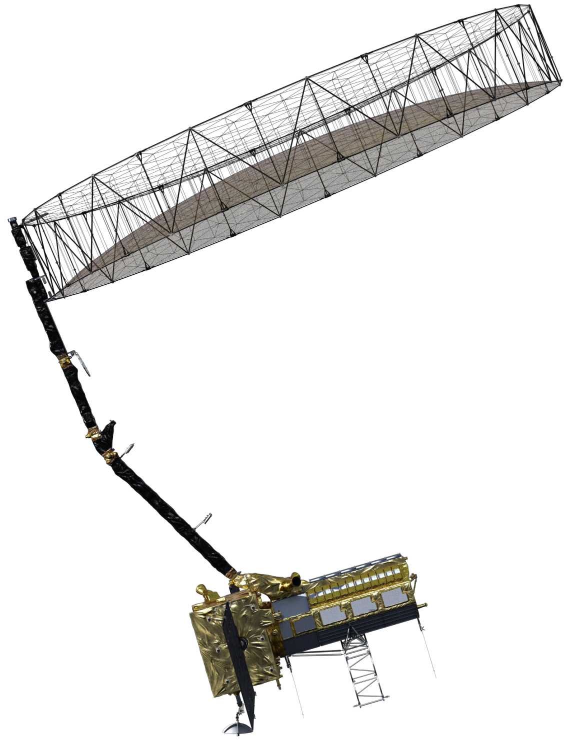
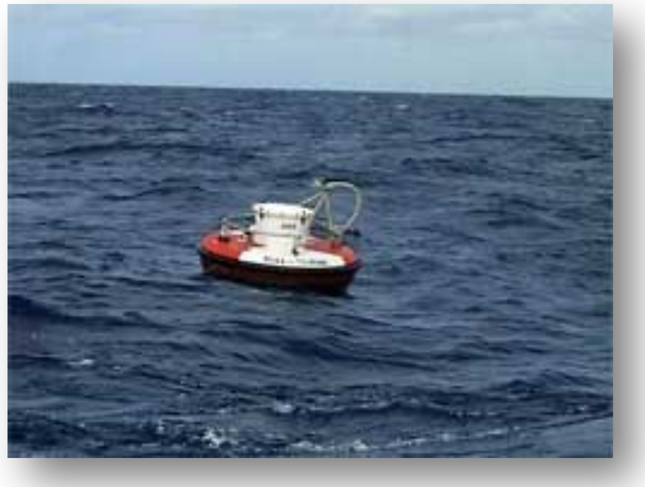
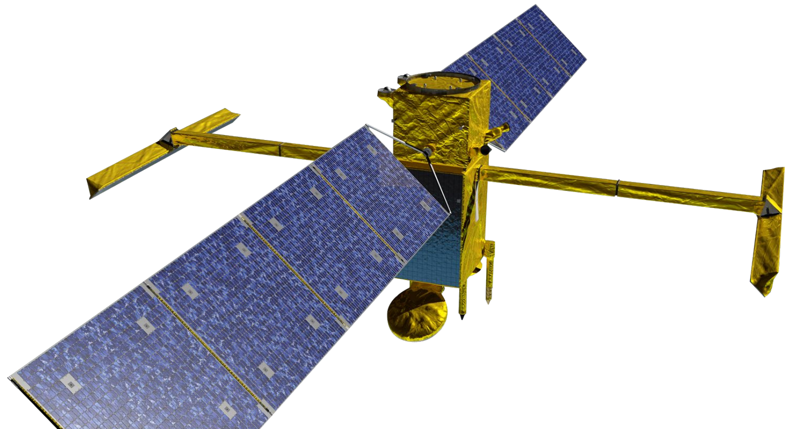
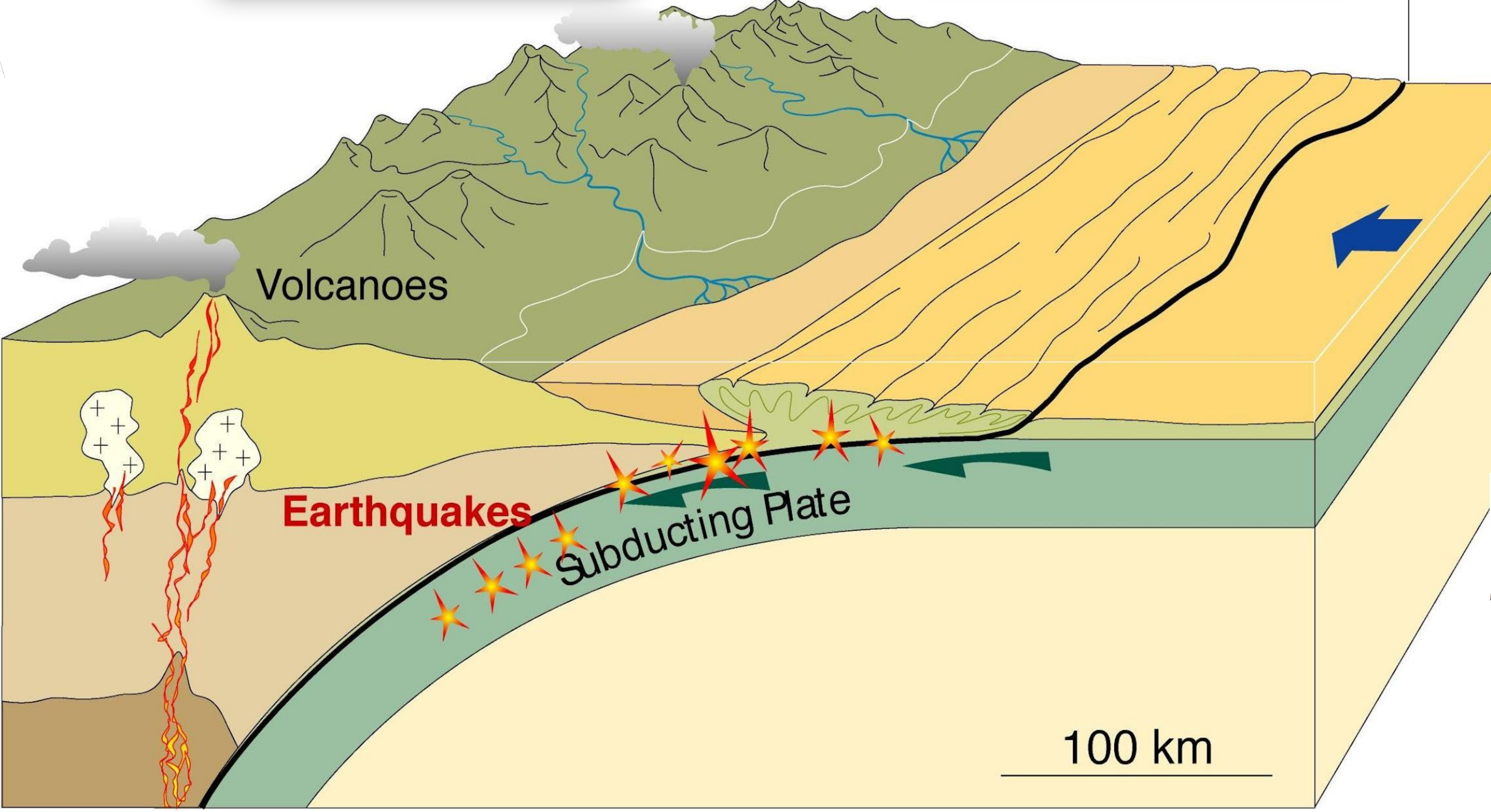
Heterogeneous Coupling of the Megathrust from Minutes to Many Millennia

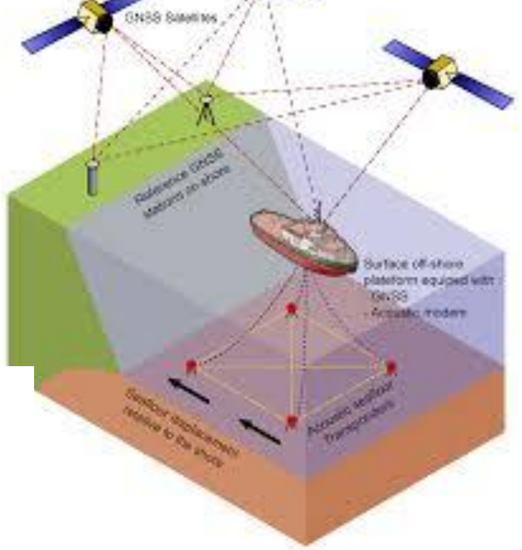
A kinematic perspective





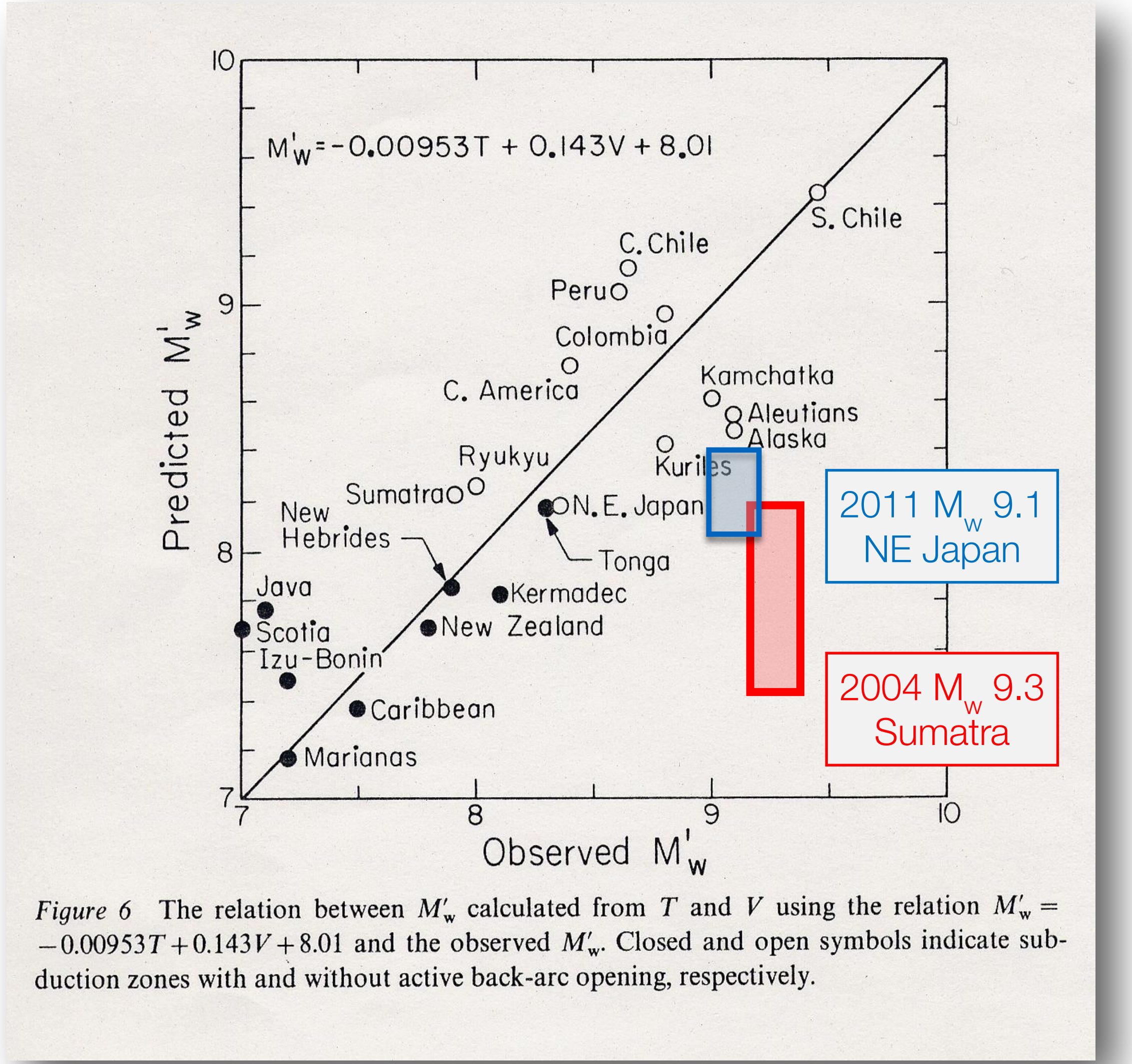






Mark Simons
simons@caltech.edu

Evolving from an inter- to an intra-subduction zone perspective on seismogenic behavior



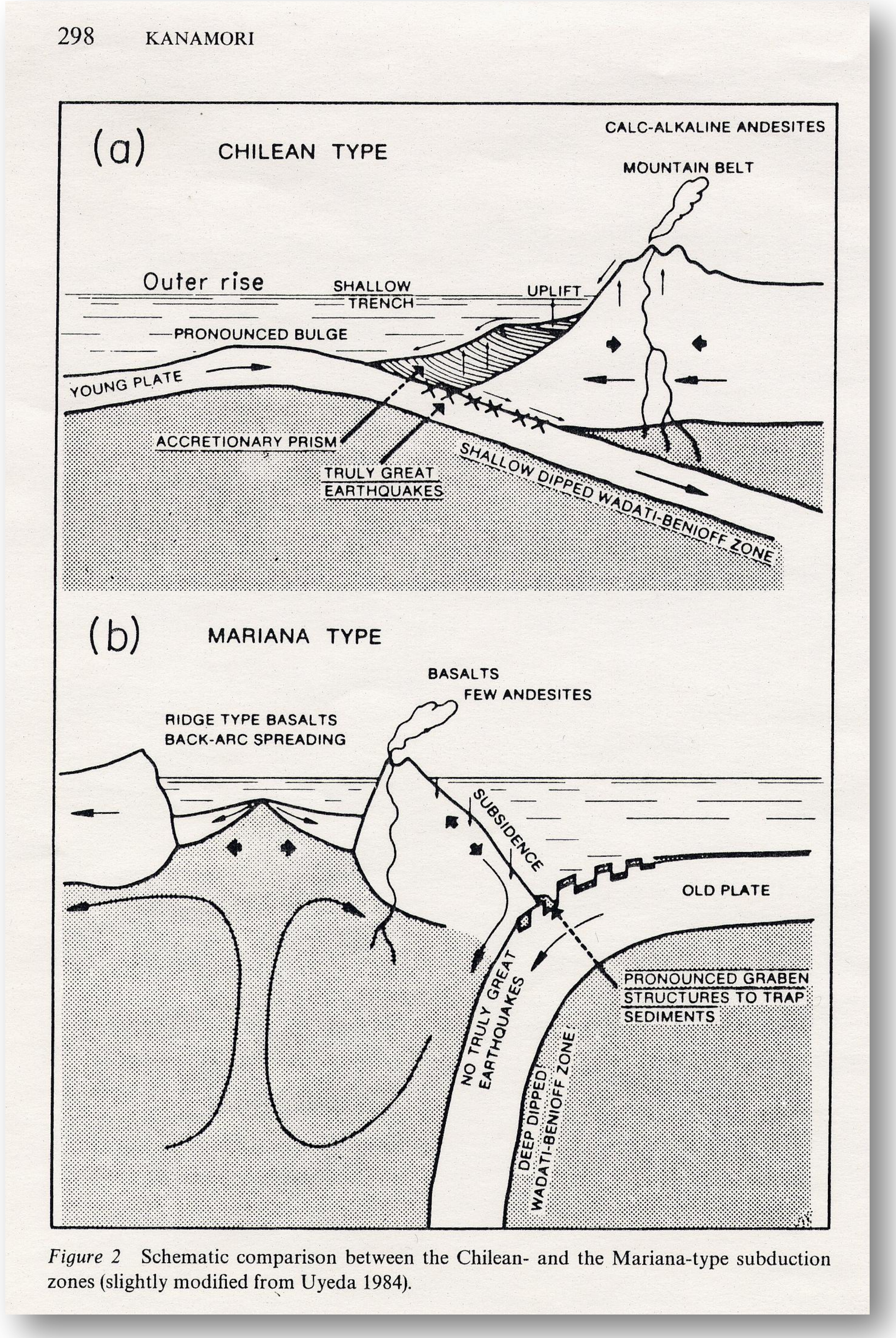
2011 M_w 9.1
NE Japan

2004 M_w 9.3
Sumatra

Figure 6 The relation between M'_w calculated from T and V using the relation $M'_w = -0.00953T + 0.143V + 8.01$ and the observed M'_w. Closed and open symbols indicate subduction zones with and without active back-arc opening, respectively.

