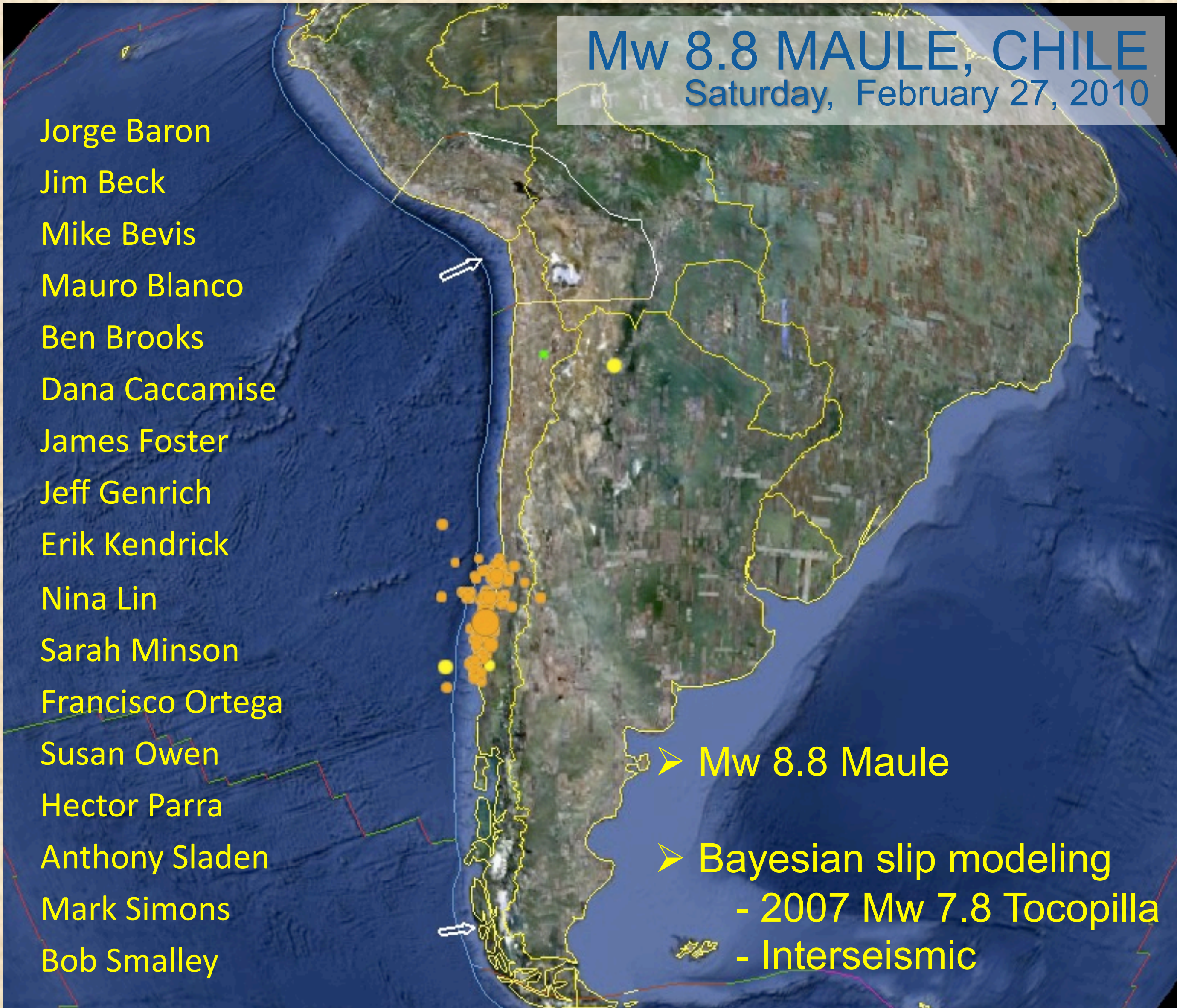
News from the Chilean Front



Jorge Baron
Jim Beck
Mike Bevis
Mauro Blanco
Ben Brooks
Dana Caccamise
James Foster
Jeff Genrich
Erik Kendrick
Nina Lin
Sarah Minson
Francisco Ortega
Susan Owen
Hector Parra
Anthony Sladen
Mark Simons
Bob Smalley

- Mw 8.8 Maule
- Bayesian slip modeling
  - 2007 Mw 7.8 Tocopilla
  - Interseismic

Seismological Laboratory
California Institute of Technology

Largest earthquakes (M ≥ 8.8) since 1906

1906 M8.8 Ecuador
1952 M9.0 Kamchatka
1960 M9.5 Chile
1964 M9.2 Alaska
2004 M9.1 Sumatra ***
2010 M8.8 Chile ***

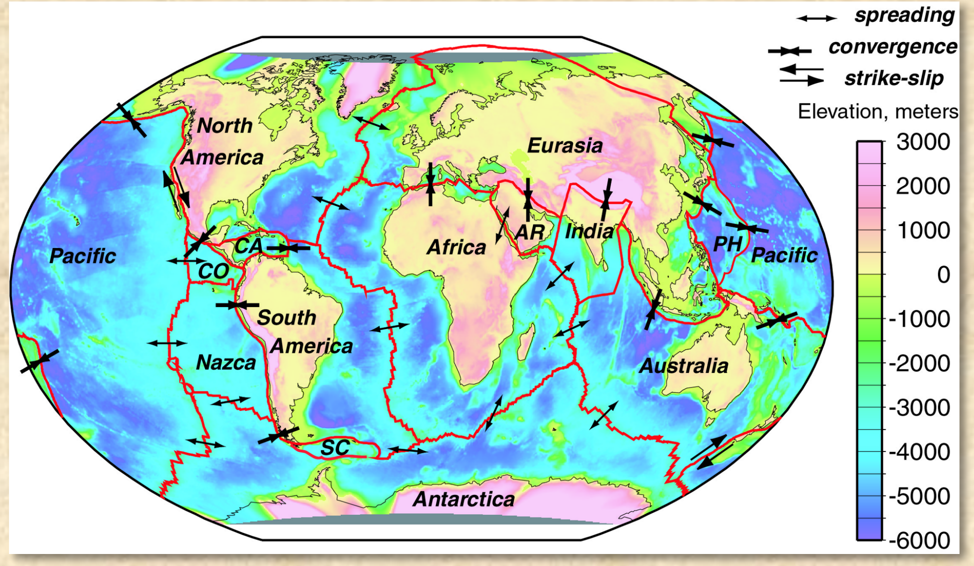


Figure from J. Stock

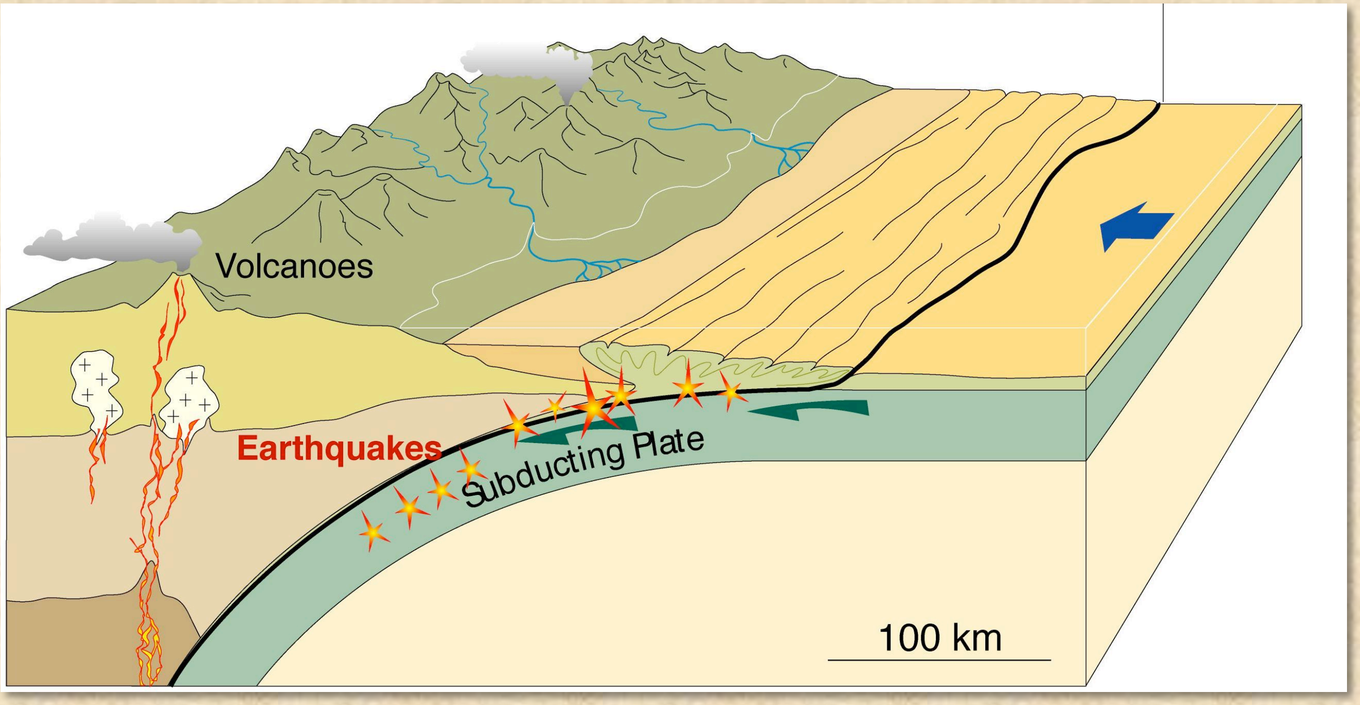
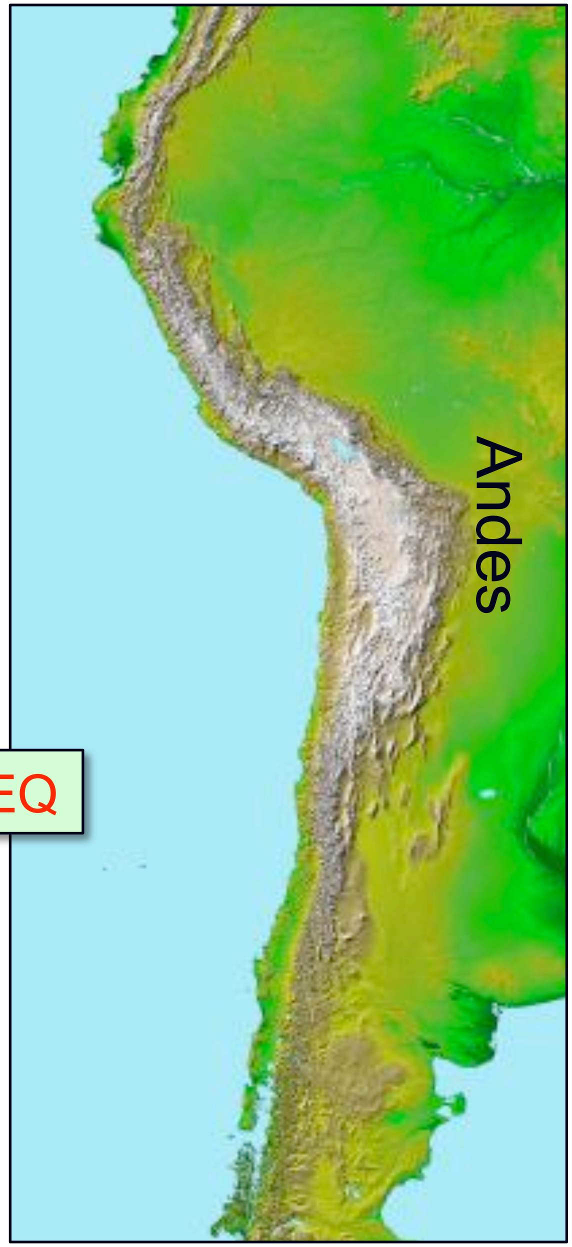
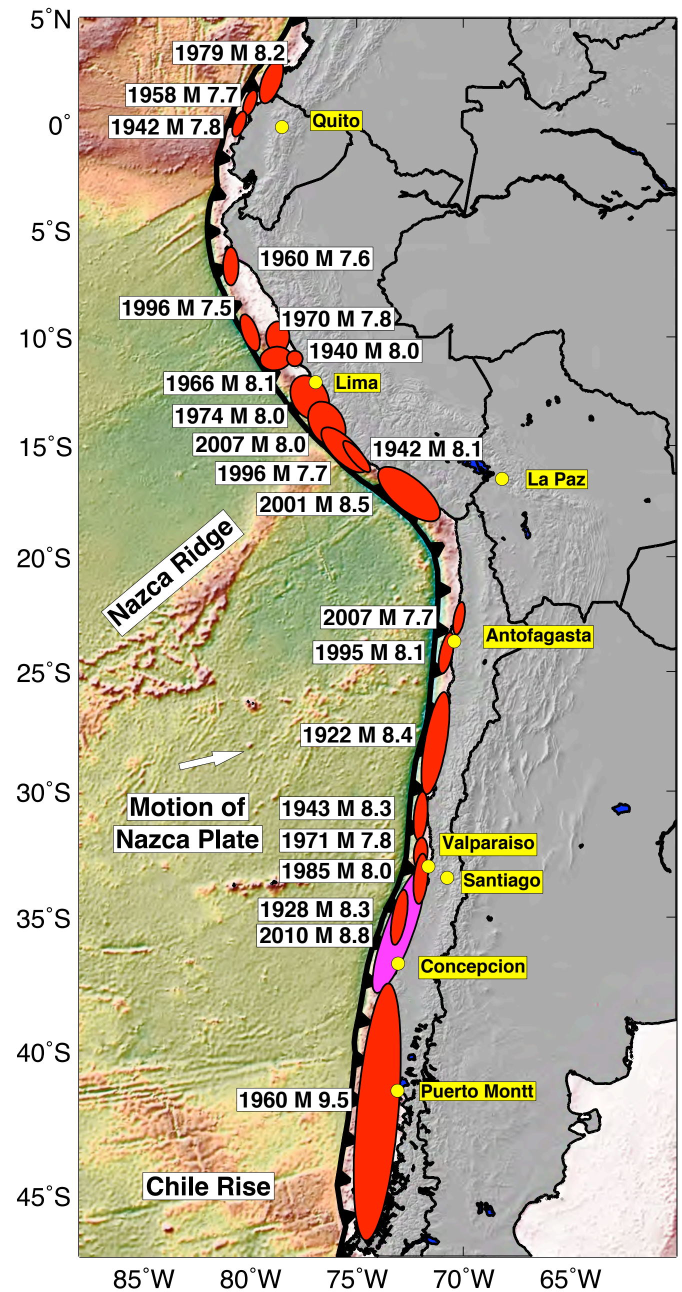


Figure from J.P. Avouac

Last 100 years of large earthquakes on the western margin of South America





Chile ≈ 500 x Haiti EQ

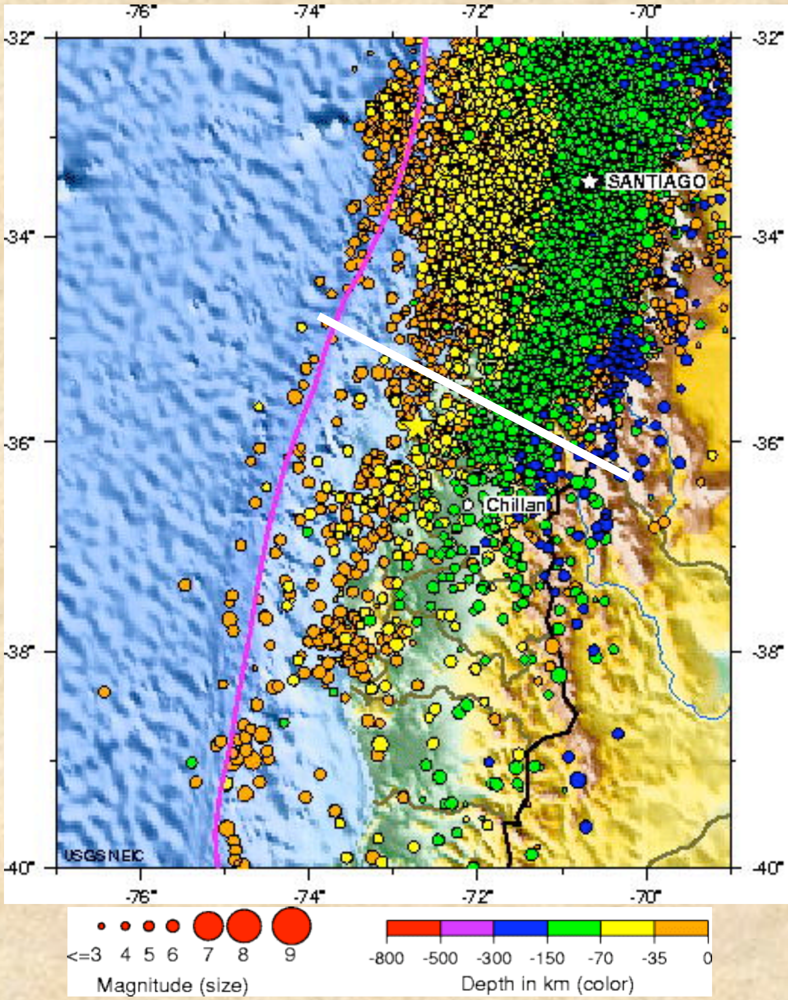
Figure from M. Pritchard

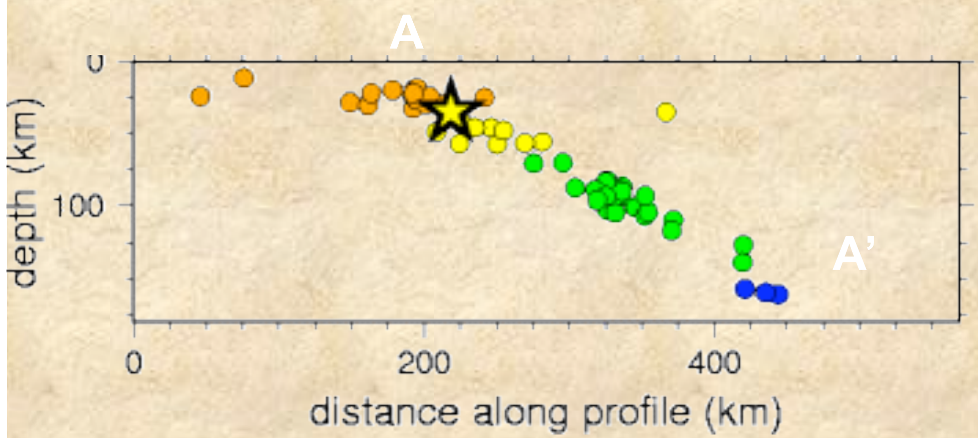
Despite impressive pictures, damage relatively limited given Mw

VICTOR
879
RIVEIRA
1213
DON CH
3742

Magnitude 8.8 OFFSHORE MAULE, CHILE
Saturday, February 27, 2010 at 06:34:17 UTC

Historic earthquake activity near the epicenter from 1990 to present.





Last similar EQ 1835

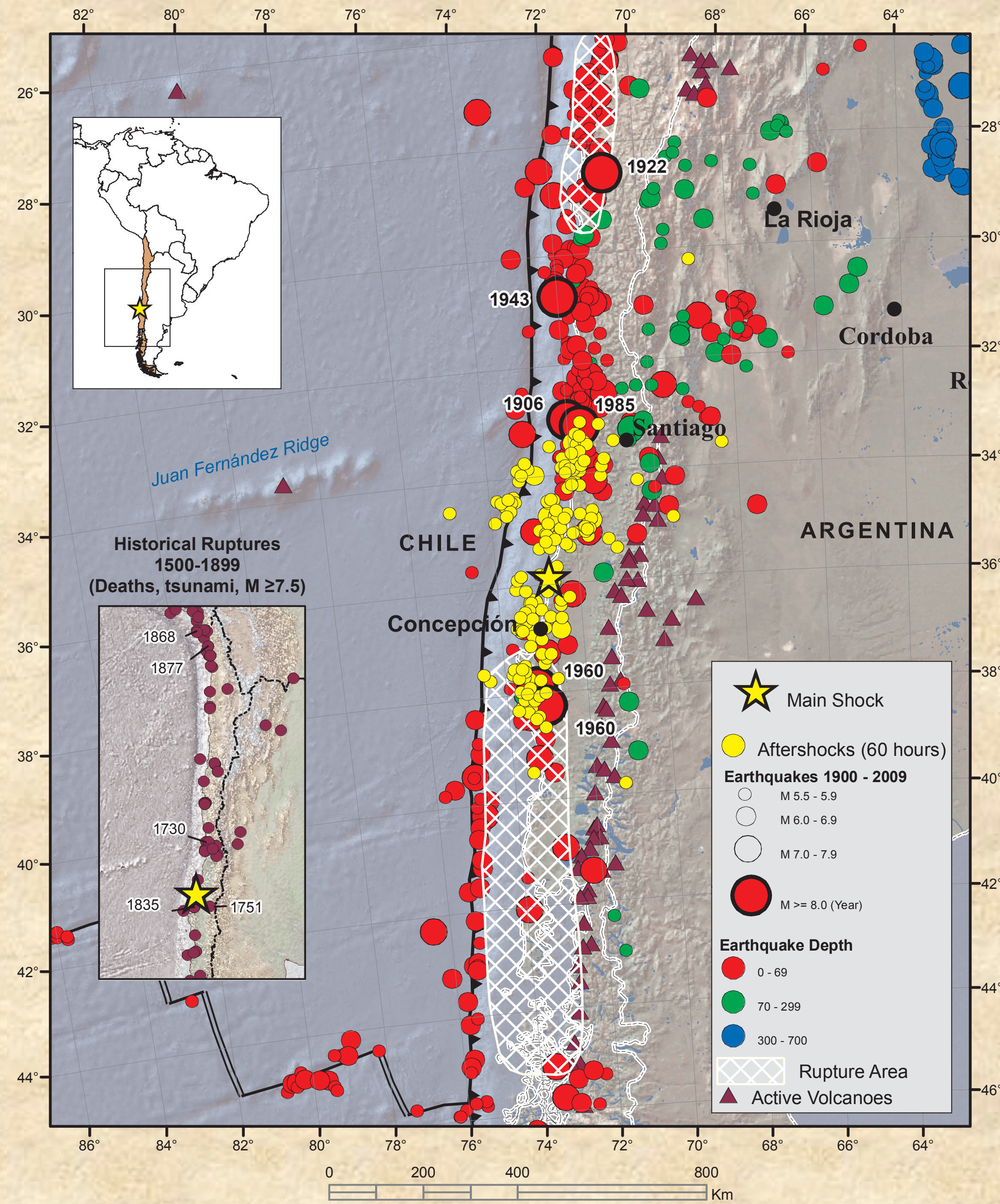


Figure from NEIC/USGS

Is this a repeat of the 1835 event described by Darwin?

