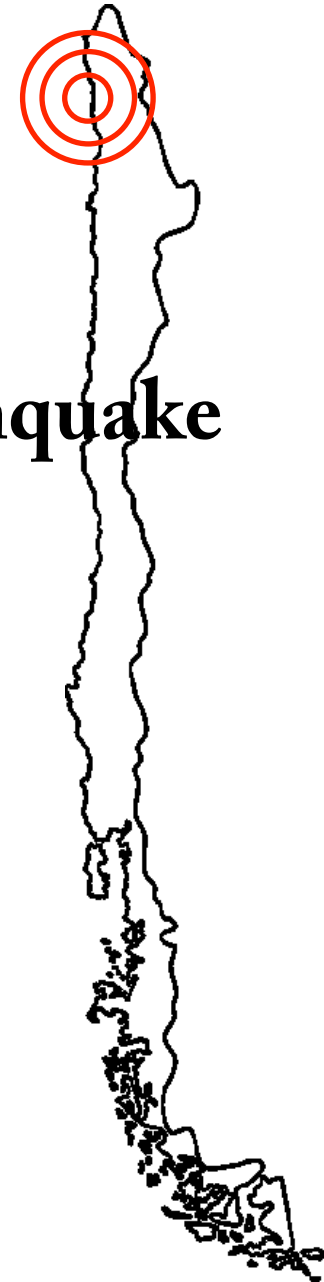




Centro de Sismologia da USP  
IAG / IEE



# The North Chile seismic gap: waiting for the next megathrust earthquake

Hans Agurto-Detzel

Thanks to: Marcelo Bianchi, Mauricio Bologna

São Paulo, 27-March-2014

# M6.7 - 60km WNW of Iquique, Chile

2014-03-16 21:16:30 UTC

PAGER - YELLOW

ShakeMap - VII

DYFI? - VI

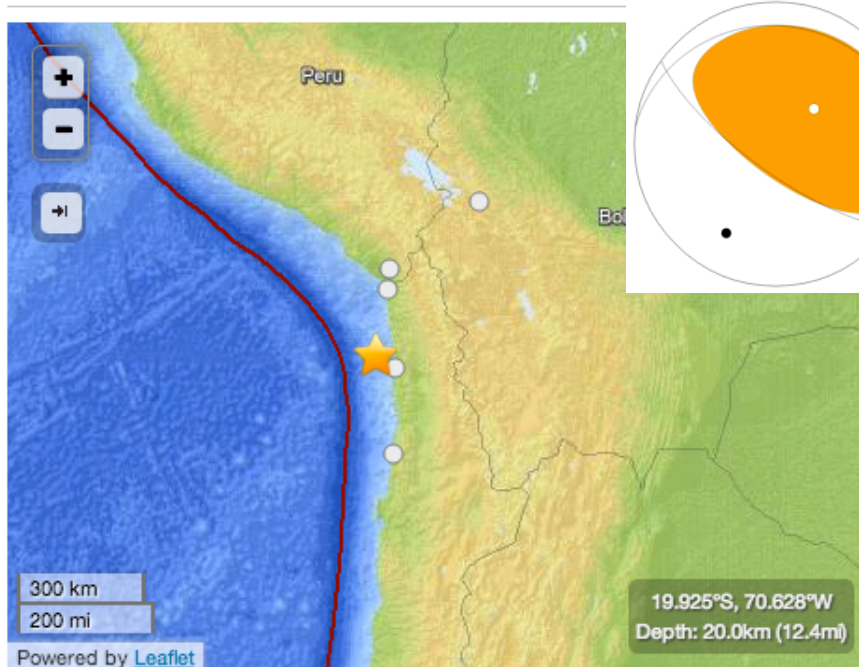


[Google Earth KML](#)

[Return to the EQ List/Map/Search](#)

## Summary

Location and Magnitude contributed by: [USGS National Earthquake Information Center](#)



### Event Time

2014-03-16 21:16:30 UTC

2014-03-16 16:16:30 UTC-05:00 at epicenter

2014-03-16 18:16:30 UTC-03:00 system time

### Location

19.925°S 70.628°W depth=20.0km (12.4mi)

### Nearby Cities

- 60km (37mi) WNW of **Iquique, Chile**
- 164km (102mi) SSW of **Arica, Chile**
- 216km (134mi) S of **Tacna, Peru**
- 244km (152mi) N of **Tocopilla, Chile**
- 460km (286mi) SW of **La Paz, Bolivia**

### Related Links

- [Additional earthquake information for Chile](#)
- [View location in Google Maps](#)

<http://earthquake.usgs.gov/>

## E-mail alert from Sismologia-IGAG on the 16<sup>th</sup> of March

From: suporte <sisfec@iag.usp.br>

Subject: **Event Located**

Date: 16 March 2014 18:20:45 GMT-03:00

---

earthquake, 3 minutes ago, Chile-Bolivia Border Region, magnitude 6.0, depth 217 kilometers

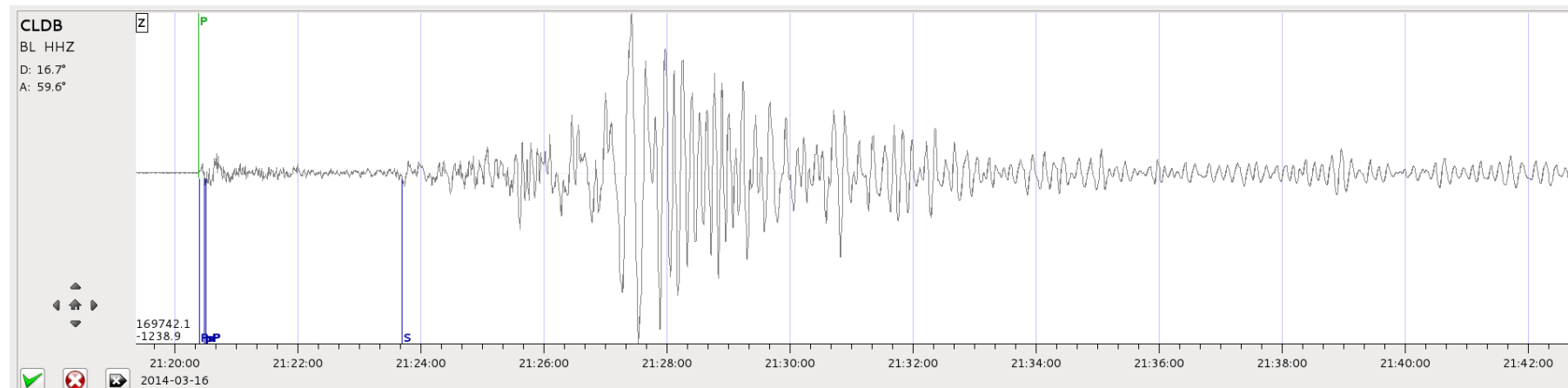
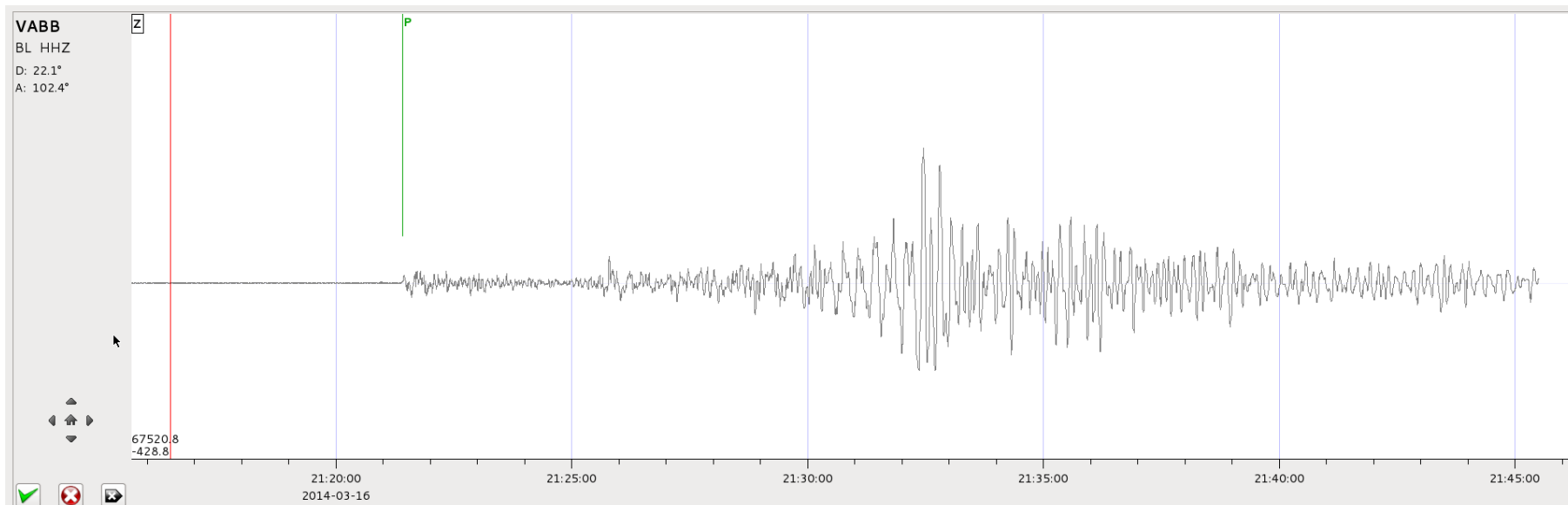
ATTENTION DISCLAIMER: Some of these detections may have been done automatically. This email can handle an event that did not exist or was poorly located. Please check before making any announcement.