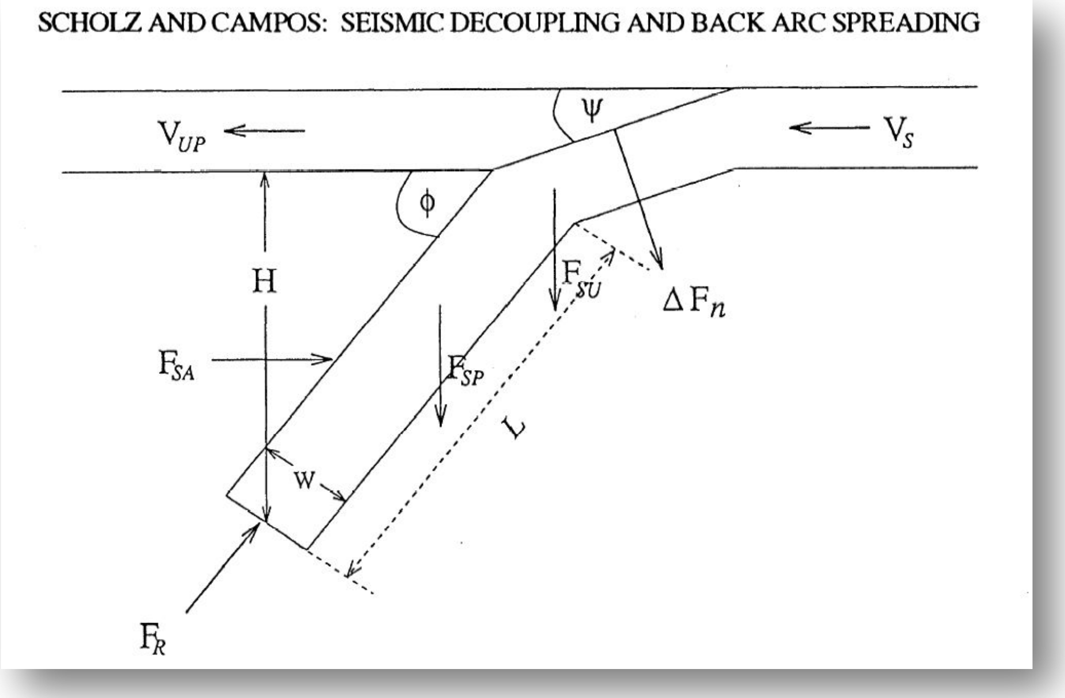
H. Kanamori and colleagues

What follows is a lot of examples



298 KANAMORI

Figure 2 Schematic comparison between the Chilean- and the Mariana-type subduction zones (slightly modified from Uyeda 1984).



SCHOLZ AND CAMPOS: SEISMIC DECOUPLING AND BACK ARC SPREADING

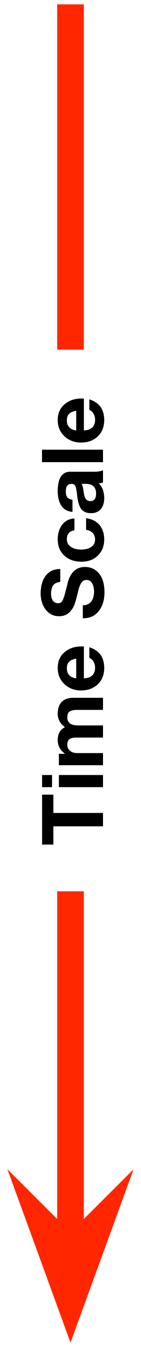
Historically, we adopted a trench perpendicular perspective

Seismic potential driven by variability in <u>normal</u> tractions which are controlled by plate age (buoyancy) and convergence velocity

Last 2 decades:

- Variations within subduction zones are as large as those between them
- Sumatra and NE Japan EQs

A sampling of important intertwined questions



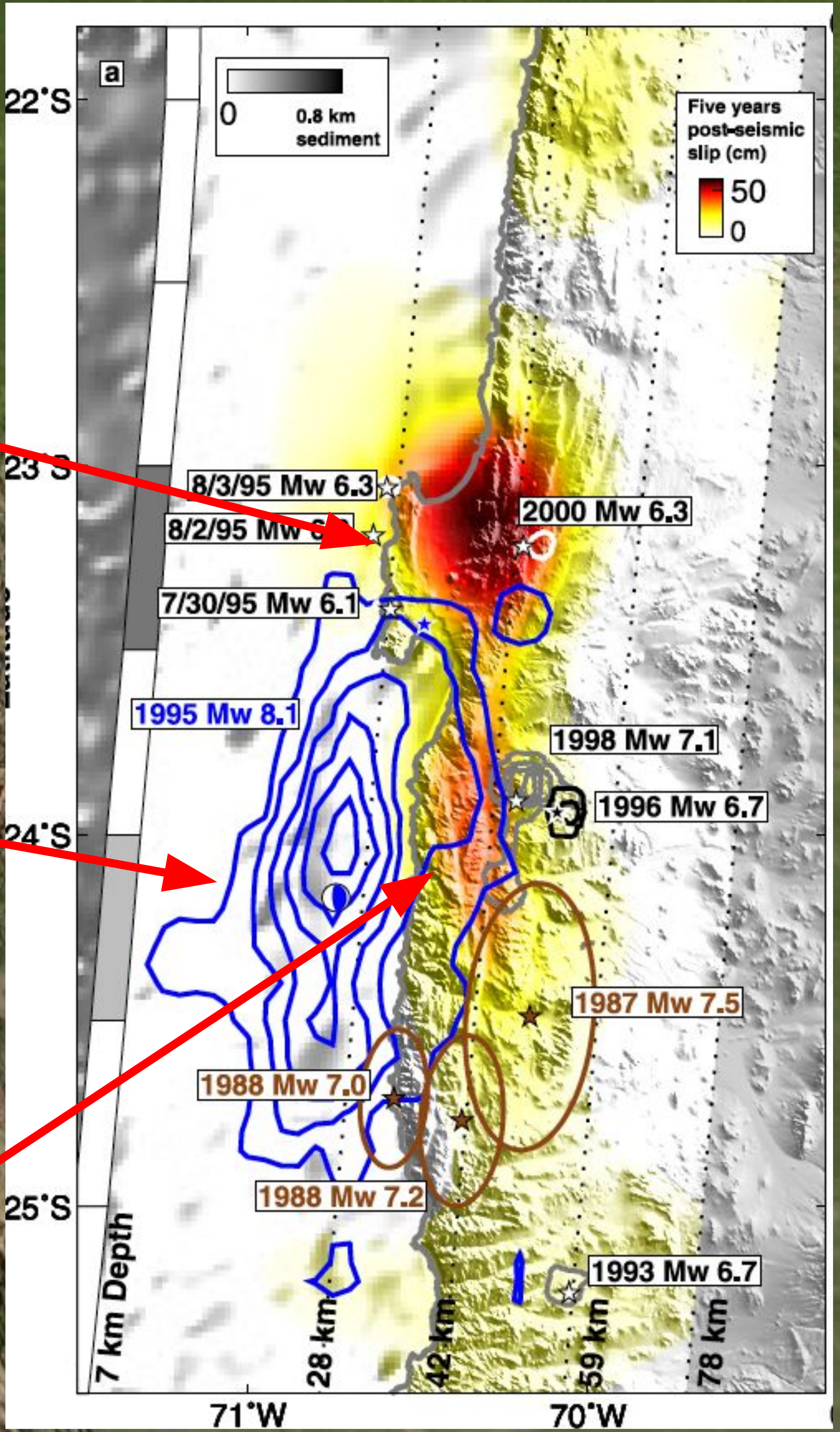
- Do major seismogenic “asperities” only slip seismically?
- Role of conditional stability (e.g., near trench)?
- Do most creeping segments only creep?
- Is pre-seismic creep (EQ swarms?) ubiquitous?
- What are the relationships between post-seismic creep, transients, tremor and seismicity (rate, repeat intervals, location…)?
- What is the role of off-fault quasi-permanent deformation (damage, VEP…)?
- What drives the large along-strike variations in forearc structure as seen in gravity and topography?
- Is there a relationship between short term behavior and geologic evolution of the forearc?

I will only touch on a few of these today

Only recently have the necessary data and computational tools been available to permit the spatial resolution needed to begin to address some of these questions with any level of confidence

Complexity of slip behavior on a single fault

- Negligible coseismic slip at the hypocenter
- Megathrust below the peninsula appears “aseismic”?
- Little overlap between co- / post-seismic
- Along strike variability in behavior
- A large number of aftershocks surround aseismic patch
- Aseismic transient event downdip of main rupture superimposed on post-seismic afterslip



