Tectonic Relief Basins – Andes Workshop
May 18th 2022
Presentations and discussions

Workshop

The South American Andes have for many years been one of the main study areas of researchers at ISTerre, and some people may ask what is left worth studying in the Andes today. For providing a clear answer to this question and to discuss current and future research efforts in and around the Andes, ranging from geodynamic question related to subduction style, the occurrence of serpentinites, mountain building, metamorphic events, foreland or forearc basin evolution, over resources, weathering, environmental geochemistry to natural hazards, surface processes, paleoclimate and biodiversity evolution, the TRB team of ISTerre is organizing a 1-day workshop May 18th 2022 (also accessible online via zoom) with contributions from students and researchers at ISTerre and possibly other laboratories and institutions.

Workshop organization

The objective is to provide an overview on our research activities in and around the Andes via **15-minute presentations followed by 5 minutes** for immediate discussions. At the end 30 minutes will be for further **round table discussions**.

Zoom link:
Topic: Tectonics Relief Basins Andes Workshop
Time: May 18th 2022 10:00 AM Grenoble
Join Zoom Meeting
https://univ-grenoble-alpes-fr.zoom.us/j/92362273834?pwd=RWdsTjI0MHRkL20veFUyMFE5NDUyQT09

Meeting ID: 923 6227 3834
Passcode: 583369

Program:

Wednesday 18th of May 2022 (room Dolomieu)

10:00 – 10:10 Introduction

10:10 – 10:30 *Martinod and Minon*, Magmatism, tectonics, and chronology of the Andean uplift

10:30 – 10:50 *Tobon-Lopez et al.*, Seismogenic sources for PSHA in NW South America: A preliminary zonation for PSHA in Colombia

10:50 – 11:10 *Bernet et al.*, Thermal history and exhumation of the Serranía de San Lucas, Central Andes, Colombia

11:10 – 11:30 *Marconato et al.*, Active tectonics in Ecuador: study of a major crustal fault system through multi-sensor InSAR time-series analysis, geomorphology and paleoseismology

11:30 – 11:50 *Round table discussion*

Lunch break

14:00 – 14:05 Introduction

14:05 – 14:25 *Lovery et al.*, Interseismic Coupling on the South Peru Subduction Zone

14:25 – 14:45 *Gerard et al.*, Insights into the tectonic and geomorphologic evolution of the Abancay Deflection from a low-temperature thermochronologic transect in the Machu Picchu batholith (southern Peru)

14:45 – 15:05 *Lacroix et al.,* Short-term (~10 yr) vs long-term (~Myr) landslide triggering in the Siguas and Vitor valleys, Peru

10 minutes pause

15:15 – 15:35 *Muller et al.*, Orographic forcing on the location of volcanic arcs

15:35 – 15:55 Vasallo, et al., Active tectonics in Tierra del Fuego: Fault-glacier interaction

15:55 – 16:15 *Cressaux et al.*, Modelling the post-seismic deformations measured by GNSS and InSAR, following the 2014 Iquique earthquake, Chile

16:15 – 16:45 Round table discussion and closure of the workshop

Magmatisme, tectonique, et chronologie du soulèvement des Andes

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La compilation des âges du magmatisme d'arc dans les Andes depuis le Crétacé supérieur met en évidence des périodes d'extinction du volcanisme andin qui durent dans certains secteurs plusieurs dizaines de Ma. Ces événements résultent souvent de l'horizontalisation de la plaque plongeante sous le continent sud-américain. On observe que l'apparition des épisodes de subduction horizontale est corrélée à la subduction de rides asismiques (plateaux océaniques) et peut donc s'expliquer par la flottabilité de la plaque plongeante.

Les épisodes de subduction horizontale entrainent une migration de la zone de raccourcissement vers l'intérieur du continent, loin de la fosse de subduction et conduisent à l'élargissement de la chaîne andine. Ces données montrent donc que la dynamique de la subduction océanique, très variable d'un secteur à l'autre des Andes, explique en grande partie la segmentation andine et le diachronisme de l'élargissement de la chaîne. L'apparition ou l'absence de segments de subductions horizontales est un mécanisme essentiel qui explique la largeur actuelle de la chaîne, à toutes les latitudes. Ces résultats impliquent que l'augmentation d'altitude et de largeur des Andes ne suit pas un schéma simple de croissance symétrique vers le nord et vers le sud à partir de l'orocline bolivien, mais qu'il s'agit d'un phénomène moins régulier dans l'espace et dans le temps.

The compilation of the ages of arc magmatism in the Andes since the Late Cretaceous highlights periods of extinction of Andean volcanism that last in some areas several tens of Ma. These events often result from the horizontalization of the plunging plate under the South American continent. We observe that the appearance of horizontal subduction episodes is correlated to the subduction of aseismic ridges (oceanic plateaus) and can therefore be explained by the buoyancy of the plunging plate.

Horizontal subduction episodes cause a migration of the shortening zone towards the interior of the continent, far from the subduction trough and lead to the enlargement of the Andean chain. These data show that the dynamics of oceanic subduction, which is very variable from one sector of the Andes to another, largely explains the Andean segmentation and the diachronism of the chain's enlargement. The appearance or absence of horizontal subduction segments is a key mechanism that explains the current width of the chain at all latitudes. These results imply that the increase in altitude and width of the Andes does not follow a simple pattern of symmetrical northward and southward growth from the Bolivian orocline, but is a less regular phenomenon in space and time.

Seismogenic sources for PSHA in NW South America: A preliminary zonation for PSHA in Colombia

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Colombia is located in the North Andes, one of the most tectonically complex areas of South America. The long-term interaction of the Caribbean and Nazca plates with the South American margin has accumulated significant internal deformation within the crust, along plate boundaries and crustal faults. This region is underlain by Caribbean slab to the southwest and the Nazca slab to the east, as shown by numerous studies that document the plate complexity in the region (Pindell and Dewey, 1982; Mann and Corrigan, 1990; Kellogg et al., 1995; Taboada et al., 2000; Trenkamp et al., 2002; Bezada et al., 2010; Chiarabba et al., 2016; Syracuse et al., 2016; Wagner et al., 2017, among others). While seismic hazard studies have been carried out at the country scale (Arcila et al., 2020), the increasing amount of available data coming from geophysical and geodetic studies brings the need of a review of such models each few years. Our work aims to produce an updated seismotectonic zonation and develop a source model for PSHA in northwestern South America, revisiting the current knowledge on regional seismotectonics.

Diverse seismologic, geologic, and geodetic studies highlight the tectonic complexity and diversity along the northwestern margin of the South American plate in Colombia. A careful analysis of all the integrated geological and seismological information allows us to identify seismogenic sources by observations on the GPS velocity field, stress/strain distribution, fault patterns and clustered seismicity (Camacho et al., 2010; Jouanne et al., 2011; Prieto et al., 2012; Nocquet et al., 2014; Gómez-Alba et al., 2016; Mora-Páez et al., 2019; Arcila and Muñoz-Martín, 2020). Area source zones have been delineated, establishing boundaries according to the data quality and seismotectonic relevance. We also compiled a variety of reverences in order to constrain the geometric extent of the seismogenic structures in depth (Monsalve-Jaramillo et al., 2018; Poveda et al., 2018; Londoño et al., 2019; Bishop et al., 2021; León et al., 2021).

