Enhancement of Interplate Coupling in Adjacent Segments after Recent Megathrust Earthquakes

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SPACE GEODESY

Accelerated Plate Tectonics

Abstract. *The concept of a stressed elastic lithospheric plate riding on a viscous asthenosphere is used to calculate the recurrence interval of great earthquakes at convergent plate boundaries, the separation of decoupling and lithospheric earthquakes, and the migration pattern of large earthquakes along an arc. It is proposed that plate motions accelerate after great decoupling earthquakes and that most of the observed plate motions occur during short periods of time, separated by periods of relative quiescence.*

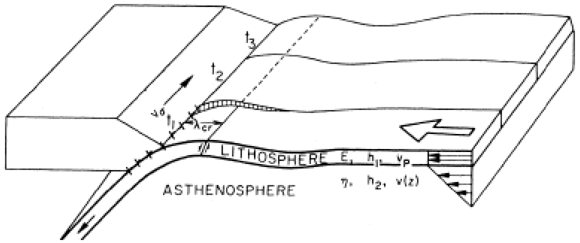
From the magnetic record sea floor spreading appears to be uniform over periods of many millions of years. However, from seismic data we know that motions at plate boundaries are not continuous, but occur mainly in jerks separated by tens to hundreds of years. It also appears that major earthquakes are not random in time and location but have some relation to each other. Mogi (*1*), in particular, has investigated the time-space sequence of global seismic activity and has proposed several migration patterns. For example, active seismic areas migrated systematically from Japan to Alaska in the last 35 years, during which this seismic belt was almost completely covered by aftershock areas of great earthquakes. Another pattern started in Central America and migrated to southern Chile in the same period of time. Migration velocities in these belts are 150 to 270 km/year. A particularly clear example of earthquake migration occurred on the Anatolian fault in Turkey after the great earthquake of 1939. The average migration rate, 50 to 100 km/year, has decreased with time. It has been suggested (*2*) that variations in the rotation rate of the earth and great decoupling earthquakes may be related to the start of a migration pattern.

In this report I quantify some of the implications of a simple model of an elastic plate riding on a viscous foundation. This model can be used to estimate the recurrence interval of large earthquakes, the time interval between large earthquakes along an arc, and the distance between decoupling and lithospheric (*3*) earthquakes. The model shows that relative plate rates can be calculated from seismicity only if long enough periods of time are considered.

diffusion. Recurrence rates can be estimated from a simple elastic model involving the loading of a plate.

Kanamori (*3*) introduced the concepts of decoupling and lithospheric earthquakes. The first are trench earthquakes in which the boundary between the underthrusting plate and the adjacent restraining plate is broken, temporarily decoupling the two converging lithospheres. A lithospheric earthquake is one that breaks the entire oceanic lithosphere, seaward of the trench. What are the consequences of a great decoupling earthquake? First, one would expect accelerated plate motions in the vicinity of th fact, are ob earthquakes stants of the earthquake per year ha large earthq underthrusti of the dowr approach o can be expe frictional contact between the oceanic and continental lithospheres is reduced. Continental rebound (sinking) and reduction of the oceanic lithospheric bulge (*6*), previously supported by the

relieved stresses, will also occur. The second consequence is that the stress discontinuity resulting from the earthquake will diffuse away from the fault plane and trigger activity along adjacent parts of the arc. In a purely elastic situation this information will flow at elastic wave speeds, and adjacent segments of the arc will know within seconds or minutes that they must support more of the stress imposed by the approaching lithosphere; the immediate aftershocks are presumably triggered by this mechanism. In an elastic layer over a viscous asthenosphere part of the information travels more slowly and damps rapidly. Adjacent segments of the arc will be stressed at a more rapid rate than before the decoupling earthquake, because of both accelerated oceanic plate motions in the vicinity of the decoupling earthquake and the stress wave diffusion from the earthquake. The critical distance, λ_{cr}, from the boundary between the plates (the location of the decoupling earthquake) ... $\sigma = 0.25$, λ_{cr} is 90 km. This is about the separation between the 1896 decoupling earthquake and the 1933 lithosphere earthquake of Sanriku (*3*). In the period between large earth-



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Accelerated pacific plate subduction following interplate thrust earthquakes at the Japan trench

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Postseismic Enhanced Coupling

(found by GNSS in Japan and Chile)

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL071845

This article is a companion to *Loveless* [2017] doi:10.1002/2017GL072525.

Key Points:

- A decade of GPS measurements across the Andes image the megathrust seismic cycle before and between two

The super-interseismic phase of the megathrust earthquake cycle in Chile

Daniel Melnick[1,2], Marcos Moreno[3], Javier Quinteros[3], Juan Carlos Baez[4], Zhiguo Deng[3], Shaoyang Li[3], and Onno Oncken[3]

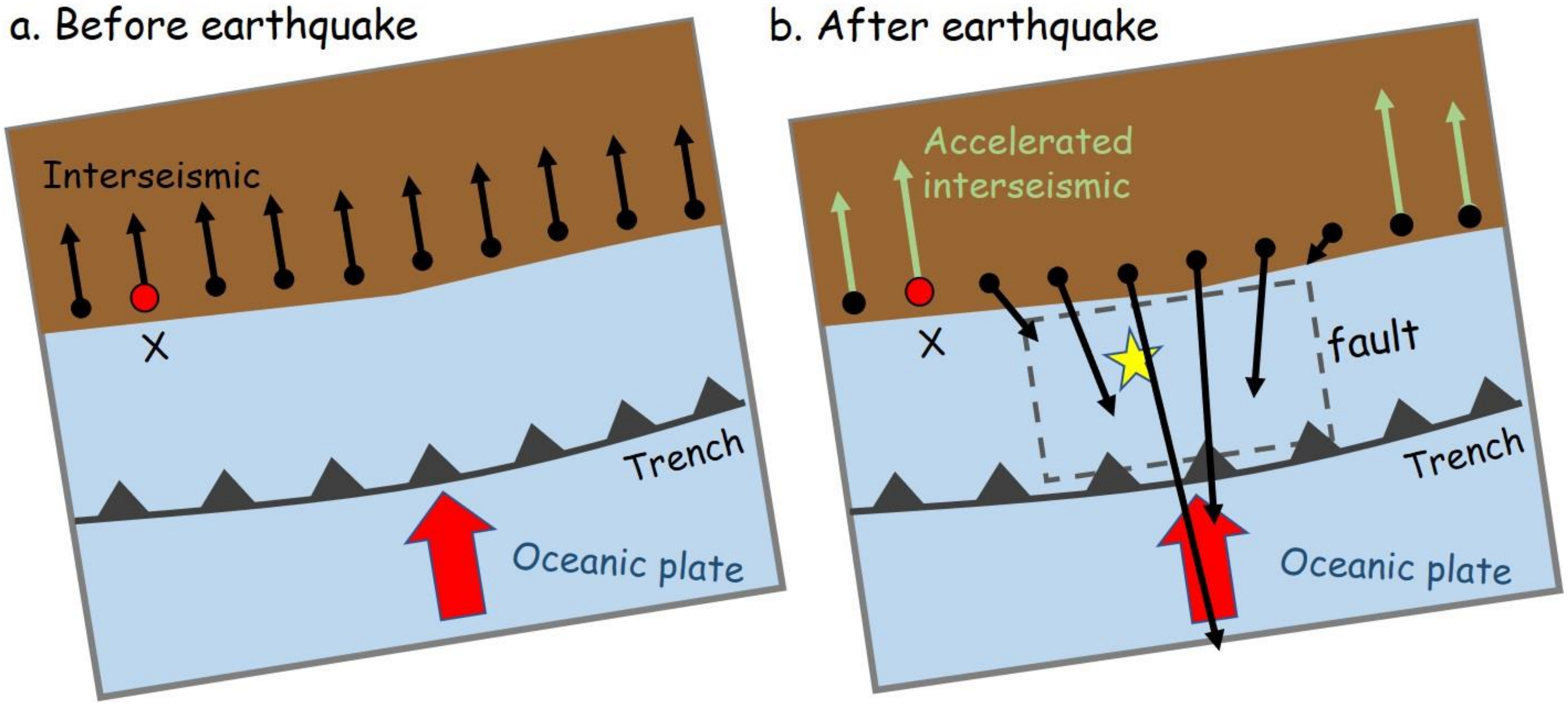
[1]Institute of Earth and Environmental Sciences, University of Potsdam, Potsdam, Germany, [2]Instituto de Ciencias de la Tierra, TAQUACH, Universidad Austral de Chile, Valdivia, Chile, [3]GFZ Helmholtz Centre Potsdam, Potsdam, Germany, [4]Centro Sismológico National, Universidad de Chile, Santiago, Chile

Accelerated subduction?

(hypothesized by Heki and Mitsui, 2013)

What kind of phenomenon?

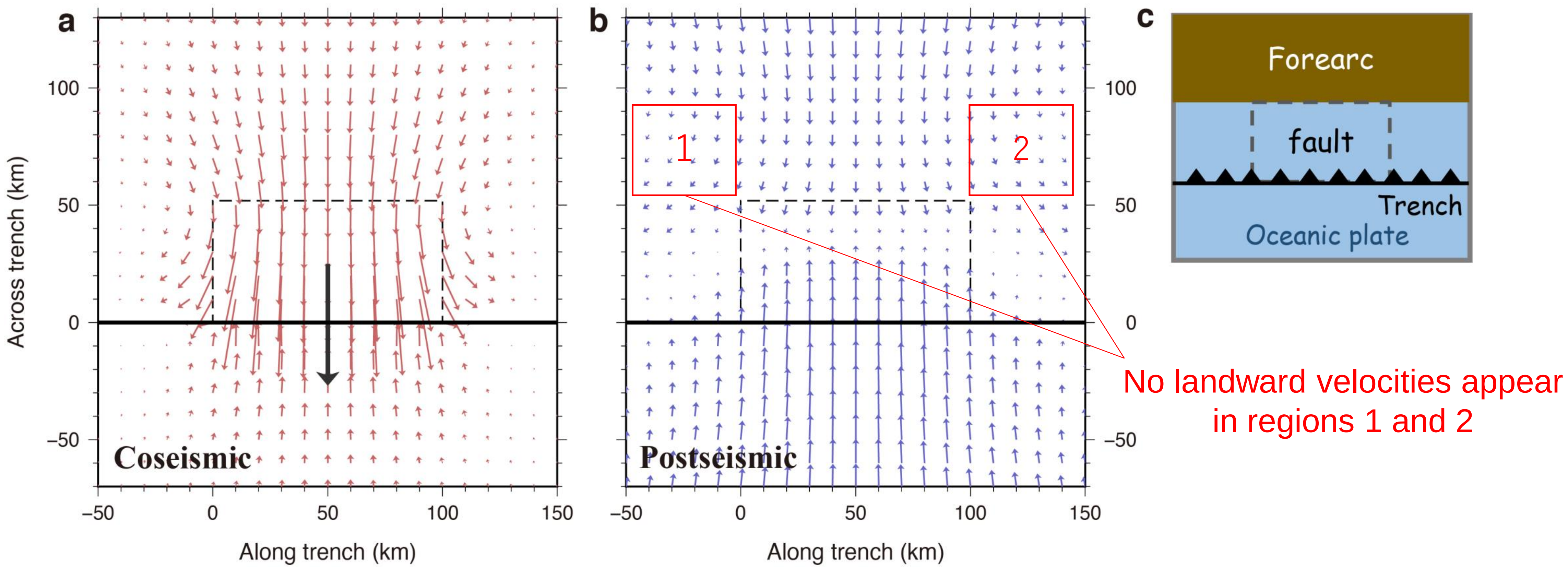
Accelerated landward movement in the neighboring segments of the rupture



This phenomenon cannot be explained by simple viscoelastic relaxation?

Can viscoelastic relaxation explain it?

Postseismic viscoelastic relaxation generates only trenchward movement for forearc GNSS stations.

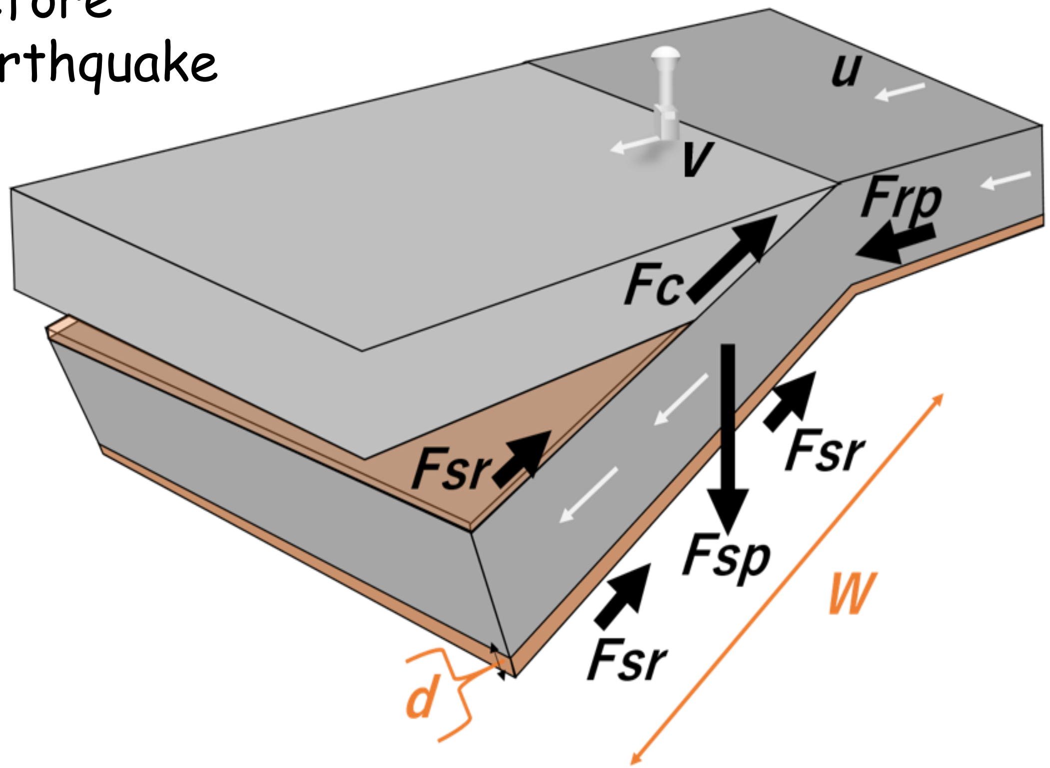


Calculated using the software package by Fukahata and Matsu'ura (2005; 2006)