<http://sismo.iag.usp.br/portal/events>

# Used Stations



# Waveform Examples

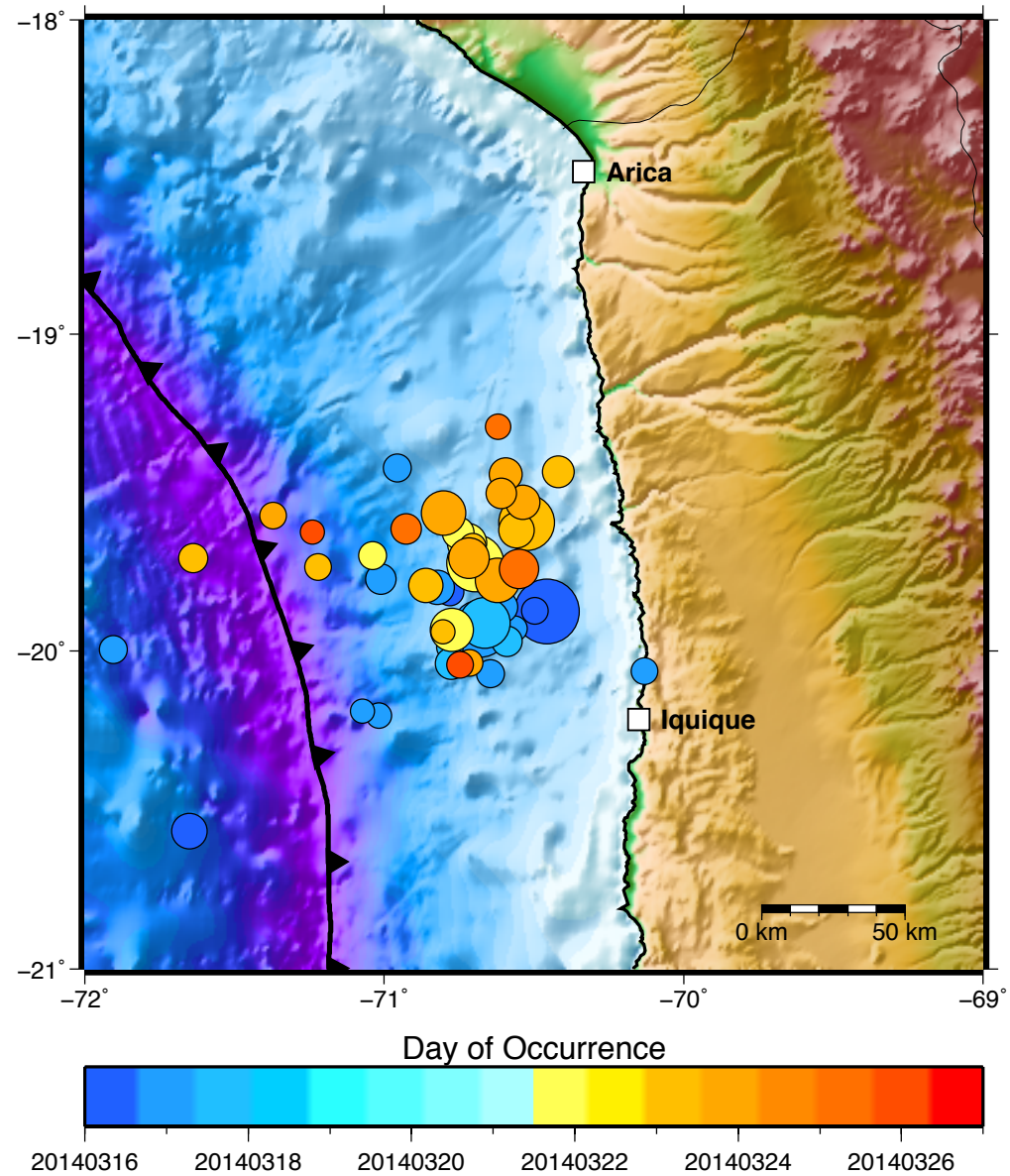


## Evolution of Automatic/Manual Location

2014-03-16 21:16:29	6.6	M	29	19.88 S 70.46 W	10 km	M	USP	Near Coast of Northern Chile	usp2014fgvj
<div style="margin-left: 20px;">             ▾ <i>Origins</i> </div>									
... 21:16:29	-	-	29	19.88 S 70.46 W	10 km	M	USP	Near Coast of Northern Chile	Origin#20140317120401.874046.36915
... 21:16:30	-	-	39	19.87 S 70.54 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316213812.065284.26454
... 21:16:30	-	-	39	19.87 S 70.54 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316213523.082565.26355
... 21:16:30	-	-	39	19.87 S 70.54 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316213125.950212.26245
... 21:16:30	-	-	38	19.87 S 70.53 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316213105.265858.26222
... 21:16:30	-	-	37	19.87 S 70.53 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316213028.679083.26199
... 21:16:30	-	-	36	19.87 S 70.52 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316212945.24532.26171
... 21:16:30	-	-	35	19.87 S 70.52 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316212637.308426.26115
... 21:16:30	-	-	34	19.87 S 70.52 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316212601.845768.26097
... 21:16:29	-	-	33	19.90 S 70.57 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316212539.865238.26084
... 21:16:29	-	-	32	19.90 S 70.57 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316212345.831244.26017
... 21:16:30	-	-	30	19.91 S 70.54 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316212329.738657.25991
... 21:16:30	-	-	29	19.91 S 70.54 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316212255.643776.25941
... 21:16:30	-	-	24	19.89 S 70.51 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316212240.813212.25895
... 21:16:31	-	-	20	19.90 S 70.45 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316212230.810325.25850
... 21:16:34	-	-	17	19.92 S 70.10 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316212217.954194.25814
... 21:16:34	-	-	16	19.91 S 70.10 W	10 km	A	USP	Near Coast of Northern Chile	Origin#20140316212203.753401.25791
... 21:16:40	-	-	13	19.47 S 70.58 W	155 km	A	USP	Near Coast of Northern Chile	Origin#20140316212156.284469.25754
... 21:16:40	-	-	12	19.46 S 70.56 W	158 km	A	USP	Near Coast of Northern Chile	Origin#20140316212140.798968.25725
... 21:16:39	-	-	10	19.48 S 70.60 W	158 km	A	USP	Near Coast of Northern Chile	Origin#20140316212135.79754.25704
... 21:16:40	-	-	9	19.46 S 70.53 W	158 km	A	USP	Near Coast of Northern Chile	Origin#20140316212130.422033.25686
... 21:17:00	-	-	8	18.62 S 68.87 W	217 km	A	USP	Chile-Bolivia Border Region	Origin#20140316212119.530754.25662

Hora	Latitude	Longitude	Profundidade	Magnitude (#estacoes)	Onde	Avaliação	Author
2014-03-24 04:08:34	-23.30	-67.55	358	3.4 M (7)	Chile-Argentina Border Region	A	scautoloc
2014-03-23 23:55:49	-19.94	-70.80	10	4.1 M (6)	Near Coast of Northern Chile	A	scautoloc
2014-03-23 22:04:29	-19.43	-70.42	10	4.6 M (15)	Near Coast of Northern Chile	A	scautoloc
2014-03-23 21:17:27	-19.62	-70.56	10	4.8 M (13)	Near Coast of Northern Chile	A	scautoloc
2014-03-23 20:23:03	-19.79	-70.86	10	4.8 M (13)	Near Coast of Northern Chile	A	scautoloc
2014-03-23 20:07:16	-19.70	-70.94	67	4.3 M (10)	Near Coast of Northern Chile	A	scautoloc
2014-03-23 18:20:05	-19.59	-70.45	41	6.1 M (21)	Near Coast of Northern Chile	M	mbianchi
2014-03-23 14:57:50	11.08	-73.92	10	5.3 M (5)	Near North Coast of Colombia	A	scautoloc
2014-03-23 12:48:00	-19.71	-71.64	10	4.4 M (6)	Off Coast of Northern Chile	A	scautoloc
2014-03-23 10:23:02	-19.74	-71.22	10	4.2 M (8)	Off Coast of Northern Chile	A	scautoloc
2014-03-23 10:10:53	-20.00	-68.90	137	3.9 M (13)	Chile-Bolivia Border Region	A	scautoloc
2014-03-23 04:30:46	-20.16	-178.74	411	5.8 M (6)	Fiji Islands Region	A	scautoloc
2014-03-22 22:15:02	-19.64	-70.65	42	4.5 M (13)	Near Coast of Northern Chile	M	mbianchi
2014-03-22 15:52:32	-19.69	-70.94	43	4.4 M (12)	Near Coast of Northern Chile	M	mbianchi
2014-03-22 14:18:47	29.31	139.28	418	5.6 M (6)	Southeast of Honshu, Japan	M	mbianchi
2014-03-22 14:15:40	-19.79	-70.64	10	4.5 M (12)	Near Coast of Northern Chile	A	scautoloc
2014-03-22 13:29:59	-19.66	-70.72	13	5.1 M (22)	Near Coast of Northern Chile	M	mbianchi
2014-03-22 13:14:59	-19.94	-70.77	10	5.4 M (12)	Near Coast of Northern Chile	A	scautoloc
2014-03-22 13:00:02	-19.72	-70.74	46	6.1 M (22)	Near Coast of Northern Chile	M	mbianchi
2014-03-22 11:58:30	-22.10	-69.48	132	3.9 M (10)	Northern Chile	A	scautoloc
2014-03-22 05:56:07	-17.95	-69.45	130	4.0 M (15)	Peru-Bolivia Border Region	A	scautoloc
2014-03-22 00:39:09	-5.59	-78.06	10	4.7 M (11)	Northern Peru	A	scautoloc
2014-03-21 13:41:09	6.78	97.64	10	6.2 M (3)	Nicobar Islands, India Region	A	scautoloc
2014-03-20 21:15:10	-4.70	152.79	10	5.7 M (3)	New Britain Region, P.N.G.	A	scautoloc
2014-03-20 18:44:12	-4.96	152.33	10	5.6 mb (2)	New Britain Region, P.N.G.	M	JRoberto
2014-03-20 18:41:22	-23.99	-69.33	10	5.2 M (17)	Northern Chile	M	Cleusa
2014-03-20 17:55:44	11.75	-87.60	10	4.9 mb (13)	Near Coast of Nicaragua	M	JRoberto
2014-03-20 17:01:19	-5.00	153.05	10	5.3 M (3)	New Ireland Region, P.N.G.	A	scautoloc
2014-03-20 13:48:47	-23.71	-51.75	0	3.3 MLv (3)	Brazil	M	JRoberto
2014-03-19 20:17:44	-60.52	-25.70	10	5.5 mb (21)	South Sandwich Islands Region	M	JRoberto
2014-03-19 12:19:35	24.74	121.85	68	5.3 M (7)	Taiwan	A	scautoloc
2014-03-19 00:41:06	-17.63	-142.53	26	5.5 mb (12)	Tuamotu Archipelago Region	M	JRoberto
2014-03-18 21:56:15	-18.97	-68.75	158	4.2 M (8)	Chile-Bolivia Border Region	A	scautoloc
2014-03-18 21:26:47	-19.91	-70.66	10	5.8 M (19)	Near Coast of Northern Chile	M	Cleusa
2014-03-18 16:06:39	-19.92	-43.81	0	3.3 MLv (3)	Brazil	M	JRoberto
2014-03-18 16:04:04	-19.48	-43.72	0	3.4 MLv (3)	Brazil	M	JRoberto
2014-03-18 14:59:01	-18.59	-70.32	100	4.4 M (7)	Near Coast of Northern Chile	M	Cleusa
2014-03-18 14:35:56	-20.04	-70.78	10	4.6 M (17)	Near Coast of Northern Chile	M	Cleusa
2014-03-18 14:18:35	-19.99	-70.78	10	4.3 M (12)	Near Coast of Northern Chile	M	Cleusa
2014-03-18 13:35:55	-18.65	-69.68	138	3.8 M (7)	Northern Chile	A	scautoloc
2014-03-18 09:30:27	-19.97	-70.59	10	4.6 M (12)	Near Coast of Northern Chile	M	Cleusa
2014-03-17 23:03:03	-28.29	-66.56	134	4.0 M (12)	Catamarca Province, Argentina	A	scautoloc
2014-03-17 19:05:26	-19.92	-70.66	0	4.9 mb (16)	Near Coast of Northern Chile	M	Cleusa
2014-03-17 13:24:49	-53.46	-32.27	10	5.4 M (22)	South Georgia Island Region	A	scautoloc
2014-03-17 11:29:41	-20.50	-70.94	110	4.3 M (8)	Near Coast of Northern Chile	A	scautoloc
2014-03-17 11:12:13	-19.80	-70.82	0	4.8 M (19)	Near Coast of Northern Chile	M	Cleusa
2014-03-17 08:51:03	-19.78	-71.01	10	4.5 M (12)	Off Coast of Northern Chile	M	Cleusa
2014-03-17 07:55:01	-19.92	-70.64	10	4.4 M (13)	Near Coast of Northern Chile	A	scautoloc
2014-03-17 07:18:14	-20.22	-72.78	10	4.3 M (6)	Off Coast of Northern Chile	A	scautoloc
2014-03-17 05:11:34	-19.93	-70.68	10	6.2 M (19)	Near Coast of Northern Chile	M	Cleusa
2014-03-17 04:59:24	-20.19	-71.07	85	4.0 M (7)	Off Coast of Northern Chile	A	scautoloc
2014-03-17 04:14:56	-17.94	-70.08	97	4.0 M (7)	Near Coast of Peru	A	scautoloc
2014-03-17 03:28:29	-20.06	-70.13	10	4.2 M (10)	Near Coast of Northern Chile	A	scautoloc
2014-03-17 02:41:55	-19.42	-70.96	10	4.3 M (6)	Near Coast of Northern Chile	A	scautoloc
2014-03-17 02:05:49	-20.00	-71.90	10	4.3 M (7)	Off Coast of Northern Chile	A	scautoloc
2014-03-17 01:34:56	-19.86	-70.61	10	4.6 M (19)	Near Coast of Northern Chile	M	Cleusa
2014-03-17 00:55:10	-20.20	-71.02	84	4.1 M (7)	Off Coast of Northern Chile	A	scautoloc
2014-03-17 00:12:12	-19.93	-70.57	10	4.1 M (8)	Near Coast of Northern Chile	A	scautoloc
2014-03-16 23:08:18	-19.96	-70.38	10	4.4 M (9)	Near Coast of Northern Chile	A	scautoloc
2014-03-16 22:54:07	-19.82	-70.78	10	4.3 M (9)	Near Coast of Northern Chile	A	scautoloc
2014-03-16 22:36:51	-20.57	-71.65	10	4.9 M (6)	Off Coast of Northern Chile	M	Cleusa
2014-03-16 22:23:36	-19.79	-70.70	10	4.3 M (12)	Near Coast of Northern Chile	M	Cleusa
2014-03-16 21:16:29	-19.88	-70.46	10	6.6 M (23)	Near Coast of Northern Chile	M	Cleusa

