Gobierno de Chile

Tectonic Controls on Volcanism in Southern Andes

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Talk outline

Introducction

- The big picture: geodynamics and active tectonics
- Arc architecture
- Magmas and magmatic evolution

Quaternary tectonics in Southern Andes

- Long-term evidences
- Short-term evidences
- Volcanoes as tectonic stress indicators

Arc Tectonic controls on volcanism

- Long-term geological evidence
- Volcano morphology and neotectonics
- Recent case-studies

External controls on volcanism

- Remote triggering by subduction earthquakes
- Deglaciation and isostatic rebound

Summary and conclusions

- Work in progress
- Highlights

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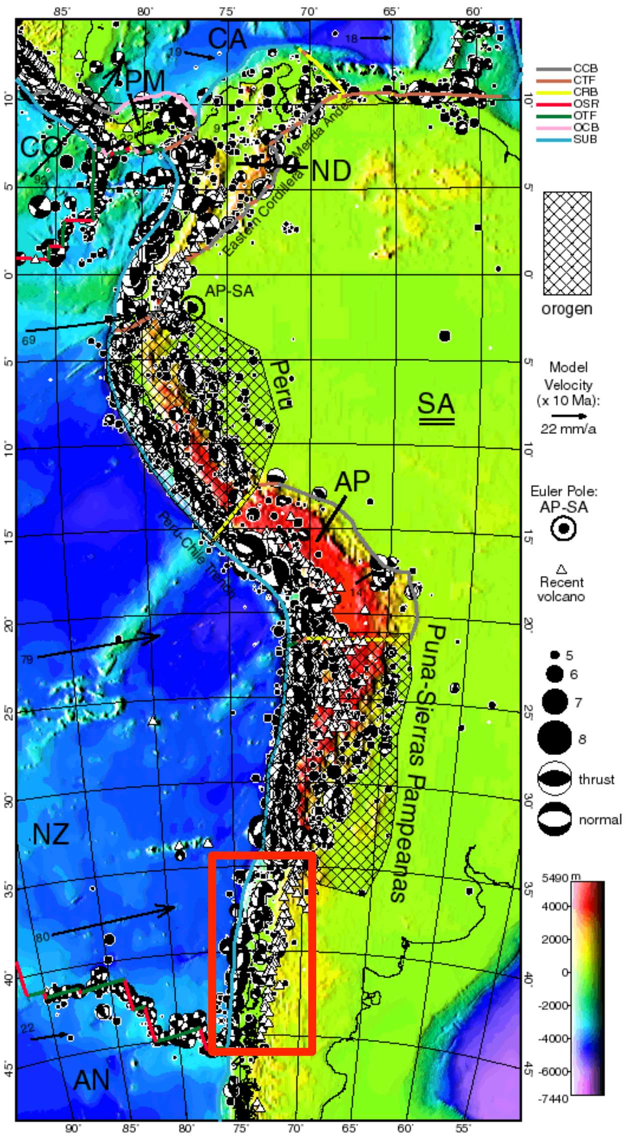
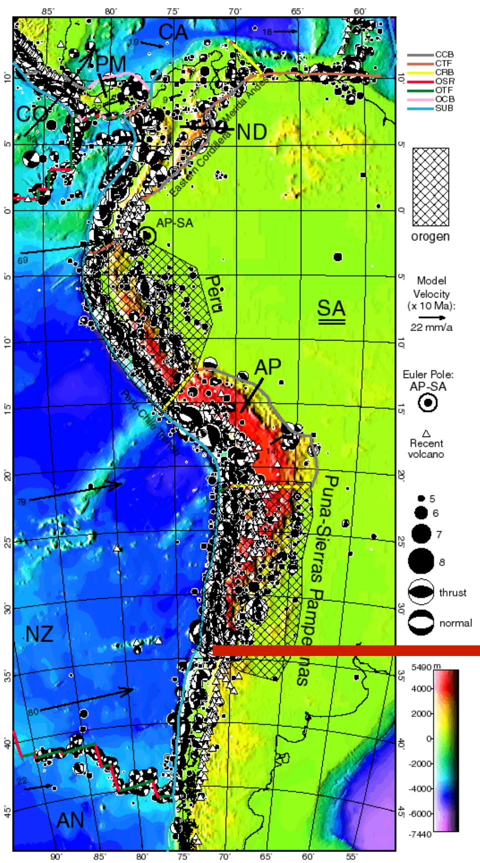
Introduction The big picture: geodynamics and active tectonics



- Oblique convergence (78) between Nazca and South American plates at *ca*. 7-8 cm/yr since 25 Ma
- Subduction of the active Chile Rise since *ca*. 6 Ma
- Liquiñe-Ofqui Fault Zone (LOFZ), a righ-lateral 1200 km long fault system

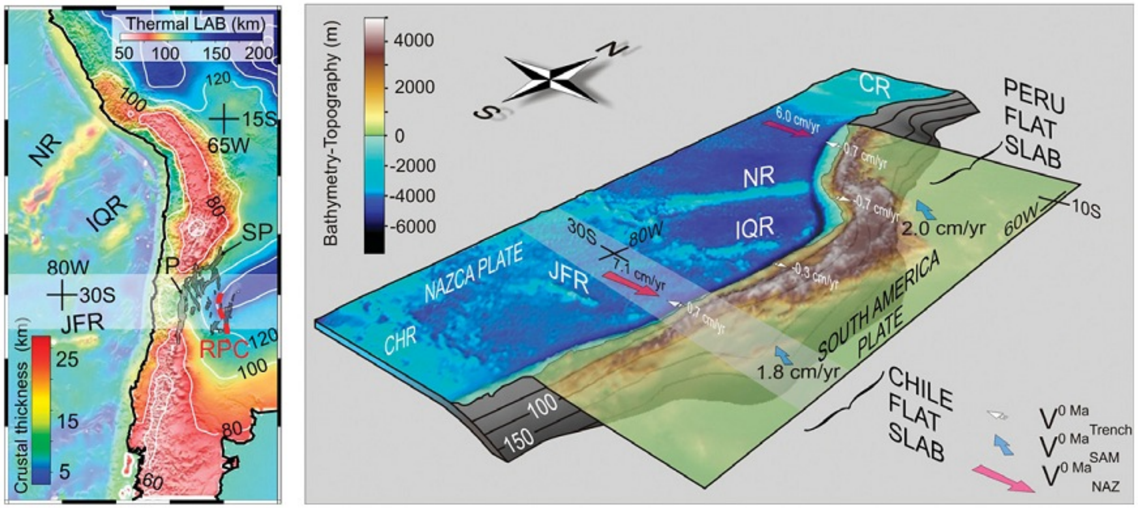
Bird, 2010

Introduction
The big picture: geodynamics and active tectonics



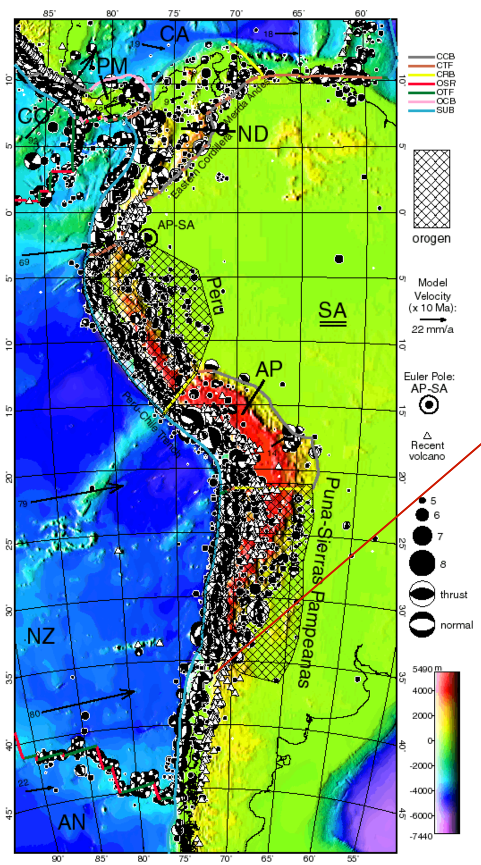
North edge:

- Collision of the aseismic Juan Fernandez Ridge
- Pampean flat slab segment



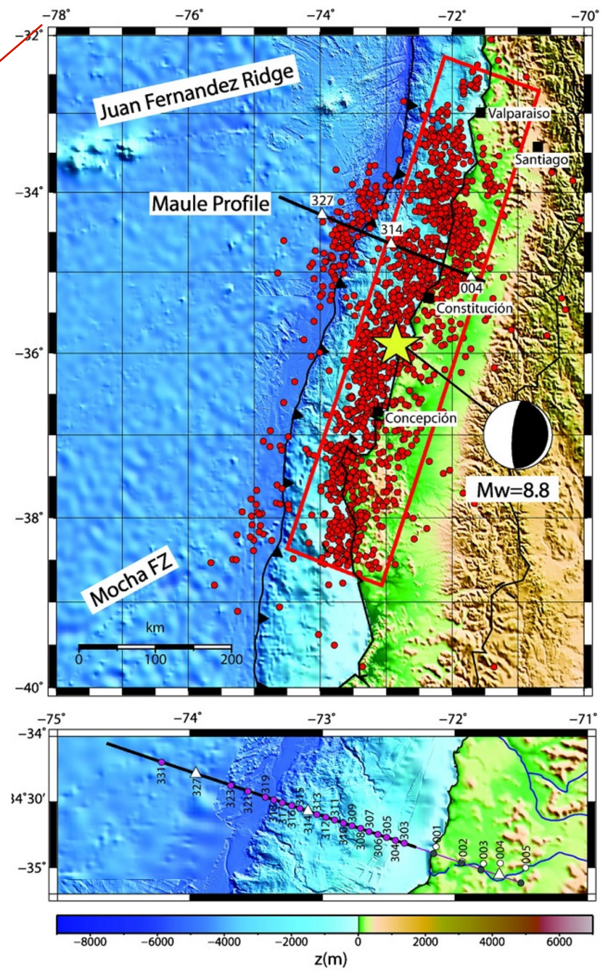
Manea et al., 2012

Introduction The big picture: geodynamics and active tectonics



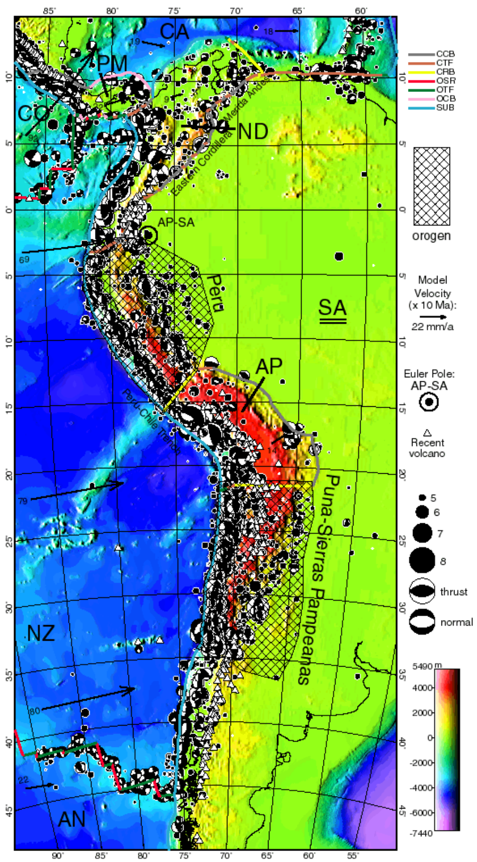
North edge:

- Megathrust segmentation Maule, 2010 earthquake



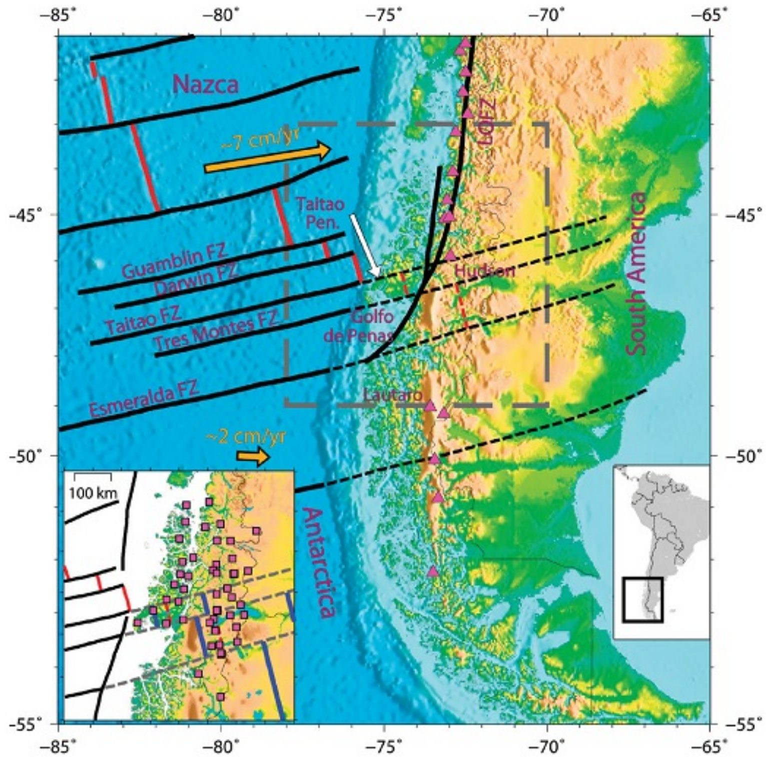
Moscoso et al., 2011

Introduction
The big picture: geodynamics and active tectonics



South edge:

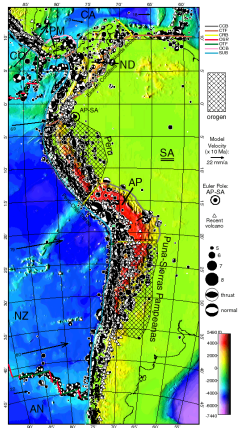
- Collision of the active Chile Ridge (spreading at ca. 7cm/yr (De Mets *et al.*, 1994)
- Patagonian slab window



Russo et al., 2010

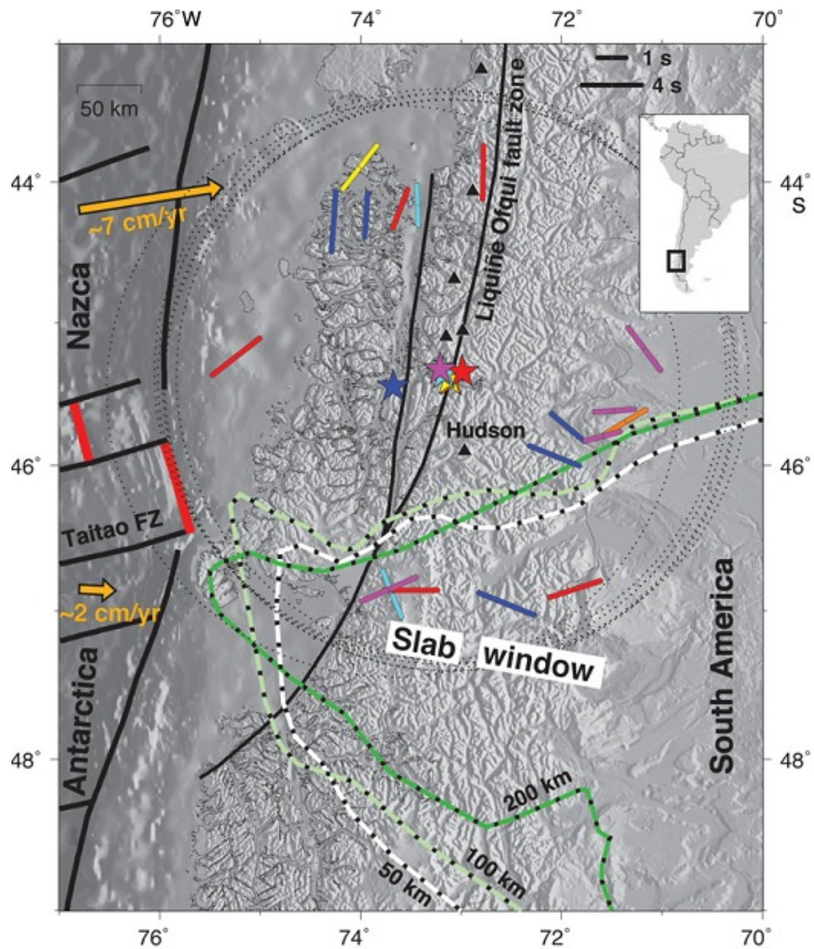
Introduction

The big picture: geodynamics and active tectonics

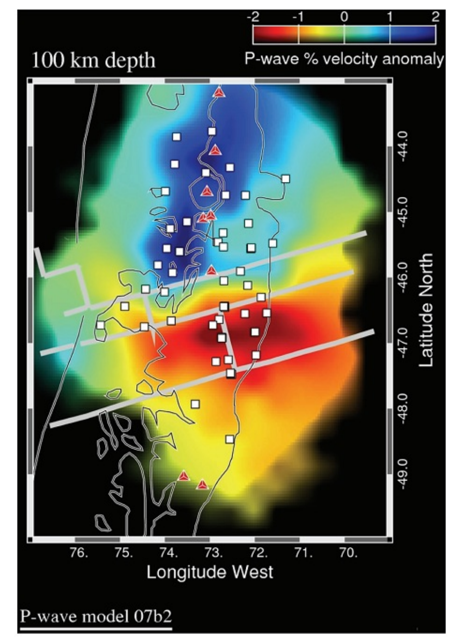


South edge:

- Collision of the active Chile Ridge



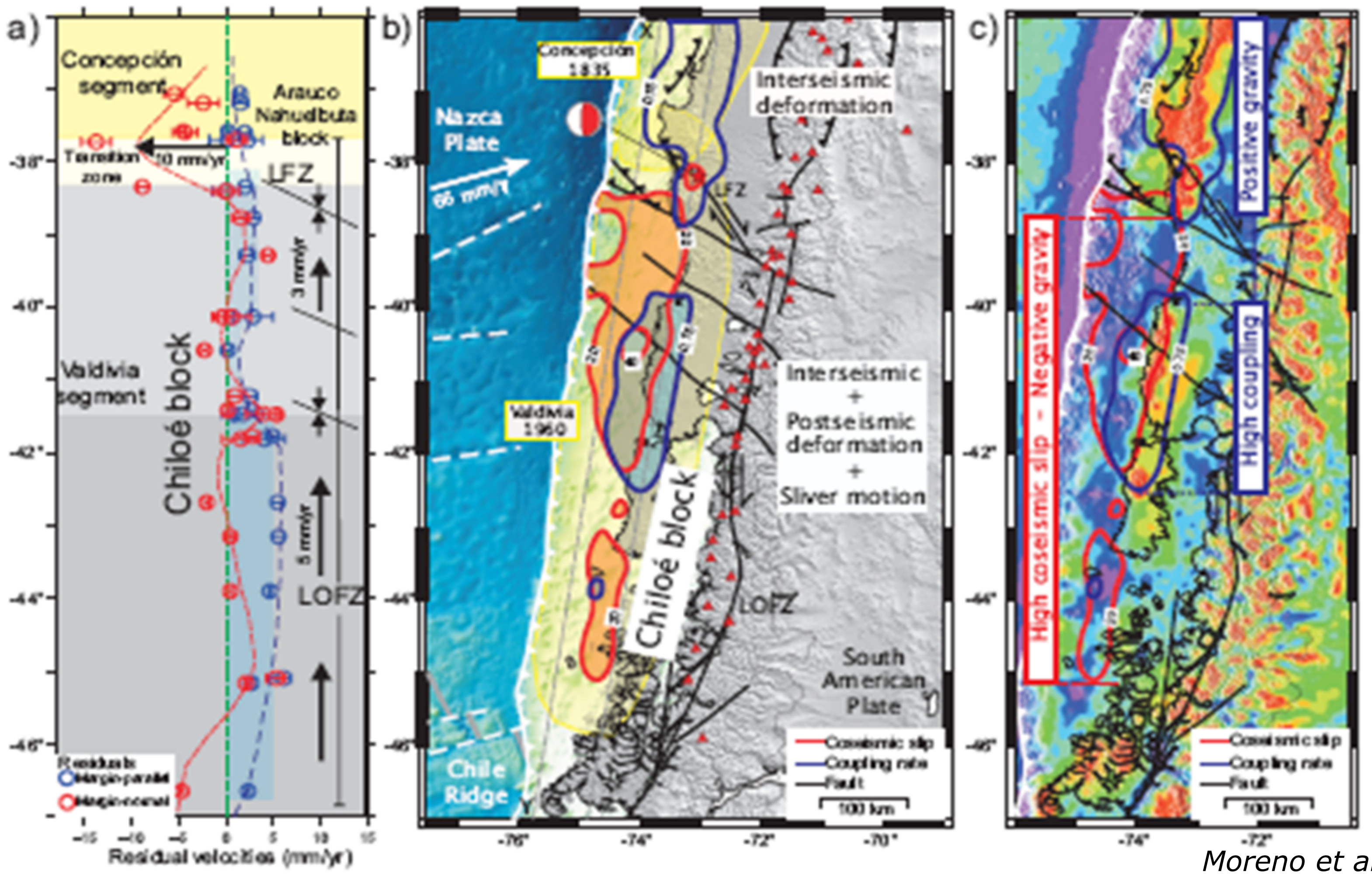
Shear wave splitting measurements and P-wave tomography



Russo et al., 2010

Introduction

The big picture: geodynamics and active tectonics

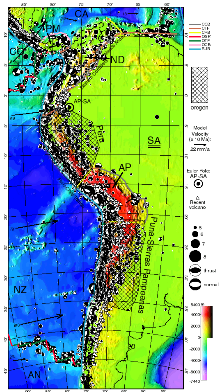


Moreno et al., 2009

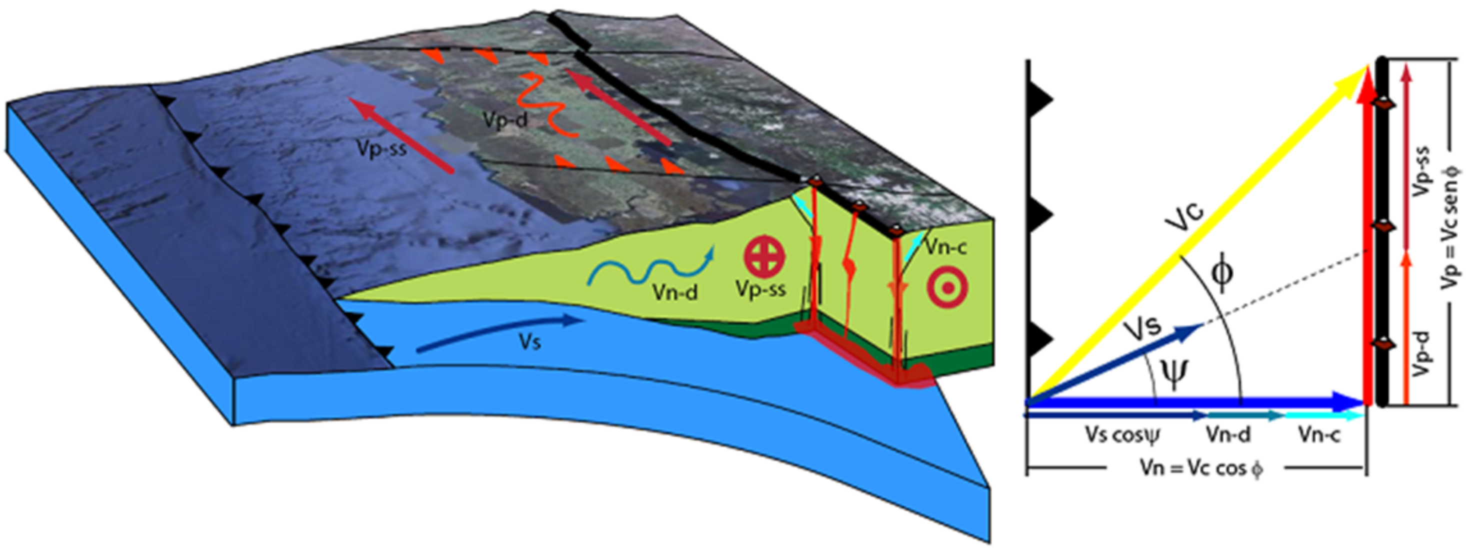
A complex scenario of postseismic (1960 eq, now 2010 eq) and intracrustal strain along the volcanic arc