We use the available active fault datasets published over the years (Audemard et al., 2000; Paris et al., 2000; Veloza et al., 2012; Costa et al., 2020) and the integrated seismic catalog (SGC, 2020), including historical events, from 1610 to 2020, to delineate source zones and propose alternatives for geometry and kinematics. We will identify, among all the active faults, the ones that show the surface expression of major tectonic boundaries from the ones that correspond to secondary crustal faults that distribute within and across identified areas. Crustal faults will include local active faults, major fracture zones, plate boundary limits and thrust-fault deformed belts. For subduction zones, we take into consideration the changes in the subduction angle and the presence of oceanic features along the trench. The reliability of the boundaries between the area and fault sources will eventually be assessed, so that further research can keep track of the uncertainties coming from the proposed seismotectonic zonation.

We plan to discuss and include recent datasets evidencing geological and seismological features controlling the segmentation, both for the subductions and the crustal faults (Ramos and Folguera, 2009; Velandia et al., 2020; McGirr et al., 2020; Wagner et al., 2020; León et al., 2021). Additionally, the presence of ancient faults that bound accreted terranes (Escalona and Mann, 2011; Mora-Bohórquez et al., 2017; León et al., 2018; Mora-Bohórquez et al., 2018; Montes et al., 2019) is also considered as the tectonic footprint of the sutures could allow such structures to be reactivated and thus enhance current seismic activity (Mora et al., 2006; Vinasco and Cordani, 2012; Caballero et al., 2013; Bayona et al., 2013; Jiménez et al., 2014; García-Delgado et al., 2021). The purpose of this research is to provide a robust seismotectonic boundary database, useful to incorporate active crustal faults into PSHA, as has been recently done for regions of high, moderate and low activity (Meletti et al., 2008; Baize et al., 2013; Yepes et al., 2016; Alvarado et al., 2017). Moreover, the harmonization of the data across country boundaries from Ecuador to Venezuela and Panama will be a key perspective to consistently integrate relevant tectonic features, from local to continental scale.

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Thermal history and exhumation of the Serranía de San Lucas, Central Andes, Colombia

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The Northern Andes of north-western South America consist of the Western, Central and Eastern Cordilleras of Colombia, including the Santander Massif and the Sierra Nevada de Santa Marta, and the Merída Andes of Venezuela (Fig. 1). Most of the mountain building in the Northern Andes occurred since the Late Cretaceous, because of plate convergence between and subduction of the Farallones/Nazca and Caribbean plates beneath the South America plate, accretion of oceanic terrains, block rotation, and collision of the Panama-Chocó block with South America (e.g. Cediel, 2003). In contrast to other mountain belts, such as the European Alps or the Himalayas, where magmatism is negligible, the Northern Andes of Colombia are characterized by several episodes of magmatic activity in different areas at different times, since the Mesozoic. For example, evidence of wide-spread Late Triassic to Early Jurassic arc magmatism can be found in the Central Cordillera, Santander Massif and the Sierra Nevada de Santa Marta (Lopéz-Isaza and Zuluaga, 2020). Furthermore, there is evidence of Late Cretaceous intrusions such as the Antioquia batholith in the Central Cordillera (Restrepo-Moreno, 2007; Ibañez et al., 2007; Ordoñez et al., 2010; Leal-Mejía, 2011; Villagómez et al., 2011), the Eocene plutonism in the Sierra Nevada de Santa Marta (e.g. Piraquive 2017), the late Miocene Combia Formation volcanism in the Amagá basin between the Western and Central Cordilleras (e.g. Marín-Ceron et al., 2019; Bernet et al., 2020), the Pliocene-Pleistocene magmatism of the Paipa-Iza complex in the Eastern Cordillera (Bernet et al., 2016), and the present-day volcanism in the Central Cordillera (Marín-Ceron et al., 2019).

The basement of the Central and Eastern Cordilleras of the Northern Andes is made up of Precambrian and Paleozoic crystalline rocks and Late Triassic to Early Jurassic magmatic arc rocks, which are in some areas overlain by Late Jurassic, Cretaceous and Tertiary sedimentary cover rocks. Plutonic, volcanic and volcanoclastic rocks of the Early Jurassic Noreán Formation and sedimentary rocks of the Late Jurassic Arenal Formation are exposed on the eastern flank of the Serranía de San Lucas to the north-east of the Central Cordillera (Fig. 2). The Noreán Formation is related to the magmatic arc that existed during the Late Triassic to Early Jurassic along the western margin of South America (Lopéz-Isaza and Zuluaga, 2020). Constraining the post-magmatic thermal history and the timing of exhumation of the Serranía de San Lucas rocks provides valuable information for discussing the regional tectonic evolution of this part of the Central Cordillera with respect to the rest of the Central Cordillera, the Santander Massif to the east and the Sierra Nevada de Santa Marta to the north.

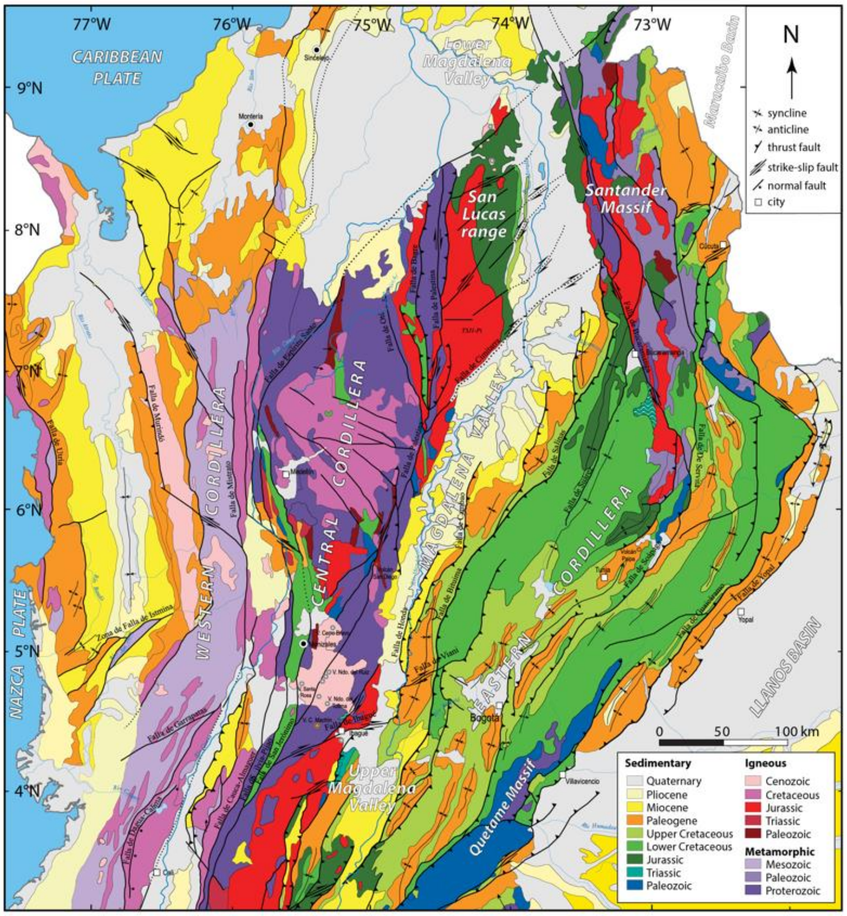

Fig. 1 Simplified geological map of the Central and Eastern Cordillera and the Santander Massif of Colombia (modified from Horton et al. 2015).