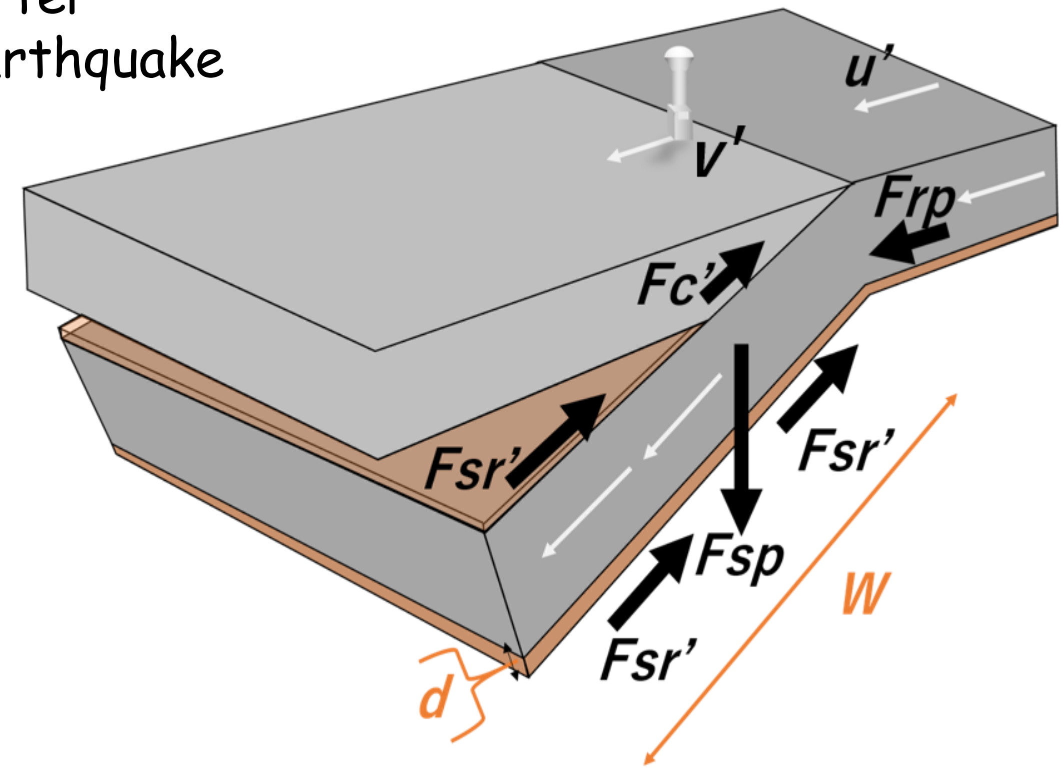
These landward velocities need to be explained by some other mechanisms.

Slab acceleration model by Heki and Mitsui (2013 EPSL)

Before earthquake



After earthquake



Slab pull ***Fsp*** balances with plate coupling ***Fc*** and viscous traction ***Fsr***

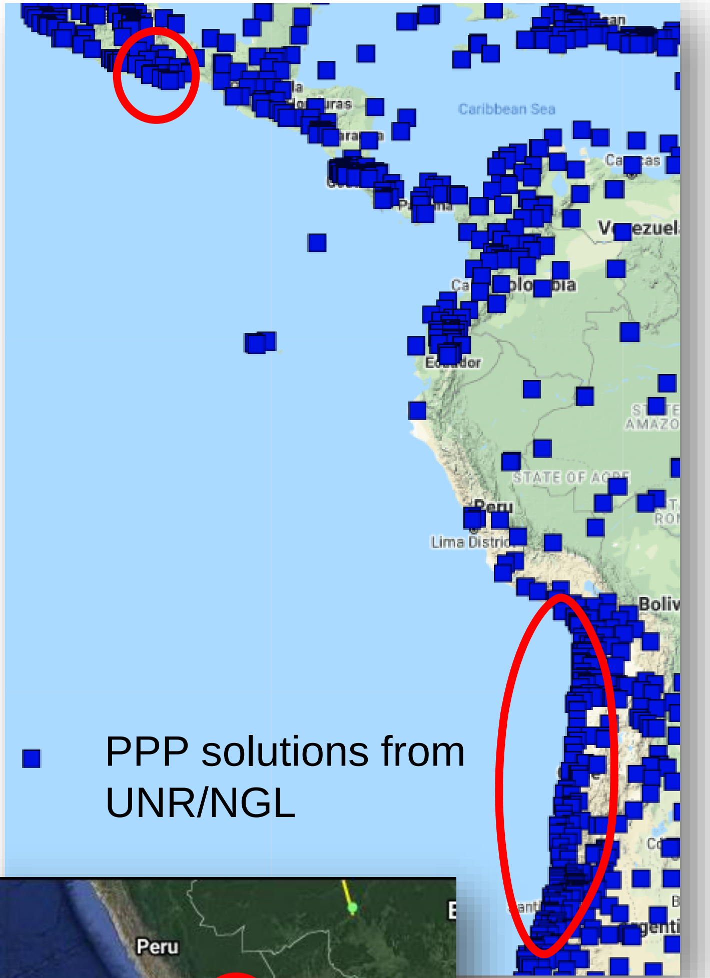
Reduced coupling compensated by increase of viscous traction realized by acceleration

Fsp: slab pull, *Frp*: ridge push, *Fc*: interplate coupling, *Fsr*: side resistance, *v*: surface velocity, *u*: slab velocity, *W*: Total trench-normal length of slab where viscous braking works, *d* is the thickness of the thin low viscosity layer at the lithosphere-asthenosphere boundary, *μ:* viscosity of the low-viscosity layer.

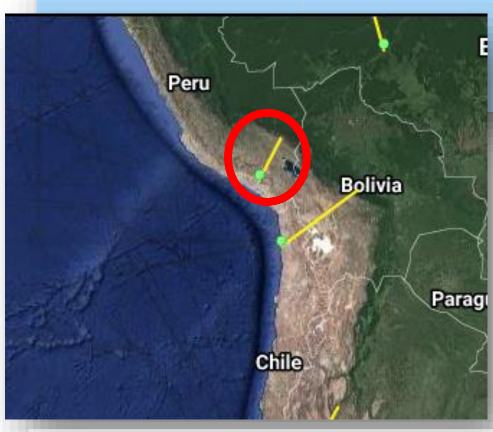
Data and Method

GNSS Data

We analyze GNSS daily coordinate data available in forearc regions of subduction zones, western Sumatra, NE Japan, central and northern Chile, and Oaxaca, Mexico.

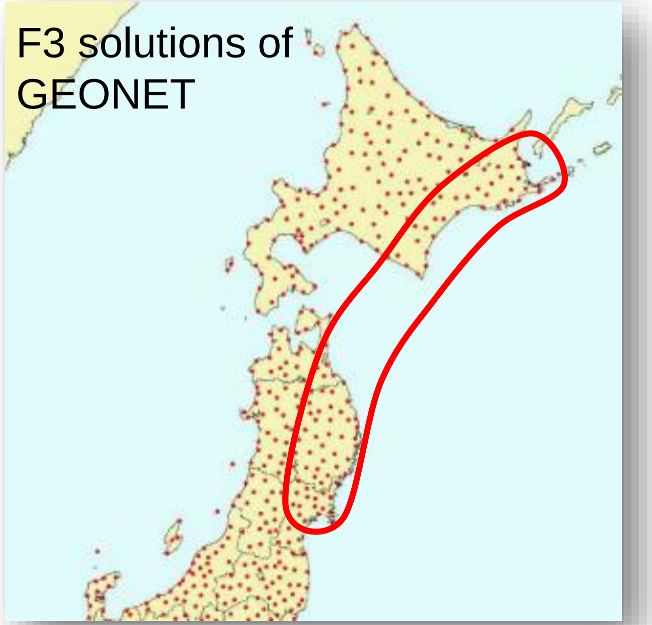


PPP solutions from UNR/NGL



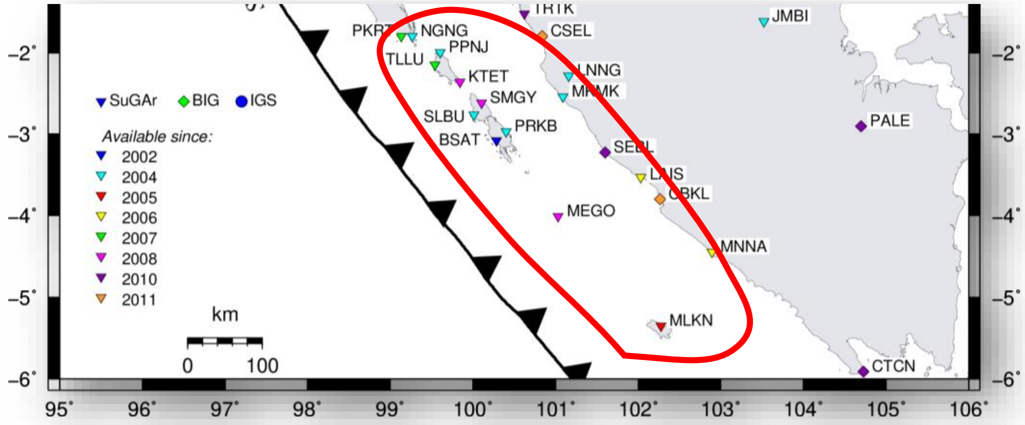
Partly from JPL
sideshow.jpl.nasa.gov/post/series.html.

ITRF velocities converted to those relative to the landward plate using nnr-MORVEL56