Introduction

The big picture: geodynamics and active tectonics

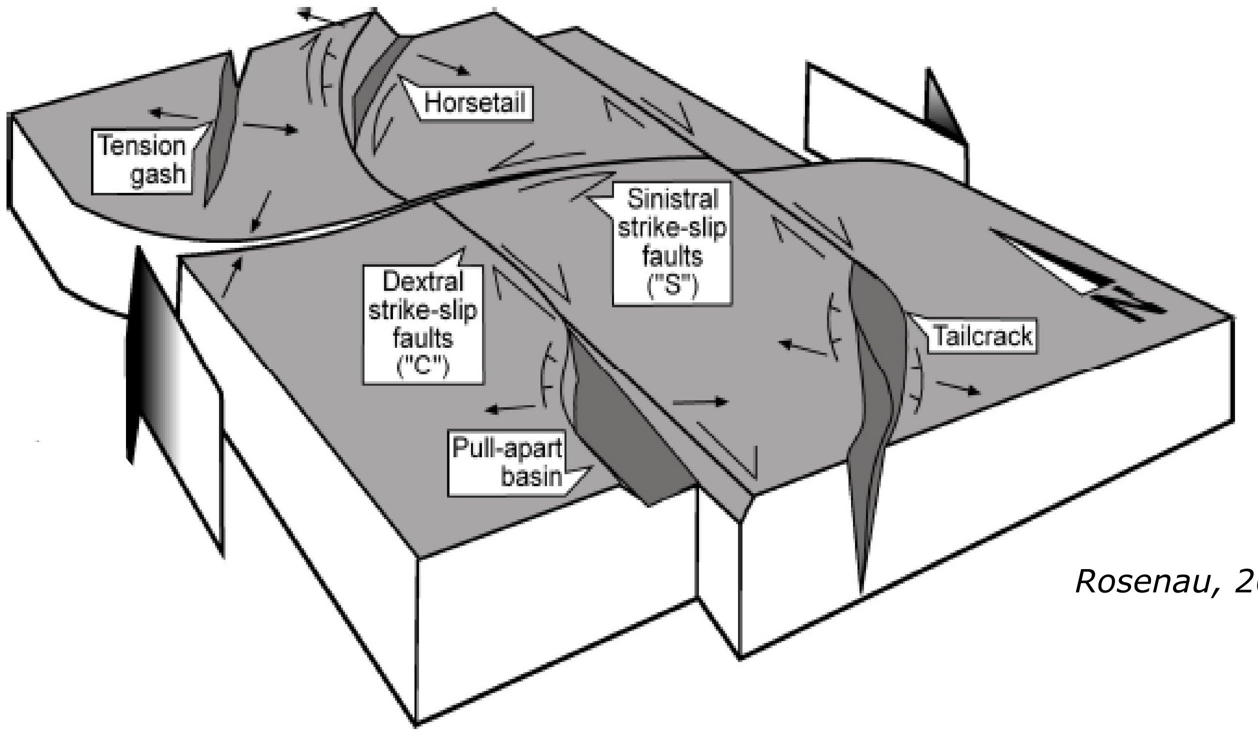


- Partial strain partitioning
- Righ-lateral transpresion along the arc



A. Tassara

Introduction The big picture: geodynamics and active tectonics

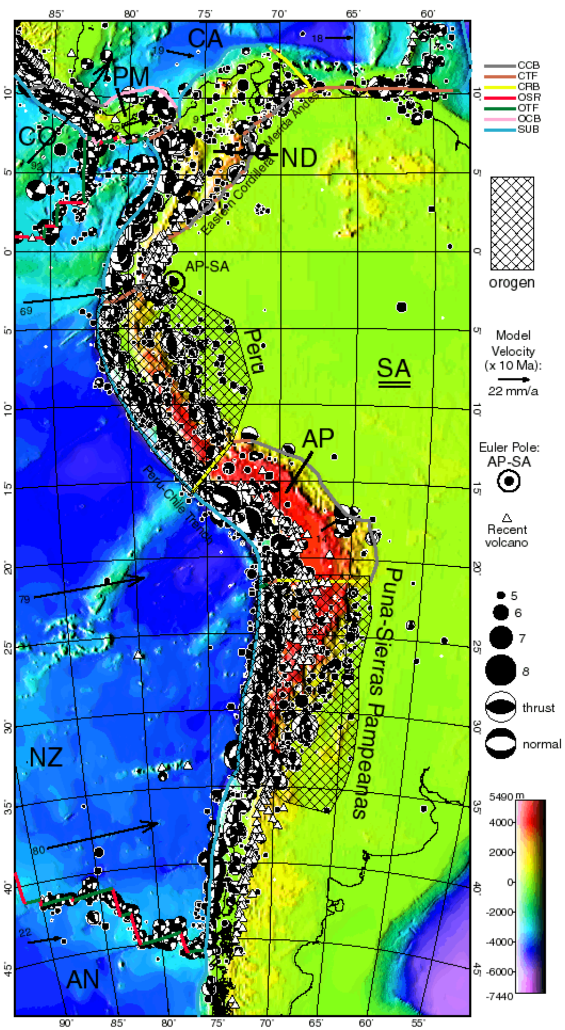


Rosenau, 2004

- Partial strain partitioning
- Righ-lateral transpresion along the arc and mesoscale compatible structures (faults, fractures and cracks)

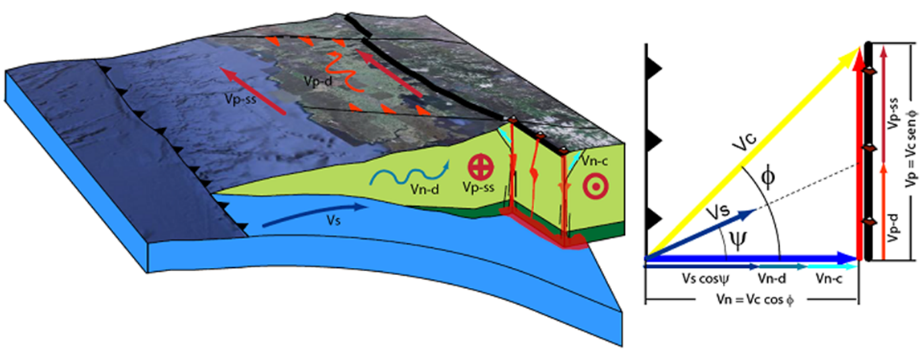
Introduction

The big picture: geodynamics and active tectonics



…but there is a problem: why such a relevant strain partitioning with so low oblique convergence?

R: thermal weakening because the magmatic arc…
so it seems there is a two-way coupling between tectonics and magmatism is SVZ



Introduction

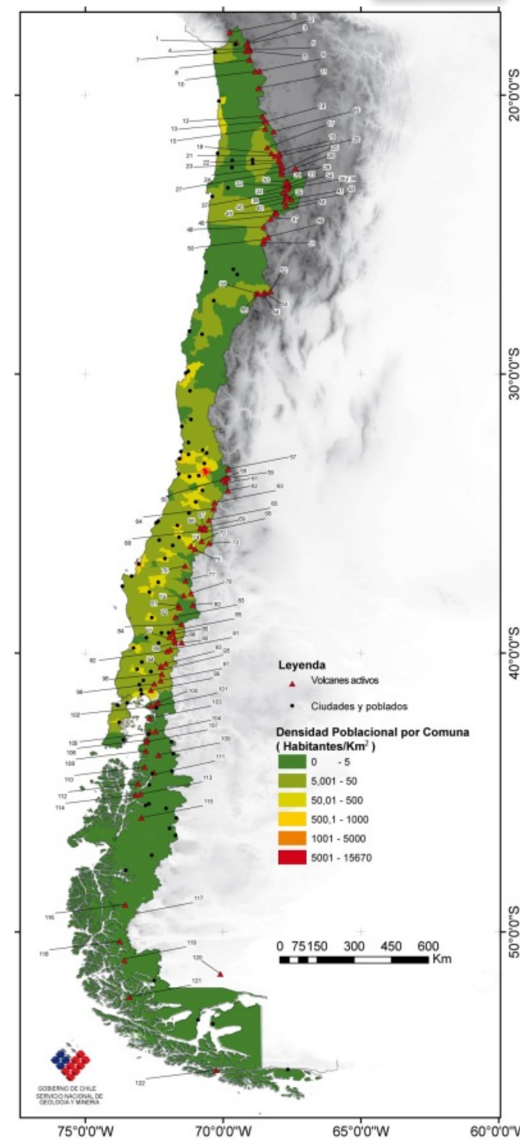
Arc architecture and crustal tectonics

Chile mainland has 91 volcanes 'geologically' active volcanoes ; 51 of them are located in the SVZ and include some of the most active volcanoes in South America.

Roughly 16% of the continental territory is directly threatened by volcanic eruptions and even *ca*. 50% could be affected in some way.

Since XVIth century, 412 volcanic events (minor eruptions and hydrothermal explosions included) have been reported.

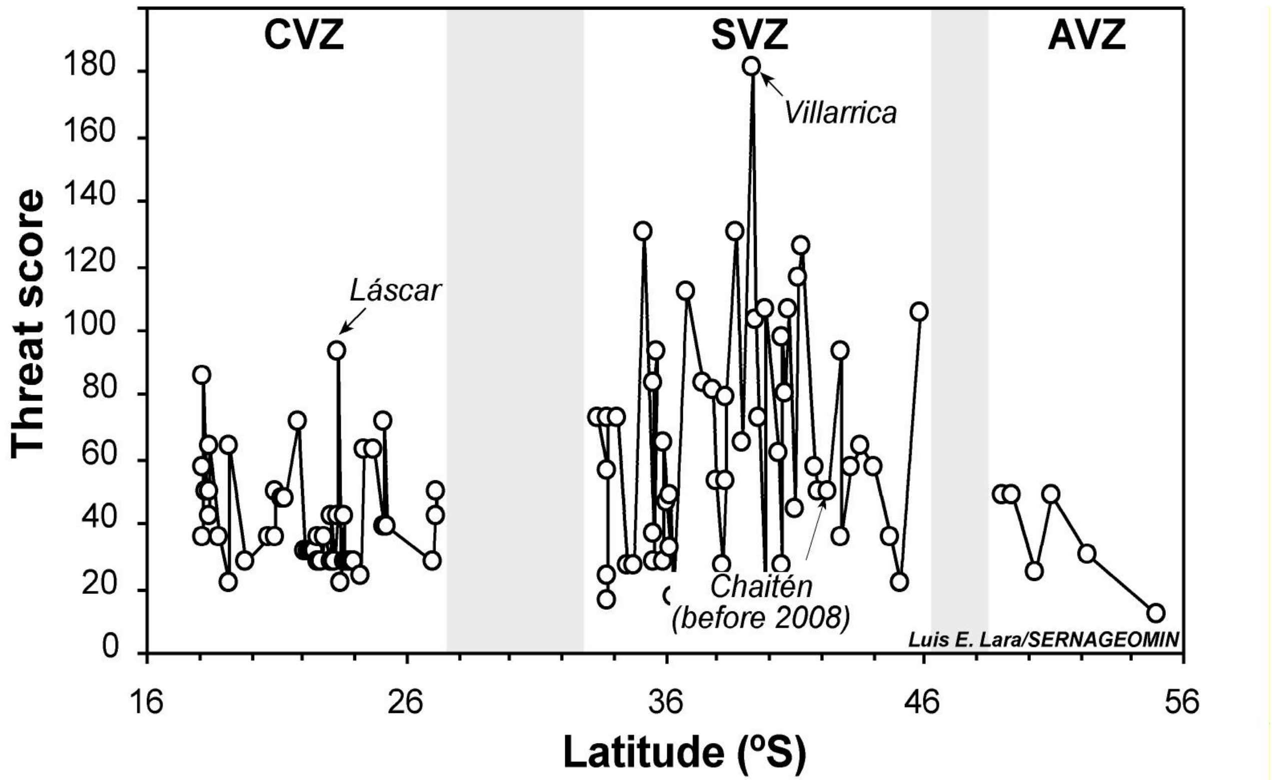
A significant (VEI>3) eruption occurs each 8-10 years in average; in the last 5 years 2 VEI 4-5 occurred.



Lara et al., 2011a

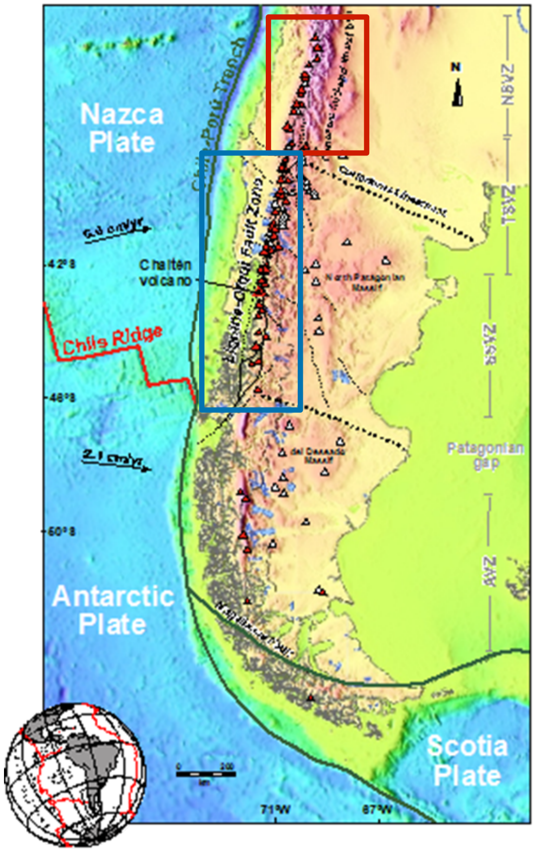
Introduction Arc architecture and crustal tectonics

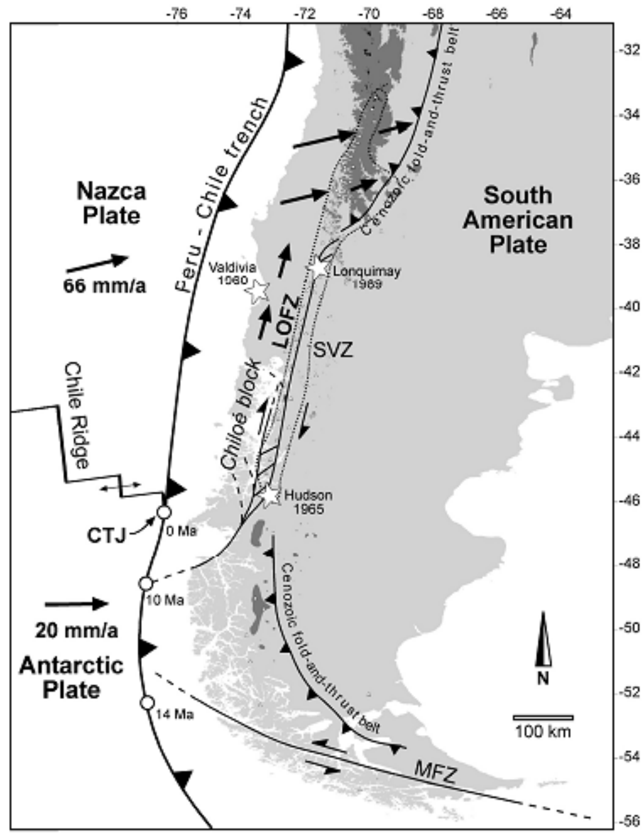
The most hazardous volcanoes in Chile are also located in Southern Andes. The threat is higher there because of both the high hazard posed by volcanoes and the population distribution



Lara et al., 2011a

Introduction Arc architecture and crustal tectonics





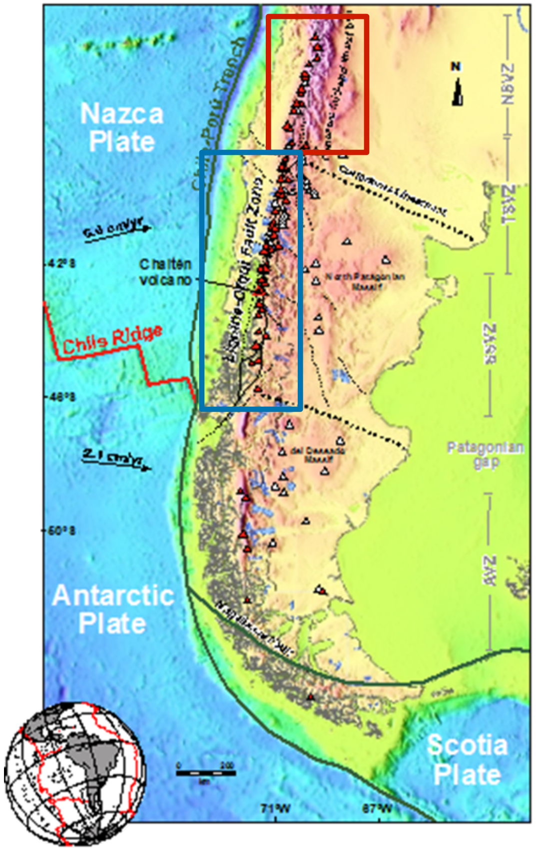
Lara et al., 2008

First-order segmentation:

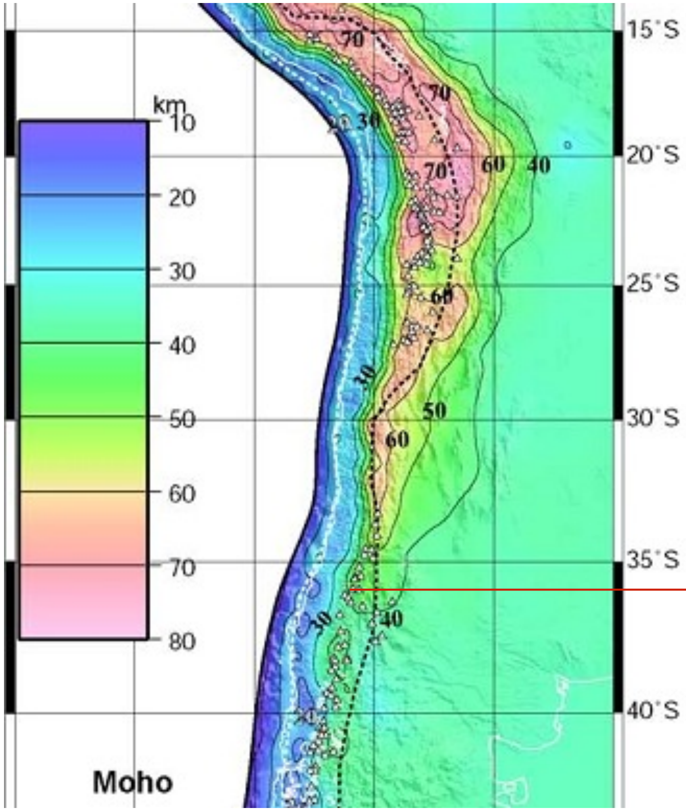
- NSVZ+TSVZ (no strain partitioning and higher crustal thickness)
- CSVZ+SSVZ (strain partitioning and lower crustal thickness)

Introduction

Arc architecture and crustal tectonics



Lara et al., 2008



thick crust (50 km)

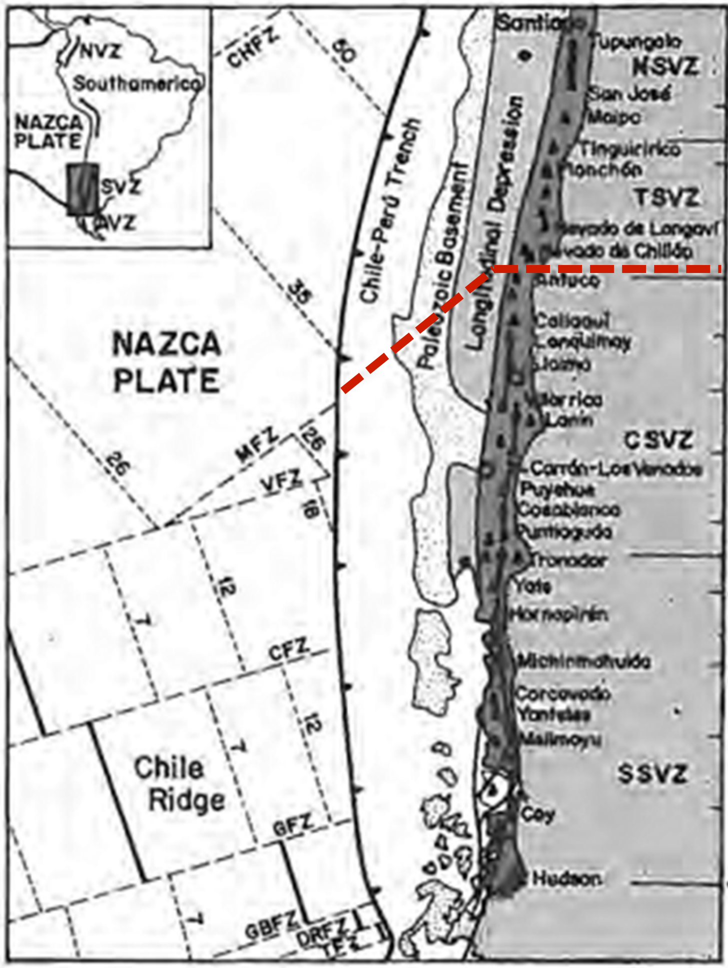
thin crust (35 km)

First-order segmentation:

- NSVZ+TSVZ (no strain partitioning and higher crustal thickness)
- CSVZ+SSVZ (strain partitioning and lower crustal thickness)

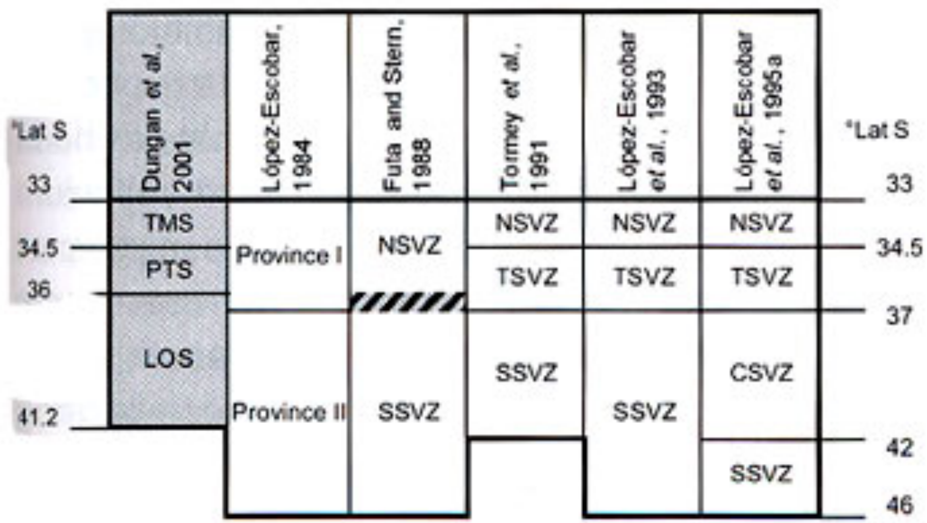
Introduction

Arc architecture of SVZ in terms of volcanic provinces



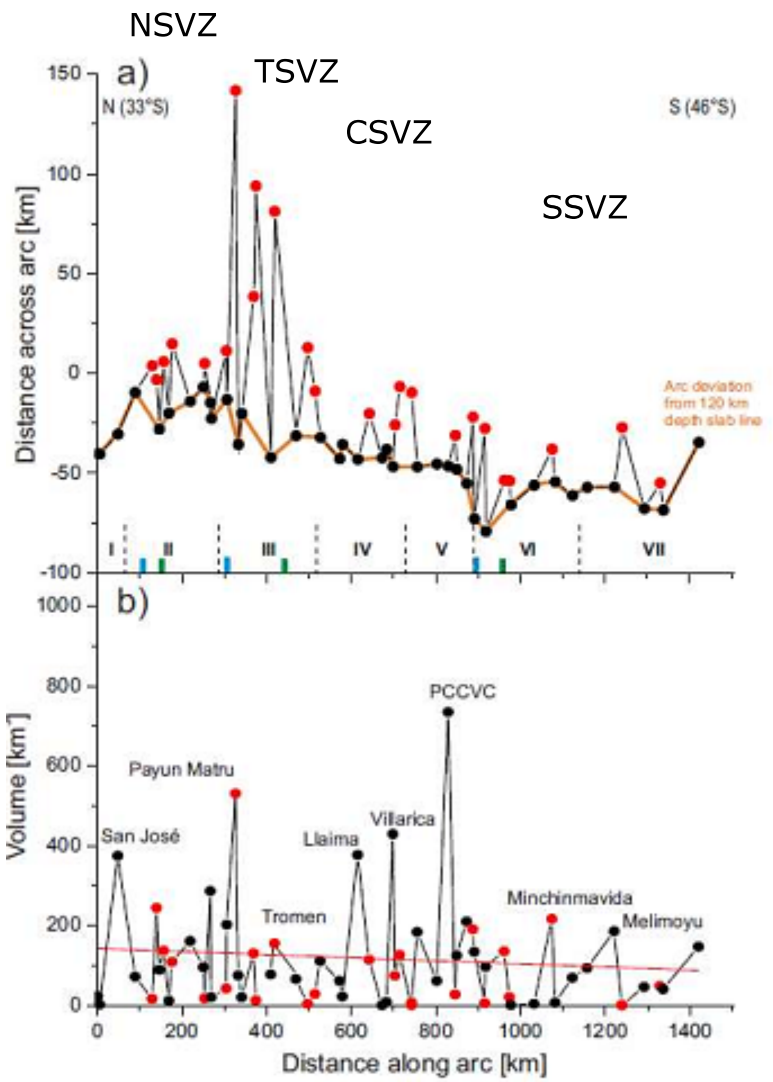
- **NSVZ: 33-34.5ºS**
- **TSVZ: 34.5-37ºS**

- **CSVZ: 37-41.5ºS**
- **SSVZ: 41.5-46ºS**



For a complete review see Stern, 2004. Andean Geology and Stern *et al*. 2007. The Geology of Chile (T Moreno & W Gibbons, eds.).

