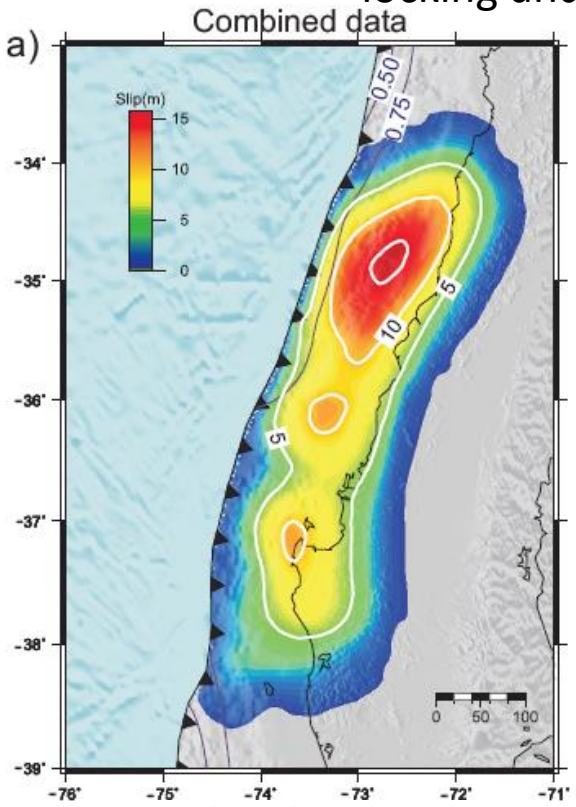
Preseismic locking and coseismic slip – the 8.8. Maule earthquake of 27.2.2010

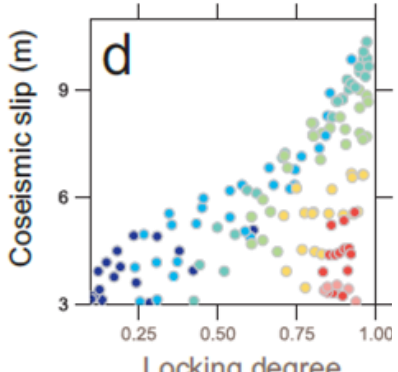
coseismic displacement

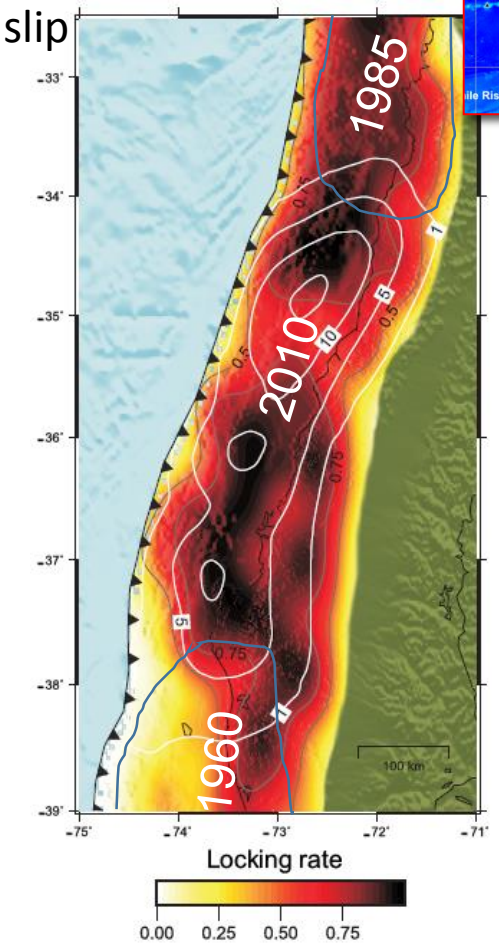


(Moreno et al. EPSL 2012)

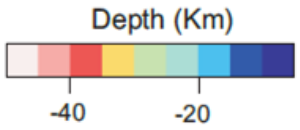
locking and slip



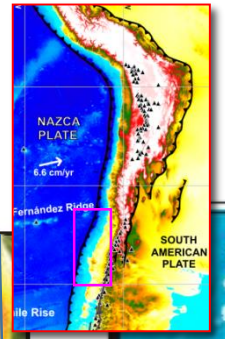


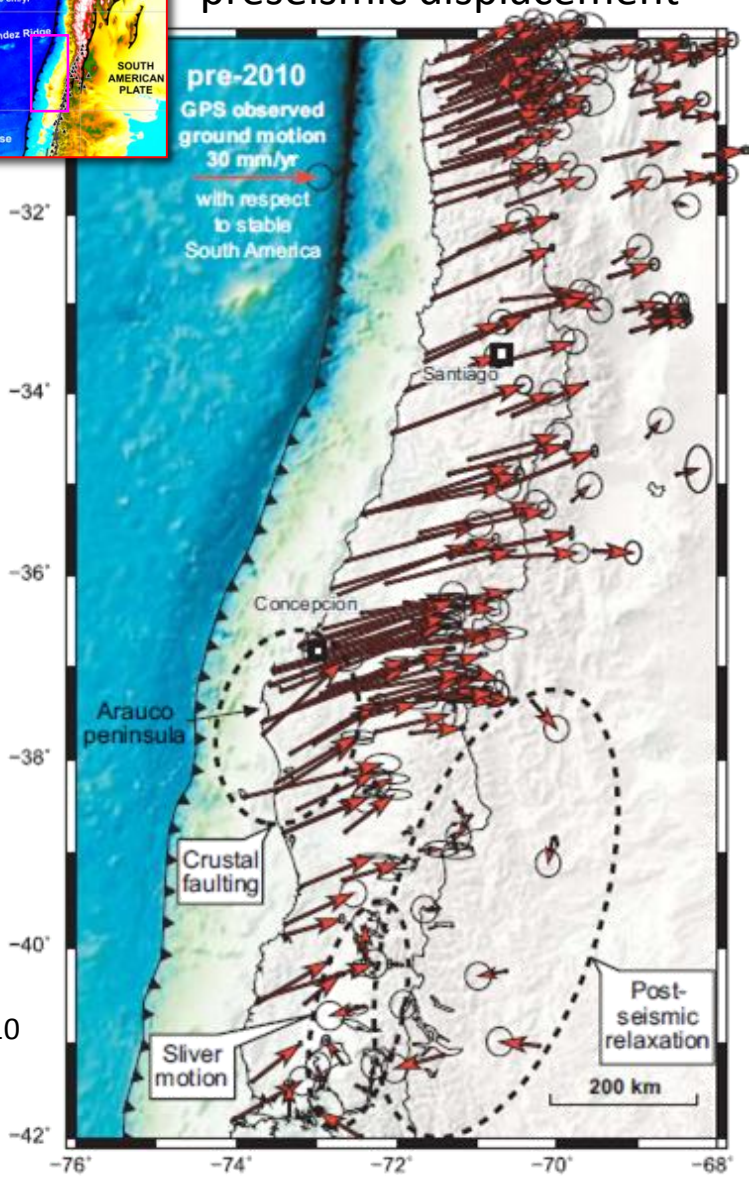


Moreno, Rosenau & Oncken, Nature 2010



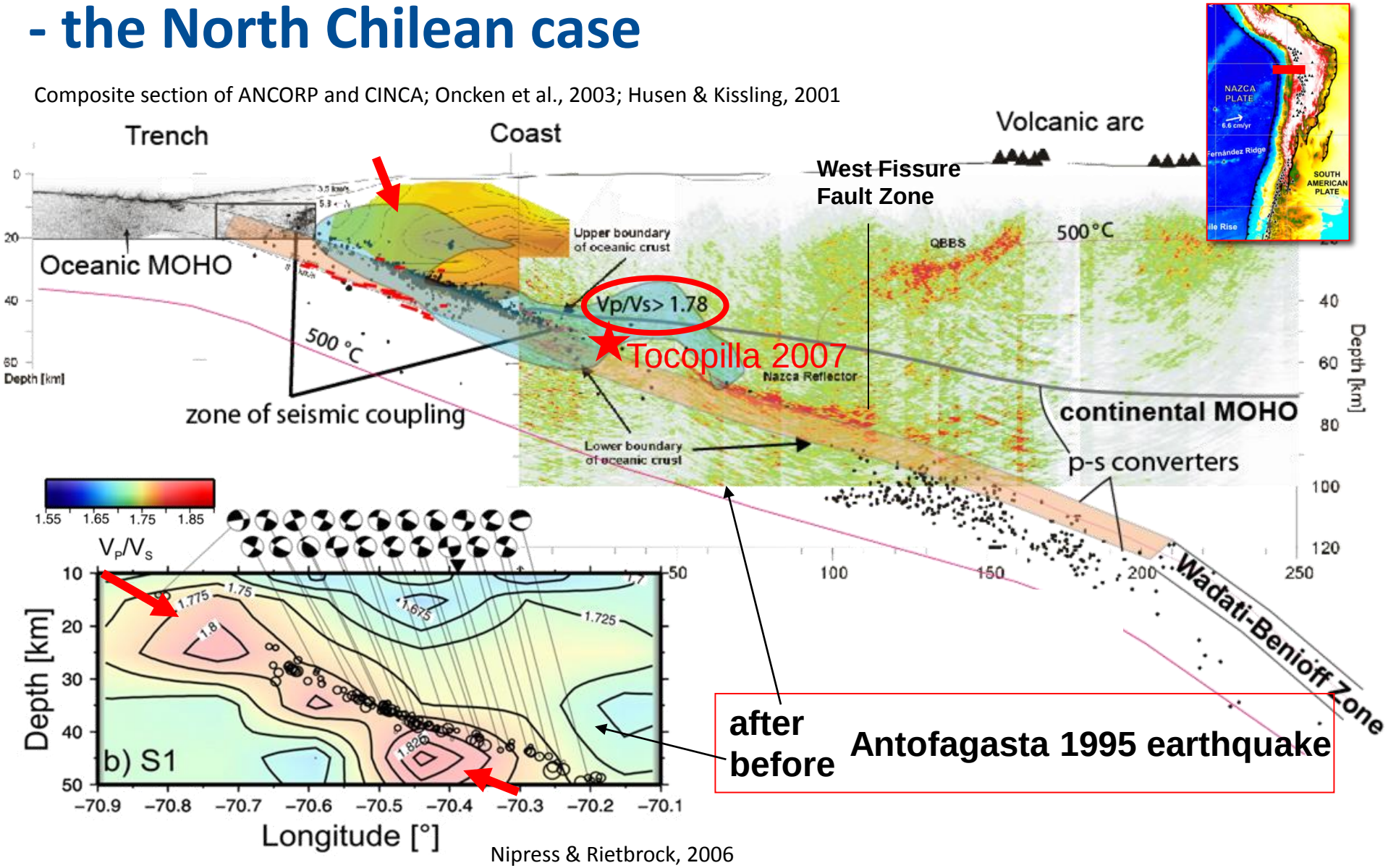
preseismic displacement





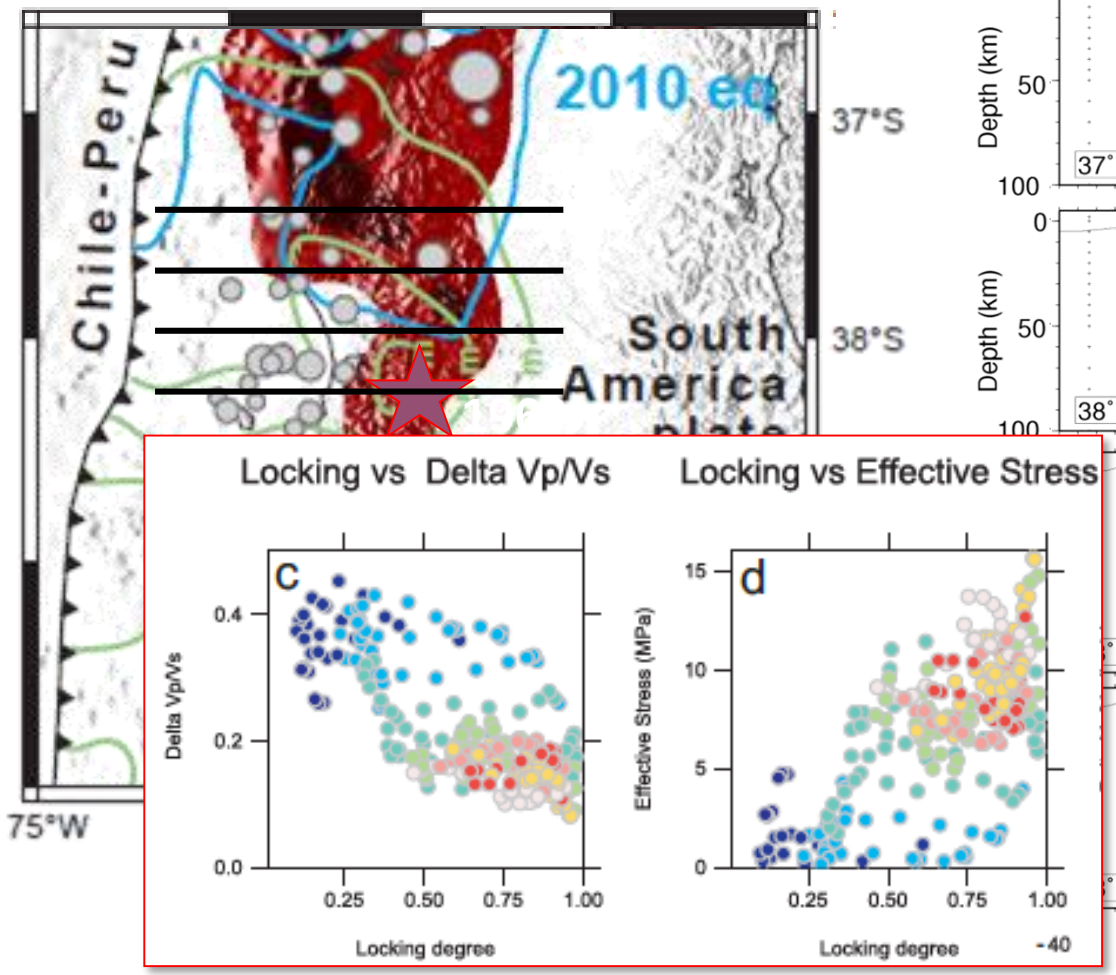
Seismological image reveals hydraulic transients - the North Chilean case

Composite section of ANCORP and CINCA; Oncken et al., 2003; Husen & Kissling, 2001

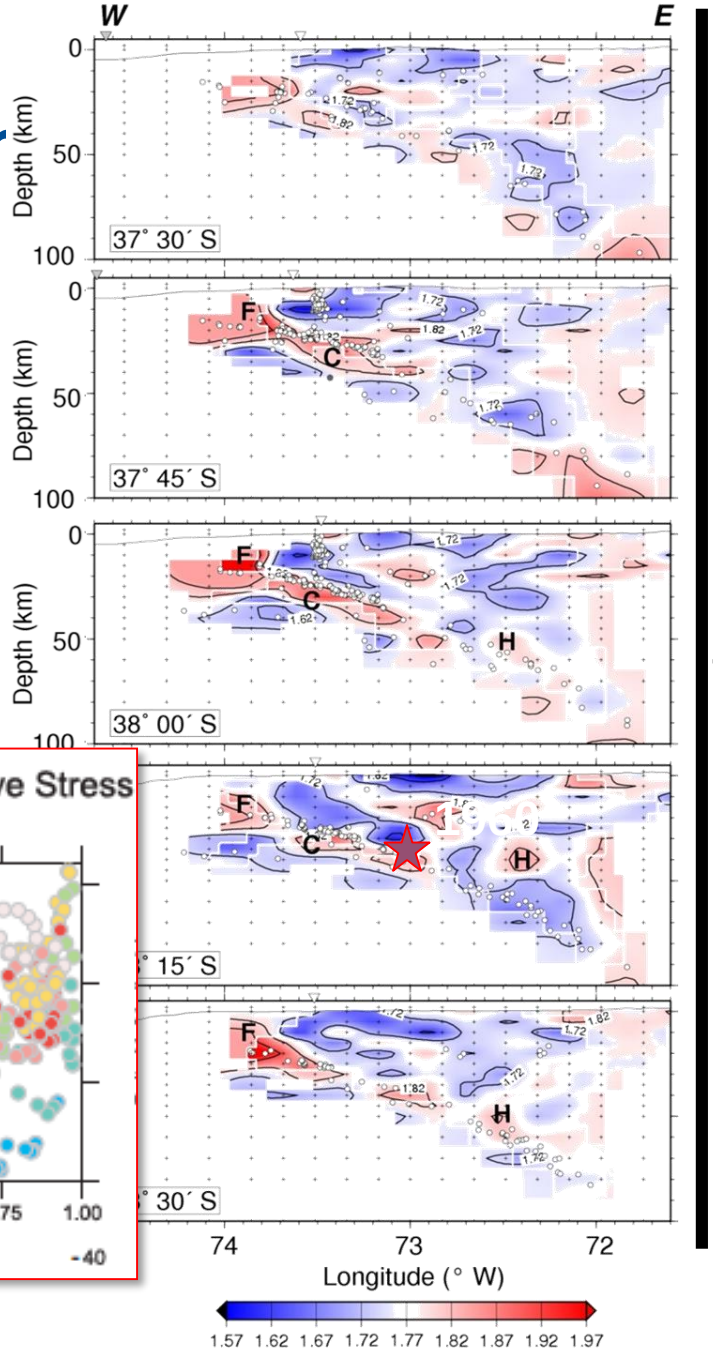


Nipress & Rietbrock, 2006

Background seismicity and Vp/Vs ratio show correlation with geodetic locking



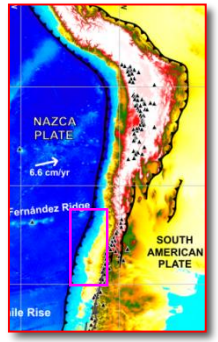
Moreno et al., 2014



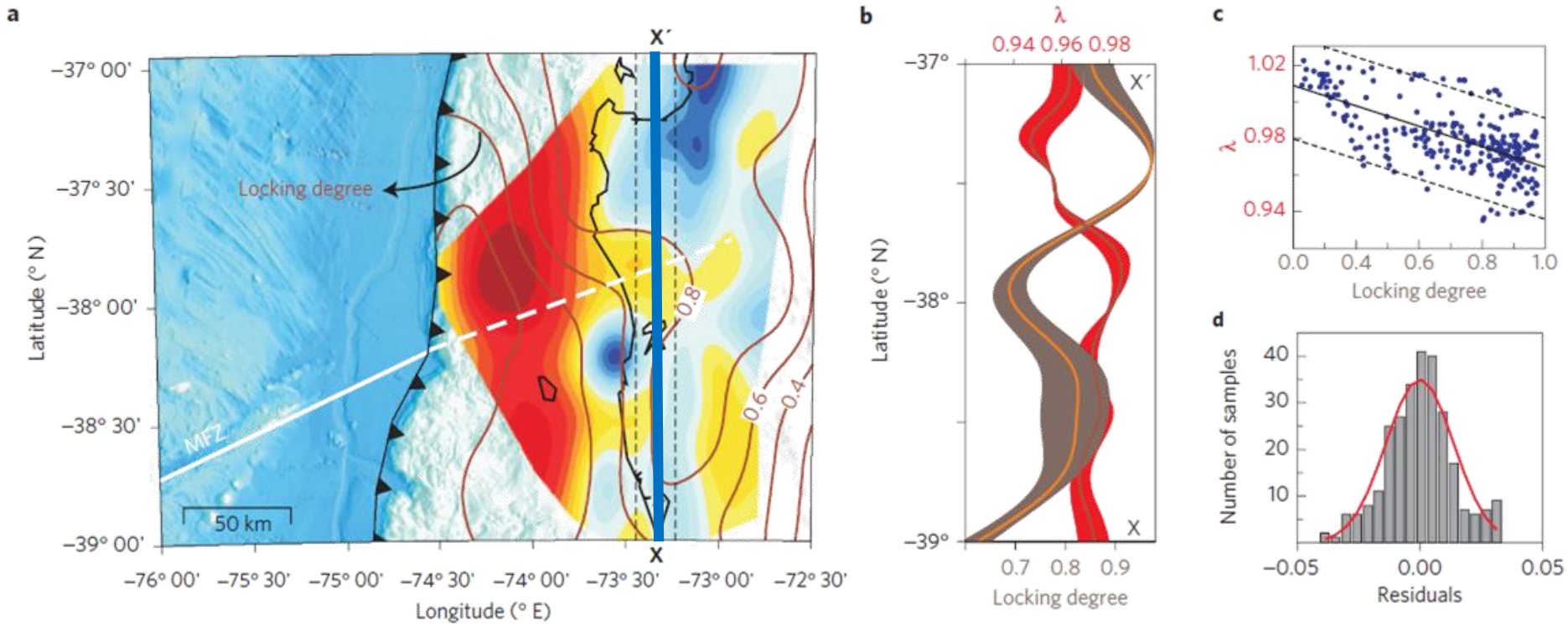
Haberland et al. 2009 v_p/v_s

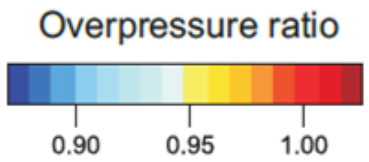
2010 Maule rupture zone

1960 Valdivia rupture zone



Pore pressure controls locking?