5 years of continuous rapid after slip under the peninsula

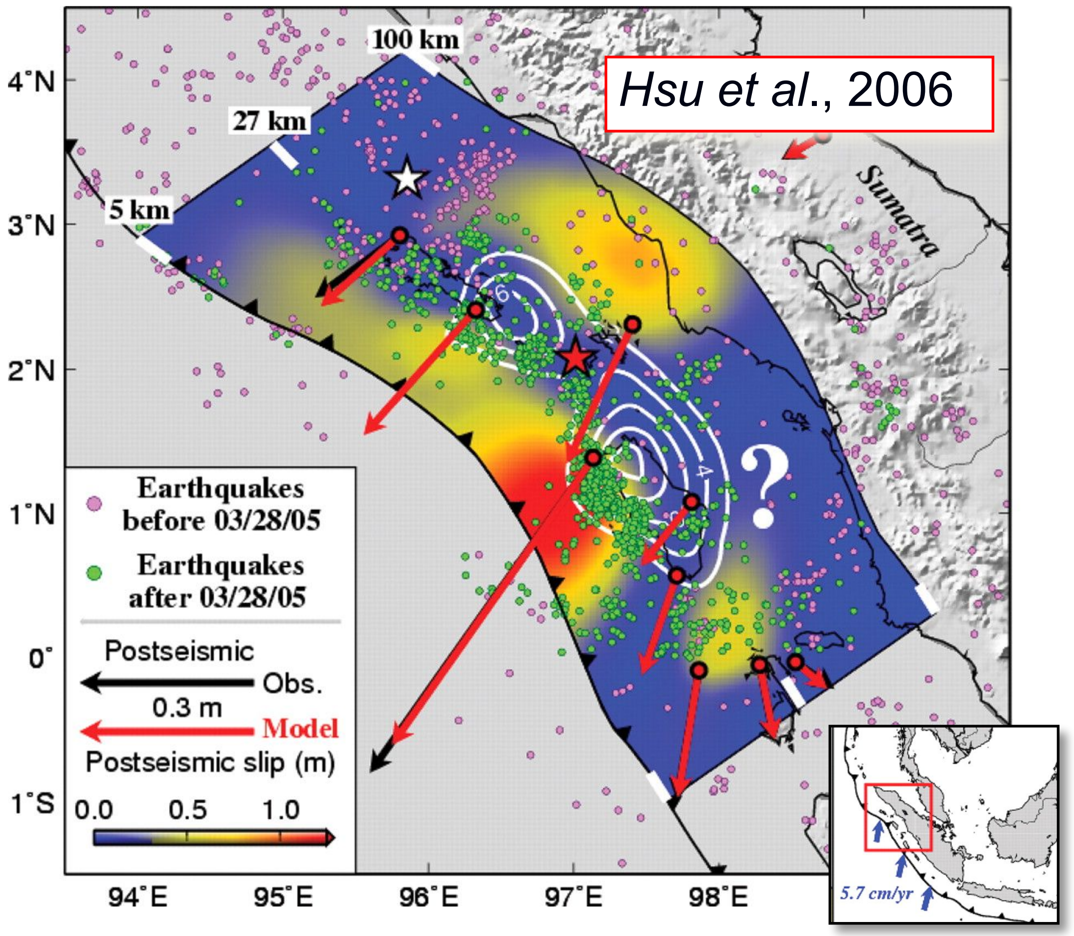
1995 Mw 8.1

Aseismic pulse 3 yrs after

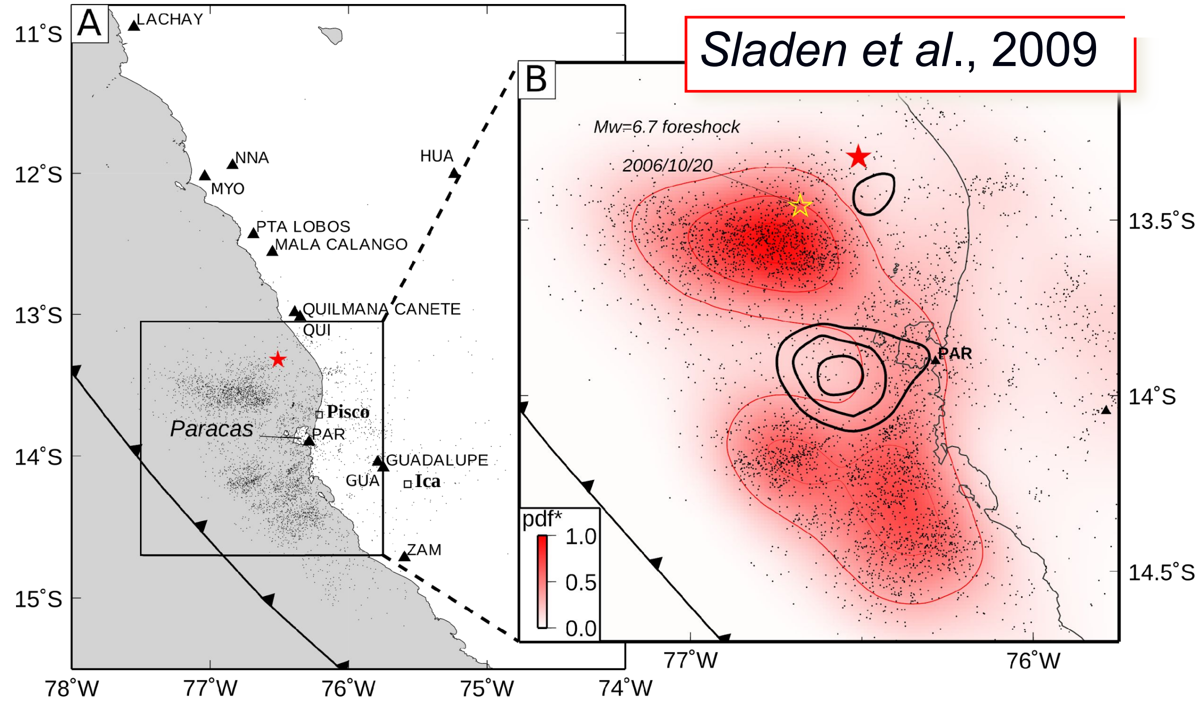
2 decades ago

Pritchard & Simons, 2006

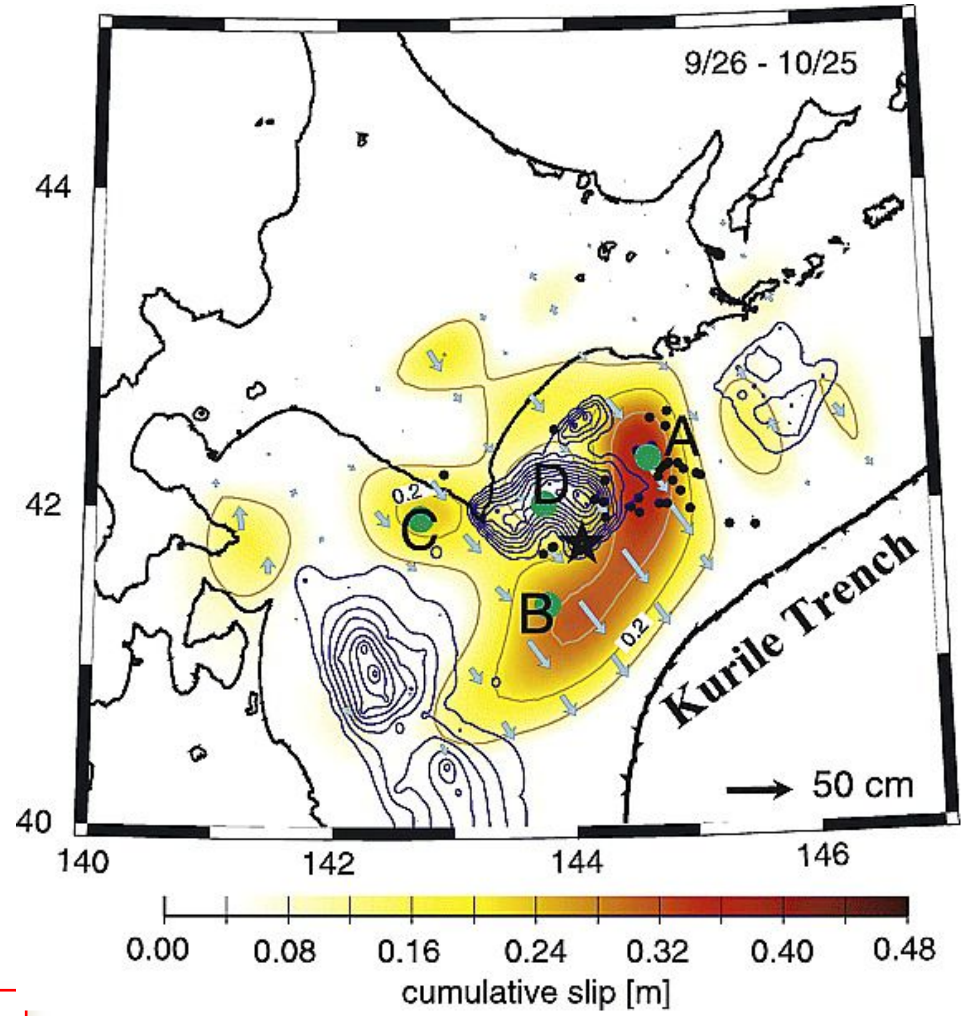
2005 M_w 8.7 Nias, Sumatra


Hsu et al., 2006

2007 Mw 8.0 Pisco, Peru

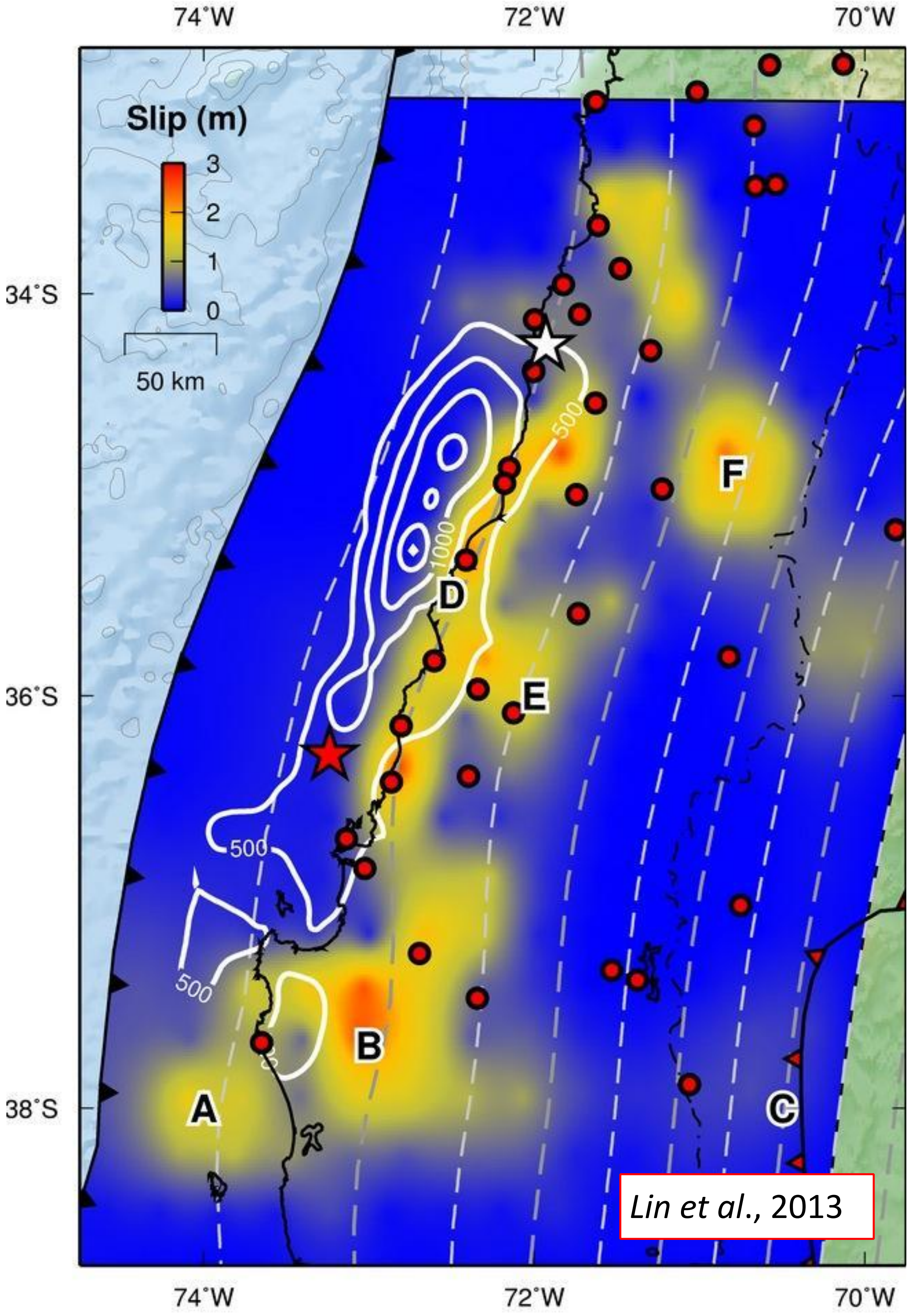

Sladen et al., 2009

2003 M_w 8.3 Tokachi-Oki, Japan

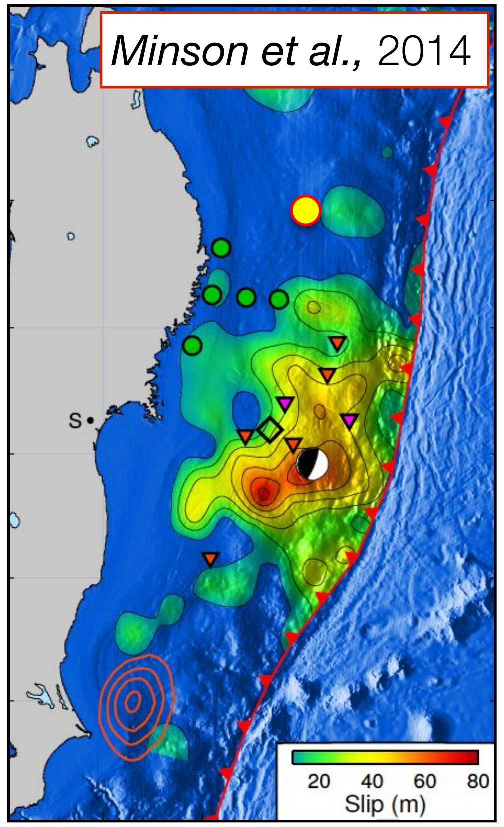


1952, 1968, 2003, Yamanaka & Kikuchi, 2004
2003 postseismic, Miyazaki et al, 2004

2010 M_w 8.8 Maule, Chile


Lin et al., 2013

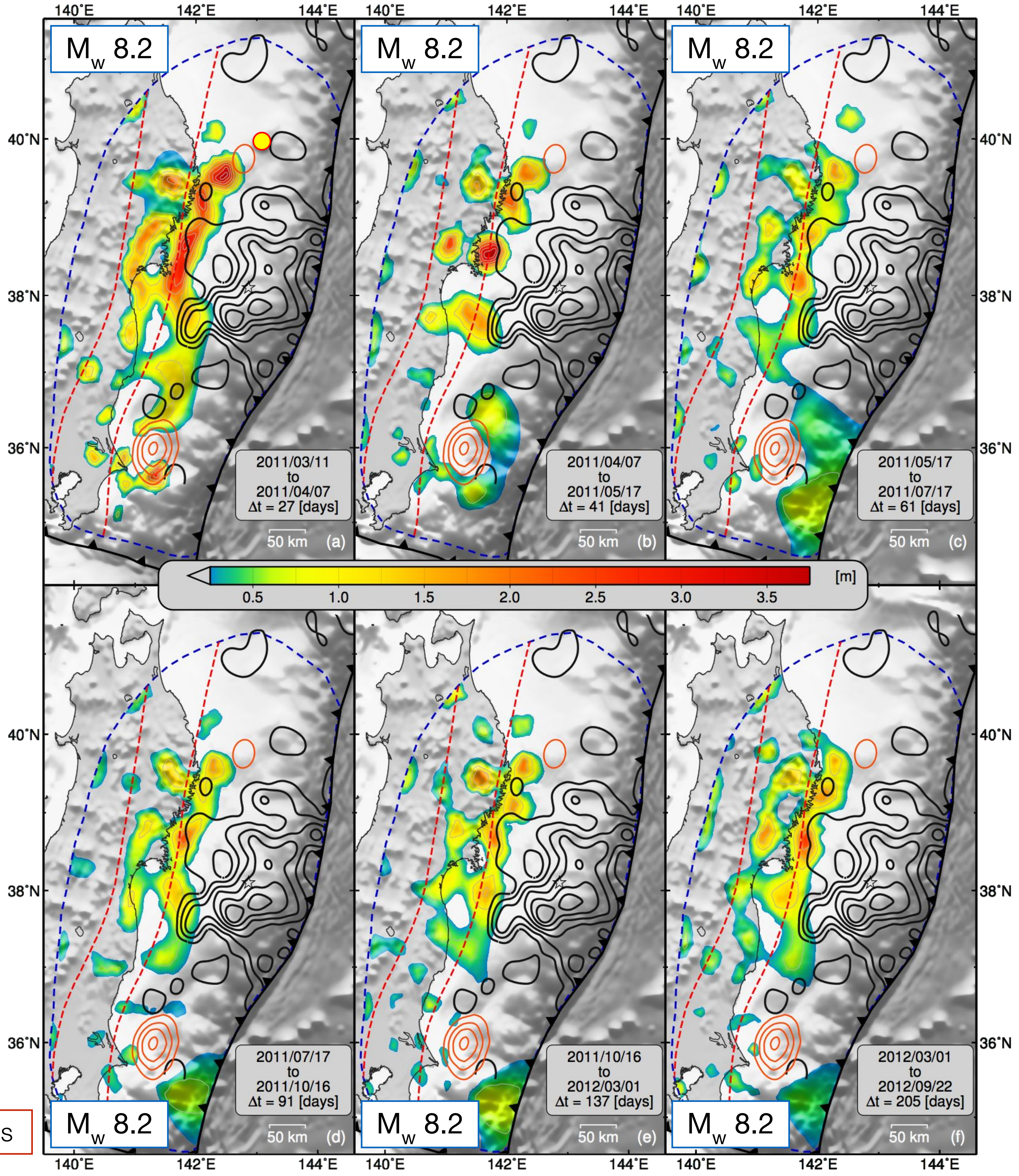
2011 Tohoku-Oki, Japan



Post-seismic afterslip:

- Total time = 1.5 years
- Mutually exclusive time windows of increasing duration
- Independent inversions
- Fixed color scale
- M_w 8.2 in each time window

$\Delta t_{i+1} = 1.5 \times \Delta t_i$



F. Ortega, Ph.D. thesis

Why did these regions not slip coseismically?

My bias: Spatial heterogeneity of frictional properties of the megathrust not nonlinear complexity (memory) of the friction law.

Implication: Long-lived seismogenic asperities

- Ignores any potential VE component
- Vanishingly low resolution by the trench

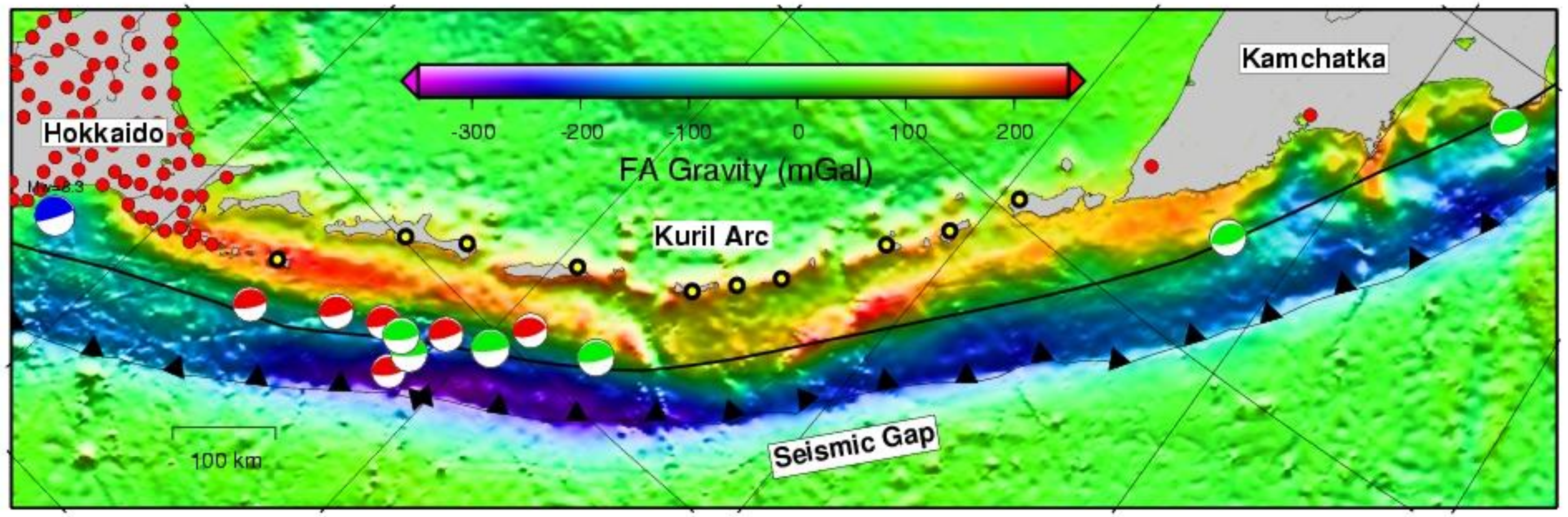
A Crazy Hypothesis

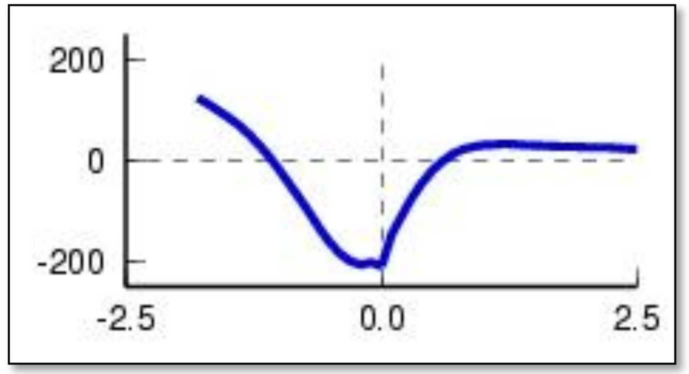
TPGA = Trench Parallel Gravity Anomaly

All else being equal, variations in forearc gravity and topography serve as a proxy for long-lived variations in tractions on the plate boundary interface

