Earthquake Source Dynamics and seismic radiation From large Chilean earthquakes

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PLAN

1. RECENT SEISMIC EVENTS IN CHILE
2. SPECTRAL PROPERTIES OF LARGE EARTHQUAKES
3. THE Mw 6.9 VALPARAISO EARTHQUAKE OF 24/04/2017
4. DYNAMIC INVERSION

The new Chilean earthquake network

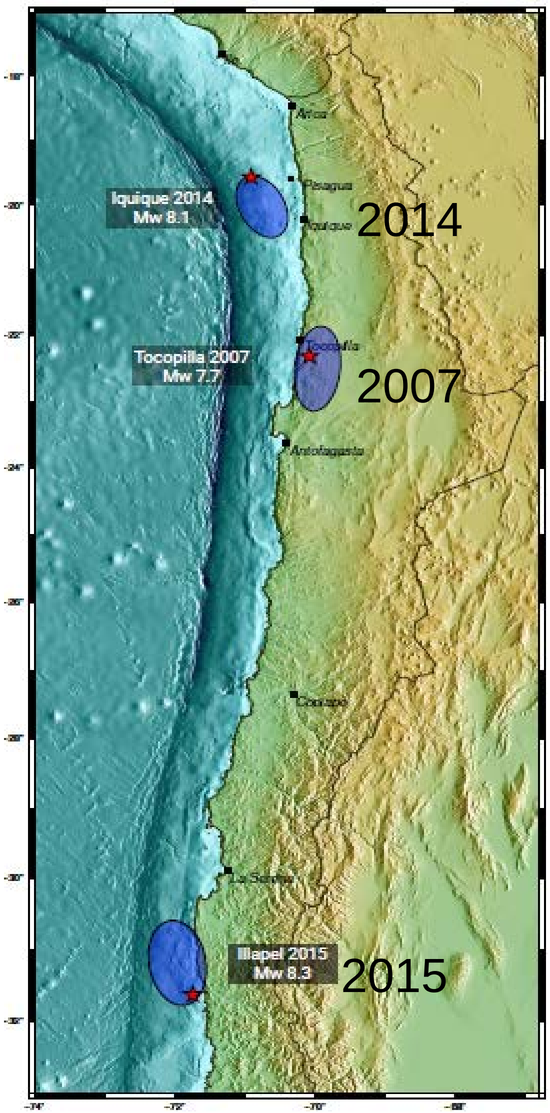
- 400 sites
- 200 STS2 or equivalent
- 200 GNSS
- 400 Guralp or Episensor accelerometers

http://evtdb.csn.uchile.cl

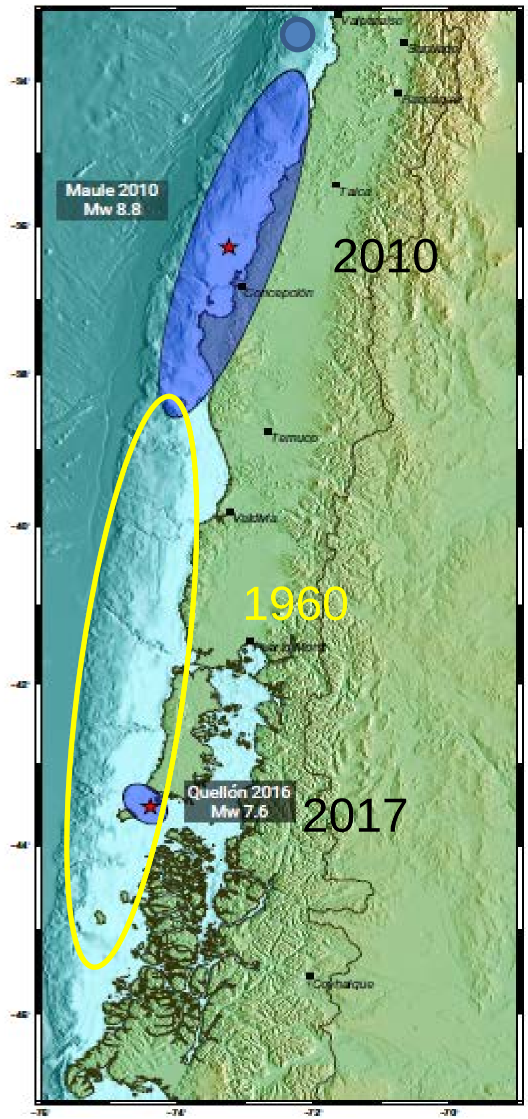
HOW TO MAKE PROGRESS WITH THIS NEW NETWORK

1. In Chile we want to understand large earthquakes in some detail
2. Use GNSS+ accelerograms together because BB seismograms saturate for large earthquakes
3. Precursors are everywhere (foreshocks, slow slip, gravity). How can we use them?
4. Large historical earthquakes were also preceded by foreshocks (1960, 1730)
5. How can we provide early tsunami warning

Chilean seismicity increased significantly in the last 10 years

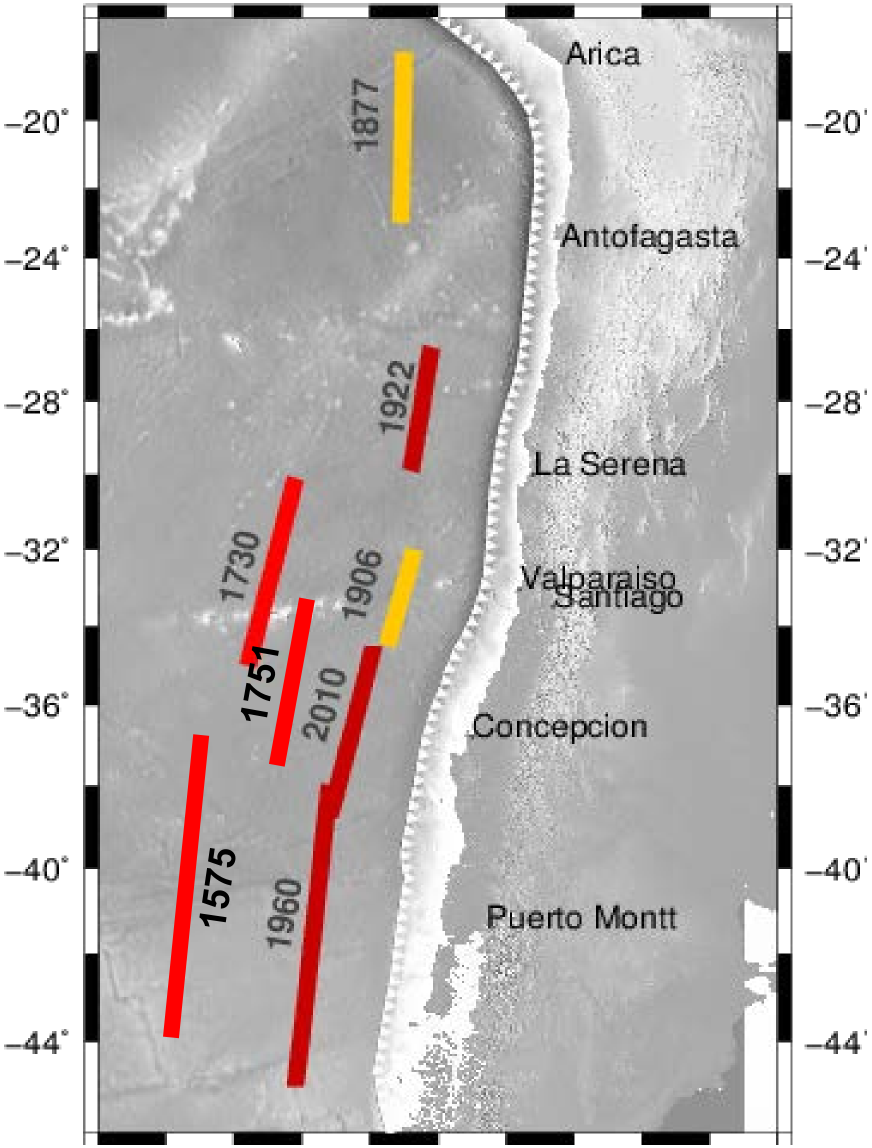


24 April 2017



Ruiz, Madariaga,
Tectonophysics 2018

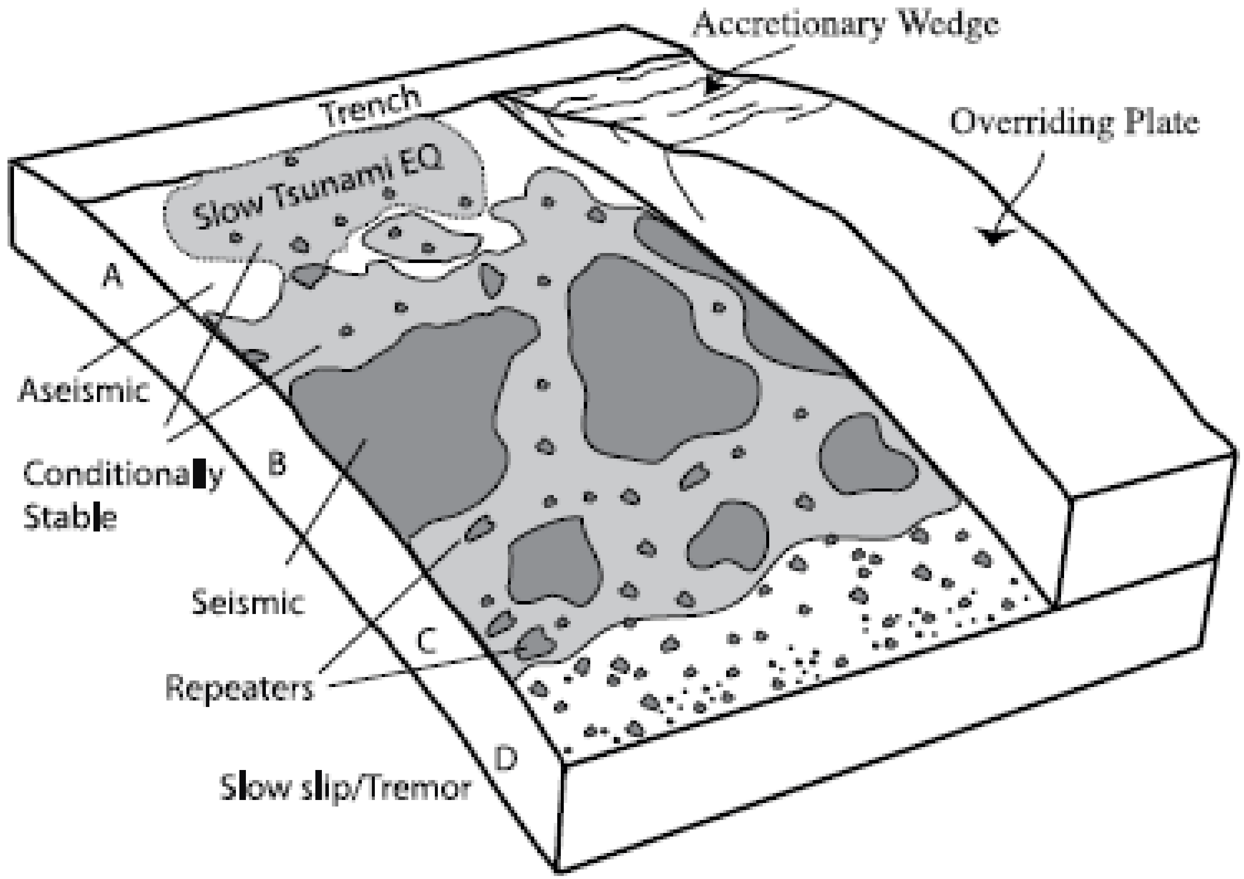
The history of huge earthquakesMw>8.6



Very large earthquakes of the last 450 years

Udias et al, BSSA 2012
M. Cisternas et al 2016-2018
Ruiz, Madariaga, 2018

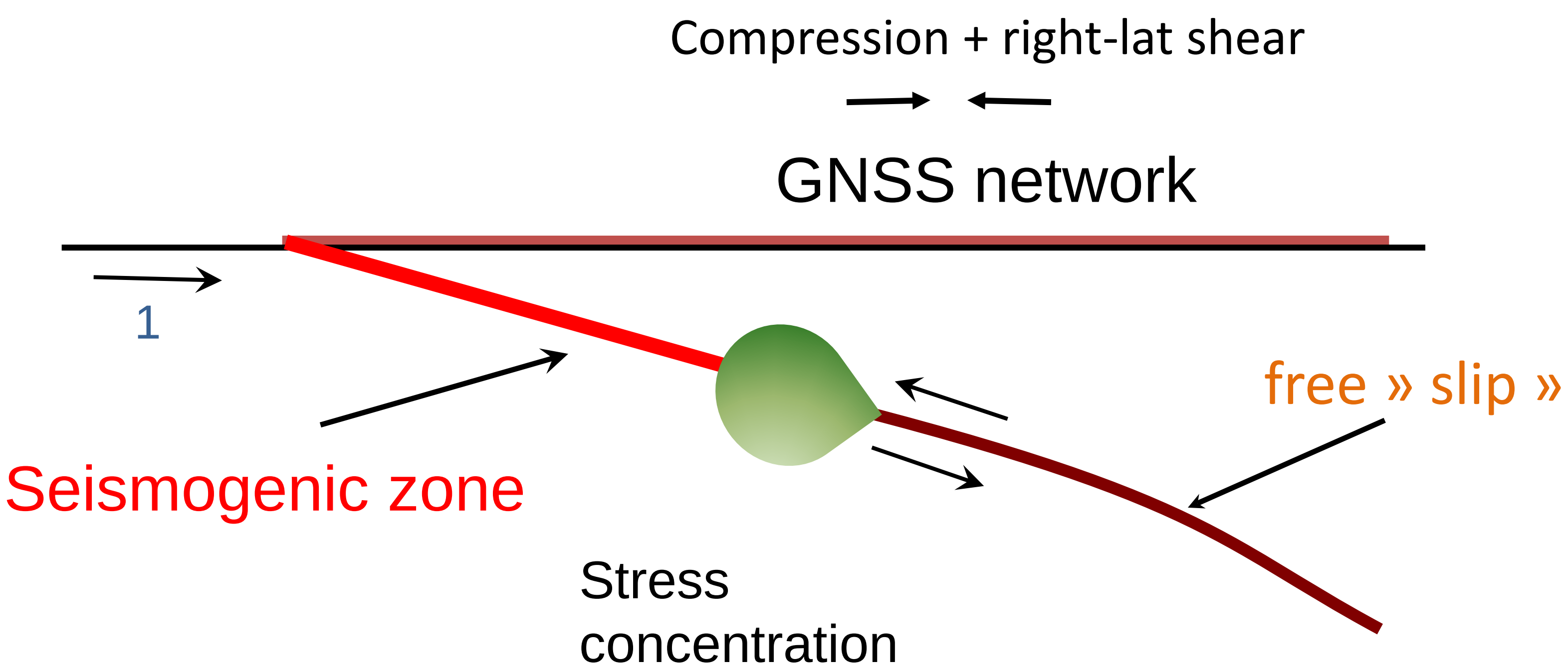
A simplified model of a subduction zone



After Lay et al, J. geophys. Res. 2012

Seismic coupling in a subduction zone

Classical Back slip model by Savage



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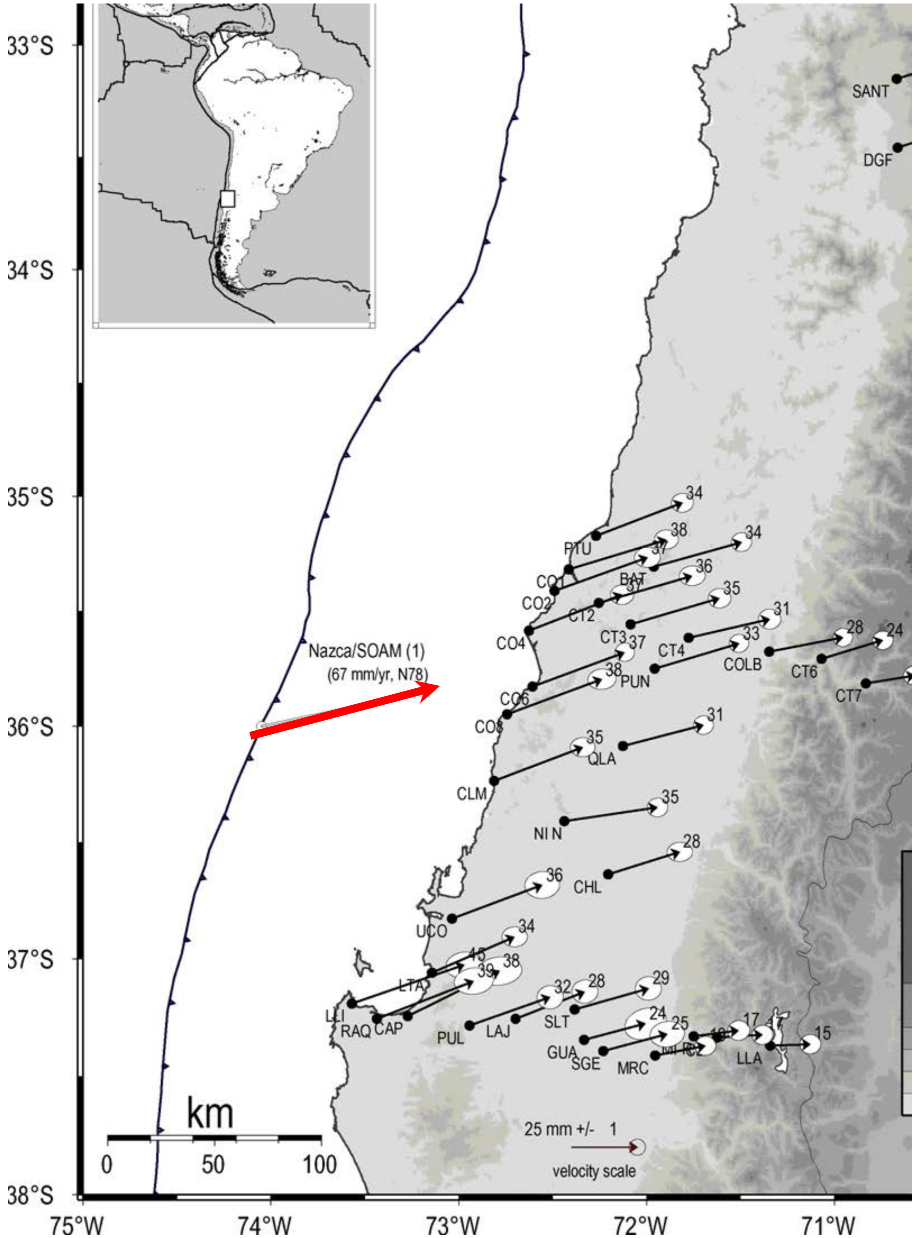
Deformation before the Maule earthquake 1998-2009



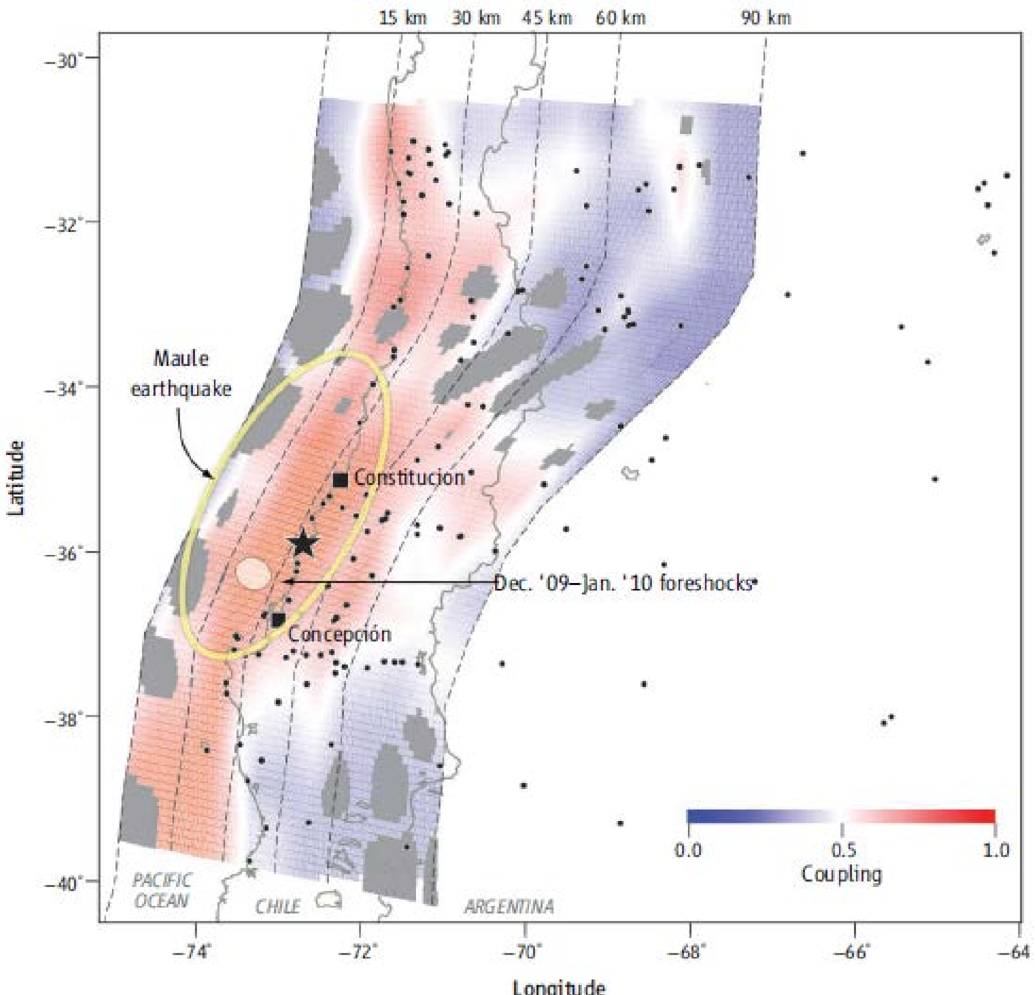
« We would then conclude that the southern part of the Concepción–Constitución
gap has accumulated a slip deficit that is large enough to produce a very large earthquake of about Mw= 8.0–8.5. »

This is of course a worst case scenario that needs to be refined by additional work.

Please note left-hand rotation

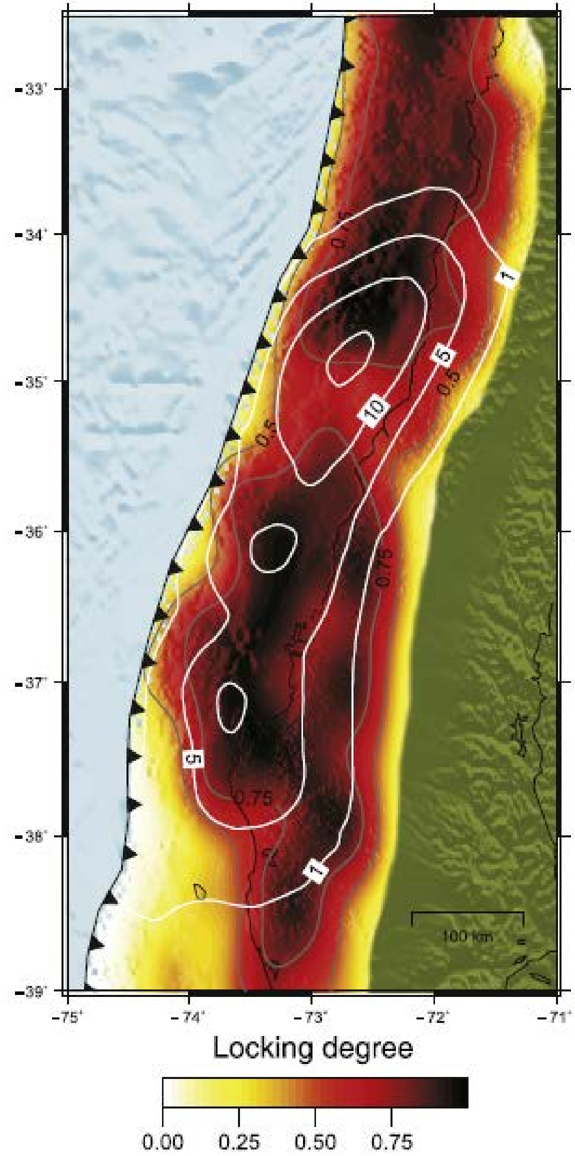
(Campos, Ruegg, Vigny, R.M. et al, 2002, 2003, 2009)

Coupling of the plates before the Maule earthquake.



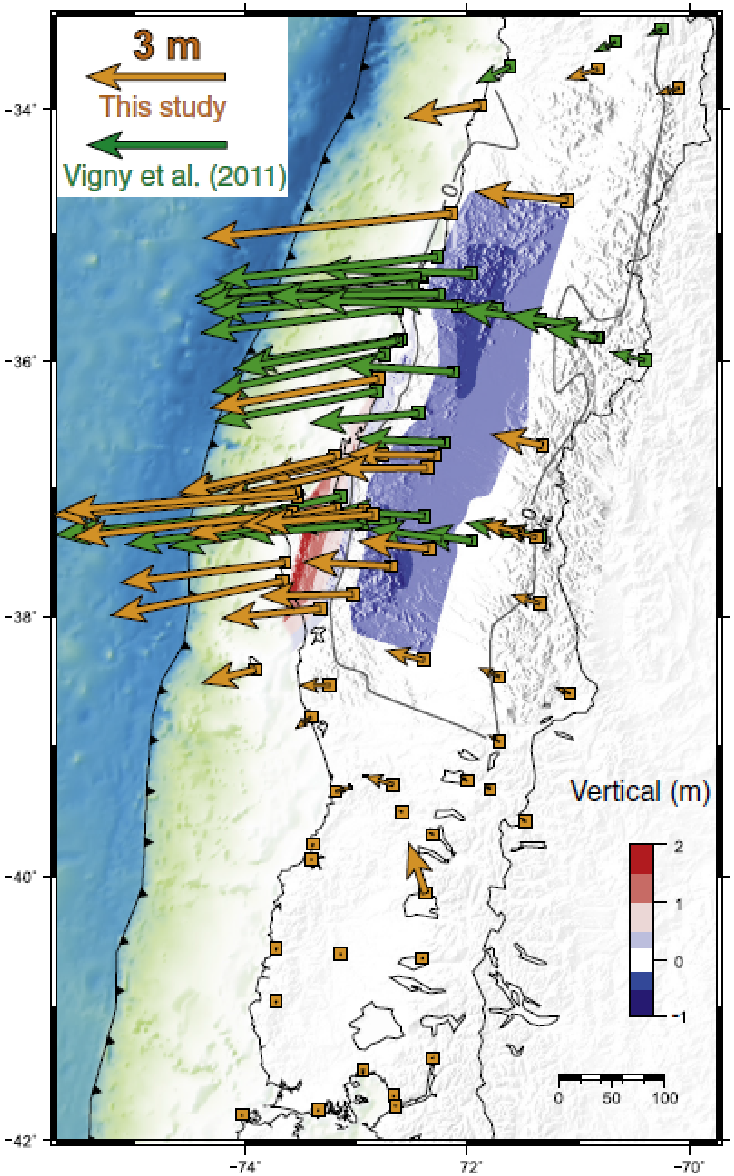
M. Métois

Madariaga et al, Science, 2010



Moreno et al, 2012

At the time of the Maule earthquake Chile jumps into the sea



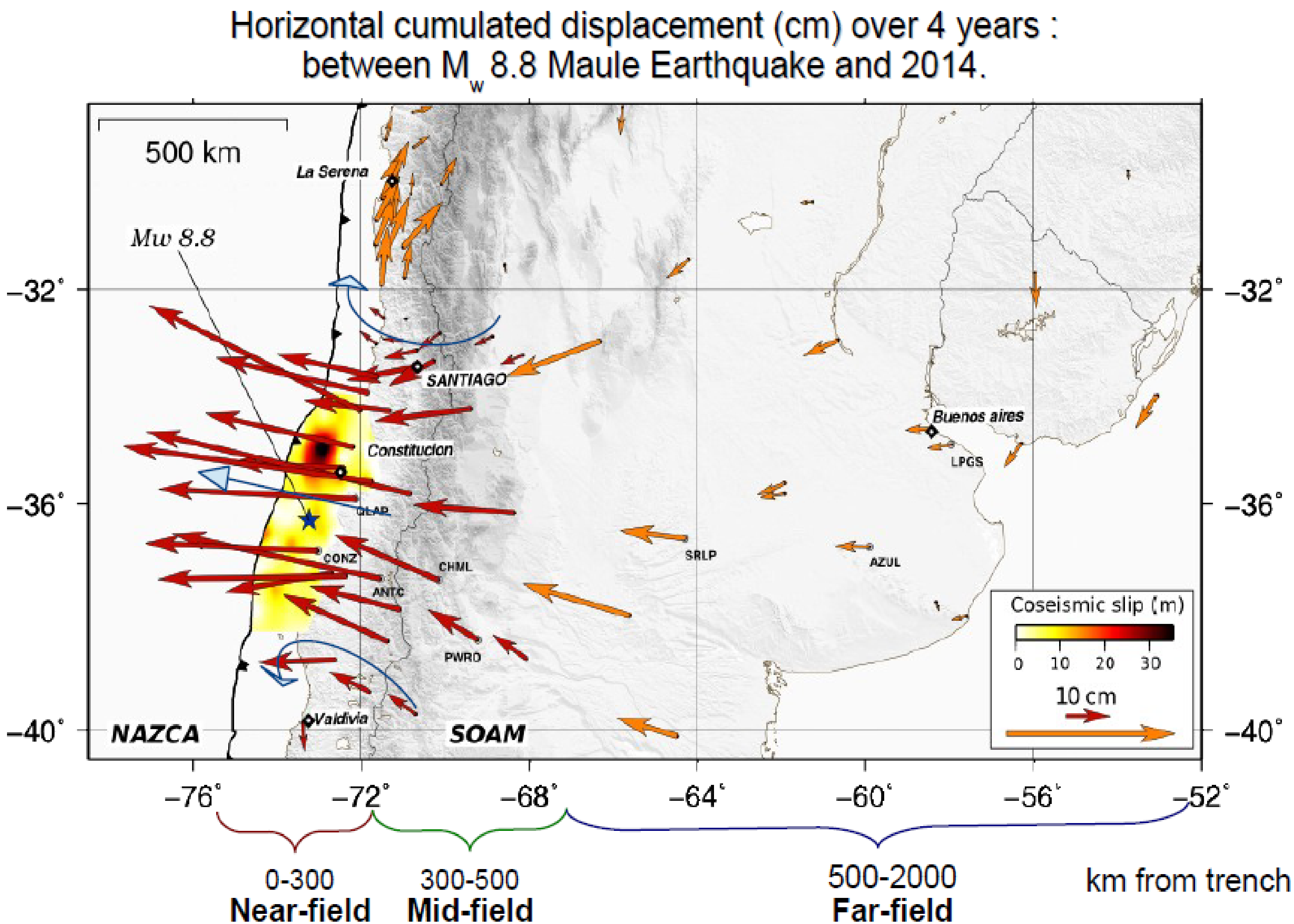
The coast moves up, specially
The Arauco peninsula

And the Central valley sinks

Please note the right hand rotation of flow lines

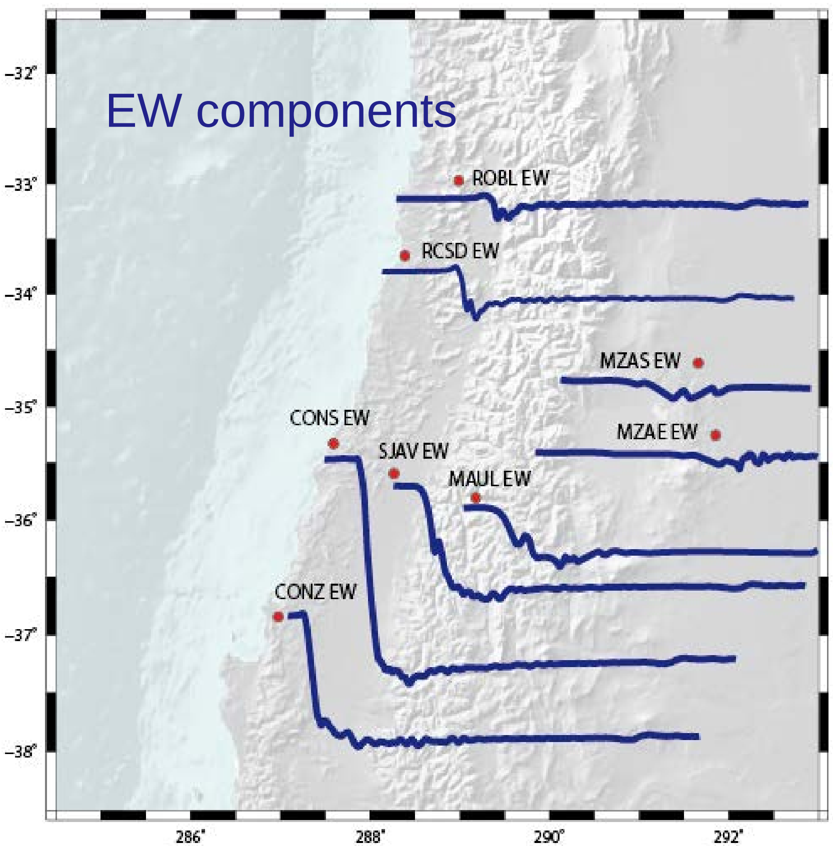
Moreno et al, EPSL 2012

Postseismic deformation after Maule

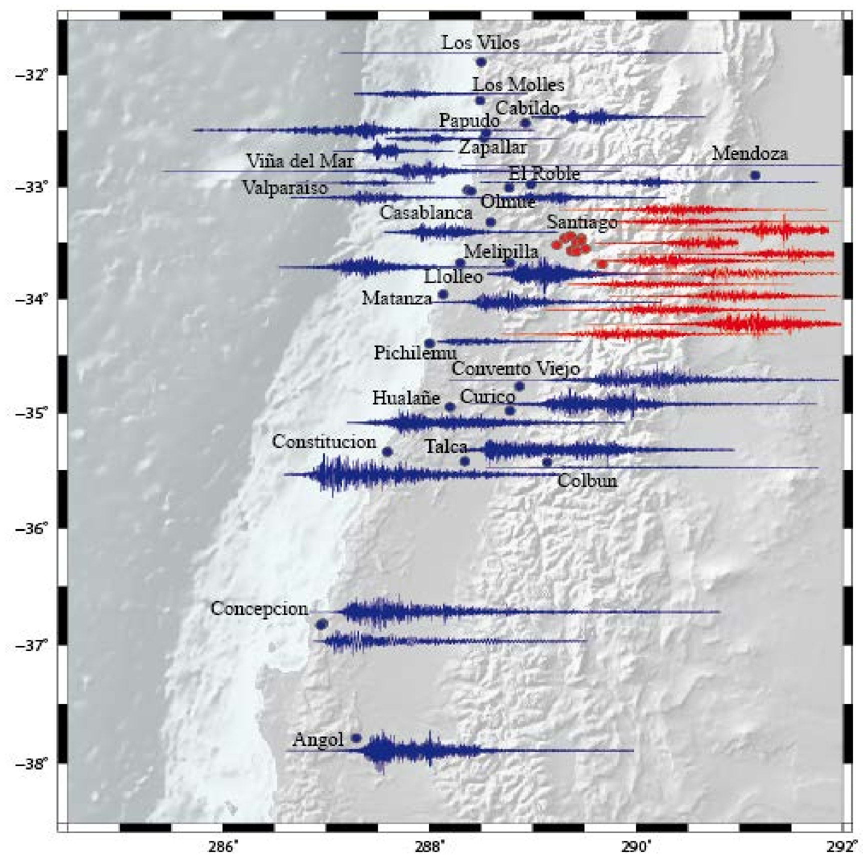


E. Klein et al, 2015, Ruiz et al, 2015

Low Frequency - High Frequency
cGPS (0 - 0.5 Hz) - Strong Motion (0.01 - 25 Hz)



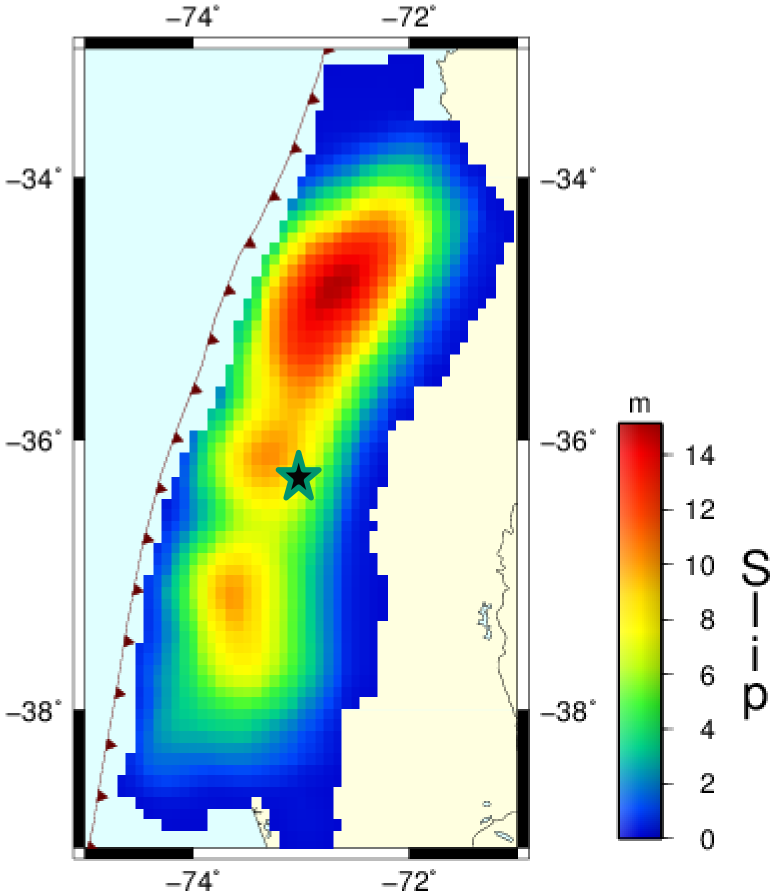
cGPS



Strong Motion

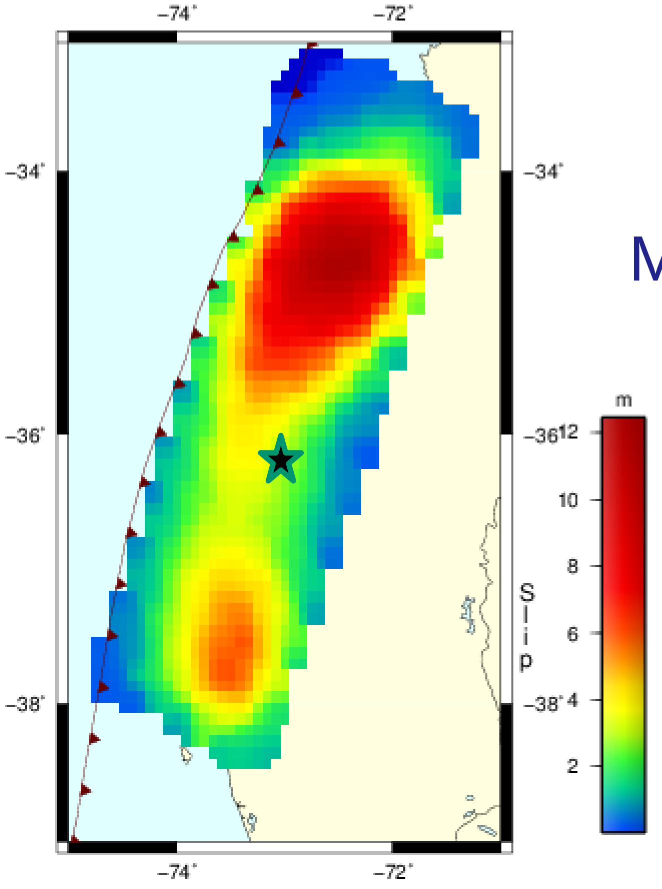
Maule 2010: Static and dynamic GPS

Slip from static GPS



Moreno et al (EPSL, 2012)