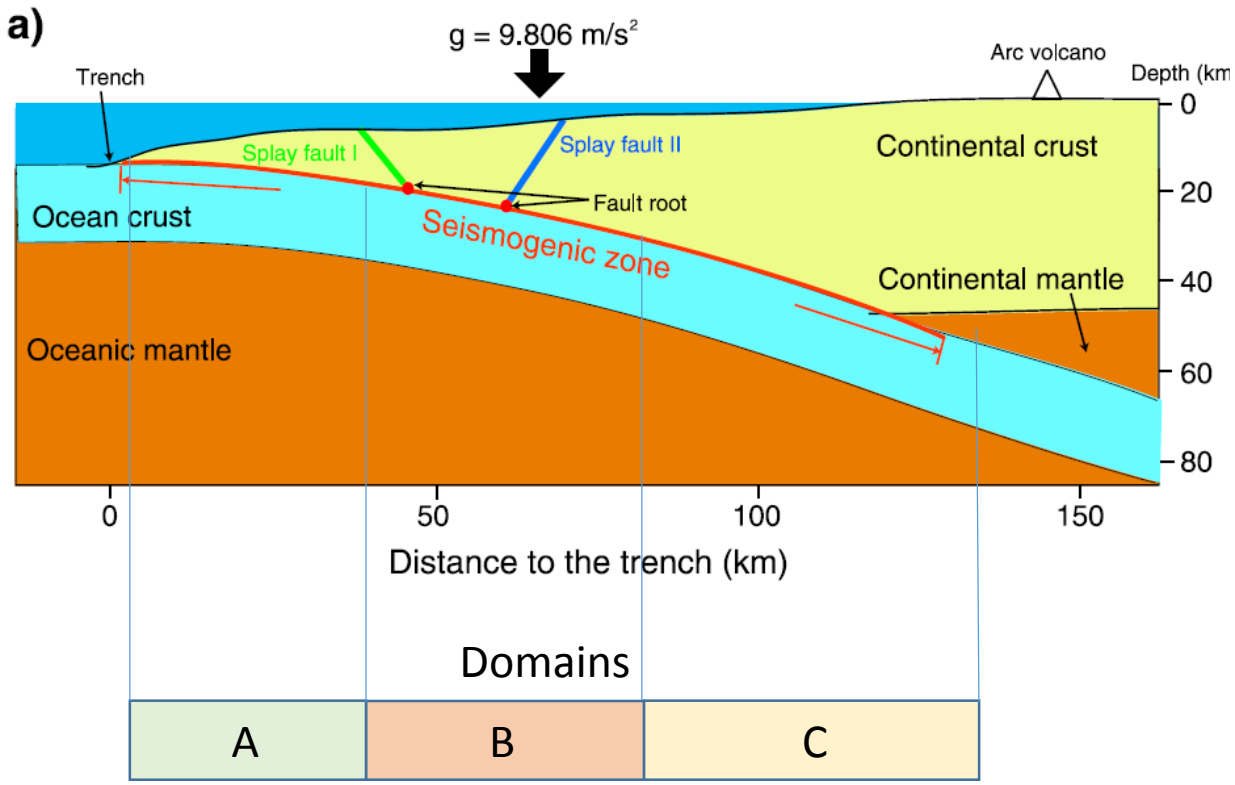
Moreno et al., Nature Geoscience 2014

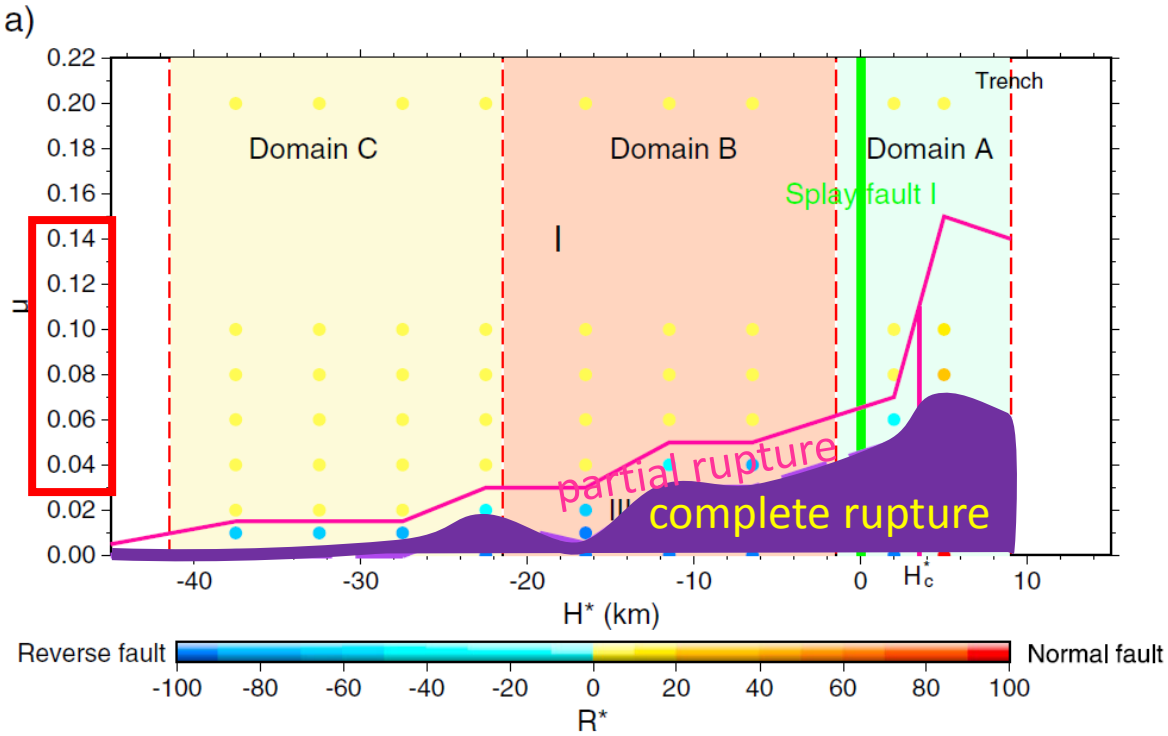
$\lambda = p_f / p_l$ $\tau = C + \sigma_{zz}\ \mu\ (1 - \lambda)$

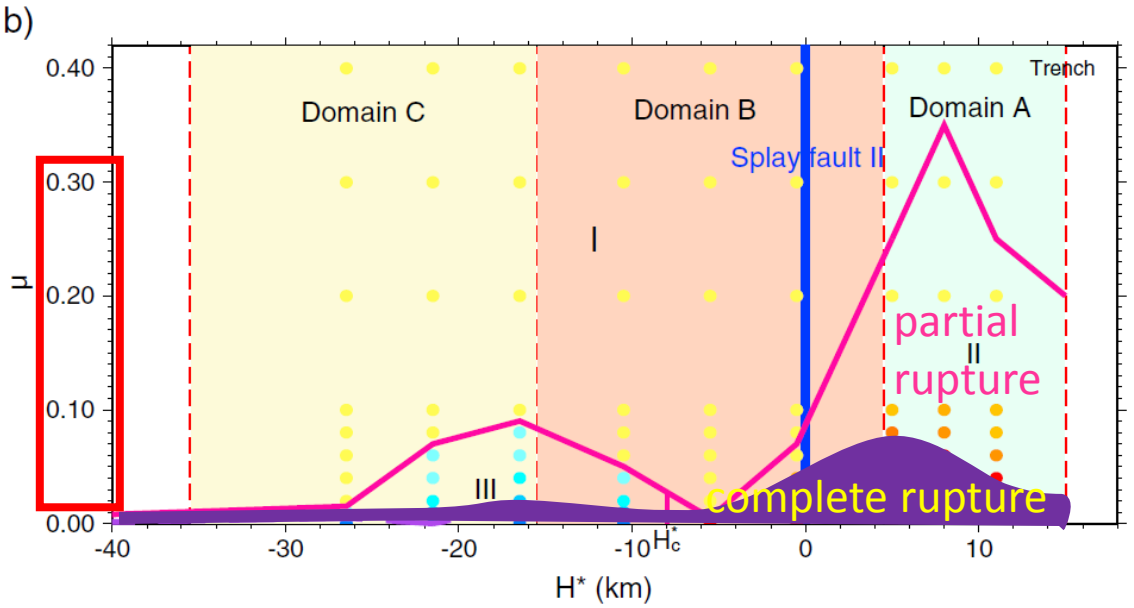
$\lambda_b \approx 0.90$ to 1.00

μ_{eff} on plate interface ≤ 0.05

Strength constraints for forearc faulting

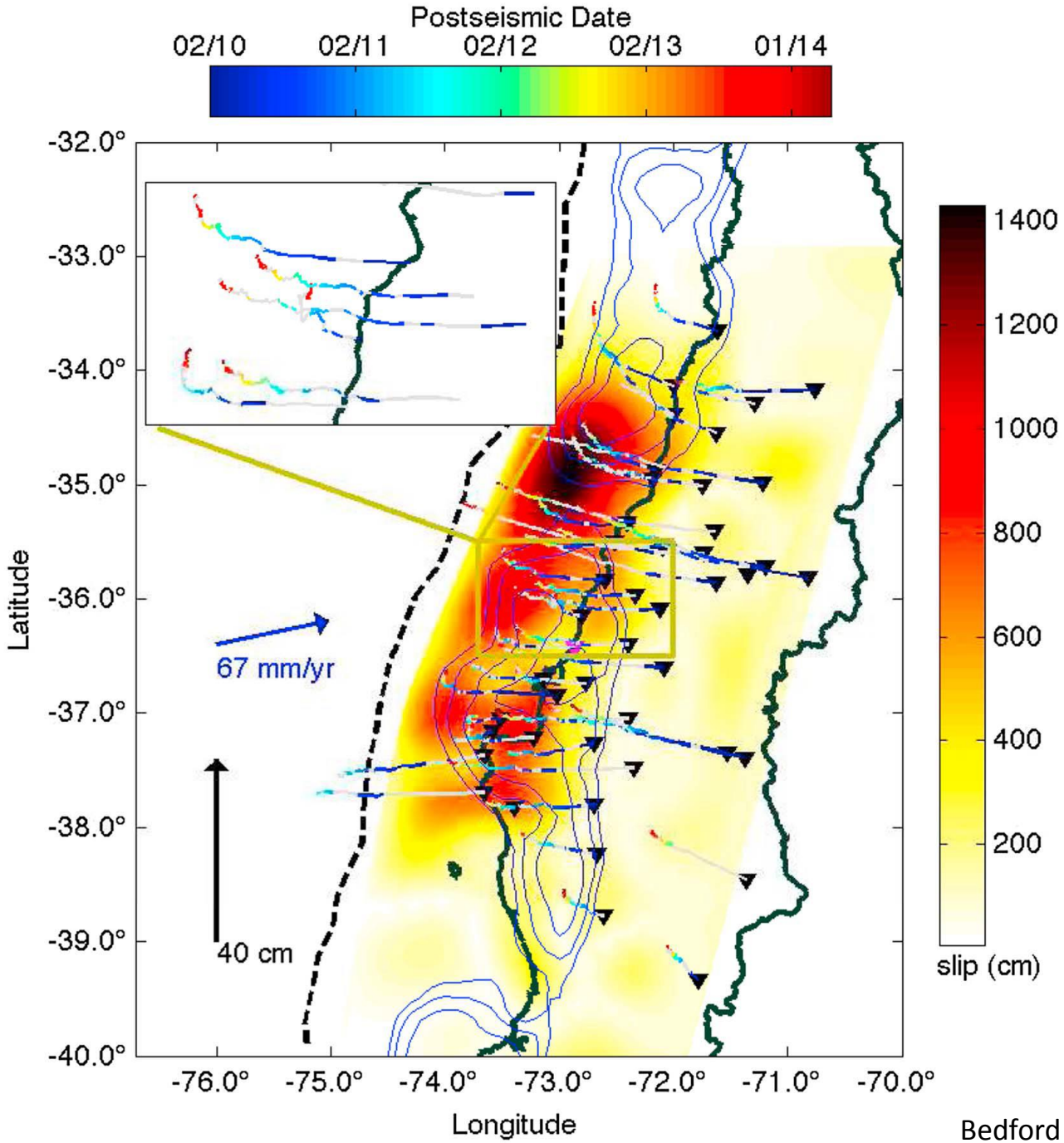


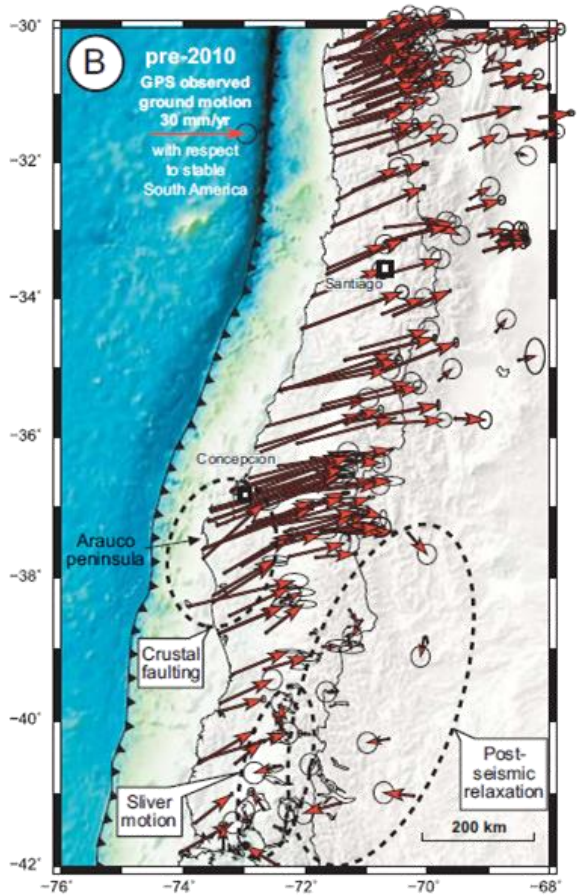




Li et al., 2014

Fault healing and relocking after the Maule 2010 earthquake within 1 year

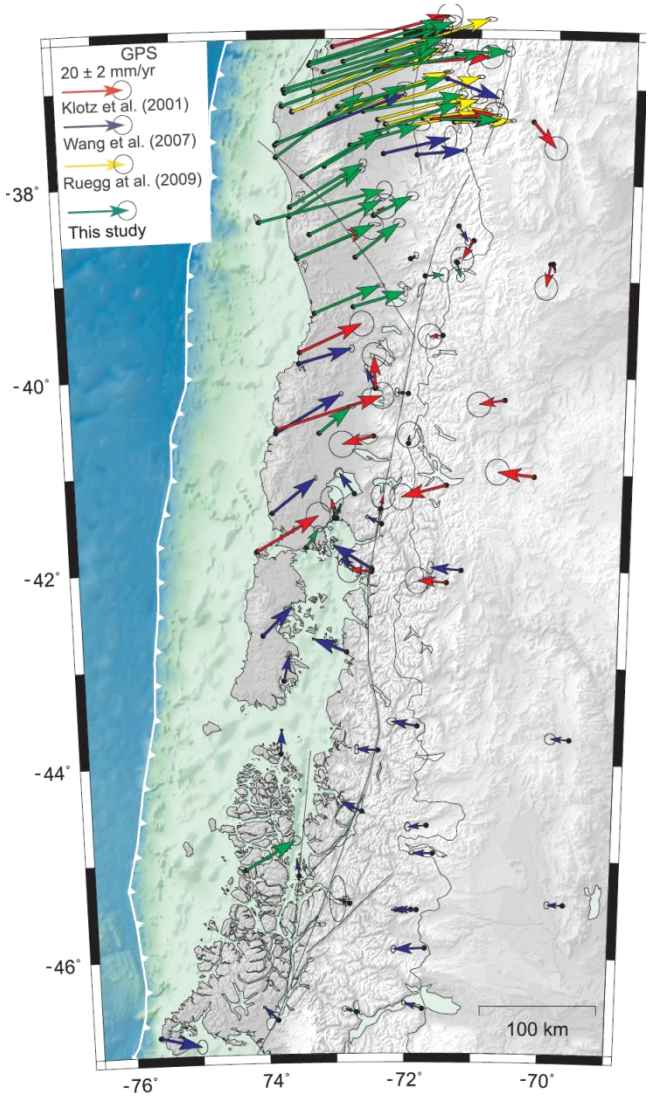


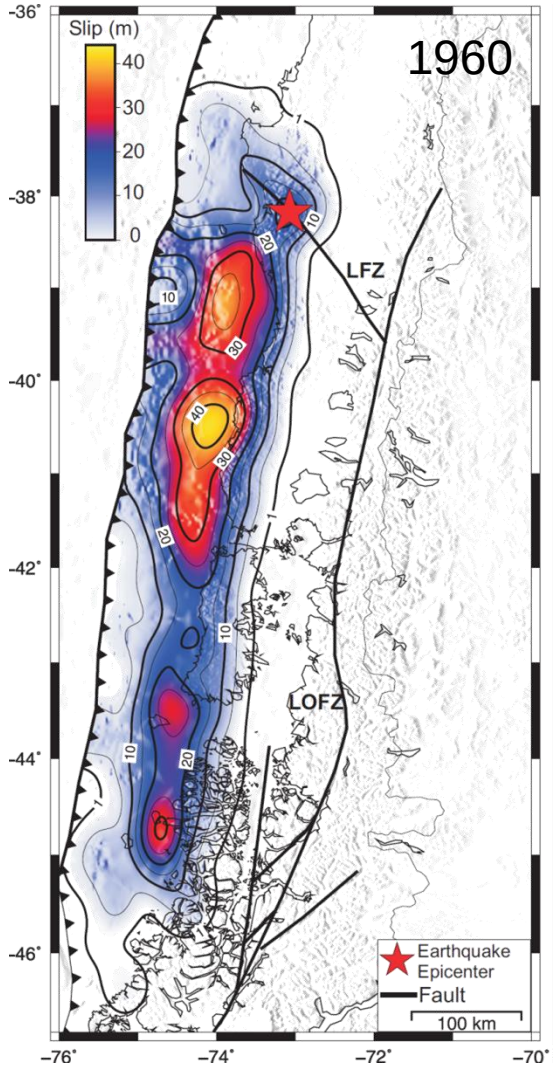


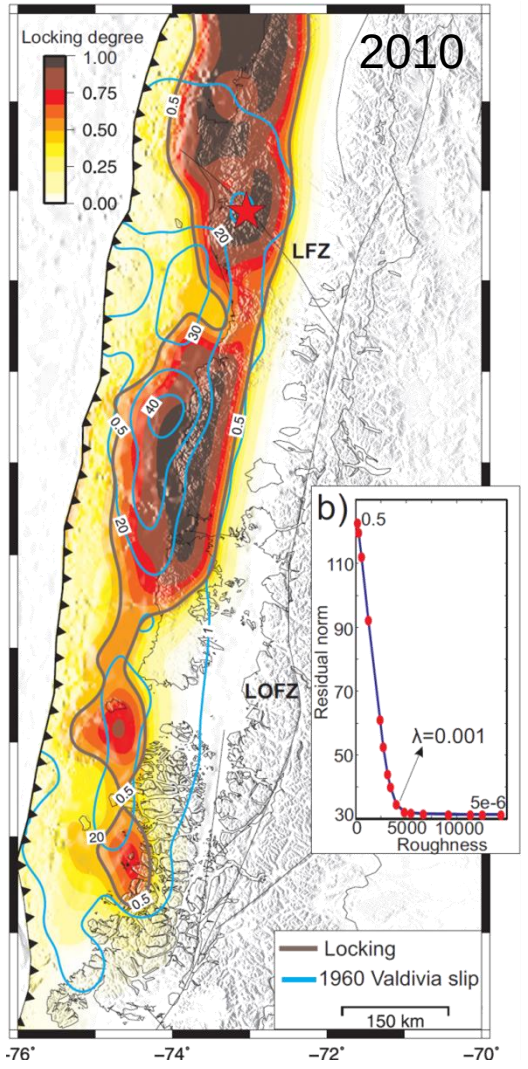
pre-Maule interseismic loading

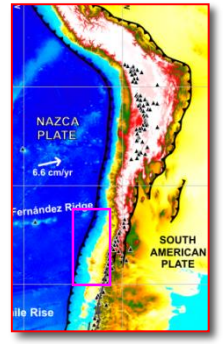
Bedford et al. 2016

Postseismic locking recovers at maximum slip domain – the Mw 9.5 Chile earthquake of 22.5.1960