Song & Simons, 2003; *Wells et al.*, 2003

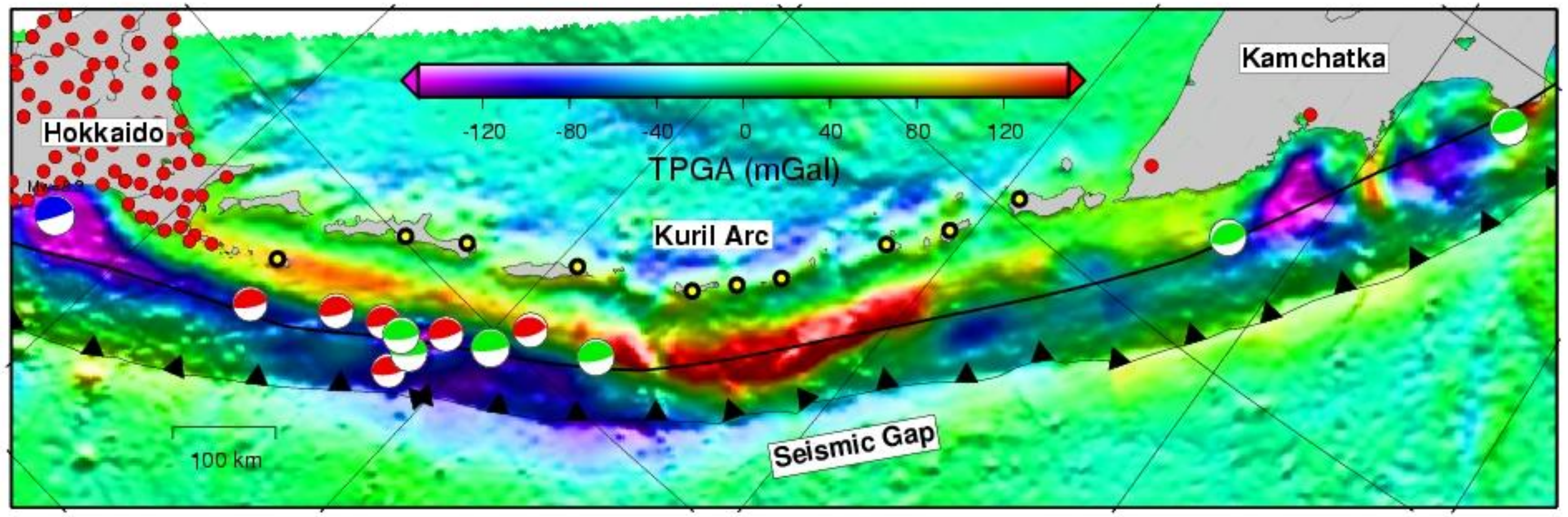
Free Air Anomaly

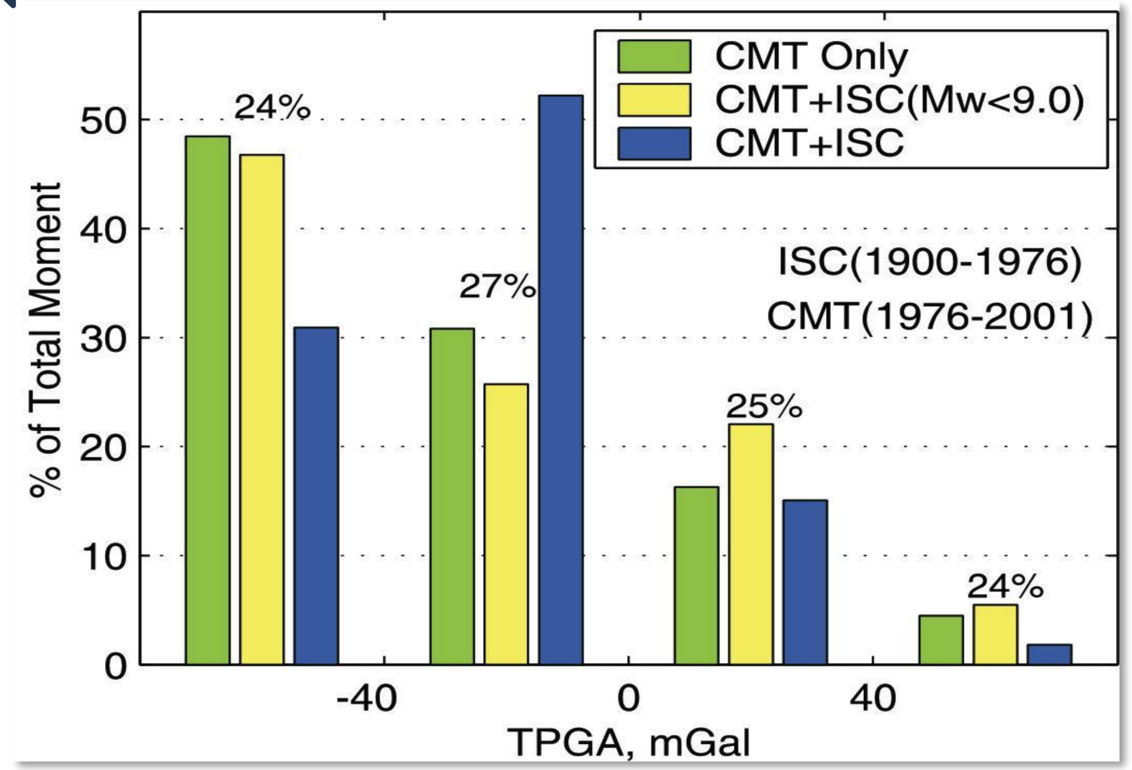




Average Trench Perpendicular Profile

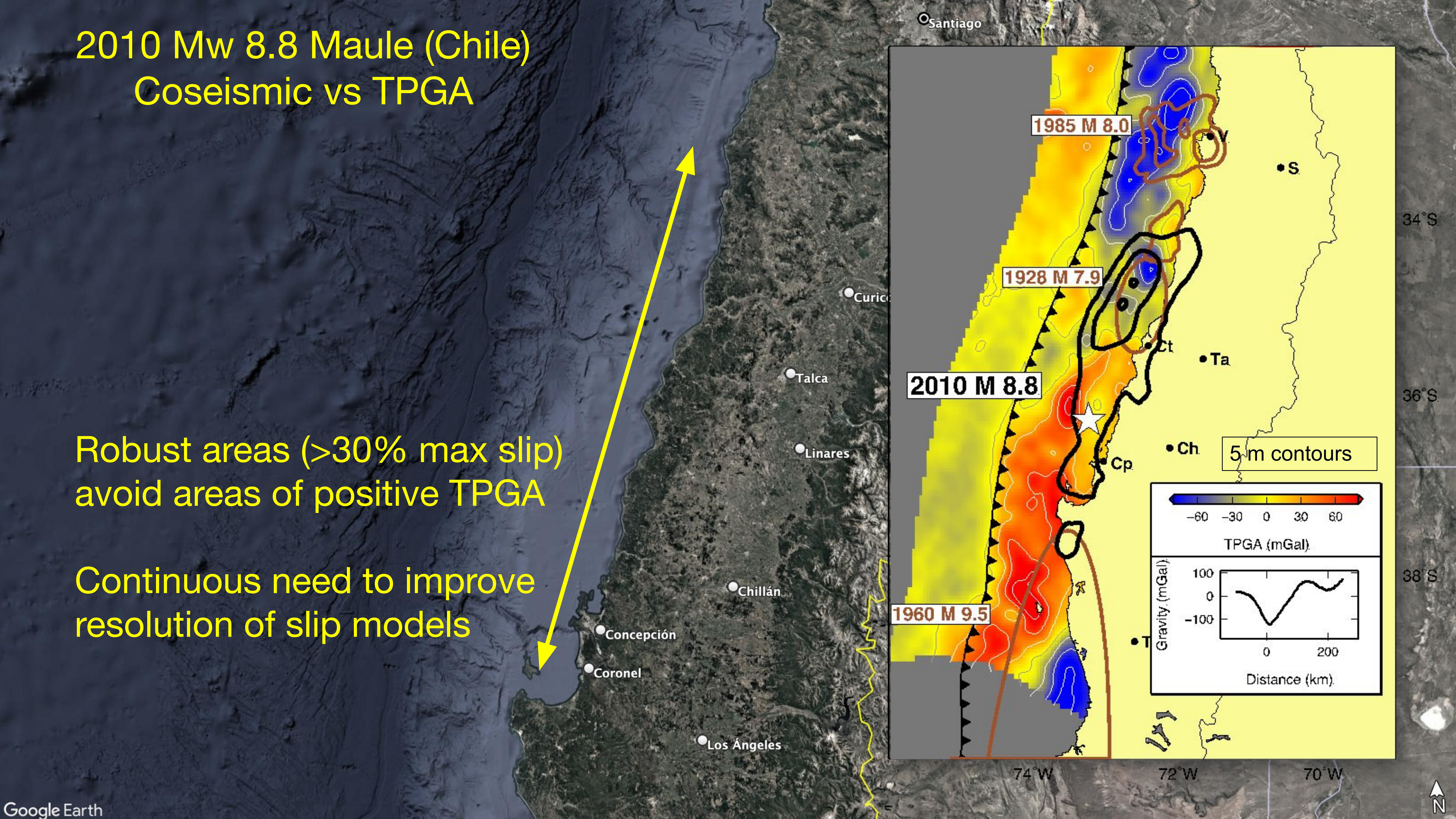
TPGA





TPGA < 0 in region of large earthquakes

2010 Mw 8.8 Maule (Chile)
Coseismic vs TPGA



Robust areas (>30% max slip) avoid areas of positive TPGA

Continuous need to improve resolution of slip models

TPGA
Sumatra/Andaman

2004 Mw 9.3

Slip-weighted average TPGA: -30 mGals

Caution: Sparse geodetic coverage

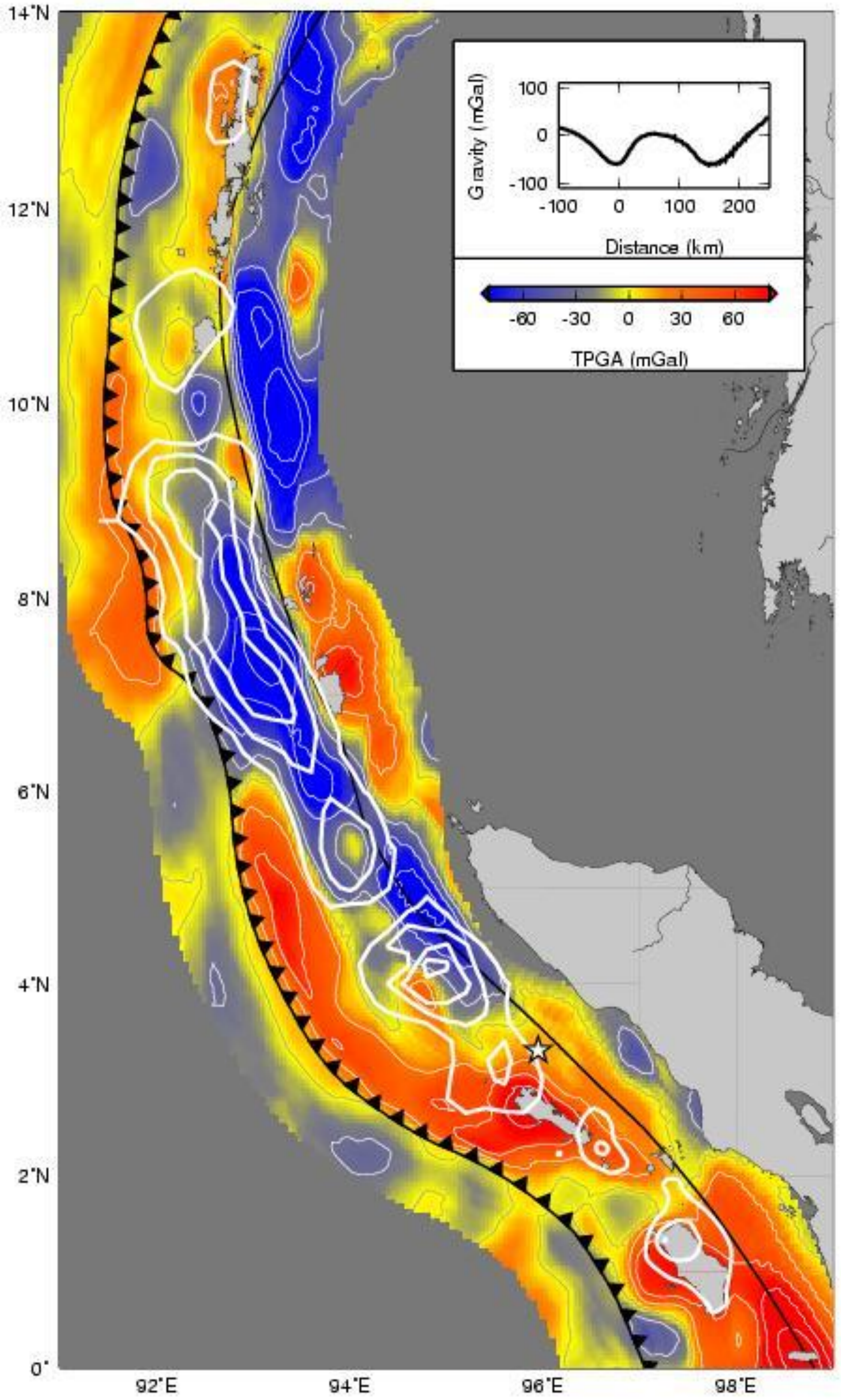
Slip model from *Chlieh et al*., 2007

2005 Mw 8.7

Better geodetic coverage

Slip model from *Hsu et al*., 2007

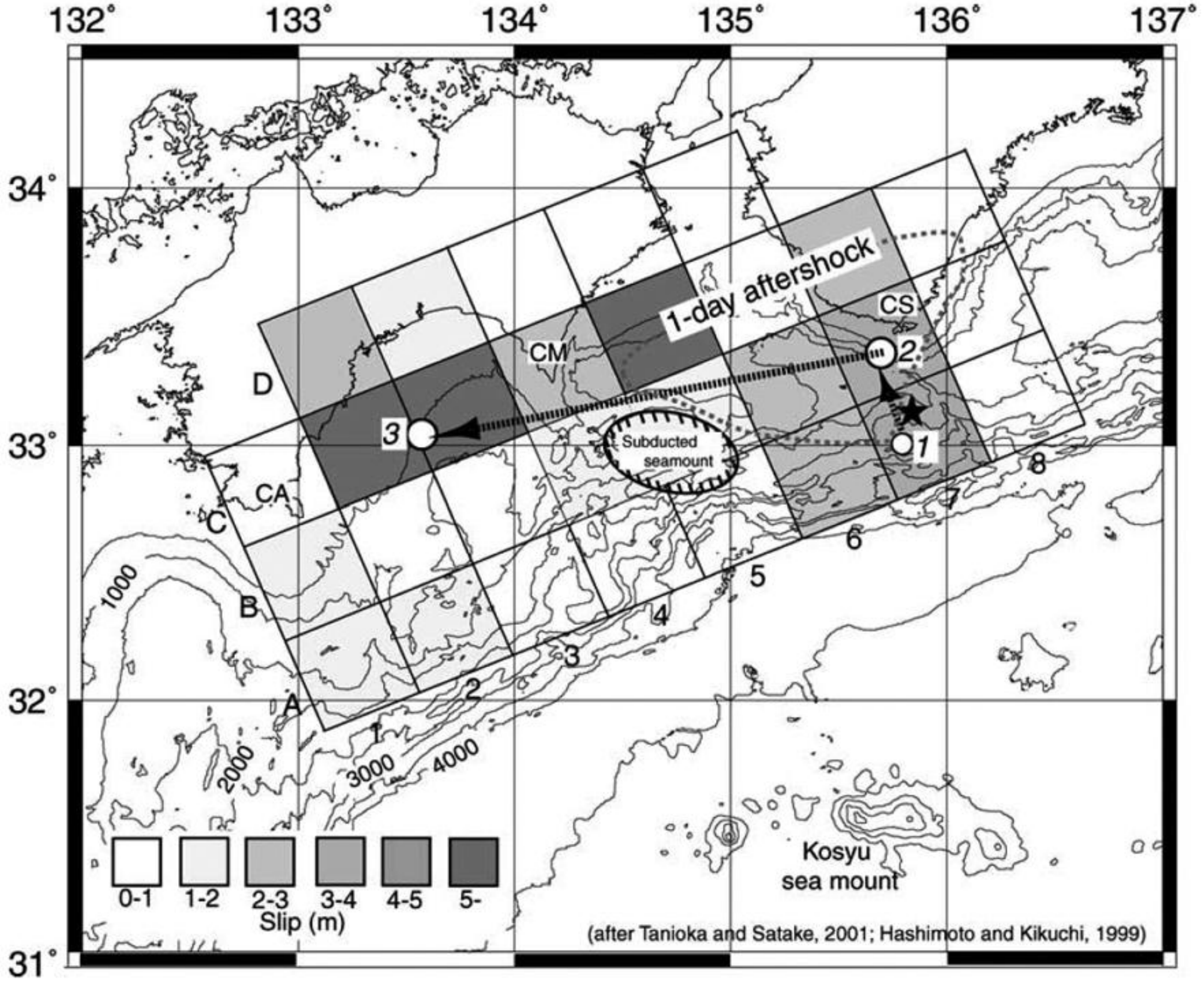
Can somebody explain the islands to me? Are they fossils?



