Slow Slip Events
Interseismic Locking
Seismic Rupture
Afterslip

Towards an Integrated View of the Earthquake Cycle after the 2016 Pedernales Earthquake, Ecuador

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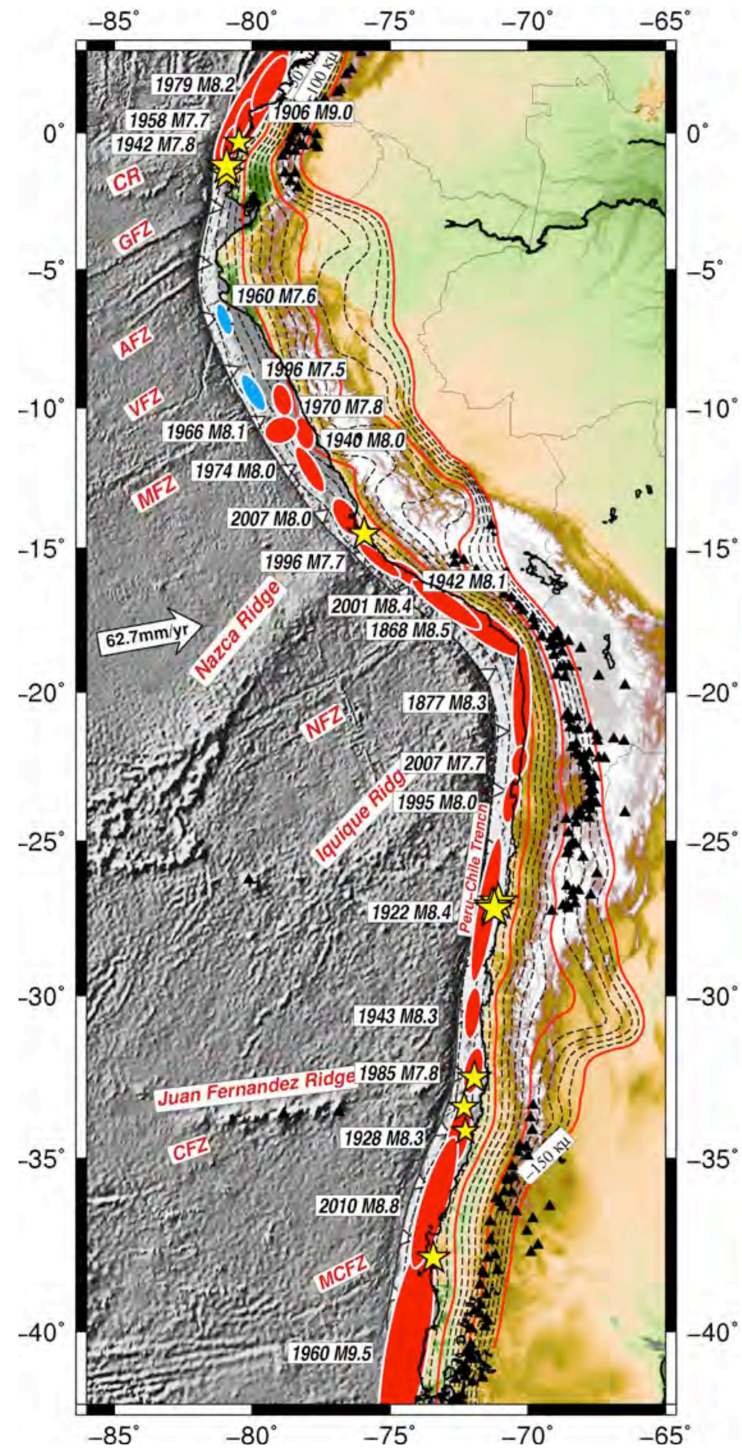
Great Earthquakes: Observations and Modelling, Collège de France, 30 Novembre 2017

Great Earthquakes along the Nazca/South America subduction zone

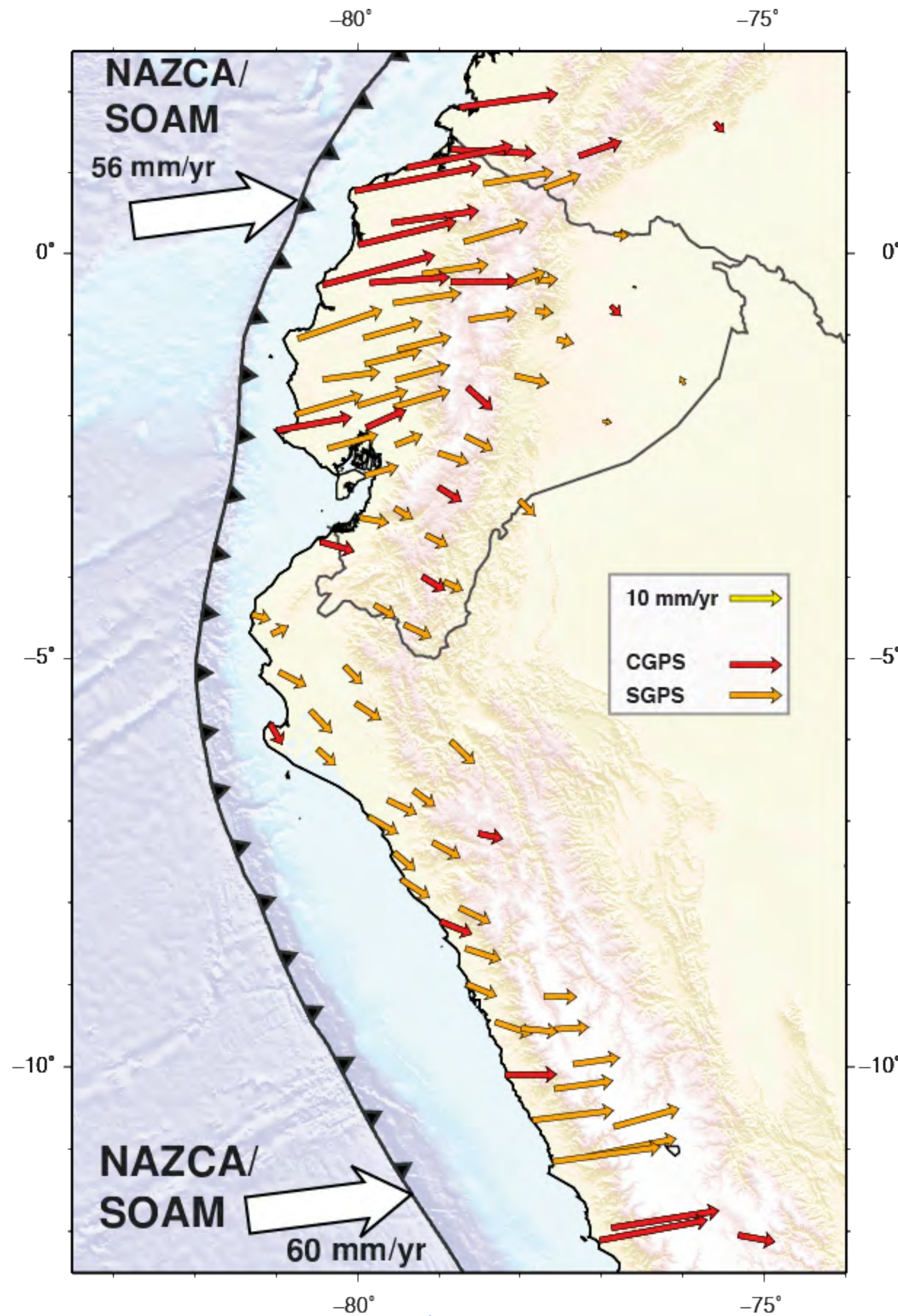
- Almost the entire length of the Nazca/South America subuction interface has ruptured during great earthquakes (Mw>8.5) since the 1500’s
- Exception in northern Peru/southern Ecuador
- Observational approach:
  - Regional scale GPS (horizontal) velocity field
  - Multi-parameters Broadband Seism./Acc./HR-GPS



From Villegas et al., JGR, 2016

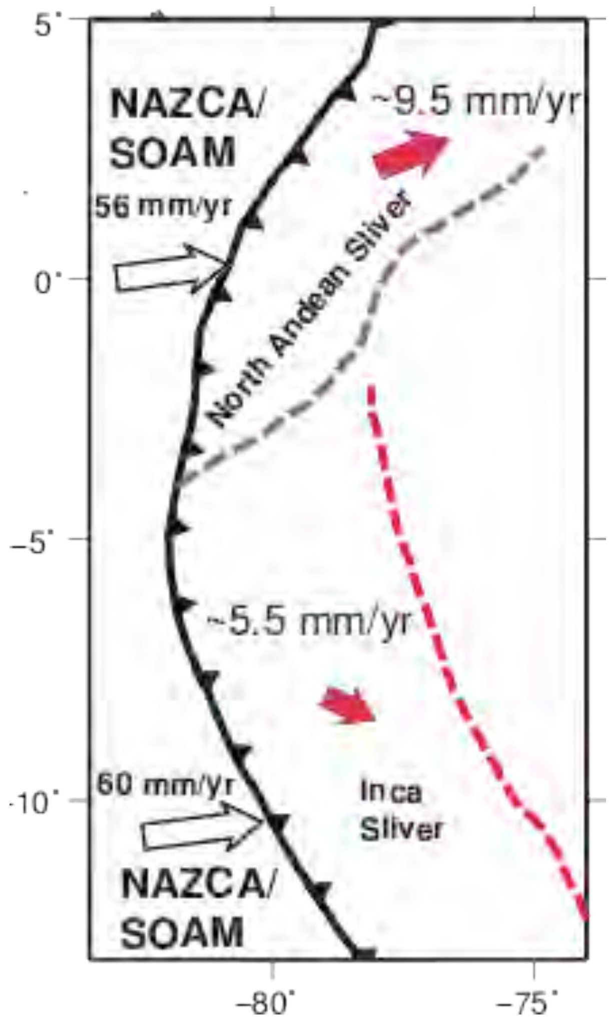
GPS VELOCITY FIELD

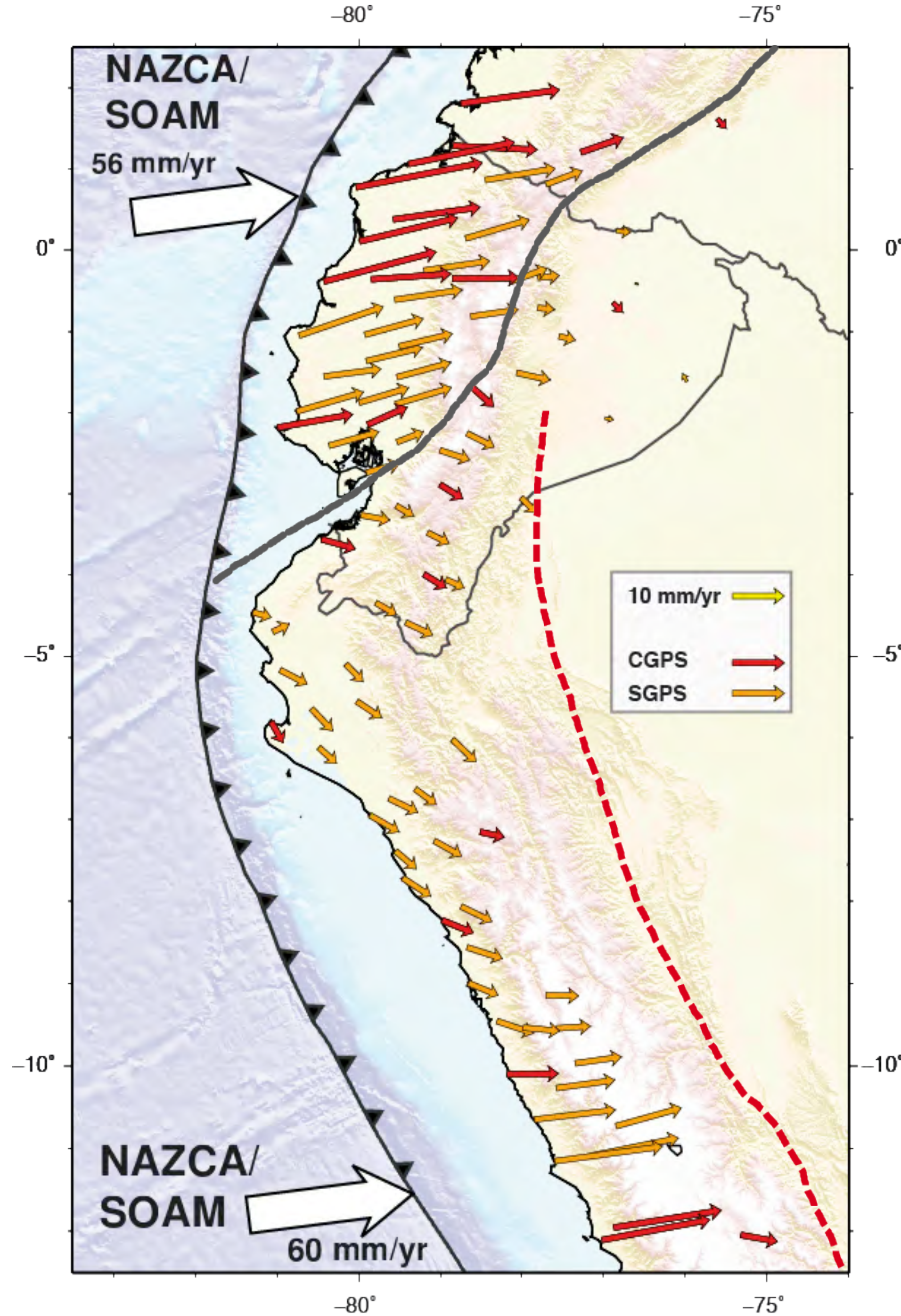
- 130 sites in south America
- 65 campaign sites
  - 1994-2012 for Ecuador
  - 2008-2012 for Peru
- 35 CGPS (since 2007-2008)
- GAMIT/GLOBK 10.60
- Expressed wrt stable South America
- The velocity field includes two contributions:
  - Motion of diverging continental slivers
  - Elastic strain induced by coupling along the subduction interface



Nocquet et al., Nat. Geosc., 2014

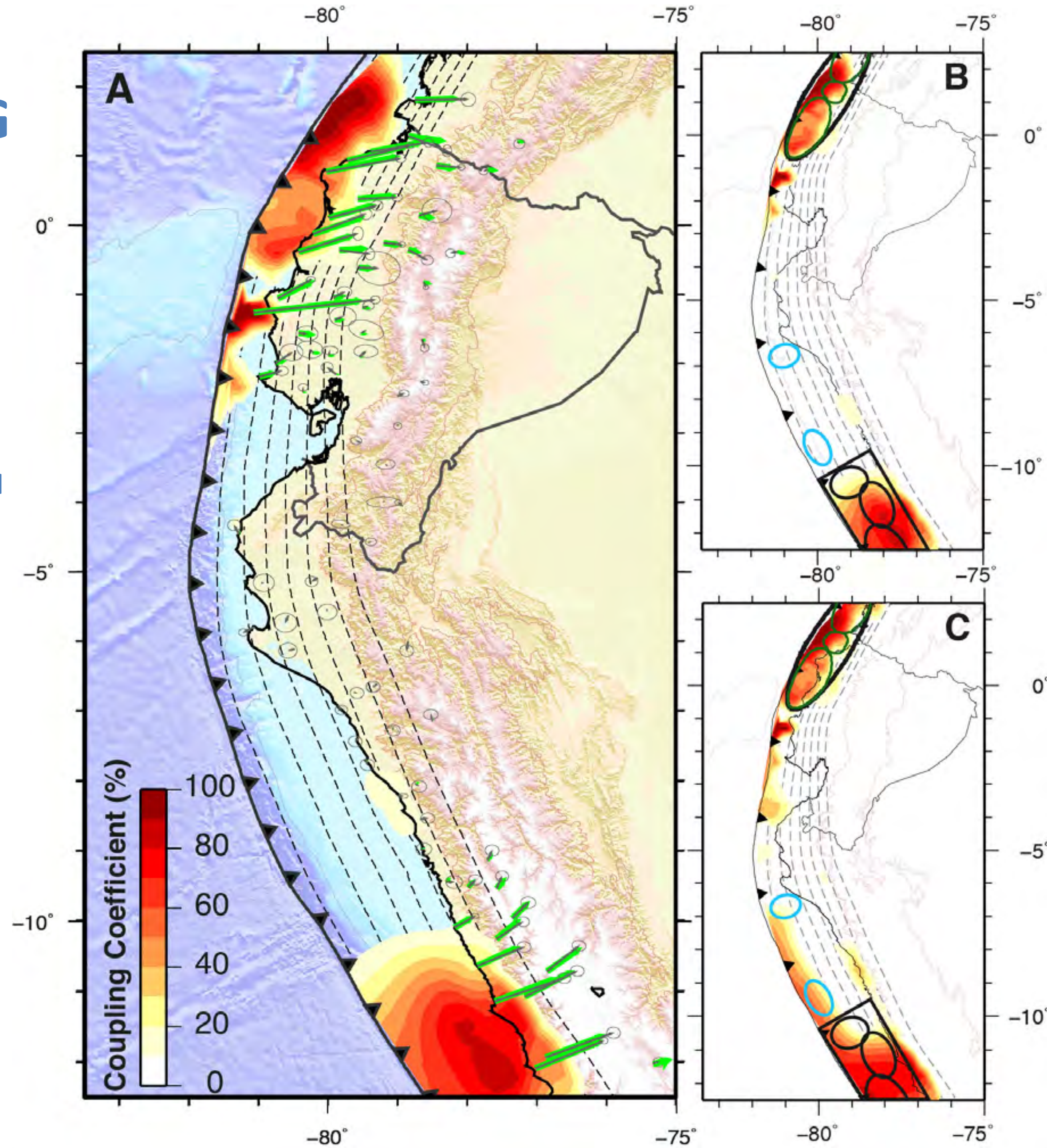
THE NORTH ANDEAN & INCA SLIVERS





LARGE SCALE INTERSEISMIC COUPLING

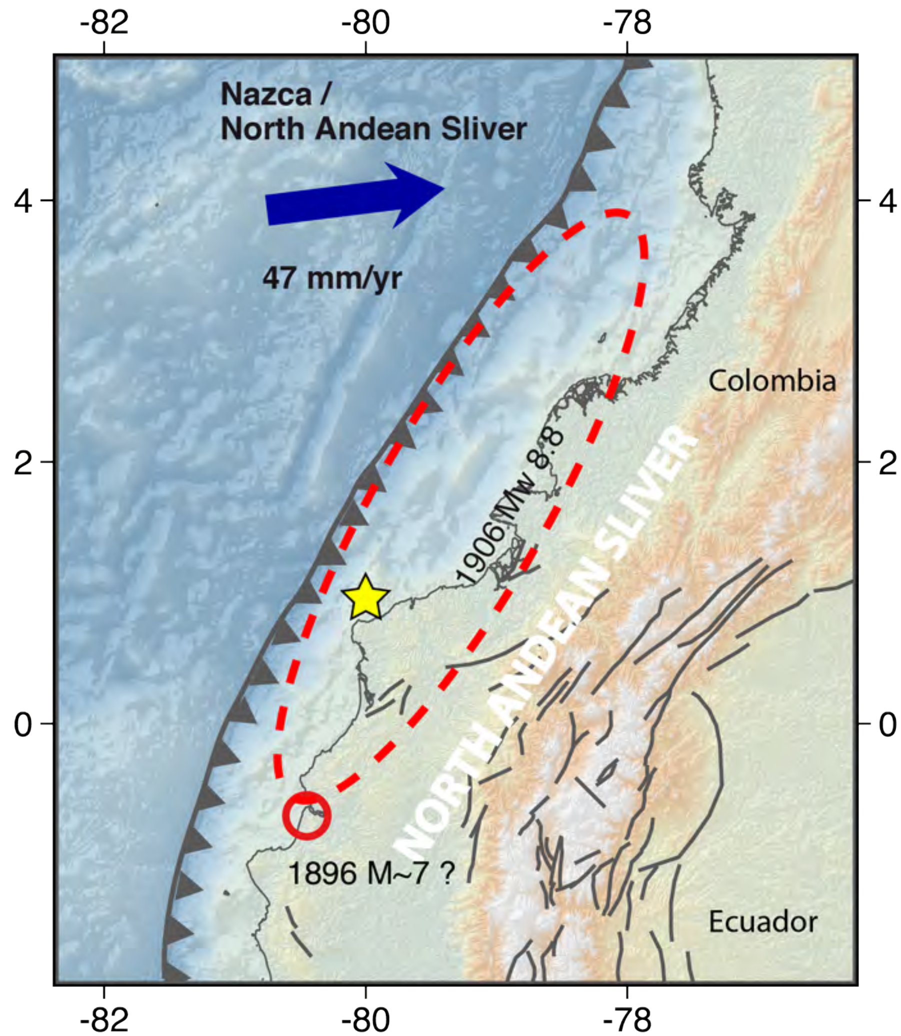
- High coupling areas correlate with rupture of great earthquakes
- High coupling until a depth of 50-55km is found in central Peru
- High coupling is also found in northern Ecuador/southern Ecuador but does not exceed 35km
- Tsunami earthquakes have occurred in areas of weak average coupling, but where GPS data do not exclude significant coupling along the shallowest portion of the interface



Nocquet et al., Nat. Geosc., 2014

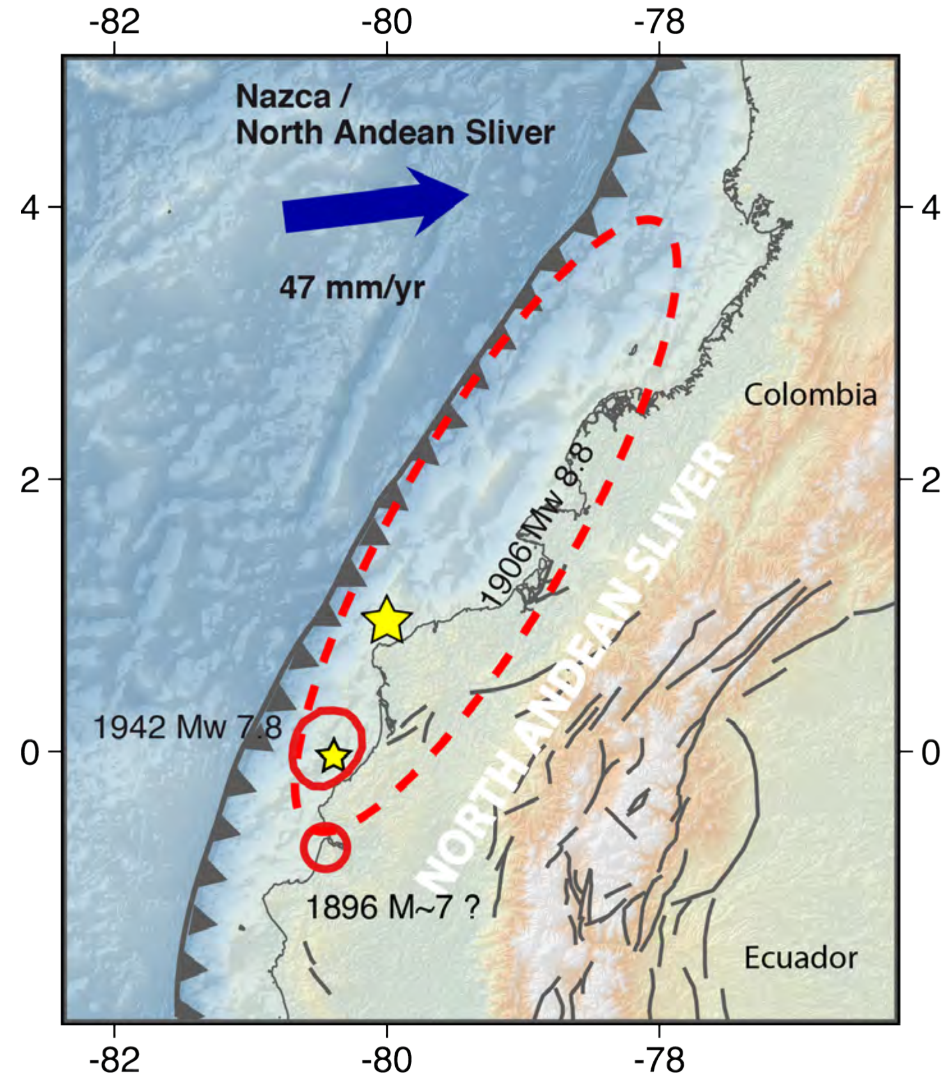
THE SEISMIC SEQUENCE AT THE ECUADOR-COLOMBIA SUBDUCTION ZONE SINCE 1906

- 1906: recorded at several global seismometers
- Magnitude: Mw 8.4-8.8
  McNally & Kanamori (1982), Okal (1992), Ye et al. (2016),
- Southern extent of the rupture uncertain



THE SEISMIC SEQUENCE AT THE ECUADOR-COLOMBIA SUBDUCTION ZONE SINCE 1906

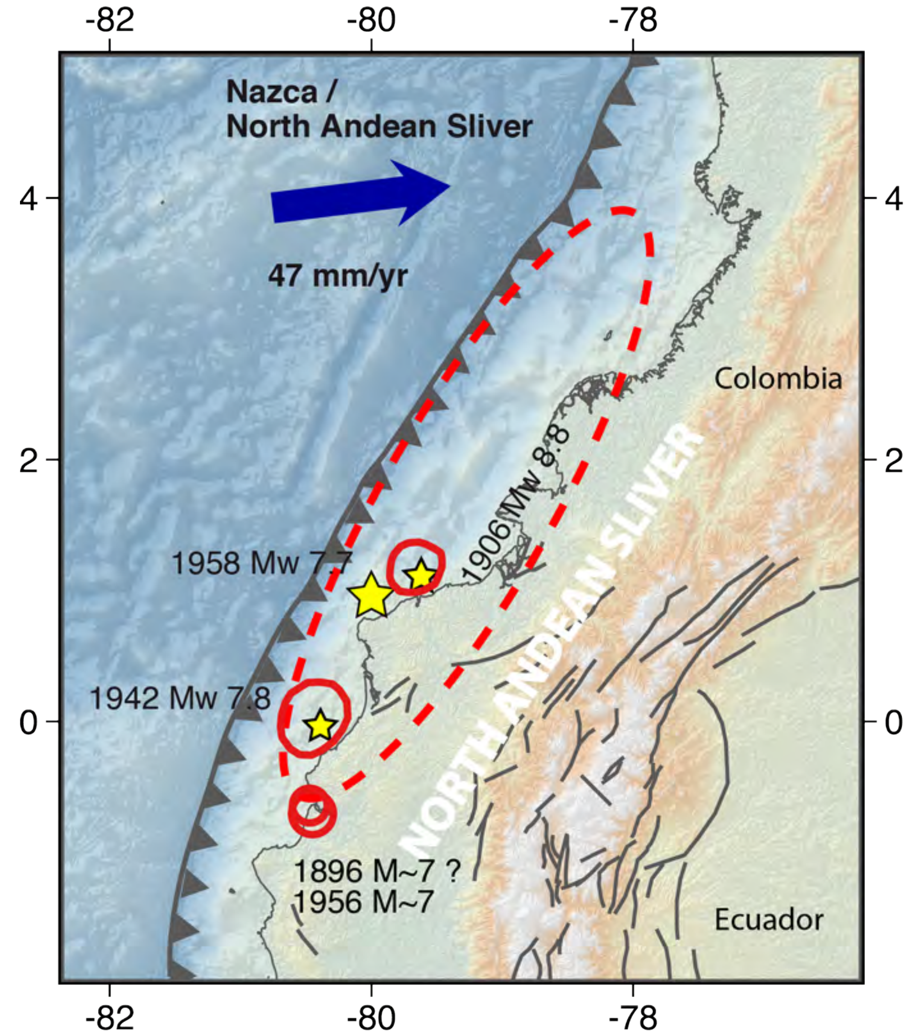
- 1942: recorded at several global seismometers
- Mw 7.8-7.9 (Ms 7.5)
- Swenson & Beck (1996), Ye et al. (2016)



