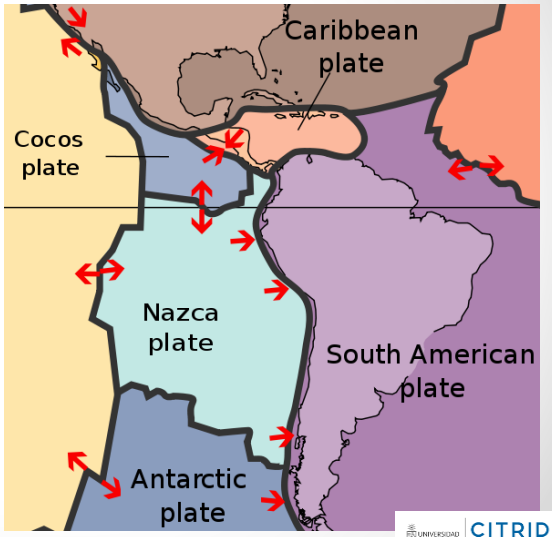
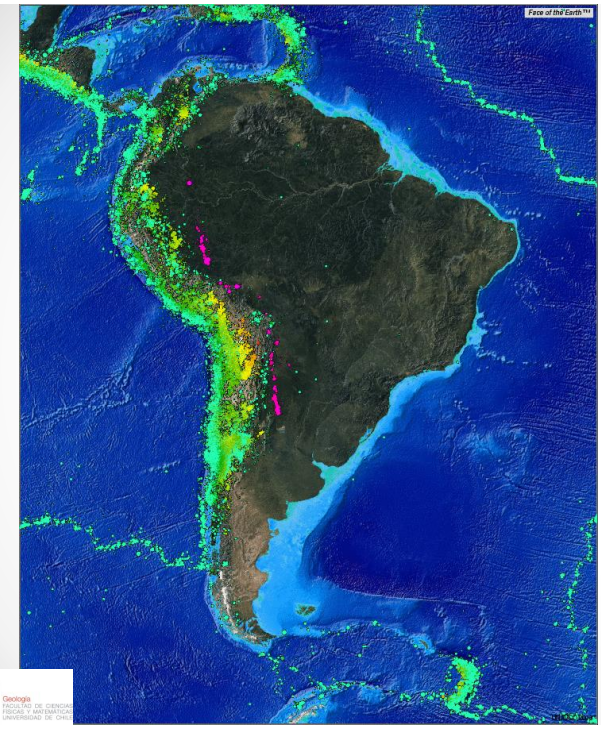
Outline of the talk

- **Chilean Andes seismo-tectonic framework**
- **Case Studies on Earthquake-induced landslides**
  - The 2007 Aysén earthquake (Mw 6.2)
  - The 2010 Maule earthquake (Mw 8.8)
- **Megalandslides in the Andes, a seismic origin?**
- **Examples of catastophic debris flow and mudflows events**
  - The 1987 Parraguirre landslide-debris flow
  - The 1991 Antofagasta mudflows
  - The 2015 Atacama mudflows
  - The 1993 Santiago debris flows
- **Conclusions**

Tectonic setting

- Convergent boundary
- Nazca plate subduction, about 7 cm/year

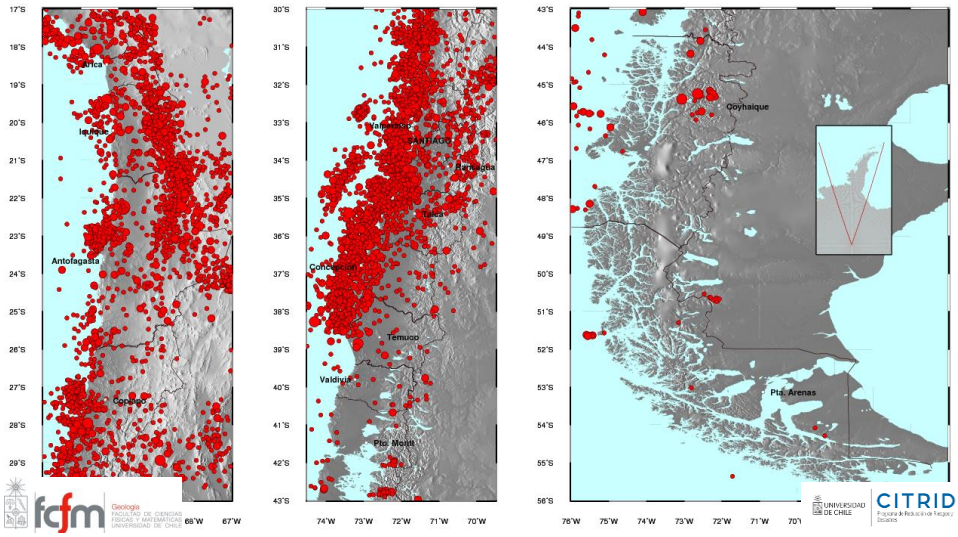




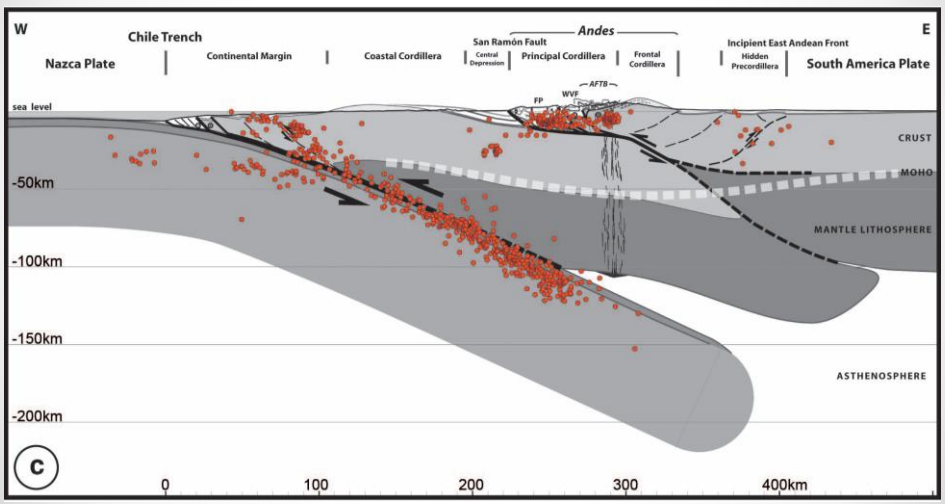
Earthquake Epicentres

Seismicity in Chile 2000 - 2010

(Magnitudes M > 4.0 ; Servicio Sismológico, U. de Chile)