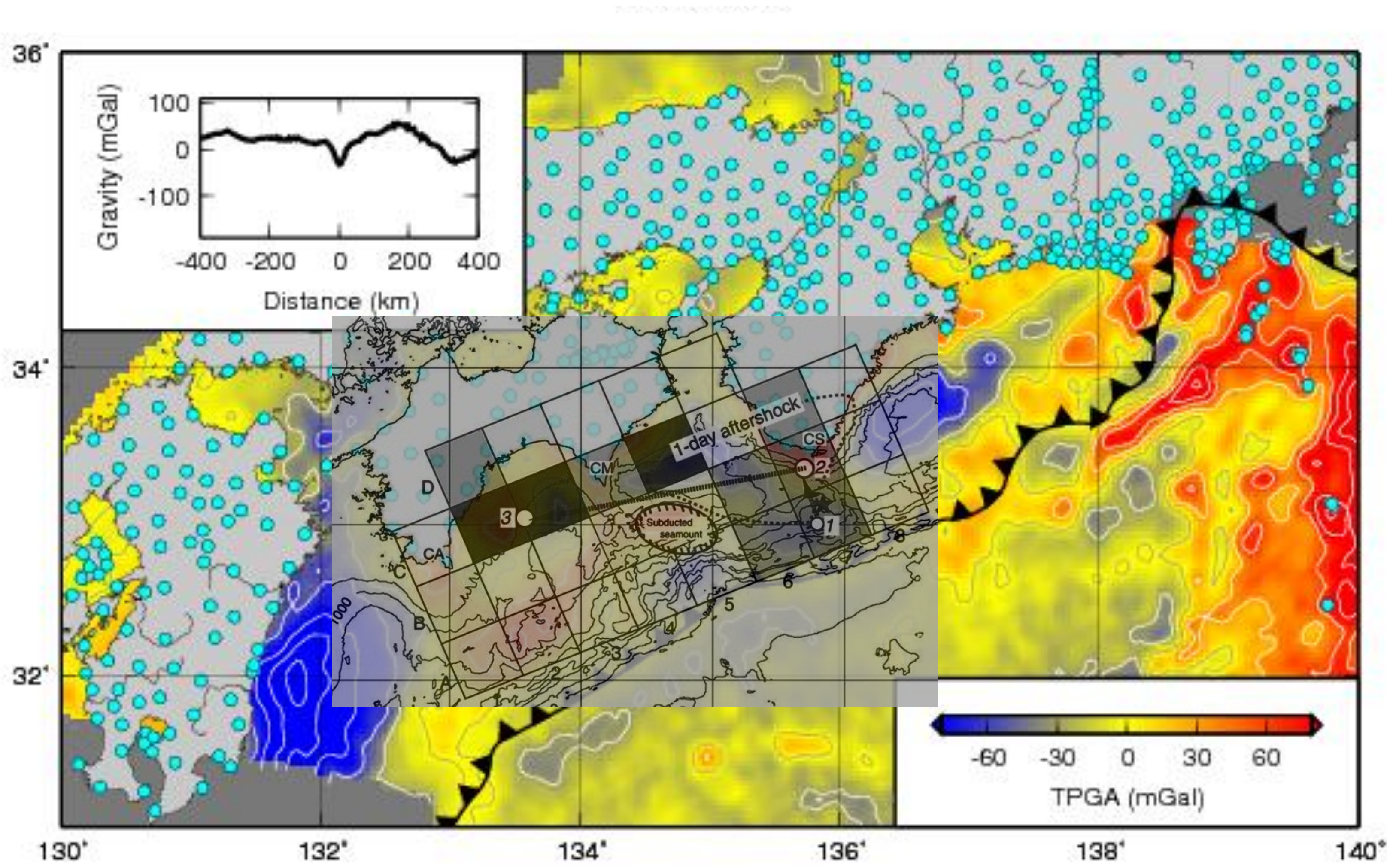
TPGA - Nankai

1946 Mw 8.4 Nankai, Japan

Note: Low res and smoothed

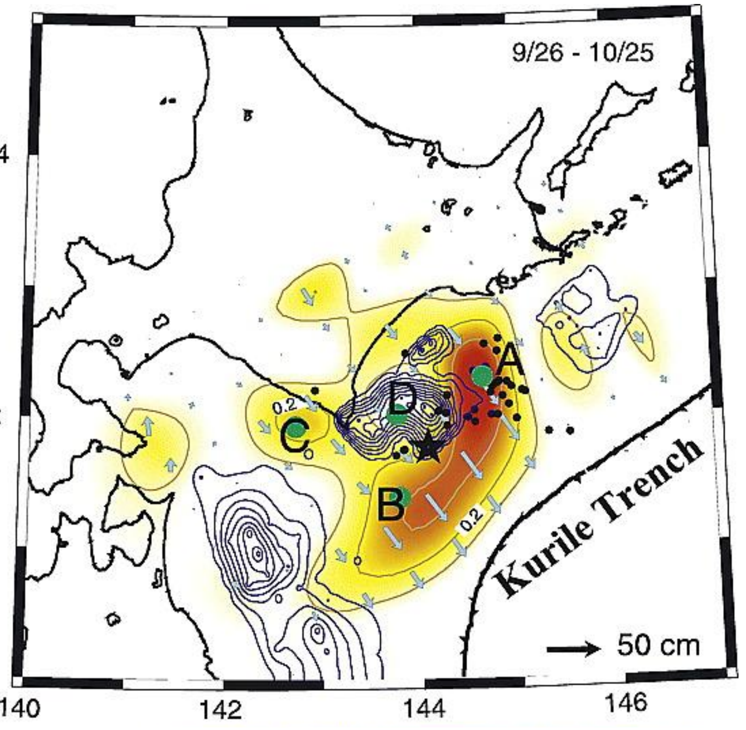


Kodaira et al., 2002



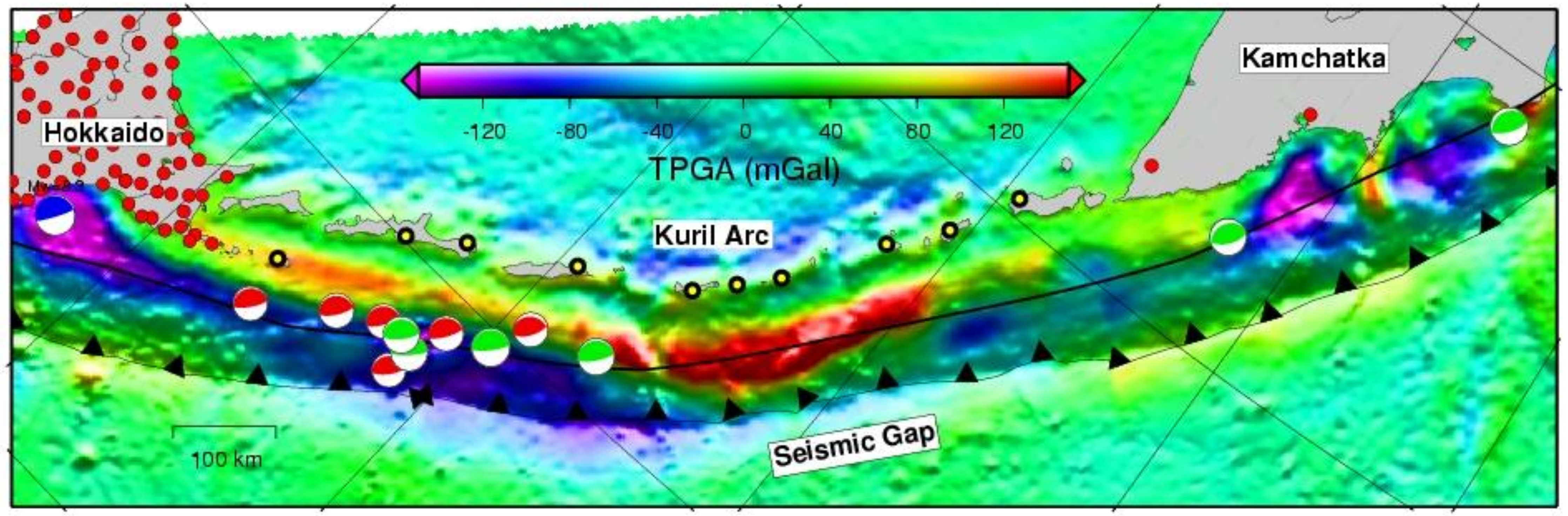
2003 M_w 8.3
Tokachi-Oki, Japan

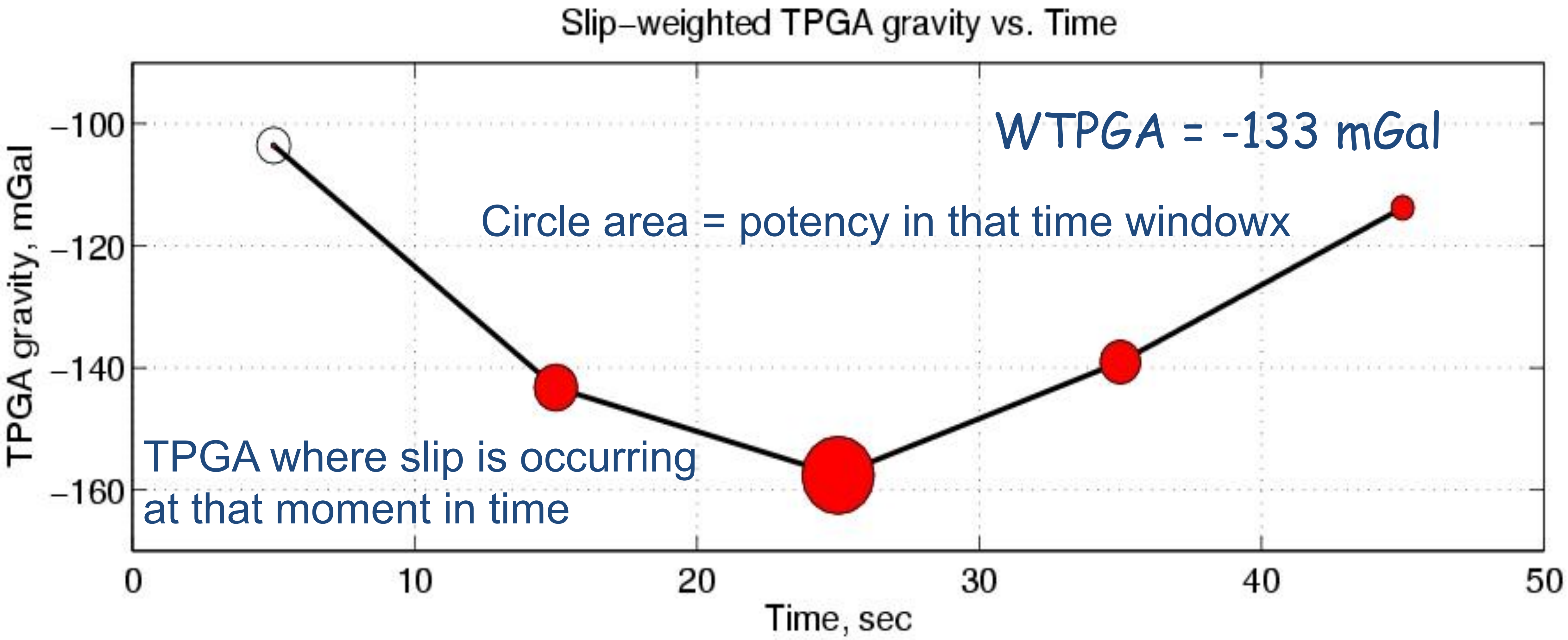
Coseismic(time) vs TPGA



Miyazaki et al, 2004

EQ in region of very low TPGA





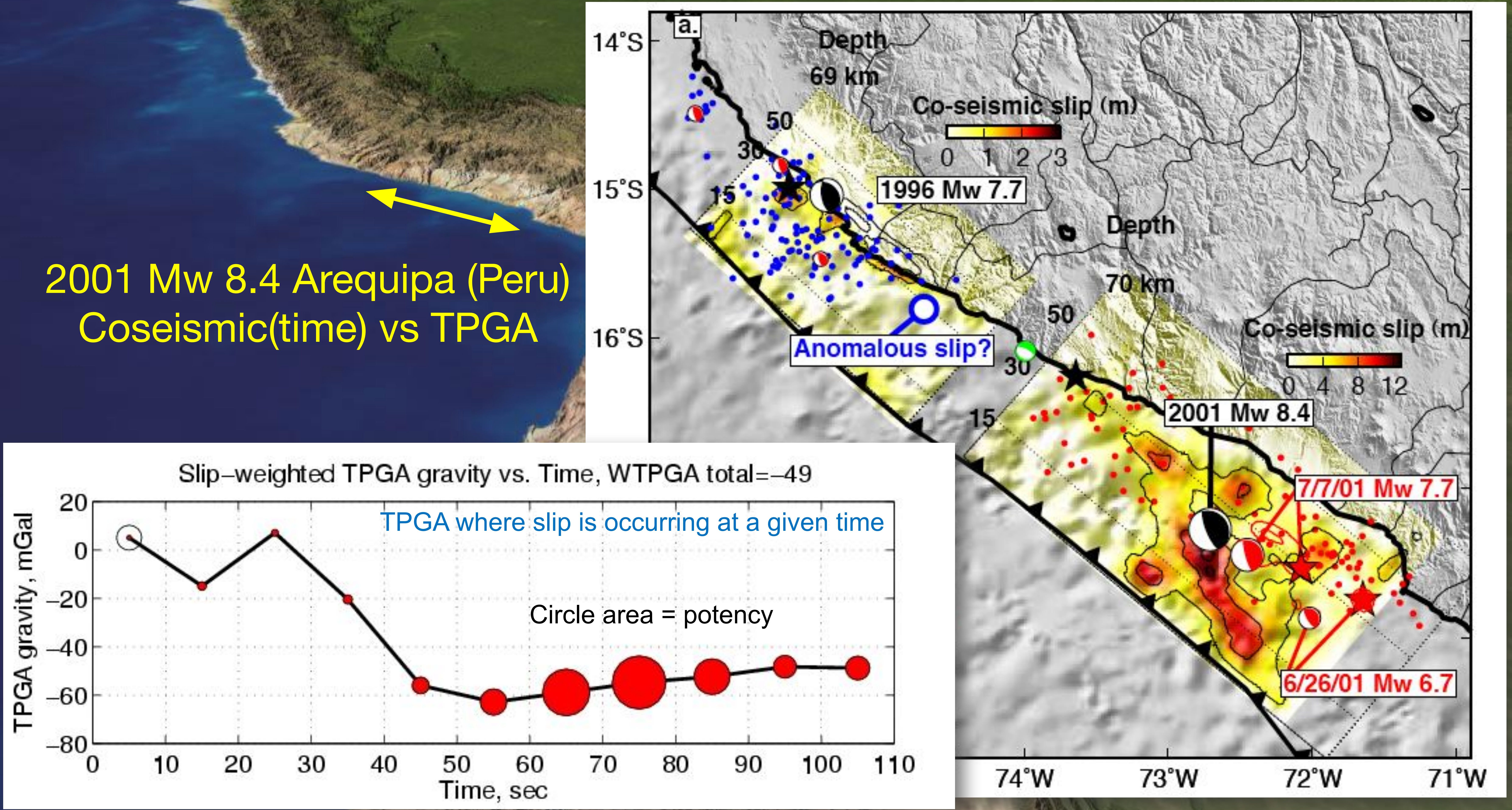
WTPGA = -133 mGal

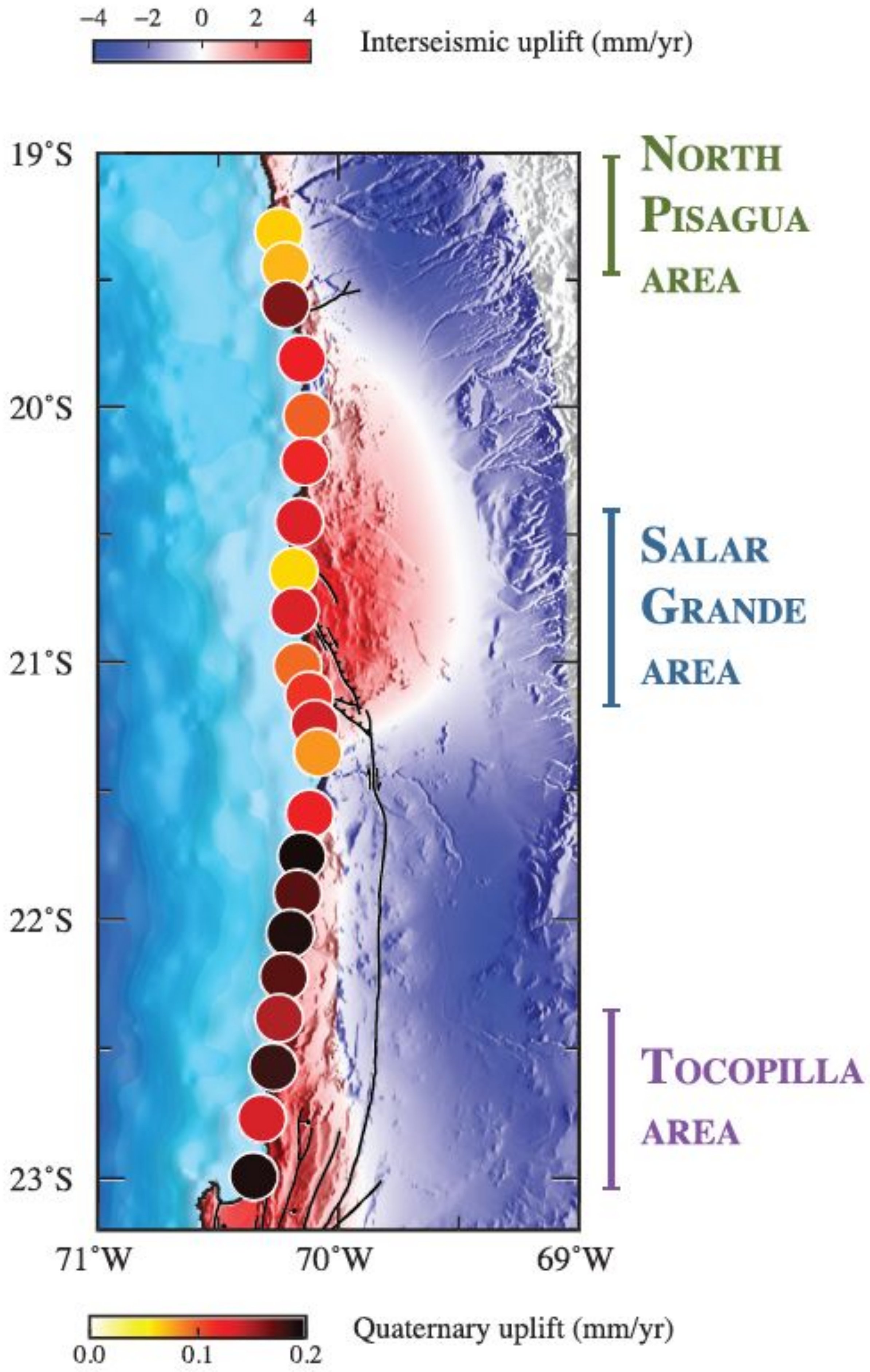
Circle area = potency in that time windowx