Voyage of the Beagle (1839)
Chapter 14


Charles Darwin

February 20, 1835: This day has been memorable in the annals of Valdivia, for the most severe earthquake experienced by the oldest inhabitant. I happened to be on shore, and was lying down in the wood to rest myself. It came on suddenly, and lasted two minutes, but the time appeared much longer …

Captain Fitz Roy and some officers were at the town during the shock, and there the scene was more striking; for although the houses, from being built of wood, did not fall, they were violently shaken, and the boards creaked and rattled together ...

The great shock took place at the time of low water; and an old woman who was on the beach told me that the water flowed very quickly, but not in great waves, to high- water mark, and then as quickly returned to its proper level…

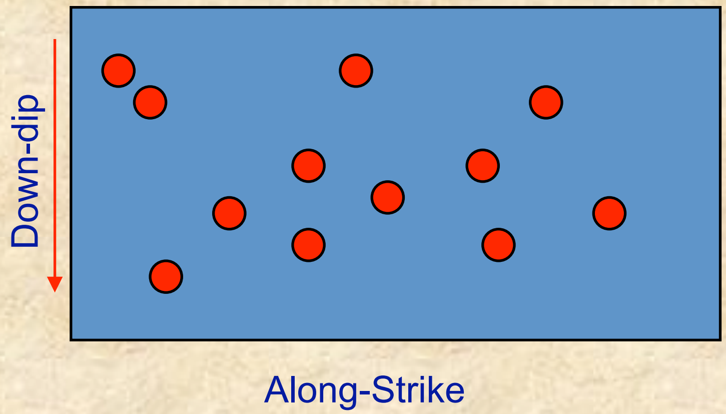
More…

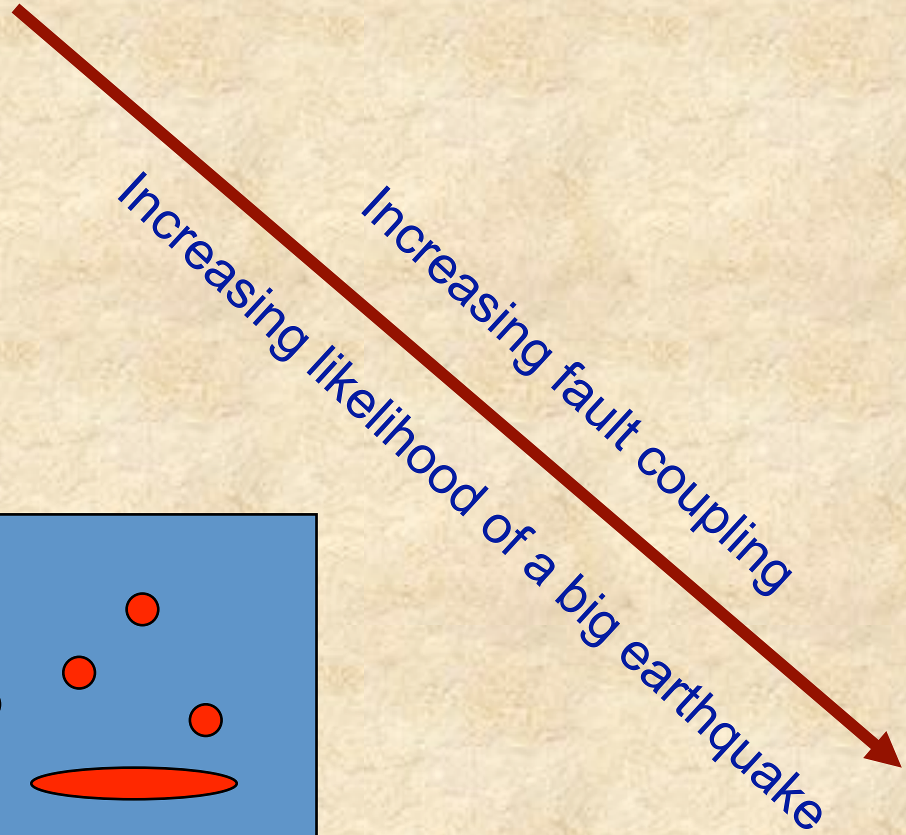
The most remarkable effect of this earthquake was the permanent elevation of the land...

There can be no doubt that the land round the Bay of Concepcion was upraised two or three feet ...

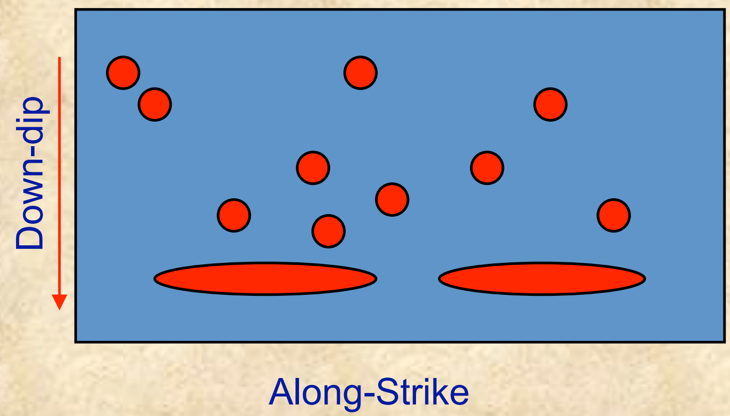
At the island of S. Maria (about thirty miles distant) the elevation was greater; on one part, Captain Fitz Roy founds beds of putrid mussel-shells still adhering to the rocks, ten feet above high-water mark: the inhabitants had formerly dived at lower-water spring-tides for these shells.

The elevation of this province is particularly interesting, from its having been the theatre of several other violent earthquakes, and from the vast numbers of sea-shells scattered over the land, up to a height of certainly 600, and I believe, of 1000 feet … it is hardly possible to doubt that this great elevation has been effected by successive small uprisings, such as that which accompanied or caused the earthquake of this year, and likewise by an insensibly slow rise, which is certainly in progress on some parts of this coast.



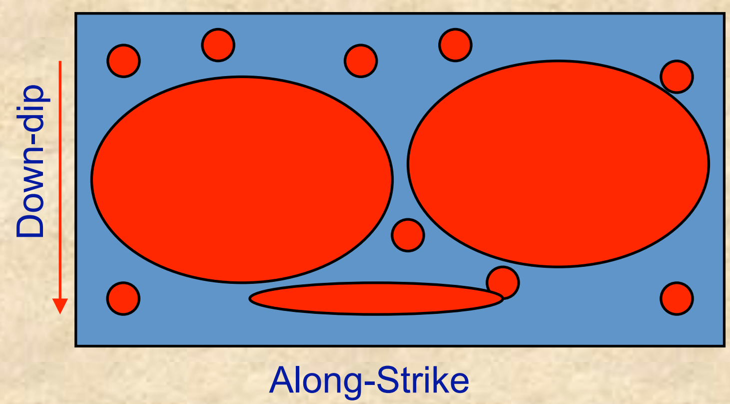


Looking at fault behavior



How much did a given spot on the fault slip?

How much of a given fault area is truly stuck most of the time and only slipping during large earthquakes?



Some Very Basic Earthquake Science Questions

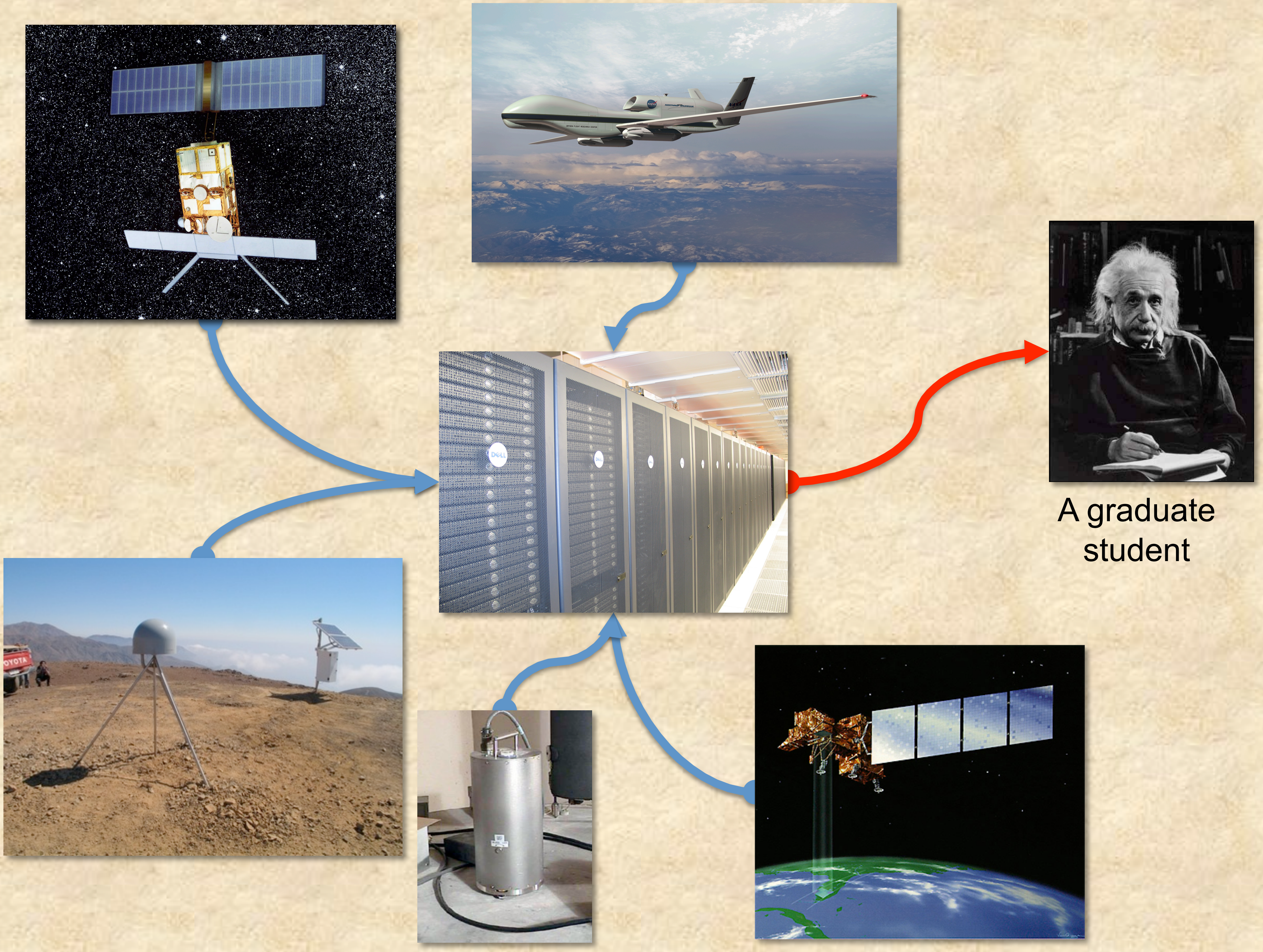
- Do significant portions of a fault slip both seismically and creep aseismically at different times, or are these behaviors more-or-less mutually exclusive?

- Is the style of fault slip the same over many earthquake cycles?

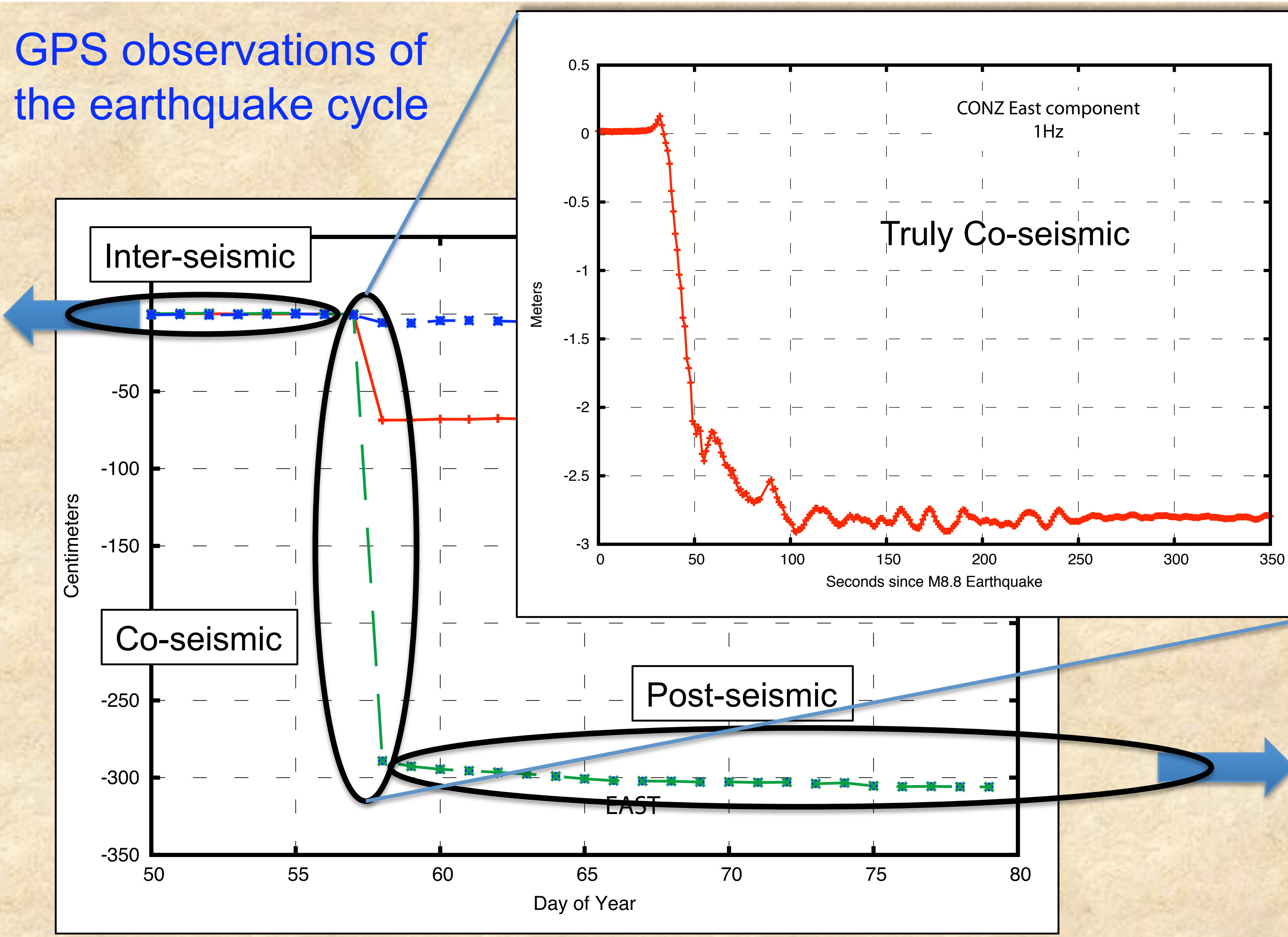
- Is there a relationship between variations in the seismogenic behavior of a given megathrust and geologic evolution of the plate margin?

- Predictability (in time, in space)

“New Technologies”

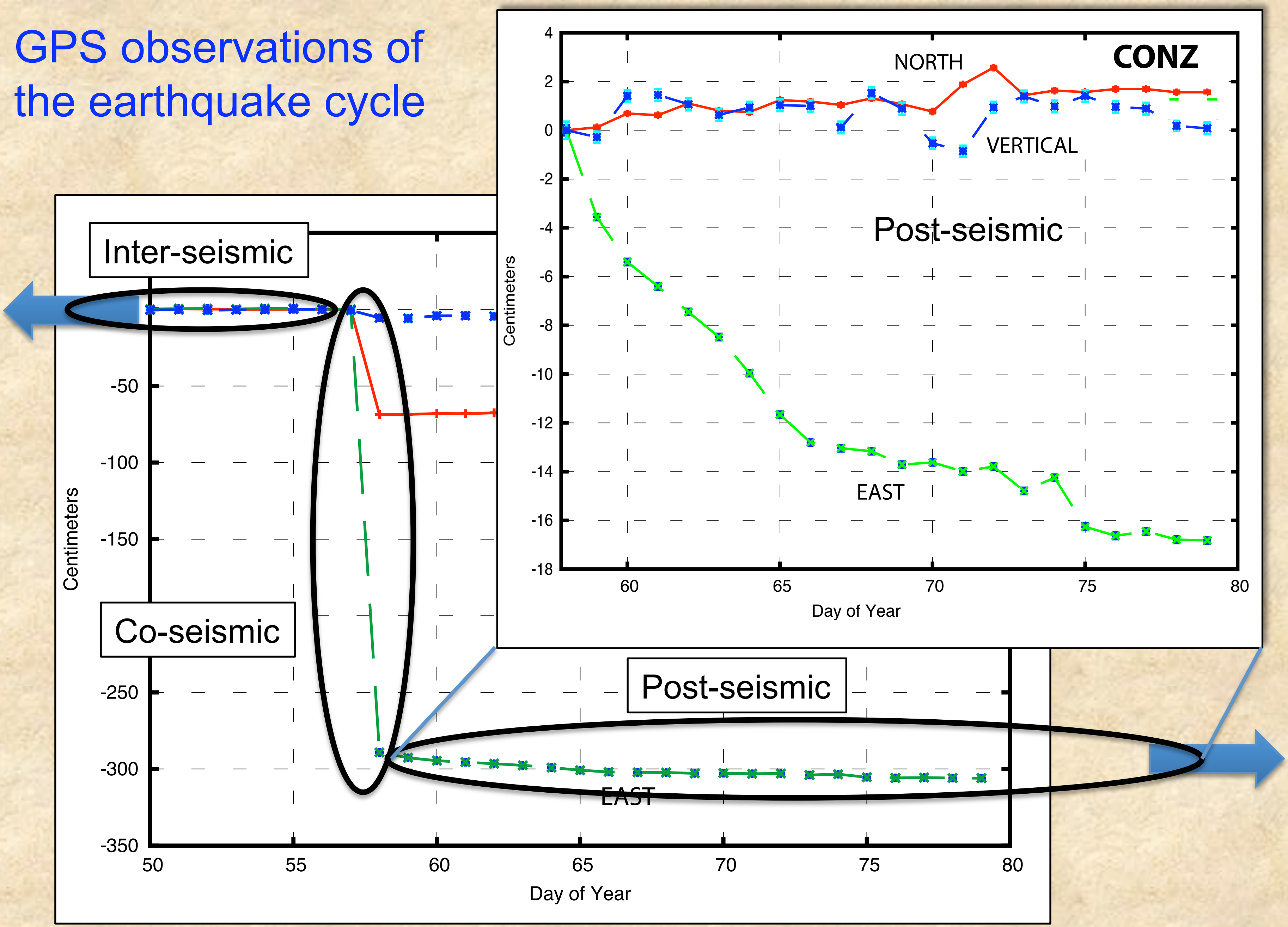

A graduate
student

GPS observations of the earthquake cycle



data processed by Susan Owen (JPL)

GPS observations of the earthquake cycle



data processed by Susan Owen (JPL)

