Interseismic loading and megathrust rupture potential in North Chile - South Peru

Anne Socquet
Juan Carlos Villegas
Mohamed Chlieh

IGP
UGA Université Grenoble Alpes
IRD Institut de Recherche pour le Développement FRANCE
ISTerre Institut des Sciences de la Terre

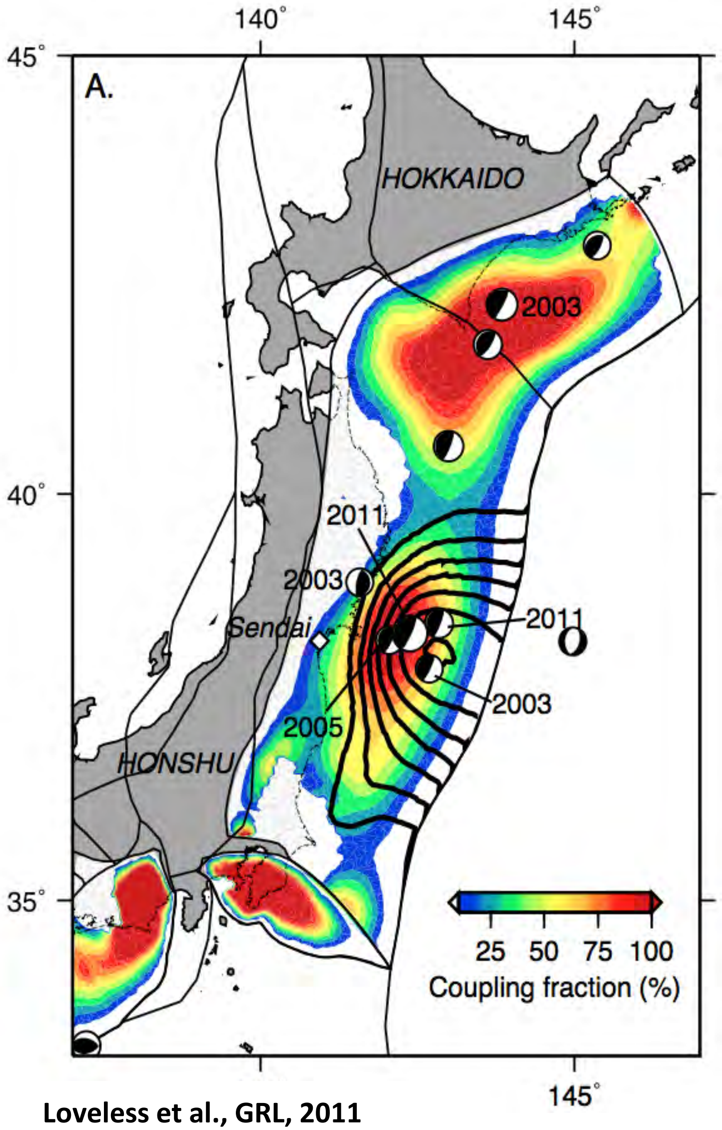
Tsunami in Arica, 1877

unesco

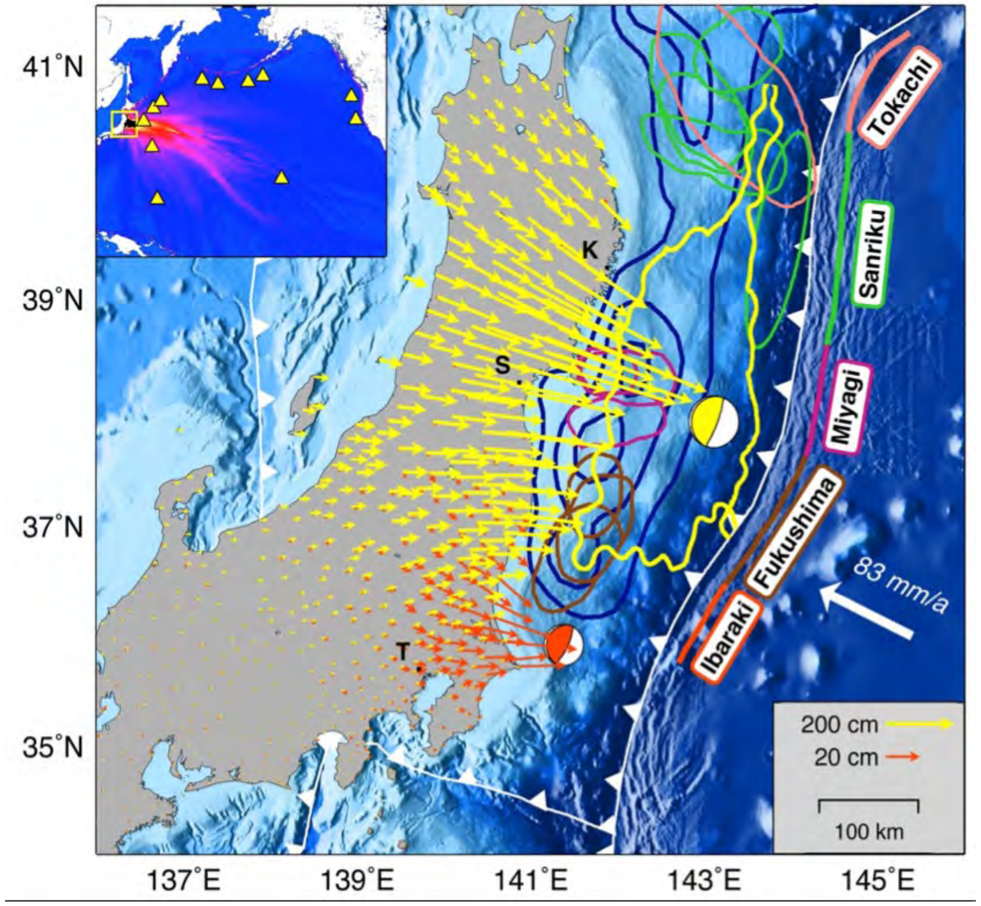
Meeting of Experts on tsunami sources and hazard in southern Peru and northern Chile
22-25 August 2023 -Arica, Chile

Last megathrust earthquakes ruptured fault sections that were interseismically locked

JAPAN 2011



Loveless et al., GRL, 2011



Simons et al.,Science, 2011

Last megathrust earthquakes ruptured fault sections that were interseismically locked

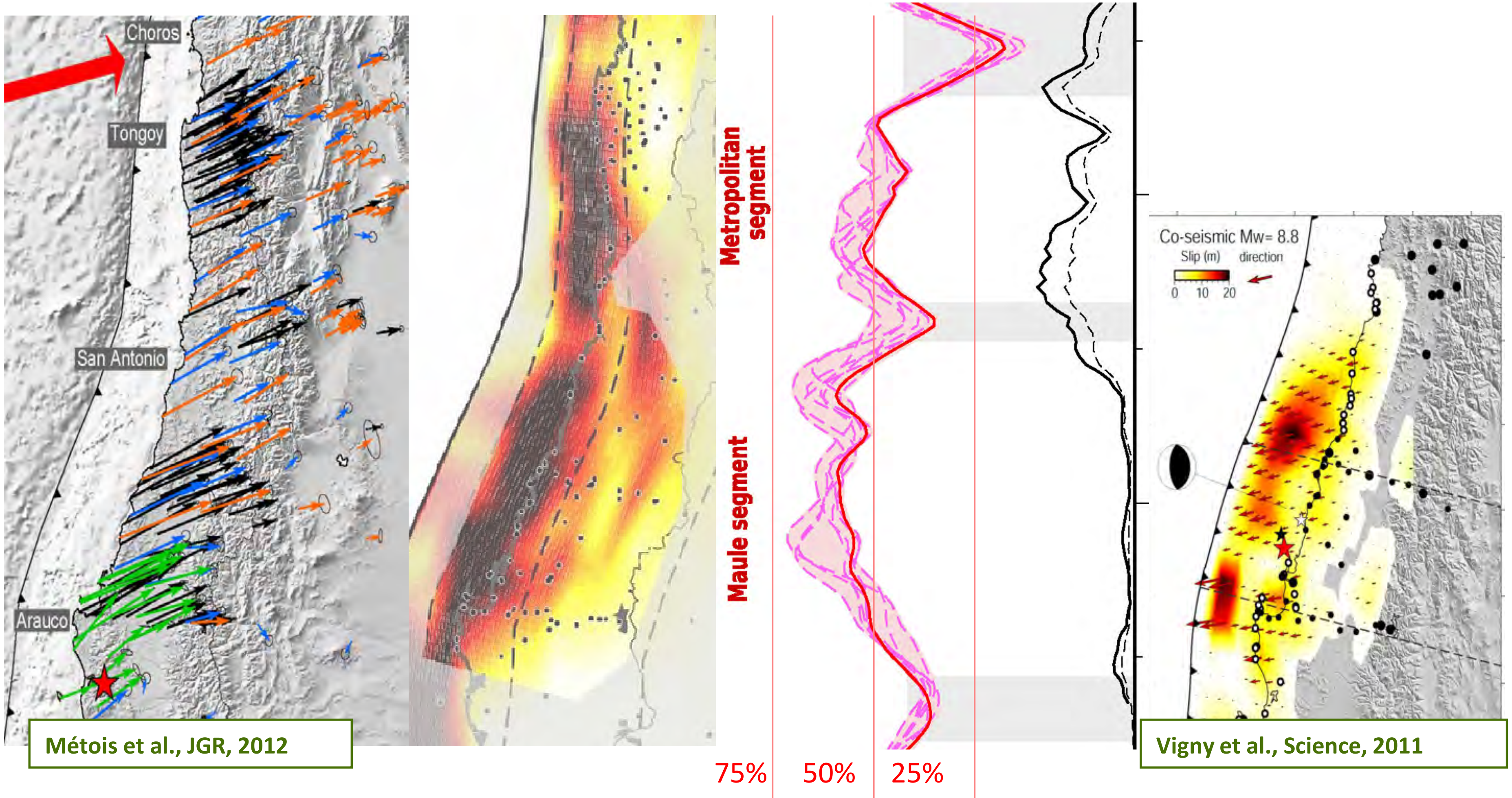
CHILE 2010

GPS data

Coupling distribution

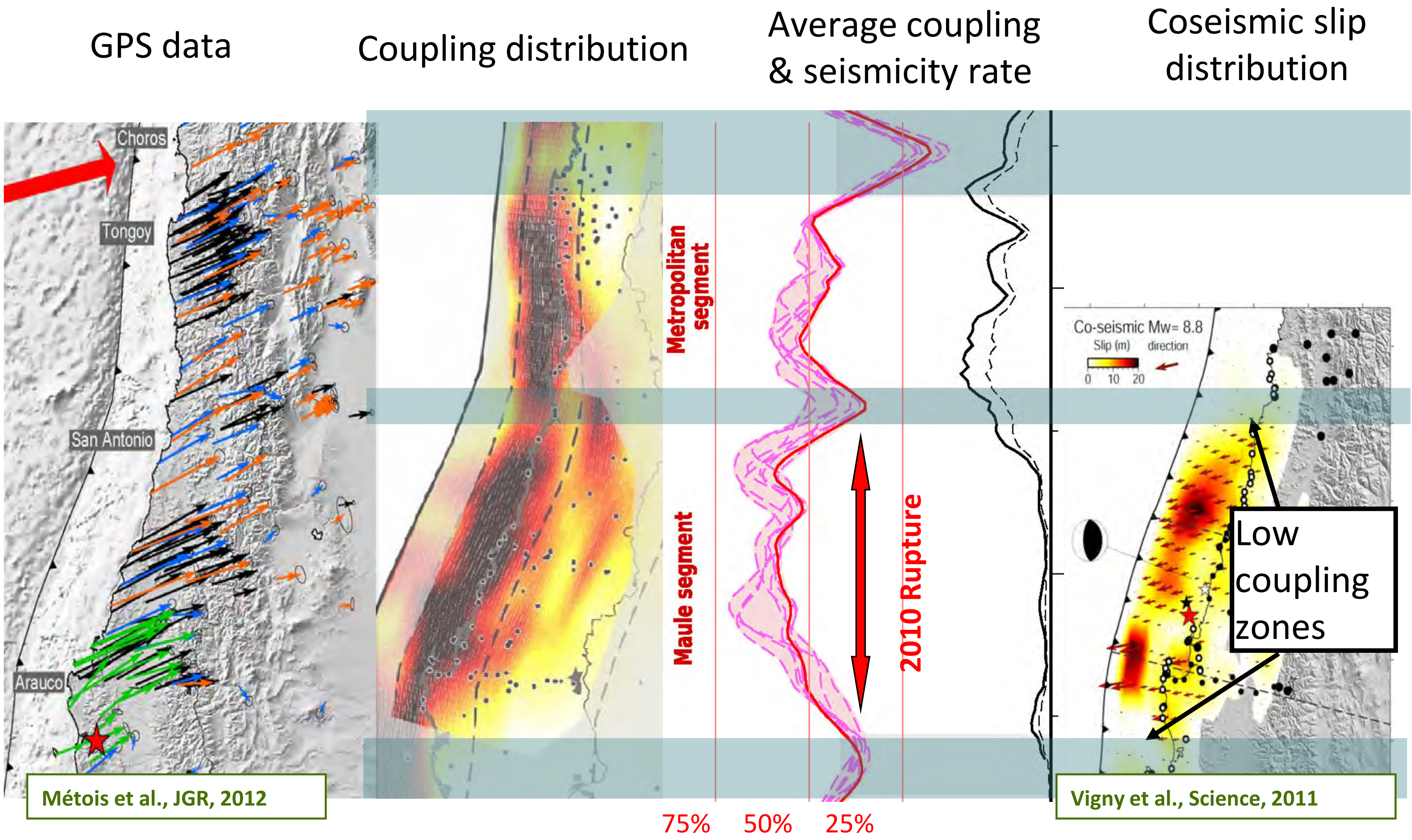
Average coupling & seismicity rate

Coseismic slip distribution



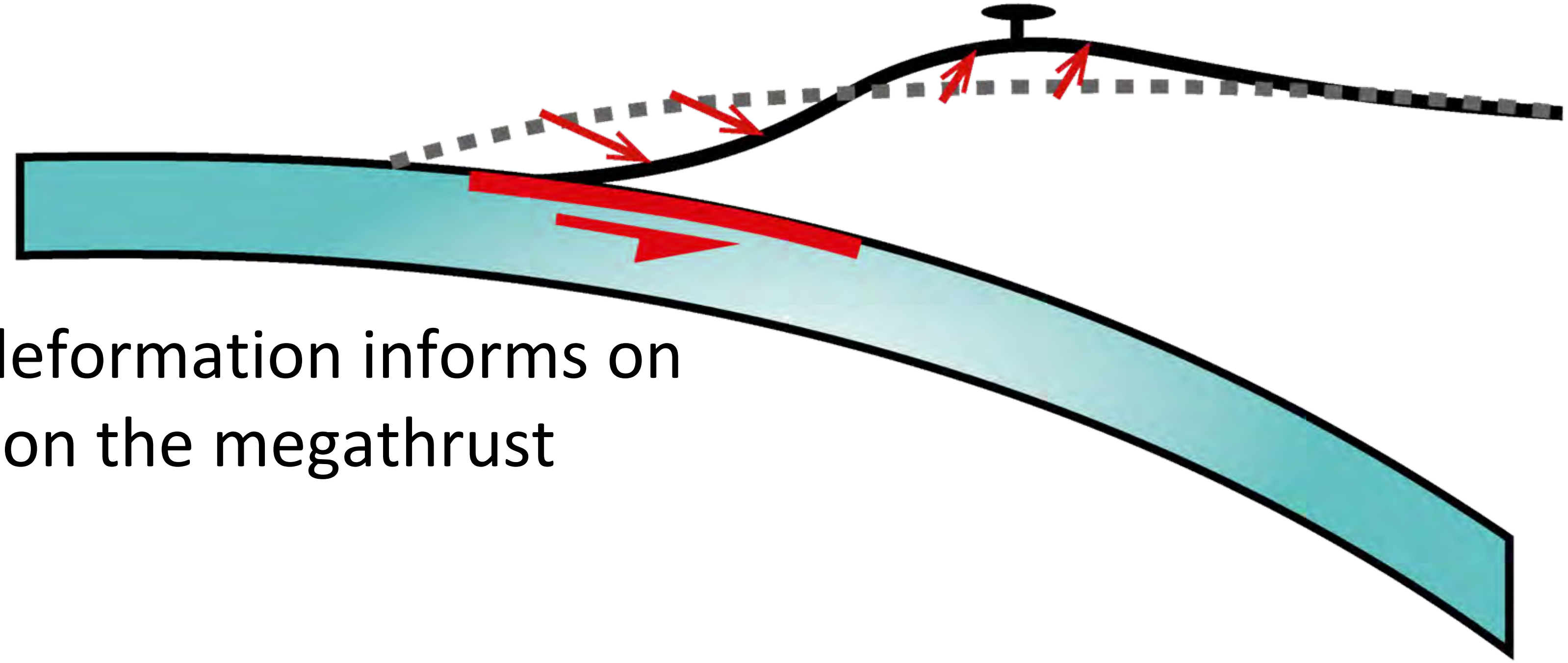
Last megathrust earthquakes ruptured fault sections that were interseismically locked

CHILE 2010



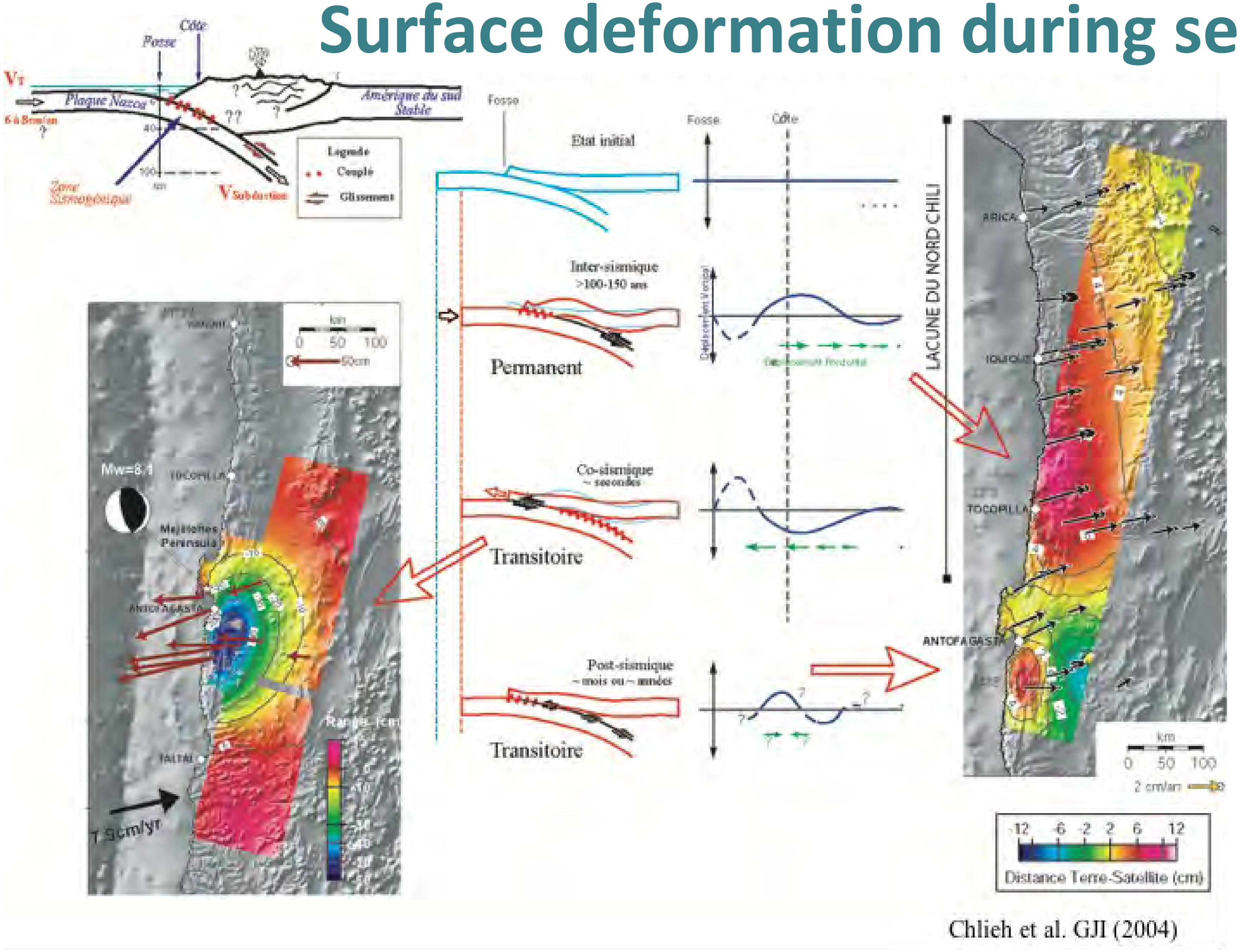
→ Mapping interseismic coupling from surface deformation can inform on seismic potential

Space geodesy measures surface deformation



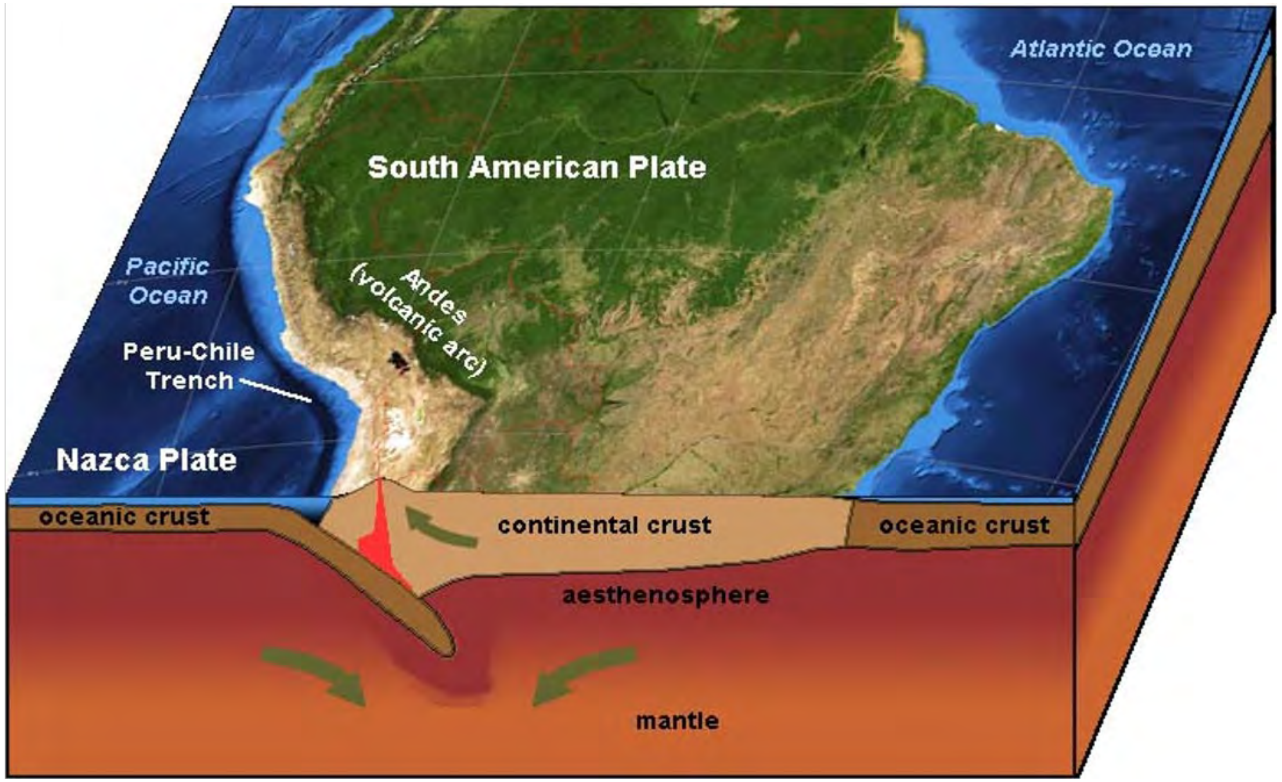
Surface deformation informs on coupling on the megathrust

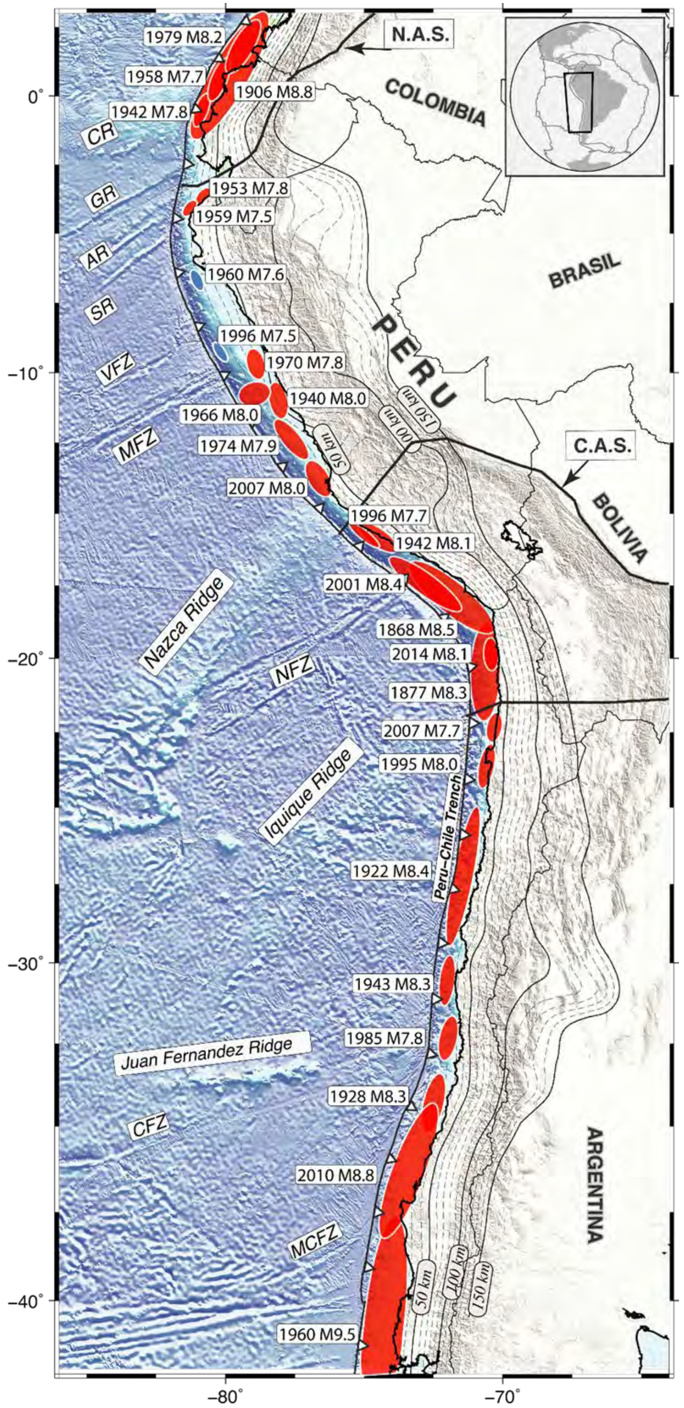
Surface deformation during seismic cycle



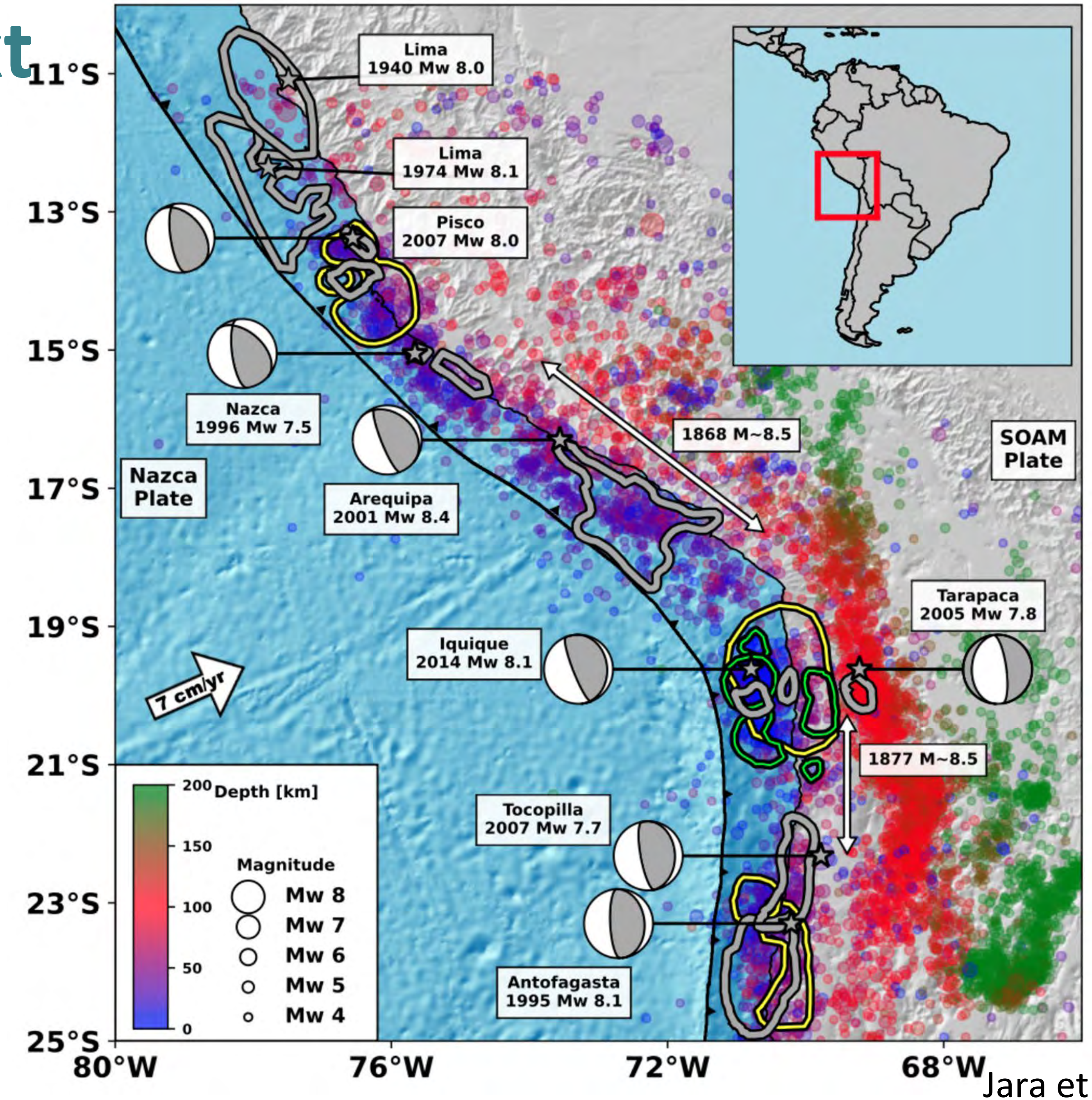
Chlieh et al. GJI (2004)

Seismotectonic context





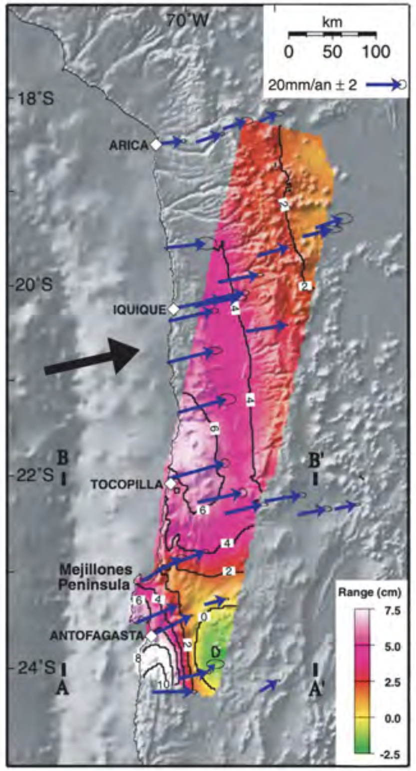
Seismotectonic context



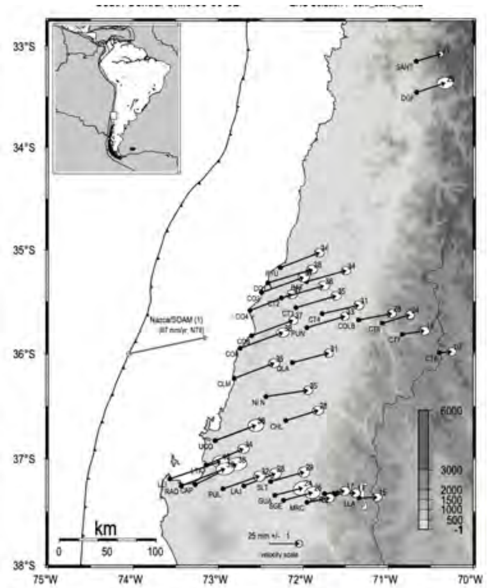
Jara et al. subm

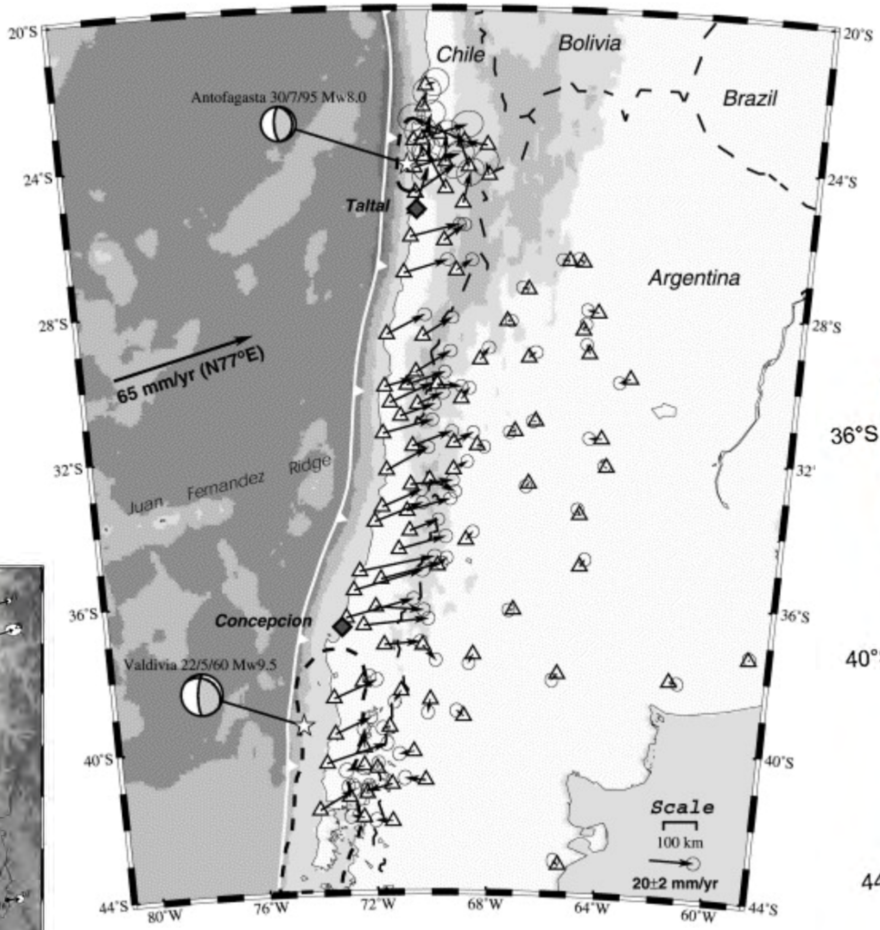
Estimating active deformation in the Andes

A long term international effort that started in the 90s
(groups from Chile, USA, Germany, France, Peru)