THE SEISMIC SEQUENCE AT THE ECUADOR-COLOMBIA SUBDUCTION ZONE SINCE 1896

- 1958
- Mw 7.7 followed by tsunami

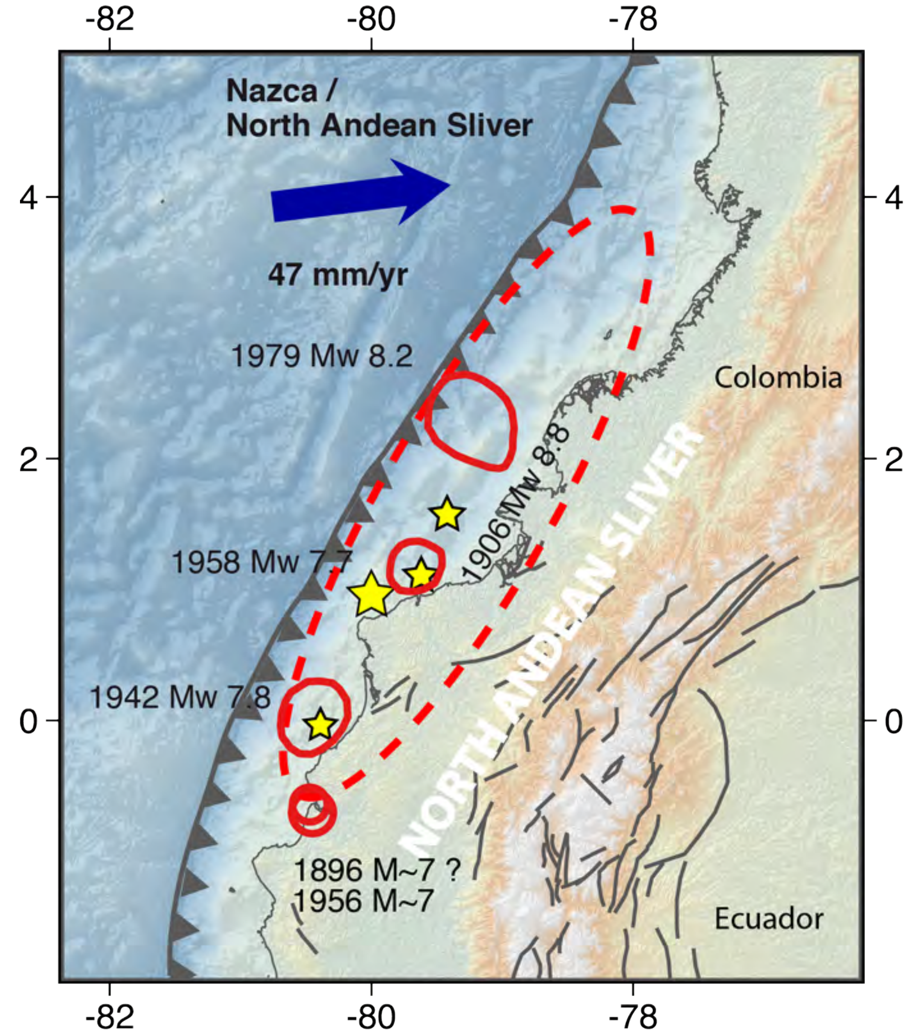
Swenson & Beck (1996)



THE SEISMIC SEQUENCE AT THE ECUADOR-COLOMBIA SUBDUCTION ZONE SINCE 1896

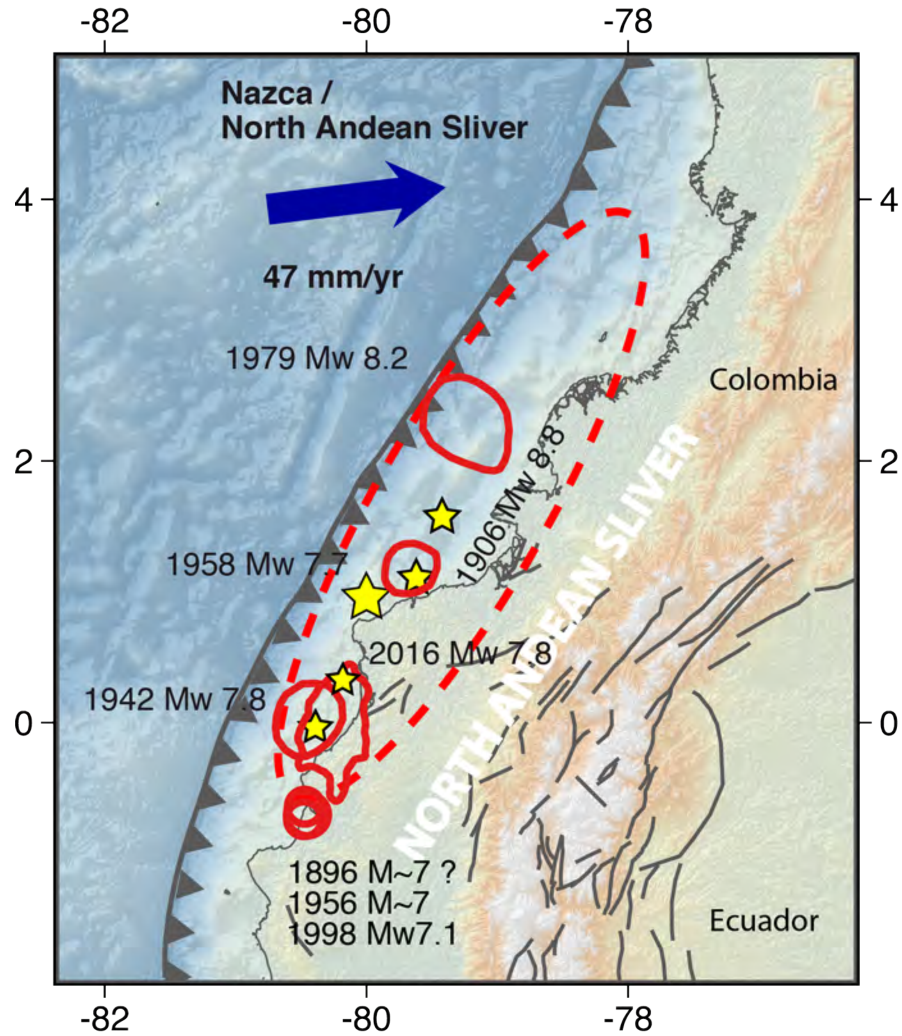
- 1979
- Mw 8.1-8.2 followed by tsunami

Kanamori & Mc Nally (1982)

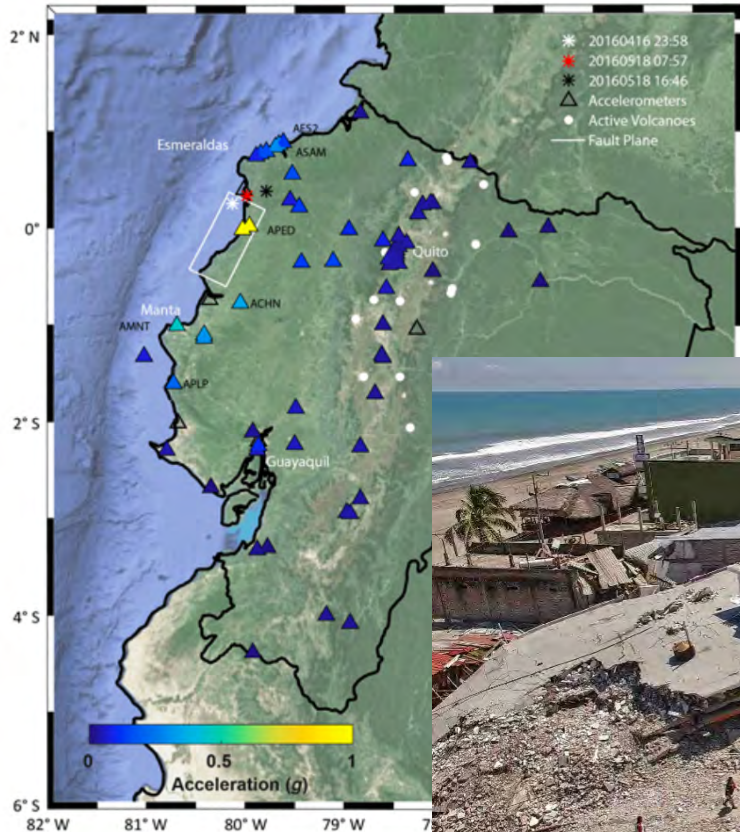


THE SEISMIC SEQUENCE AT THE ECUADOR-COLOMBIA SUBDUCTION ZONE SINCE 1896

- 2016
- Mw 7.8

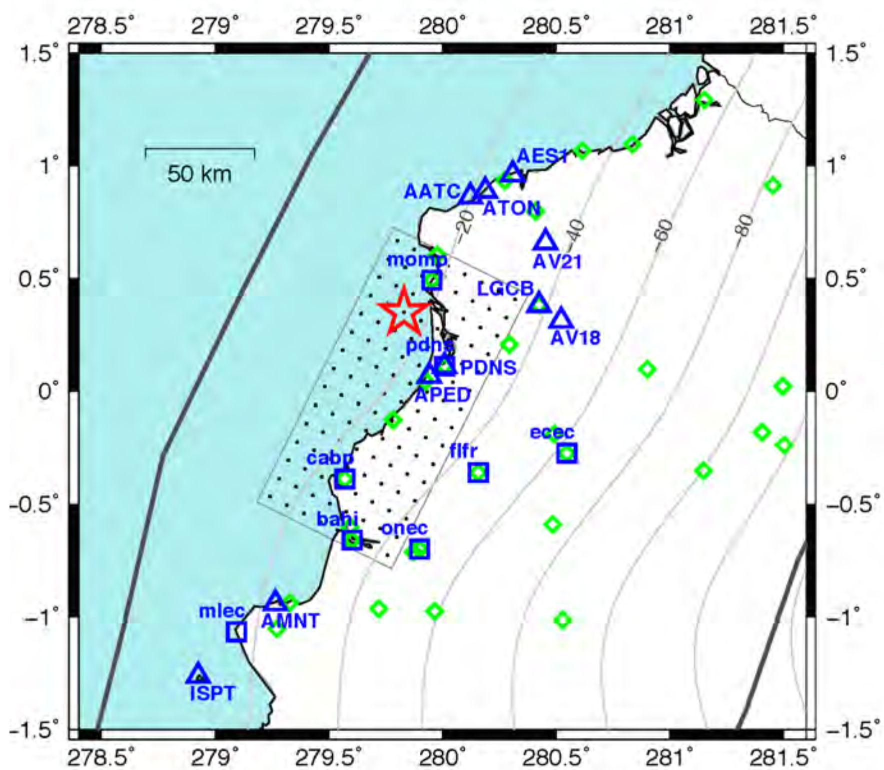


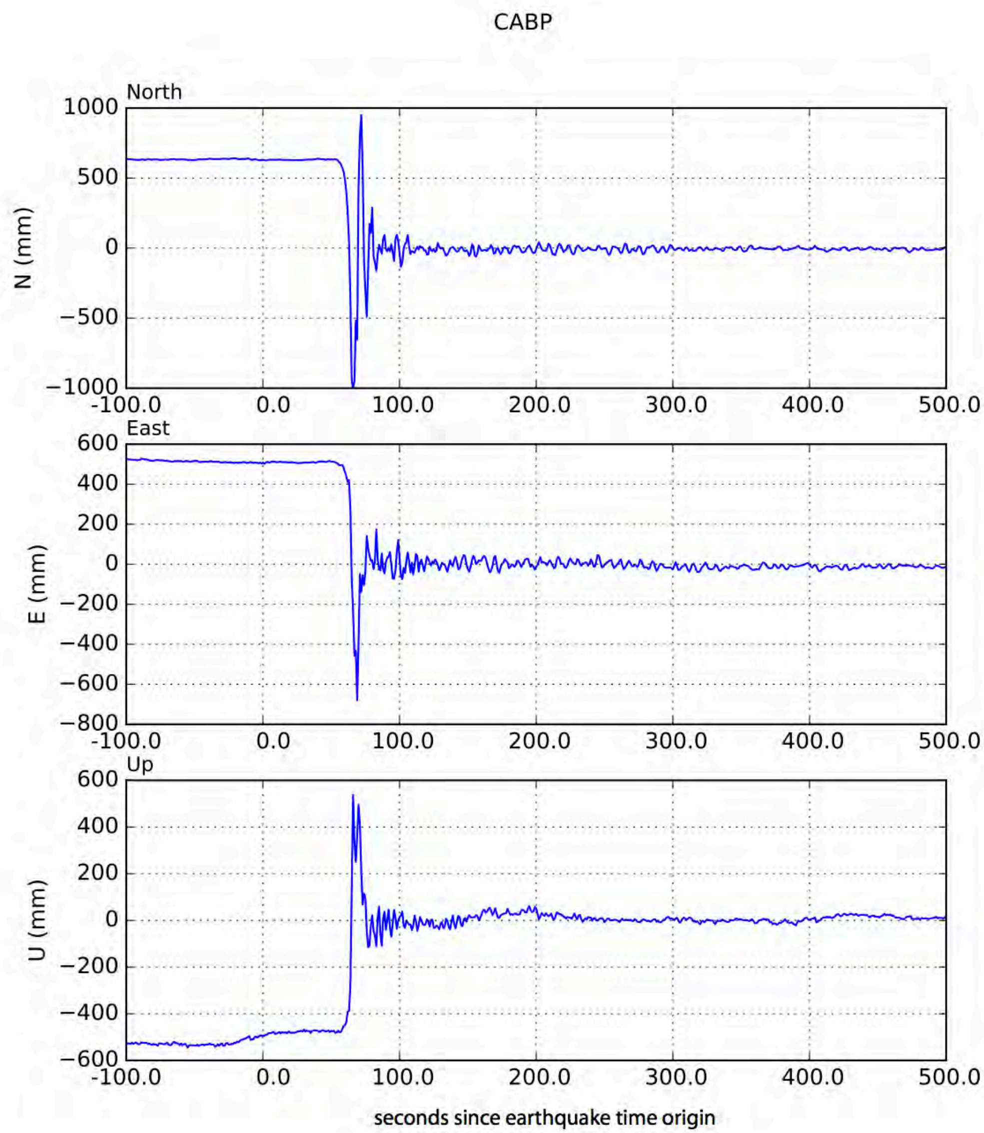
THE PEDERNALES APRIL 16 2016 ECUADOR EARTHQUAKE (MW 7.8)



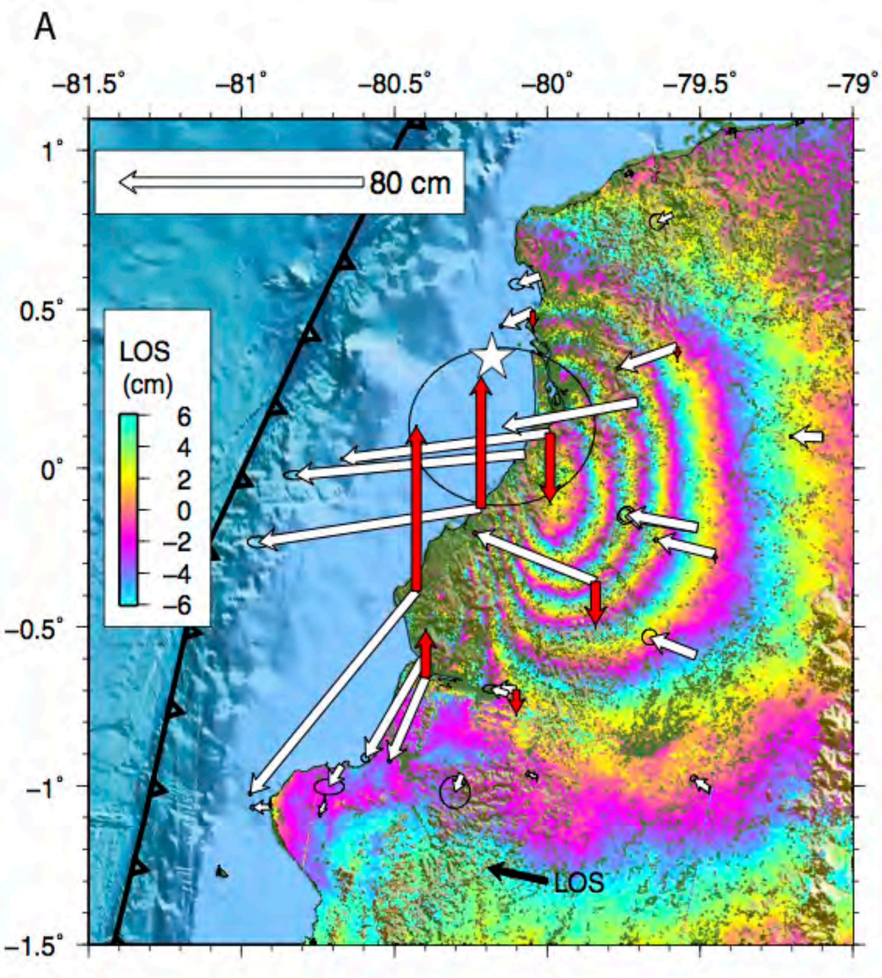
Beauval et al.,
BSSA, 2017

NEAR FIELD HIGH RATE GPS & ACCELEROGRAMS

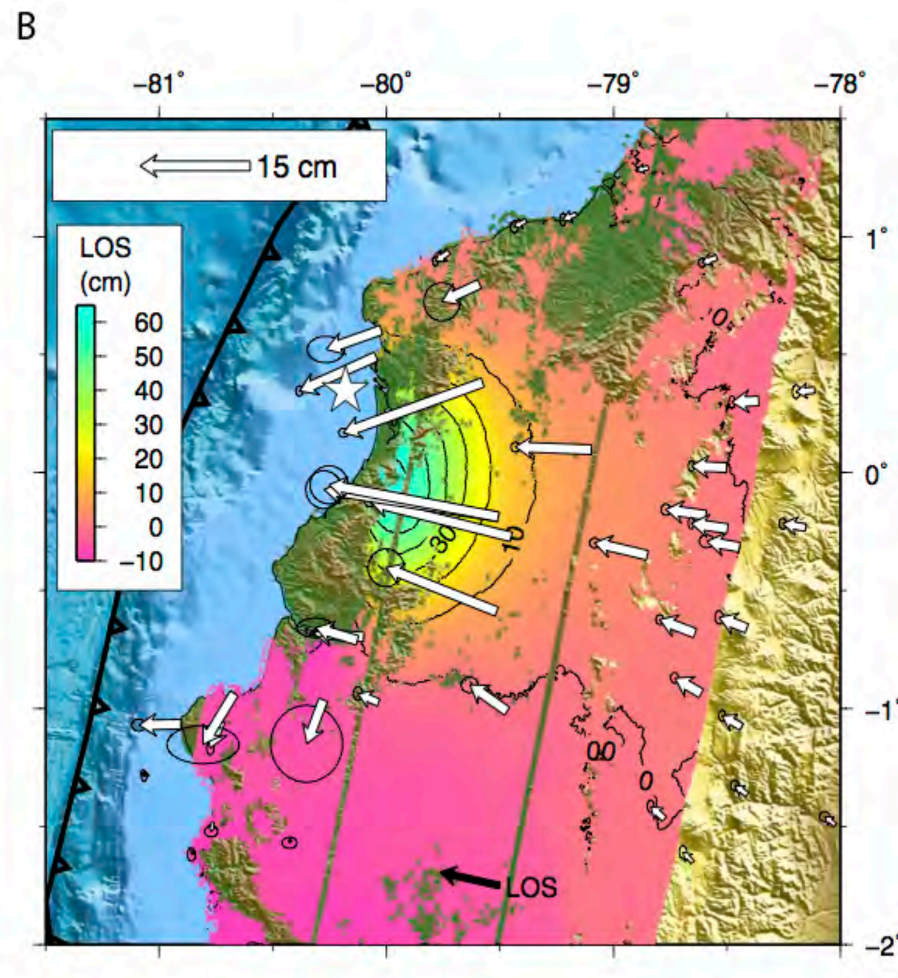




COSEISMIC STATIC DISPLACEMENT FROM GPS & INSAR

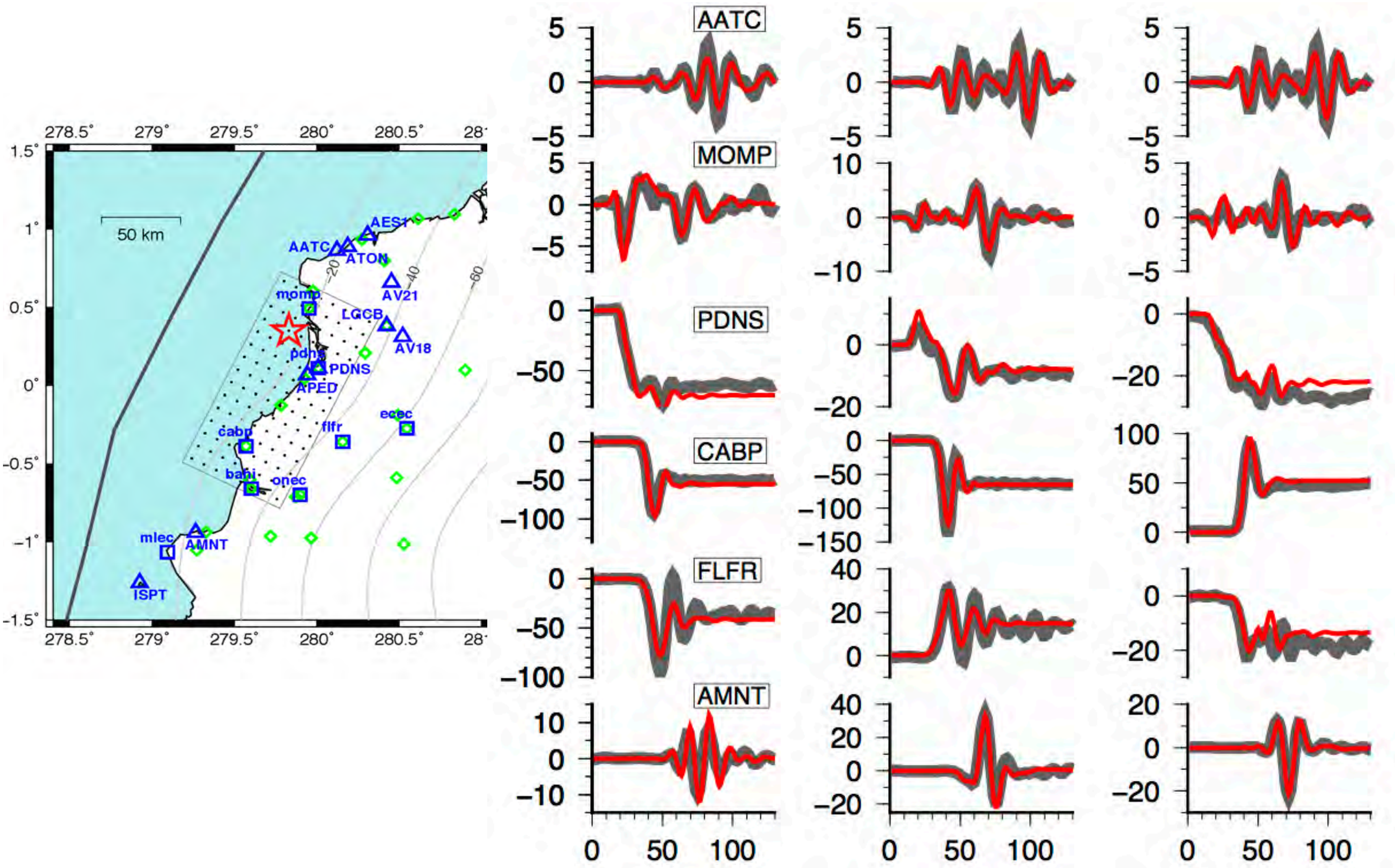


ALOS-2 descending tracks wrapped
L-band (24.55 cm)
2016/04/01-2016/04/29



Sentinel-1 descending tracks
C-banded (5.55 cm)
2016/04/12-2016/04/24

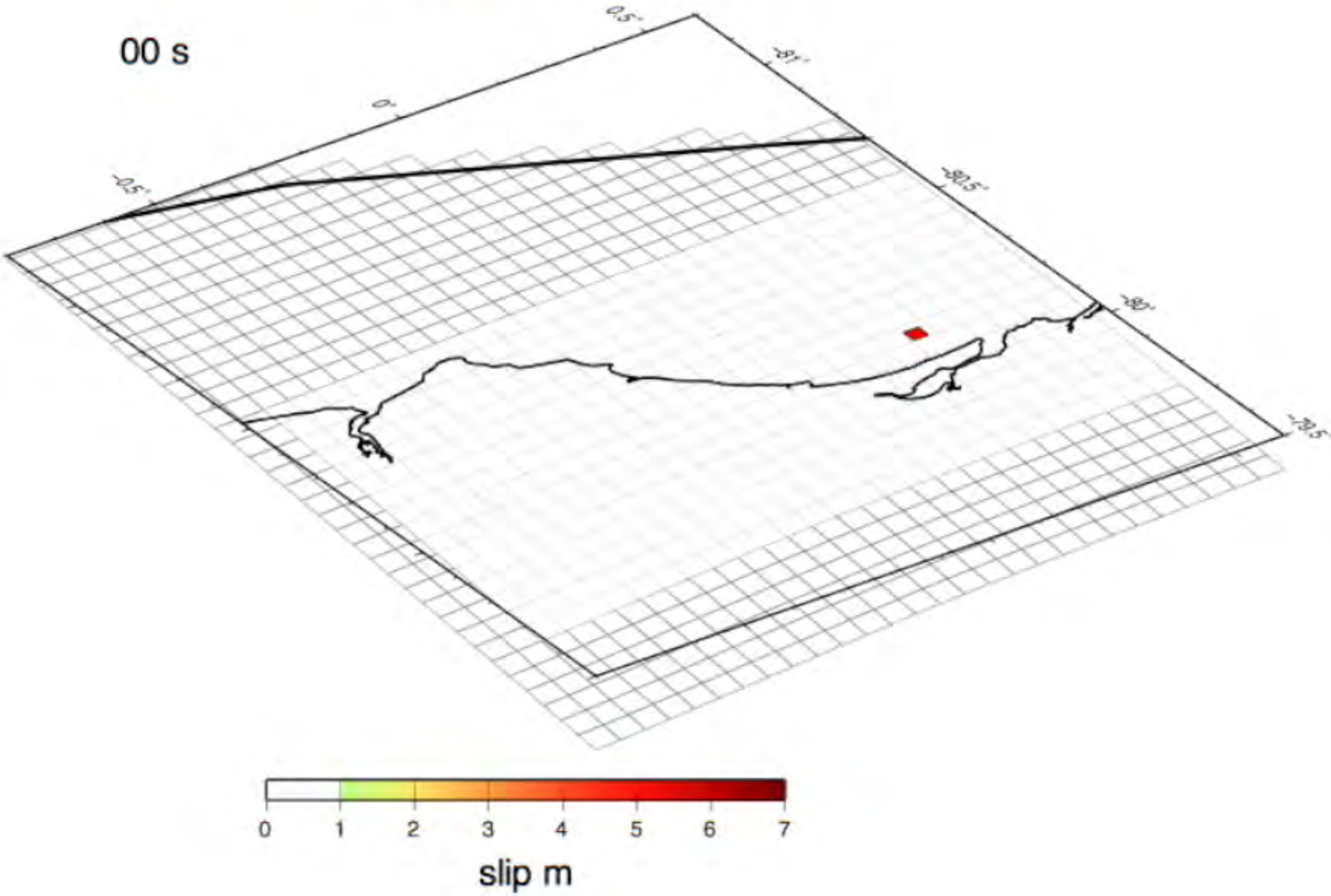
NEAR FIELD HIGH RATE GPS & ACCELEROGRAMS (FILTERED)