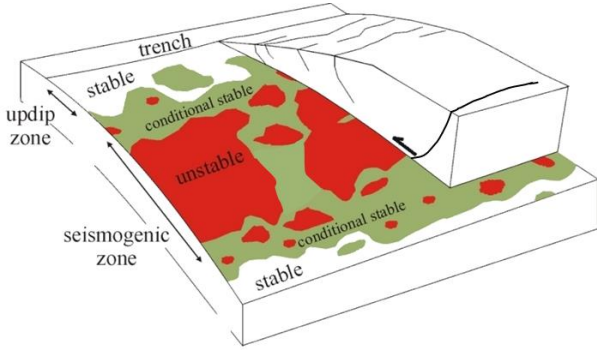






Moreno et al., 2009; Moreno et al, 2012

Conclusions and questions



- The plate interface is extremely weak and has transient strength evolution, *all due to hydraulic system and its transients?*

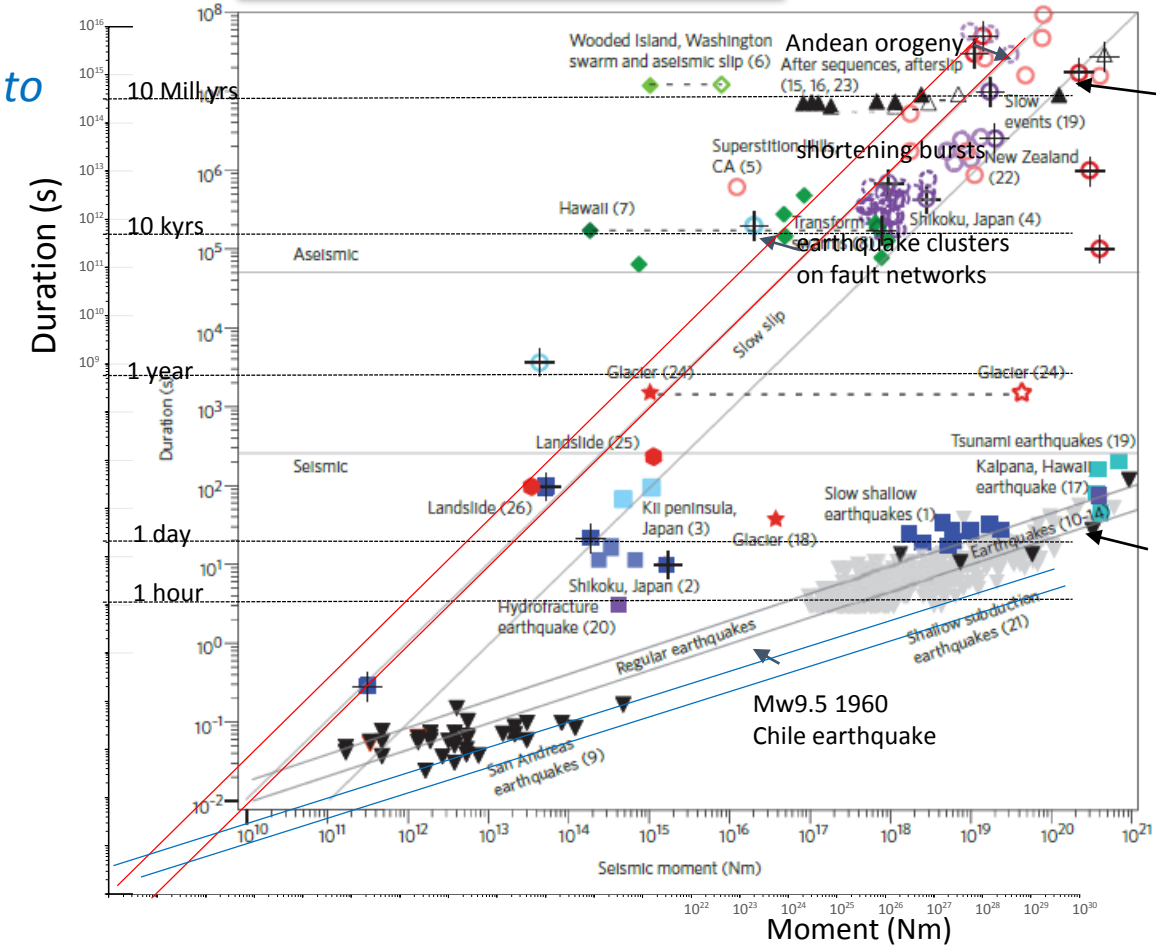
- Faults may creep **or** break **and** they respond to very small stress changes, *but what makes them respond to stress changes of just a few 10s kPa?*

- Locking and asperities at interface appear stable and control localization of upper plate deformation, *but over which time scales and is it always the hydraulic system and its variability?*

- Upper plate deformation and faulting occurs in ?cyclic mode driven by megathrust cycle, *but how well synchronized and why do faults break in earthquake clusters?*

- upper plate response may be compressional or extensional postseismically, *dependent on ratio of slip/slip-deficit every cycle?*

Energy release / time ≈ const.



shortening bursts, earthquake clusters on fault networks

$M_o \propto t$

$M_o \propto t^3$

Peng & Gomberg 2010

What this means ….

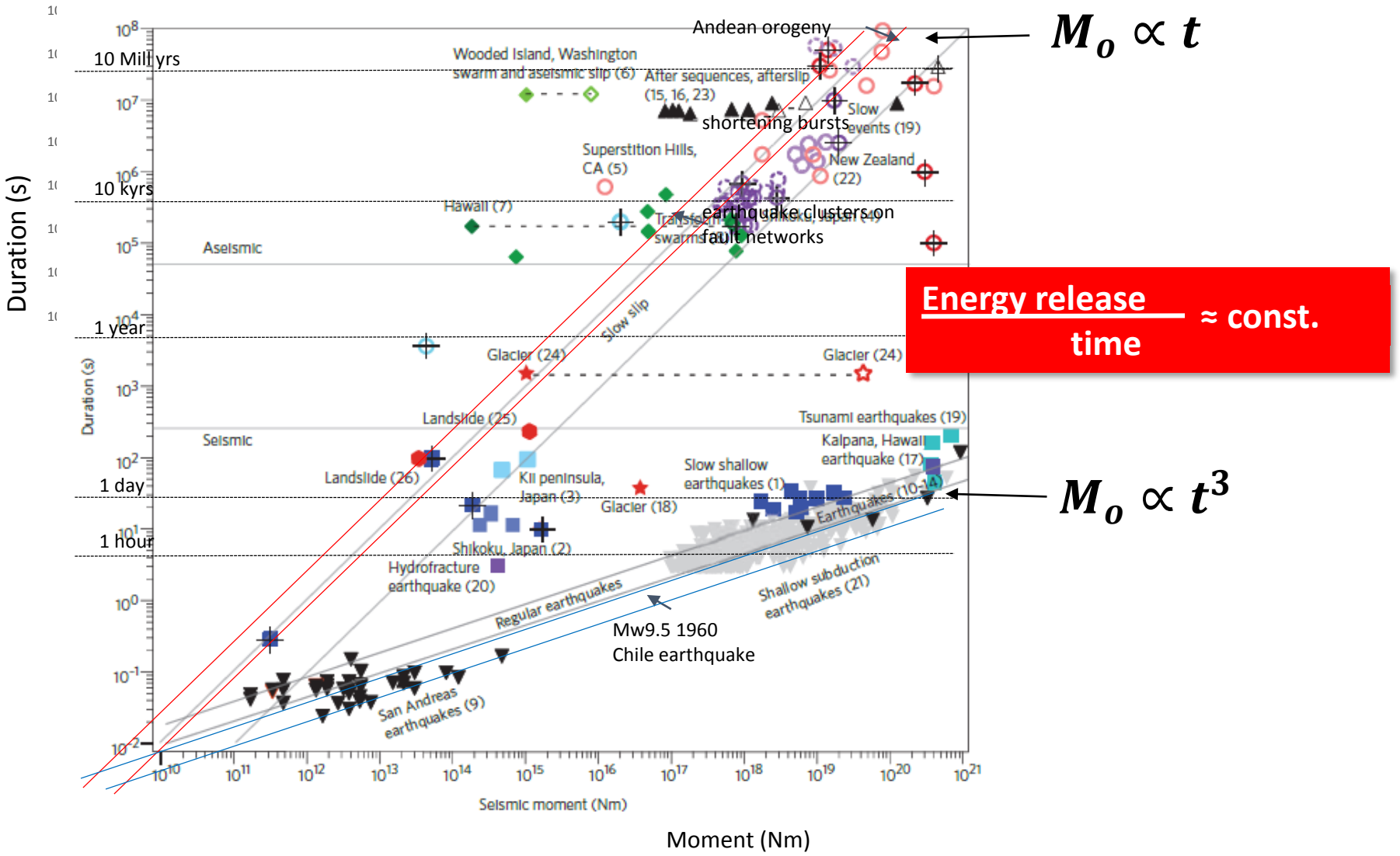
effective coefficient of friction on plate interface	≤ 0.05
friction of banana peel	≈ 0.07

Awarded with 2014 Ig Nobel Prize

PHYSICS PRIZE:
for measuring the amount of friction between a shoe and a banana skin, and between a banana skin and the floor, when a person steps on a banana skin that's on the floor.
REFERENCE: "Frictional Coefficient under Banana Skin," Kiyoshi Mabuchi, Kensei Tanaka, Daichi Uchijima and Rina Sakai, Tribology Online 7, no. 3, 2012, pp. 147-151.

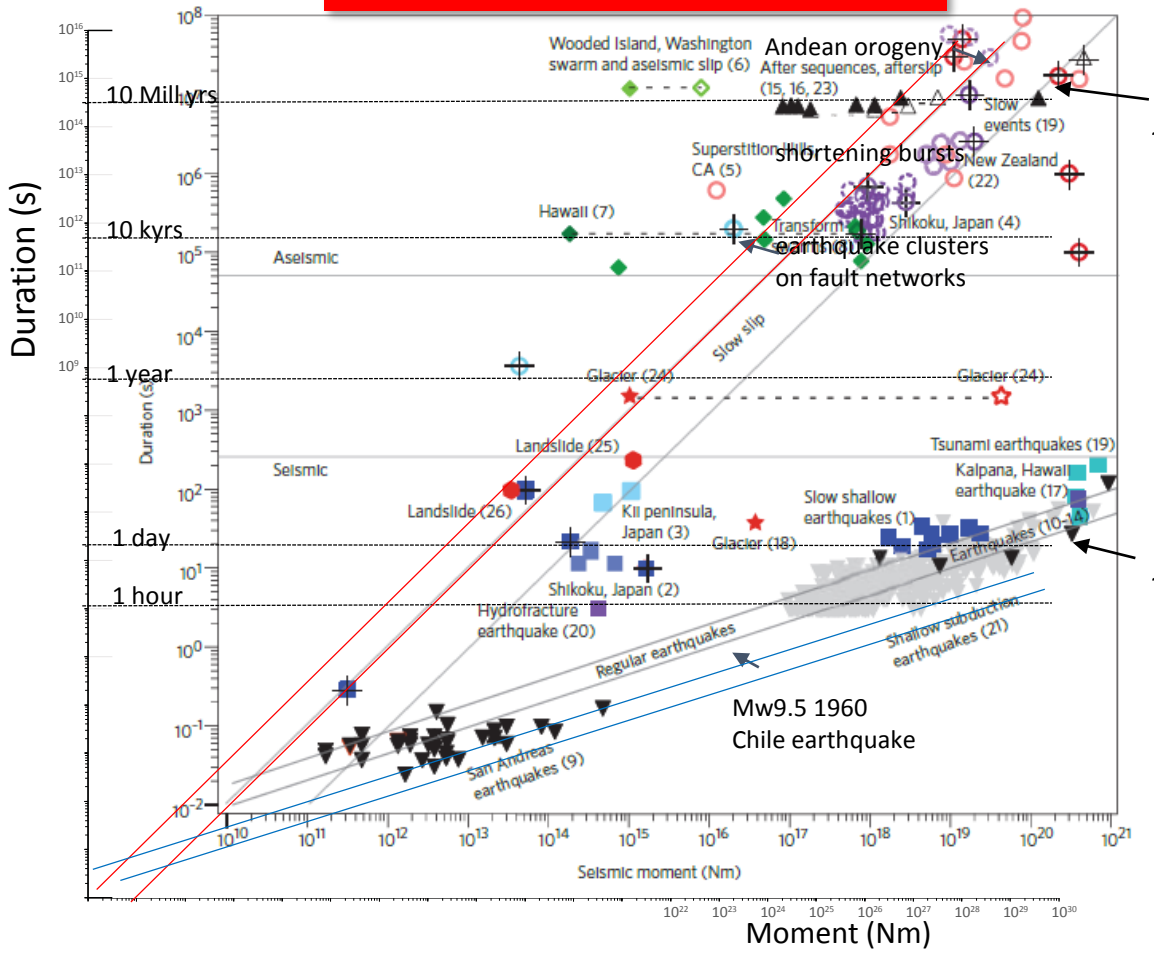
… plate interfaces are weaker than banana peels !

Extending the slow earthquake scaling law



Peng & Gomberg 2010

Energy release / time ≈ const.



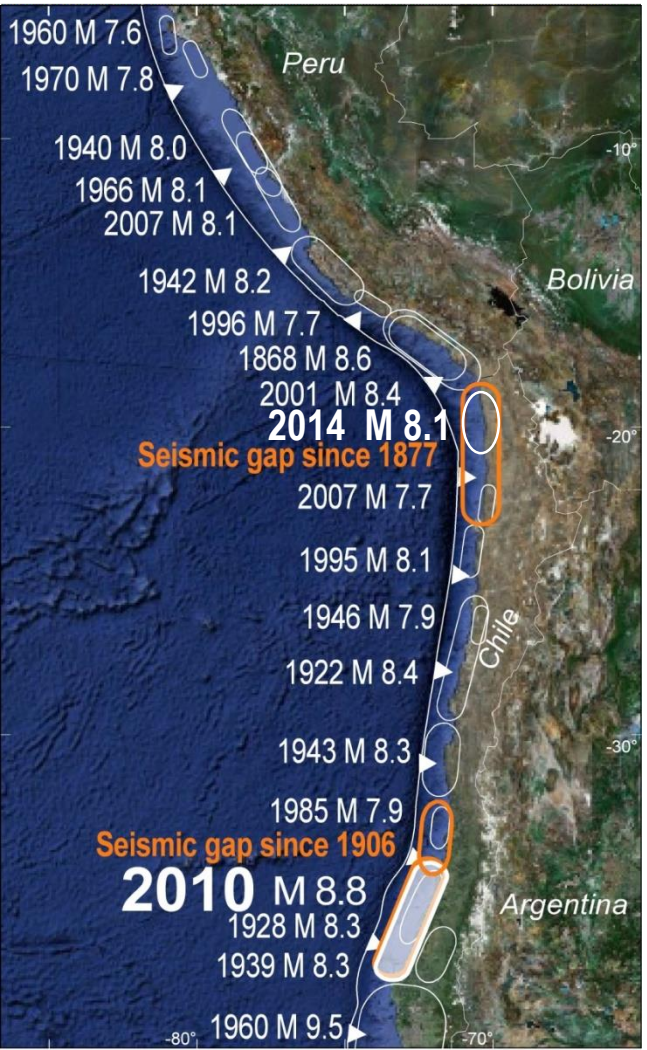
$M_o \propto t$

shortening bursts

earthquake clusters on fault networks

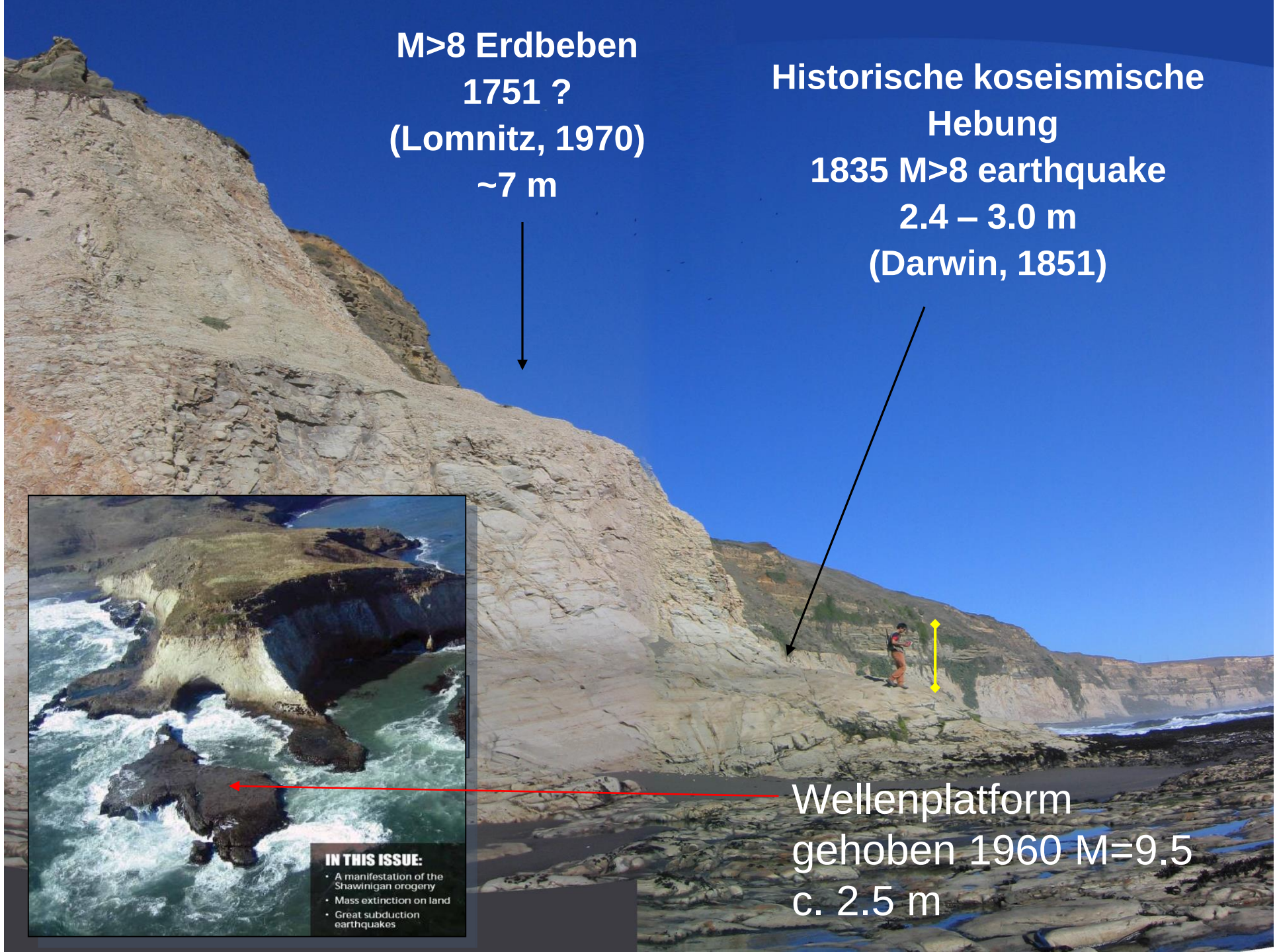
$M_o \propto t^3$

Peng & Gomberg 2010

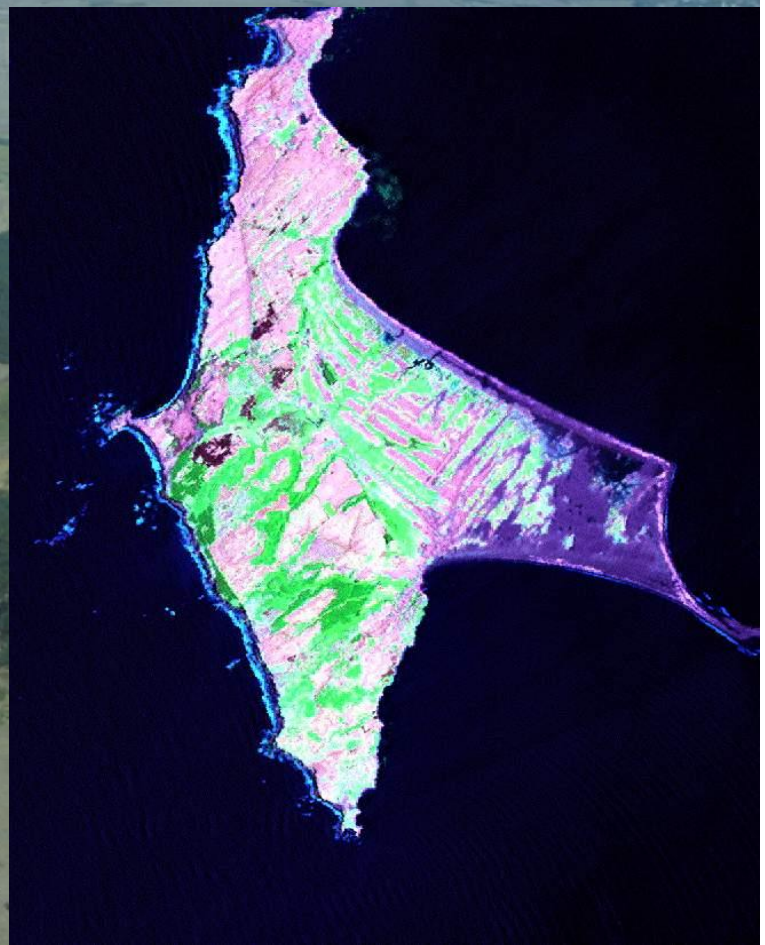

1960 M 7.6
1970 M 7.8
1940 M 8.0
1966 M 8.1
2007 M 8.1
1942 M 8.2
1996 M 7.7
1868 M 8.6
2001 M 8.4
2014 M 8.1
Seismic gap since 1877
2007 M 7.7
1995 M 8.1
1946 M 7.9
1922 M 8.4
1943 M 8.3
1985 M 7.9
Seismic gap since 1906
2010 M 8.8
1928 M 8.3
1939 M 8.3
1960 M 9.5
Peru
Bolivia
Chile
Argentina
-10°
-20°
-30°
-80°
-70°