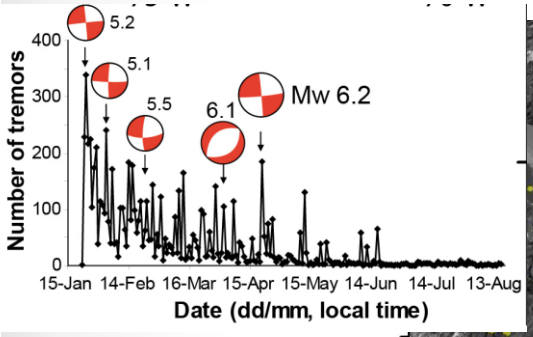


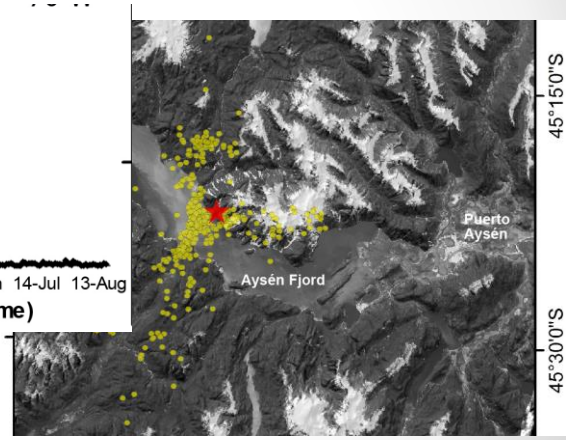
Earthquake Types



Schematic cross section at 33,5º, Armijo et al. (2010)

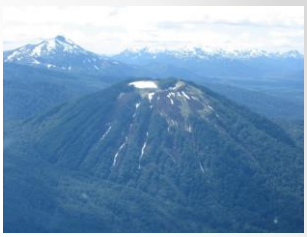
Earthquake-induced landslides
The 2007 Aysén Fjord Earthquake





Liquiñe-Ofqui fault zone

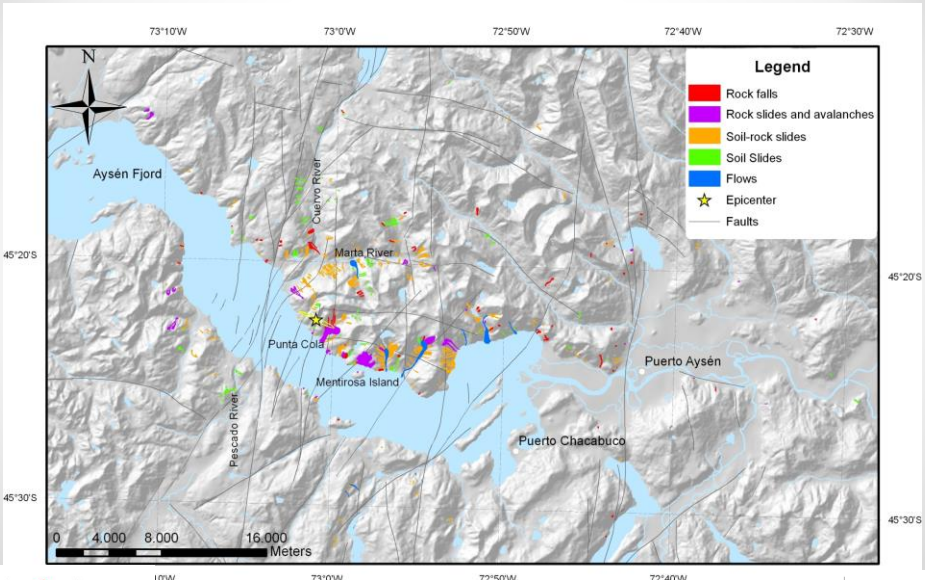
Vargas et al. 2013; Legrand et al. 2011



The 21 April 2007 Earthquake

- Mw 6.2, shallow crustal
- Little to moderate damage in nearby towns (IMM=VII)
- Landslides induced by the earthquake in the fjord coast triggered a tsunami wave.
- Tsunami and debris flows caused 10 fatalities and significant damage in salmon farms, causing geomorphic changes in the shoreline.

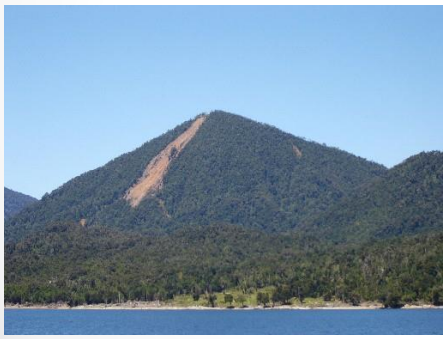
Earthquake-triggered landslides



Sepulveda et al. 2010

Earthquake-triggered landslides

- Disrupted, shallow soil and soil-rock slides



Earthquake-triggered landslides

- Massive rock slides

- Rock block slides and falls

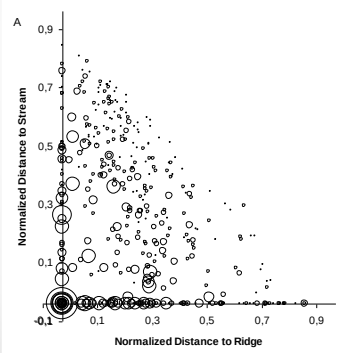
Earthquake-triggered landslides

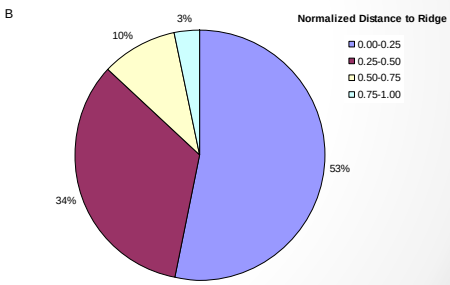
- Debris Flows

- Rock Avalanche

Topographic amplification?