# North Chile events detected in our network





**...but aftershock sequences typically follow some rules:**

Omori's Law:

Aftershock rate decreases quickly, proportionally to the inverse of time

$$n = \frac{C}{(K + t)^P}$$

But on the 23/03 (one week after) → +50 quakes M>2 in the area

Båth's Law:

Usually the difference between the magnitudes of the mainshock and the largest aftershock is around 1.1-1.2 units

mainshock of 6.7 → largest aftershock should be around 5.5 (not 6.2!)

**...so what is happening in North Chile?**

...first let's clarify two concepts:

**The North Chile seismic gap:  
waiting for the next megathrust earthquake**

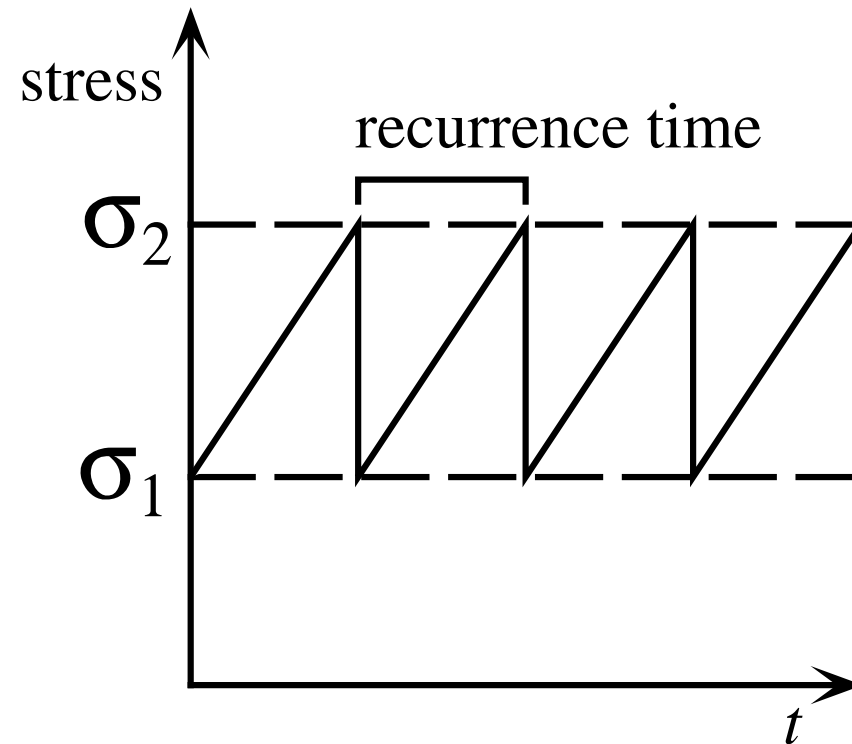
## What is a 'seismic gap'?

The seismic gap hypothesis implies that earthquake hazard is **small** immediately following a large earthquake and **increases** with time thereafter on a certain fault or plate boundaries

- Earthquakes occur periodically or quasi-periodically
- A fault that has broken recently is “safe”
- A fault that has not broken for a period of time represents a “gap” that can break soon

## What is a 'seismic gap'?

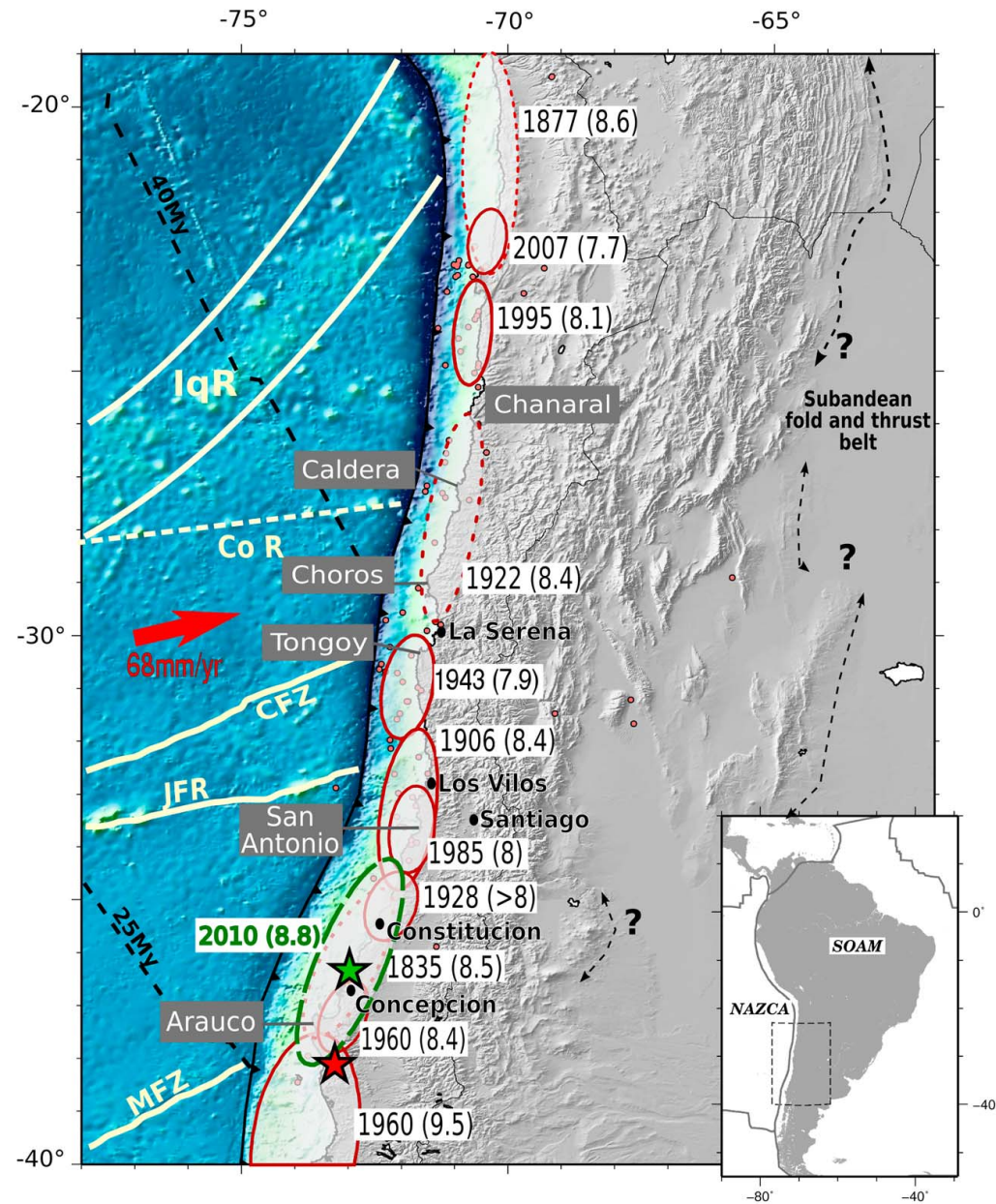
Stress is "low" after a large earthquake and must rebuild before another large quake can occur.