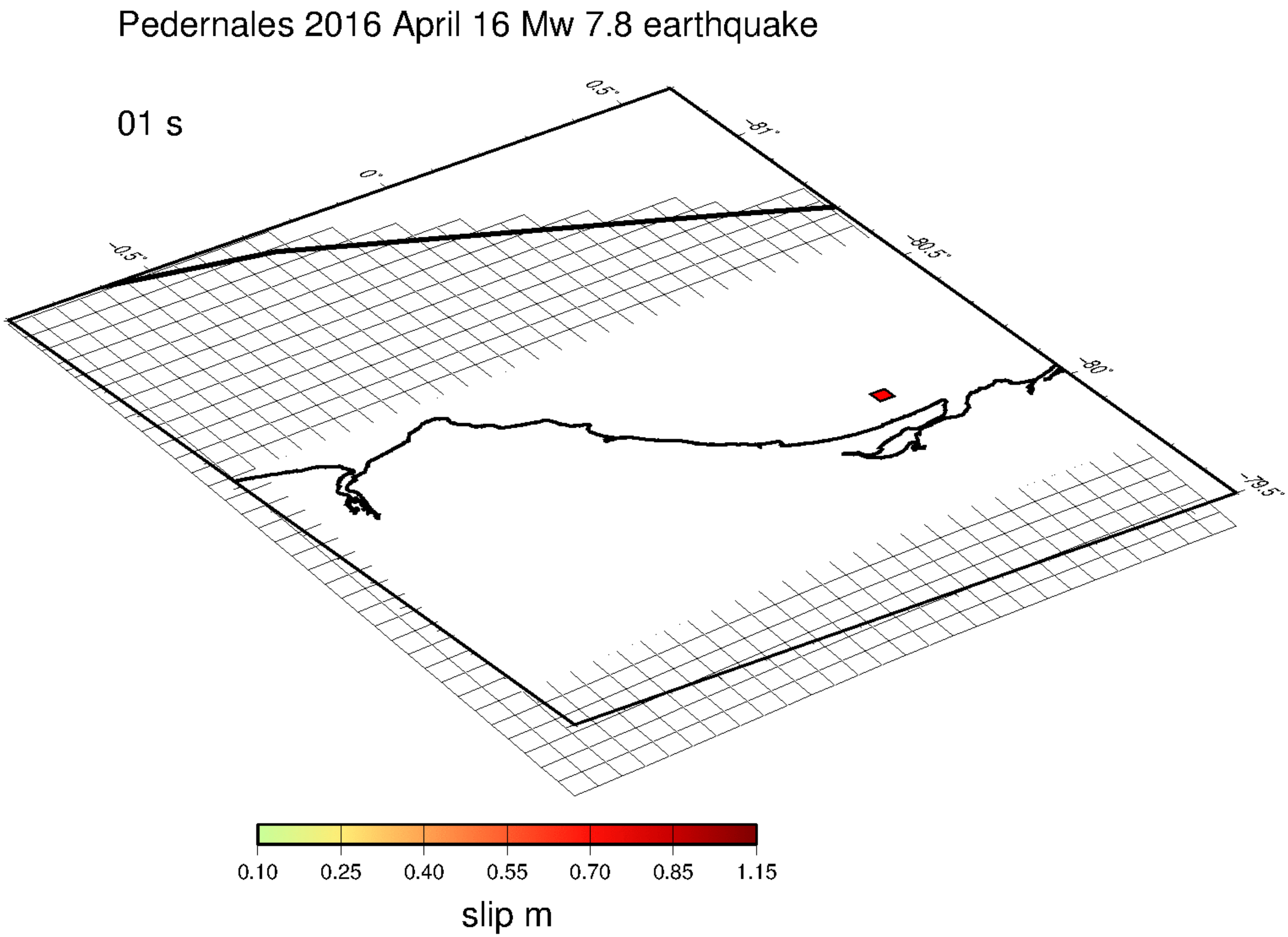


Nocquet et al., Nat. Geosc., 2017

Pedernales 2016 April 16 Mw 7.8 earthquake

00 s




Pedernales 2016 April 16 Mw 7.8 earthquake
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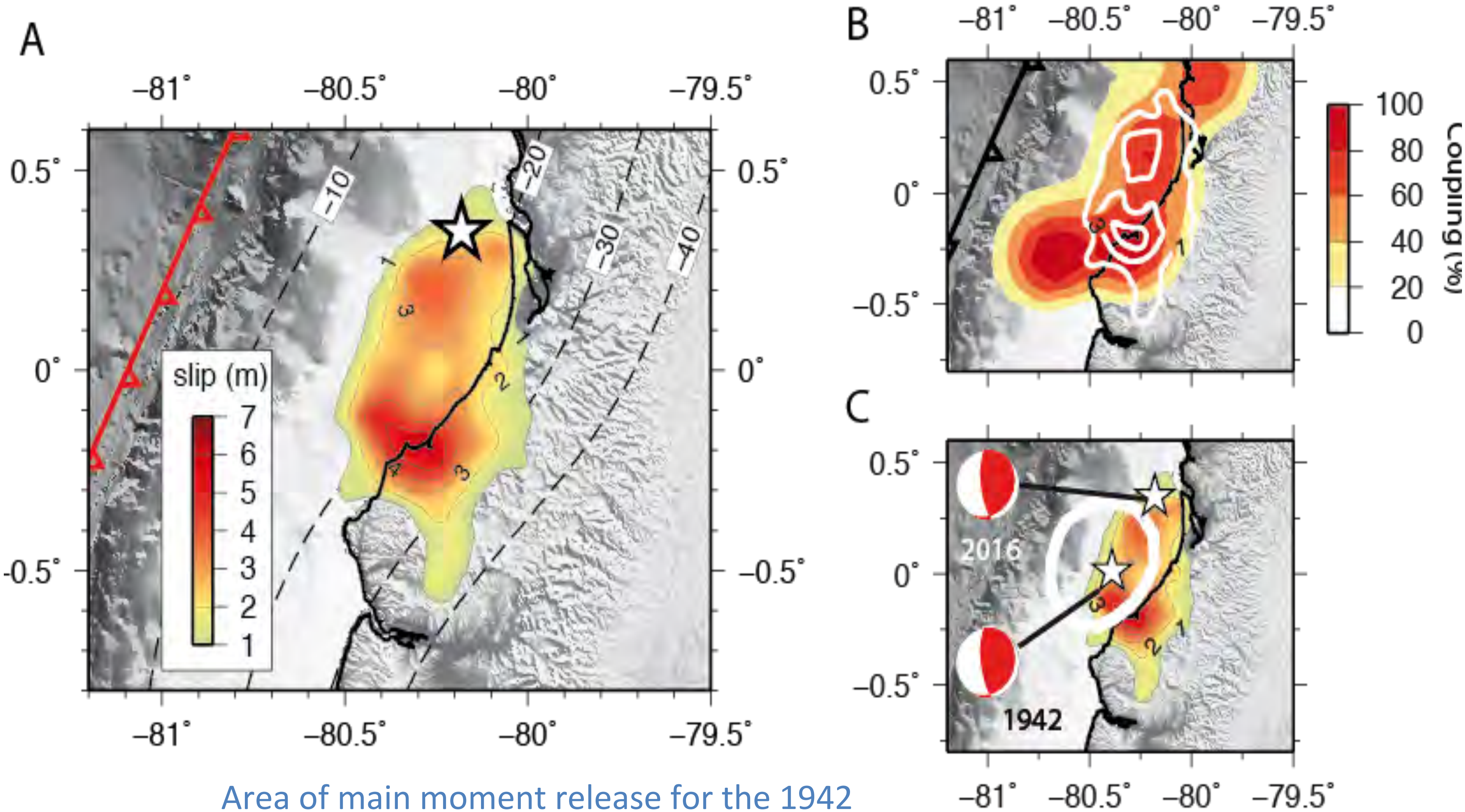
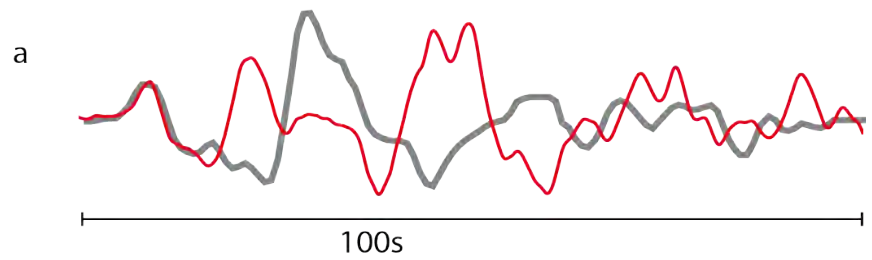
-0.5°
-81°
-80.5°
-80°
-79.5°
0.10
0.25
0.40
0.55
0.70
0.85
1.15
slip m

SLIP DISTRIBUTION , INTERSEISMIC COUPLING AND THE 1942 Mw 7.8 RUPTURE



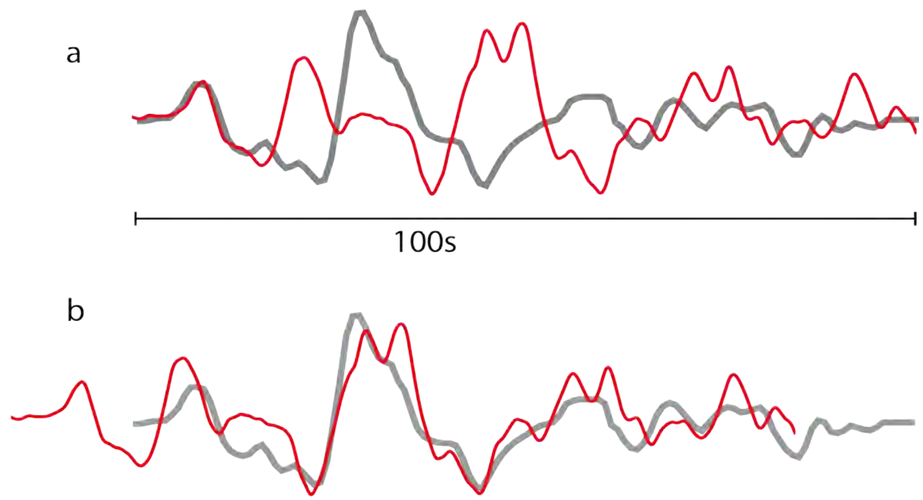
Area of main moment release for the 1942 earthquake from Swenson & Beck, 1996

COMPARISON OF SEISMOGRAMS AT DBN (THE NETHERLANDS) SEISMOLOGICAL STATION



- Red curve: 2016 waveform reconvolved by the response of the 1942 sensor

COMPARISON OF SEISMOGRAMS AT DBN (THE NETHERLANDS) SEISMOLOGICAL STATION



- Red curve: 2016 waveform reconvolved by the response of the 1942 sensor

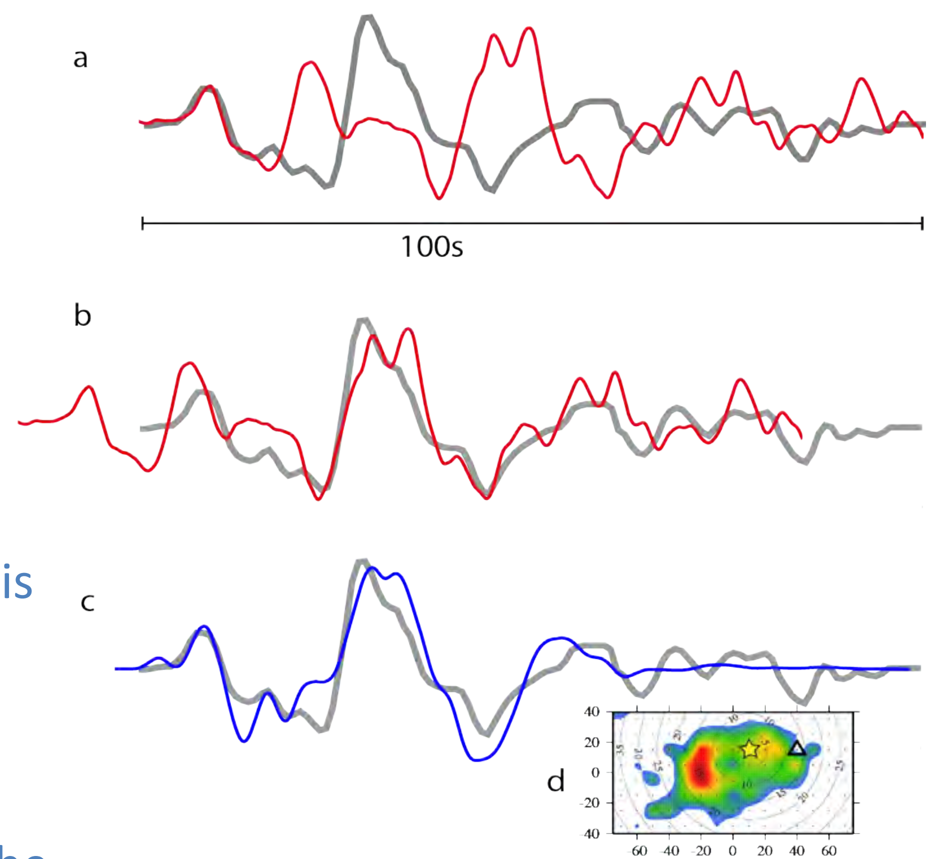
- Similar waveform when a ~15s shift is applied

COMPARISON OF SEISMOGRAMS AT DBN (THE NETHERLANDS) SEISMOLOGICAL STATION

- Red curve: 2016 waveform reconvolved by the response of the 1942 sensor

- Similar waveform when a ~15s shift is applied

- The 1942 waveform is well reproduced for a virtual EQ having the same slip distribution as the the 2016 EQ, the same rupture velocity but an hypocenter located in the middle of the rupture area

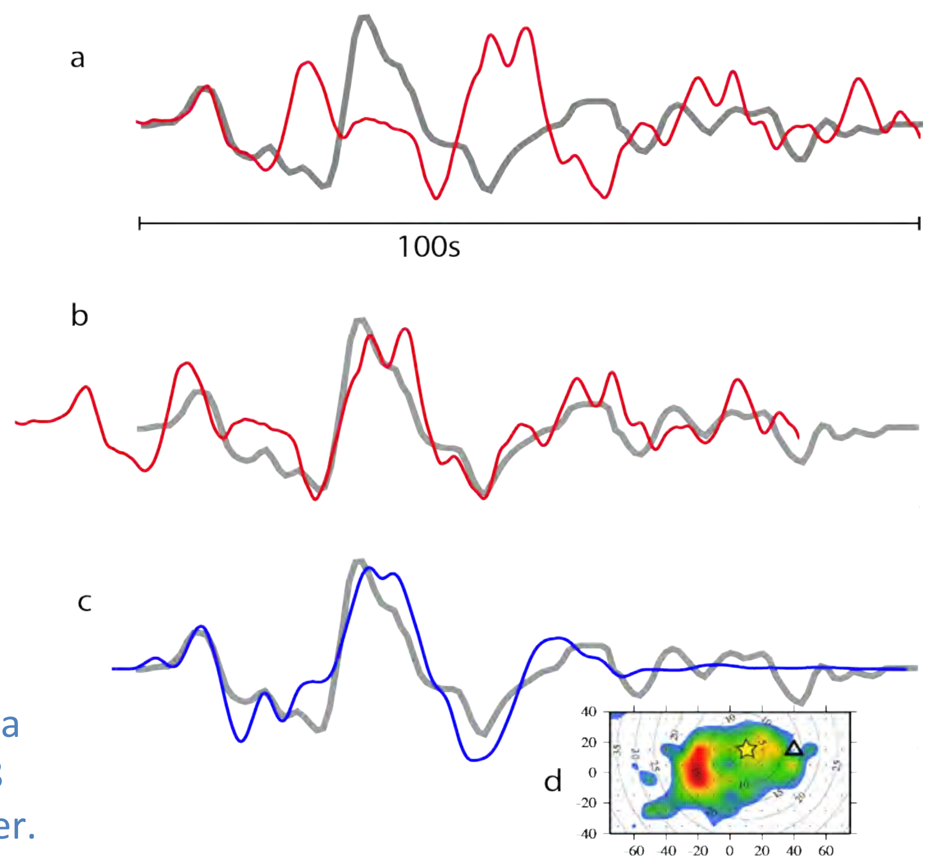


COMPARISON OF SEISMOGRAMS AT DBN (THE NETHERLANDS) SEISMOLOGICAL STATION

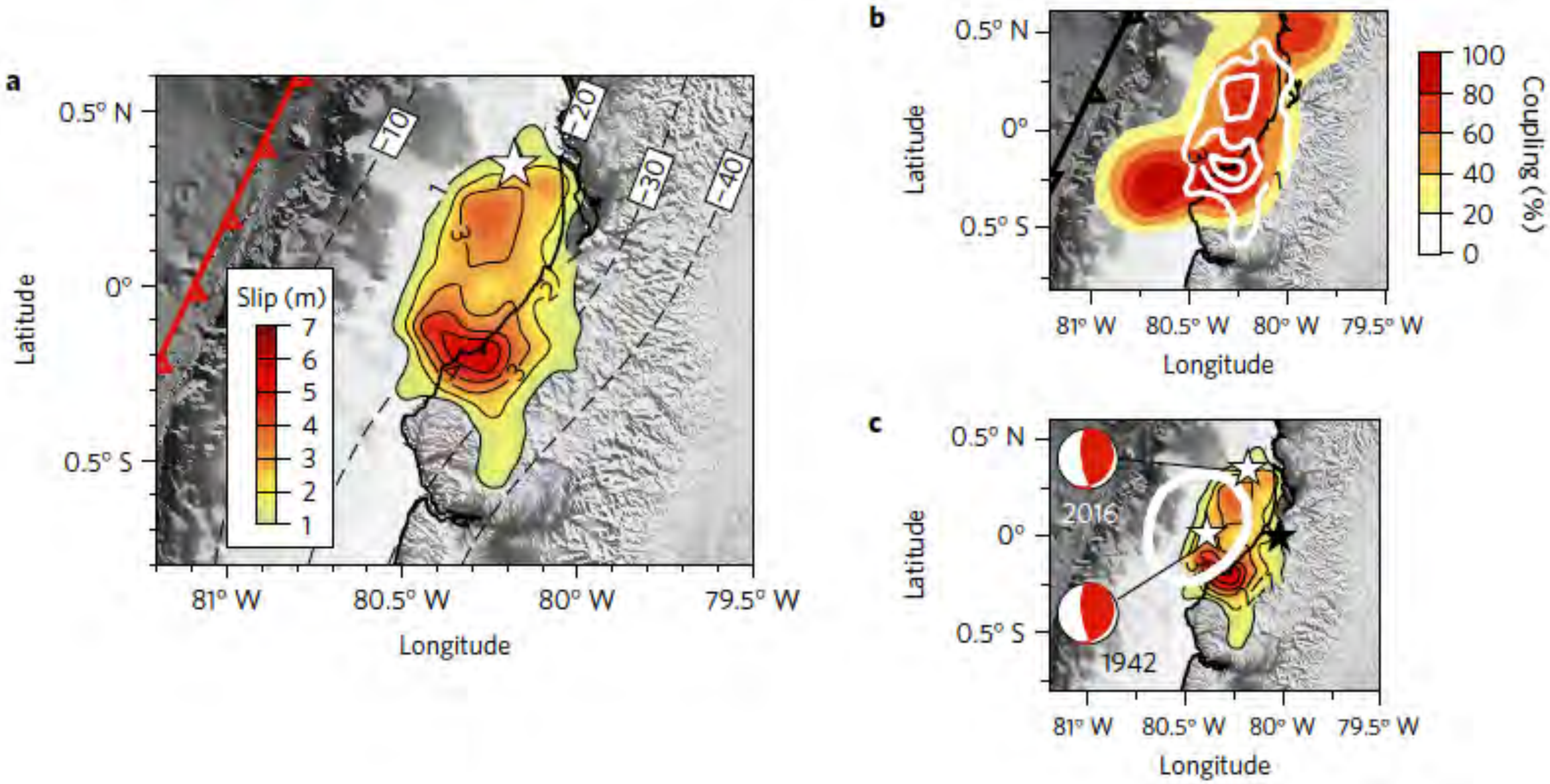
- **Conclusions**

  - The similarity of waveform suggests a similar location and focal mechanism

  - The short source time function suggests a bilateral propagation to achieve Mw~7.8 over ~25s and high slip near the epicenter.

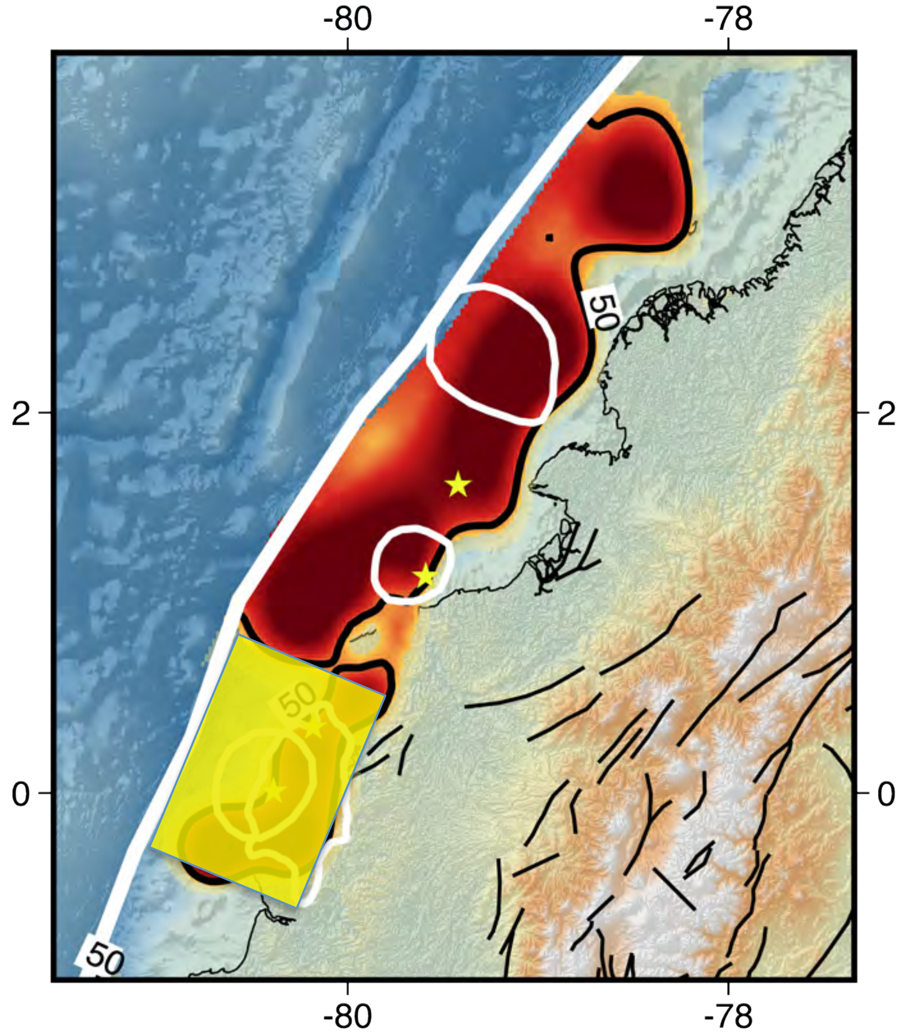


SLIP & MOMENT BUDGETS 1942-2016



- Assuming that the 1942 earthquake ruptured the same asperity, the maximum slip deficit is 74 x 0.0475 = 3.4 m, smaller than the 6 m of peak coseismic slip
- Integrated over the 2016 rupture area, the 2016 slip exceeds by 30-60% the slip deficit accumulated since 1942 at the present-day (1994-2016) rate
- The same calculation for 1906-1942 shows that the 1942 EQ had a moment 3-5 times larger than expected from moment deficit rate accumulation

MOMENT BUDGETS AT THE PEDERNALES SEGMENT



Moment deficit rate:

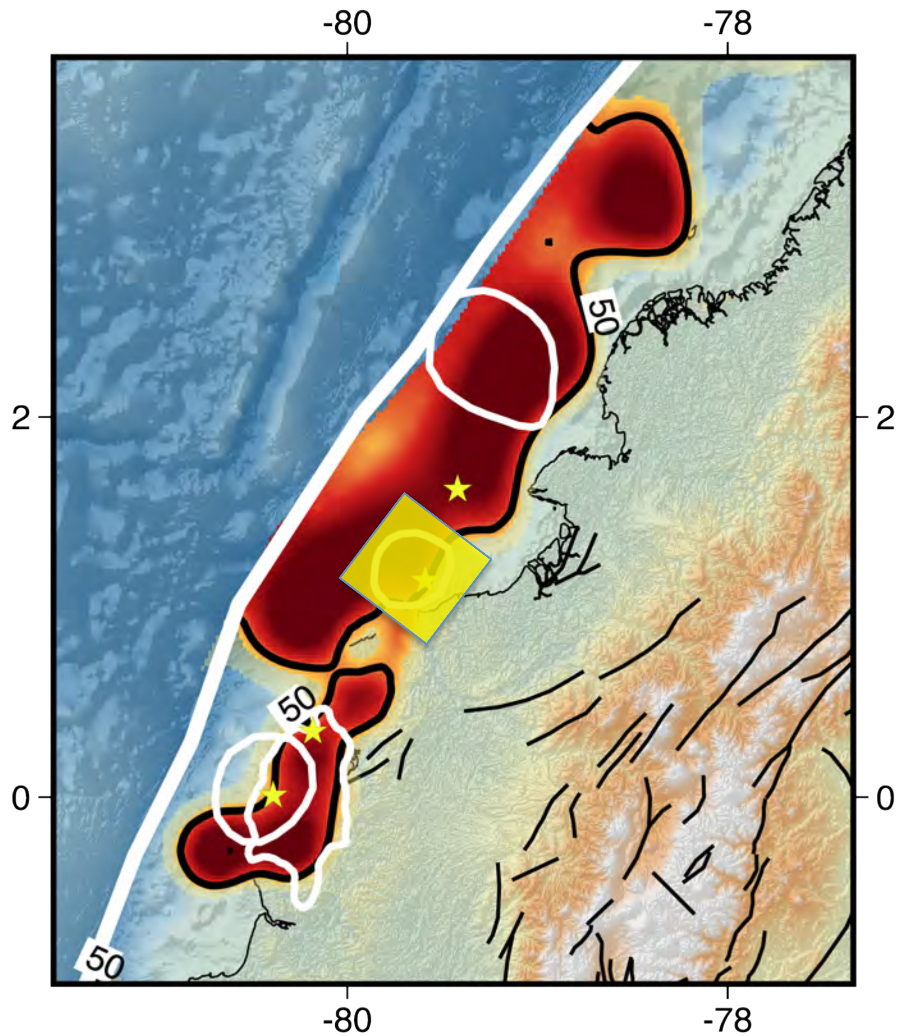
8+-1.5 10^{18} Nm/yr

1942 + 2016 EQ also released more moment than the deficit accumulated since 1906

EQ 1.1-2.0 x accumulated moment deficit

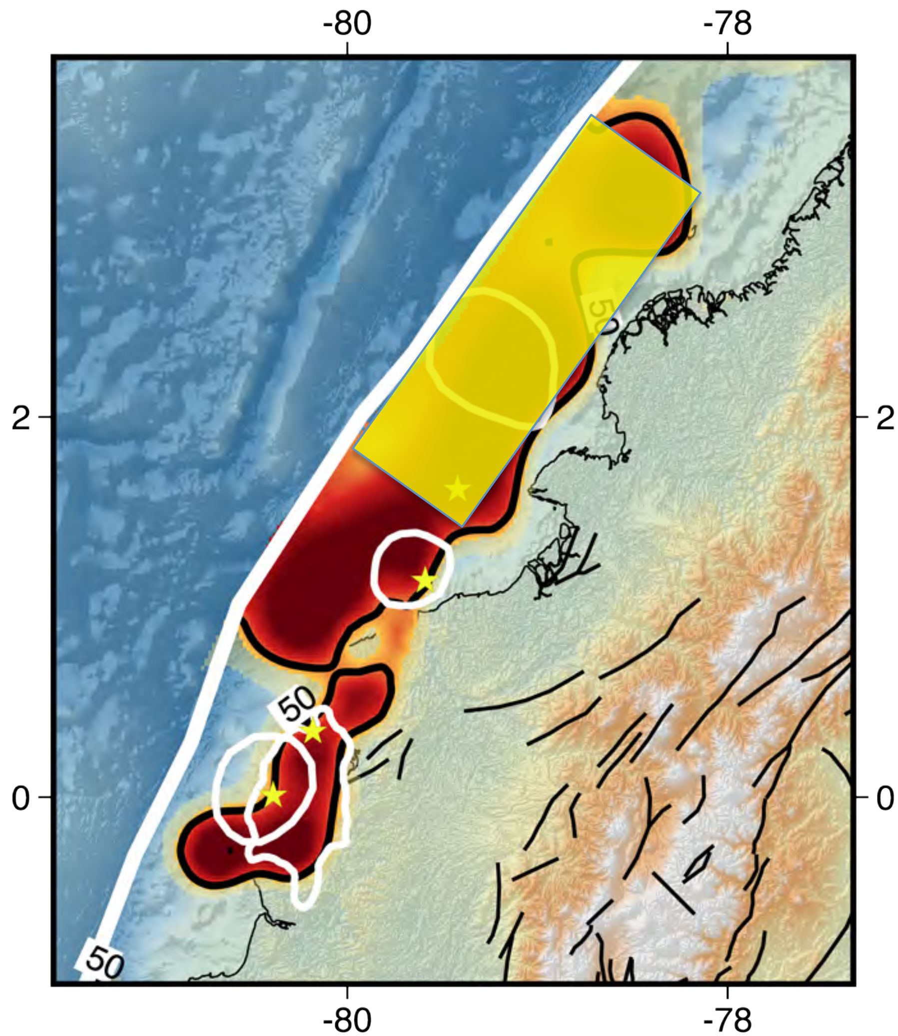
Contrast with the seismic quiescence before 1906: no earthquake known during the 18th and 19th centuries, although reports for crustal earthquakes do exist