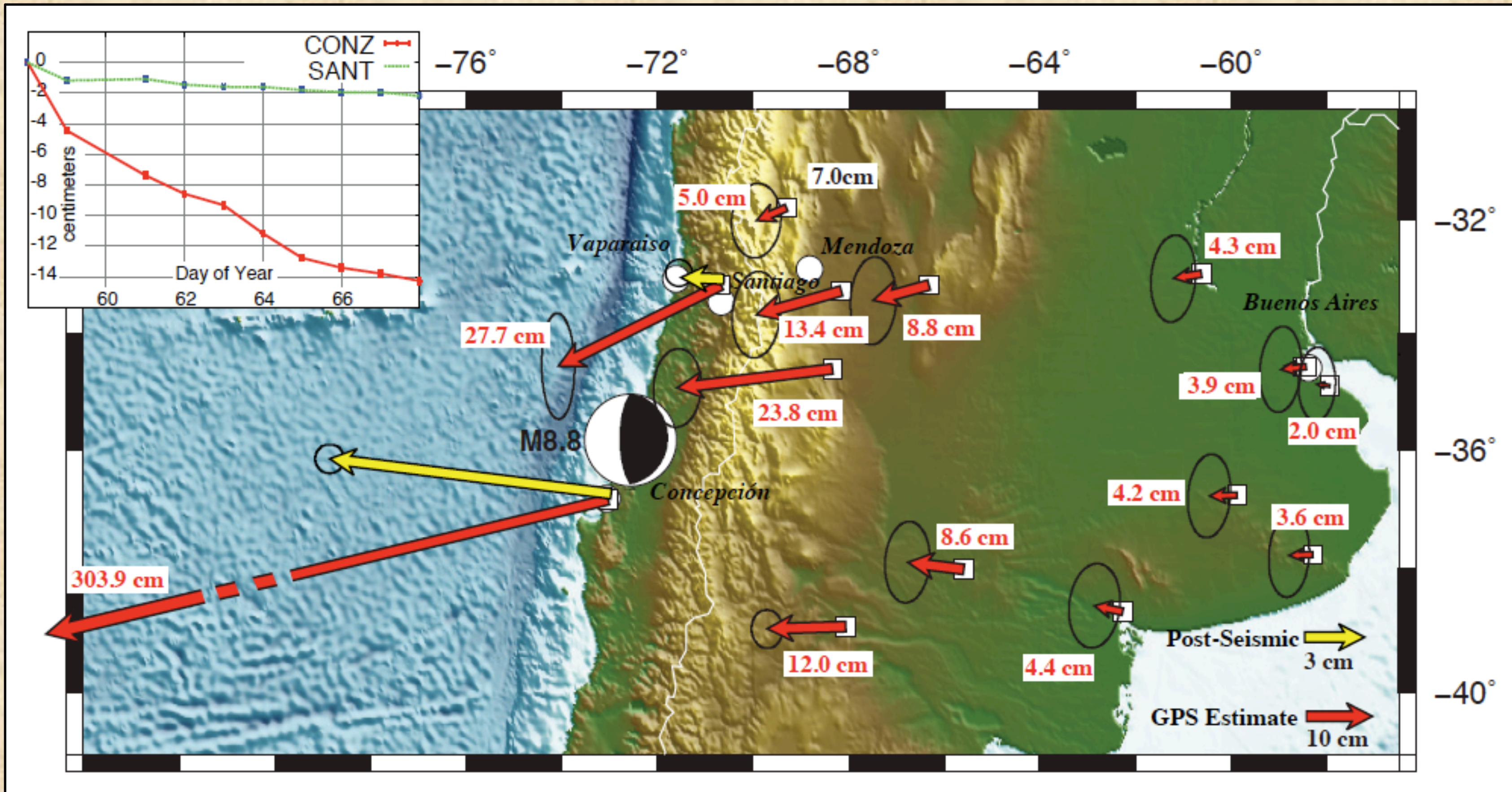
GPS data

Focus on the coseismic phase

Over 3m in Concepcion
A few cm in Argentina

Co-seismic data processed by Foster & Brooks (U. Hawaii)

GPS data



- During the earthquake: Over 3m displacement (E) in Concepcion and even a few cm in Argentina
- Over a 20 day period after the earthquake, the ground moved an additional 17cm (and continues to do so). Note the directional change.

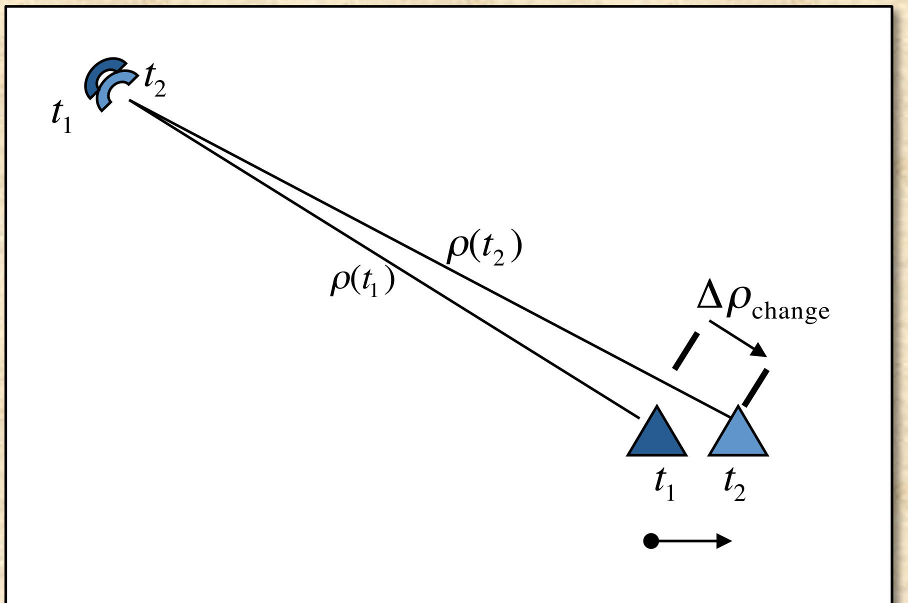
Co-seismic data processed by Foster & Brooks (U. Hawaii)
Post-seismic data processed by Susan Owen (JPL)

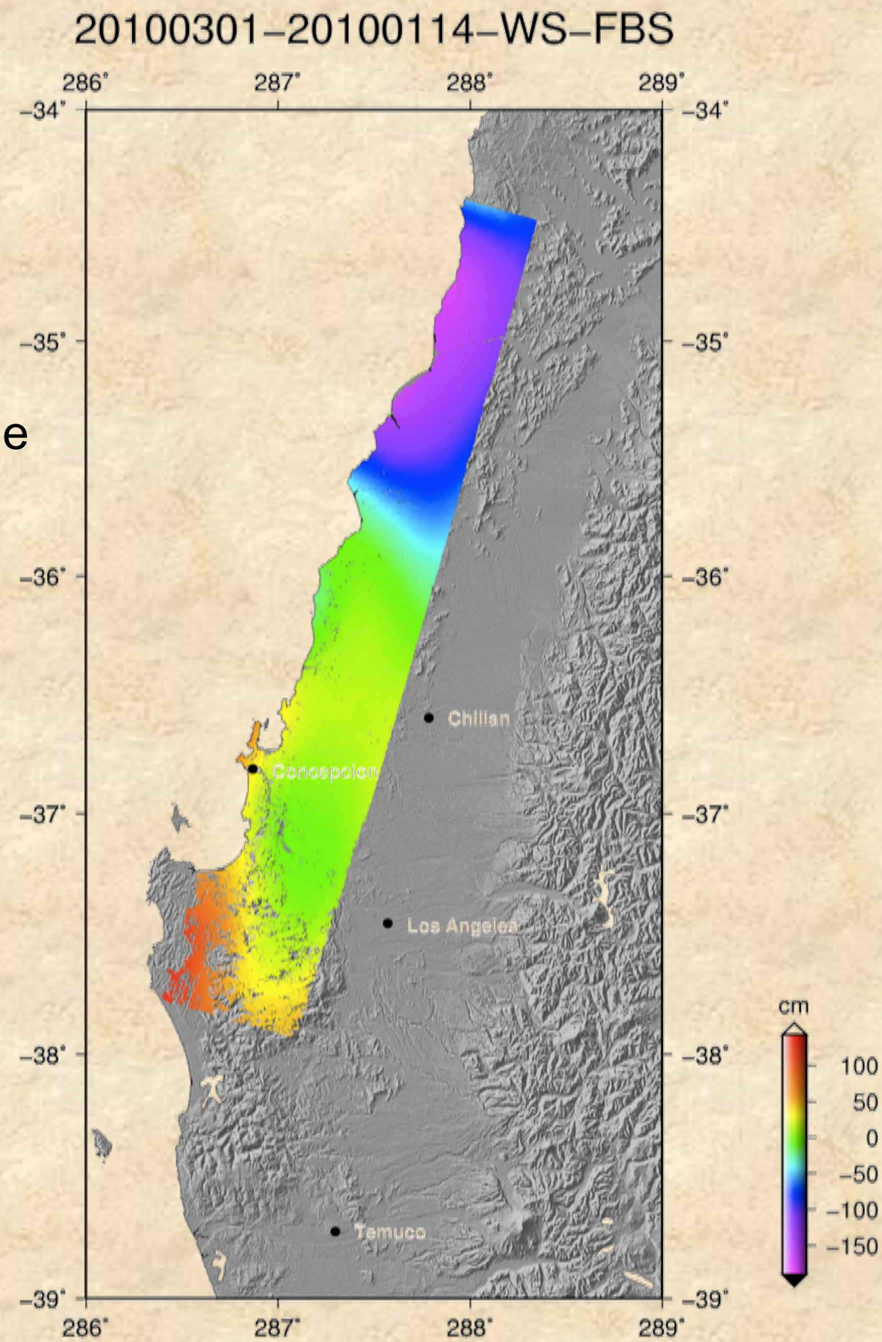
InSAR data

Interferometric Synthetic Aperture Radar

ALOS radar satellite (JAXA)

Area affected much larger than width of image

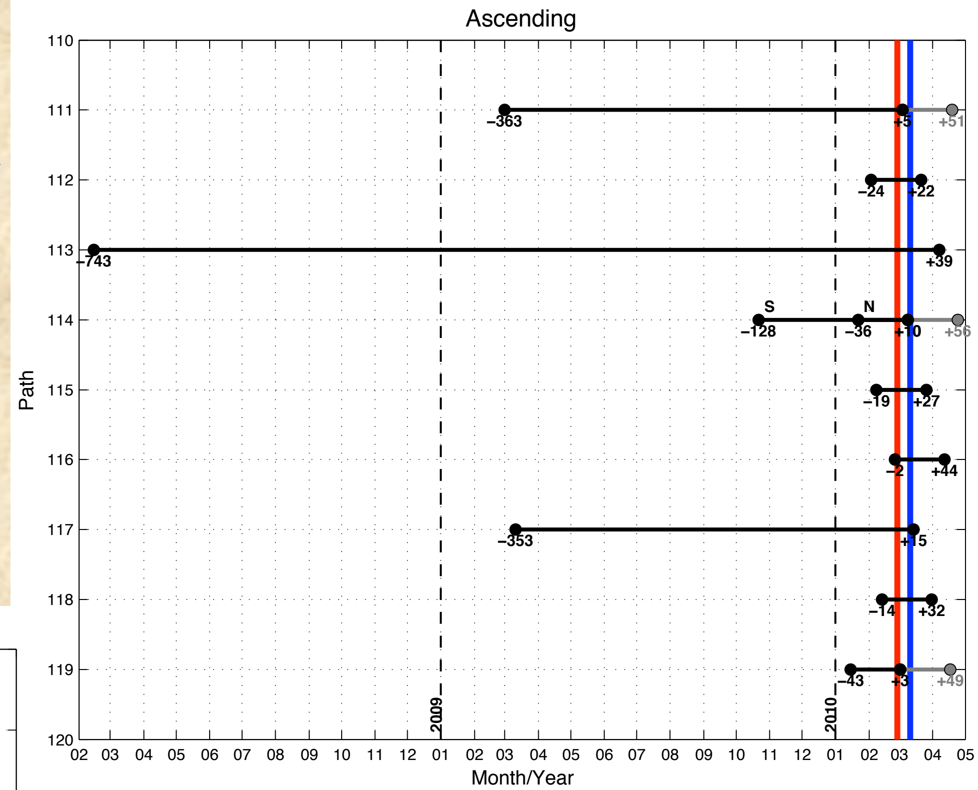


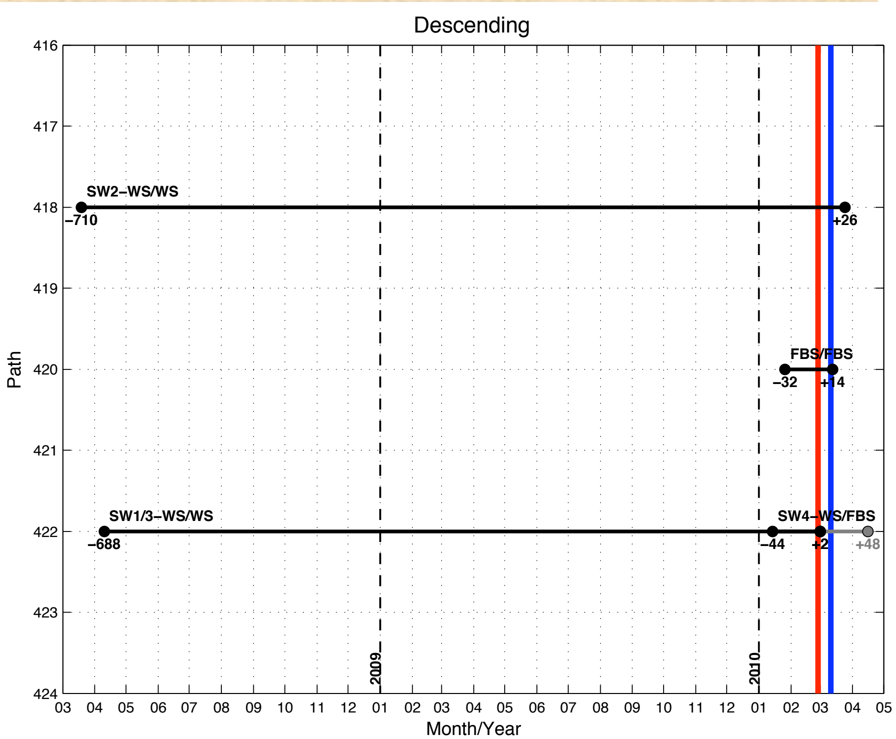


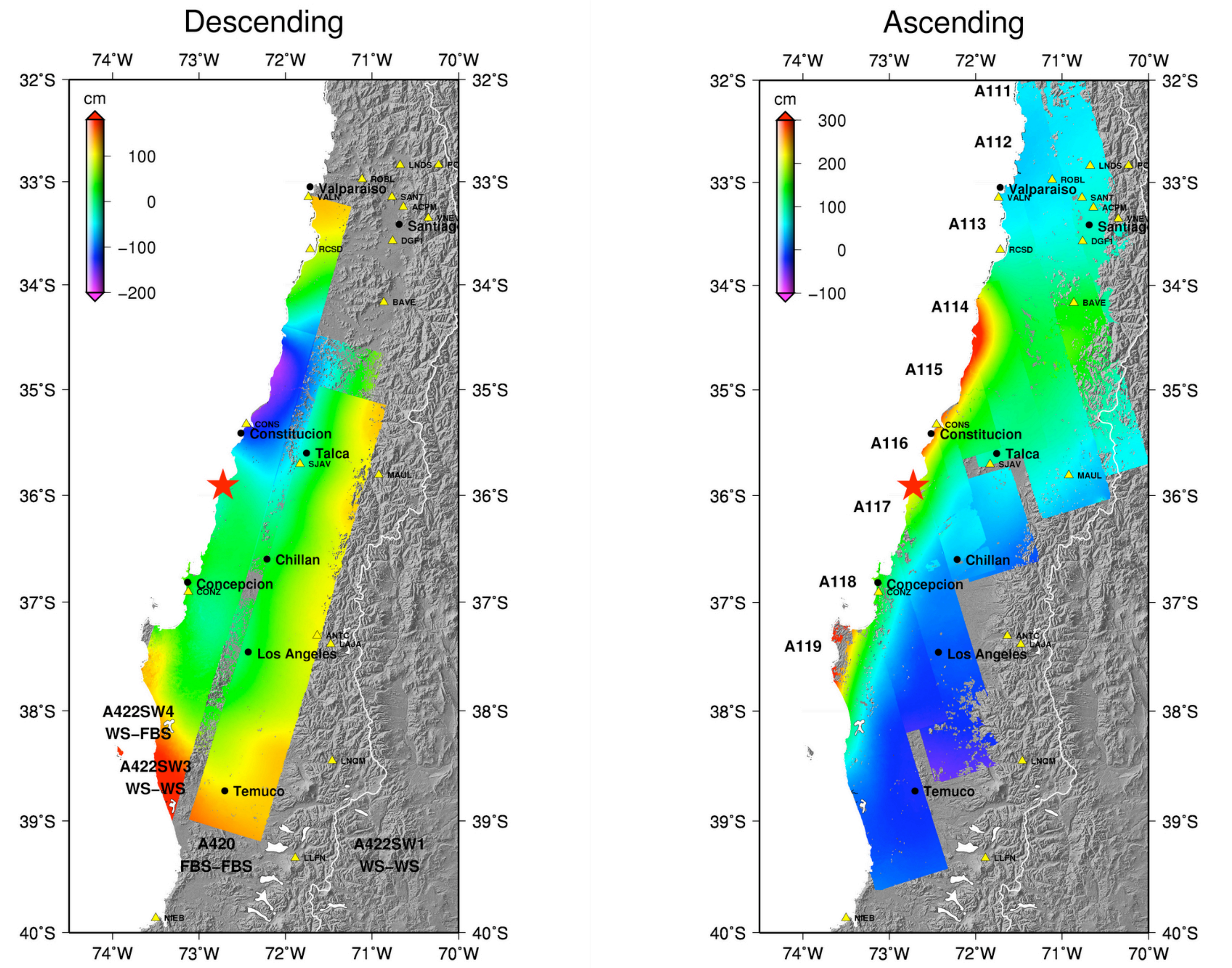
InSAR data

Interferometric Synthetic Aperture Radar

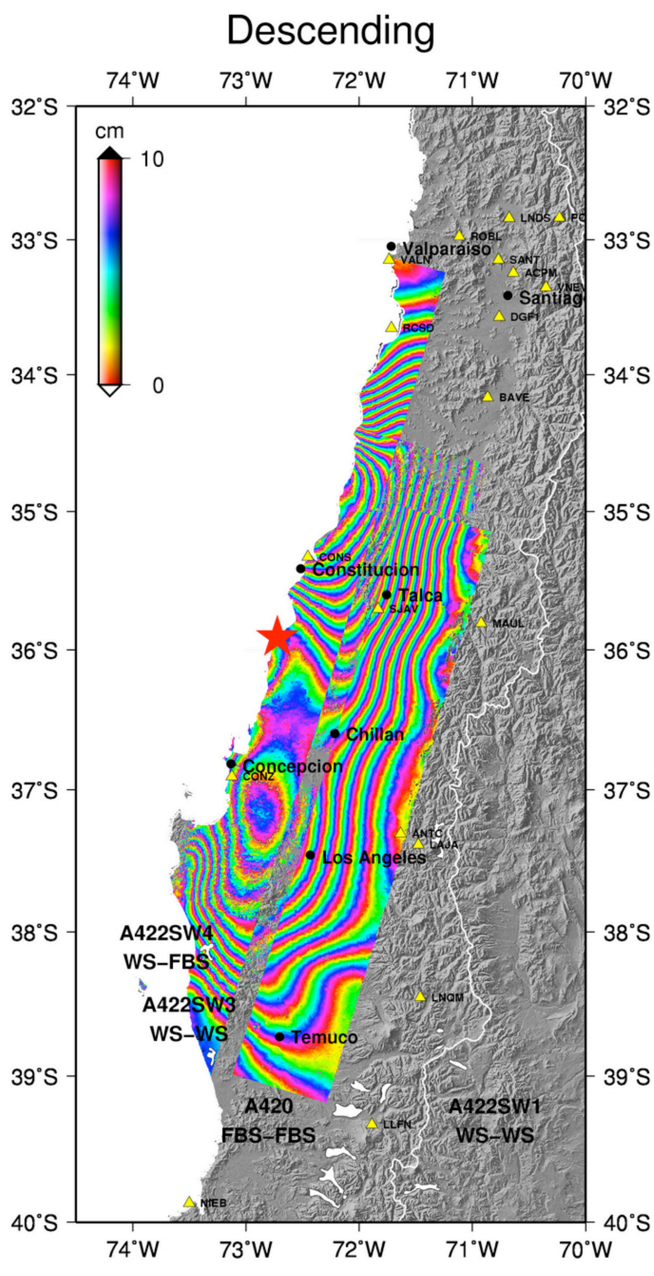
ALOS radar satellite (JAXA)