Introduction Arc architecture of SVZ

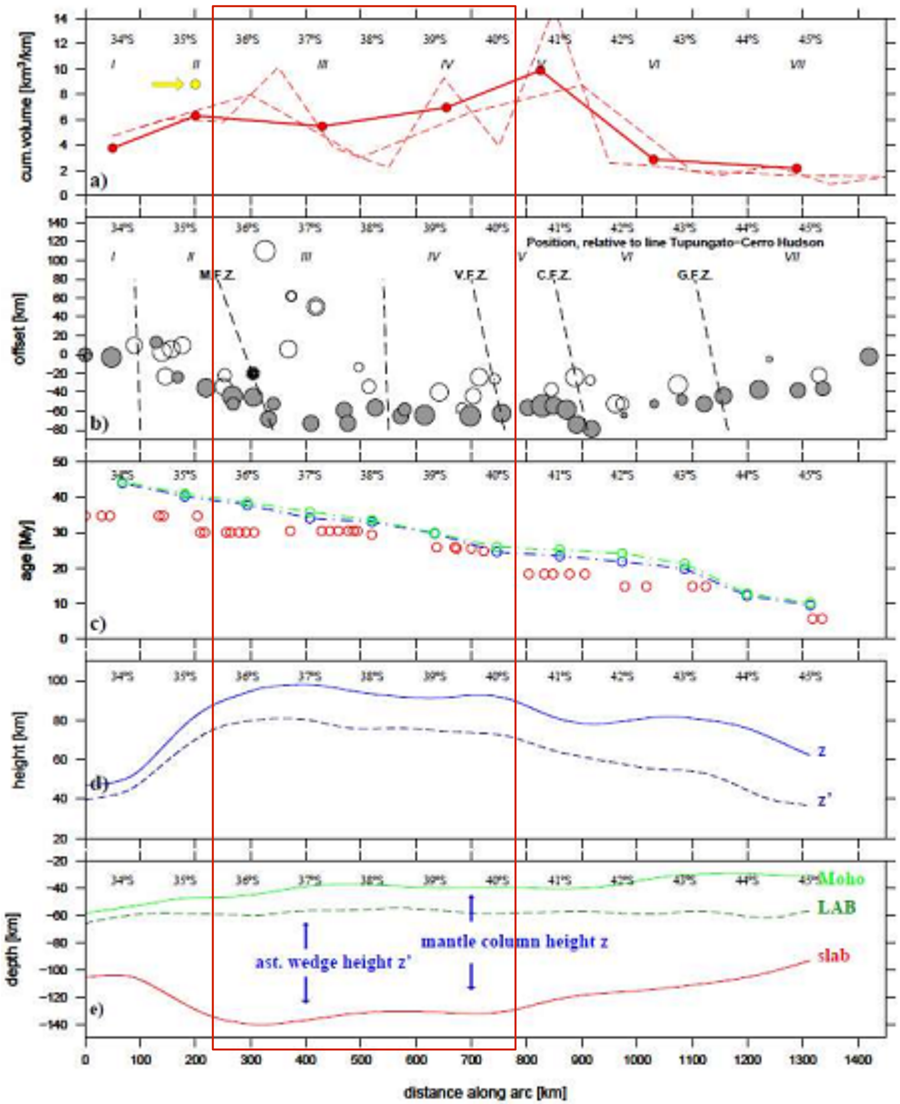


Volker et al., 2011

a) Position of volcanoes relative to the 120 km isobath of the subducting slab (Tassara *et al*., 2006). The orange curve displays the distance of arc volcano positions normal to this line. Black dots represent arc volcanoes whereas red dots indicate back arc volcanoes. Poison distance at front is *ca.* 50 km

b) Volumes of individual edifices along the arc, split into arc and back arc volcanoes. Red line represents a regression line showing a slight northward increase of edifice volumes… but not exactly correct (irregular basement topography mostly due to glacial processes; volcano erosion because of Pleistocene glaciations and collapse)

Introduction
Arc architecture of SVZ



Volker et al., 2011

Variation of subduction parameters along a straight line from the northern end of the SVZ (Tupungato) to the southern end (Hudson)

a)Cumulative volumes of volcanic edifices, normalized to segment length in cubic kilometers per kilometer arc length (red circles and solid line).

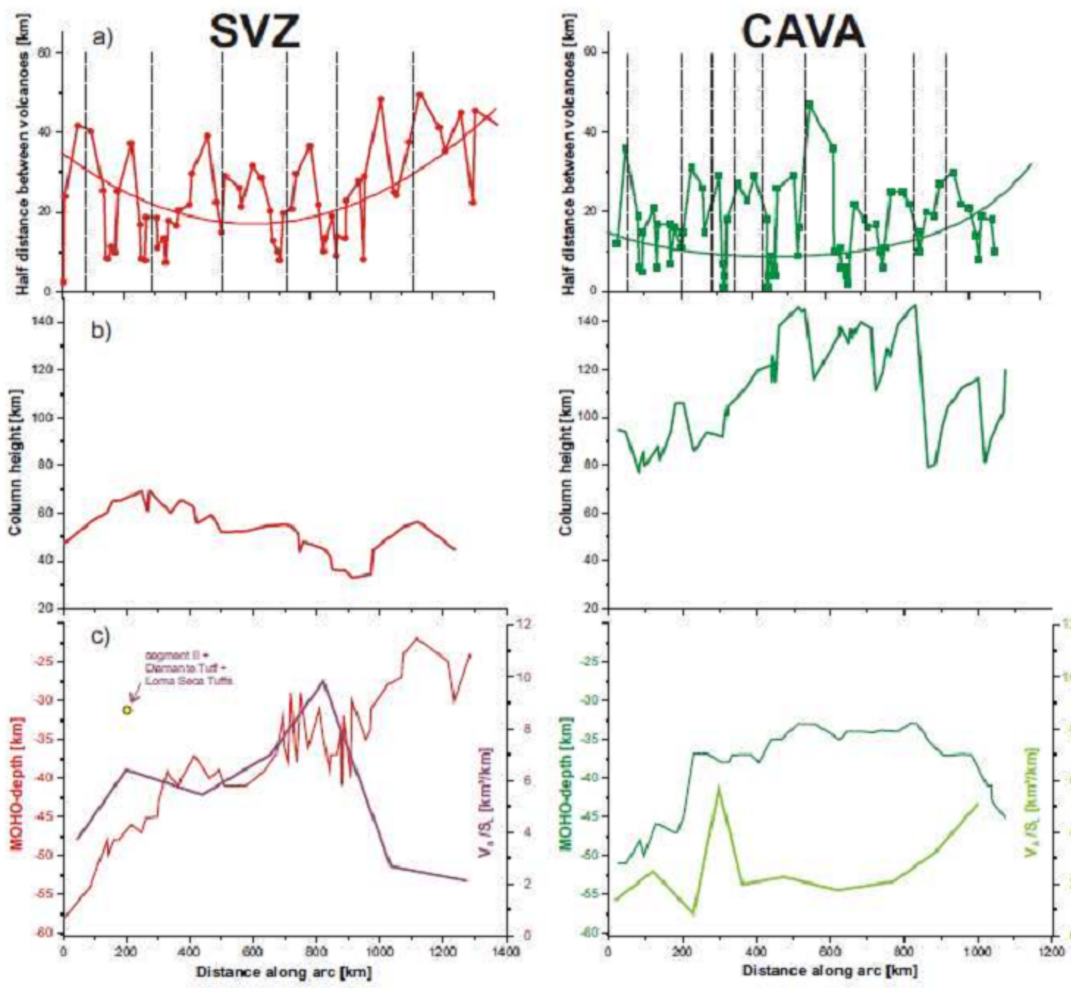
b)Spatial distribution of volcanic edifices along the arc in relation to the reference line (Tupungatito to Hudson). Filled symbols: arc volcanoes, open symbols: back arc volcanoes. Symbol size is scaled logarithmically to the edifice volume.

c)Along-arc variation of the plate age at the trench (red circles), below the volcanic front (blue circles) and below the back arc volcanoes (green circles).

d)Variation of the melting column height z and asthenospheric mantle wedge thickness z’

e)Variation of Moho depth and slab depth. LAB = lithosphere/asthenosphere boundary; M.F.Z = Mocha Fracture Zone; V.F.Z = Valdivia Fracture Zone; C.F.Z = Chiloe Fracture Zone; G.F.Z. = Guafo Fracture Zone.

Introduction Arc architecture of SVZ and comparison with CAVA



Comparison between SVZ and CAVA with respect to:

a) edifice positions, edifice density and edifice volumes (segmentation boundaries are overlain)

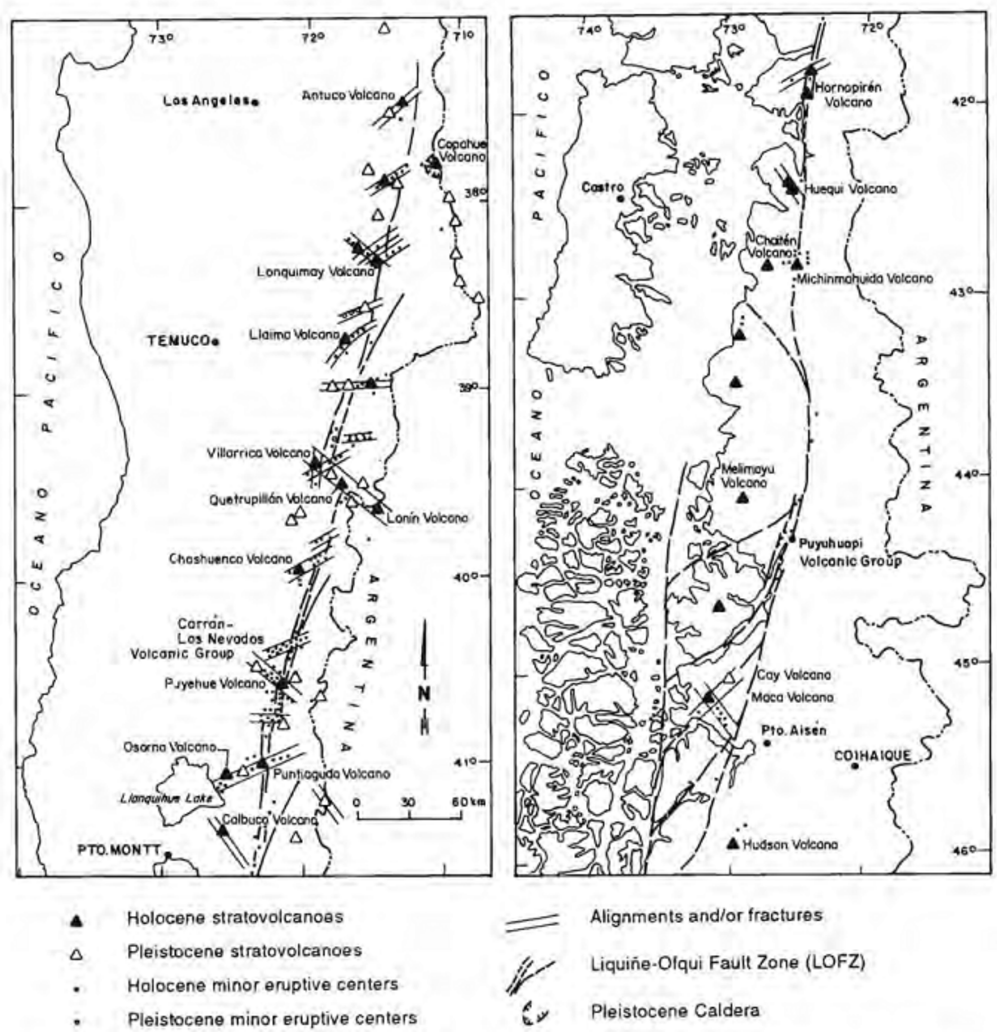
b) Melting column height

c) Moho-depth below the respective arcs.

Volker et al., 2011
Syracuse and Abers (2006).

Introduction

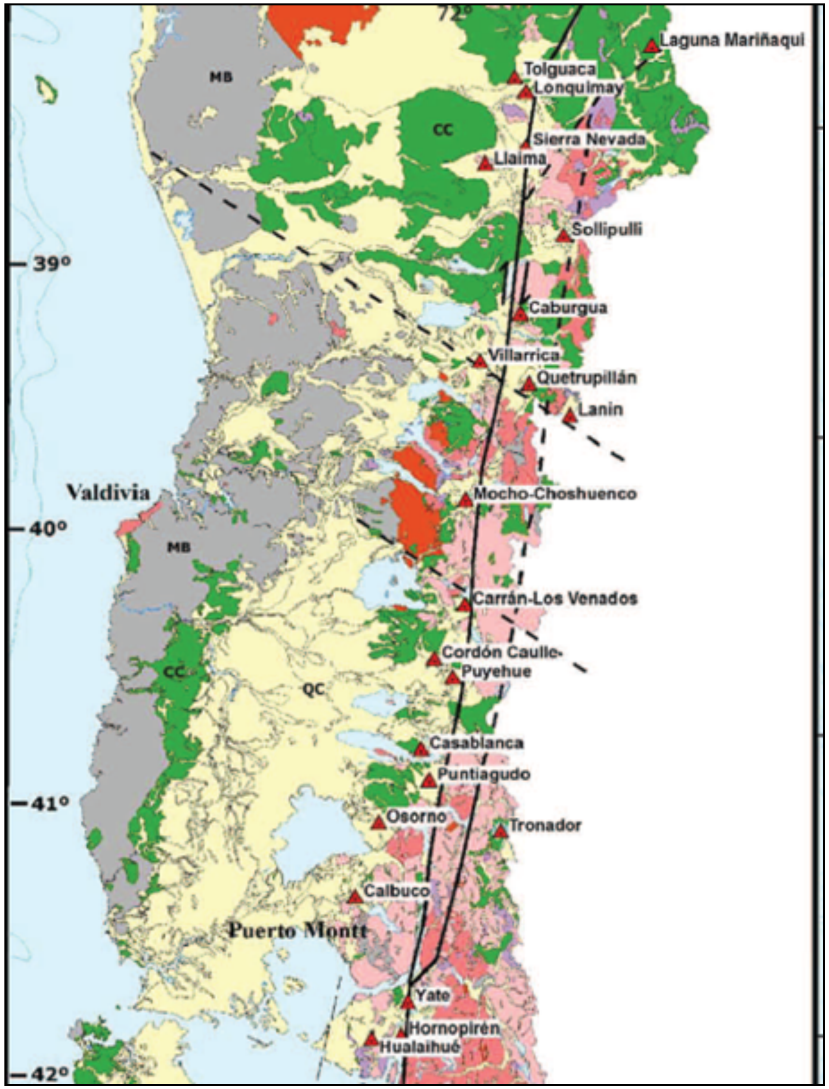
Arc architecture of SVZ at regional scale



- NW-trending transversal chains of stratovolcanoes
- NE-trending transversal chains of scoria cones and small shield volcanoes
- NS alignments of monogenetic cones atop the LOFZ

López-Escobar et al., 1995

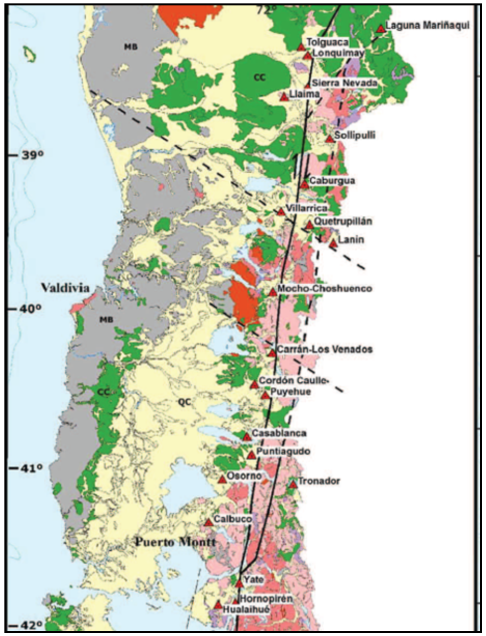
Introduction
Arc architecture at regional scale



- NW-trending transversal chains of stratovolcanoes, related to ancient faults of the basement
- NE-trending transversal chains of scoria cones and small shield volcanoes
- NS alignments of monogenetic centers atop the LOFZ

Cembrano and Lara, 2009

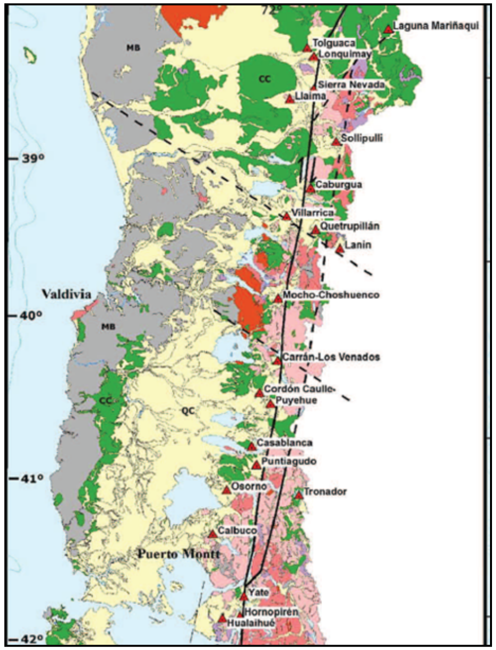
Introduction Arc architecture at regional scale



Cembrano and Lara, 2009

- NW-trending transversal chains of stratovolcanoes, related to ancient faults of the basement (Villarrica-Lanín; Puyehue-Cordón Caulle, etc.)

Introduction Arc architecture at regional scale

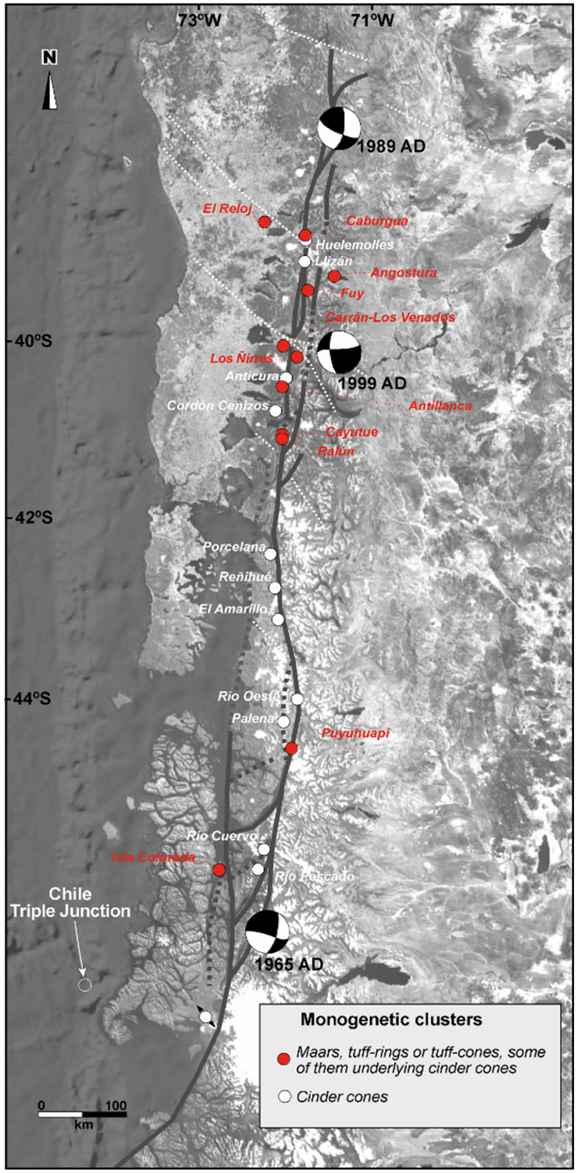


Cembrano and Lara, 2009

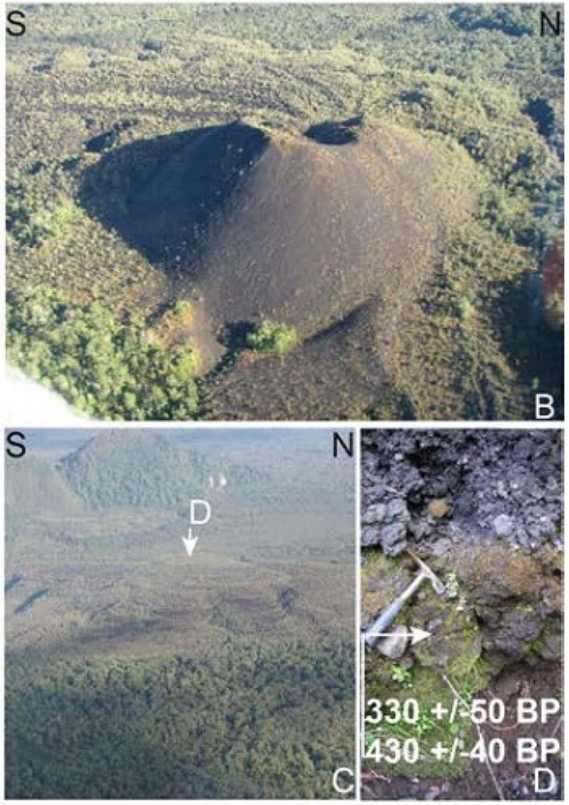
- NE-trending transversal chains of scoria cones and small shield volcanoes (Osorno-Puntiagudo; Carrán-Los Venados, etc.)