MOMENT BUDGETS 1906-1958



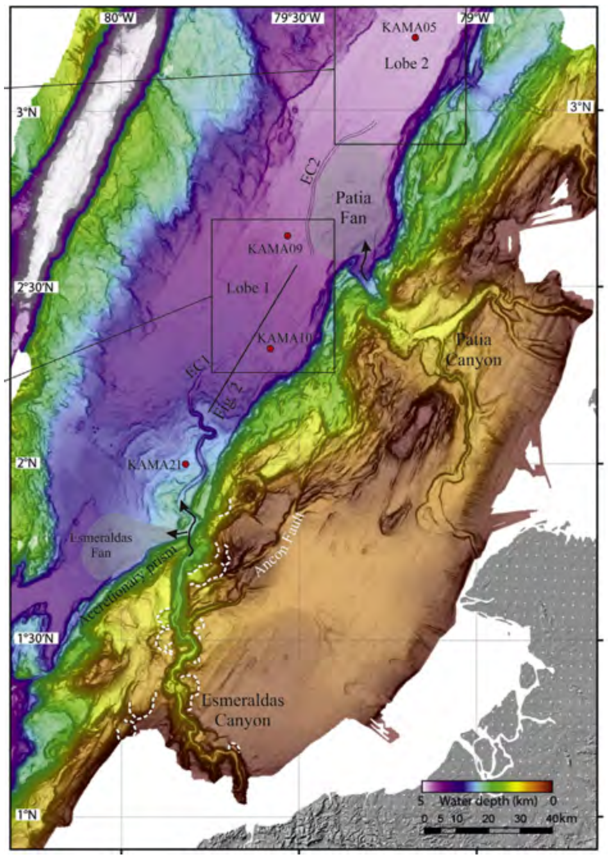
- Assuming 100% coupling
- 50 x 50 km^2 * 52 years * 4.7 cm/yr * $3x10^{10}$ Pa
  = 1.9 x 10^{20} N.m (Mw 7.5)
- Moment 1958 EQ
  = 2.8-5.2 x 10^{20} N.m (Mw 7.7-7.8)
- EQ 1.5-2.7 x accumulated moment deficit

MOMENT BUDGETS 1906-1979

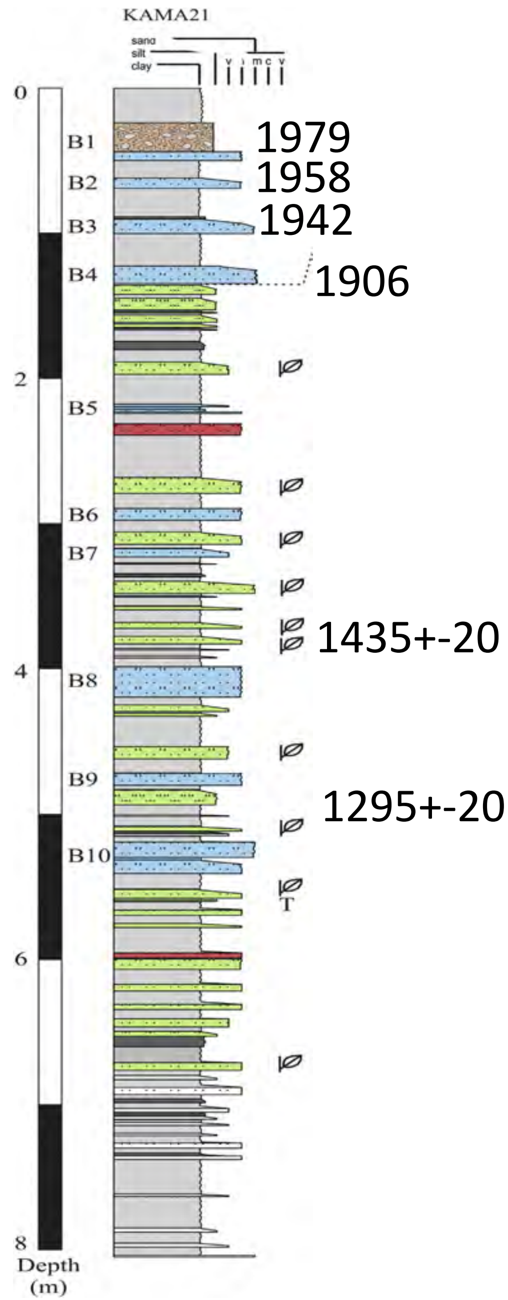


- 240 x 70 km^2 * 73 years * 4.7 cm/yr * 3x10^{10} Pa
  = 1.7 x 10^{21} N.m
- Moment 1979 EQ
  = 2.9 x 10^{21} N.m
- EQ 1.7 x accumulated moment deficit

FIRST MARINE PALEOSEISMOLOGY RESULTS

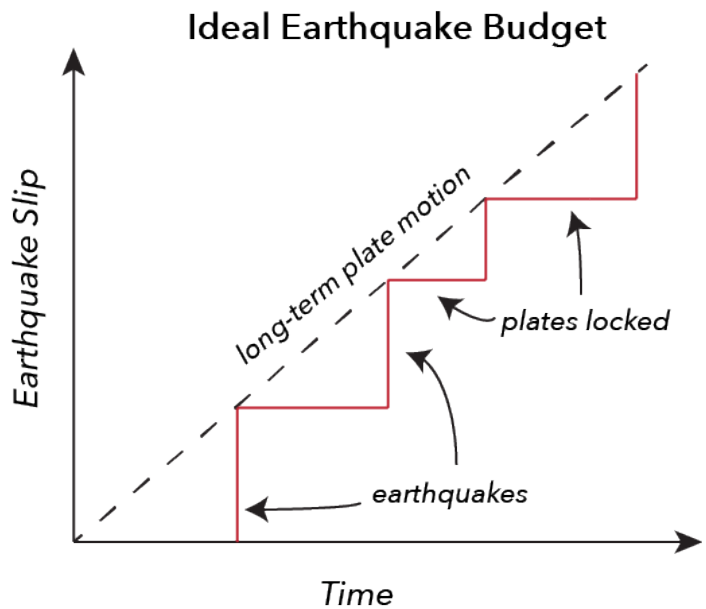


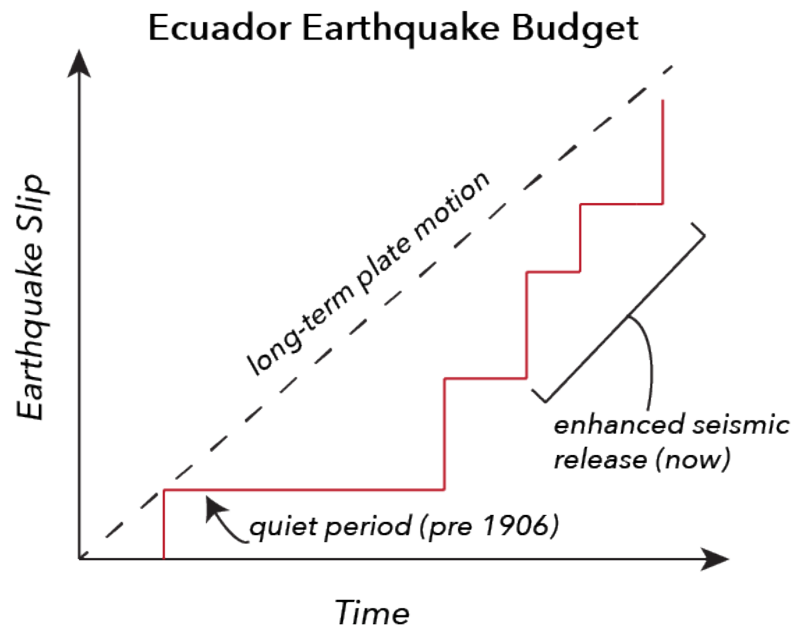
Migeon et al., Mar. Geol., 2017



- Previous 1906-type EQ ~550-630 years before 1906
- No earthquake triggered turbidites for 2-3 centuries before 1906

CONCLUSIONS

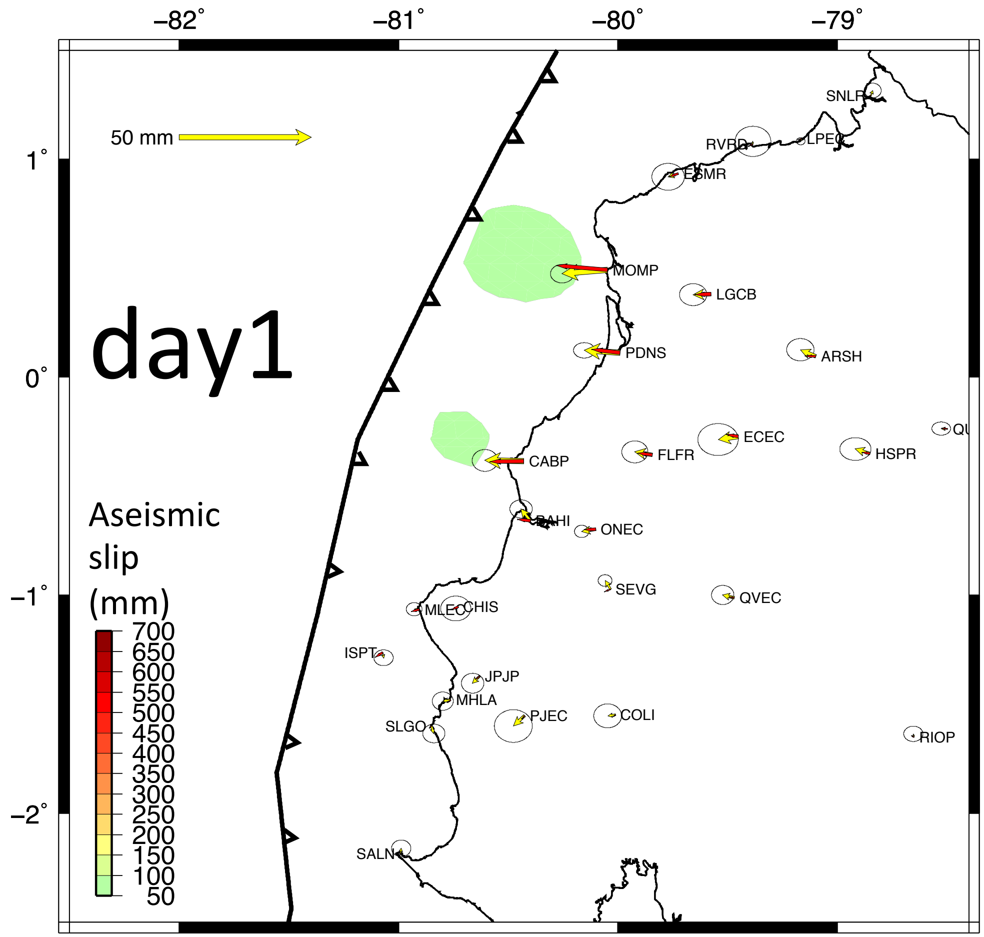


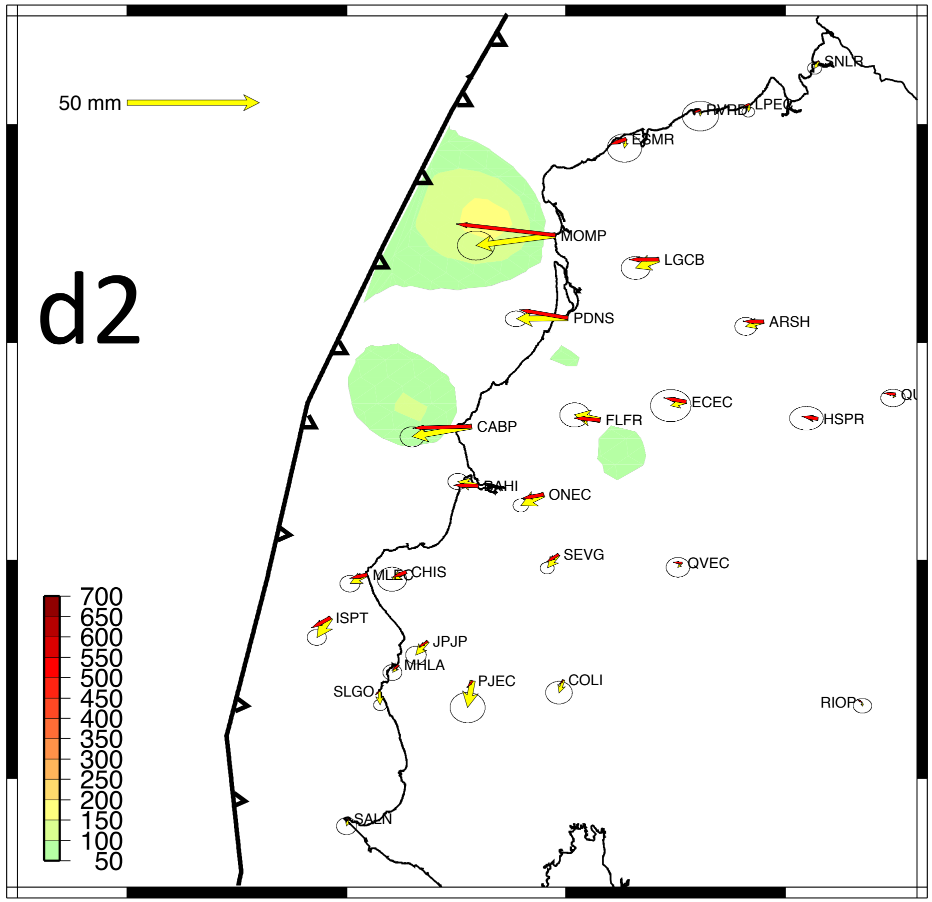


From http://temblor.net/earthquake-insights/why-have-there-been-so-many-large-earthquakes-in-ecuador-2035

- The Ecuador-Colombia shows an abnormally large seismic moment release with respect to its present-day rate of strain accumulation
- It rather corresponds to a release of moment deficit accumulated over ~2-3 centuries before 1906
- Historical & first paleoseismology results support this view
- Similarity with earthquake **supercycles** found in other subduction zones
  - (Cisternas et al., 2005, Sieh et al., 2008)
- Enhanced Seismic Hazard scenario for the Ecuador-Colombia margin should be considered

ONE MONTH POST-SEISMIC SLIP





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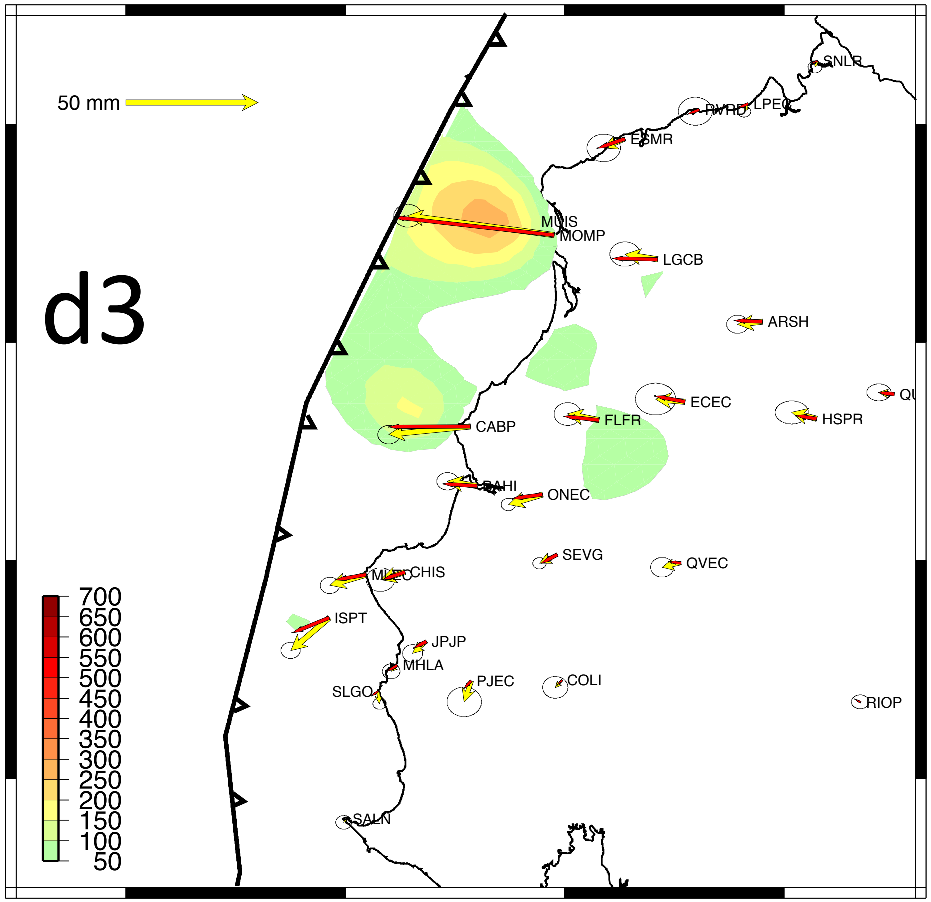
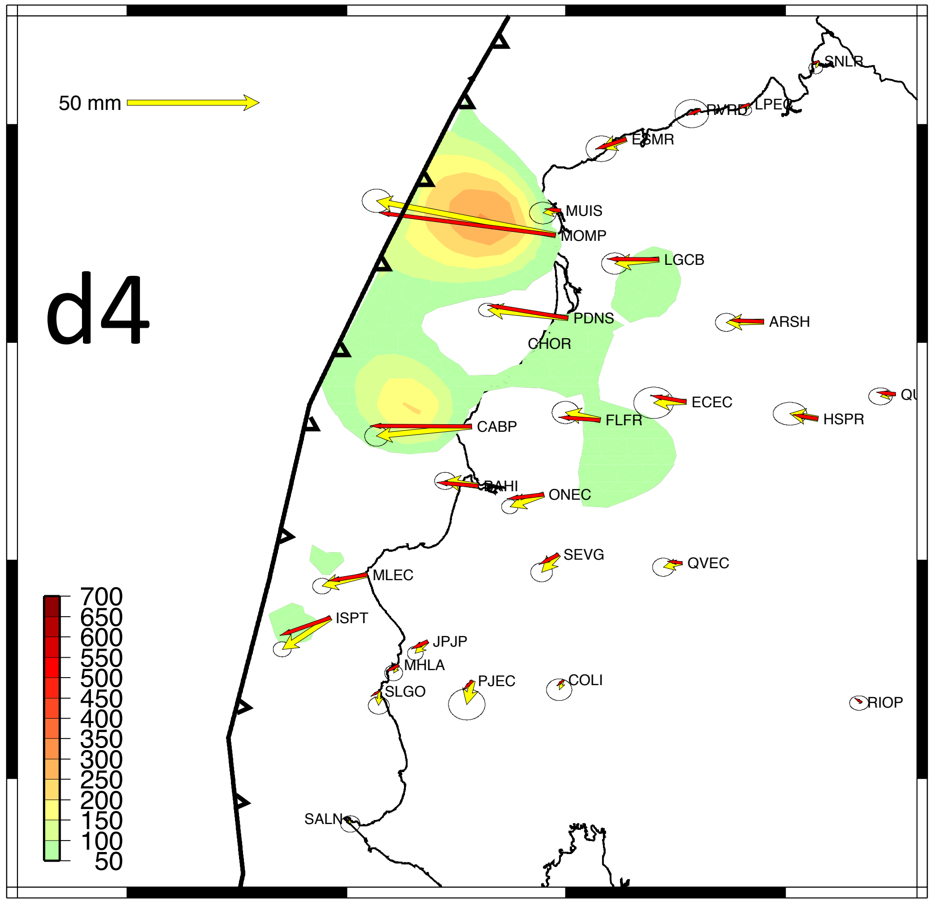
Onset of a Slow Slip Event





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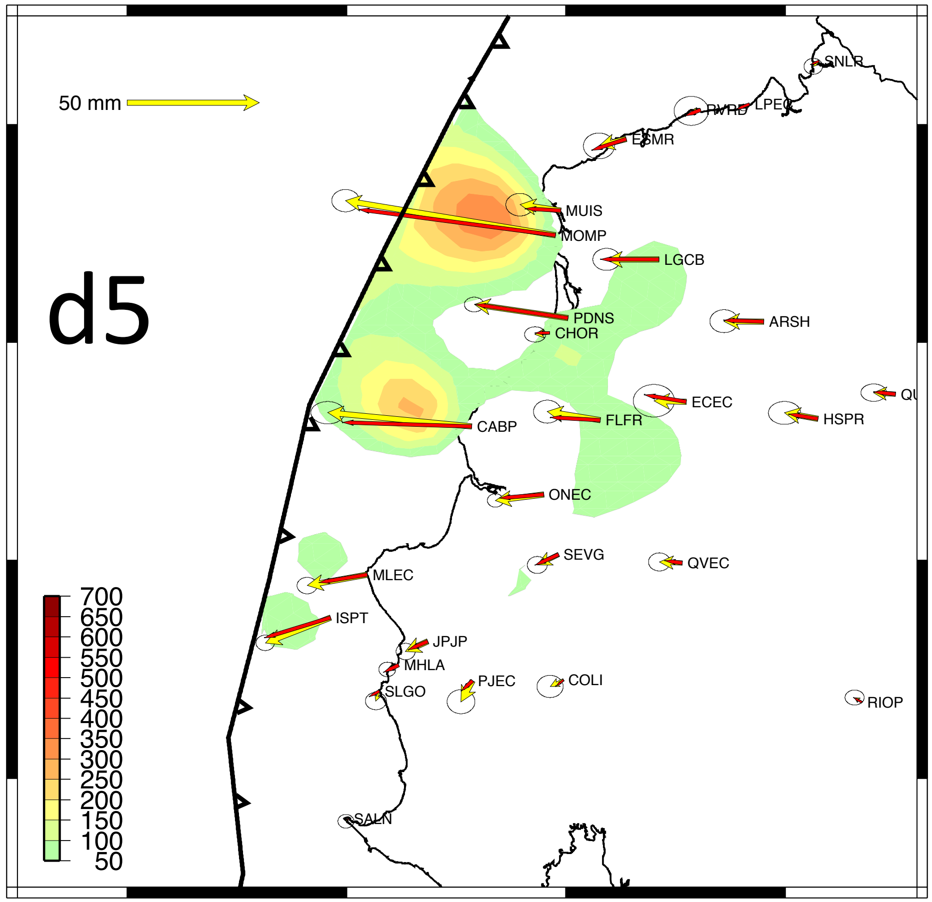