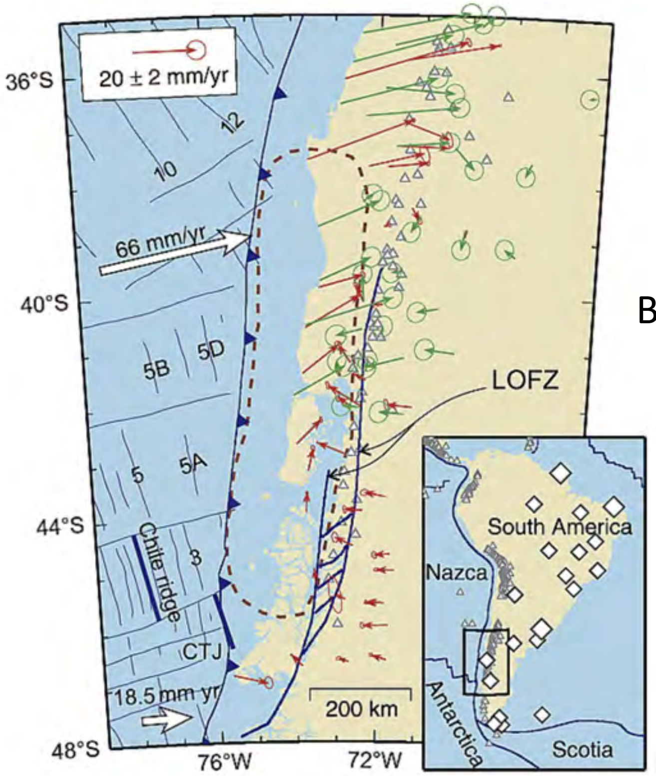
Chlieh et al. 2004

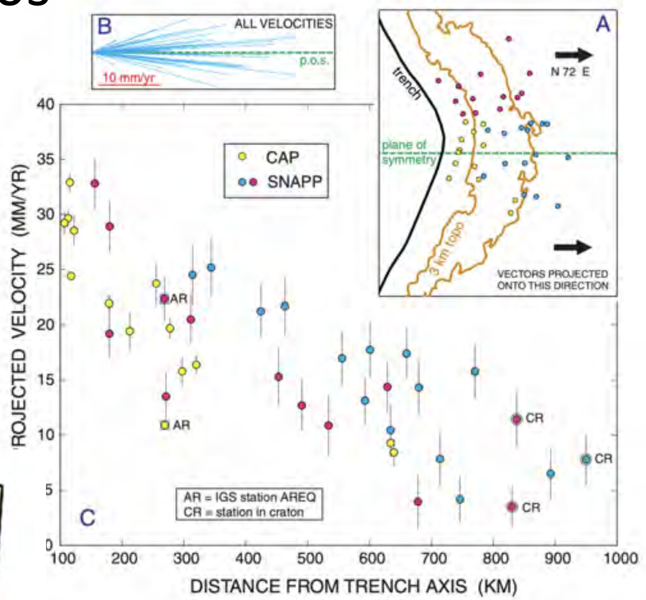




Ruegg et al. 2008
Ruegg, Campos et al. 1996, 2002,

Klotz et al., 2001
Khazaradze, Klotz, Angermann et al. 1999, 2001, 2002, 2003,…

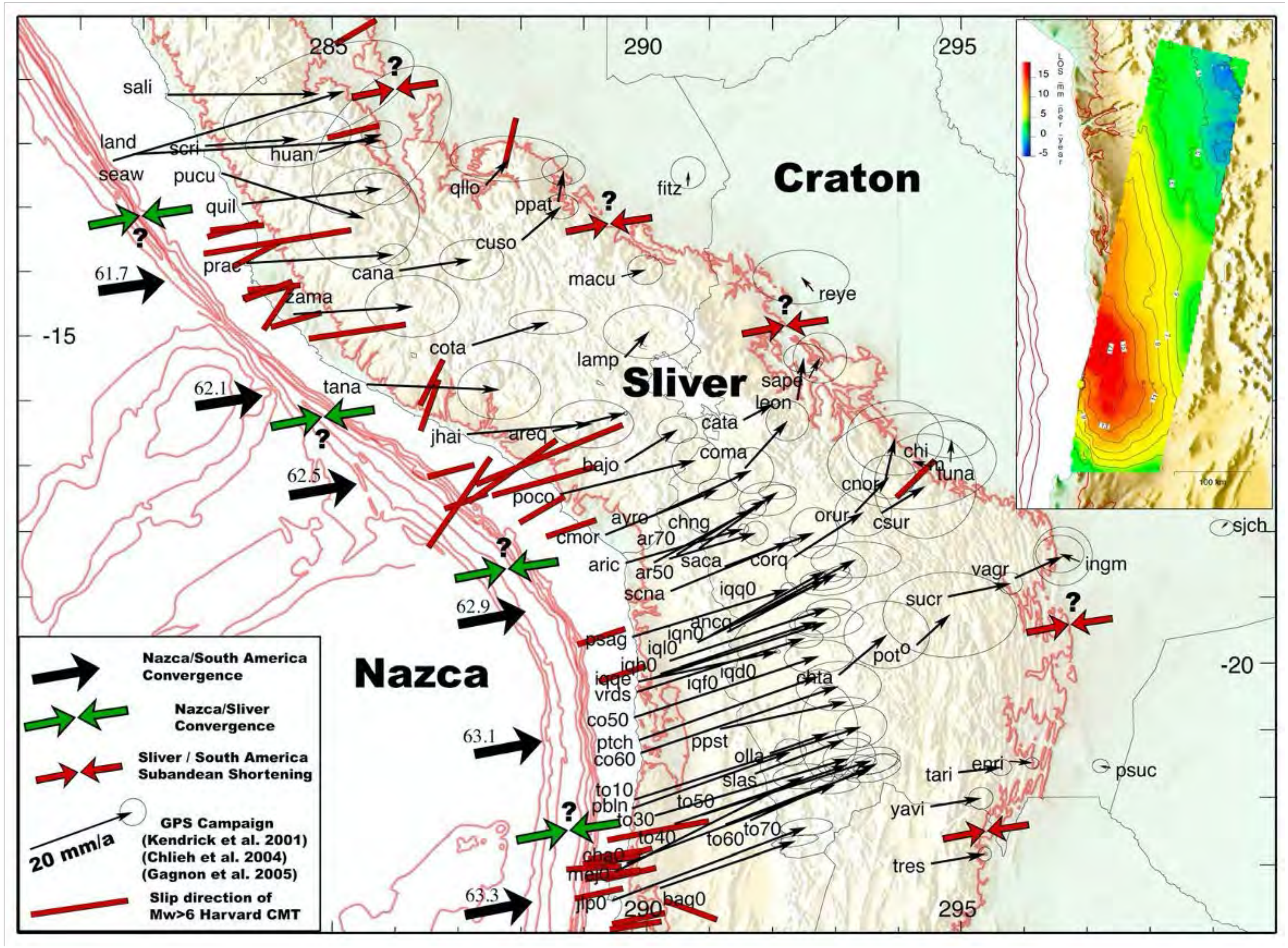




Norabuena et al., 1998
Bevis et al., 1999
Kendrick, Bevis et al. 2001
Brooks, Bevis, Smalley, Kendrick et al. 2000, 2001, 2003, …2011,

Wang et al., 2007

Combined velocity field in the Central Andes



GPS velocity field for central Andes (1994 - 2004)

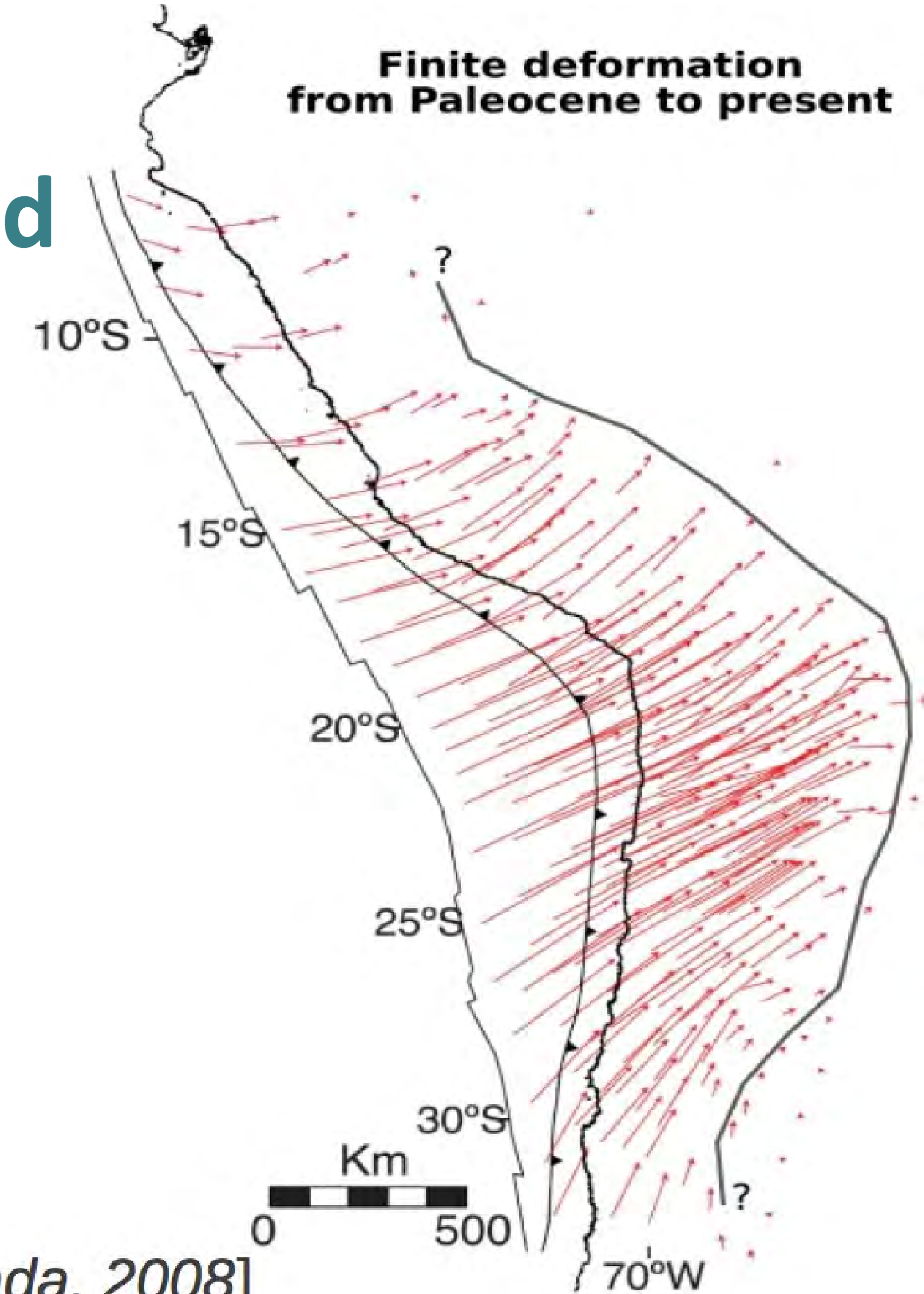
Chlieh et al. 2011

Chlieh et al., (1998)
Norabuena et al., (1998)
Bevis et al., (1999)
Kendrick, Bevis et al., (2001)
Brooks, Bevis, Smalley, Kendrick et al., (2000, 2001, 2003, 2011)

Internal deformation of the Andes
Rotations on both sides of Arica bend

Clockwise rotation S. of Arica bend
Anticlockwise rotation N. of Arica bend

Internal deformation in the Andes must be taken into account for a proper modelling of interseismic loading



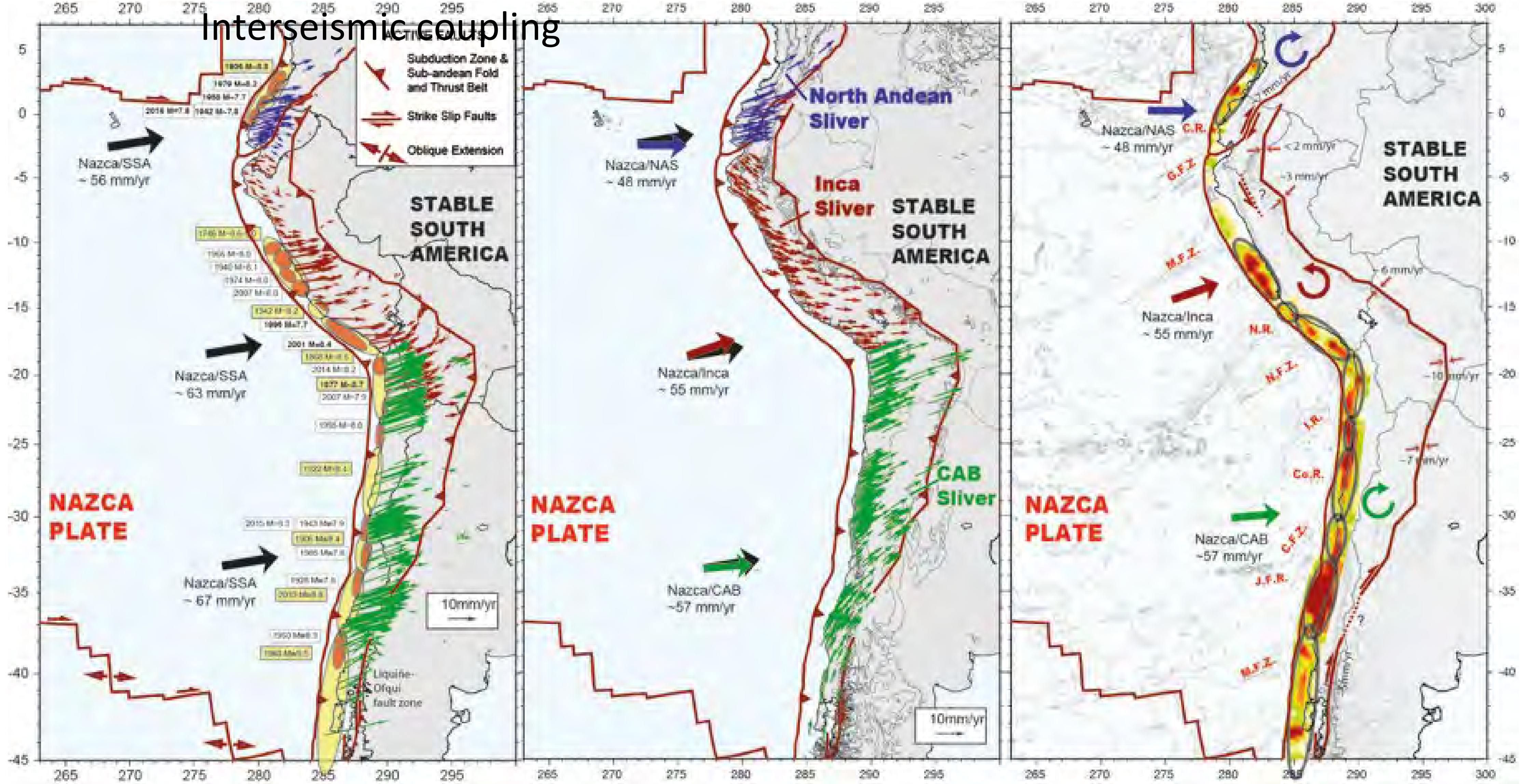
[Arriagada, 2008]

Sliver motion in South America

Velocity field

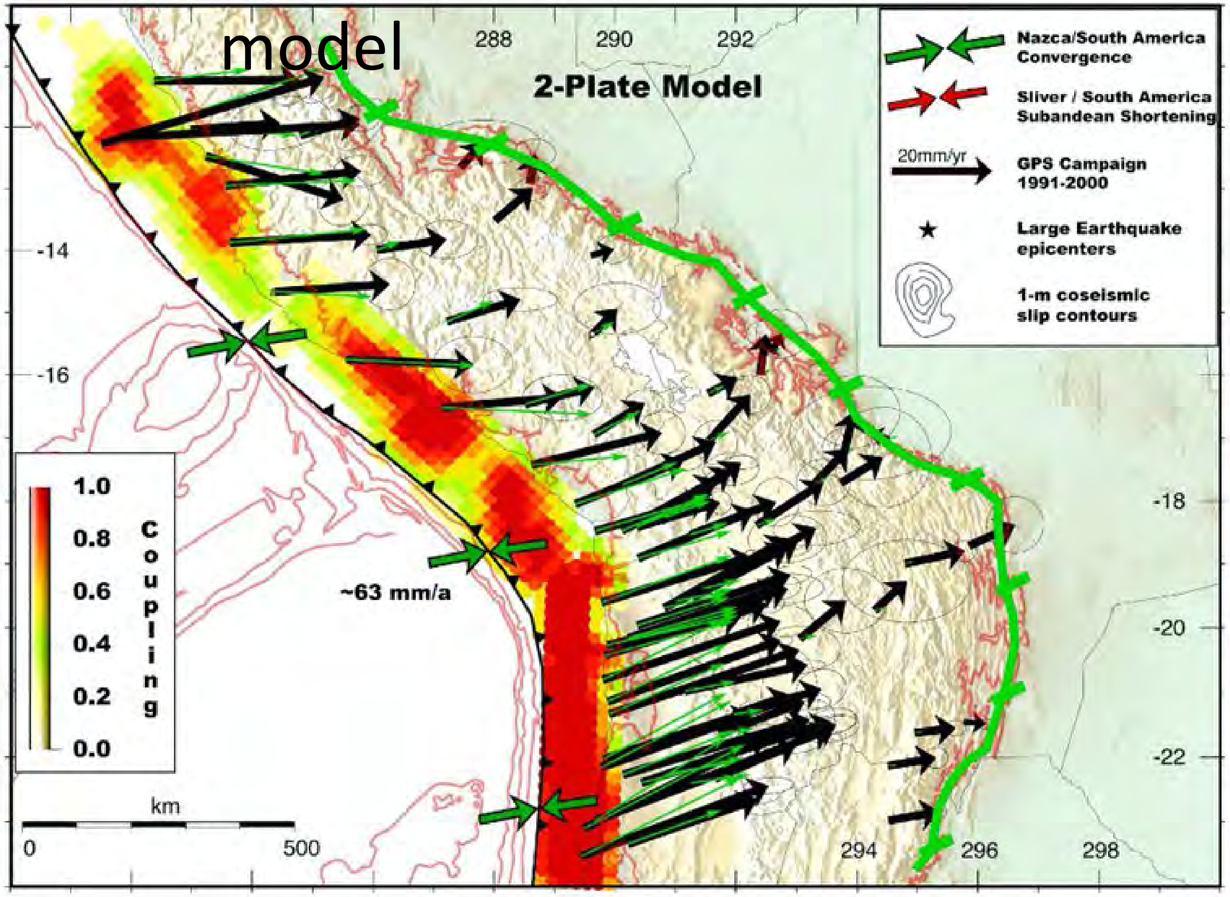
Rigid sliver motion

Interseismic coupling

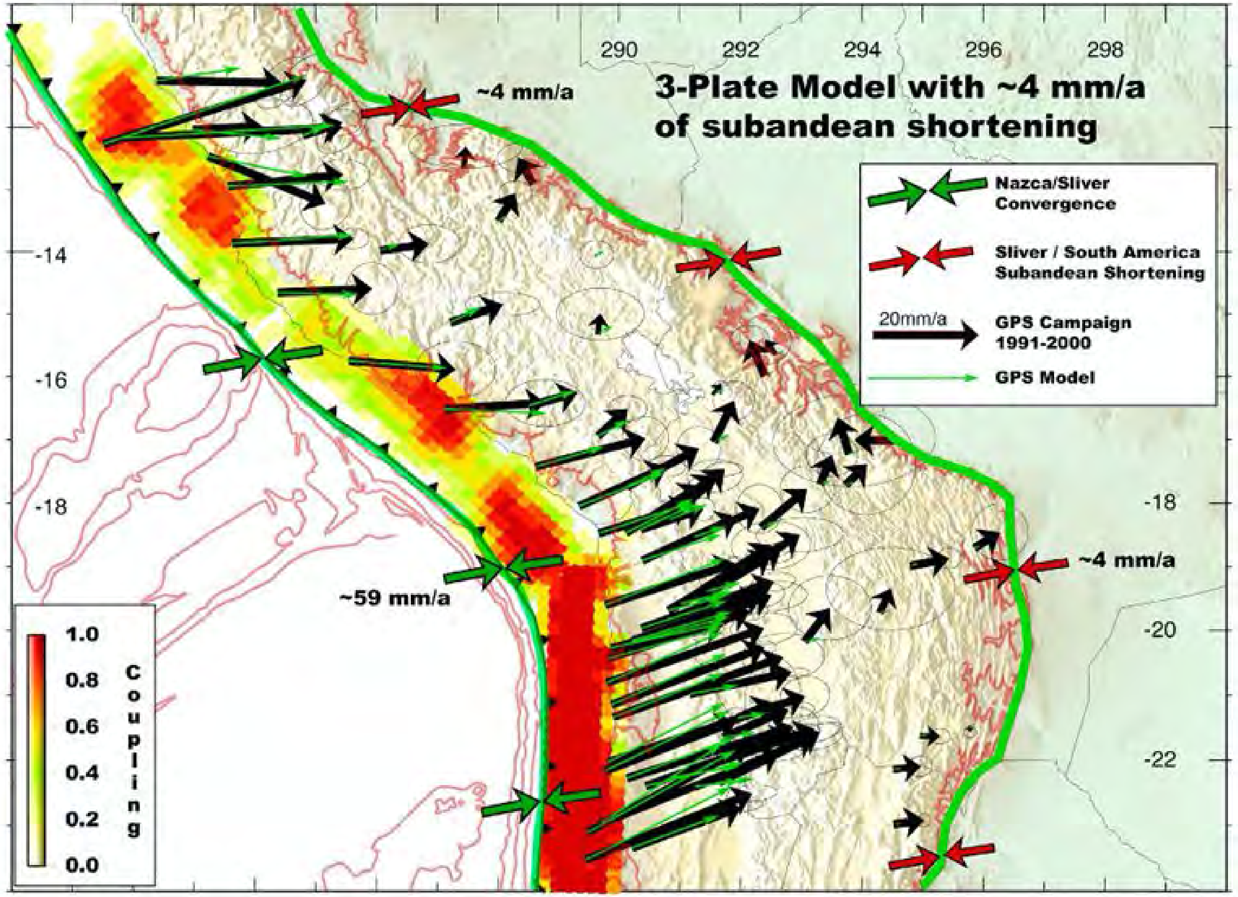


Effect of sliver on coupling

2-plate model



3-plate model

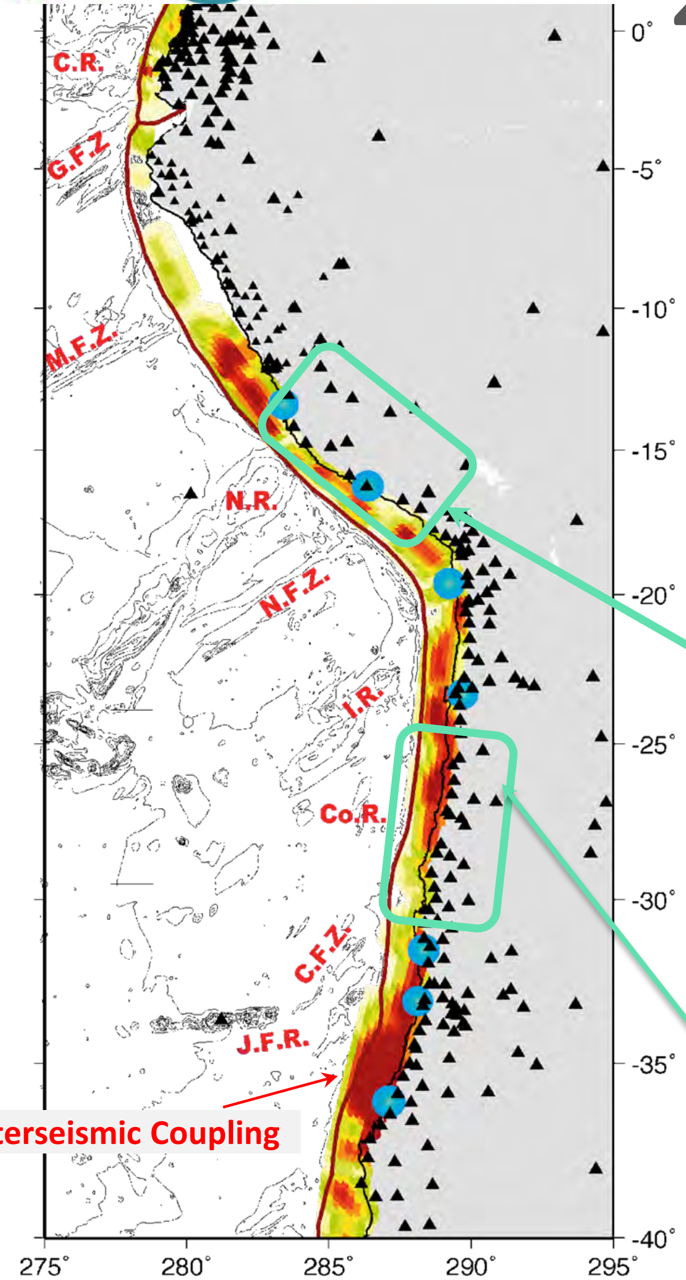


Chlieh et al. 2011

erc DEEPtrigger

Recent instrumentation efforts

2 targets along the South American subduction



that share the following characteristics:

- **Gap of cGPS stations / sparse seismological network**
- **Low interseismic coupling** steady creep or bursts of slow slip ?
- **'seismic gaps'** is an earthquake being prepared there ?
- **Subduction of oceanic ridge**

 barrier for earthquake propagation & rate strengthening behavior? *(prone to slow slip)*

 several large earthquakes have nucleated in similar geometric barriers

South Peru / Nazca : 8 cGPS stations + 24 seismo

- **Located in between 2001 & 2007 ruptures**
- **Subduction of Nazca oceanic ridge**

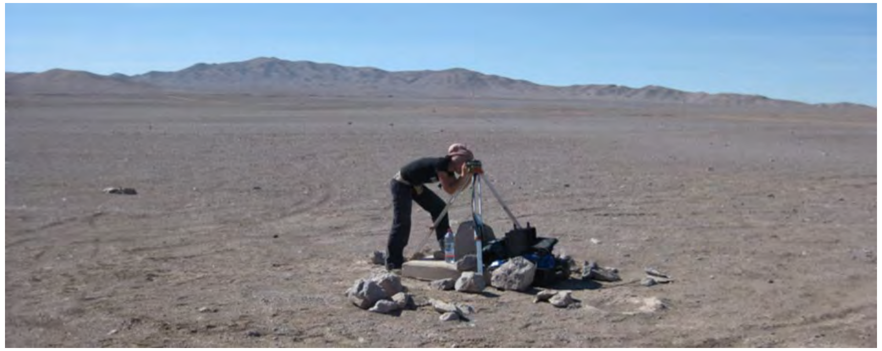
IGP | IRD Institut de Recherche pour le Développement FRANCE | ISTerre Institut des Sciences de la Terre

Atacama region (Tal-Tal - Copiapo – La Serena, 26-31°S): 9 cGPS stations + 25 seismo + ANILLO project: 16 cGPS + 80 seismo

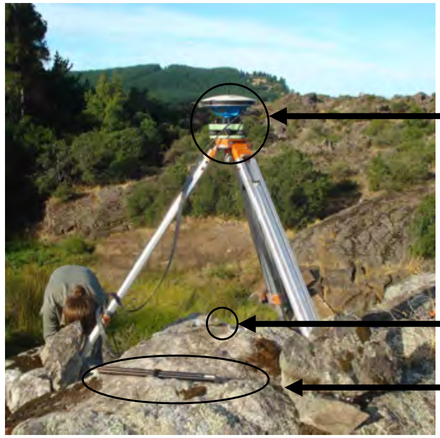
- **Slow slip discovered (Klein 2018)**
- **last earthquakes Mw8.5+ 1819 et 1922**
- **Subduction of Copiapo oceanic ridge**

fcfm FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS UNIVERSIDAD DE CHILE | GFZ Helmholtz-Zentrum Potsdam | ISTerre Institut des Sciences de la Terre

Estimating interseismic coupling in Chile



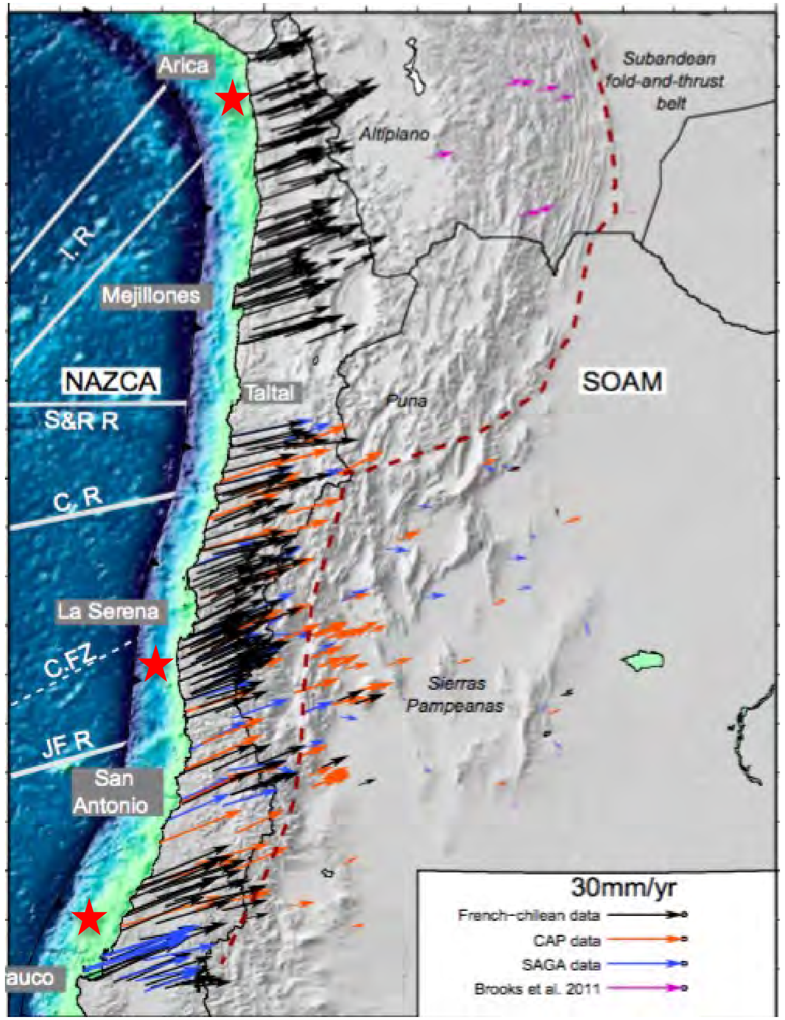
Densification efforts in the decade following Maule



GPS antenna

Geodetic marker sealed in bedrock

Graduated rod to measure antenna height

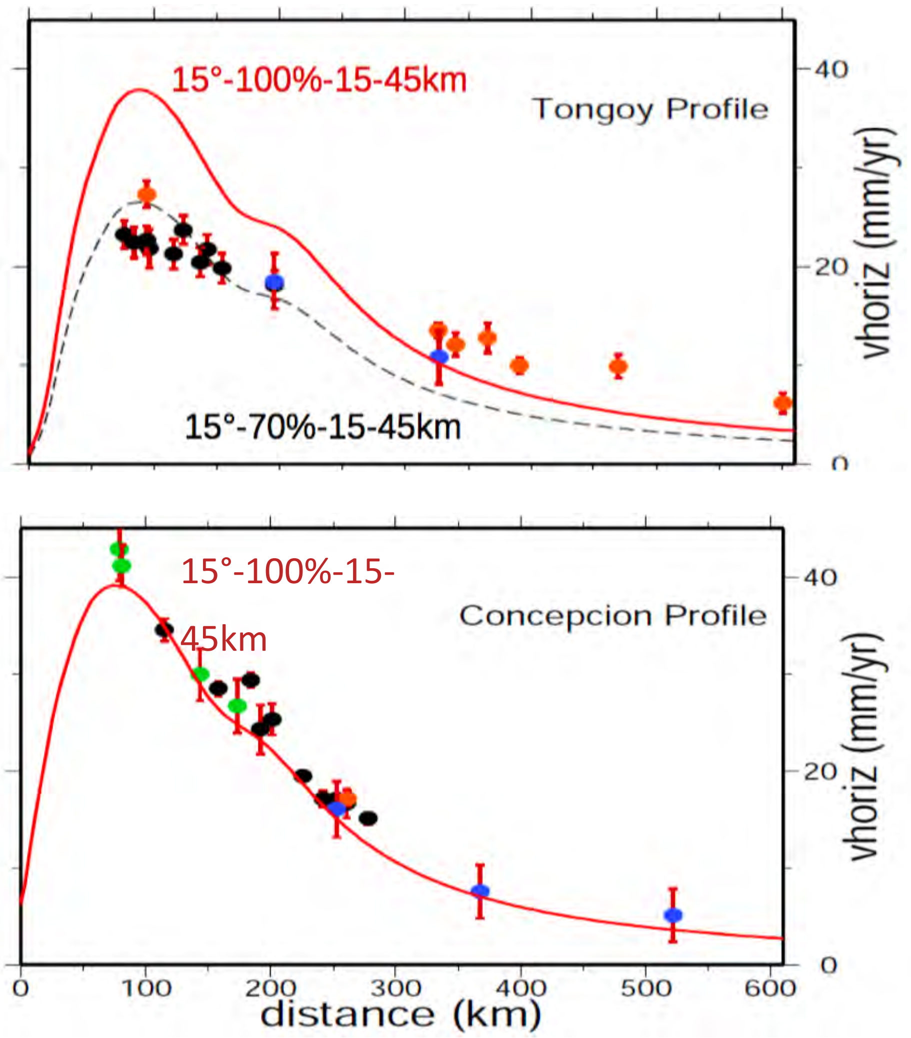


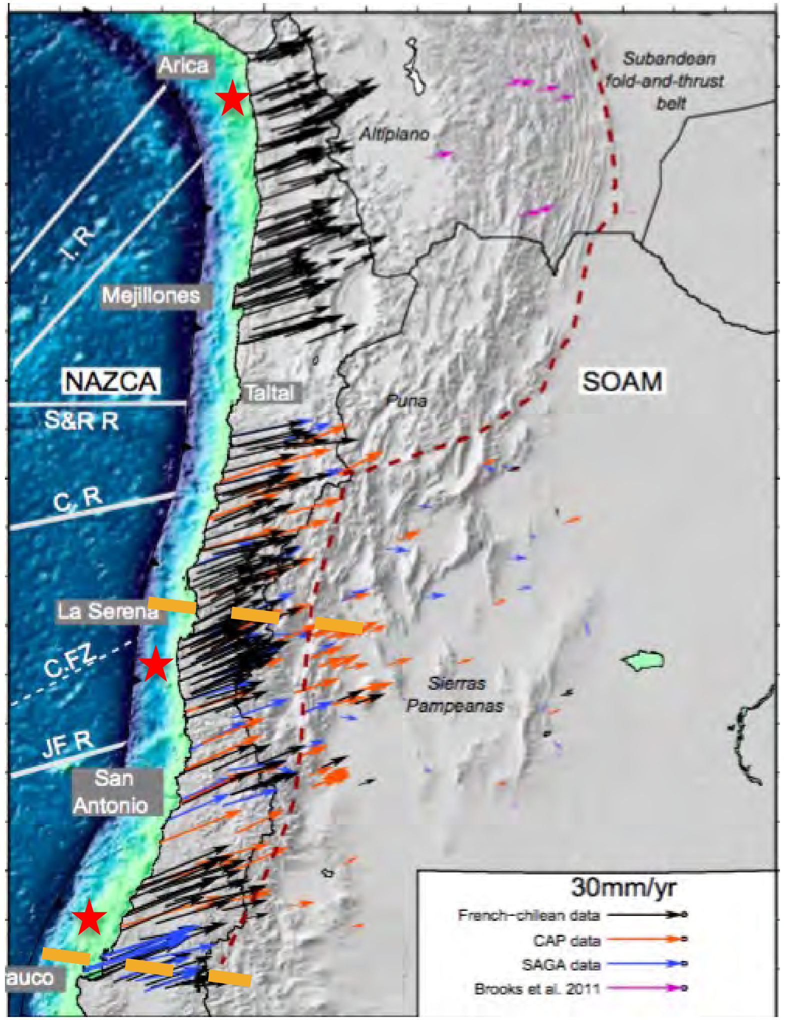
Vigny, Socquet, Métois, Klein, et al. 2009, 2012, 2016, 2018 …

Bedford, Moreno, Tassara, Baez et al. 2013, 2014, 2016, 2018, ..