The Serranía de San Lucas has so far received relatively little attention in thermochronological studies. Some apatite fission-track (AFT) and apatite (AHe) and zircon (ZHe) (U-Th)/He data have been published for the Serranía de San Lucas and surrounding areas by Caballero et al. (2013) and Gonzales et al. (2015). A few AFT ages are available for the northern Santander Massif from Shagam et al., (1984) and van der Lelji et al., (2016). We attempt to somewhat reduce this regional data gap by presenting a set of 11 apatite (AFT) and 12 zircon (ZFT) bedrock fission-track ages for the Serranía de San Lucas and one new AFT age for the northern Santander Massif. These new fission-track data are used for time-temperature (t-T) history modelling and they are interpreted in a regional context together with published thermochronological data of the Central and Eastern Cordilleras, the Santander Massif and the Sierra Nevada de Santa Marta.

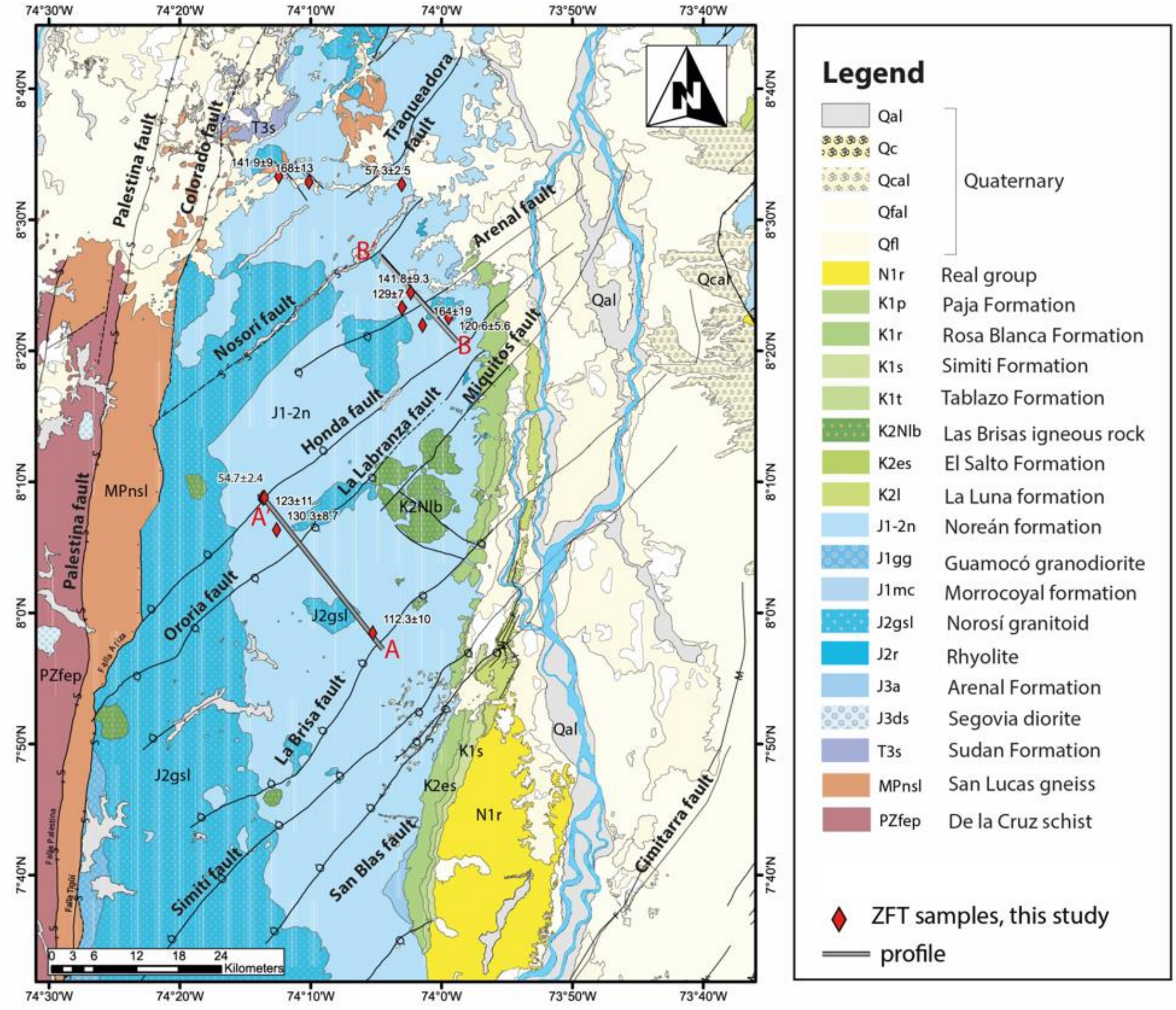

Fig. 2 Simplified geological map of the Serranía de San Lucas, with location on zircon fission-track samples. Fission-track ages are given in Ma with 2 sigma errors.

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Active tectonics in Ecuador: study of a major crustal fault system through multi-sensor InSAR time-series analysis, geomorphology and paleoseismology

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Tectonics of Ecuador is dominated by the subduction of the Nazca plate underneath the South American plate, at a convergence rate of 5 to 6 cm/year. Most of this convergence occurs at the subduction interface, producing regularly Mw7-8 earthquakes (5 in the last 50 years), however, a part of the convergence is accommodated by the north-eastward motion North-Andean sliver, by about 5-10 mm/year with respect to stable South America (*Nocquet et al., 2014*). This crustal strain is mainly localized along the large Chingual-Cosanga-Puna-Pallatanga (CCPP) fault zone. Crustal earthquakes with important magnitudes happened in this area in the historical period (*Beauval et al., 2010*), yet the associated source faults are either unknown or not much investigated. Recent results using block-modeling of GNSS data (*Jarrin 2021*) also raise important question about the partitioning and the localization of the deformation both inside and at the limits of the North-Andean sliver.

Therefore, this project, carried through the PhD of L. Marconato and the post-doc of N. Harrichhausen, aims to produce new observations constraining the geometry and kinematics of the deformation along the CCPP fault system, a critical task to improve seismic hazard assessment in Ecuador. To do so, we will use complementary approaches: InSAR analysis, paleoseismology and geomorphology.

Synthetic Aperture Radar Interferometry (InSAR) is now a widely used technique to monitor the deformation of Earth surface due to tectonic or other processes. The exponentially increasing amount of SAR data has been hardly used for tectonics purpose in Ecuador, because of vegetation, strong relief and ionosphere issues. We aim to study the CCPP fault system using InSAR time series analysis, potentially together with GNSS time series, in order to picture the surface deformation field along active faults. This study implies the use of SAR data from several satellites (Sentinel-1, ALOS-1, ALOS-2), and methodological developments in order to adapt the processing chain (NSBAS, *Doin et al., 2011*) to the local constraints. In particular, ionospheric perturbation can become the main source of noise in InSAR using L-band sensors in Equatorial regions. We thus implemented an ionospheric compensation module for ALOS-1 data to tackle this issue (*Gomba et al., 2015*).

This approach will be completed by the mapping of morphological evidence of the main active faults segments in the CCPP system and the digging of paleoseismological trenches. A global mapping of the potential active segments in the CCPP fault system has already been proposed (*Alvarado et al., 2012, 2016*), and the first paleoseismological and geomorphological study has been carried, uncovering evidence of several large (M7+) paleoearthquakes (*Baize et al., 2015, 2020*). However, several segments, such as the Latacunga-Quito segment still need to be explored in further detail. This will be done using new high-resolution DEMs produced from Pleiades images and through fieldwork to bring more detailed information in some key areas. InSAR results may also help to target the more suitable fault strands for field studies. Finally, paleoseismological trenching will allow to estimate the long-term loading rates on the fault system and to characterize potential past earthquakes on the fault system.