Gehobene Küste

Maule Erdbeben, 27.2.2010


M>8 Erdbeben
1751 ?
(Lomnitz, 1970)
~7 m
Historische koseismische Hebung
1835 M>8 earthquake
2.4 – 3.0 m
(Darwin, 1851)
IN THIS ISSUE:
• A manifestation of the Shawinigan orogeny
• Mass extinction on land
• Great subduction earthquakes
Wellenplatform
gehoben 1960 M=9.5
c. 2.5 m

Strandlinien auf Santa Maria (Südchile)



… und vor 58 Jahren

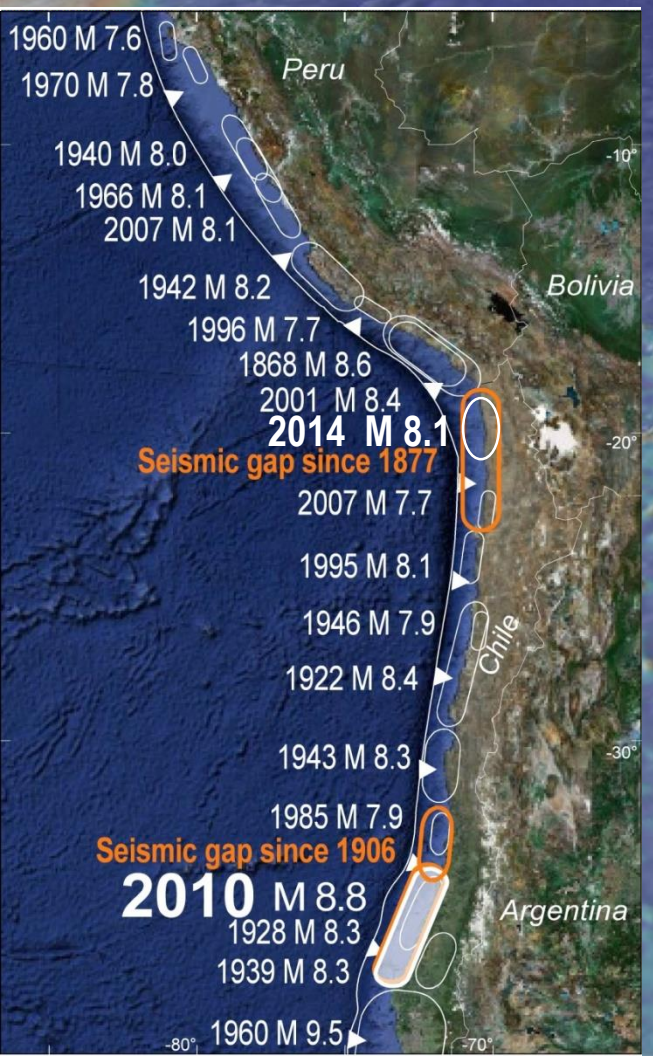
1960

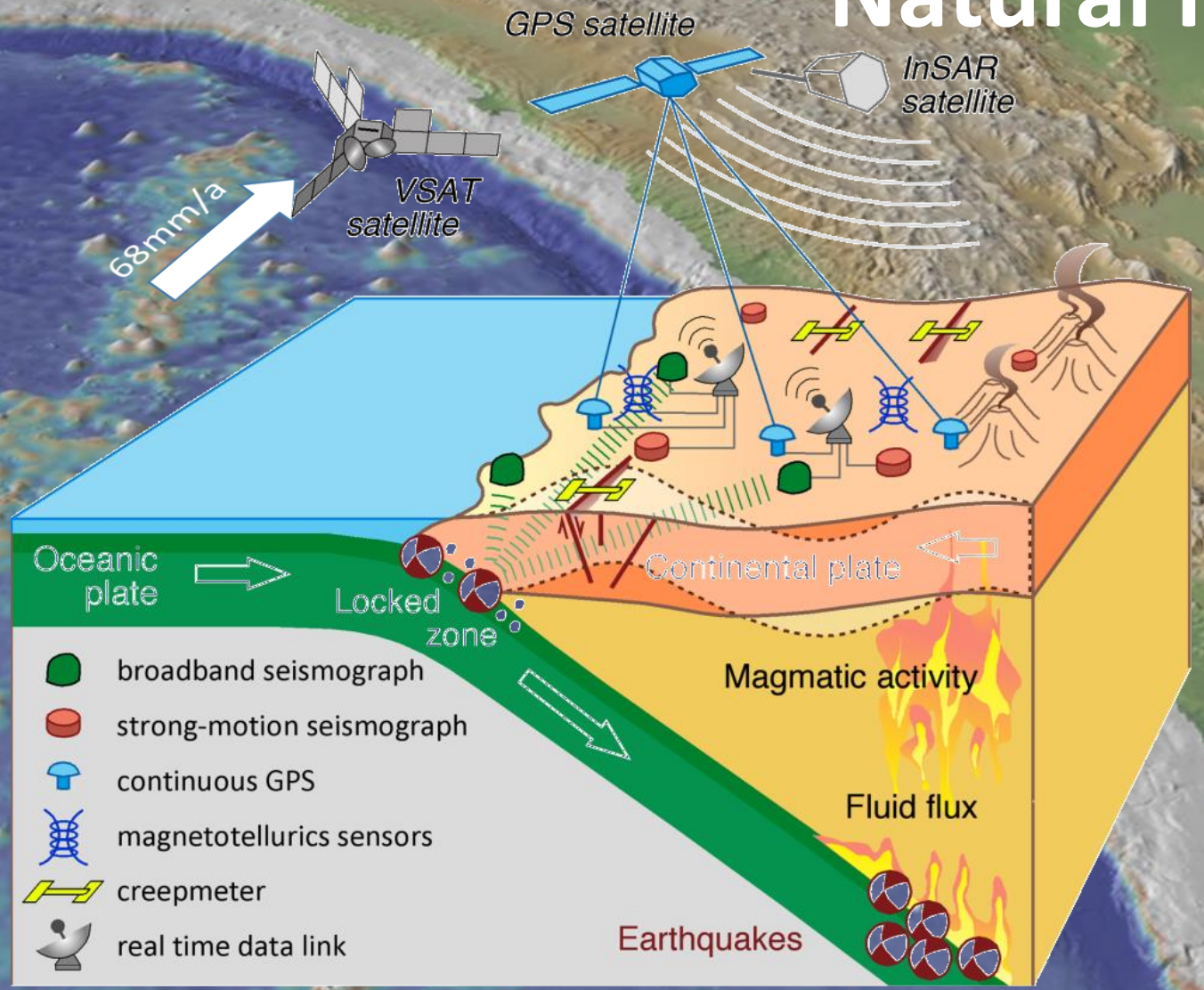
1837

1737

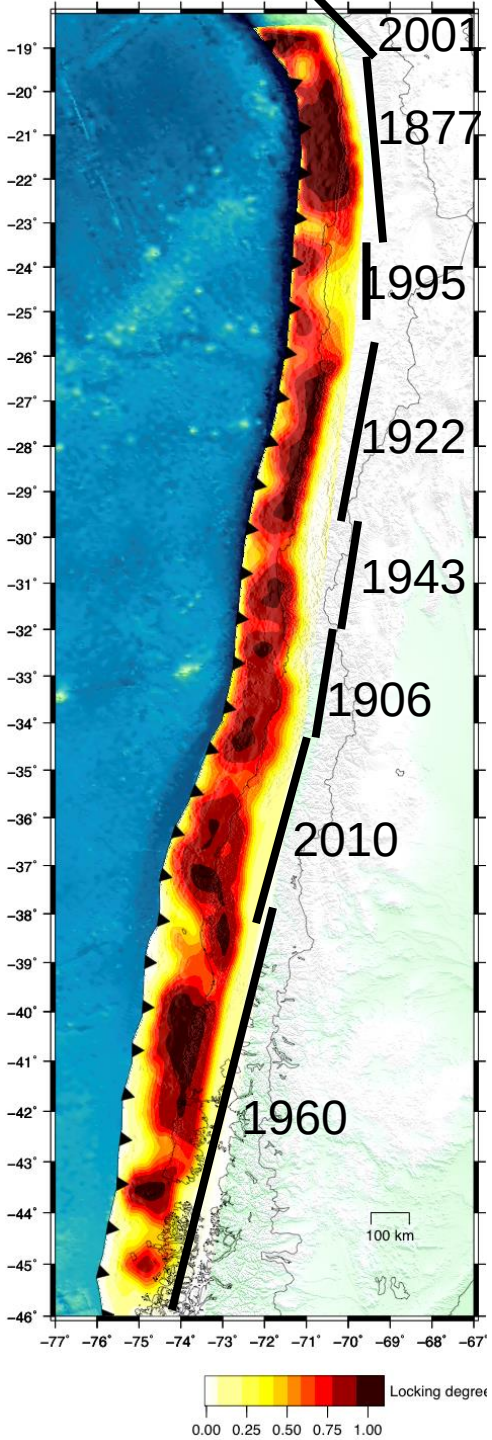
Moreno et al., 2009

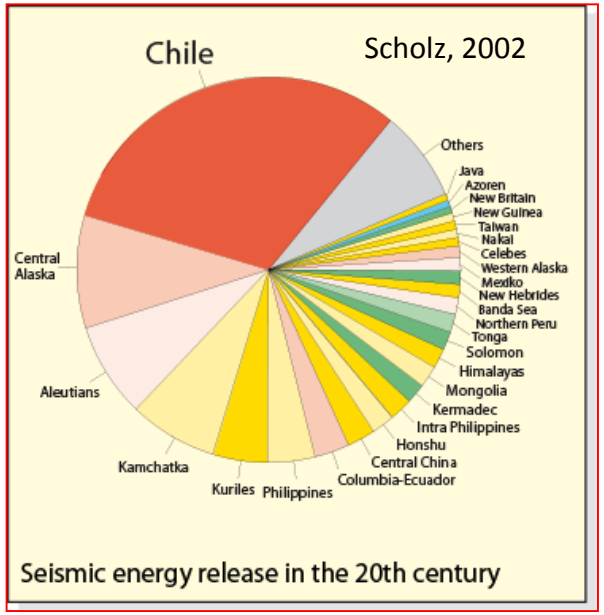
Natural lab Chile





Locking, earthquakes and why Chile is a perfect natural lab





Moreno et al., in prep.