[Metois et al., 2016, *PAGeoph*]

Estimating interseismic coupling in Chile

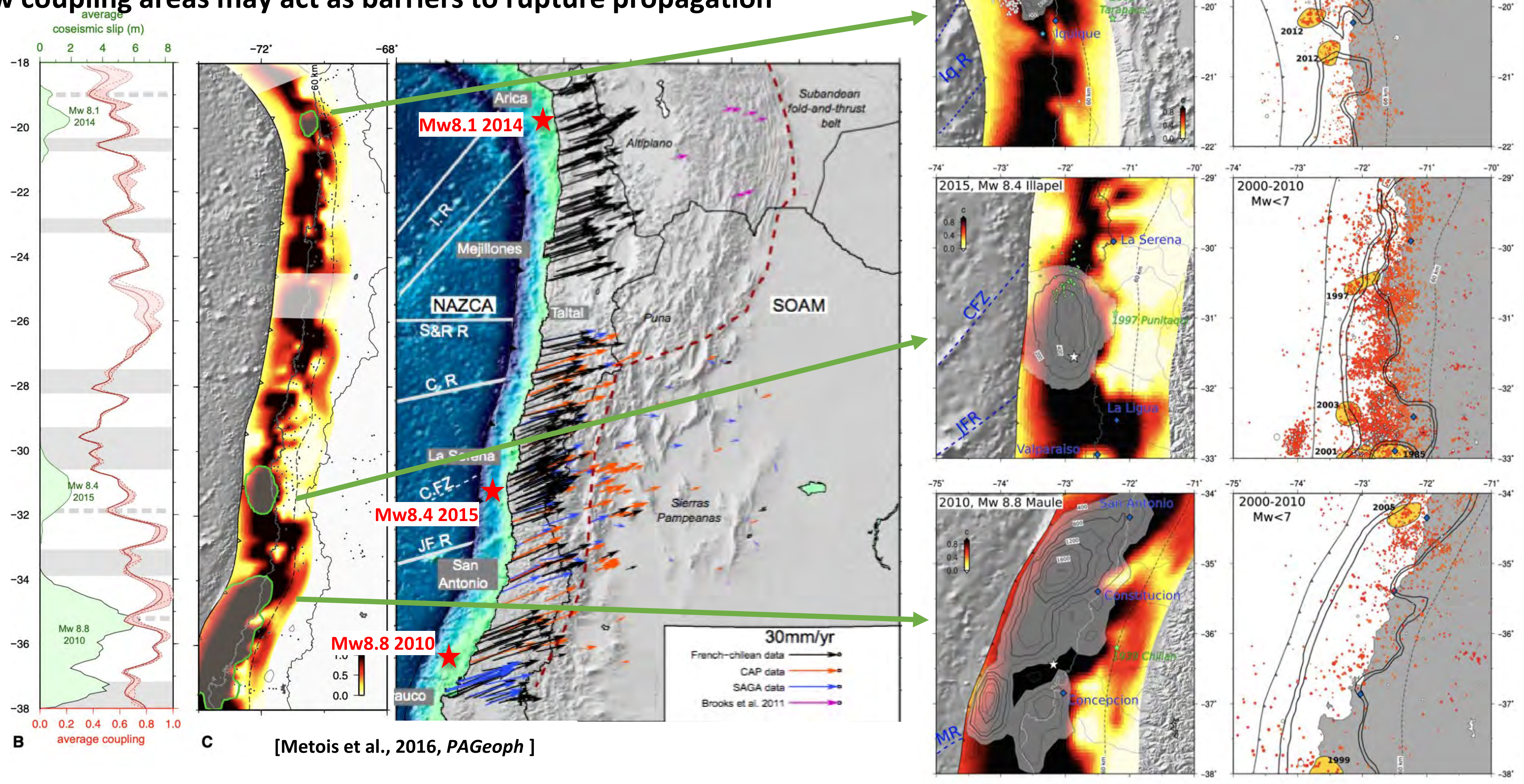




[Metois et al., 2016, *PAGeoph*]

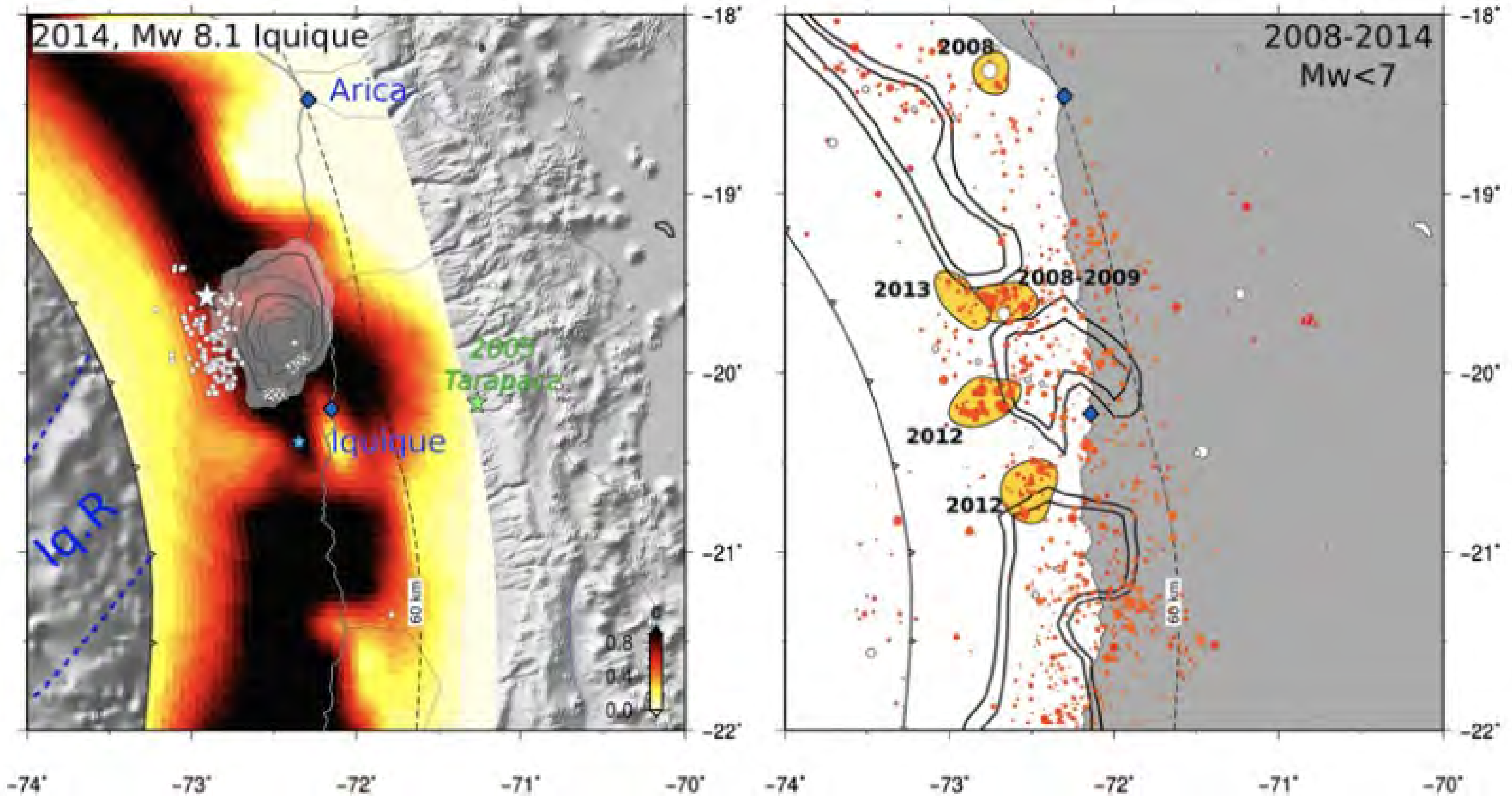
Interseismic coupling in Chile

Large earthquakes occur in interseismically highly coupled areas and low coupling areas may act as barriers to rupture propagation



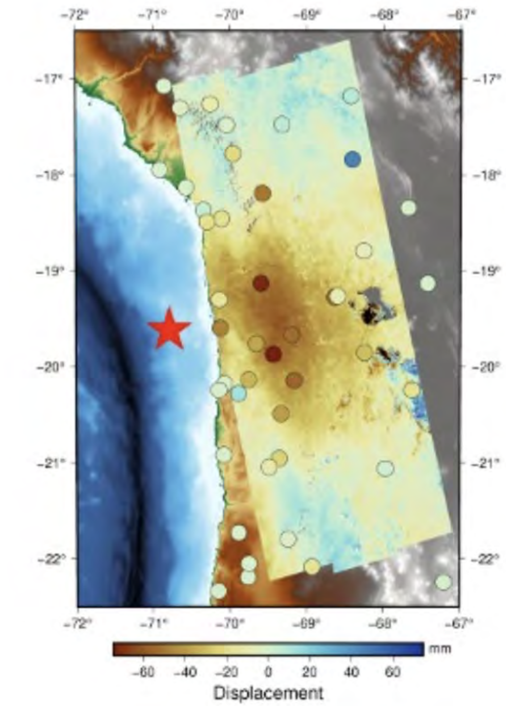
[Metois et al., 2016, *PAGeoph*]

Interseismic coupling in North Chile

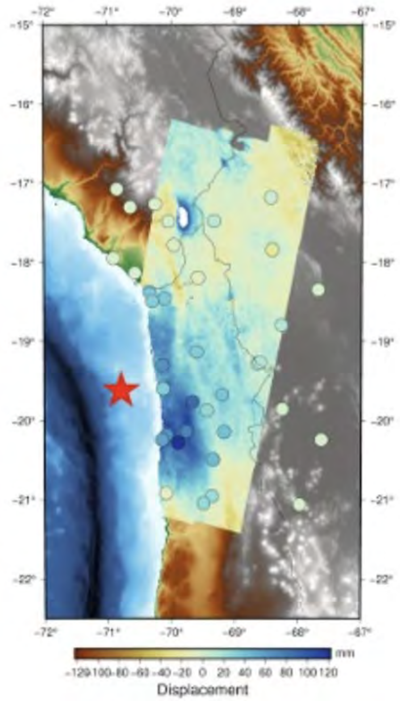


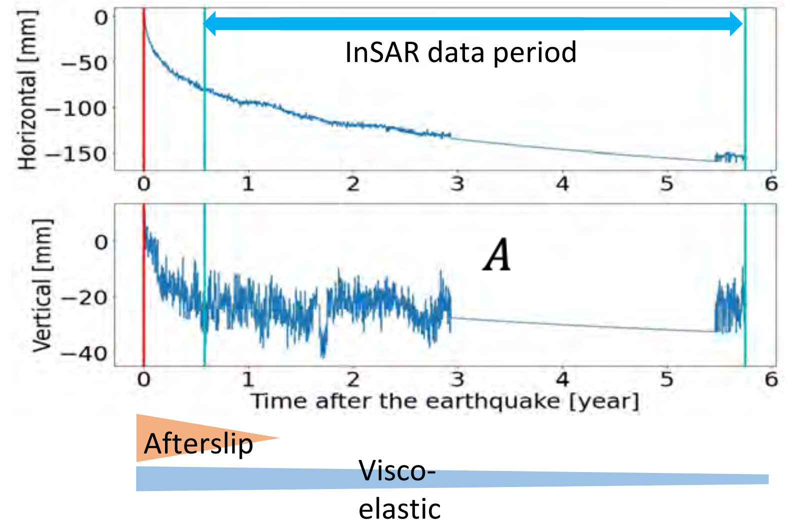
Viscoelastic relaxation in the mantle wedge following Iquique

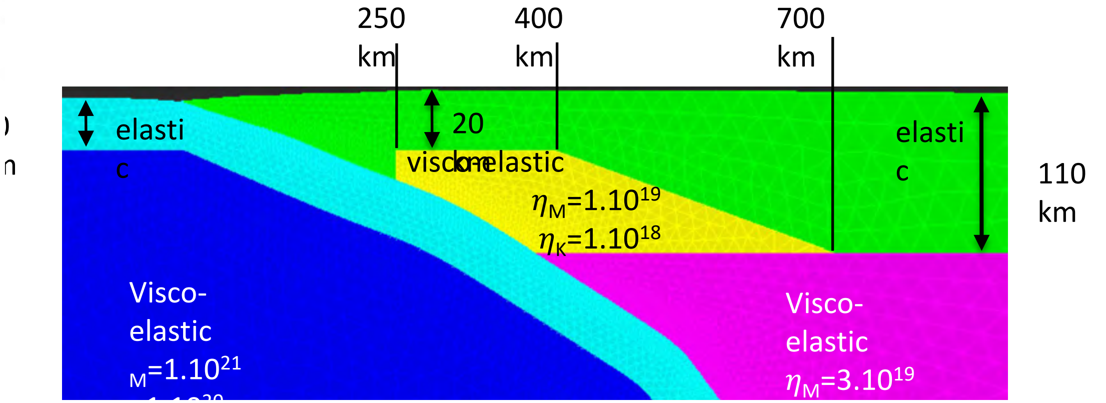
InSAR A149 and GPS in LOS

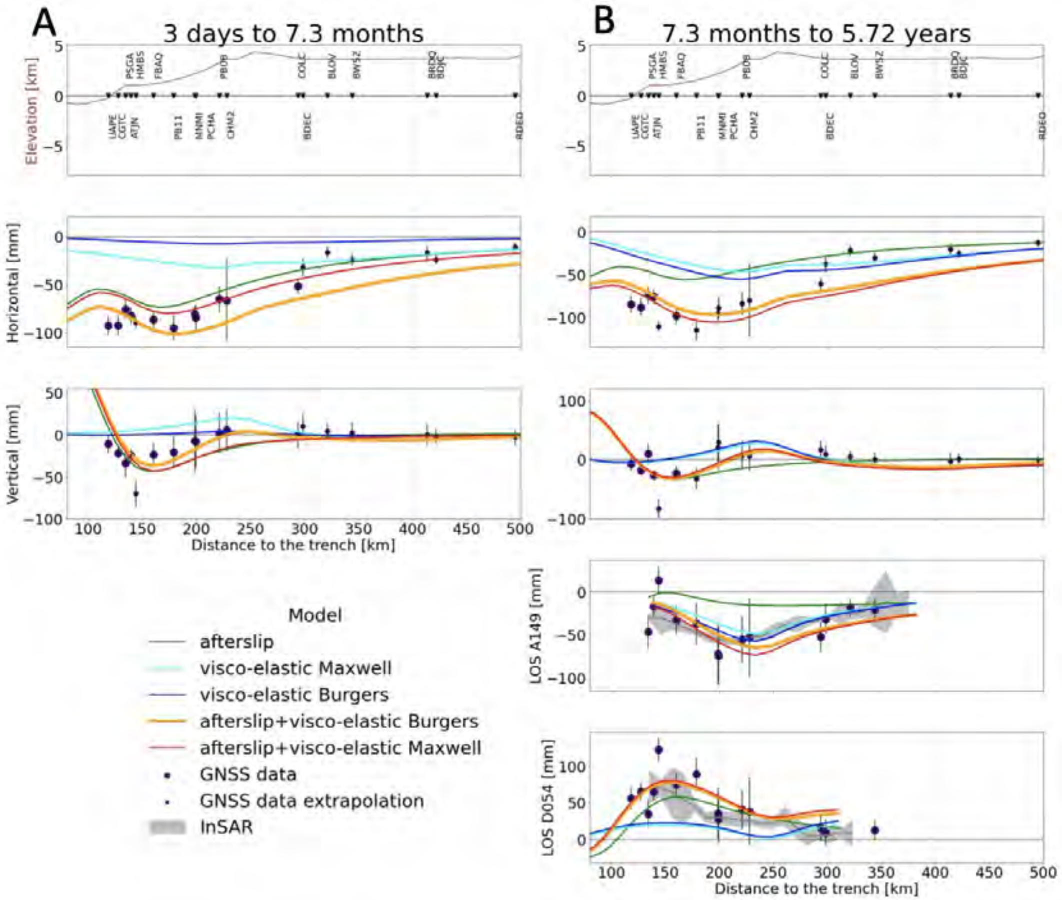


InSAR D054 and GPS in LOS



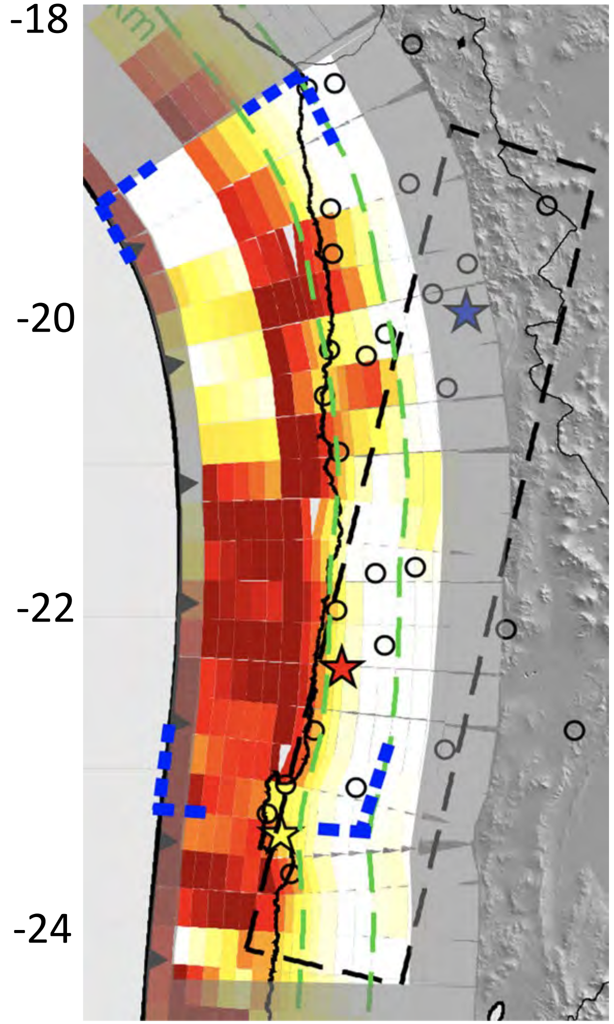




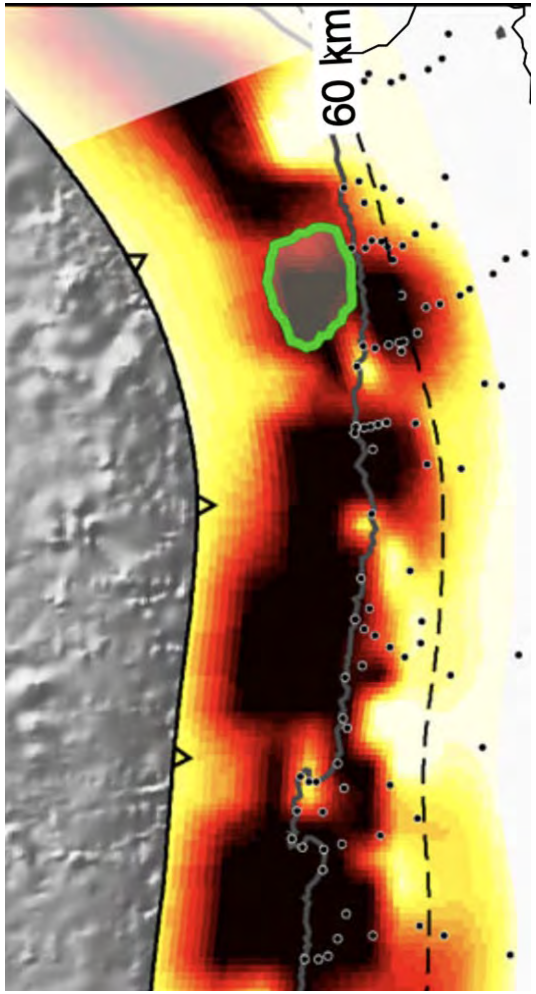


DEEPtrigger

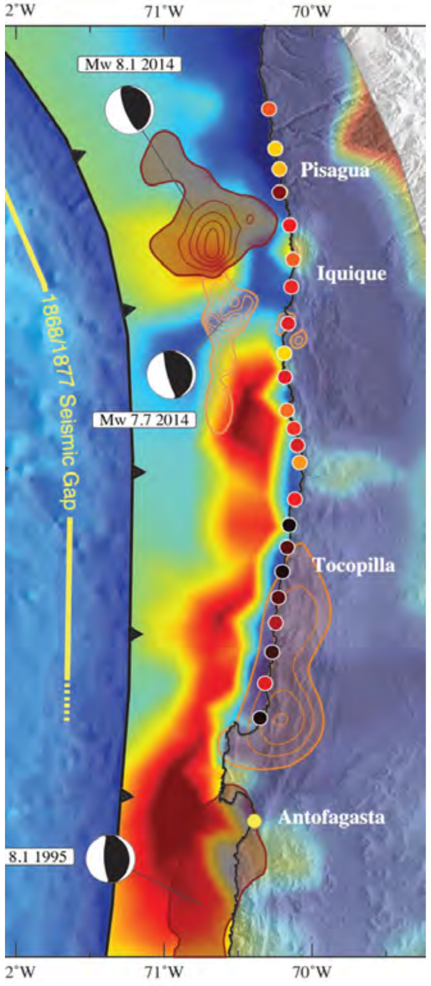
Various interseismic coupling models in North Chile



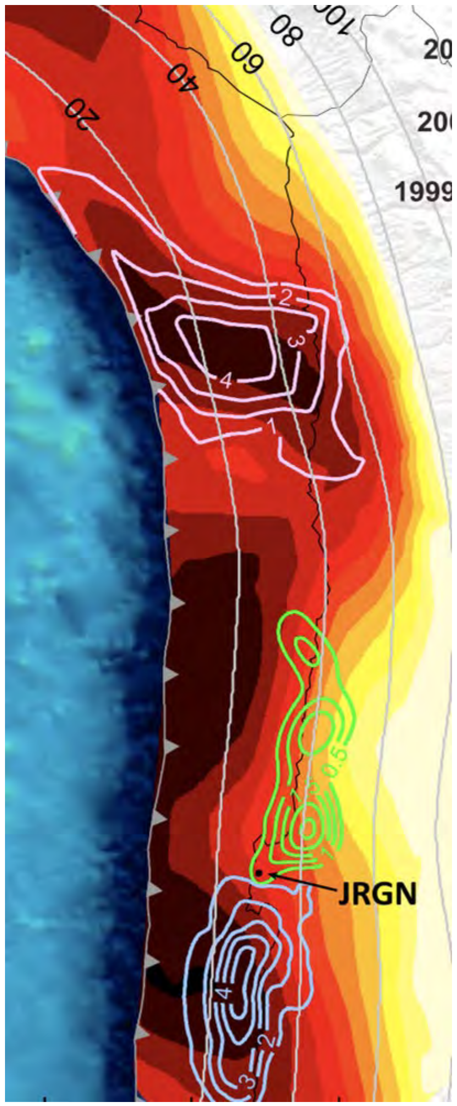
Bejar PIzarro et al. 2013



Metois et al. 2018

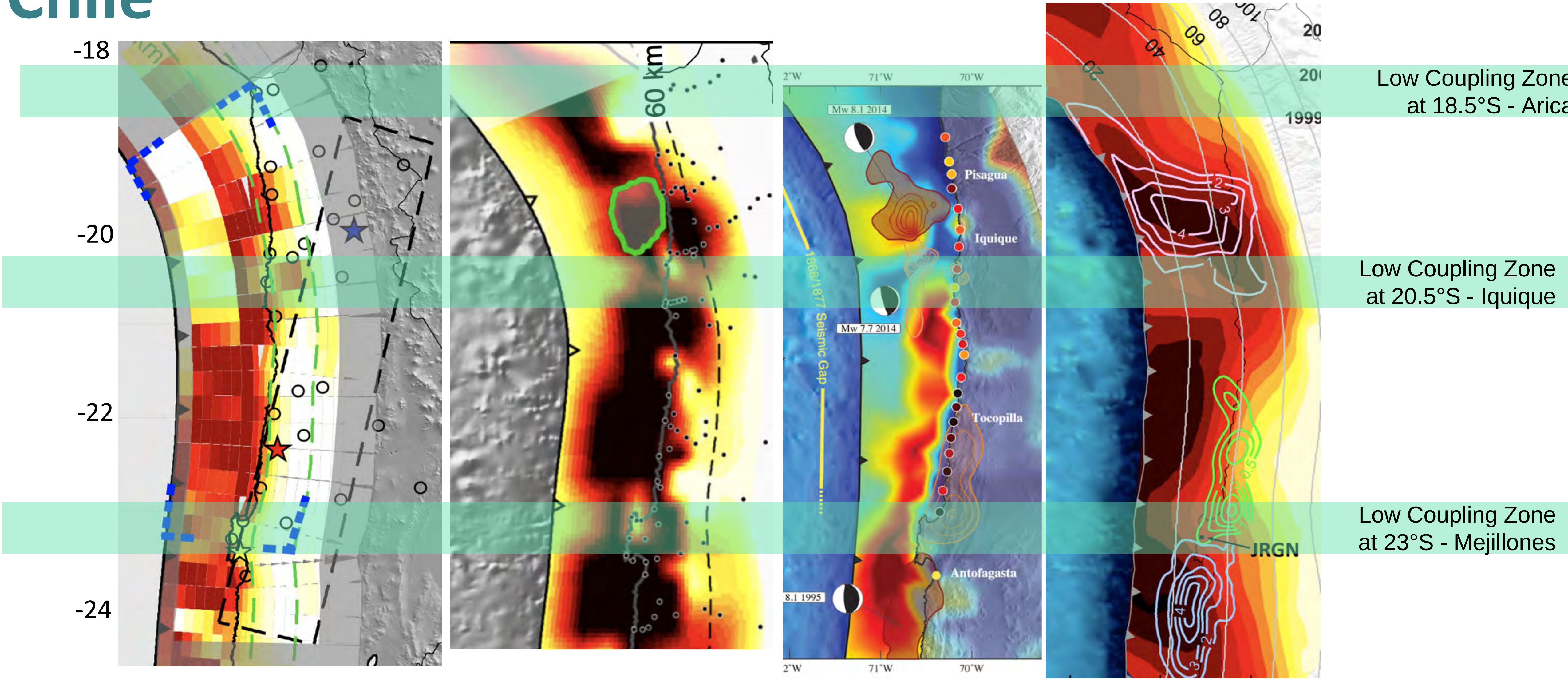


Jolivet et al. 2020



Li et al 2015

Various interseismic coupling models in North Chile



Bejar PIzarro et al. 2013

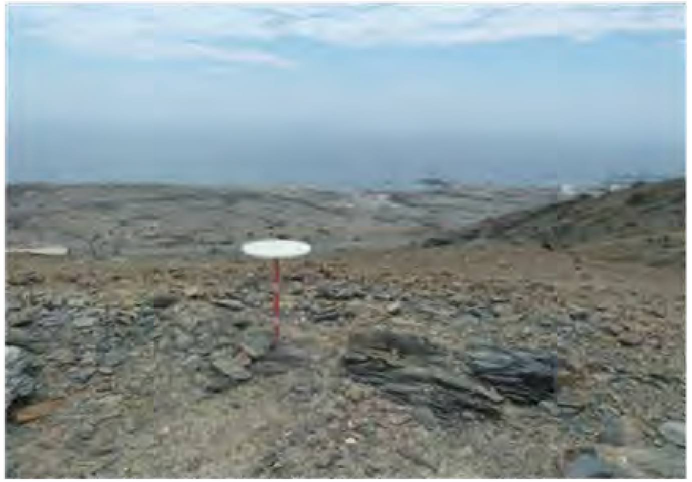
Metois et al. 2018

Jolivet et al. 2020

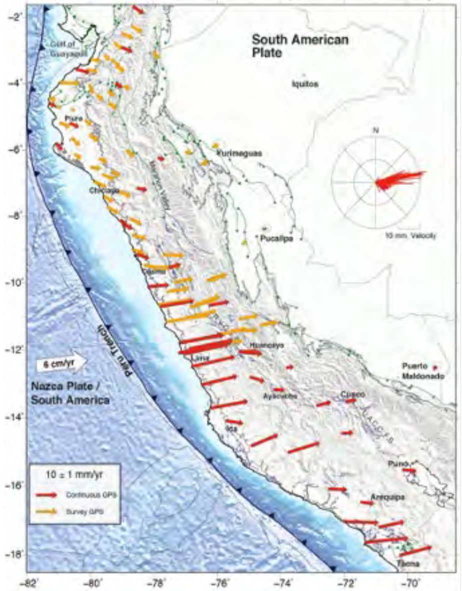
Li et al 2015

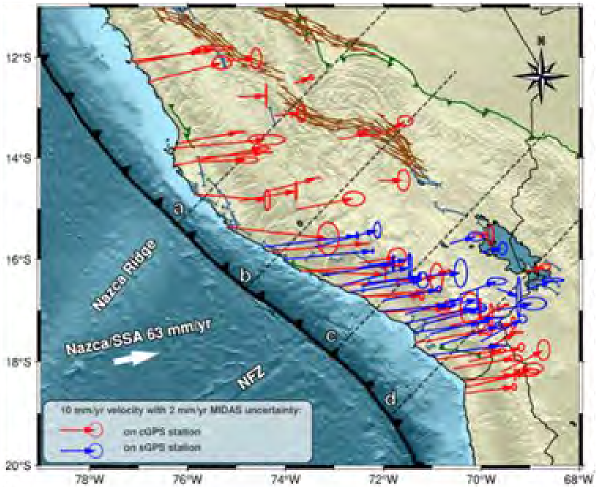
Interseismic coupling in south Peru subduction zone

Juan Carlos Villegas



Norabuena et al (1998)
Chlieh et al (2011)
Quiroz (2015)
Villegas-Lanza, et al (2016)
Lovery et al (submitted)





- M. Chlieh, H. Perfettini, H. Tavera, J.P. Avouac, D. Remy, J-M. Nocquet, F. Rolandone, F. Bondoux, G. Gabalda, & S. Bonvalot
- JC. Villegas, M. Chlieh, J.-M. Nocquet, H. Tavera, P. Baby, J. Chire-Chira, C. Sierra-Farfán, A. Socquet
- B. Lovery , M. Chlieh , E. Norabuena , J.C. Villegas , M. Radiguet , N. Cotte , M. Langlais , W. Quiroz , C. Sierra, M. Simons , J.M.Nocquet , H.Tavera , A. Socquet

PERÚ Ministerio del Ambiente IGP IRD UGA Université Grenoble Alpes ISTerre

Seismotectonic setting of southern Peru subduction zone

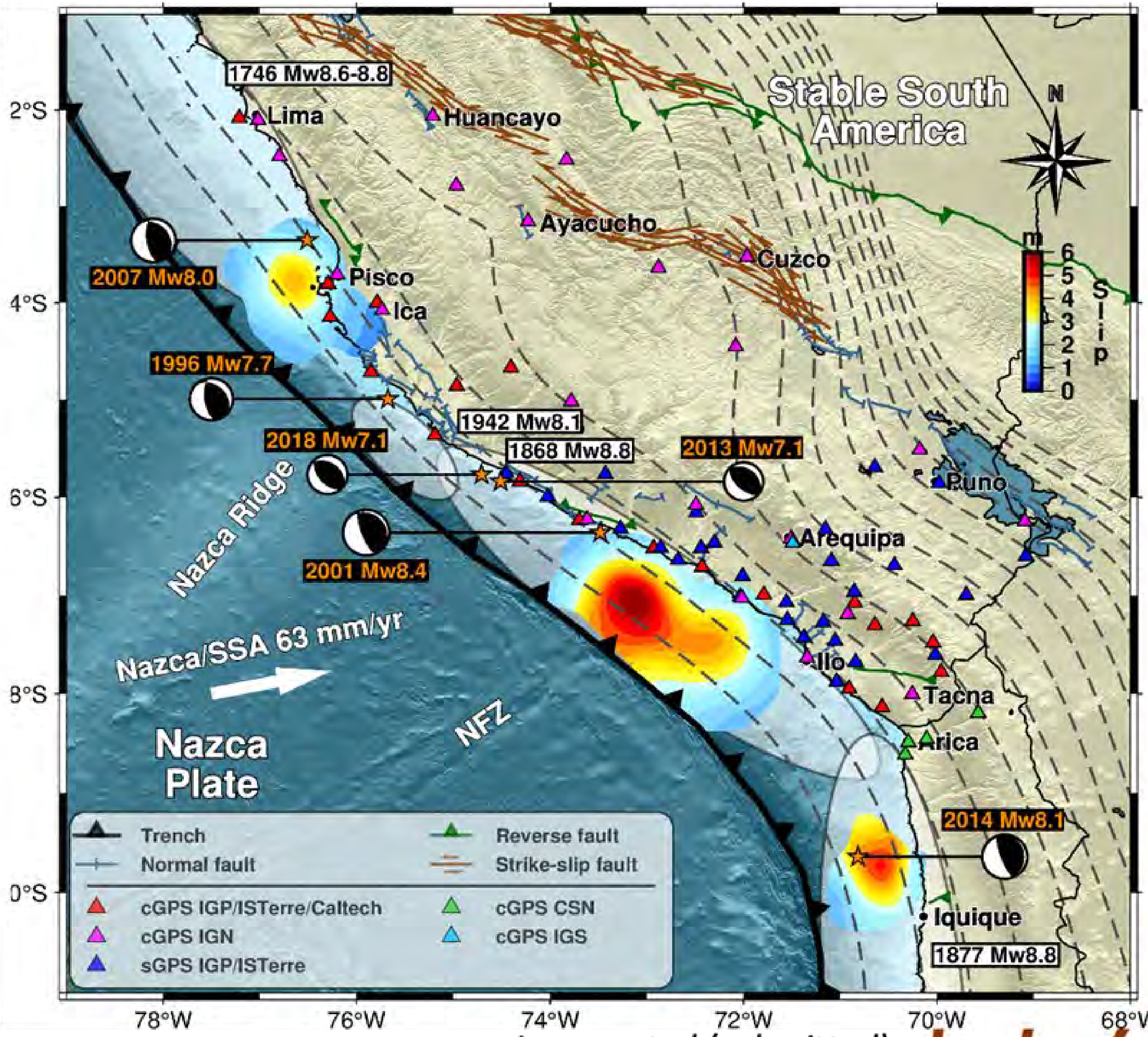
The Nazca plate is subducting the SOAM plate at an average rate of ~63 mm/yr

Southern Perú is characterized by the occurrence of large megathrust EQs

- Acarí 2013 & 2018 (7.1Mw)
- Pisco 2007 (8.0Mw)
- Arequipa 2001 (8.4Mw)

Presence of oceanic & continental features

- Nazca Ridge / N. Fracture Zone
- Altiplano
- Fault systems in Forearc & Subandean

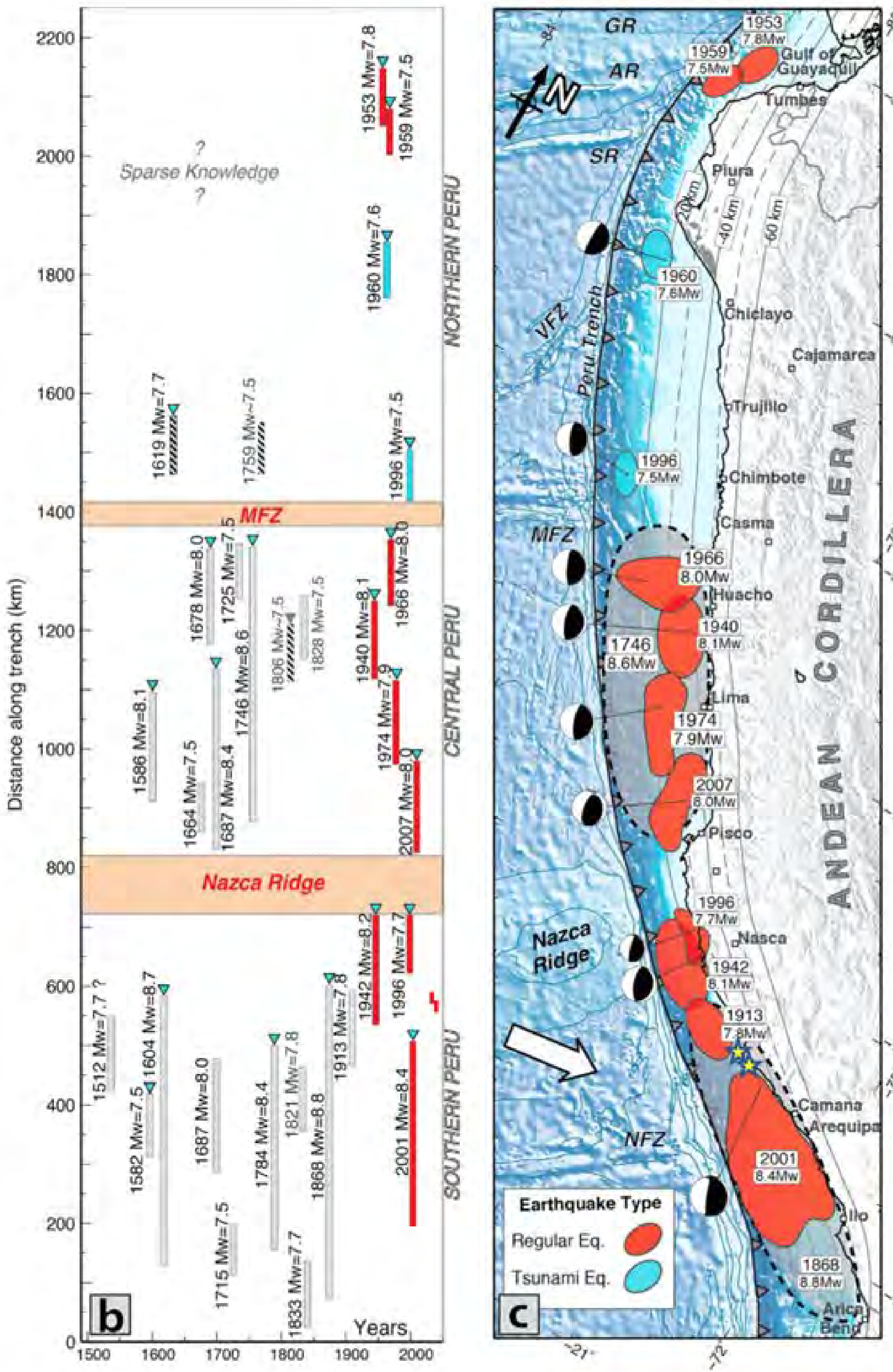


Lovery et al (submitted)

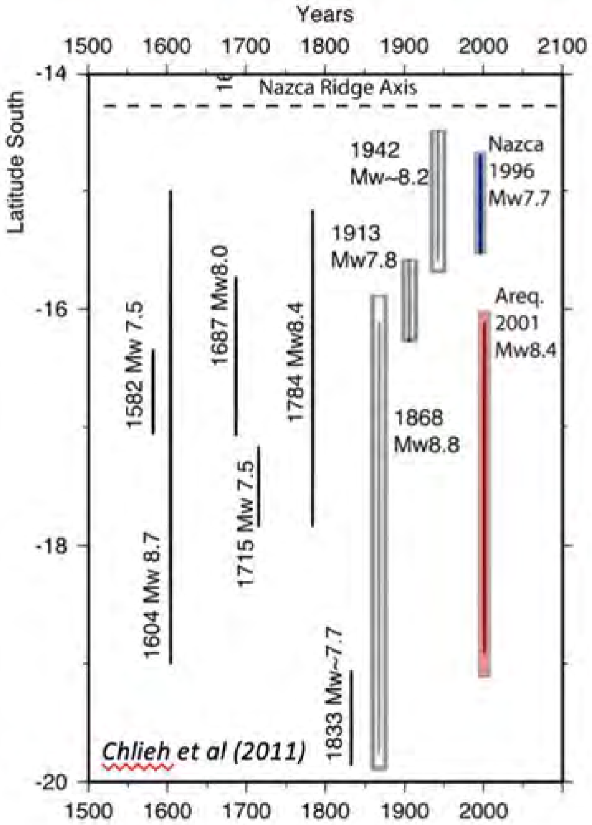
Earthquake history, approximated rupture areas along the Peruvian subduction zone

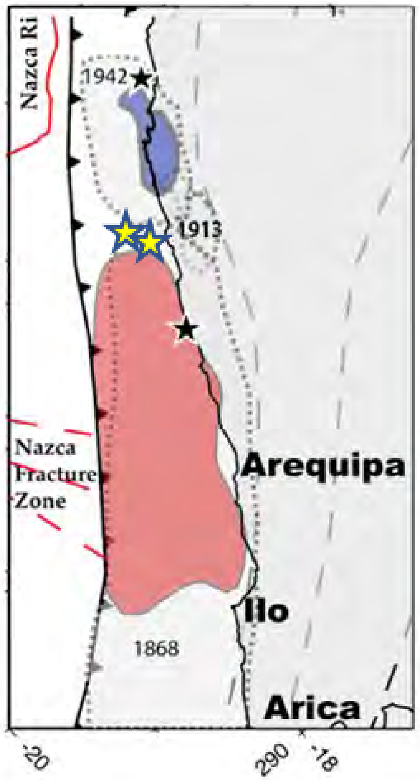
Earthquake history in Peru dates back to XVI century

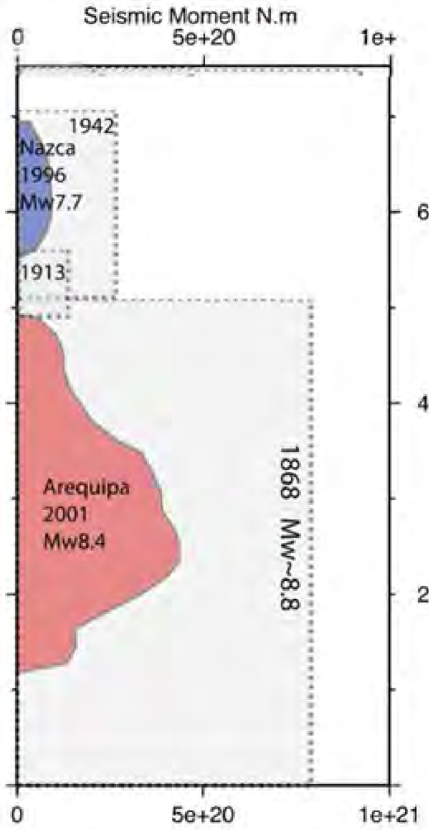
Approximated ruptures areas



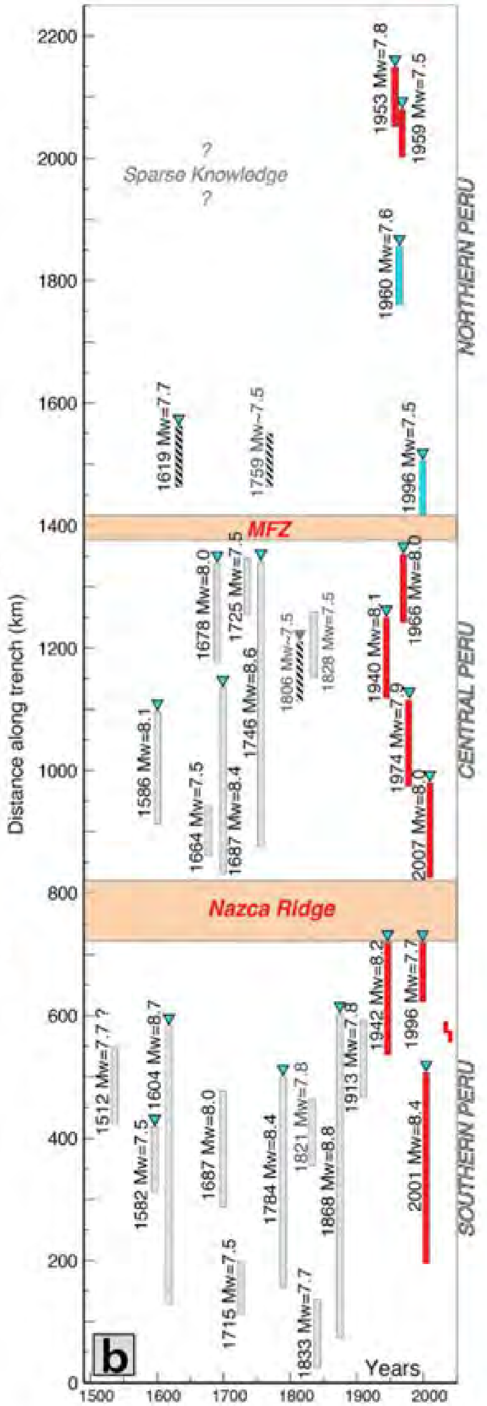
Earthquake history, approximated rupture areas along the Peruvian subduction zone