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Interseismic Coupling on the South Peru Subduction Zone

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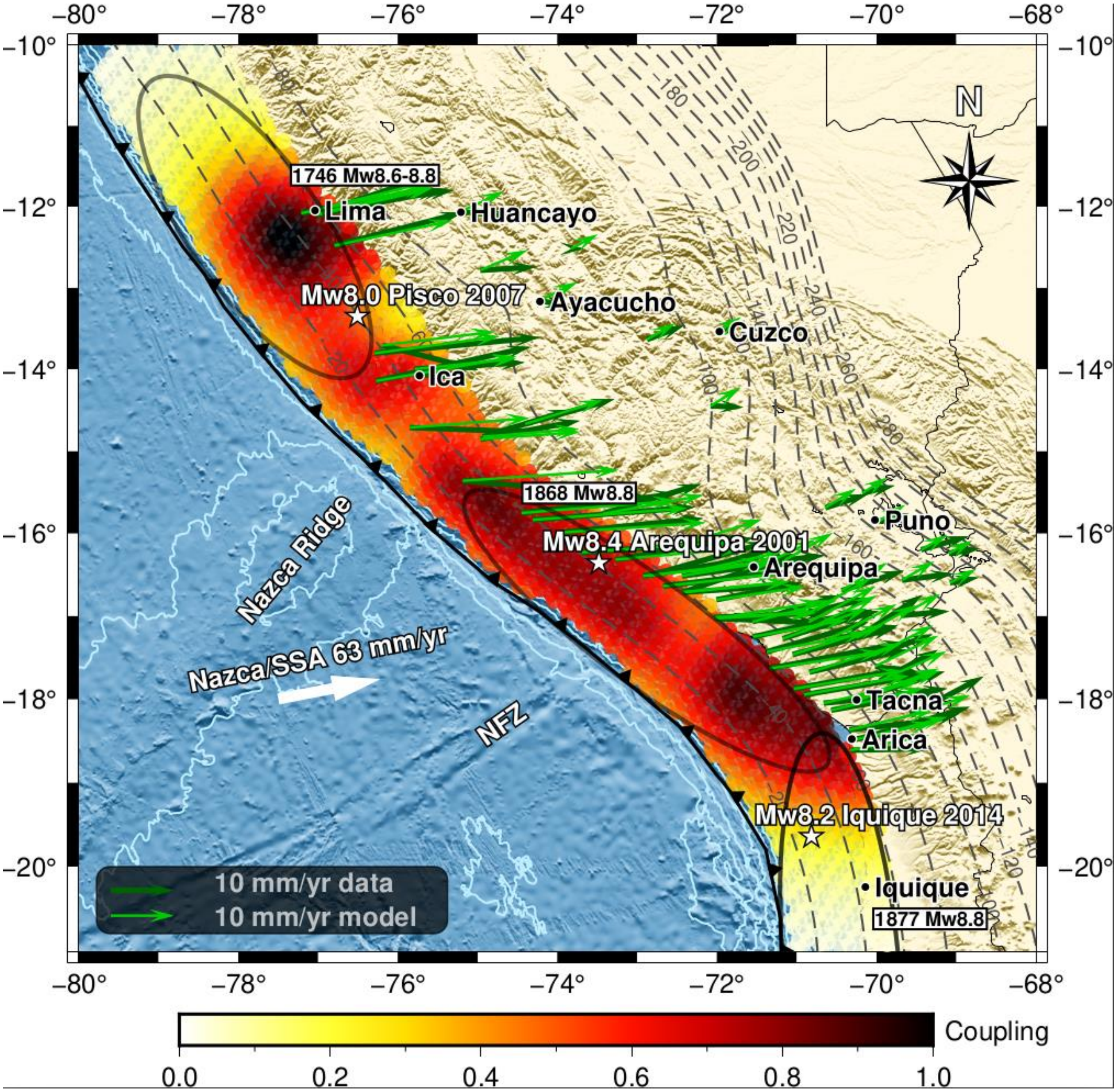
In this study, we focus on the interseismic coupling along the South Peru subduction zone that extent from Lima to Arica. This subduction zone between the Nazca and South American plates has been the theater of numerous great earthquakes like the one of Arequipa in 2001 with a moment magnitude Mw=8.4 or the one from Pisco in 2007 with a magnitude Mw=8.0.
A better knowledge of the interplate coupling distribution and seismic cycles in this area is thereby fundamental for improving the seismic hazard assessment. In this purpose, we dispose of new geodetic data covering more than a decade and acquired by fifty continuous GPS stations, as well as GPS campaigns on several years at thirty different locations. A detailed analysis of the trajectory model based on the approach of Bevis & Brown (2014) is applied to the GPS time series to isolate the average interseismic velocities during the last decade from seismic, postseismic and aseismic transients. Then, we inverted the GPS velocities using a least square regularization from the approach of Tarantola & Valette (1982). It provides us a detailed interseismic coupling map on the slab interface, that we put into perspective with instrumental and historical seismicity to realize a moment budget analysis. So, we seek to estimate the maximum magnitude of an upcoming earthquake, as well as its recurrence time.
This model, essentially based on GPS measurements, could henceforward be improved by integrating the InSAR time-series from the FLATSIM-Andes project, as
well as a more refine rheology through finite elements models.



Interseismic coupling distribution from our inversion of interseismic velocities in the Stable South America frame. The arrows represent the observed (dark green) and modeled (light green) GPS velocities. Approximate past earthquake rupture areas are depicted by ellipses. Slab contours (dashed lines) are reported every 20 km depth, from the Slab2 model (Hayes et al. 2018). The interseismic coupling is highly heterogeneous reflecting strong variations of the frictional properties of the slab interface. Thus, there are four highly-coupled areas: a very-highly coupled area close to Lima, a less highly-coupled area near Ica, a large band of high-coupling between the Nazca Ridge and the Nazca Fracture Zone, and a highly-coupled area between the Nazca Fracture Zone and the Arica bend. Discontinuities can be observed where the Nazca Ridge and the Nazca Fracture Zone are subducting bellow the South America plate. Finally, the total moment deficit on the slab interface is $4.46.10^{20}$ N.m/yr.

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Insights into the tectonic and geomorphologic evolution of the Abancay Deflection from a low-temperature thermochronologic transect in the Machu Picchu batholith (southern Peru)

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The Abancay Deflection, forming the northern edge of the Altiplano in the Peruvian Andes, is a remarkable geomorphic feature marking the along-strike segmentation of the Andes. It marks the transition from the southern and wide (~400 km) to the northern and narrower (~200 km) Andes. It also corresponds to one of the few Peruvian regions with >6000 m peaks (*e.g.* Nevado Salcantay, 6271 m) and carved by >2 km deep canyons (*e.g.* Apurimac and Urubamba rivers). But little is known about the timing and spatial distribution of exhumation in this remote area, nor its drivers.