TPGA where slip is occurring
at that moment in time

EQ nucleates at relatively higher TPGA, most potency at lower TPGA

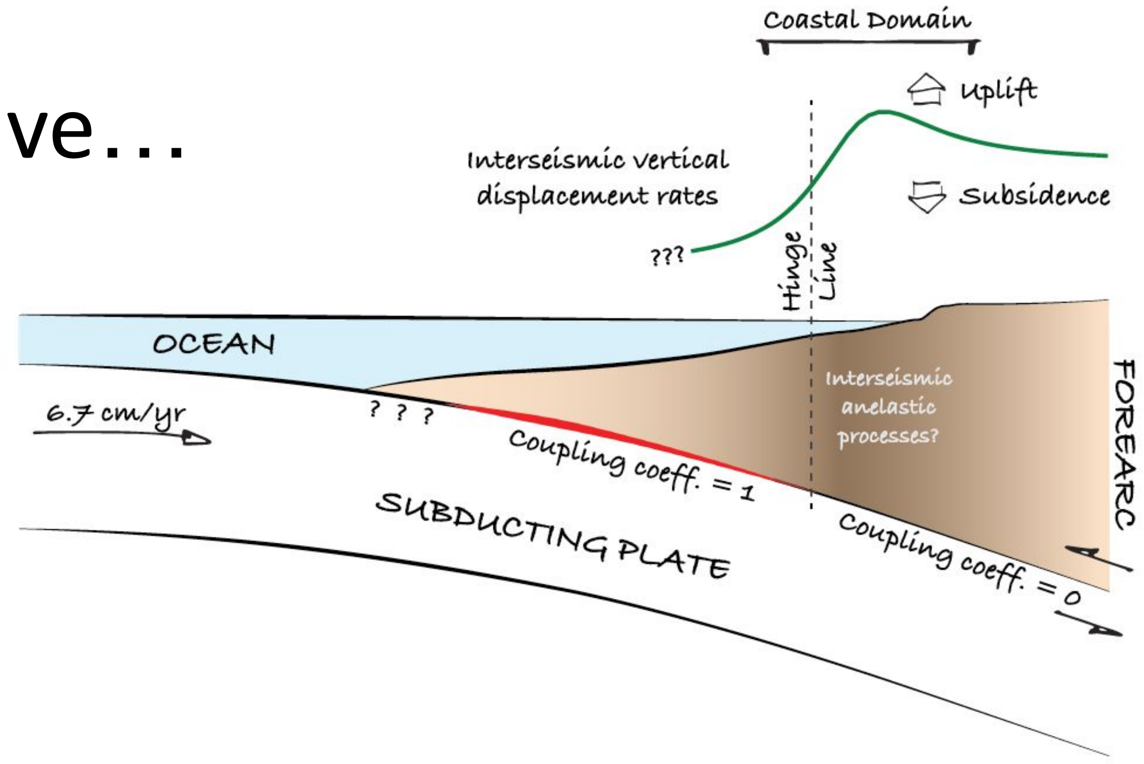
2001 Mw 8.4 Arequipa (Peru) Coseismic(time) vs TPGA





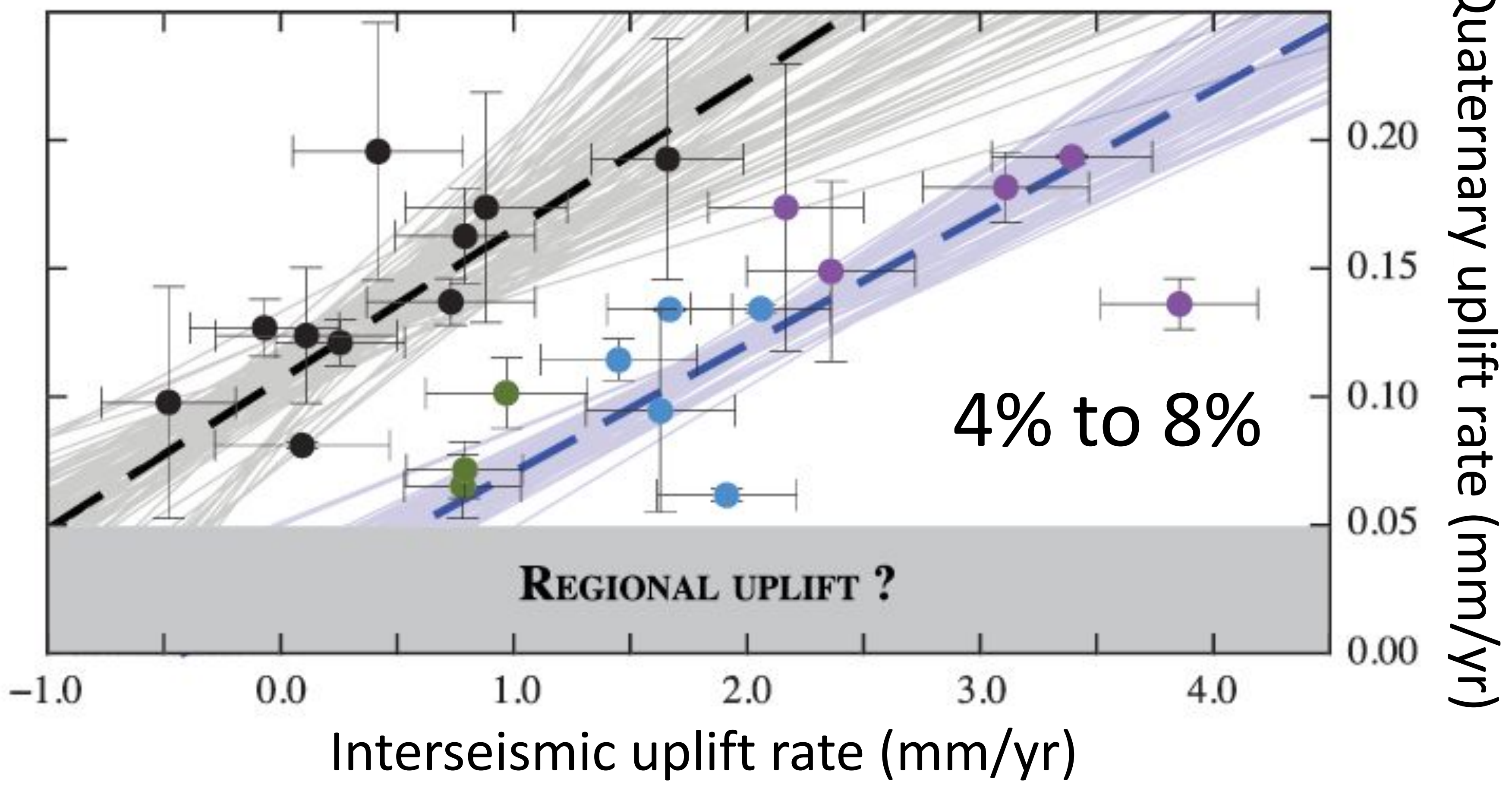
Suggestive…

.



Black: Quaternary faulting not identified

Blue: Quaternary active faulting has been identified



4% to 8%

Jolivet et al., 2020 – using data from *Melnick*, 2016 and *Allmendinger & González*, 2010)

Things that keep me up at night

2010 M_w 9.0 Tohoku-Oki (Japan)

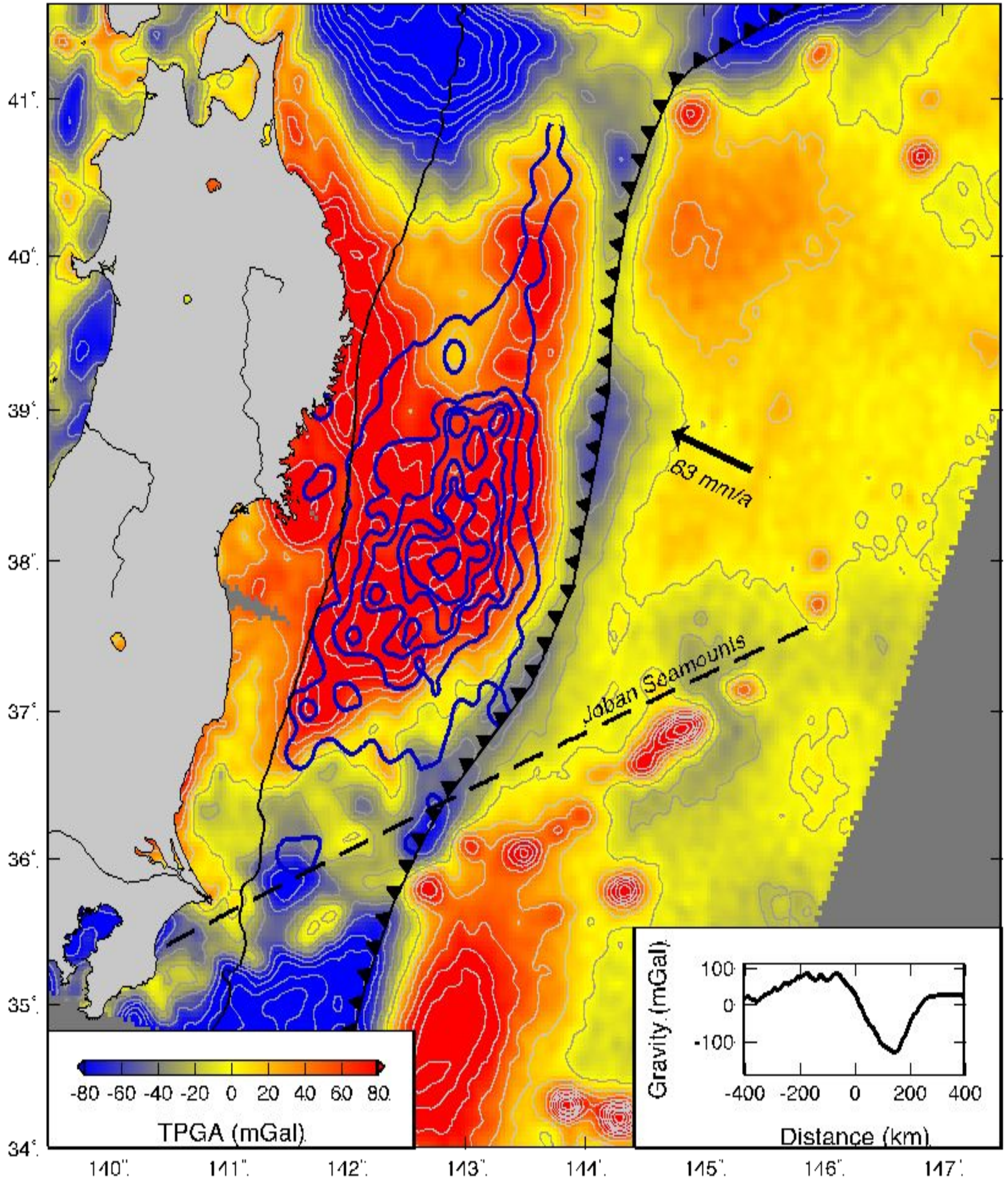
- Correlation w/ TPGA is amazing
- Wrong sign

Original Hypothesis:

All else being equal, variations in forearc gravity and topography serve as a proxy for long-lived variations in tractions on the plate boundary interface

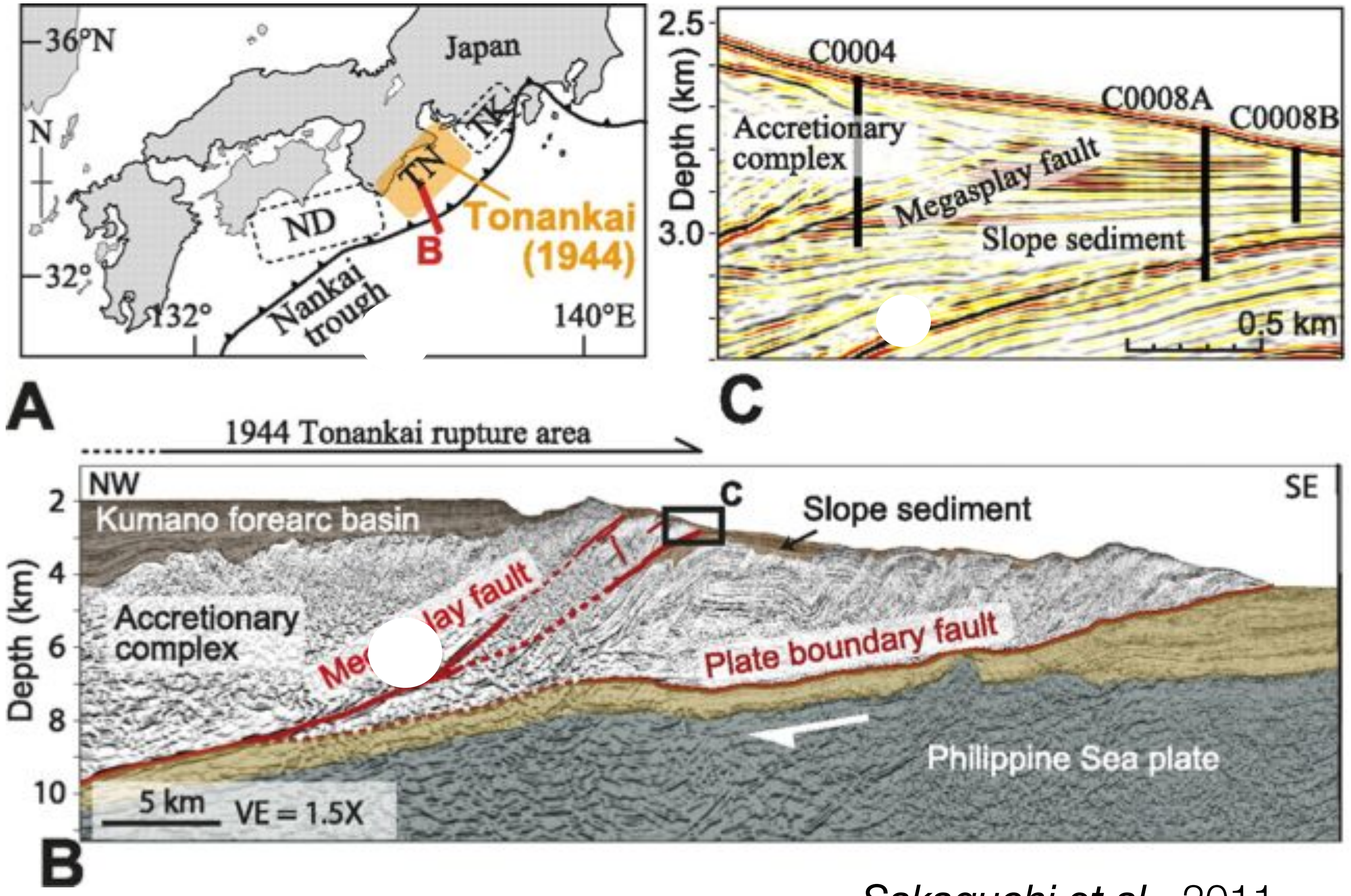
Options:

- Nature is more complicated (all else is not equal)
- Hypothesis is simply wrong