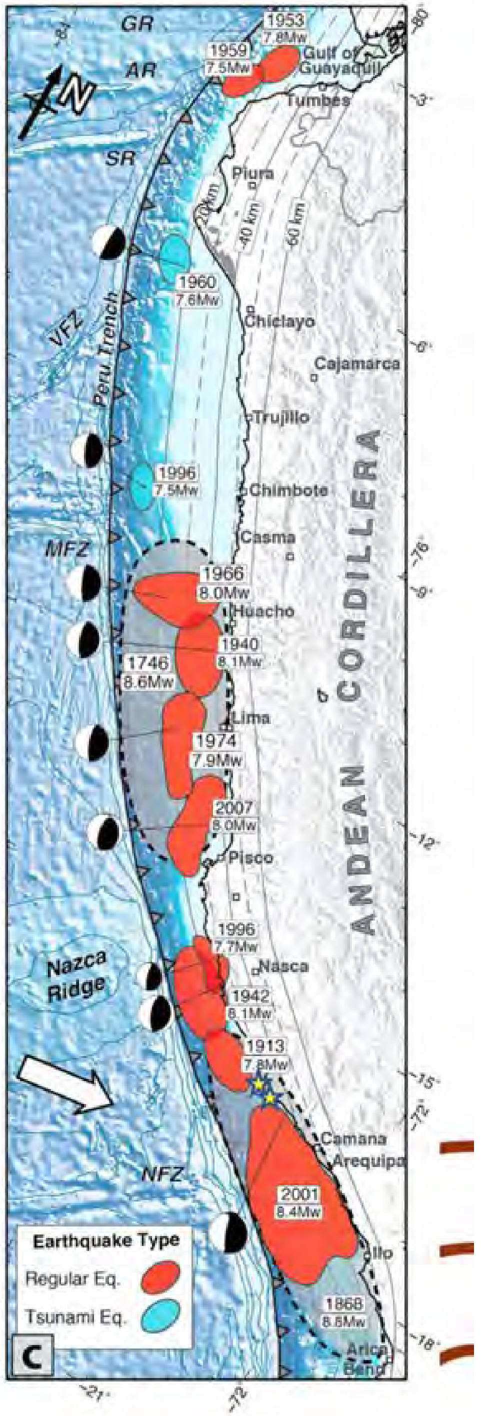




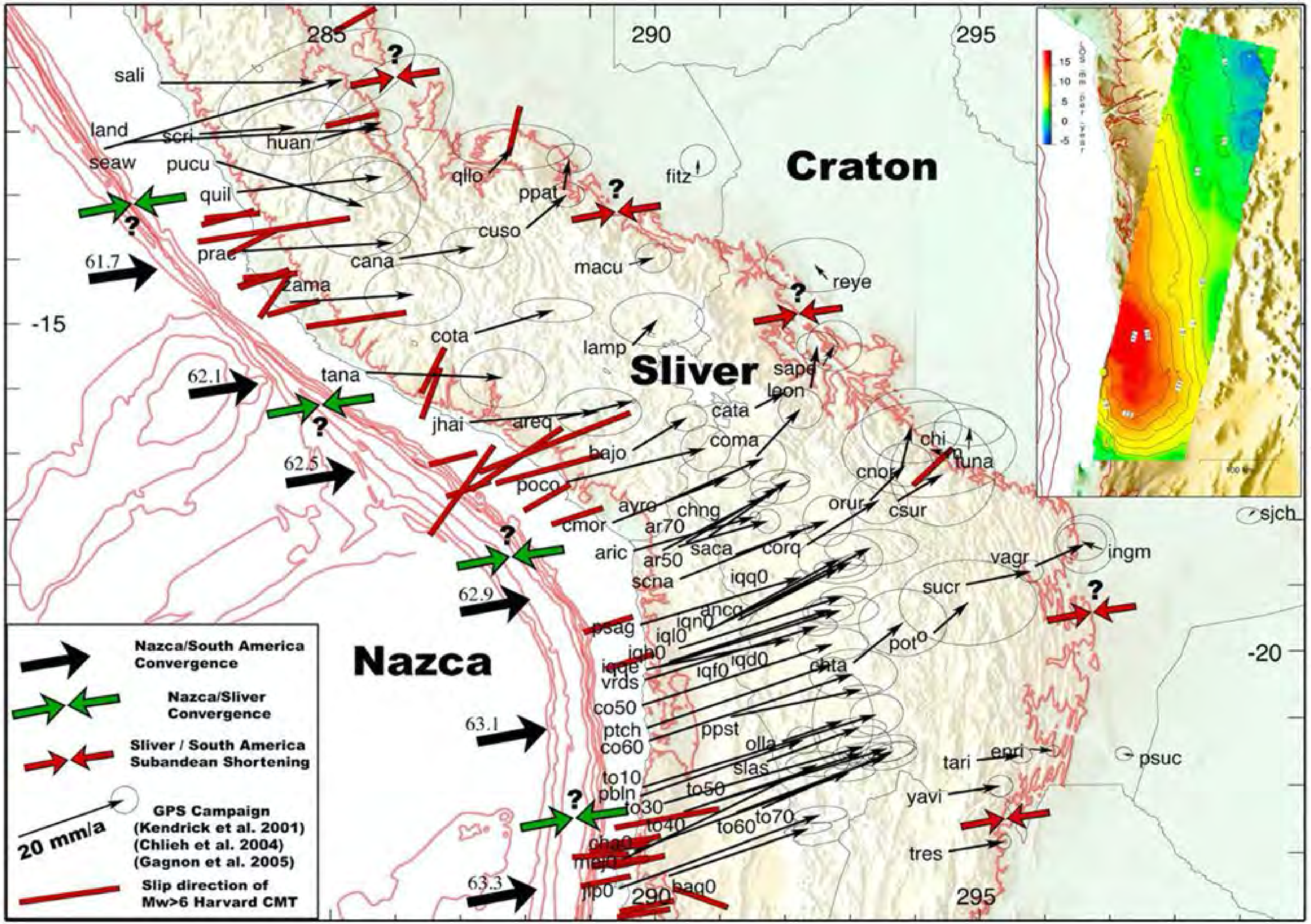


Along-trench variations of the seismic moment released associated to each earthquake





Combined GPS& InSAR velocity field (1994-2011) for southern Peru



Norabuena et al., (1998)
Bevis et al., (1999)
Kendrick, Bevis et al., (2001)
Brooks, Bevis, Smalley, Kendrick et al., (2000, 2001, 2003, 2011)

Chlieh et al., (2011)

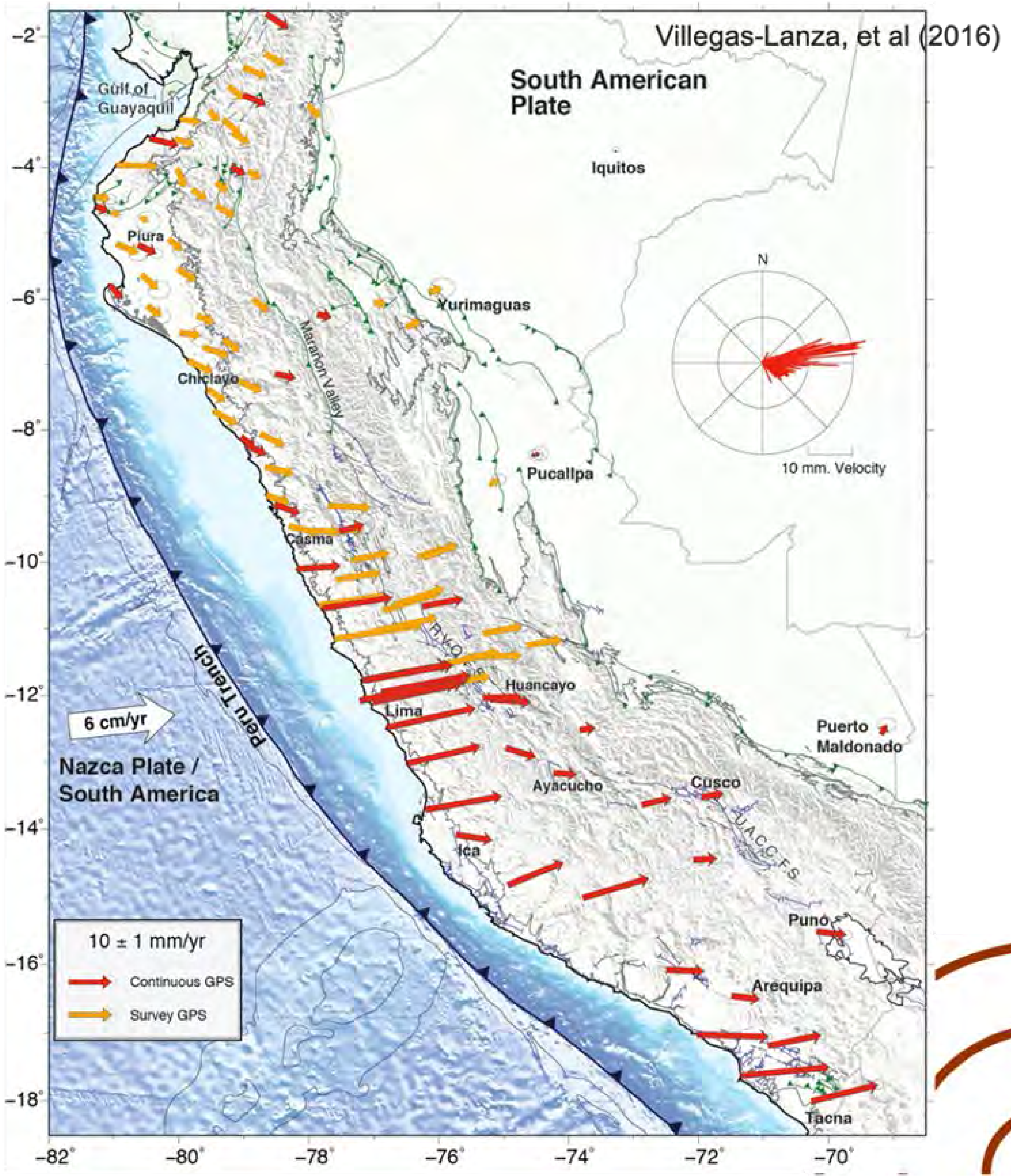
GPS velocity field (2007-2014 wrt SSA) for the entire PSZ

Distinct patterns:

- High velocities in the convergence direction

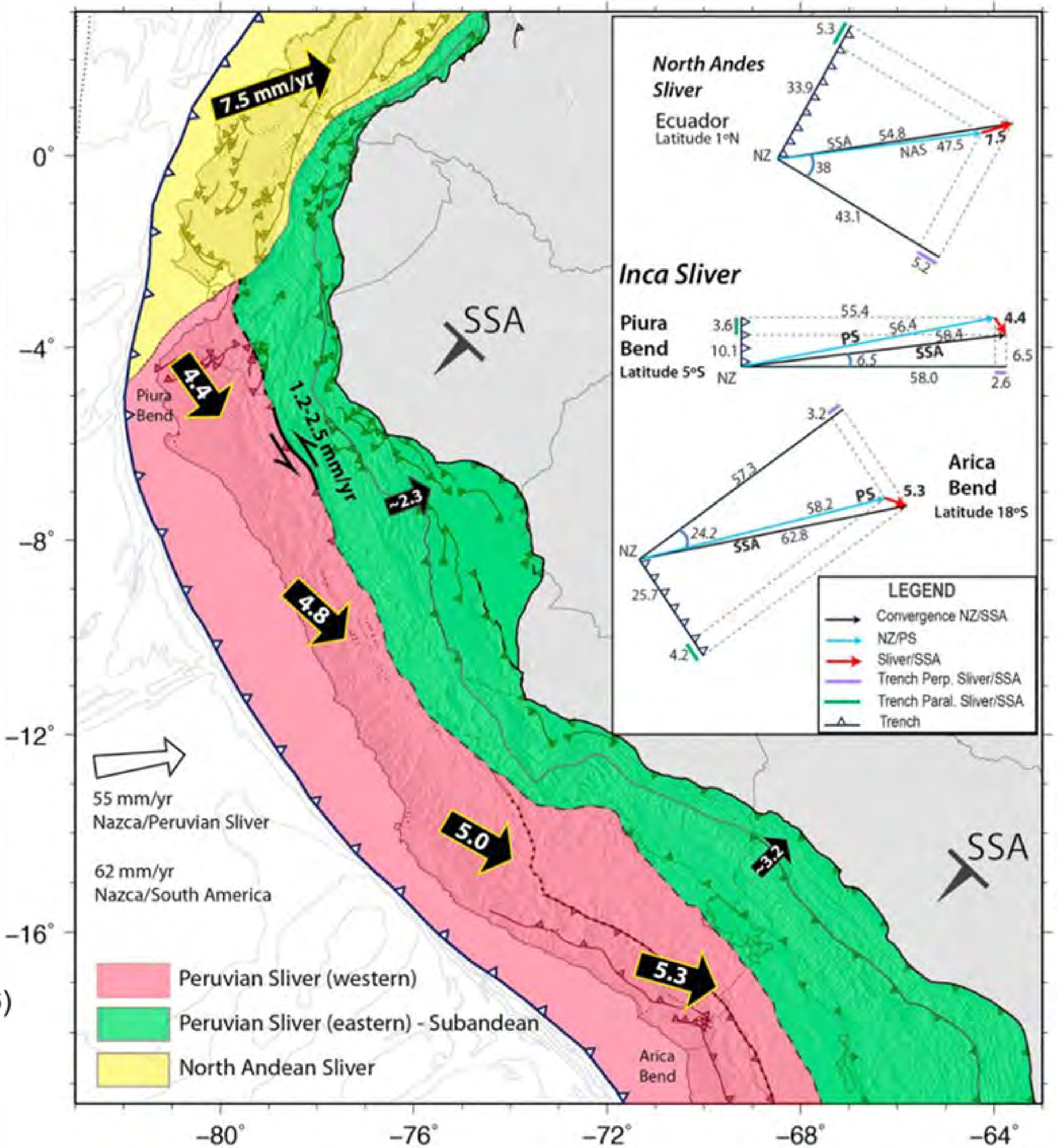
- Consistent motion and velocities in northern Peru modeled by a rigid block motion.

- Subandean velocities show a consistent motion vel & direction (counterclockwise rotation)



Continental slivers contributing to deformation partitioning of the peruvian margin

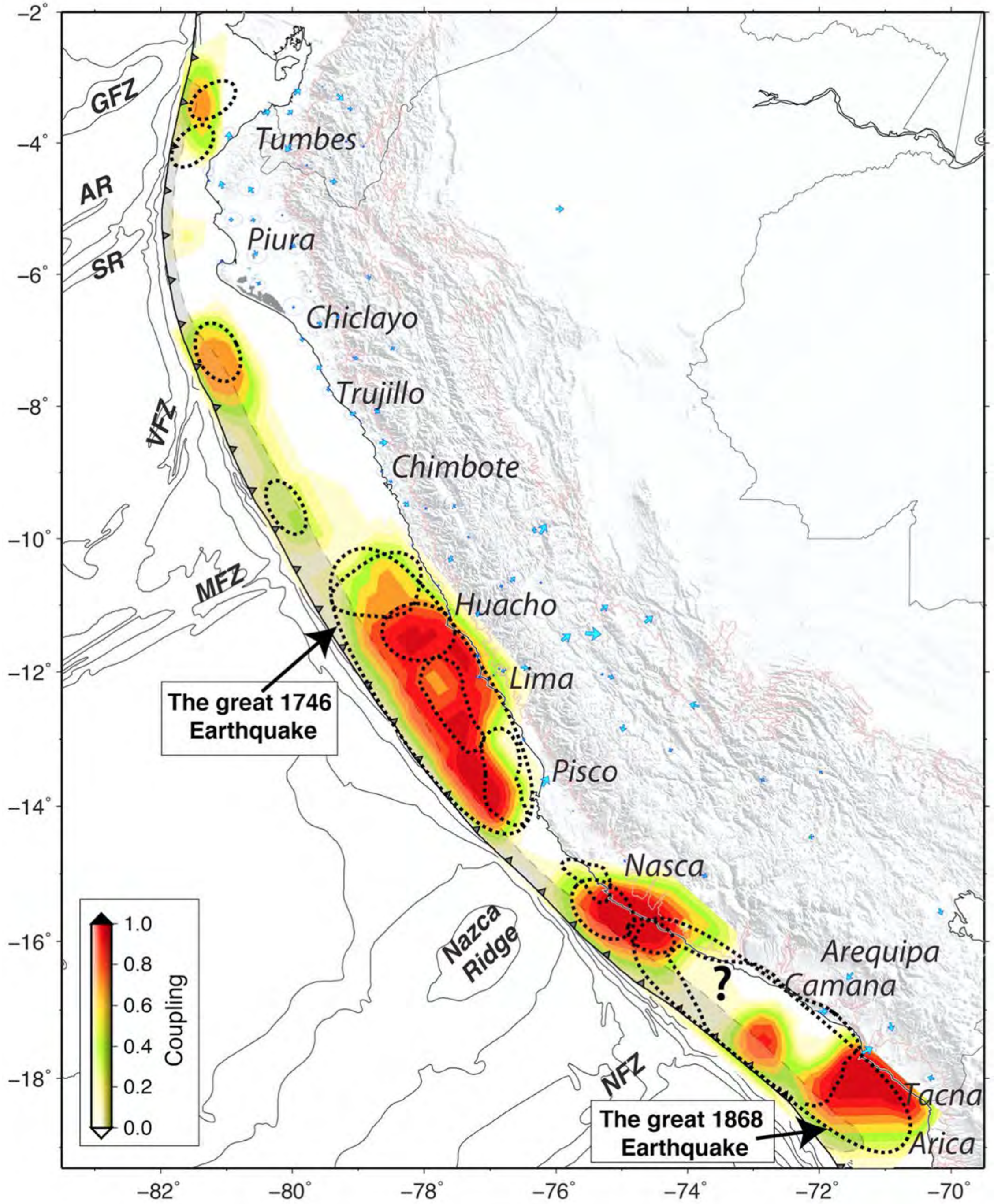
Villegas-Lanza, et al (2016)



Interseismic coupling along the Peruvian Subduction Zone

Heterogeneous high and deep coupling
1 in central Peru(400 km long)
2 in south Peru (>100km)

Model correlates with geomorphic structures on the subducting plate (fractures&ridge) and approximate rupture areas of large EQ + current seismicity

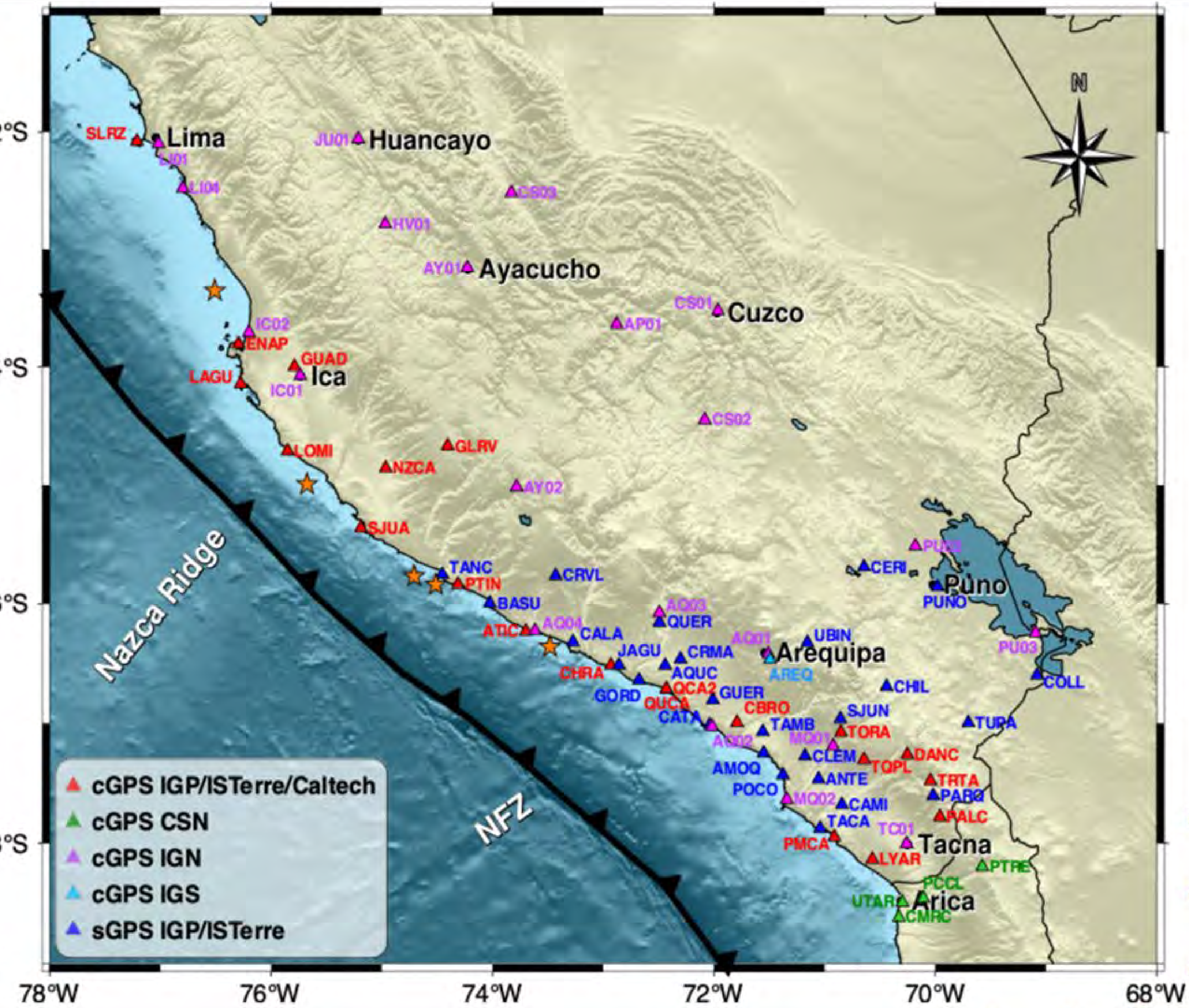


Current GNSS network in south Peru

80 GNSS points:

- ~ 50 continuous stations
- ~ 30 survey sites

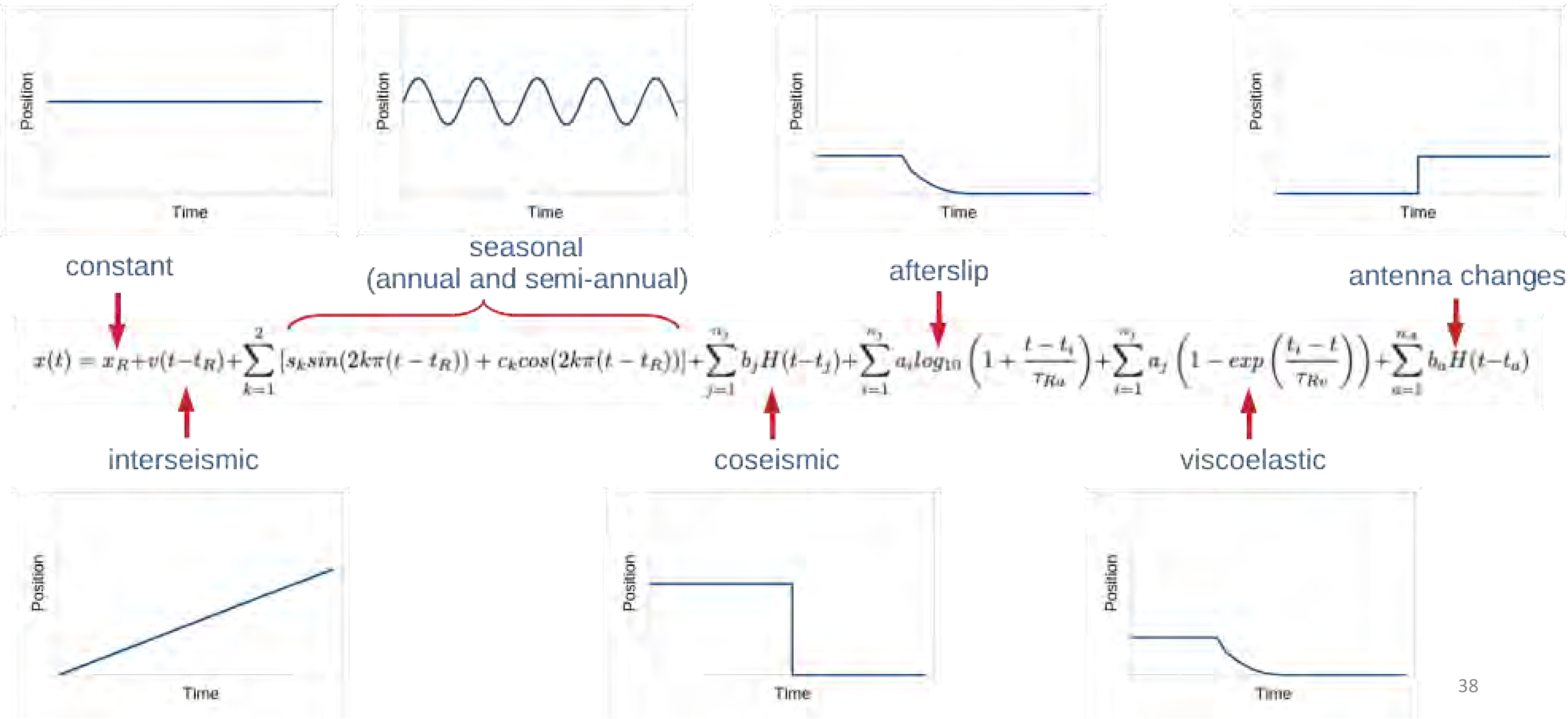
from ~2007 to ~2023



Lovery, et al (submitted)

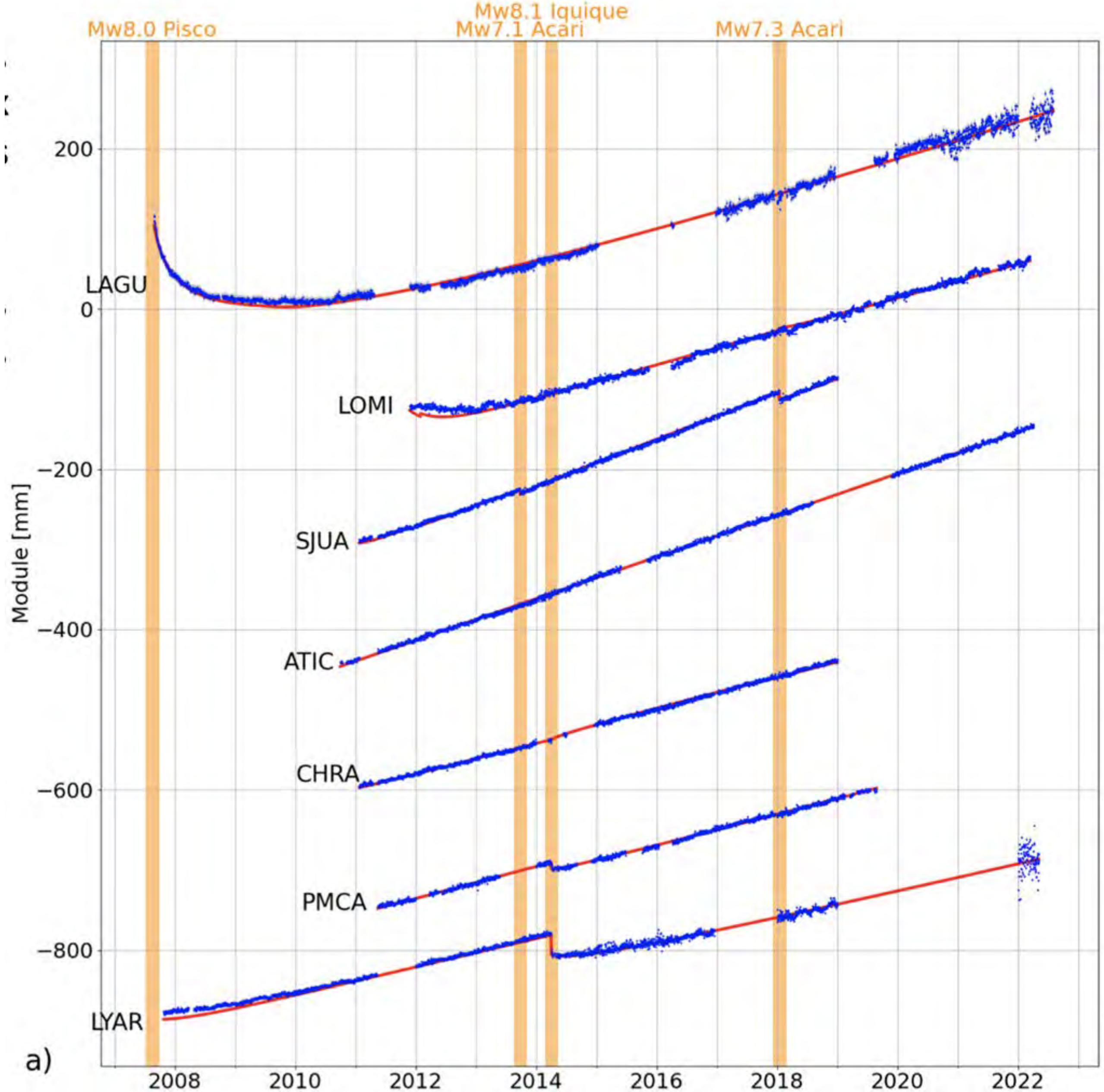
Trajectory model on GNSS time series

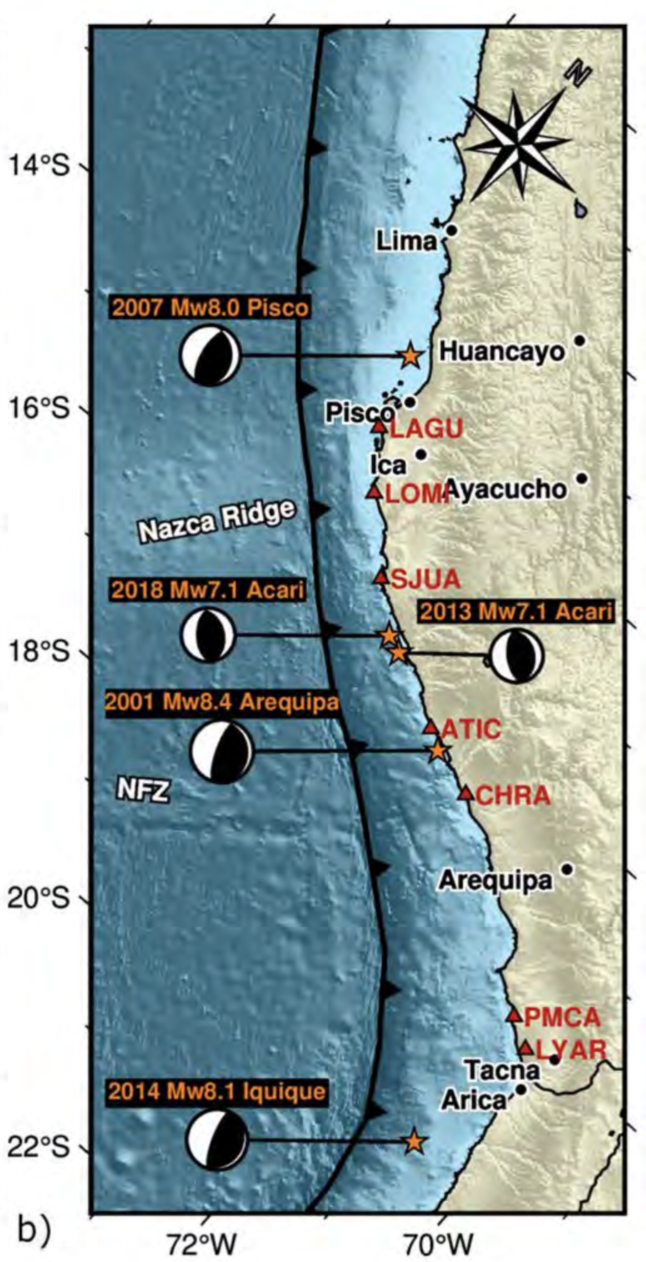
We use the trajectory model from Bevis & Brown (2014), implemented in the ITSA software (Marill et al. 2021):



$$x(t) = x_R + v(t-t_R) + \sum_{k=1}^{2}[s_k sin(2k\pi(t-t_R)) + c_k cos(2k\pi(t-t_R))] + \sum_{j=1}^{n_j} b_j H(t-t_j) + \sum_{i=1}^{n_i} a_i log_{10}\left(1+\frac{t-t_i}{\tau_{Ra}}\right) + \sum_{i=1}^{n_i} a_i\left(1-exp\left(\frac{t_i-t}{\tau_{Rv}}\right)\right) + \sum_{a=1}^{n_a} b_a H(t-t_a)$$

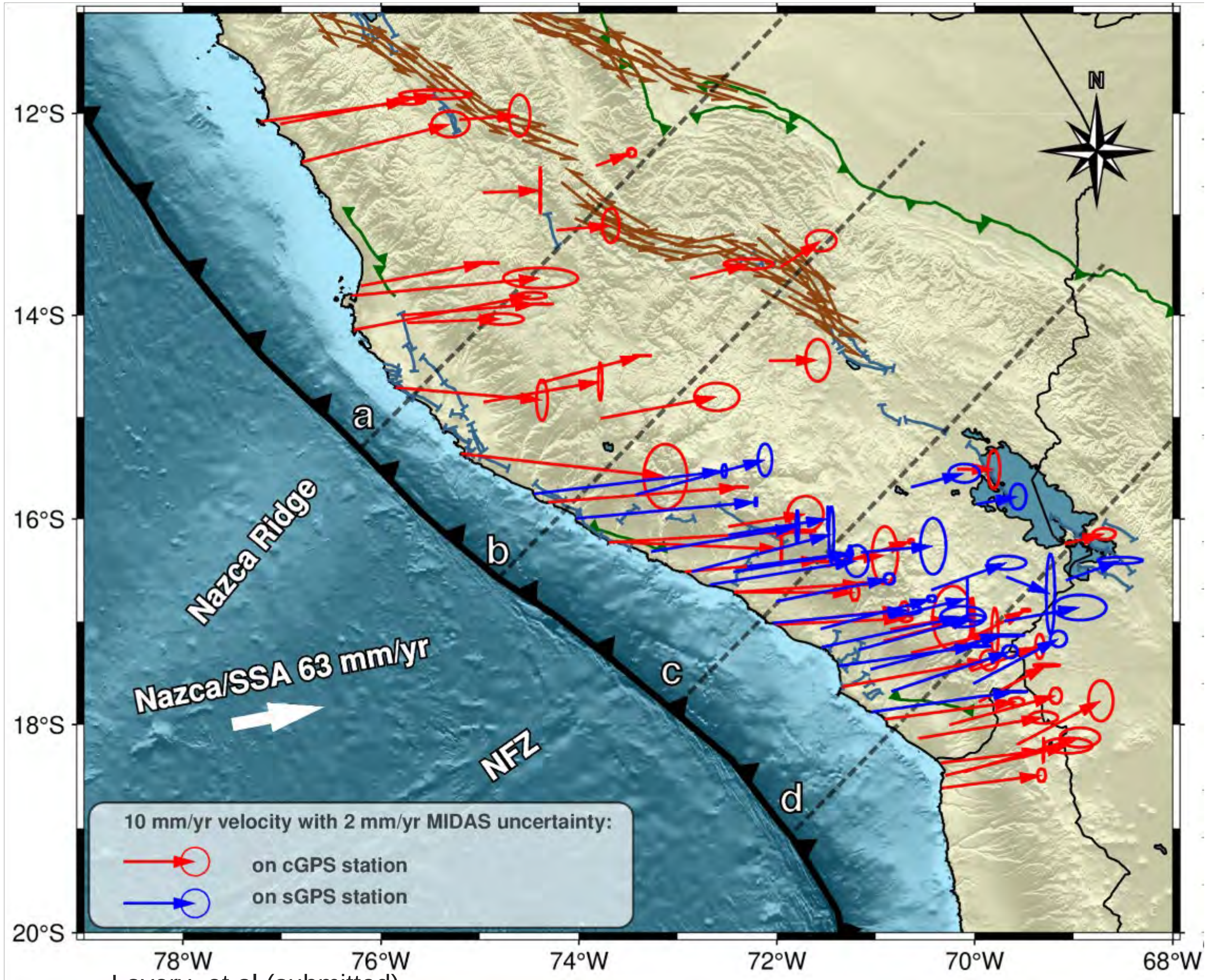
GNSS position time series at coastal stations