To constrain the exhumation history of the Abancay Deflection, we present apatite and zircon (U-Th)/He (AHe & ZHe respectively) and fission-track (AFT & ZFT respectively) thermochronology data from samples collected along an elevation transect at Machu Picchu (222+/-7 Ma granite; Carlier et al., 1982). Most of the thermochronologic ages obtained are within a 2-8 Ma range, and the age-elevation profile shows a homogeneous trend between the different thermochronometers, indicating an apparent exhumation rate of ~0.9 km/Myr for the last 4 Ma. Thermochronologically derived cooling rates from apatite data are converted into exhumation using geothermal gradients between ∼16° and ∼26°C/km. Time-temperature inversions (QTQt; Gallagher, 2012) imply steady and slow exhumation (∼0.04 km/Myr) between 20 and 4 Ma, followed by rapid exhumation (∼1.1 km/Myr) since 4 Ma (Gérard et al., 2021).

ZFT data present ages older than those obtained with other thermochronological data, as usually expected, whereas the ZHe data interestingly present ages similar to those obtained with AHe, which is uncommon. It has been proposed that He retention in zircon is linked to the damage dose (total radiation damage that had accumulated in the crystal lattice, mostly due to α recoil), with an evolution of the closure temperature from low values associated with a low α-dose ($<10^{16}$ α/g), subsequently increasing before decreasing again at a very high α-dose ($>10^{18}$ α/g). Studies have focused on He diffusion behaviour at high α-doses (Gautheron et al., 2020; Guenthner, 2021), but little is known at low doses. We propose that the ZHe closure temperature at α-dose ranging from 6×10^{15} to 4×10^{16} α/g is in the range of ~60-80°C. This value is lower than the one proposed in the current damage model ZRDAAM (Guenthner, 2021) and demonstrates that the ZHe and AHe methods could have similar closure temperatures at low α-doses (*i.e.,* similar ages; Gérard et al., 2022).

The timing of rapid exhumation, combined with the geomorphic analysis (normalized steepness index (k_{sn}) and normalized integrated drainage area (χ) parameters), suggests that fluvial capture of the previously endorheic Altiplano by the Urubamba River drove recent and ongoing incision and exhumation. Depending on the value of the geothermal gradient used, total exhumation since 4 Ma can be explained by river incision alone (with a 26°C/km geotherm) or requires additional exhumation (with a 16°C/km geotherm) that must be driven by tectonics.

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Climate forcing on the erosion and fluvial transport processes in the western Peruvian Andes

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Erosion is a key parameter involved in the evolution of the Earth's surface, and regulates the coupling between climatic and tectonic processes. The quantification of erosion at different spatial and temporal scales is a major challenge in Earth sciences to better understand the nature and importance of these interactions. In addition, erosion processes are associated with significant natural hazards like landslides and debris flow. These relatively low-frequency but high-intensity events seem to play an important role in erosion budgets and in the long-term landscape evolution. The aim of this study is to understand the erosion processes associated with different types of fluvial deposits that correspond to different climatic conditions.

We focused on the ideal case of the western Peruvian Andes between Lima and Pisco (12°S and 13°S), where the hyper arid environment allows unequaled preservation of Pleistocene alluvial archives. This area presents several alluvial deposits including at least three mega-alluvial fans resulting from the upstream erosion of the western Andes and located at the outlet of the Rio Rimac in Lima, Rio Omas and Rio Cañete. These alluvial mega-deposits are mainly made up of rounded pebbles with a sandy matrix intercalated by sand layers (conglomeratic deposits) and levels of debris-flow deposits. Debris flow deposits are associated with high-intensity precipitation events, conglomeratic deposits are associated with relative humid conditions that experienced the western Peruvian Andes during the Pleistocene and modern river sand correspond to the erosion of the Andes under the nowadays arid conditions.

We measured the paleo-erosion rates using *in-situ* produced cosmogenic ^{10}Be concentrations in quartz and feldspar in the alluvial and debris flow deposits. Additionally, to obtain the chronological framework of the erosive events, we dated the deposits by ^{14}C of roots preserved on of the conglomeratic deposits and by Optically-Stimulated Luminescence (OSL).

Dating results show ages ranging from 10 to 90 ka and ^{10}Be results show that the measured paleo-erosion rates differ depending on the type of deposits and the source of the eroded material. In the fine angular grain debris-flow deposits, the paleo-erosion rates are of the same order of magnitude as the erosion rates measured in the current rivers, ranging from 10 to 100 mm/ka. However, paleo-erosion rates measured in conglomeratic deposits are ranging from 200 to 600 mm/ka and are therefore higher than the ones measured in both modern river sands and any debris-flow deposits.

Short-term (~10 yr) vs long-term (~Myr) landslide triggering in the Siguas and Vitor valleys, Peru

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The valleys of Siguas and Vitor are incisions of almost 200m depth throughout the Miocene conglomerate and sediment filling the Central Depression in South Peru in a currently desertic environment. Since the 1950's, large agricultural projects on the surrounding plateaus have been developed, accompanied by irrigation canals diverting rivers from the higher Andes. This intensive irrigation triggers and re-activates giant landslides (~10-100Mm3) on the flanks of those valleys. Their rates of motion reach several m/yr, with retrogressive movements, that pose a risk both for the populations below and on the plateaus. These landslides are monitored by kinematic measurements (satellite and GPS, Lacroix et al., 2019, 2020), as well as by piezometric measurements (Graber et al., 2021).

On the non-irrigated side of the valleys, other mega (>km3), but inactive, landslides are observed (Hermanns et al., 2012; Delgado et al., accepted). They are of the same typology as the ones re-activated by the anthropogenic irrigation. Several internal ruptures can be observed on Google Earth, suggesting past activities over a long period of time. Moreover, possible relics of paleo-lake sediments that are trapped behind the slide-masses strongly suggest that those paleo-landslides were active during a very different climate than nowadays, possibly under the same hydro-geological conditions as produced by the current anthropogenic irrigation. However, their ages of onset as well as their timing of activity are unknown.

As a main idea, we think that those two case-studies (active and paleo- landslides) can feed each other. More specifically, the ideas of this project are (1) to use the monitoring of active landslides as well as the dating of paleo landslides to better understand the climatic conditions required to develop these mega landslides, and (2) to use the scenarios of mega landslide development to assess the possible evolution and thus the risk posed by the active landslides.

As this project is at an embryonic step, more than nice results, we will present you with nice ideas!

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Orographic forcing on the location of volcanic arcs

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Convergent orogens and volcanic arcs are the surface expression of tectonic processes involving subduction, magmatism, and lithospheric deformation (Gianni and Luján, 2021). Once in the surface, they interact with the atmospheric system being subject to different degrees of erosion, constituting a narrow link between geomorphology and climate (Valla *et al.*, 2011). At the same time, different orographic erosional gradients can also change the distribution of strain in the crust (Willett, 1999), and having the structures as preferential channels for fluid circulation (Reyes *et al.*, 2021), they can also change the paths for magma upwelling. Although the link between erosion and deformation is being well demonstrated empirically, and by analogue, analytical and numerical modeling (Willett, 1999), the role of erosion on affecting the magmatic paths, and consequently the location of a volcanic arc, is still overlooked.