- Geomorphological parameters suggest topographic amplification site effects on the slopes





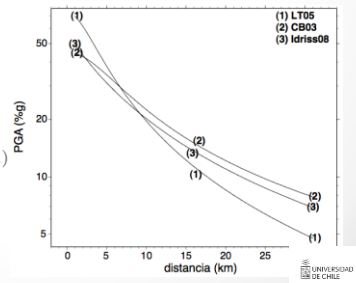
Sepulveda et al., 2010

Stability back-analyses

Rock Slide		PGA (g) Attenuation Rel. Idriss (2008)	PGA (g) Limit Equilibrium Analyses						PGA (g) Newmark Analyses
			Kv=0		Kh=2 Kv		Kh=Kv		
			Kh= 0.5 PGA	Kh= 1/3 PGA	Kh= 0.5 PGA	Kh= 1/3 PGA	Kh= 0.5 PGA	Kh= 1/3 PGA	
North Shore	In front of Mentirosa Island	0.27	1.46	2.19	1.16	1.74	0.94	1.41	1.28
	Acantilada Bay	0.17	2,00	3,00	1.50	2.25	1.18	1.77	1.54
	Rio Cuervo	0.33	2.60	3.90	1.80	2.70	1.38	2.07	2.08
	Punta Cola	0.43	2.30	3.45	1.64	2.46	1.26	1.89	1.81
	Pérez Bay E	0.09	2.60	3.90	1.80	2.70	1.36	2.04	2.01
	Pérez Bay W	0.09	2.30	3.45	1.68	2.52	1.32	1.98	1.85
	Fernández Creek	0.19	2.20	3.30	1.60	2.40	1.24	1.86	1.73
	Frio Creek	0.24	1.56	2.34	1.26	1.89	1.04	1.56	1.31
South Shore	Rio Negro	0.16	2.66	3.99	1.80	2.70	1.34	2.01	2.03
	W Rio Negro	0.16	1.86	2.79	1.46	2.19	1.18	1.77	1.51

Estimated PGA (horizontal) for main massive rock slides

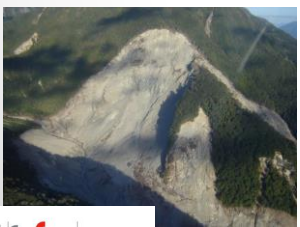
Serey, 2011; Sepulveda et al. 2011



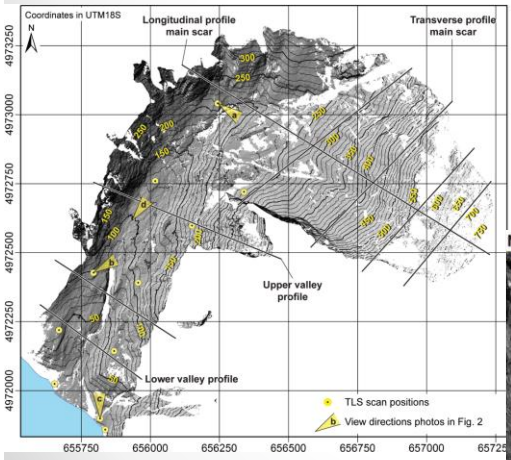
Attenuation relationships for Ms 6.3: (1) Liu & Tsai (2005), (2) Campbell & Bozorgnia (2003) y (3) Idriss (2008).

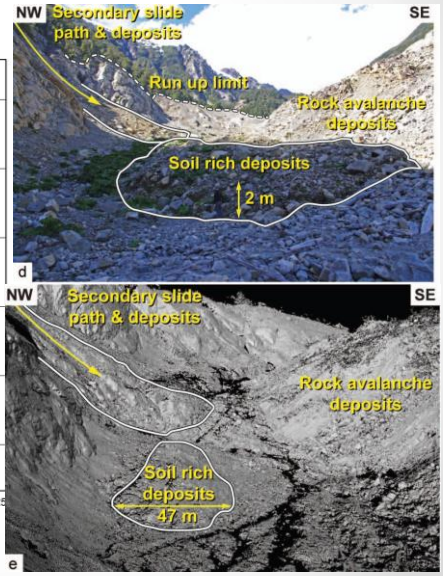
Landslide-induced Tsunami

- Impact from 2 large rock slides/avalanches plus other minor ones triggered a local tsunami, waves over 10 m observed by witnesses.
- Waves penetrated inland for dozens of meters in gullies and rivers, leaving eroded the fjord shoreline clean of vegetation