Implications of real structure

Structure of the Nankai SZ



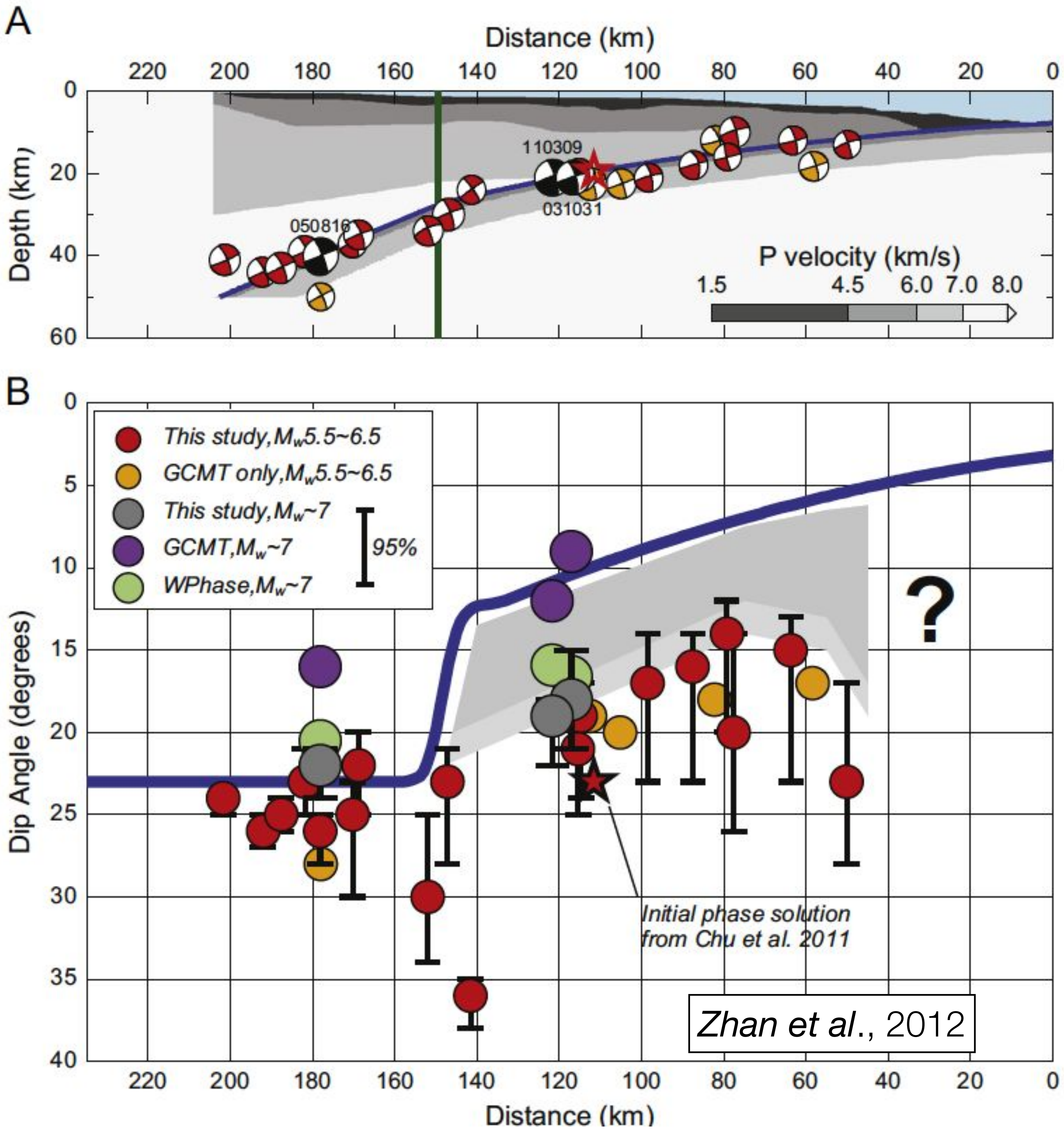
Sakaguchi et al., 2011

Structural and material heterogeneity

vs

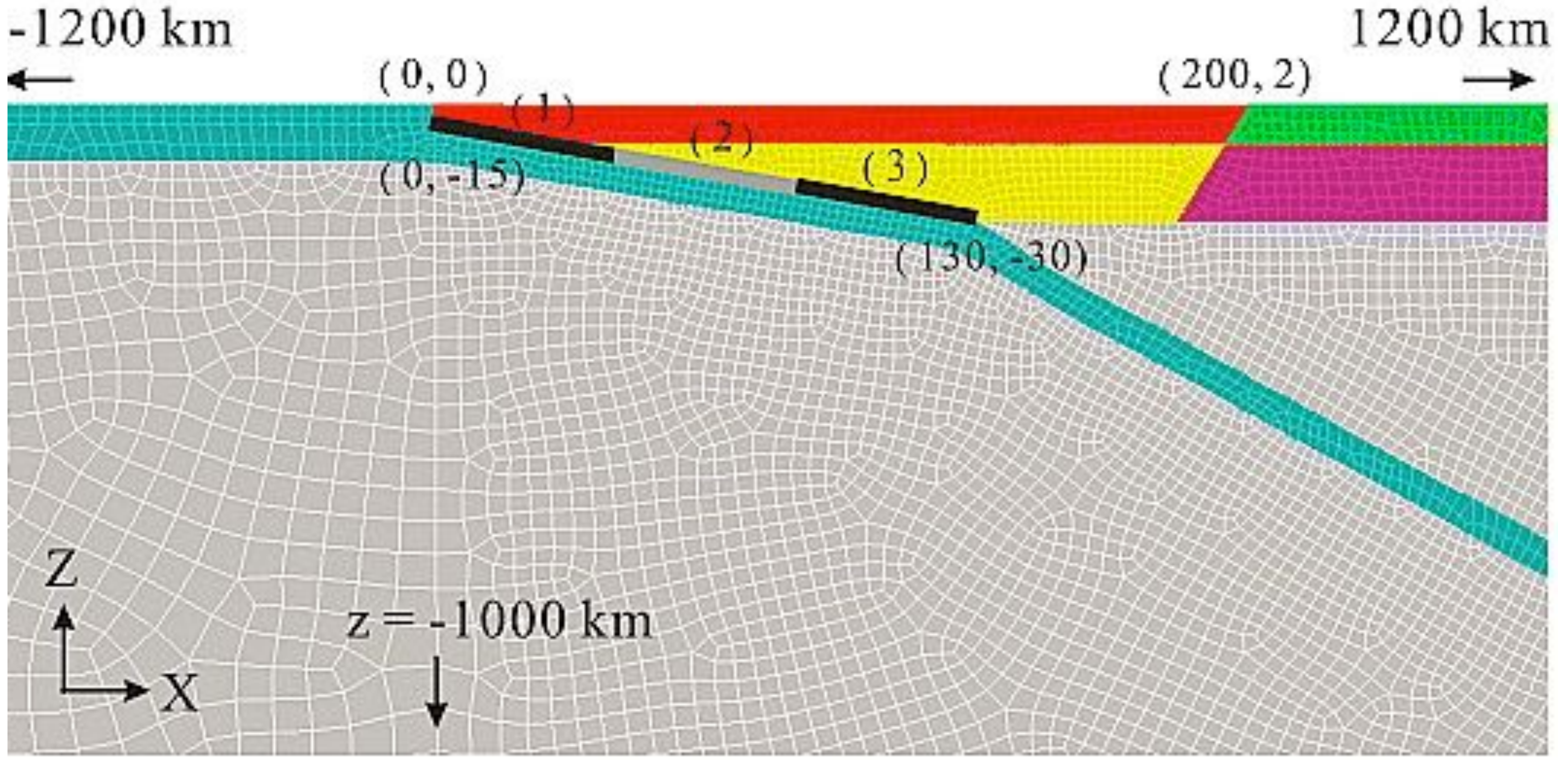
non-linear frictional laws

Complex Faulting on the N. Japan Megathrust



Zhan et al., 2012

Effects of heterogenous properties



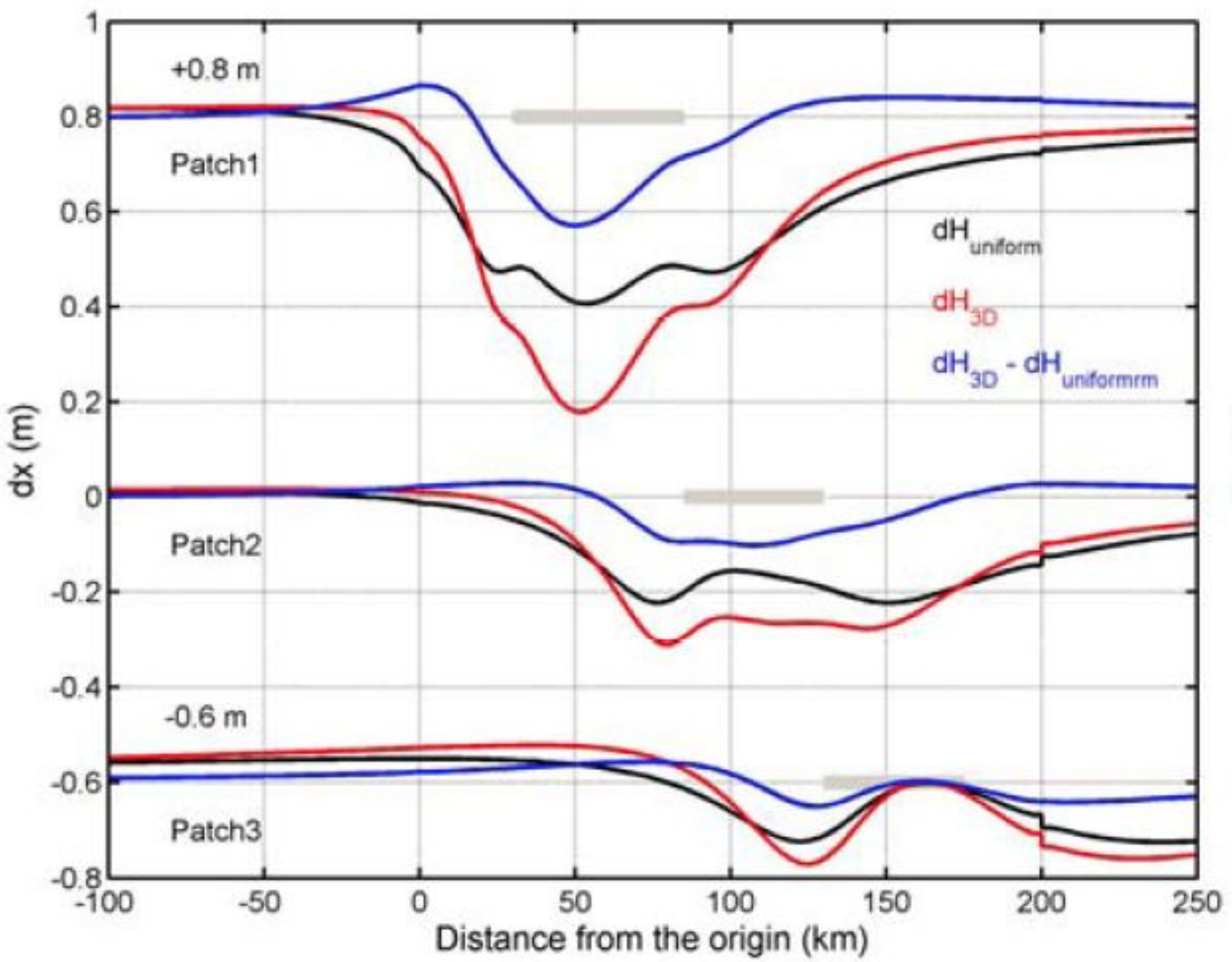
$$p(\mathbf{m}|\mathbf{d}_{\text{obs}}) \propto p(\mathbf{m}) \exp\left[-\frac{1}{2}(\mathbf{d}-\mathbf{Gm})^T \mathbf{C}_\chi^{-1} (\mathbf{d}-\mathbf{Gm})\right]$$

$$\mathbf{C}_\chi = \mathbf{C}_d + \mathbf{C}_p$$

Prediction error is **highly correlated** and depends on the **strength** and **spatial distribution** of the source! We **must** account for it when inferring slip.