Inversion using cGPS
as farfield seismograms



Mw = 8.8

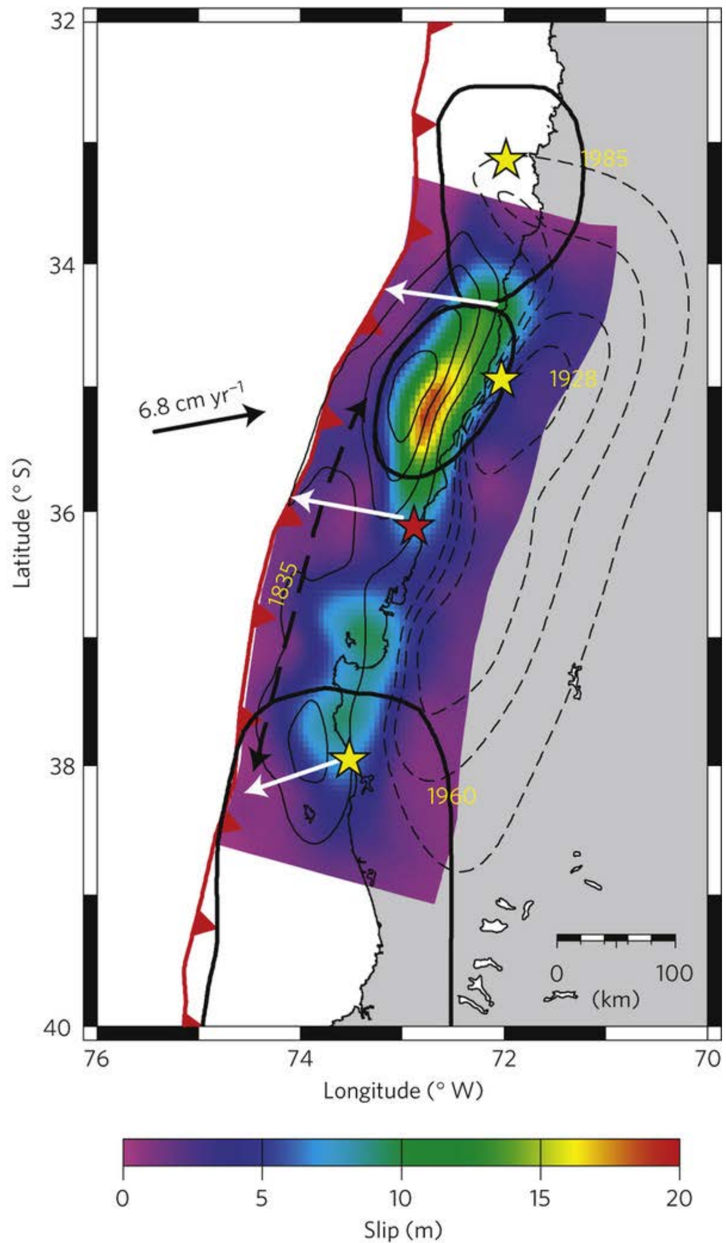
Pro, Bufon, Madariaga (EGU 2013)

The tsunami problem

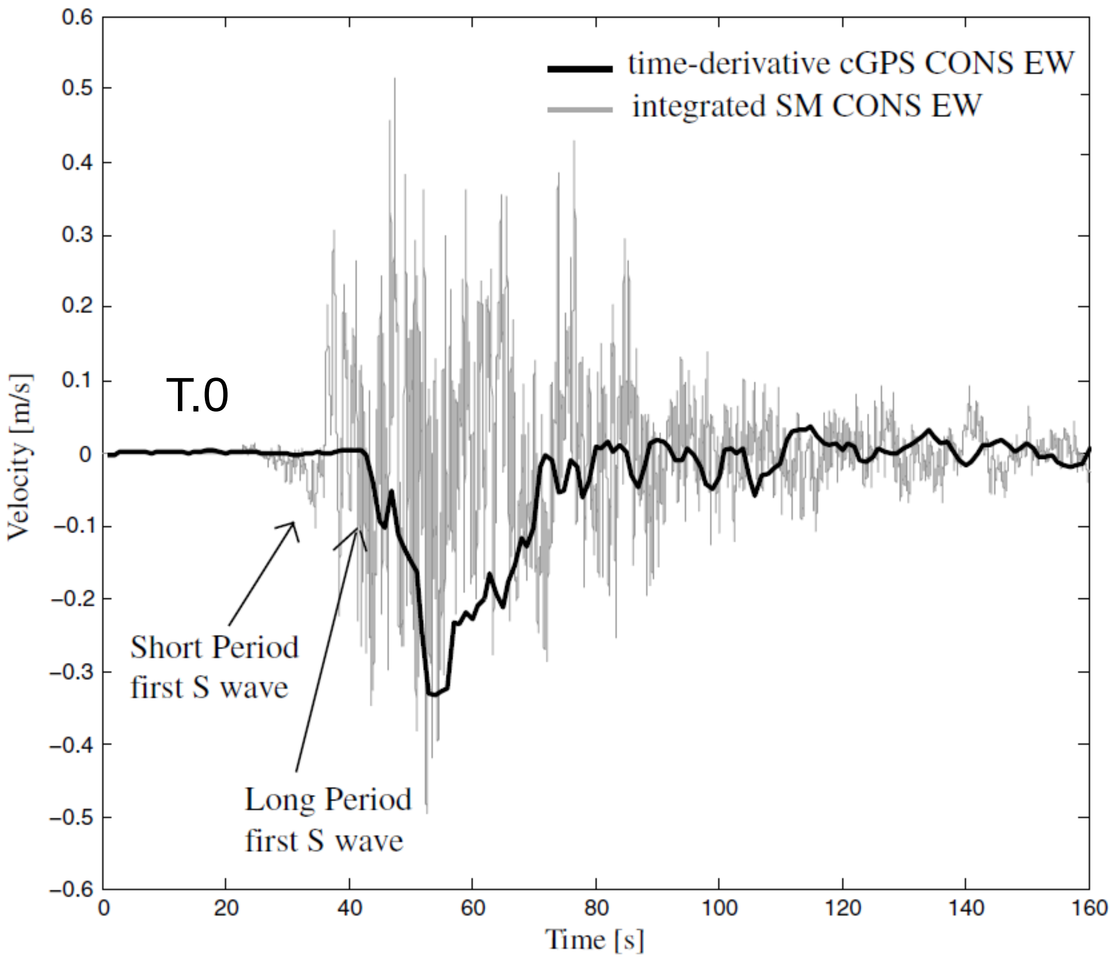
Phase velocity of the 20-30 min
Tsunami waves was underestimated
In classical shallow water models

Corrected by

Tsai et al (2013)
Watada et al (2014)
Allgeyer Cullins (2014)



Concepción GPS and Accelerometer



Unfortunately,
Accelerogram does not
Have reference time

Yoffe – Heaton pulse
in Mode II

Duration T = 30 s

Rupture front width= 105 km

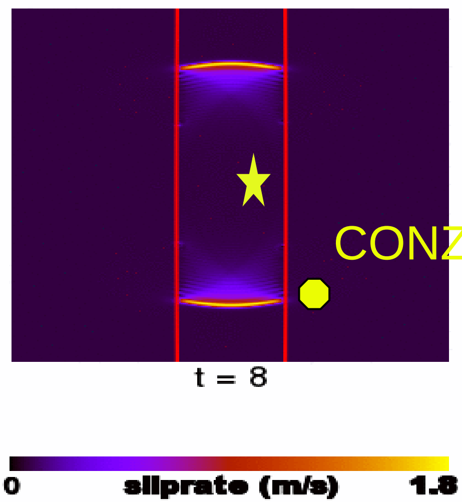
Slip = 4 m

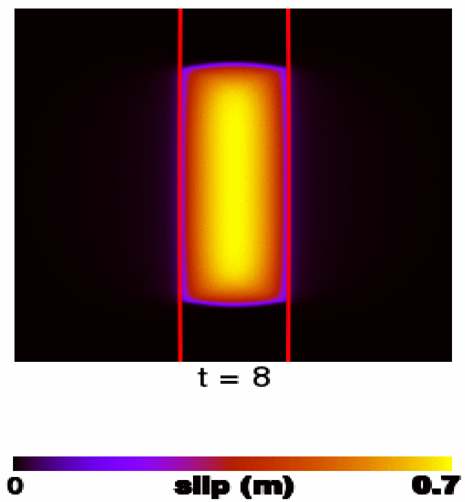
Stress drop 16 MPa

Ruiz et al., Earthquake spectra, 2012

Maule earthquake as a propagating crack

Slip rate



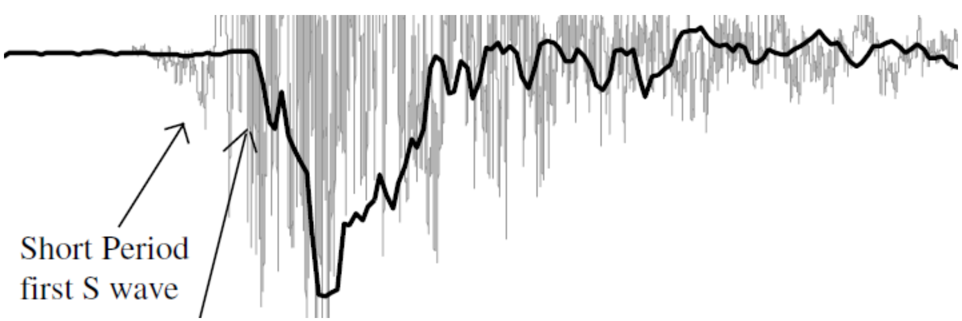


slip

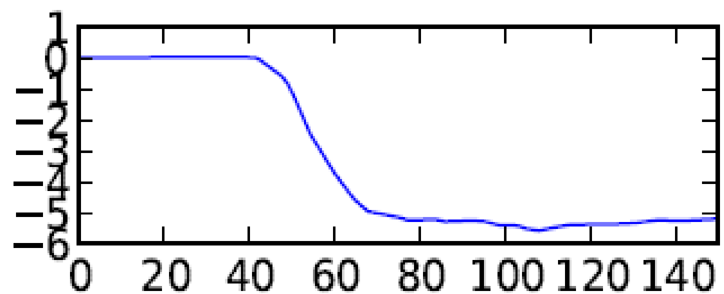
CONS

EW

Velocity

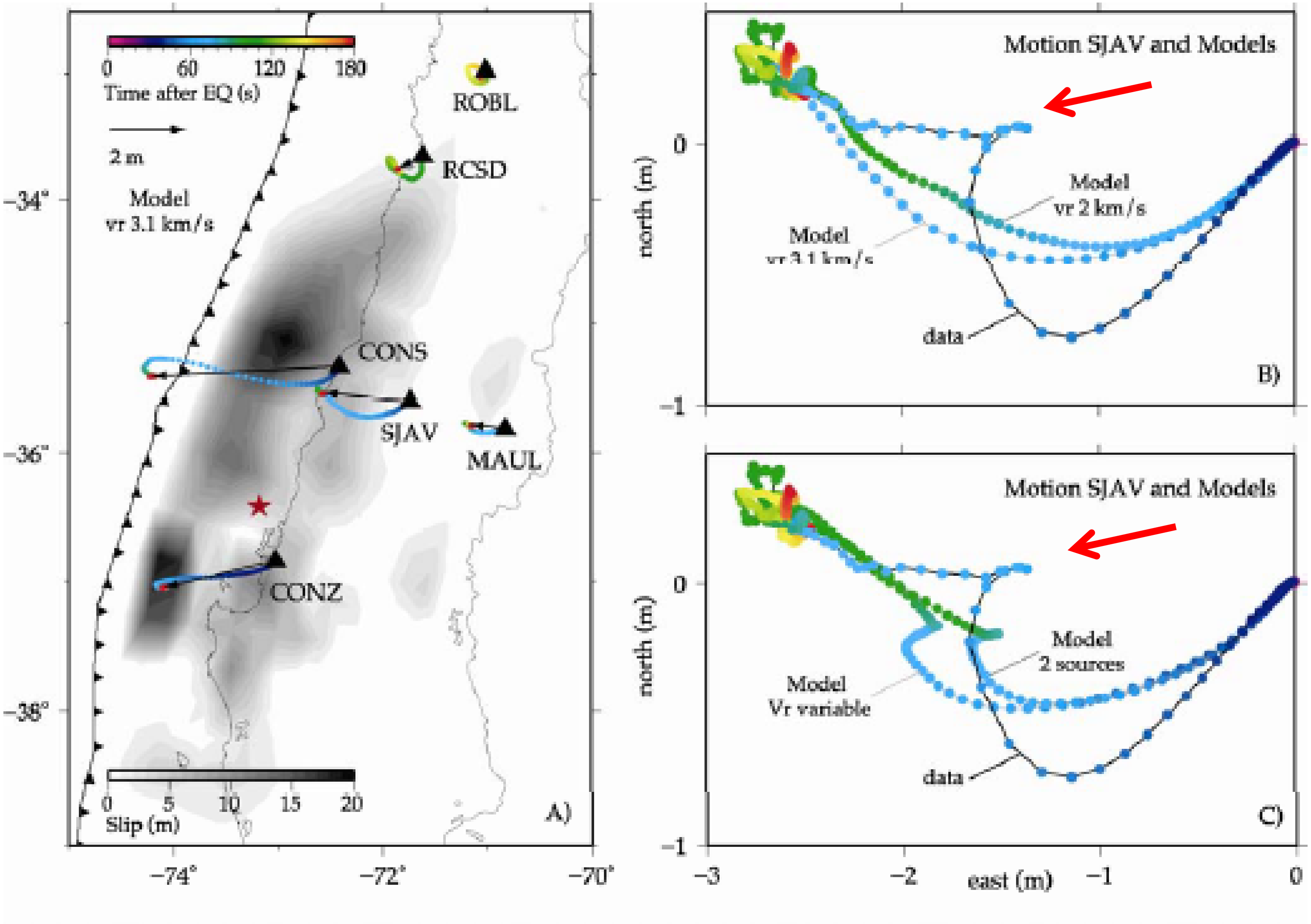


Displacement



Madariaga, AGU 2011

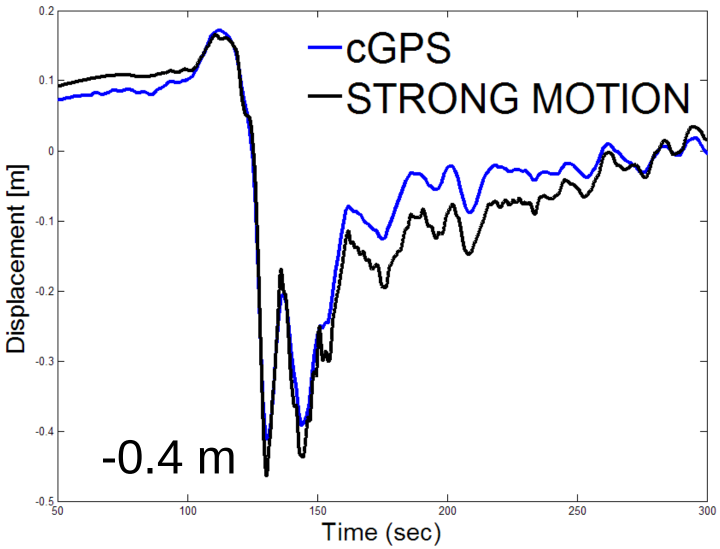
Particle motion at cGPS stations



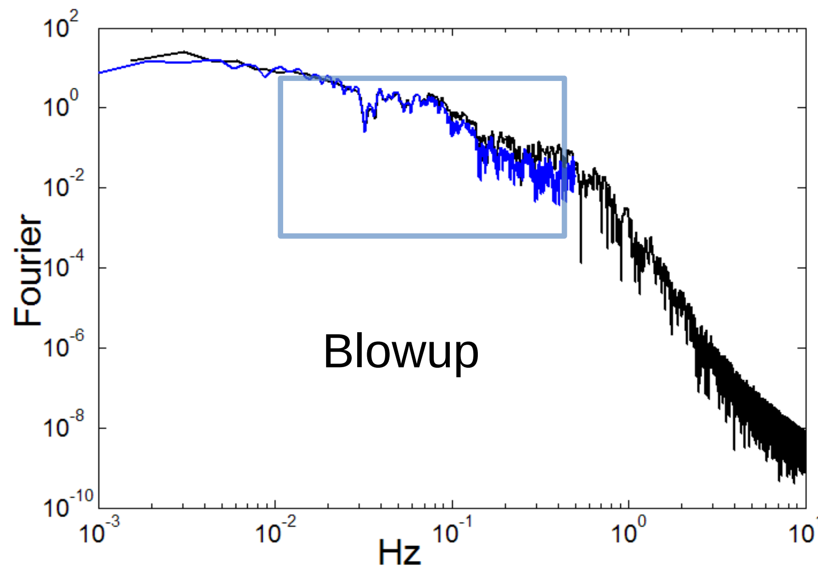
From Peyrat, Soquet 2011

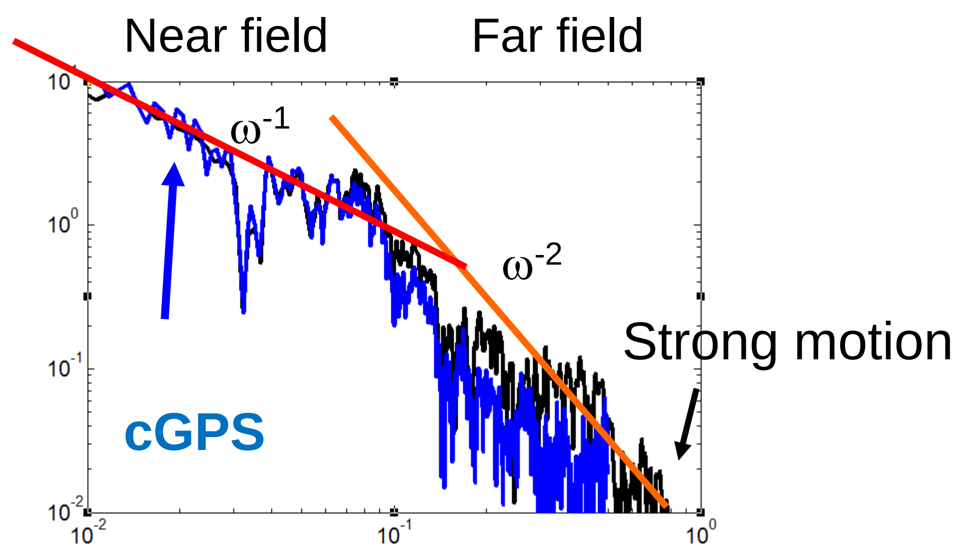
Modern instruments: motograms (cGPS) and accelerograms

El Roble (50 km from Santiago)



From Lancieri and Ruiz





Spectral cross over band

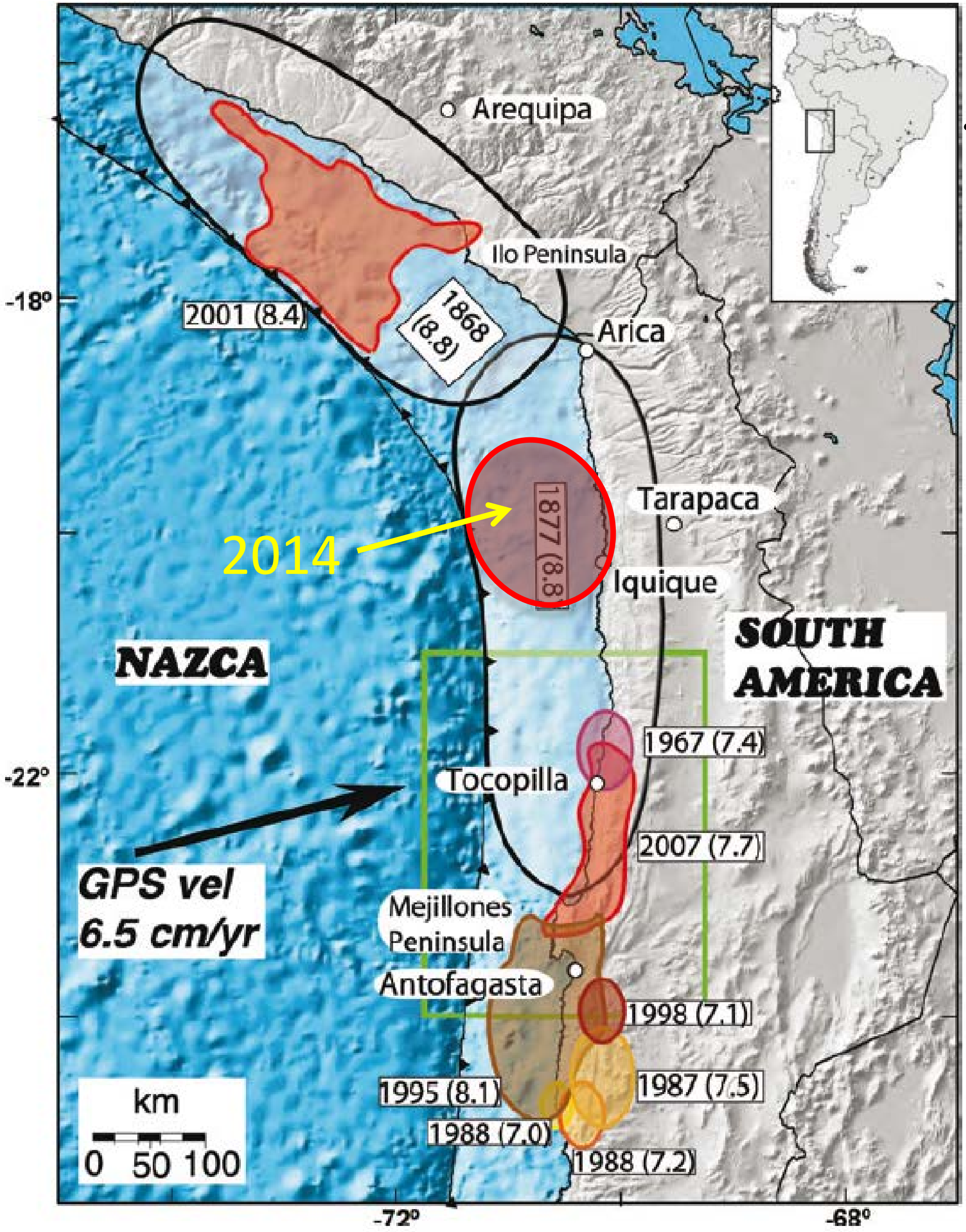
0.01 - 0.5 Hz

Actually

0.03 - 0.16 Hz

IQUIQUE 2014

A major slow slip event lasting up to 10 years preceeded the main event



The Northern Chile gap

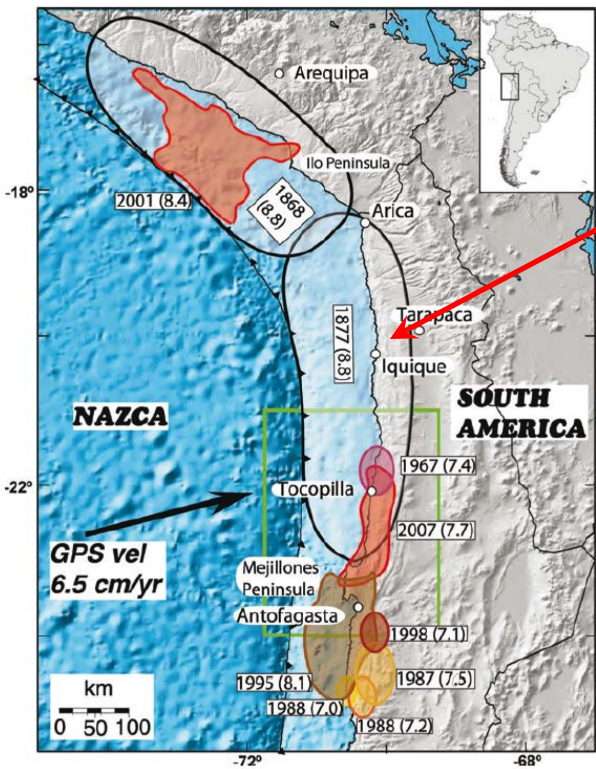
1877-

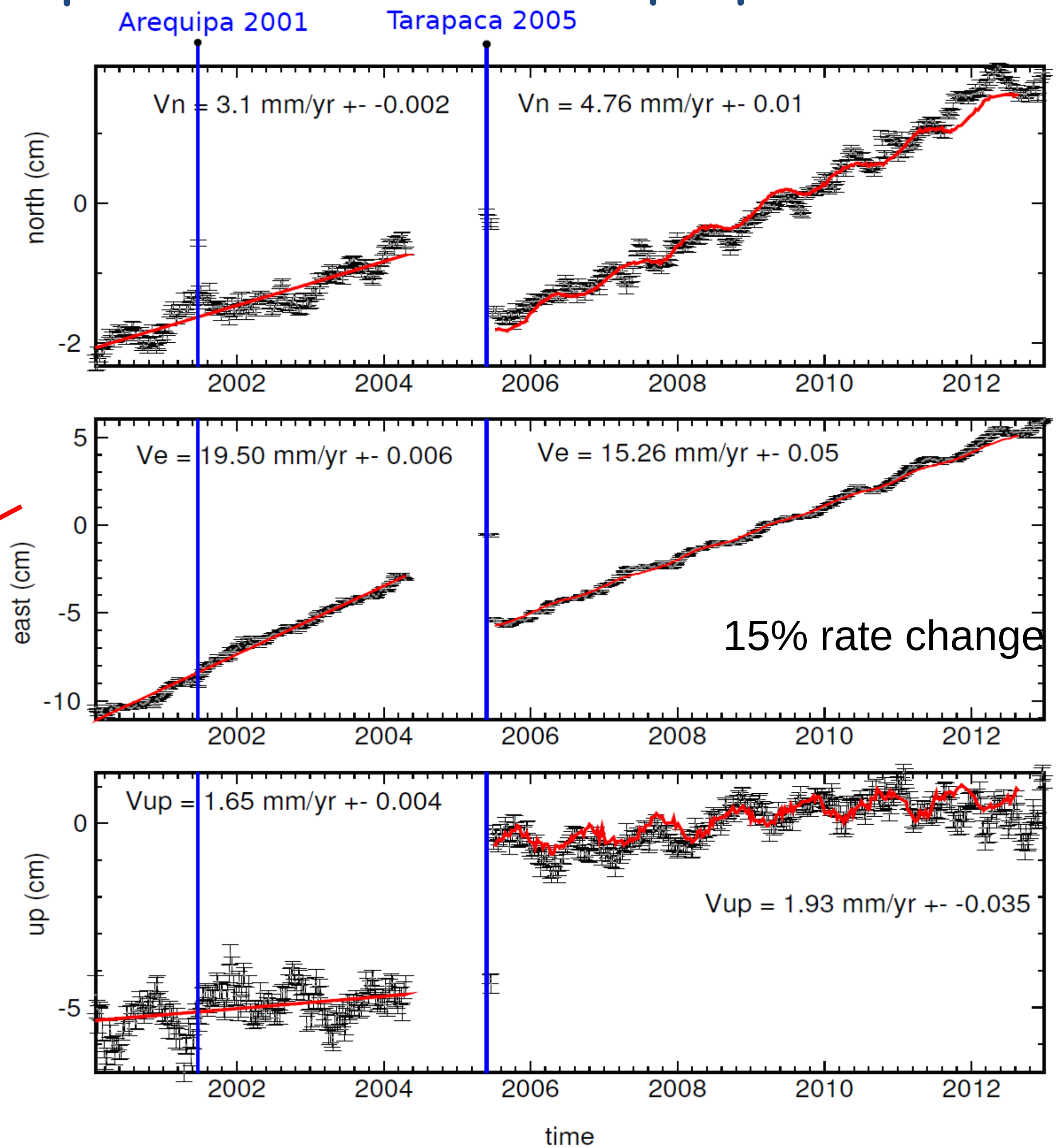
The main event of 1 april 2014

was preceded by 2 major Foreshocks on 16 and 23 March

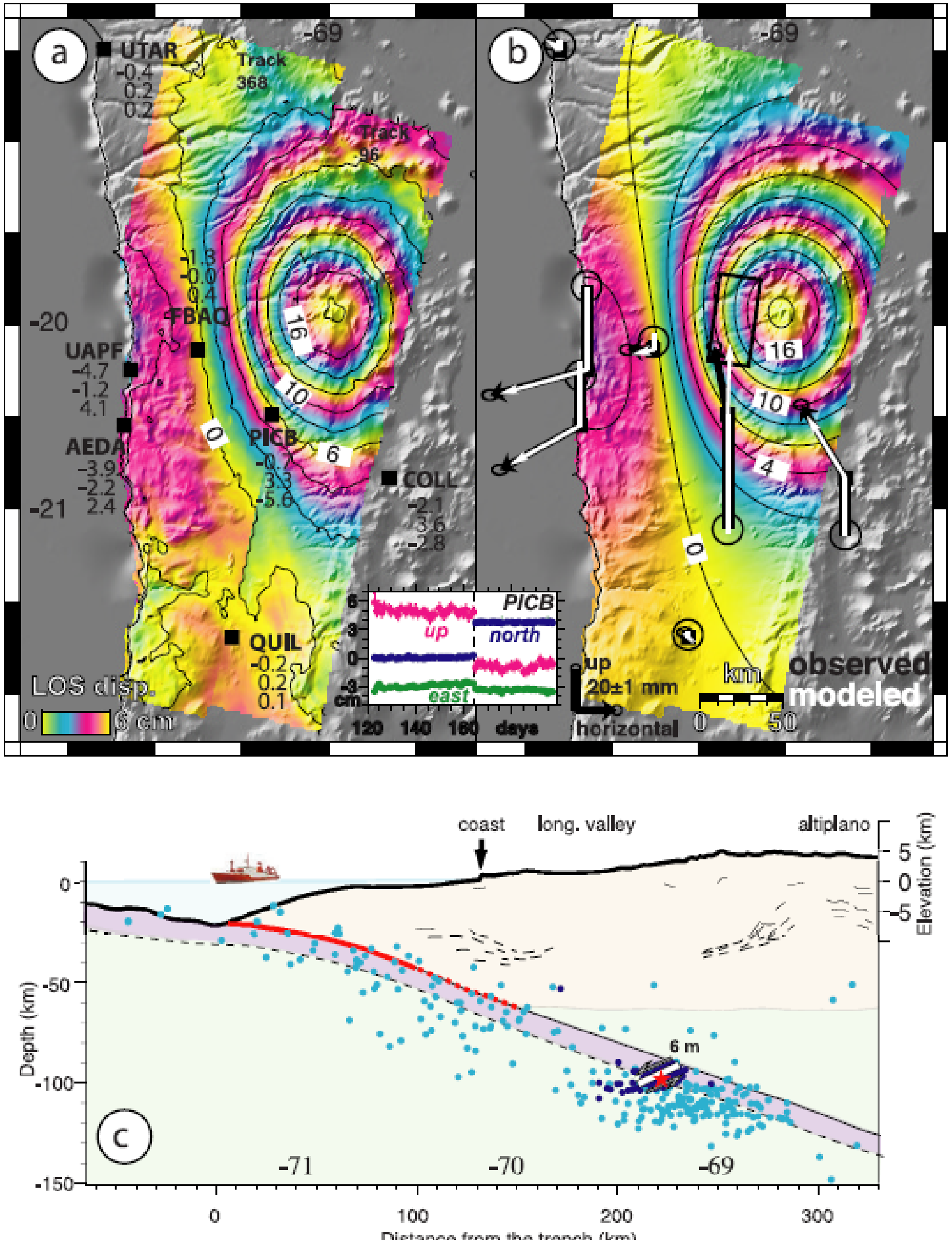
Previous big megathrust in November 1604

Long term geodetic precursor at the Iquique GPS





Observed Computed



The 1995 Tarapaca (Pica) Earthquake

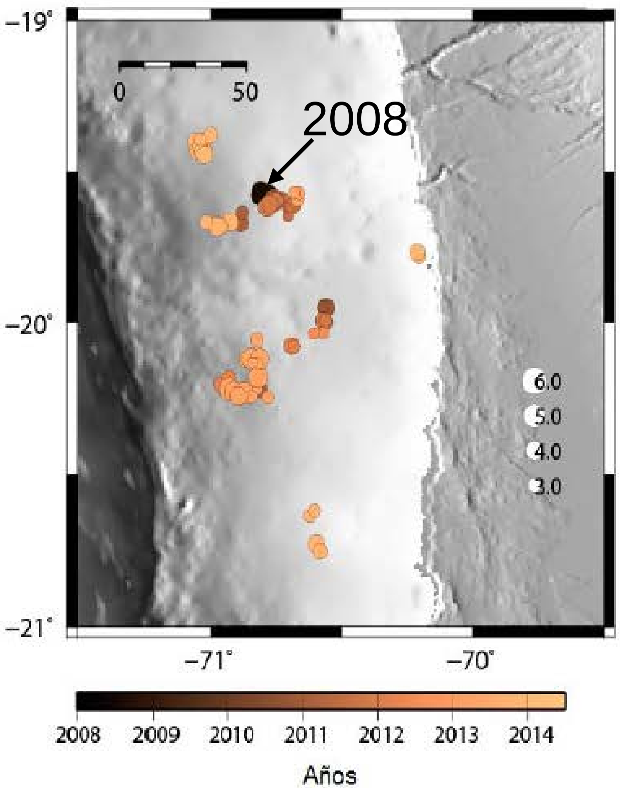
Mw 7.8

13 June 2005

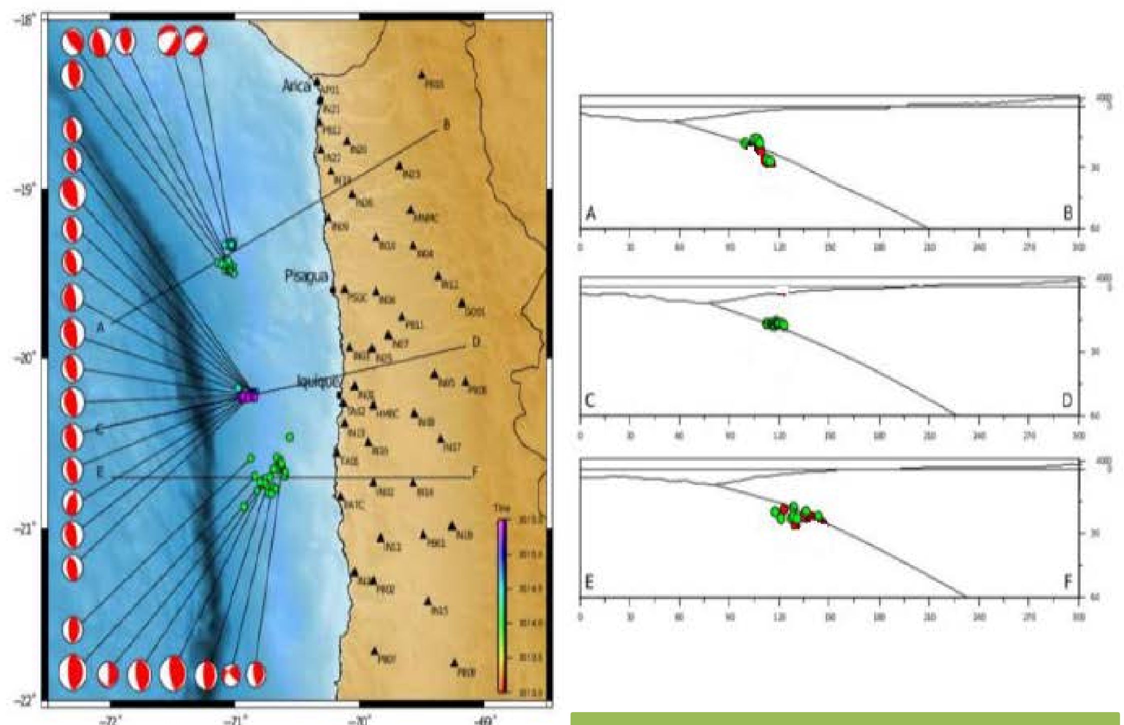
Peyrat et al (GRL, 2007)

Seismicity clusters preceeding the Iquique earthquake

They started in 2008 and increased after 2013



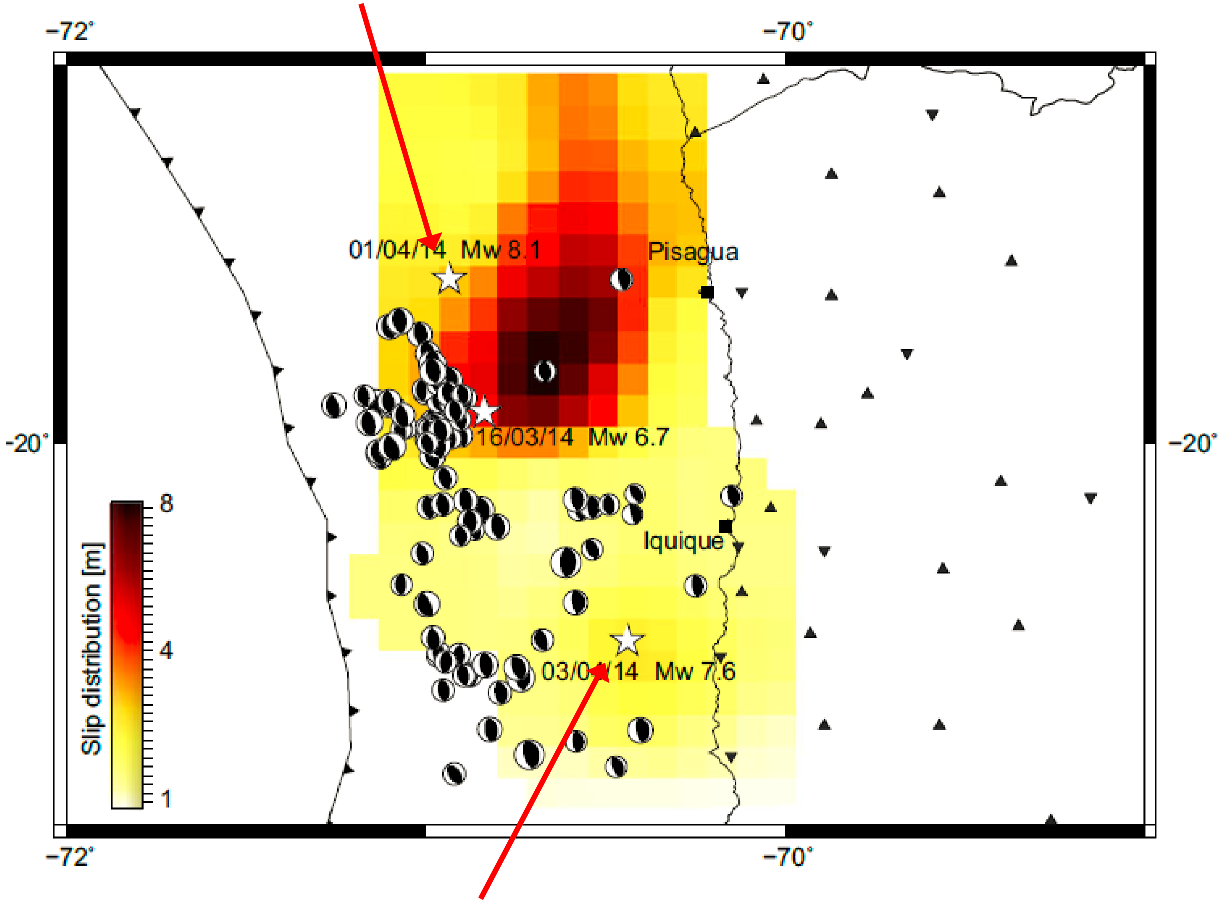
The Northern Chile network
Was installed in 2007