Introduction Arc architecture

- NS alignments of monogenetic cones atop the LOFZ

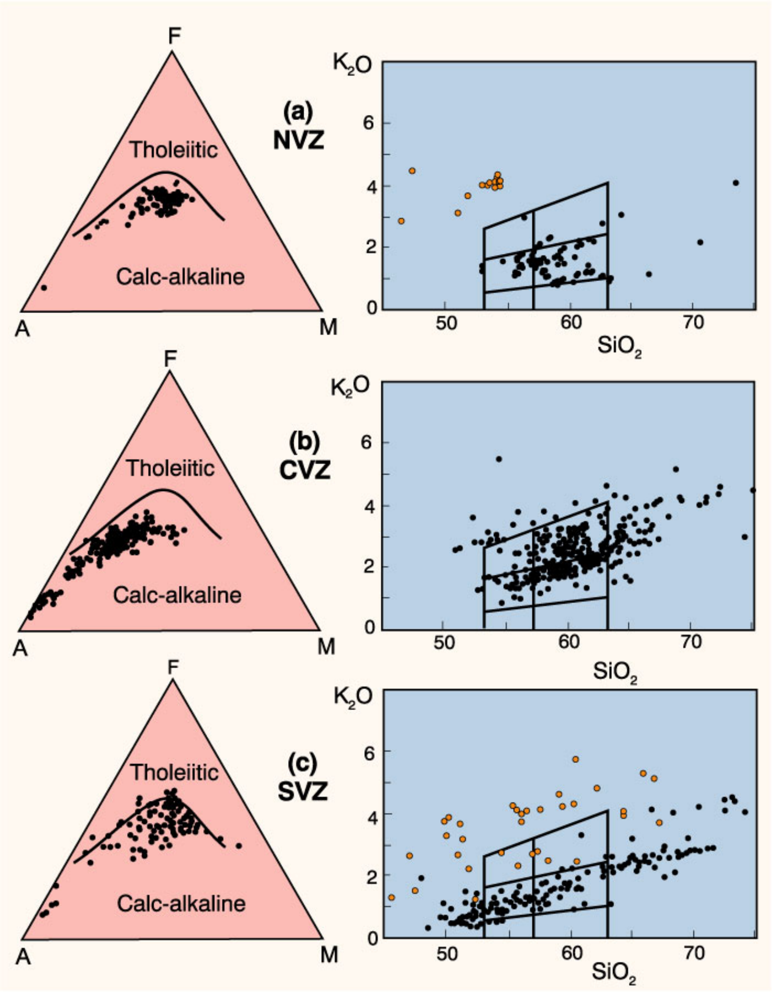


Lara et al., 2009

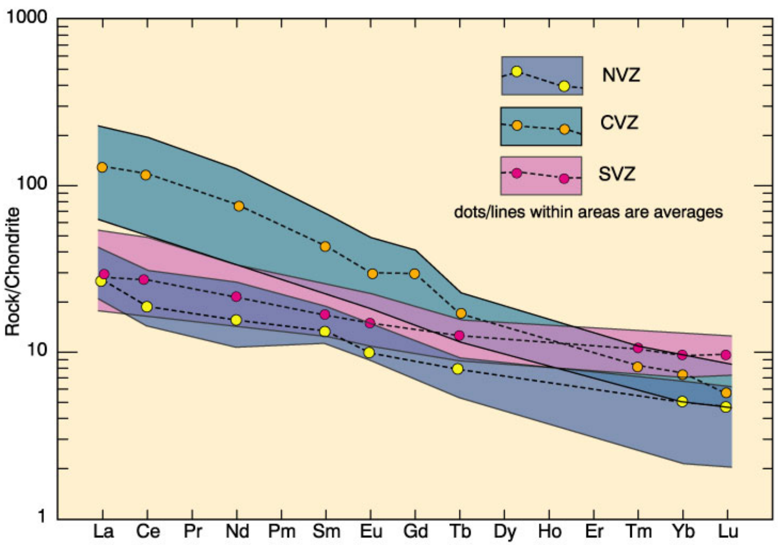


Vargas et al., 2013

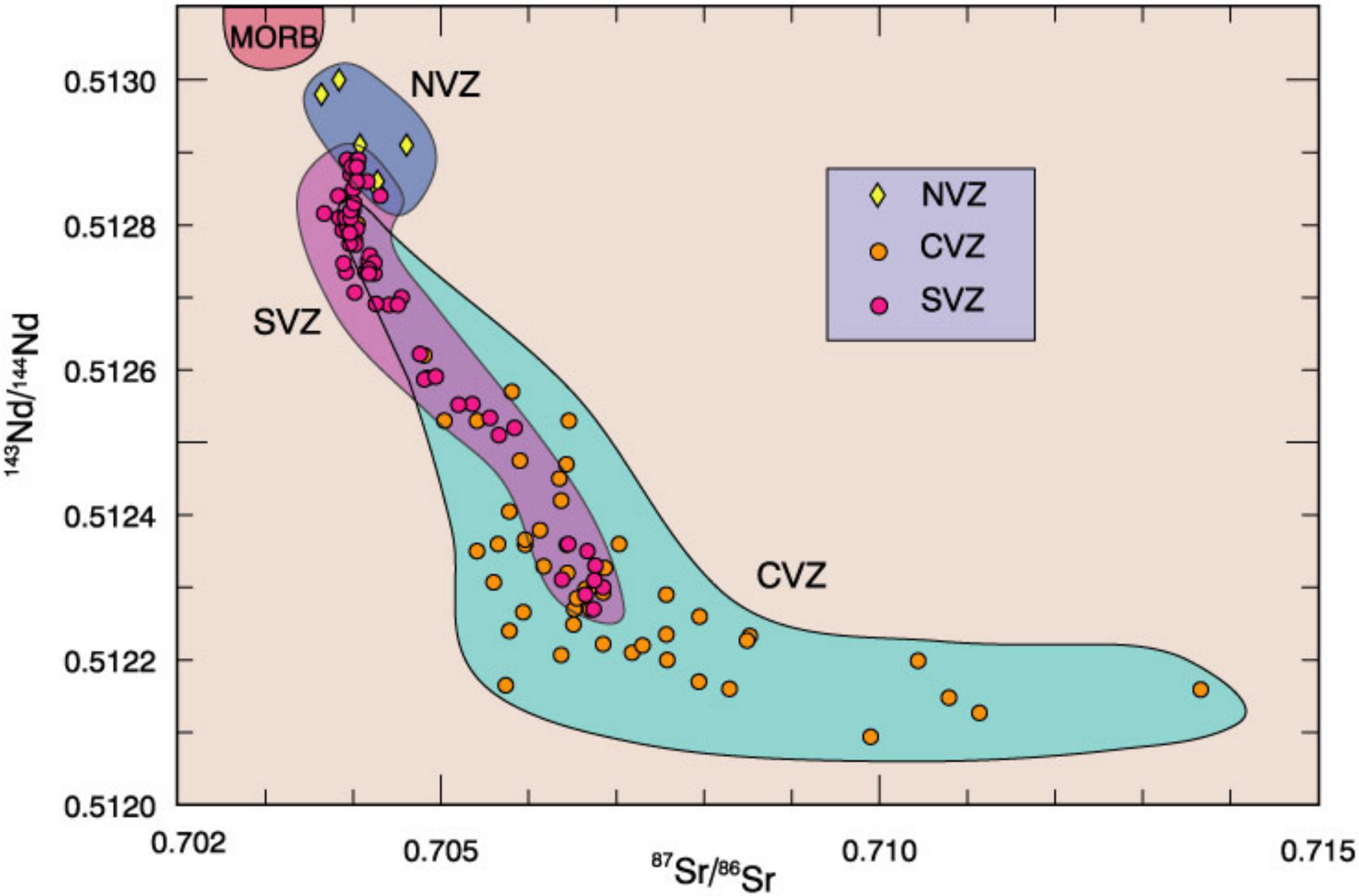
Introduction Magmas and magmatic evolution



- Tholeiitic to Calc-alkaline magmas in SVZ
- LREE/HREE ratios (basalts) decrease southward as crustal thikness

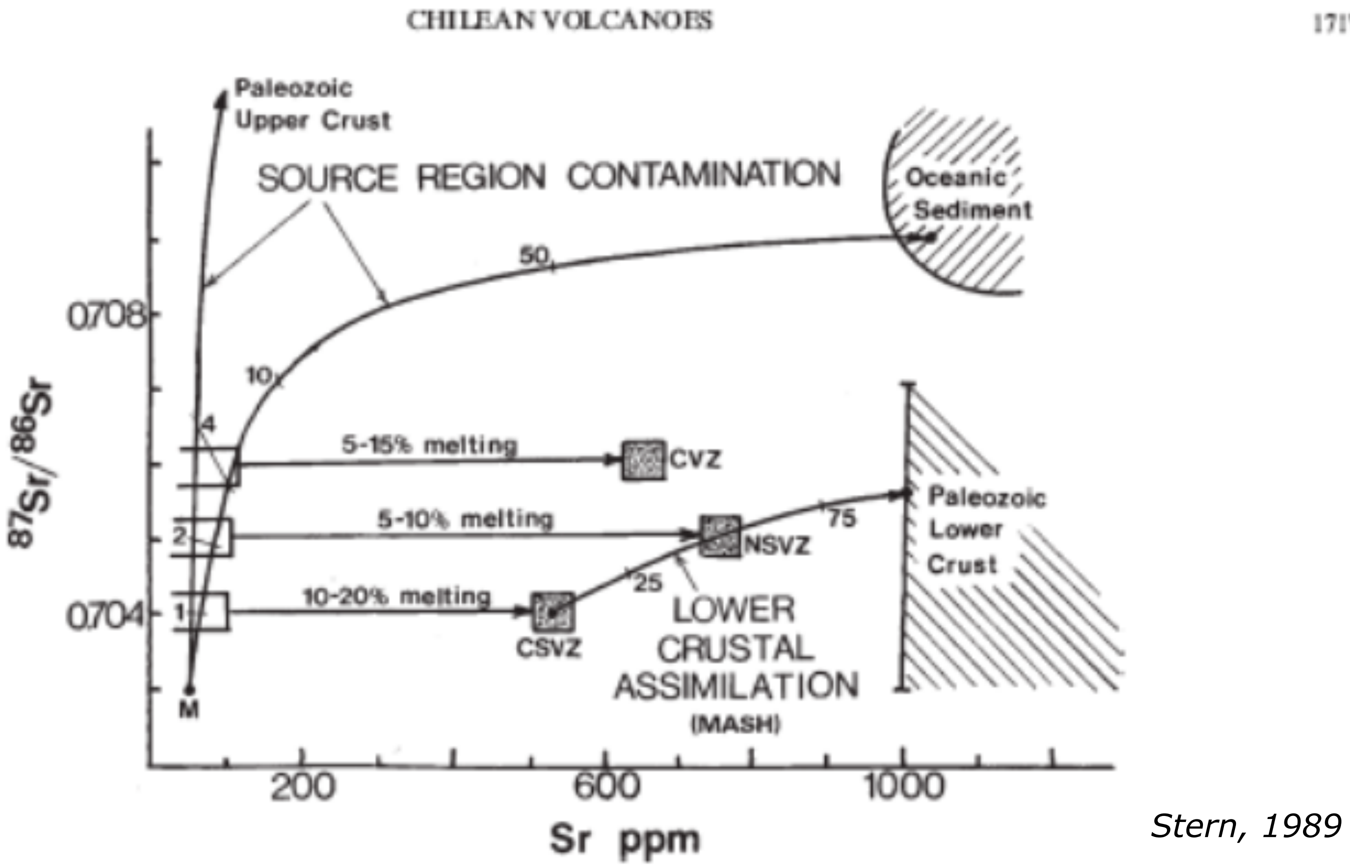


Introduction Magmas and magmatic evolution



Data from James *et al*. (1976), Hawkesworth *et al*. (1979), James (1982), Harmon *et al*. (1984), Frey *et al*. (1984), Thorpe *et al*. (1984), Hickey *et al*. (1986), Hildreth and Moorbath (1988), Davidson (pers. comm.), Wörner *et al*. (1988), Walker *et al*. (1991), de Silva (1991), Kay *et al*. (1991), Davidson and deSilva (1992). Winter (2001)

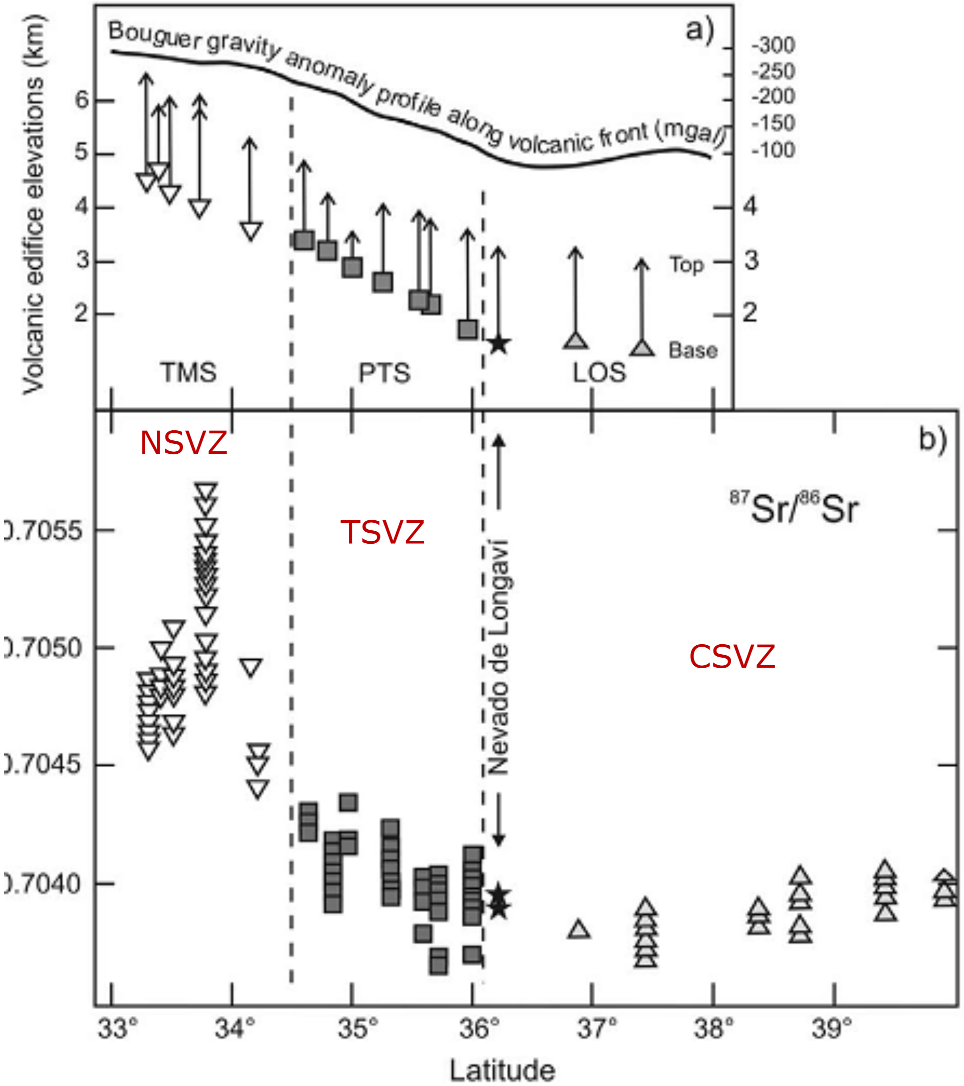
Introduction Magmas and magmatic evolution



Stern, 1989

Some weak crustal signature decreases southward. This pattern has been asigned to higher subduction erosion in the north (Stern, 1998; Kay et al., 2005) or higher crustal assimilation because of the thicker crust (Hildreth and Moorbath, 1988).

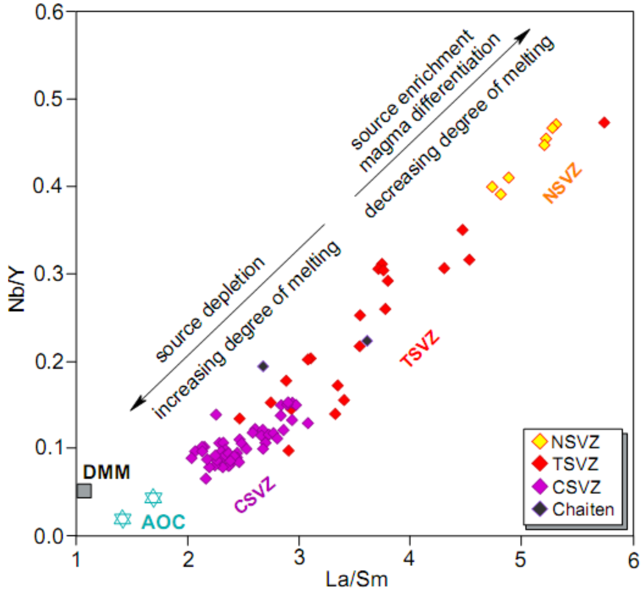
Introduction Magmas and magmatic evolution



Sellés et al., 2004

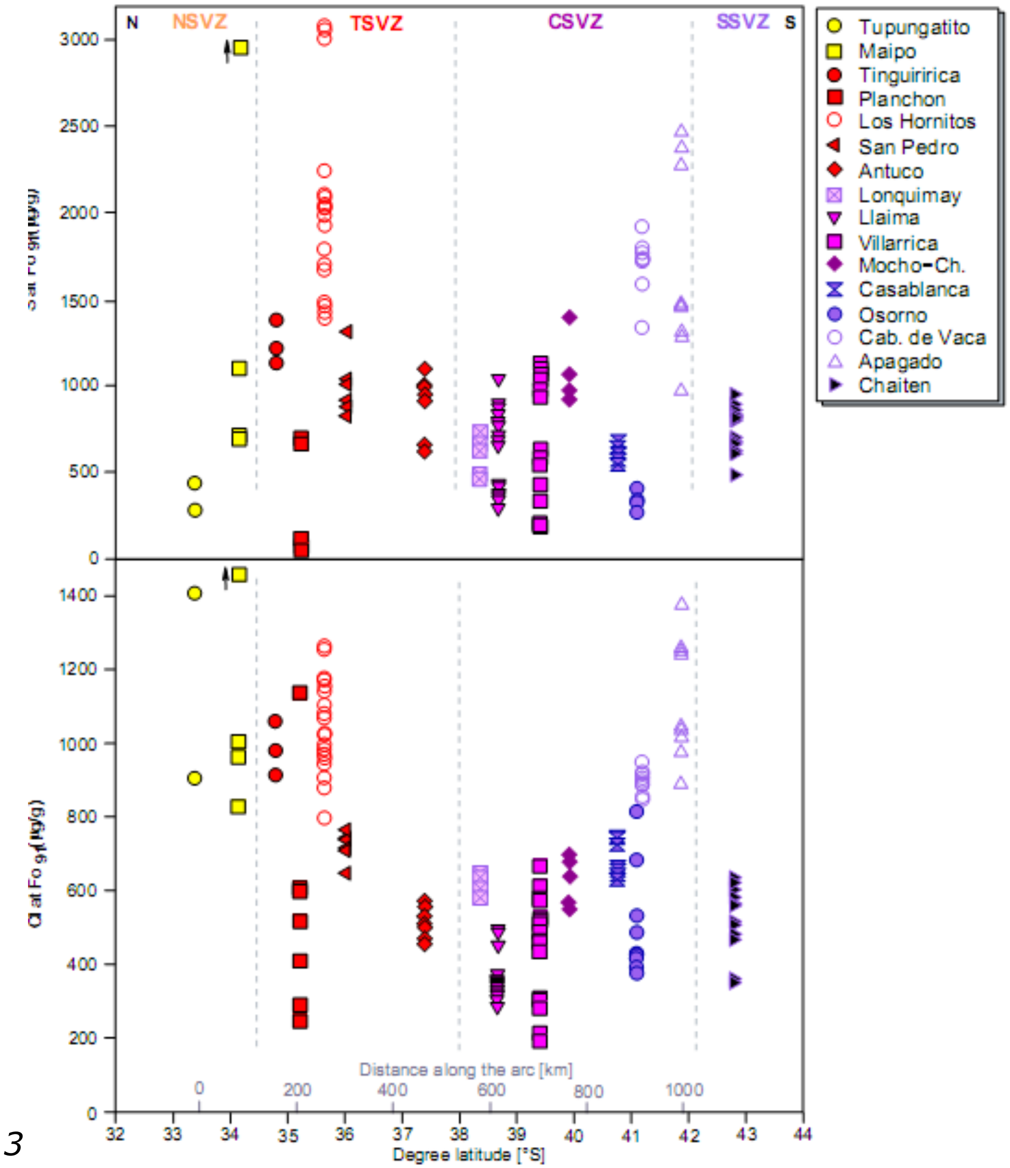
Crustal signature decreases southward

Introduction Magmas and magmatic evolution



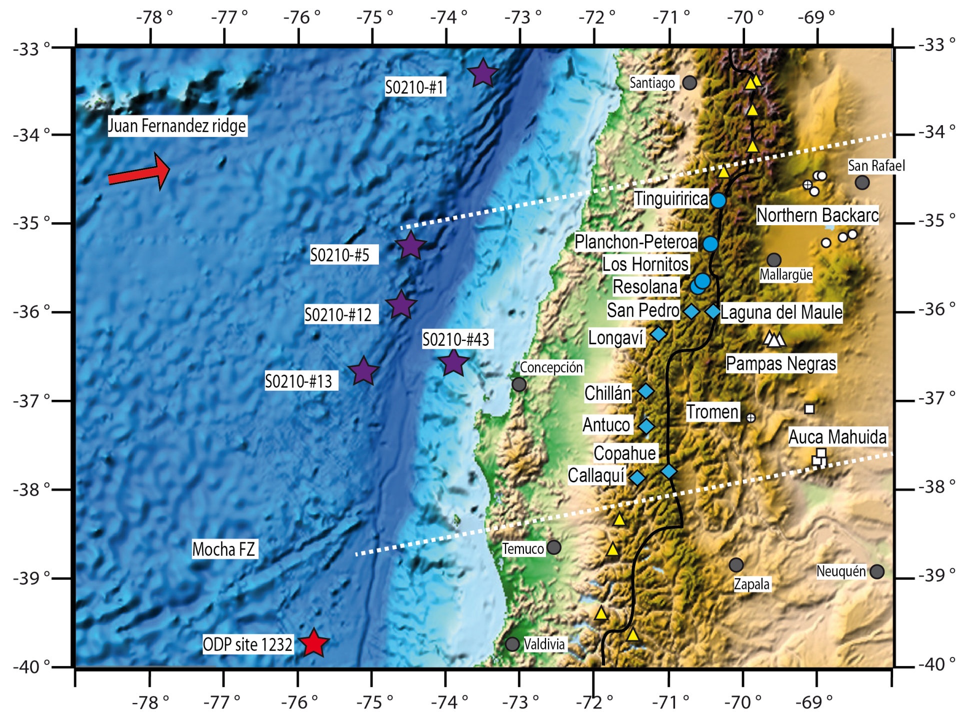
Differences at source and/or acquired during the differentiaton process are also evident in trace elements and volatiles in melt inclusions.

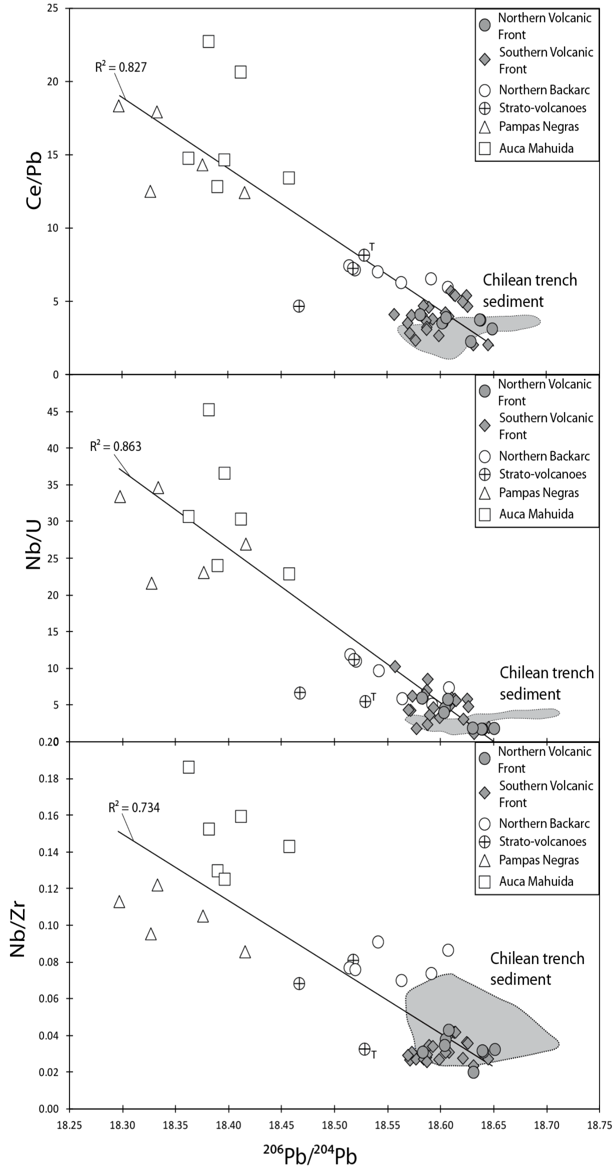
Volatiles-rich magmas related with the Mocha fracture zone?