lpoc-network.org

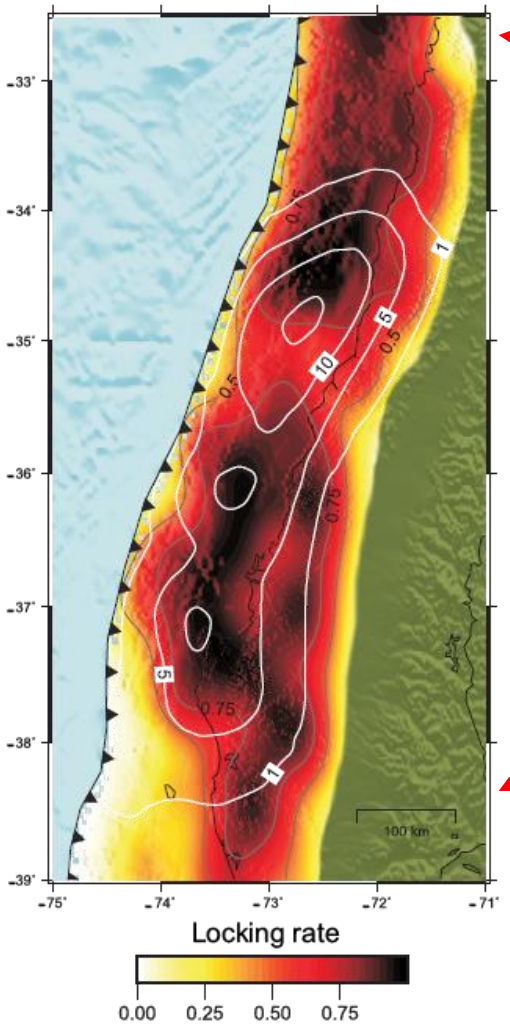
>100 yrs since last event

7 months of afterslip and aftershocks – the 8.8. Maule earthquake of 27.2.2010

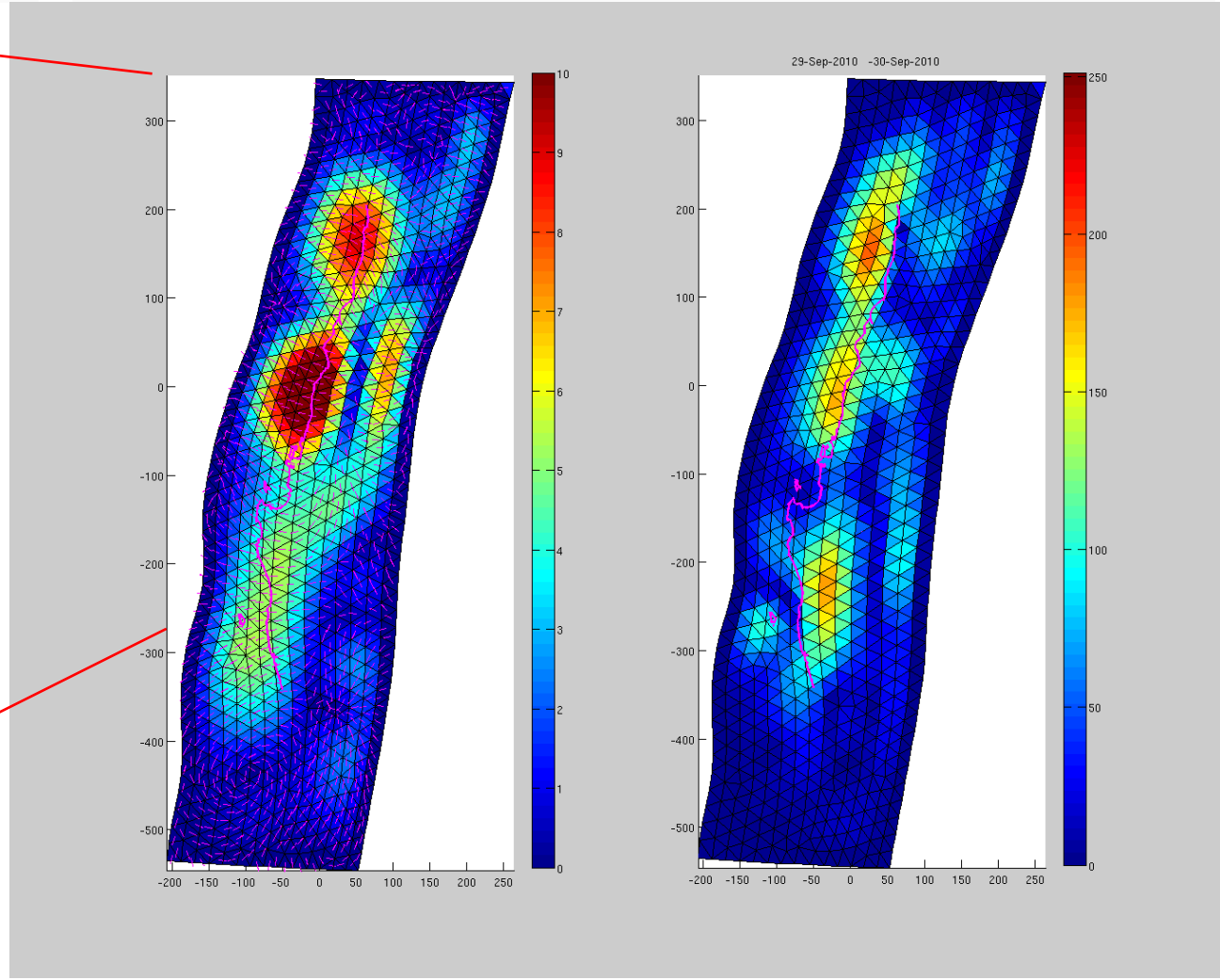
Slip and locking

Daily slip solution

Cumulative slip

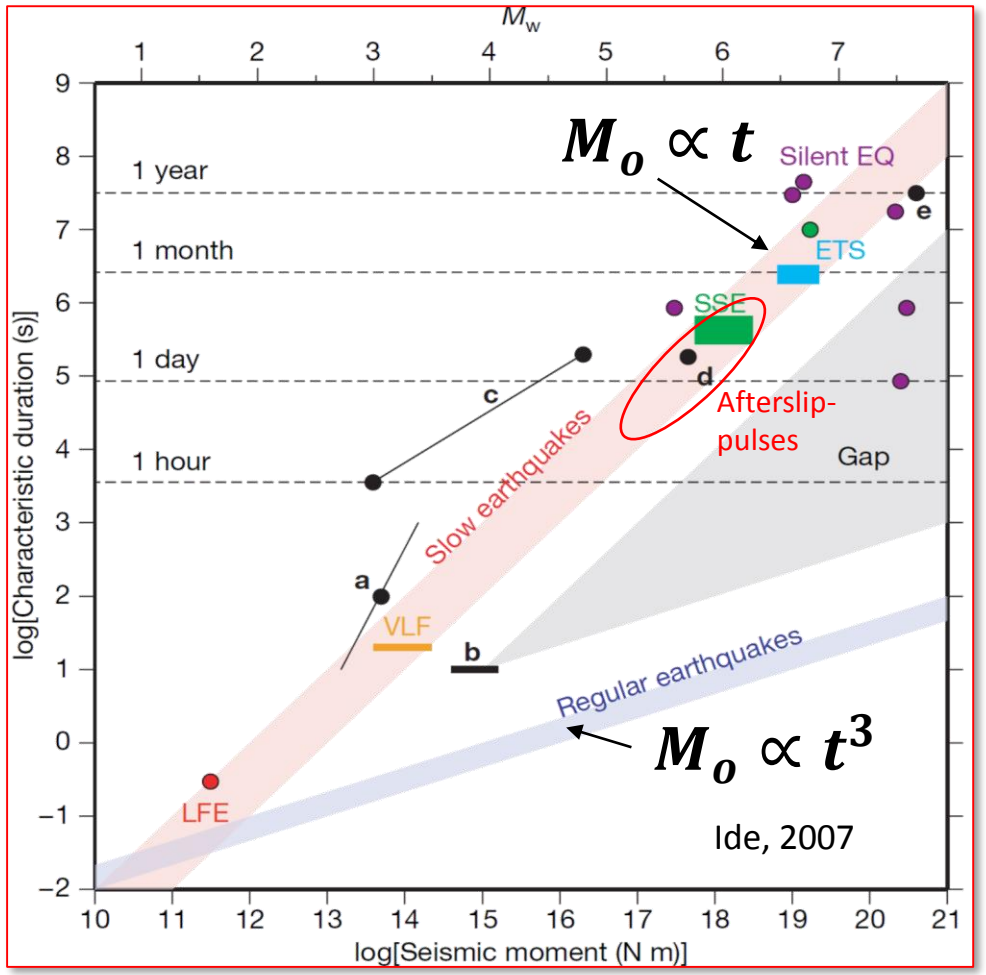


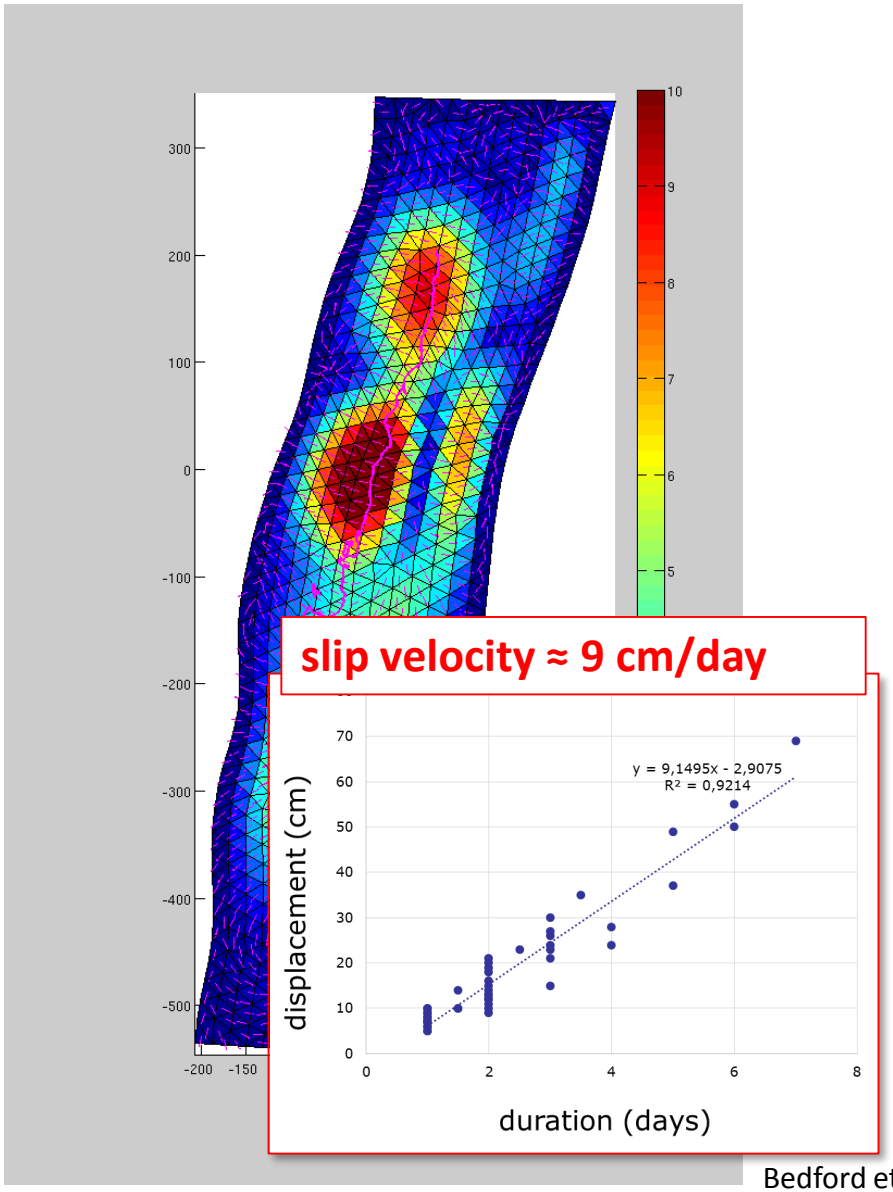
Moreno et al., 2010



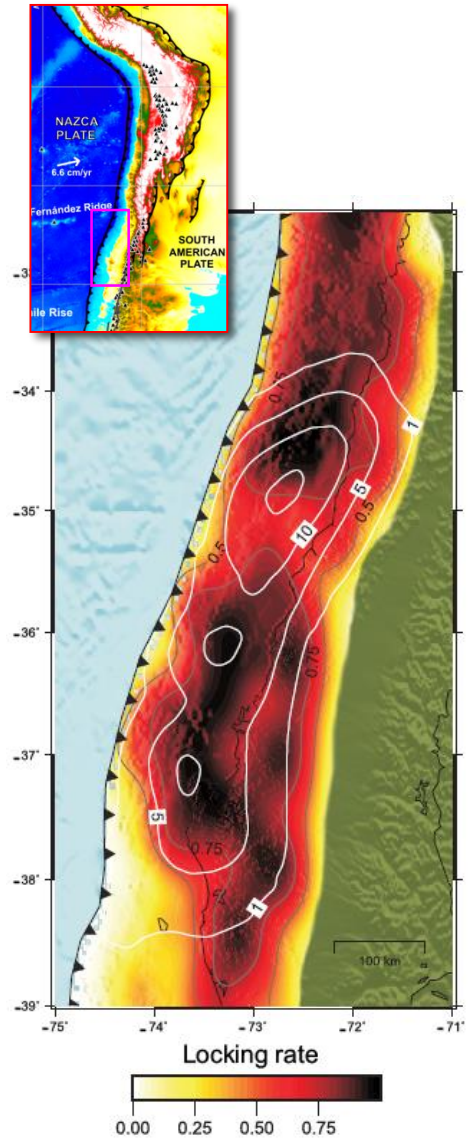
Bedford et al., 2013

Daily slip solutions reveal two velocity regimes for M8.8., 2010 Maule earthquake 7-month afterslip evolution

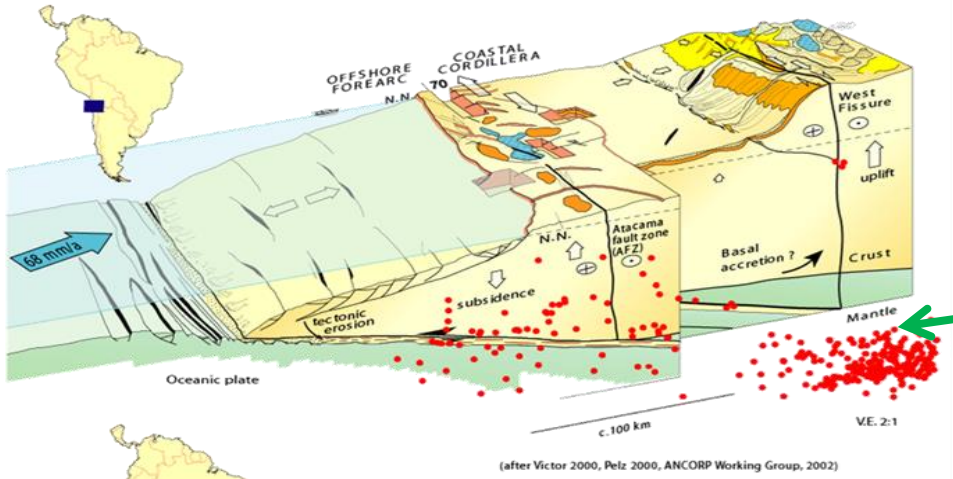




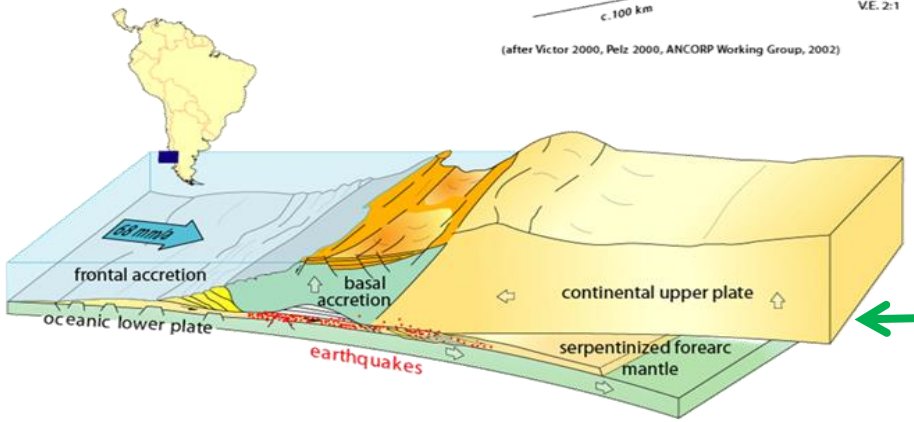
Bedford et al. EPSL, 2013



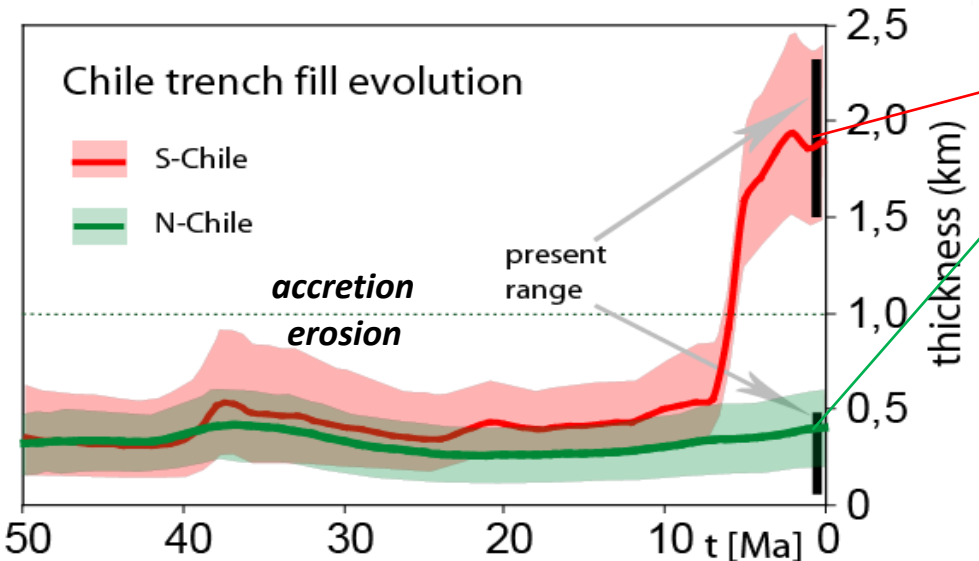
Moreno, Rosenau & Oncken, Nature 2010



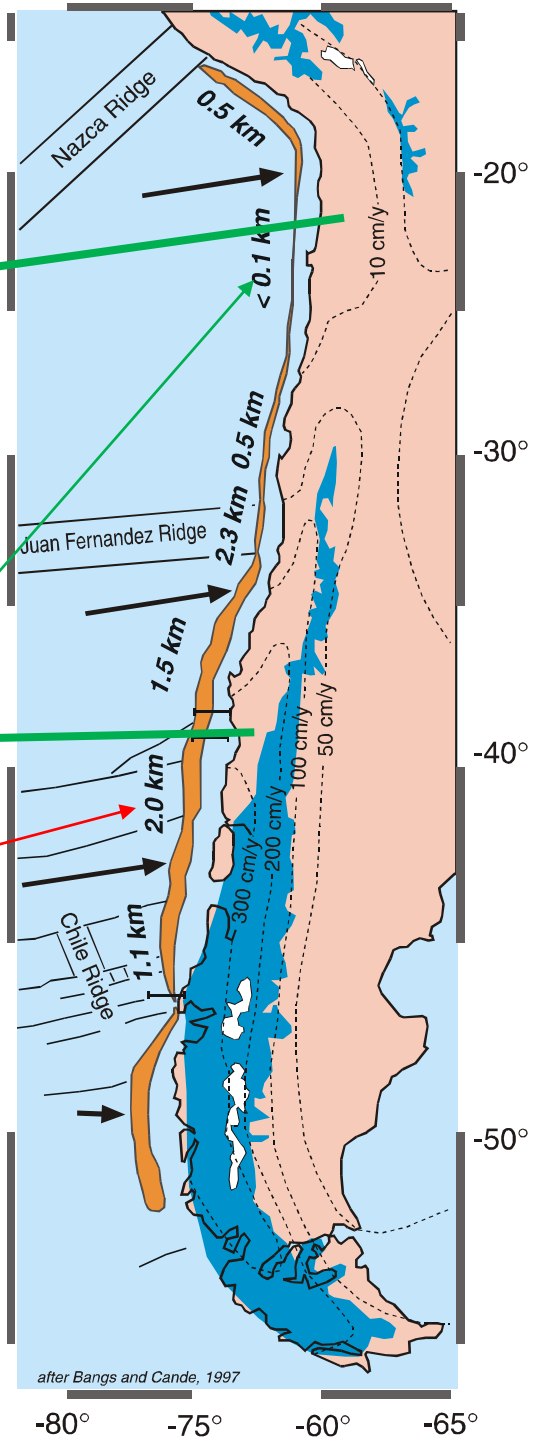
(after Victor 2000, Pelz 2000, ANCORP Working Group, 2002)



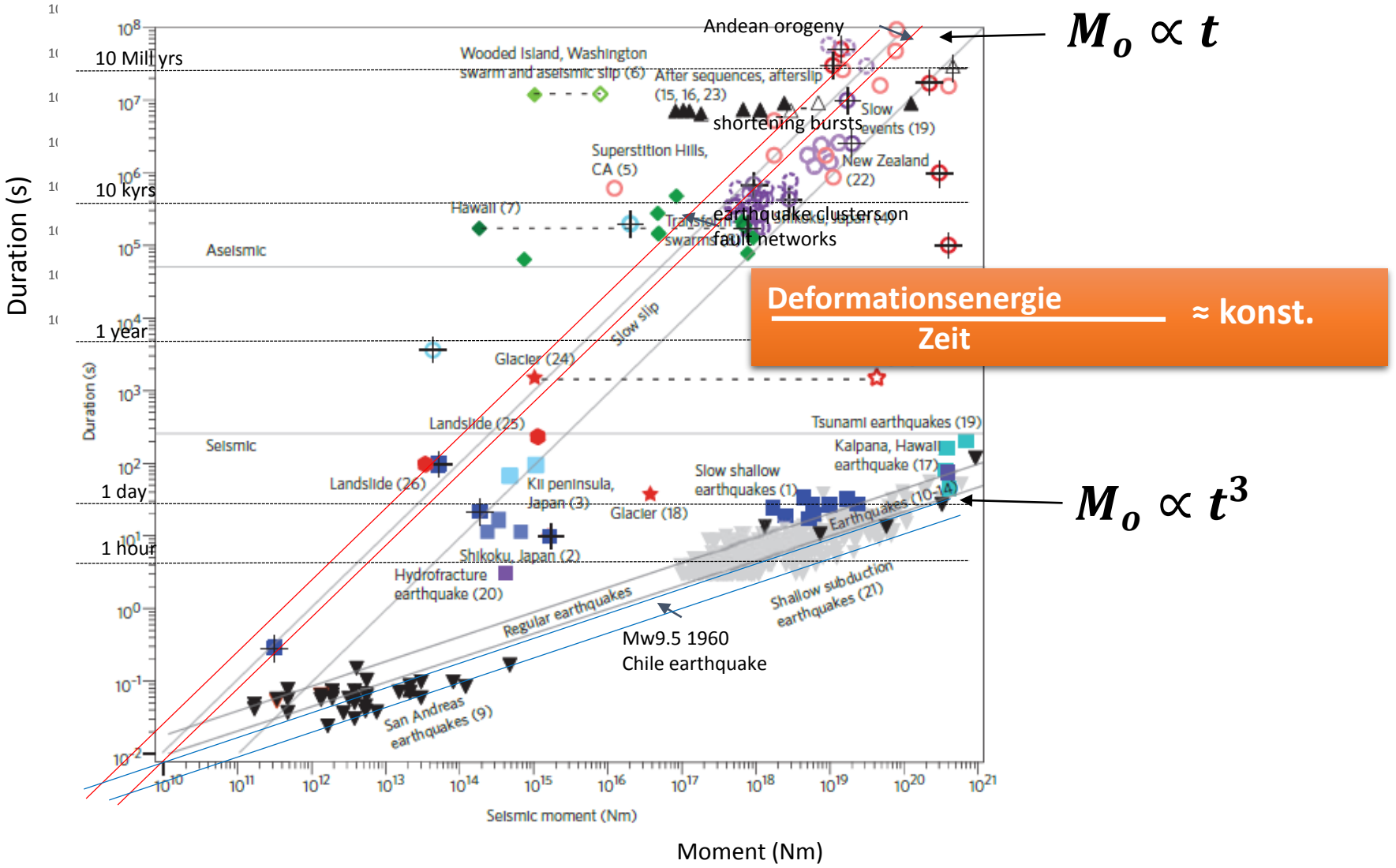
Controls on subduction erosion: the trench fill



Oncken et al., 2006



Der erweiterte Erdbeben-/‘Transienten‘-Zoo



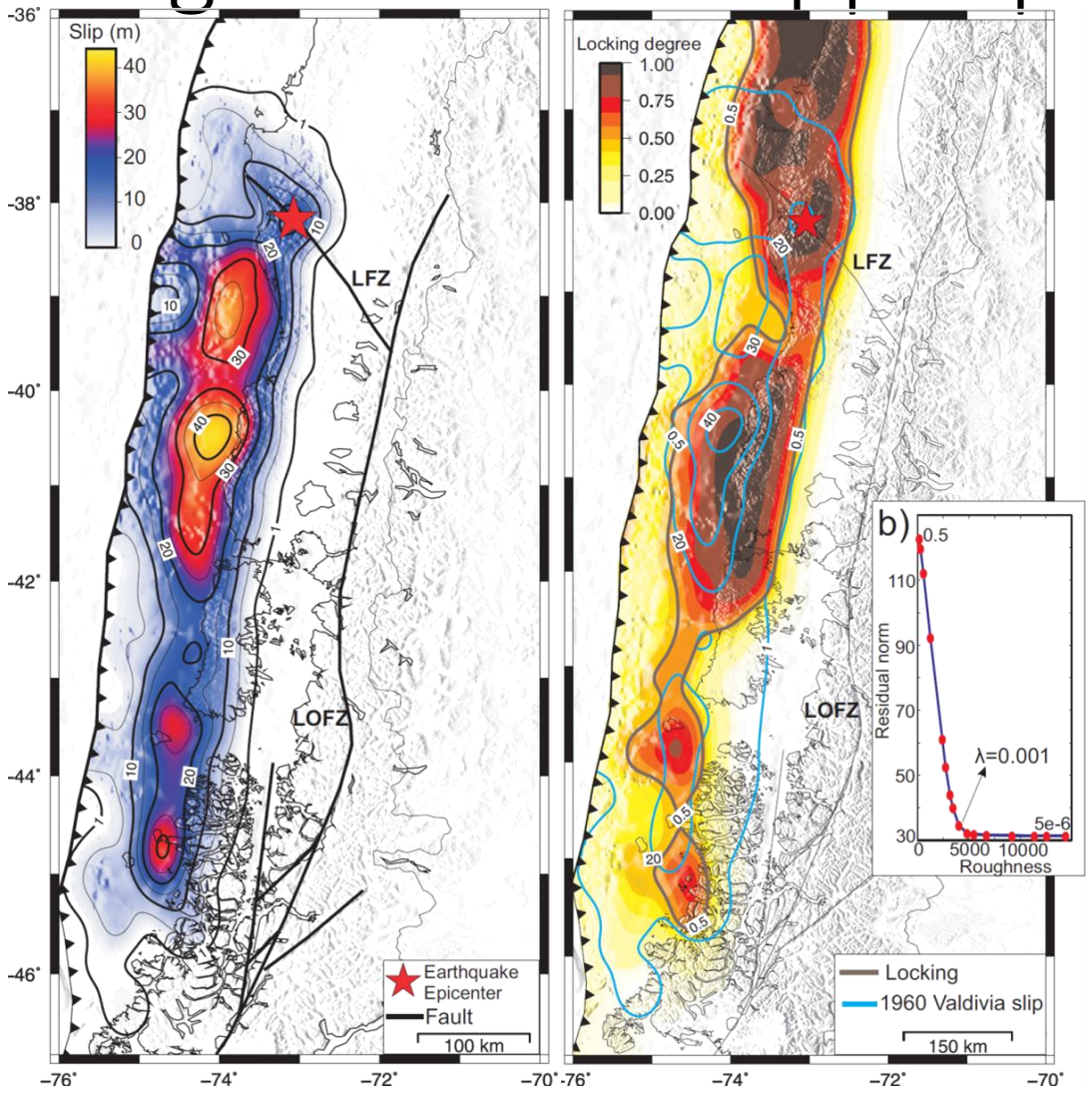
$M_o \propto t$

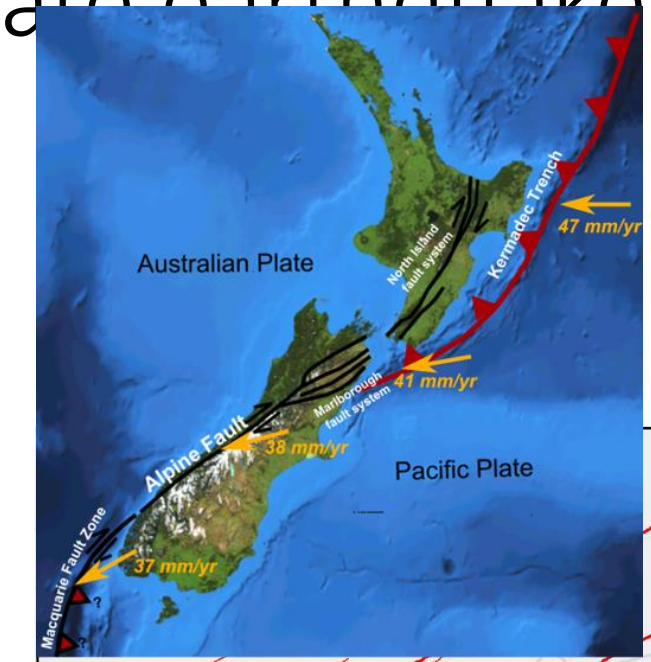
Deformationsenergie / Zeit ≈ konst.