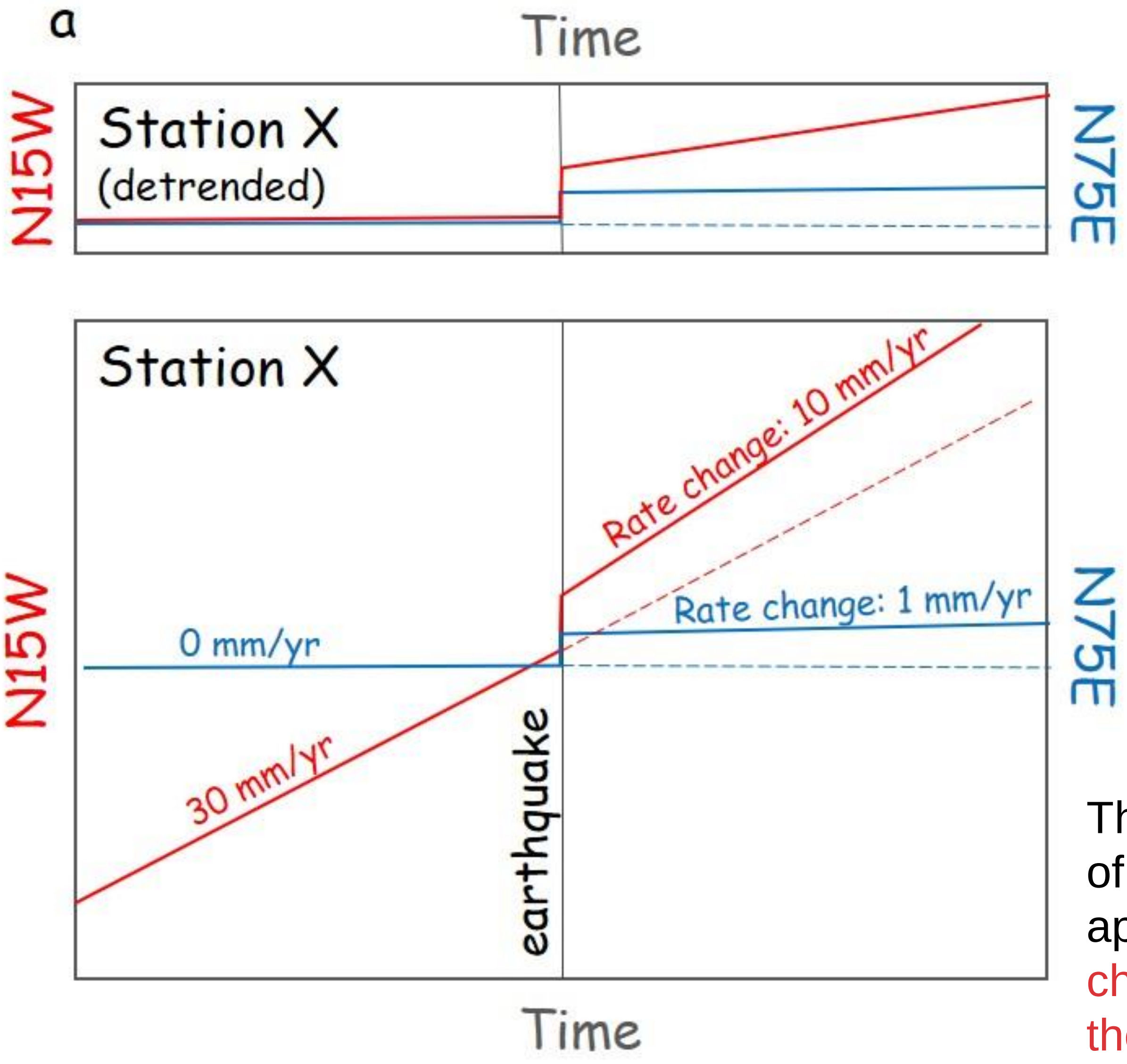


F3 solutions of GEONET

The Sumatran GPS Array (SuGAr) solutions by GAMIT 10.5 by ITB

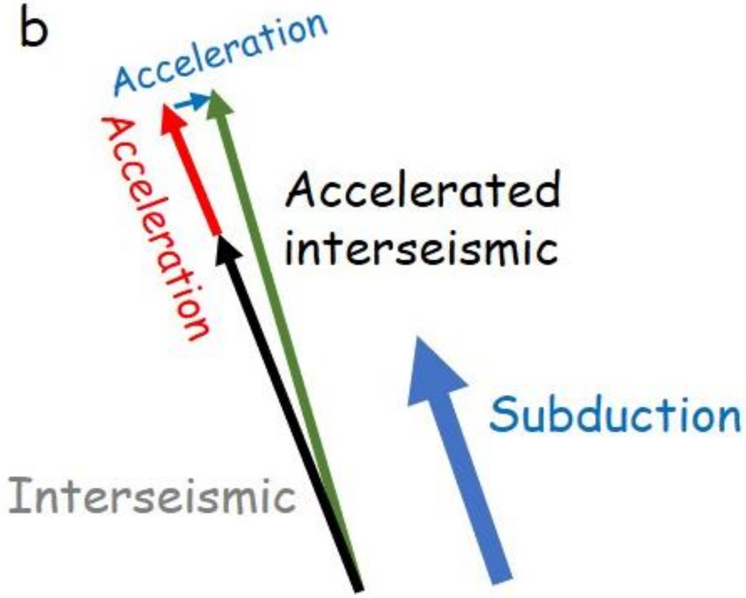


Acceleration diagram



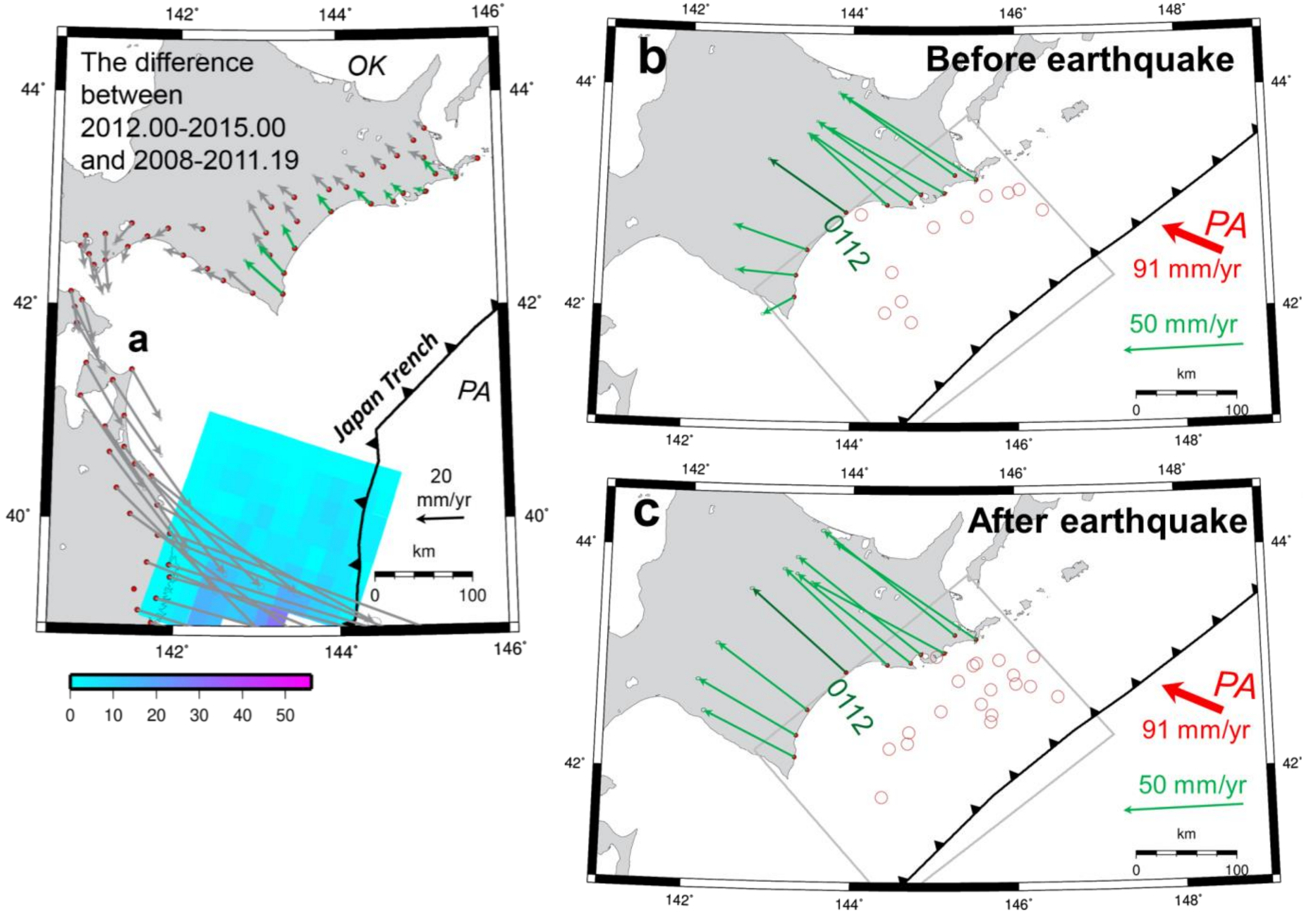
We rotate the two horizontal axes (north and east) so that the two components coincide with the direction parallel or perpendicular to the interseismic movement of the station before the earthquakes (normally in the direction of the subducting oceanic plate).

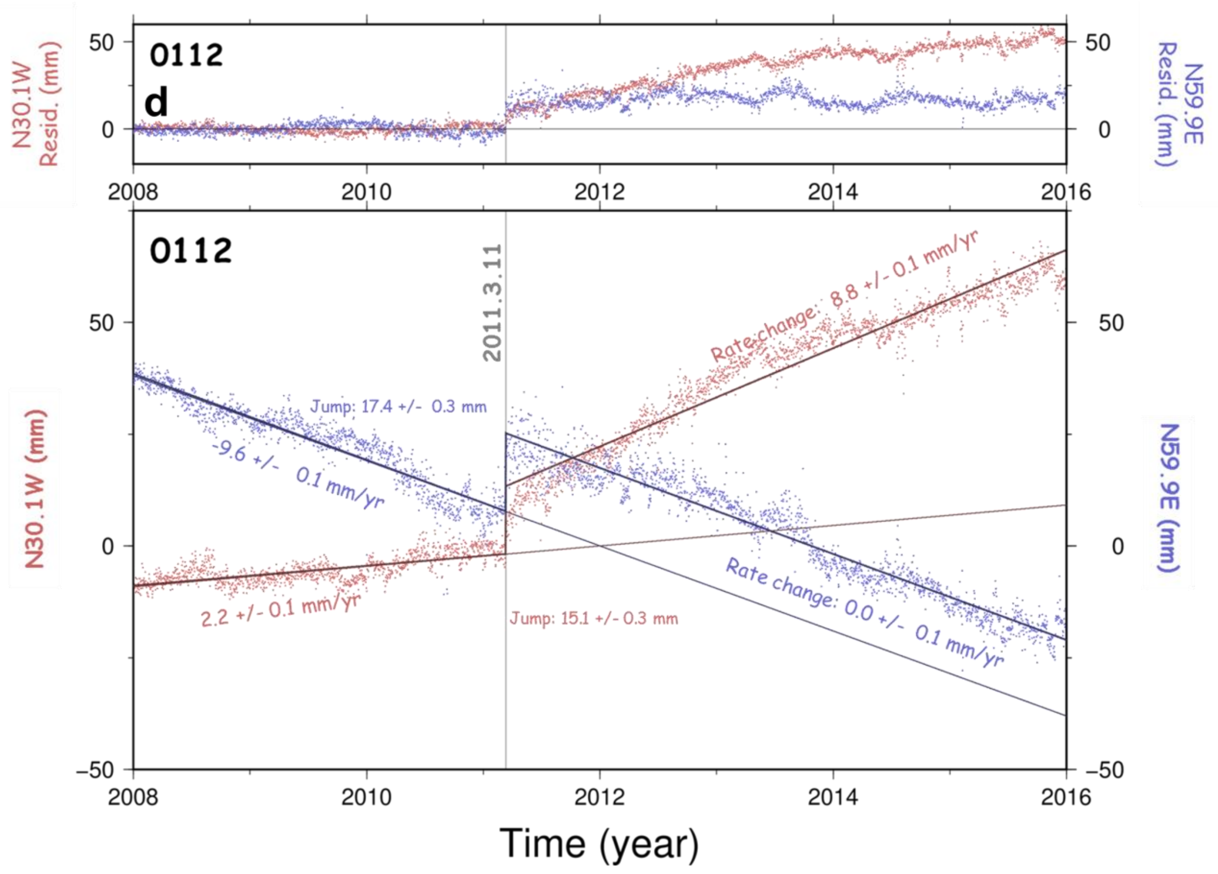
The coseismic increase of the landward velocity appears as the positive change in the slope of the red time series



6 cases in 4 subduction zones of postseismic enhancement of interplate coupling

The 2011 Tohoku-oki earthquake (M_w 9.0)