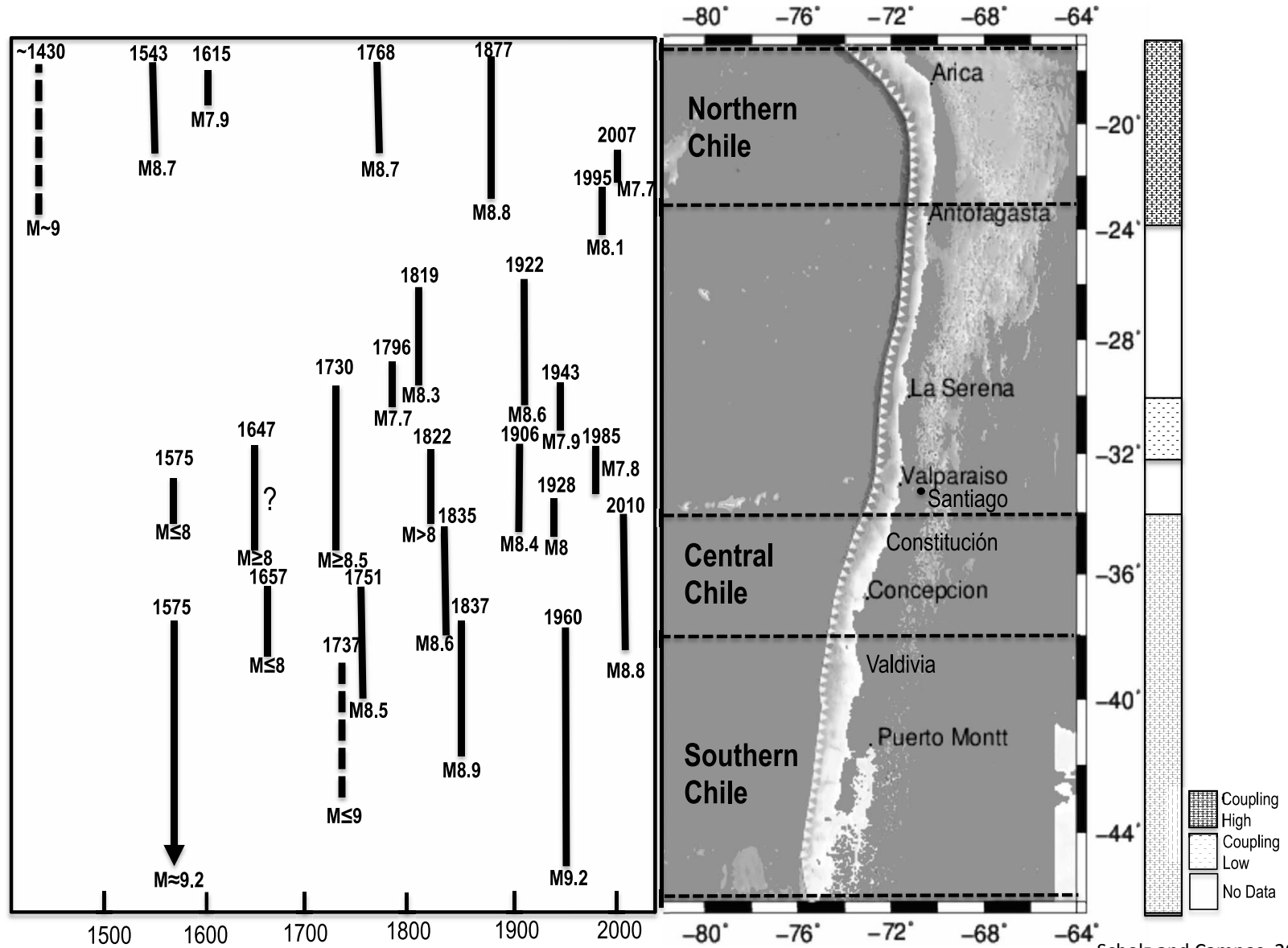
# What is a 'seismic gap'?



# What is a 'seismic gap'?



# What is a 'seismic gap'?

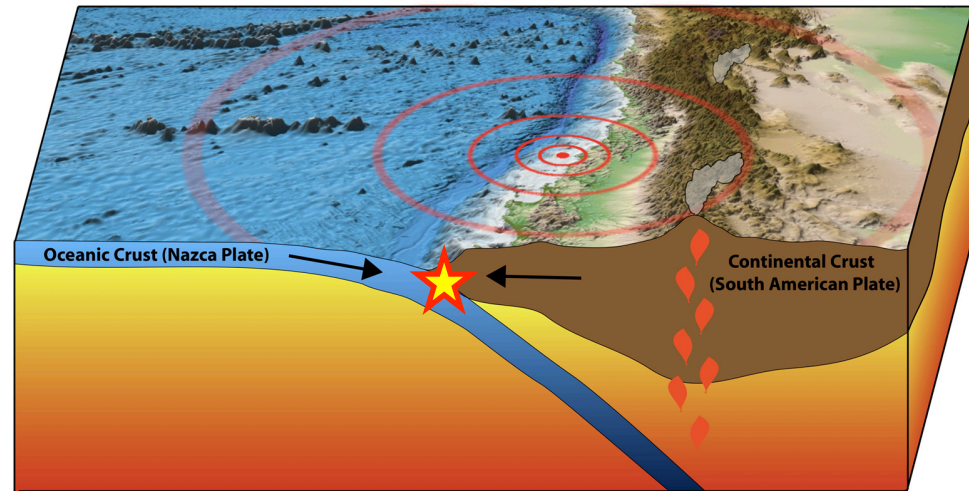


# What is a megathrust earthquake?

Largest and most destructive earthquakes on Earth

Occur at subduction zones

Can reach magnitudes above 9

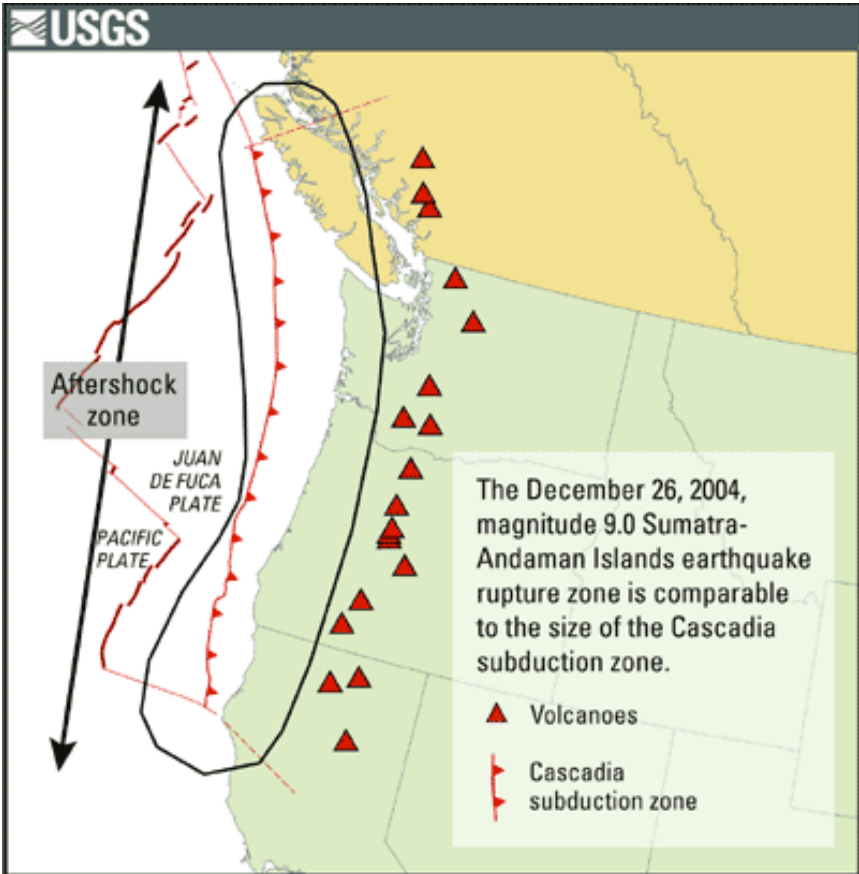


Earthquake	Magnitude	Fatalities	Rupture Length	Slip	Tsunami Height
Sumatra 2004	9.1	227898	1000 km	30 m	15 m
Chile 2010	8.8	525	500 km	16 m	10 m
Japan 2011	9.0	18517	500 km	50 m	37 m

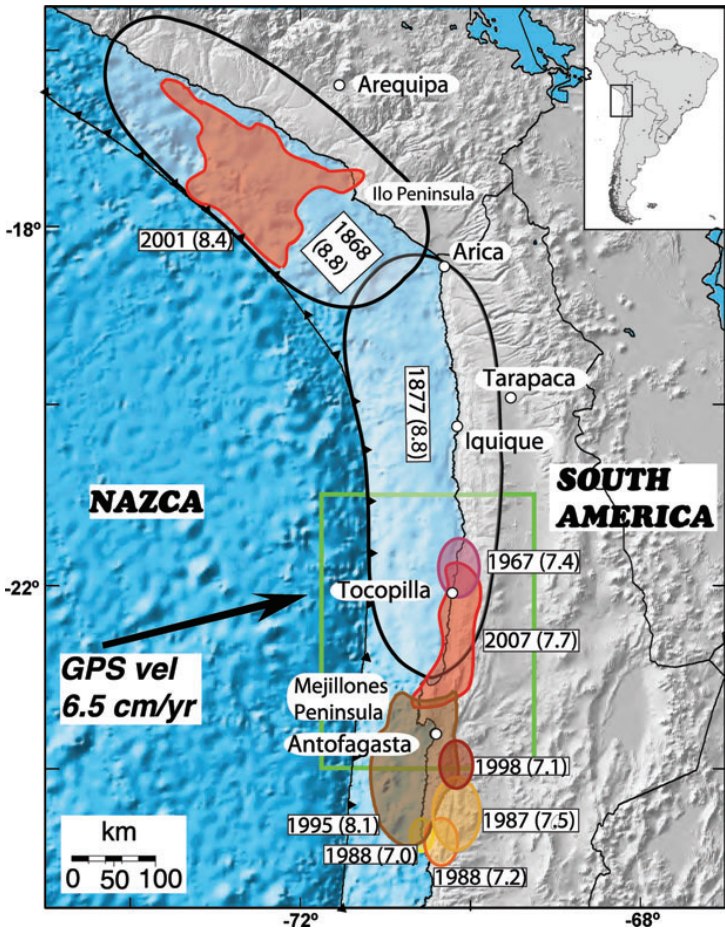


# What will be the next megathrust earthquake?

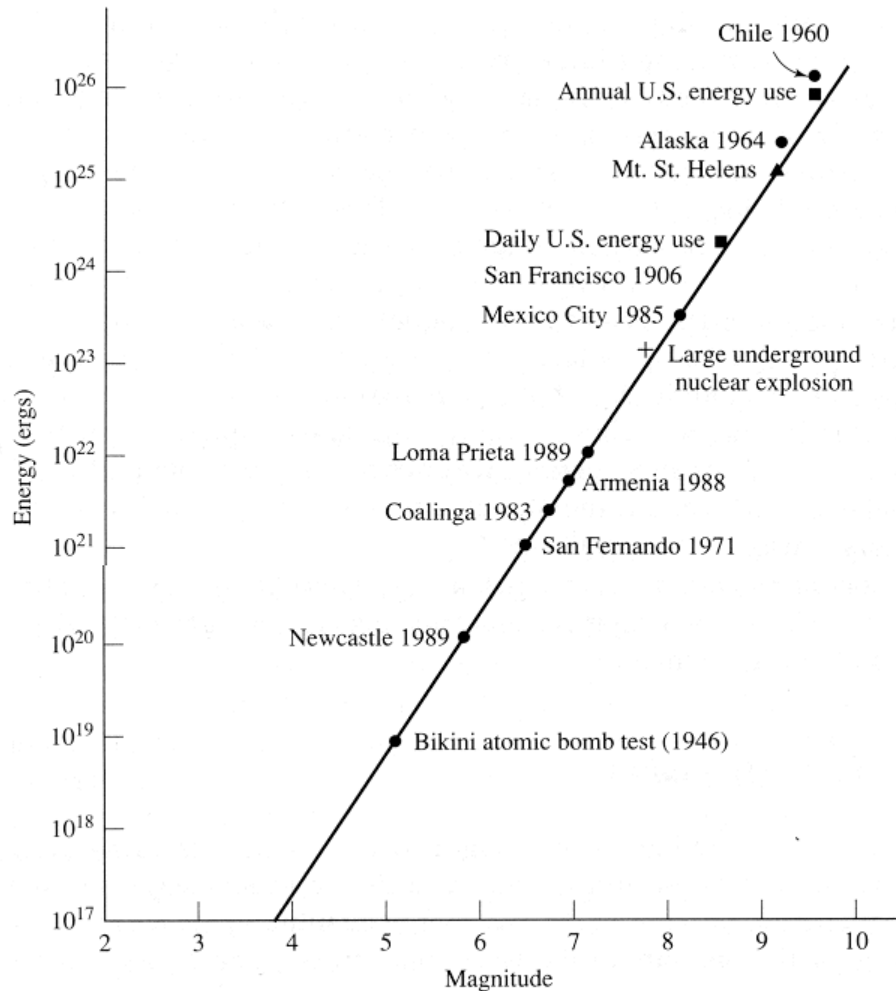
## Cascadia Subduction Zone



## North Chile



# How 'mega' is a megathrust earthquake?



In terms of energy release:

0.1 unit magnitude  $\sim 1.4X$   
1 unit magnitude  $\sim 32X$

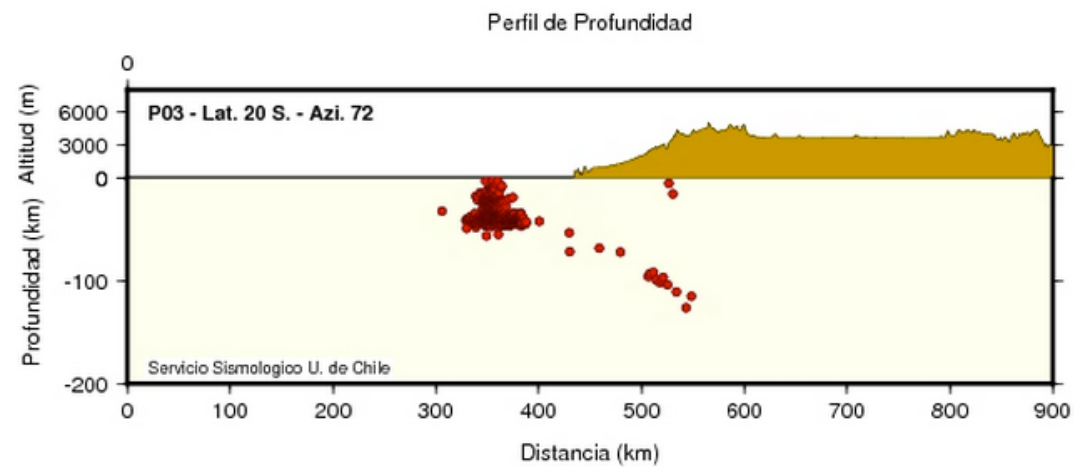
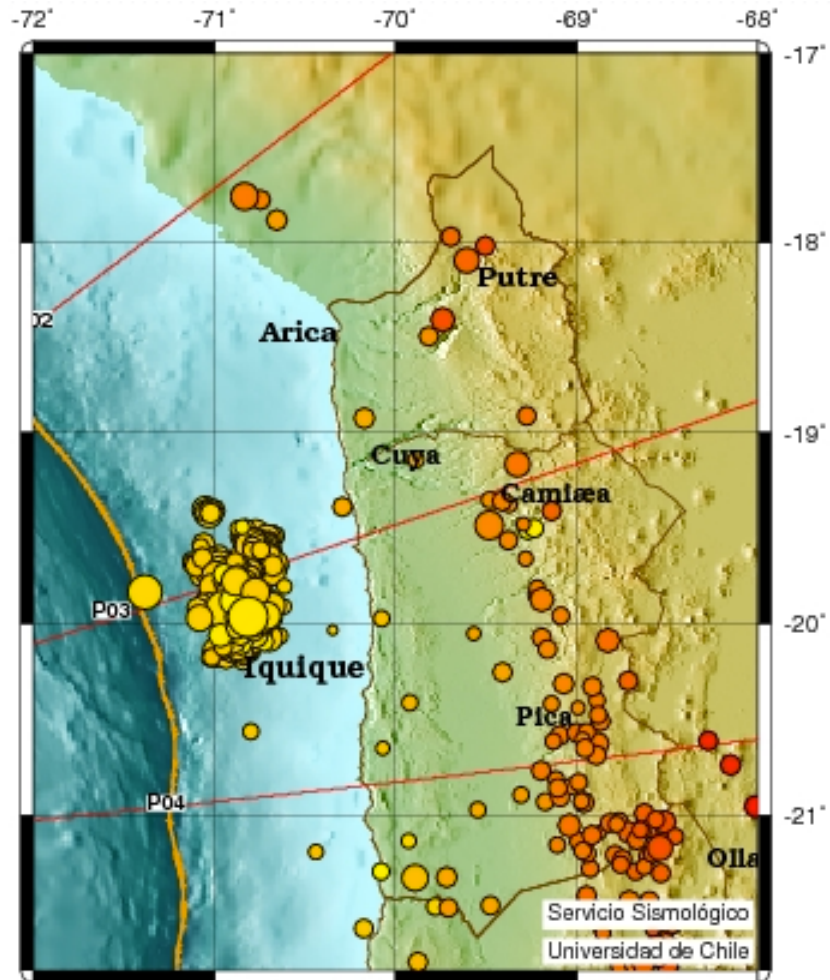
**M9 is 32 times stronger than M8**  
**and**  
**1000 stronger than M7**

Japan 2011 M=9 was 1000 times stronger than Haiti 2010 M=7

# How 'mega' is a megathrust earthquake?

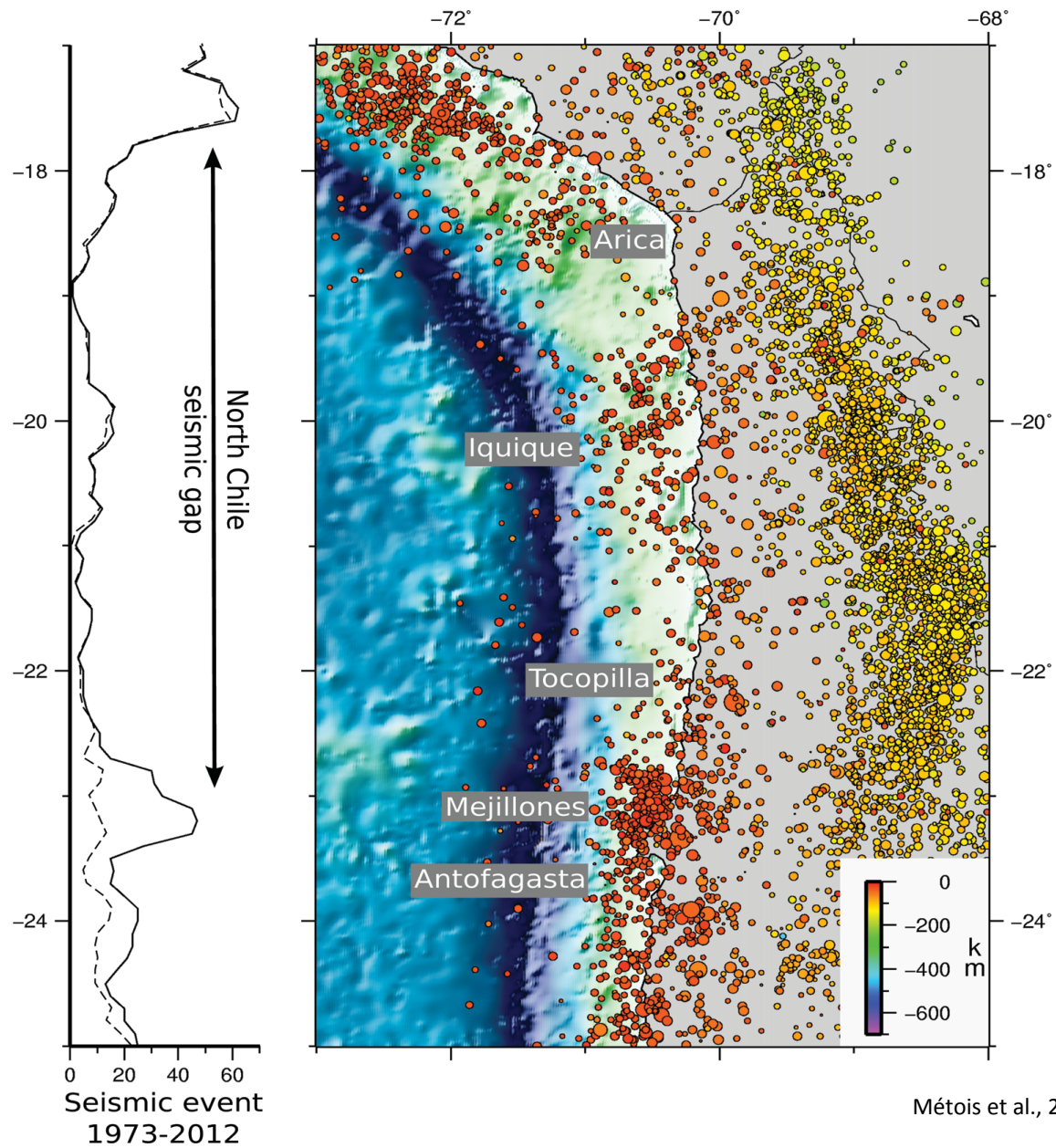


# North of Chile



GoogleEarth

# North of Chile



# North of Chile

Seismic gap present since 1877  
+137 years accumulating stress !

6.5 cm x 137 yr = **9 m** of slip !!