Wehrman et al., 2013

Introduction Magmas and magmatic evolution





Differences from volcanic front to back arc volcanoes as an effect of the variation of slab fluids, depth of the melting column, etc.

Jacques et al., 2013

Talk outline

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- Magmas and magmatic evolution

Quaternary tectonics in Southern Andes

- Long-term evidences
- Short-term evidences
- Volcanoes as tectonic stress indicators

Arc Tectonic controls on volcanism

- Long-term geological evidence
- Volcano morphology and neotectonics
- Recent case-studies

External controls on volcanism

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Summary and conclusions

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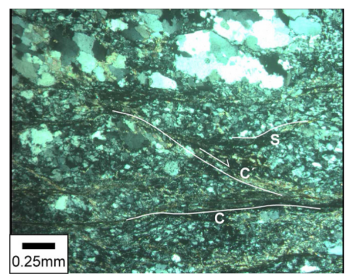
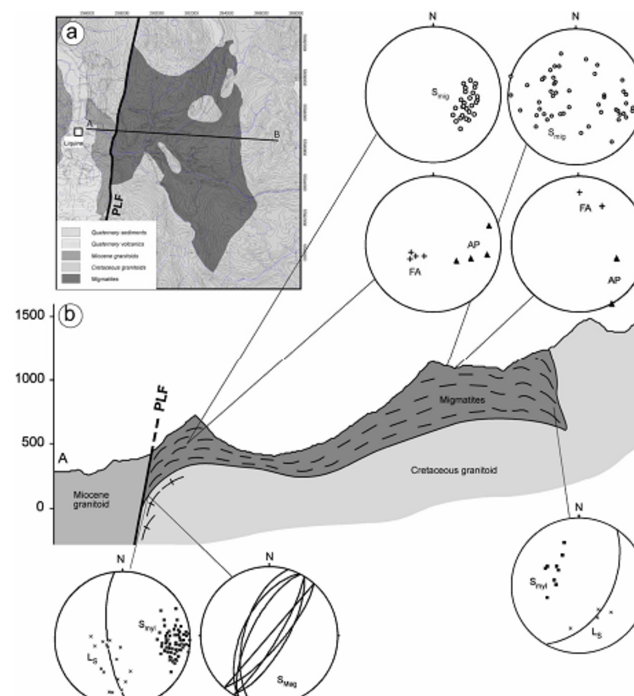
Quaternary tectonics in Southern Andes

Long-term evidence from Miocene plutons and shear zones

- Ductile to brittle dextral deformation at 3.8 Ma on K plutons Schermer *et al.* (1995)

- Ductile to brittle dextral deformation at 4.4 Ma from shear bands on a 10 Ma (U-Pb) pluton (Cembrano, 1998)



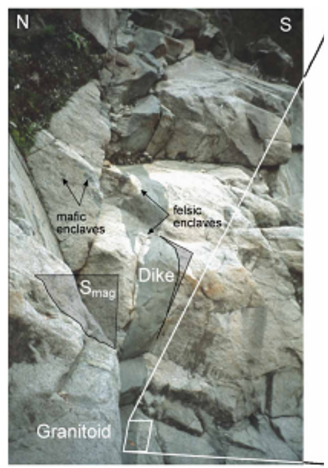


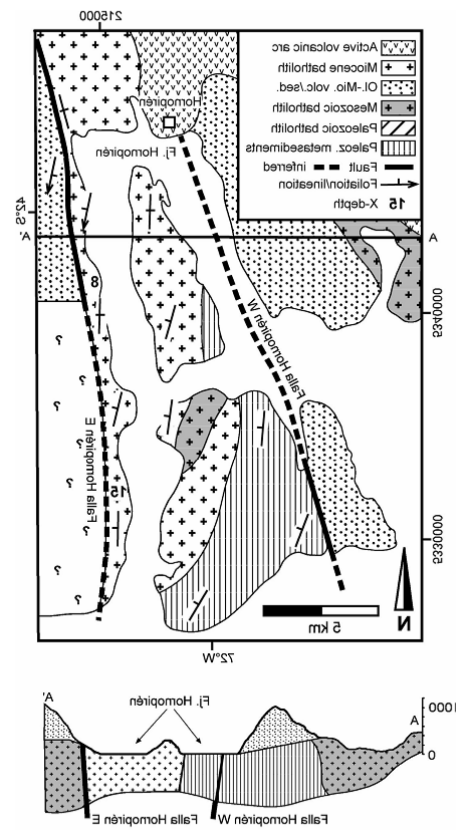
Quaternary tectonics in Southern Andes

Long-term evidence from Miocene plutons and shear zones

- Ductile to brittle dextral deformation at 3.8 Ma on K plutons Schermer *et al.* (1995)

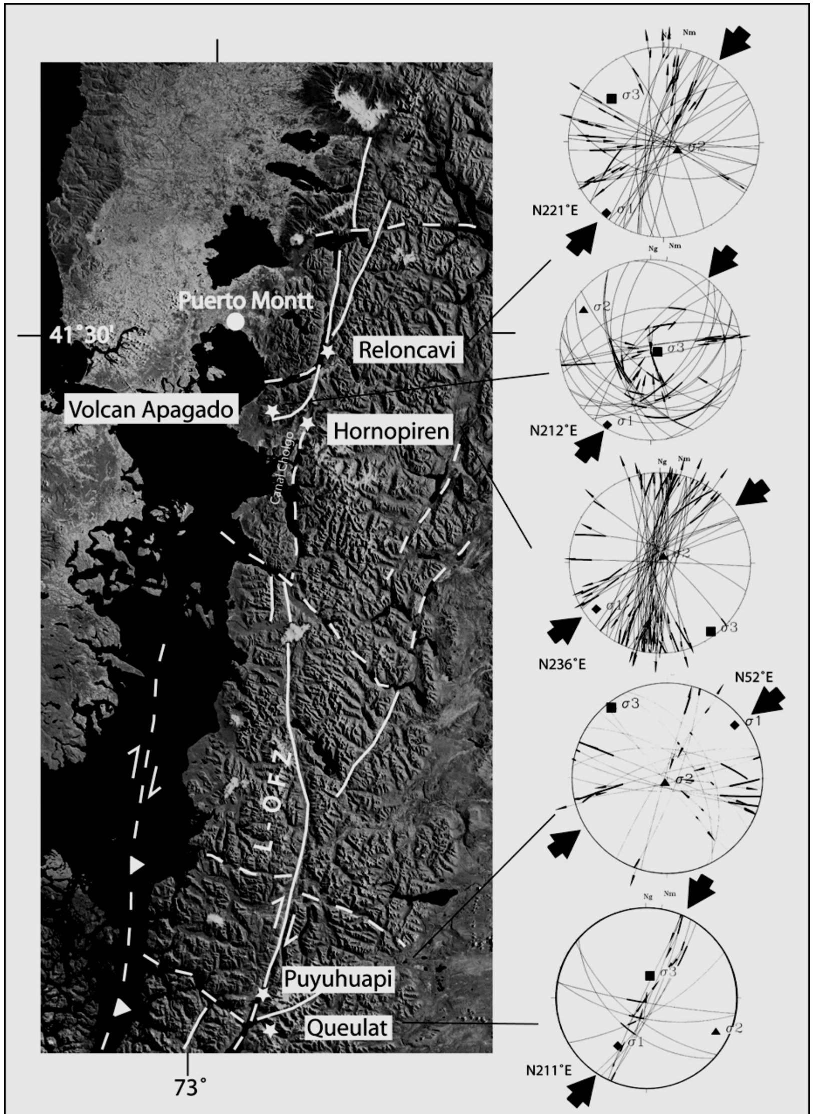
- Ductile to brittle dextral deformation at 4.4 Ma from shear bands on a 10 Ma (U-Pb) pluton (Cembrano, 1998)



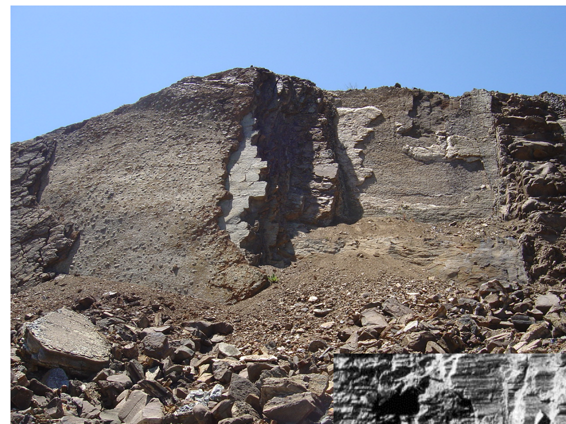


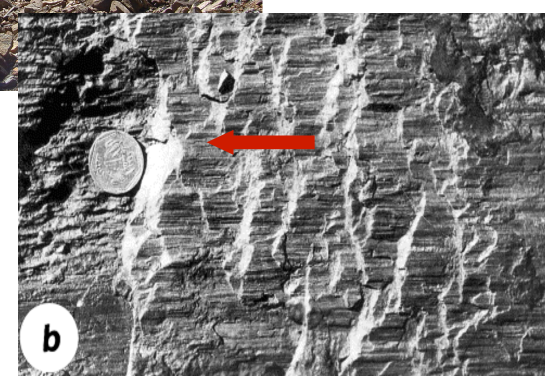
Quaternary tectonics in Southern Andes

Long-term evidence from mesoscale faults at LOFZ



Quaternary brittle dextral deformation superimposed to ductile deformation

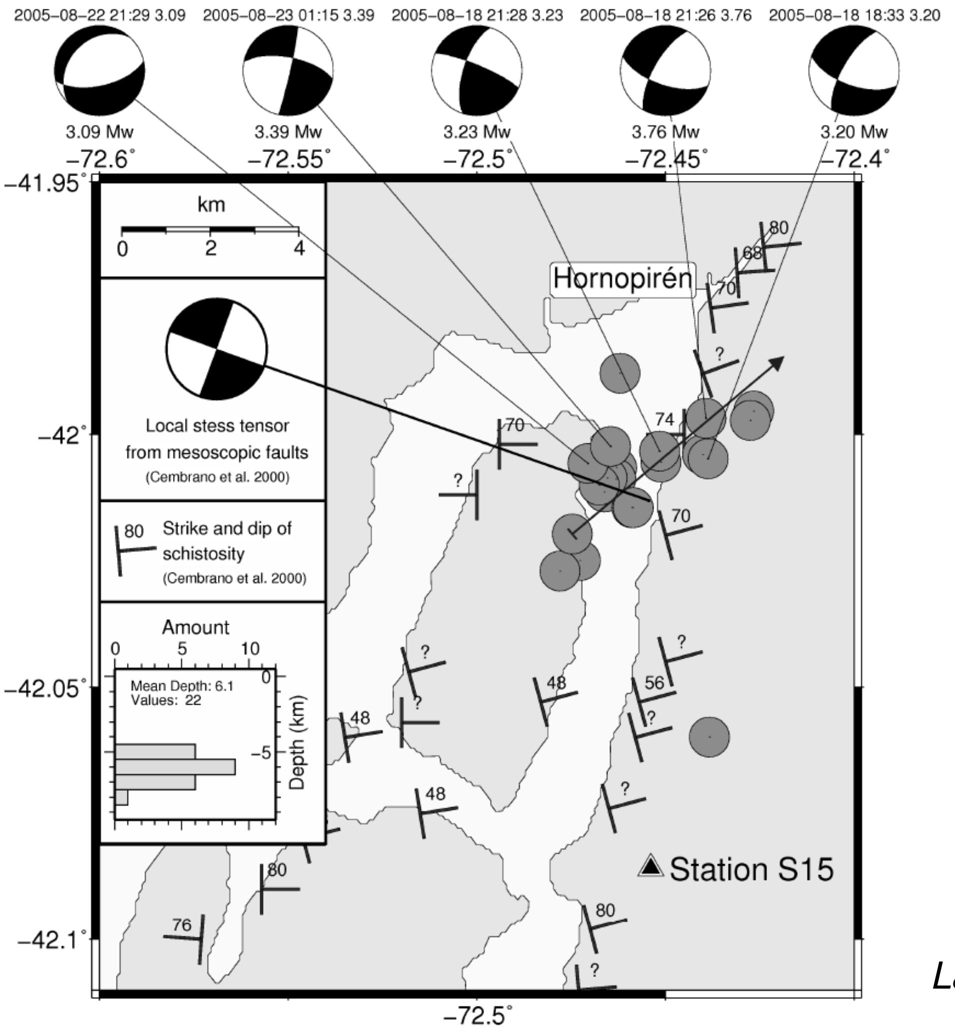




Lavenu and Cembrano (1999)

Quaternary tectonics in Southern Andes

Long-term evidence from mesoscale faults at LOFZ

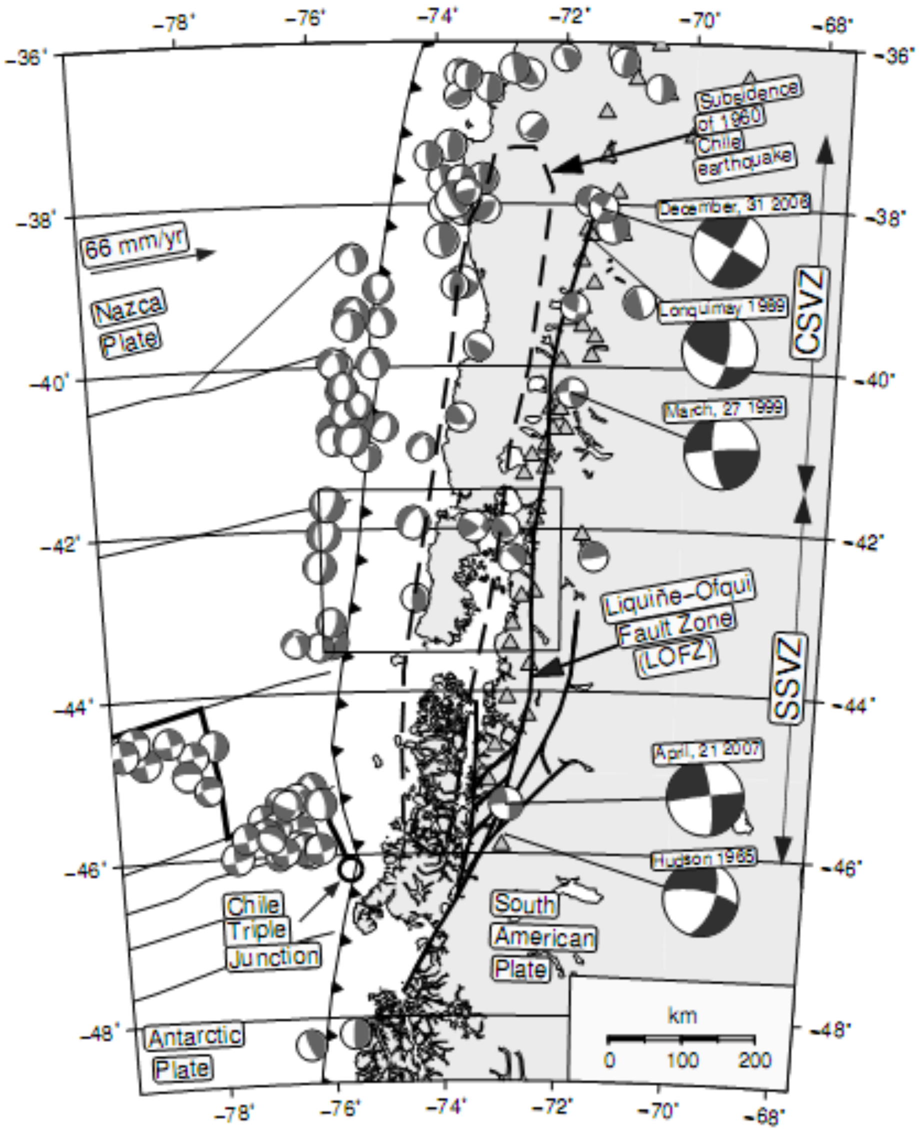


Quaternary brittle dextral deformation superimposed to ductile deformation

Lange et al. (2007)

Quaternary tectonics in Southern Andes

Short-term evidence from focal mechanisms for crustal earthquakes

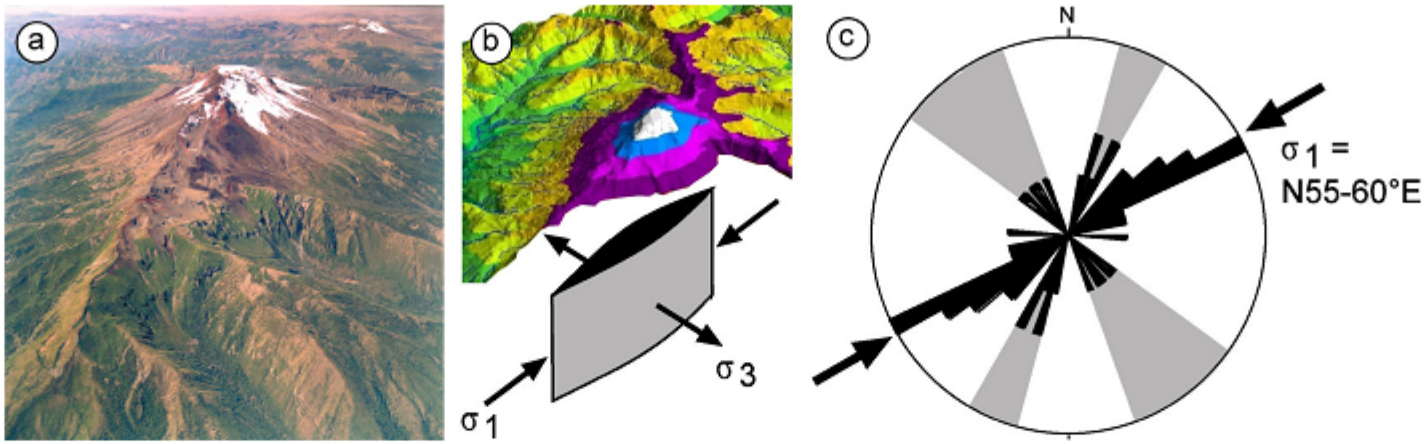


Focal mechanisms with dextral strike-slip solutions (NE-trending SHmax)

Lange (2007)

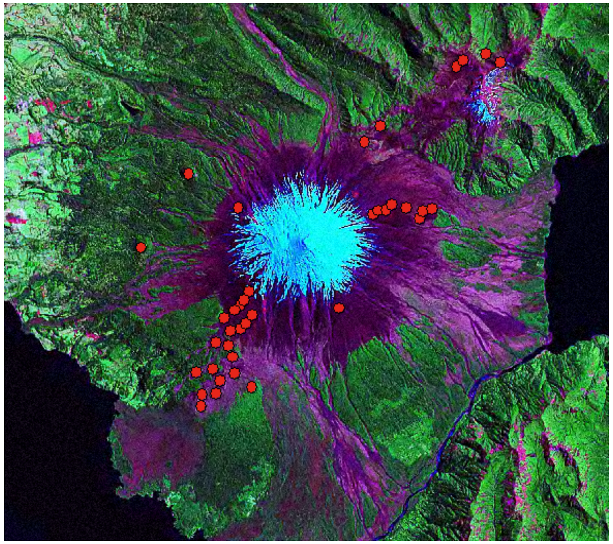
Quaternary tectonics in Southern Andes

Short-term evidence: volcanoes as stress indicators



Rosenau, 2004

Flank cones on stratovolcanoes and transversal chains of monogenetic centres are NE-trending along the arc, so the Shmax can be inferred from that according to Nakumara's principle (Nakamura, 1977).



Lara et al., 2011b

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- Arc architecture
- Magmas and magmatic evolution

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- Long-term evidences
- Short-term evidences
- Volcanoes as tectonic stress indicators

Arc Tectonic controls on volcanism

- Long-term geological evidence
- Volcano morphology and neotectonics
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Arc tectonic control of volcanism

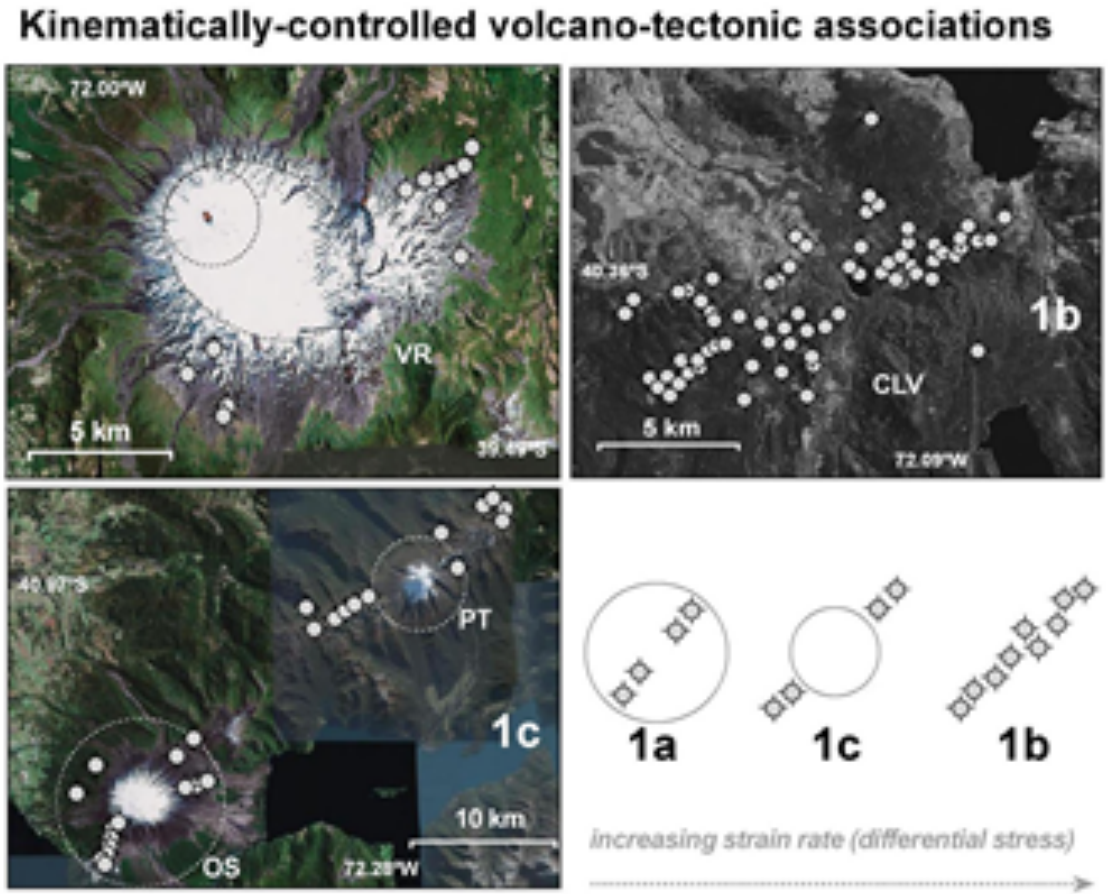
…of course, we are not the first who noted these relations and speculate about that…

On the connection of certain volcanic phenomena in South America and on the formation of mountain chains and volcanoes, as the effect of the same power by which continents are elevated.
Charles DARWIN, London, 1838

El 18 de enero de 1835 cuando anclaban por segunda vez en la bahía de San Carlos, Darwin tuvo la oportunidad de ver un fenómeno extraordinario. Fue esa noche cuando el volcán Osorno, a unos 150 km tierra adentro, entró en erupción. «A las doce de la noche el centinela observó algo semejante a una gran estrella que aumentó gradualmente de tamaño». El espectáculo era magnífico; con la ayuda de un vidrio, en medio del fuerte brillo rojizo de la luz, se podía observar una continua sucesión de objetos oscuros que eran lanzados hacia lo alto y luego caían. Por la mañana el volcán parecía haber recobrado la calma». Se quedaron asombrados al enterarse más tarde de que el Aconcagua, 750 km al norte, y el Conseguina, 4320 km al norte, también habían entrado en erupción la misma noche. Diario de Viaje, cap 5.