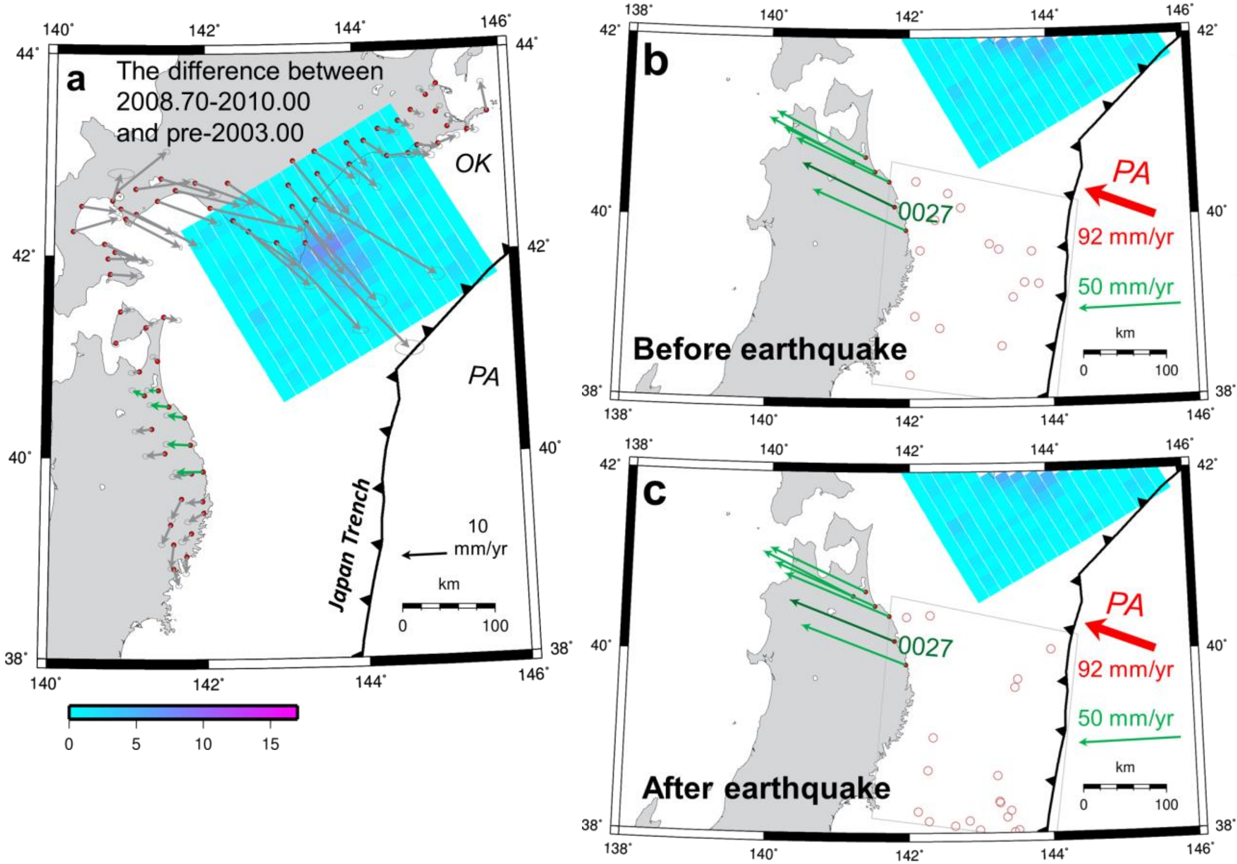


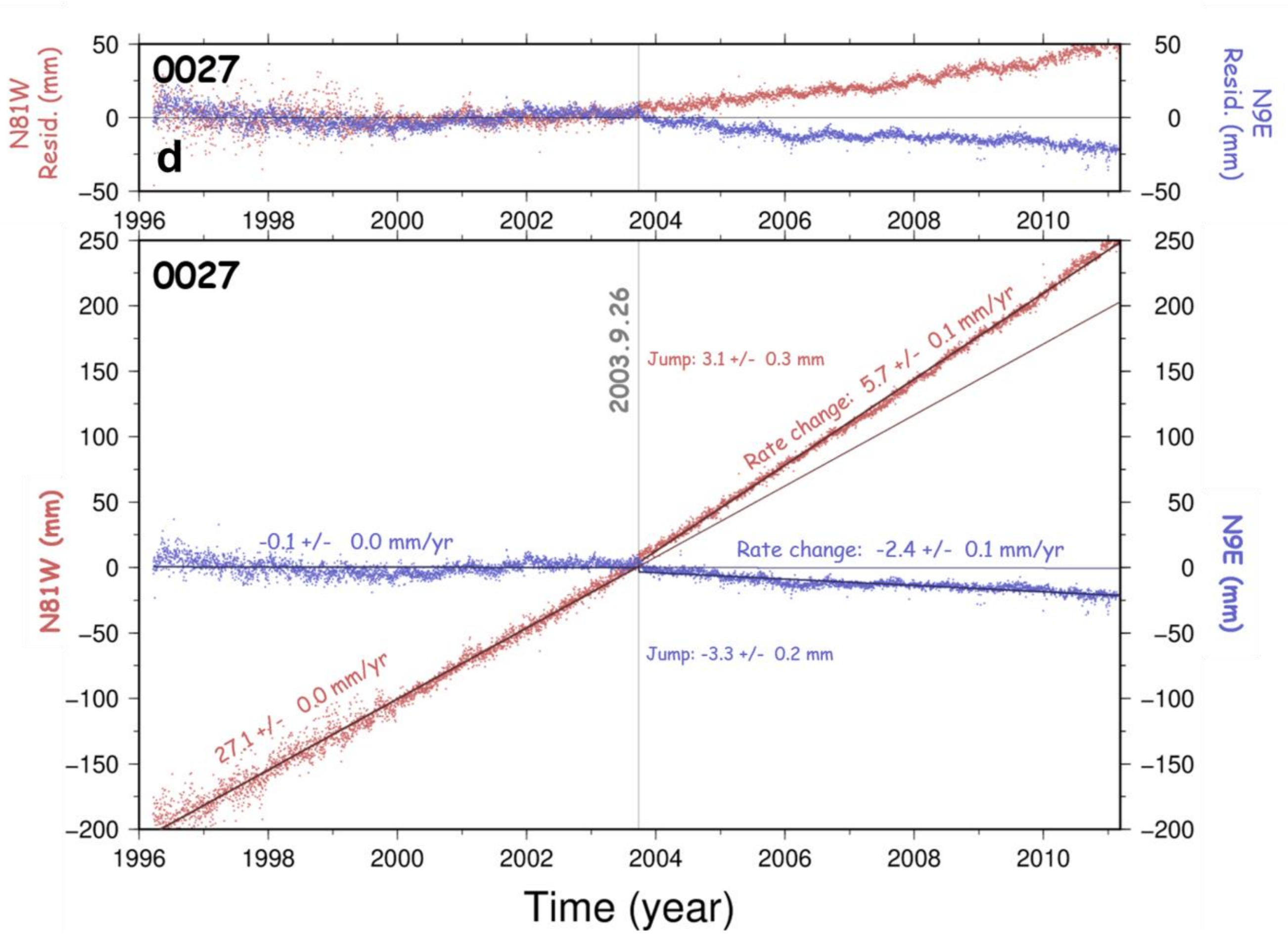


The pre-earthquake landward movement of the GNSS stations has been accelerated after the 2011 Tohoku-oki earthquake.

Positive change in the slope of the red time series.

The 2003 Tokachi-oki Earthquake (Mw 8.3)

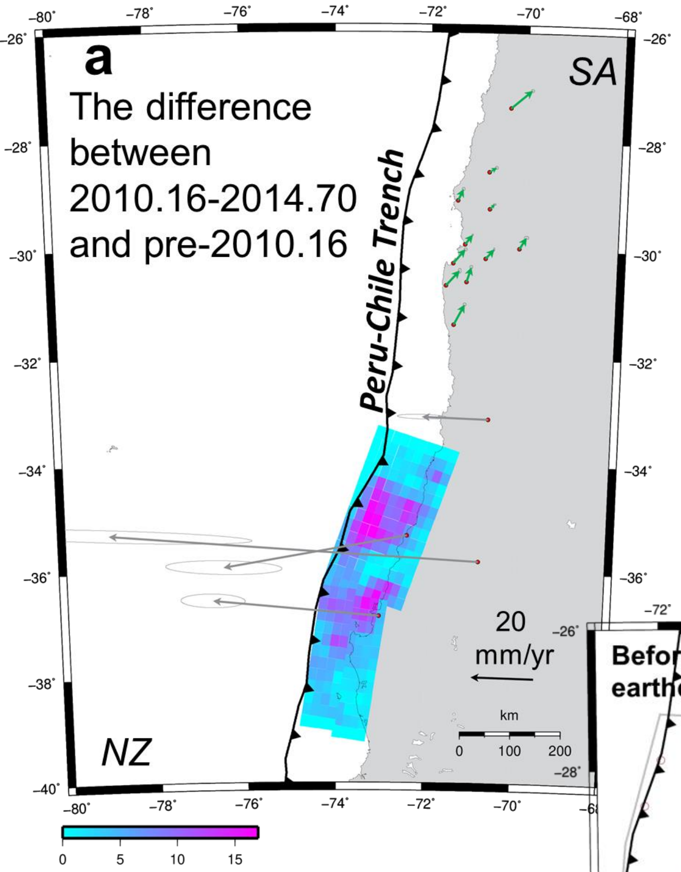




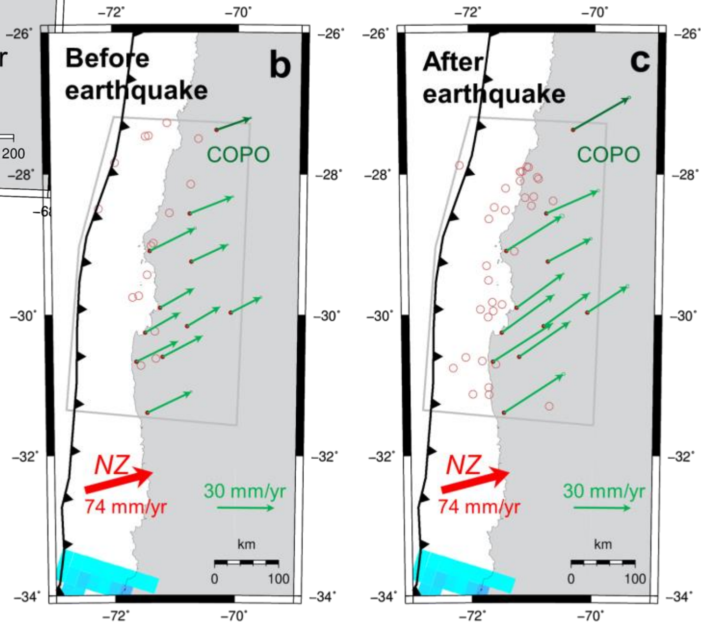
The pre-earthquake landward movement of the GNSS stations has been accelerated after the 2003 Tokachi-oki earthquake.

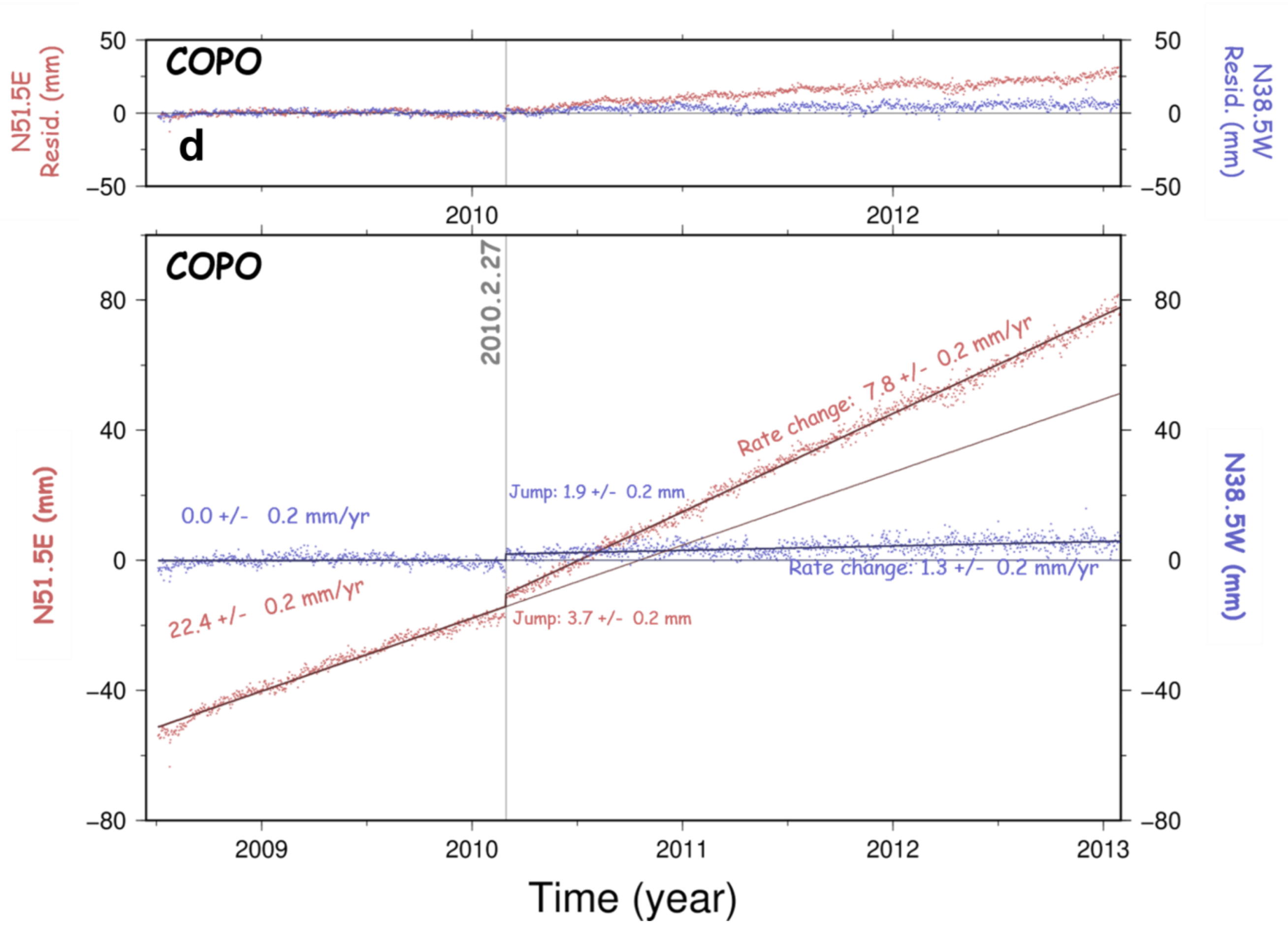
Positive change in the slope of the red time series.

The 2010 Maule Earthquake (Mw 8.8)



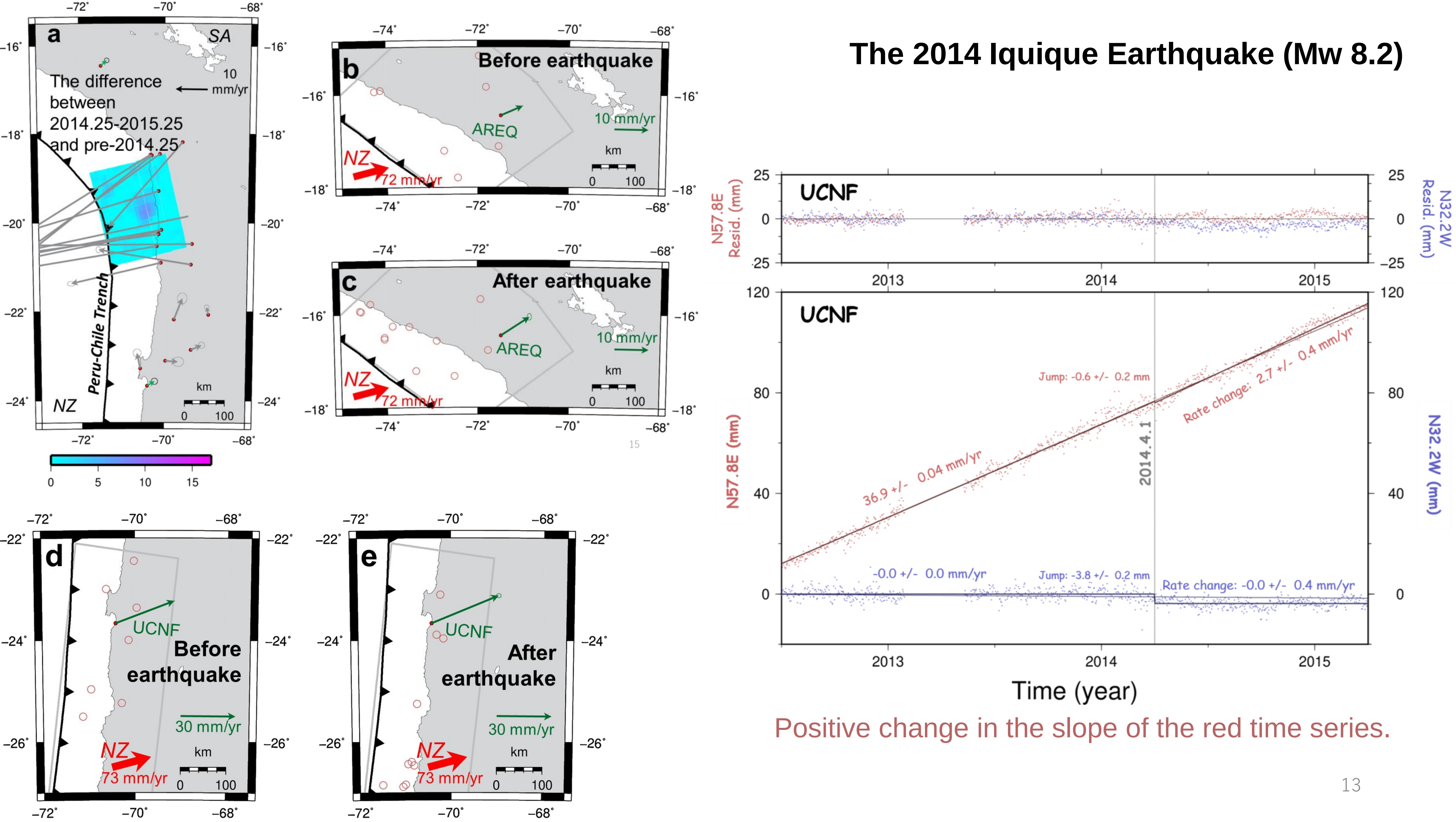
The pre-earthquake landward movement of the GNSS stations has been accelerated after the 2010 Maule earthquake.