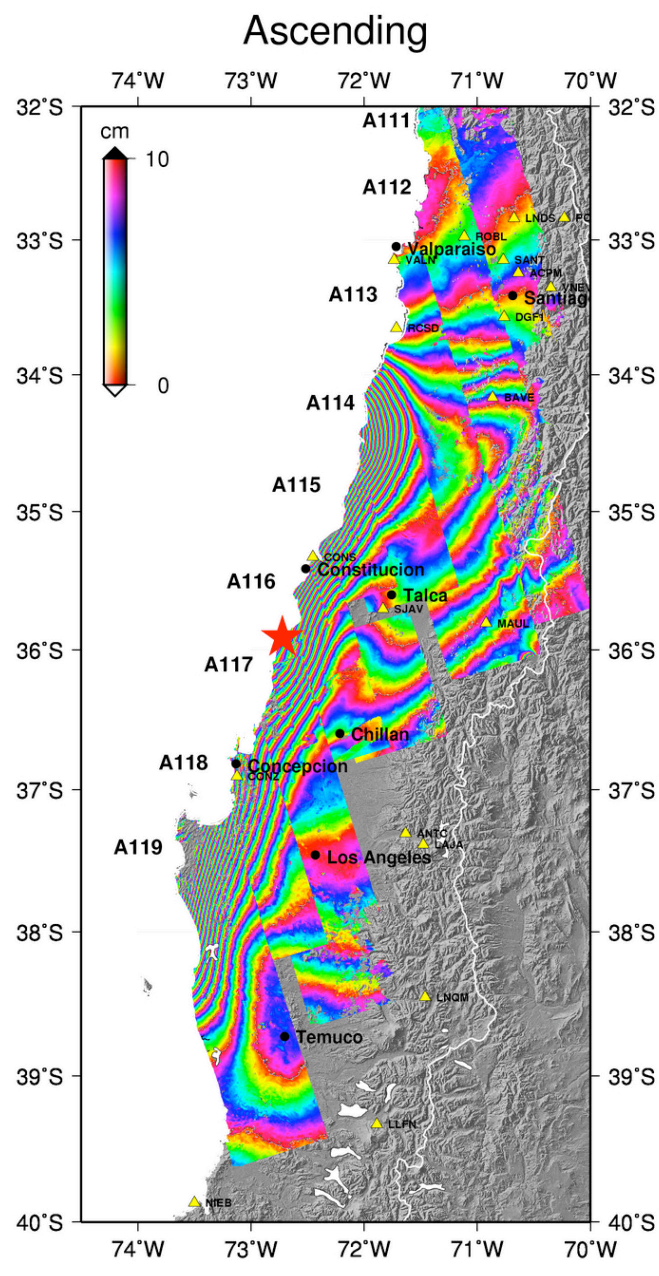




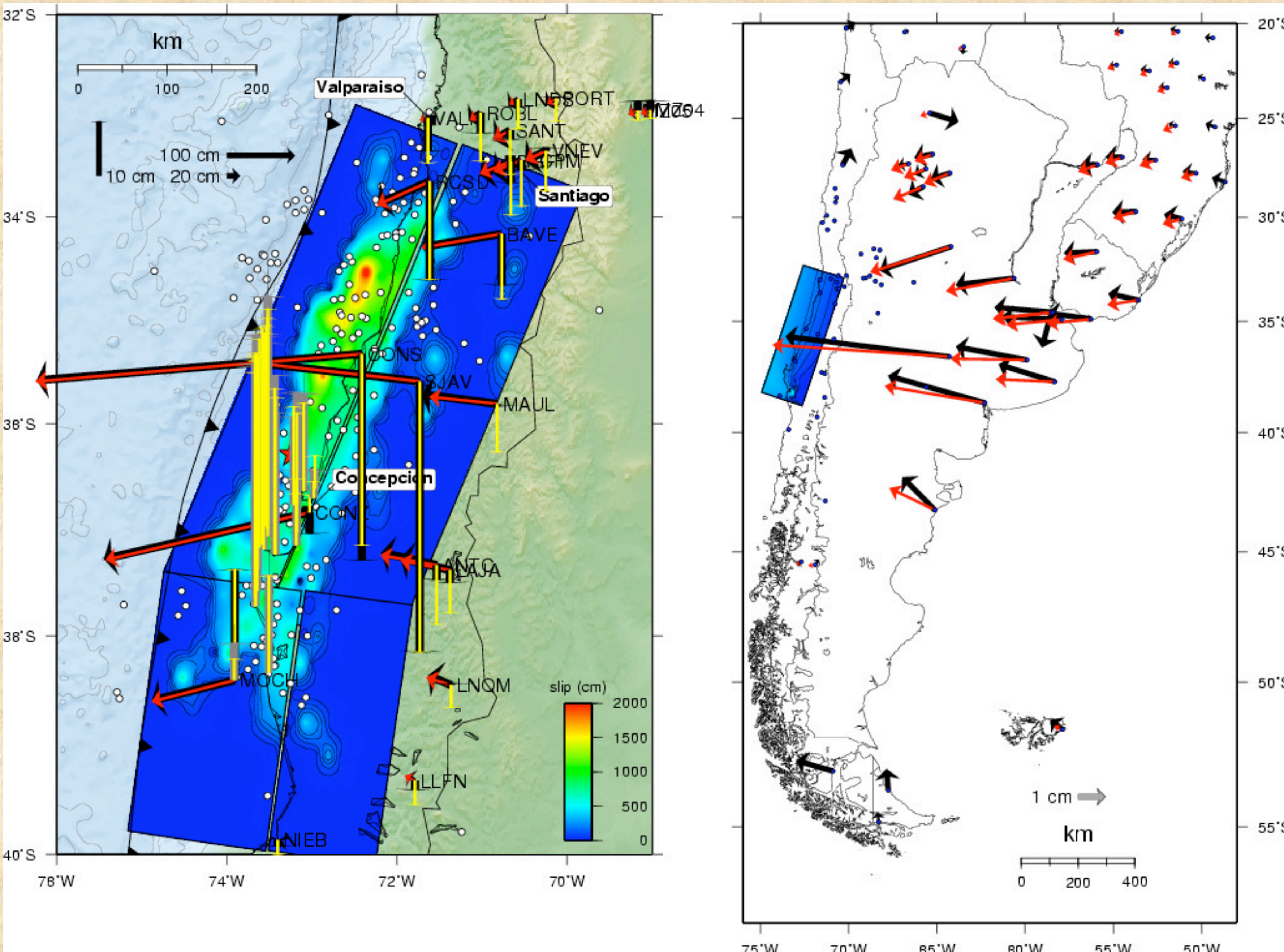
Descending
Ascending
74˚W
73˚W
72˚W
71˚W
70˚W
32˚S
33˚S
34˚S
35˚S
36˚S
37˚S
38˚S
39˚S
40˚S
cm
100
0
−100
−200
300
200
100
0
−100
Valparaiso
Santiago
Constitucion
Talca
Chillan
Concepcion
Los Angeles
Temuco
LNDS
ROBL
VALN
SANT
ACPM
VNE
DGF1
RCSD
BAVE
CONS
SJAV
MAUL
CONZ
ANTC
LAJA
LNCM
LLFN
NIEB
A422SW4
WS−FBS
A422SW3
WS−WS
A420
FBS−FBS
A422SW1
WS−WS
A111
A112
A113
A114
A115
A116
A117
A118
A119



Descending
74°W
73°W
72°W
71°W
70°W
32°S
33°S
34°S
35°S
36°S
37°S
38°S
39°S
40°S
cm
10
0
Valparaiso
Santiago
Constitucion
Talca
Chillan
Concepcion
Los Angeles
Temuco
A422SW4
WS-FBS
A422SW3
WS-WS
A420
FBS-FBS
A422SW1
WS-WS



Ascending
74°W
73°W
72°W
71°W
70°W
32°S
33°S
34°S
35°S
36°S
37°S
38°S
39°S
40°S
cm
10
0
A111
A112
A113
A114
A115
A116
A117
A118
A119
Valparaiso
Santiago
Constitucion
Talca
Chillan
Concepcion
Los Angeles
Temuco



km
0
100
200
100 cm
10 cm
20 cm
Valparaiso
Santiago
Concepcion
VALL
ROBL
SANT
VNEV
RCSD
BAVE
CONS
SJAV
MAUL
ANTC
MOCH
LNQM
LLFN
NIEB
slip (cm)
2000
1500
1000
500
0
32°S
34°S
36°S
38°S
40°S
76°W
74°W
72°W
70°W
1 cm
km
0
200
400
20°S
25°S
30°S
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40°S
45°S
50°S
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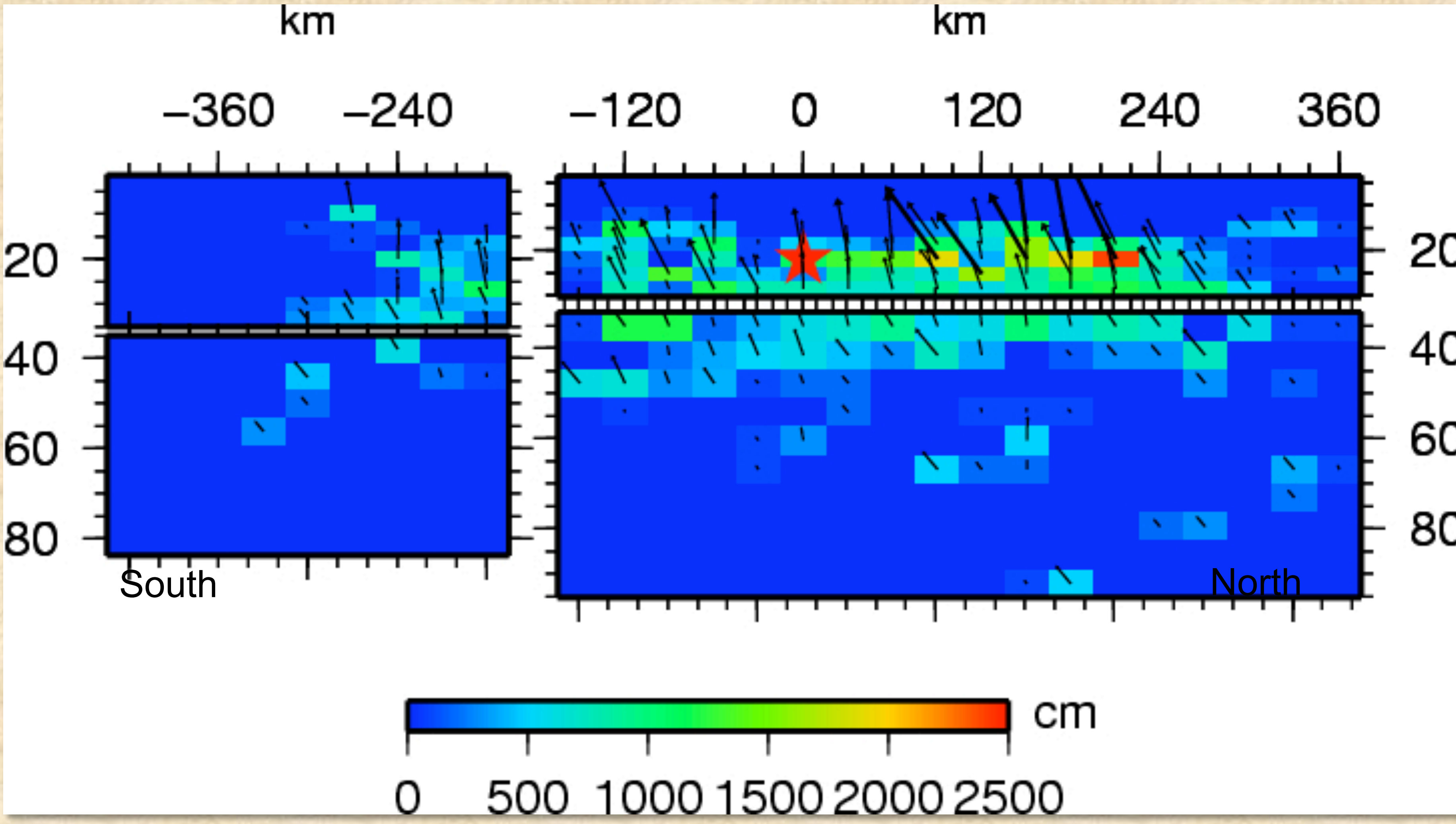
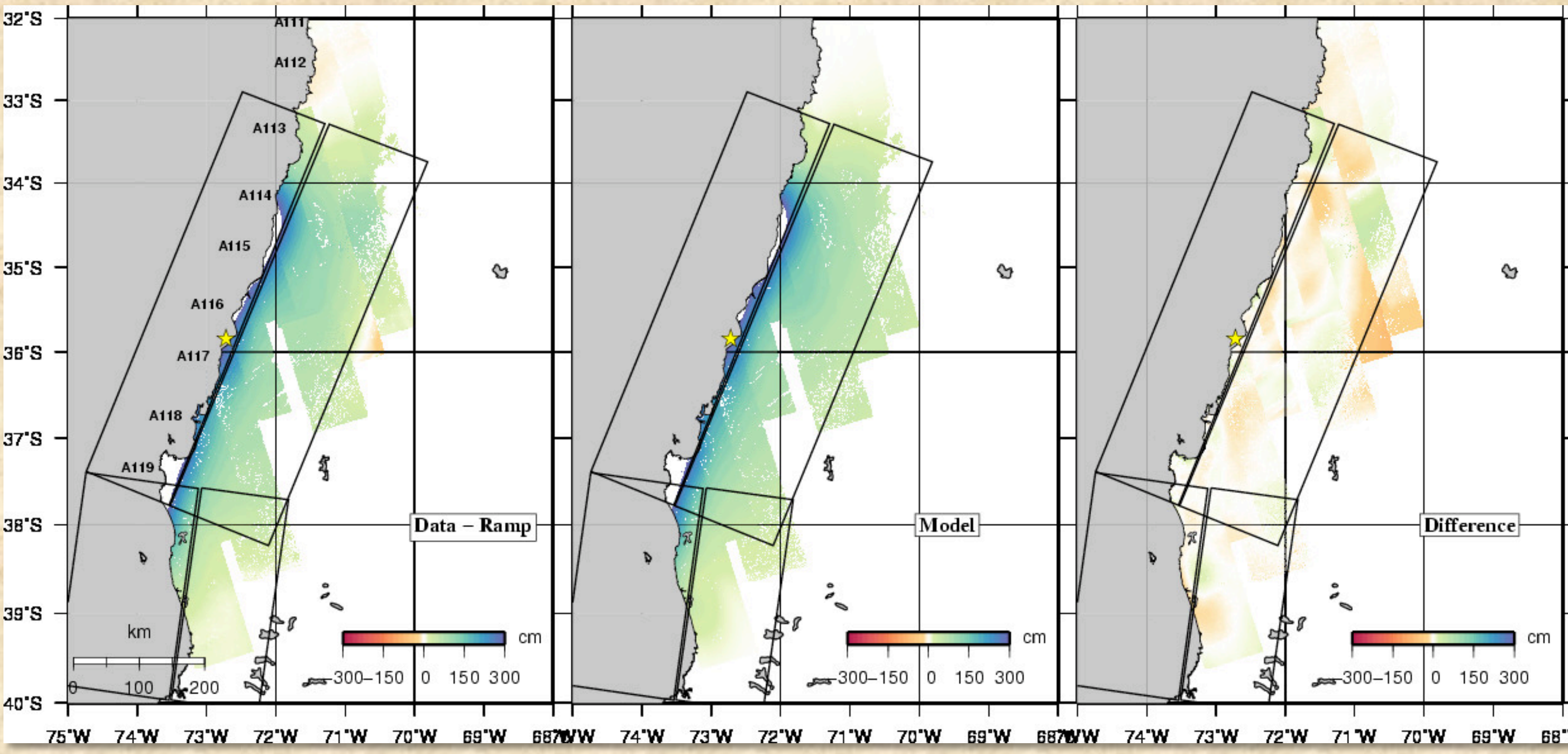
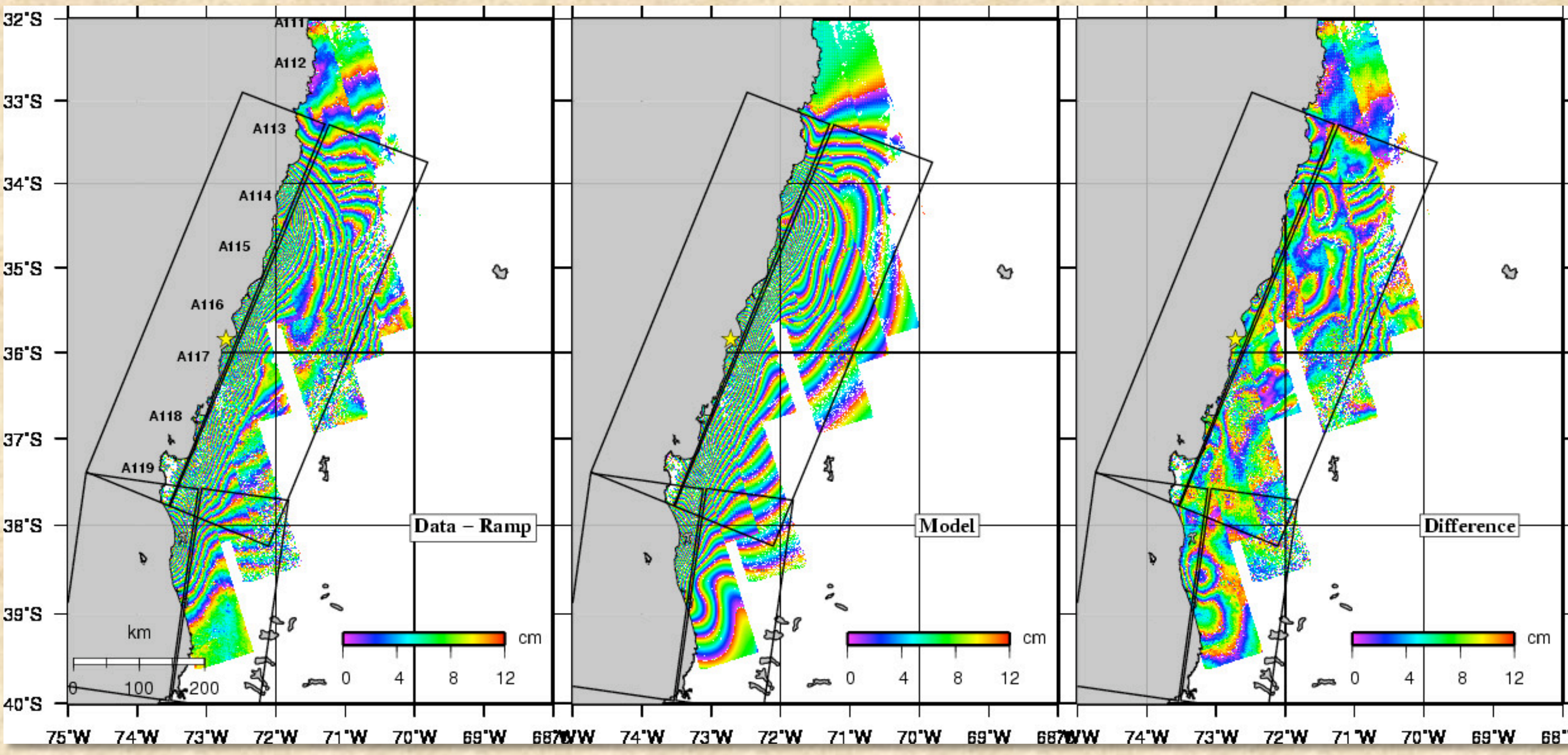
70°W
65°W
60°W
55°W
50°W



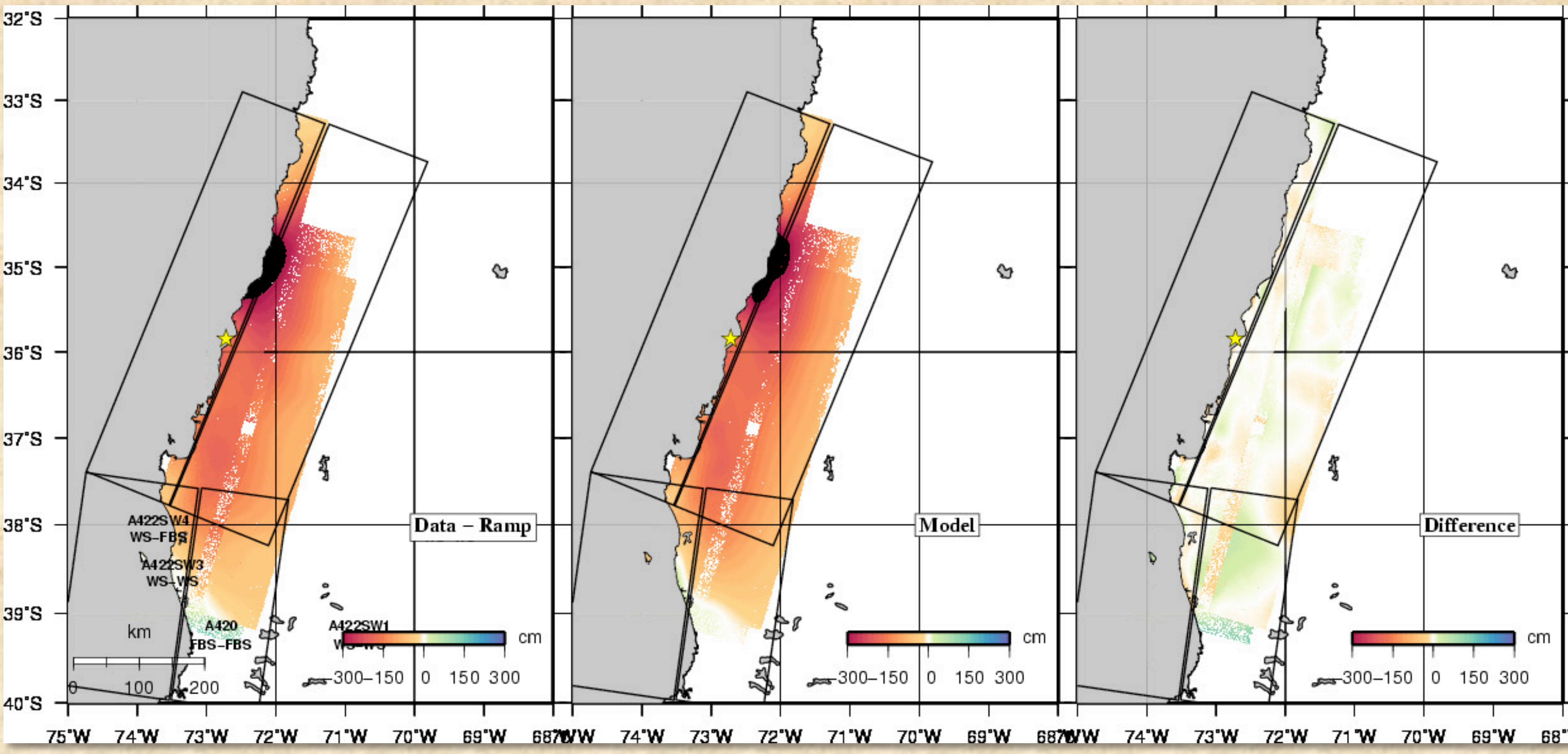
Rake pretty consistent with plate convergence direction