Leon et al, 2015

The main rupture of Iquique 1 April 2014

hypocenter



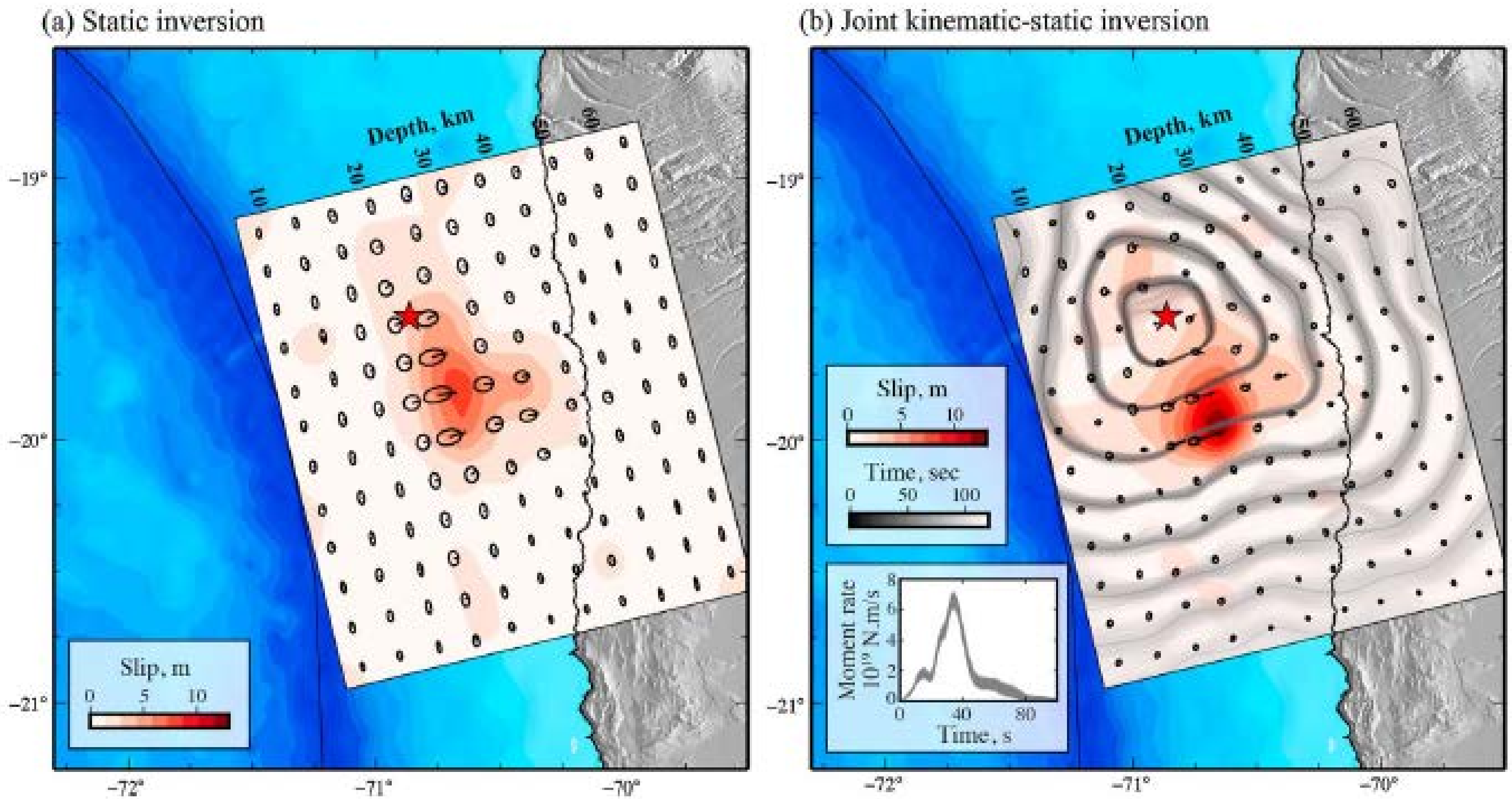
Main aftershock on
3 April 2014

The main rupture
(dark colors)
occurred away from
precursory seismicity

The hypocenter
was about 50 km
away from the main slip
zone and the main
aftershock
of 3 April 2014

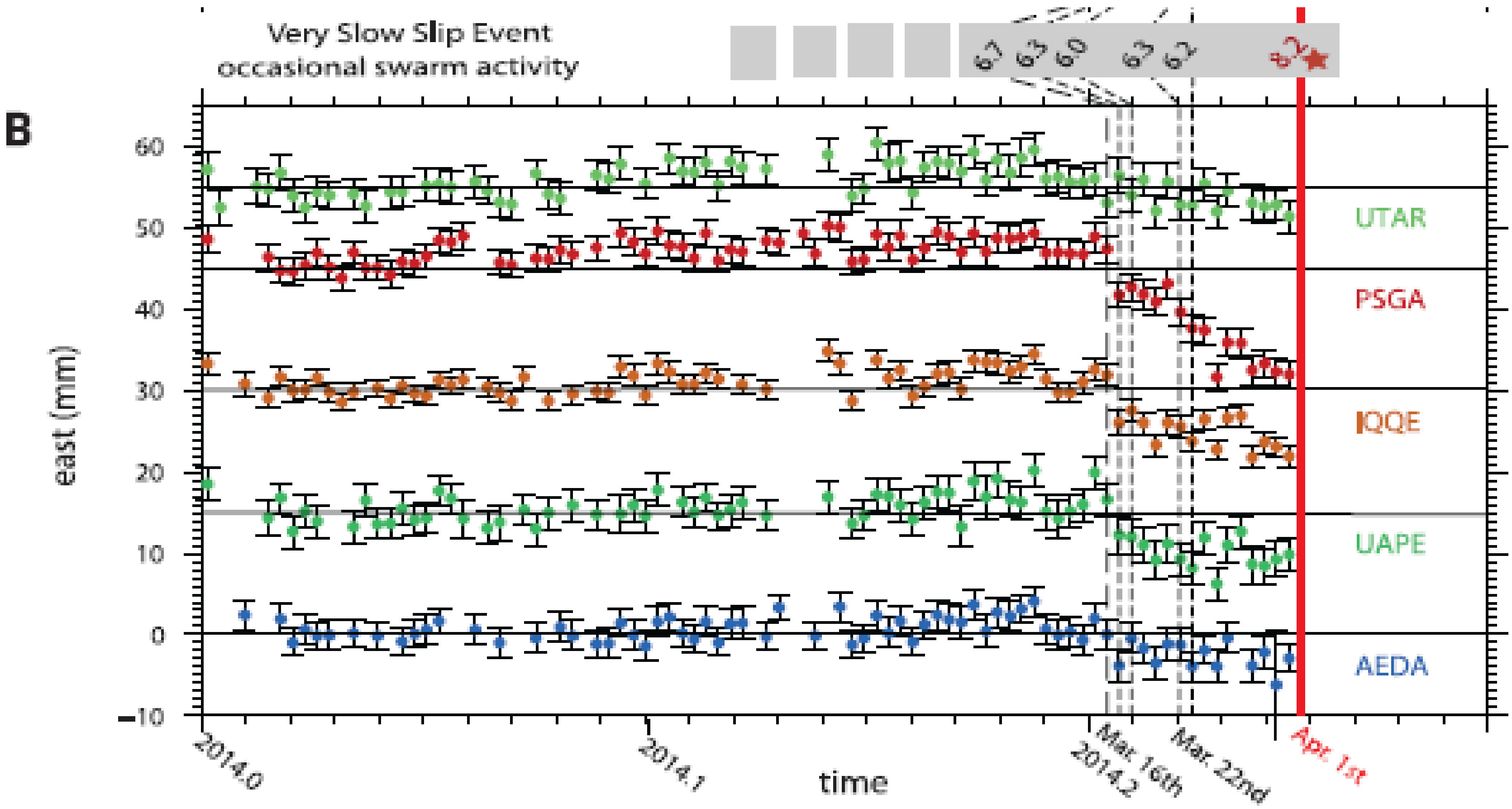
Classical inversion by Ruiz et al, Science, 2014

Main rupture of 1 April 2014



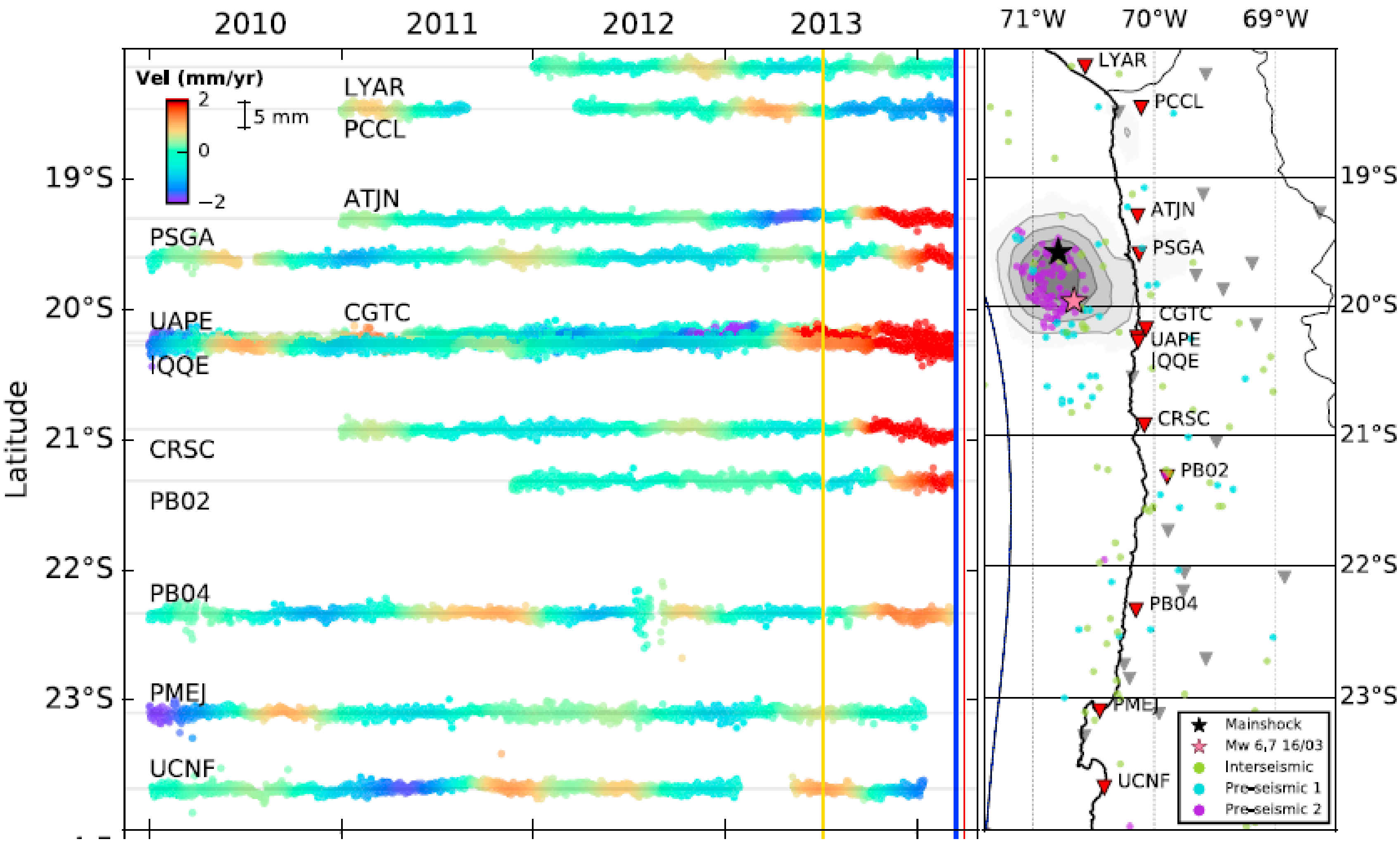
Bayesian inversion From Duputel et al, 2015

Geodetic precursor and slow slip event



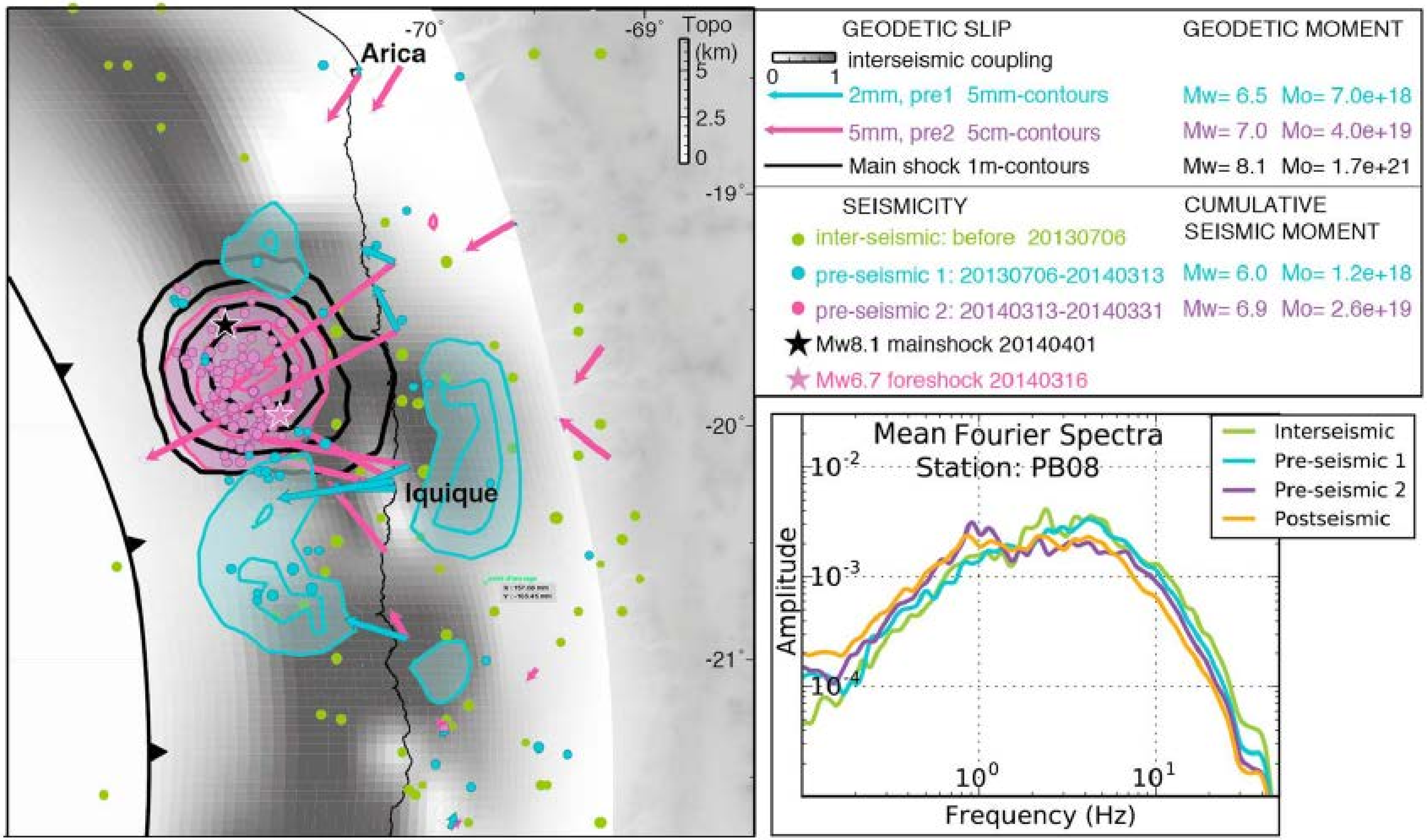
(Ruiz et al, Science, 2014)

Recent work on the geodesy of Iquique earthquake



A. Socquet, Jara et al, GRL, 2017

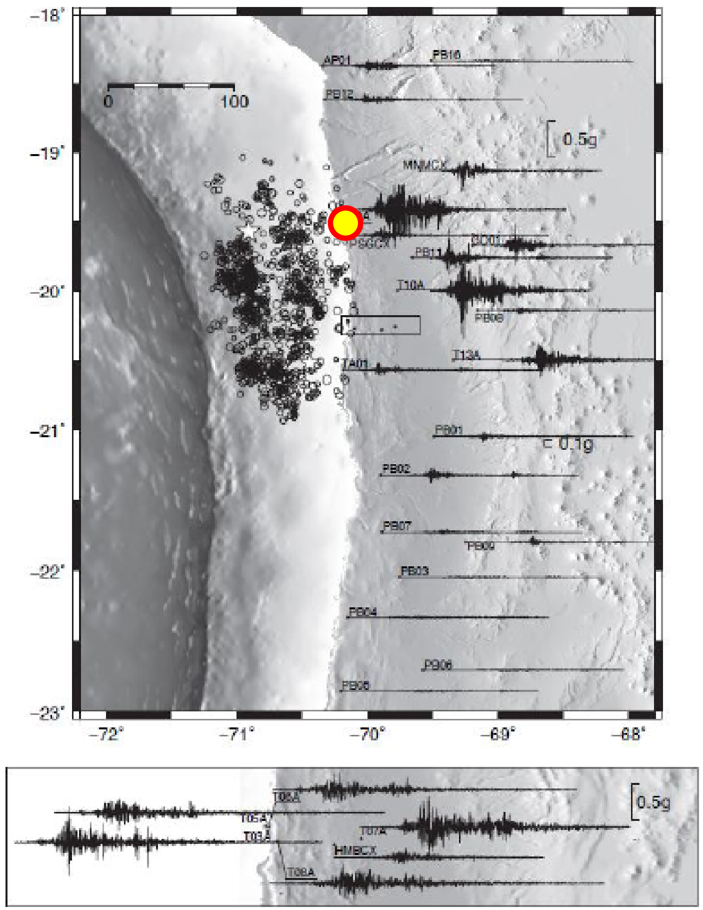
Pre slip in the Iquique earthquake zone



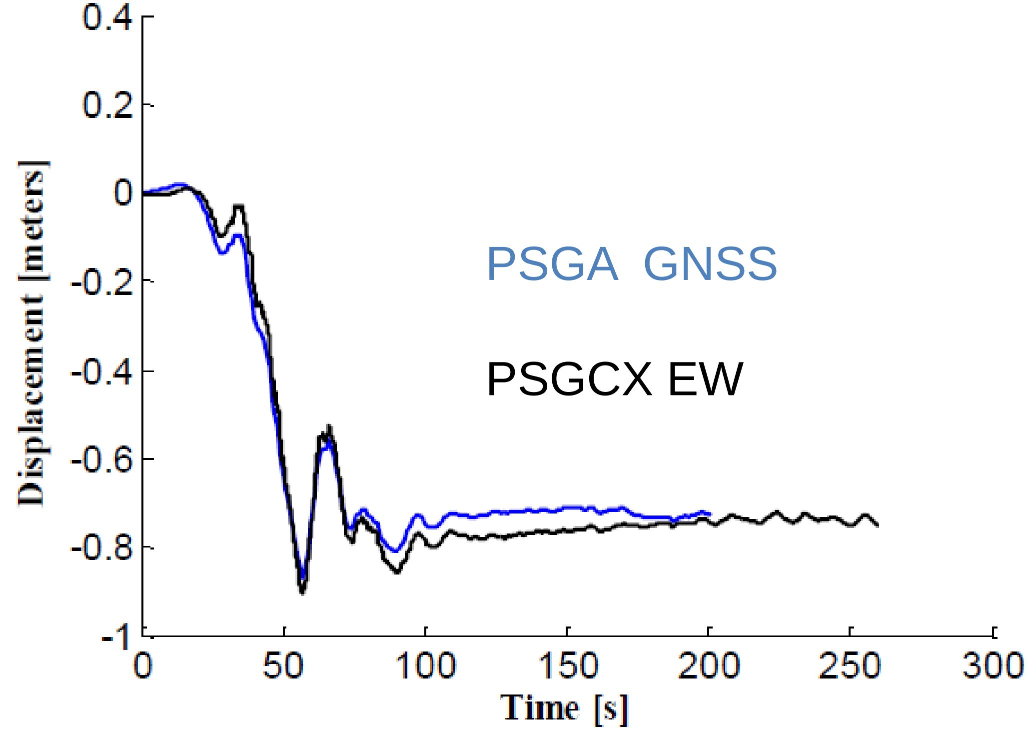
A. Socquet, Jara et al, GRL, 2017

Comparison of ground velocity from accelerograms and GPS

(a)



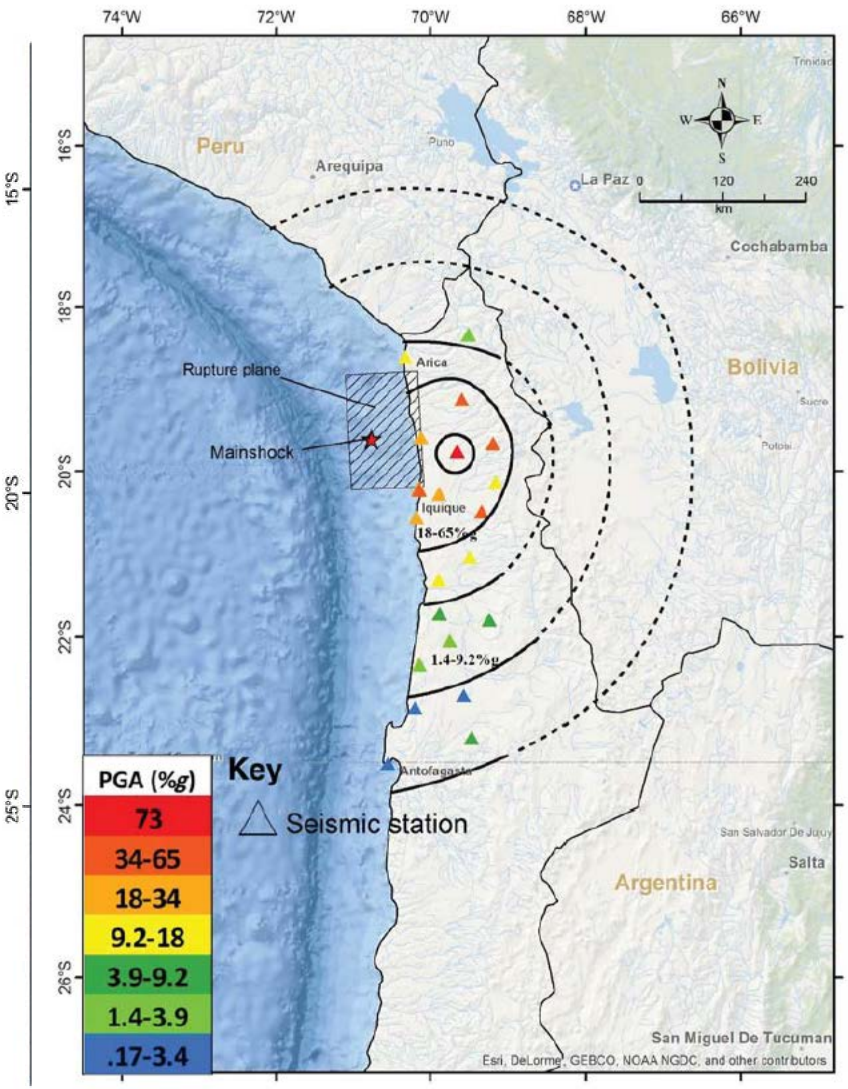
(b)



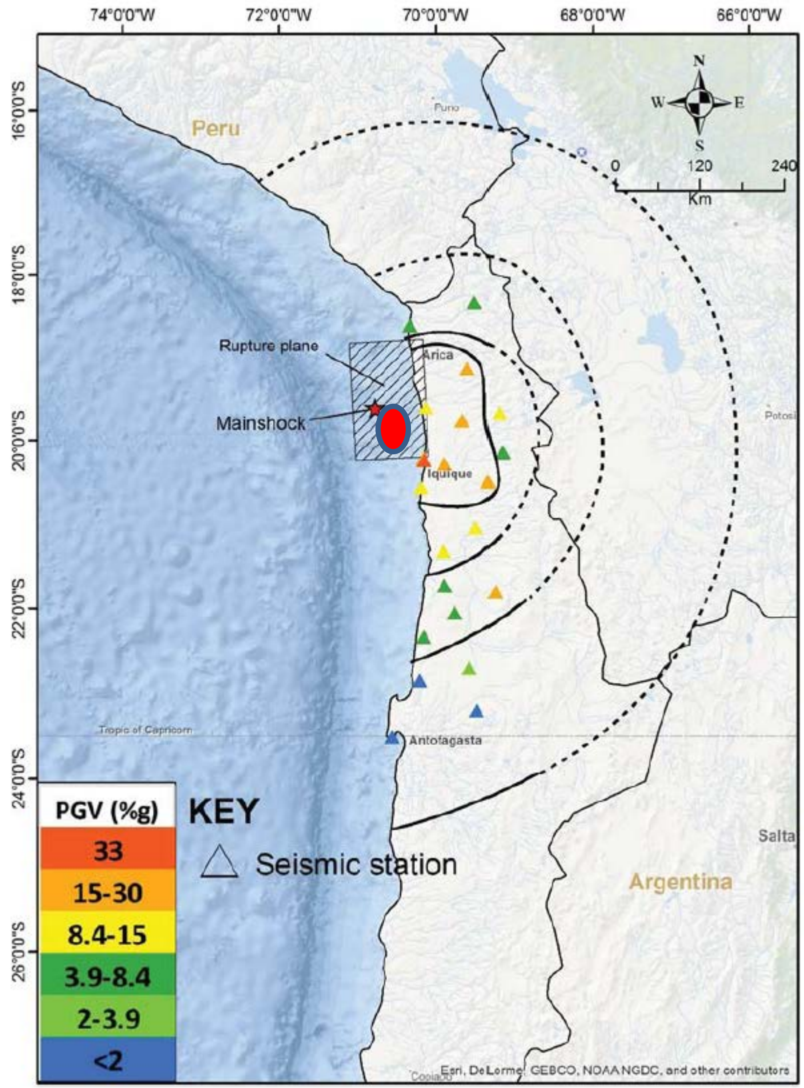
Ruiz et al, 2016, CSN-Uchile

Iquique 2015 earthquake intensities and PGV

Intensity

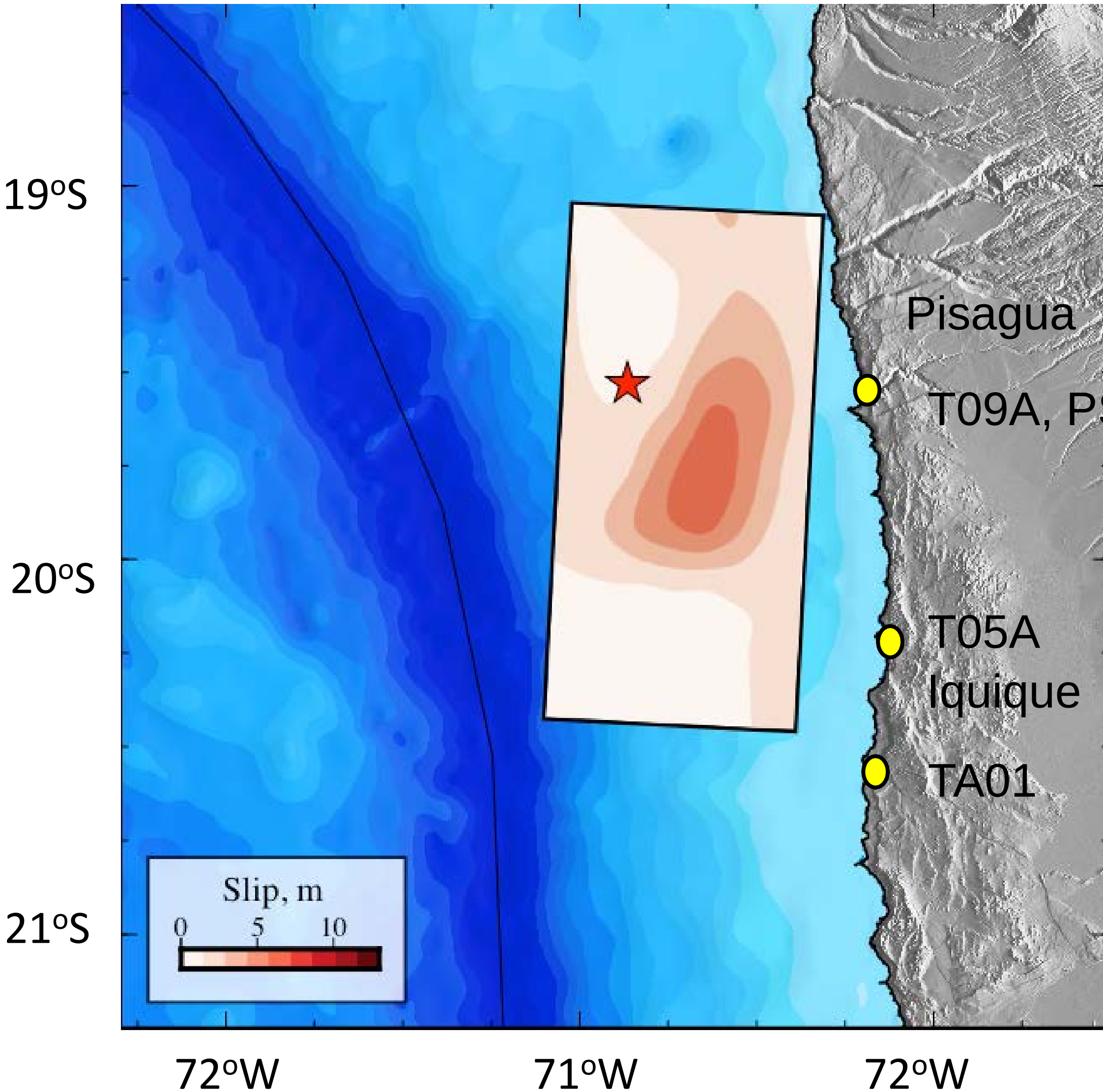


PGA



Cilia et al, SRL, 2017

The Main rupture of the Iquique earthquake of 1 April 2014



Complex event

With a 17 s delay between
Starting phase
and main rupture

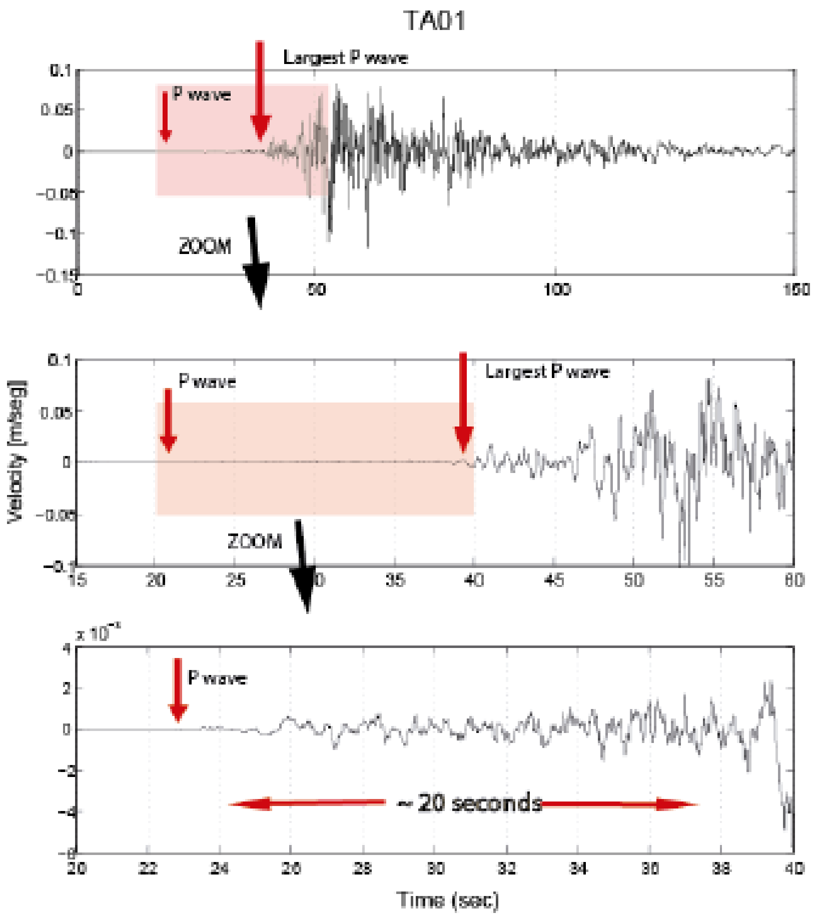
More than 50 acccelerograms

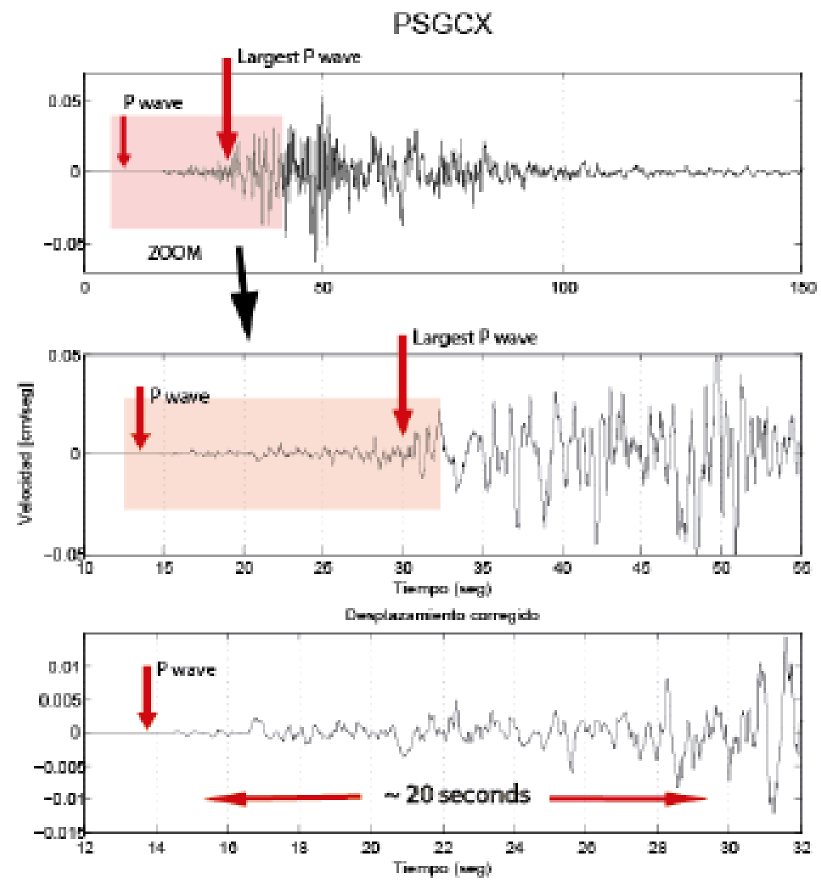
Many with continuous recording

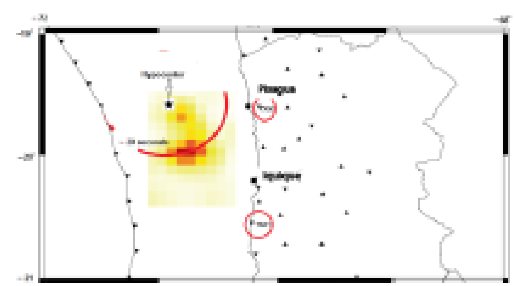
And 24 bit dynamic range

Ruiz et al, Science, 2014

Iquique 2014 The main event had an immediate precursor 17s before the main-shock







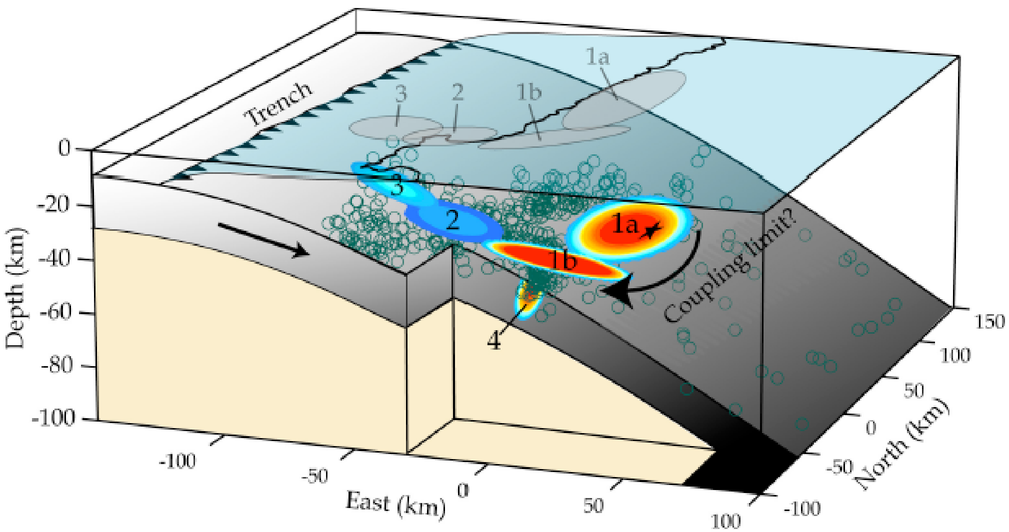
From Ruiz et al, 2014

ACCELEROGRAMS AND GNSS

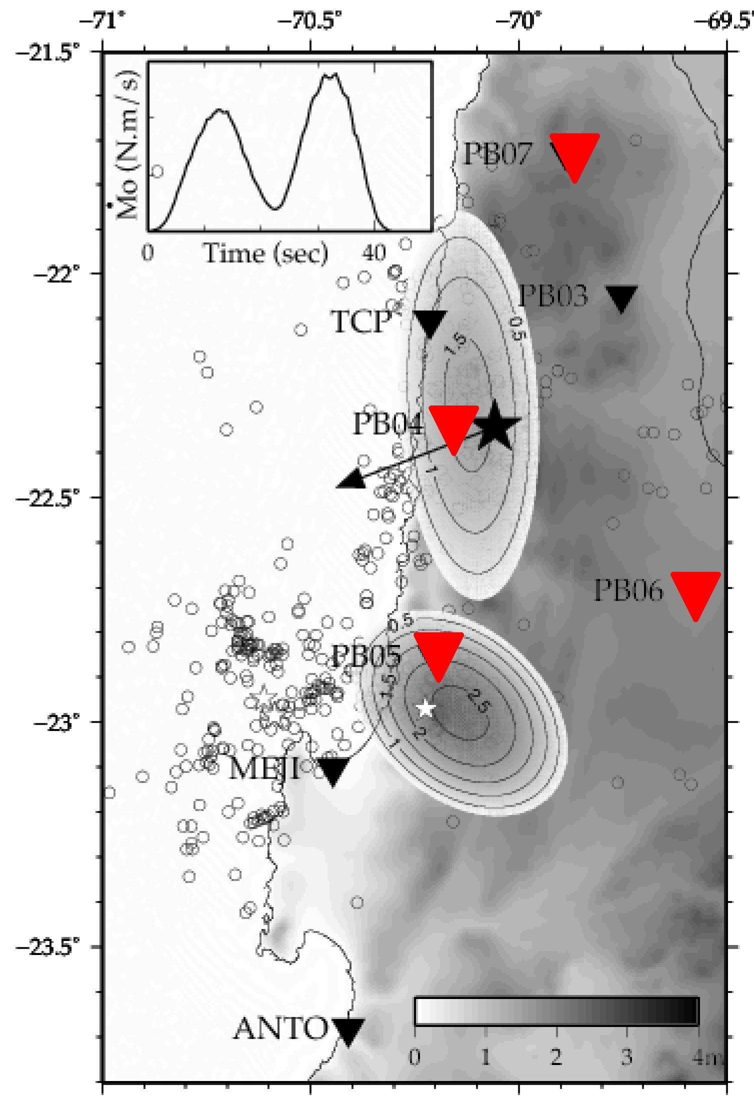
The Tocopilla Earthquake of 21 November 2007