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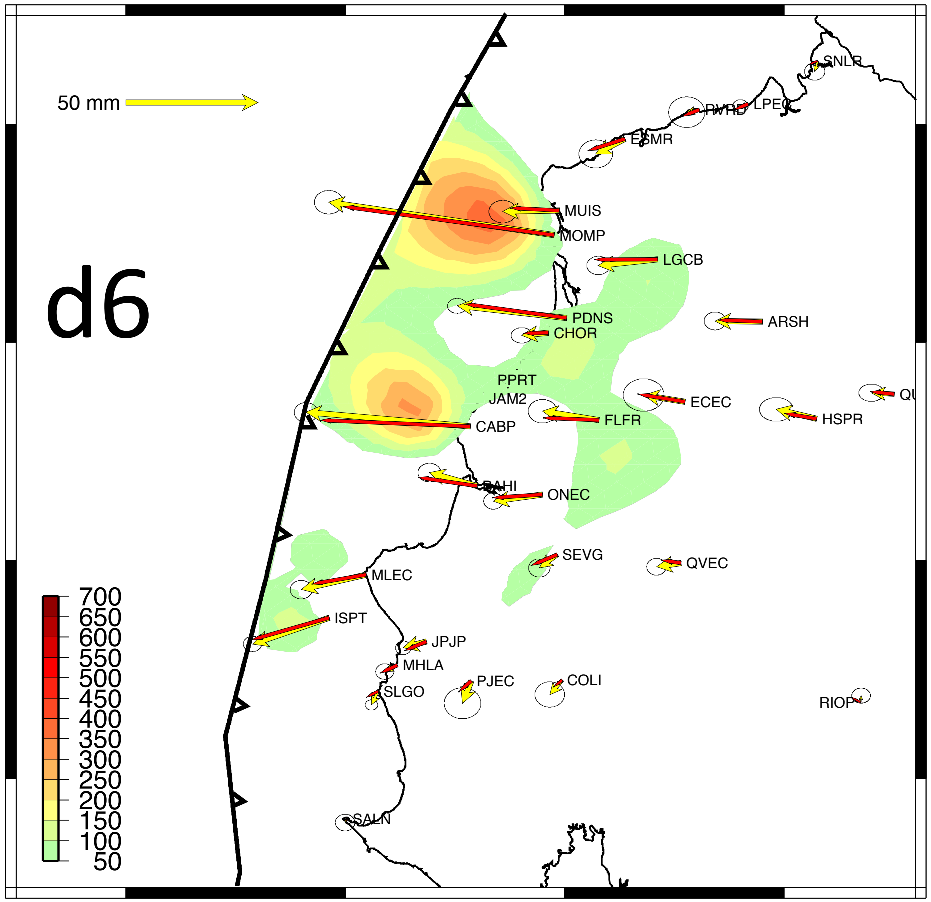
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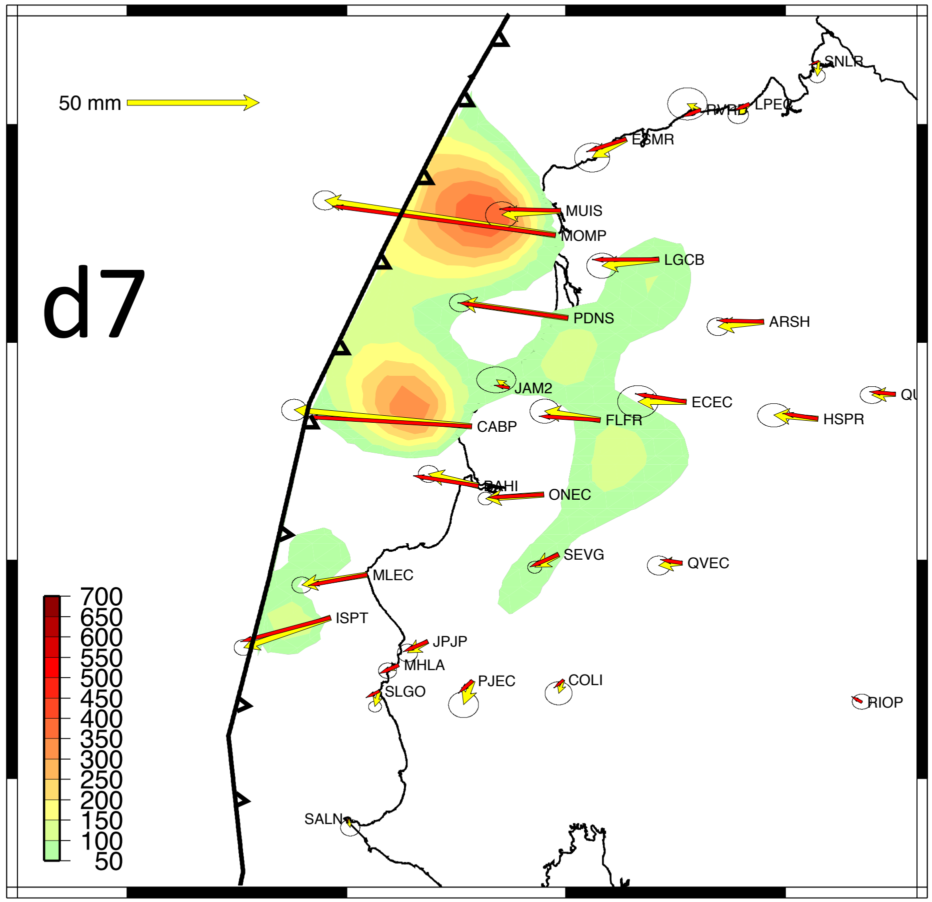

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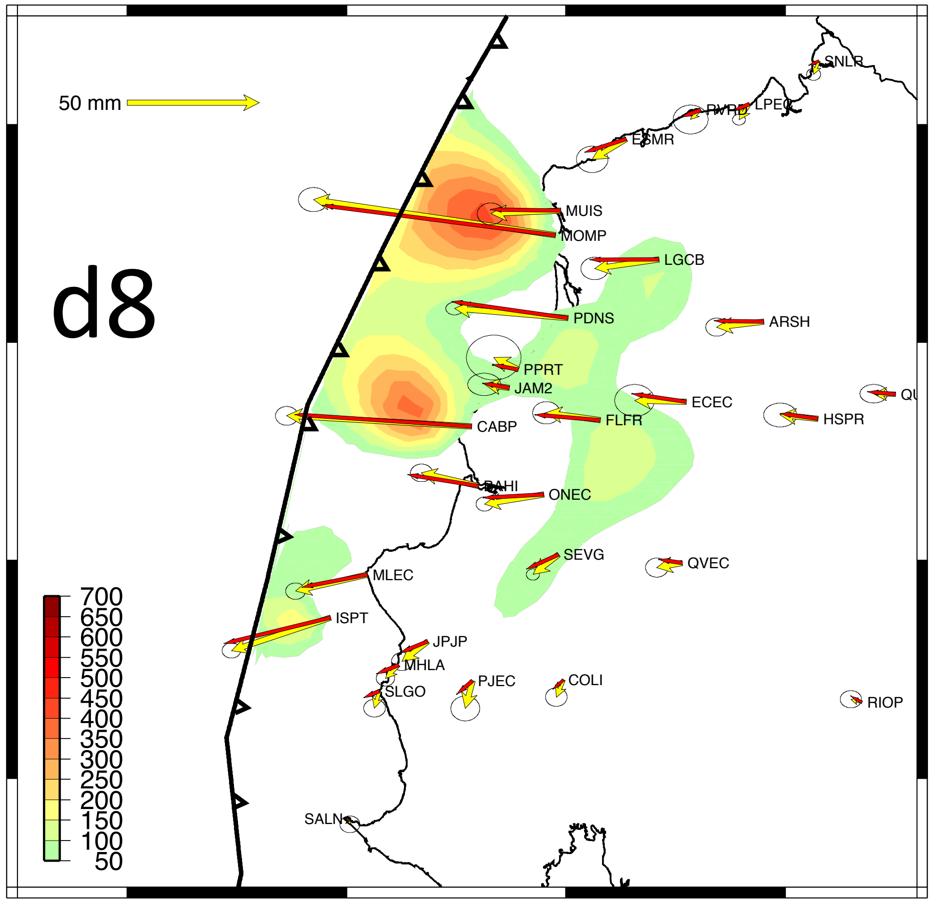

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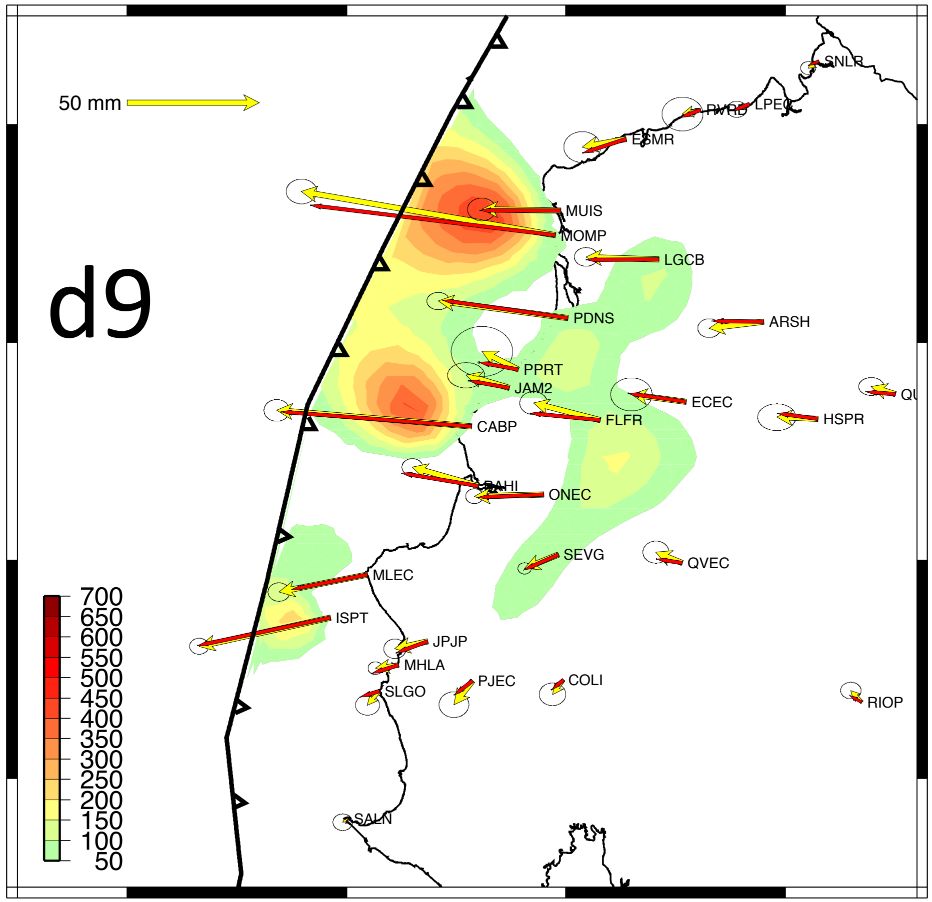

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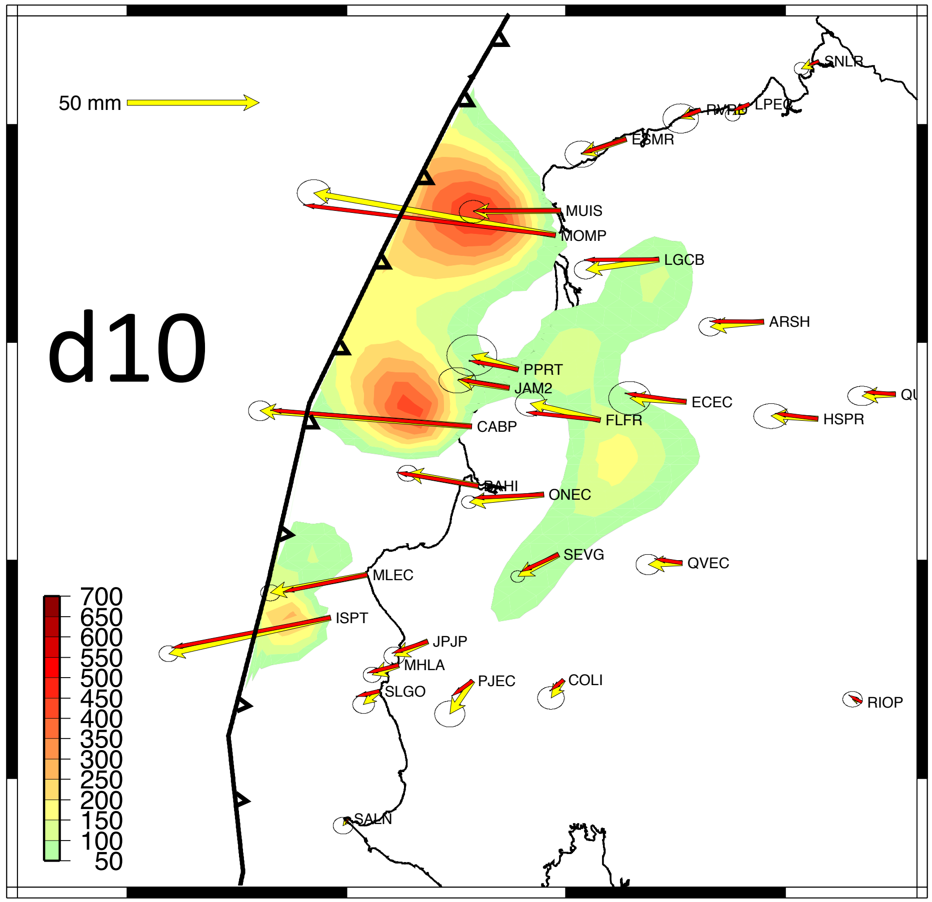

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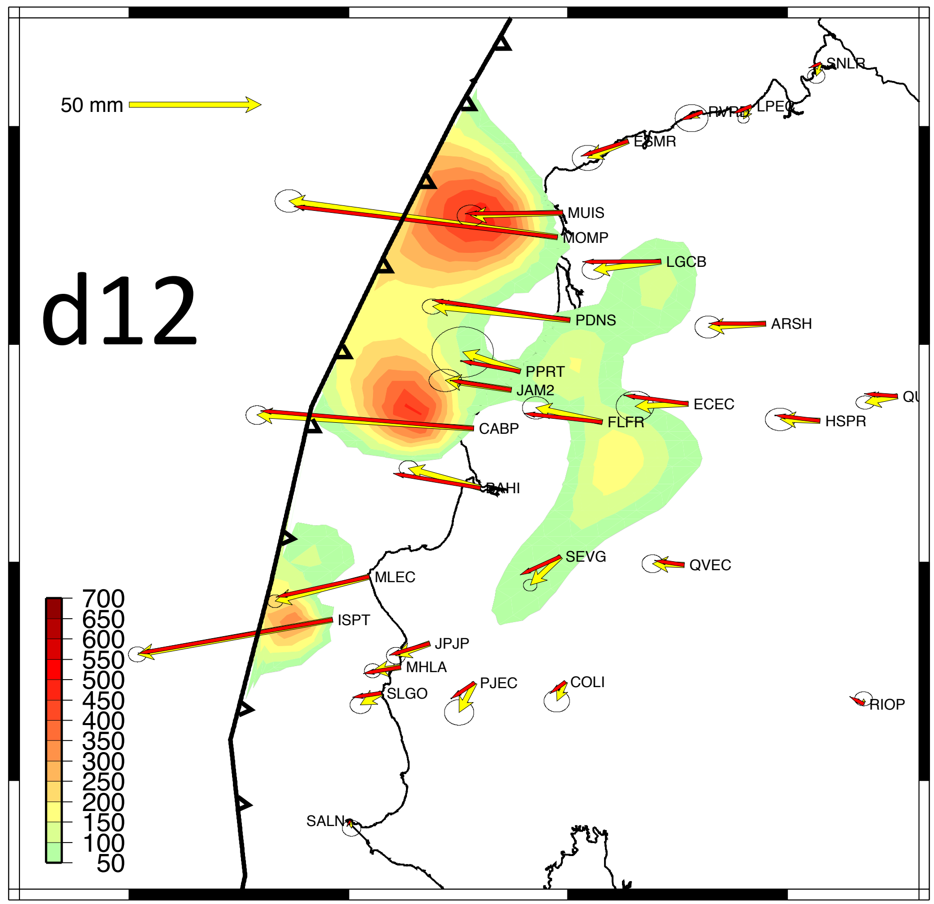

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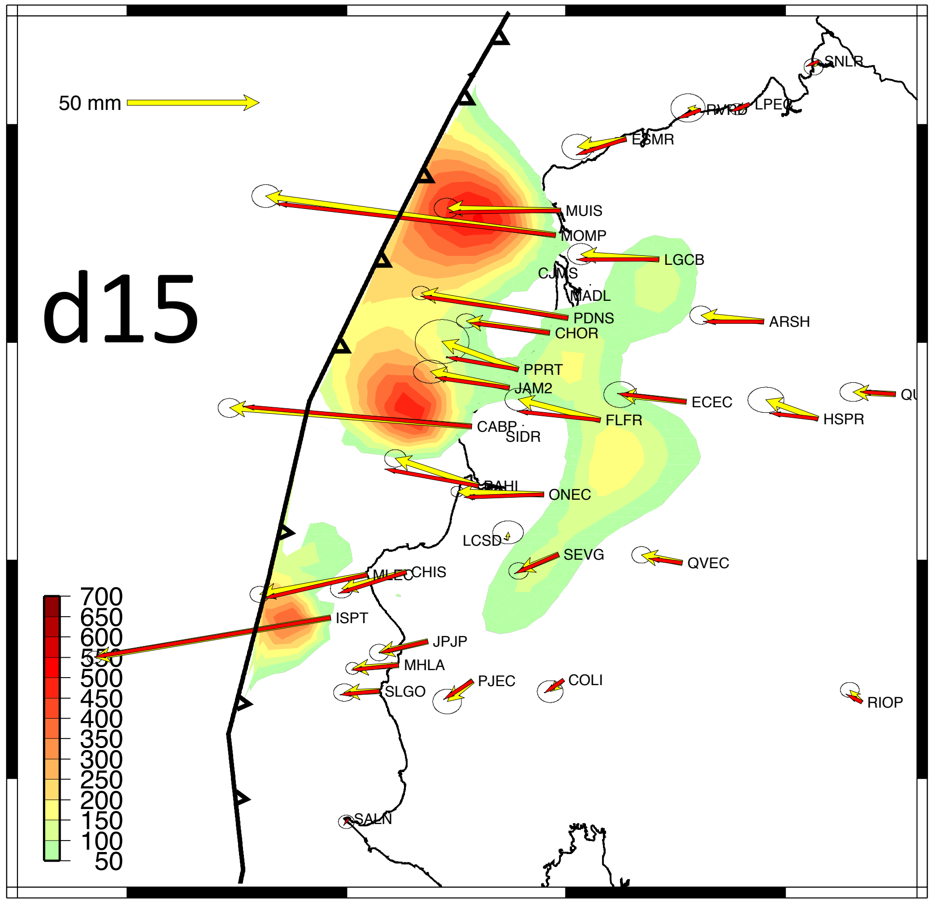

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HSPR
CABP
SIDR
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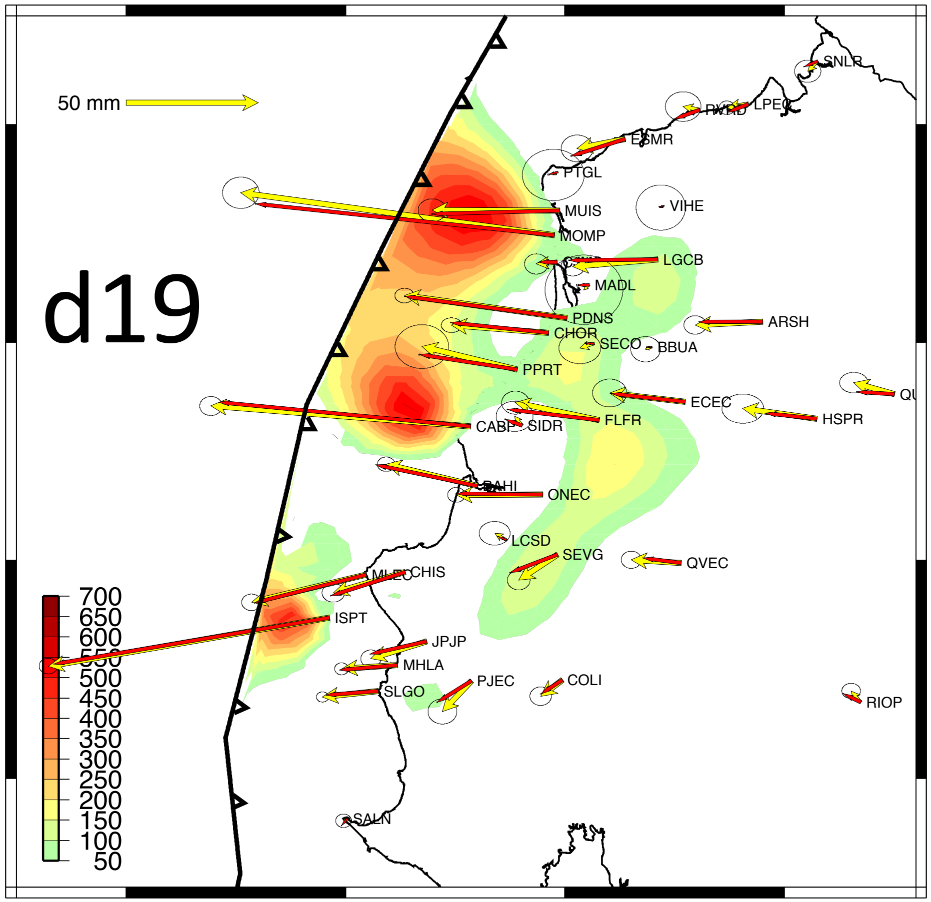
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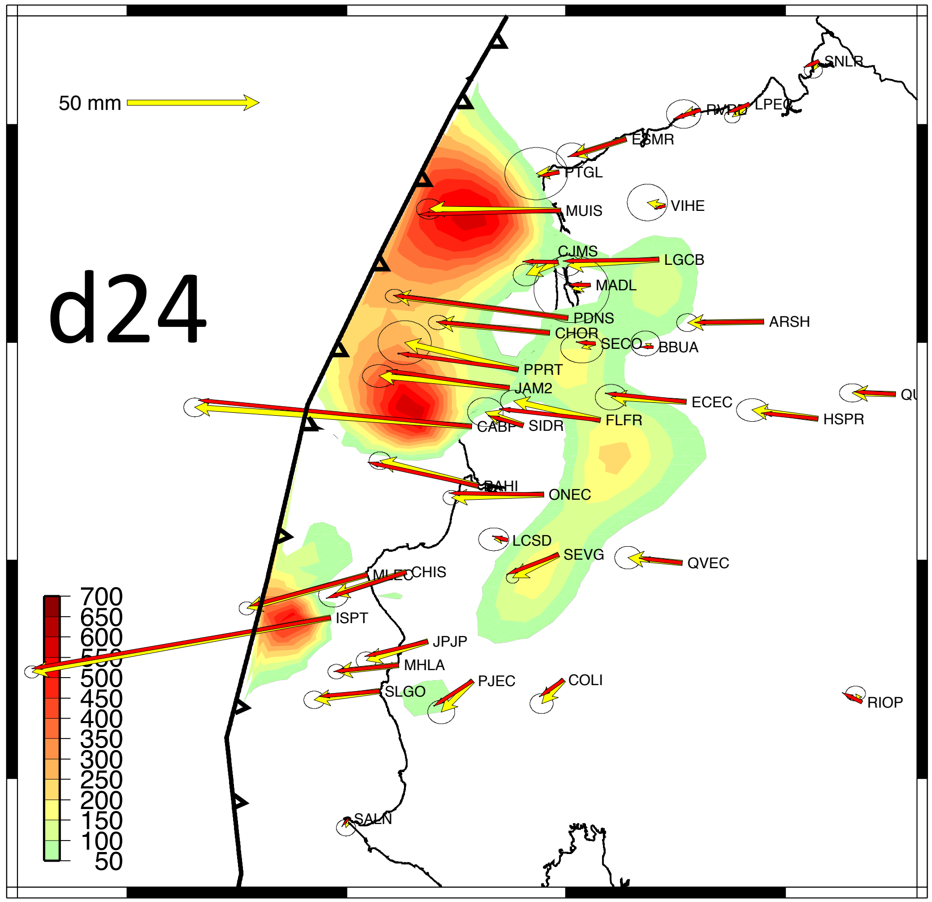

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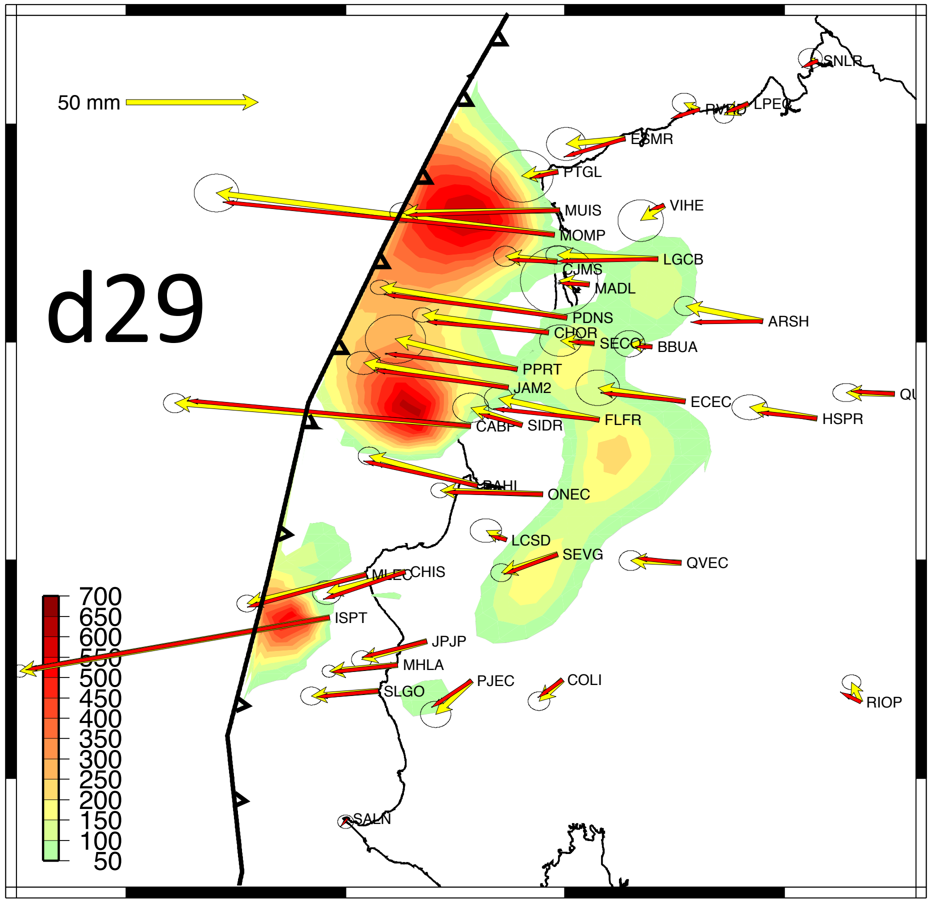

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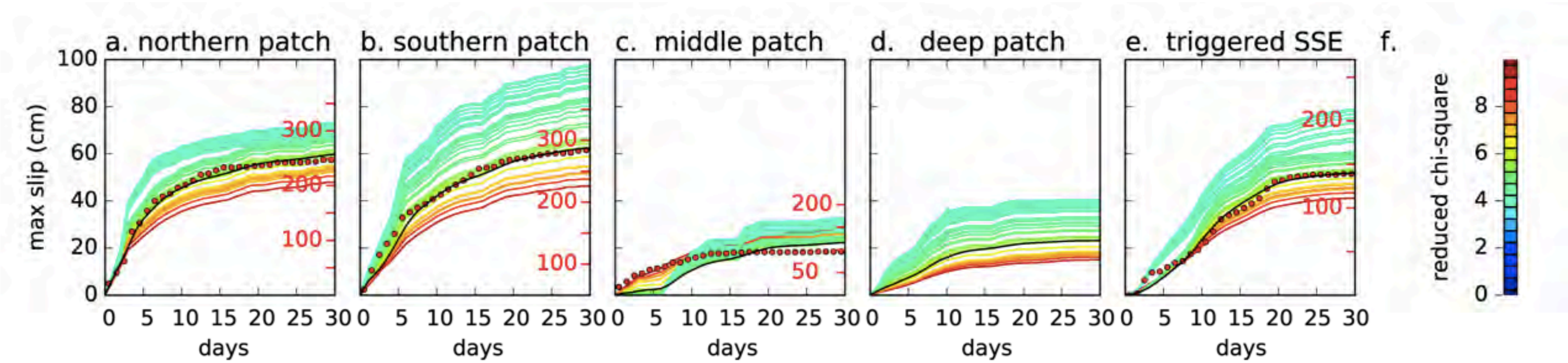
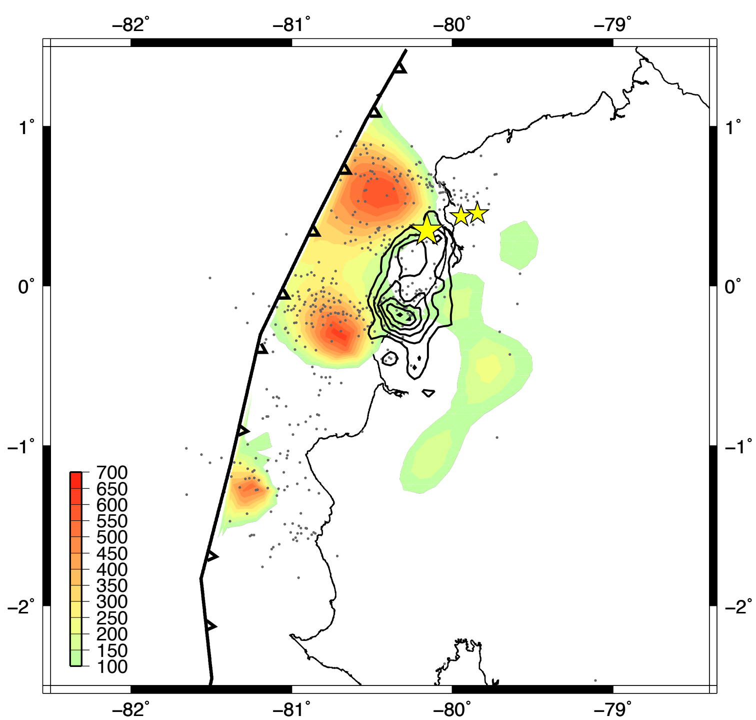
EARLY AFTERSLIP & AFTERSHOCKS