Arc tectonics control son volcanism in Southern Andes

Towards a typology of volcano-tectonic associations in Southern Andes:



1a *Flank cones on stratovolcanoes*

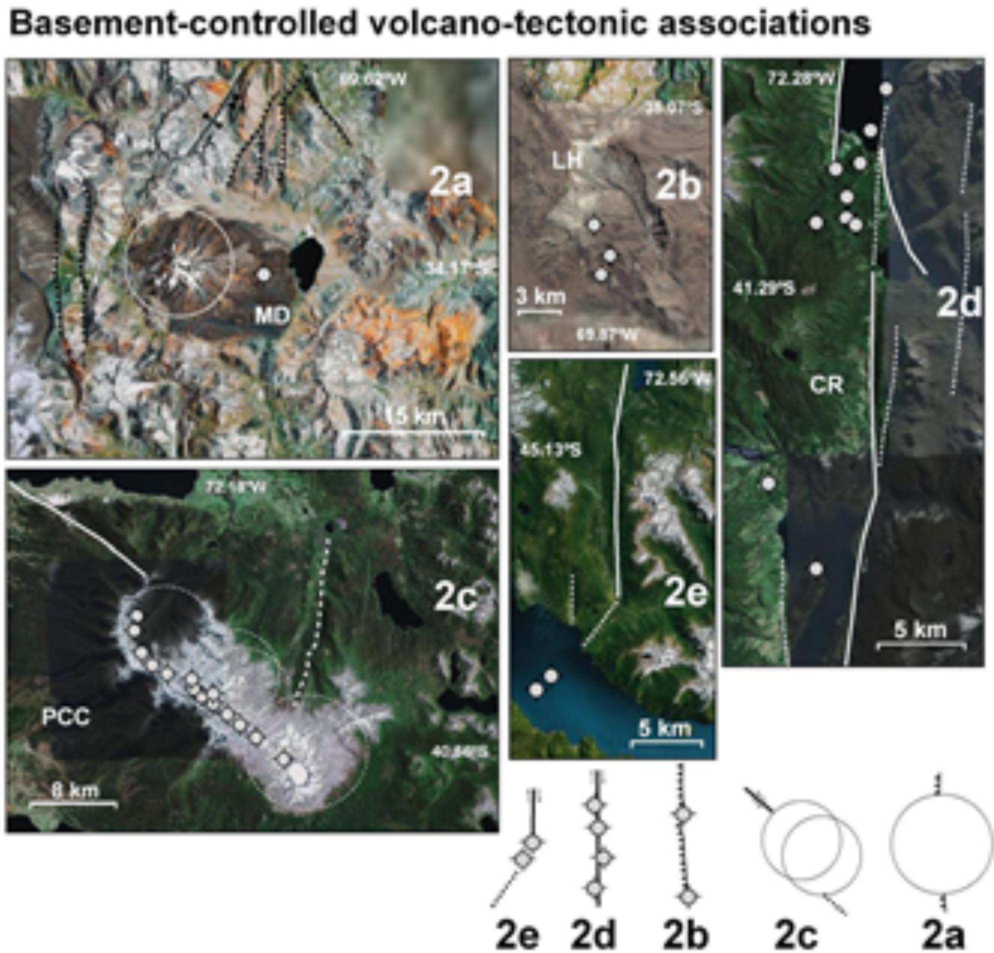
1b *Oriented clusters of monogenetic centers*

1c *Alignments of stratocones and monogenetic centers*

Cembrano and Lara, 2009

Arc tectonics control on volcanism in Southern Andes

Towards a typology of volcano-tectonic associations in Southern Andes:



***2a** Stratovolcanoes above active reverse faults*

***2b** Monogenetic centers above active reverse faults*

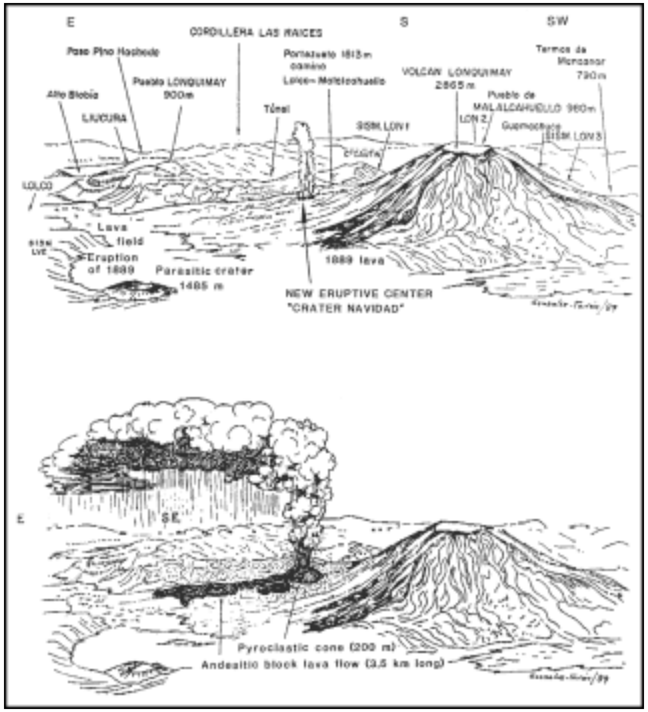
***2c** Stratovolcanoes above ancient strike-slip basement faults*

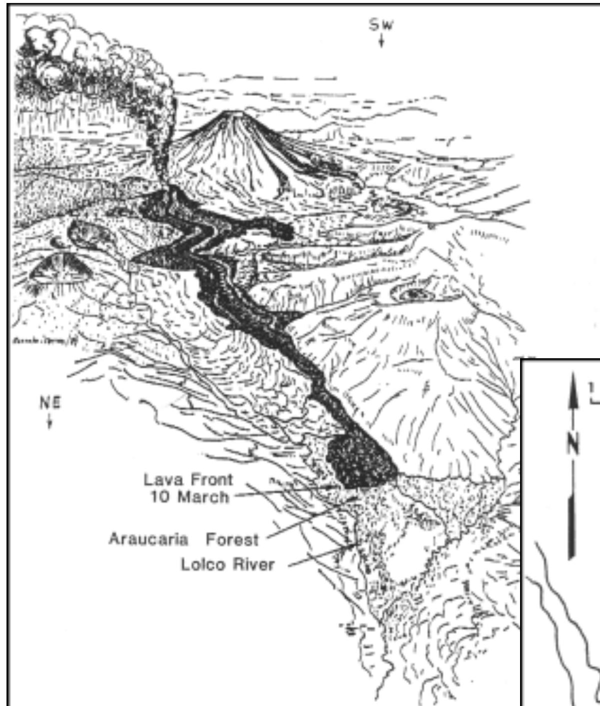
***2d** Monogenetic centers above active strike-slip faults*

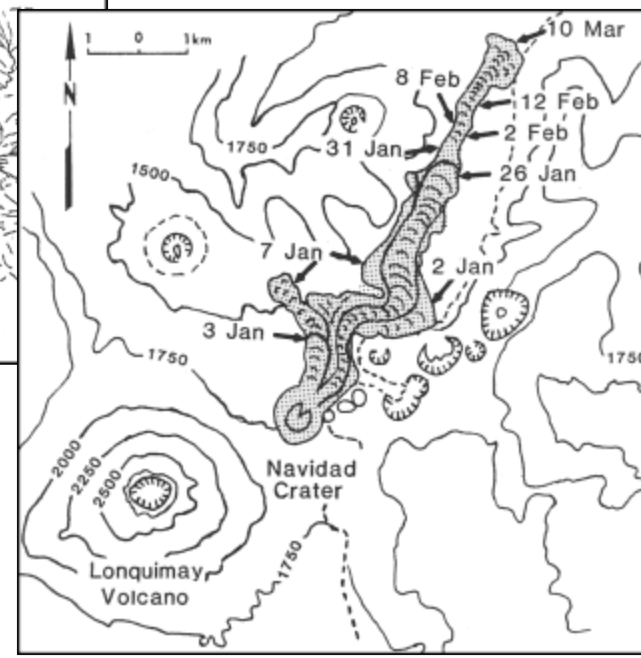
***2e** Monogenetic centers in tail cracks of active strike-slip faults*

Cembrano and Lara, 2009

Arc tectonics control on volcanism in Southern Andes: recent case-studies, the Lonquimay 1988-1989 eruption



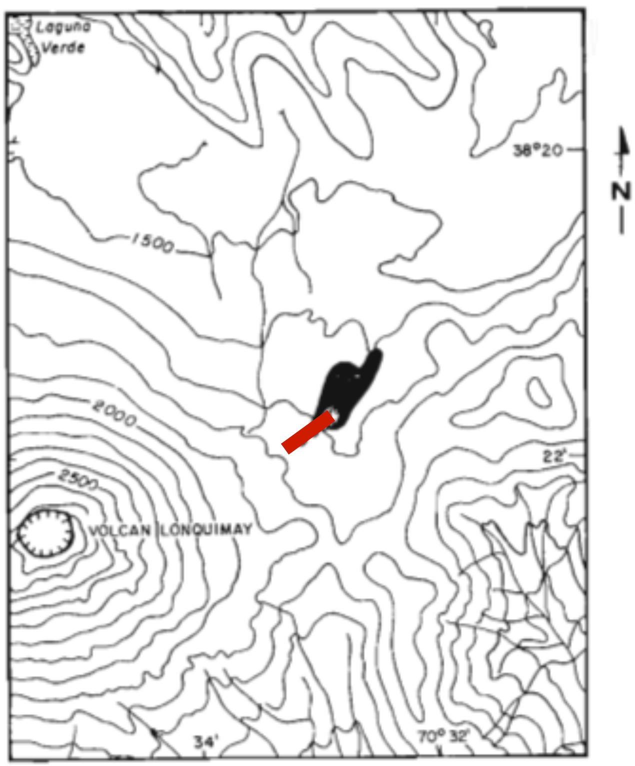




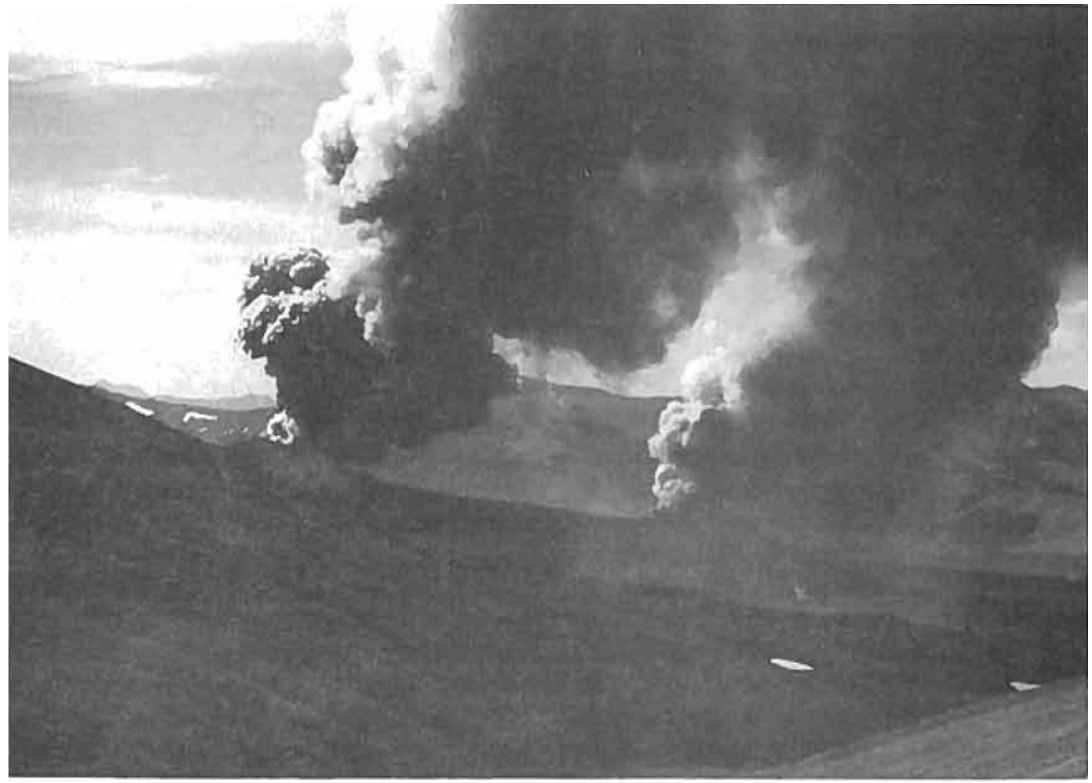
After a persistent seismic swarm, a Strombolian eruption started in December 25, 1988

Moreno and Gardeweg, 1989

Arc tectonics control on volcanism in Southern Andes: recent case-studies, the Lonquimay 1988-1989 eruption



a. 27-12-88, 19:00 horas.



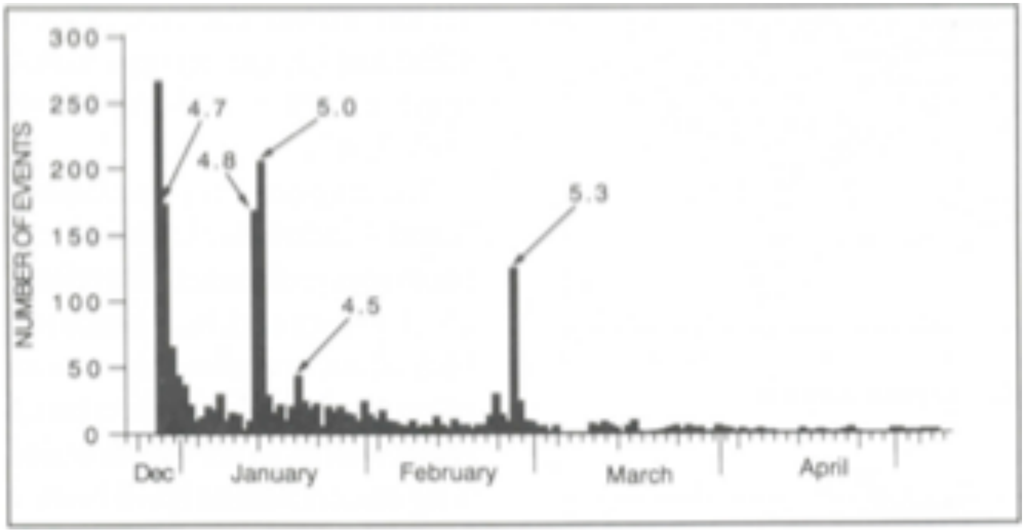
b. 29-12-88, 12:00 horas.

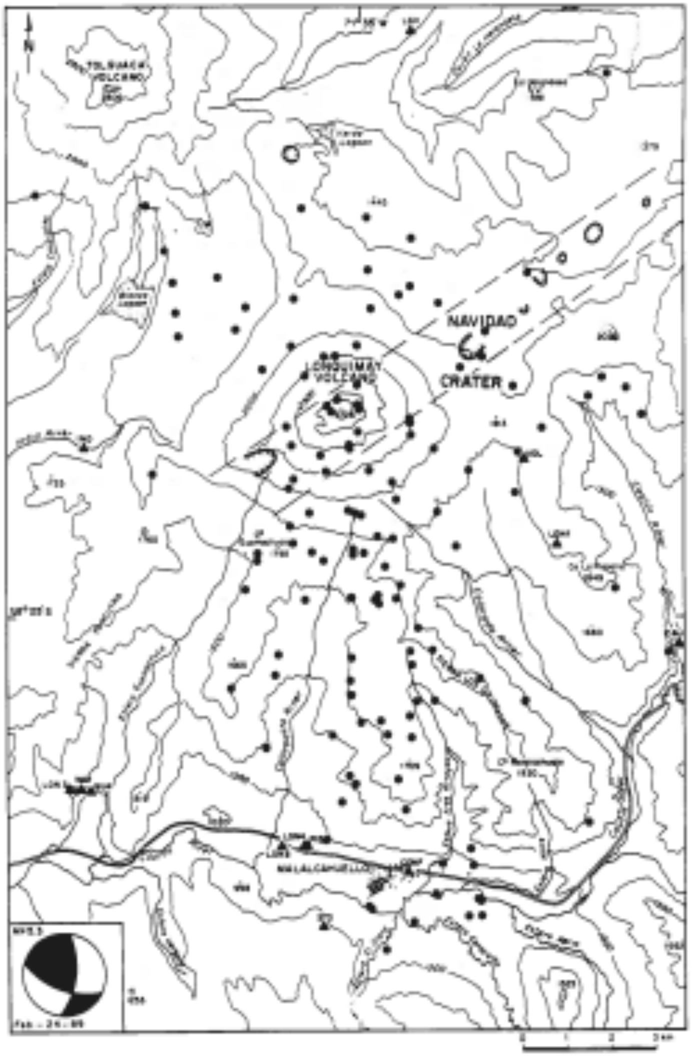
0 1 2 km

At the beginning of the eruption, a NE-trending fissure was formed but after that covered by the growing pyroclastic cone.

Moreno and Gardeweg, 1989

Arc tectonics control on volcanism in Southern Andes: recent case-studies, the Lonquimay 1988-1989 eruption



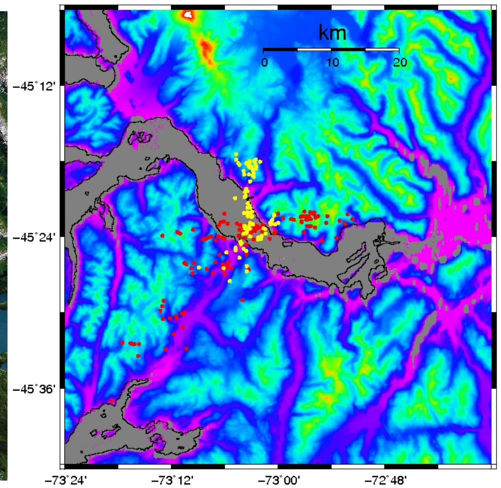


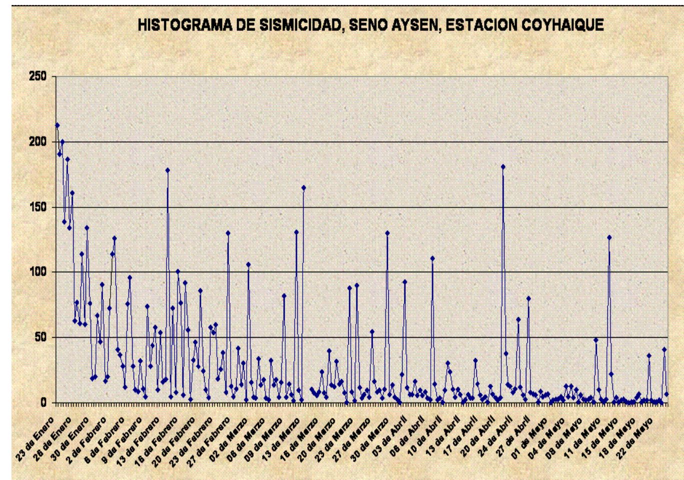
A Mw 5.3 strike-slip earthquake occurred on March 23th

The epicentral area roughly defined a ‘dog bone’ pattern a mimic extensional cracks in a strike-slip setting (Hill, 1977 model)

Barrientos and Acevedo, 1992

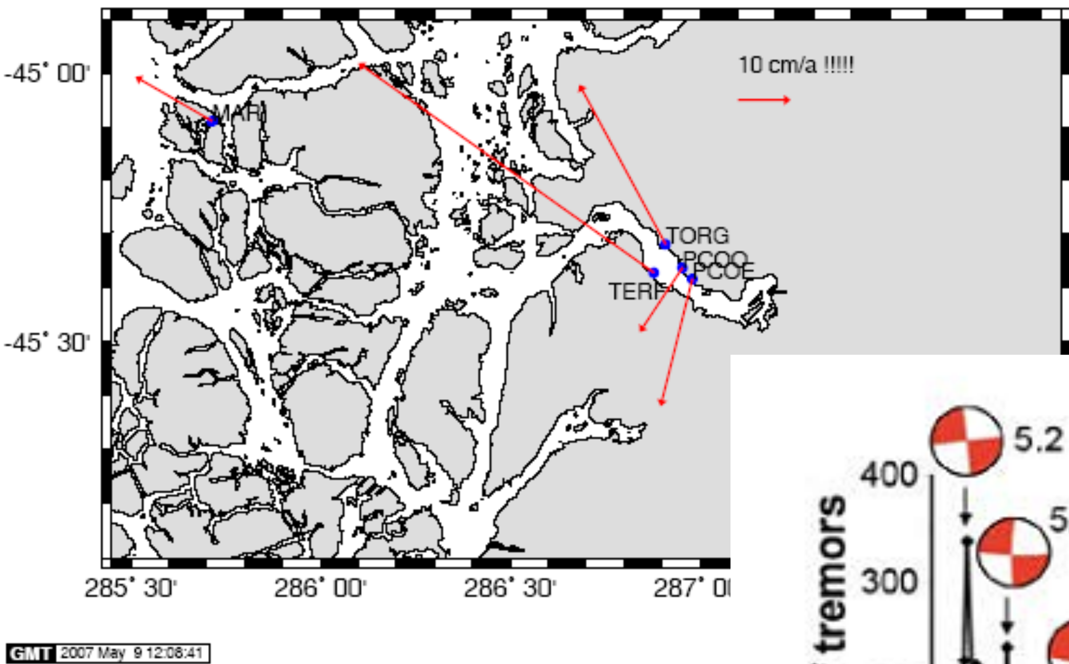
Arc tectonics control on volcanism in Southern Andes: recent case-studies, the Aysén 2007 seismic swarm





Four months of sustained seismicity along the LOFZ with a Mw 6.3 earthquake on April 21, 2007, caused landslides and tsunami but no eruption

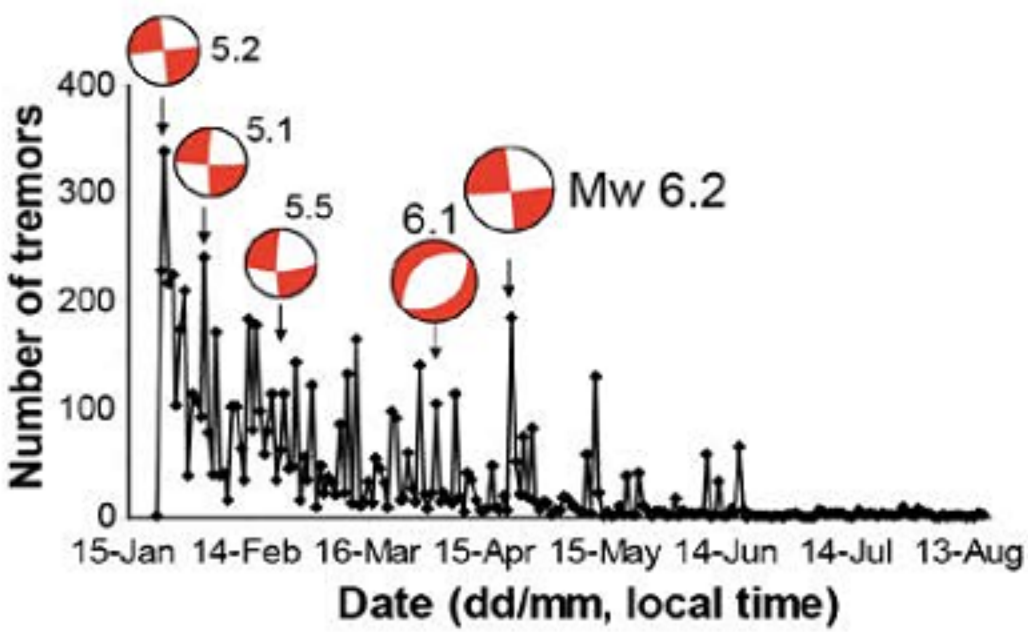
Arc tectonics control on volcanism in Southern Andes: recent case-studies, the Aysén 2007 seismic swarm



The fluid-driven tectonic swarm of Aysen Fjord, Chile (2007) associated with two earthquakes (Mw=6.1 and Mw=6.2) within the Liquiñe-Ofqui Fault Zone

D. Legrand [a,*], S. Barrientos [a], K. Bataille [b], J. Cembrano [c], A. Pavez [a]

[a] Universidad de Chile, Departamento de Geofísica, Blanco Encalada 2002, Santiago, Chile
[b] Universidad de Concepción, Facultad de Ciencias Químicas, Departamento de Ciencias de la Tierra, Casilla 160-C, Concepción, Chile
[c] Pontificia Universidad Católica de Chile, Departamento de Ingeniería Estructural y Geotécnica, Vicuña Mackenna 4860, Santiago, Chile



High b-value (2.59) more typical of a fluid-related process

Legrand et al. (2010)

Arc tectonic controls on volcanism

Case-study: Chaitén 2008 eruption…only passive structural control?