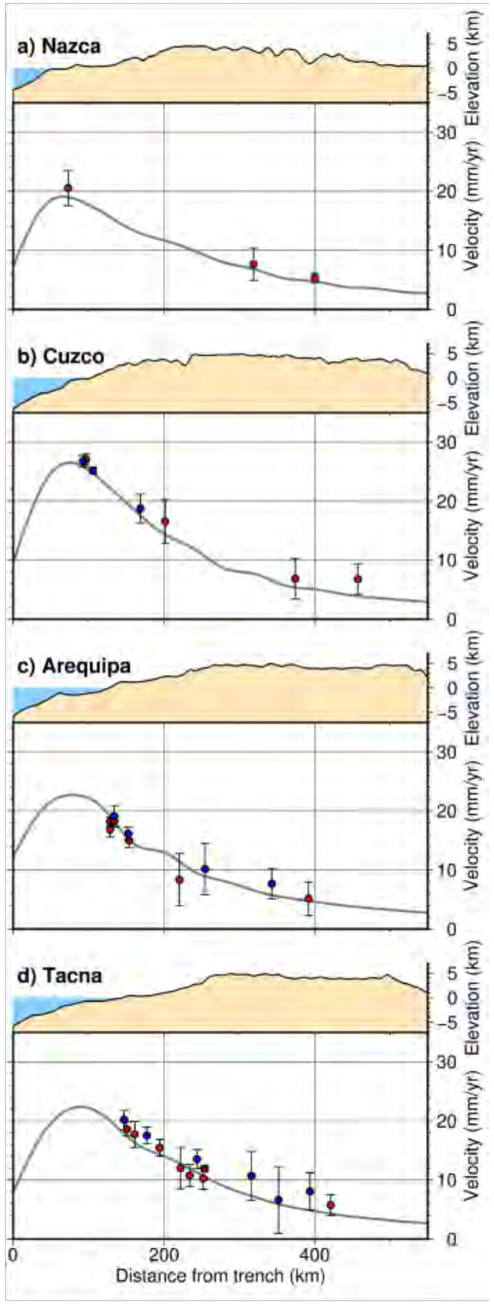




Lovery, et al (submitted)

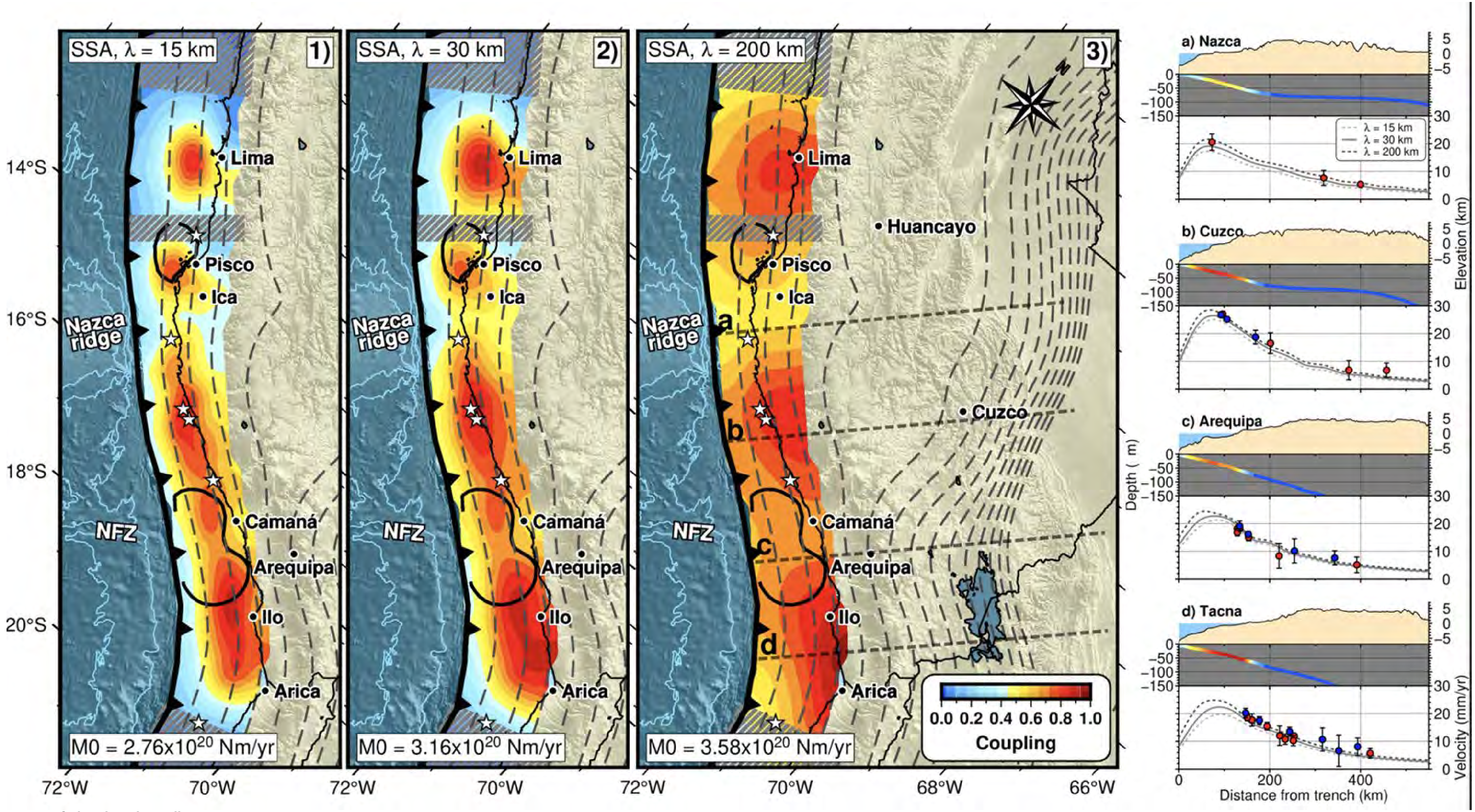
New GNSS velocity field (2007-2023)





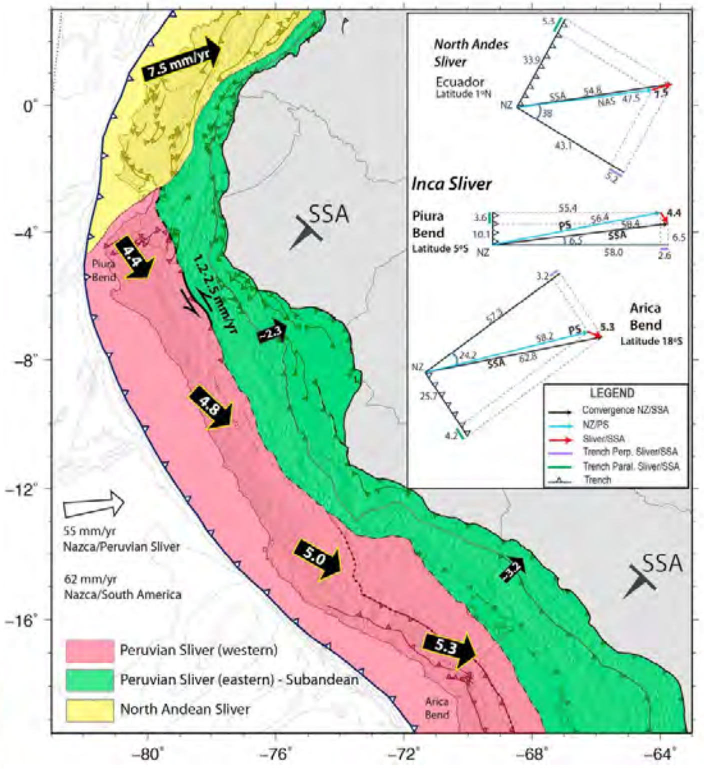
Lovery, et al (submitted)

Coupling models wrt SSA



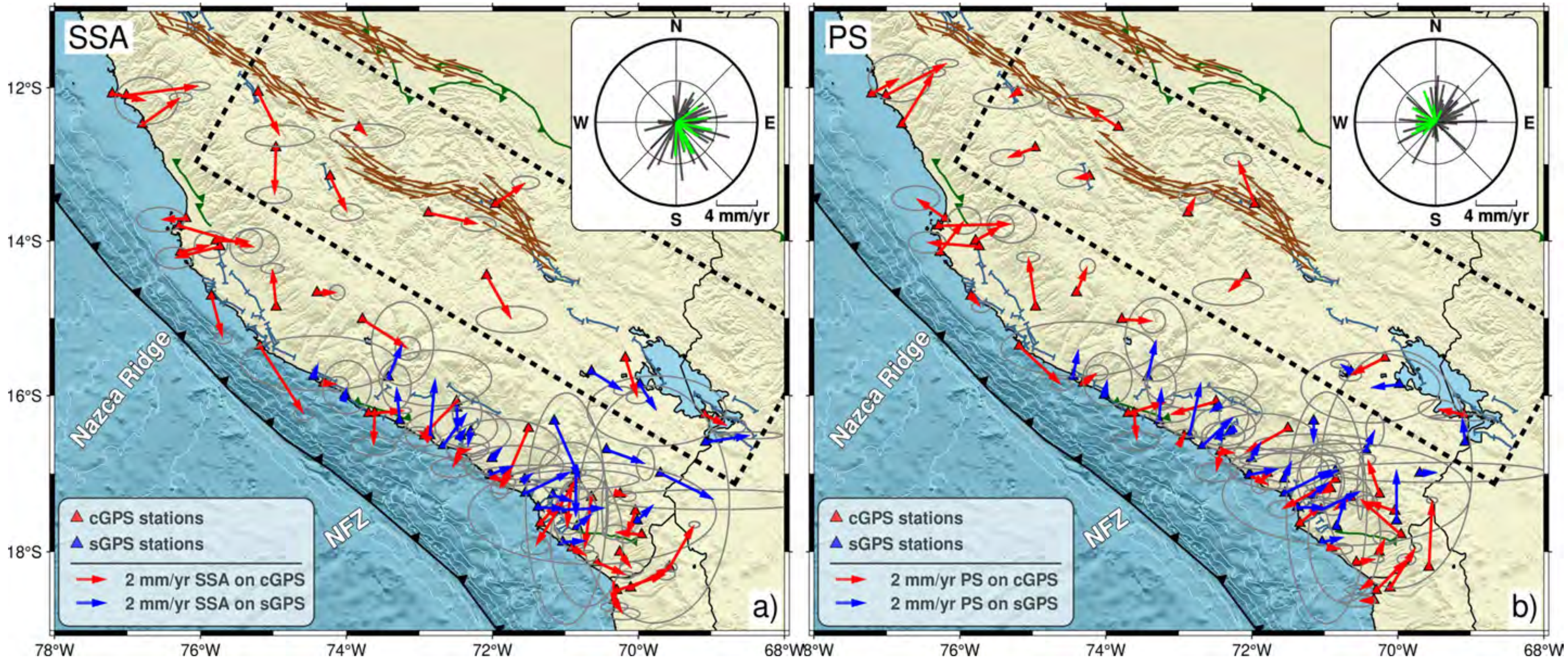
Lovery, et al (submitted)

Taking the peruvian sliver into account

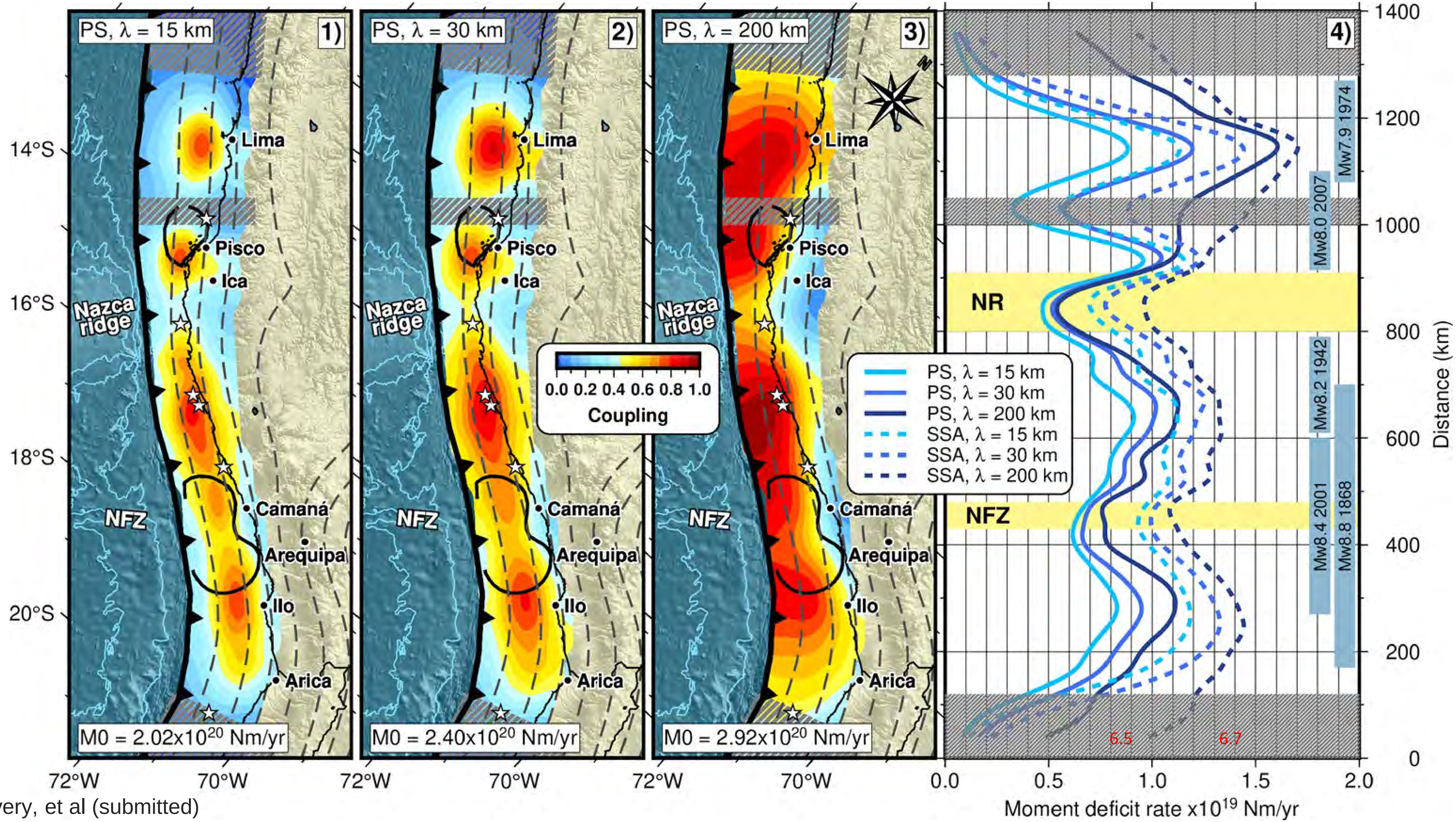


Data are better fit when the sliver's movement is used in the model

Lovery, et al (submitted)

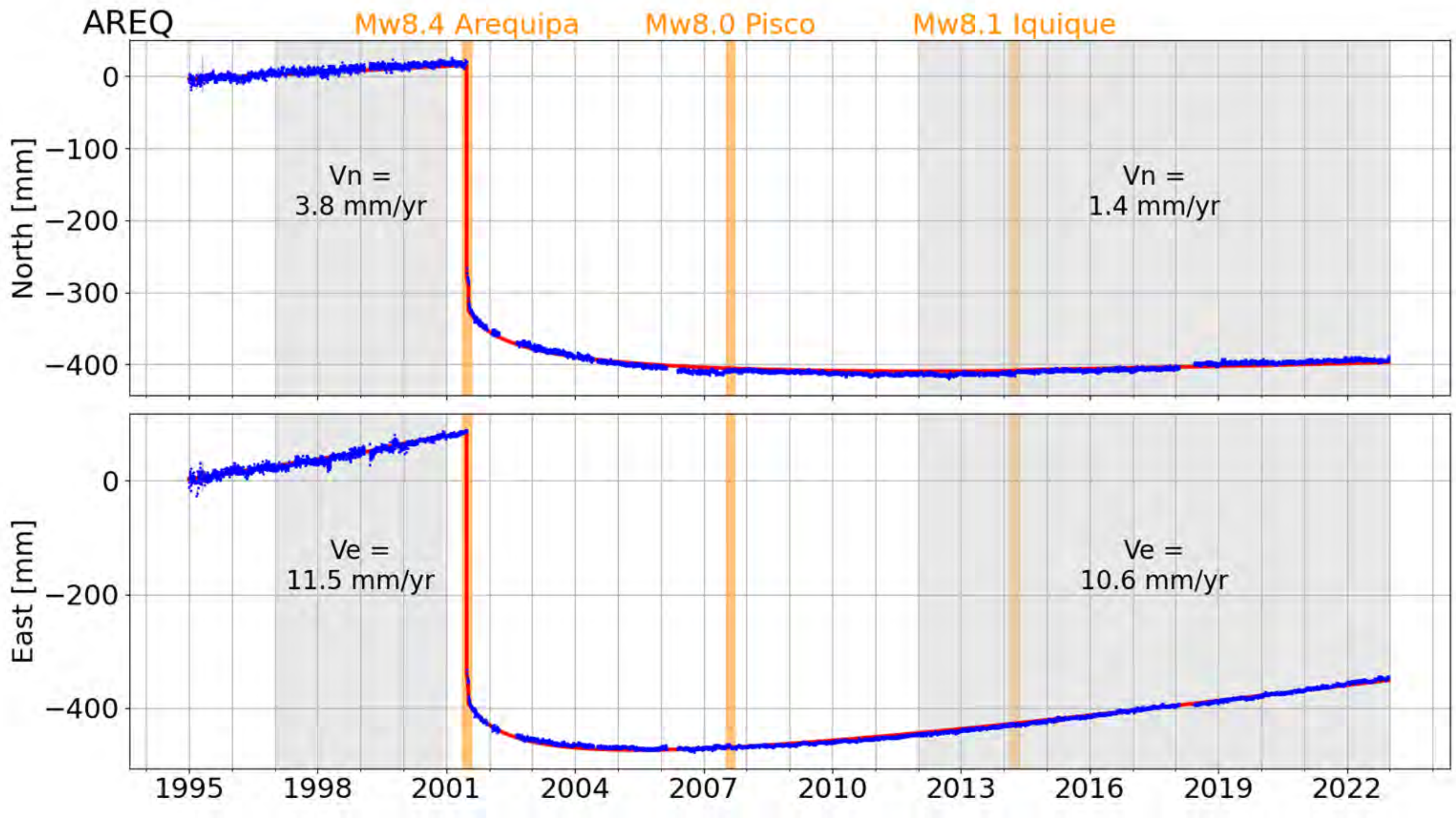


Interseismic coupling wrt PS - Segmentation



Lovery, et al (submitted)

GNSS time series at Arequipa



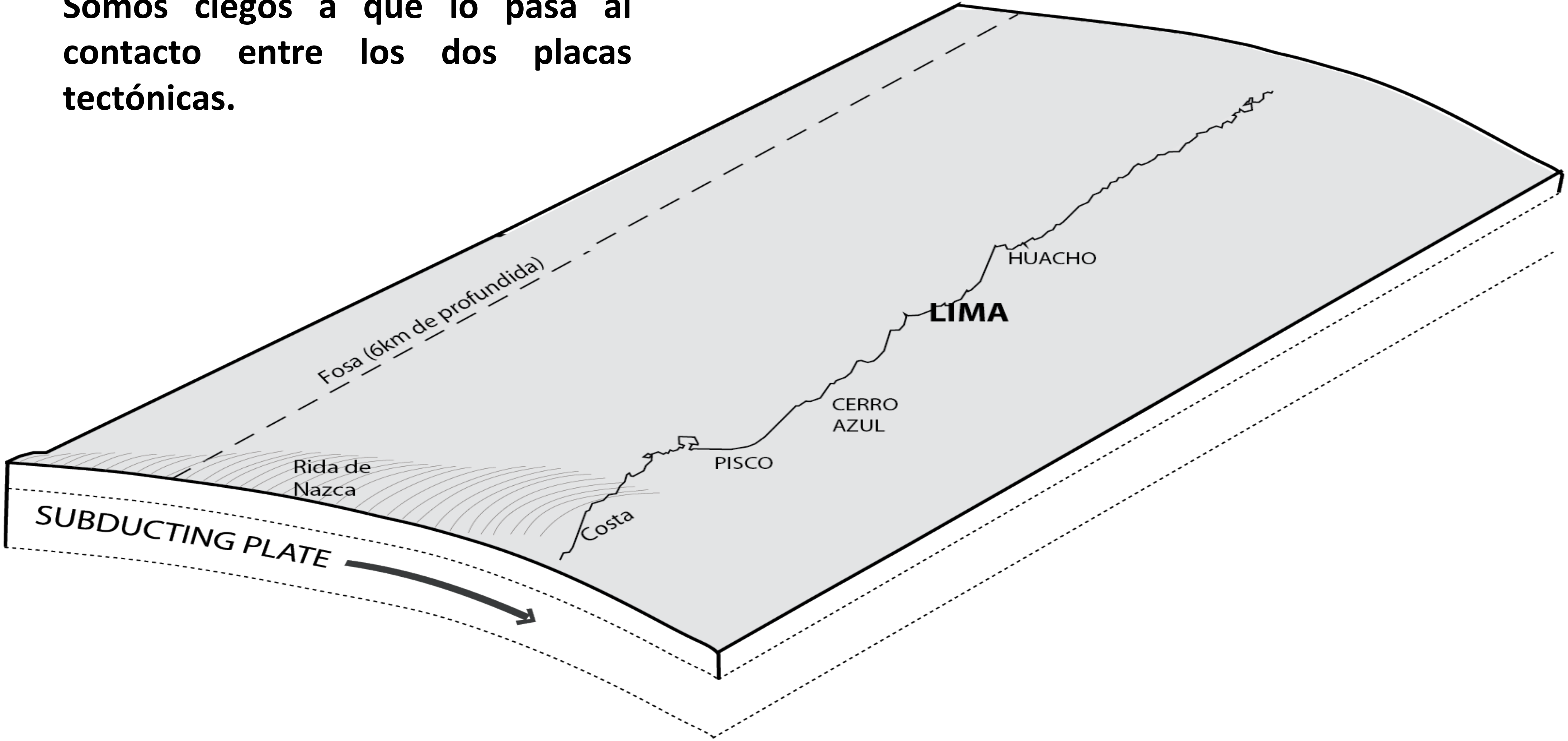
Lovery, et al (submitted)

- The return time is around 7 years after the 2001 earthquake.
- During the observation period of this study (2012-2022 for many stations), the interseismic velocity measured at the AREQ station is reduced by around 15% in the SSA reference frame and by around 30% in the PS reference frame, compared with its pre-2001 value.
- However, these estimates of 15% (SSA) and 30% (PS) should be interpreted as a maximum post-seismic effect on the moment deficit rate, as the AREQ station is close to the centroid (< 200 km).

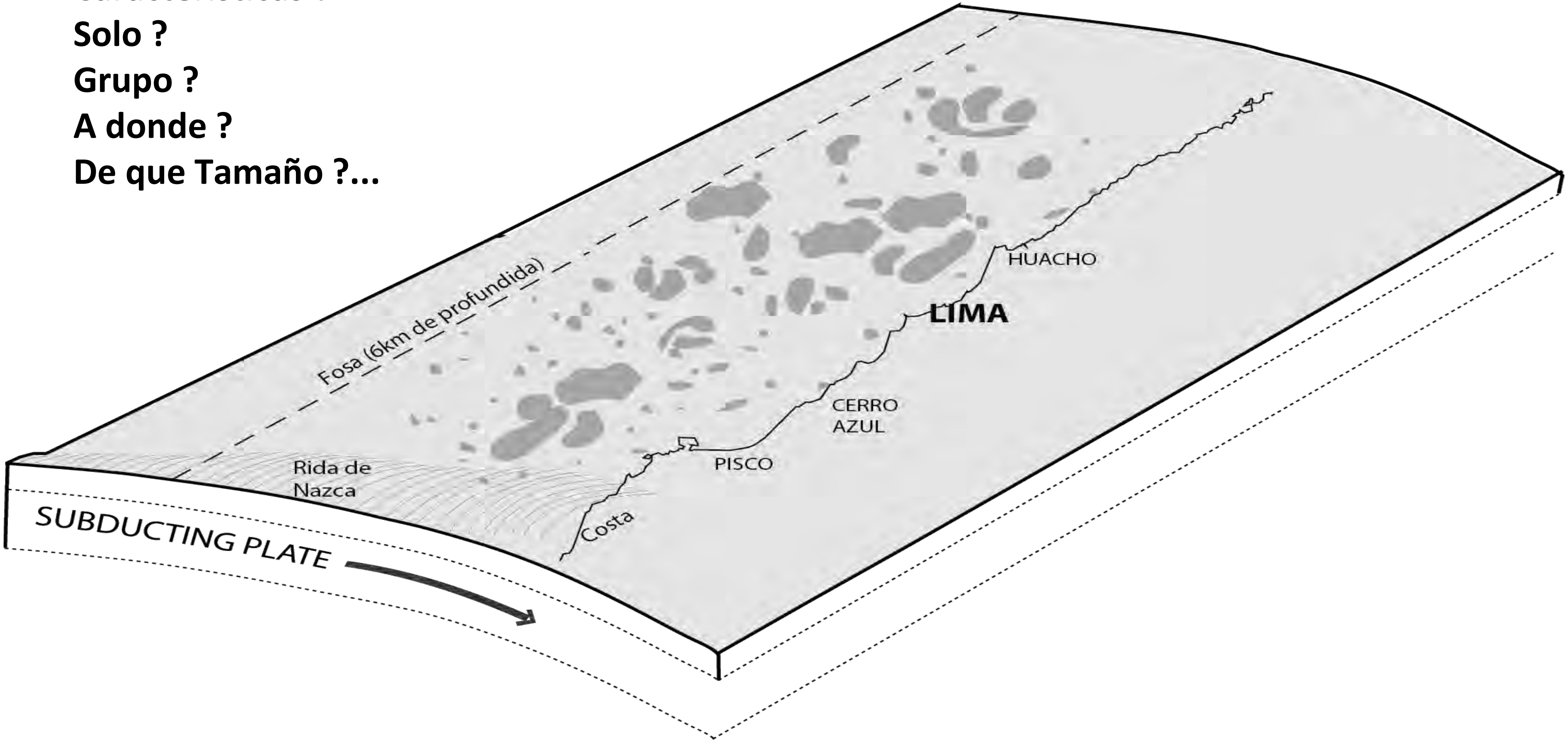
synthèse et budget de moment : mohamed

Al contacto entre los dos placas tectonicas

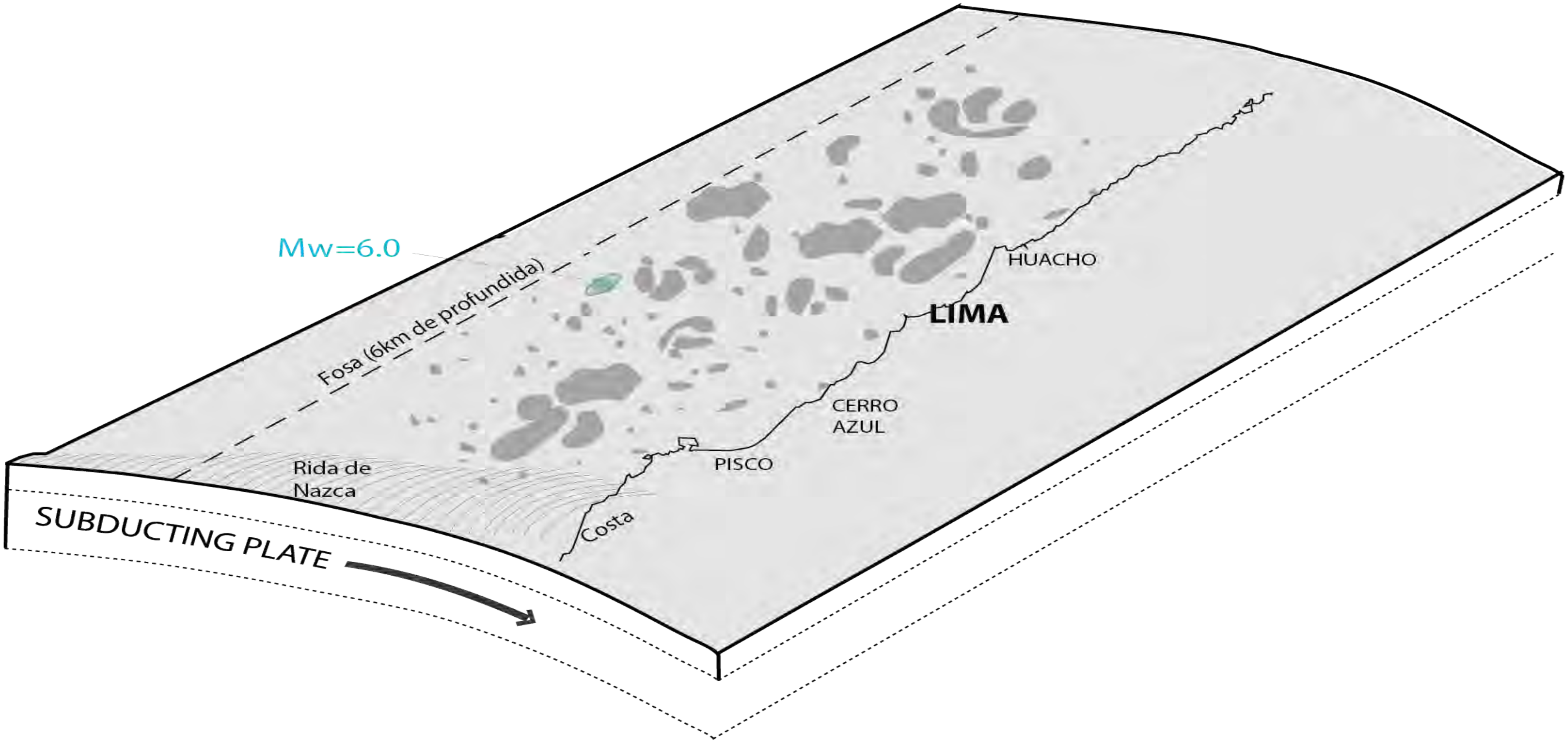
Somos ciegos a que lo pasa al contacto entre los dos placas tectónicas.



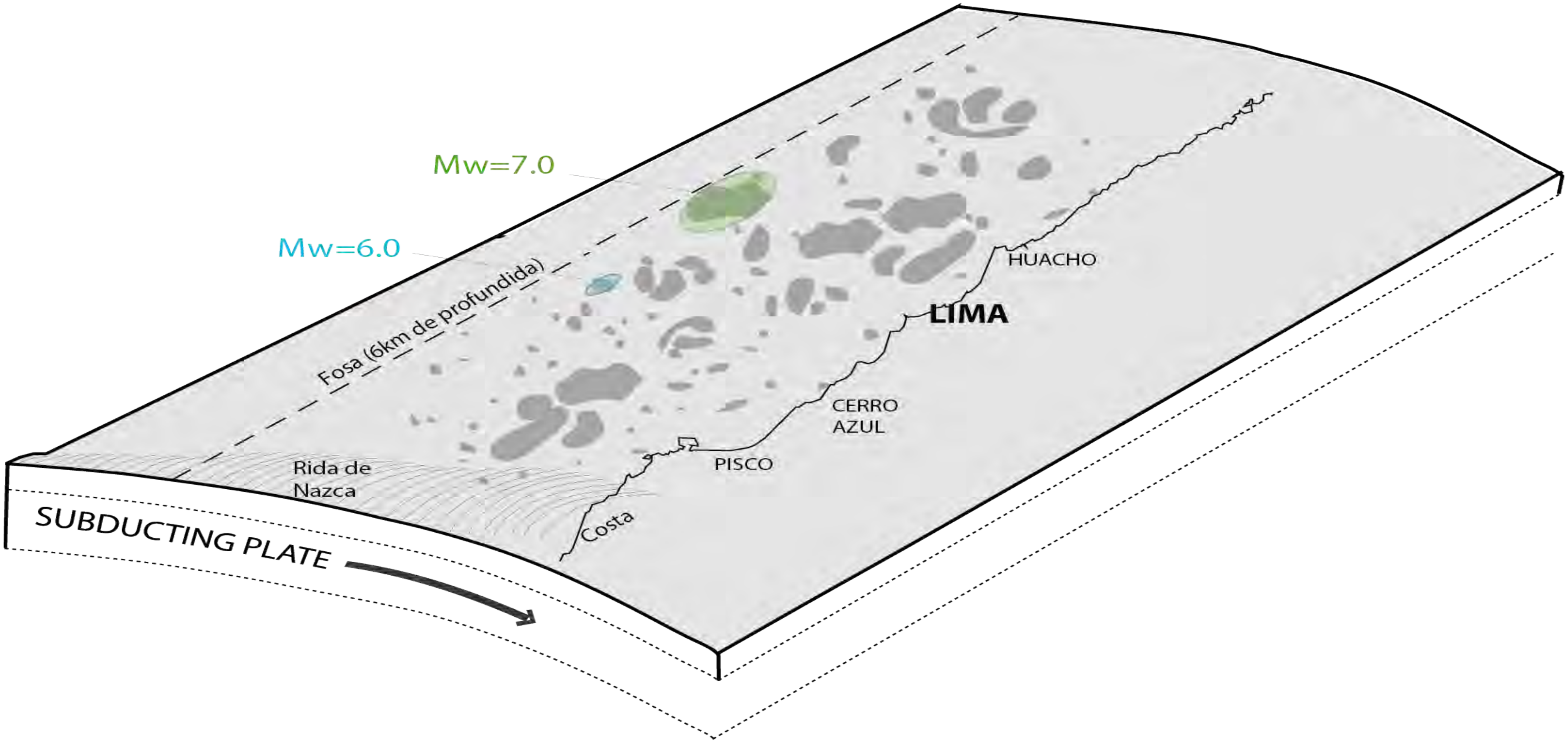
Las Asperezas son escondidas al contacto entre los dos placas tectónicas
Características ?
Solo ?
Grupo ?
A donde ?
De que Tamaño ?...