Seismic/aseismic budget for 1 month:

Total postseismic moment Mw 7.4
30% of the co-seismic moment released

Seismicity accounts for ~10 % of the postseismic deformation

Spatial and temporal correlation aftershocks/aseismic slip

Aftershocks primarily driven by afterslip

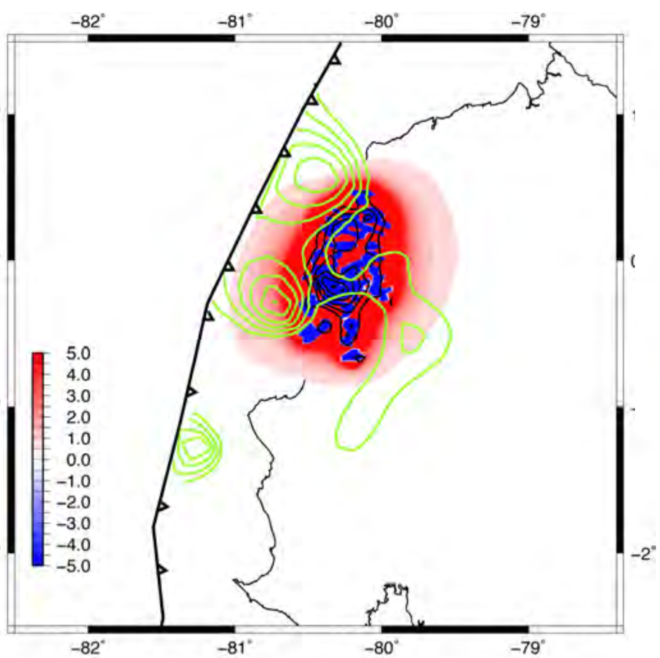
Rolandone et al., in revision

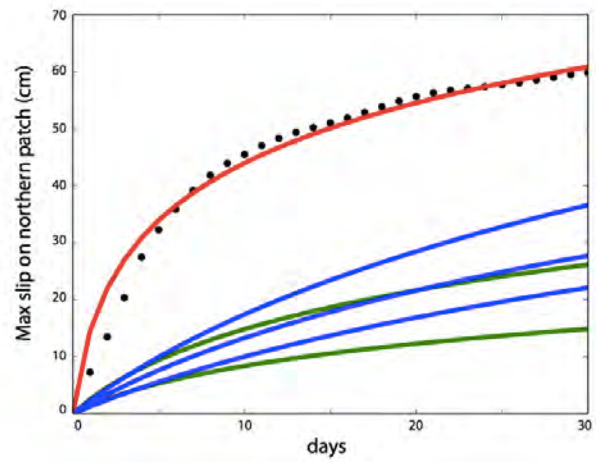
3 UNUSUAL PROPERTIES OF AFTERSLIP

1- little spatial correlation with the highest static stress perturbations induced by the 2016 EQ

2- amount of afterslip is abnormally rapid and large

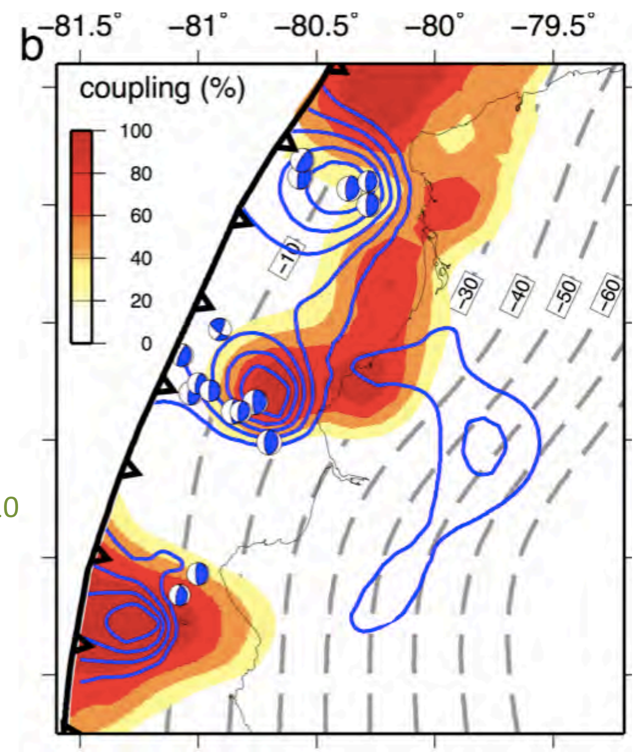
3- shallow afterslip involves areas that were locked prior to the Pedernales EQ





Pisco Mw 8.0 EQ (Perfettini et al. 2010

Maule Mw 8.8 EQ (Lin et al., 2013)

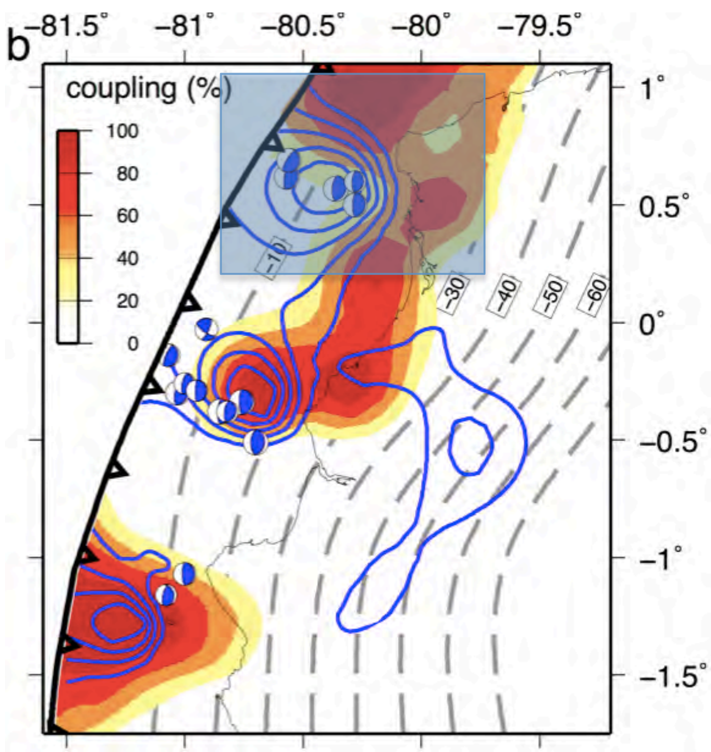


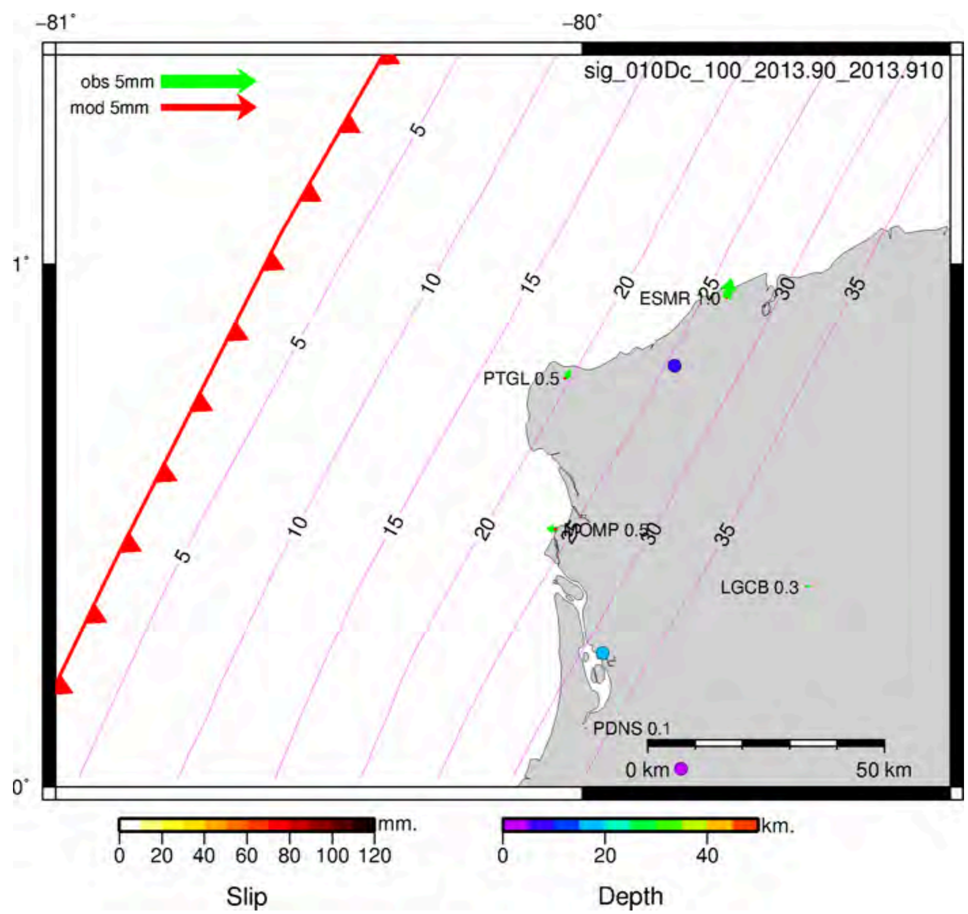
Rolandone et al., in revision

SSE in Ecuador, north of the Pedernales rupture

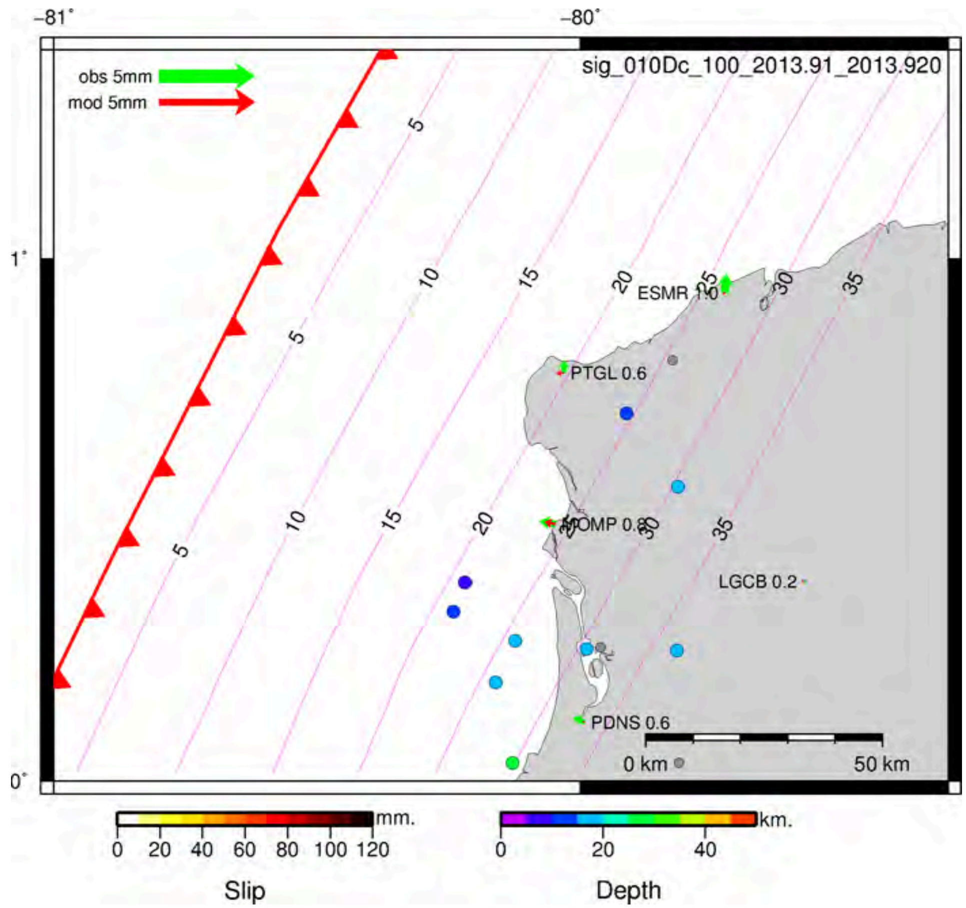
Slip kinematic inversion every 3 days and micro-seismicity

November 2013 – January 2014





Vaca et al., in revision



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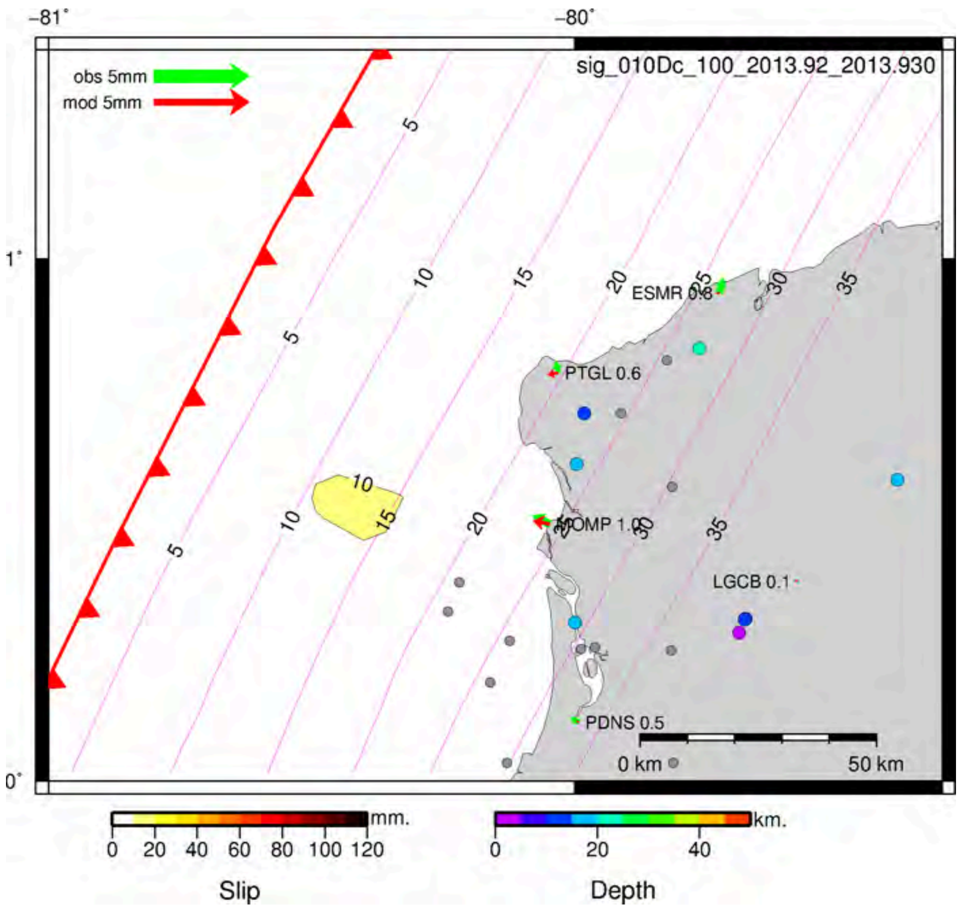
Slip
km.
0 20 40
Depth



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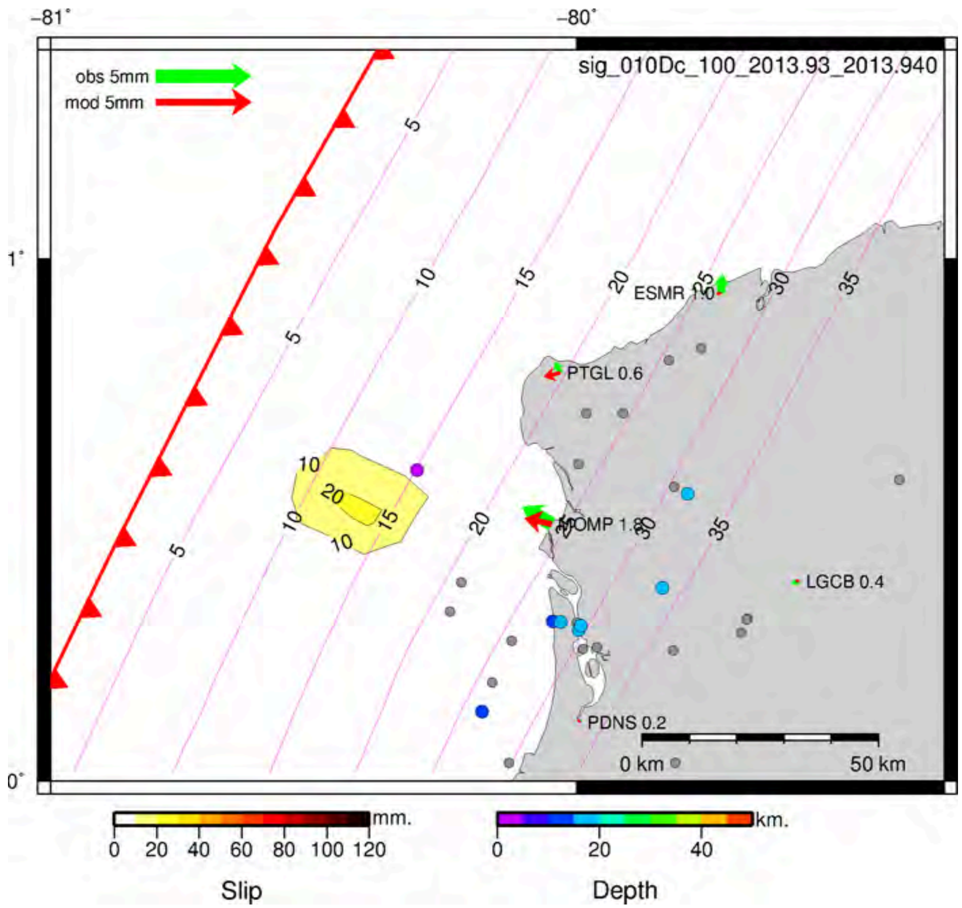

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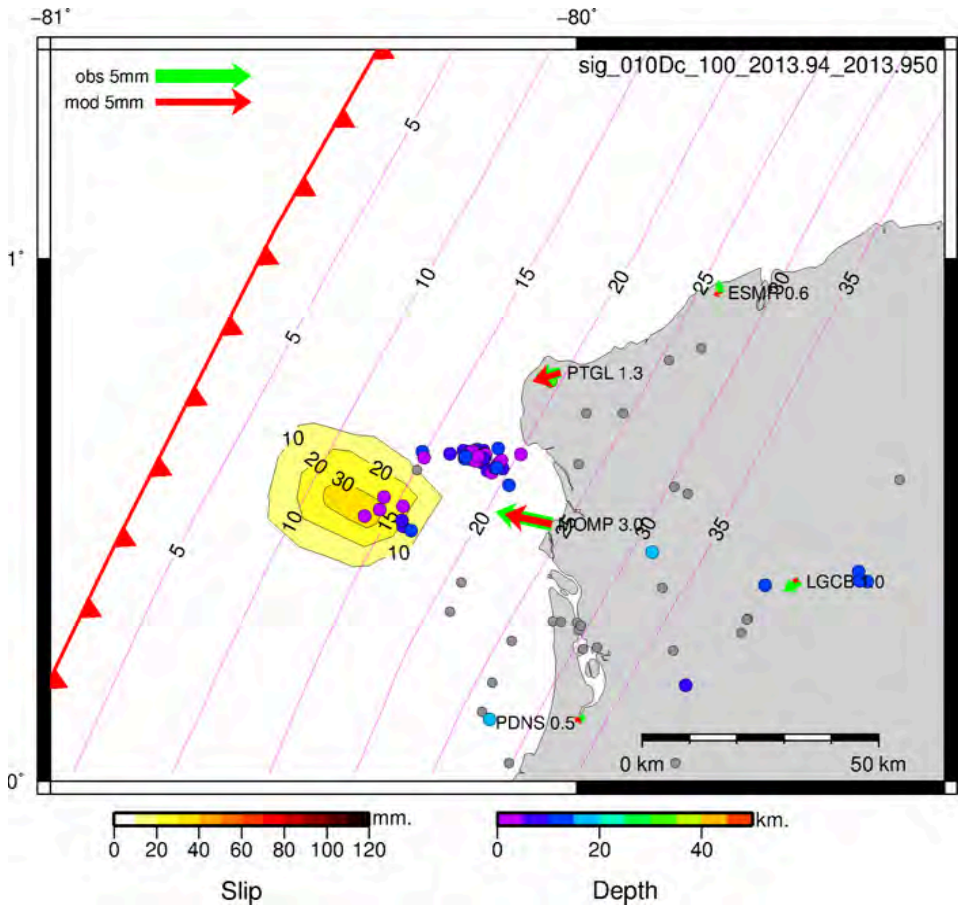

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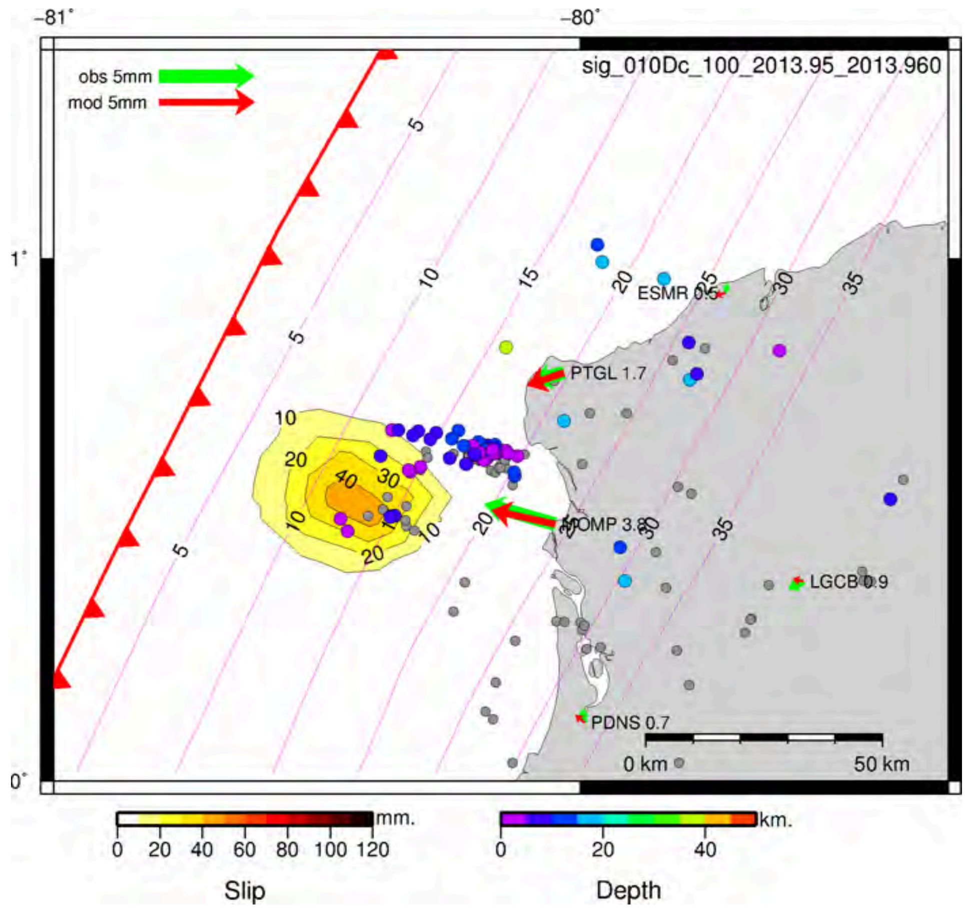

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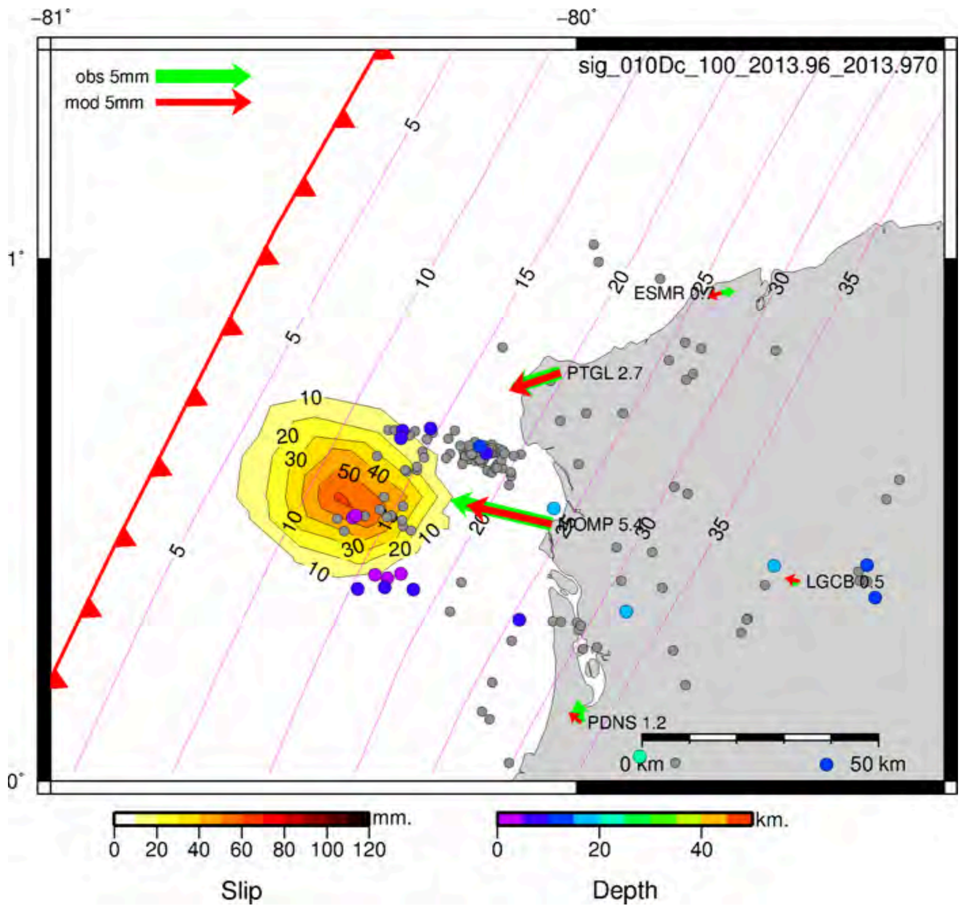