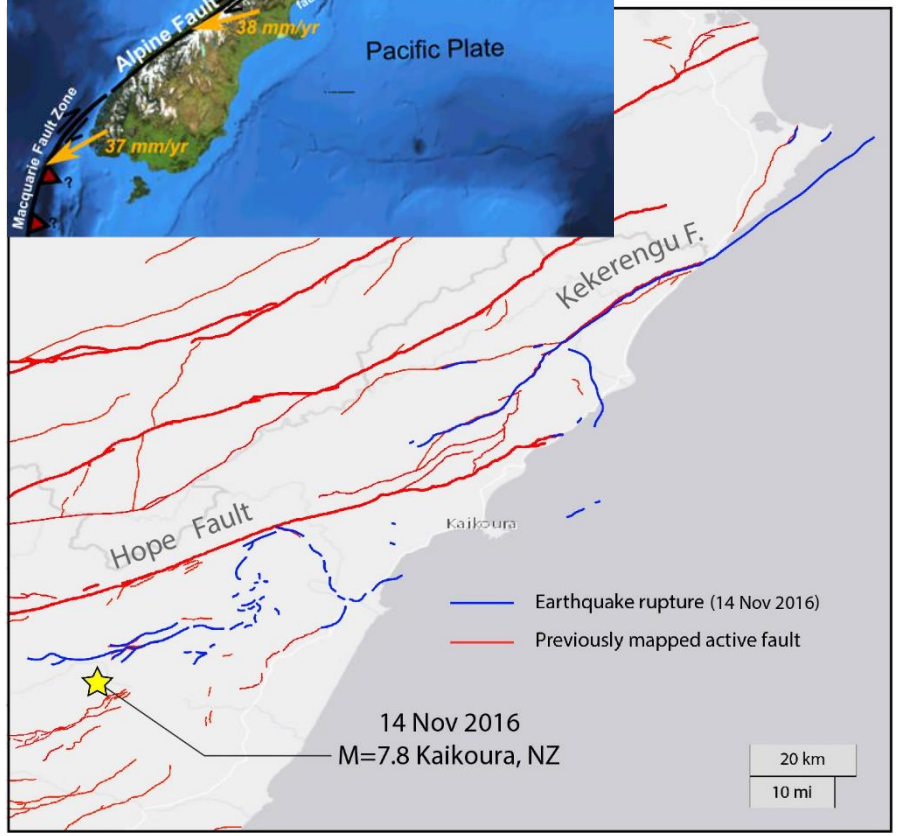
$M_o \propto t^3$

Peng & Gomberg 2010

Megathrust and upper plate earthquakes cluster?

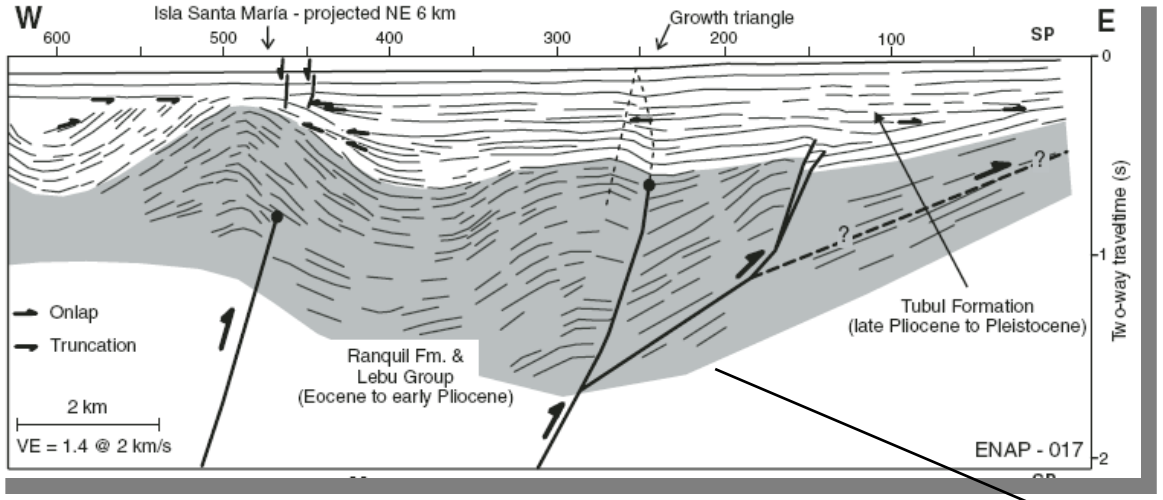


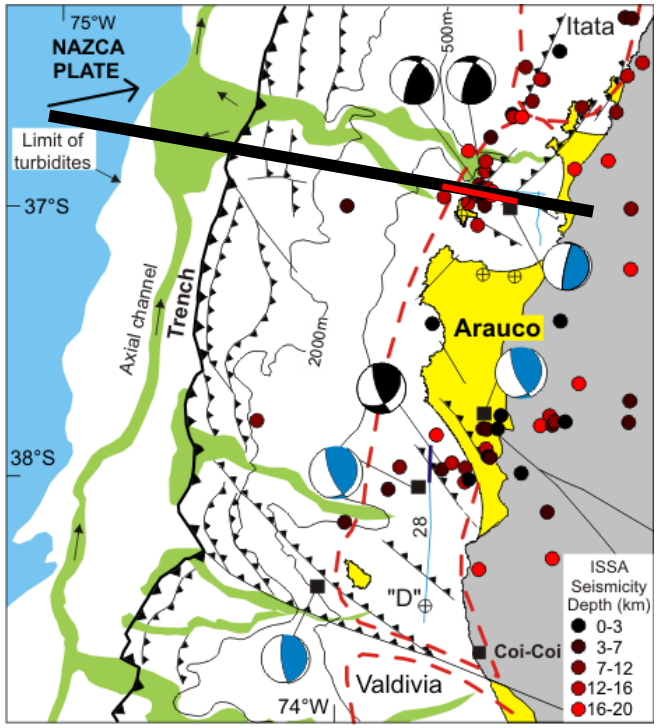


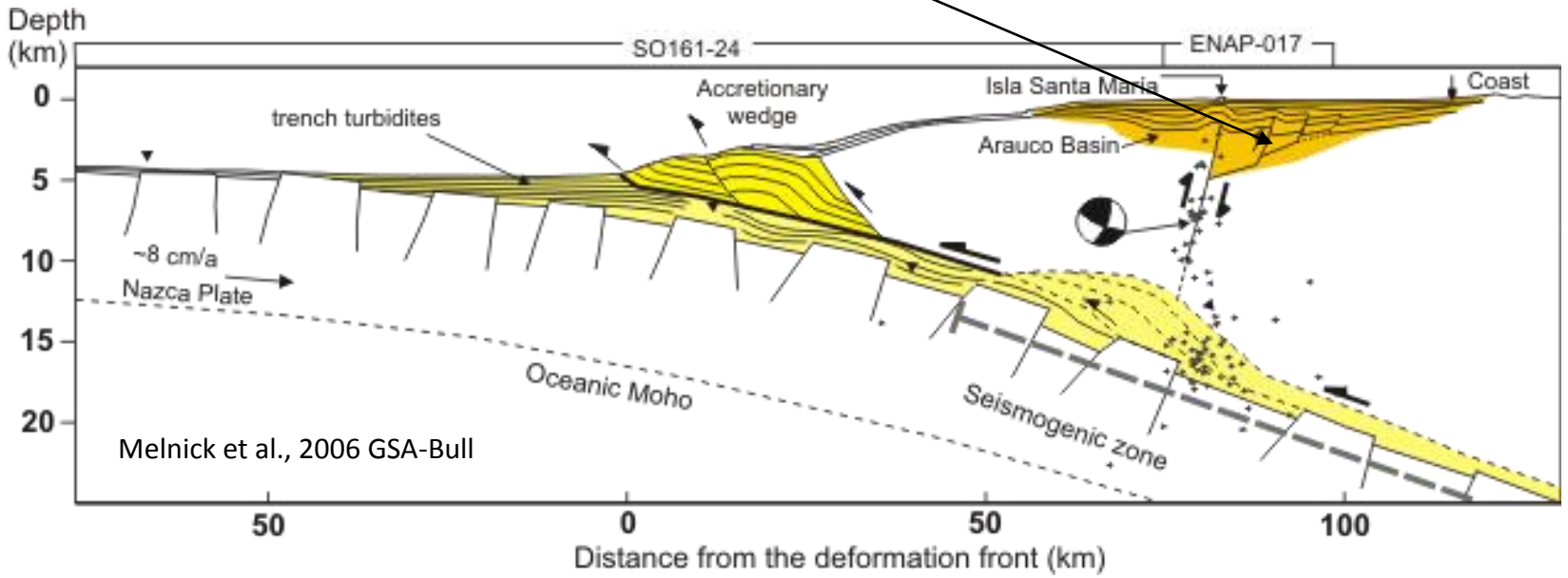


Moreno et al., 2009;
Moreno et al, 2012

Arauco Basin: Stop and go inversion & uplift since 3.6 Ma

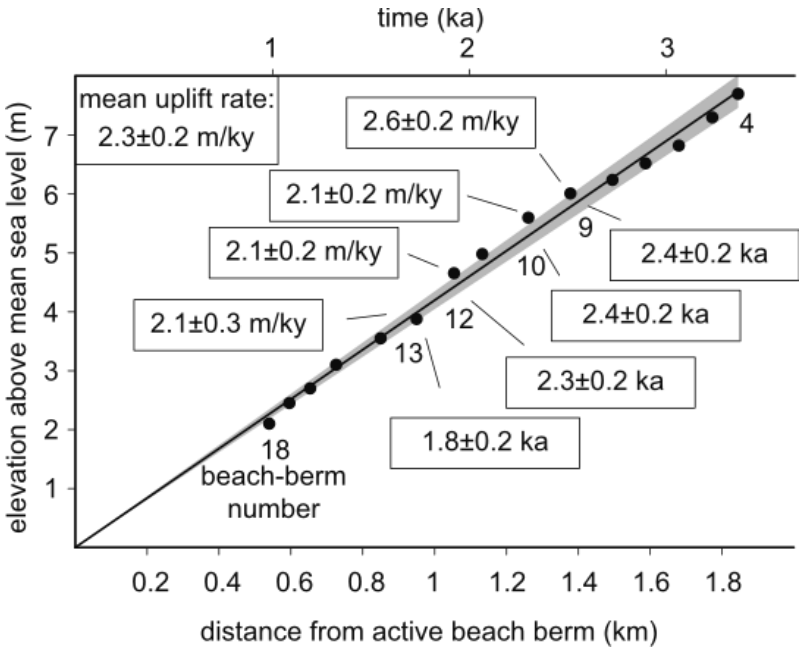






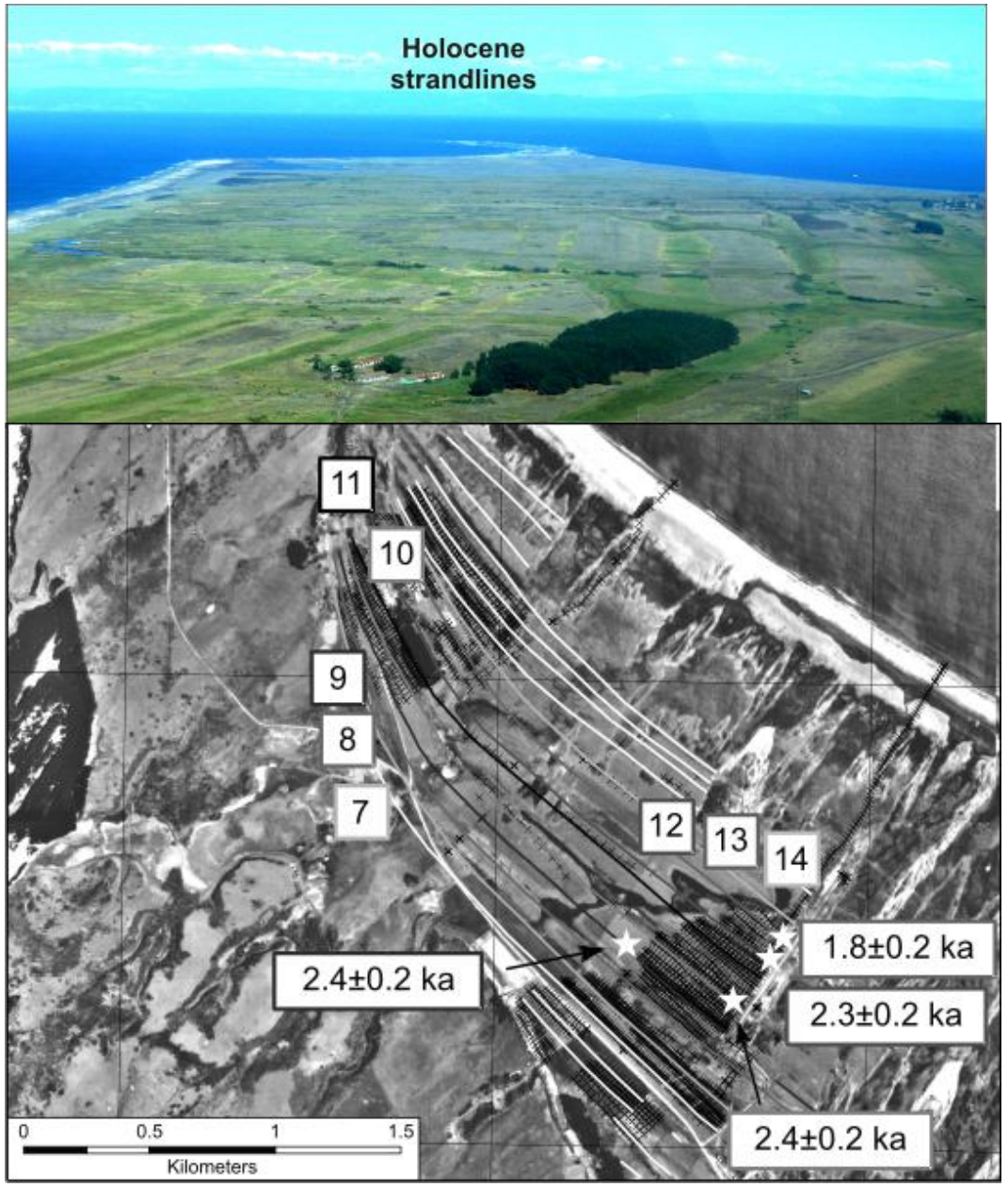
Melnick et al., 2006 GSA-Bull

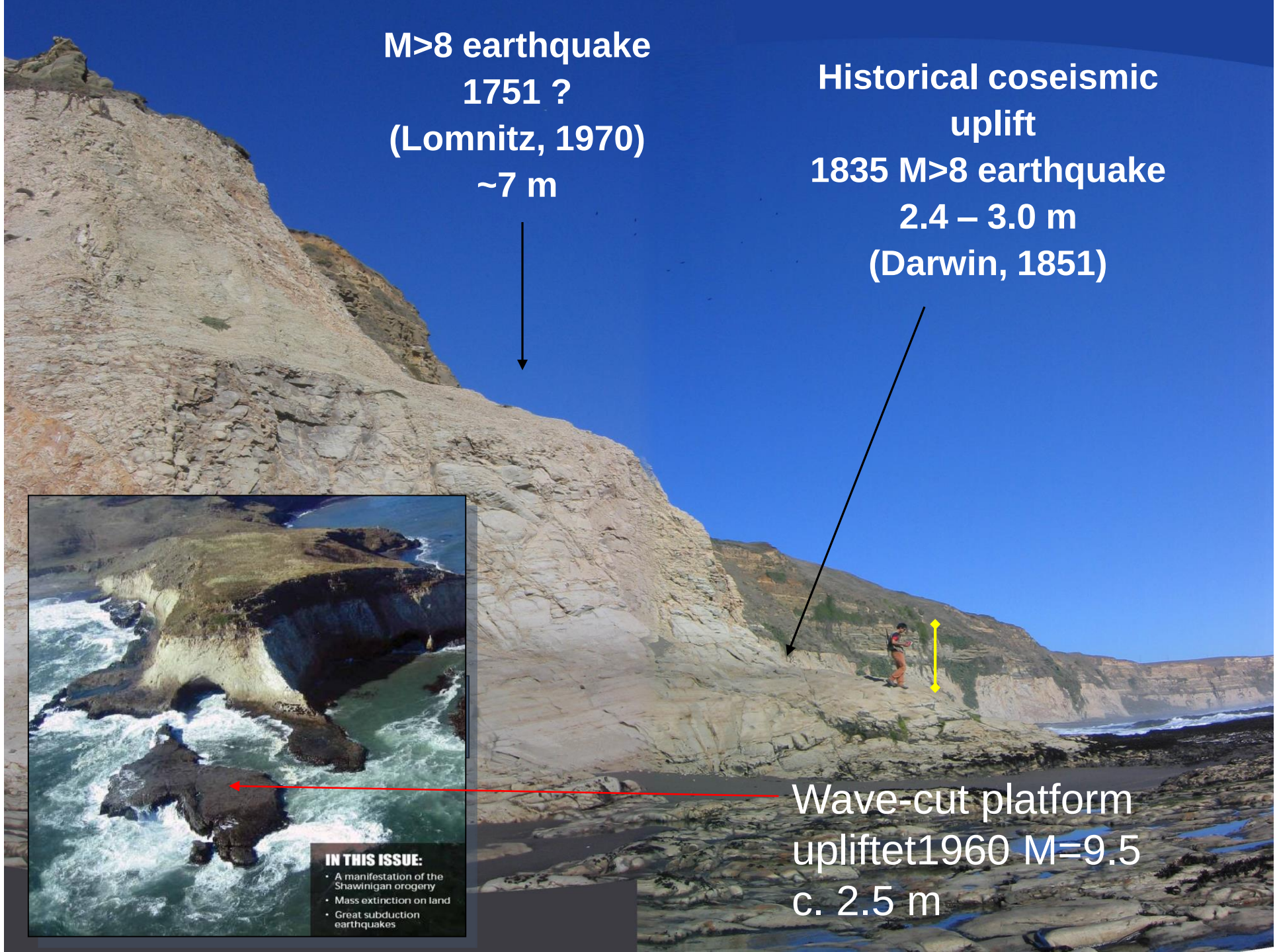
Seismic cycle-related evolution of uplift



Bookhagen et al., 2006

Earthquake recurrence
~ 185 yrs




M>8 earthquake
1751 ?
(Lomnitz, 1970)
~7 m
Historical coseismic
uplift
1835 M>8 earthquake
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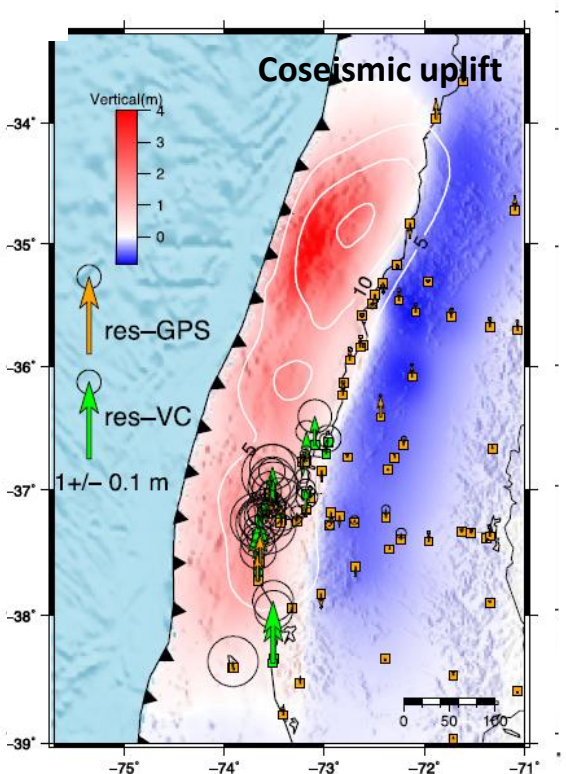
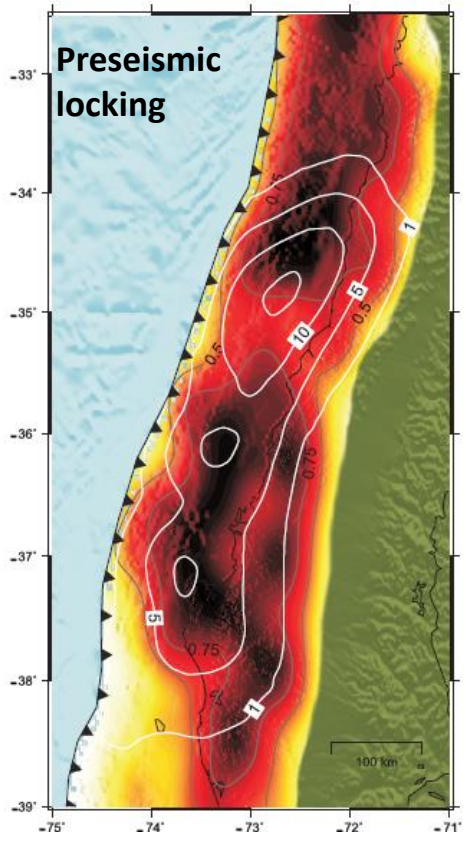
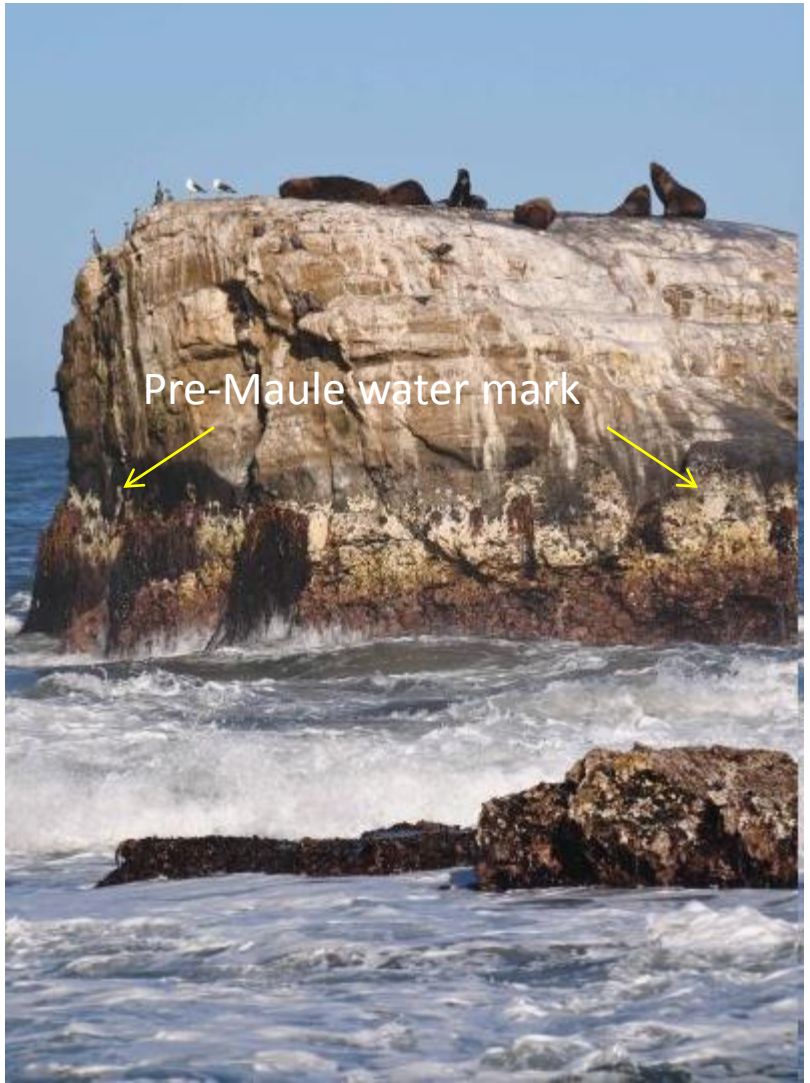
Wave-cut platform
upliftet1960 M=9.5
c. 2.5 m