LETTER

doi:10.1038/nature10541

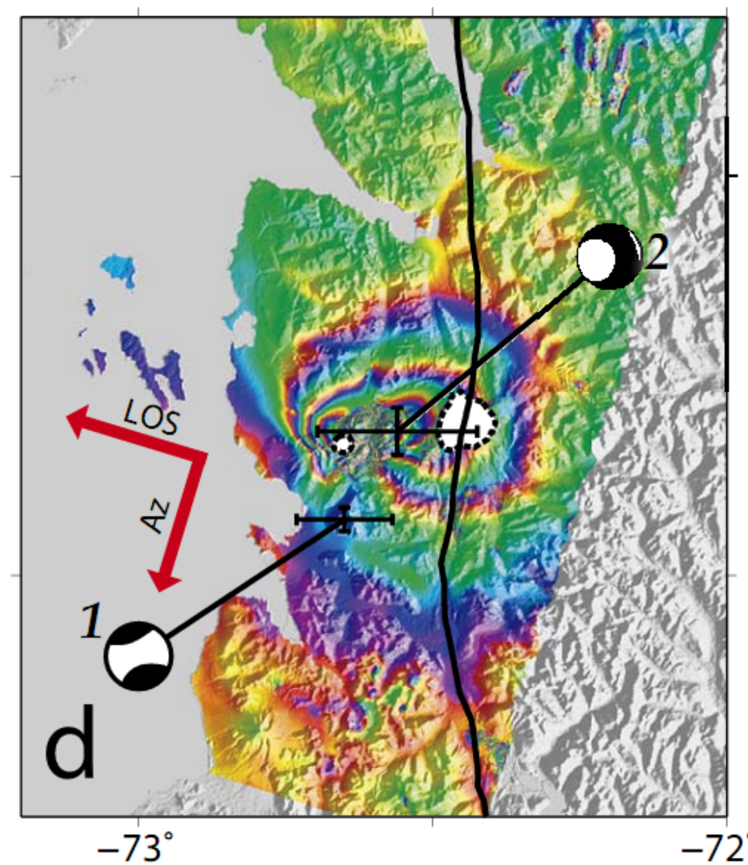
The role of dyking and fault control in the rapid onset of eruption at Chaitén volcano, Chile

Charles Wicks[1], Juan Carlos de la Llera[2], Luis E. Lara[3] & Jacob Lowenstern[1]

Rhyolite is the most viscous of liquid magmas, so it was surprising that on 2 May 2008 at Chaitén Volcano, located in Chile's southern Andean volcanic zone, rhyolitic magma migrated from more than 5 km depth in less than 4 hours (ref. 1) and erupted explosively with only two days of detected precursory seismic activity[2]. The last major rhyolite eruption before that at Chaitén was the largest volcanic eruption in the twentieth century, at Novarupta volcano, Alaska, in 1912. Because of the historically rare and explosive nature of rhyolite eruptions and because of the surprisingly short warning before the eruption of the Chaitén volcano, any information about the workings of the magmatic system at Chaitén, and rhyolitic systems in general, is important from both the scientific and hazard perspectives. Here we present surface deformation data related to the Chaitén eruption based on radar interferometry observations from the Japan Aerospace Exploration Agency (JAXA) DAICHI (ALOS) satellite. The data on this explosive rhyolite eruption indicate that the rapid ascent of rhyolite occurred through dyking and that melt segregation and magma storage were controlled by existing faults.

Chaitén volcano is situated on a forearc sliver between the Chile–Peru subduction zone and the Liquiñe–Ofqui fault zone (LOFZ; Fig. 1). The LOFZ is a long-lived shear zone[3] that has accommodated transpressional (northward translational and eastward compressional) movement of the forearc sliver for at least the past ~4 Myr (refs 4, 5). Chaitén has a caldera roughly 3 km in diameter that is part of the Michimahuida–Chaitén volcanic complex (Fig. 1). The dacitic to basaltic Michimahuida volcano, located in the LOFZ about 15 km east of Chaitén, has a larger caldera about 8 km in diameter that probably formed in the Early Holocene and was subsequently filled by dacite and later basalt effusions[6].

Although the study area is heavily vegetated and the time intervals between acquisitions are long, the 23.6-cm wavelength of the radar instrument enabled us to calculate useful interferograms (Fig. 1b–d and Supplementary Figs 1 and 2). In 2010 JAXA acquired descending-

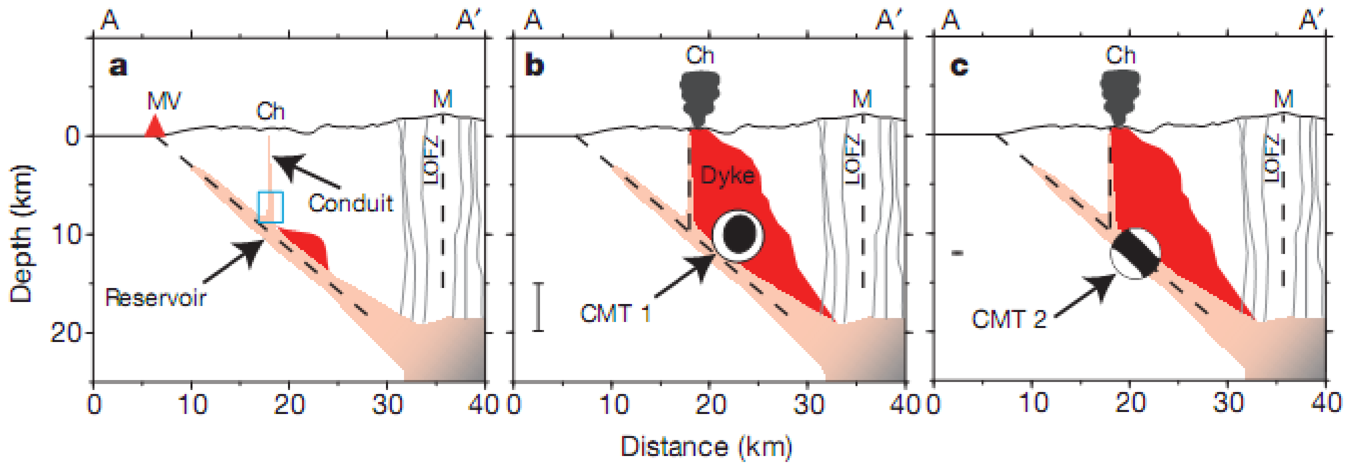


Wicks *et al*. (2011)

InSAR was combined with focal mechanisms (inverted from seismic waves) in order to propose a plausible explanation for such a rapid magma ascent (*ca*. 0.5 m/sec)

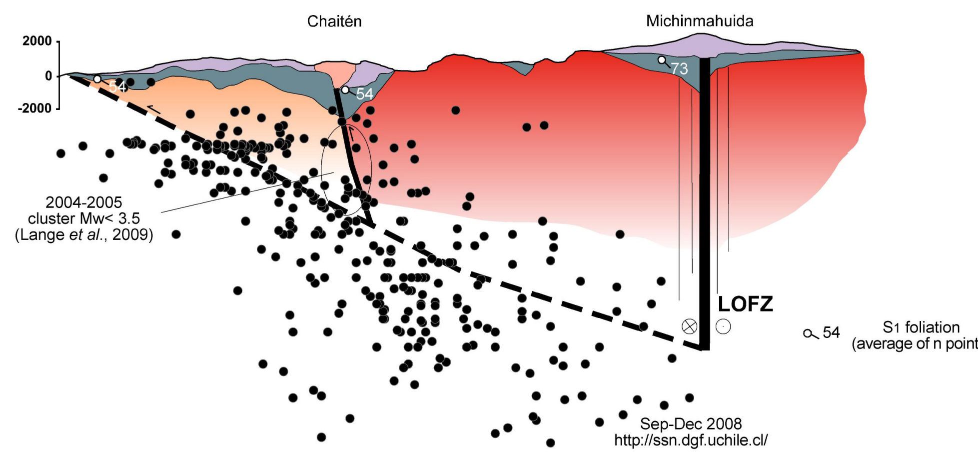
Arc tectonic controls on volcanism

Case-study: Chaitén 2008 eruption…only passive structural control?



Wicks et al. (2011)

Dike and reservoir nested in a 'pop up' structure of the LOFZ?...catalog of events seems to delineate this geometry



Piña-Gauthier *et al*. (2013)

For a complete overview of Chaitén 2008 eruption see the incoming special issue of Andean Geology journal at www.andeangeology.cl

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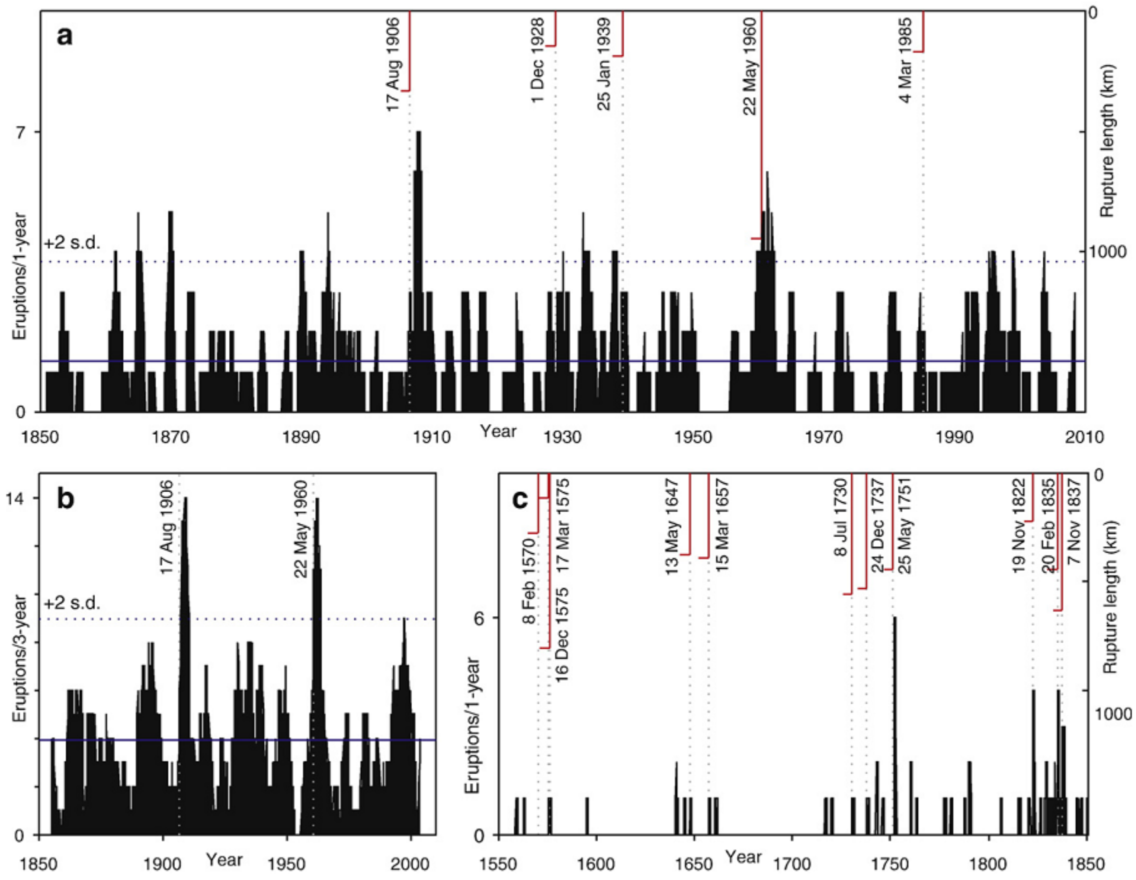
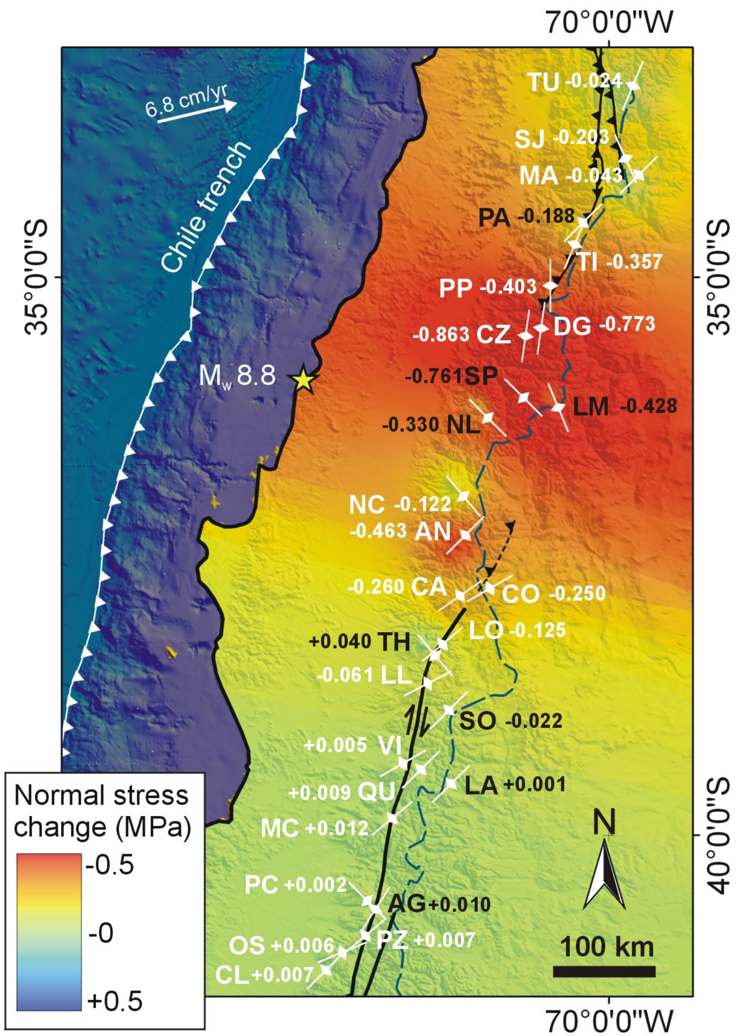
External controls on volcanism   Remote triggering

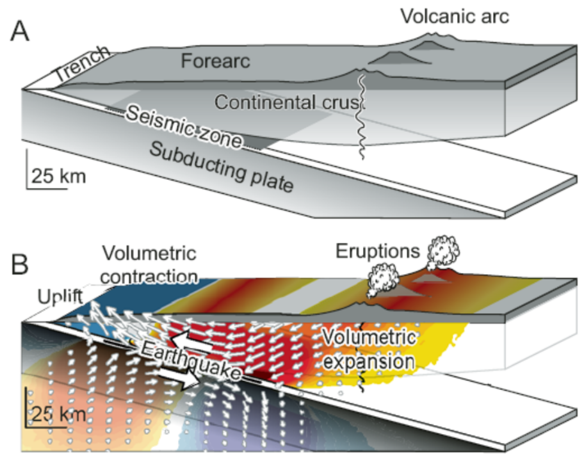


(Watt et al., 2009)

Eruptive frequency is *ca*. **1/yr** in Southern Andes, and seems to increase to **3-4/yr** after large subduction zone earthquakes

External controls on volcanism Remote triggering



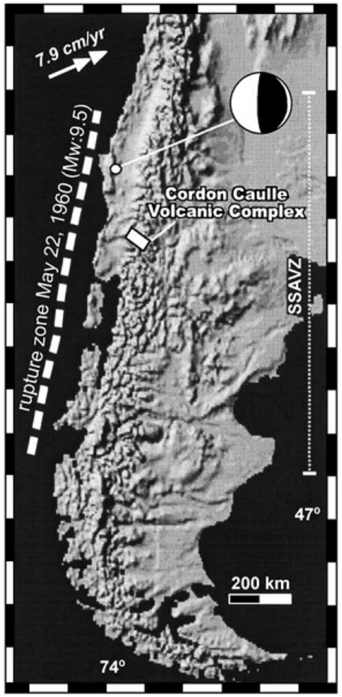


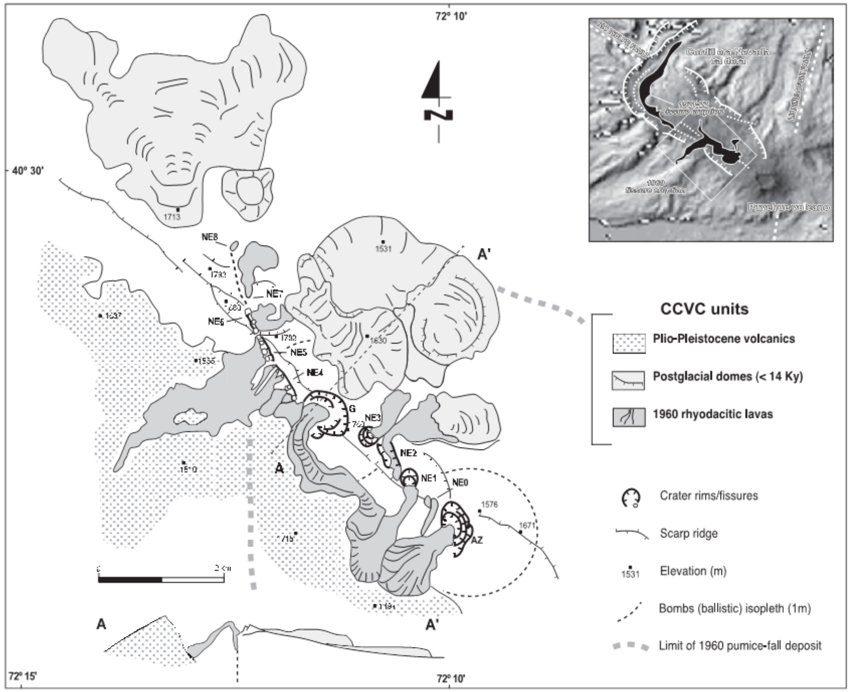
Walter and Amelung, 2007

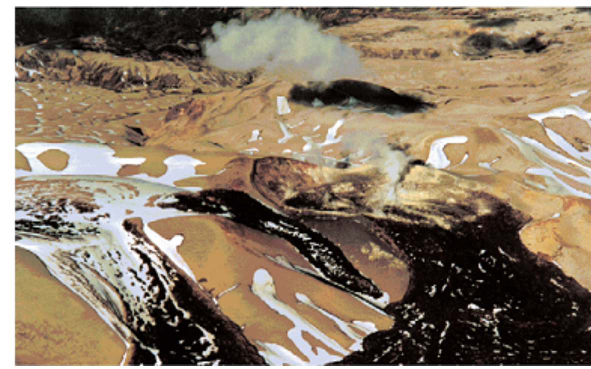
Coseismic volumetric expansion could works, but the effect depends also on the local structure (receiver fault-fracture network or plumbing system) so the specific 'unclamping' is important

Bonali et al., 2013,

External controls on volcanism Remote triggering



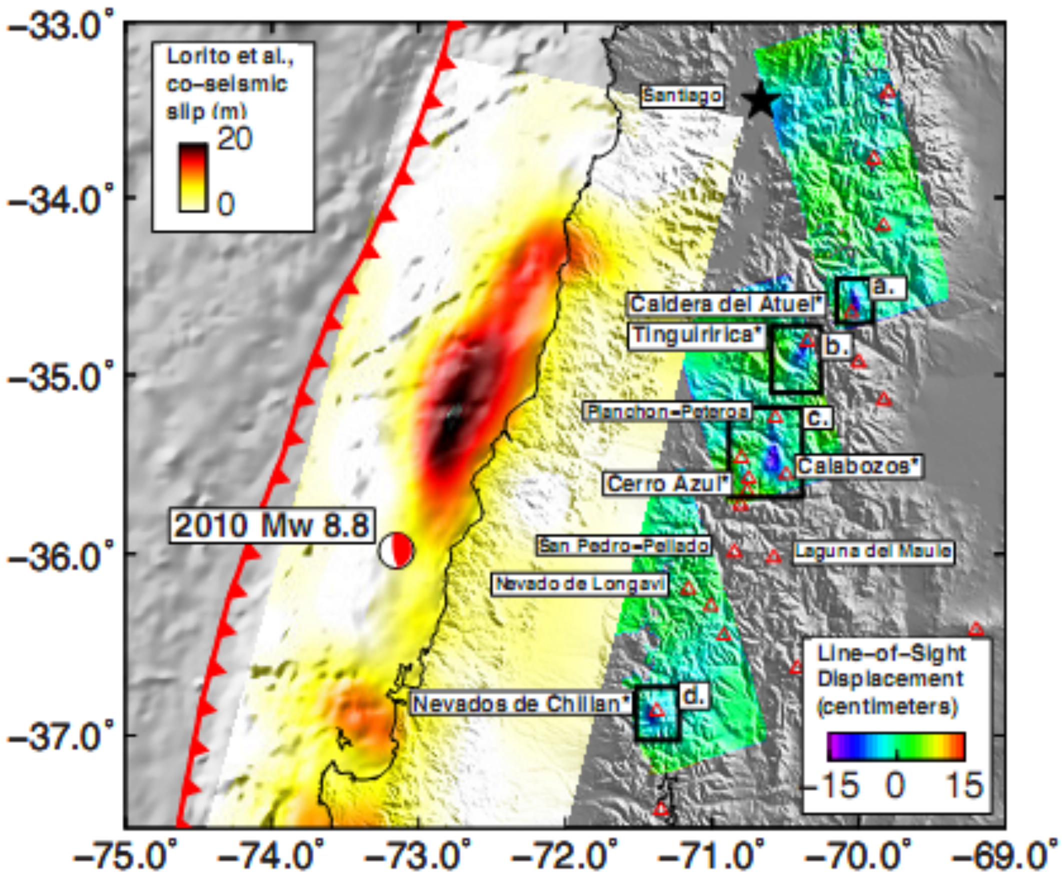


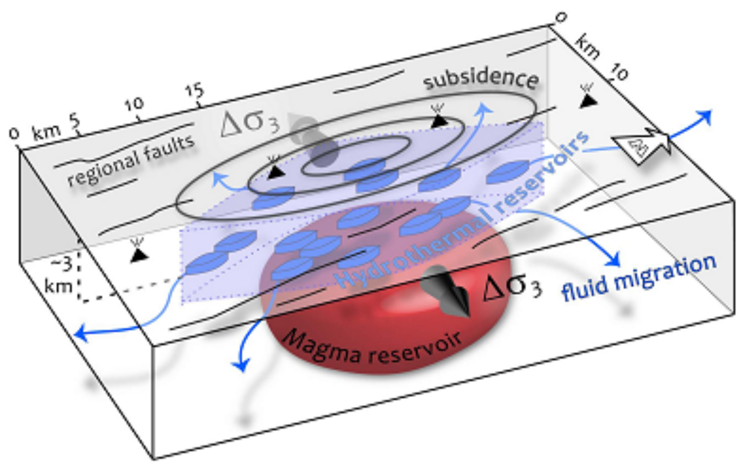


Lara et al., 2004

Cordón Caulle 1960 eruption is an archetypical example of remote triggering by subduction earthquakes. That time eruptive fissure evacuated rhyodacitic magma from a number of vents organized in two *en-échelon* alignments, which we interpreted as surface rupture due to the transfer of dynamic strain.