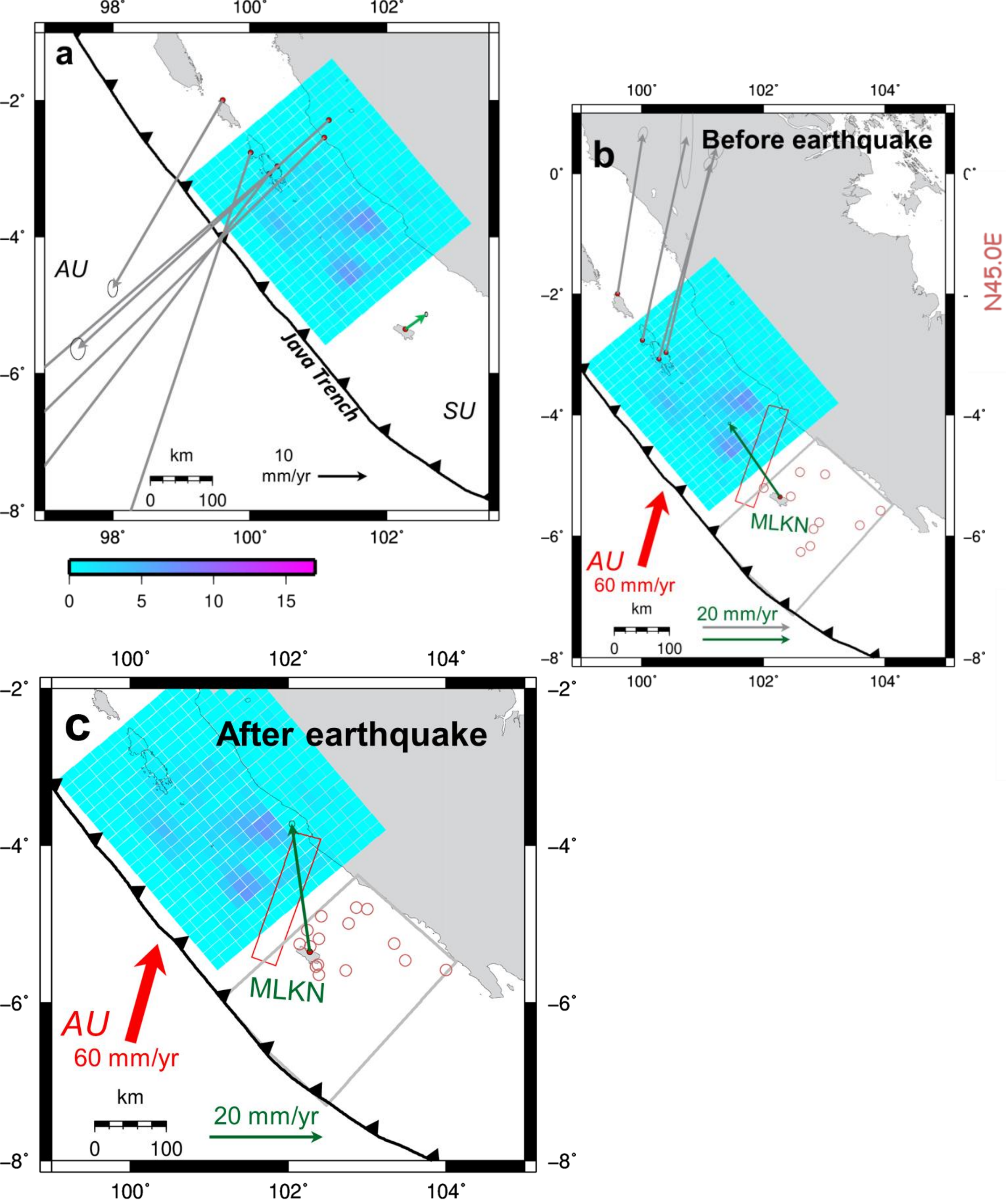
Positive change in the slope of the red time series.

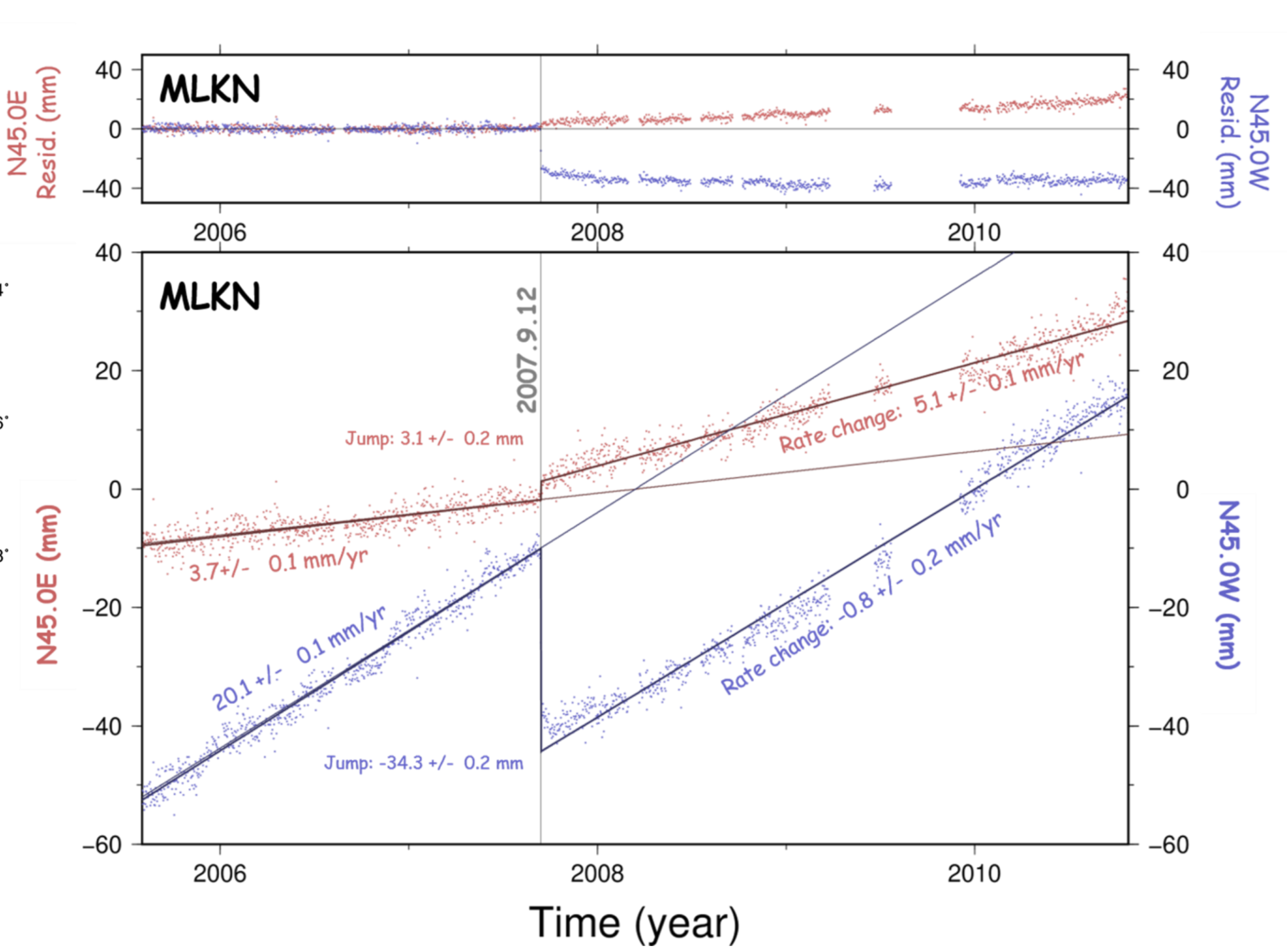
The 2014 Iquique Earthquake (Mw 8.2)



Positive change in the slope of the red time series.

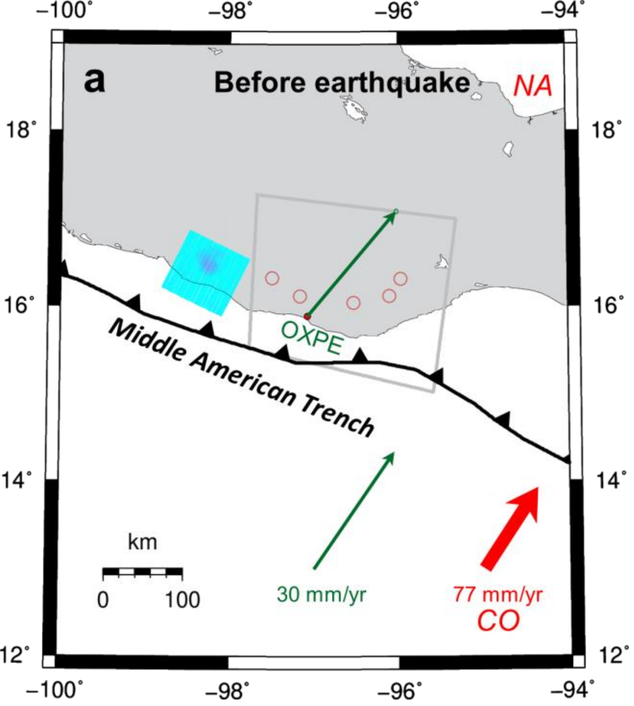
The 2007 Bengkulu Earthquake (Mw 8.4)

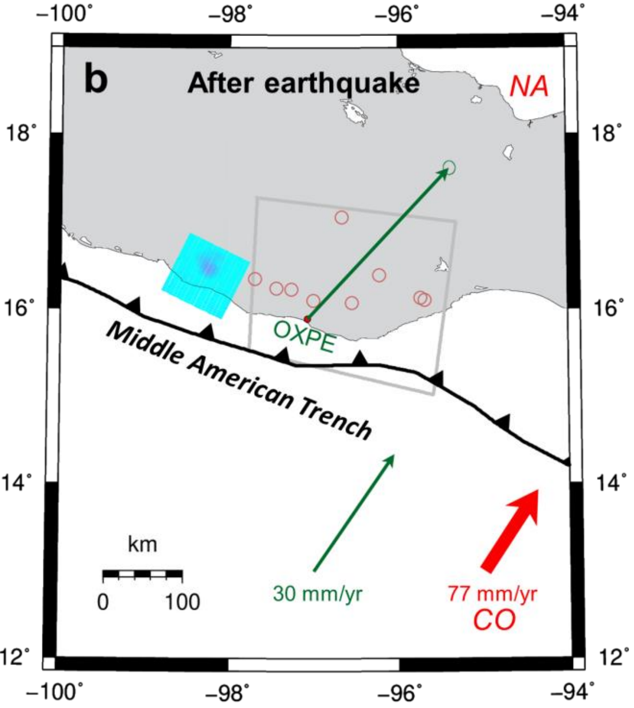




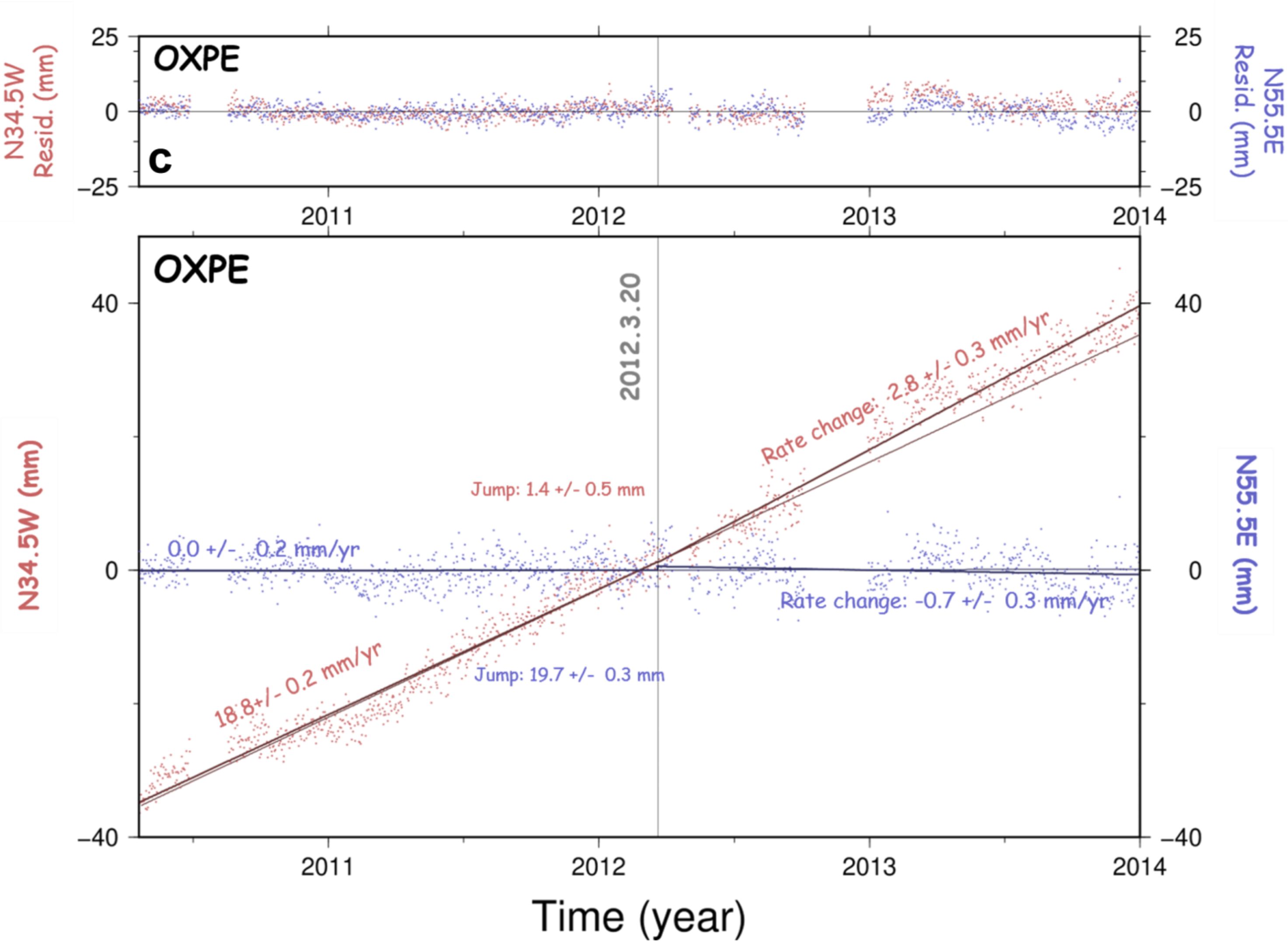
Positive change in the slope of the red time series.