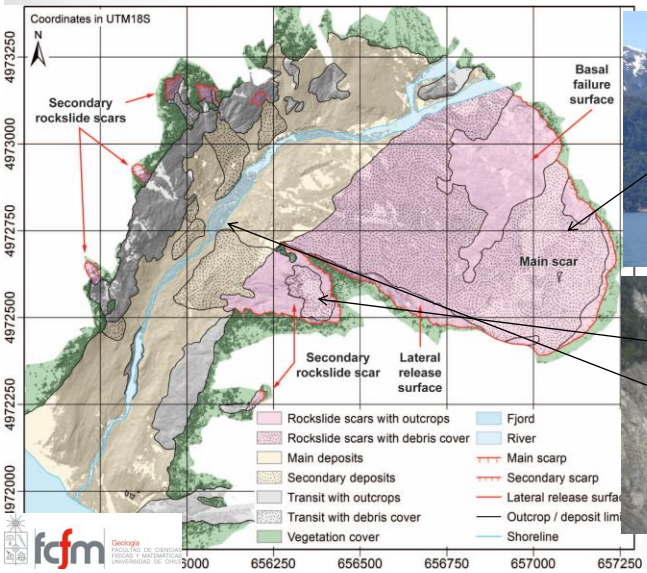
Punta Cola rock avalanche
Lidar survey





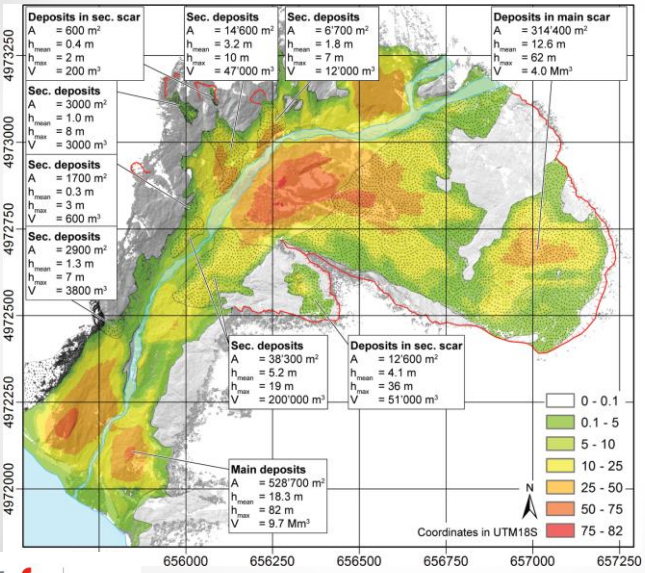
Oppikofer et al., 2012

Punta Cola - Geomorphology



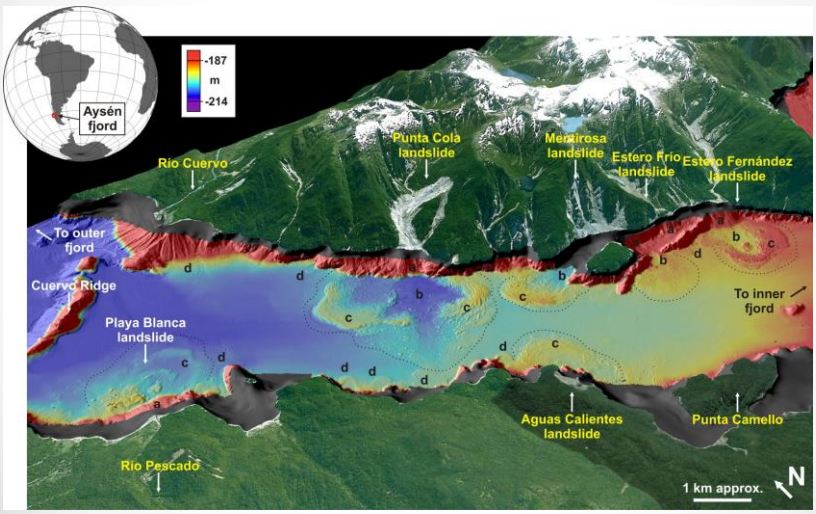
Oppikofer et al., 2012

Punta Cola – Deposits & Volumes

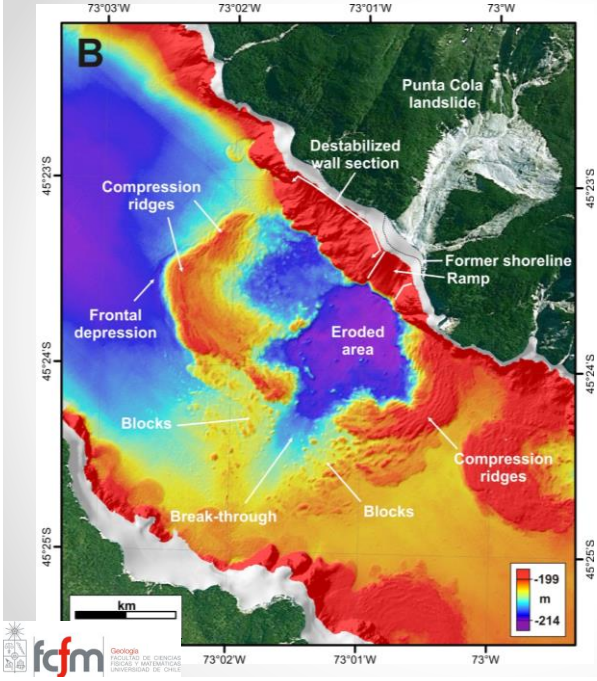


Oppikofer et al., 2012

Landslide effects on sea bottom



Lastras et al. 2013



- Punta Cola rock avalanche effects on sea bottom

Hermanns et al., 2014

The 2010 Maule earthquake

- Megathrust (Interplate), Mw 8.8

Santiago

Linares

Concepcion

Constitución 2010

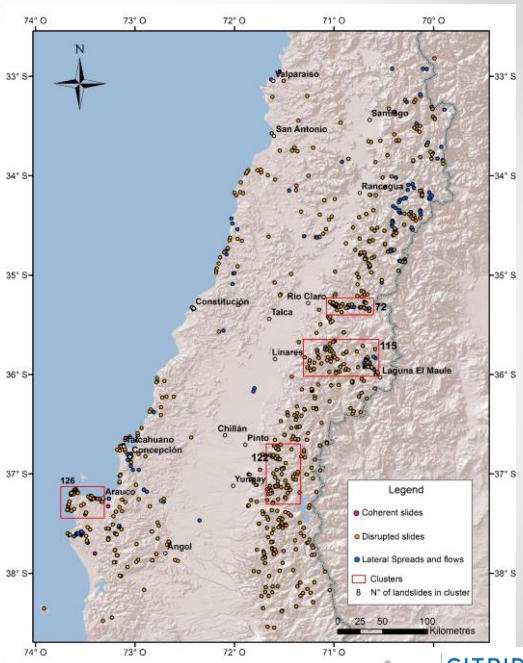
2010 Earthquake-induced Landslides

Coastal areas

Highland areas

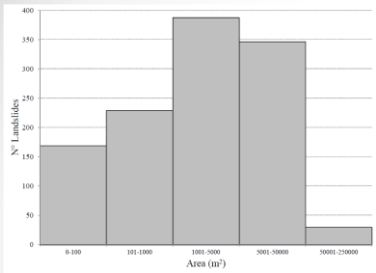
Maule Inventory

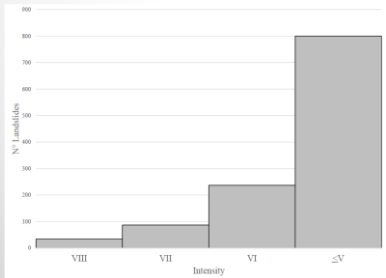
8	Coherent slides
1035	Disrupted slides
49	Lateral spread
109	Flows
1201	Total

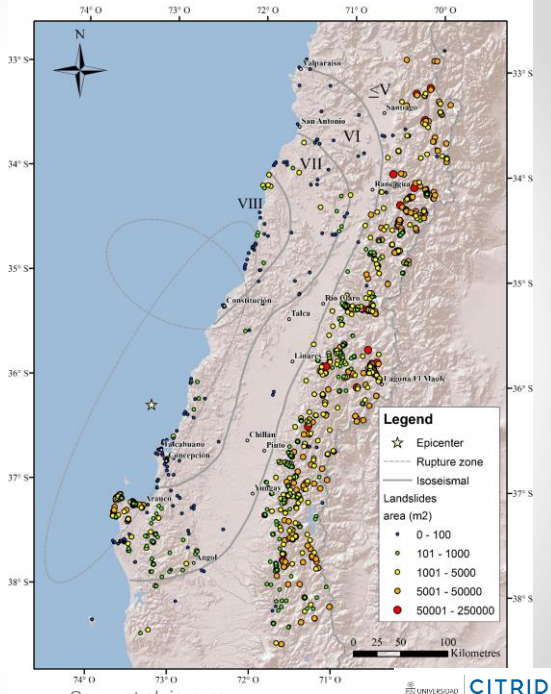


Serey et al. in prep.