External controls on volcanism Remote triggering

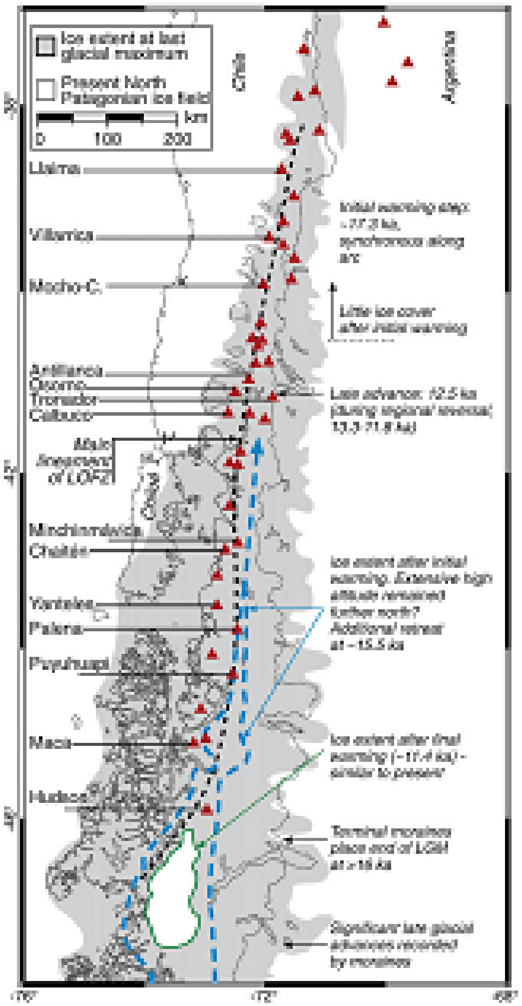


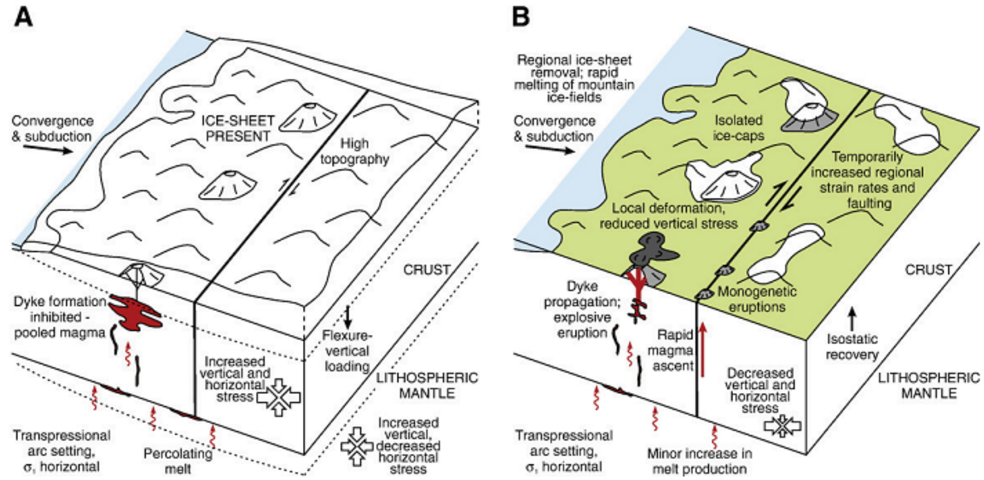


Pritchard et al., 2013

…but the effect is variable and some times related to hydrothermal system response. The Maule 2010 earthquake triggered multiple volcanoes to subside, but few (if any) to erupt (same as Japan)

External controls on volcanism Deglaciation

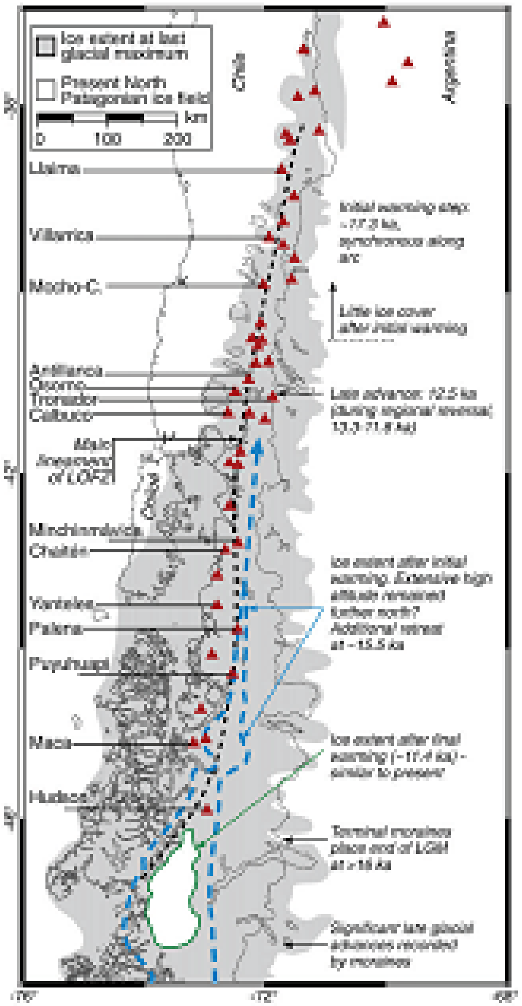




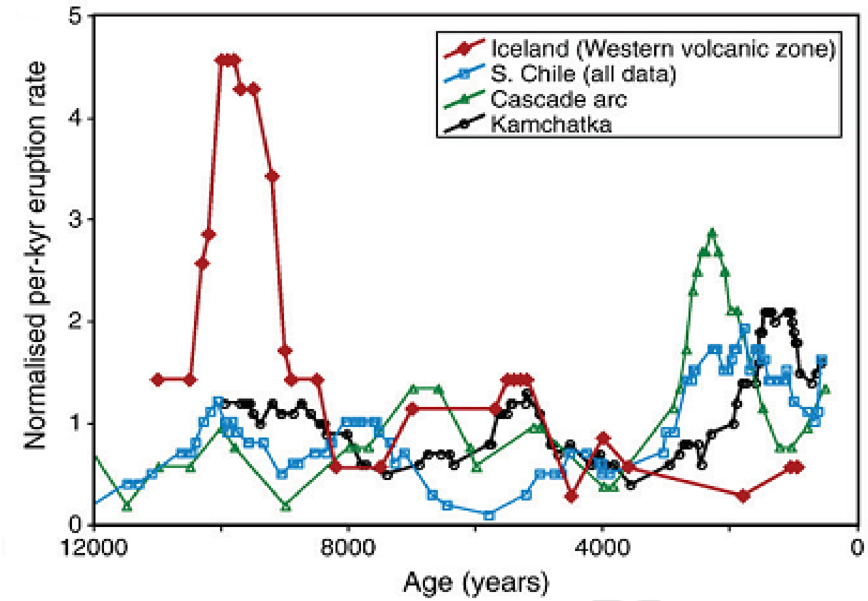
Watt et al., 2013

Rapid and massive ice retreat should decompress the upper crust and volcanic edifices triggering eruptions and seismic activity

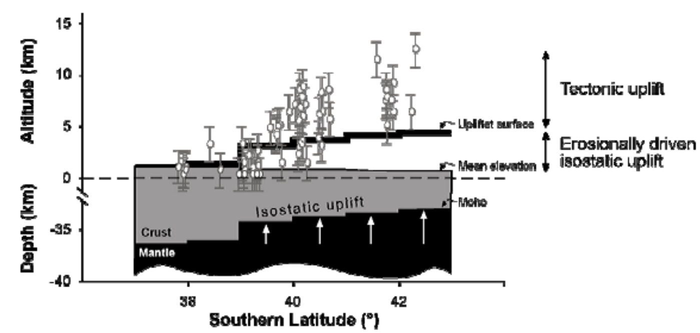
External controls on volcanism Deglaciation



Watt et al., 2013



But there is not significant correlation between deglaciation in Southern Andes (at regional scale) as do occur in Iceland. Exhumation and uplift rates are controlled by both tectonics and erosional processes



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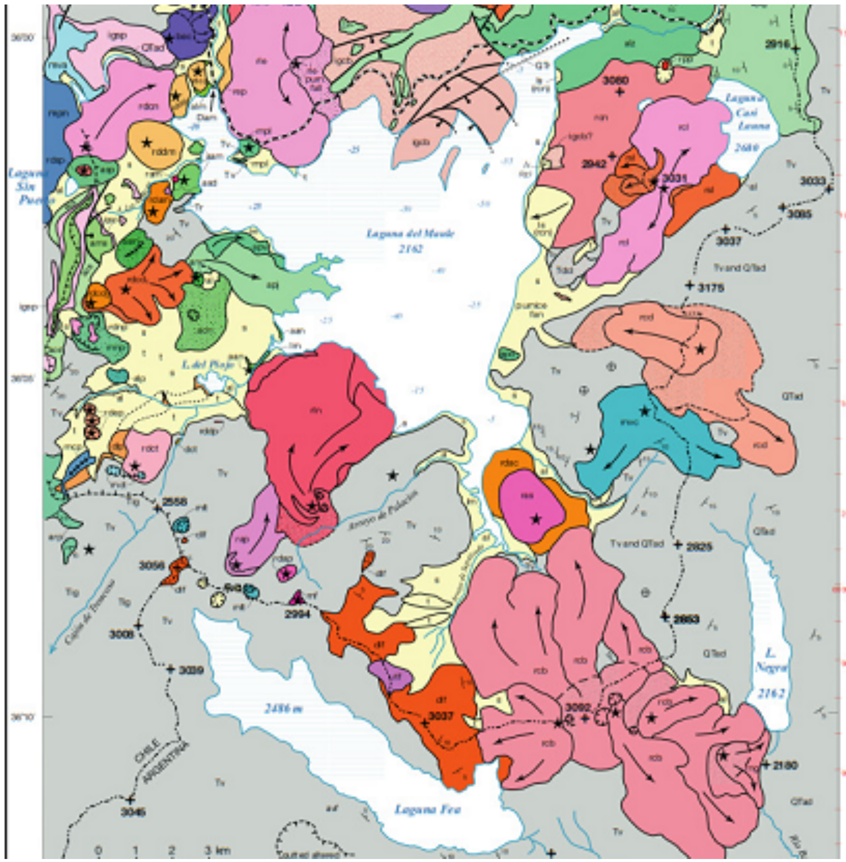
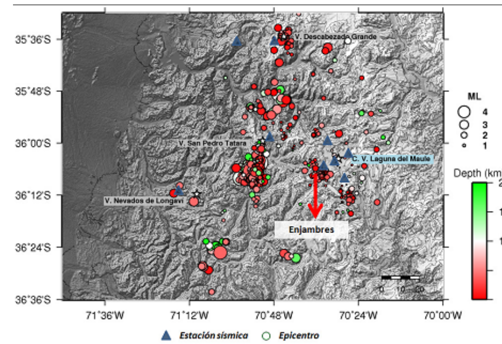
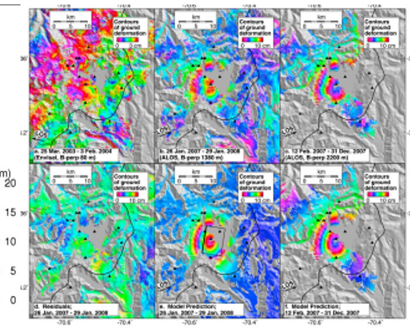
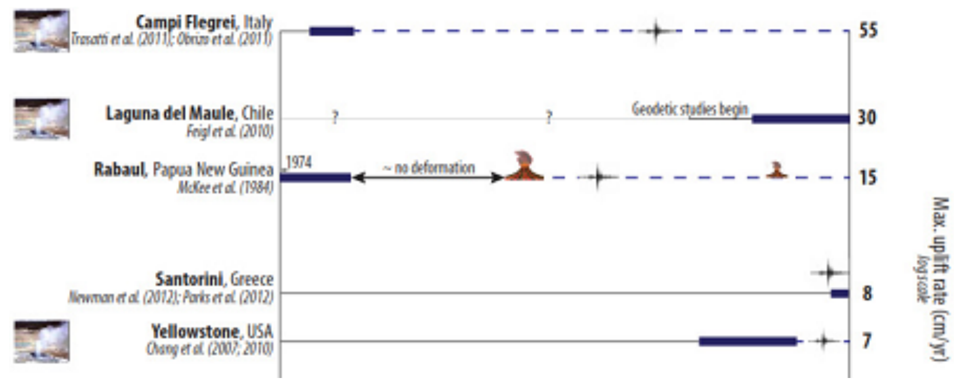
Summary and Conclusions Work in Progress





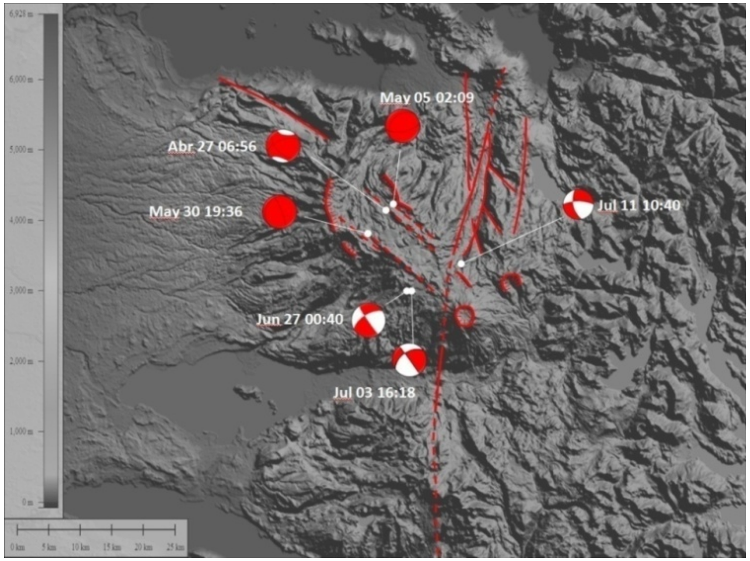


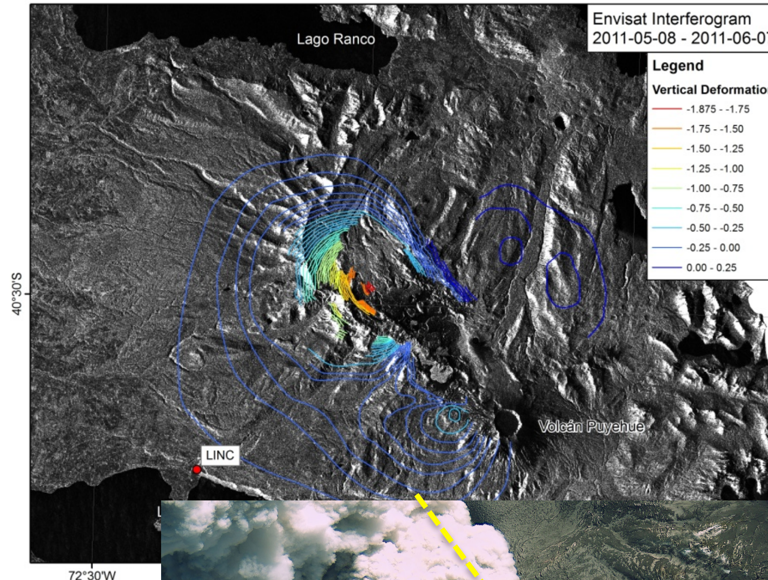


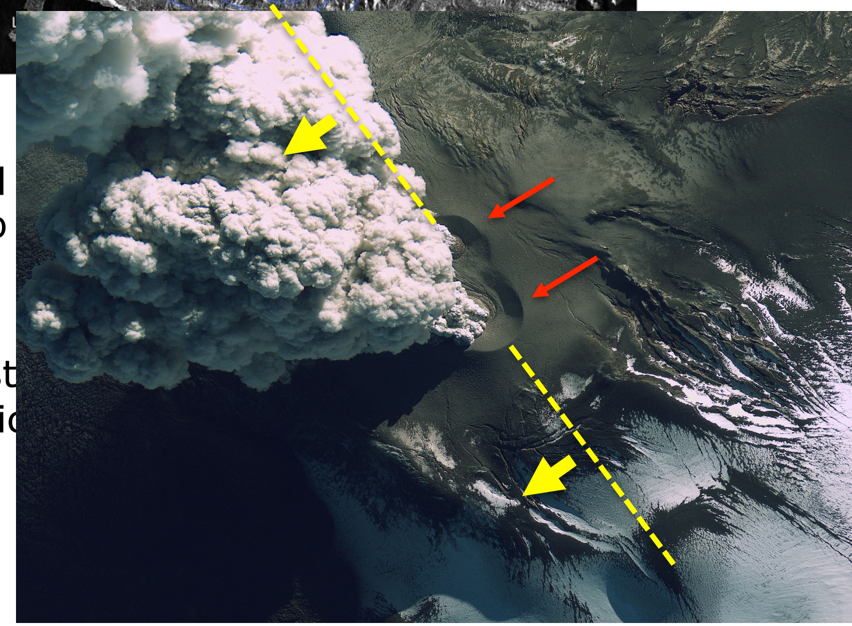
C. Cardona

Laguna del Maule world-class unrest process that seems to be very sensitive to both local and remote seismicity. Collaborative work of Sernageomin, Universidad de Concepcióna and University of Wisconsin-Madison

Summary and Conclusions Work in Progress



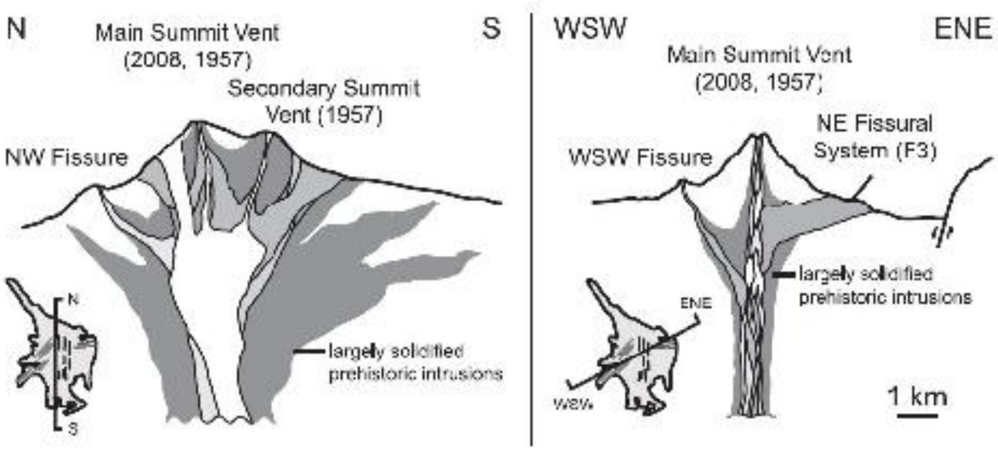




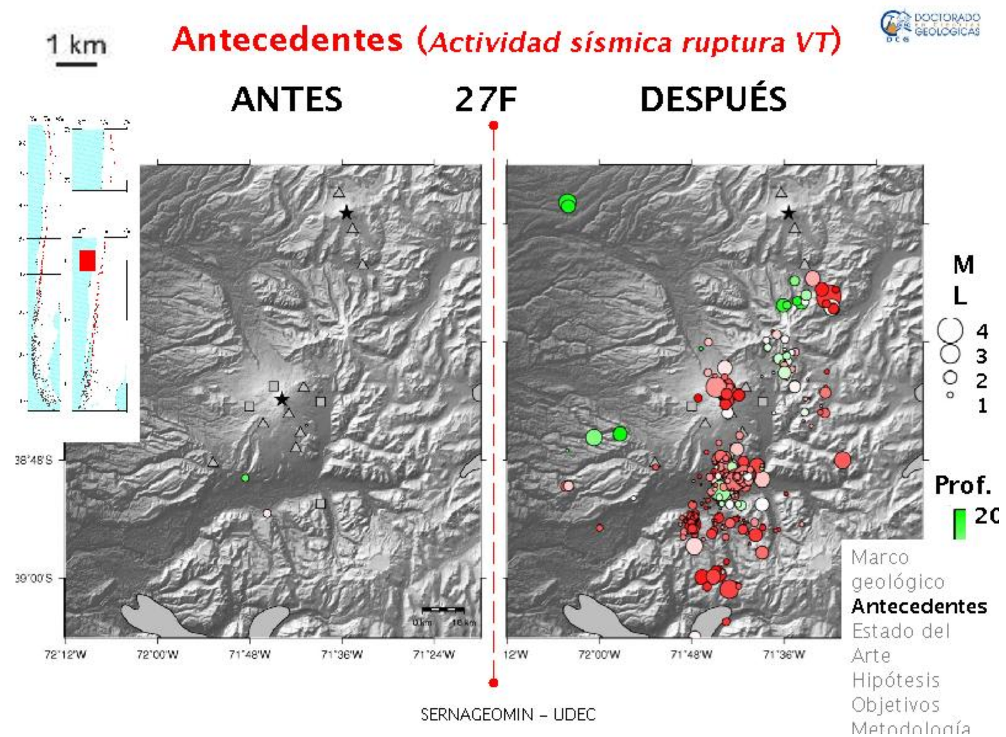
Puyehue- Cordón Caulle is a basement-coupled system related with ancient fault that seems to be very sensitive to remote triggering.

Ongoing deformation of the surrounding basement is related to the LOFZ, which suggest the subduction cycle is coupled with arc tectoni over different scales. Collaborative work with a number of groups.

Summary and Conclusions Work in Progress

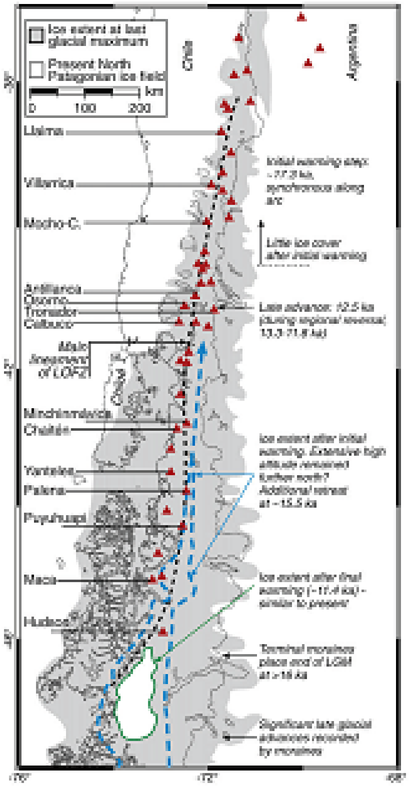


Llaima volcano is a kinematically-coupled volcano sensitive to arc tectonics. Crustal seismicity increased after the Maule 2010 earthquake but volcano seismicity and degassing suddenly decreased.



L. Franco

Summary and Conclusions Higlights



The SVZ (as CAVA) is natural lab to study interactions of tectonic and magmatic processes because of:

- Wide diversity of magmas
- Wide variety of volcanic landforms
- Very productive arc segment
- Strong coupled subduction zone
- Latitudinal variation of climatic forcing
- Growing geophysical network
- Growing scientific community in Earth Sciences

..and nice people to work with

Thank you for your atention

Gracias.

Gobierno de Chile

www.gob.cl