The Southern Andes and the Cascadia Range constitute examples of ocean-continent convergent orogens with a magmatic arc active since at least the Miocene (Folguera and Ramos, 2011; Mullen *et al.*, 2018). They are located in the eastern continental margin of North and South America, respectively, acting as an orographic barrier to the Pacific westerly winds. Similarly, both orogens present a latitudinal climate gradient, in which current precipitation rates increase with latitude and at the western leeside of the belt (Fig. 1 a,c). Correspondent to this orographic effect, the topographic water divide is located far from the subduction trench where the precipitation rates are higher than 2 m/yr and glacial erosional processes dominates. The low-temperature thermochronological record on both orogens show higher erosion rates at the locus of enhanced precipitation, meaning that orography is likely a long-term effect since at least 7 Ma, corresponding to the beginning of Cenozoic glaciations (Reiners *et al.*, 2002; Thomson *et al.*, 2010). Regarding the current position of the Quaternary volcanoes, they are located around the topographic water divide where precipitation rates are low, and systematically shifted towards the west of it where precipitation and erosion rates are enhanced (Fig. 1). At the latitude of these erosion hotspots we compilate data of different isotopic systems that provide the emplacement ages of the magmatic arcs (Fig. 1 b,d), and show a magmatic migration towards the west since at least 12 Ma (Fig. 1). Having these orogens an stable tectonic configuration with approximated uniform plate's convergence rate and slab dip angles along the strike since at least the Miocene (Echaurren *et al.*, 2016; Long, 2016), but instead presenting different structural architectures and slab ages (Cembrano and Lara, 2009; Long, 2016), it lacks a clear and shared tectonic explanation for the magmatic migration towards the region of topographic unload due to orographic erosion.

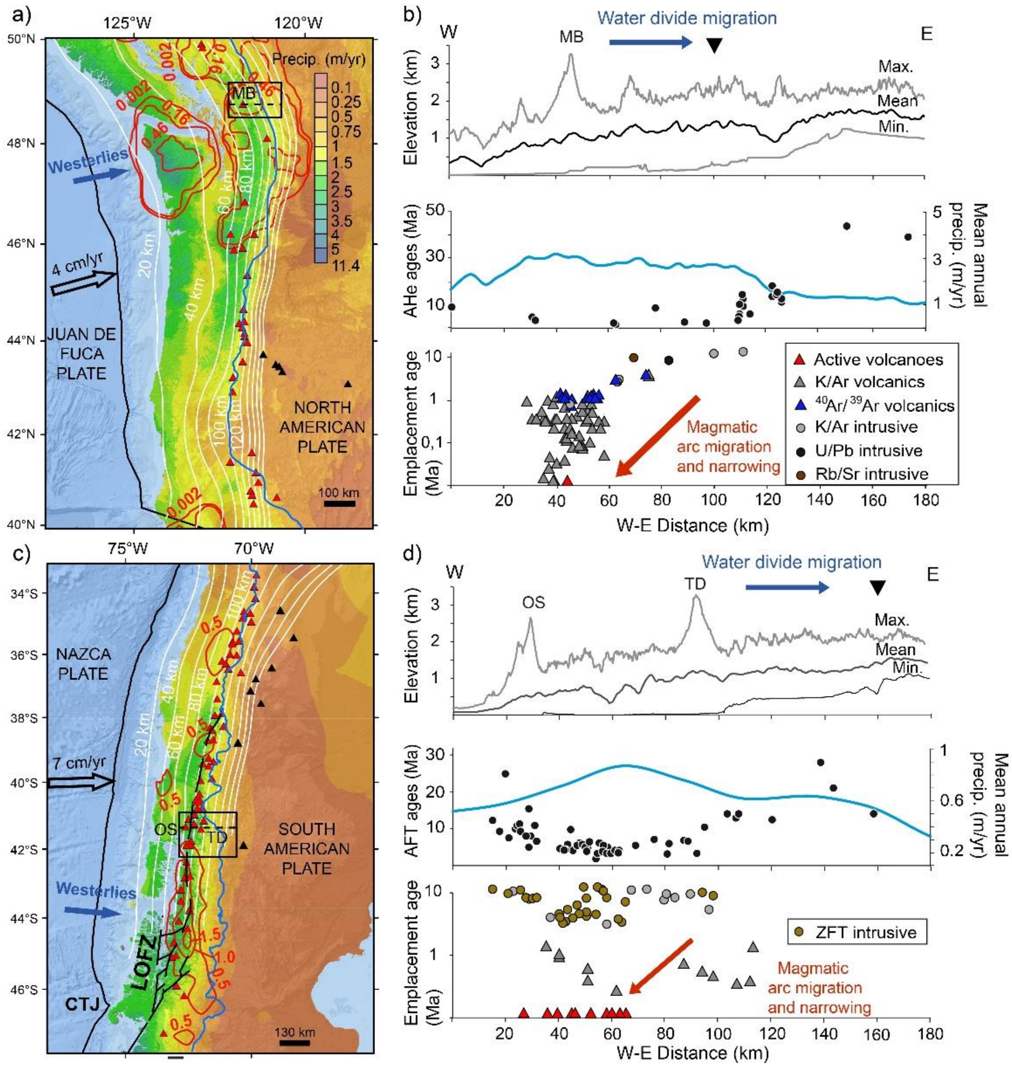

Fig. 1. Data compilation from the Cascade Range and the Southern Andes. (a, c) Maps of the Cascade Range and Southern Andes with mean annual precipitation, Quaternary volcanoes: red triangles – arc volcanoes; black triangles – within-plate volcanoes, convergence velocity, white isolines are isodepths of the top of the slab, red lines are the Quaternary exhumation rates, blue line is the topographic water divide, and black line is the subduction trench. The insets show where the thermochronological data plotted in (b, d) were compiled and the dashed lines show the location of the east-west profiles through the Mt. Baker (MB) in the Cascade Range, and Osorno (OS) and Tronador (TD) volcanoes in the Southern Andes. CTJ: Chile Triple Junction; LOFZ: Liquiñe-Ofqui Fault Zone. **(b, d)**. Top panels show the minimum, mean and maximum elevations (water divide location shown by black downward triangle). Central panels show the mean annual precipitation rates and apatite (U-Th)/He (AHe) and fission tracks (AFT) ages (Reiners *et al.*, 2002; Adriasola *et al.*, 2006; Thomson *et al.*, 2010; Simon-Labric *et al.*, 2014). Bottom panels show emplacement ages of intrusive and volcanic rocks (Tabor *et al.*, 1994; SERNAGEOMIN-BGRM, 1995; Lara *et al.*, 2001; Hildreth *et al.*, 2003; Mella *et al.*, 2005; Adriasola *et al.*, 2006).

To test the hypothesis of a climatic forcing on the location of volcanic arcs via orographic erosion, we use coupled thermo-mechanical (visco-elasto-plastic) geodynamic and stream power erosion numerical models based on the finite differences with marker-in-cell technique (Gerya, 2019). The model domain is 200 km wide and 120 km thick, subdivided mechanically into asthenosphere, lithospheric mantle, crust, and sticky air. A circular mantle melting zone (MMZ) of 20 km diameter is imposed in the center of the model domain at 100 km depth, and the upward transfer and emplacement of magma into the crust occurs by buoyancy through a 3 km wide magmatic channel. Three parameters were tested based on variations on the estimated thickness of the rheological layers in the two orogens (Tassara and Echaurren, 2012; Zhao and Hua, 2021): (1) crustal thickness (Ch) between 35 and 45 km; (2) thermal lithospheric thickness (Lh) between 90 and 100 km; and (3) initial depth of the magmatic channel upper tip (Dmc) between 15, 20 and 25 km. All parametric combinations were tested with an initial topography up to 2.5 km elevation at the center of the model domain (i.e., above the MMZ, Fig. 2 a), and we address the problem of orographic migration of topography in two ways: (1) changing the initial position of topography 60 km towards the right, with no imposed erosion (Fig. 2 b); and (2) imposing asymmetric erosion rates that are up to 20 times higher in the slopes facing left respect to the slopes facing right.