Maule Inventory

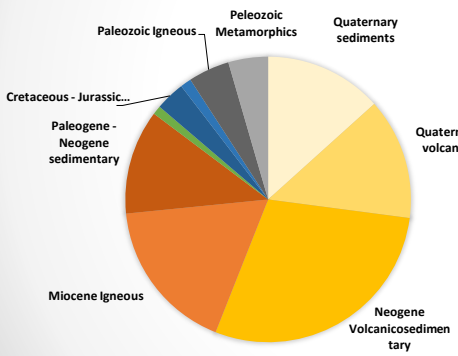


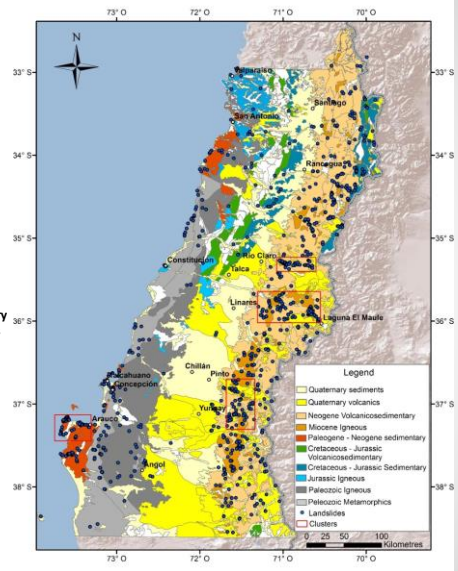




Serey et al. in prep.

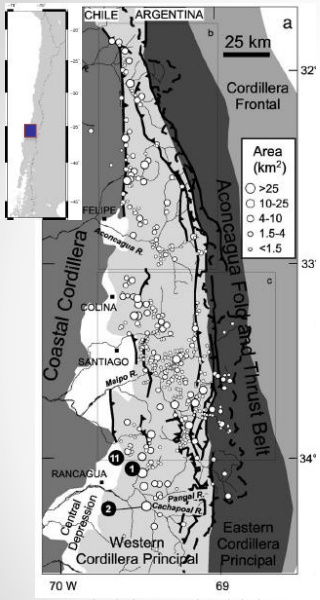
Lithological control?





Serey et al. in prep.

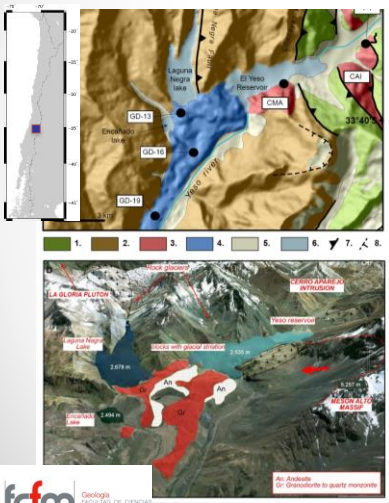
Megalandslides in the Andes



Central Chile megalandslides, *Antinao & Gosse, 2009*

- Recent historic earthquakes suggest **more (but localized) and largest landslides related to shallow crustal earthquakes rather than megathrust earthquakes.**
- These observations raise the question on the **origin of prehistoric, giant size landslides** widely distributed in the Andes uplands, which seem to be related with regional crustal faults.
- Regional (e.g. Antinao & Gosse 2009, Moreiras & Sepulveda 2014) and specific (e.g. Welkner et al. 2010, Pinto et al. 2008, Sepulveda et al. 2012) studies suggest local faults seismic activity as most likely trigger of such megalandslides.

Mesón Alto megalandslide, Yeso valley, 4.5 km^3, 4.7±0.6 ka (Abele, 1984; Antinao y Gosse, 2009; Deckart et al. 2014). North of 1958 epicentre, Aconcagua fold and thrust belt



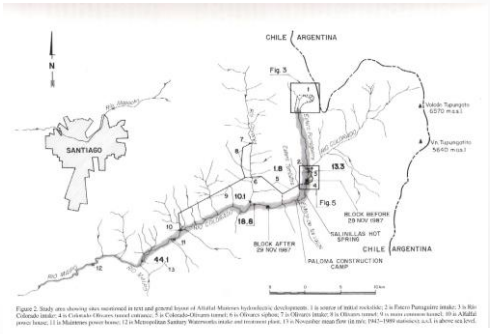
Deckart et al. 2014

Debris flows and Mudflows in Chile

- Rainfall-induced, very common along the whole country.
- In northern and central Chile, strong correlation with El Niño climatic events
- Some recent examples:
  - Alfalfal, 1987.
  - Antofagasta, 1991
  - Santiago, 1993
  - Atacama, 2015

Parraguirre-Alfalfal, 1987.

- Triggered by a rock slide on top of a glacier in Parraguirre creek, Maipo Valley, near Santiago.
- Waves up to 20-30 m in the upper sector.
- Runout of 57 km until River Maipo.
- At least 37 fatalities, mostly at Alfalfal power station in construction.



Hauser, 2002

Alfalfal, 1987.

Figure 9. Aerial view of La Paloma Camp (for location see Fig. 2) 10 days after event showing damage to buildings and machinery. Debris-flow claimed at least 37 lives at this site in Río Colorado valley. Downstream is to right.

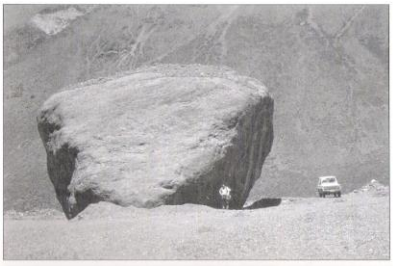
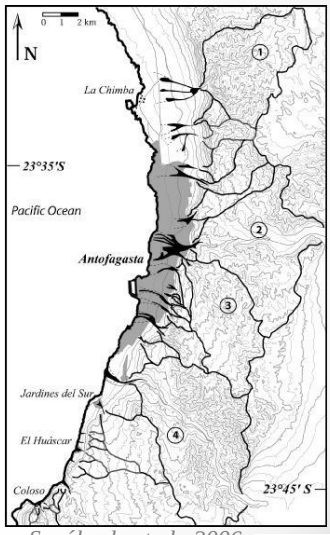


Figure 10. Huge ~2700 t boulder moved 11.0 km by debris flow in Río Colorado from Parraguirre-Colorado confluence (see Fig. 2 and Fig. 11).