Seismic Moment →  $M_0 = \mu D A$

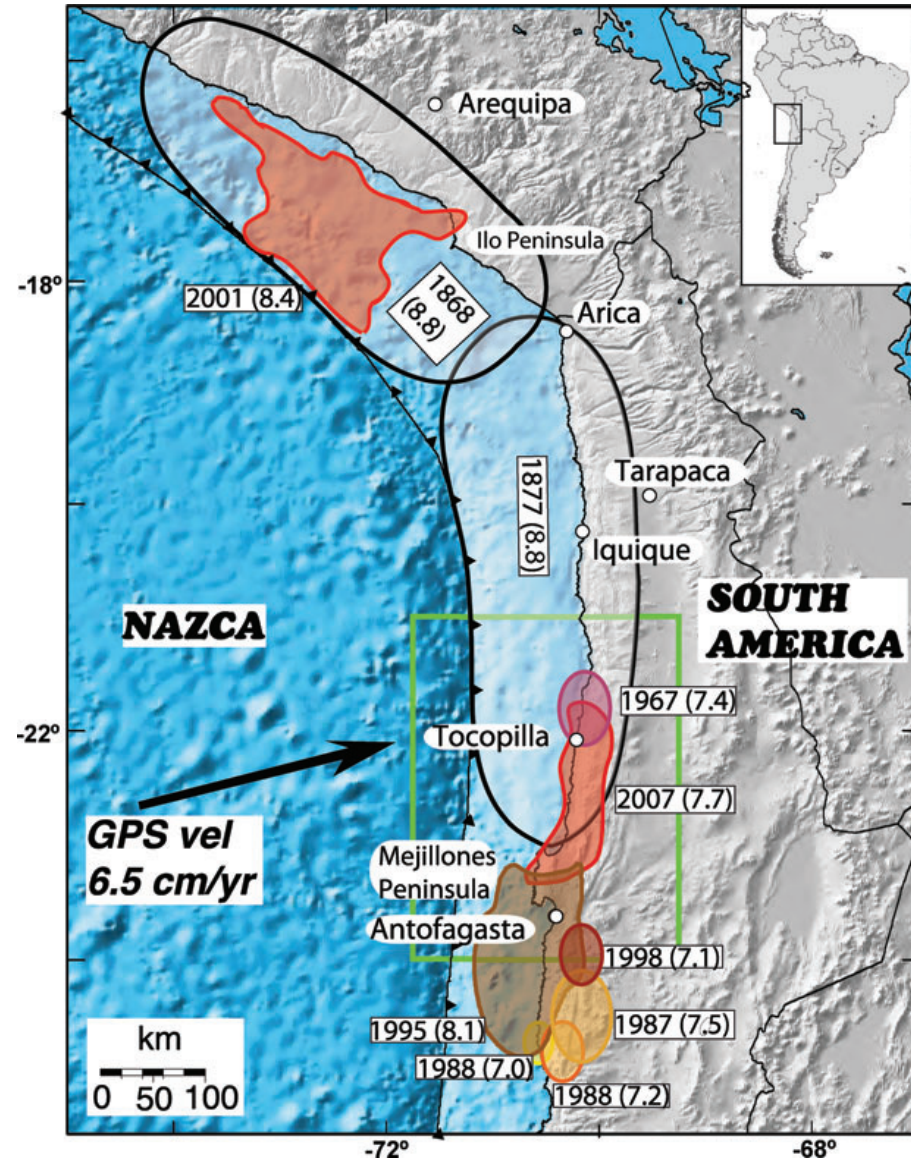
Considering rupture area =  
A = 500km x 150 km;  
and  $\mu = 35$  GPa

$$M_0 = 2.36 \text{ E}+22 \text{ N m}$$

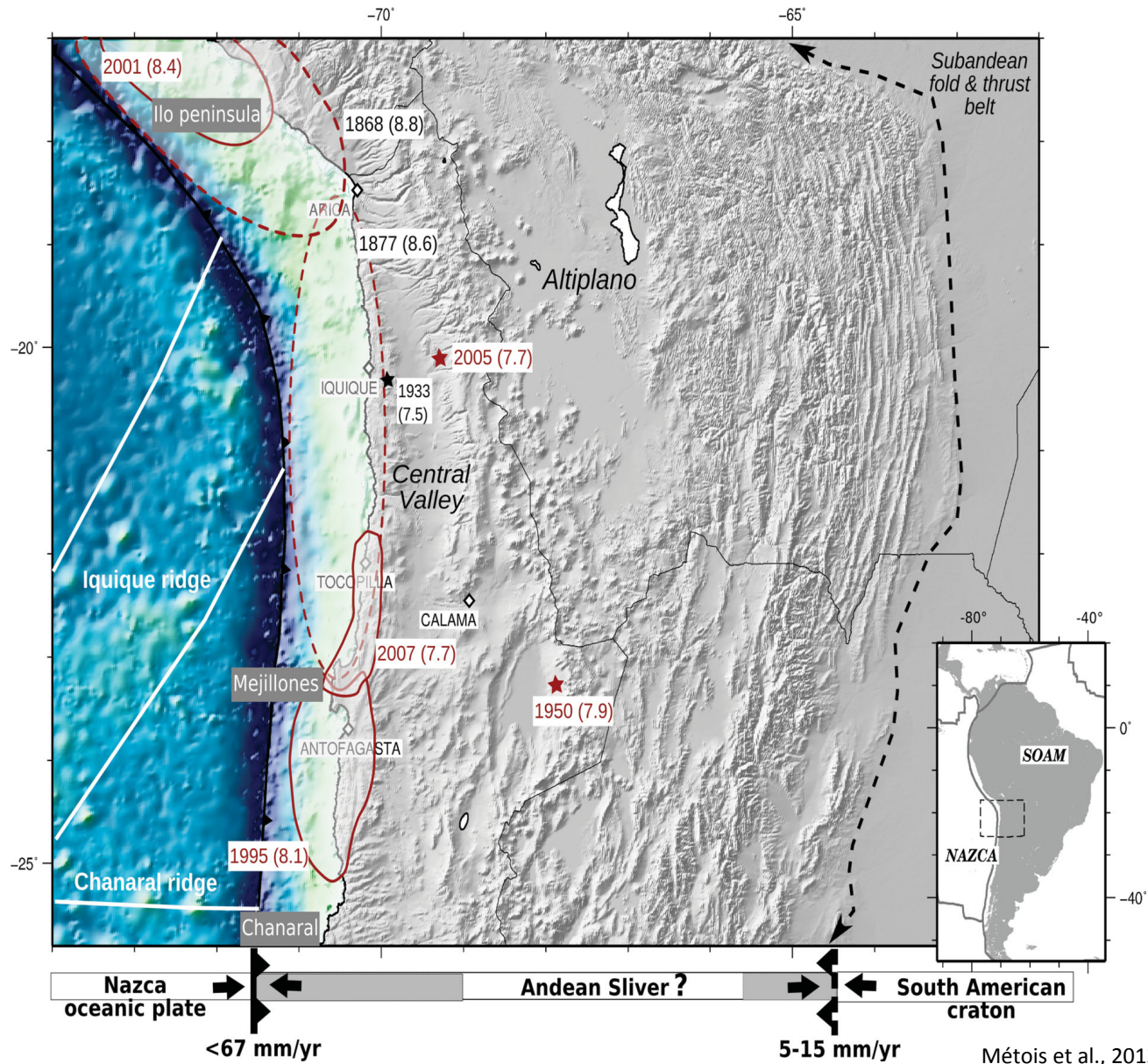
$$\text{Magnitude} = \frac{2}{3} \times [\log_{10}(\text{Moment}) - 16.1]$$

Worst case scenario:

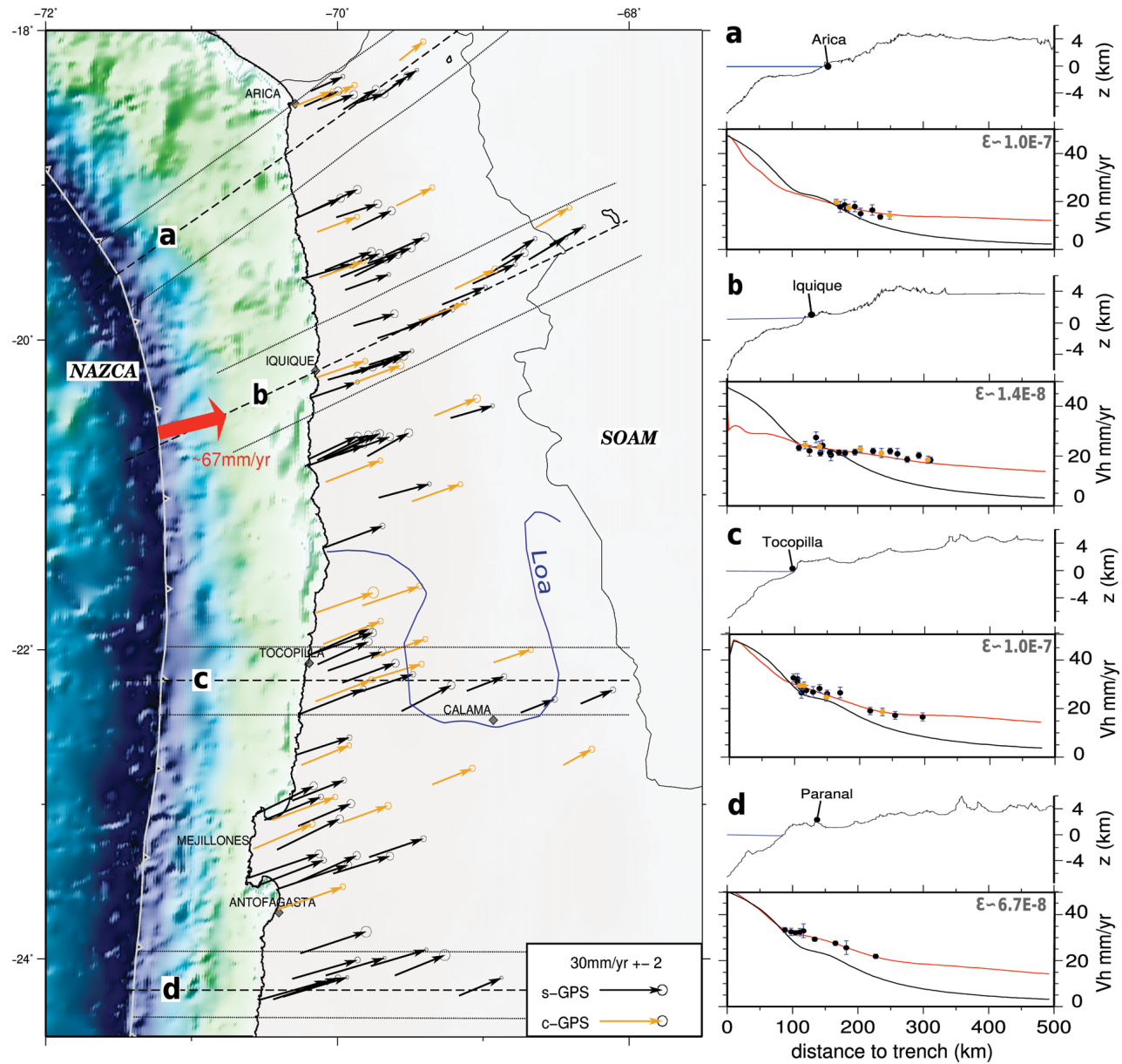
→ **Mw = 8.7-8.9**



# North of Chile

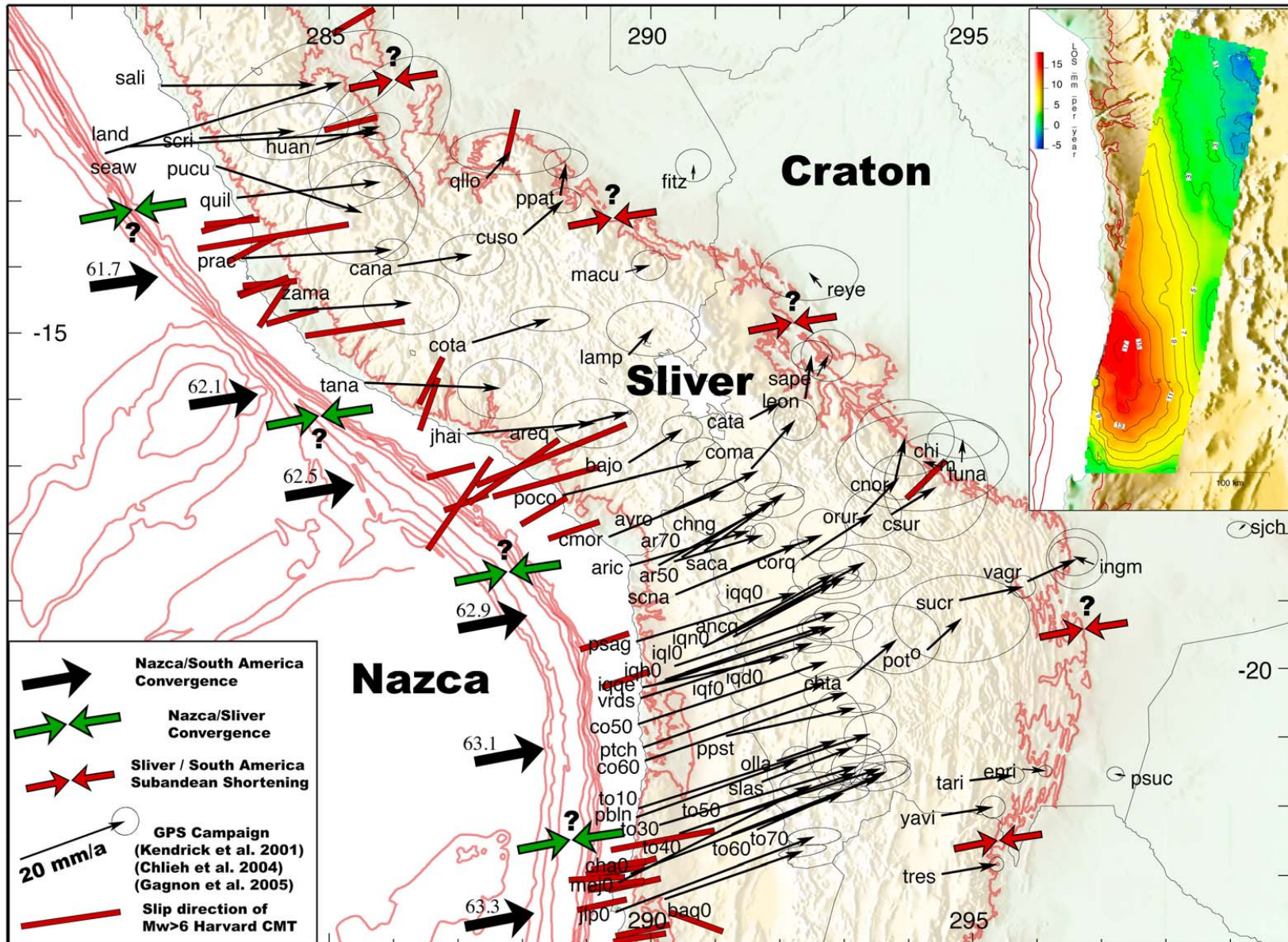


# Interseismic Displacements

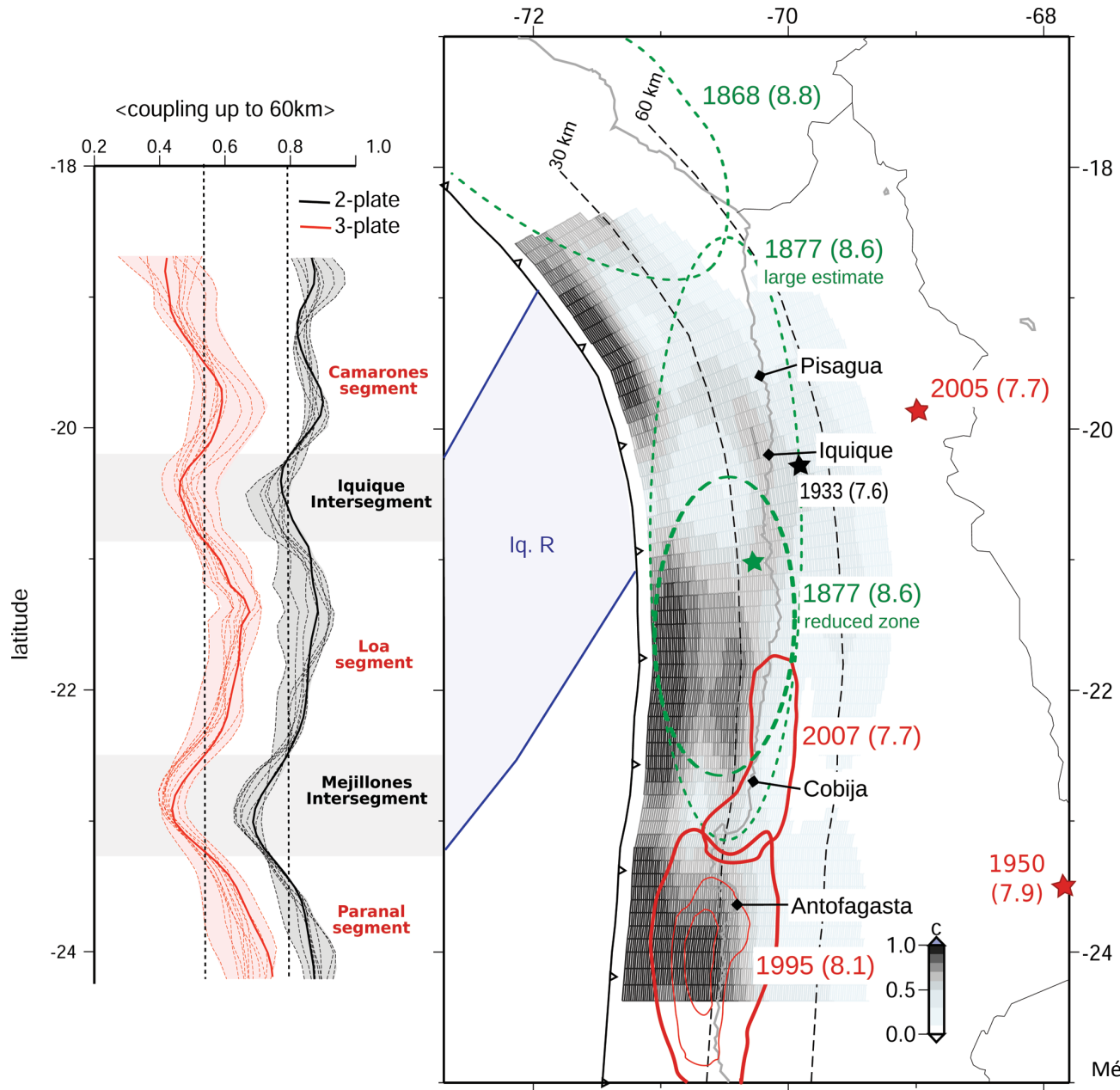




# Interseismic Displacements



# Interseismic Coupling

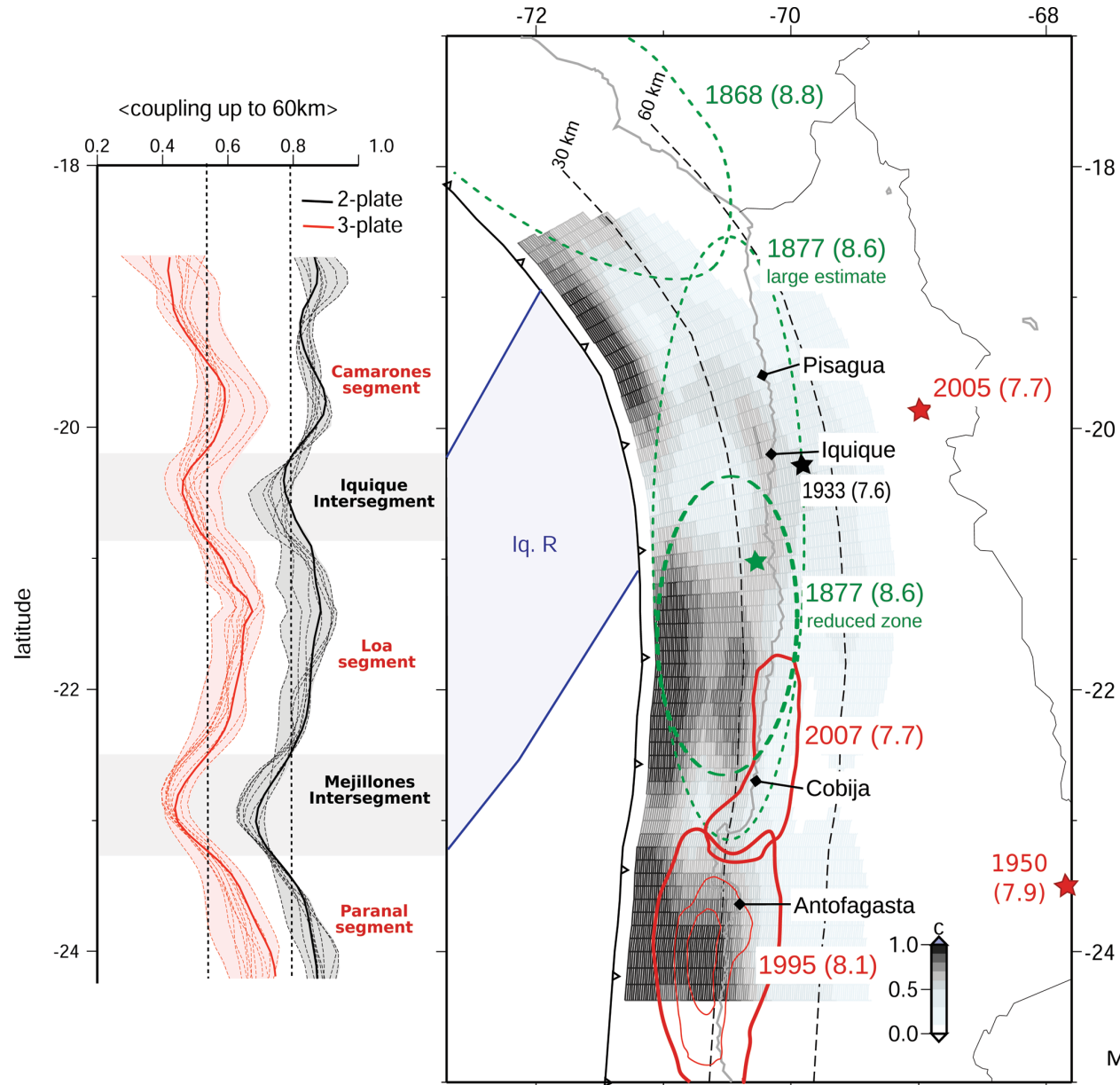


## What can we expect?

- ① Seismicity decays
- ② It breaks in smaller segments (2 x  $M \sim 8.2$  events)
- ③ It breaks the complete segment filling the North Chile seismic gap ( $M > 8.5?$ )