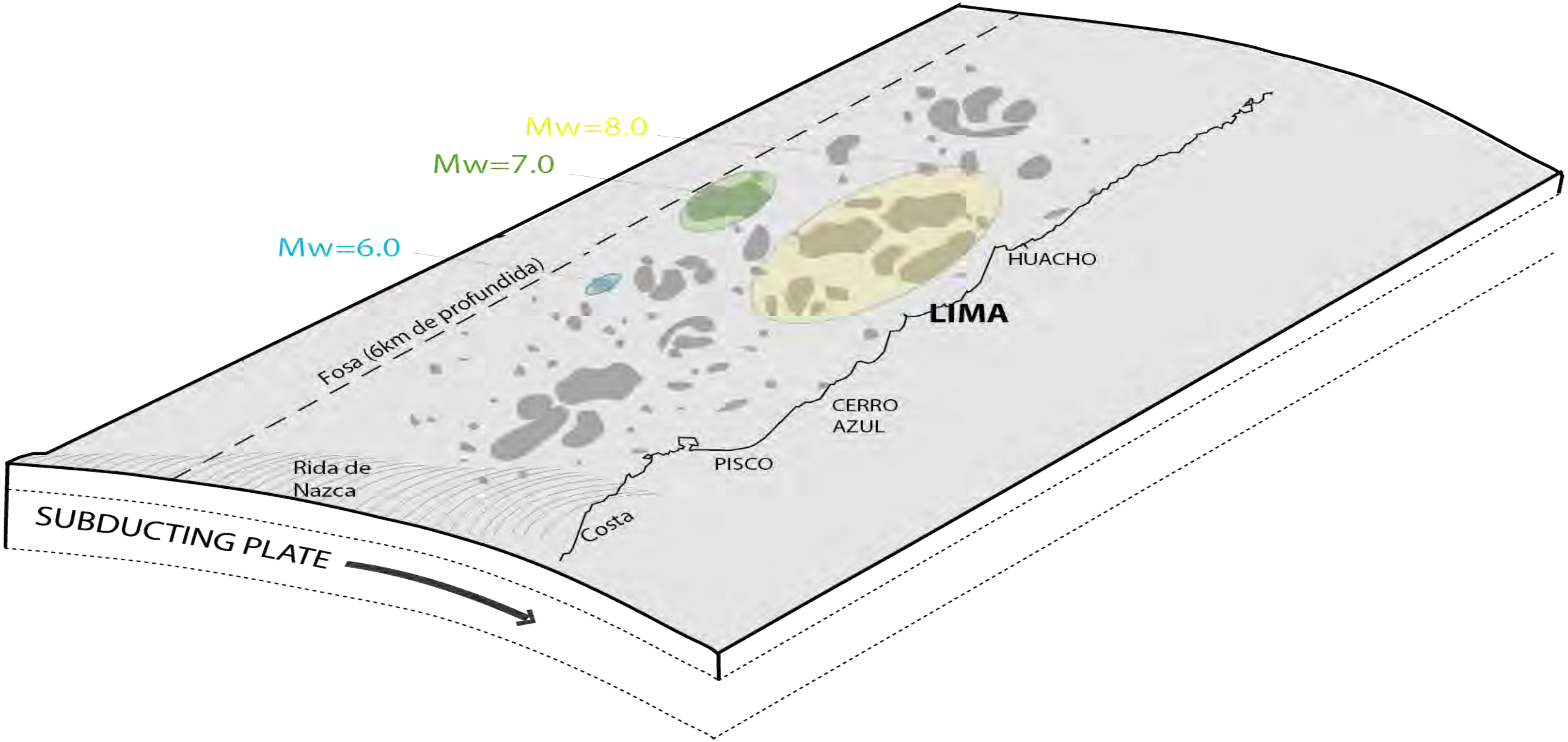
Mw ~ 6-7 ~ 10-50 km con 10cm-1m



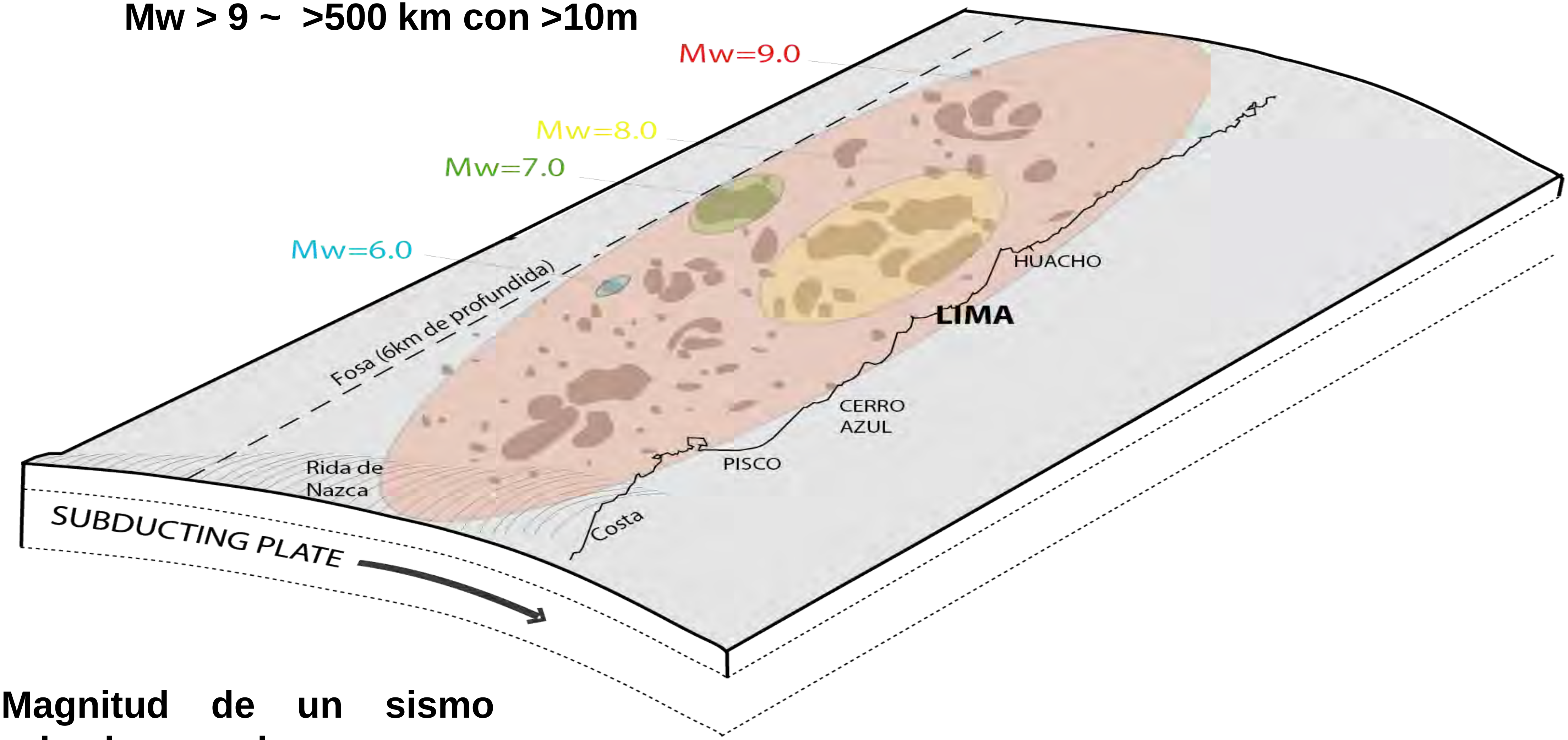
Mw ~ 6-7 ~ 10-50 km con 10cm-1m
Mw ~ 7-8 ~ 50-200 km con 1m-5m



Mw ~ 6-7 ~ 10-50 km con 10cm-1m
Mw ~ 7-8 ~ 50-200 km con 1m-5m
Mw ~ 8-9 ~ 200-500 km con 5m-10m

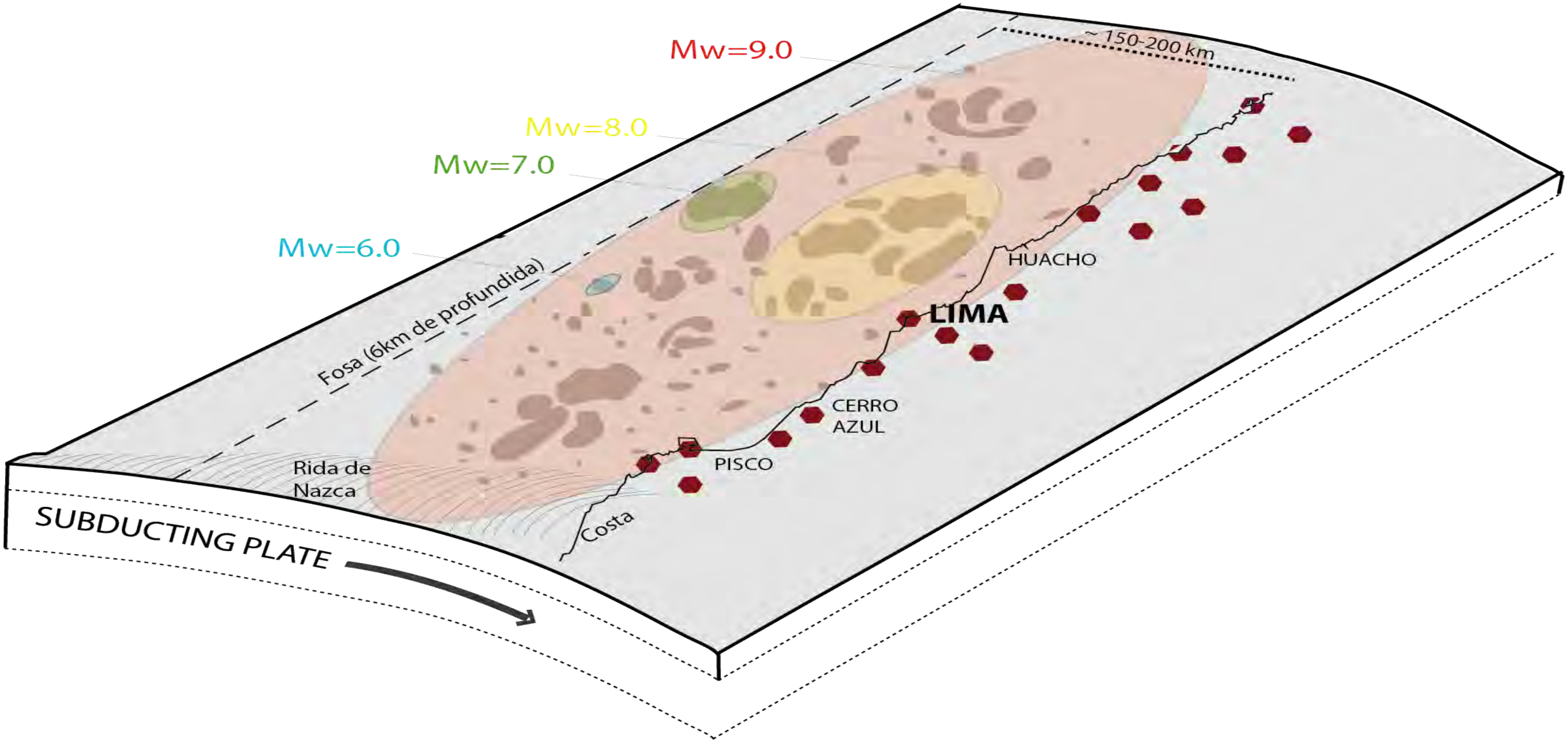


Mw ~ 6-7 ~ 10-50 km con 10cm-1m
Mw ~ 7-8 ~ 50-200 km con 1m-5m
Mw ~ 8-9 ~ 200-500 km con 5m-10m
Mw > 9 ~ >500 km con >10m



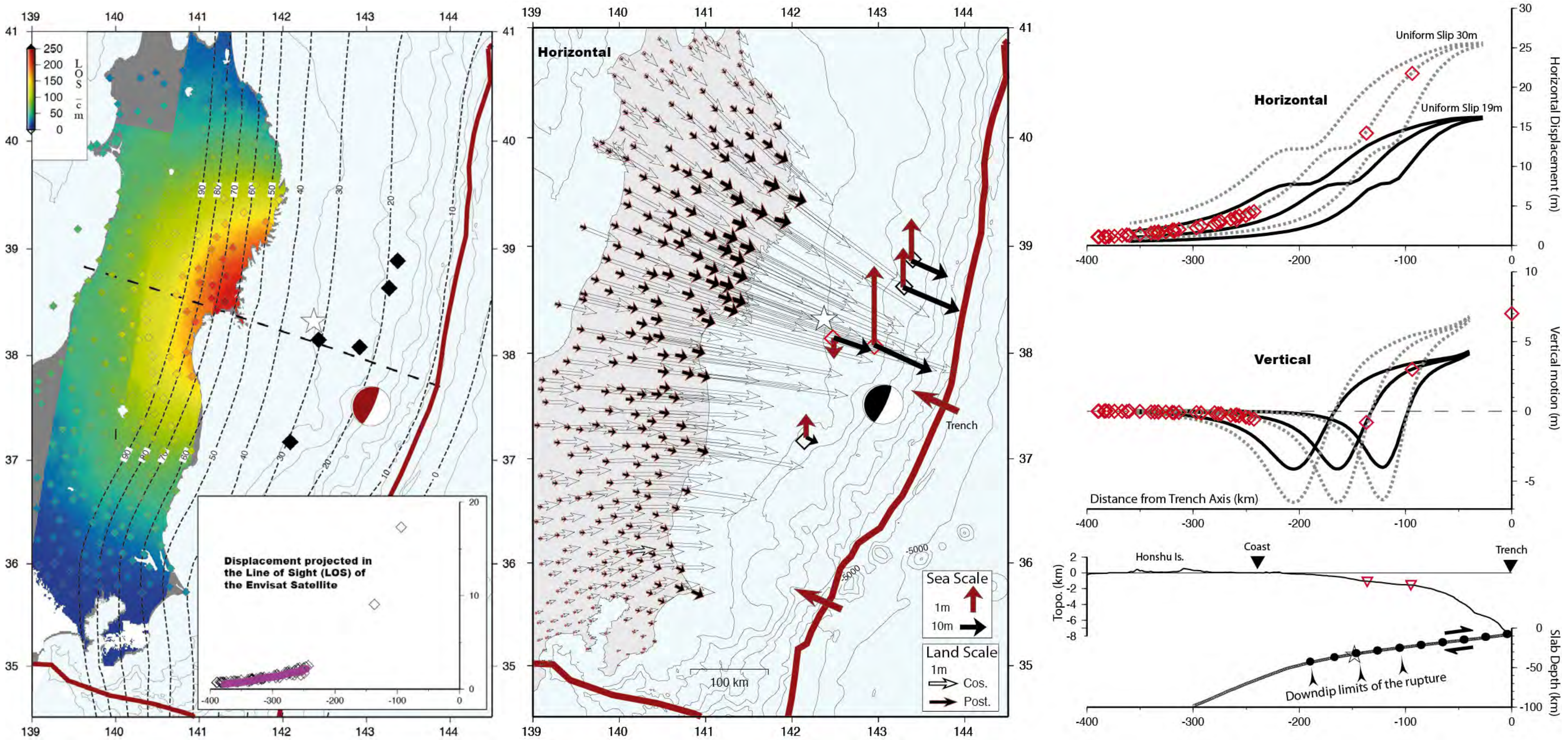
La Magnitud de un sismo depende de cuando asperezas se rompen al mismo tiempo y del desplazamiento de cada

Es posible de conocer las características de las asperezas con bastante observaciones de sismología, de geodesia, …

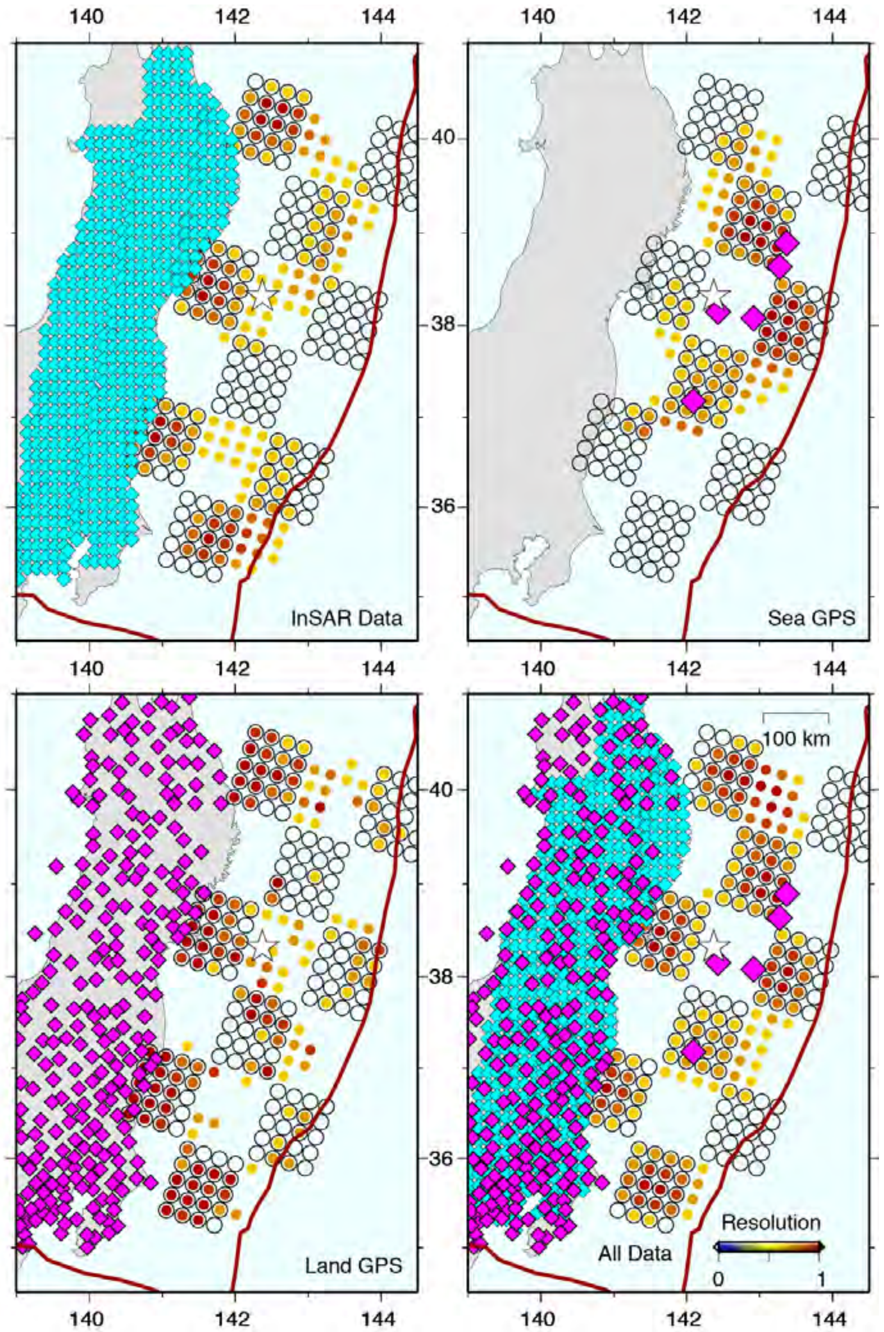


However difficult/impossible to provide a fine description without data on top of the asperities and close to the trench from observations at 100-200km !

2011 Tohoku Coseismic Deformation from InSAR, Land GPS and Sea GPS



Importance of seafloor data to improve the resolution



Checker-Board Resolution tests for Insar, Seafloor GPS and Land GPS data of the 2011 Tohoku earthquake

Homogeneous and Dense geodetic networks help to improve the resolution of slip on the megathrust interface

Need to increase seafloor geophysical observations,
especially in Subduction Zones where the trench-coast distance is high !

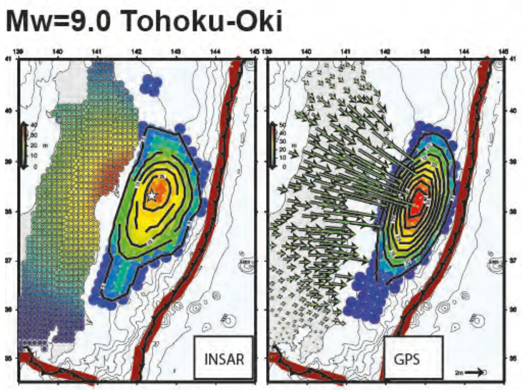
Seismic Sources of large and great subduction earthquakes

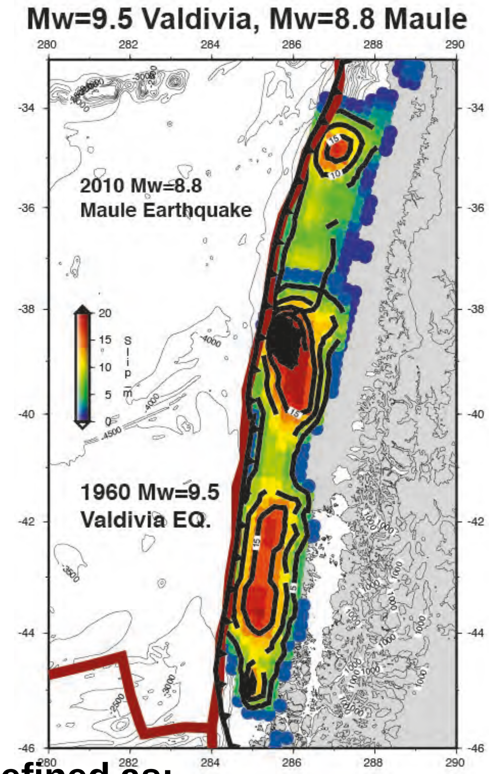
2011, MW=9.0
~400KM
~50M

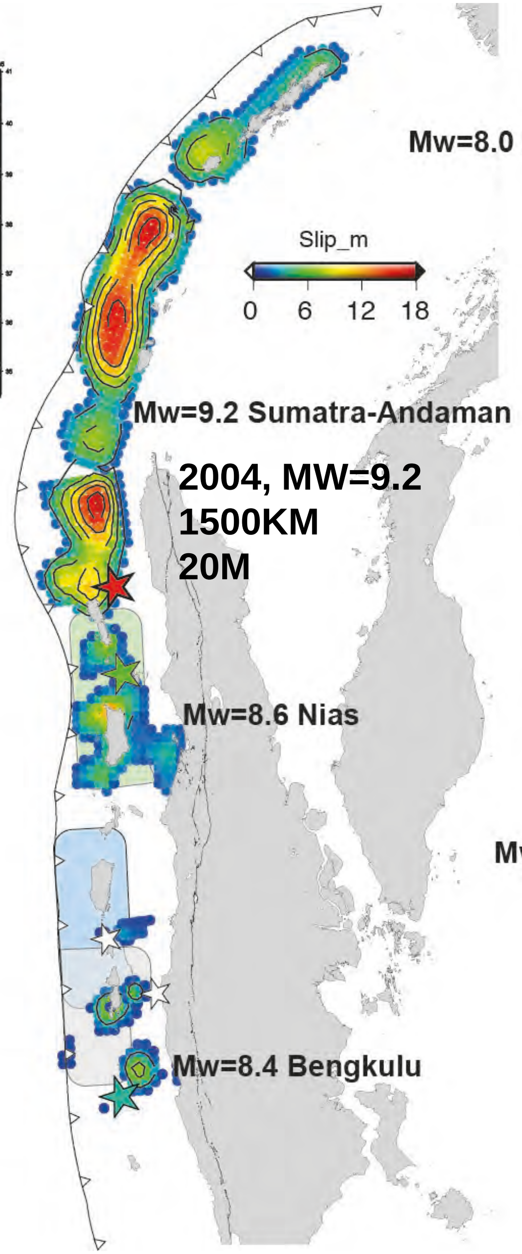
Scale
200KM

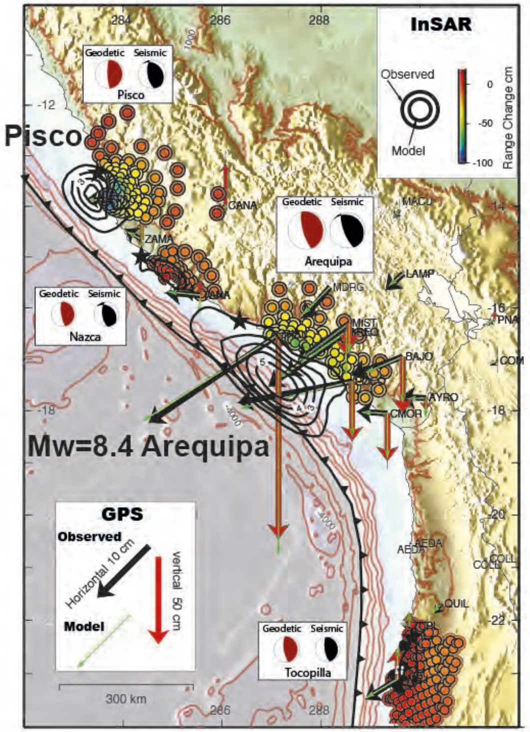
2010, MW=8.8
550KM
15M

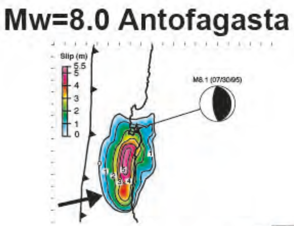
1960, MW=9.5
1000KM
30M

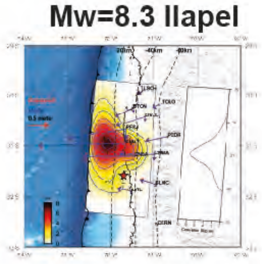












Mw=9.2 ~ 2 x Mw=9.0

Mw=9.0 ~ 2 x Mw=8.8

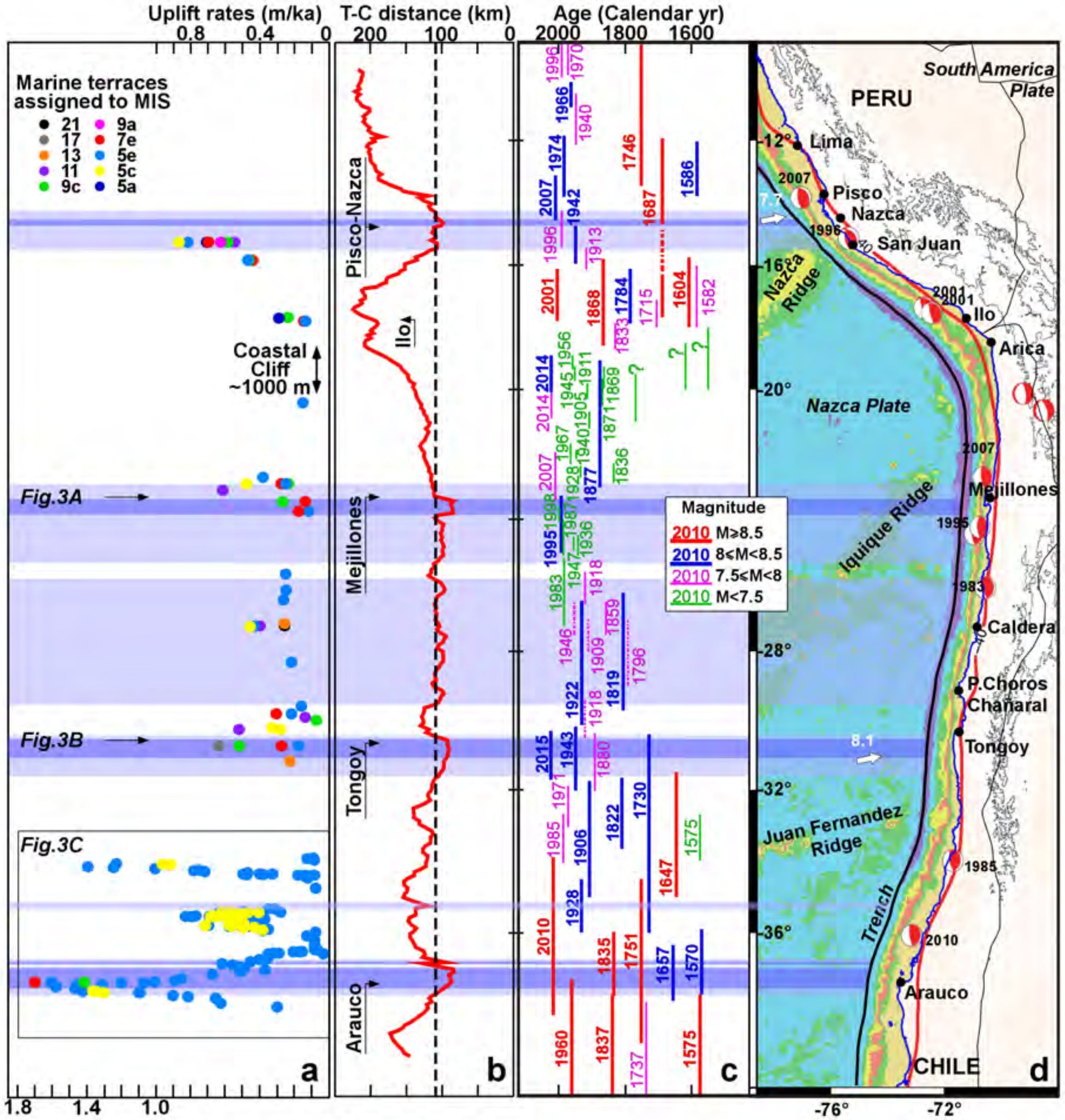
……

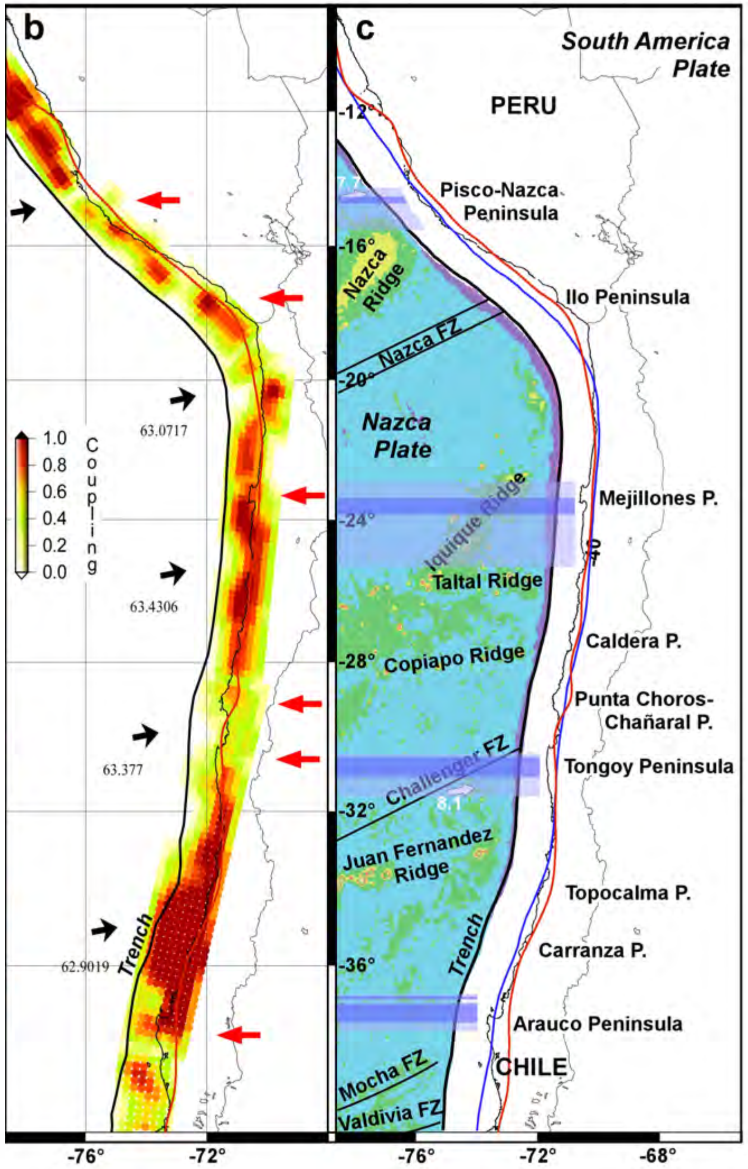
Mw=9.0 ~ 30 x Mw=8.0

Seismic Moment is defined as:
Mo = mu x Seismic Slip x Rupture Surface

Chlieh et al. 2004, 2007, 2011, 2021 Konca 2008, 2010, Shrivastana 2016

Short-term vs long-term deformation



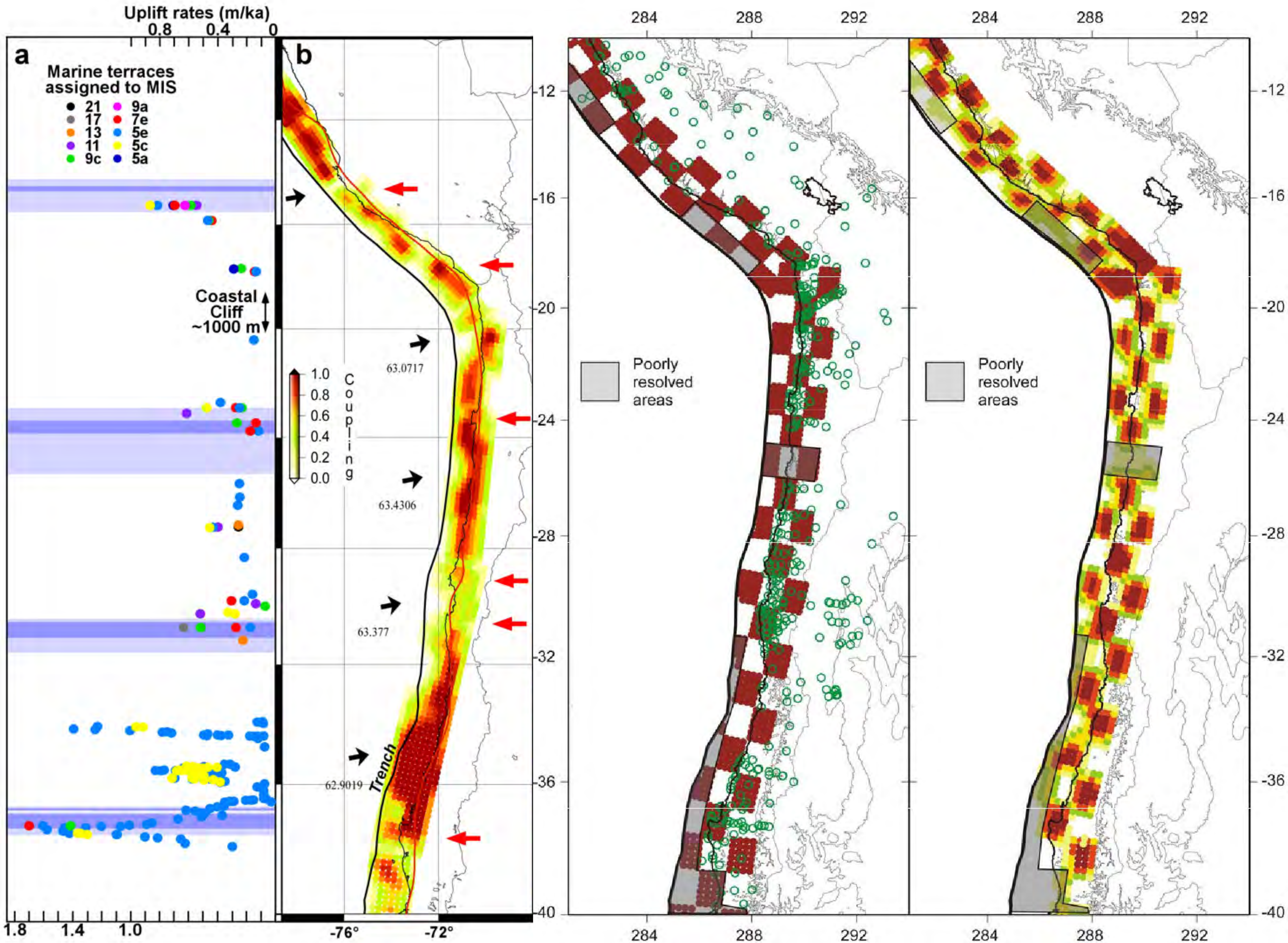


Spatial Correlation between Marine Teracesses and low coupled regions

Spatial Correlation between subducting ridges and Fracture Zones with low coupled regions

Low coupled regions play the role of seismic barriers

Saillard et al 2017



Uplift rates (m/ka)
0.8
0.4
0
a
Marine terraces
assigned to MIS
21
17
13
11
9c
9a
7e
5e
5c
5a
Coastal
Cliff
~1000 m
1.8
1.4
1.0
b
1.0
0.8
0.6
0.4
0.2
0.0
Coupling
63.0717
63.4306
63.377
62.9019
Trench
-76°
-72°
-12
-16
-20
-24
-28
-32
-36
-40
284
288
292
Poorly
resolved
areas

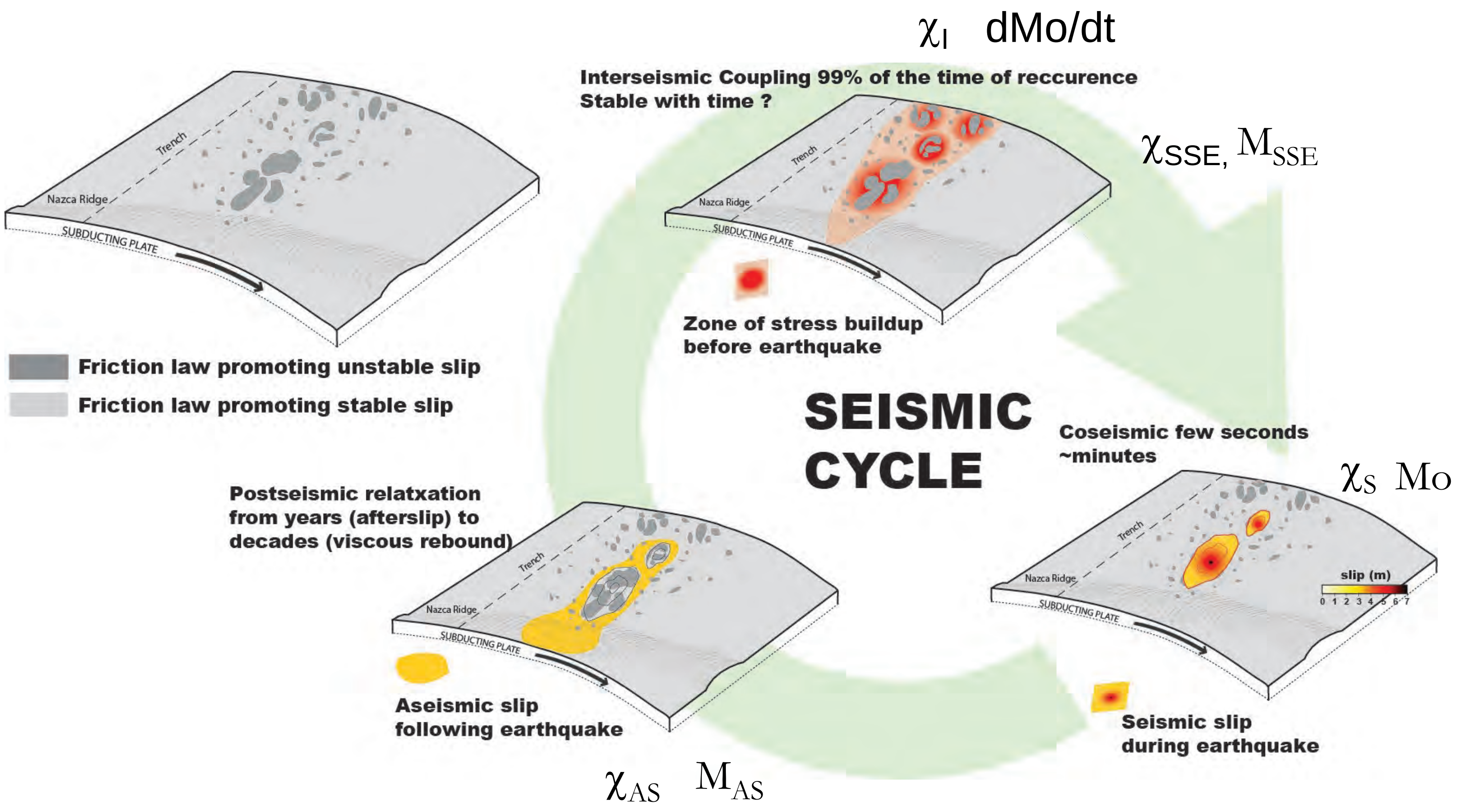
Seismic cycle and slip/moment budget on the long term

Over the long-term, the partitioning of slip during the seismic cycle can be quantified using the following quantities:

1) Interseismic coupling, χ_i, the ratio of the deficit of slip in the interseismic period to long-term slip, assumed to be stationary throughout the interseismic period.