Hauser, 2002

Antofagasta, 1991

- Coast of Atacama desert. Triggered by heavy rainfall (42 mm in 3-4 hours).
- 103 deaths, 16 missing
- 500 houses destroyed, 2500 severly damaged.
- US$ 66 million in losses



Sepúlveda et al., 2006

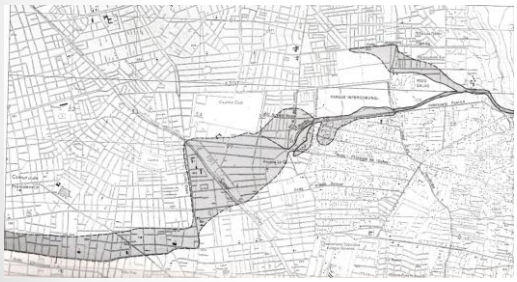
Atacama 2015

- Dozens of ravines and creeks activated by heavy rainfall in the higher mountain areas of the Atacama desert.
- Over 30 deaths and missing.
- Destruction of towns and parts of Chañaral and Copiapó cities. Road cuts across the whole region.

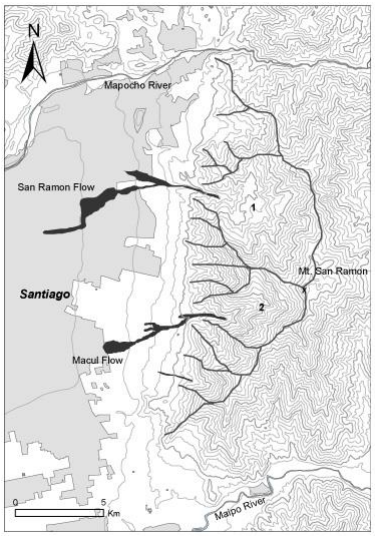
Santiago, 1993

- Heavy rainfall of about 8 mm/hr in the Santiago mountain front, triggered several debris and mudflows.
- At least 26 fatalities, 8 missing, mainly in Quebrada Macul area.
- 307 houses destroyed, over 5000 damaged.
- US$5 million in losses.

- Flows in San Ramón, Macul & Lo Cañas ravines.



Naranjo & Varela, 1996



Sepúlveda et al., 2006

Modelo Laharz
Valores c_1 = 0.03 y c_2 = 180

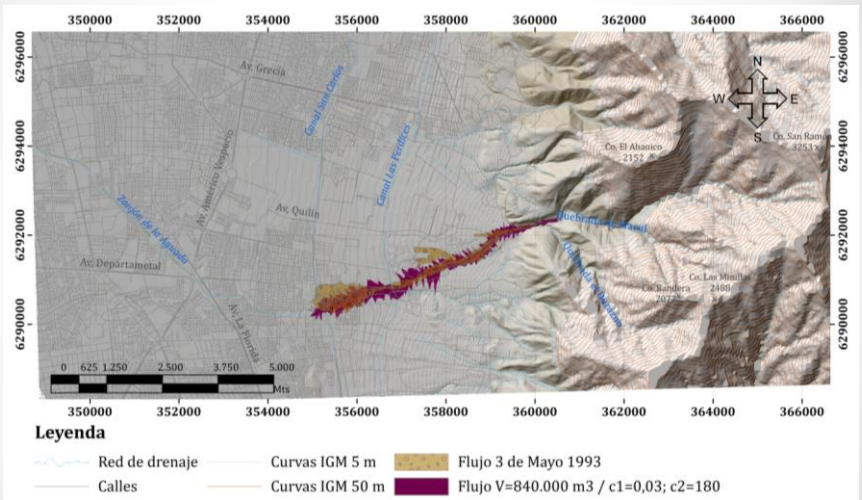


Figura 18: Modelación LAHARZ con valores c_1 = 0,03 y c_2= 180 para un volumen de 840.000 m^3, en contraste con la traza del flujo de 1993.

Garrido, 2012

Modelo Laharz V=5.841.527m³
Caudales máximos probables

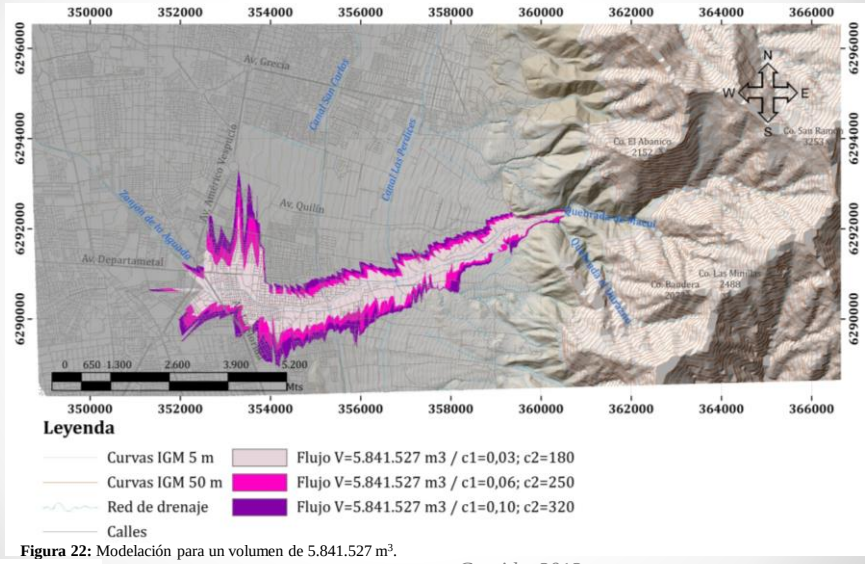


Figura 22: Modelación para un volumen de 5.841.527 m³.