A double event at the bottom
of the plate interface

Mw=7,8 Mo = 2,5 10^{20} Nm

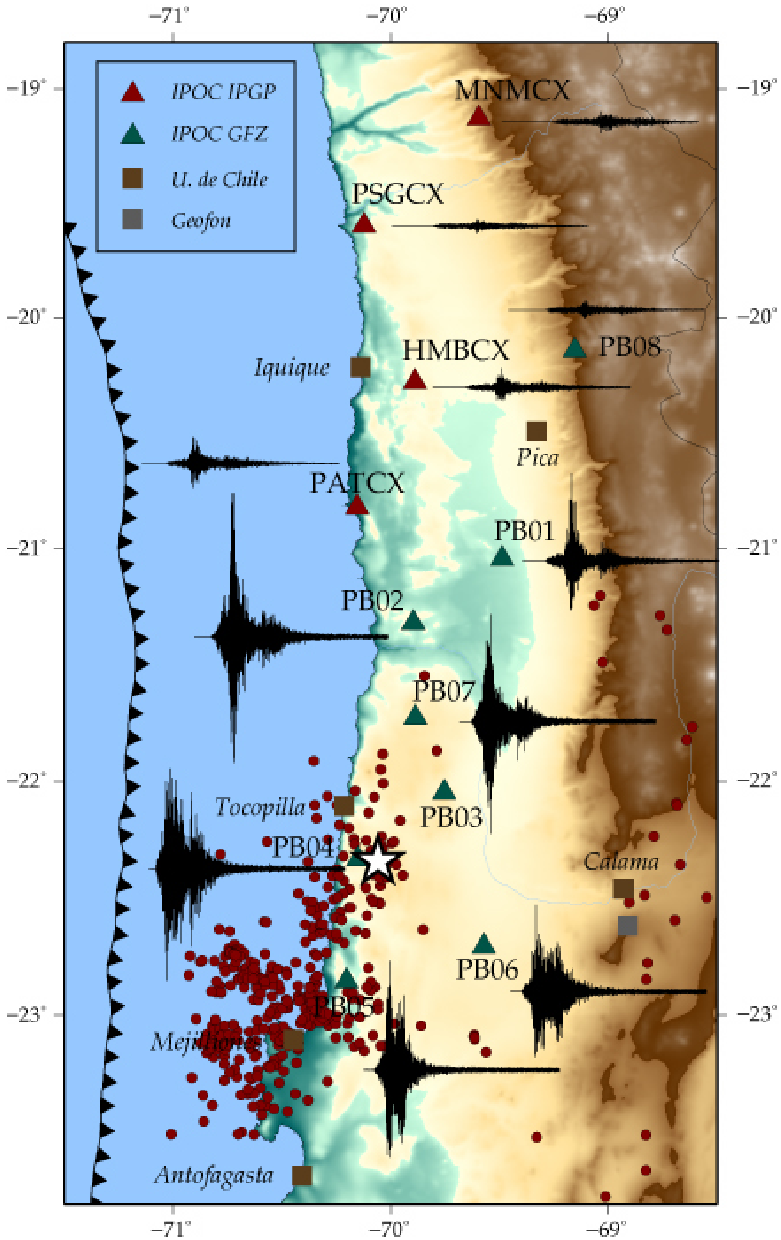


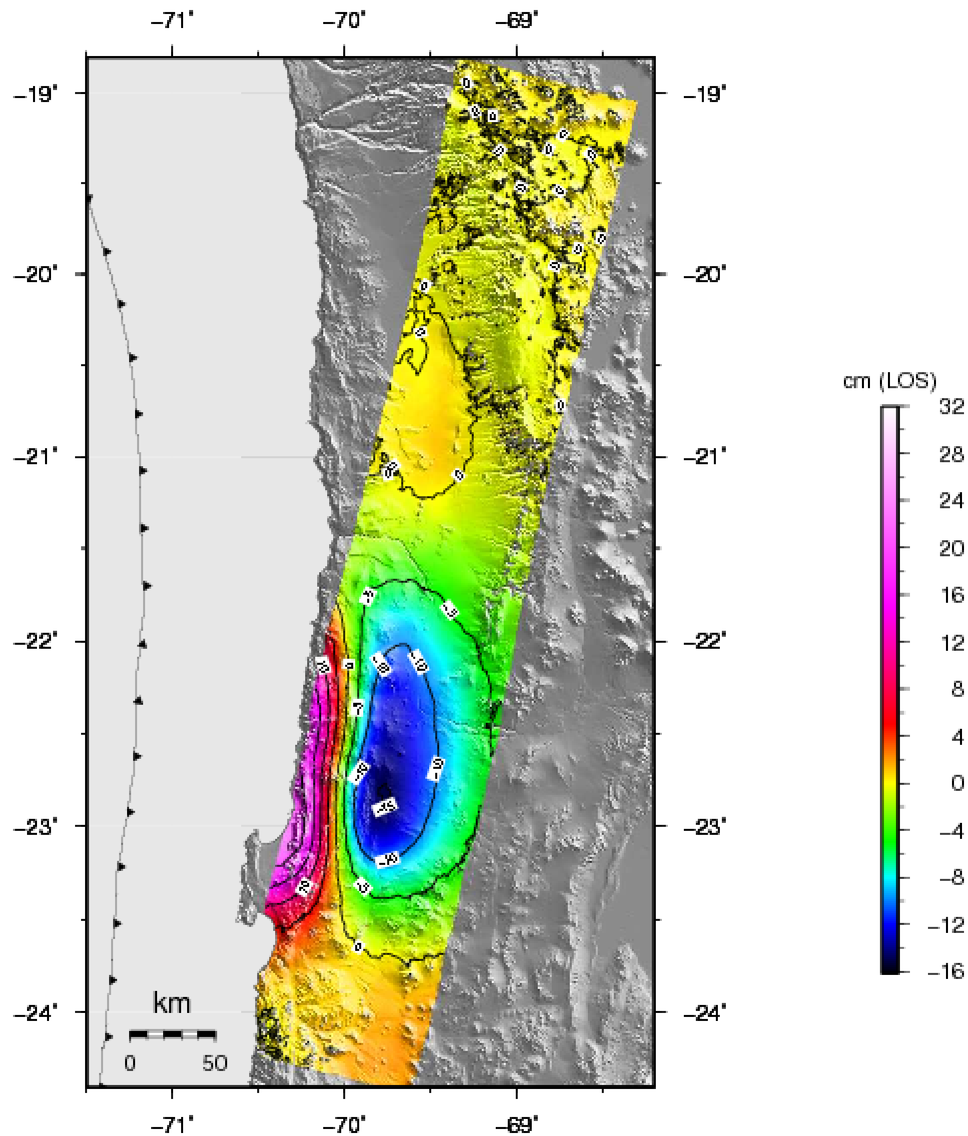
From Peyrat et al (GJI 2010)



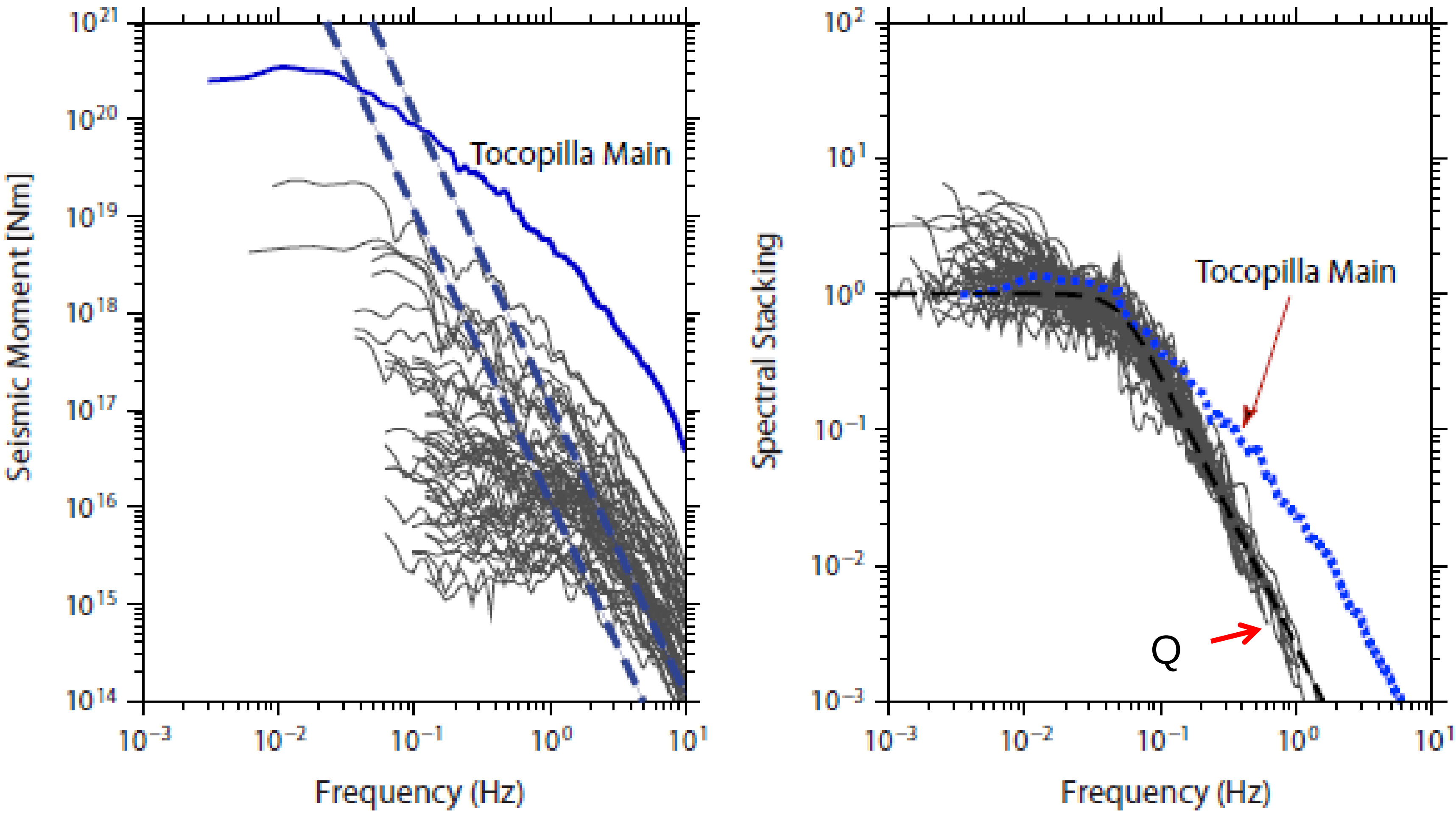
Inverted triangles accelerograms
In red PBO stations used for this study

Terremoto de Tocopilla y su zona de ruptura



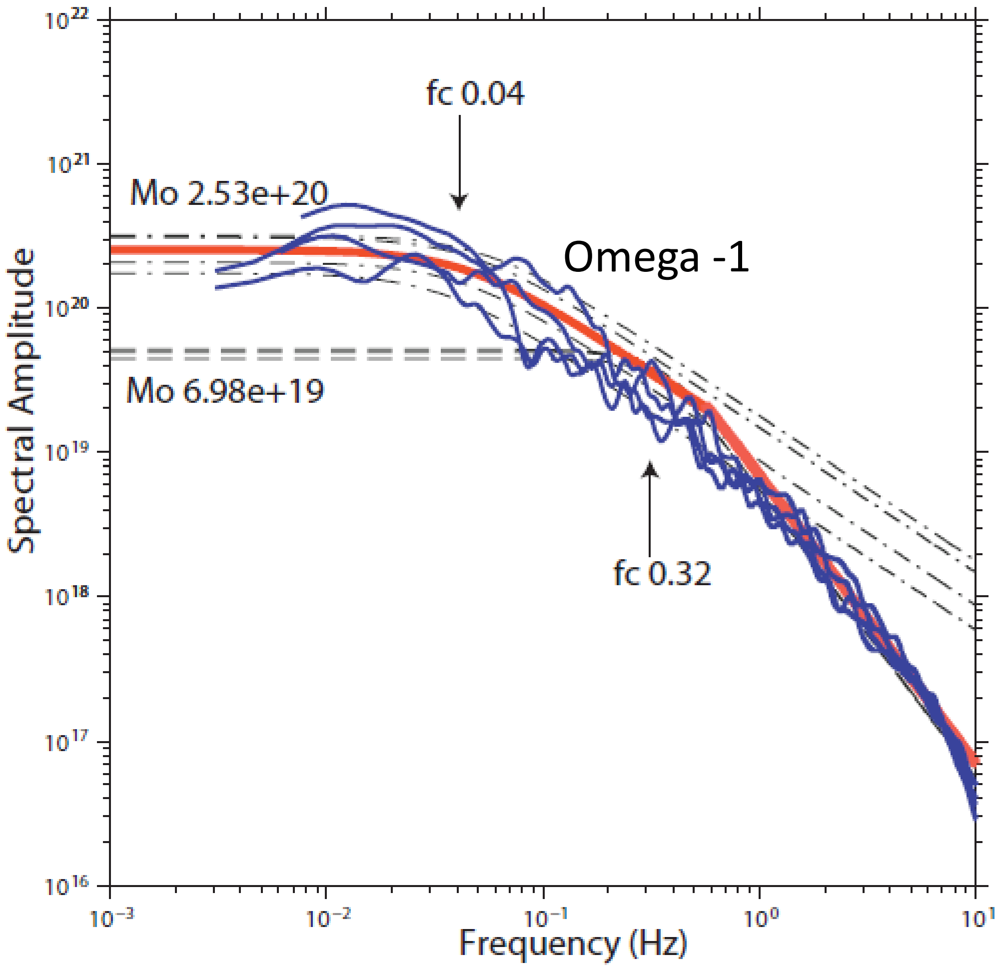


Spectral stack of a set Tocopilla aftershocks



From Lancieri et al (GJI 2012)

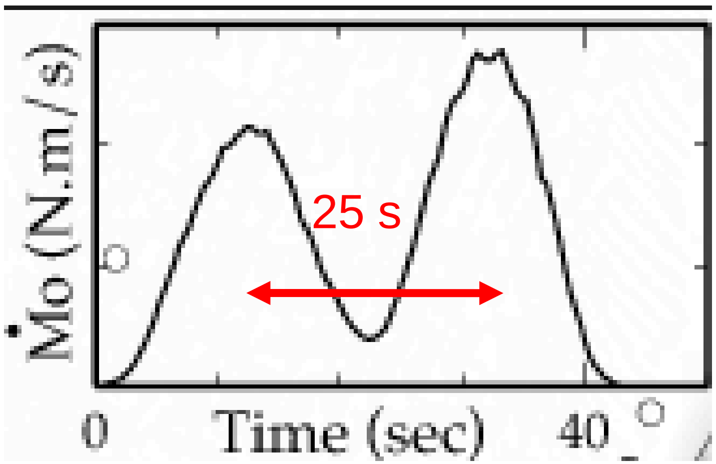
Displacement spectrum of the Tocopilla earthquae Observed at 4 accelerometers of the PBO network



Stations

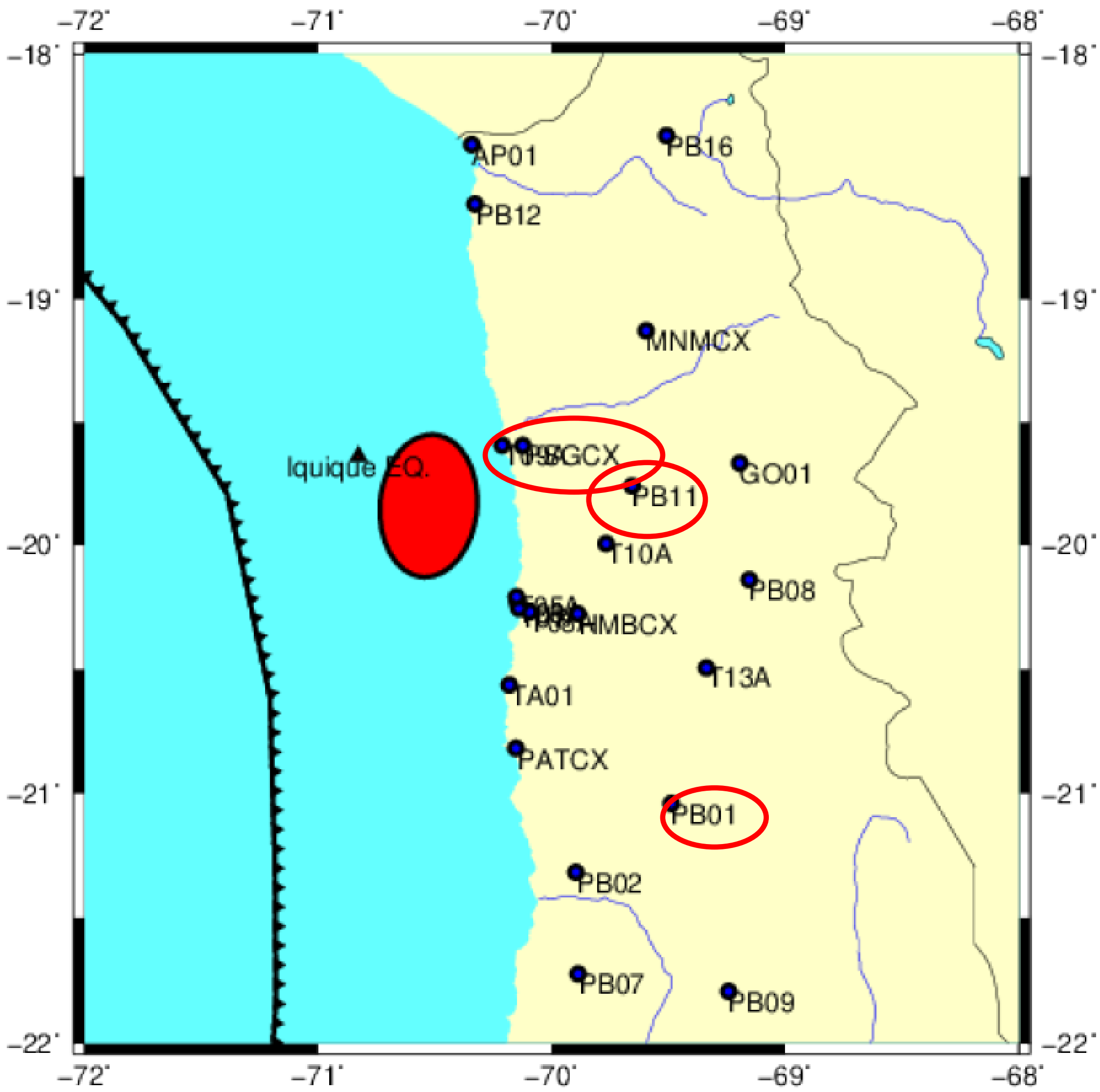
PB04
PB03
PB05
PB07

Moment rate

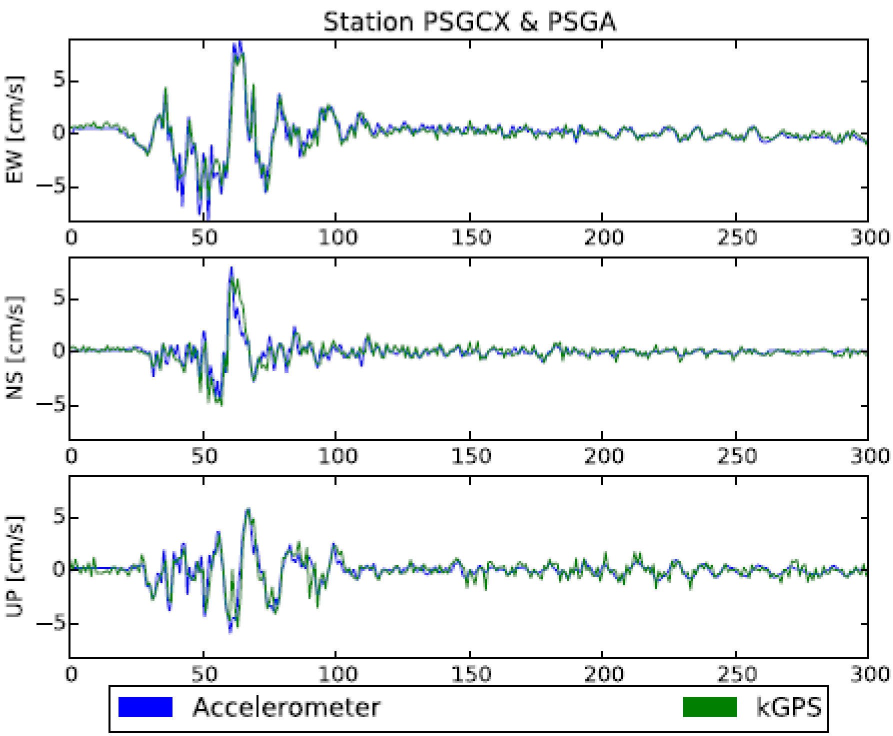


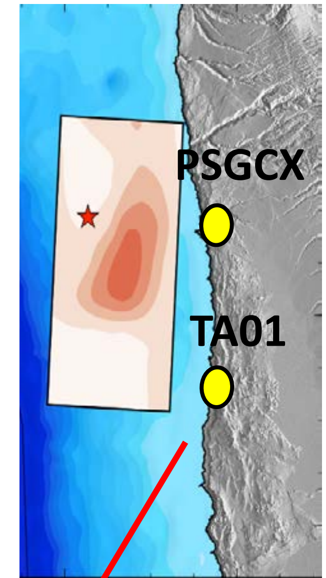
From Lancieri et al (GJI 2012) and Peyrat et al (GJI 2010)

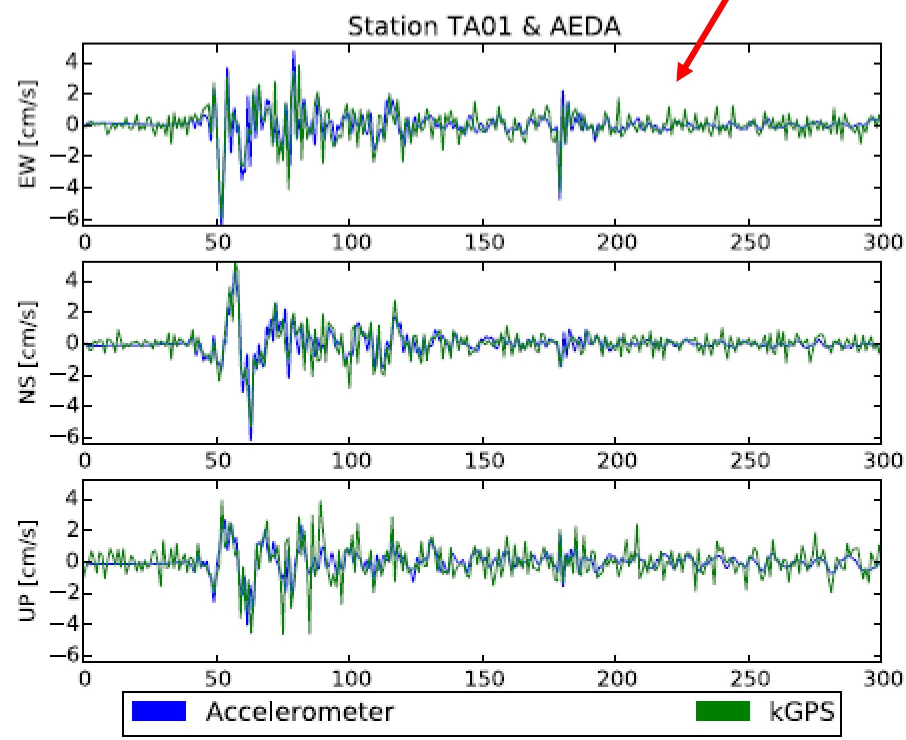
Iquique Earthquake 1 April 2014



Comparison of ground velocity from accelerograms





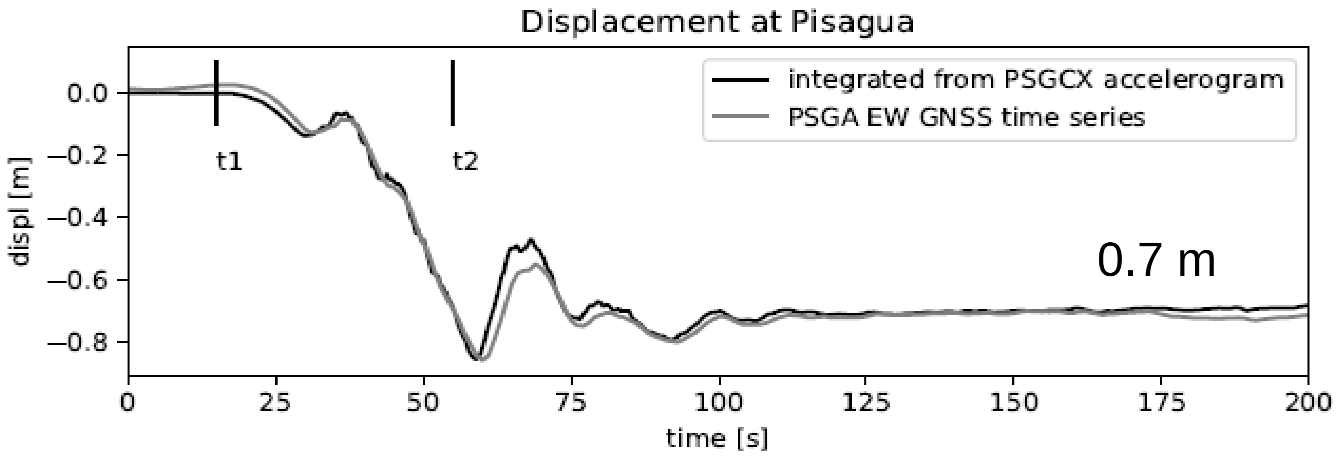


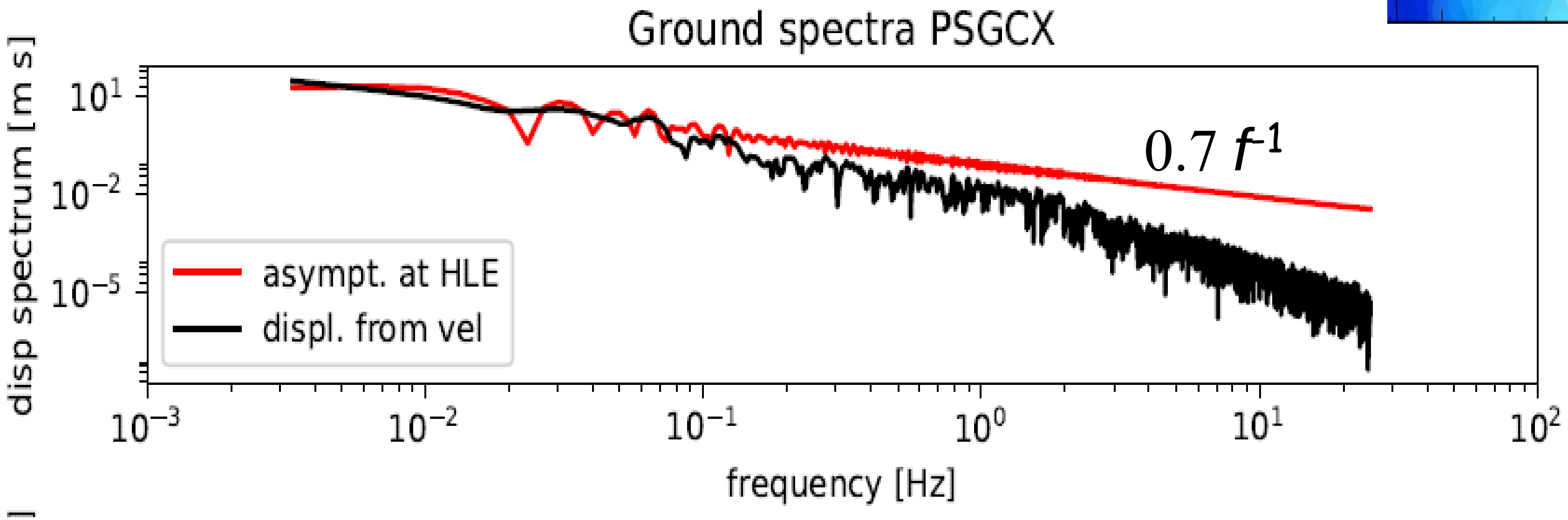
Iquique 2014 Mw 8.2

Leyton and Baez, CSN-Uchile

Iquique 2014 recorded in Pisagua.

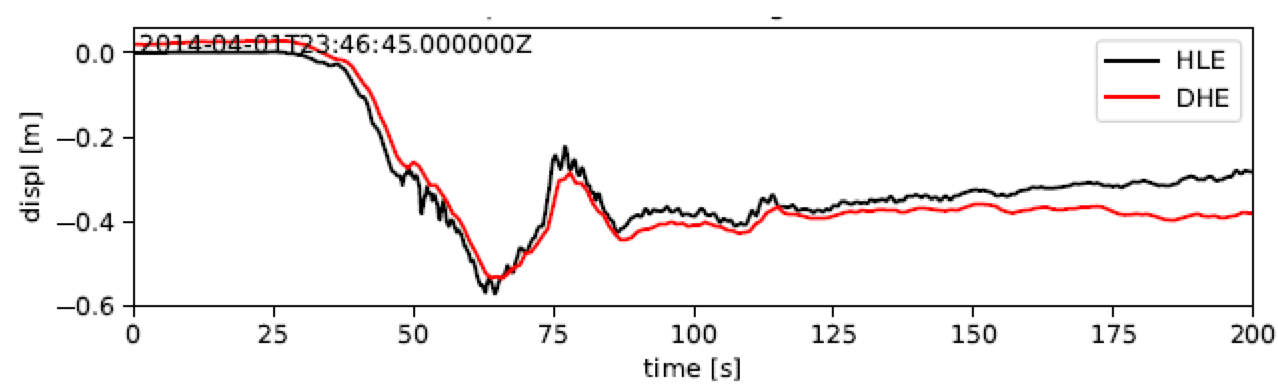
Displacement at PSGCX accelerograph   50 km



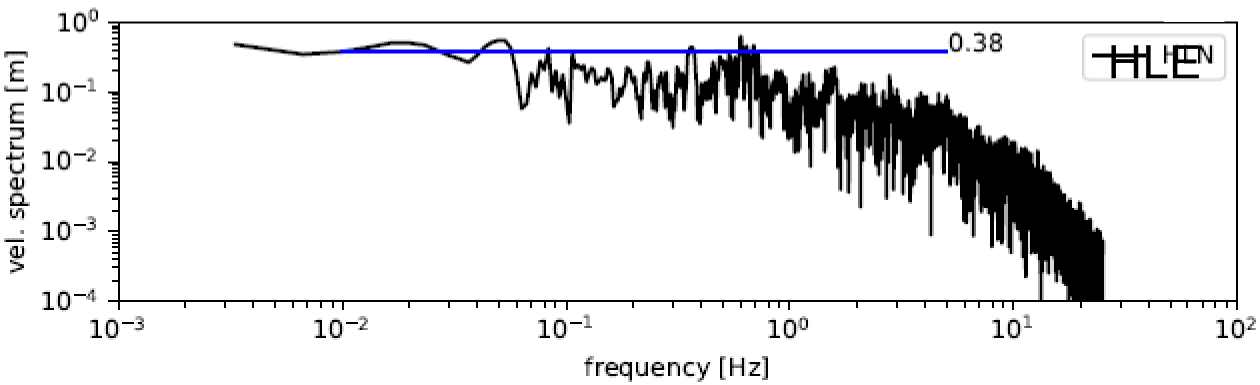


Properties of PB11 accelerogram

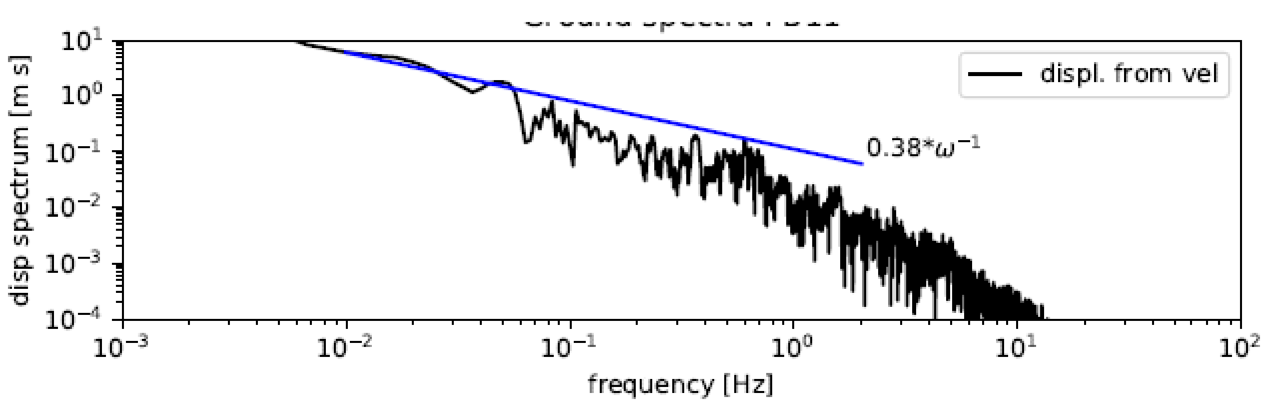
Iquique 2014



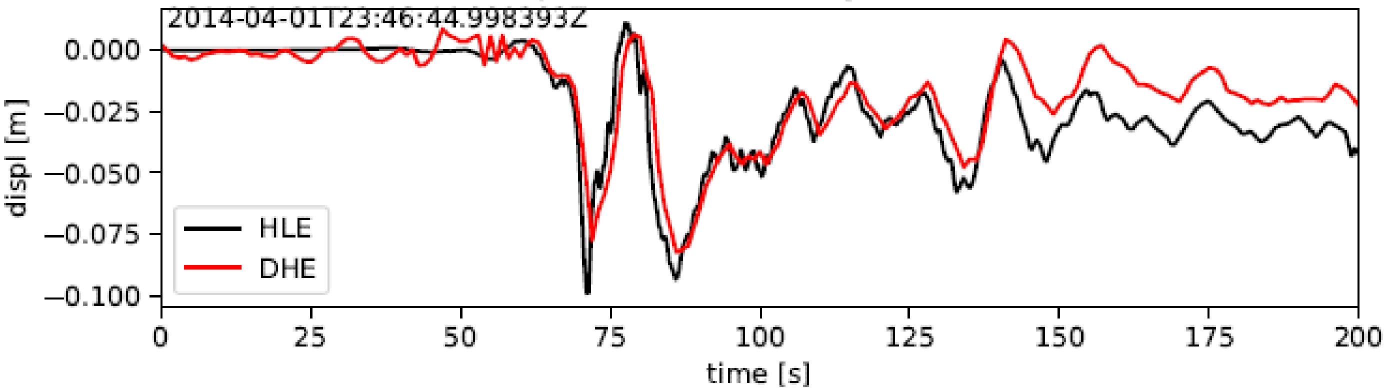
Ground velocity spectrum

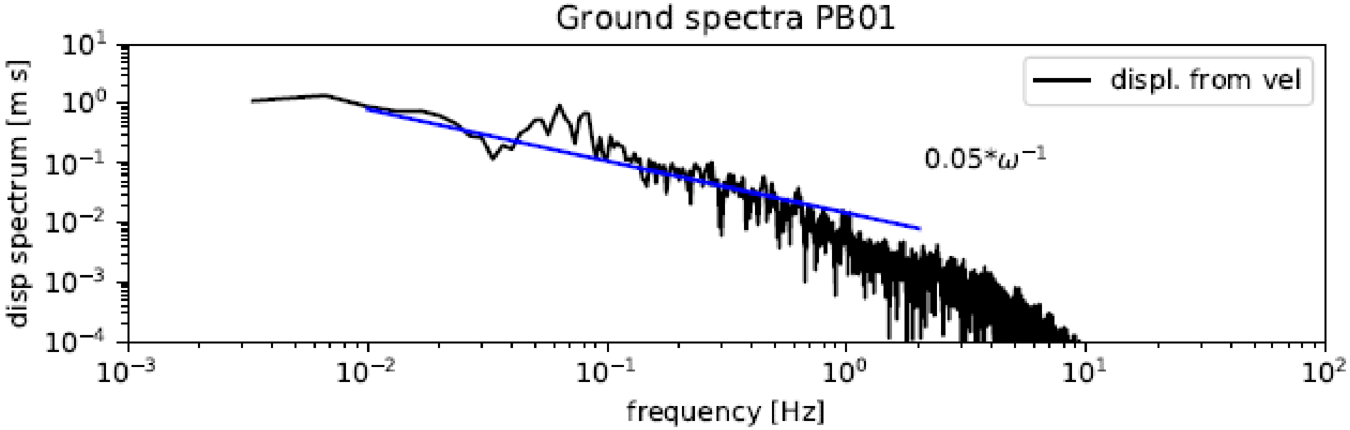


Ground displacement spectrum

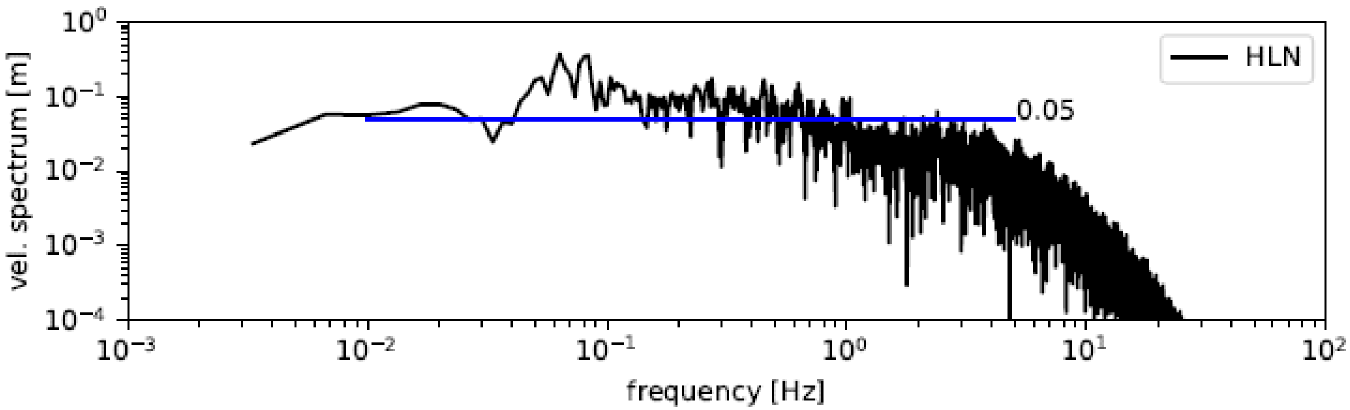


Properties of PB01 accelerogram





Displacement



Velocity

Green function's near and far field terms

The simplest expression is:

$$\tilde{u}_i(r,\omega) = \frac{M_0(\omega)}{r^2}\left[\frac{1}{4\pi\rho\alpha^2}F^{INP}(\omega r/\alpha)e^{-\frac{i\omega r}{\alpha}} - \frac{1}{4\pi\rho\beta^2}F^{INS}(\omega r/\beta)e^{-\frac{i\omega r}{\beta}}\right]$$