2) Seismic coupling, χ_s, the ratio of cumulative seismic slip to long-term slip

3) Aseismic coupling, $\chi_a = \chi_{as} + \chi_{sse}$, the ratio of cumulative aseismic transients (afterslip and SSEs) to long-term slip;



Closure of the slip budget, the condition that seismic slip and aseismic slip s to match long-term slip at any point on the fault, writes:

$$\chi_i = \chi_s + \chi_{as} + \chi_{sse}$$

Estimating the maximum magnitude (Mw_{max}) Earthquake

Interseismic coupling: $\chi_i = \chi_s + \chi_a = \chi_s + \chi_{as} + \chi_{SSE}$

Seismic (χ_s), Aseismic (χ_a), Afterslip (χ_{as}), Slow-slip events (χ_{SSE})

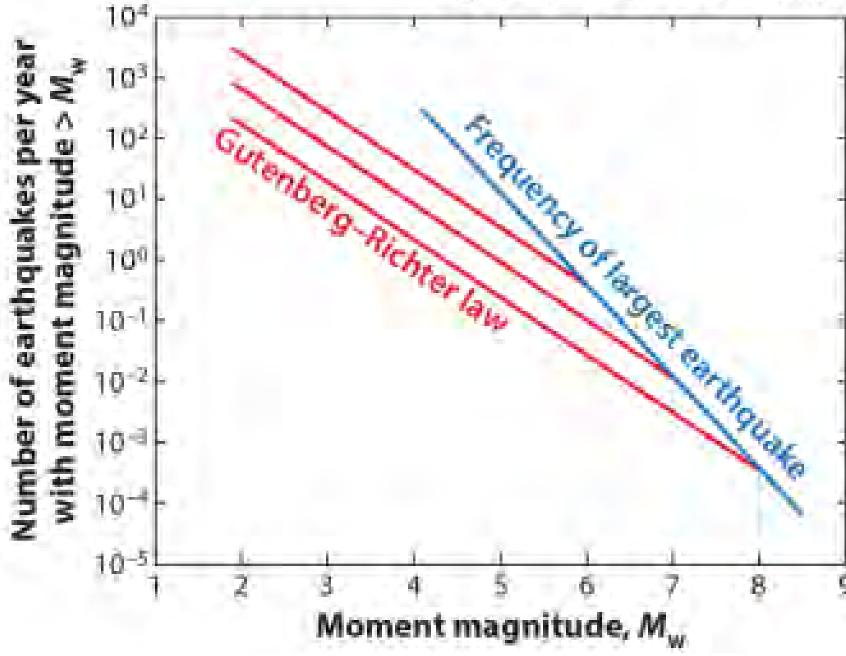
Number of earthquakes with a magnitude >Mw: $N = 10^{a - bM_w}$

Moment deficit rate: $\frac{dM_0}{dt} = \int \mu V \chi_i dS$

Return period of the maximum magnitude EQ: $T(M_{max}) = \frac{1}{(1 - 2b/3)\alpha} \frac{M_{max}}{dM_0/dt}$

Ratio of the slip that is seismic over all transient slips: $\alpha = \frac{\chi_s}{\chi_s + \chi_{as} + \chi_{SSE}}$

Figure from Avouac 2015

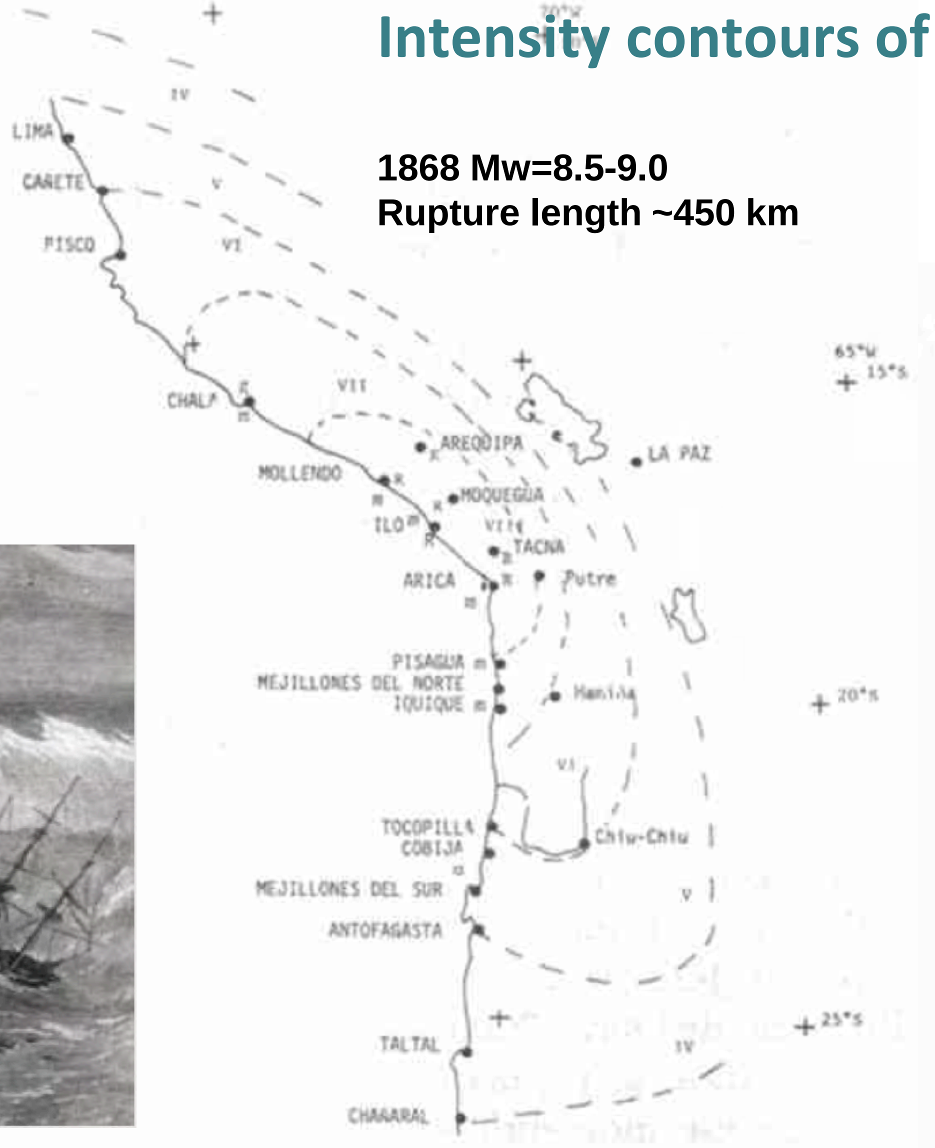


Molnar 1972, Avouac 2015

Intensity contours of 1868 & 1877 earthquakes

Tsunami in Arica, 1877

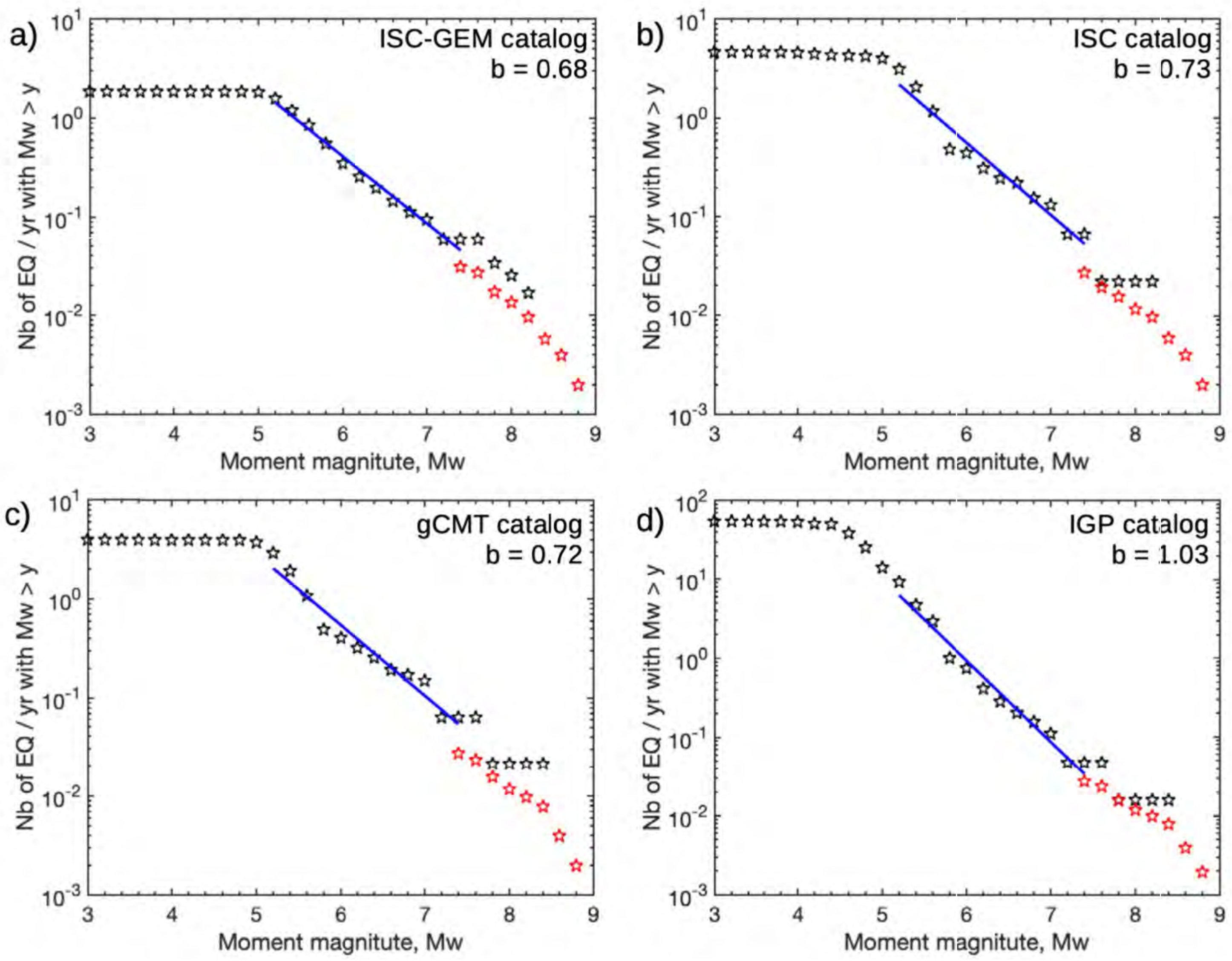
1868 Mw=8.5-9.0
Rupture length ~450 km



1877 Mw=8.5-9.0
Rupture length ~450 km

Mwmax for the South Peru

Gutenberg-Richer Law for various seismic catalogs in South Peru (from Nazca Ridge to Arica)



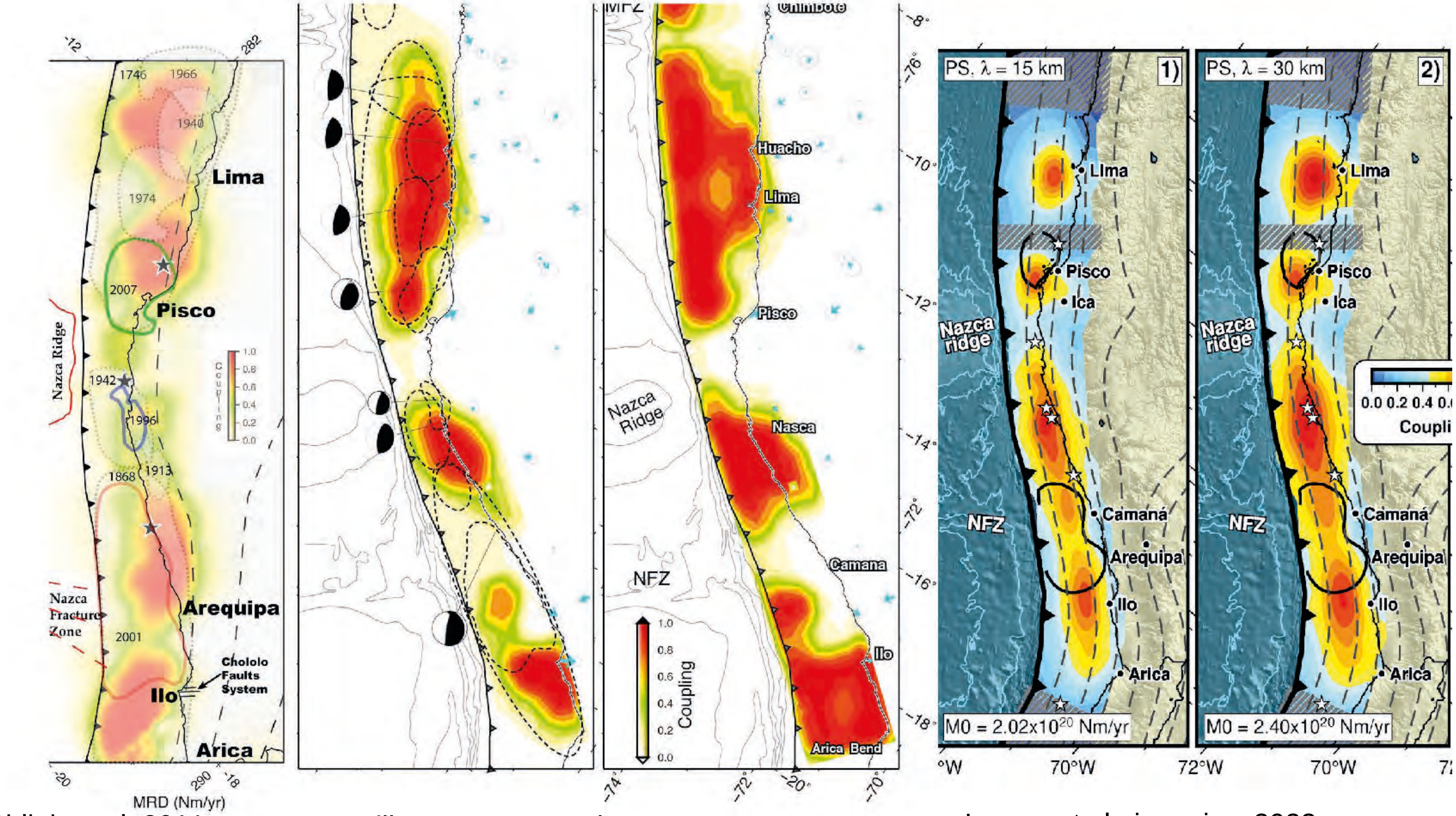
Classical statistical Methods used to determine the seismic hazard are strong mathematical tools but they have some limitations , because seismic catalogs are incomplete in the long term, missing small magnitudes, homogenized in magnitude scale

For instance such methods do not take into account :

1 – The velocity of loading of the system (coupling map and associated moment deficit rate)

2 – Aseismic slips that occur during the post-seismic period and slow slip events

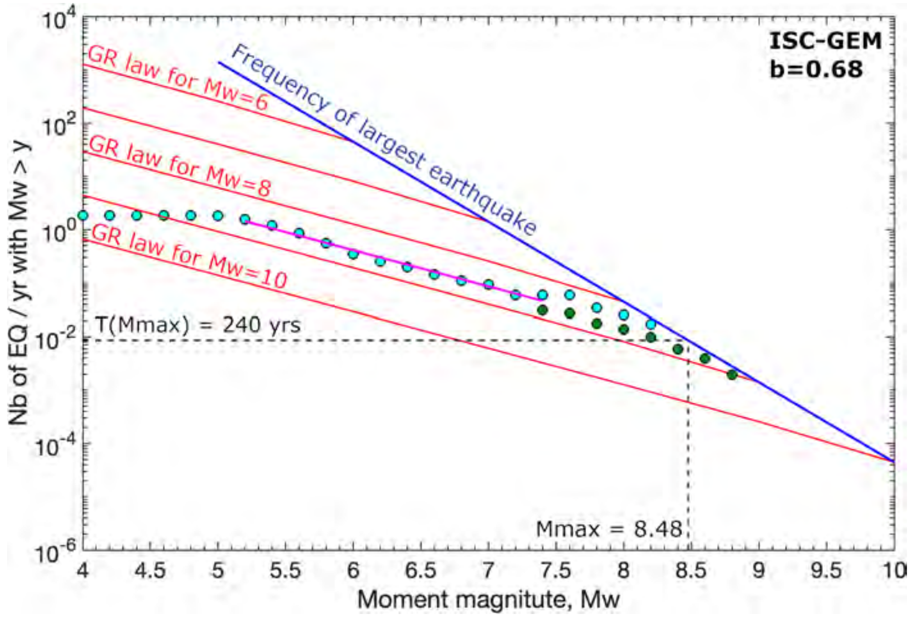
Mwmax for the South Peru

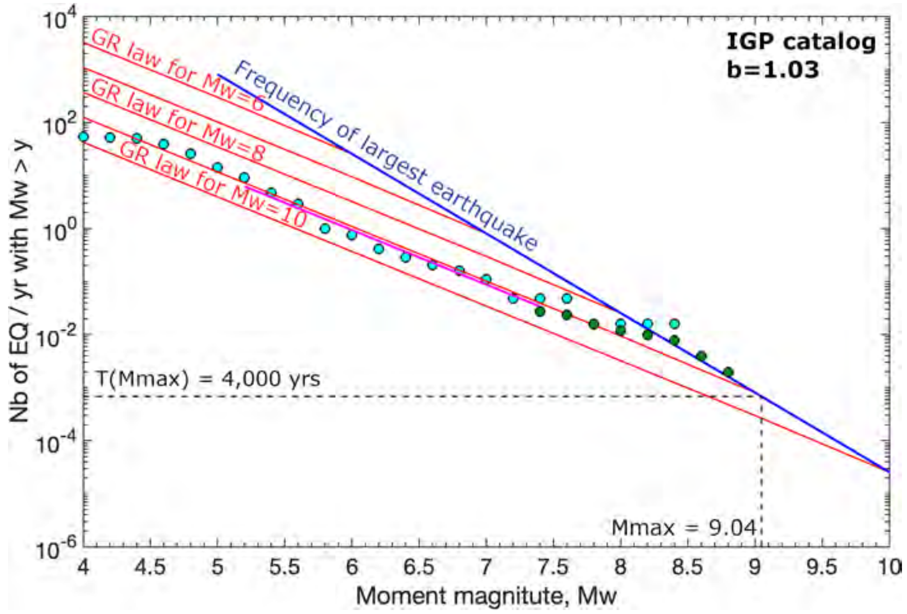


Chlieh et al. 2011 Villegas-Lanza et al., 2016 Lovery et al., in review 2023

The increase of GPS data improve relatively well the spatial location of asperities and barriers and our estimate of the annual Moment Deficit Rate (MDR in Nm/yr), Between Nazca Ridge and Arica, MRD ~ 2.4 +/- 0.4 x 10^20 Nm/yr

Mwmax for the South Peru

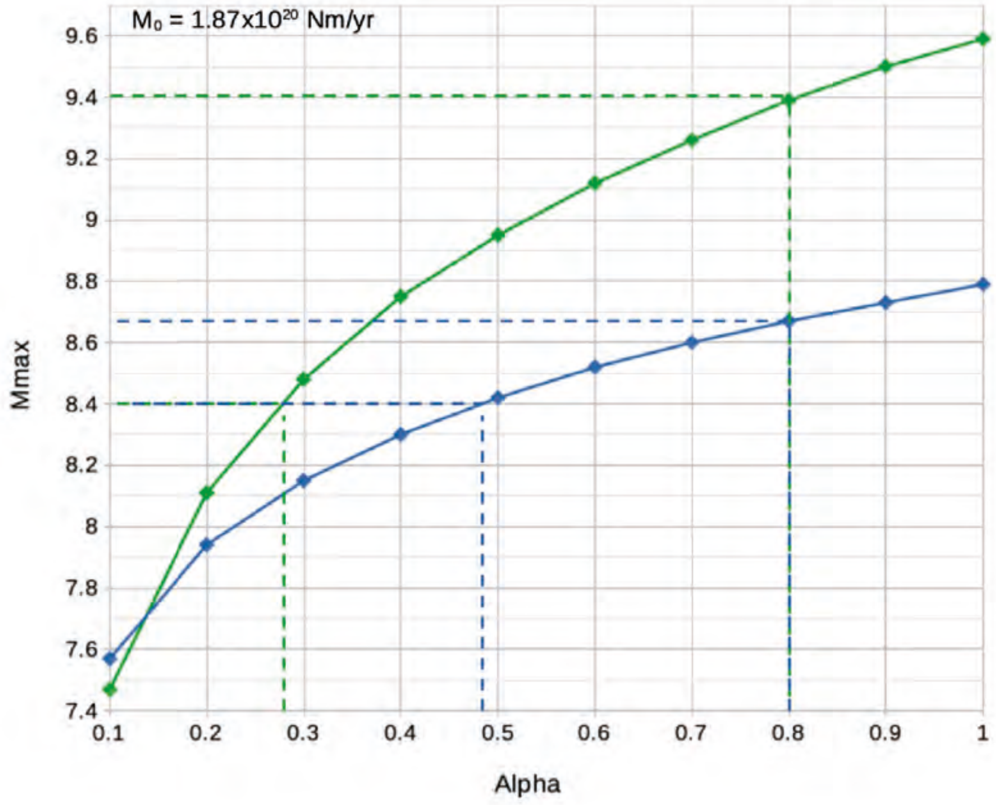




α = χs/(χs + χas + χSSE)

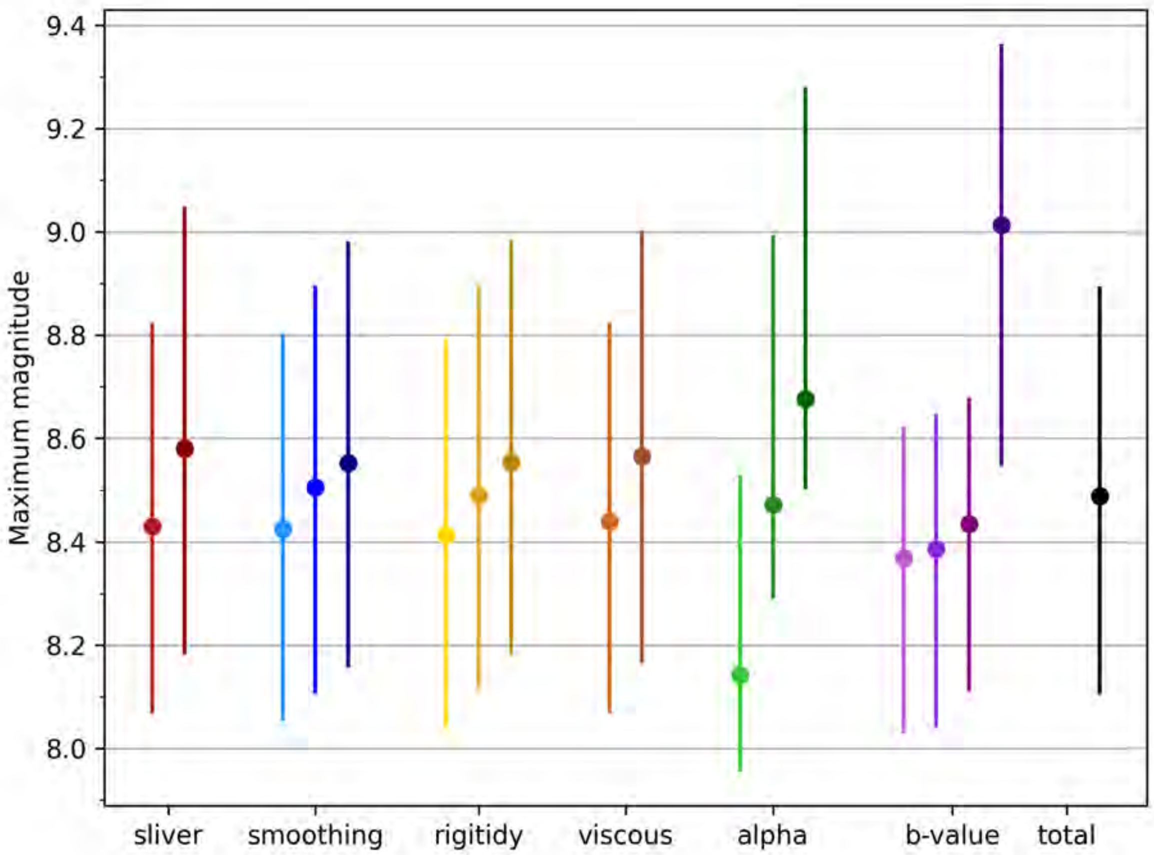
α = 1 transient slip is all seismic

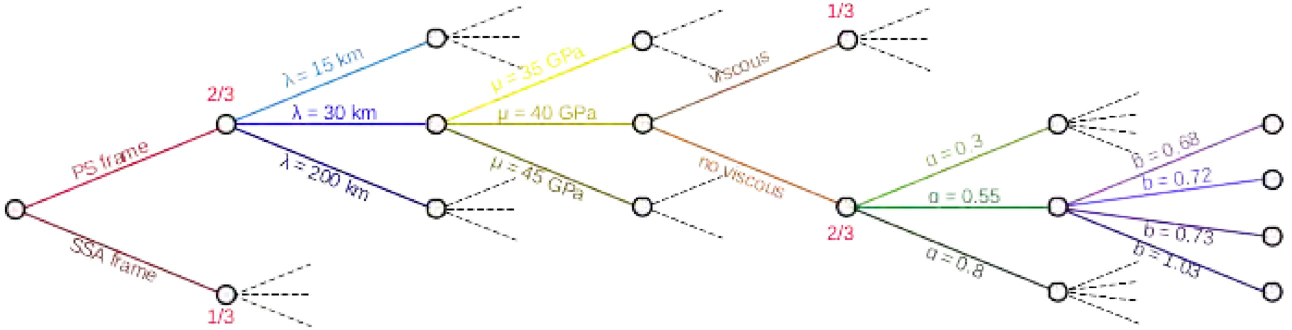
α = 0 transient slip is all aseismic



Lovery et al., in review 2023

Mmax for the South Peru





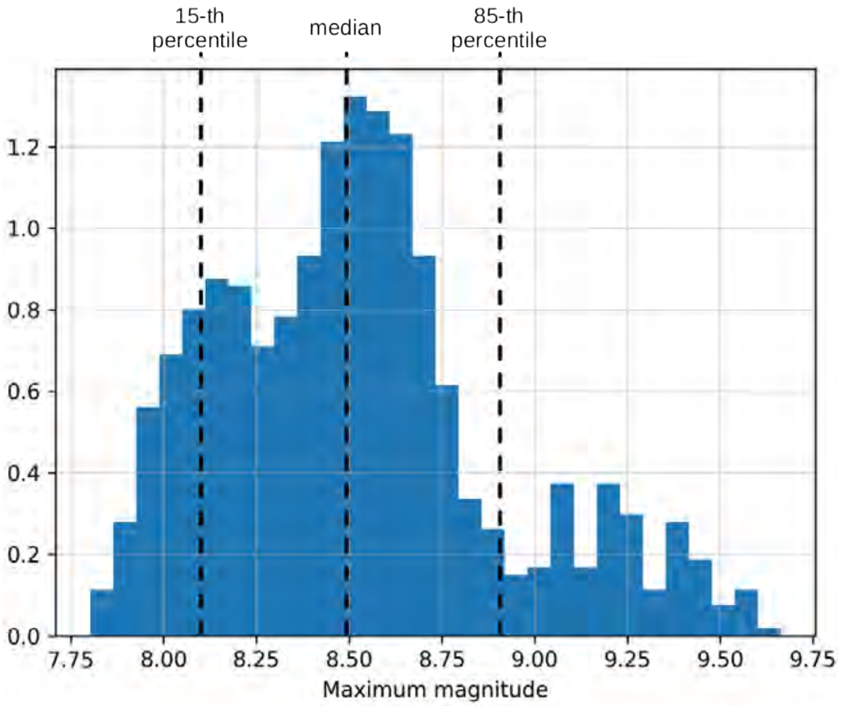
•432 combinations using various seismic catalogues (ISC, ISC-GEM, gCMT, IGP) and interseismic coupling models.

•South Peru segment (Nazca ridge to Arica) could host:

a Mw=8.4 earthquake every 100 years
to a Mw=8.9 every 900 years

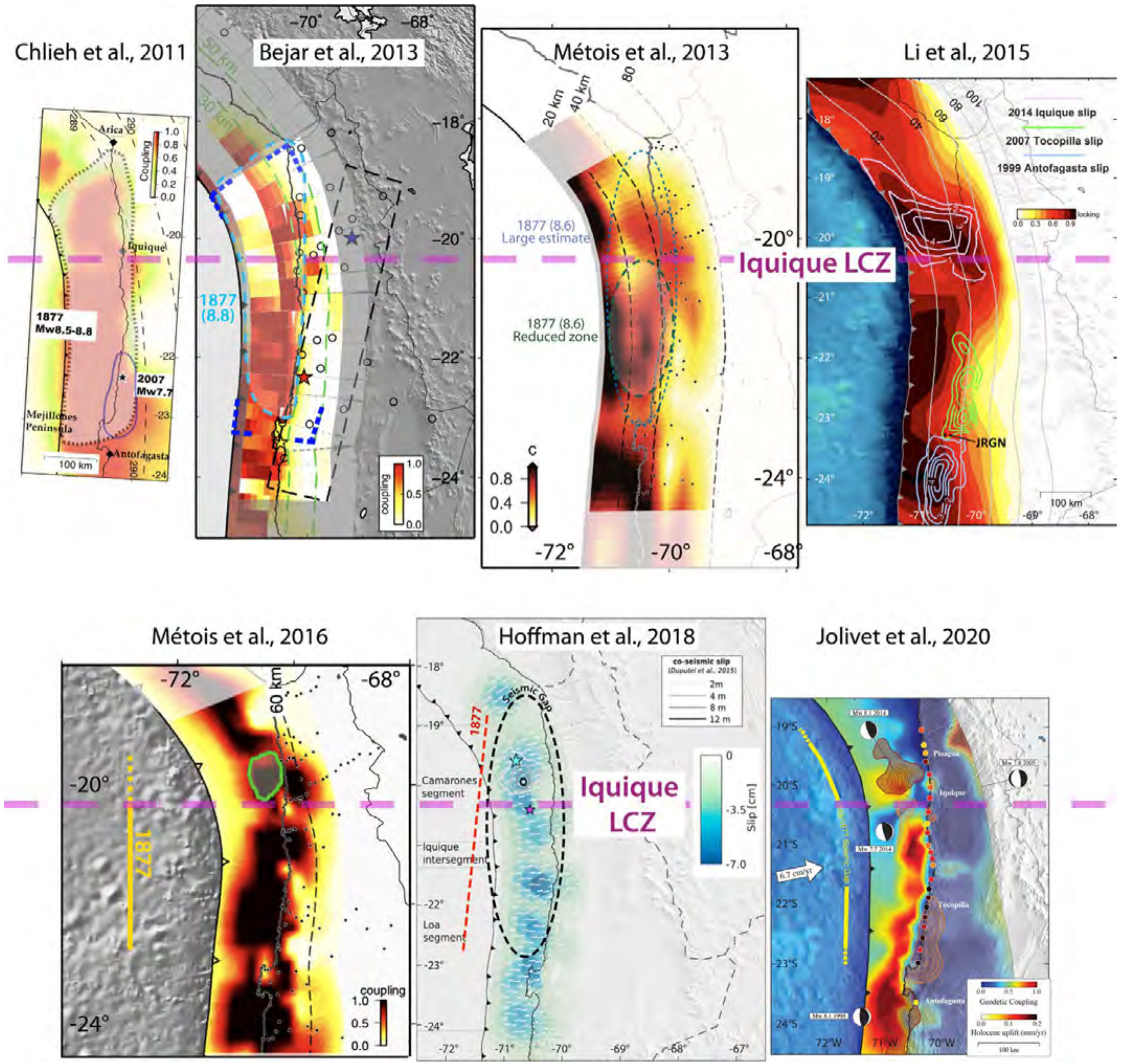
•Main uncertainties are

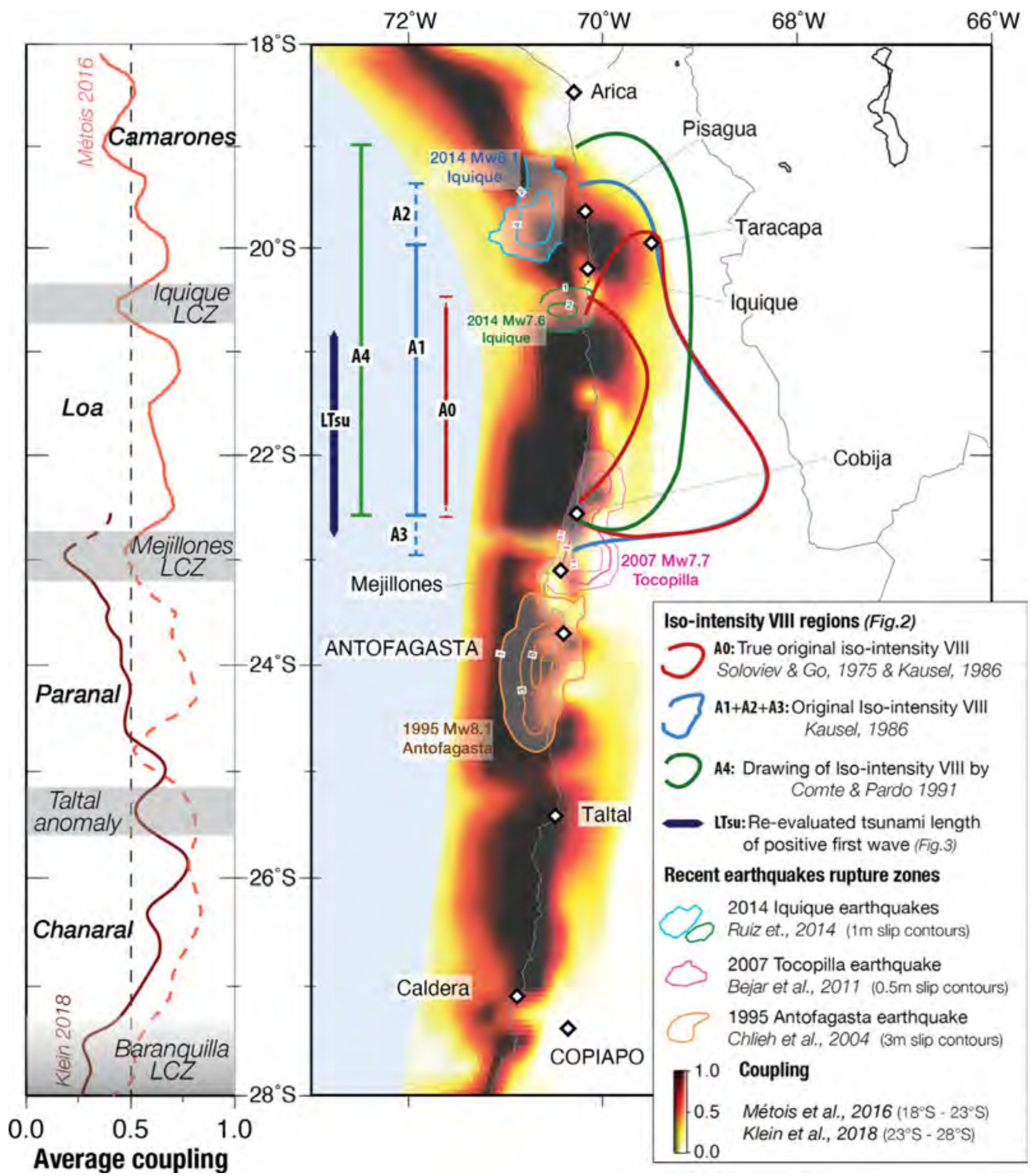
- The b-value of seismic catalogue
- Amount of aseismic slip in the long run



Lovery et al., in review 2023

Mmax for the North Chile



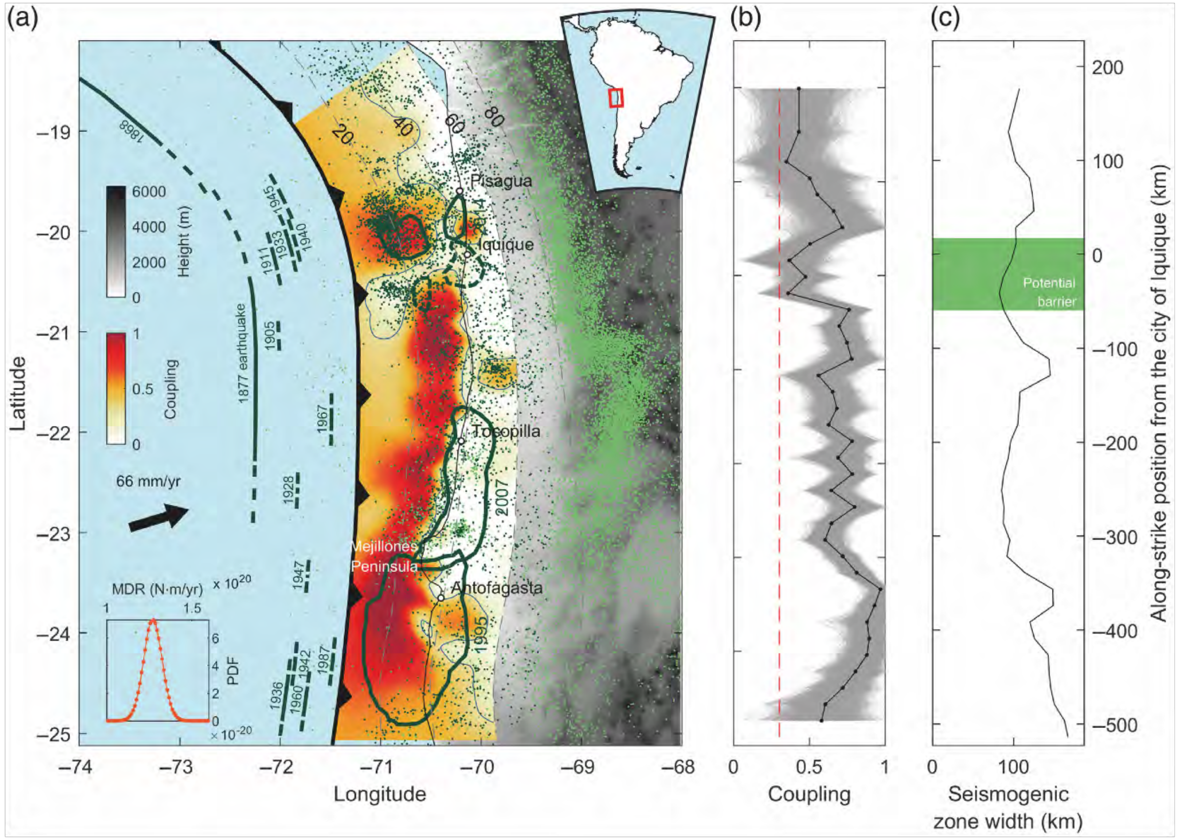


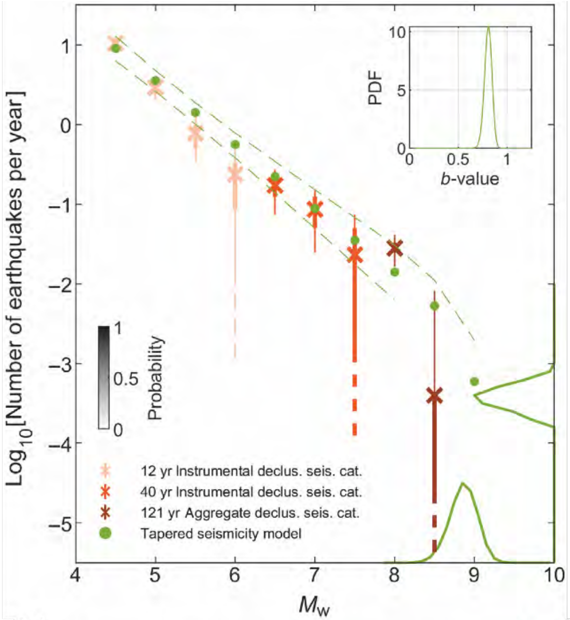
1877 Mw=8.5 ?

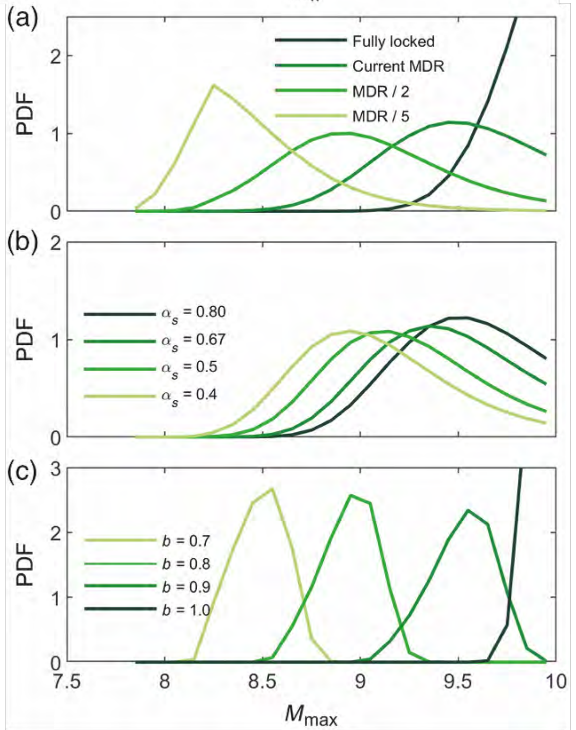
Rupture length ~225 km ??