Non ½-space prediction error vs. slip at different depths

Horizontals



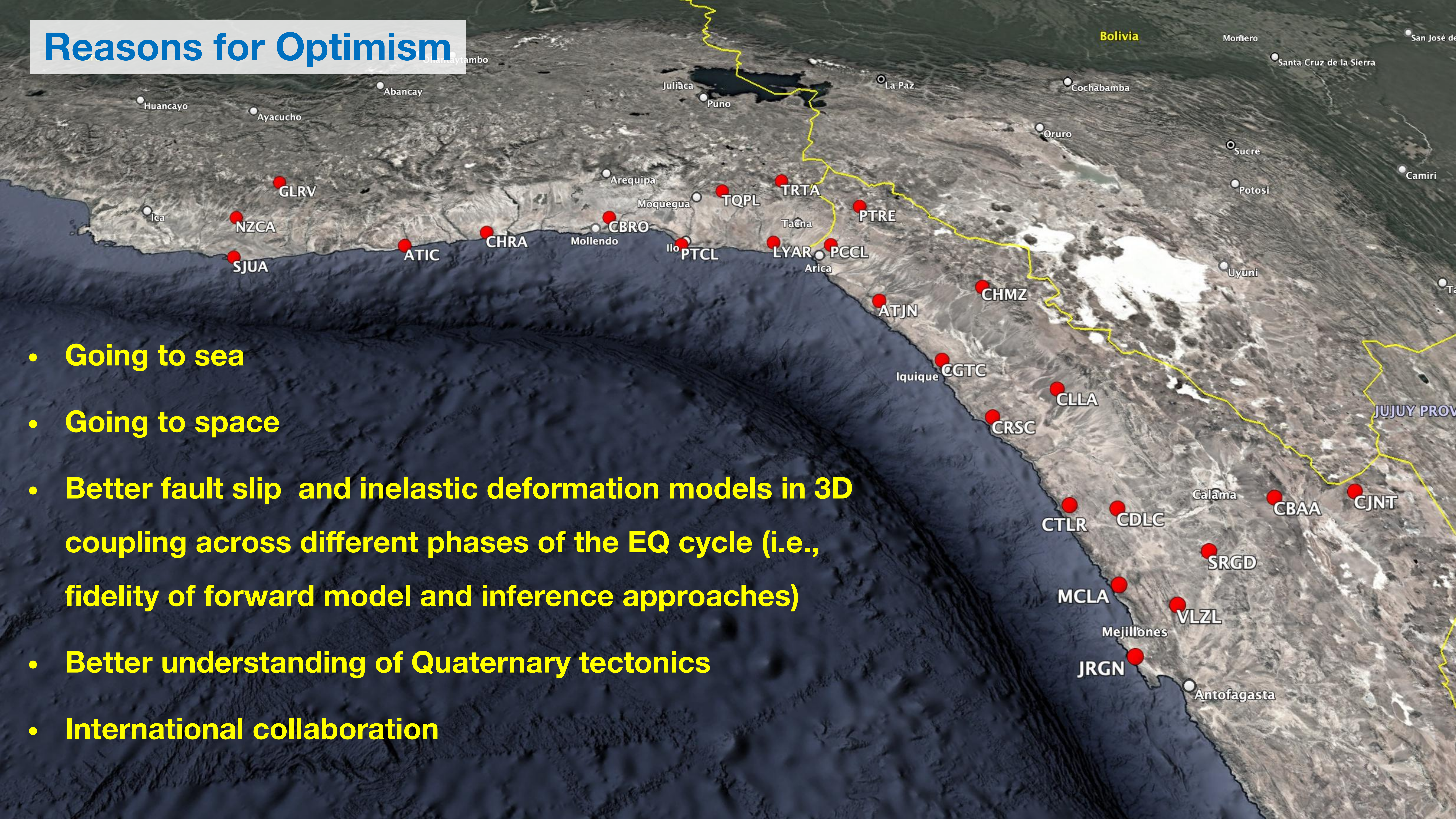
Hsu et al., 2011

Black = ½ space

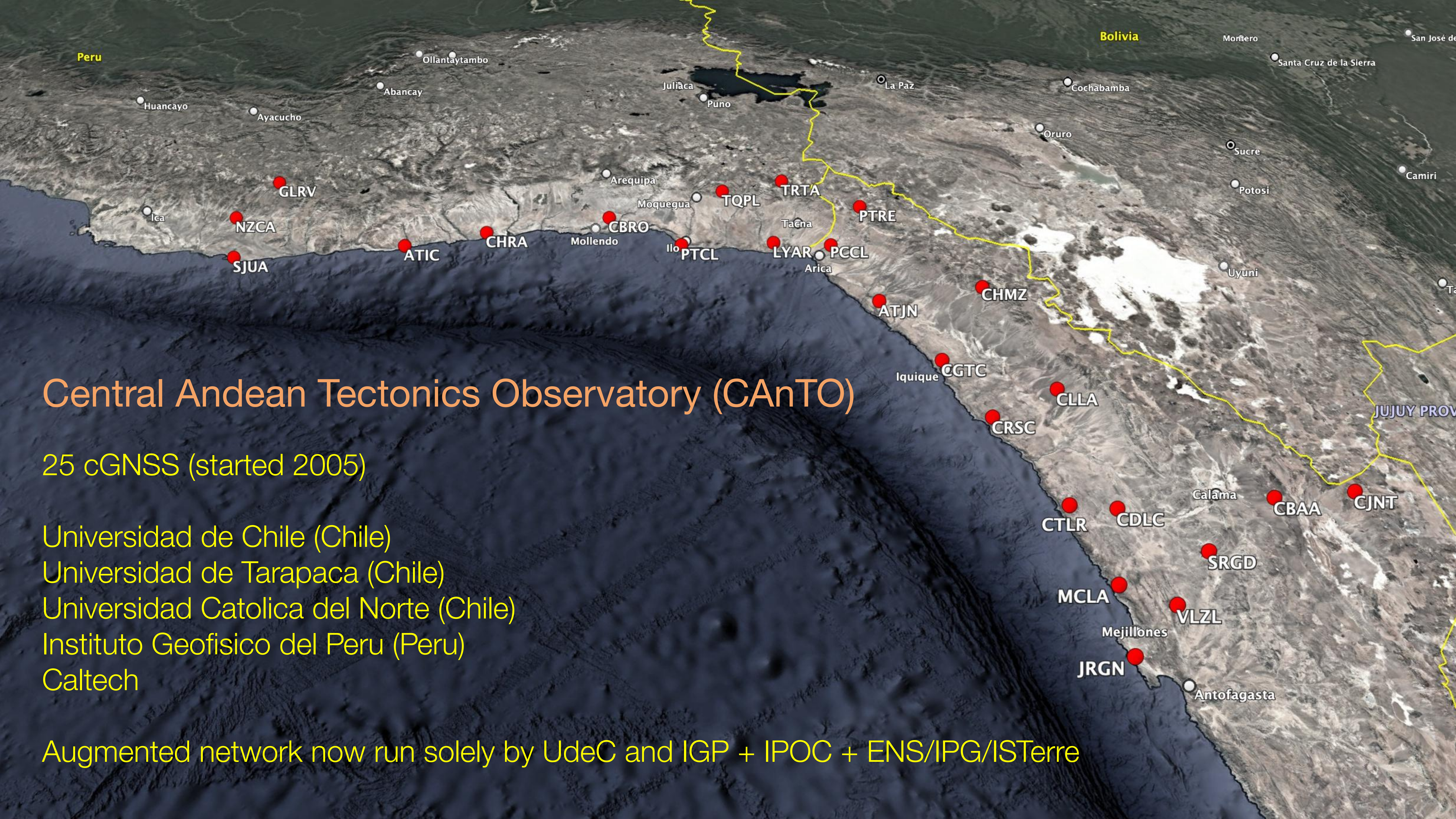
Red = not ½ space

Blue = difference (potential error)

Reasons for Optimism



- Going to sea
- Going to space
- Better fault slip and inelastic deformation models in 3D coupling across different phases of the EQ cycle (i.e., fidelity of forward model and inference approaches)
- Better understanding of Quaternary tectonics
- International collaboration

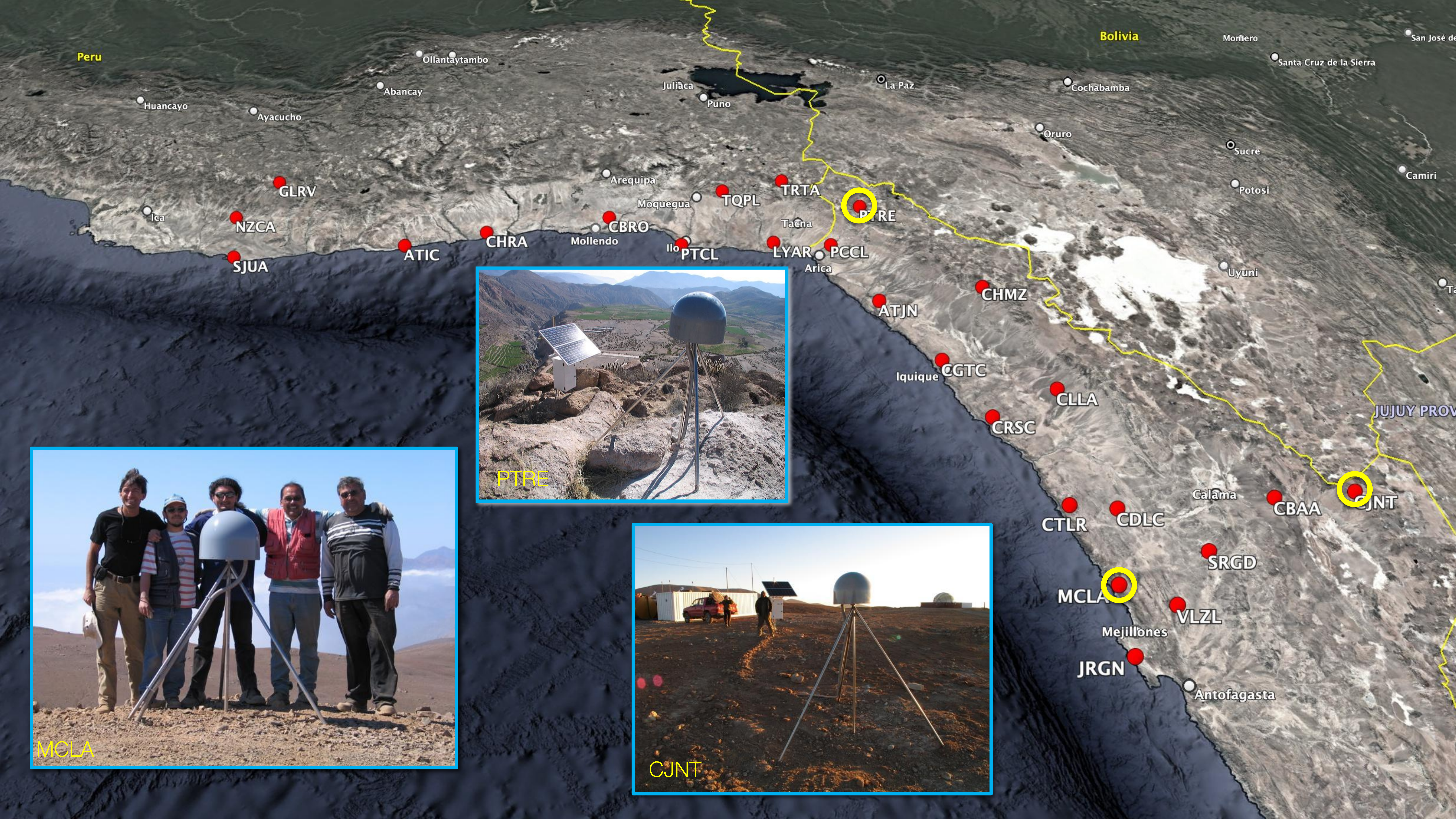


Central Andean Tectonics Observatory (CAnTO)

25 cGNSS (started 2005)

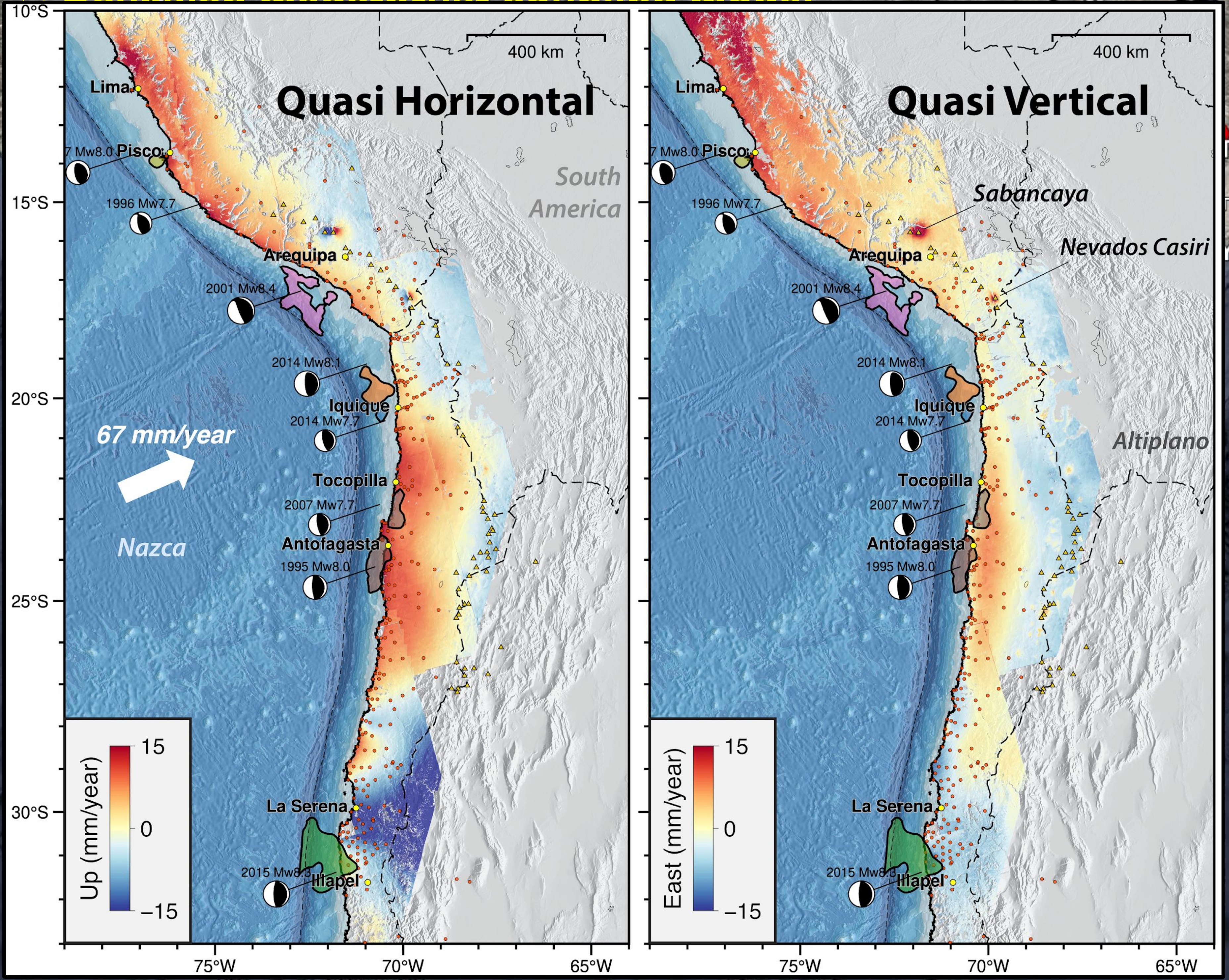
Universidad de Chile (Chile)
Universidad de Tarapaca (Chile)
Universidad Catolica del Norte (Chile)
Instituto Geofisico del Peru (Peru)
Caltech

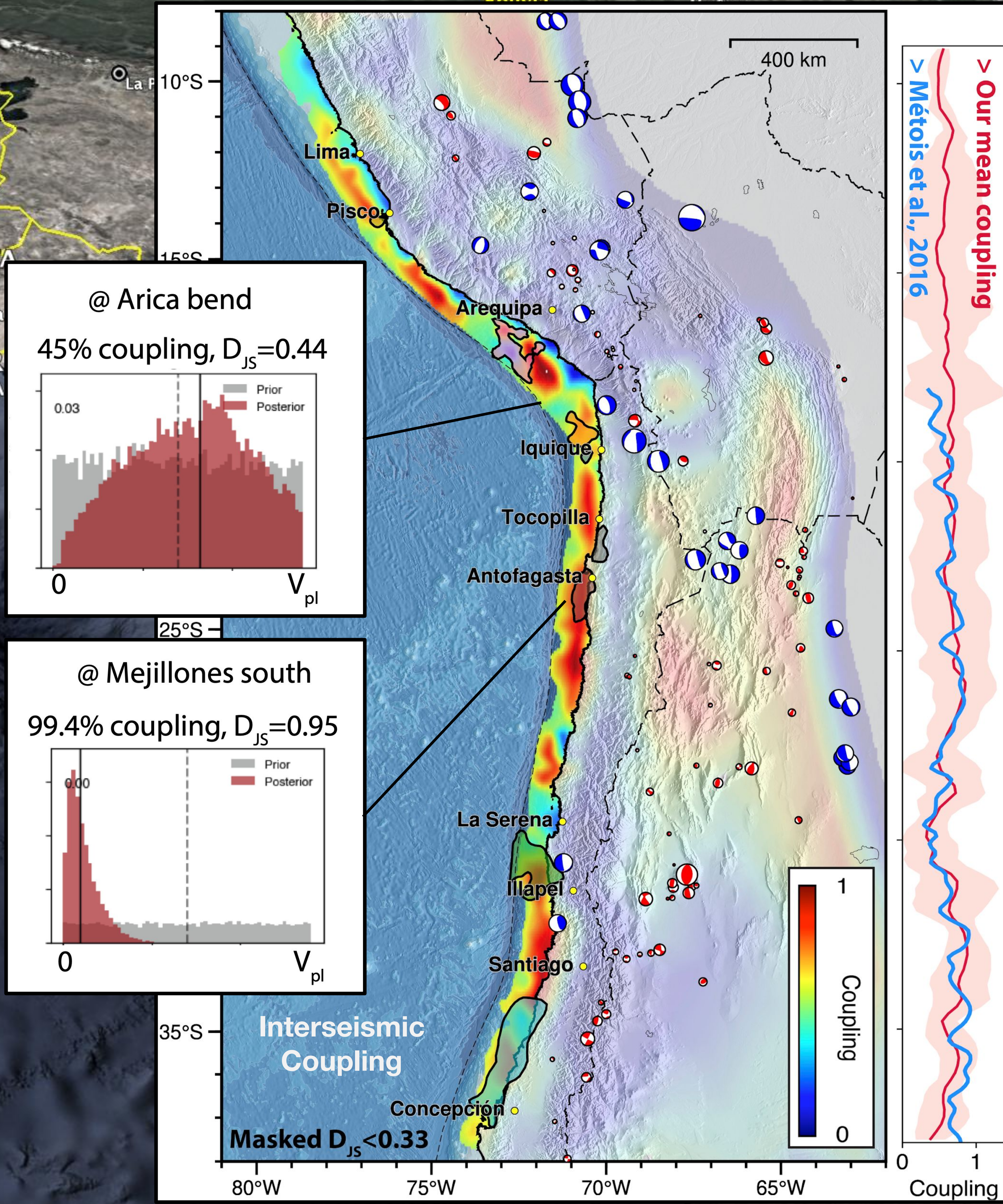
Augmented network now run solely by UdeC and IGP + IPOC + ENS/IPG/ISTerre


Peru
Bolivia
Ollantaytambo
Juliaca
Puno
La Paz
Montero
San José de
Santa Cruz de la Sierra
Cochabamba
Huancayo
Abancay
Ayacucho
Oruro
Sucre
Camiri
Potosi
Arequipa
Moquegua
GLRV
TQPL
TRTA
PTRE
Ica
NZCA
CBRO
Tacna
CHRA
Mollendo
Ilo
PTCL
LYAR
PCCL
Arica
ATIC
SJUA
Uyuni
CHMZ
ATJN
Iquique
CGTC
CLLA
CRSC
JUJUY PROV
Calama
CBAA
CJNT
CTLR
CDLC
SRGD
MCLA
VLZL
Mejillones
JRGN
Antofagasta
PTRE
MCLA
CJNT

S. Peru / N. Chile deformation: InSAR & GNSS

- Bayesian megathrust coupling model





InSAR: Sentinel-1 (A/B/C); 11 Tracks; 11 years (2014–2025)

Scale: 21,540 Interferograms + Published GNSS vectors

Yuan-Kai Liu – see poster

Go NISAR!

Launched
July 30, 2025

Global L-band (NASA) and regional S-band (ISRO)

High coherence and tracks large deformation

Designed to allow removal of ionospheric effects

"Clean" measurements

Left-looking satellite

Complements international constellation □ [E, N, U]

Consistent 12-day acquisitions (ASC+DSC)

Data will be free, open and easily accessible

The era of time series

Identify, isolate and model complex processes

Wide area mapping

Synoptic high-resolution observations

Thank you