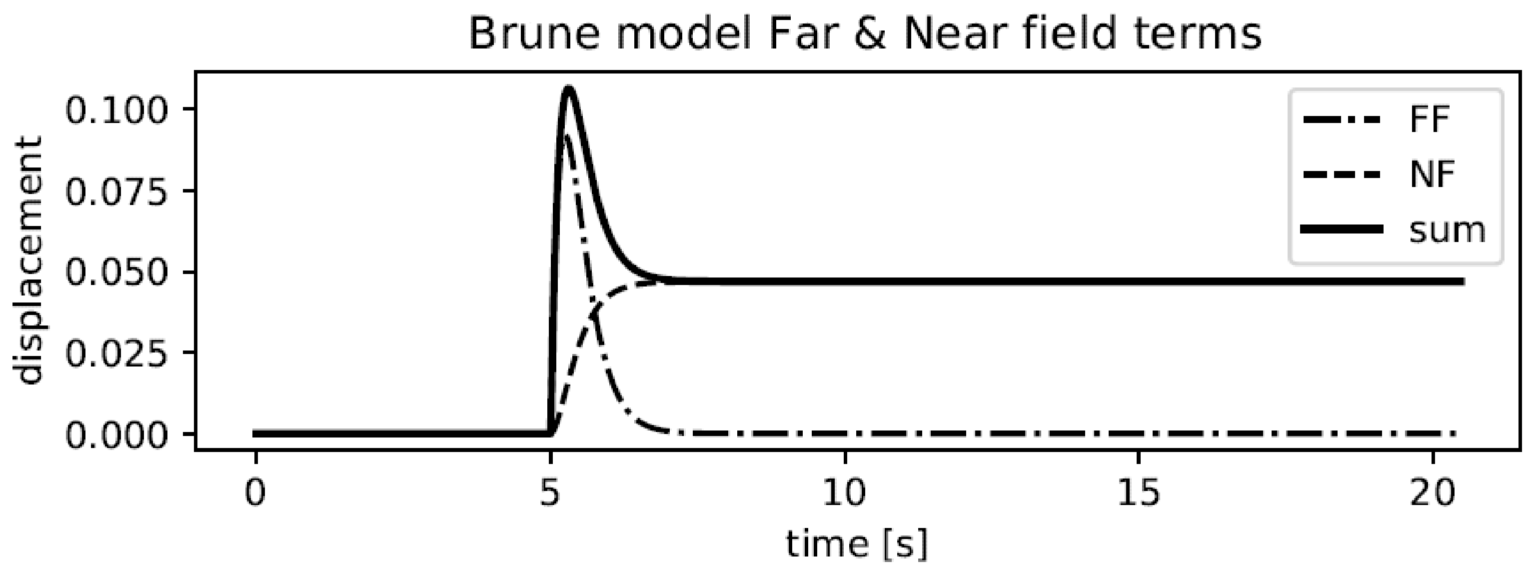
Near field proportional to M_o and r^{-2}

$$F^{NIP}\left(\frac{\omega r}{\alpha}\right) = A^N\frac{\alpha^2}{\omega^2 r^2}\left(\frac{i\omega r}{\alpha}+1\right)+A^{IP}$$

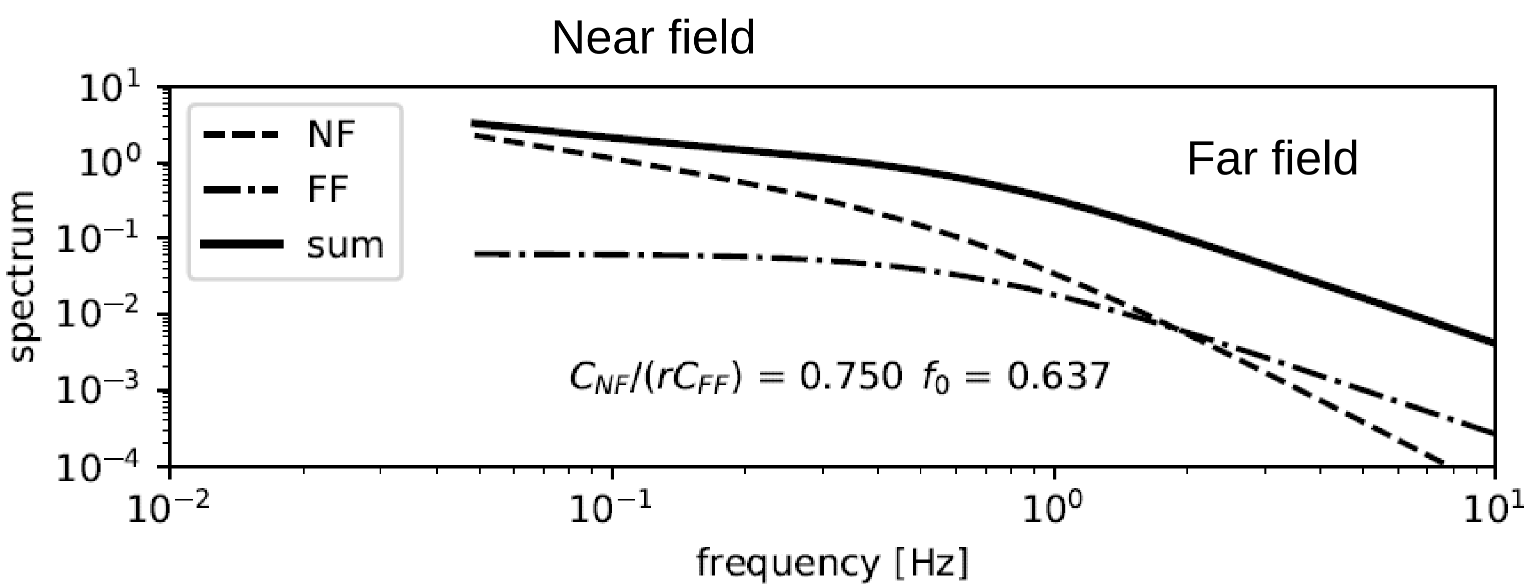
$$F^{NIS}\left(\frac{\omega r}{\beta}\right) = -A^N\frac{\beta^2}{\omega^2 r^2}\left(\frac{i\omega r}{\beta}+1\right)+A^{IS}$$

Far field proportional to M'_o and r^{-1}

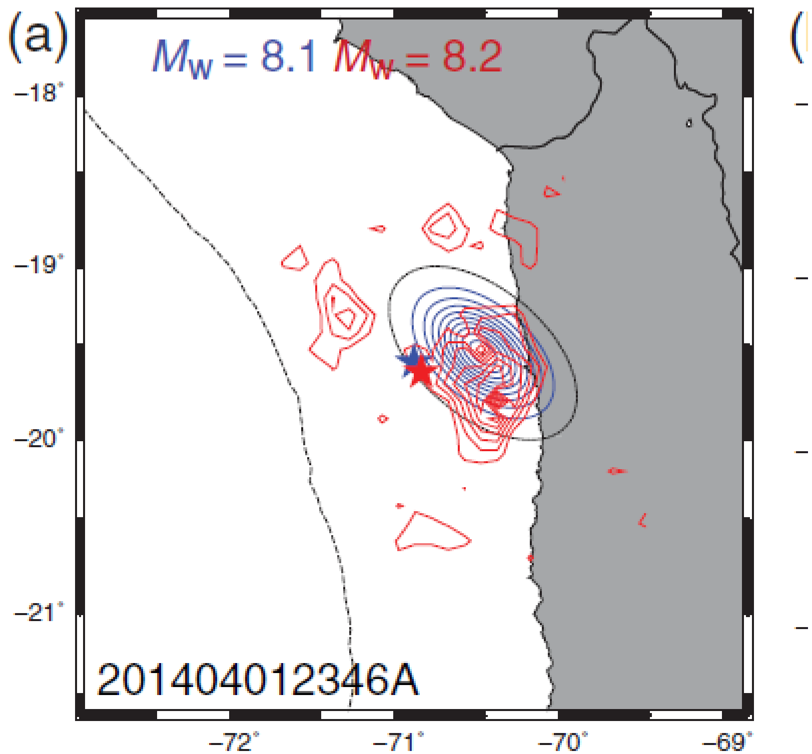
$$+\frac{\dot{M}_0(\omega)}{r}\left[\frac{1}{4\pi\rho\alpha^3}A^{FP}e^{-\frac{i\omega r}{\alpha}} + \frac{1}{4\pi\rho\beta^3}A^{FS}e^{-\frac{i\omega r}{\beta}}\right]$$



Brune model Far & Near field terms
displacement
0.100
0.075
0.050
0.025
0.000
0
5
10
15
20
time [s]
FF
NF
sum



Near field
Far field
spectrum
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
10^{0}
10^{1}
frequency [Hz]
NF
FF
sum
$C_{NF}/(rC_{FF}) = 0.750$ $f_0 = 0.637$



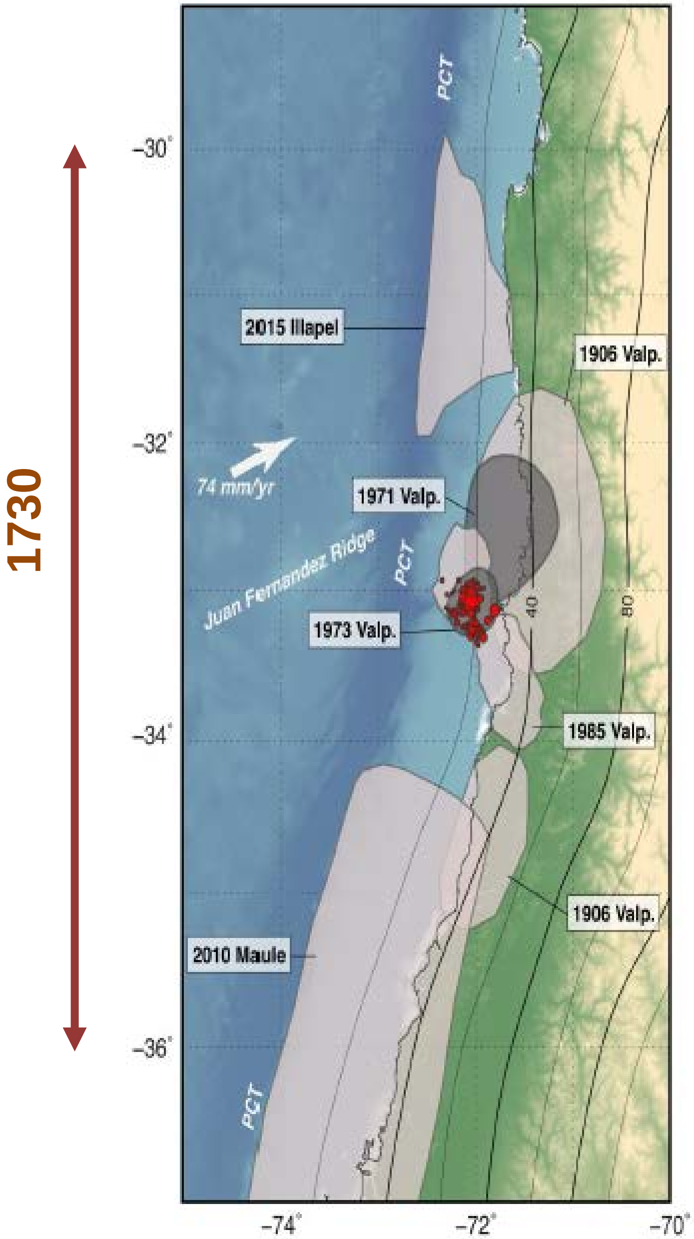
(a)
M_W = 8.1 M_W = 8.2
–18°
–19°
–20°
–21°
201404012346A
–72°
–71°
–70°
–69°

The very interesting Valparaiso Mw 6.9 earthquake of 24 April 2017

A long term aftershock of 27 February 2010 or a new event?

From Ruiz et al GRL (2017)

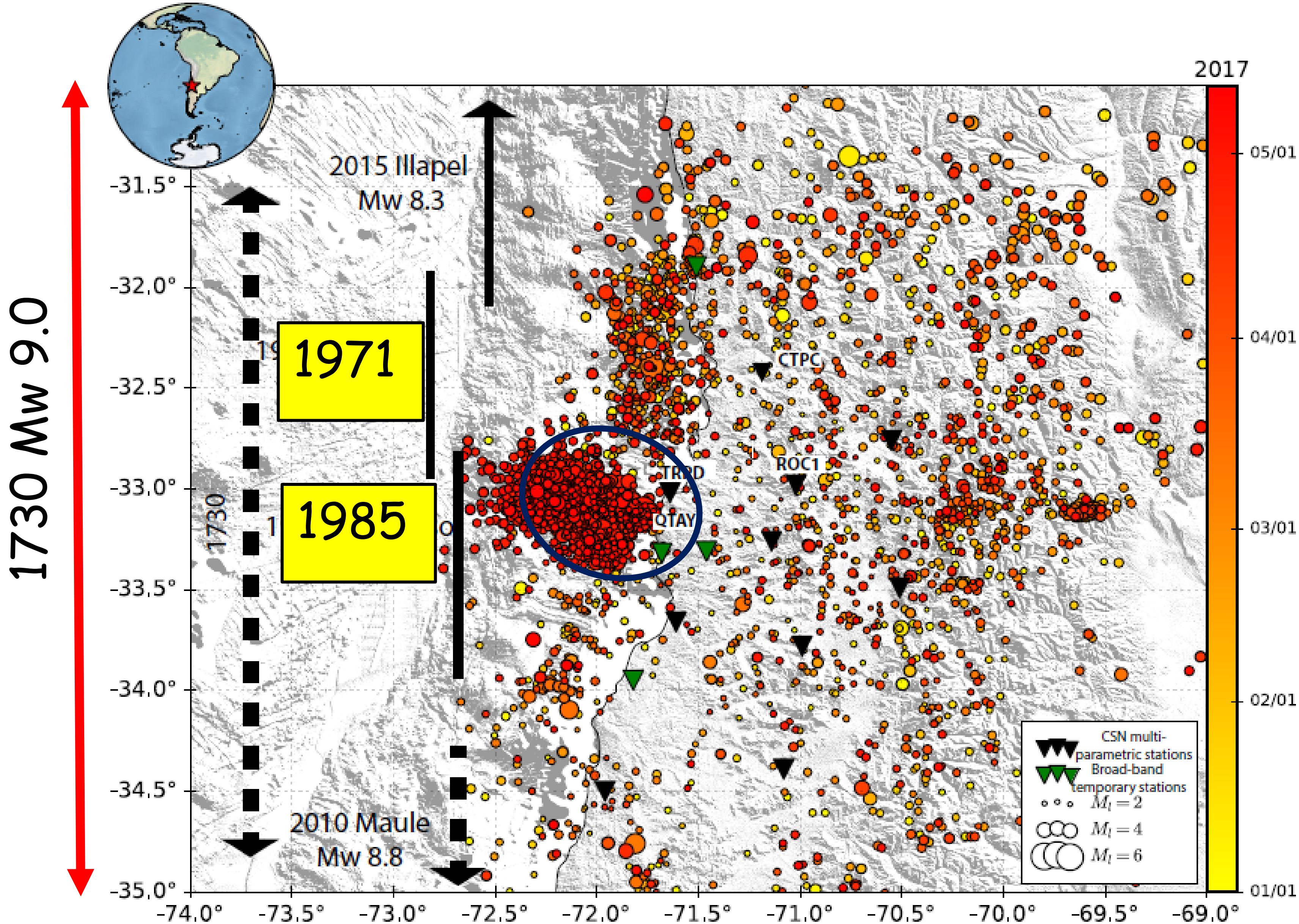
Historical Seismicity of the Valparaiso area



This gap has always been considered a Candidate for a future earthquake

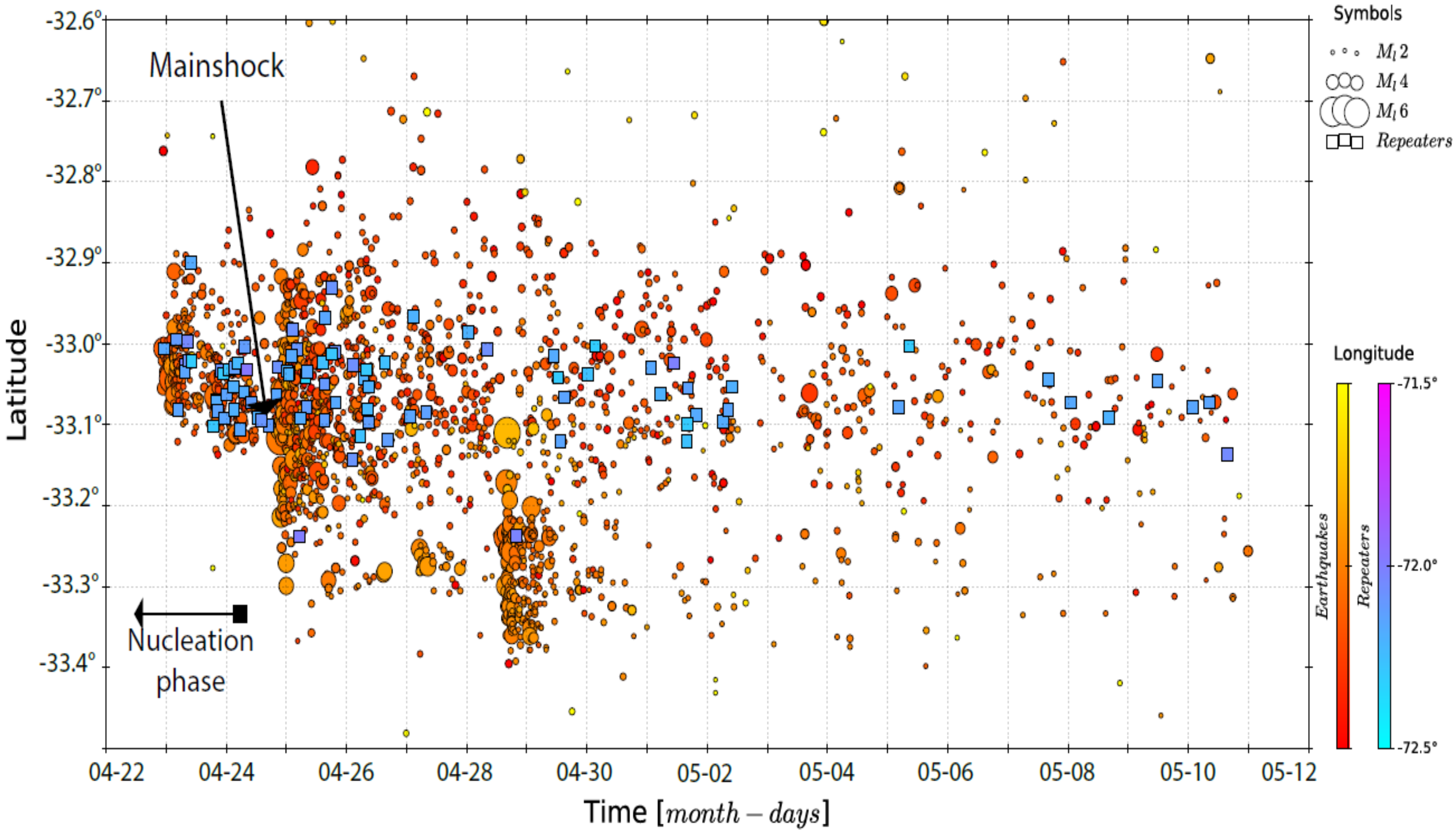
Nealy et al, 2017

Seismicity of central Chile from January to May 2017



Timeline of seismicity of the Valparaiso region

22 April – 12 May

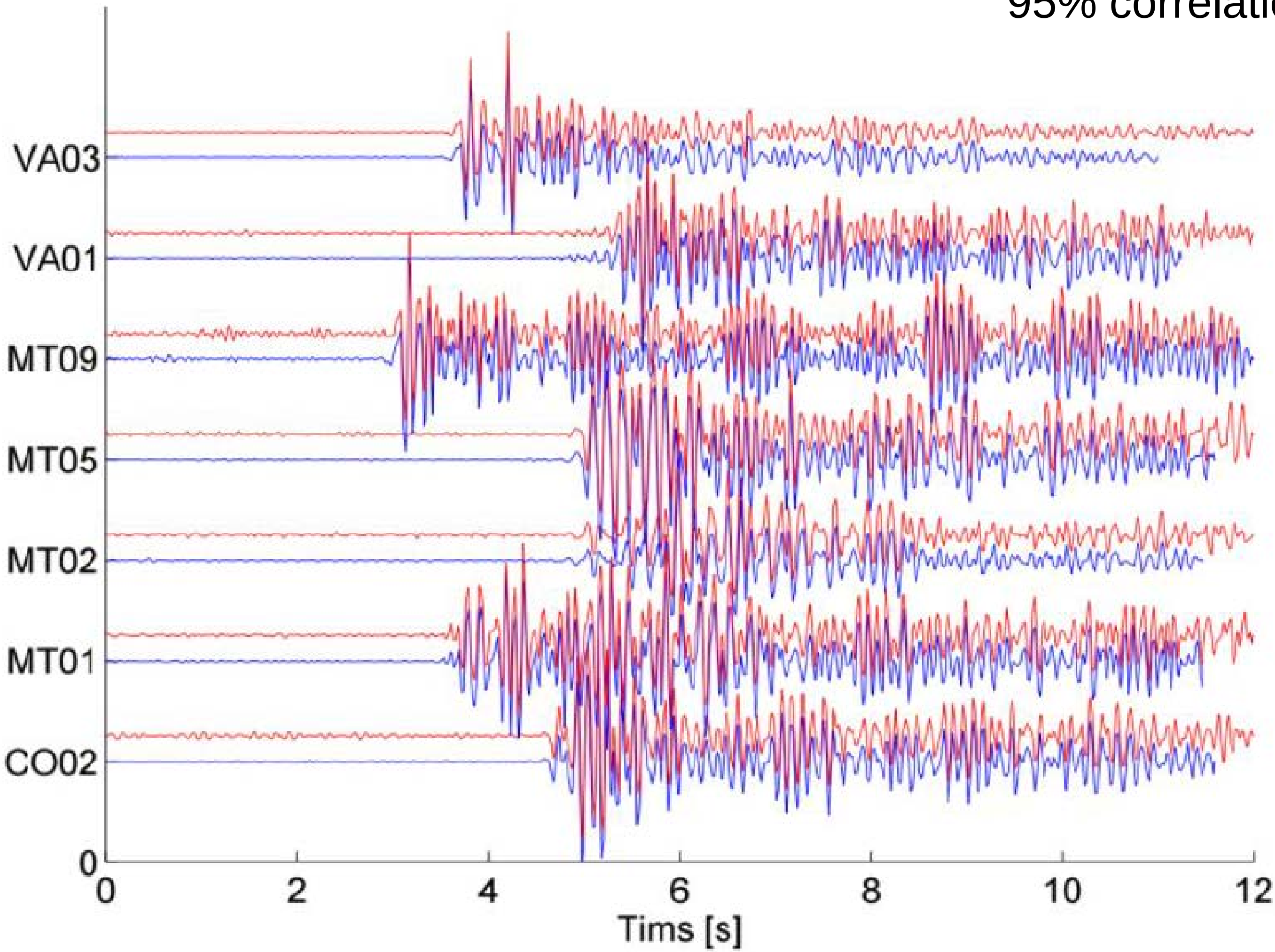


repeaters

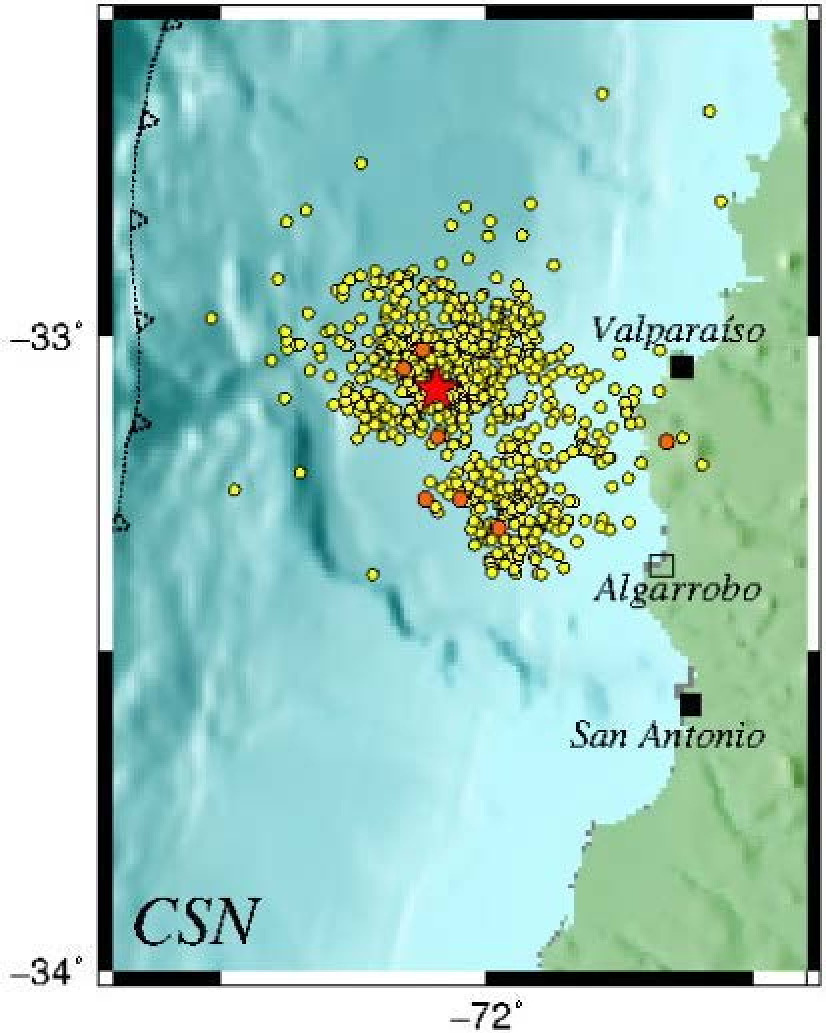
Seismic events

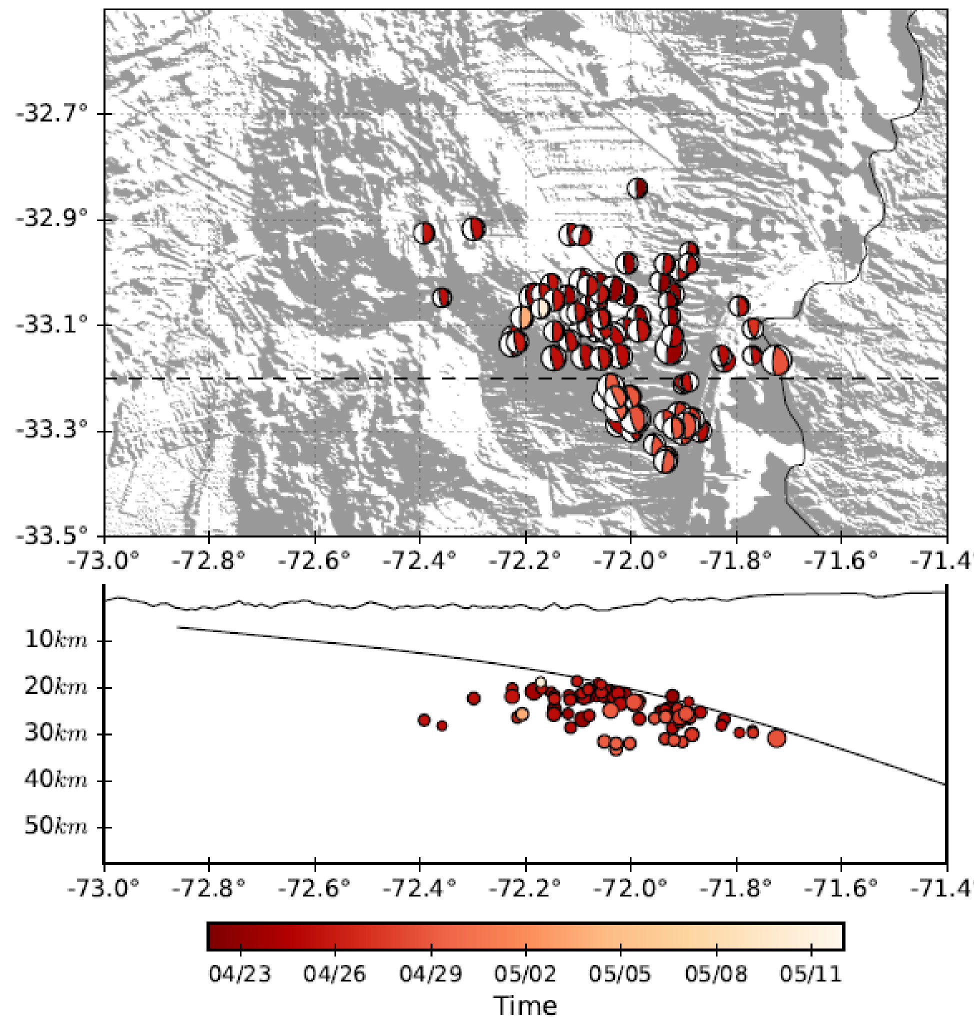
Repeaters observed at several stations

95% correlation



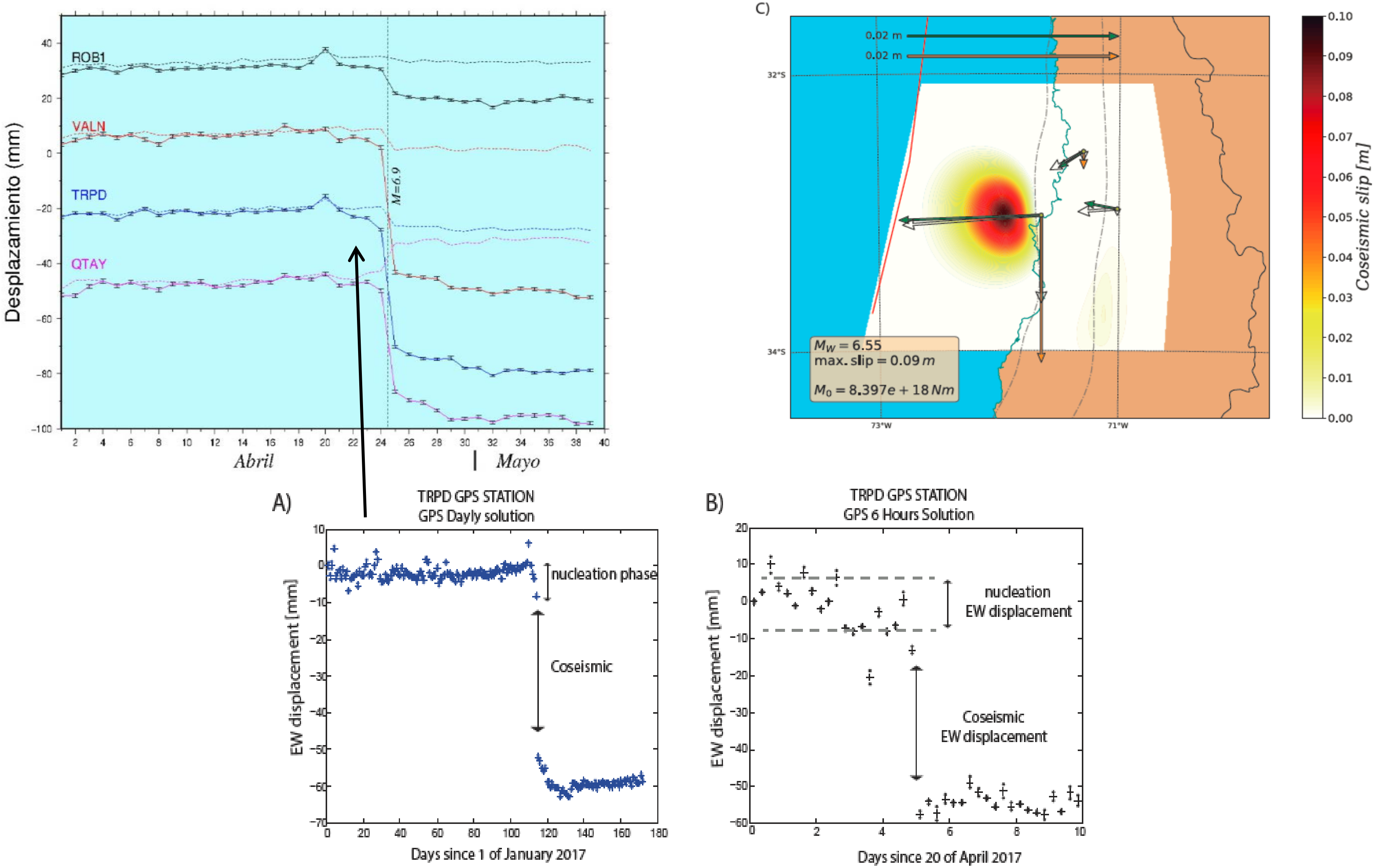
Seismicity of the 2007 Valparaiso EQ



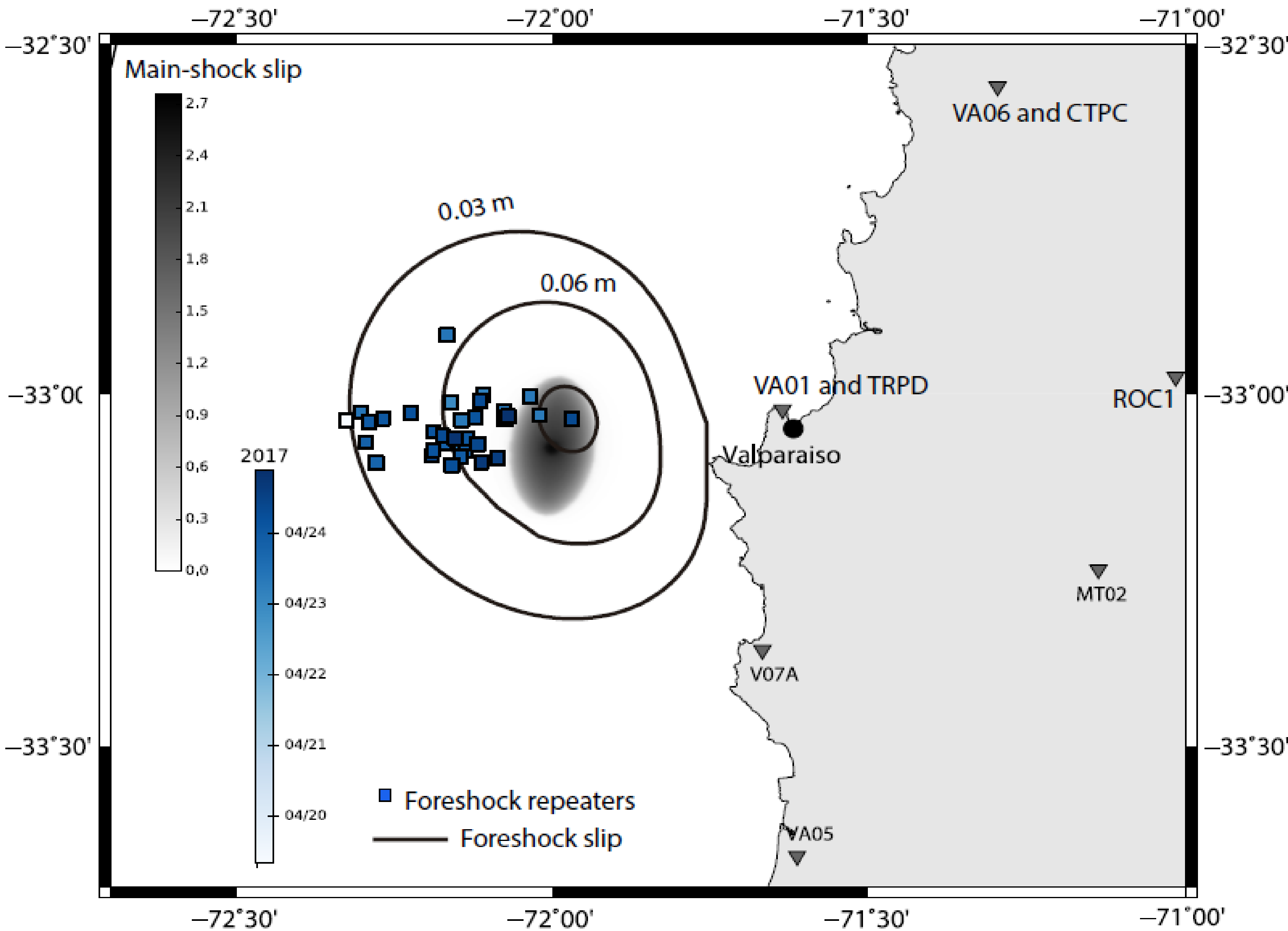


Accelerometric data

Geodesy and a possible Slow Slip precursor



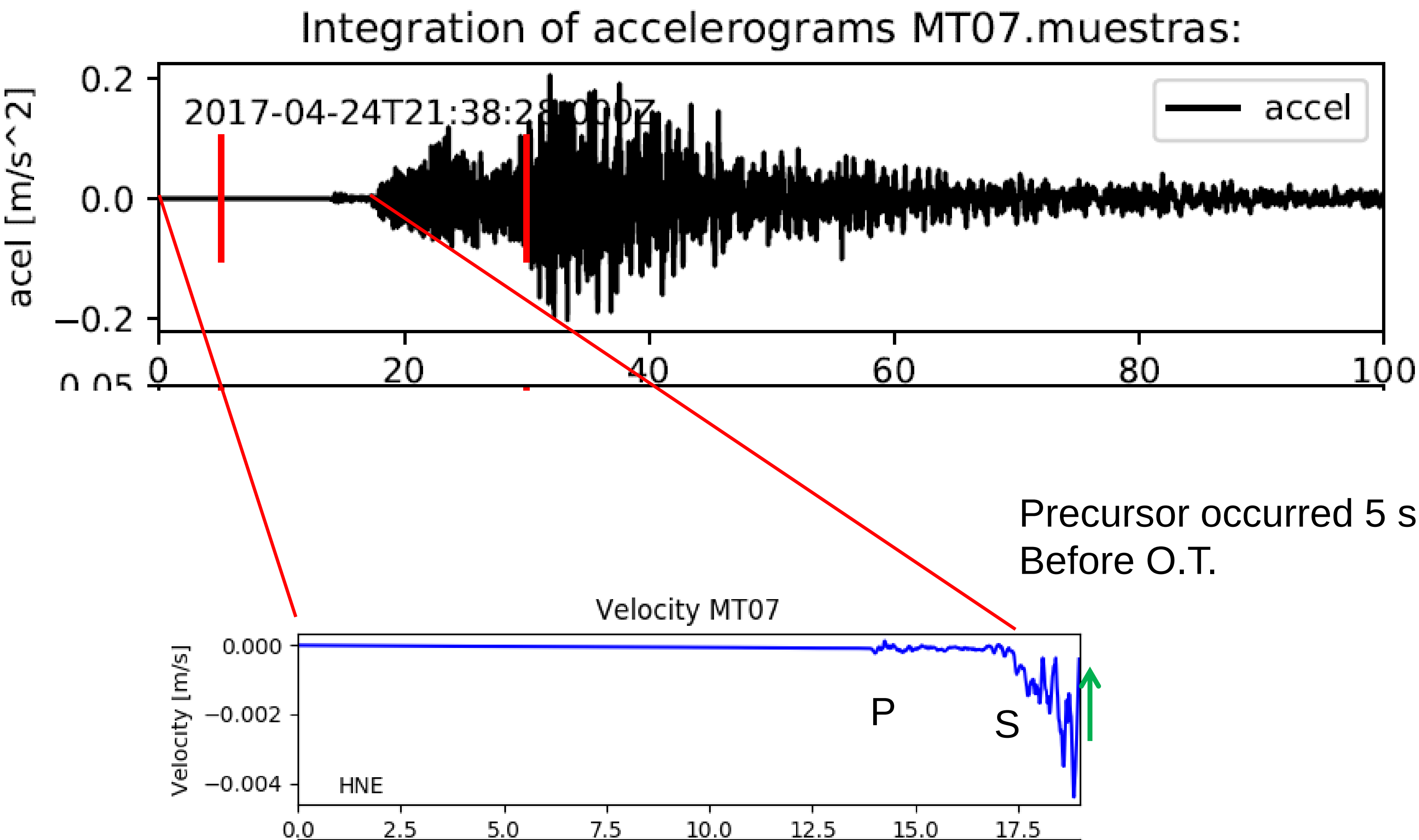
Repeaters geodesy and dynamic source



Accelerogramsof Valaparaiso earthquake

What is in them?

How did the Valparaiso earthquake start?



Precursor occurred 5 s
Before O.T.