We look for the accumulated strain and magma upwelling into the crust and throughout the surface, in response to the emplacement of plutons at the base of the crust until the MMZ depletion (~0.3 Ma). In the first set of simulations, with no imposed erosion, when the topography is initially central the brittle-ductile structures that accommodate magma emplacement are symmetric respect to the MMZ, feeding volcanoes on both sides of the topography (Fig. 2 a). When topography is initially shifted right respect to the MMZ the brittle-ductile structures are asymmetric and right-dipping, feeding volcanoes at the left-side of the model domain (Fig. 2 b). A thin crust (Ch = 35 km) and a cold lithosphere (Lh = 100 km) facilitate the brittle strain, and with the initially lateral topography the asymmetry of strain and magma upwelling is enhanced. The Dmc controls mainly the efficiency of magma transfer towards the surface, and a deep Dmc (25 km) results in an inhibition of the brittle upper crustal structures and difficult magma rise, whereas a shallow Dmc (15 km) results in a very efficient magma transfer towards the surface. When the topography is initially lateral the asymmetry of the structures increases, feeding volcanoes up to 90 km to the left of the MMZ. In the second set of simulations, the initial central topography shifts progressively towards the right due to the imposed asymmetric erosion, whereas the strain is progressively shifted towards the left, forming two main right-dipping faults by which magma can upwell. The total asymmetry of the brittle-ductile system can reach 90 km to the left respect to the MMZ, thus agreeing with the results of the first set of simulations and the proposed hypothesis.

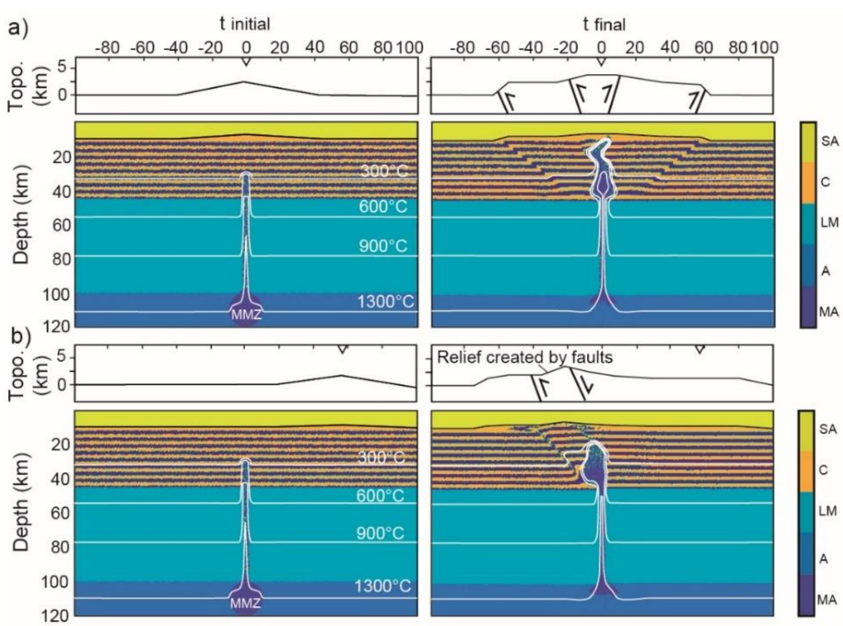

Fig. 2. Numerical outcomes of the first set of simulations (Ch = 35 km, Lh = 100 km, Dmc = 20 km). (a) Initial and final lithological and thermal distribution of the reference simulations with initial central topography, and (b) initial lateral topography. The color layering in the crust shows the deformation and the topographic profiles have 3x vertical exaggeration. SA – sticky air; C – crust; LM – lithospheric mantle; A – asthenosphere; MA – molten asthenosphere.

The westward migration of the magmatic arc in the Cascade Range is associated with a clockwise rotation of the Oregon block since the early Miocene (Wells and McCaffrey, 2013). In the Southern Andes, an arc narrowing towards the west is associated with the (re)activation of the strike-slip Liquiñe-Ofqui Fault Zone during the Pliocene, channelizing magmatism towards this region (e.g. Cembrano and Lara, 2009). Alternatively or jointly to this processes, slab steepening, acceleration of the plate's relative convergence, and increase of the geothermal gradient due to asthenospheric window opening are proposed explanations to the trench-ward magmatic migration in both volcanic arcs (Hildreth *et al.*, 2003; Folguera and Ramos, 2011; Wells and McCaffrey, 2013; Echaurren *et al.*, 2016; Mullen *et al.*, 2018). Therefore, there is no consensus about the first-order drivers for magmatic arc migration at these regions, and the available geological datasets seems to not be enough to find an unique solution to this problem. The orographic interaction with westerly Pacific winds (Fig. 1) and the mechanistic link between asymmetric erosion and crustal structures accommodating the magma upwelling paths (Fig. 2), instead, appears as a suitable along-strike forcing to drive the observed latitudinal trench-ward arc migration.

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Tectonique active en Terre de Feu : Interaction failles-glaciers

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Abstract text

Le système décrochant sénestre de failles Magellan-Fagnano constitue la frontière entre les plaques tectoniques Amérique du Sud et Scotia. Il prend naissance au niveau de la fosse de subduction chilienne, recoupe la Terre de Feu selon une direction approximativement E-W, et se poursuit dans l'Océan Atlantique en direction des îles de Géorgie du Sud (Figure 1). Il s'agit donc d'une limite entre plaques tectoniques majeures, qui recoupe l'île de Terre de Feu sur 200 km environ, en longeant le Lac Fagnano sur ~ 100 km.

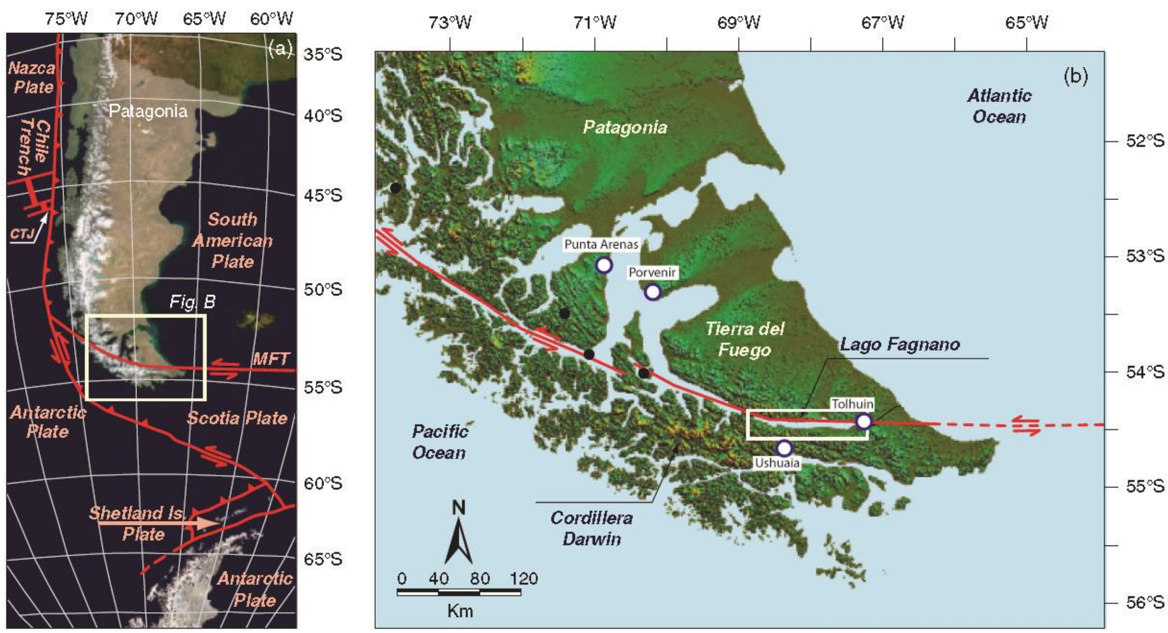

Figure 1 : *Tracé de la Faille de Magellan-Fagnano qui sépare les plaques Amérique du sud et Scotia (figure modifiée d'après Waldmann et al., 2011)*