Coseismic slip, preseismic locking and coastal uplift – Mw8.8 Maule earthquake of 27-2-2010

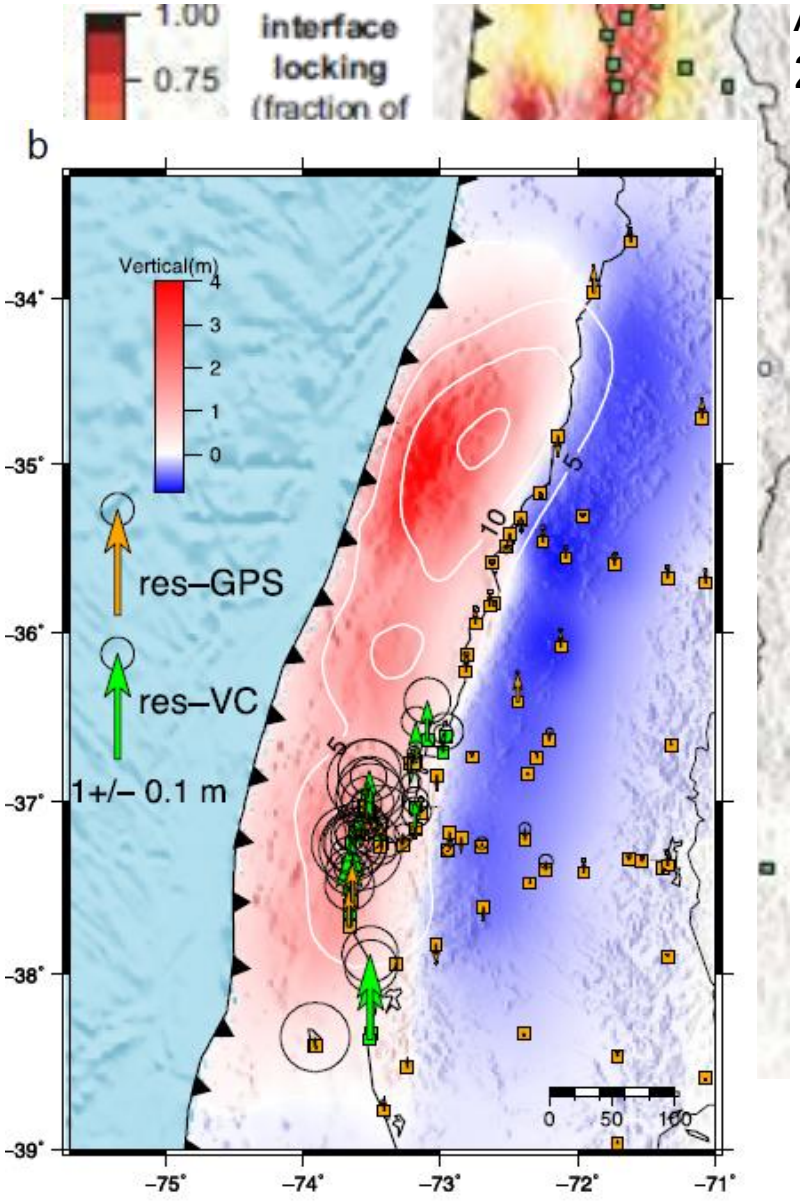
(Moreno et al. EPSL 2012)



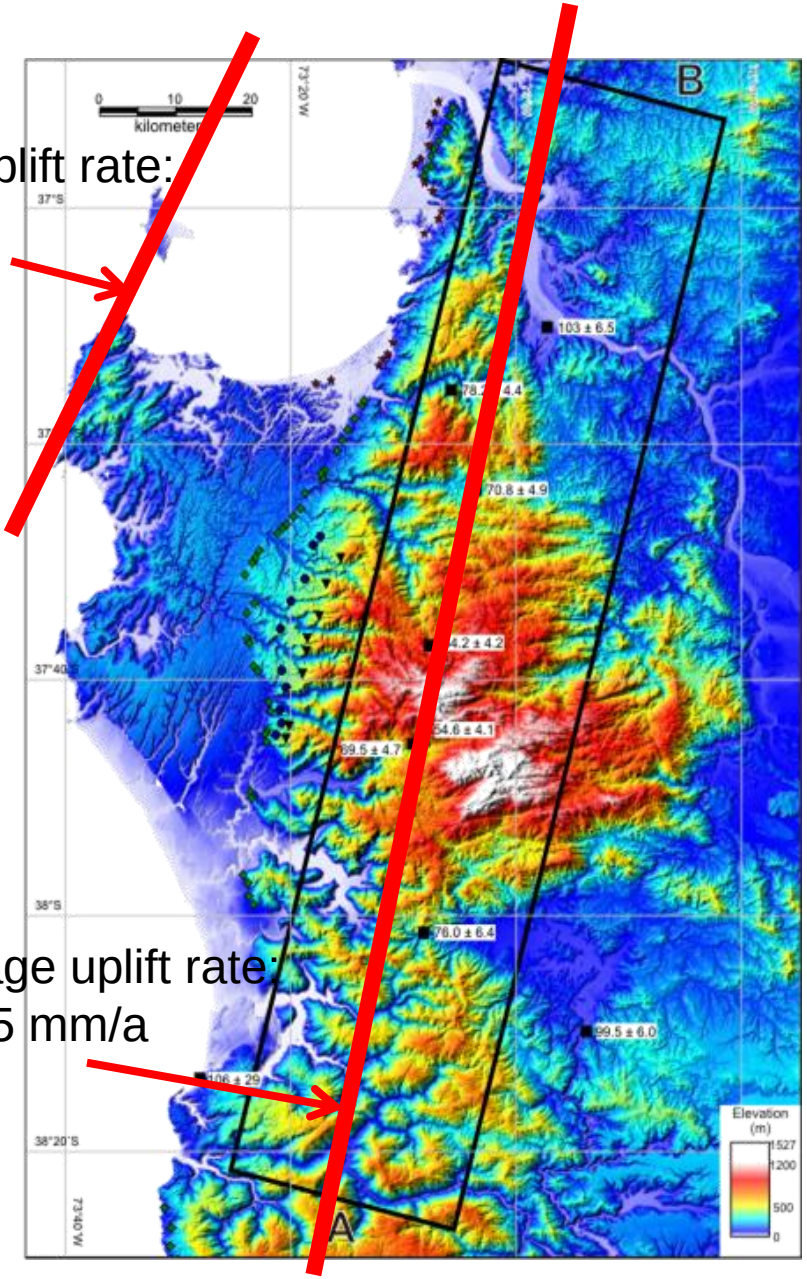




Kinematics since c.3 Ma



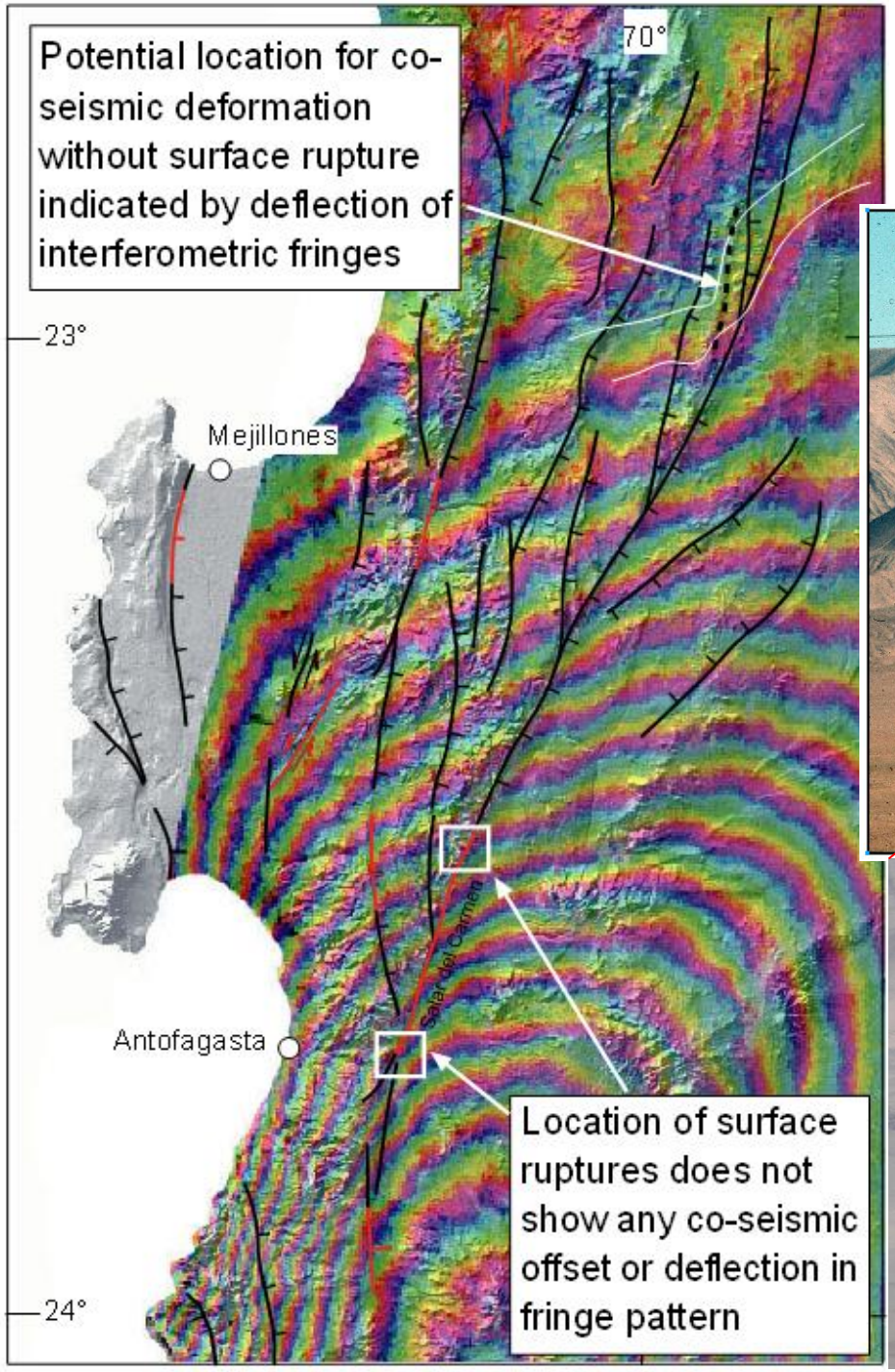
Average uplift rate:
2.3 mm/a

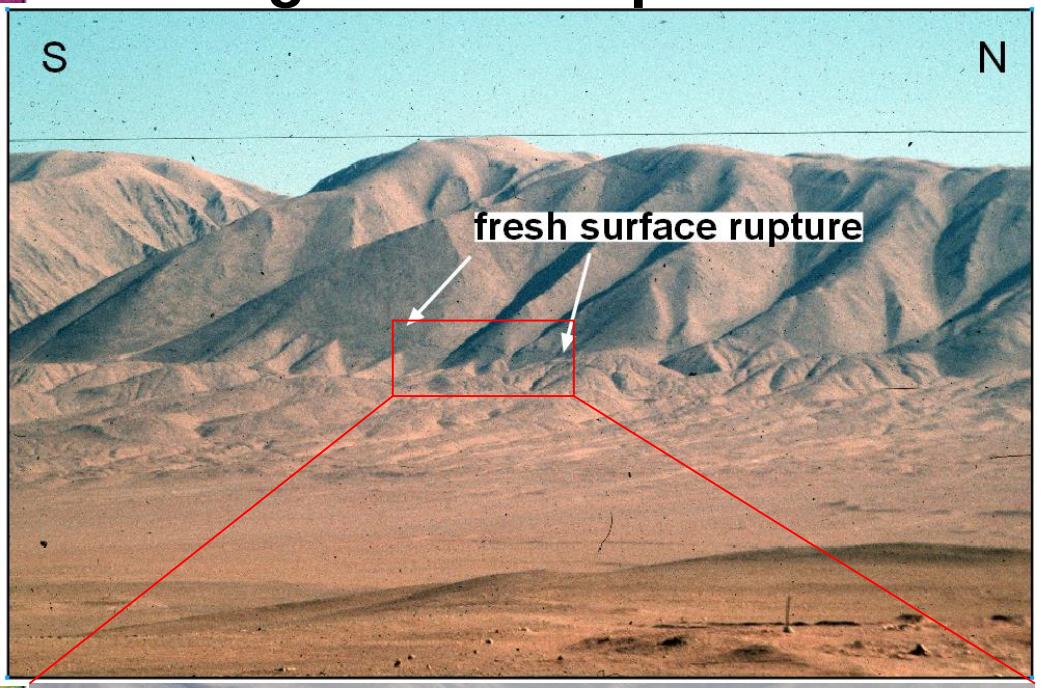


Average uplift rate:
1 - 1.5 mm/a

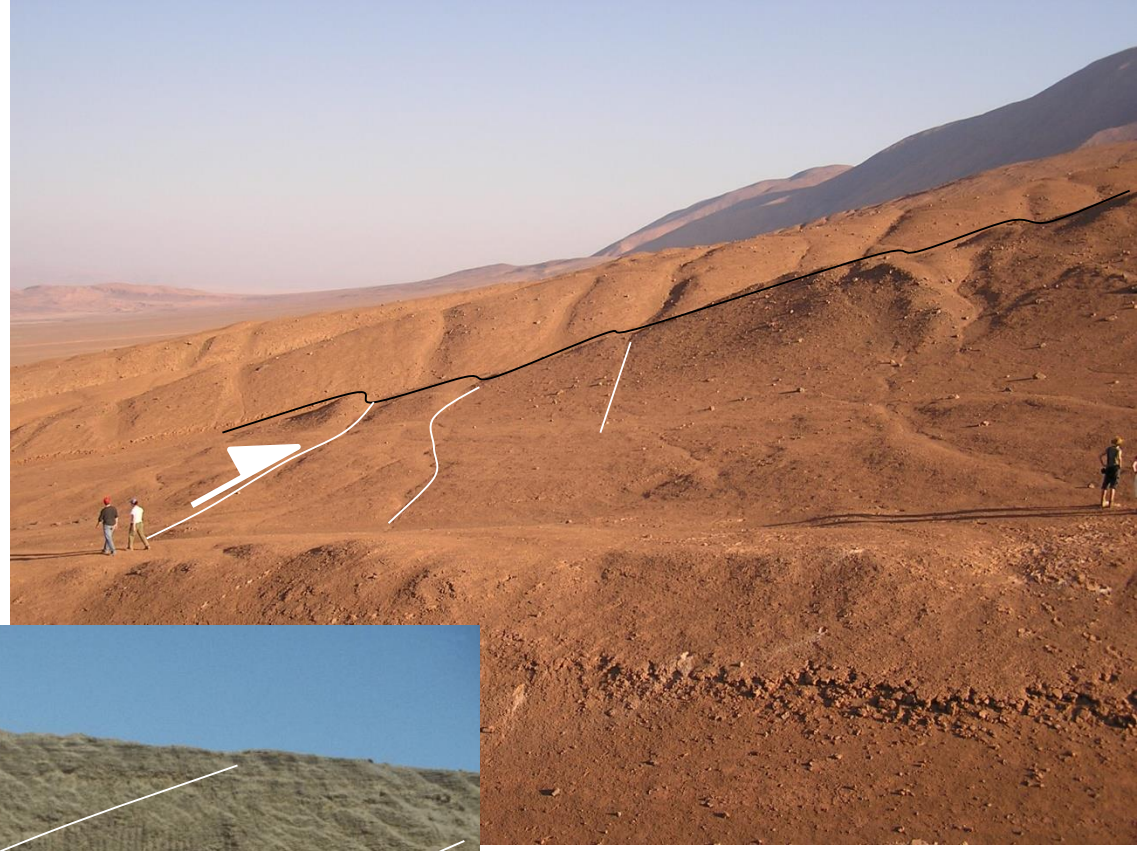
Bookhagen et al., Melnick et al, 2006, 2009

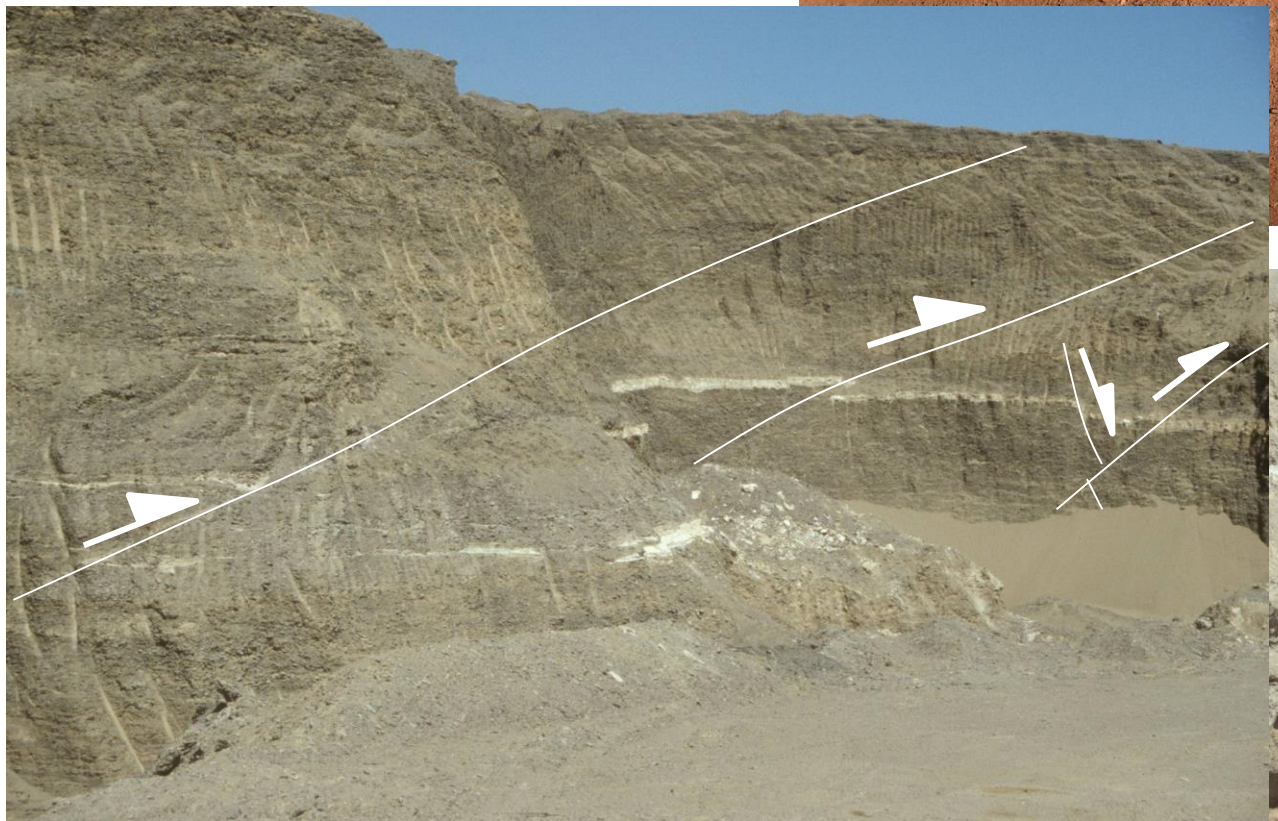
Co- and postseismic deformation of surface from Antofagasta earthquake