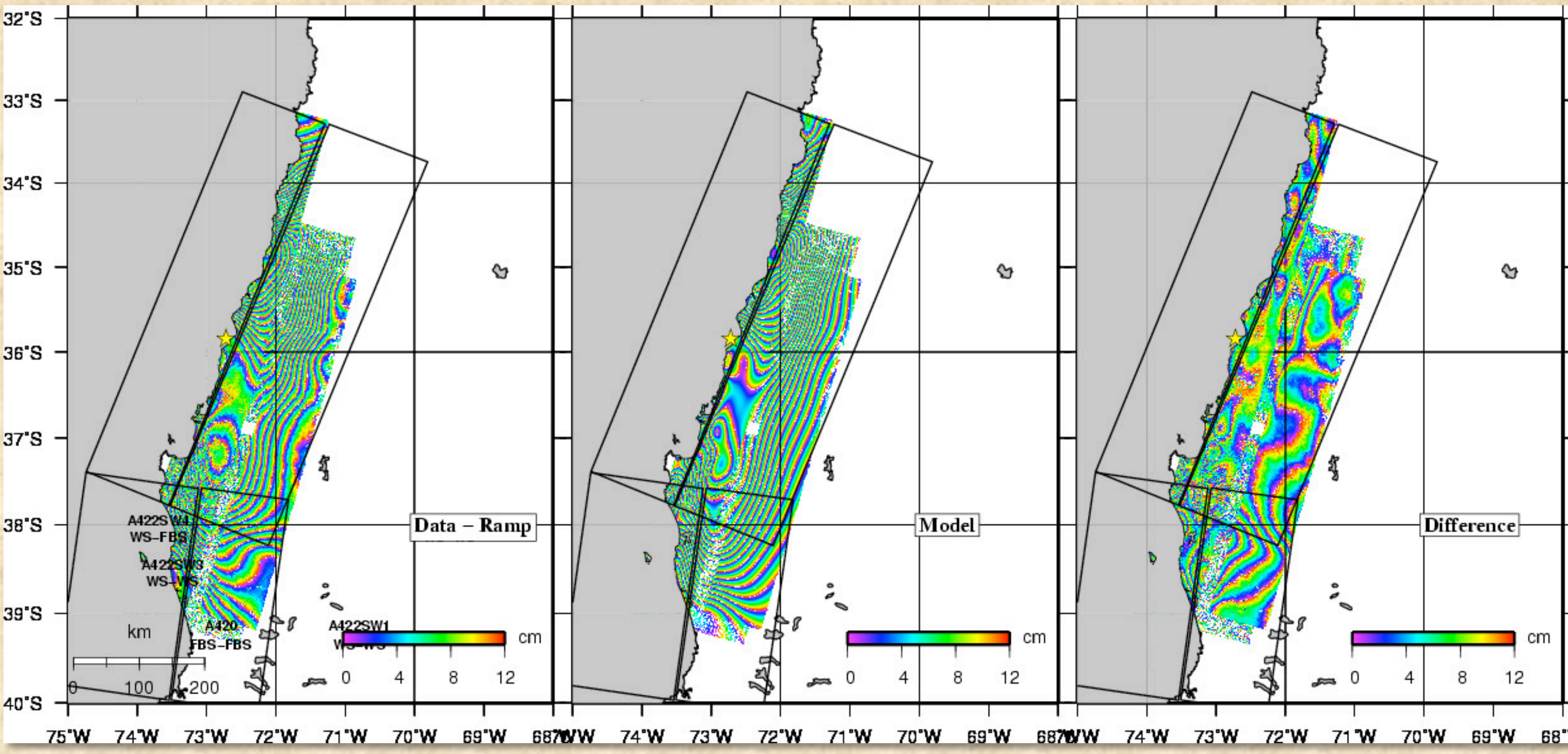
32°S
33°S
34°S
35°S
36°S
37°S
38°S
39°S
40°S
75°W
74°W
73°W
72°W
71°W
70°W
69°W
68°W
A111
A112
A113
A114
A115
A116
A117
A118
A119
Data – Ramp
Model
Difference
km
0
100
200
cm
-300
-150
0
150
300



Data – Ramp
Model
Difference
A111
A112
A113
A114
A115
A116
A117
A118
A119
km
0
100
200
cm
0
4
8
12
32°S
33°S
34°S
35°S
36°S
37°S
38°S
39°S
40°S
75°W
74°W
73°W
72°W
71°W
70°W
69°W
68°W

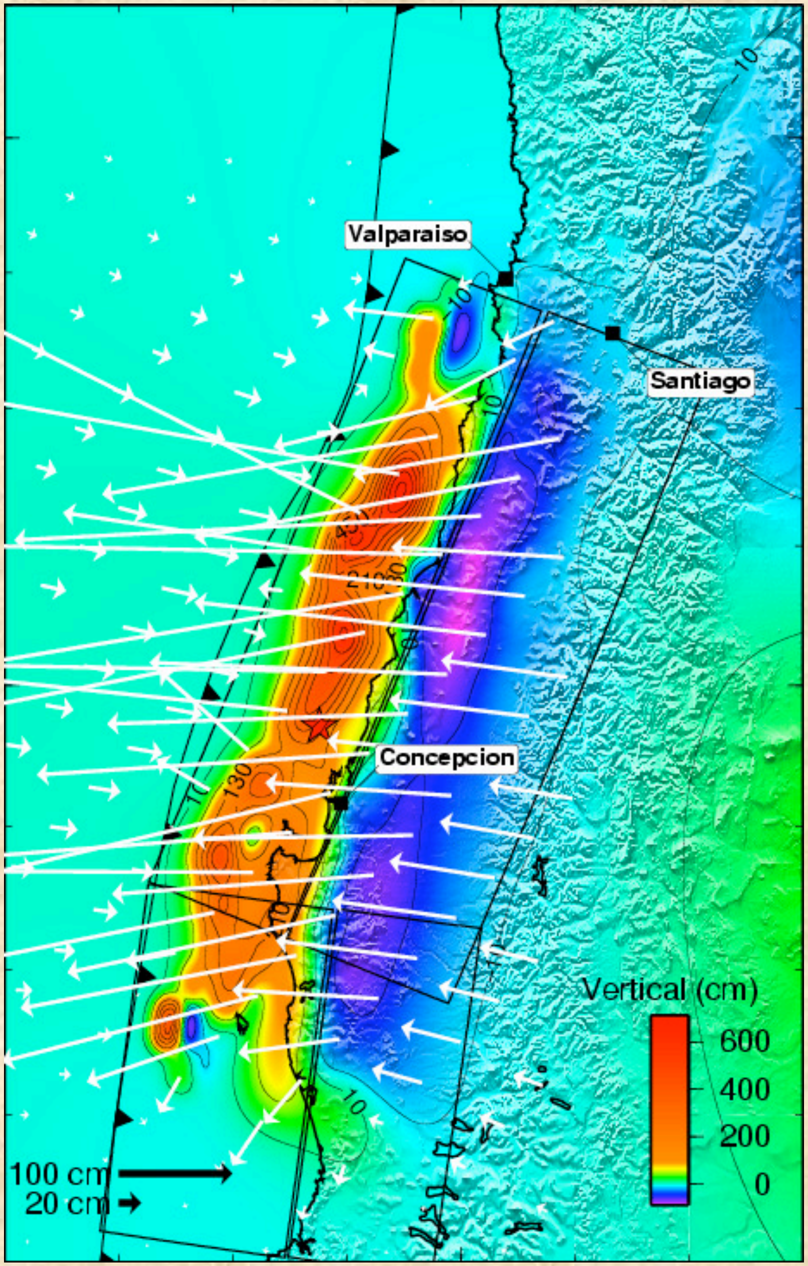


Data – Ramp
Model
Difference
A422SW4
WS–FBS
A422SW3
WS–WS
A420
FBS–FBS
A422SW1
km
0
100
200
cm
-300 -150 0 150 300
32°S
33°S
34°S
35°S
36°S
37°S
38°S
39°S
40°S
75°W
74°W
73°W
72°W
71°W
70°W
69°W
68°W



Same as before but wrapped at 12cm/fringe.
Note systematic residual near the peninsula – model deficiency

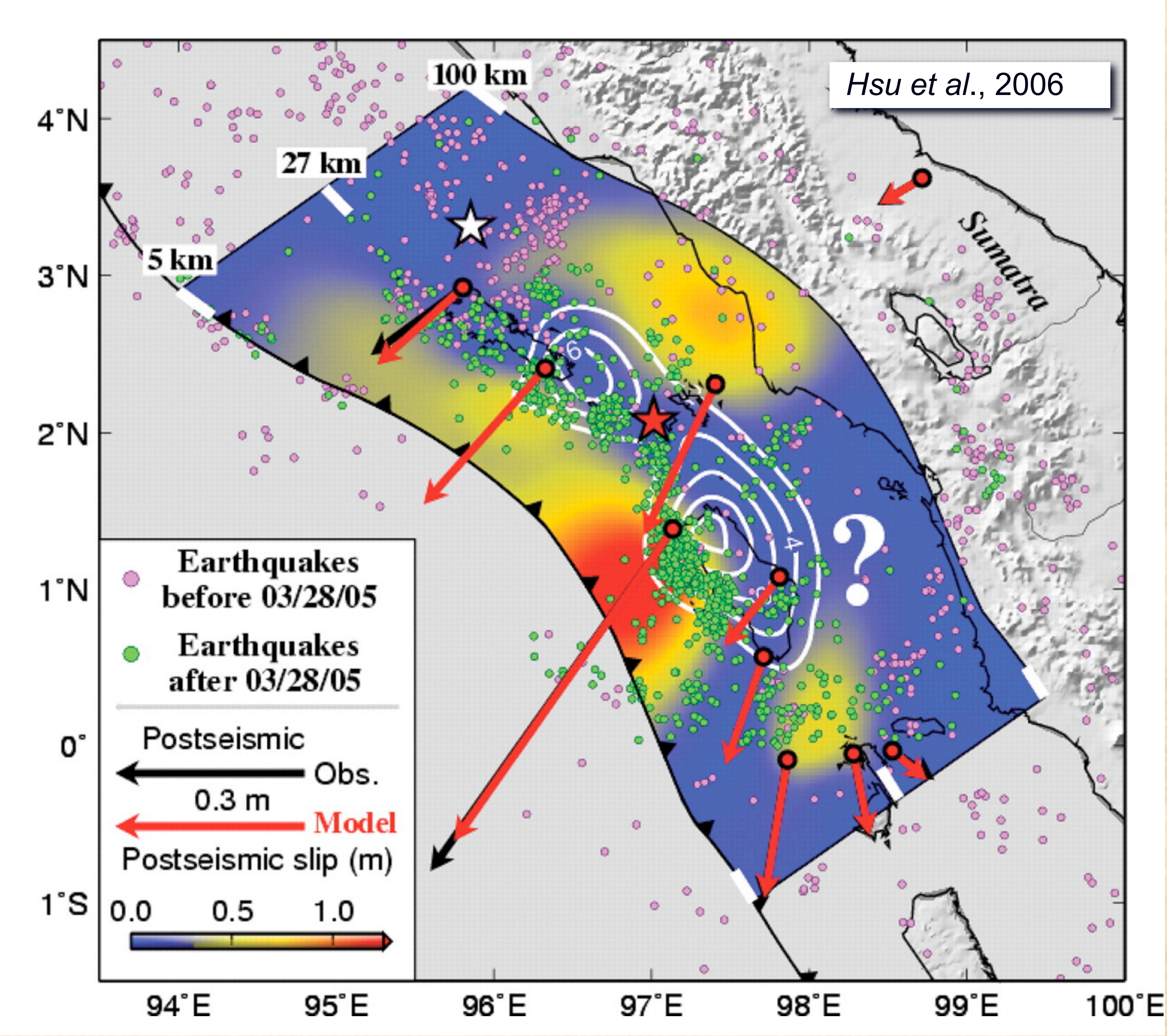

Arauco Peninsula
Large scale normal faults
uplift



Too first order, vertical motion is anticorrelated with topographic variations

Same as what was seen for the 2005 Mw 8.7 Nias & 2007 Mw 8 Pisco EQ

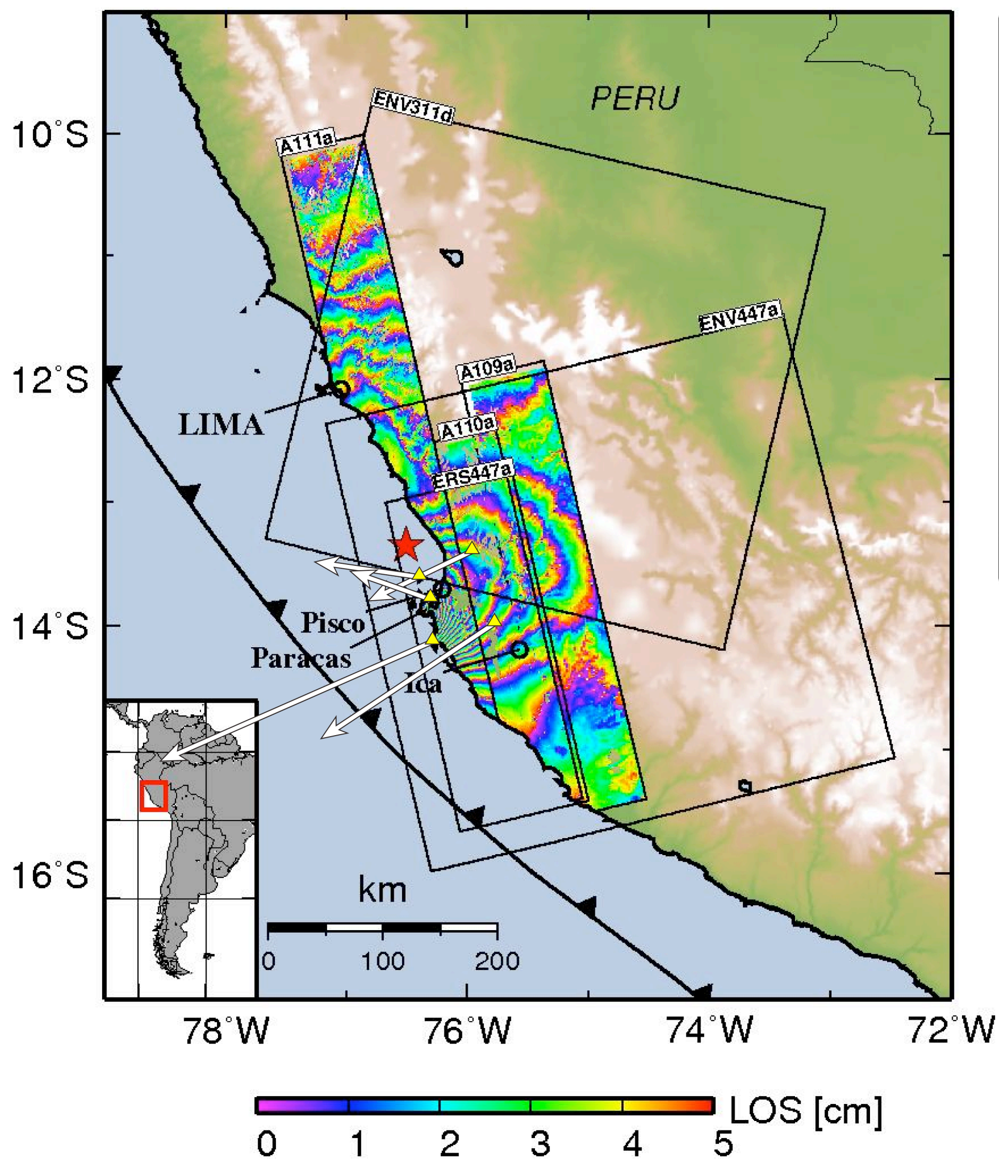
2005 M_w 8.7, Nias Earthquake

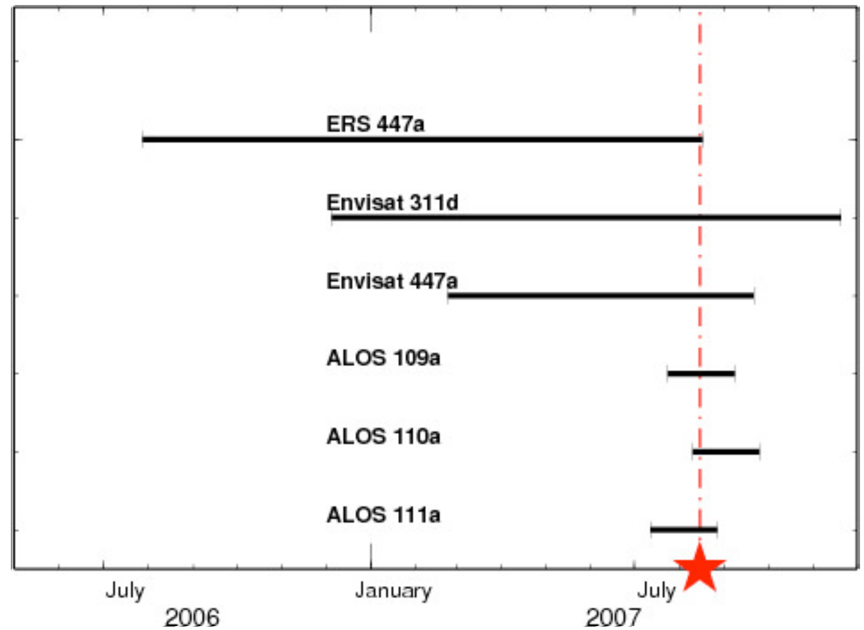


Post-seismic

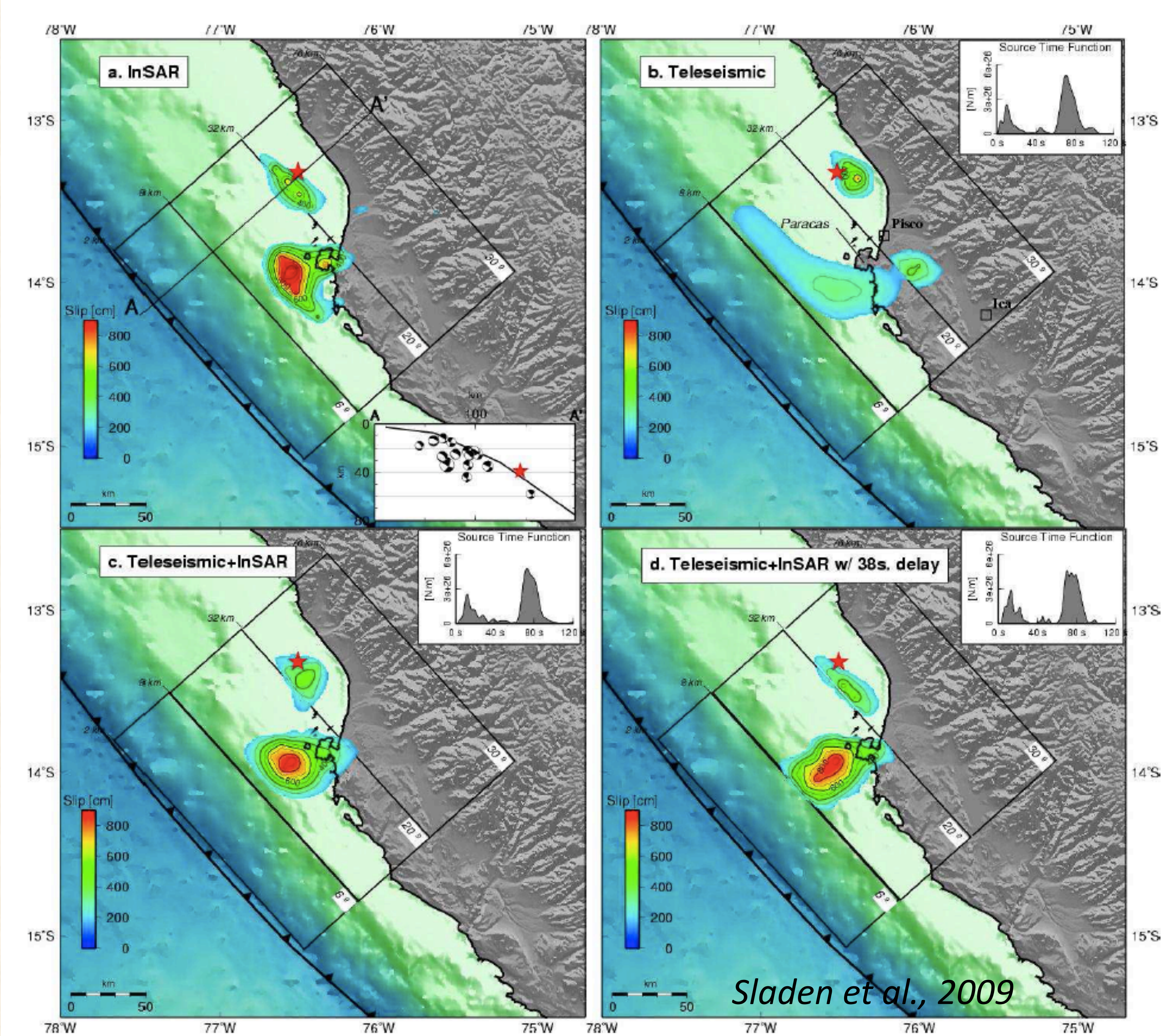
- ➲ Near-trench GPS data provide strong constraints on updip behavior
- ➲ Slip highly heterogeneous in space
- ➲ Coseismic and postseismic appear to show little overlap