The 2012 Oaxaca Earthquake (Mw 7.4)





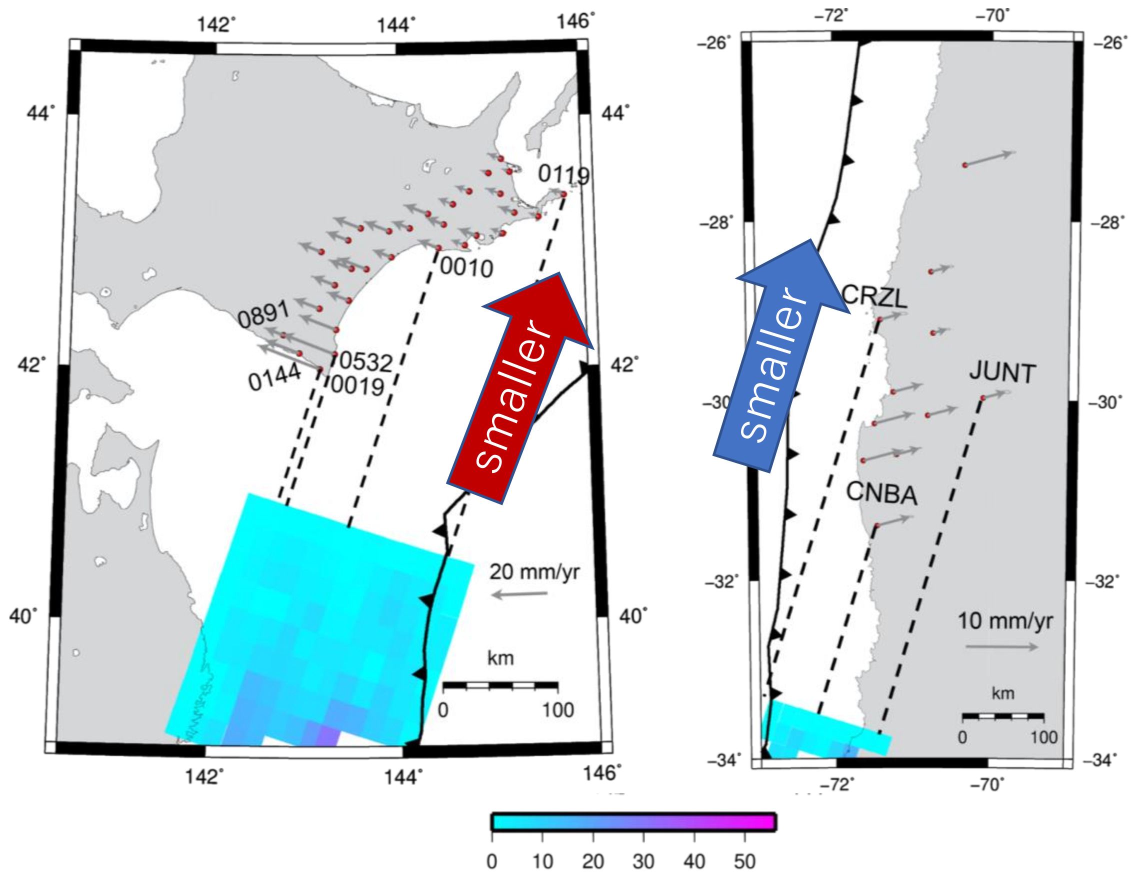
The pre-earthquake landward movement of the GNSS stations has been accelerated after the 2012 Oaxaca earthquake.



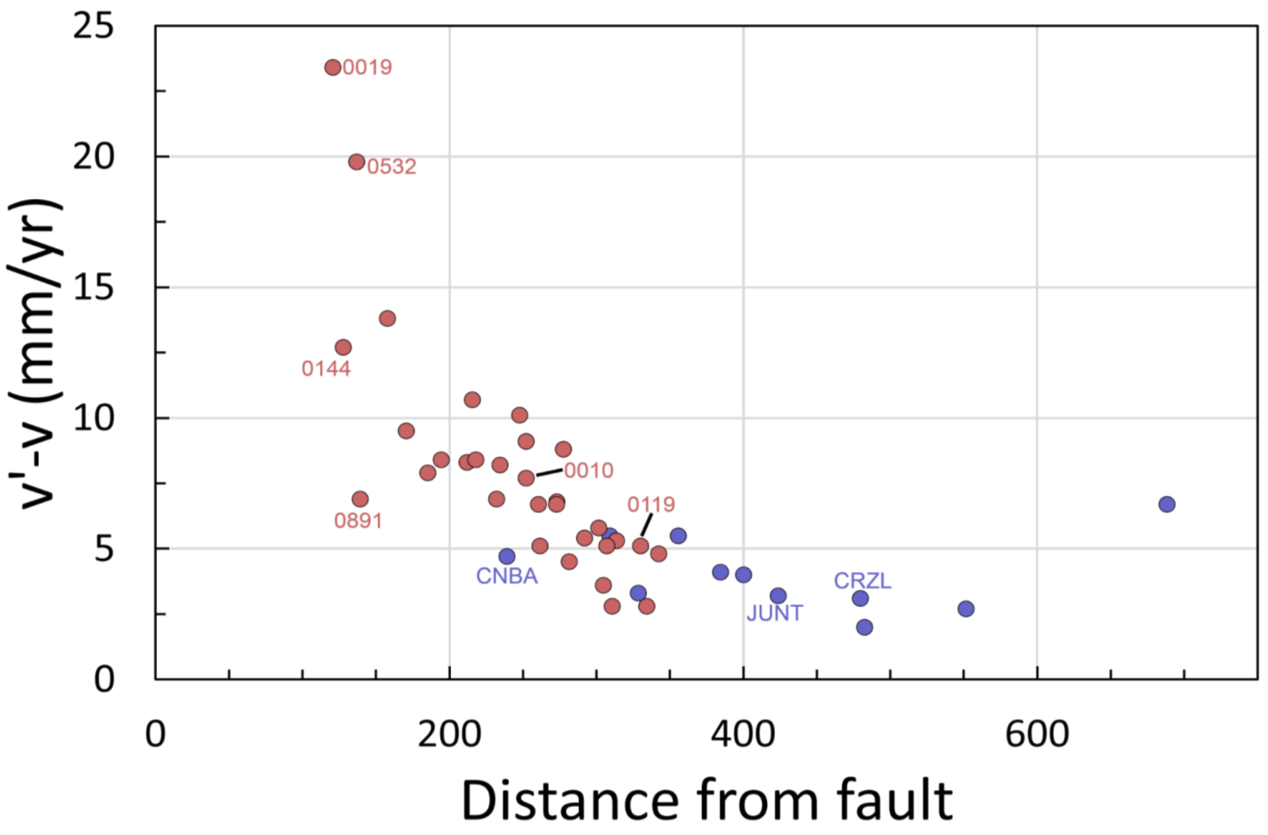
Positive change in the slope of the red time series.

Summary of observations

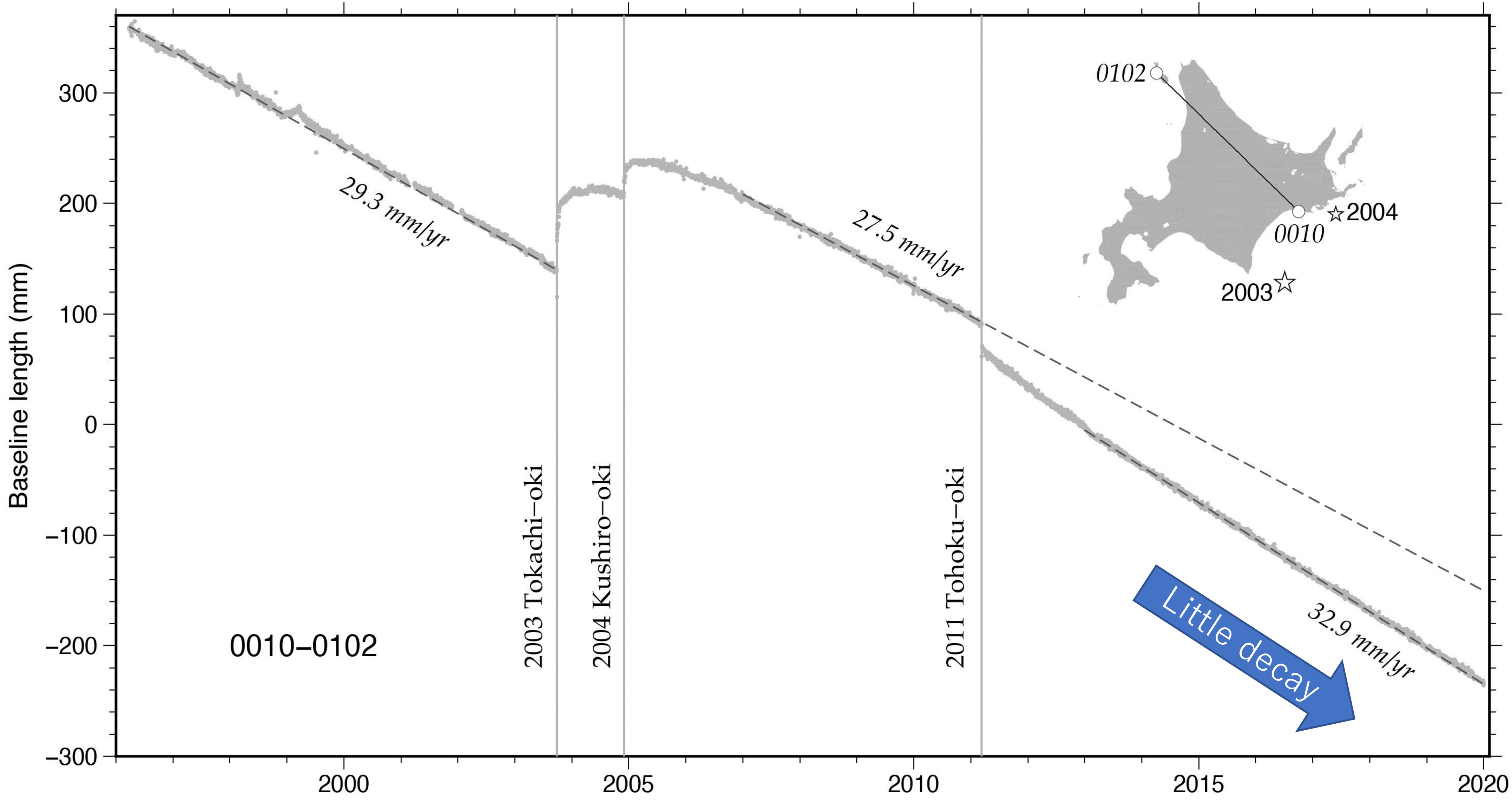
Spatial decay of the enhanced coupling



These landward velocities decay as we go away from the fault



Temporal decay of the enhanced coupling

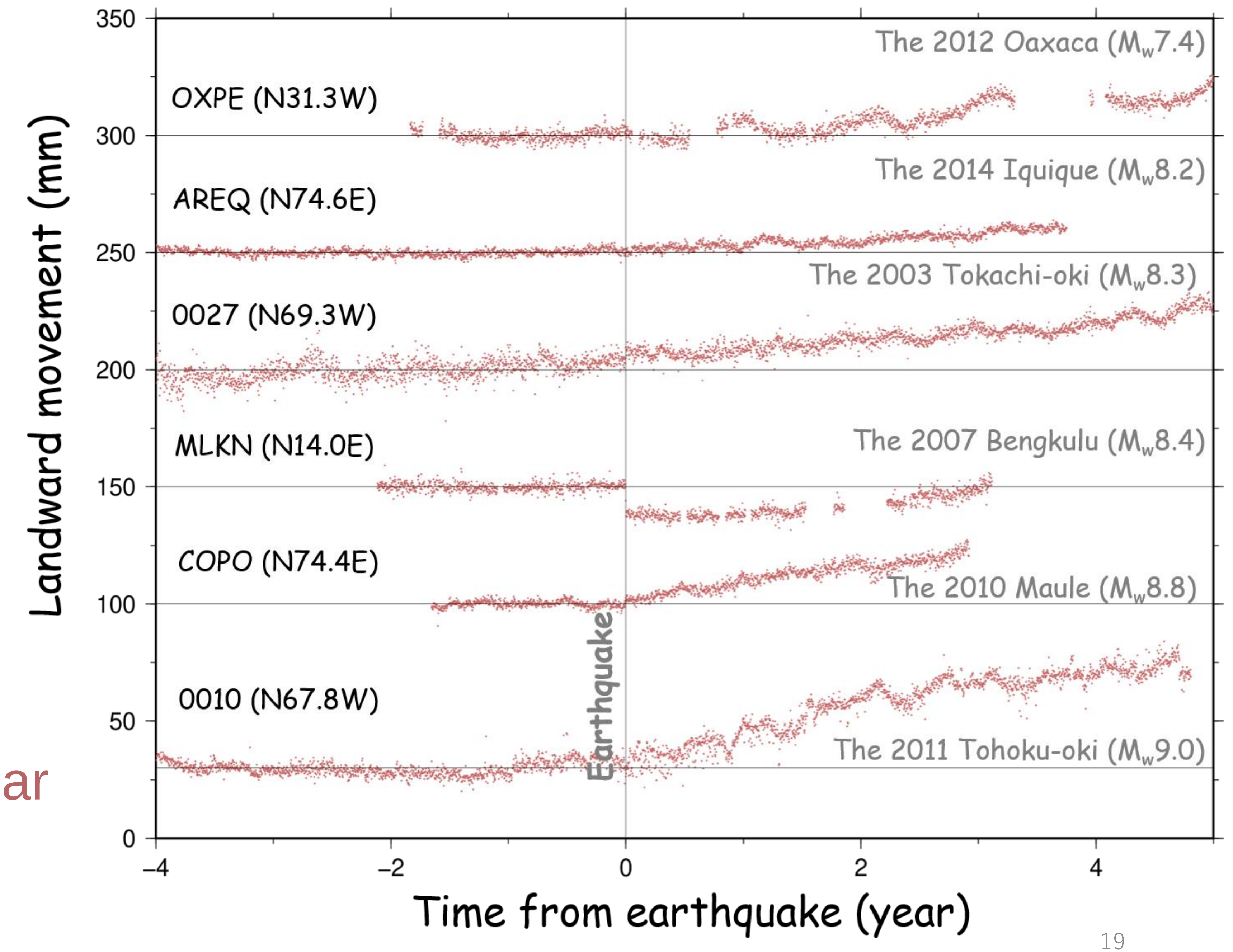


Little temporal decay of the postseismic enhanced coupling after the 2011 Tohoku-oki earthquake.