Vigny & Klein, 2022

Mmax for the North Chile







The b-value from ISC and historical catalogs peaks at about 0.8

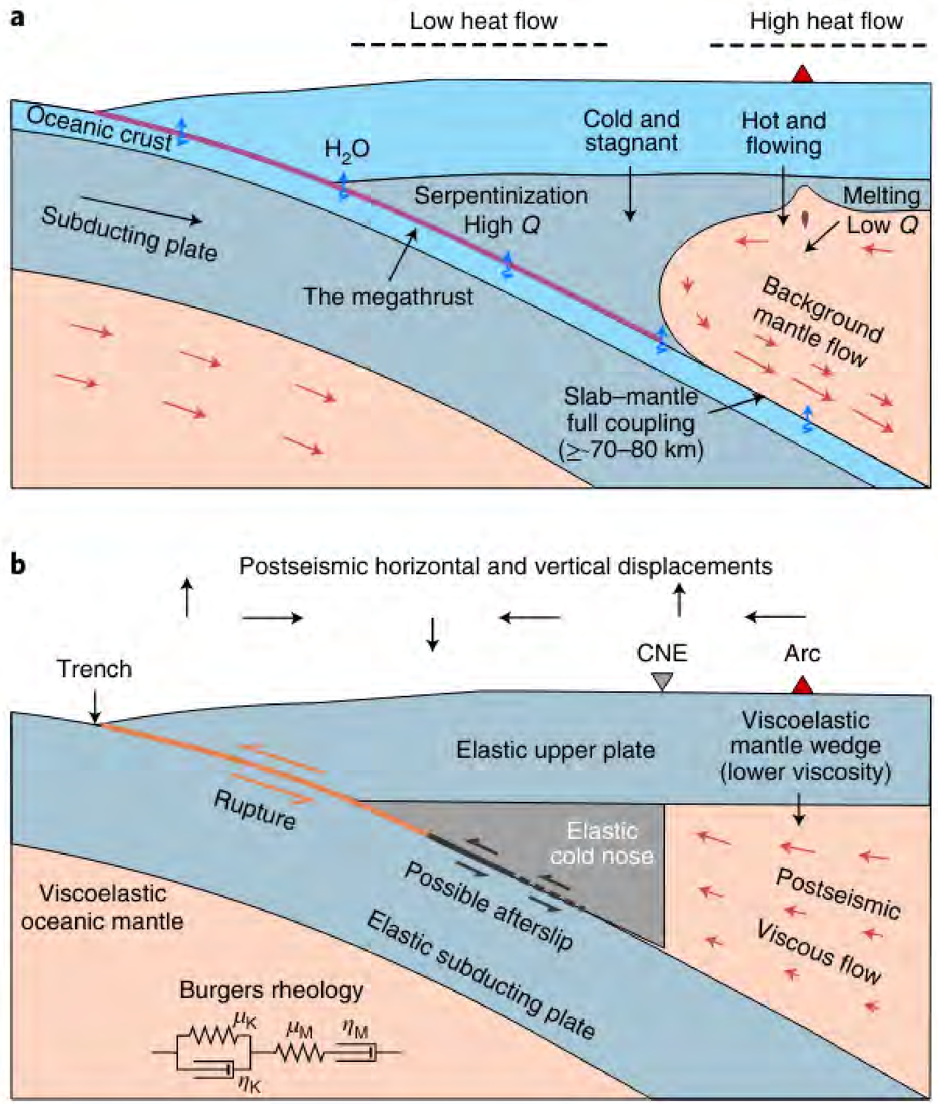
Mwmax peaks at 8.8 wth a reccurence time of ~2500 yrs (1000-6300 yrs)
Earthquakes larger than Mw 9.1 are very improbable in the region (less than 2%)

The probability of having at least an Mw > 8.8 in a 30, 100 and 1000 yr period is of ~ 1%, 4%, and 29%, respectively

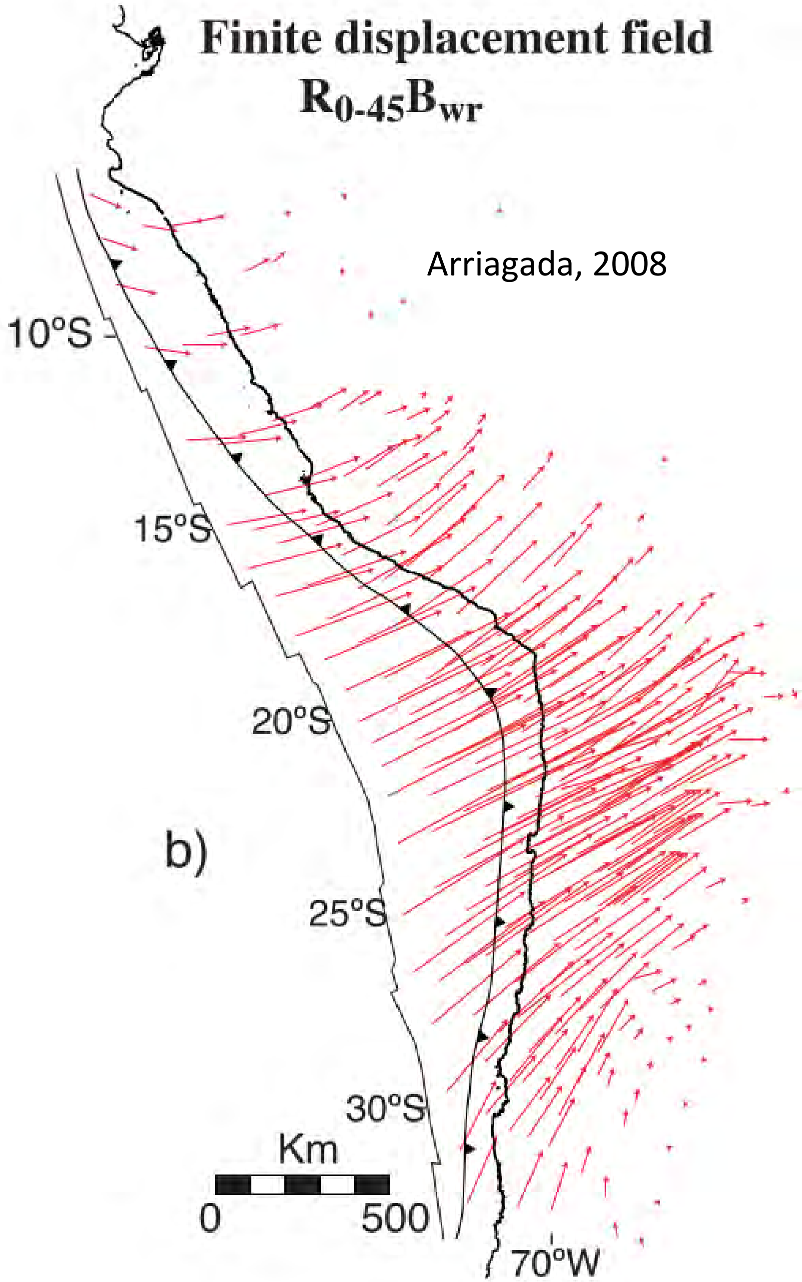
Michel et al. BSSA 2023

Modelling Challenges

Take the rheology, seismic history and internal deformation into account
To better quantify the time-dependent cumulative moment deficit

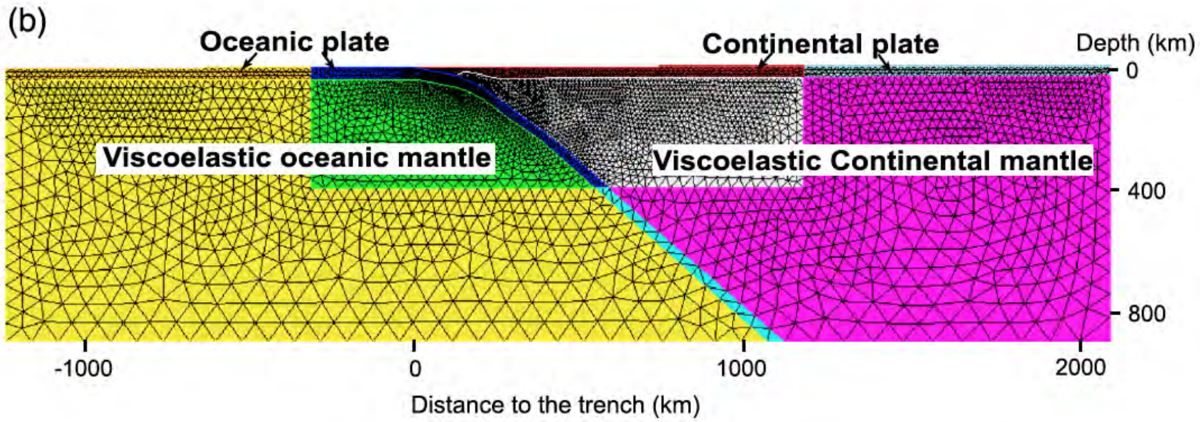


Luo & Wang 2021

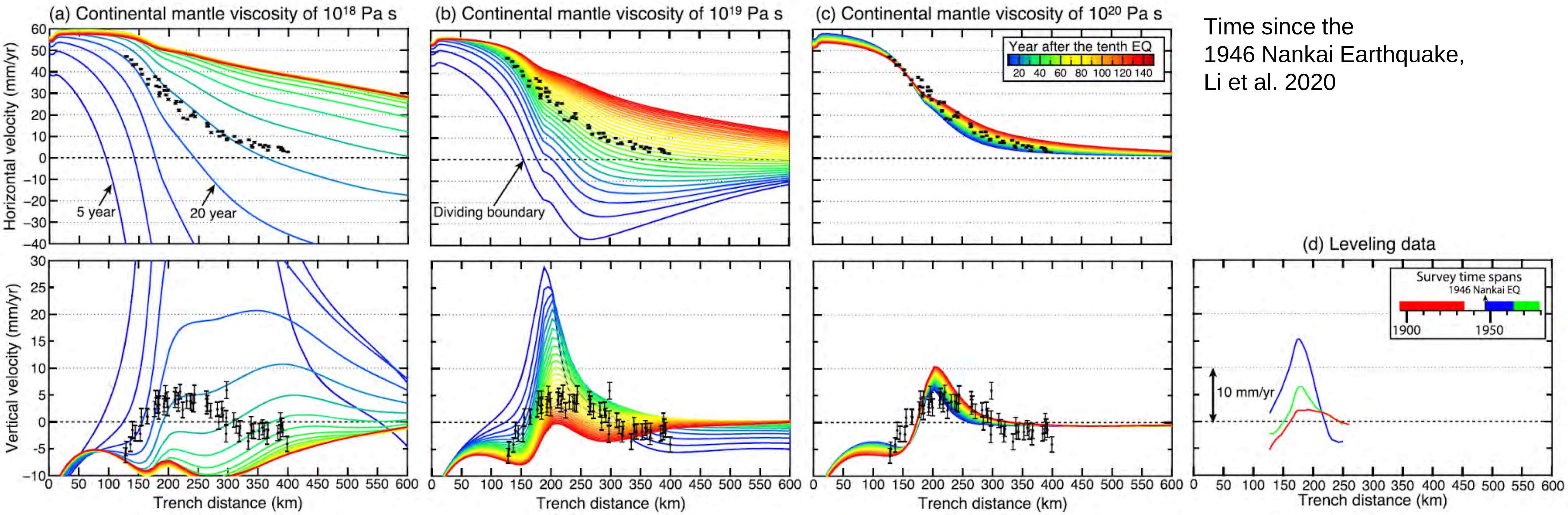


Arriagada, 2008

Viscoélastic effects on interseismic deformation

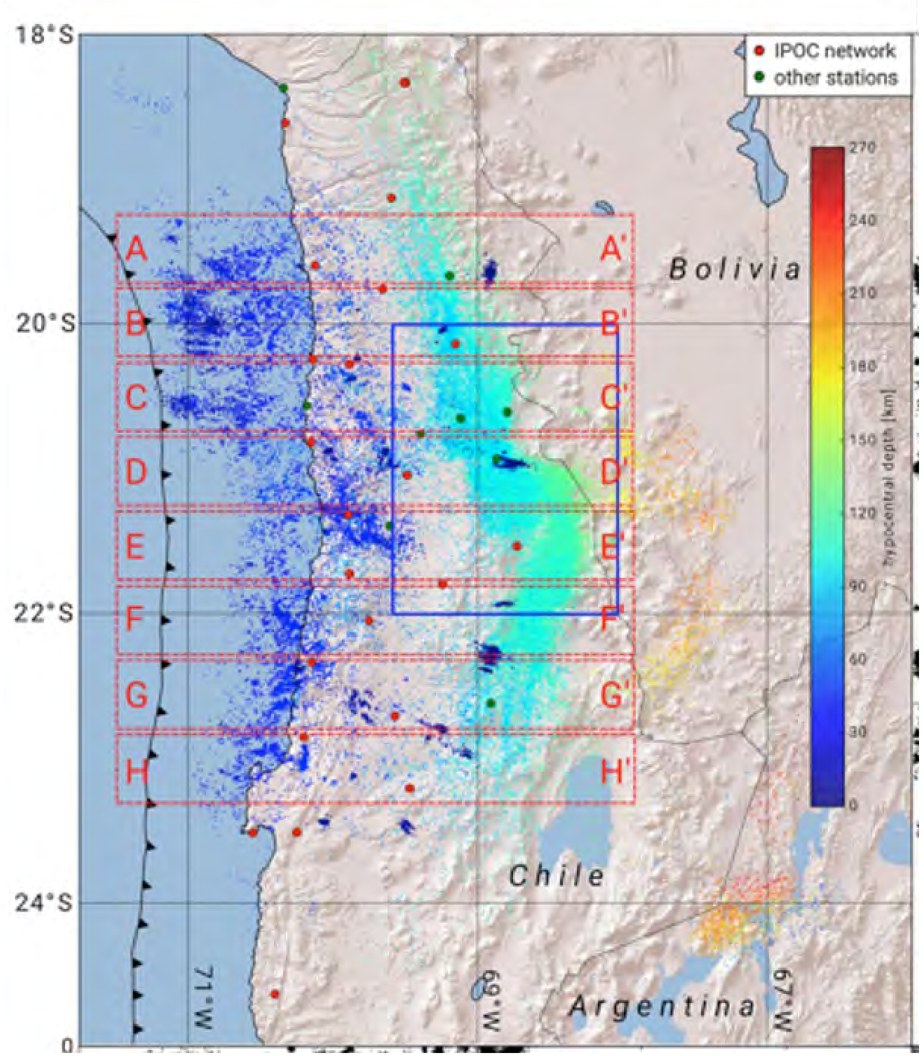


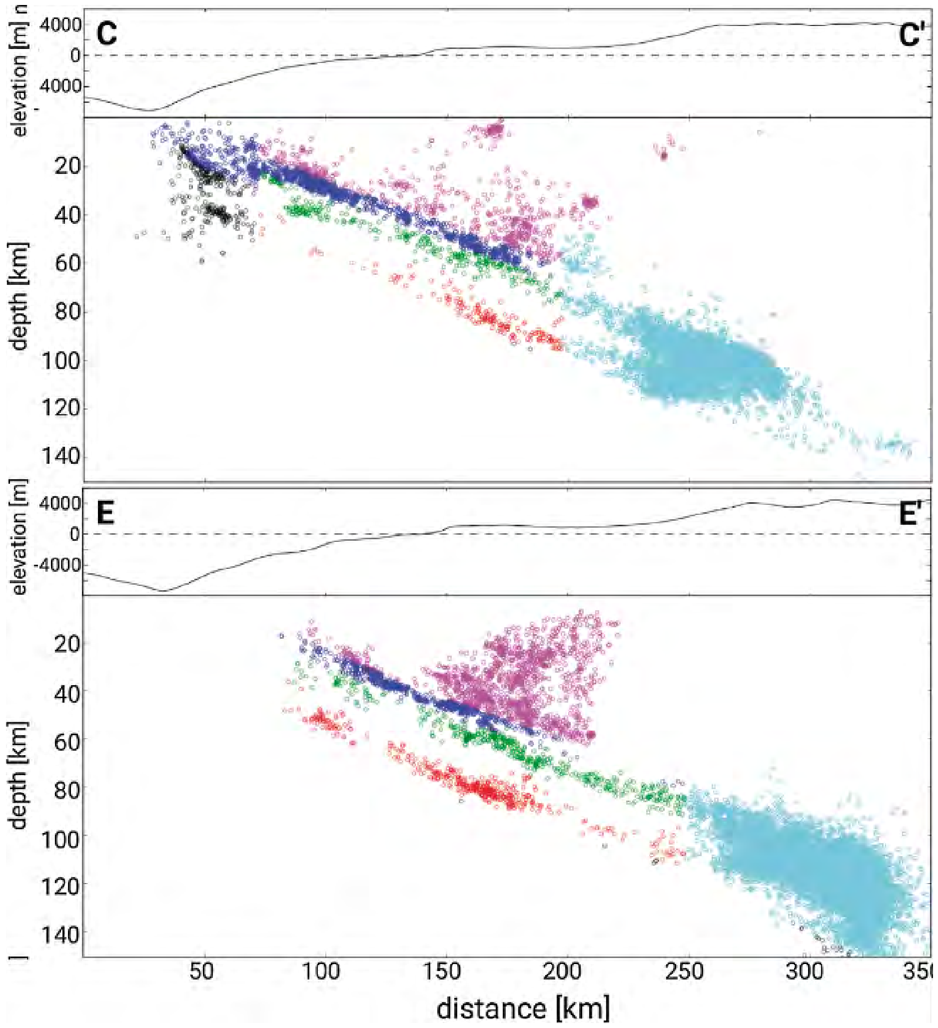
- Time-dependent modelling needed to take viscoelastic post-seismic relaxation into account



Time since the
1946 Nankai Earthquake,
Li et al. 2020

IPOC seismic catalogue:



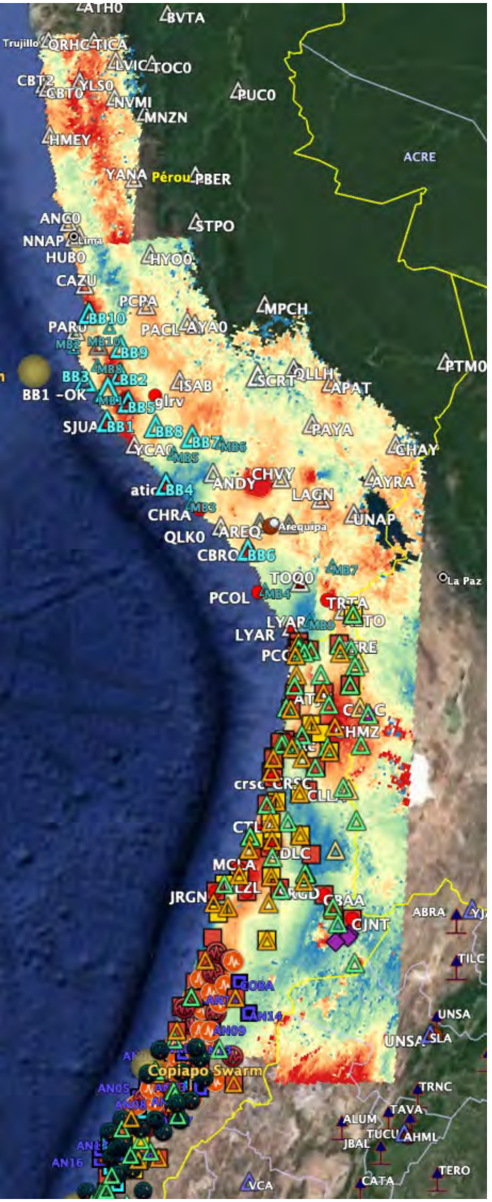


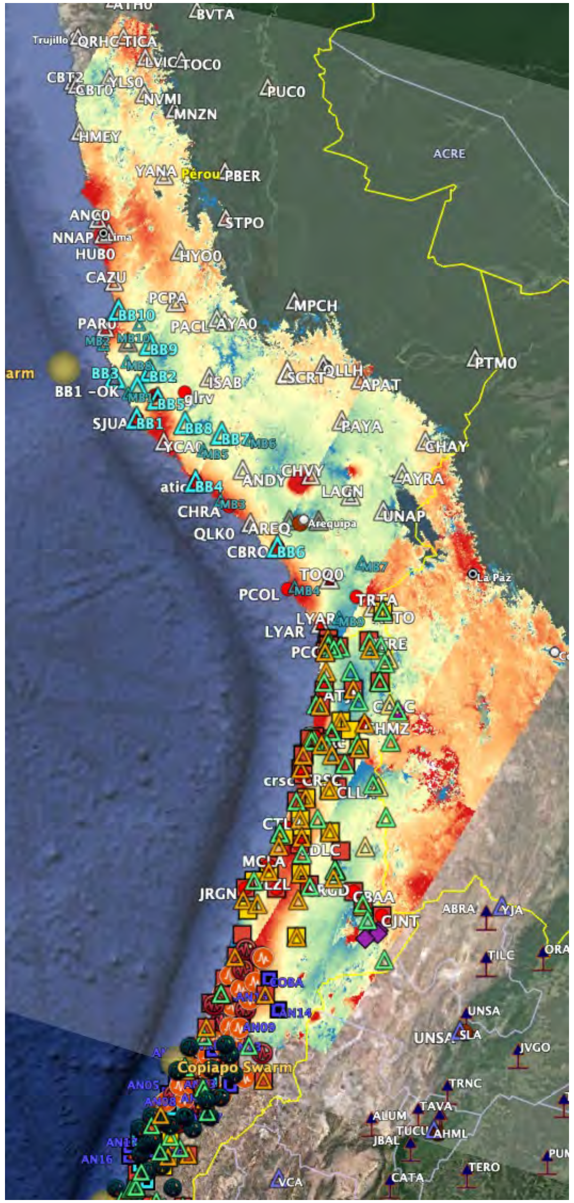
Improving seismic catalog with AI will provide better constraints on the
b-value

But also on the slab geometry and then all models based on it !

Schurr, Asch, & Kummerow (2018)
Münchmeyer et al. (2020)

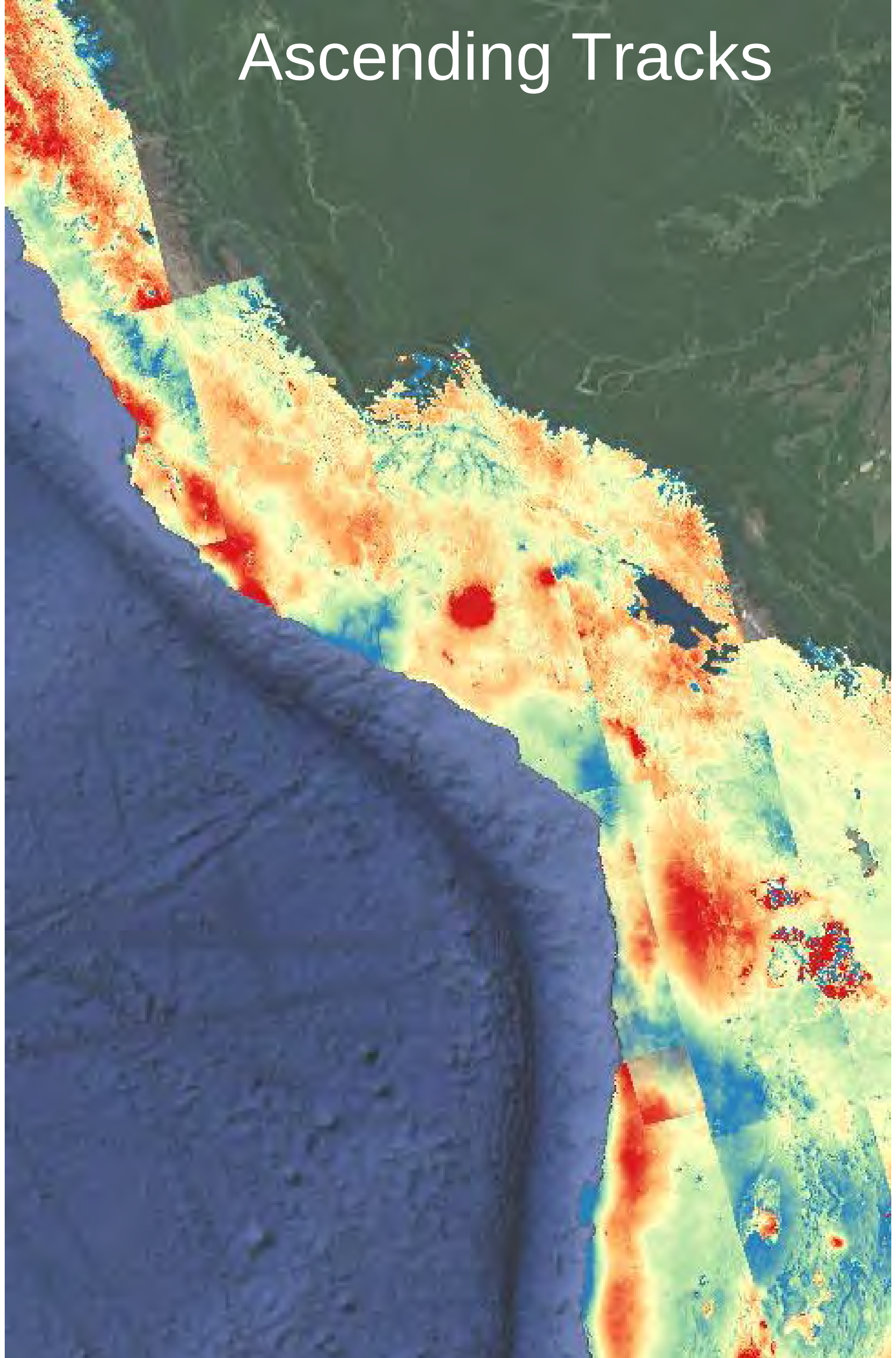
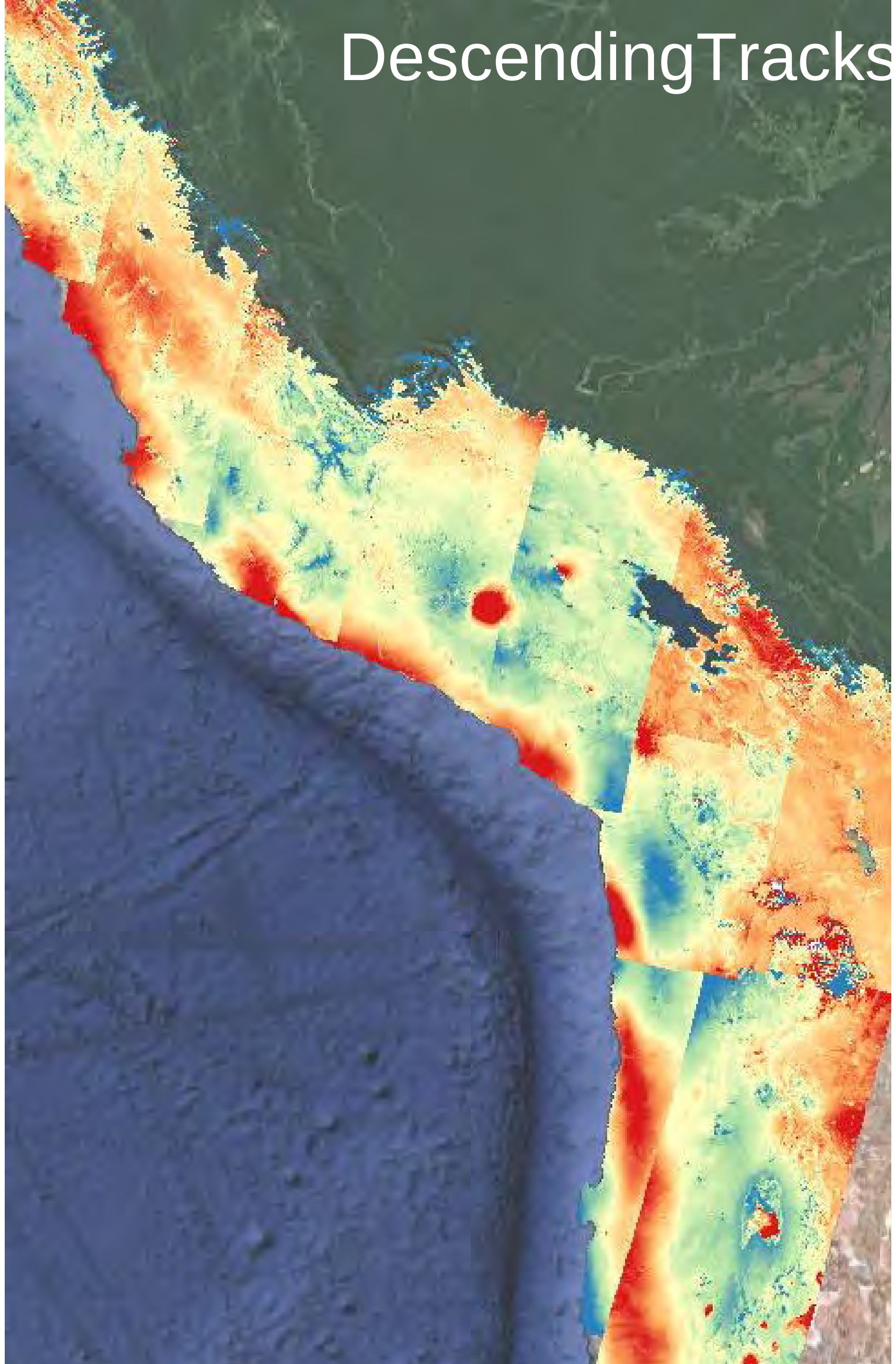
New data: integrate Sentinel InSAR time series from FLATSIM service





https://www.poleterresolide.fr/projets/en-cours/flatsim/

Processed with NSBAS (Marie-Pierre Doin et al. 2011)
12 tracks recovering an Area : ~ 1 500 000 km2
Time series between 2014 and 2021


Ascending Tracks

DescendingTracks

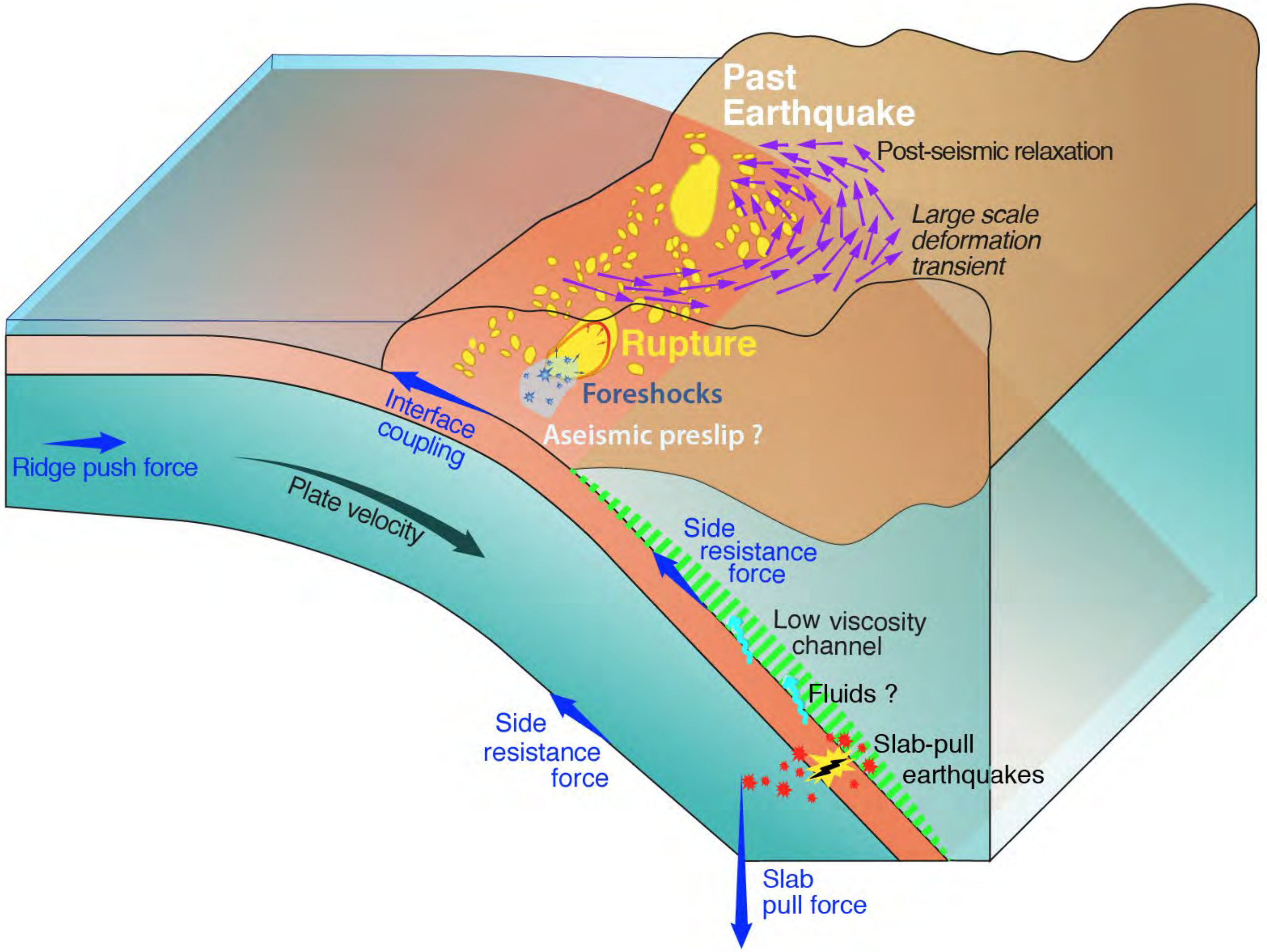
Concluding remarks and take home message

•Patches with high locking indicate the location of seismic sources

•Patches with low locking suggest the presence of seismic barriers. Define a classification
•Strong Barriers ??? : Nazca Ridge, Arica bend, Mejillones Peninsula

•Weak Barriers ??? : Nazca fracture zone, Iquique-Pisagua ridge, ….

•Mwmax will depend on how many locked patches will break simultaneously



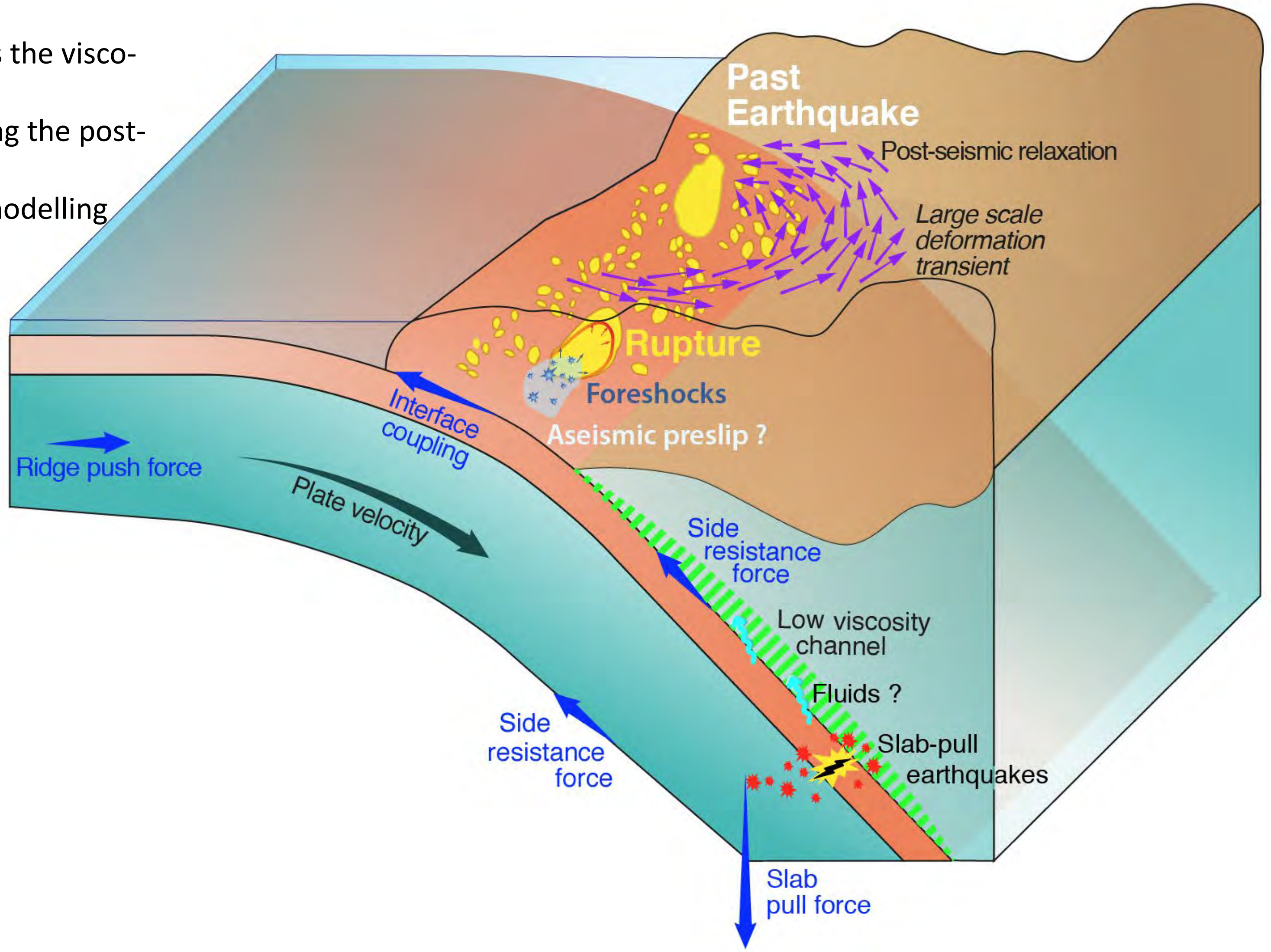
Concluding remarks and take home message

Uncertainties and challenges:

1. Improve local seismic catalog and our knowledge of historical events —> Better estimation of the b-value and slab geometry using IA
2. Improve our knowledge of the local rheology and include in models the visco-elastic deformation and intracontinental deformation
3. Quantify more precisely the transient aseismic slips that occur during the post-seismic and slow slip events

• coupling in Arica bend poorly constrained need for integrated modelling

•New data to come (insar)



Gracias

Arigatō