InSAR Data



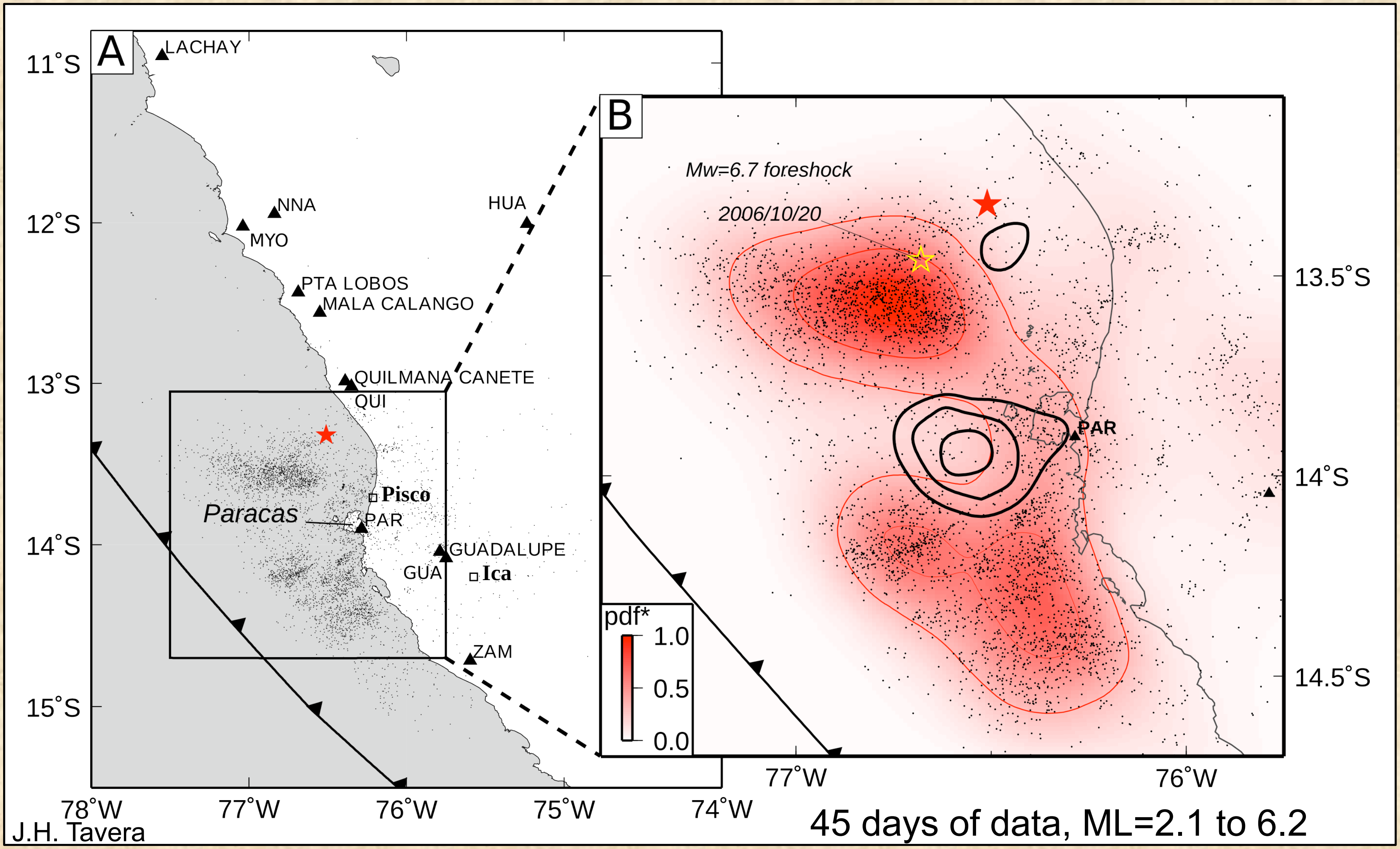


- 6 InSAR images:
  - 3 L-band,
  - 2 wide-swath,
  - 2 with descending orbit.



Sladen et al., 2009

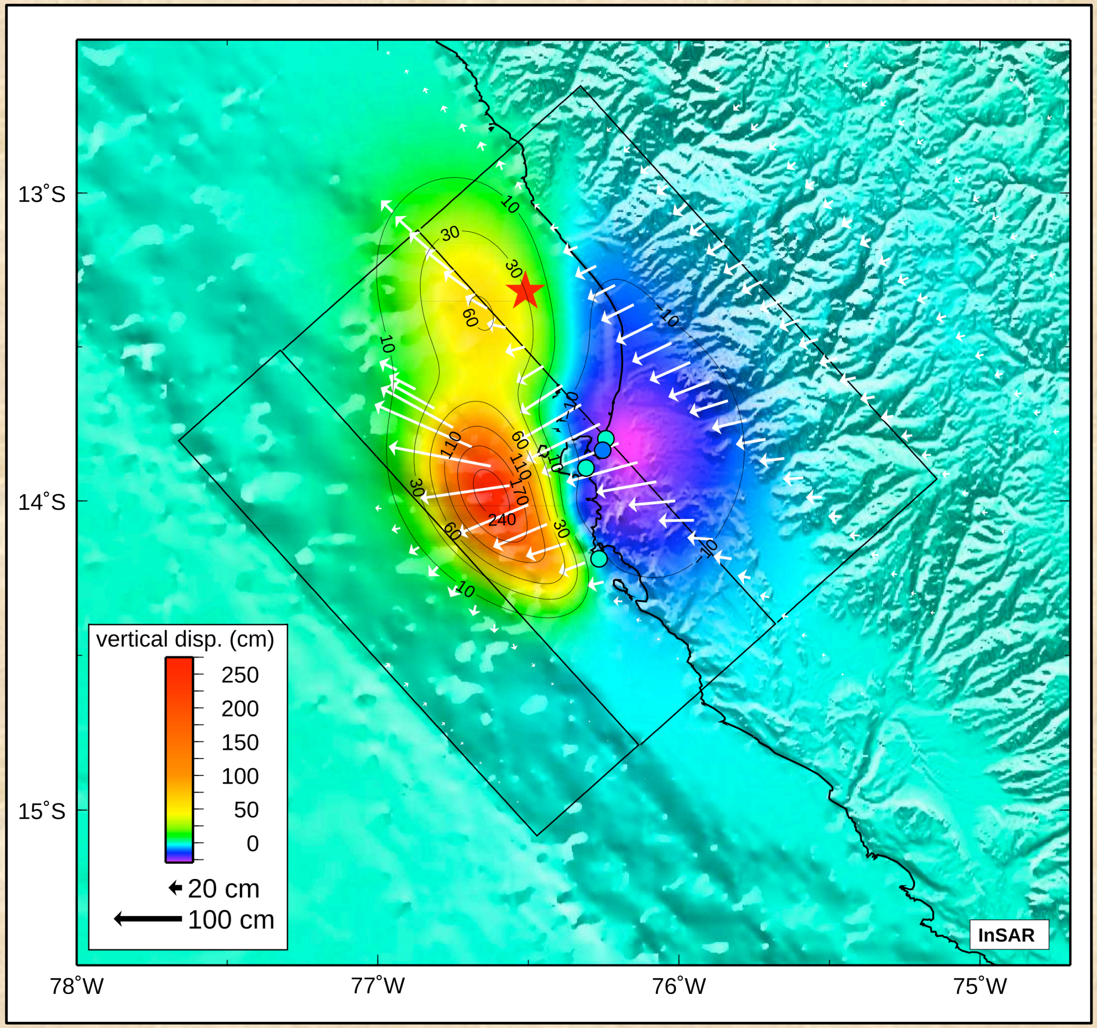
Aftershocks



Sladen et al., 2009

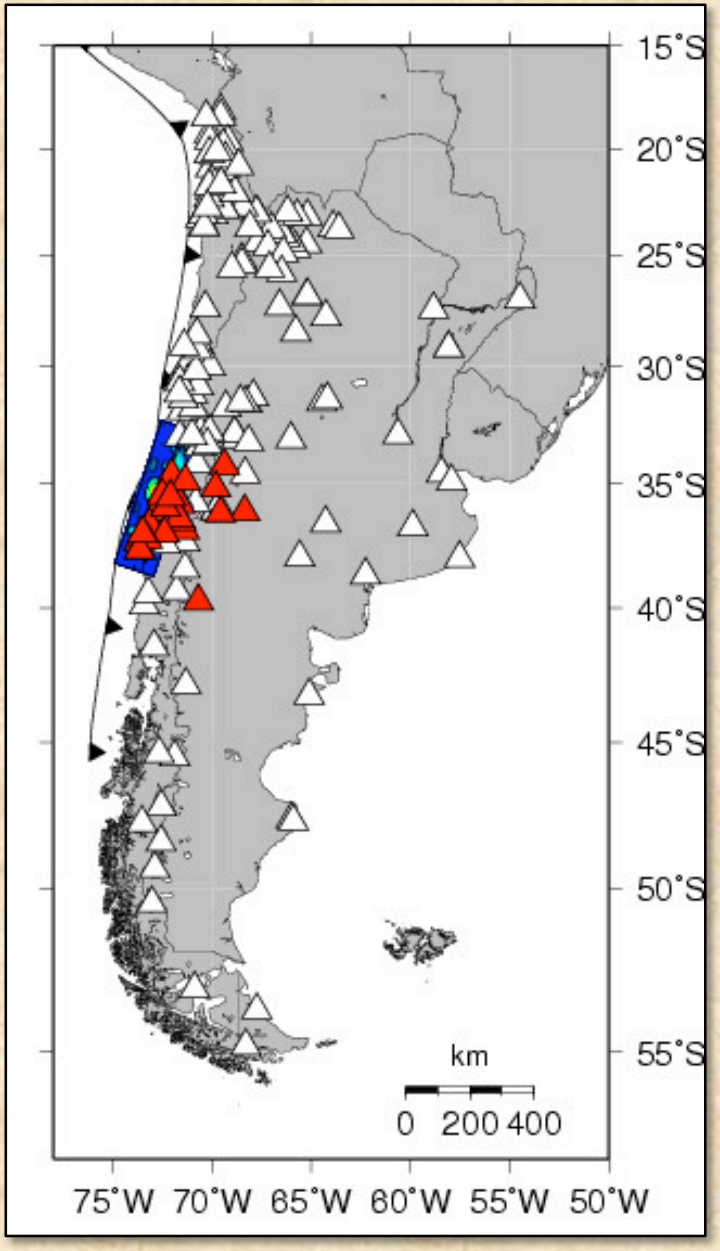
Coseismic vs long term deformation

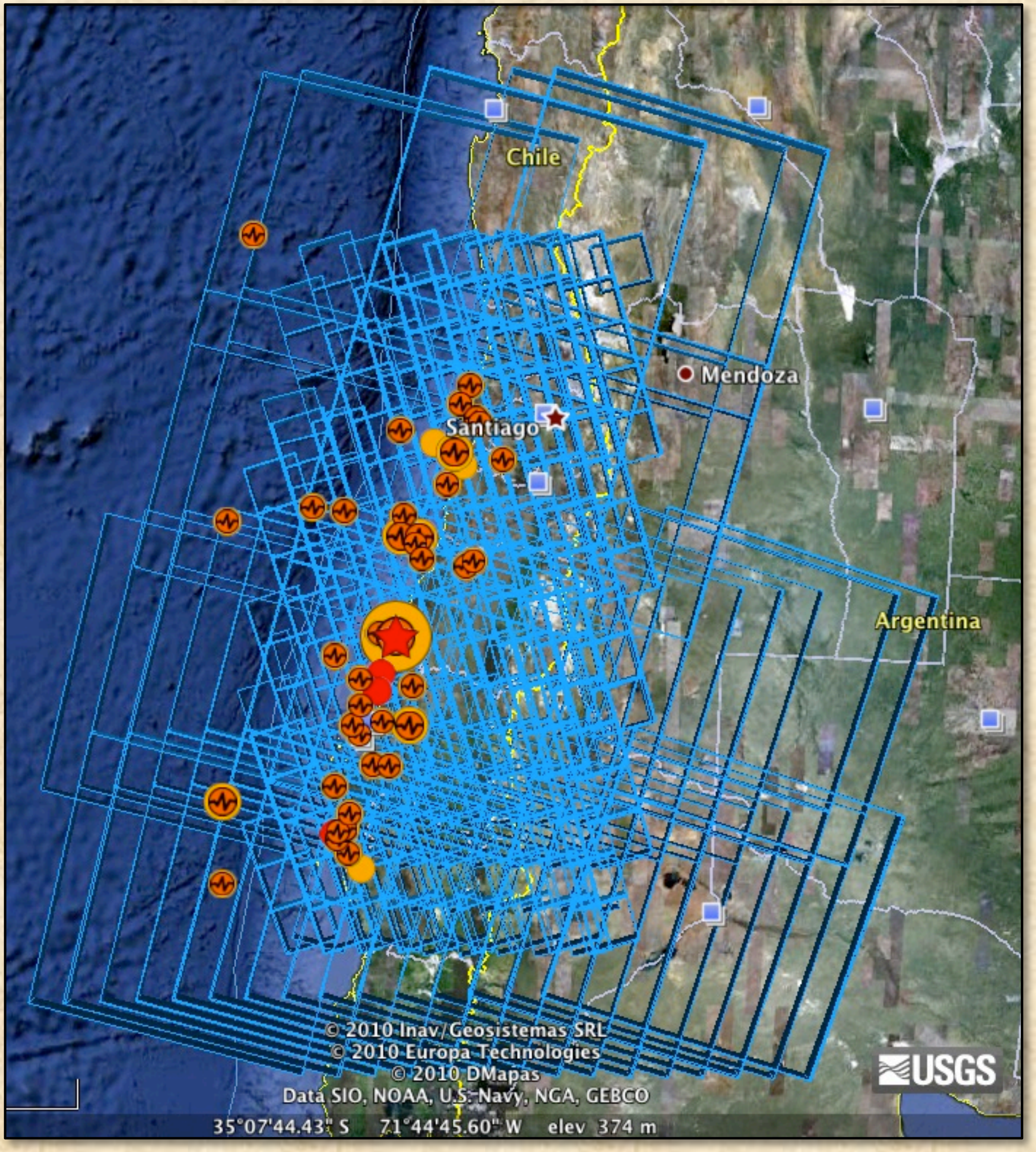
- No reported uplift along the coast (± 40 cm tide)
- Uplifted area follows the coastline
- Max. subsidence at the Paracas Peninsula
- Anticorrelation of Coseismic and long term topography suggest topography result from inelastic deformation during the interseismic

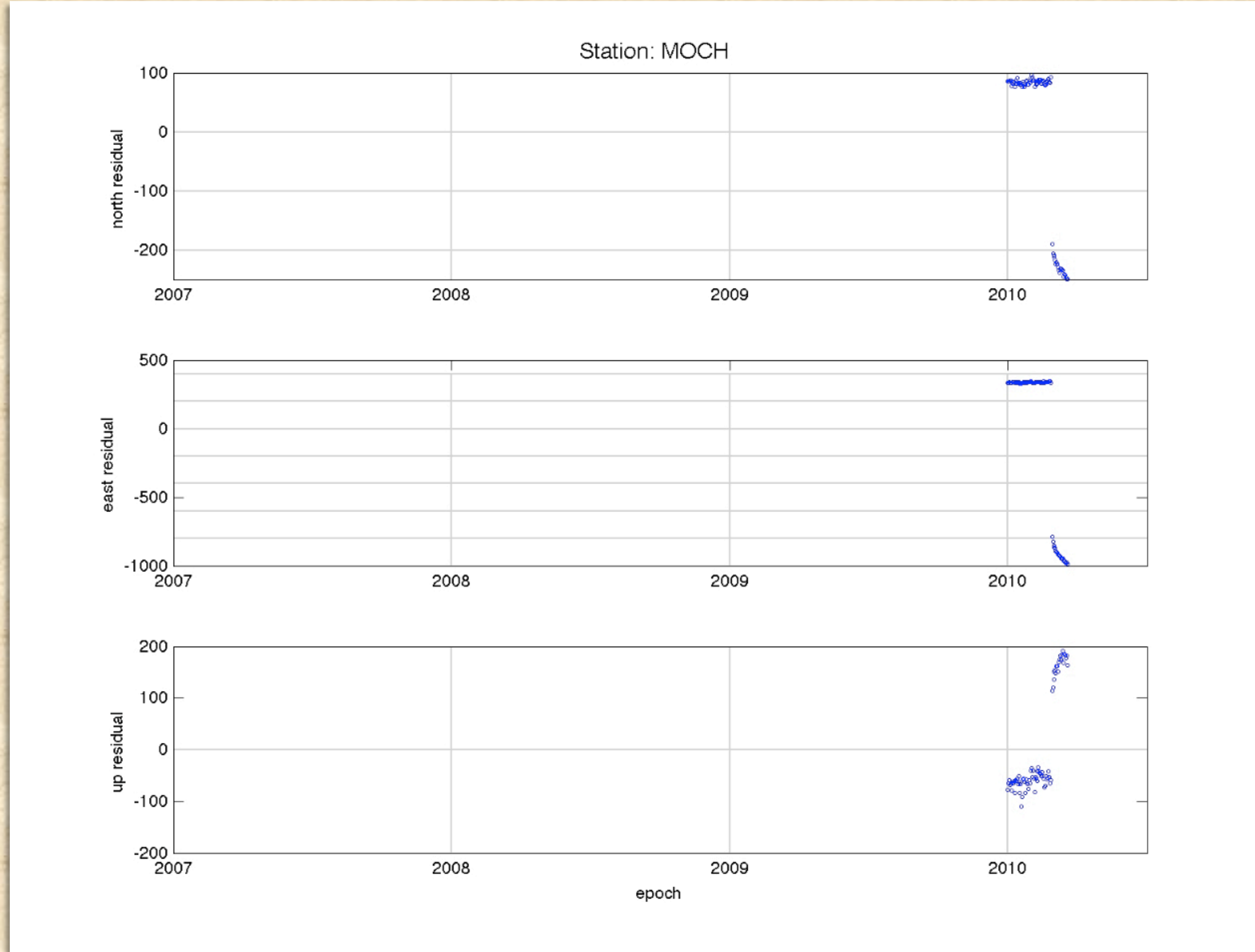


Sladen et al., 2009

Expected post-earthquake GPS and satellite InSAR coverage






Station: MOCH
north residual
100
0
-100
-200
2007
2008
2009
2010
east residual
500
0
-500
-1000
up residual
200
100
-100
-200
epoch