Garrido, 2012

Mapa de peligros

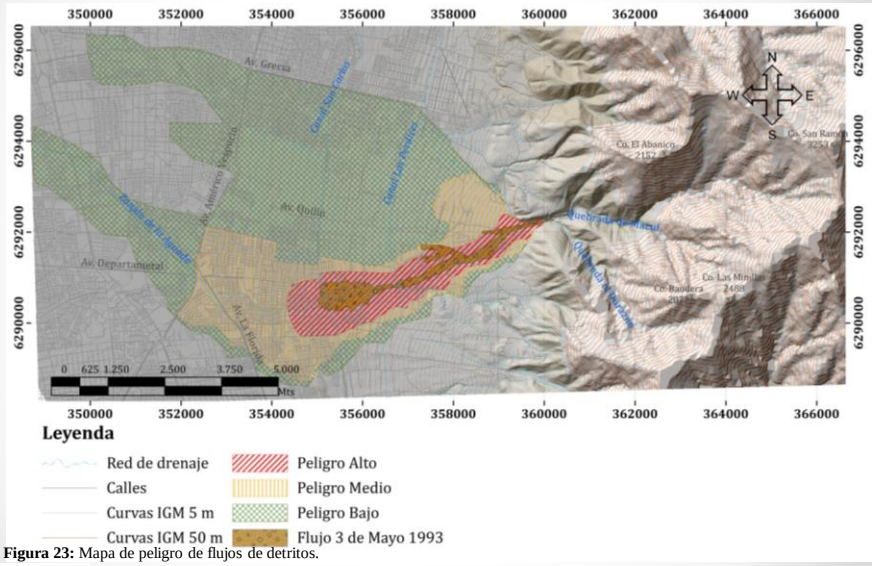


Figura 23: Mapa de peligro de flujos de detritos.

Garrido, 2012

Concluding Remarks

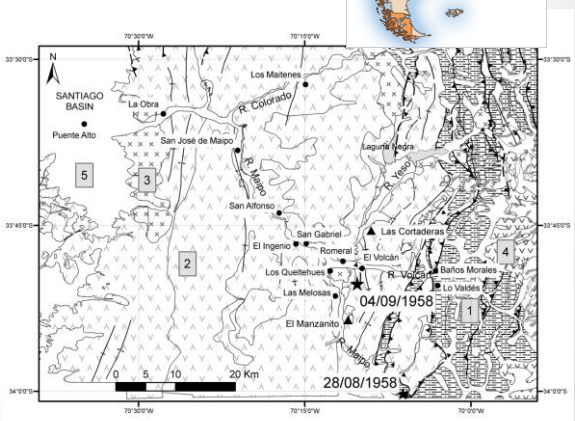
- Rainfall-induced debris and mudflows and landslides triggered by earthquakes and rainfall a main hazard in the country (also volcanic lahars and avalanches!)
- The extent, size and geographic distribution of earthquake-induced landslides seem to largely depend on the earthquake source mechanism: Landslides triggered by moderately large (M 6.0-7.0), inland shallow crustal earthquakes tend to have higher landslide density and larger volumes in comparison with those induced by large magnitude (M 7.5-9.0), megathrust earthquakes along the subduction plate boundary.
- Large volume landslides in the highlands are a potential hazard not yet considered in seismic hazard assessments and may pose an unexpected risk for local communities.

Block deposited by 1987 Parraguirre debris flow, central Chile

Tarapacá earthquake 2005 (Mw 7.8, intermediate depth intraplate). Landslides along coastal route and inland rural and mining roads.

Case 1: 1958 Las Melosas Earthquake Sequence

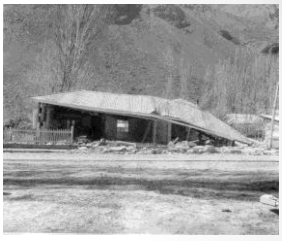
- 4th of September 1958, a sequence of 3 earthquakes M = 6.7 to 6.9, later corrected to 6.3 (Alvarado et al. 2008)
- Focal depths of 10-15 km.



Damage in epicentral area (I_{MSK} =8- 9)

Most of buildings of unreinforced stone masonry, braced wooden frame infill with adobe and stone masonry suffered severe damage.






Sepulveda et al. 2008

Earthquake-triggered Landslides

- Plenty of rock falls in the epicentral area.
- Two soil slumps were triggered, both well preserved until now.
- Las Cortaderas (Yeso Valley, ca. 15 Mm3) and El Manzanito (Maipo Valley, ca. 4 Mm3).
- Both in zone with est. Intensity over 8


Sepulveda et al. 2008

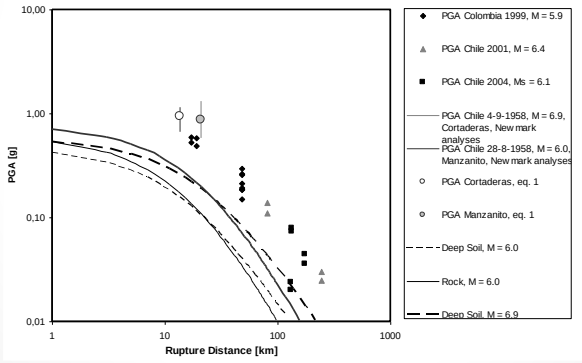
PGA Estimates From Earthquake-triggered Landslide Analyses

Landslide	A_h vs. A_v	Critical A_h [g]	PGA range from Newmark analyses[g]	I_A* [m/s]	Scaled Record	PGA from Arias Intensity-Newmark Displacement Relationships [g]
Las Cortaderas	$A_v = 0$	0.29	0.70-1.15	9.32	SM8-135	0.95
Las Cortaderas	$A_h = 2A_v$	0.26	0.66-1.10	8.08	SM8-135	0.98
Las Cortaderas	$A_h = A_v$	0.23	0.60-1.00	6.88	VO-000	0.91
El Manzanito	$A_v = 0$	0.34	0.79-1.30	11.48	SM8-135	1.05
El Manzanito	$A_h = 2A_v$	0.27	0.67-1.12	8.49	VO-000	0.89
El Manzanito	$A_h = A_v$	0.22	0.58-0.99	6.49	VO-000	0.88

Sepulveda et al.2008

Accelerations

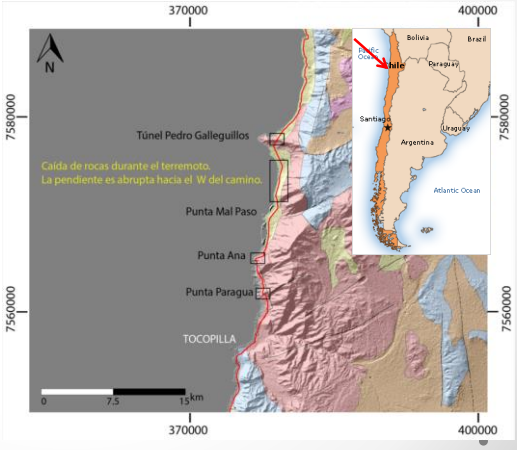
Comparison with records of other Andean shallow earthquakes and Californian attenuation relationships



Sepúlveda et al.2008

Case 3: Tocopilla earthquake 2007 (M 7.8 interplate)

- Rock falls and localized shallow rock and soil (colluvium) slides along the coastal cliff.
- Main damage to coastal highway.