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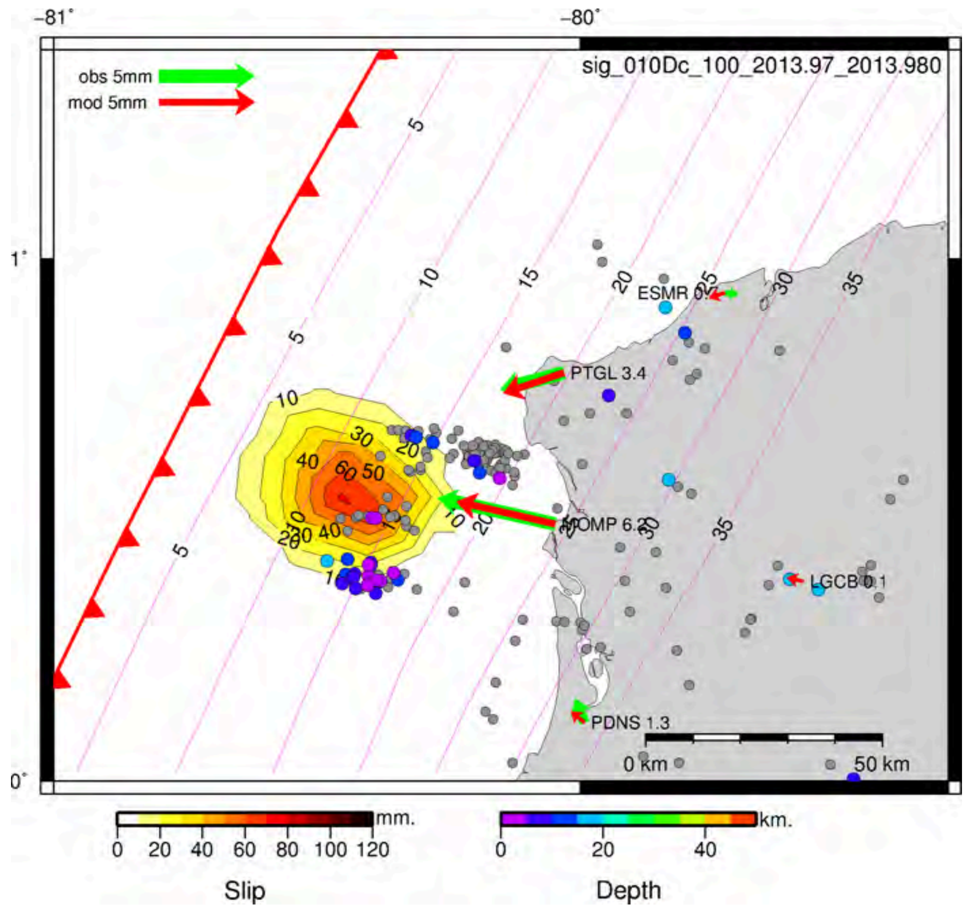

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km.
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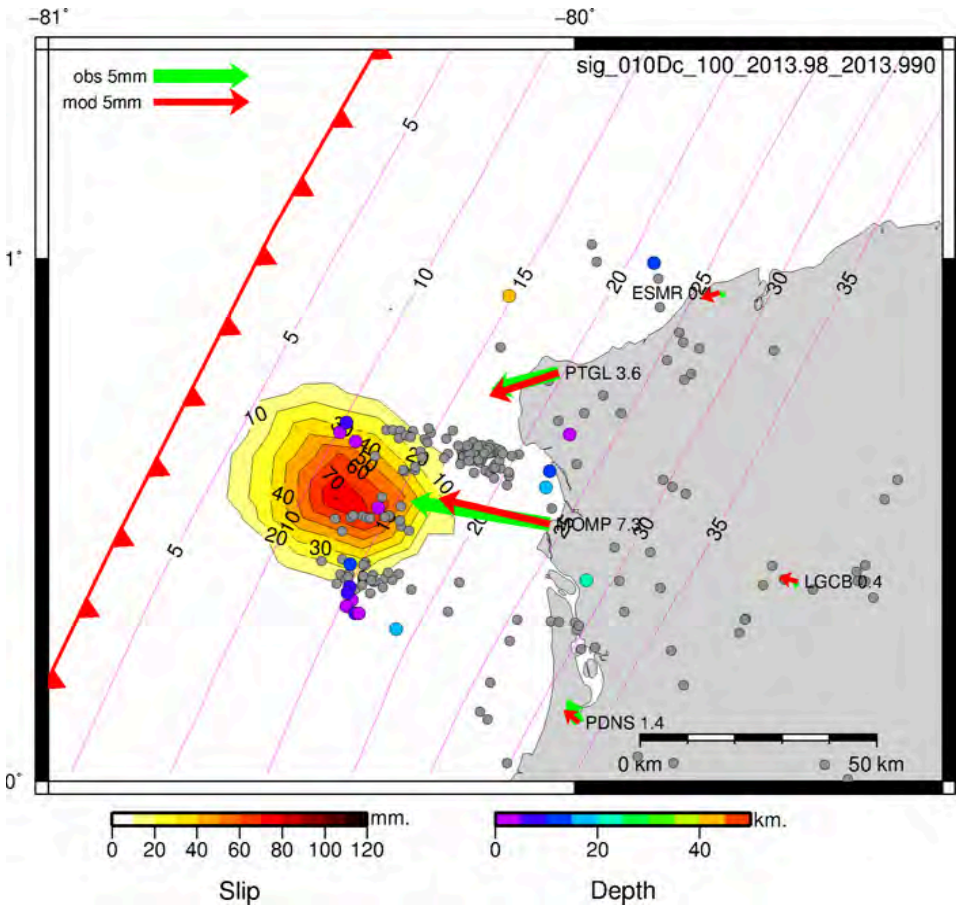

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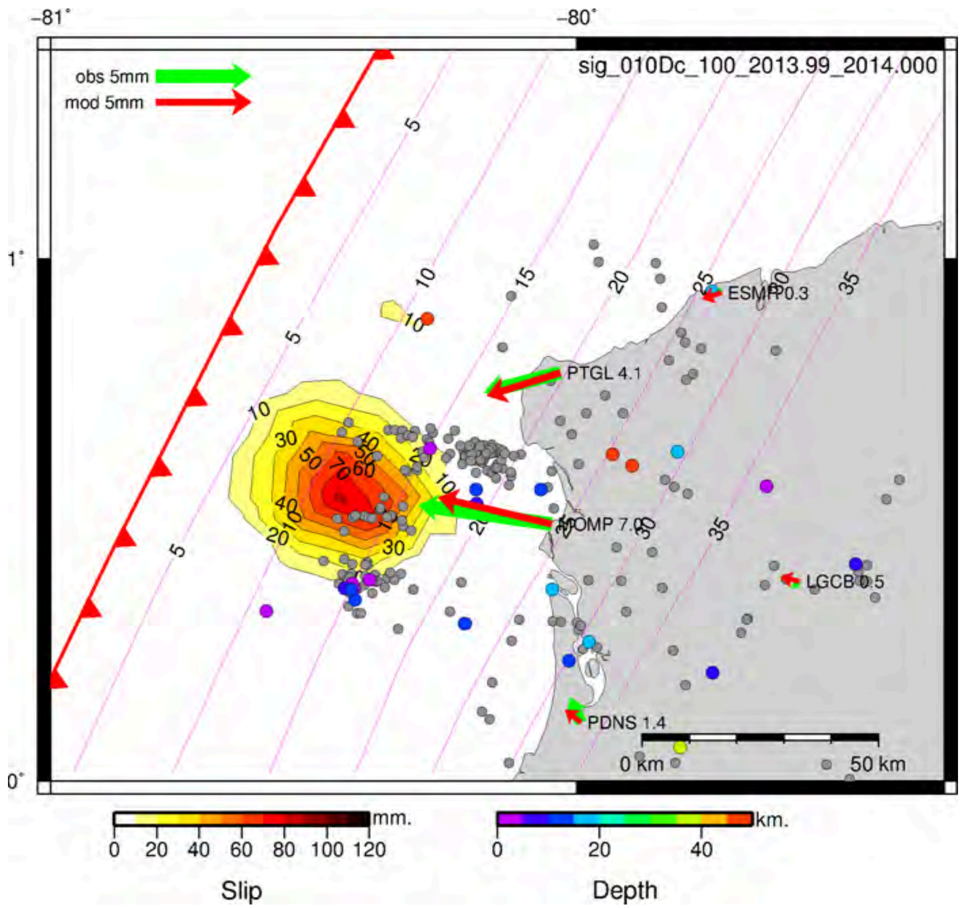
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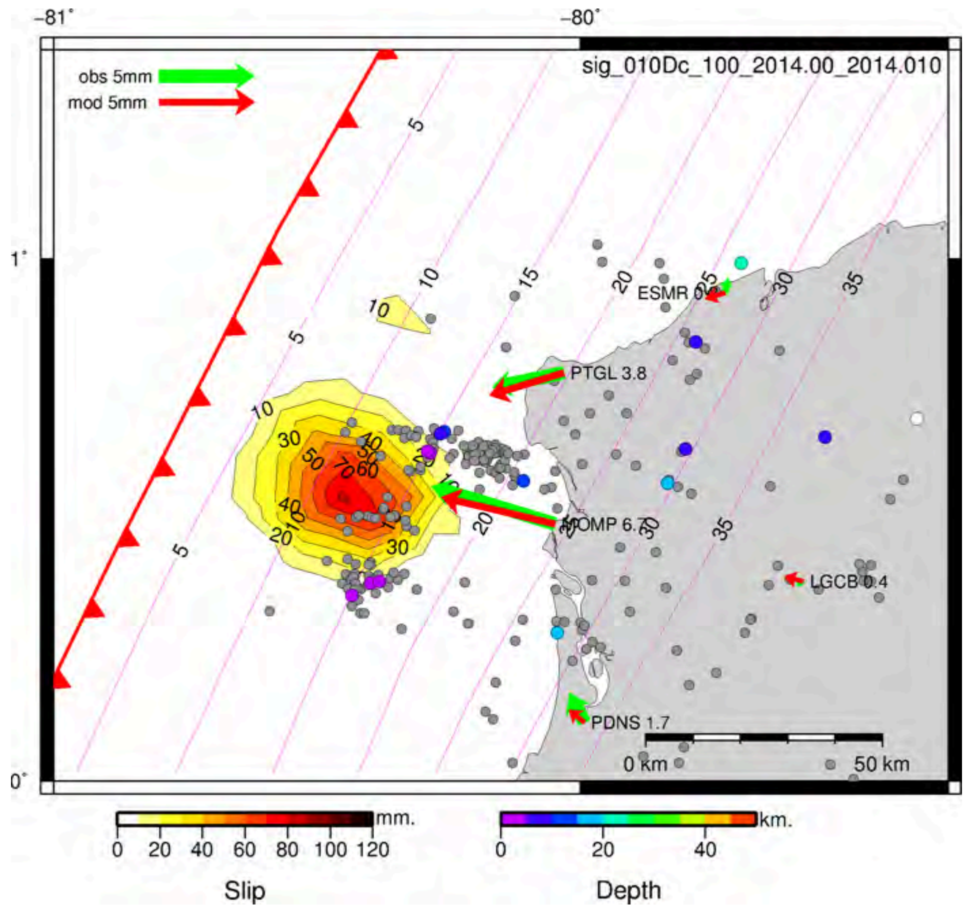

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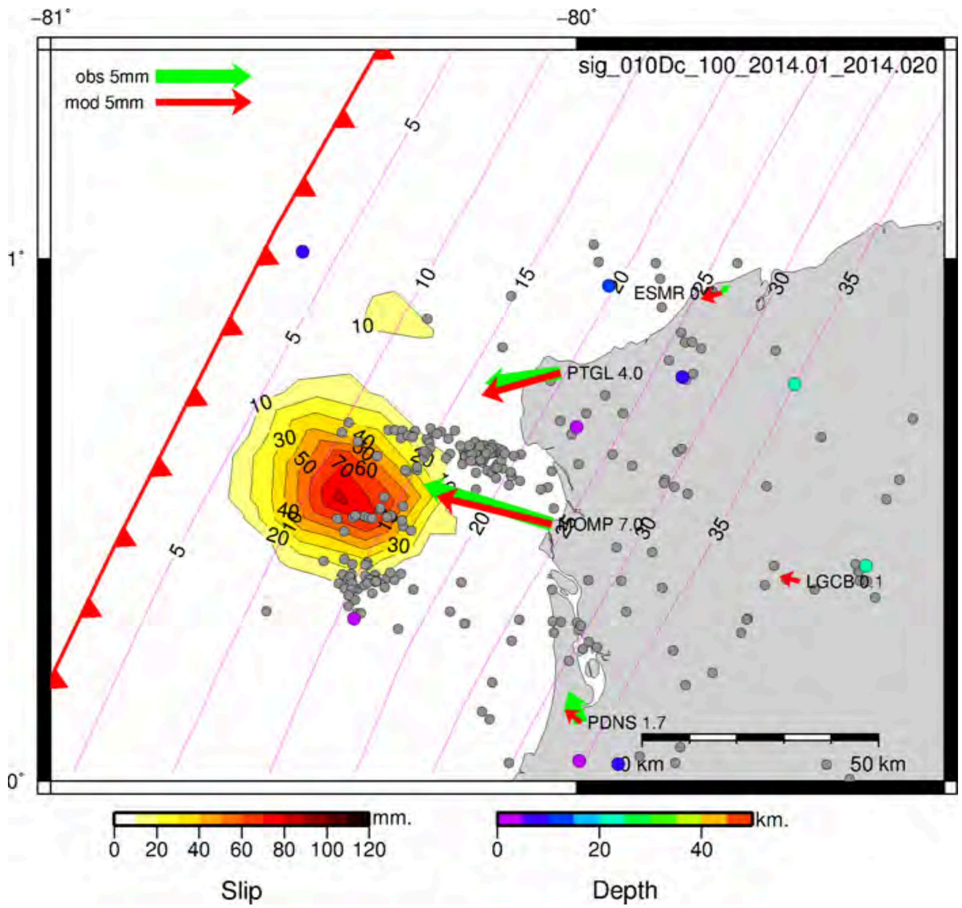
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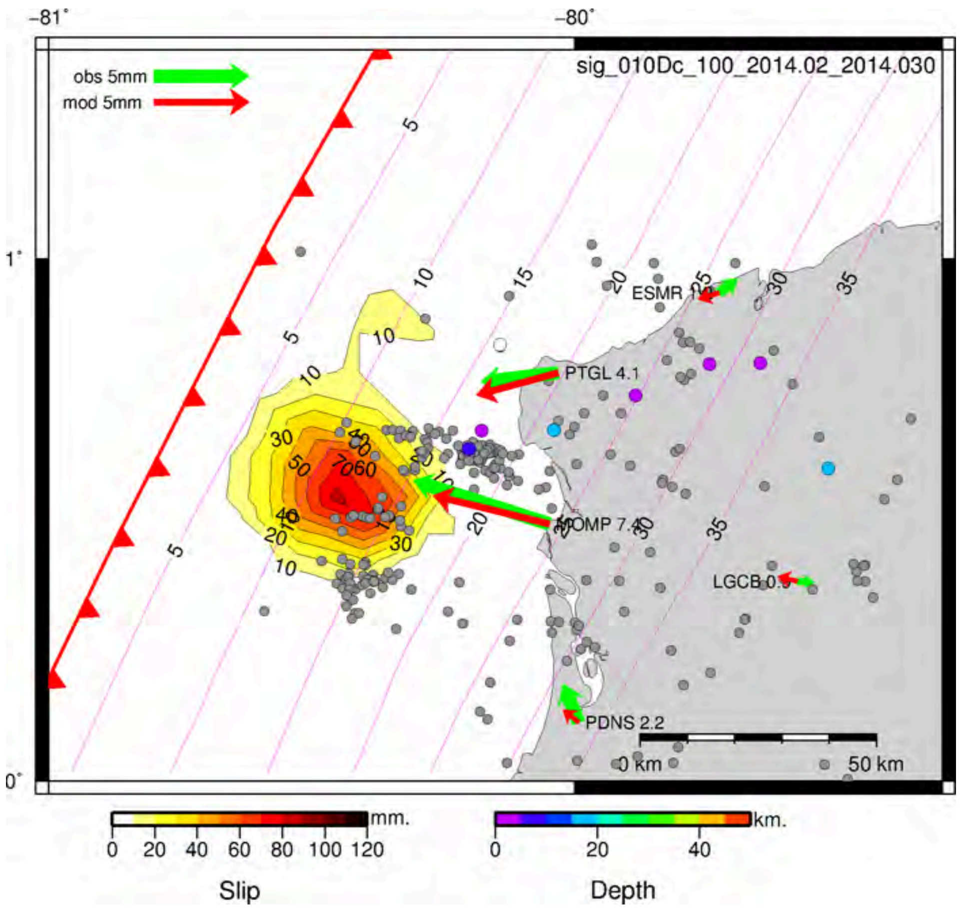

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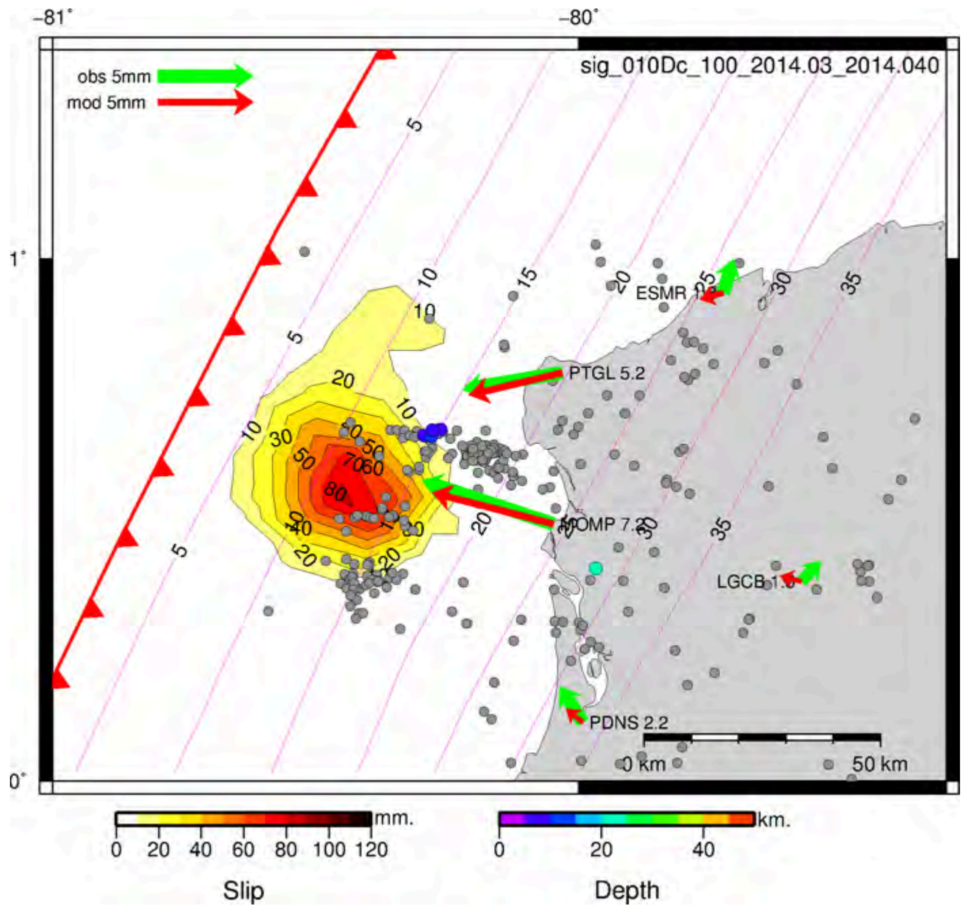

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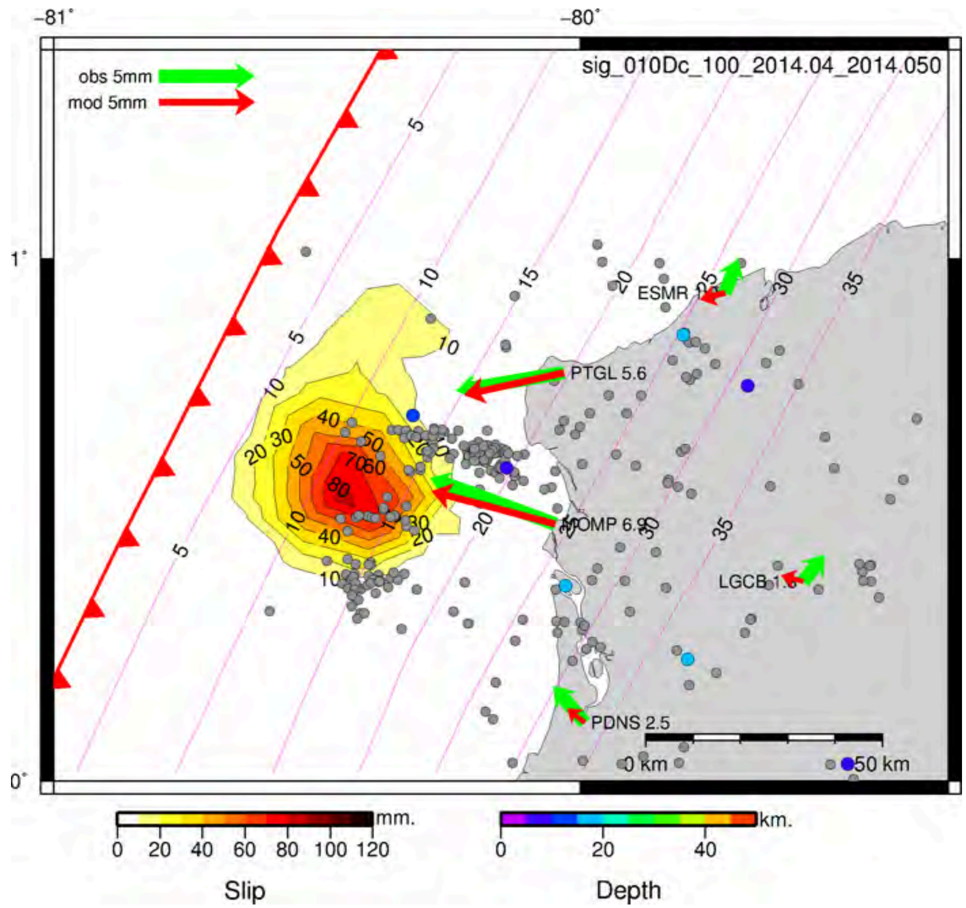

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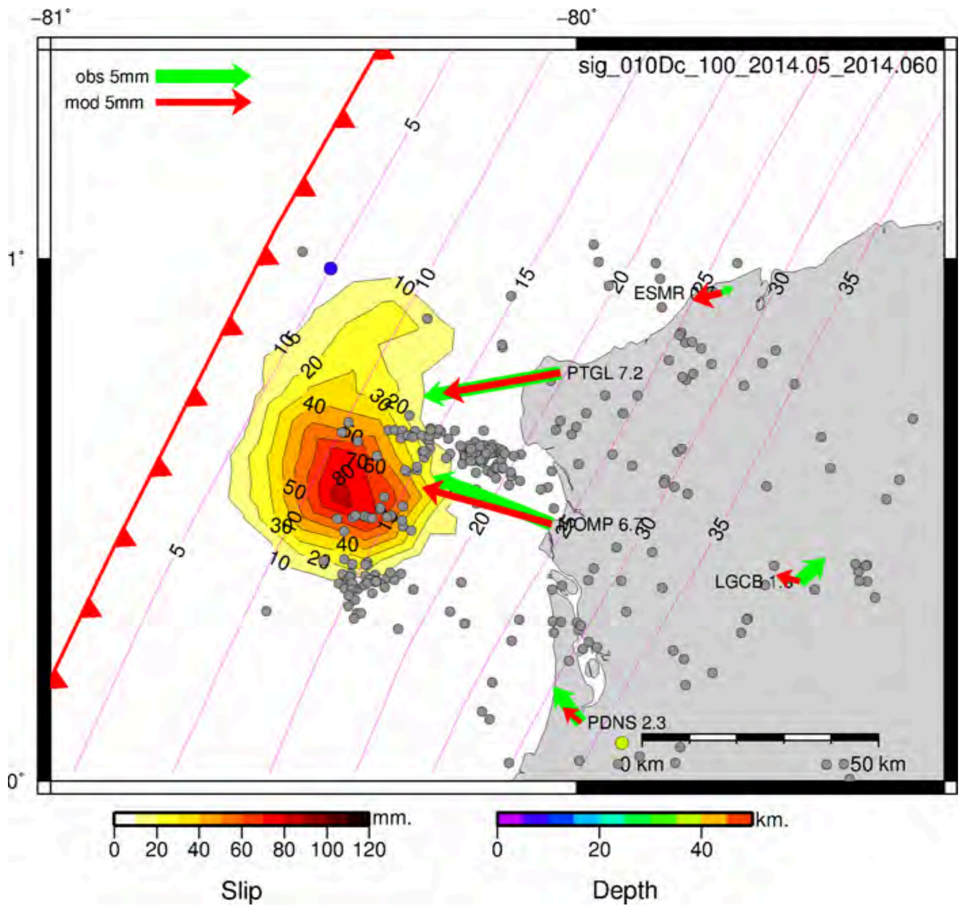

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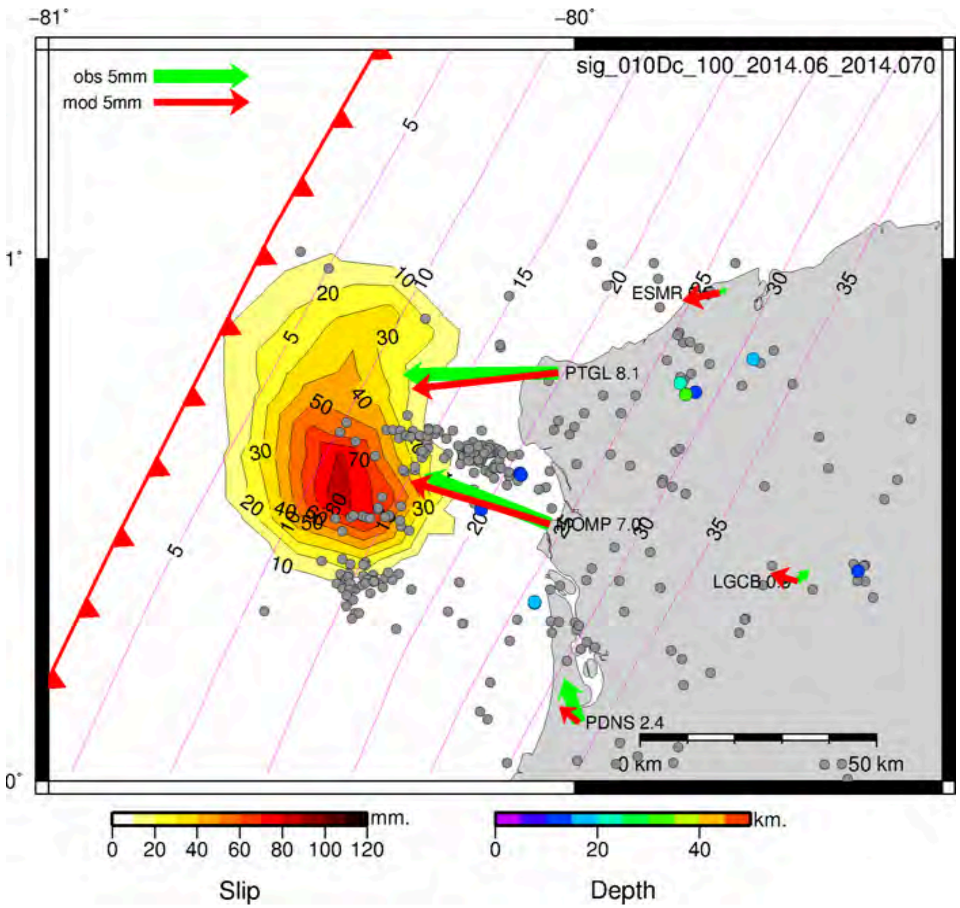