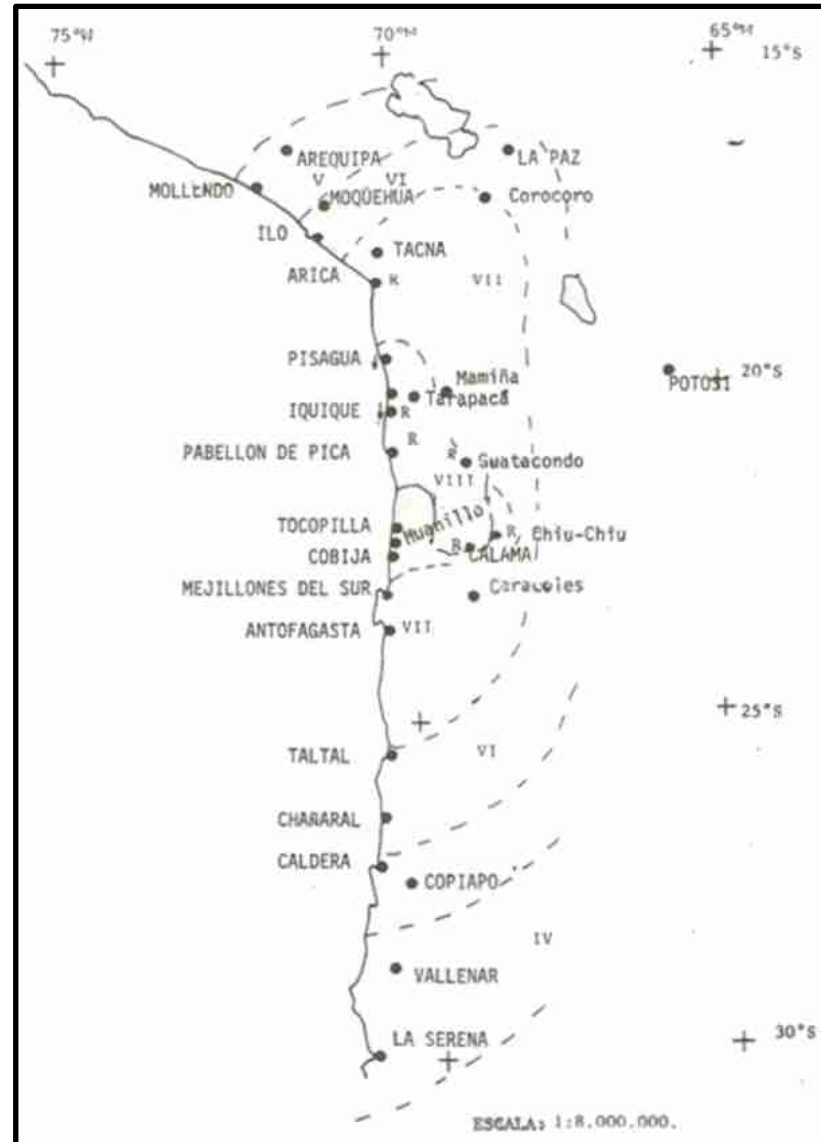
# What can we expect?

2) It breaks in smaller segments (2 x M~8.2 events)



# What can we expect?

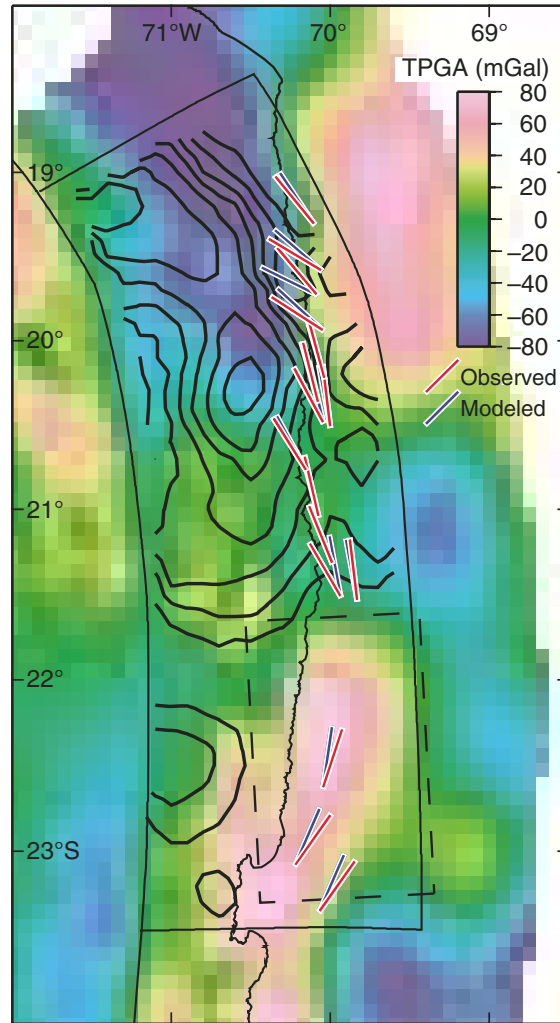
3) It breaks the complete segment filling the North Chile seismic gap ( $M > 8.5$ )



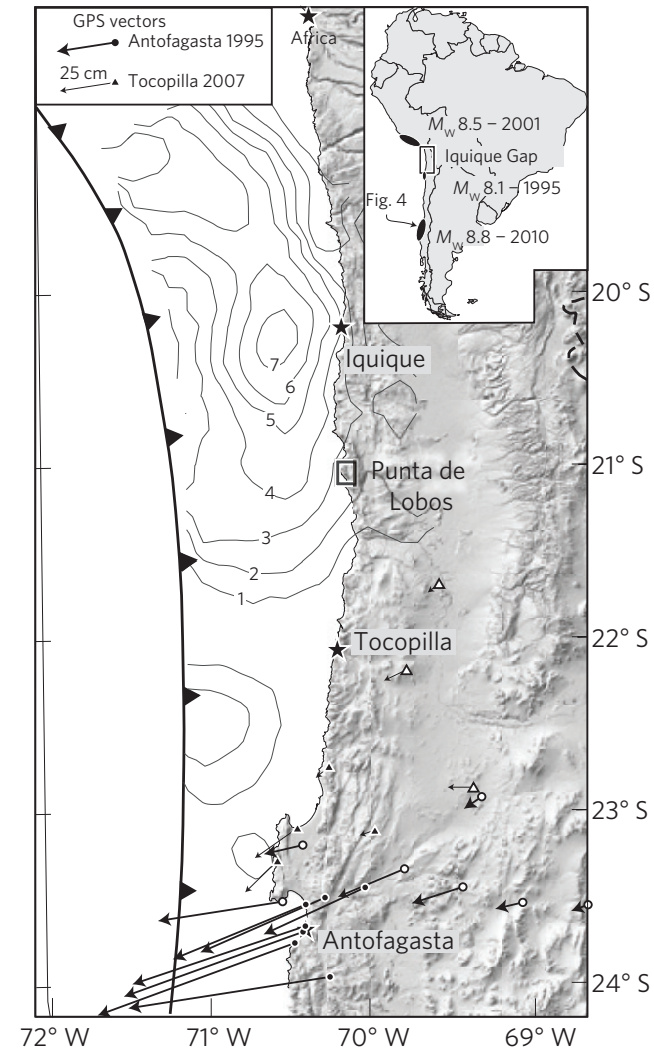
Kausel, 1986. Bol. Ac. Chilena Cs.

# What can we expect?

3) It breaks the complete segment filling the North Chile seismic gap ( $M > 8.5$ )?



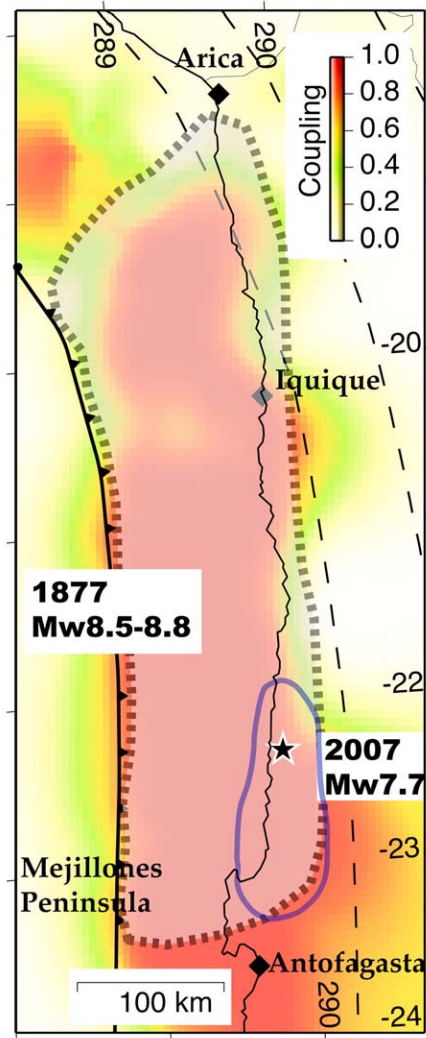
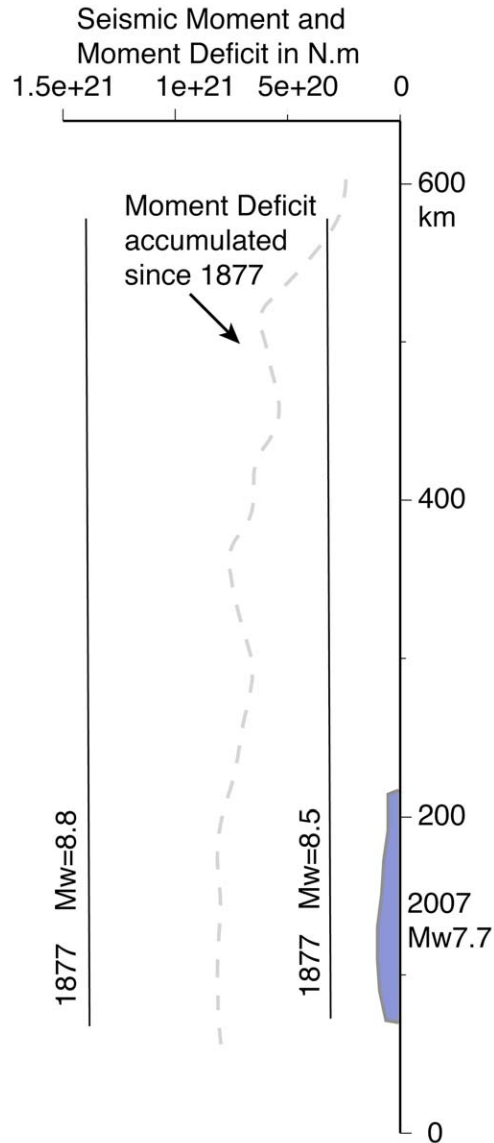
Loveless et al., 2009. Geology



Baker et al., 2013. Nat. Geosc.

# What can we expect?

3) It breaks the complete segment filling the North Chile seismic gap ( $M > 8.5$ )



Seismic Moment accumulated since 1877 =  $17.2 \cdot 10^{21}$  Nm

Tocopilla earthquake only 4% of that accumulated moment

Left:  $16.5 \cdot 10^{21}$  Nm  $\rightarrow$   $M_w \sim 8.8$

**Obrigado**