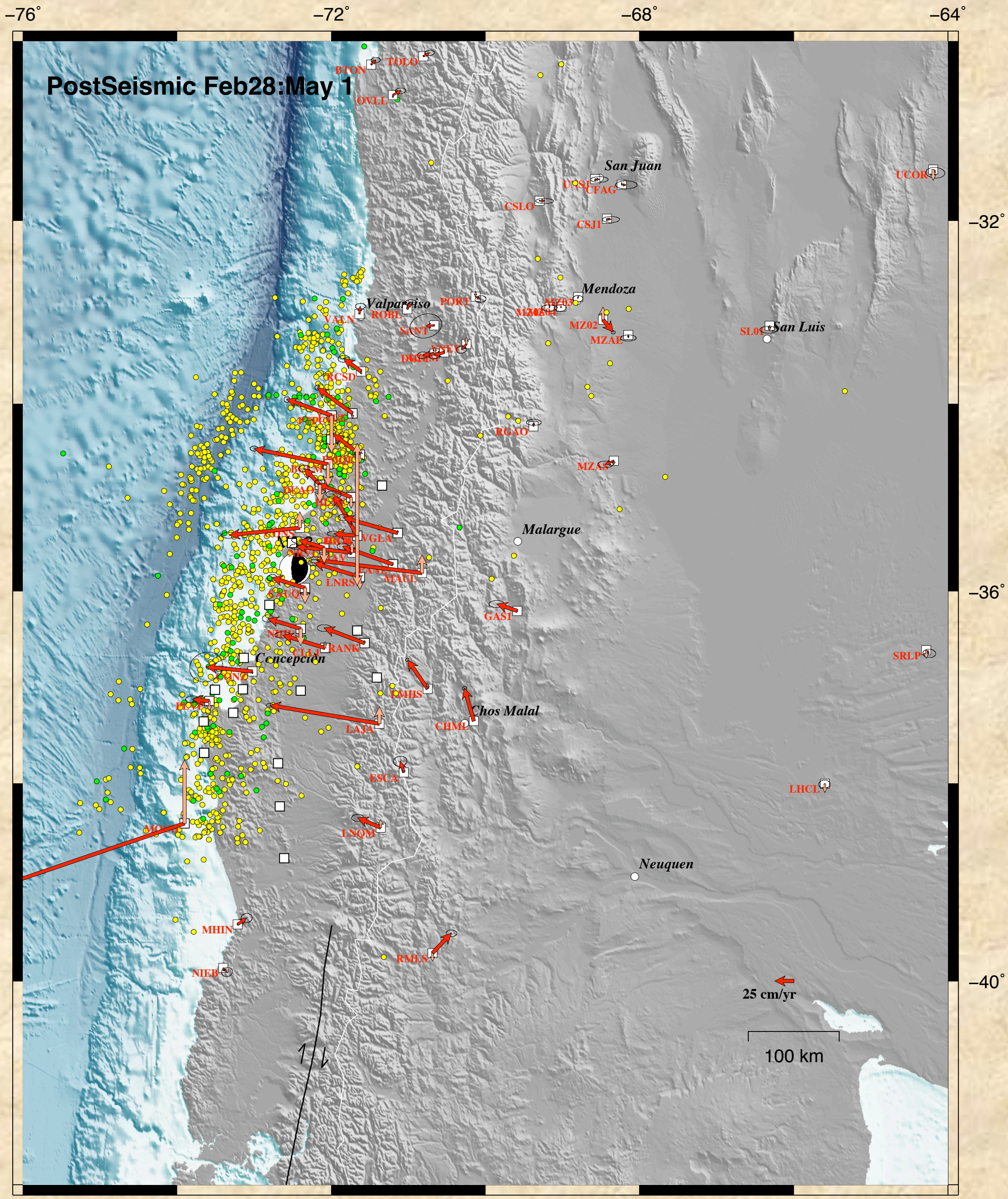
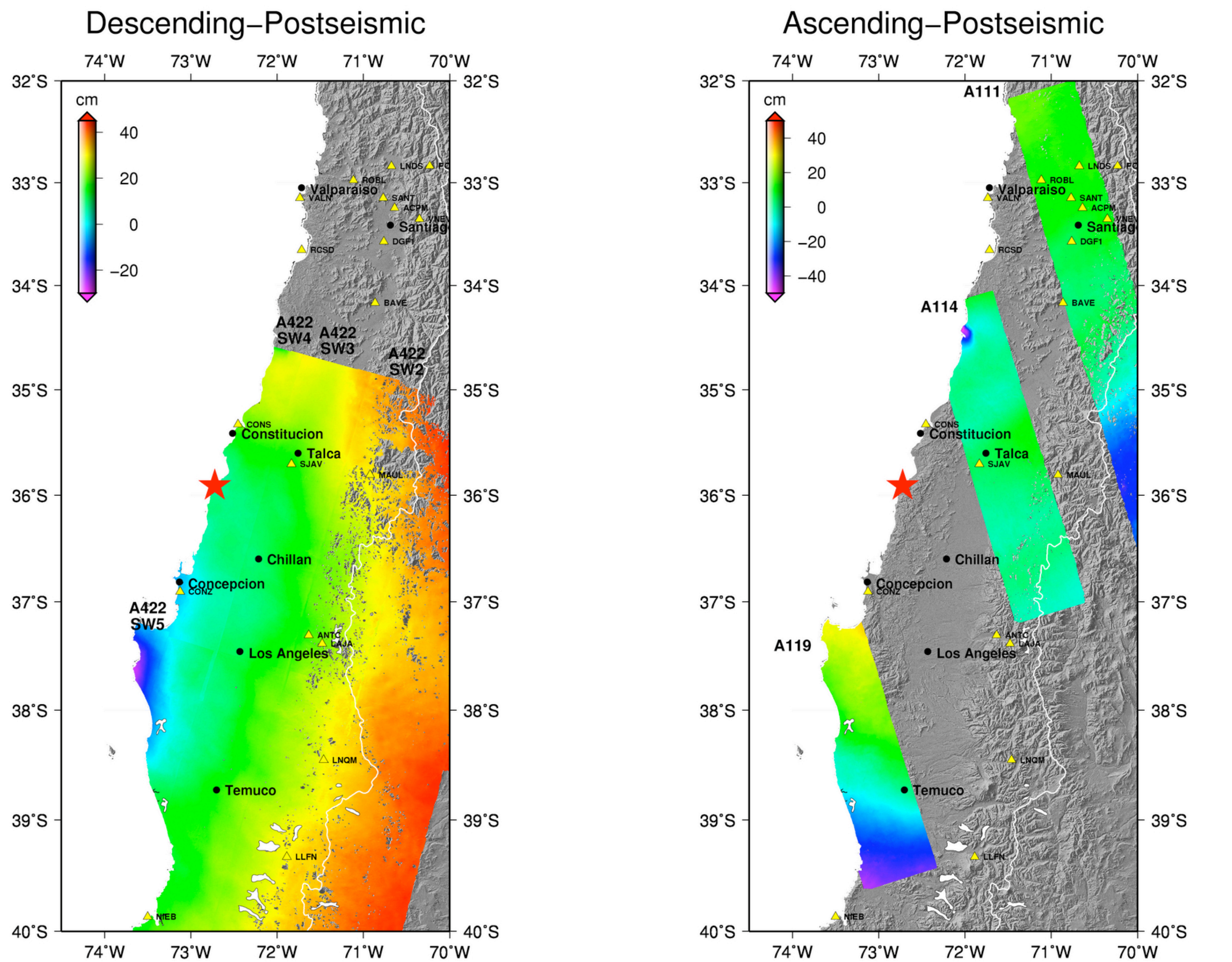


Figure from Ben Brooks



Descending–Postseismic
Ascending–Postseismic
cm
A422 SW4
A422 SW3
A422 SW2
A422 SW5
A111
A114
A119
Valparaiso
Santiago
Constitucion
Talca
Chillan
Concepcion
Los Angeles
Temuco
74°W
73°W
72°W
71°W
70°W
32°S
33°S
34°S
35°S
36°S
37°S
38°S
39°S
40°S

The Games We Normally Play

- Assume a fault geometry (the plate interface)
- Assume a mechanical model (elastic structure)
- Gather observations of surface deformation (GPS, leveling, InSAR, corals,…) and seismology
- Invert for best-fit “coupling” model => backslip

Minimize $\Phi(m) = ||G(m)-d|| + \lambda||F(m)||$ with $m>b$

F(m): smoothness, size, compactness,…

λ: By cross-validation or pseudo-Bayesian

Definitely, non-Tarantolian

A full Bayesian approach to slip modeling

- Many kinds of optimization techniques
  - Optimization only yields one solution
  - Different choices of regularization can lead to very different solutions for the same earthquake

- Determine family of acceptable models which fit data
  - Allows physical priors
  - Allows cascading of a posteriori: (a) geodetic data, (b) seismic data
  - Take advantage of embarrassingly parallel MCMC techniques
  - Limited by the "*Curse of Dimensionality*" and speed of forward model

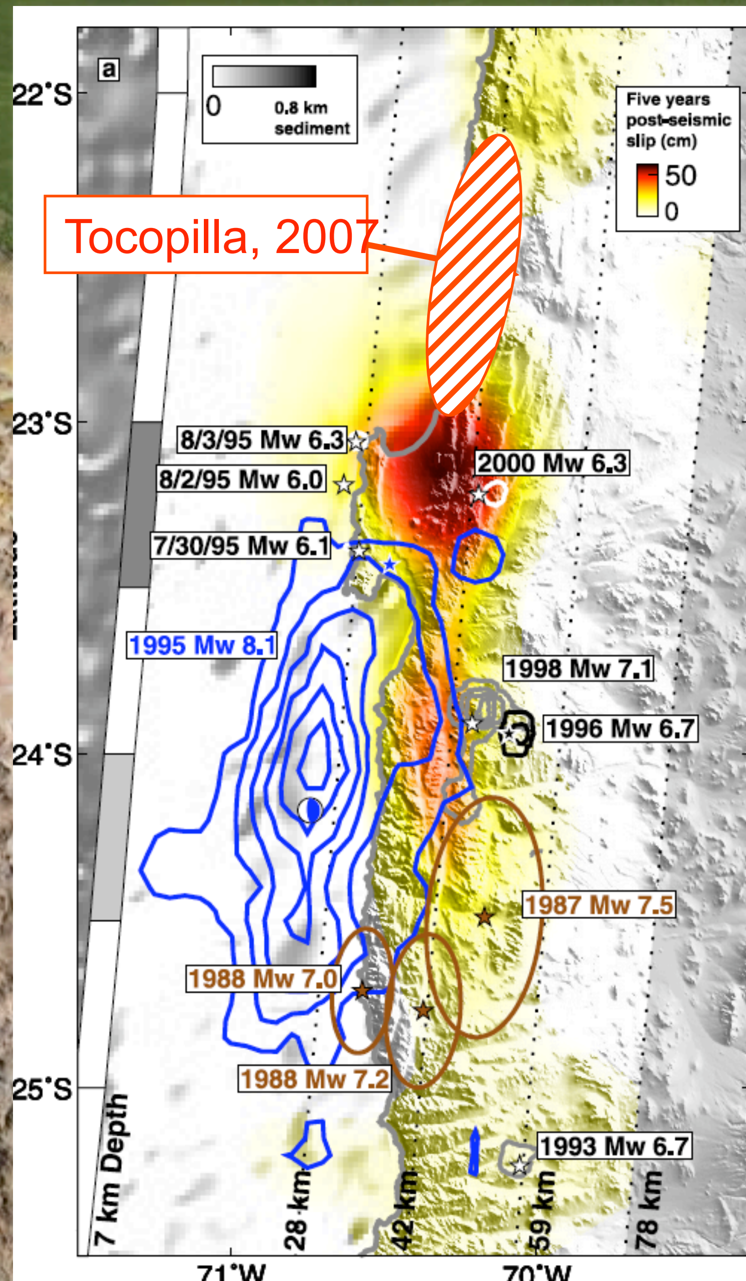
Francisco Hernán Ortega Culaciati (Interseismic) and Sarah Minson (coseismic)

Cascaded Adaptive Transitional MCMC In Parallel (CATMIP)

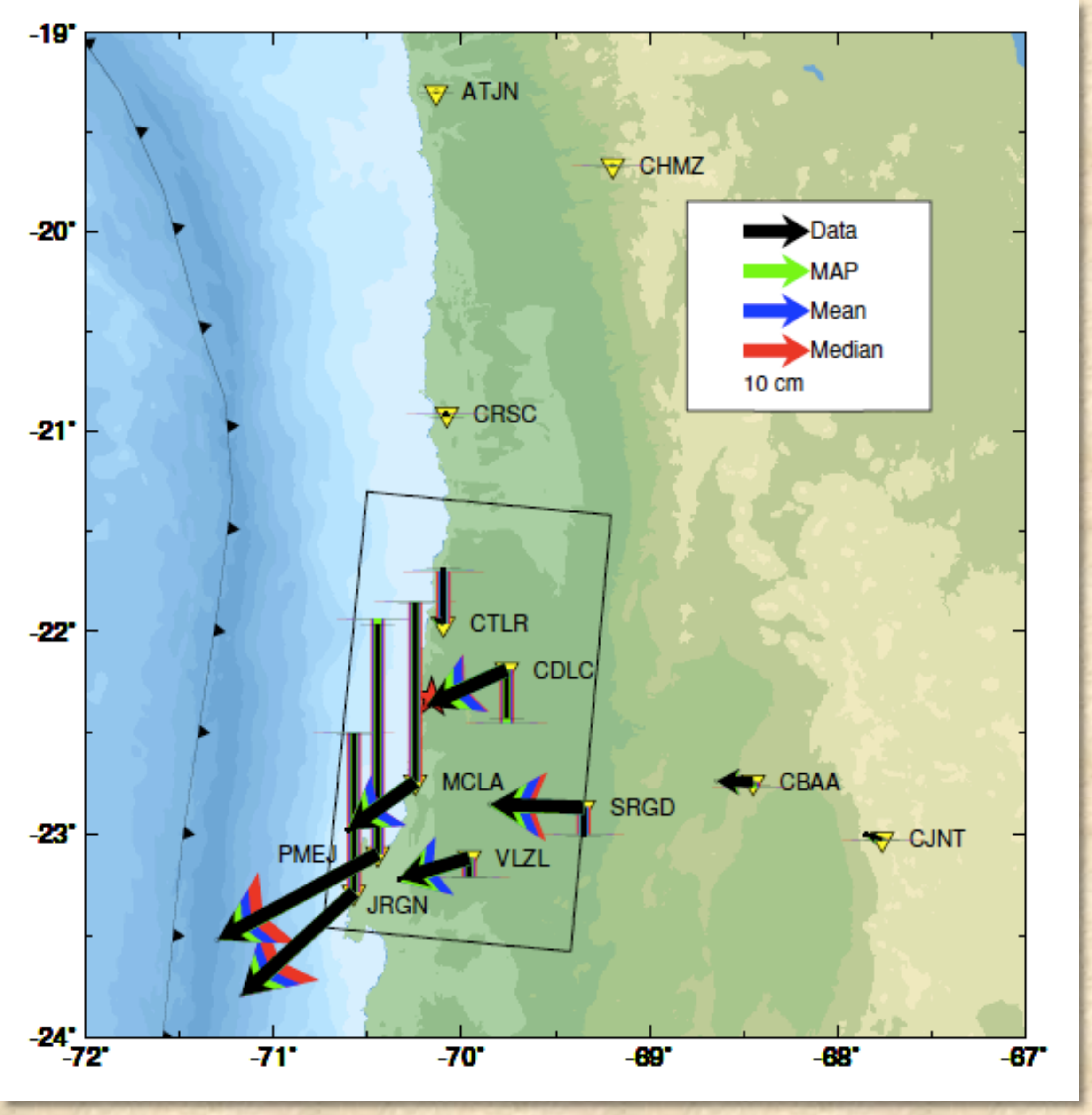
- A posteriori PDF is "tempered" or "annealed" so that we are always near equilibrium with our target PDF
  - $\mathbf{F_m(\theta) \propto p(D|\theta)^{\beta m}\, p(\theta)}$
- Not optimization (e.g., simulated annealing) – we get full a posteriori PDF.
- Many parallel Metropolis walkers - runs on O(1e3) cores
  - Information gained by ALL walkers is shared at each cooling step
  - Takes advantage of adapting model covariances in sampling
  - Insensitive to trade-offs between model parameters

A Bayesian approach to coseismic fault slip modeling (static and kinematic)

Example: N. Chile



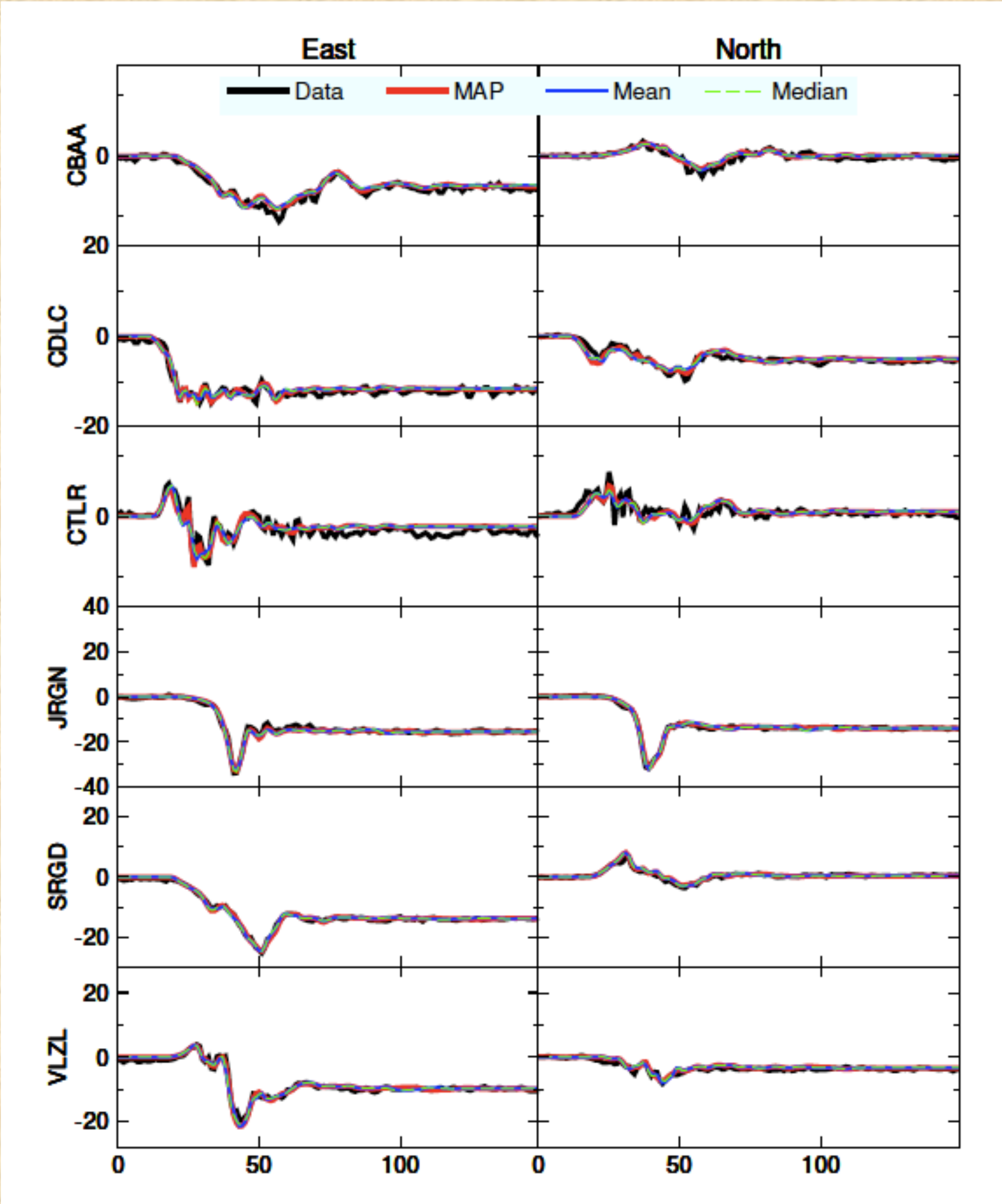
Pritchard & Simons, 2006



Coseismic displacements

Note:
Coastal uplift

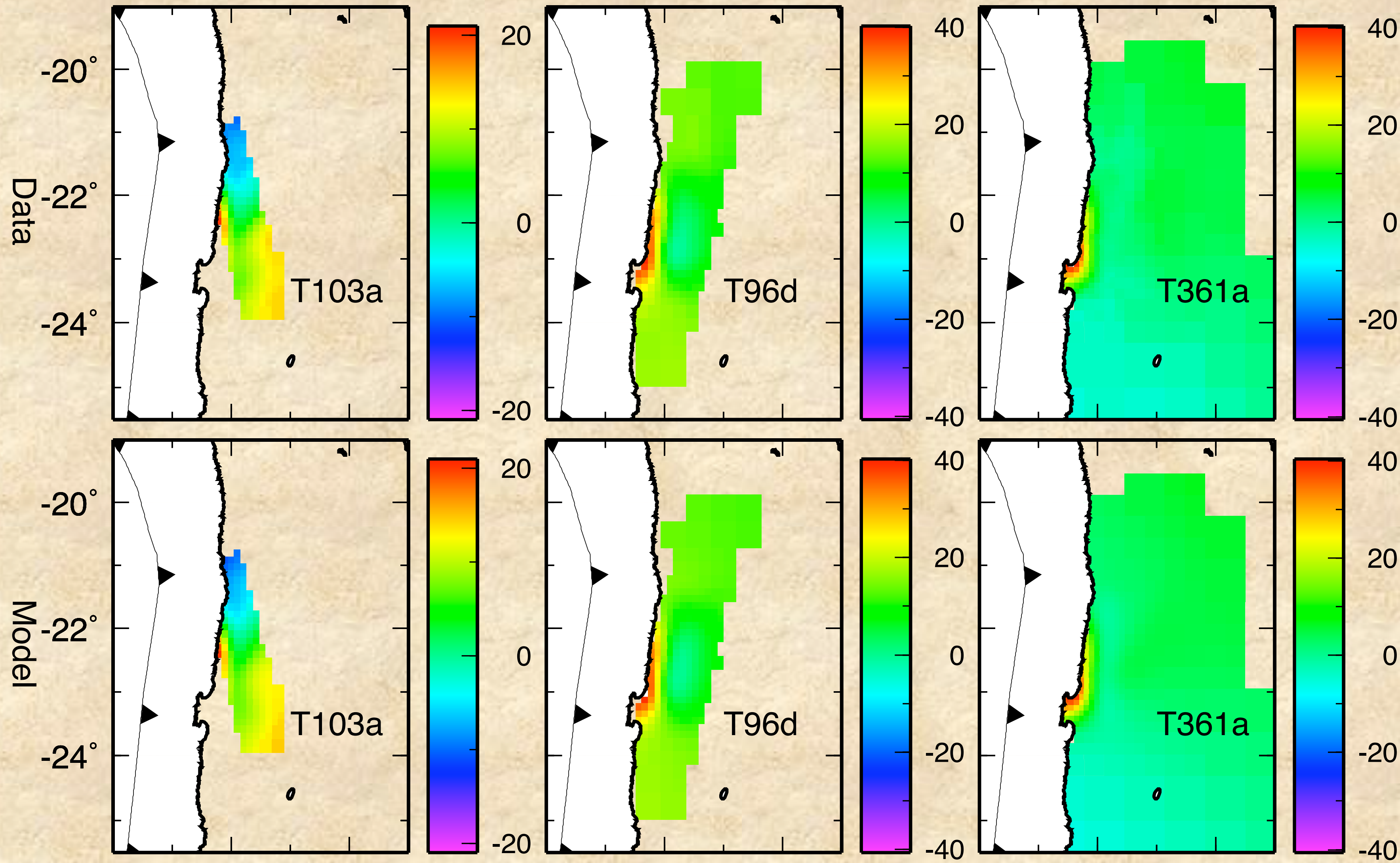
GPS:
5 samples/sec



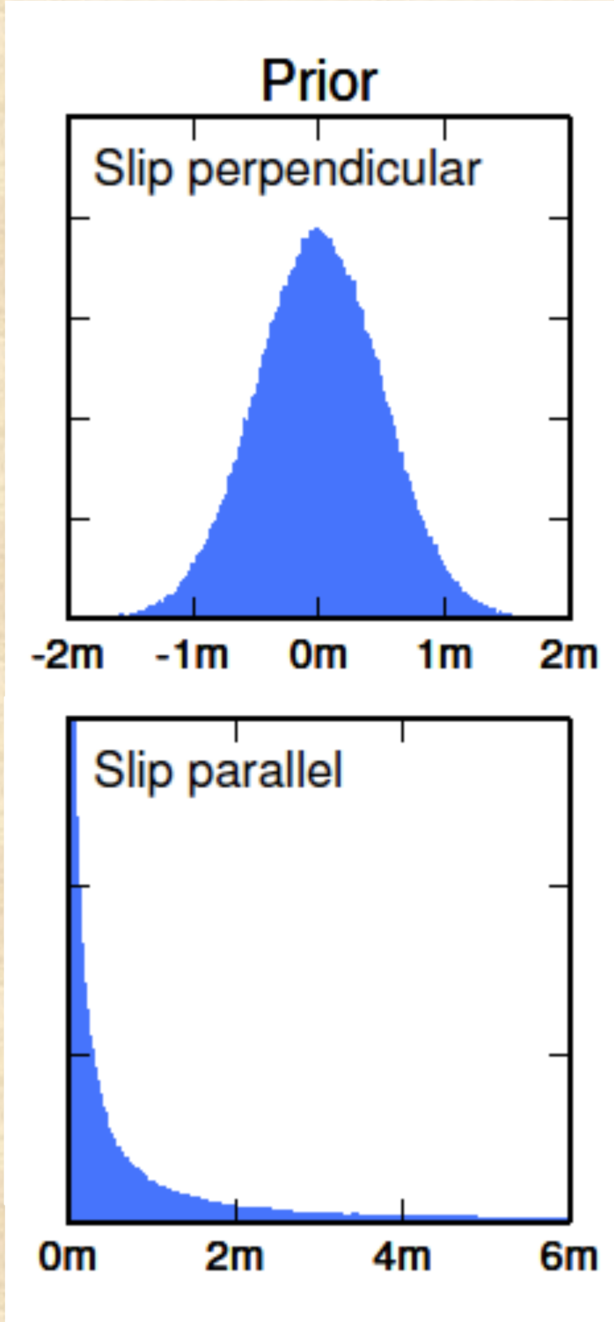
High rate GPS

InSAR (a subset)