??Interseismic shortening at low slip rates





Uplifted coast

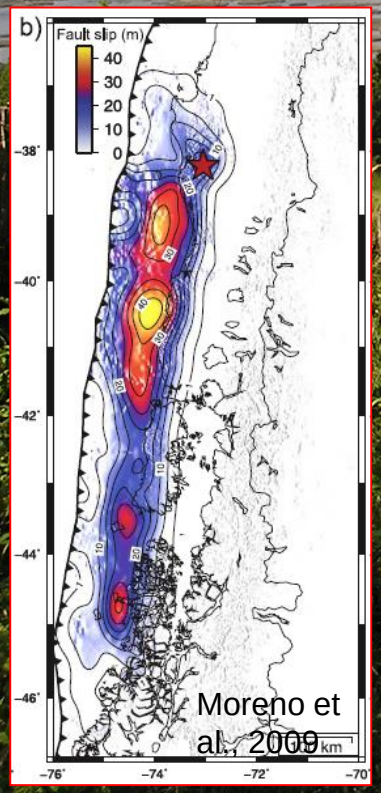
Maule earthquake, 27.2.2010

45 years later

1960

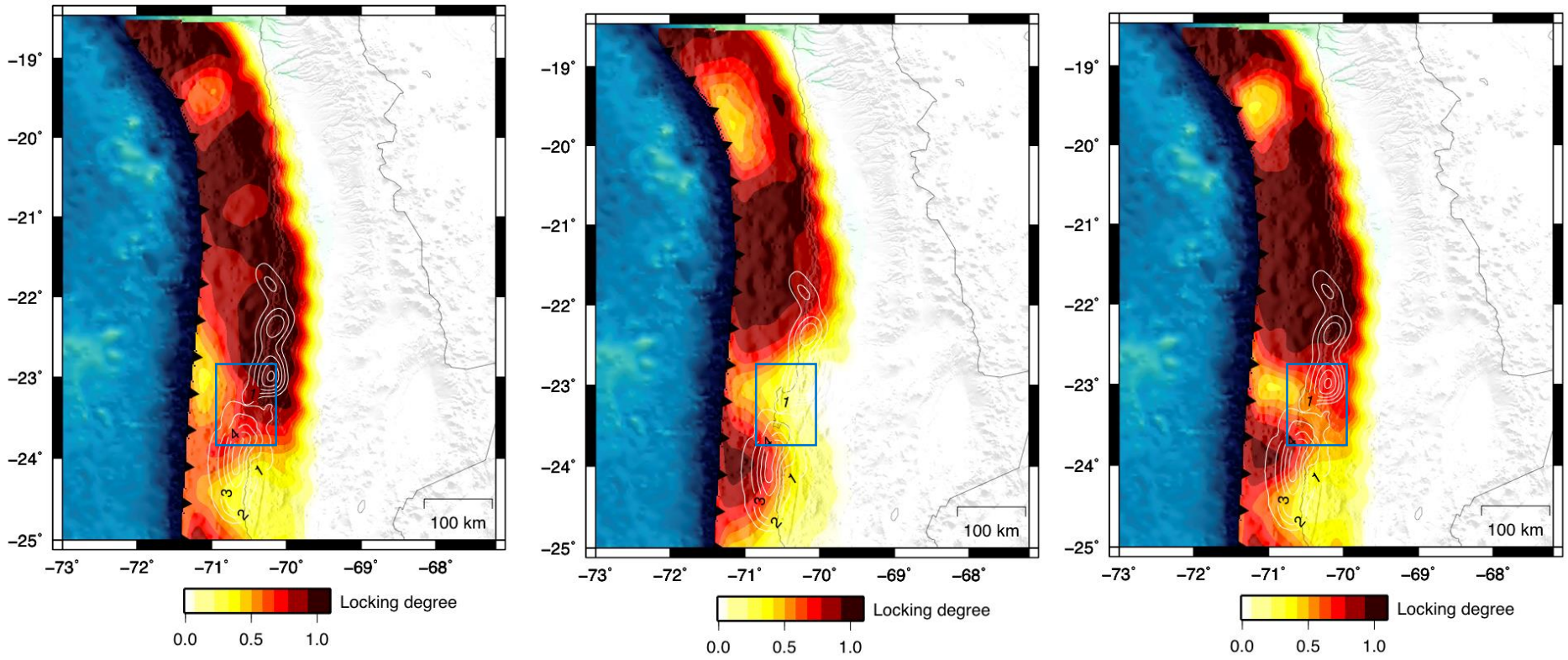
1837

1737

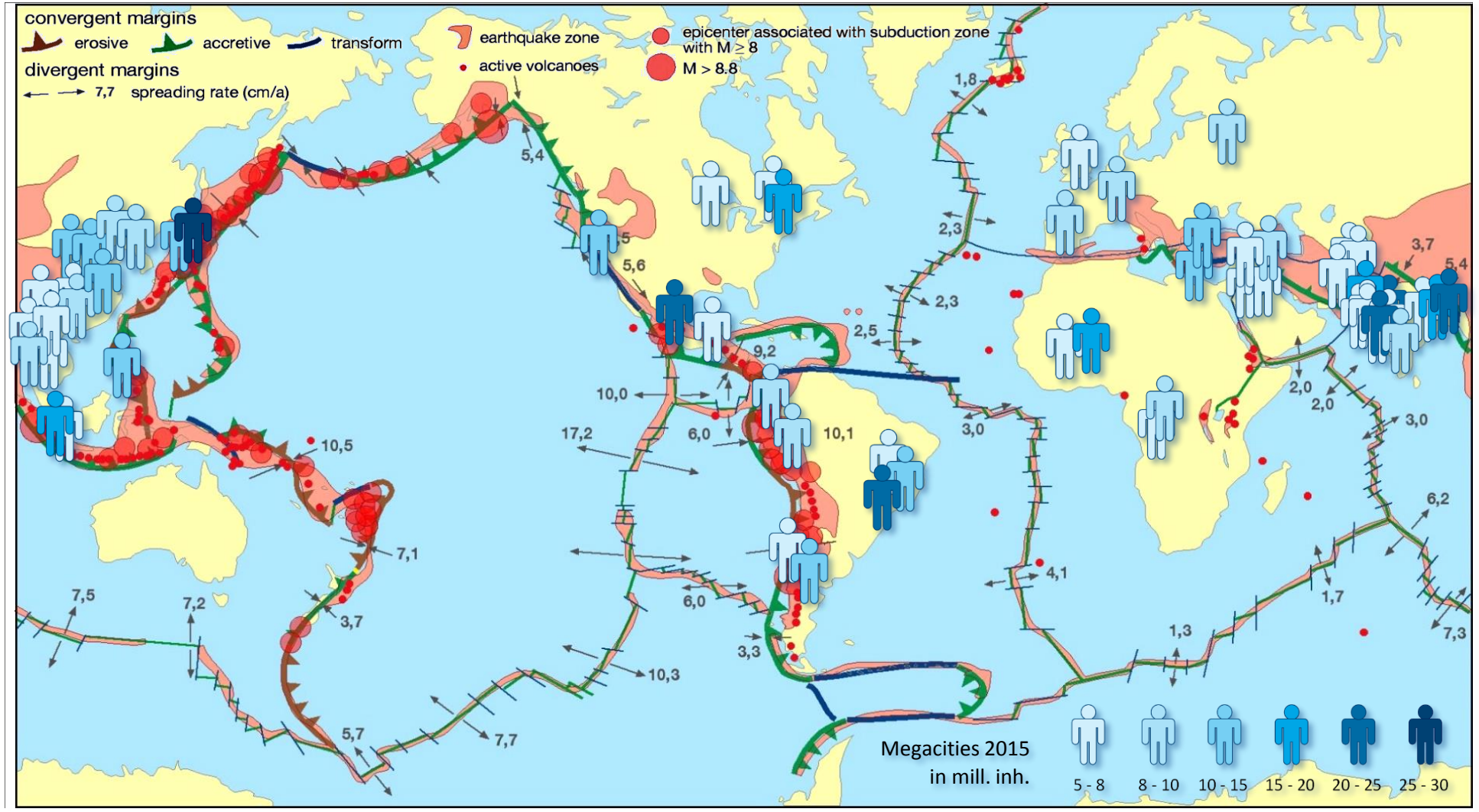


Moreno et al., 2009

Seismic barrier and the geological record – and the uncertainty



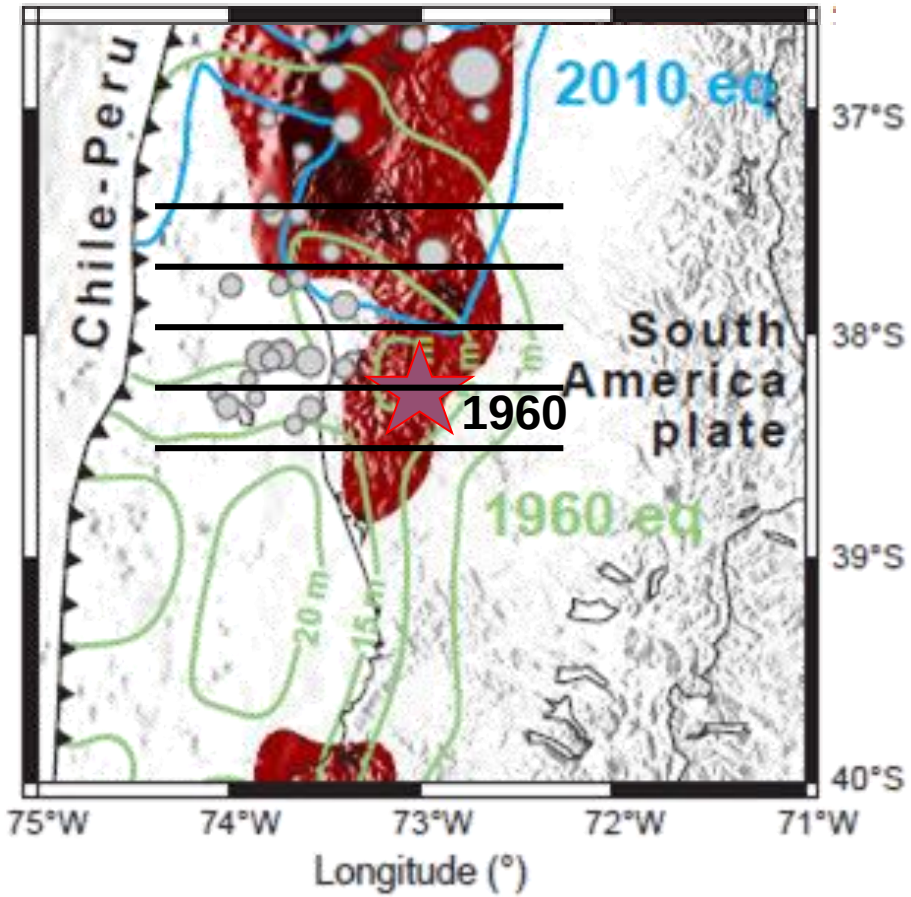
Der Erdbeben-Zoo und die Bananenschale -
was wir schon immer über Subduktionszonen wissen wollten



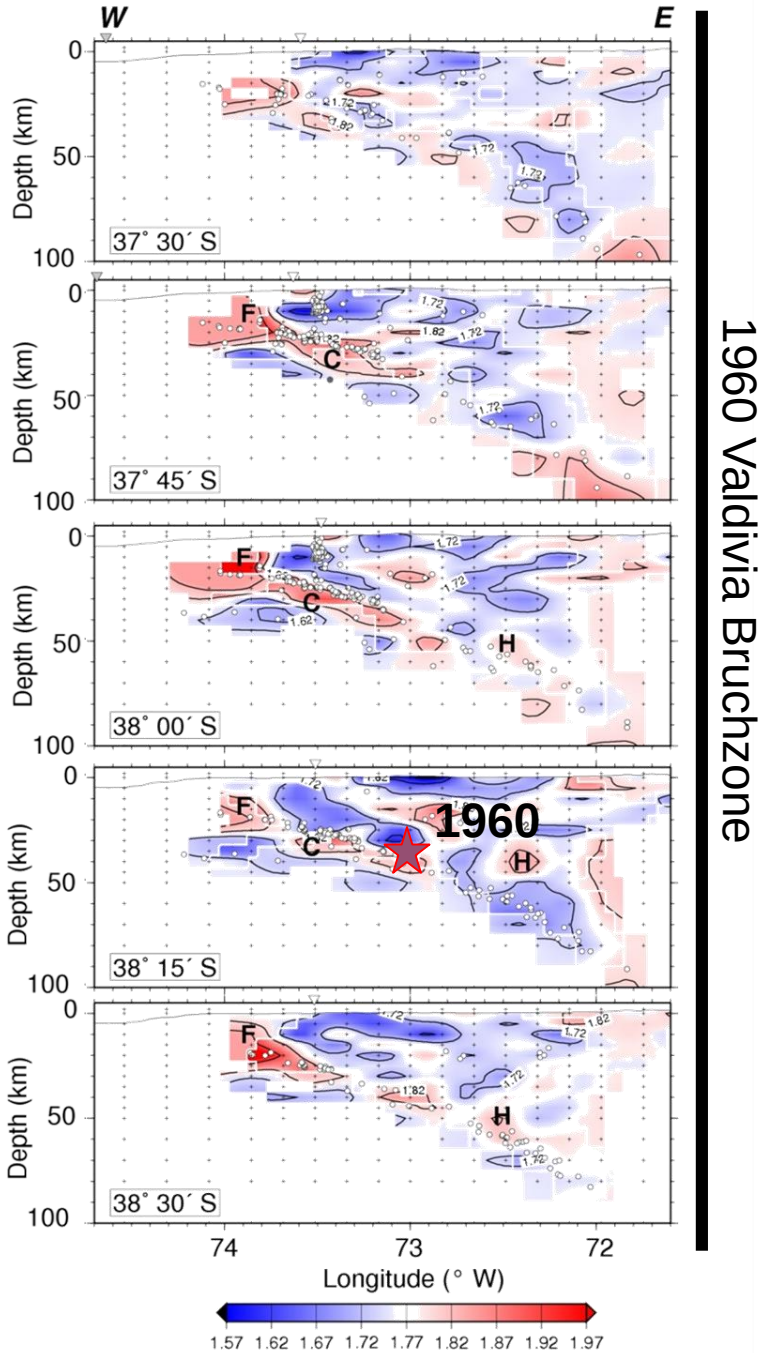
Onno Oncken, GFZ Potsdam

mit M. Moreno, J. Bedford, M. Rosenau, S. Angiboust, B. Schurr, P. Victor, V. Mouslopoulou

Erdbebenaktivität und Vp/Vs Verhältnis korrelieren mit der Kopplung !



Moreno et al., 2010

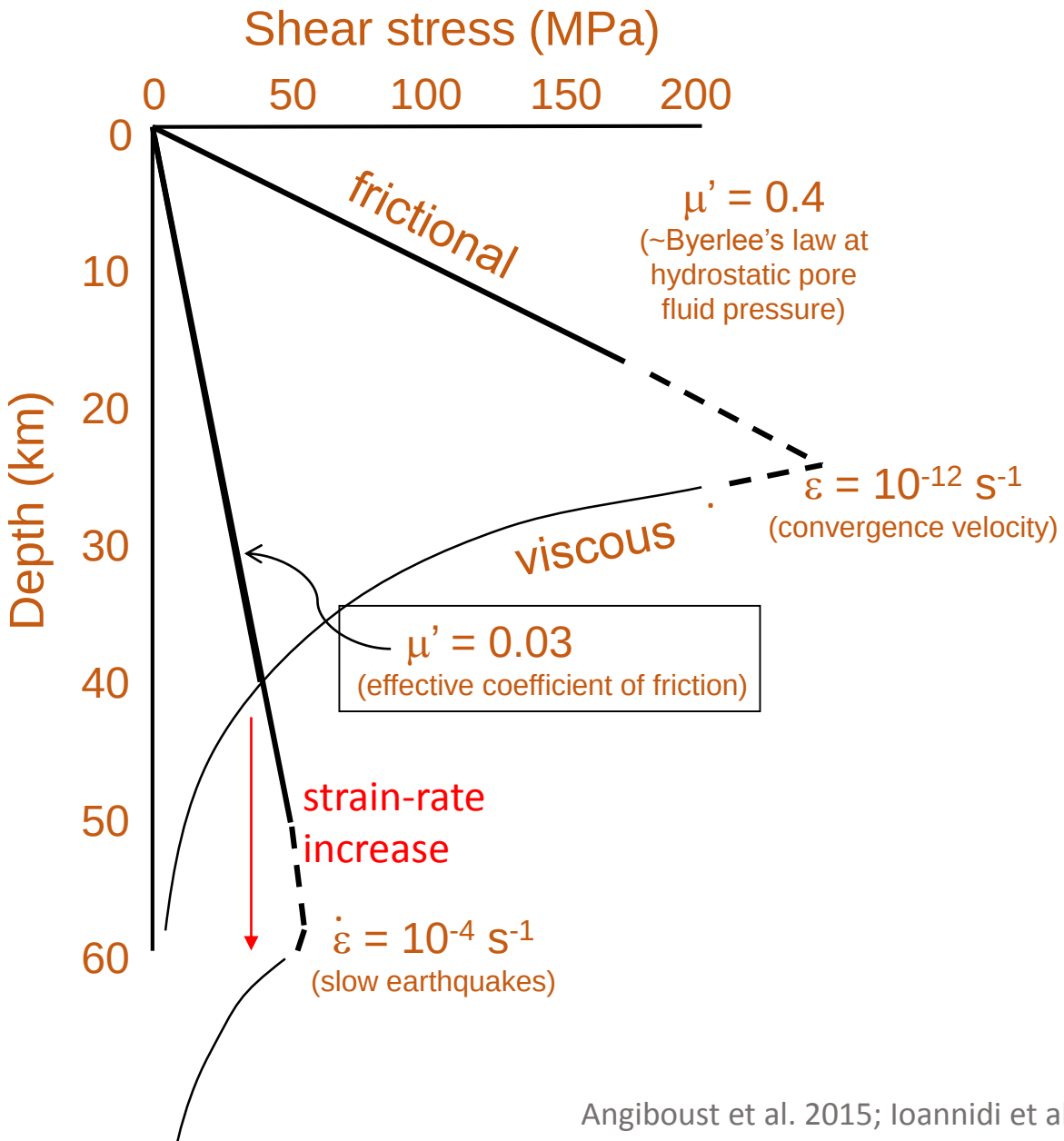


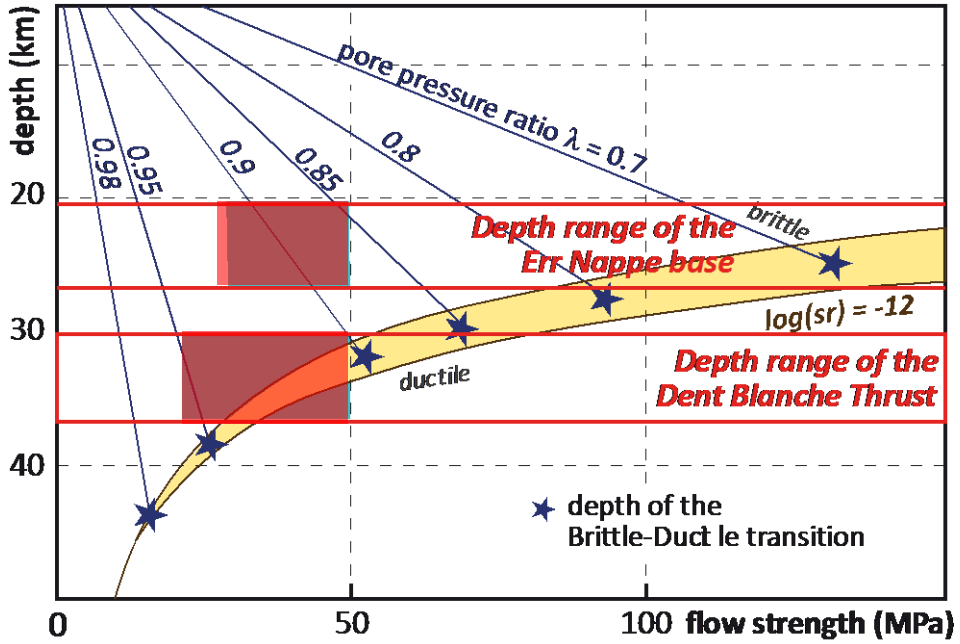
Haberland et al. 2009 v_p/v_s

2010 Maule Bruchzone

1960 Valdivia Bruchzone

Stress/fluid pressure fluctuations in transition zone





At seismic cycle time scale, transition depth depends on

(1) Pore fluid pressure

…and on

(2)Strain rate

Angiboust et al. 2015; Ioannidi et al., in prep.