Comparison of 6 cases

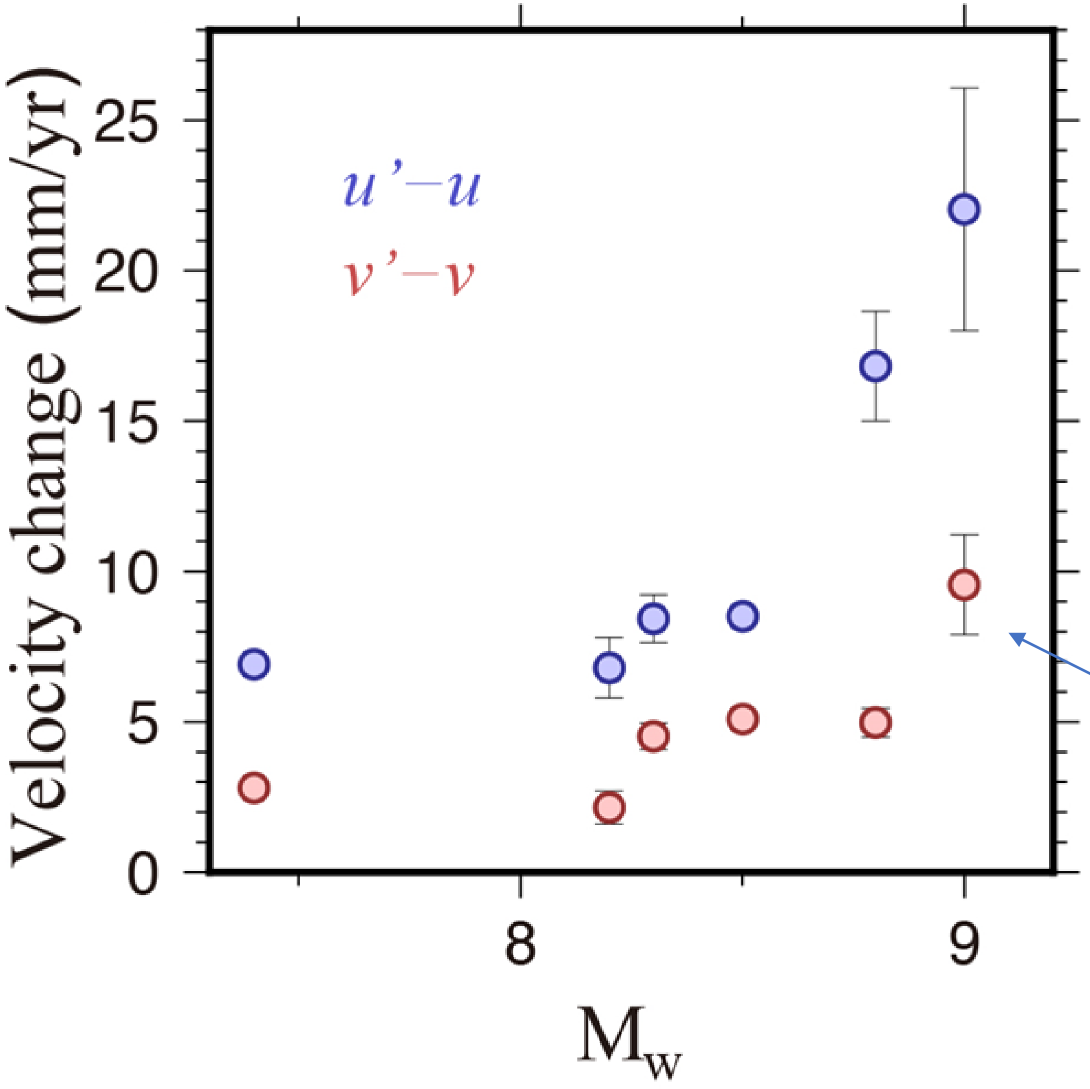
De-trended using parts before earthquakes

M_w dependence is clear



Discussion: Slab acceleration model

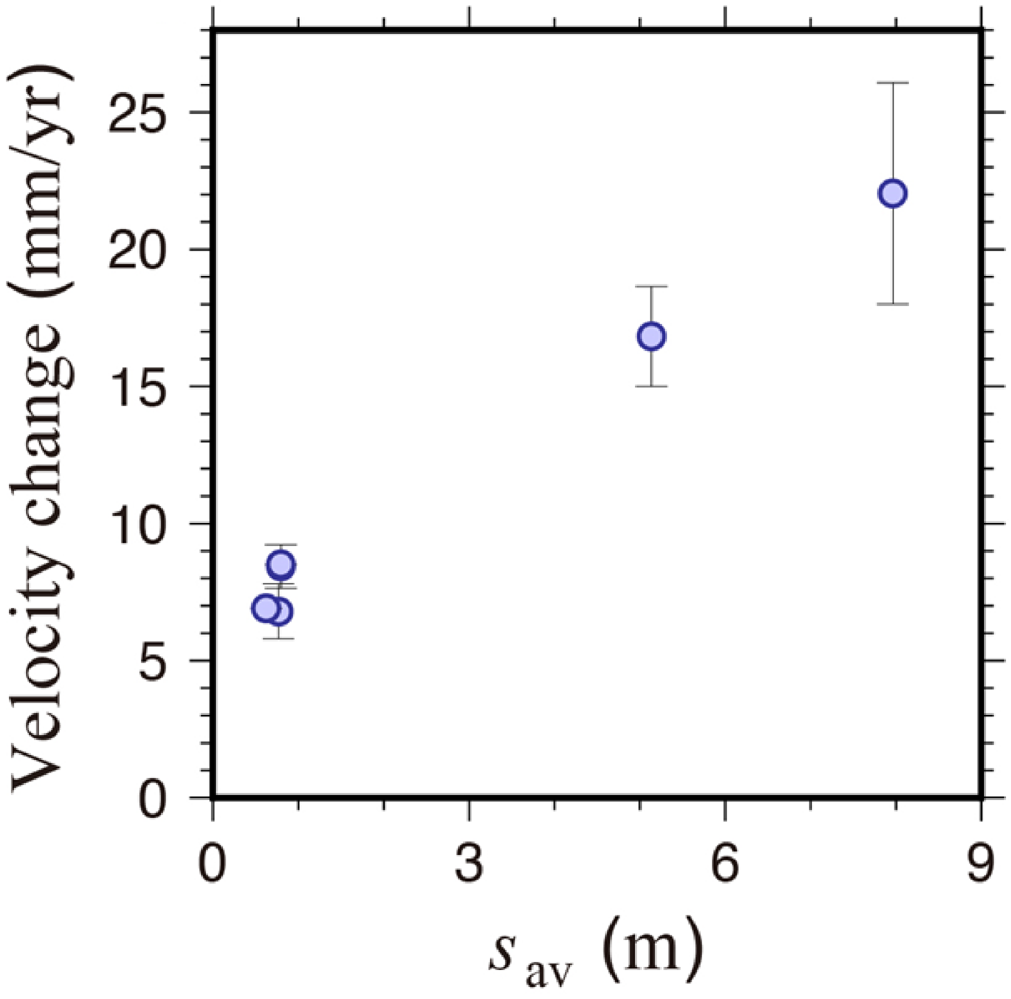
M_w dependence of acceleration?



We can see that a larger earthquake makes a larger acceleration, both forearc (v) and slab (u) velocities.

The average values and 1-sigma standard deviations of u'-u and v'-v are given for earthquakes where multiple stations are available.

Average fault slip s_{av} vs acceleration



Slab acceleration model predicts they are proportional (Heki & Mitsui, 2013)

Good correlation with s_{av}, but its not clear if they are proportional (4 eqs. with $M_w \leq 8.5$ are clustered).

Conclusions

- Confirmed previous studies for the 2003 Tokachi-oki and the 2011 Tohoku-oki (Heki and Mitsui, 2013) and the 2010 Maule (Melnick et al., 2017) earthquakes.
- Found 6 enhanced coupling cases for 4 subduction zones.
- Studied spatial and temporal decay of the enhancement signature.
- Degree of enhancement positively correlated with M_W, and possibly scales with average fault slip (Yuzariyadi and Heki, in preparation).

Acknowledgments

This study was fully supported by Indonesia Endowment Fund for Education (LPDP).

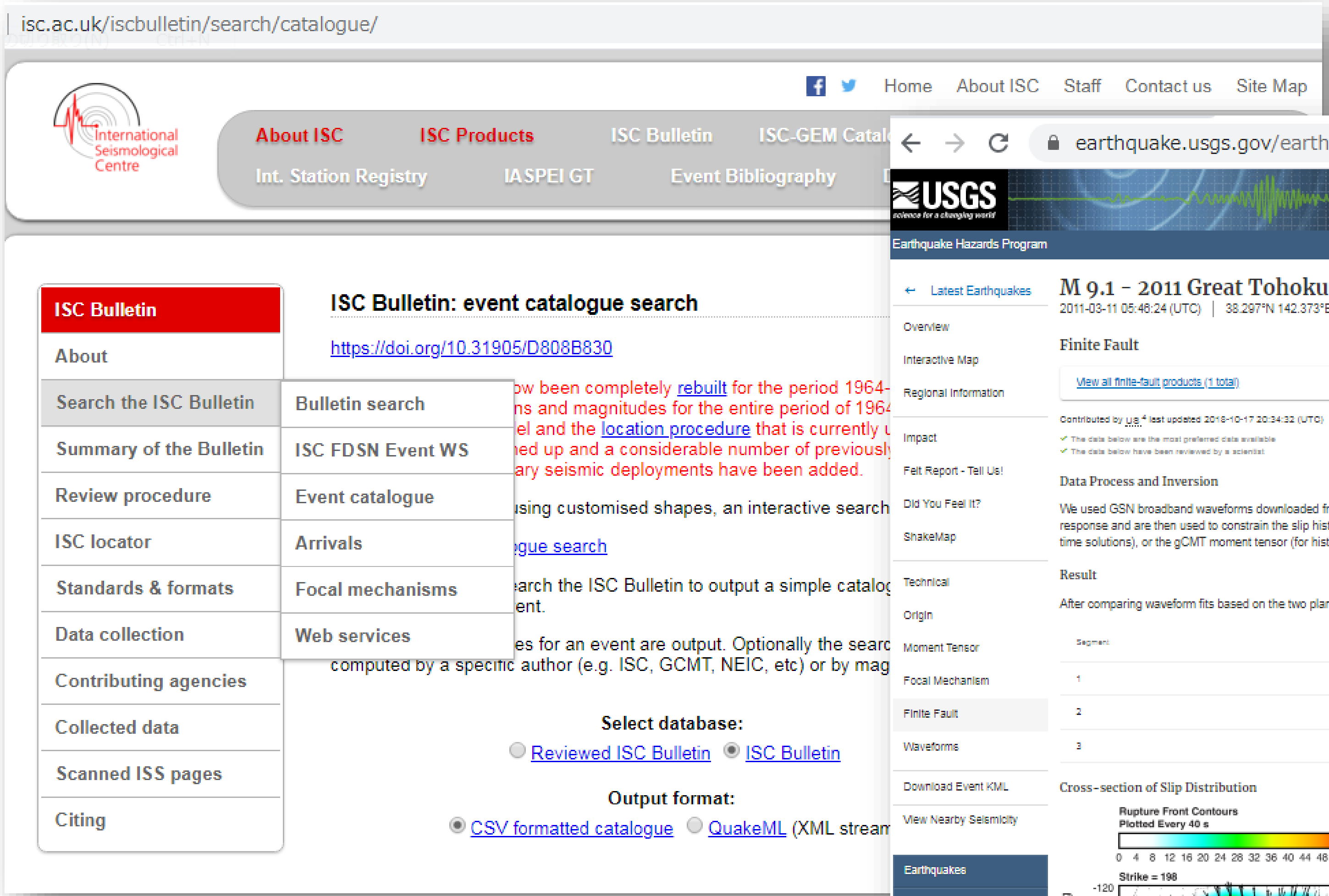
Appdix 1: Two periods used to estimate velocity changes before and after the earthquakes.

- These periods should be long enough to enable estimation of accurate velocities (>1.0 year) and hopefully be immediately before and after earthquakes.
- Actually, we often have to shift or shorten these periods to avoid unwanted transient movememnts by other smaller earthquakes during the studied periods.