ALOS - Asc/Dsc
Envisat - Dsc WS

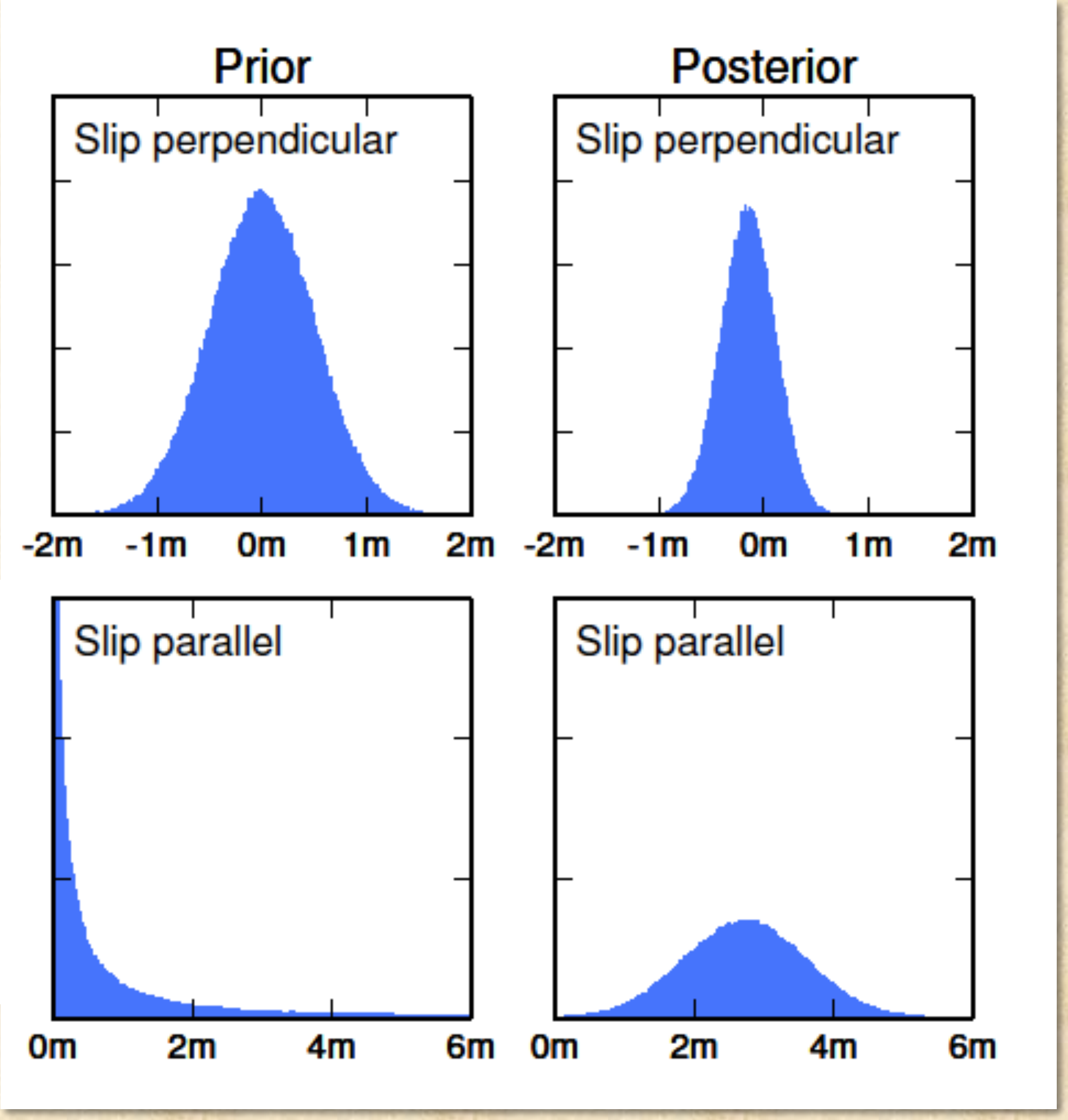


View of one of the fault patches



Dirichlet Distribution: Moment must add up to a target value

View of one of the fault patches

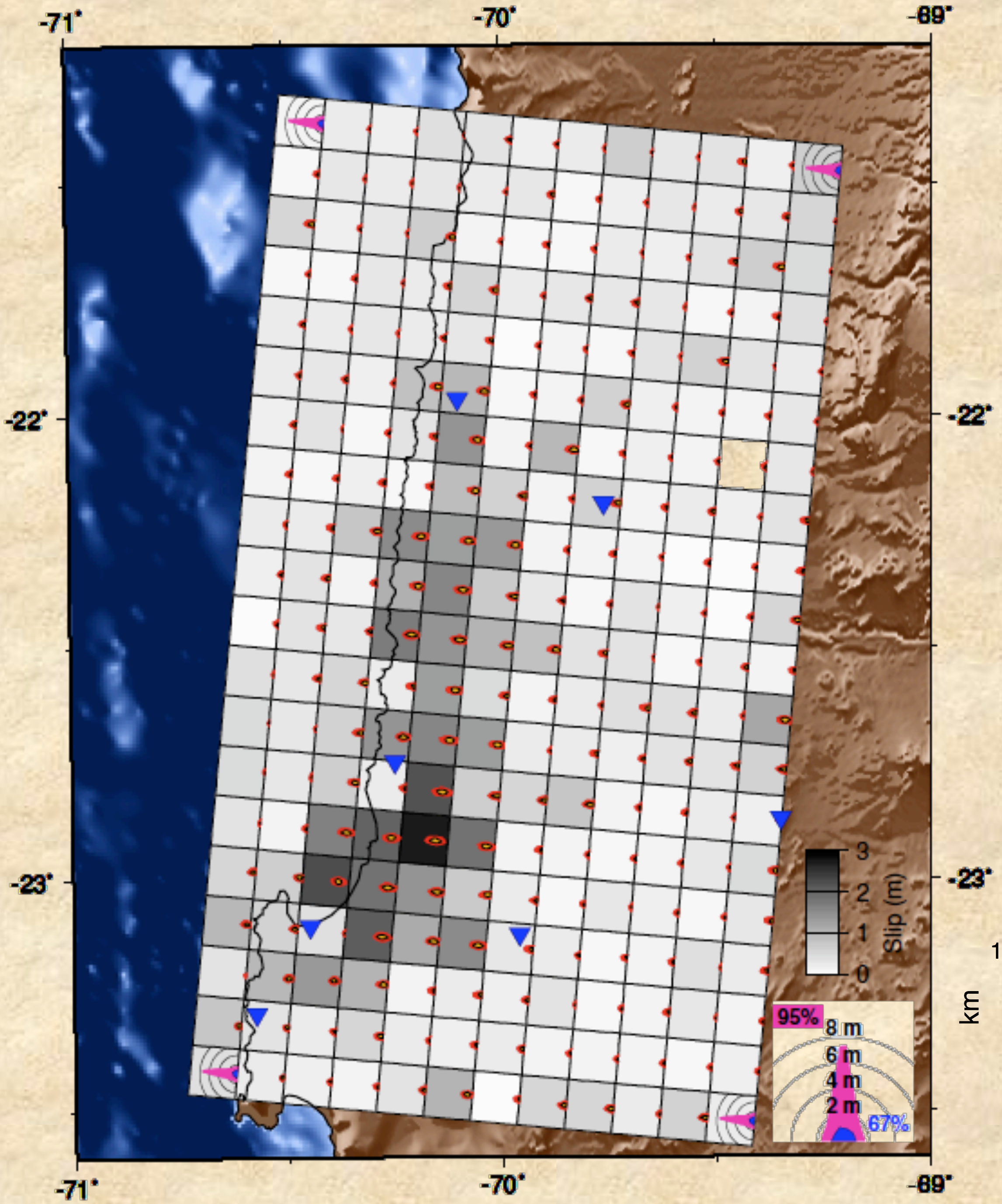


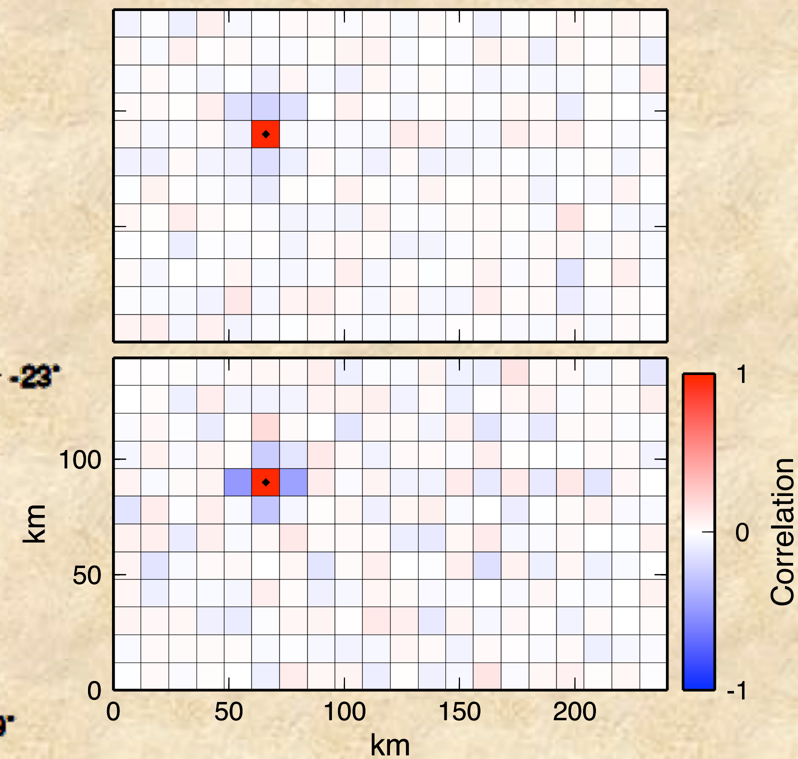
Full Bayesian approach
~ 500 parameters

CATMIP

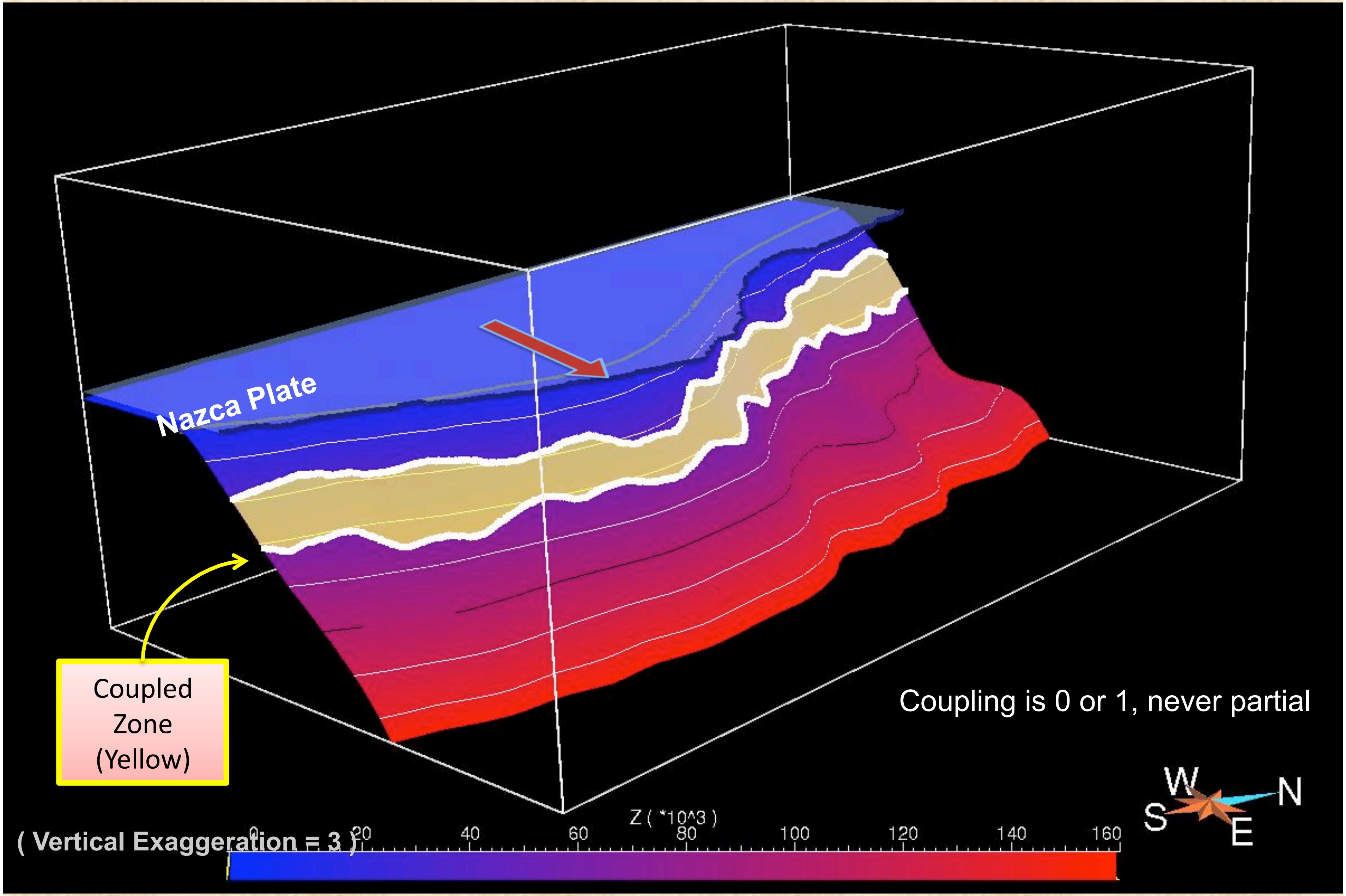
Priors on rake and moment

A posteori correlation:
“true” resolution



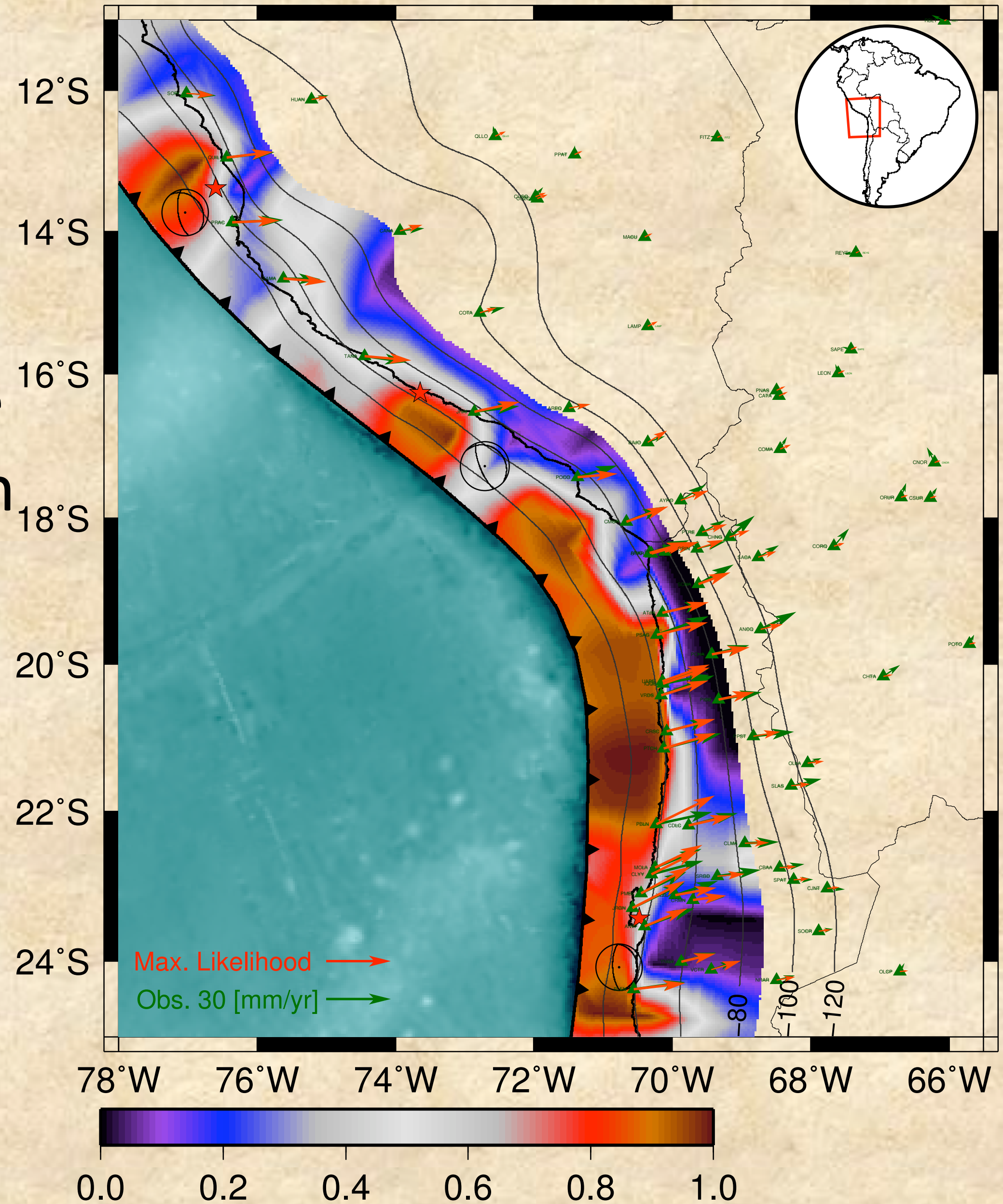


Interseismic back slip models: Model Parameterization



Probability of 100% Apparent Coupling

Grey means no information beyond the prior – it does not mean partial coupling. This model has no partial coupling in it.



Conclusions

- Lots of new data to apply to big earthquake studies
  - Important to use all of it
- Maule coseismic slip
  - negligible up dip slip.
  - Similar to other events (e.g., Pisco and Nias).
  - Role of splay faults?
  - Peninsula region not well modeled.
  - Lots of afterslip.
  - More to come…
- Bayesian approaches to estimating parameters
  - no spatial smoothing required or desired!
  - Allows quantitative questions to be asked, e.g., what is the likelihood of coseismic and postseismic slip overlapping?
- Future: Rapid ingestion of geodetic data into EQ models
  - Take note today of the impact of geodetic data on fault models