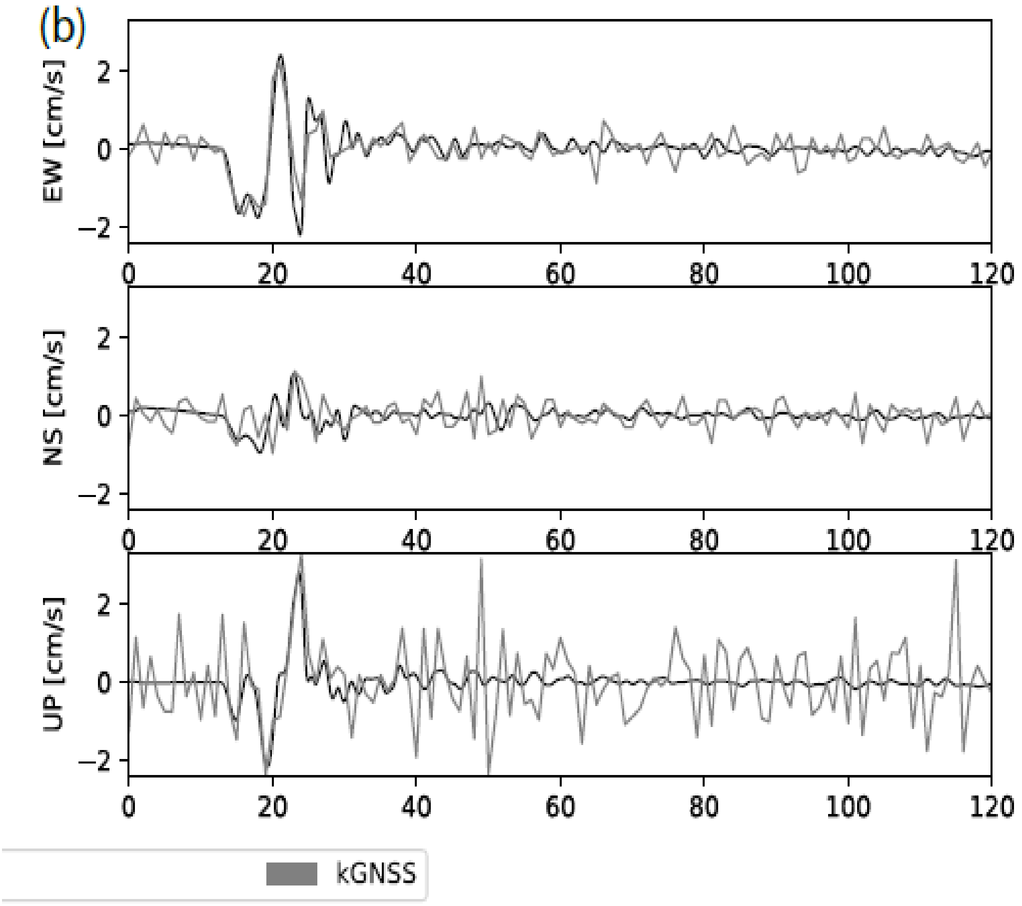
From ISC OT precursor, Mw 4.8 is 6.5s before and 6 km away from the Mainshock

Comparison of accelerogram with GPS

Ground velocity 0.01Hz 0.16 Hz

VA01 y VALN

Valparaíso 2017,

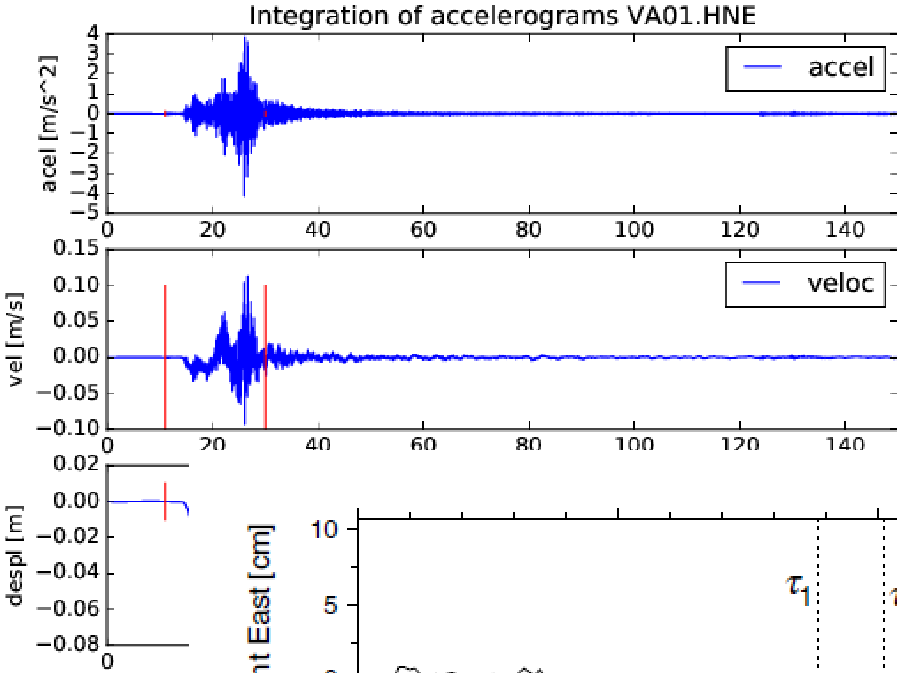


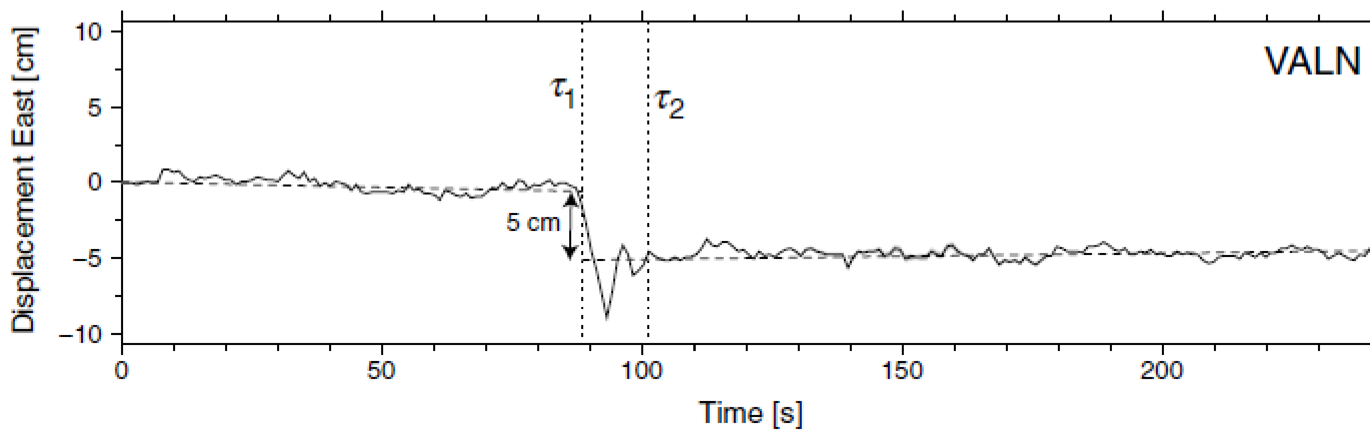
Baez et al 2017

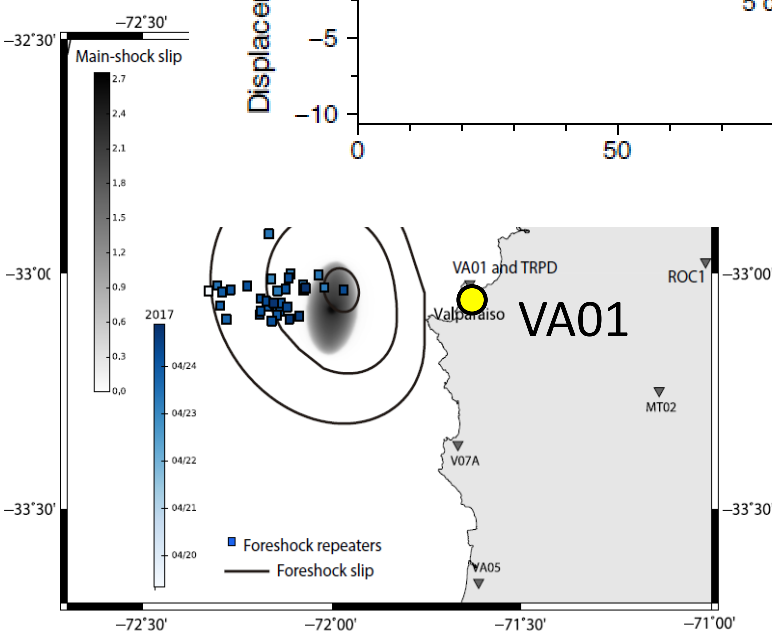
Nearest station VA01

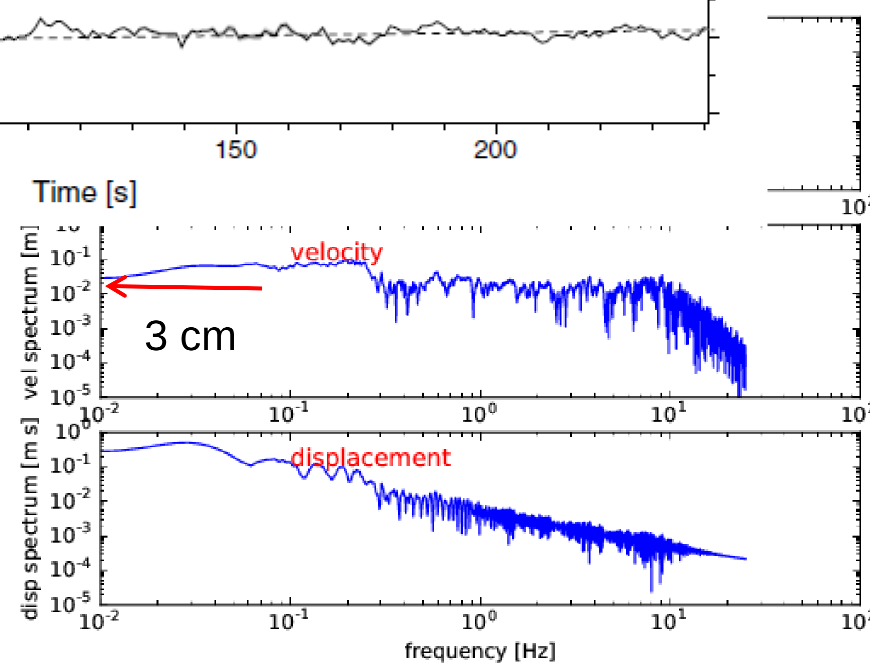
ω^{-1} spectrum

ield



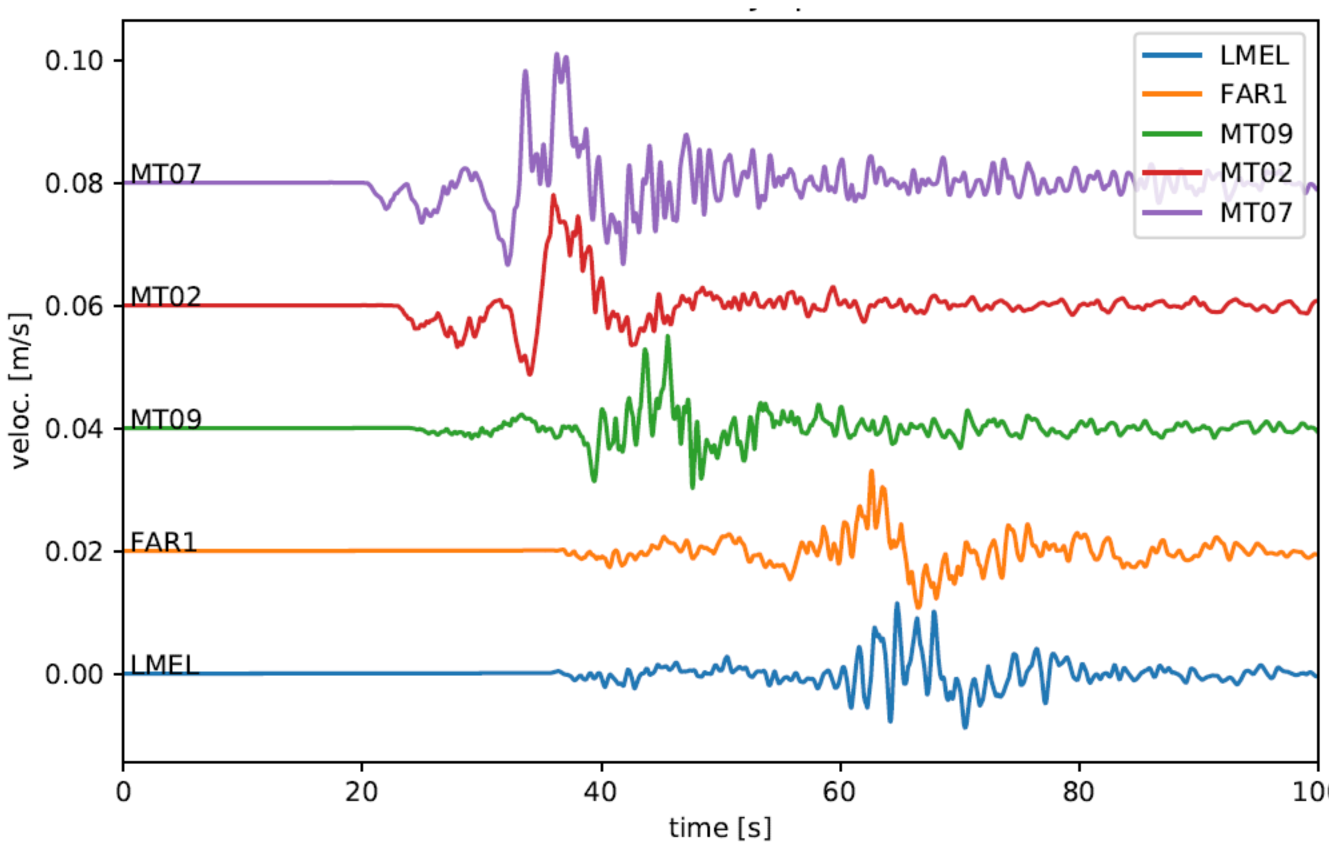


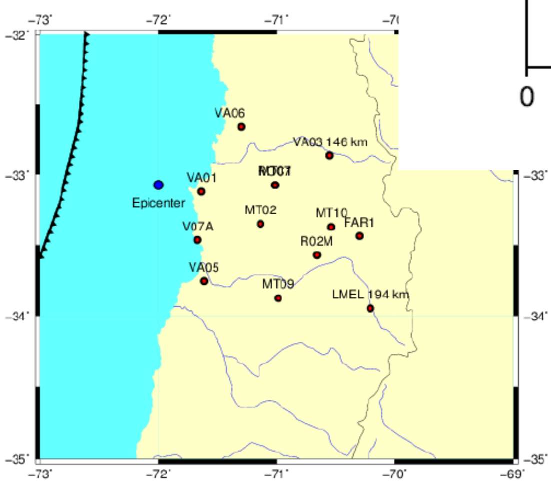


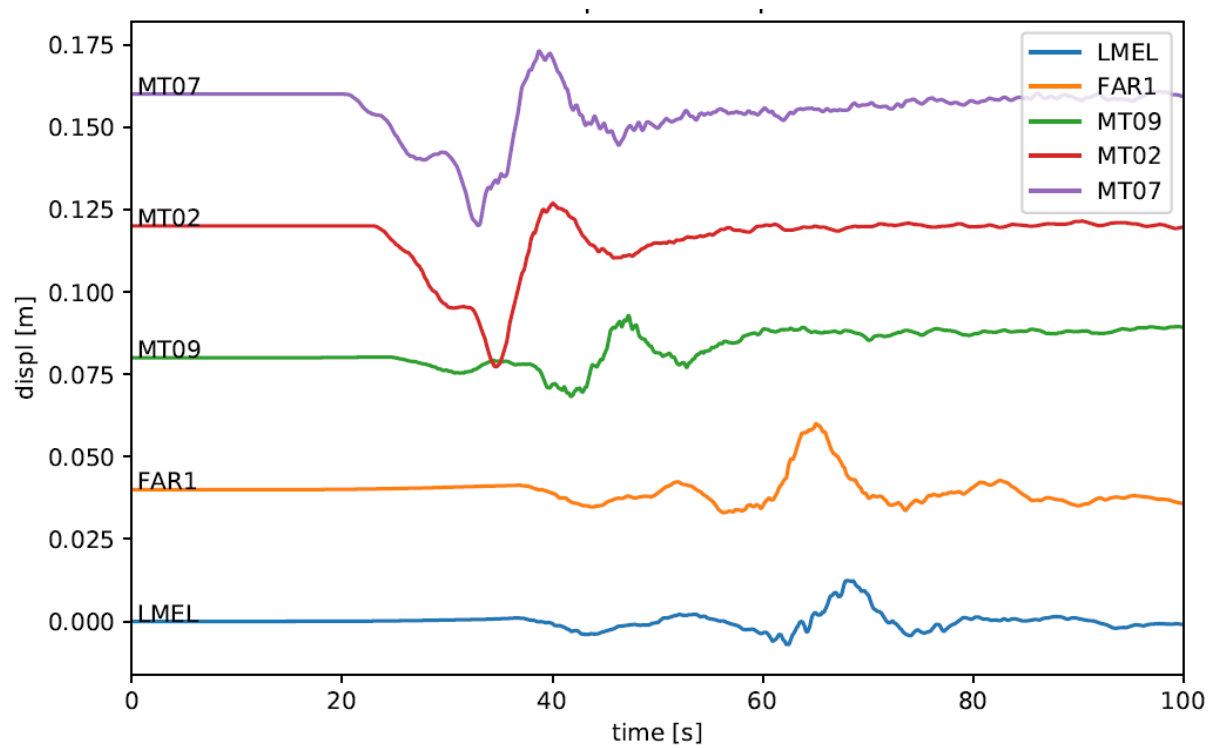


Ground velocity observed after the 2017 earthquake

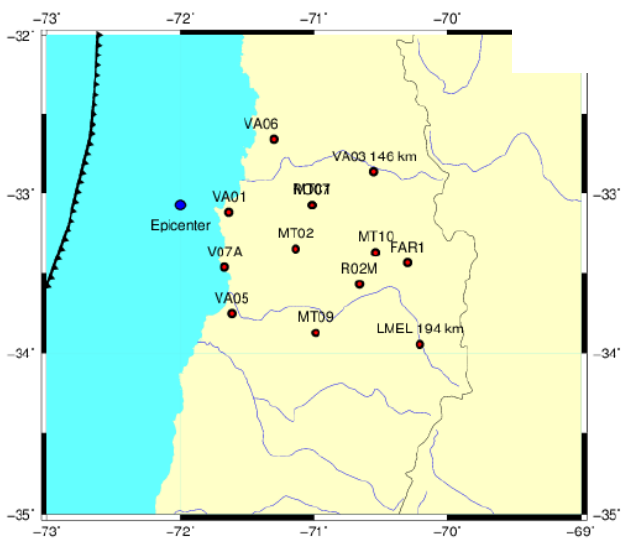
Valparaiso
24/04/17







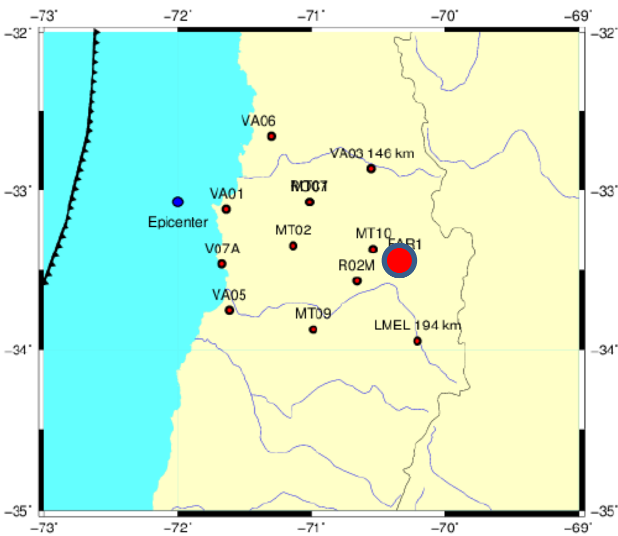
MT07
MT02
MT09
FAR1
LMEL
LMEL
FAR1
MT09
MT02
MT07
displ [m]
time [s]

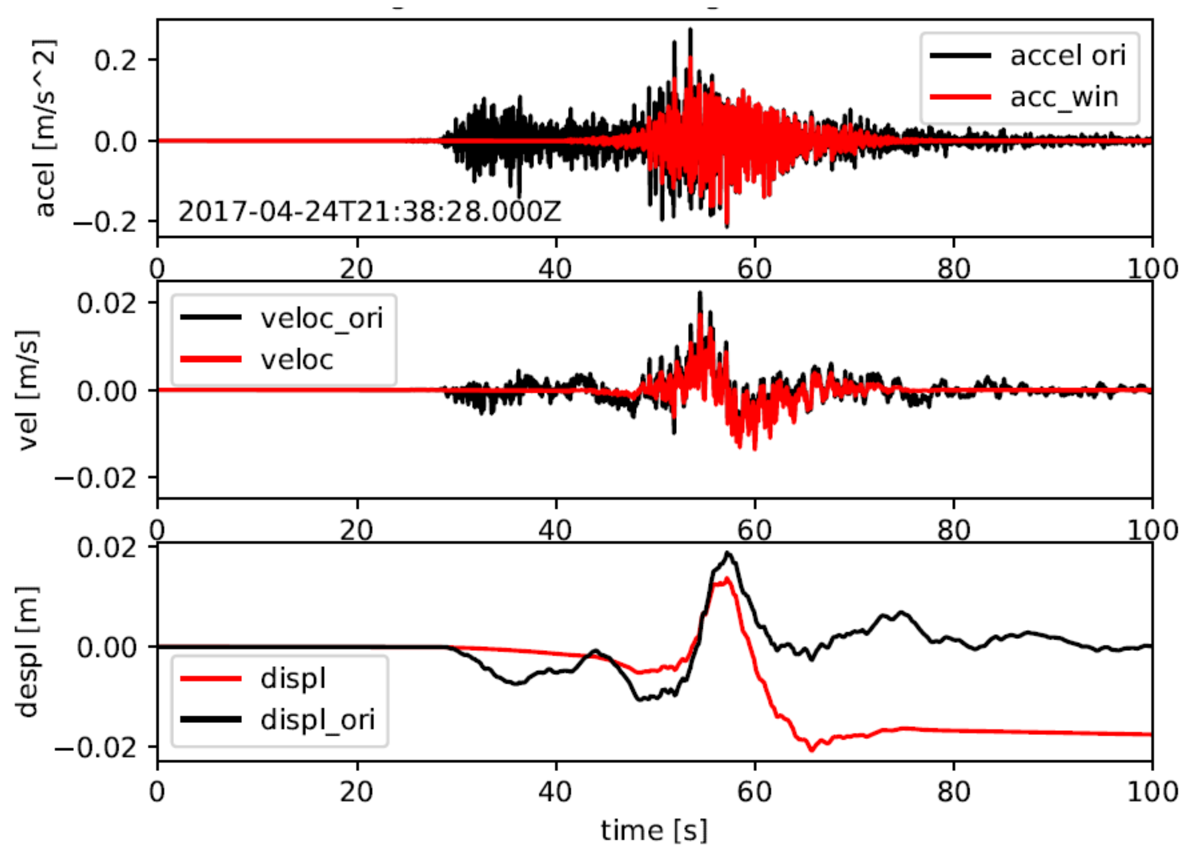


VA06
VA03 146 km
VA01
Epicenter
MT02
MT10
FAR1
V07A
R02M
VA05
MT09
LMEL 194 km

Transition to Brune spectrum at FAR1 accelerometer

S wave at 120 km

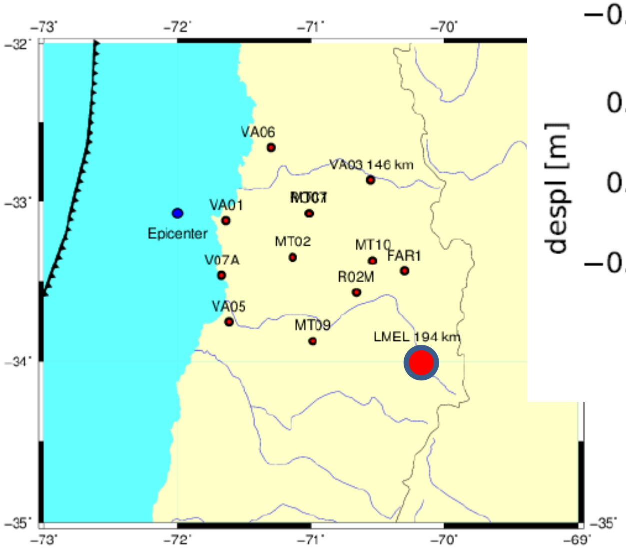


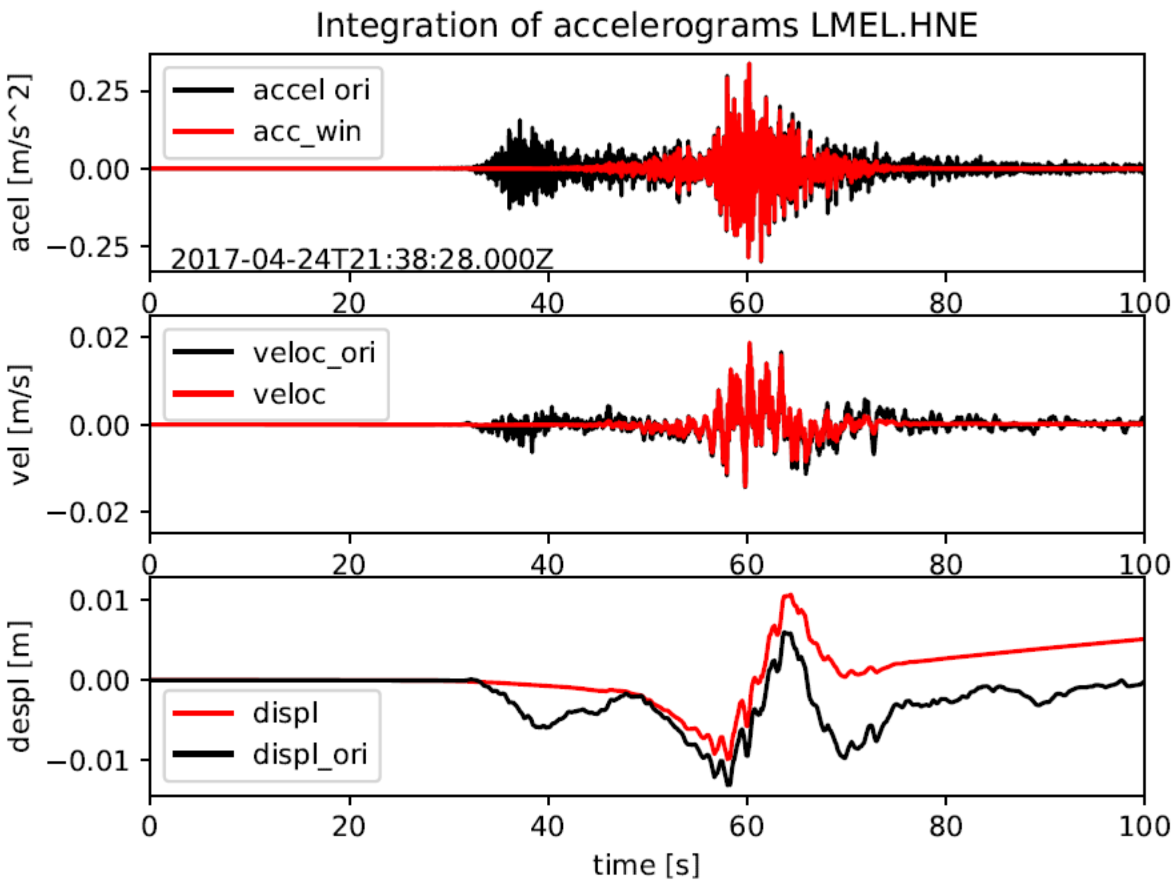


Black original accelerogram
Red windowed S wave

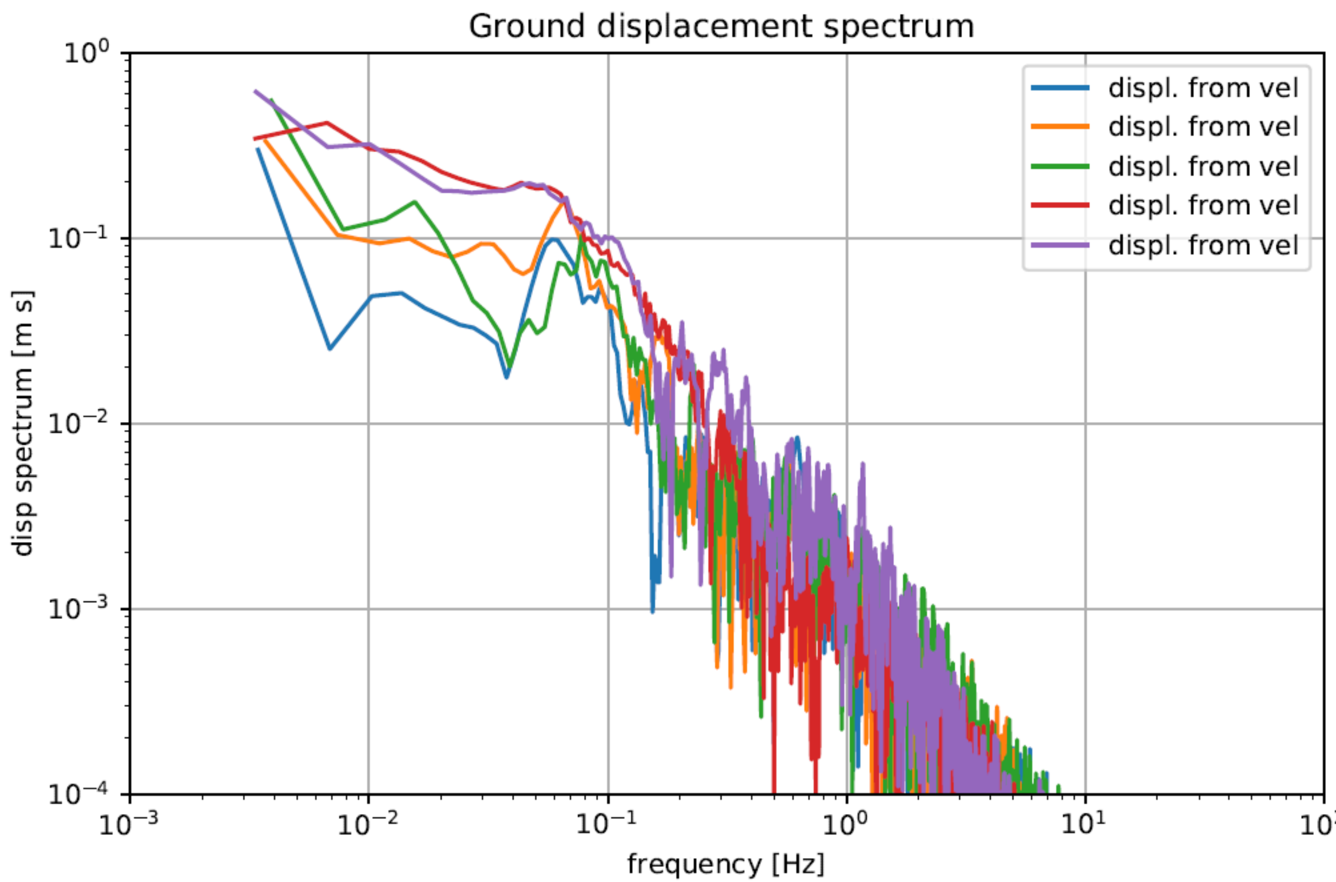
Transition to Brune spectrum at LMEL accelerometer

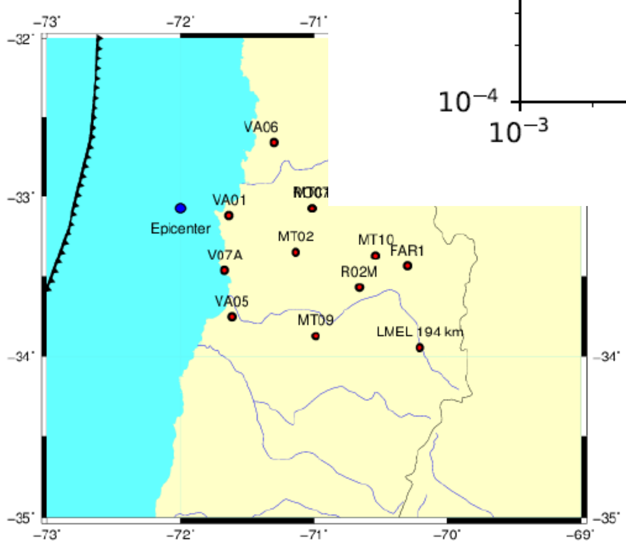
S wave at 150 km

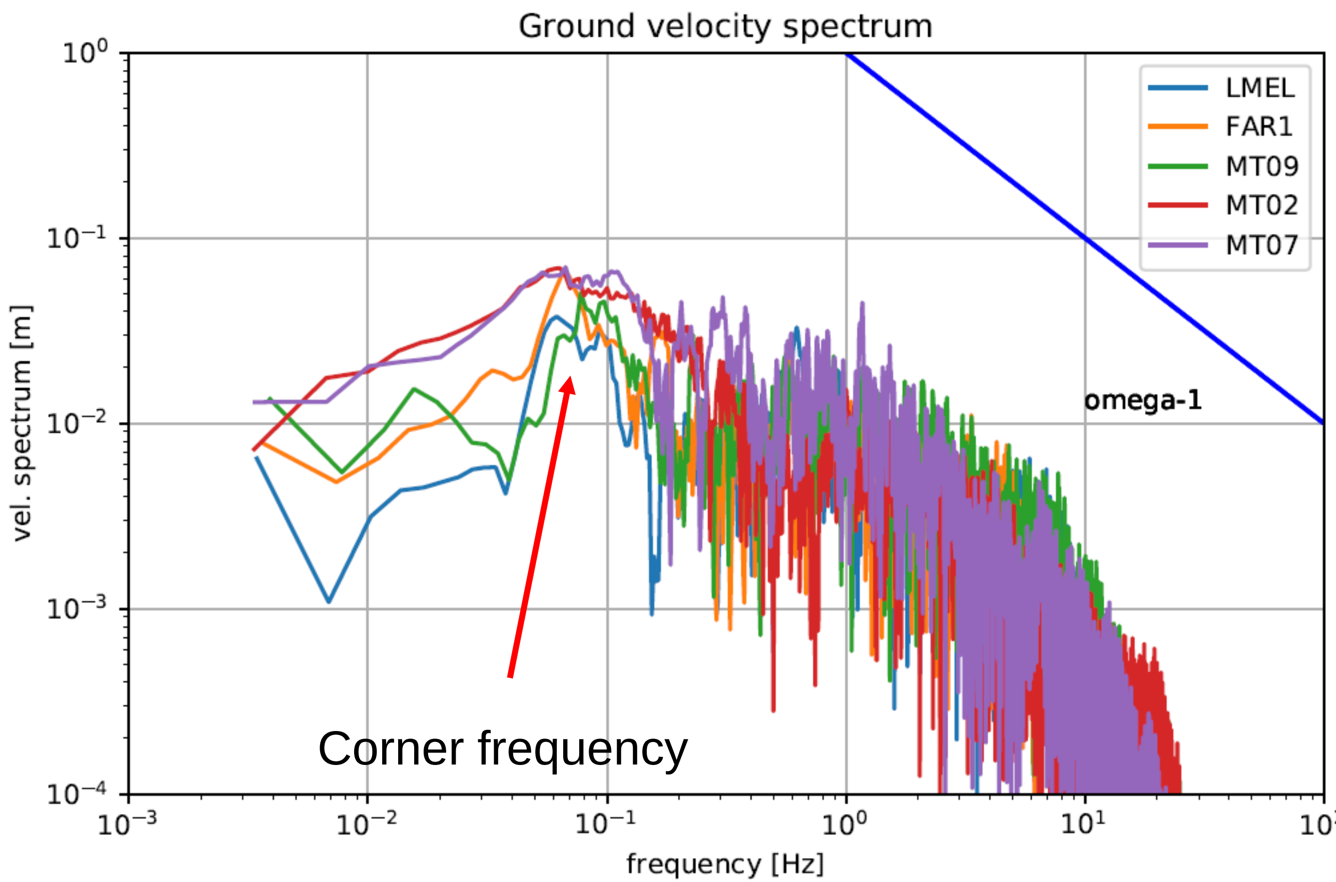


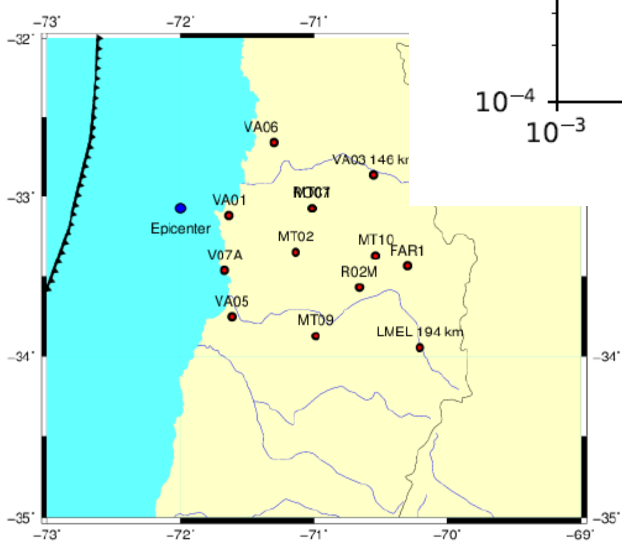


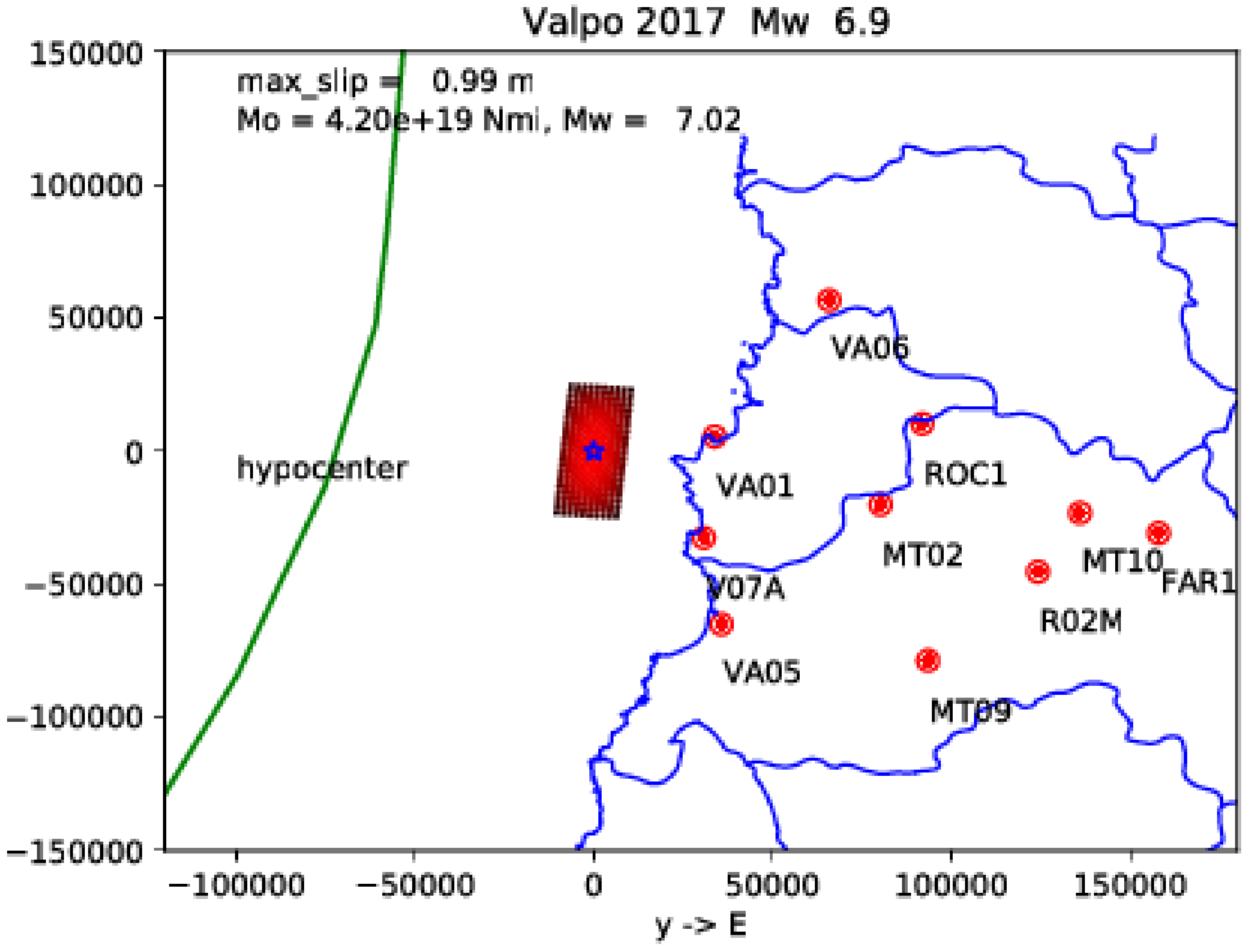
Displacement spectrum at a subset of 5 stations