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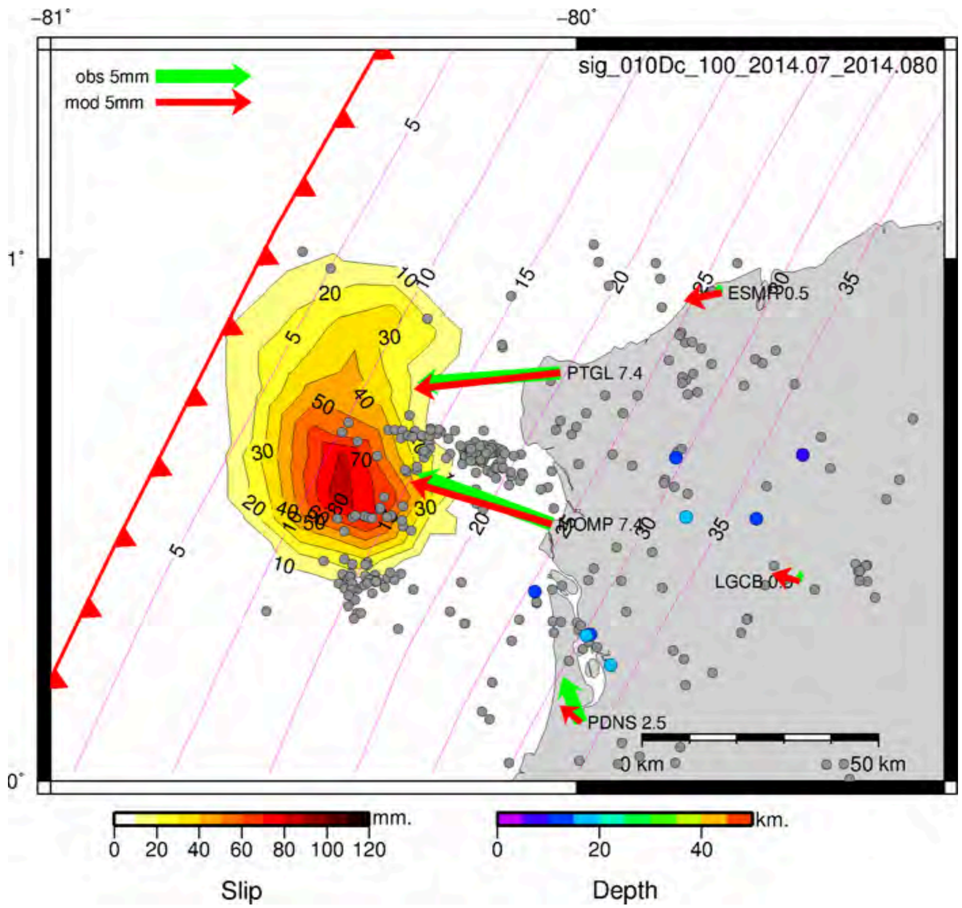

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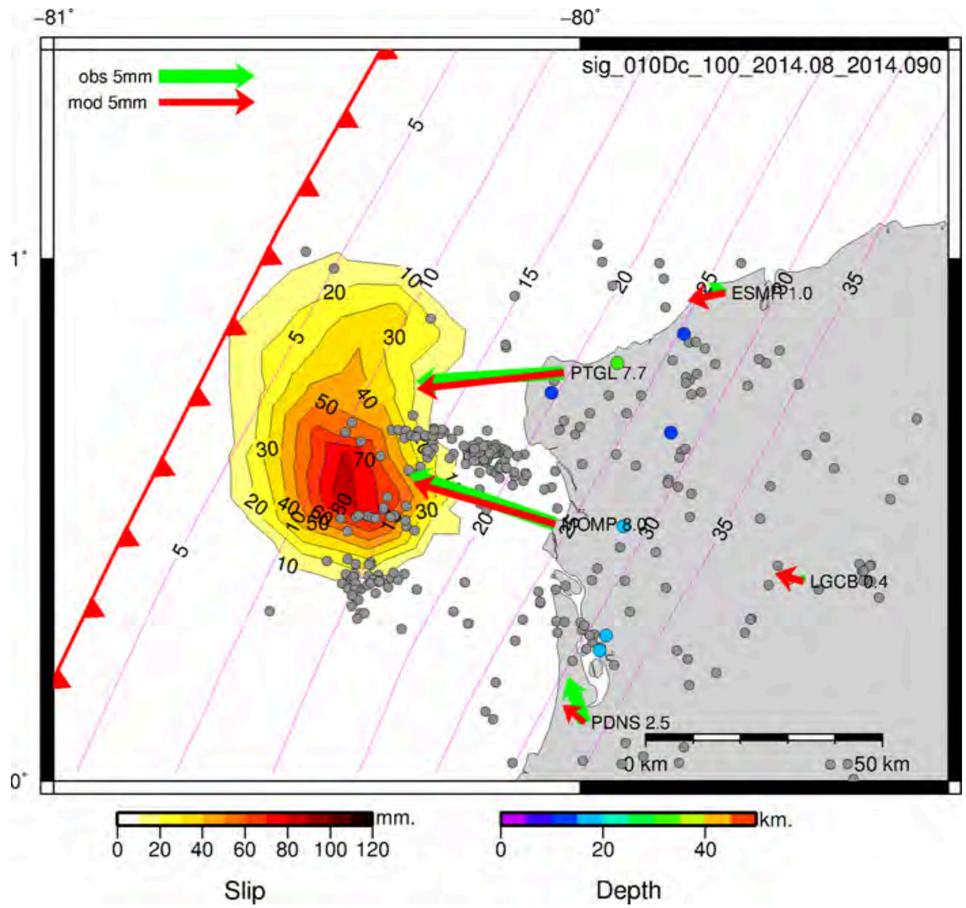
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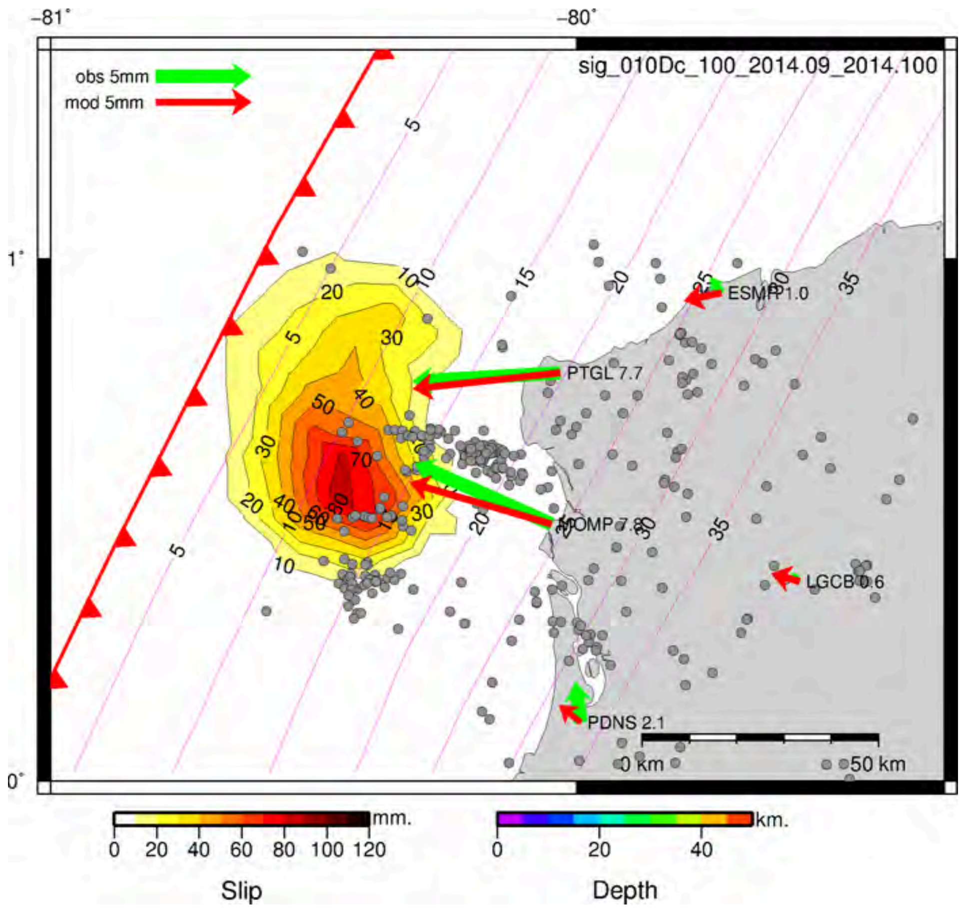

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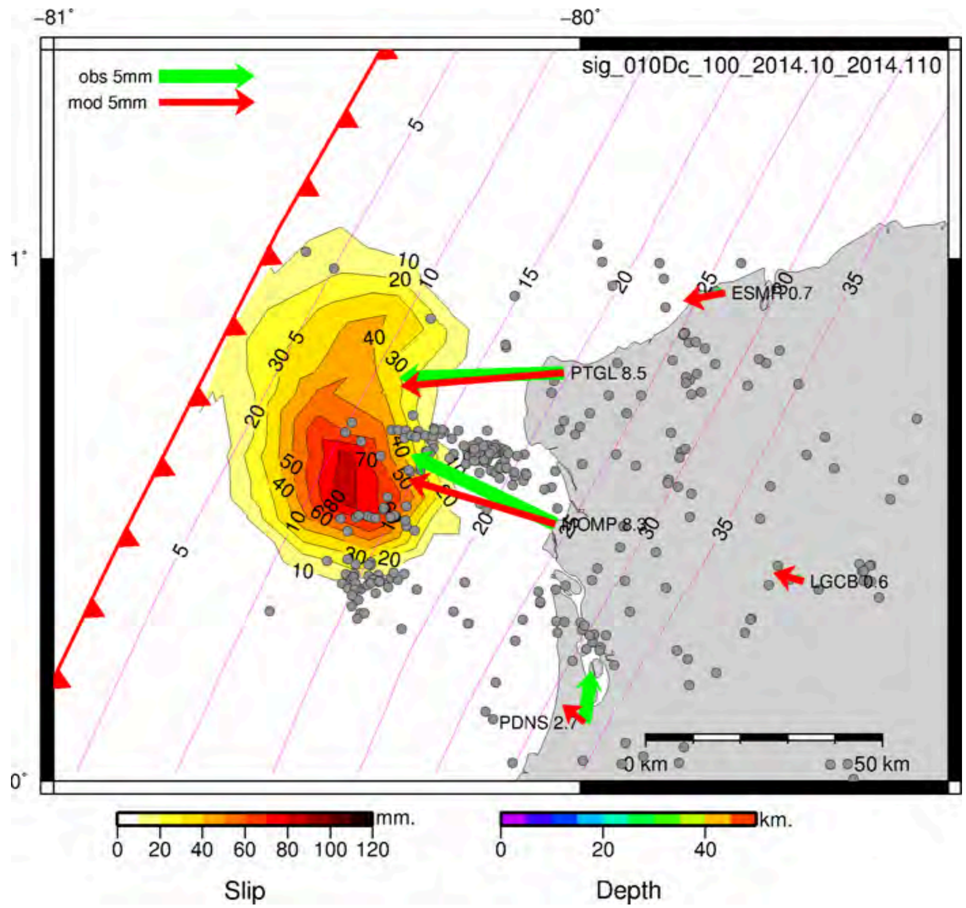
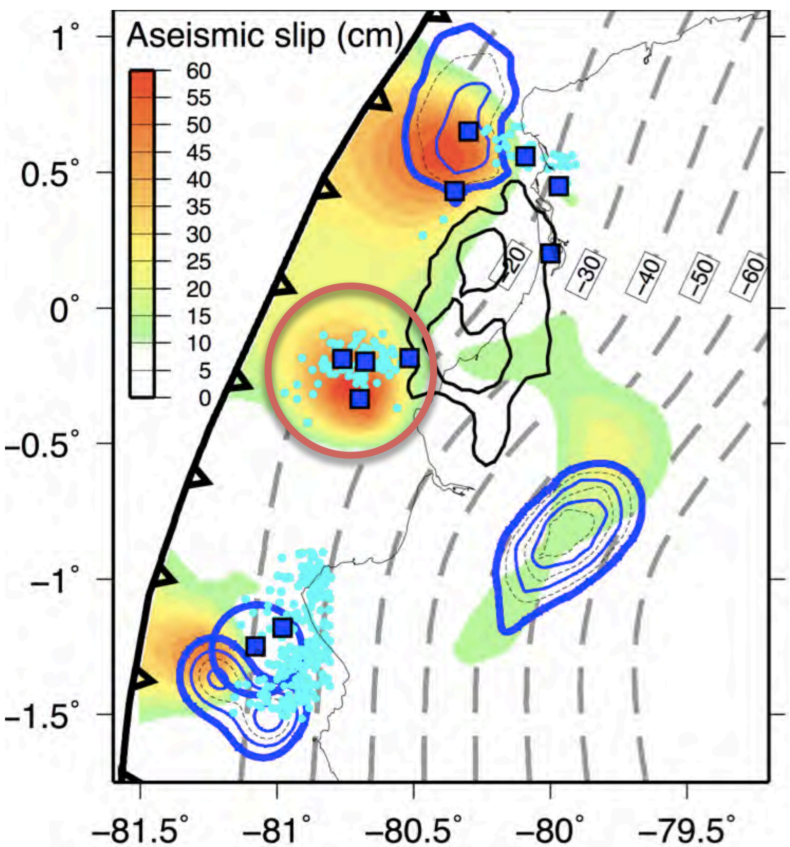
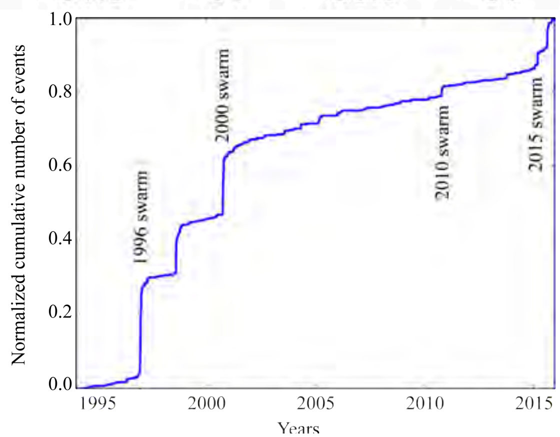
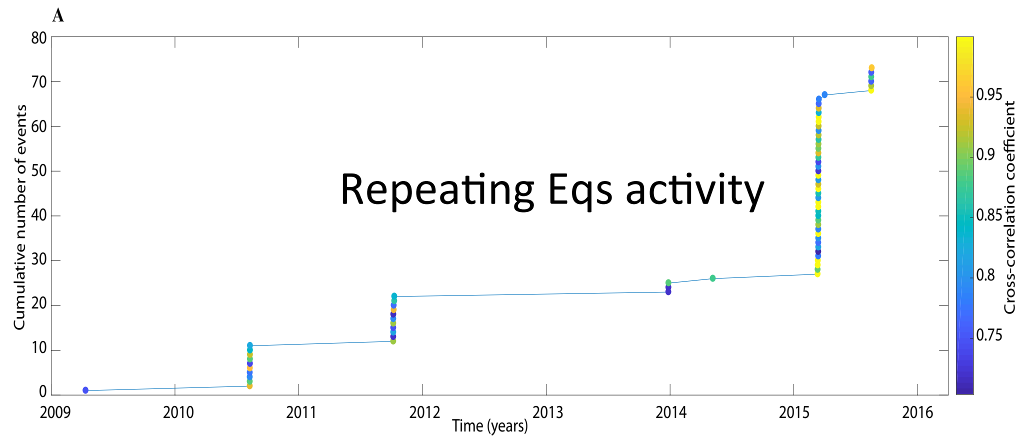


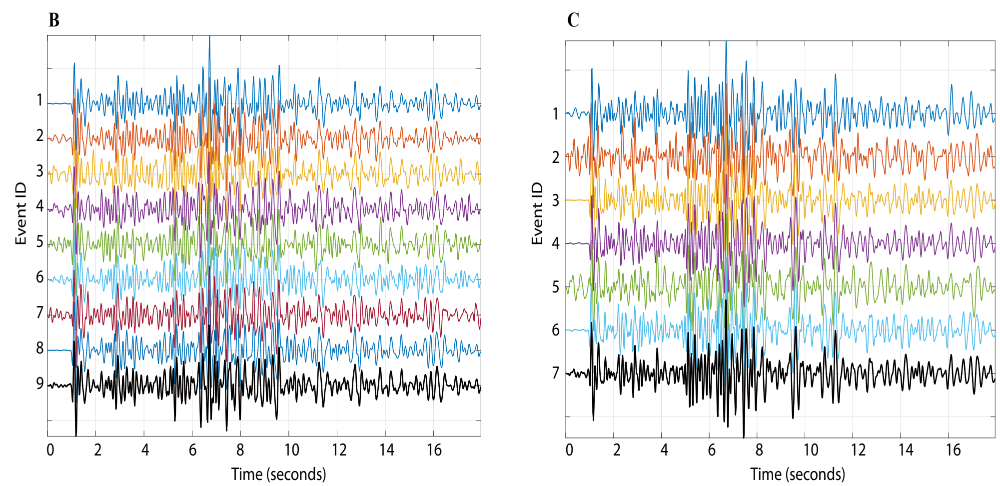
Global geodetic moment: Mw ~ 6.3

SEISMIC SWARMS AND REPEATING EARTHQUAKES AT THE SOUTHERN SHALLOW PATCH



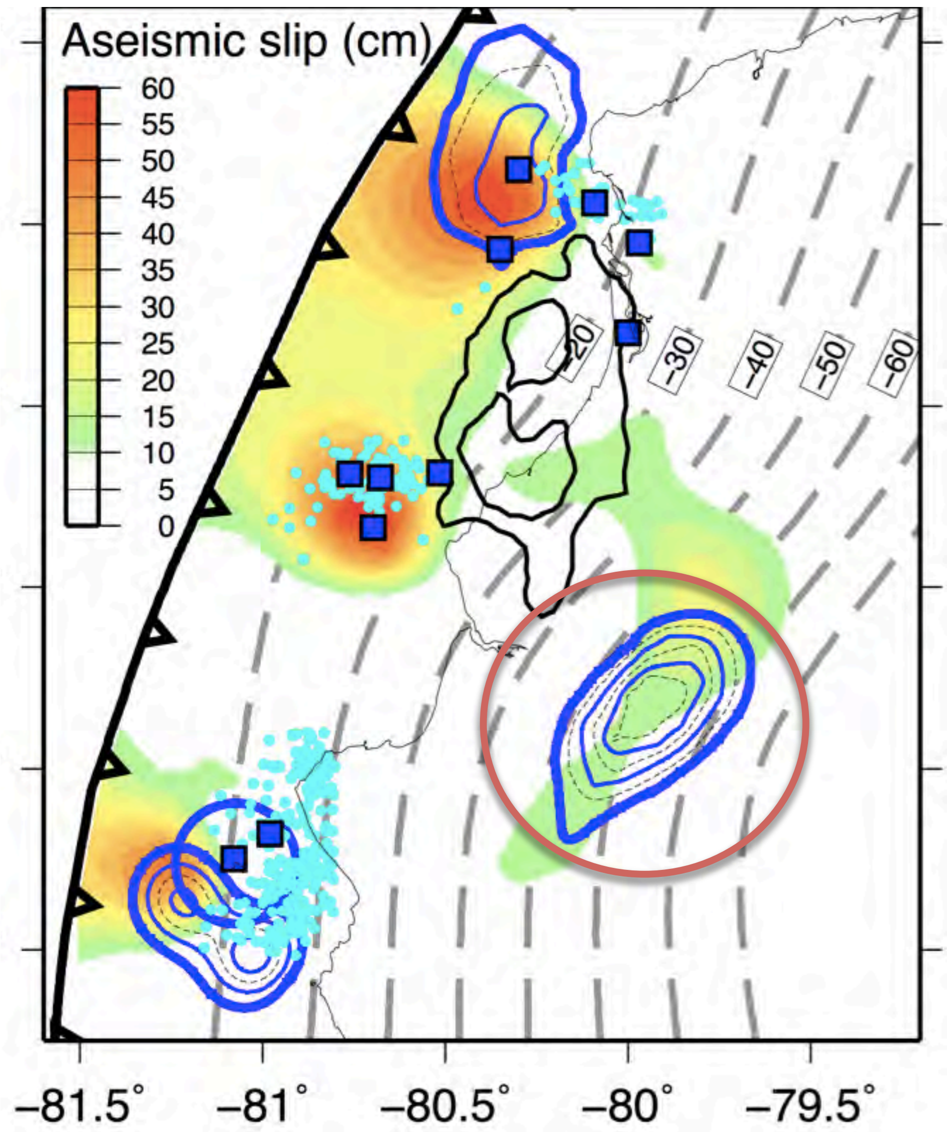




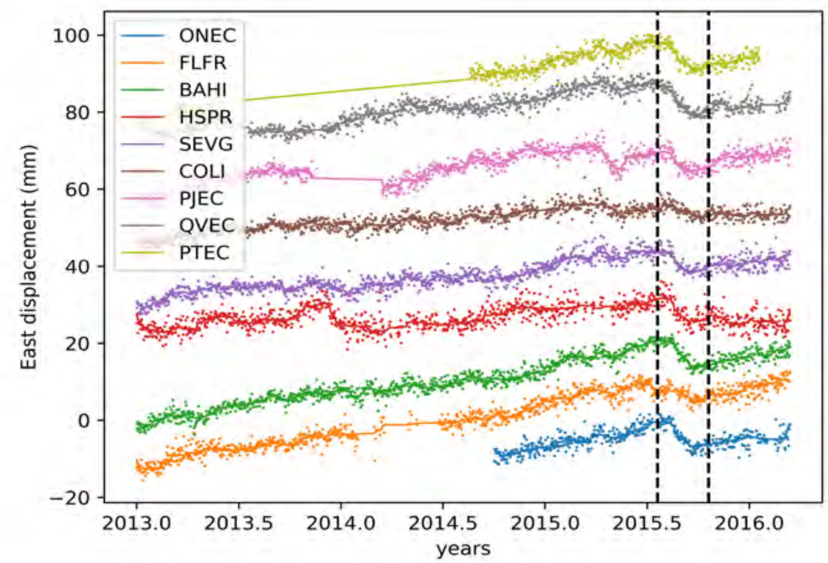


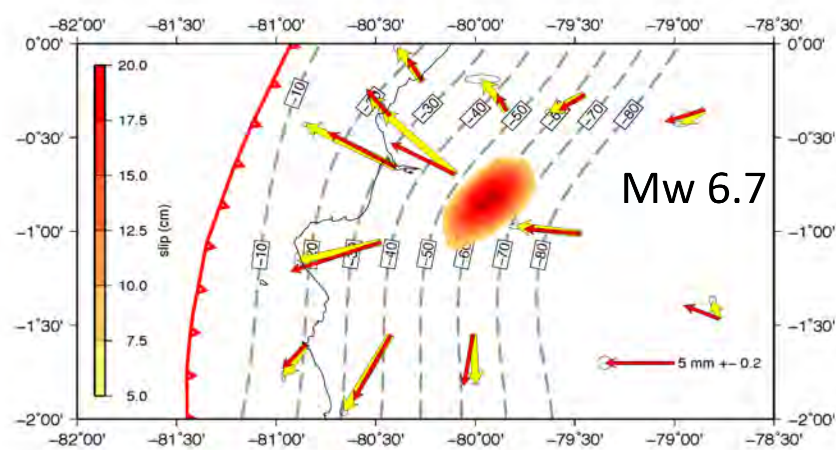
Rolandone et al., in revision

A DEEP SSE



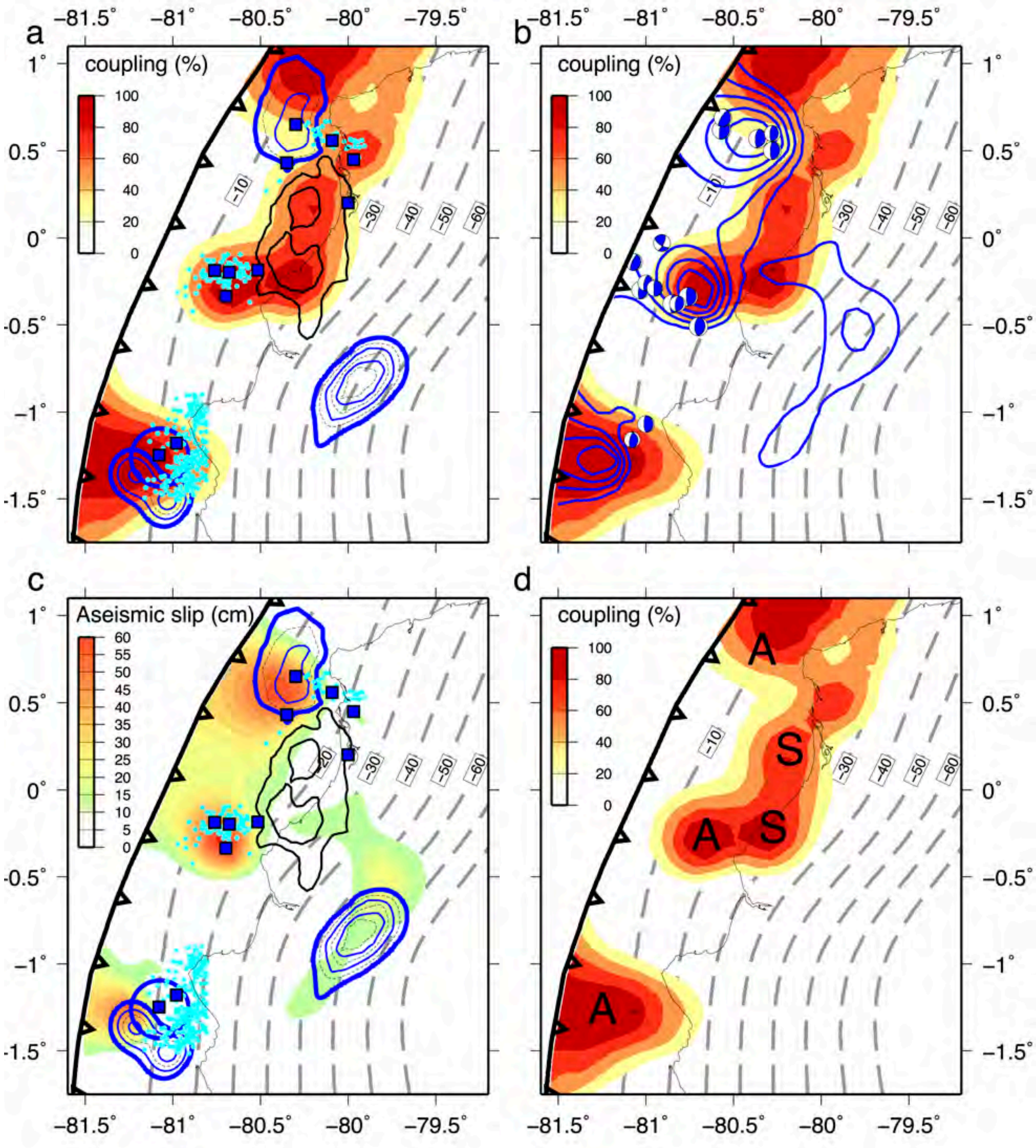
SSEs, seismic swarms & repeating earthquakes





Rolandone et al., in revision

SUMMARY OF SLIP MODES AT THE ECUADOR SUBDUCTION ZONE



Rolandone et al., in revision

Conclusions

- Spatial & temporal organization of slip modes at the Ecuador subduction zone
  - The subduction interface is made of interlaced patches, either sliding at the plate velocity or being locked
  - Although some of patches appear to be locked during a few years, some of them release stress aseismically while others are seismic

- Implication for the friction anatomy of the subduction interface
  - This view appears more complex than the classical view of seismic/velocity-weakening patches embedded within an otherwise creeping velocity-strengthening plate interface
  - Velocity weakening patches might have a great diversity of behaviours, and among them they can host afterslip

- The Ecuador case suggests that:
  - A better anticipation for the location of future large ruptures can be gained by documenting precisely and jointly Interseismic locking and episodic transient slips