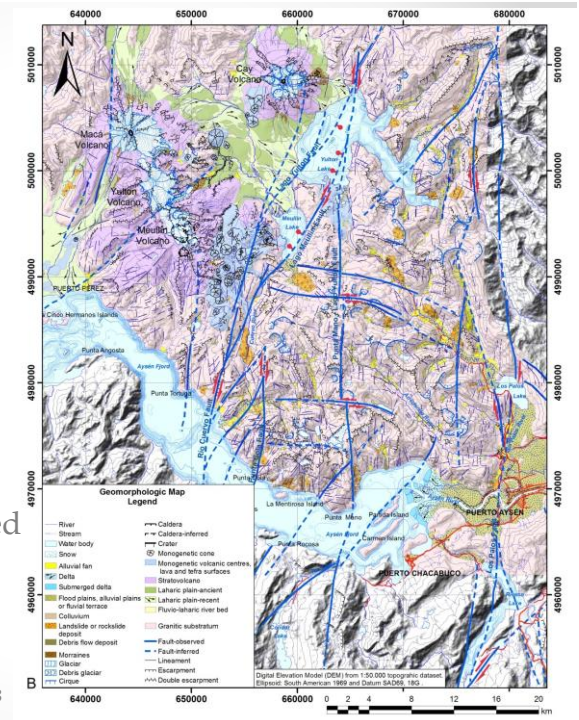
Tocopilla earthquake, 2007

Route 1

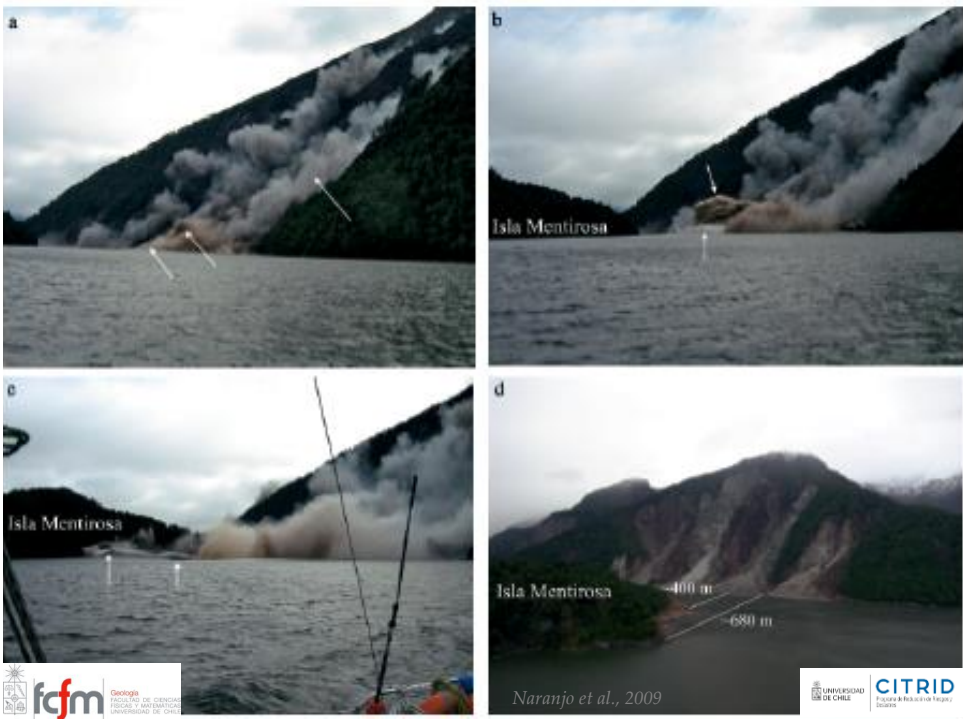
Local

Geomorphology

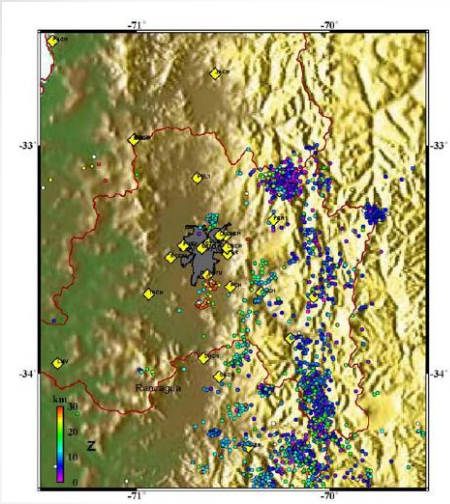
- Stratovolcanoes
- Monogenetic Volcanoes.
- Laharic plains
- Glaciers, morraines
- Alluvial and deltaic sediments.
- Landslides
- Granitic slopes covered by a thin volcanic soil layer.
- (Many) Faults



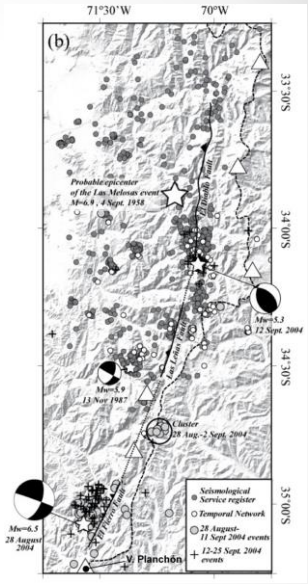
Vargas et al. 2013



Naranjo et al., 2009



Shallow seismicity in central Chile Main Range 2000-2009 (*Pérez et al., 2010*)



Seismicity El Fierro-El Diablo regional fault system (*Farías, 2007*)