Ground velocity spectrum
vel. spectrum [m]
frequency [Hz]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
LMEL
FAR1
MT09
MT02
MT07
omega-1
Corner frequency

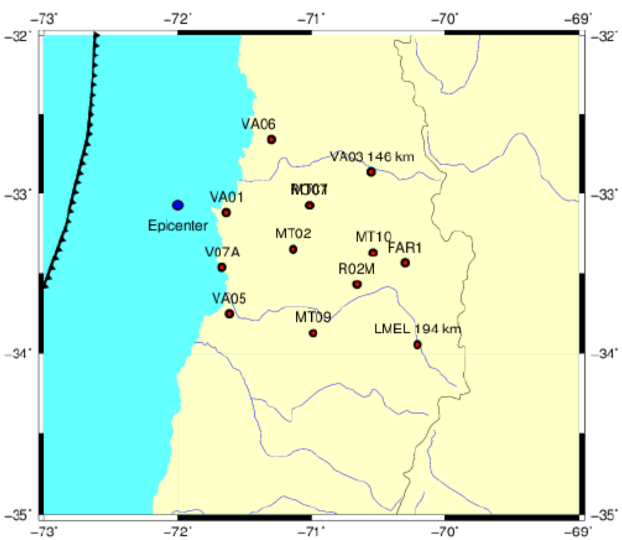

-73˚
-72˚
-71˚
-70˚
-69˚
-32˚
-33˚
-34˚
-35˚
VA06
VA03 146 km
VA01
MT07
Epicenter
MT02
MT10
FAR1
V07A
R02M
VA05
MT09
LMEL 194 km

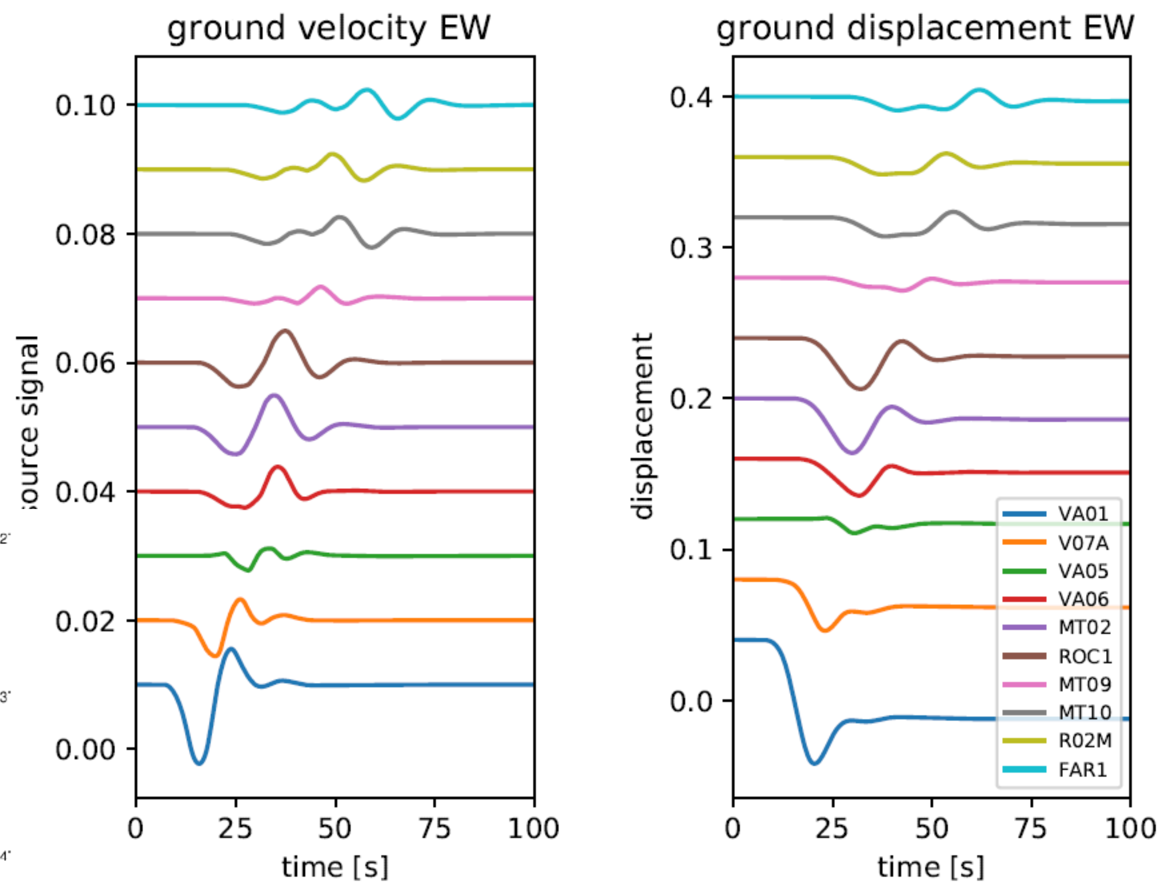


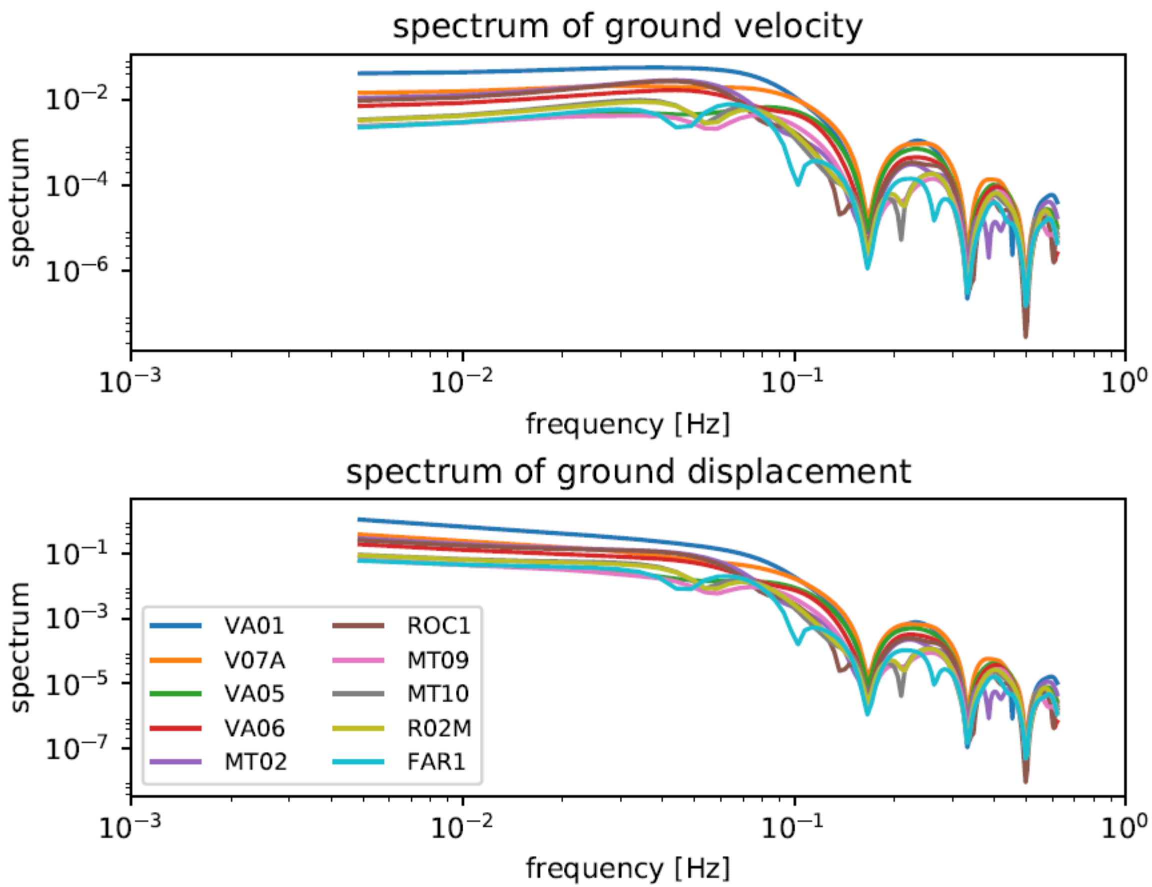
Propagation with axitra (Bouchon et al)

Vélocity model from Ruiz et al (2017)

Valparaiso earthquake 2017 :
synthetic ground motion at selected stations

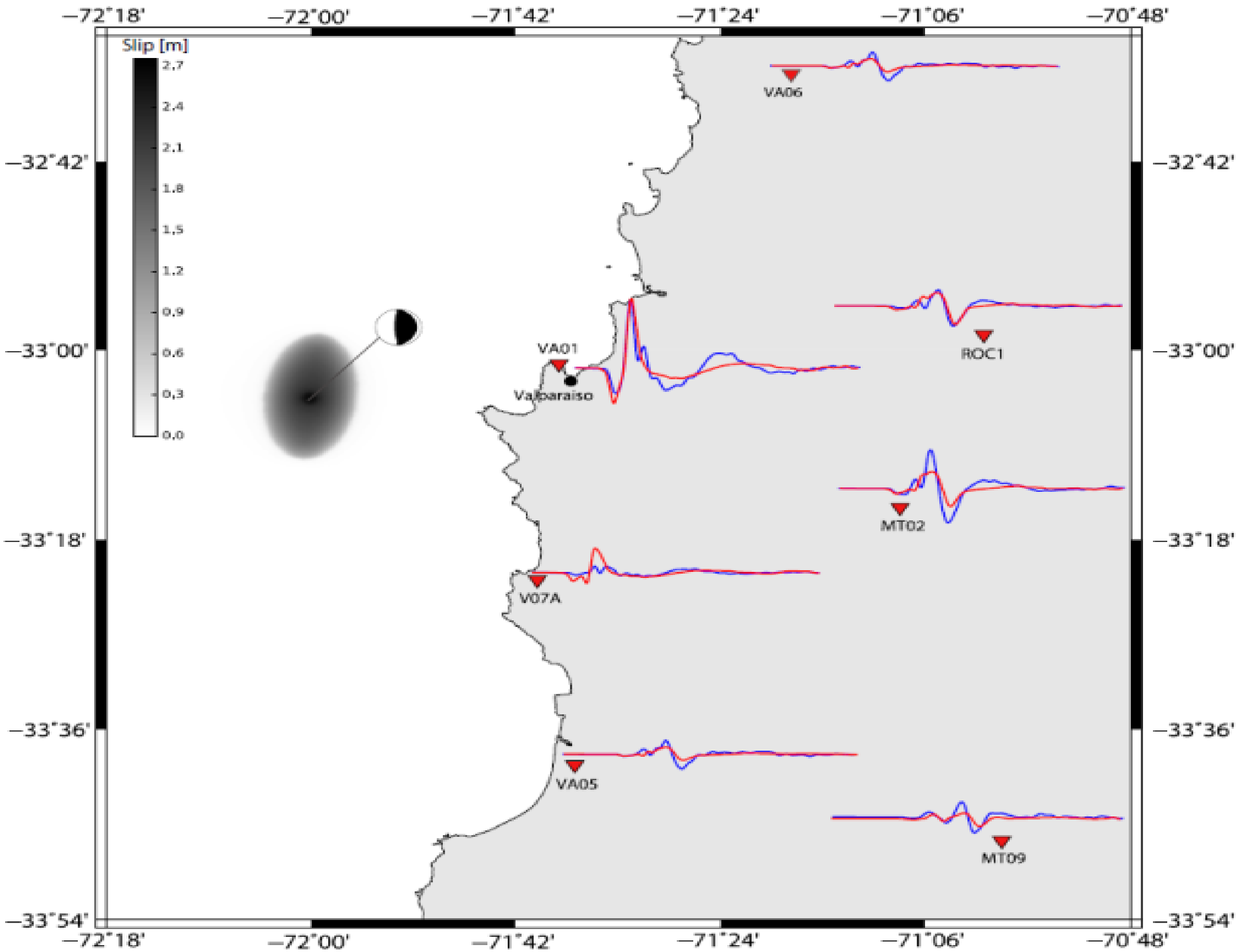






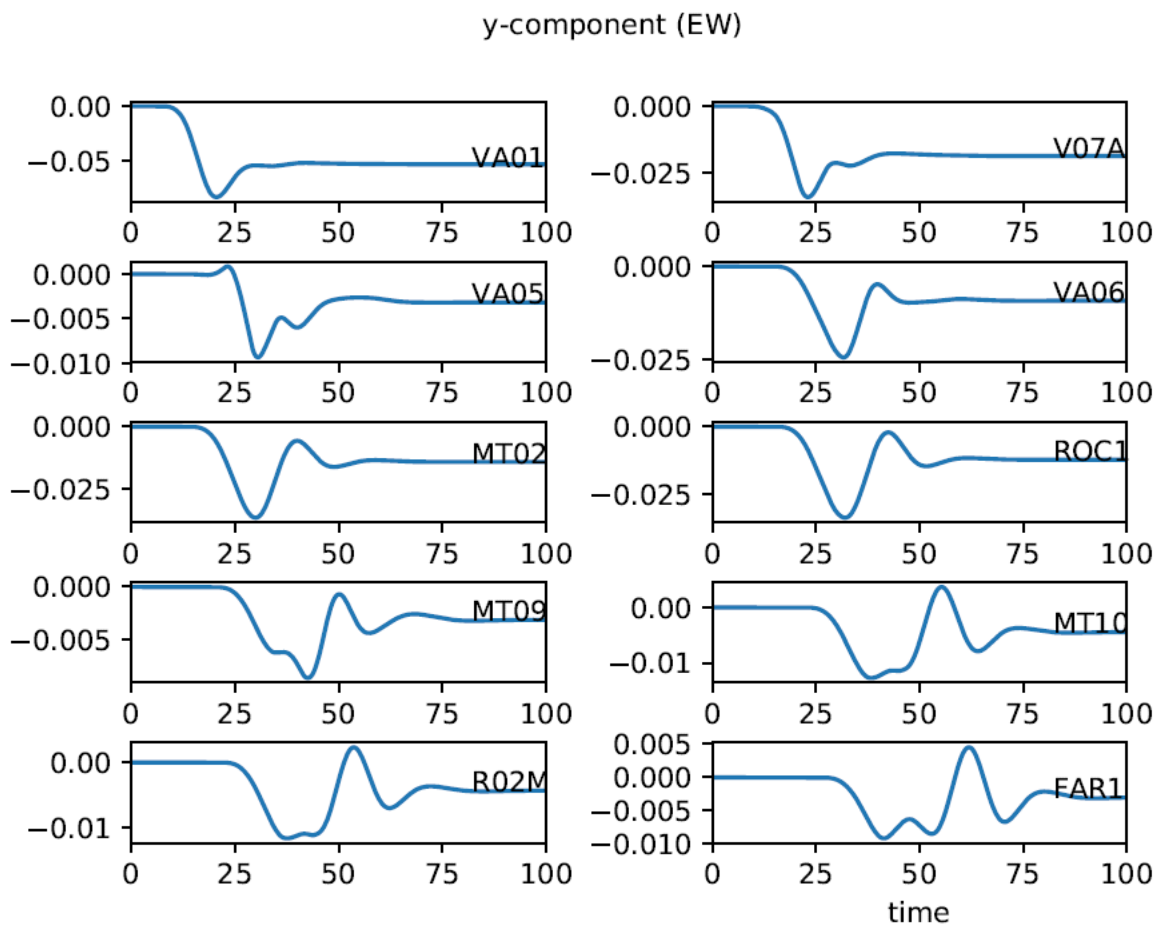
spectrum of ground velocity
spectrum
10^{-2}
10^{-4}
10^{-6}
10^{-3}
10^{-2}
10^{-1}
10^{0}
frequency [Hz]
spectrum of ground displacement
spectrum
10^{-1}
10^{-3}
10^{-5}
10^{-7}
VA01
V07A
VA05
VA06
MT02
ROC1
MT09
MT10
R02M
FAR1
10^{-3}
10^{-2}
10^{-1}
10^{0}
frequency [Hz]

Dynamic inversion of the event source

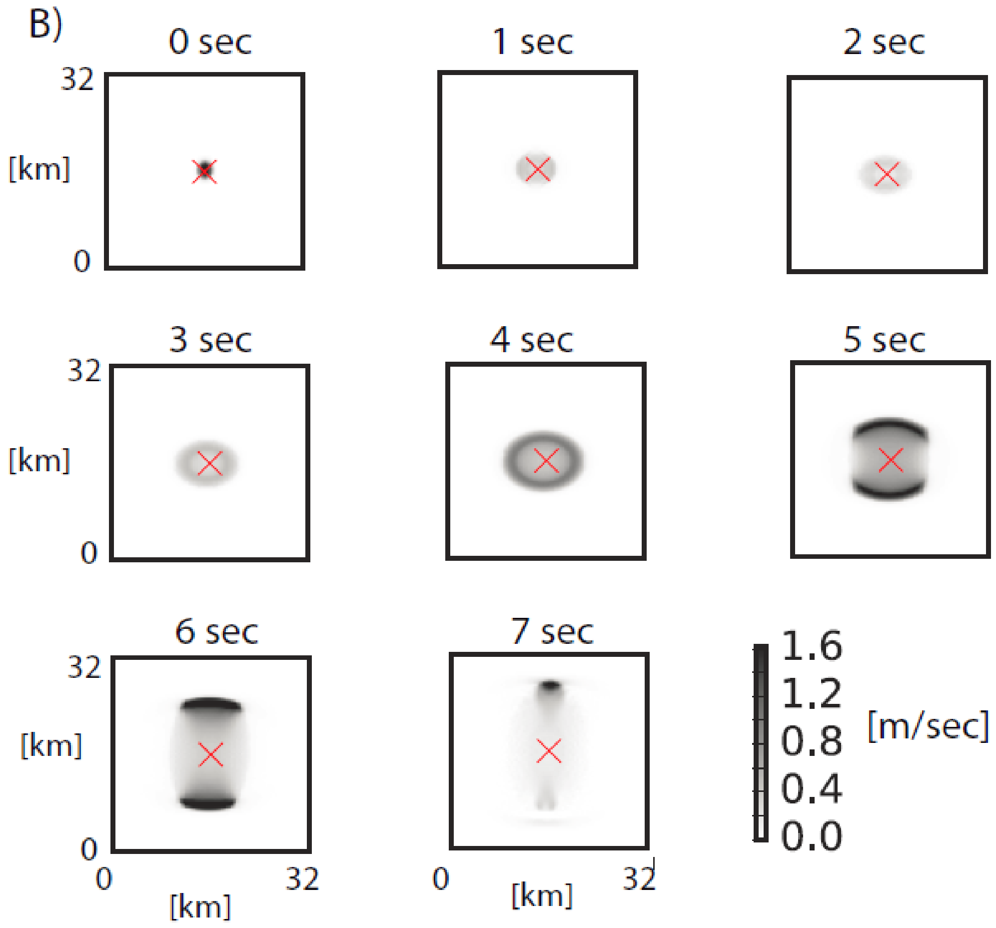


Te= 11.71 [MPa]
Tu = 17.21 [MPa]
Dc = 0.65

7 integrated accelerograms 0.02 0.1 Hz

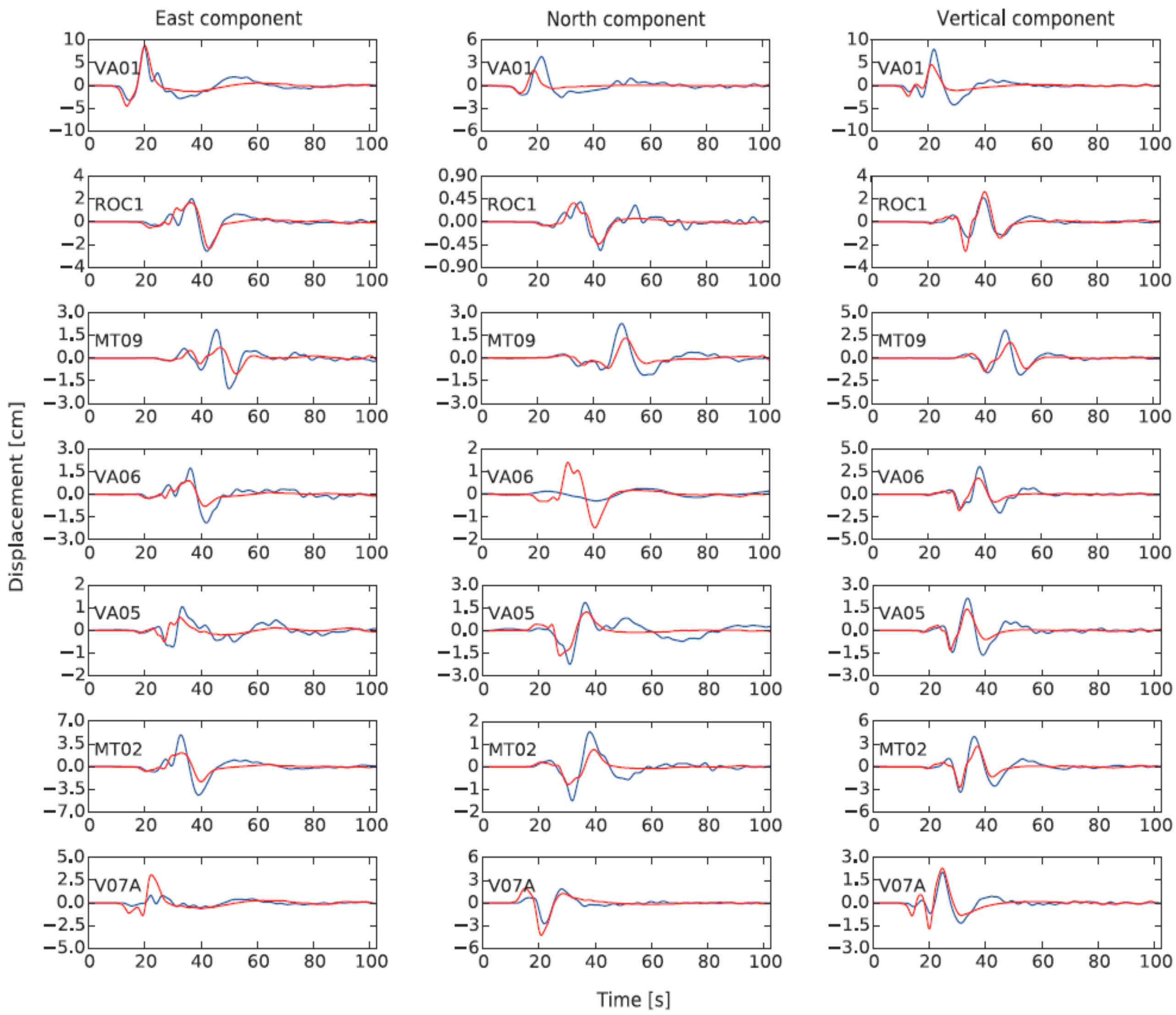

y-component (EW)
VA01
V07A
VA05
VA06
MT02
ROC1
MT09
MT10
R02M
FAR1
time

Rupture process inverted from accelerogams

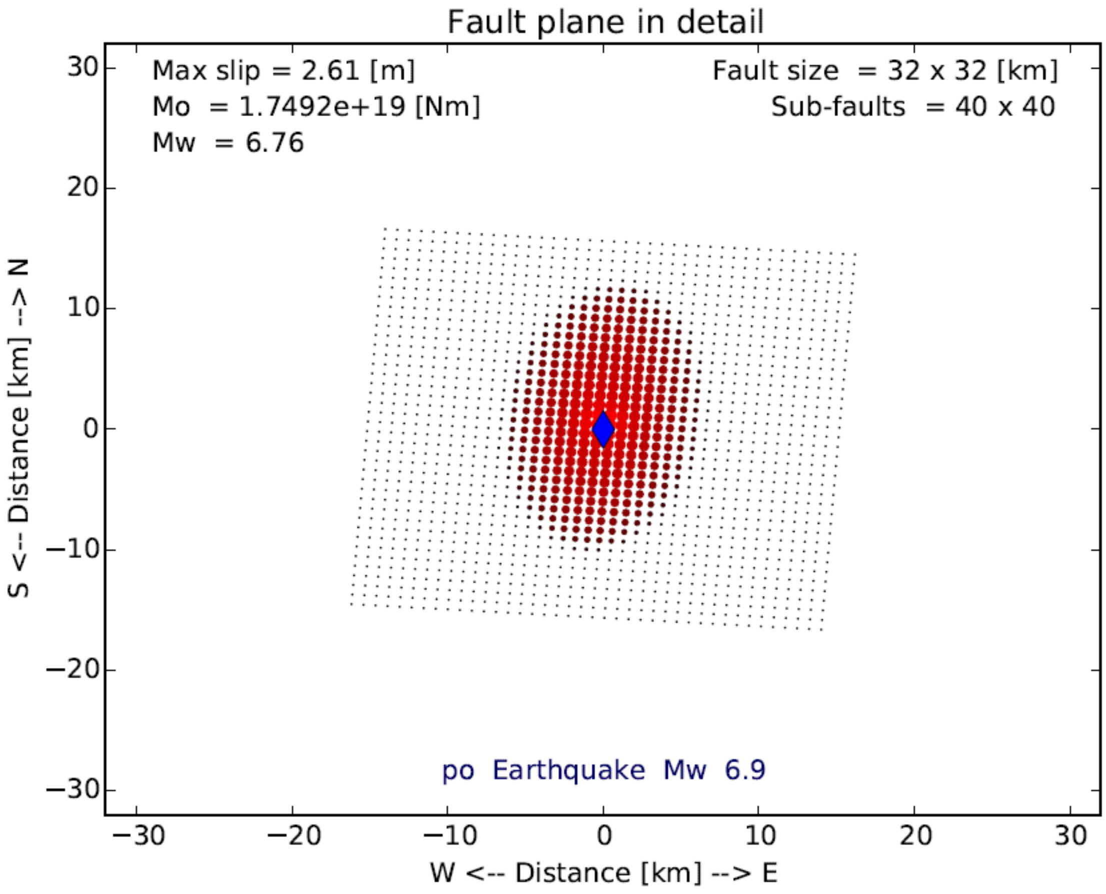


Te= 11.71 [MPa]
Tu = 17.21 [MPa]
Dc = 0.65

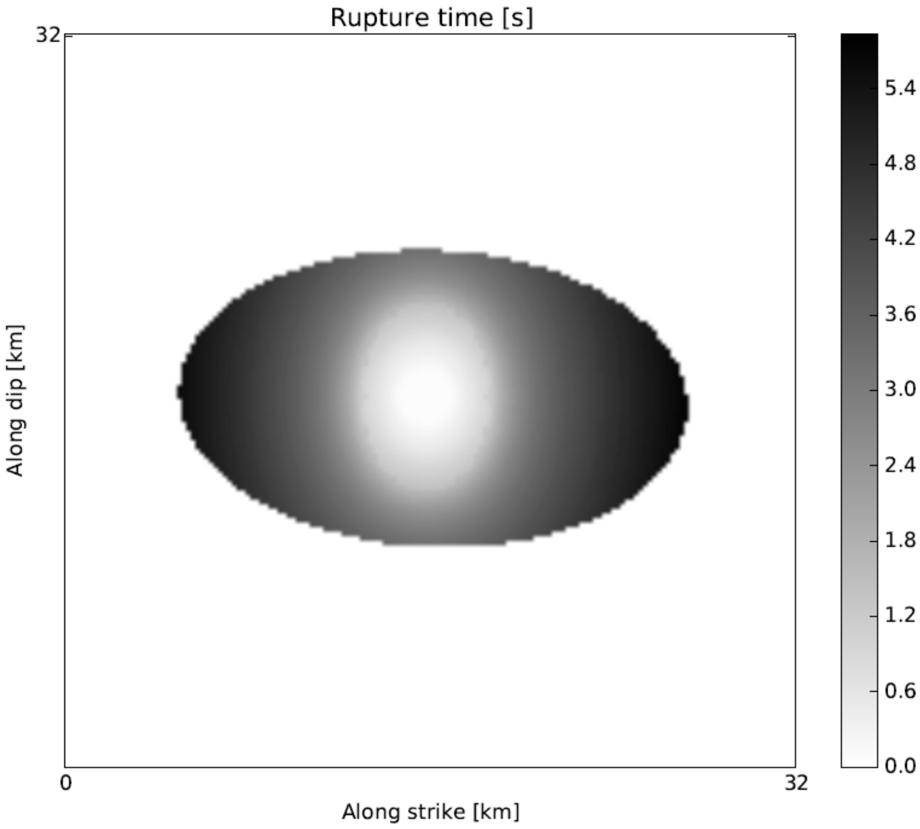
Dynamic inversion of accelerograms

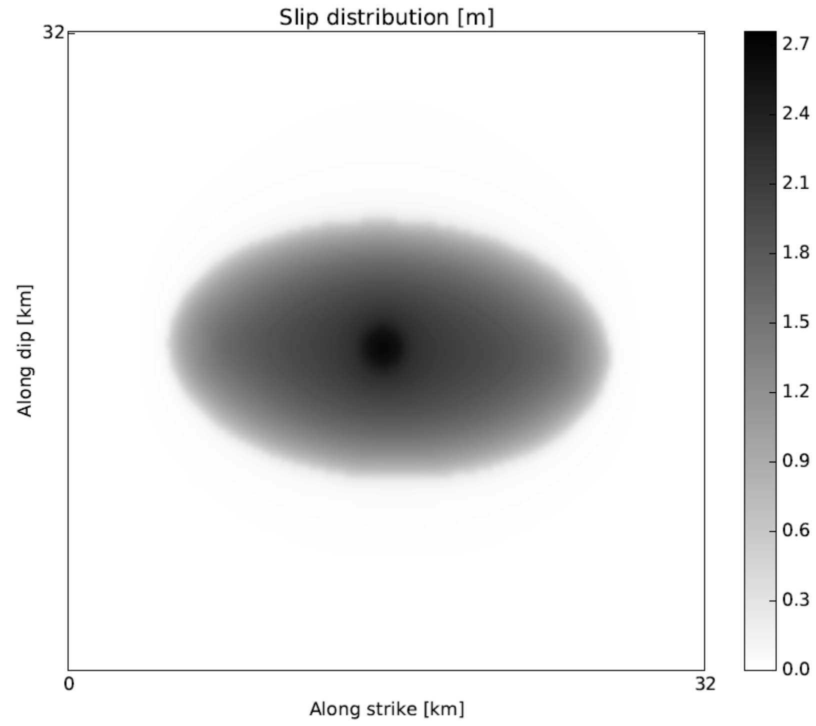


Dynamic inversion of accelerograms

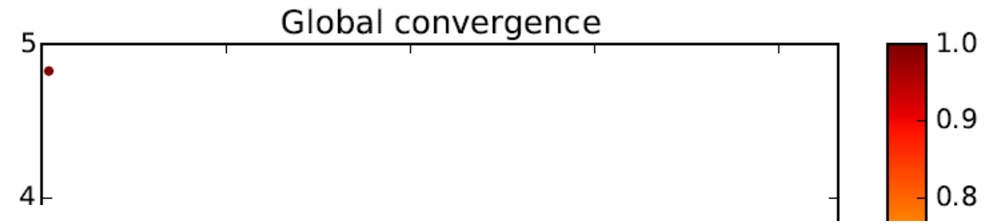


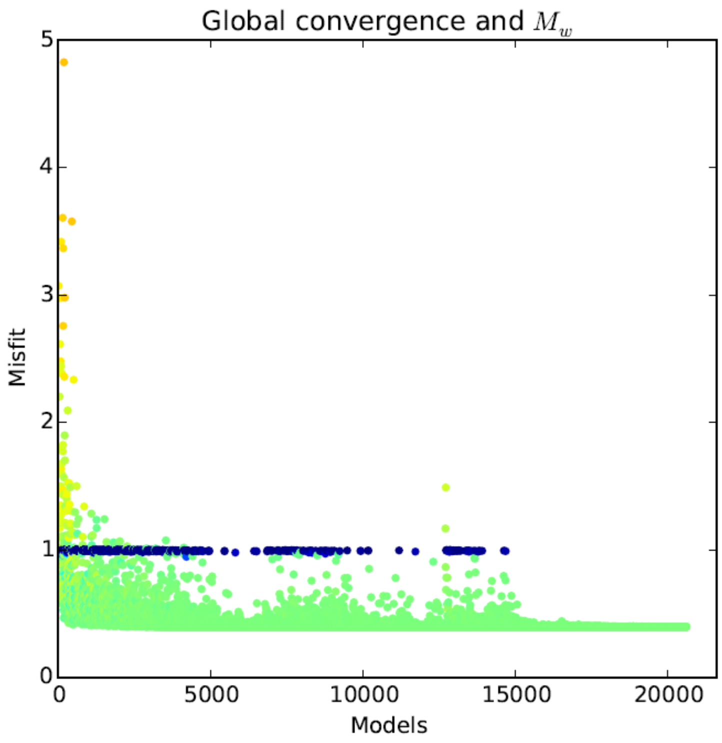
Dynamic inversion of accelerograms

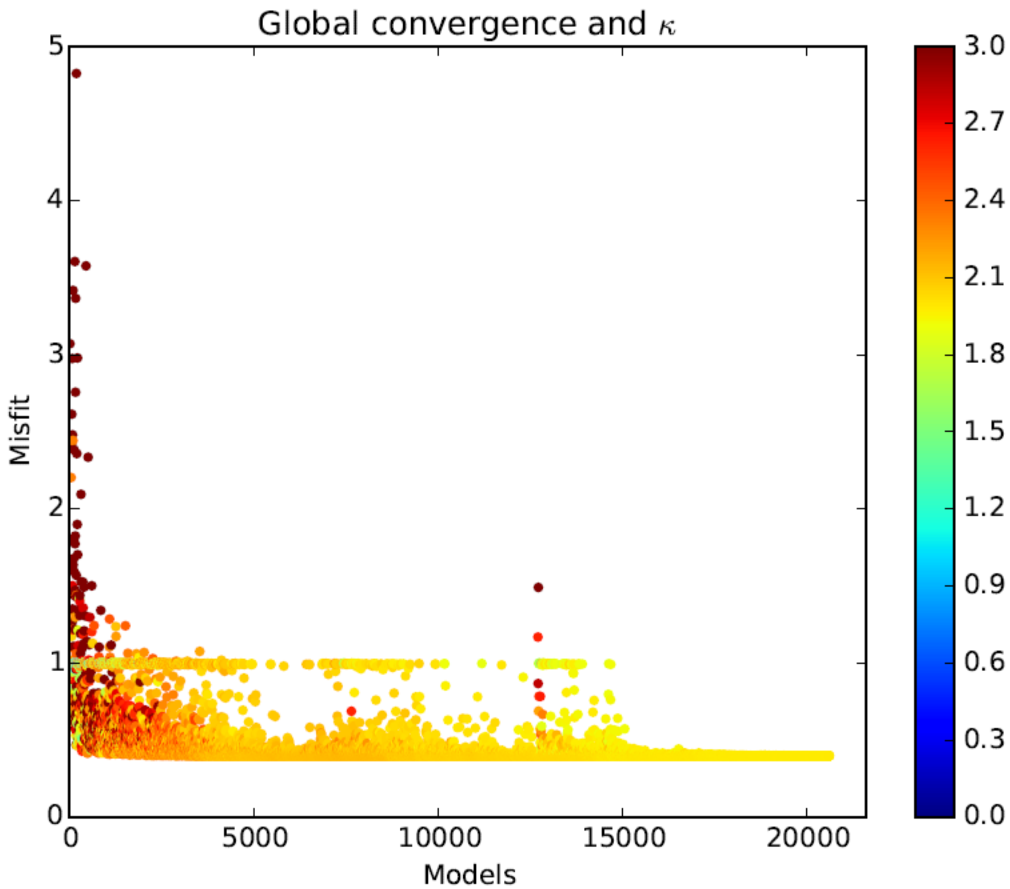


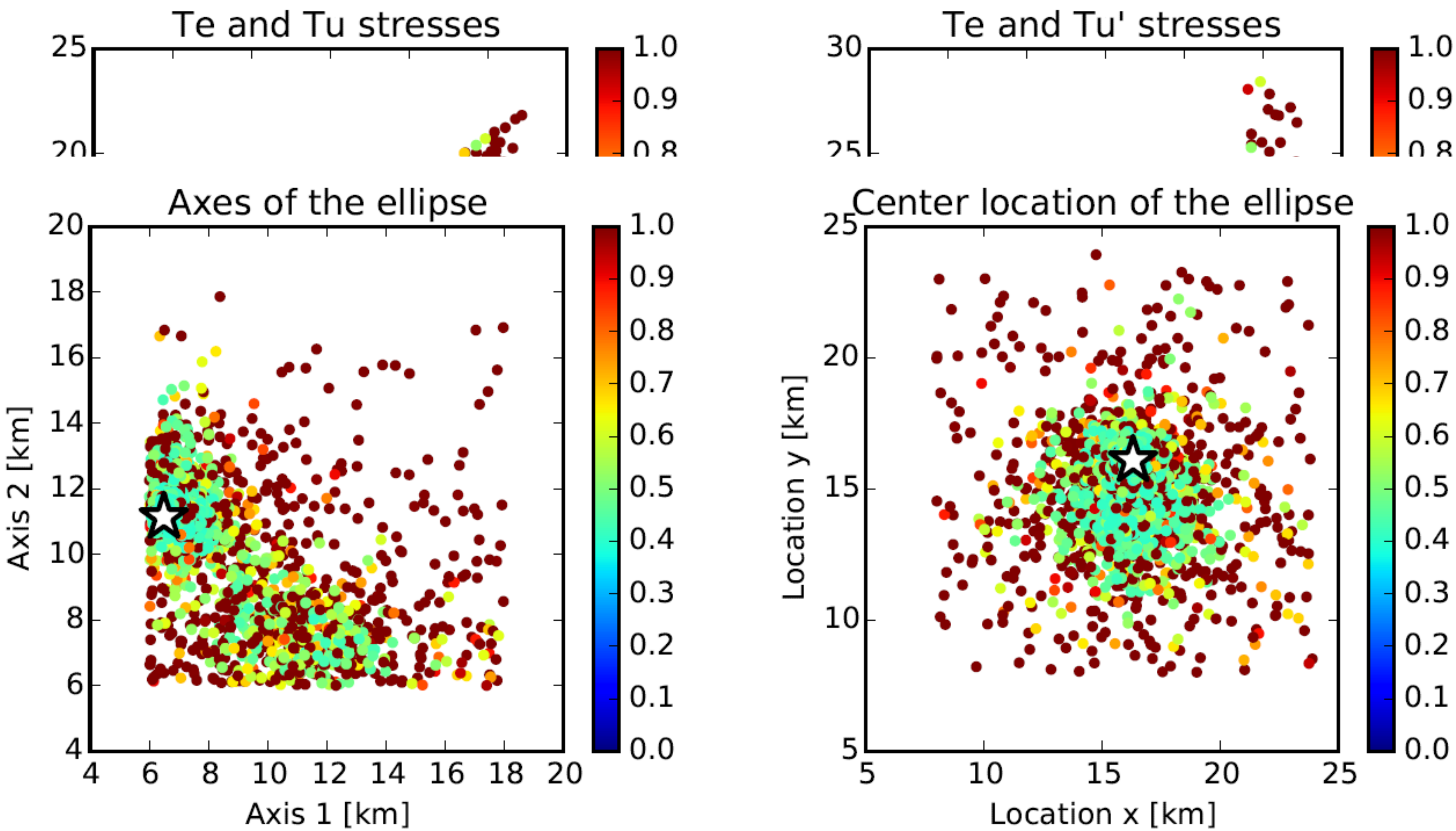


Dynamic inversion of accelerograms

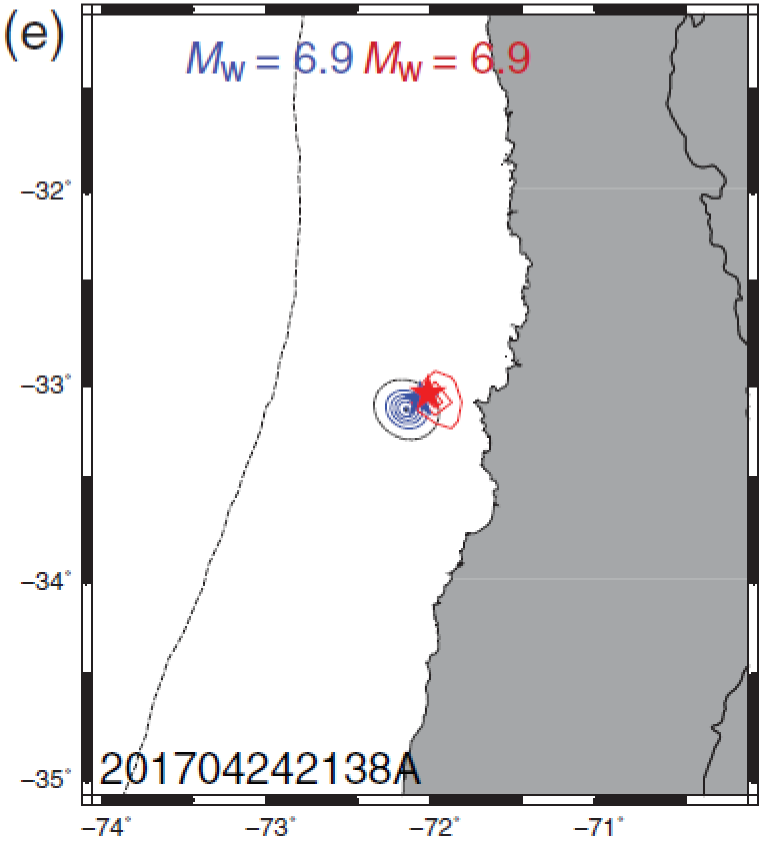







Te and Tu stresses
Te and Tu' stresses
Axes of the ellipse
Axis 1 [km]
Axis 2 [km]
Center location of the ellipse
Location x [km]
Location y [km]
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