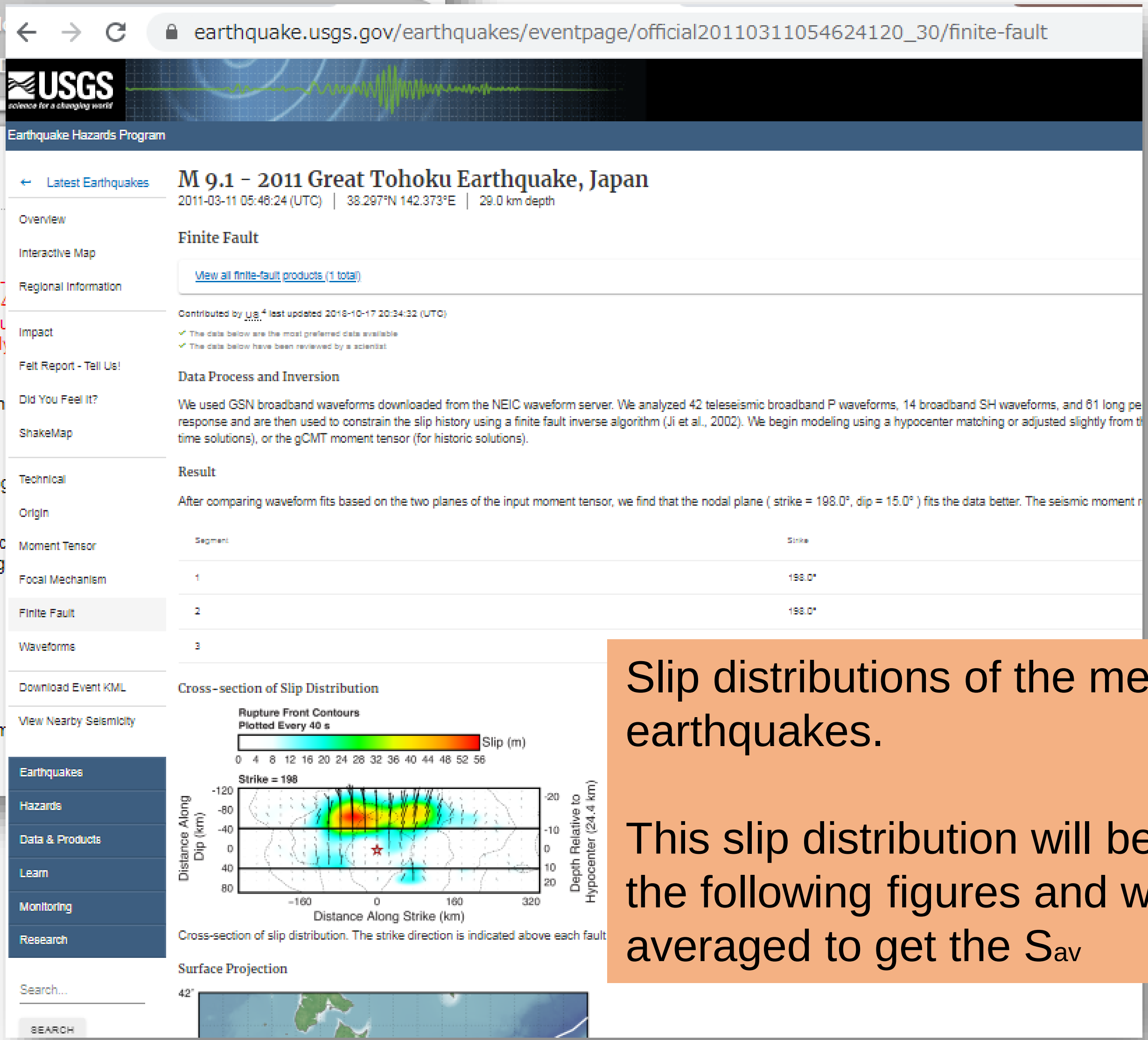
No	Earthquake (M_w)	Before earthquake	After earthquake[3]
1	2011/3/11 Tohoku-oki (9.0)	2008.00-2011.19	2011.19-2015.00
2	2003/9/25 Tokachi-oki (8.3)	1996.00-2003.74[1]	2003.74-2010.10
3	2010/2/28 Maule (8.8)	~2008.00[2]-2010.16	2010.16-2014.70
4	2014/4/1 Iquique (8.2)	~2010.00[2]-2014.25	2014.25-2015.25
5	2007/9/12 Bengkulu (8.4)	2005.50-2007.70	2007.70-2010.81[4]
6	2012/3/20 Oaxaca (7.4)	2010.38-2012.22	2012.22-2015.00

[1]Shifted to 1996.0-2003.0 to avoid influence of the Miyagi-oki earthquake (M_w 7.0) on 2003 May 26 for stations close to its epicenter
[2]Earliest possible starting times used depending on the availability of the stations
[3]The early non-linear postseismic periods avoided to draw Fig for cases of Tohoku-Oki and Tokachi-Oki earthquake case.
[4]Only data until the occurrence of the 2010 Mentawai earthquake.

Appendix 2: Supporting Data: Seismicity and fault slip distribution



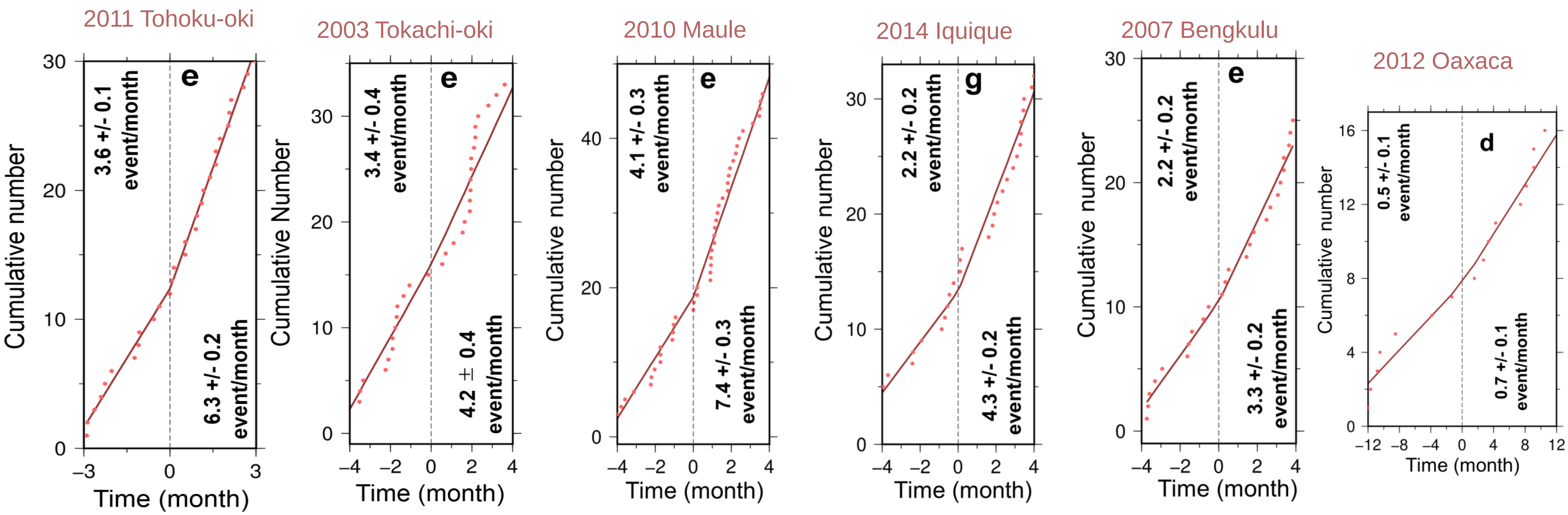
Seismicity with Mb ≥ 2 and depth ≤ 60 km.



Slip distributions of the megathrust earthquakes.

This slip distribution will be shown in the following figures and will be averaged to get the S_{av}

Appendix 3: Increase in seismicity in the 6 cases

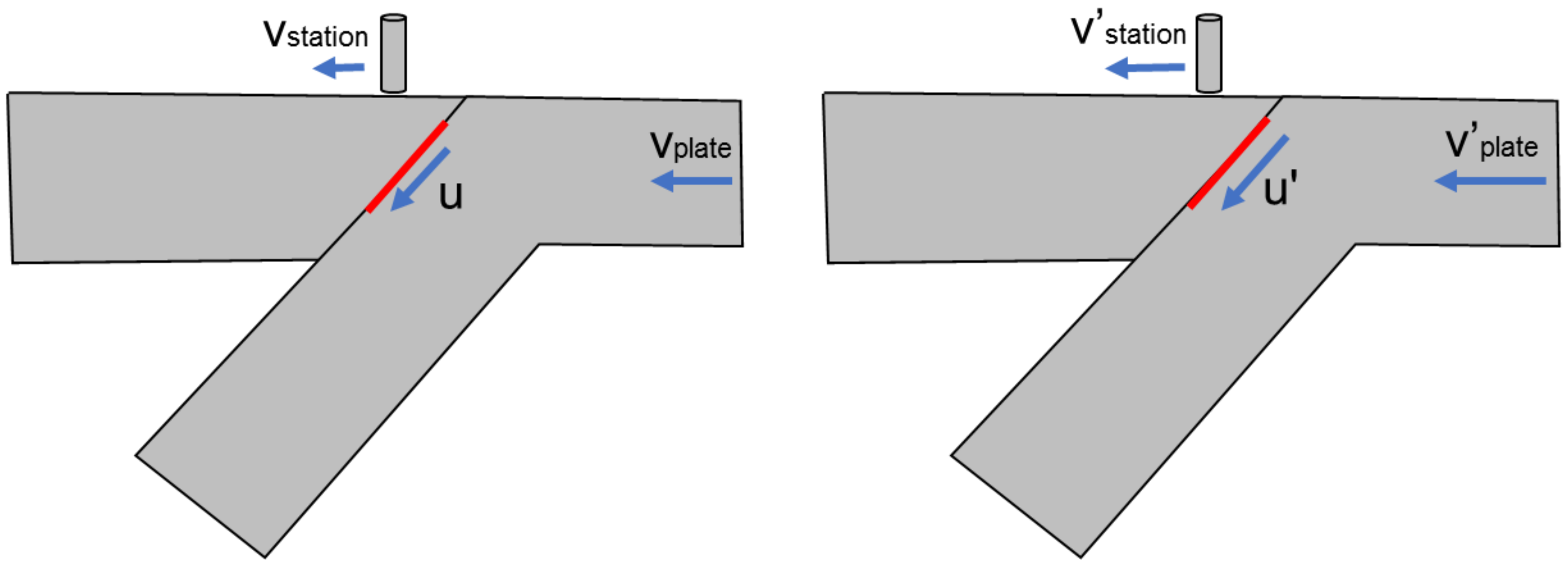


Appendix 4: Conversion from forearc acceleration *v*'-*v* to possible slab acceleration *u*'-*u*

Generally, *v* becomes larger if interplate coupling is stronger, but *v* never exceeds *u*.

Before earthquake

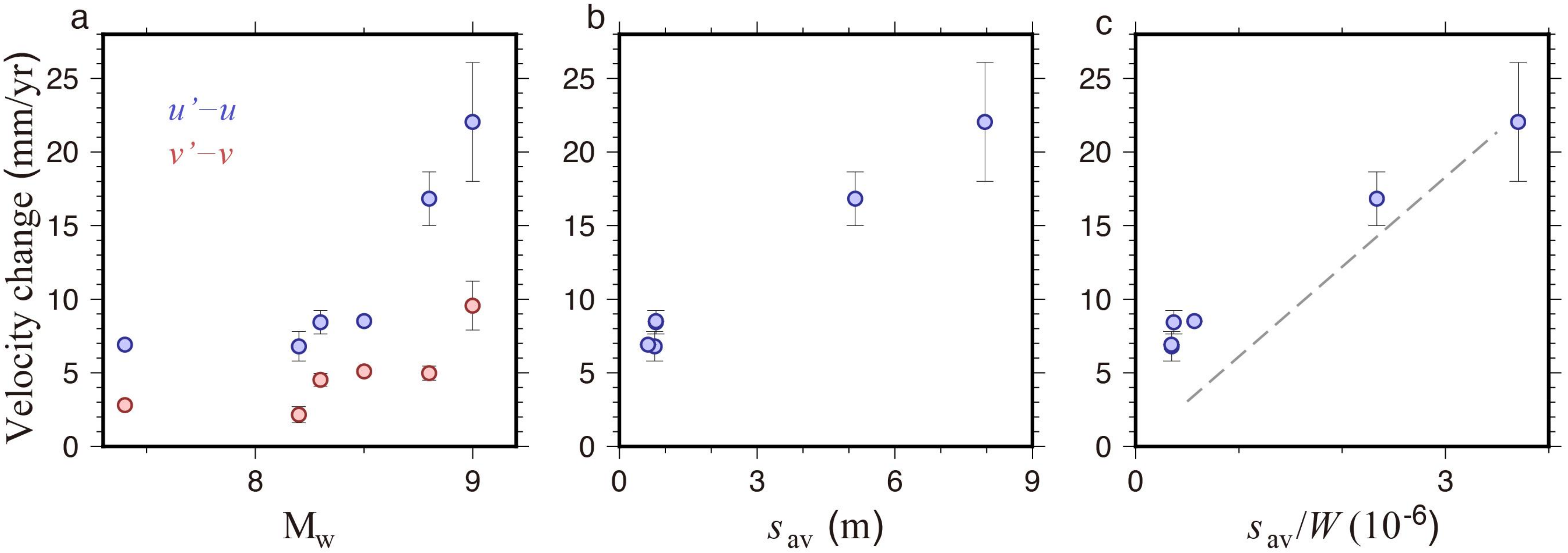
After earthquake



Subduction speed, v_{plate}, calculated by subtracting the MORVEL model velocities (Argus et al., 2011) from ITRF velocities.

$$u' - u = (v_{plate} / v_{station}) \times (v'_{station} - v_{station})$$

Appendix 5: Comparison of the data with the slab acceleration model



We can see that a larger earthquake makes a larger acceleration, both forearc (v) and slab (u) velocities.

The acceleration seems to show good correlation with s_{av} but it is not very clear if the two quantities are proportional considering the four earthquakes with $M_w \leq 8.5$ are clustered and do not contribute to the evaluation of the linearity.

Data in Figure c shows good linearity, but it is not enough to give firm support to the slab acceleration model proposed by Heki and Mitsui (2013), considering that 4 smaller earthquakes make one cluster.