Inversion using simple elliptical patches



After Leyton, Ruiz, Madariaga SRL 2018

Conclusion

In the near field the scaling of suduction earthquake spectra is completely different from the far field

Near field long period spectra is dominated by static near field

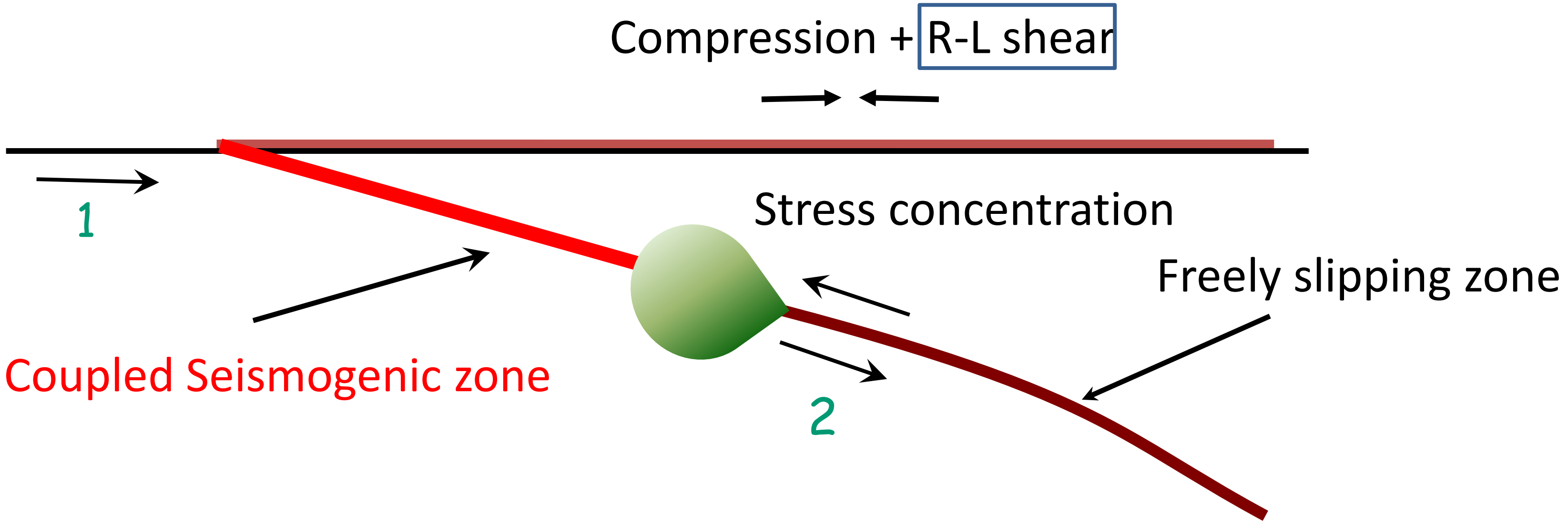
Chilean earthquakes have an earthquake spectrum that is different from Brune, Boore, Hanks, etc.

They are big in size and slip, but weak in high frequencies

Acoplamiento sismico en una zona de subduction

Modelo Clasico de Savage (o back-slip)

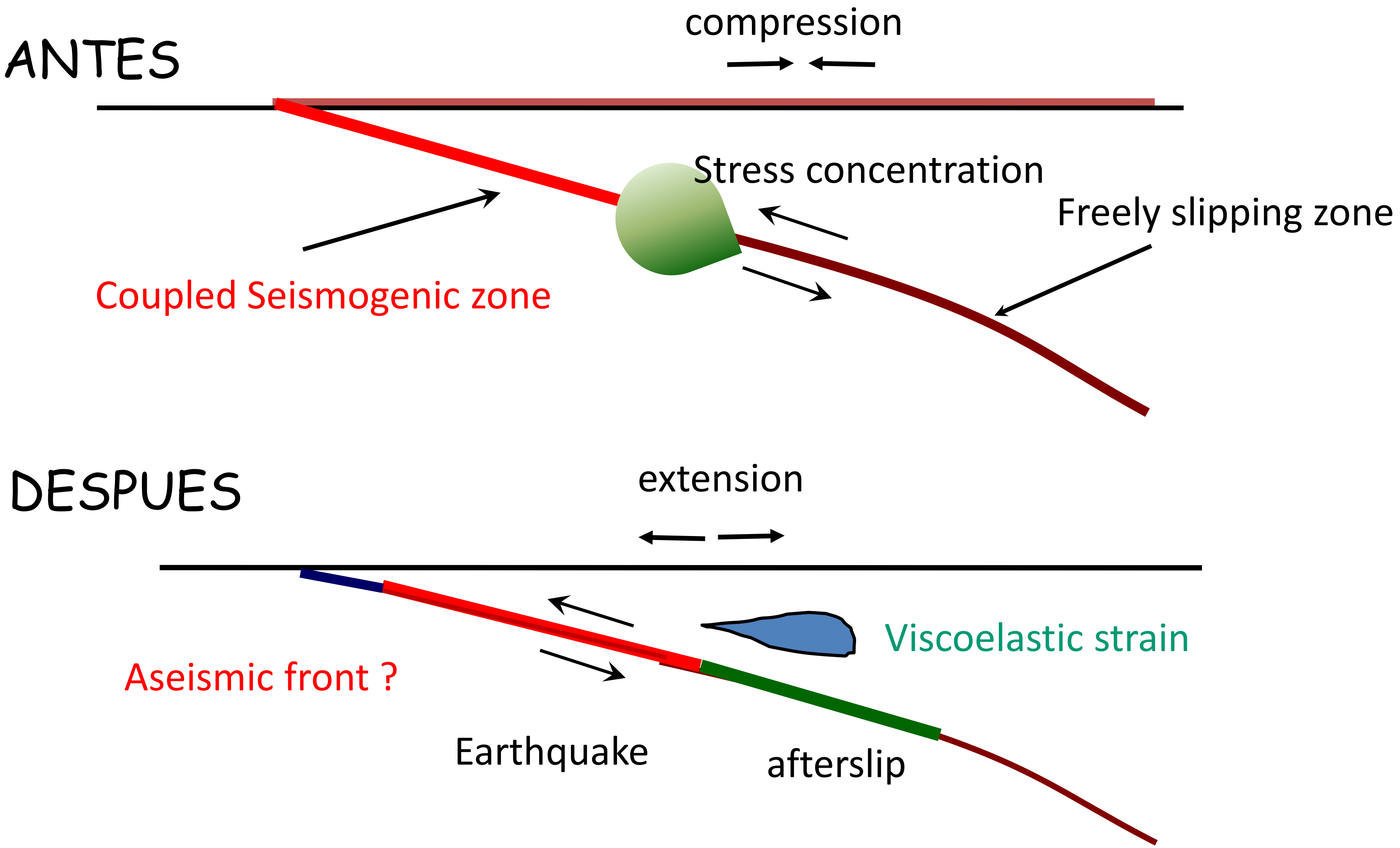
Antes



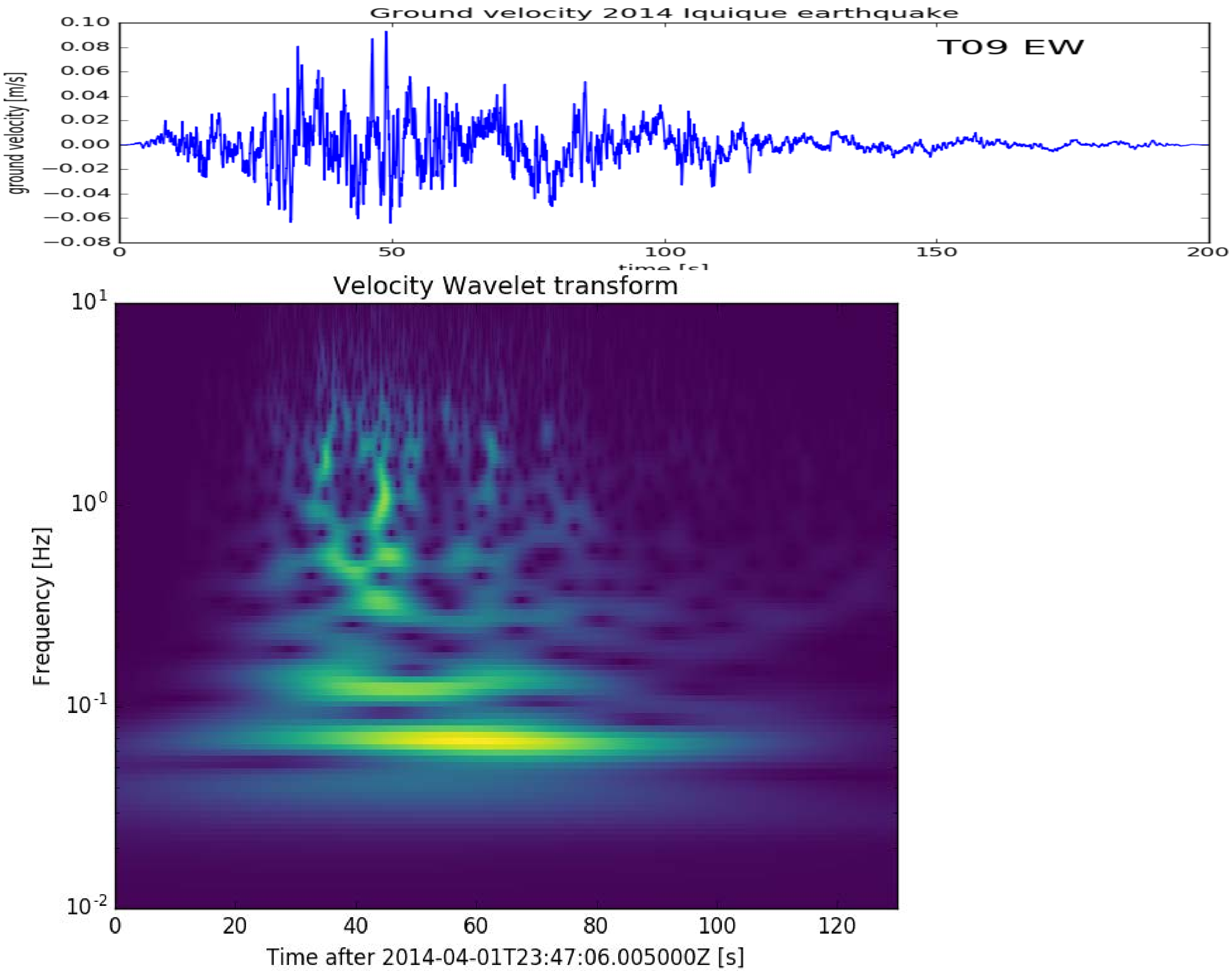
Si el tamaño (modulo) de los vectores 1 y 2 no es igual hay un problema:
Las placas se deforman de manera irregular. Si no son paralelos aun mas!

Acoplamiento sismico en una zona de subduction

Modelo Clasico de Savage (o back-slip)



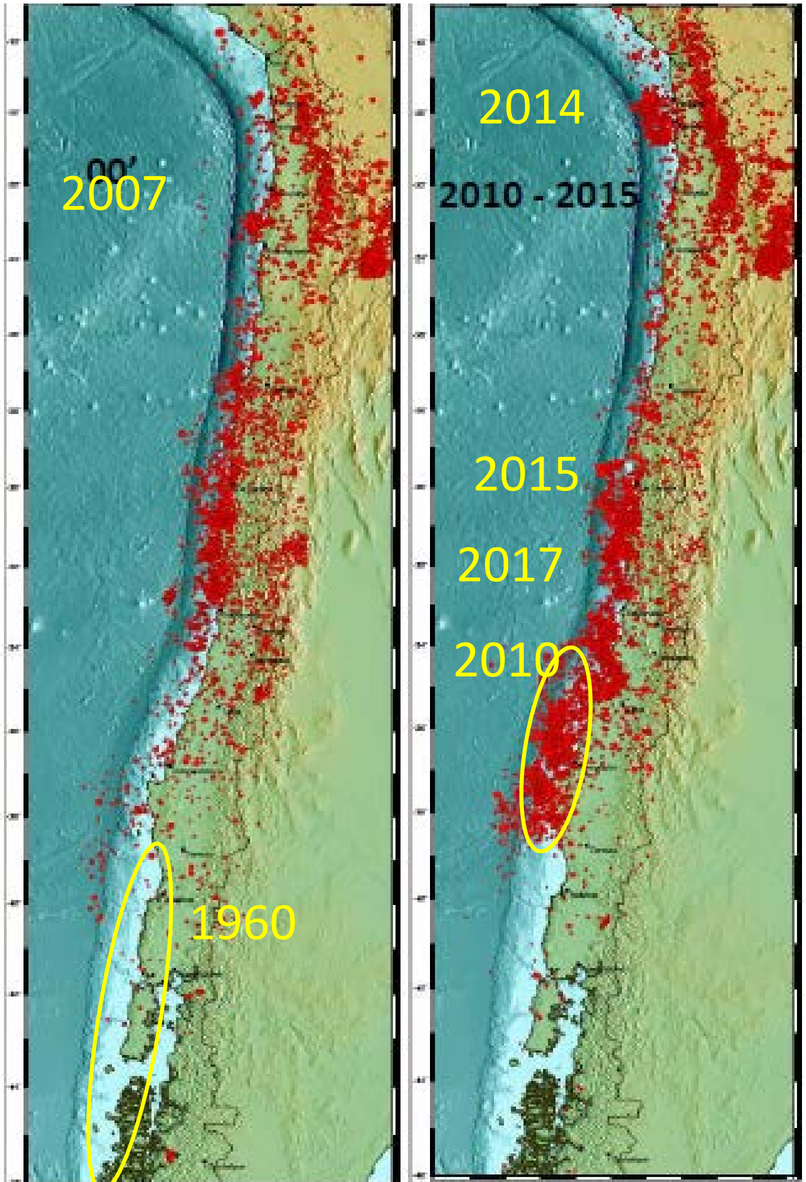
Velocity Spectrogram Iquique 2014 at T09A



Long range viscous interaction and posible slow events

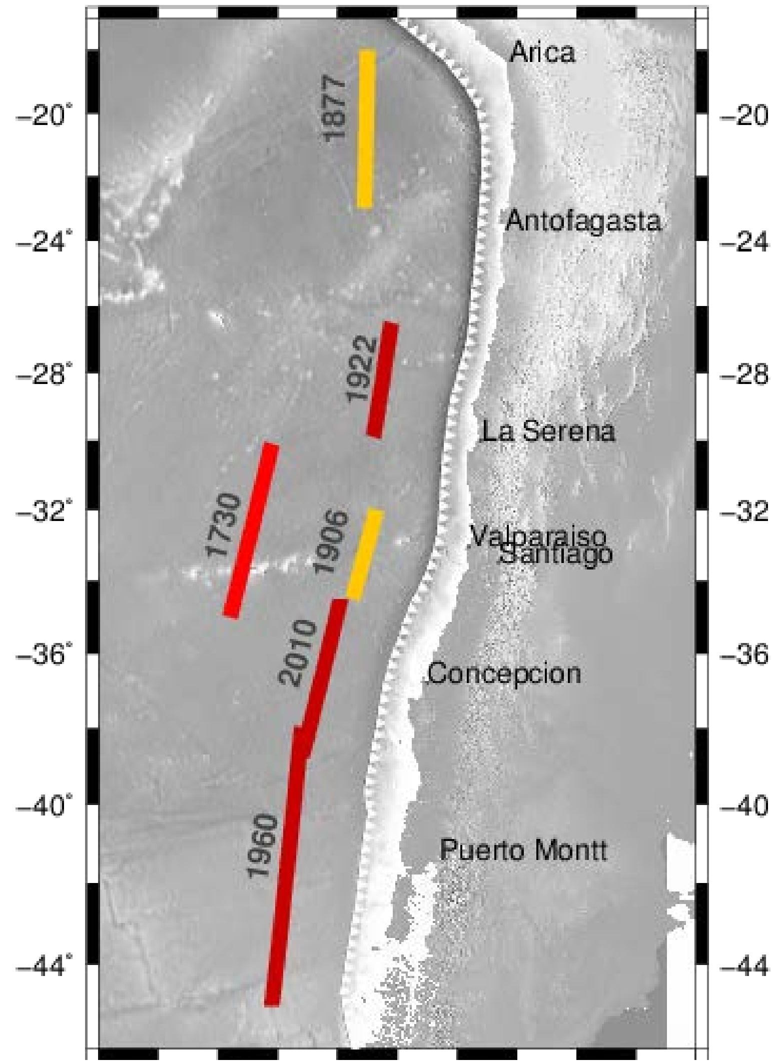
ILLAPEL 2015

Chilean seismicity 1990-2017



Data from SSN+USGS

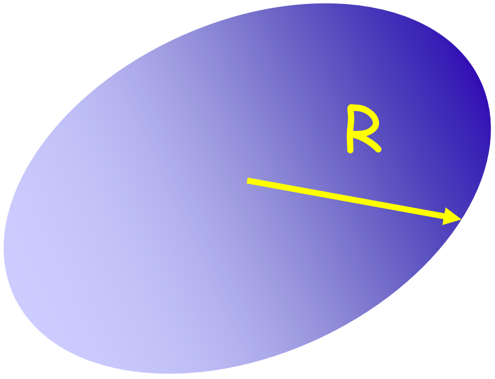
Historical Mega thrust EQs



Then birth of earthquake dynamics

In the beginning of the 1970s :

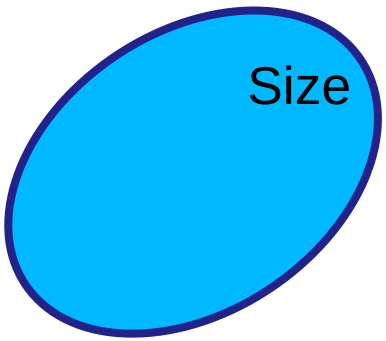
- Aki (1967) Scaling law of earthquake spectra
- Kostrov (1964, 1966) Circular crack, 2D crack, Energy
- Brune (1970) Circular crack body wave spectrum
- Madariaga (1976) put together all this.



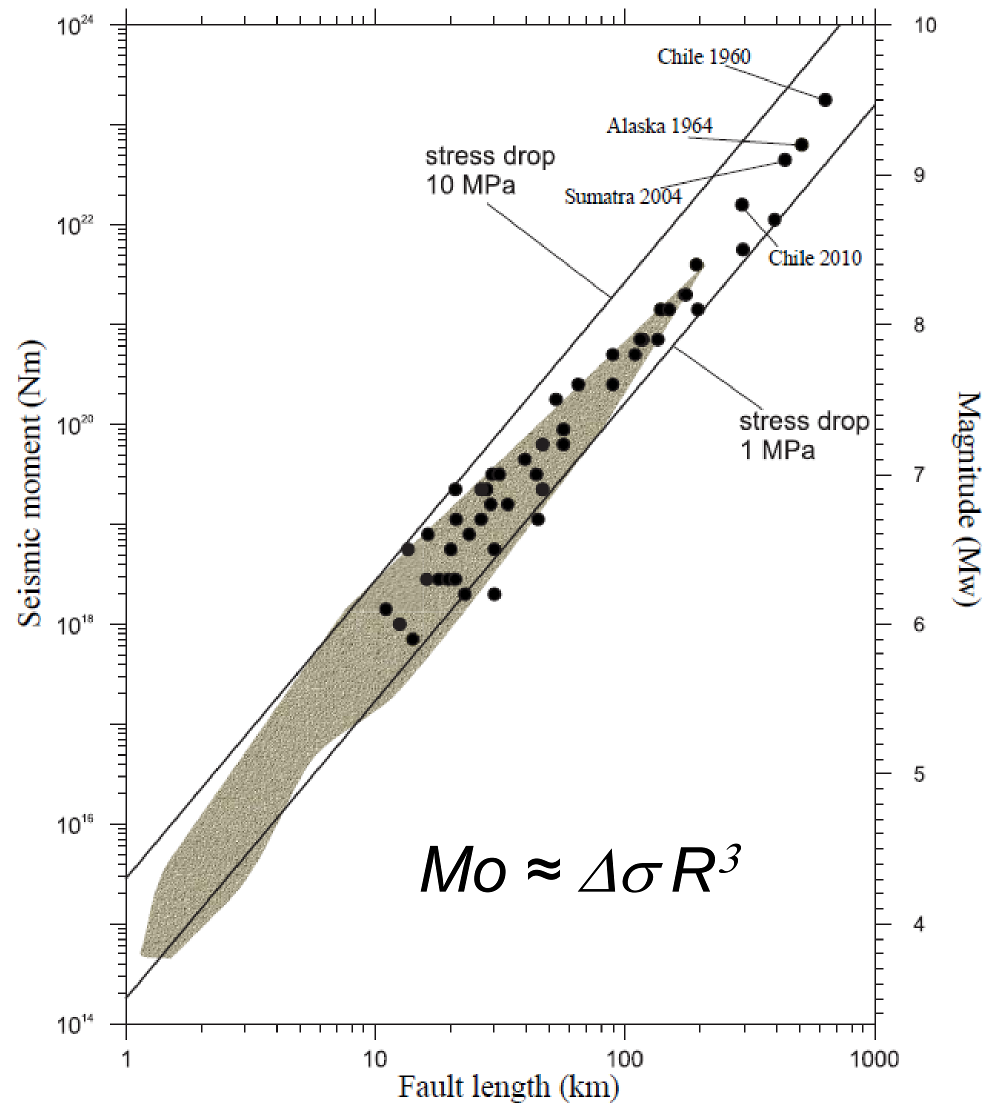
2 Parameters:
Mo
R

No definition of rupture speed

Aki's scaling law



There is only one length scale
R



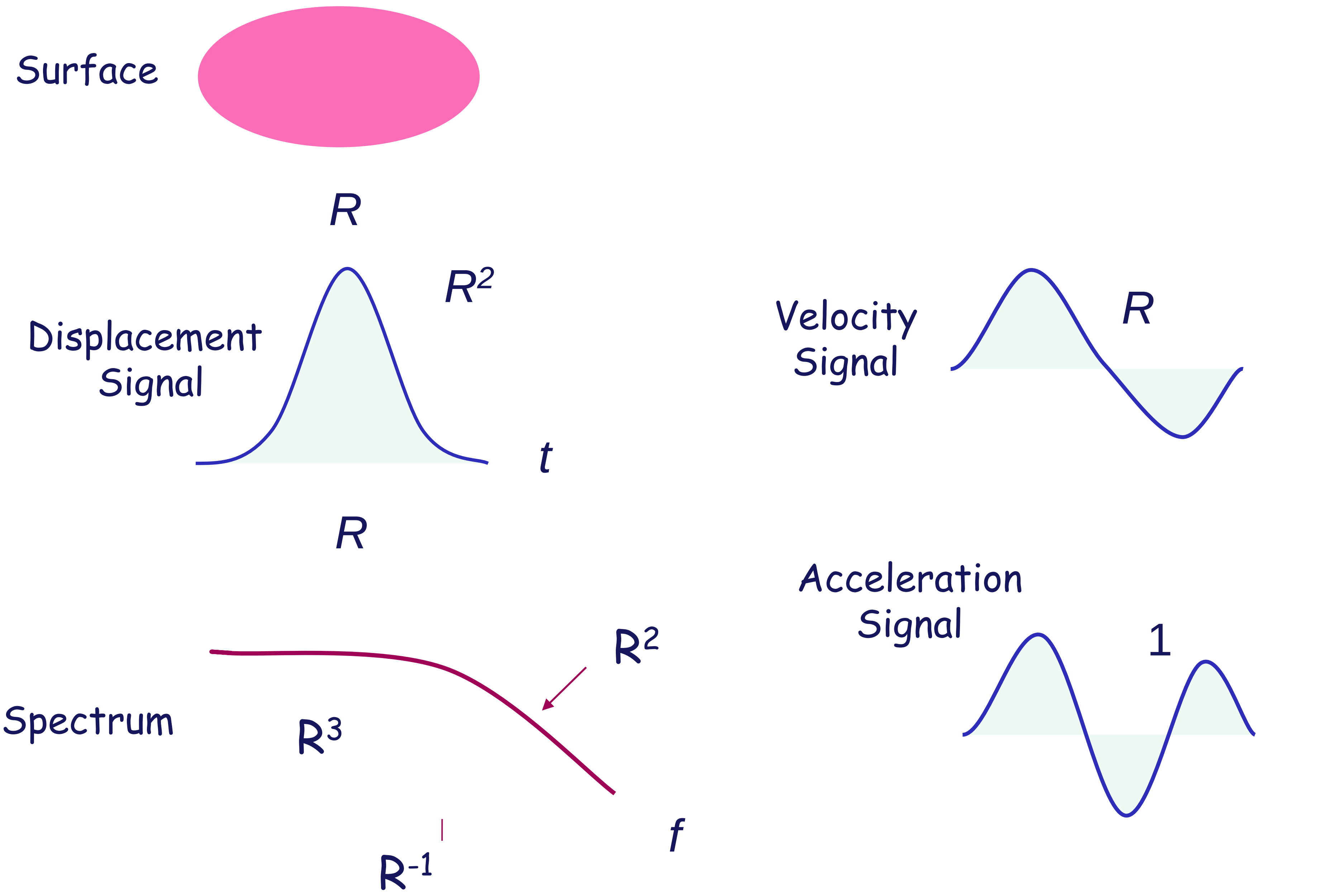
Zollo & Emolo

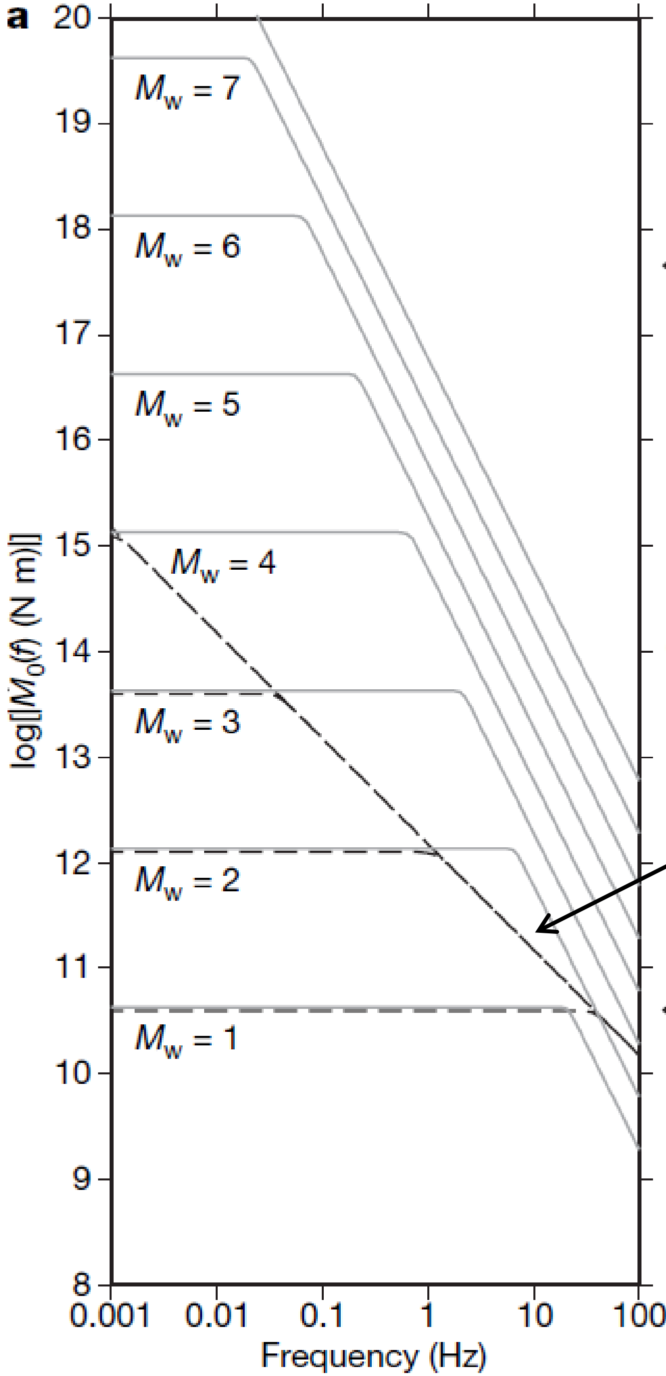
Earthquake scaling law

$$\log_{10} M_0(Nm) = 1.5M_w + 9.3$$

Magnitude (M_w)	Moment (Nm)	Radius (km)	Duration (s)	Slip (m)
10	10^{24}	1000?	300?	100?
9	3.10^{22}	300	100	30
8	10^{21}	100	30	10
7	3.10^{19}	30	10	3
6	10^{18}	10	3	1

Fundamentals of earthquake scaling





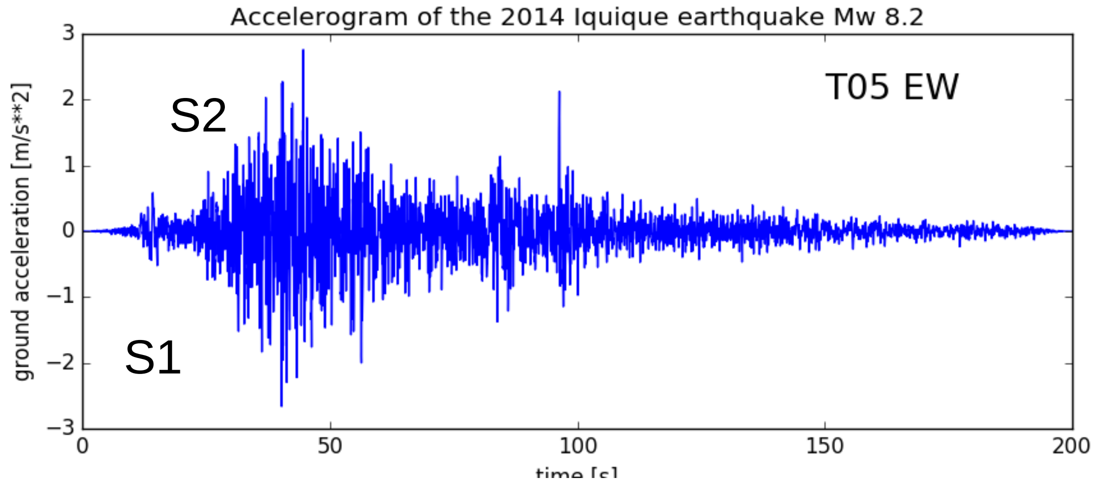
Modern version of Aki's Spectral scaling law

by

Ide et al, 2007

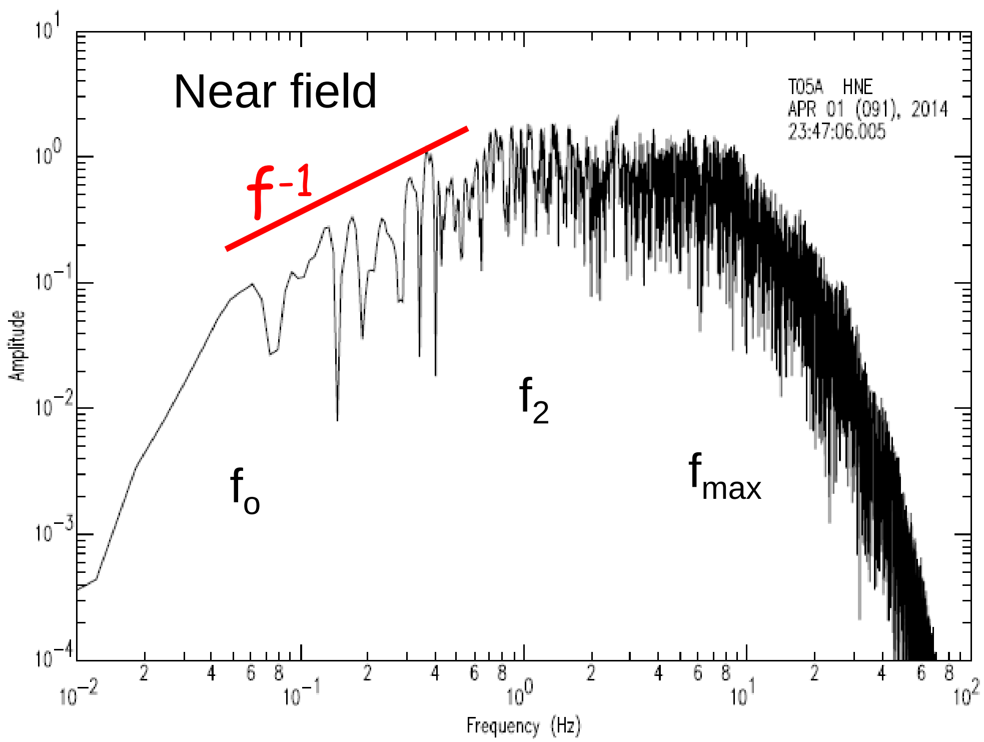
Slow earthquakes (LFEs)

Accelerogramas del sismo de Iquique 2014, Mw 8.2



PGA 30% g

R 50 km

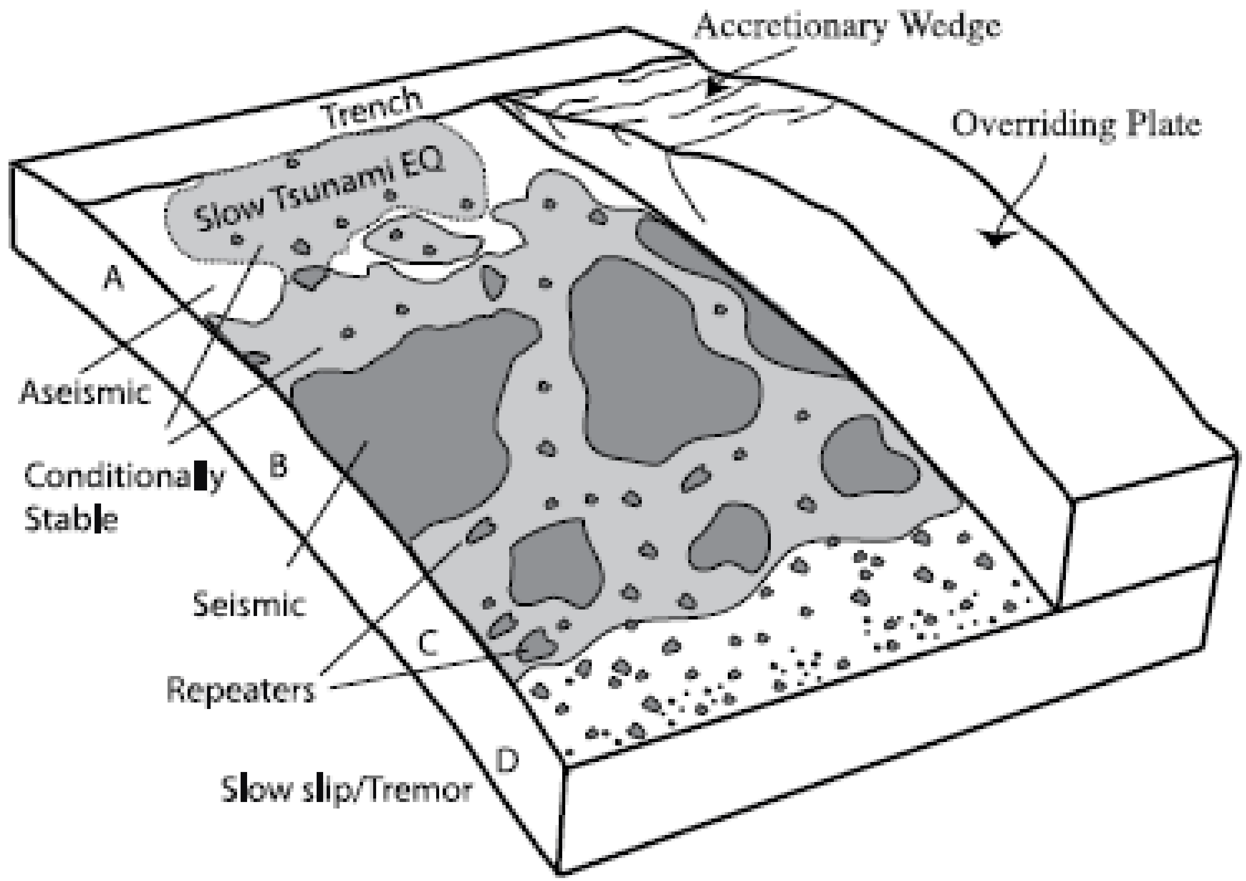


fo 0.08 Hz

f2 0.8 Hz

fmax 9 Hz

A simple explanation why subduction earthquake Produce less high frequencies



After Lay et al, J. Geophys. Res. 2012