L'étude de cette faille australe est intéressante à plusieurs titres :

- Il s'agit d'une des frontières de plaques dont la cinématique long-terme est la moins bien connue sur Terre. Le mouvement actuel de la plaque Scotia, en effet, n'est connu que grâce à un nombre restreint de points GPS, souvent situés en bordure de plaque dans des zones tectoniquement actives.
- Le cycle sismique sur la faille de Magellan-Fagnano et l'aléa associé restent à caractériser, en particulier dans le secteur chilien de la faille où aucun résultat n'a été publié à ce jour.
- La faille longe la Cordillère de Darwin, recouverte d'une calotte glaciaire dont l'étendue diminue rapidement. Il s'agit donc d'un secteur où caractériser et modéliser les liens entre les variations de contraintes associées aux changements climatiques (diminution de charge glaciaire, érosion) et la tectonique, tant pour la période actuelle que pour la fin de la dernière glaciation Pléistocène.

Nous présenterons ici les résultats majeurs obtenus sur la tectonique active de la faille, depuis l'échelle de temps de la déformation millénaire jusqu'aux séismes historiques des 2 derniers siècles (Figure 2).

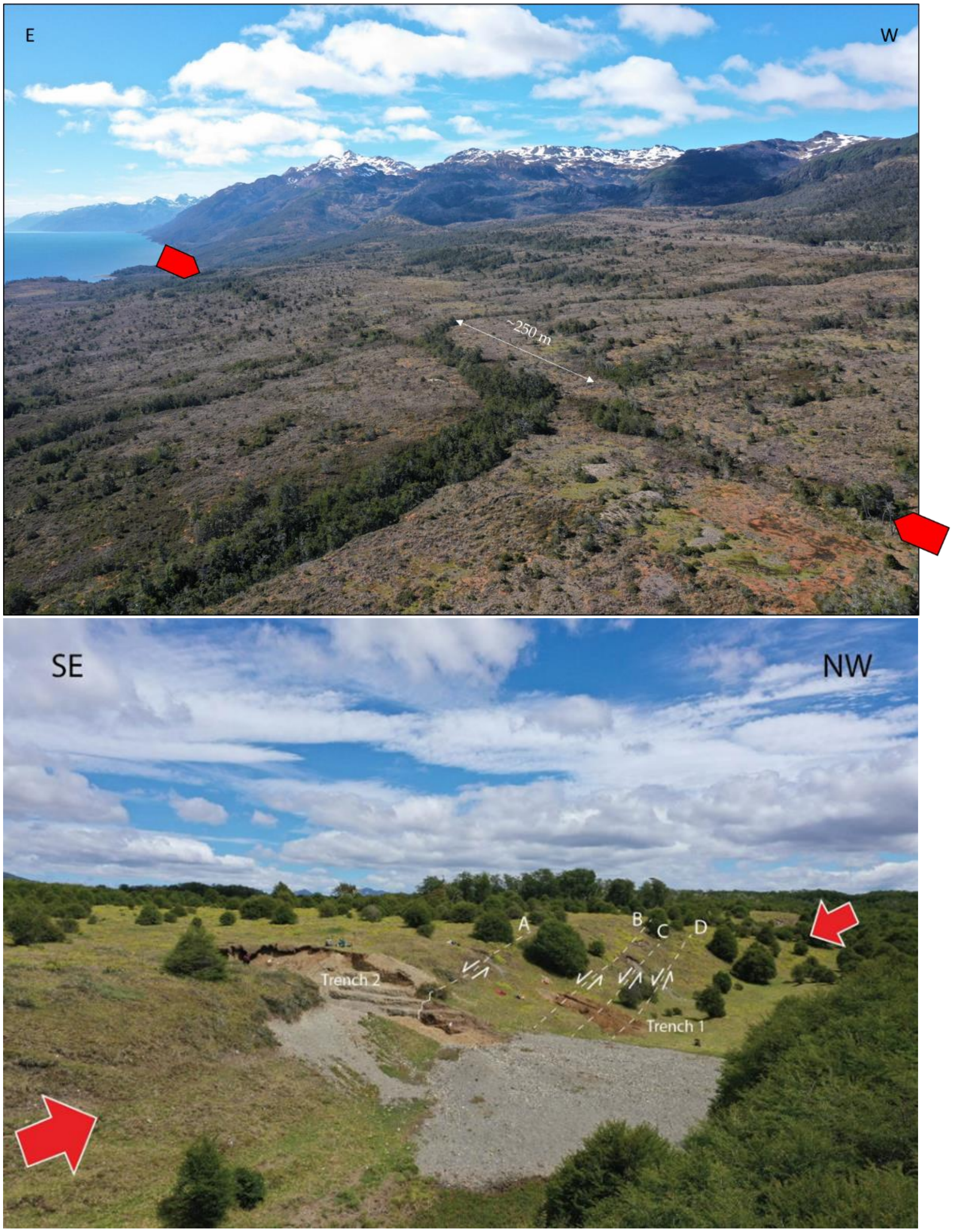

Figure 2 : La faille Magellan-Fagnano dans la morphologie : a) déformation senestre cumulée enregistrée par les cours d'eau décalés (Chili) ; b) déformation co-sismique holocène associée à des fractures de Riedel visibles en surface et en tranchée (Argentine).

Ensuite nous illustrerons les perspectives et les projets à moyen et long terme que nous souhaitons mener afin de répondre aux questions irrésolues ou soulevées par ces résultats. L'approche géologique et paléosismologique sera associée à la géodésie et à la dendrochronologie pour mieux comprendre et quantifier les processus en jeu sur différentes échelles de temps et d'espace.

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Modelling the post-seismic deformations measured by GNSS and InSAR, following the 2014 Iquique earthquake, Chile

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Large earthquakes are followed by a post-seismic period during which the stresses induced by the co-seismic phase are relaxed through different processes. This post-seismic phase participates to the redistributions of stresses in the earth, and understanding its mechanism is a key to understand interactions between earthquakes at different spatial and temporal scales. In subduction zones the most important terms are the afterslip and the visco-elastic relaxation. It is generally considered that the two mechanisms affect different spatial and temporal scales: the afterslip is prevalent the first months in the surrounding of the fault, while the visco-elastic relaxation process affects a larger area and lasts a longer time. The time-space pattern of the measured deformation can help to characterize the rheology of the underlying structure.
In this work we look at the processes involved after the Iquique earthquake.

To explore the processes driving the post-seismic deformation, we use a finite element model (FEM) (2D model, using the FEM software Pylith) that is constrained with InSAR and GNSS data. The GPS time series (processed with GipsyX) include 83 stations located in North Chile, Peru and Bolivia. The post-seismic signal is isolated using a trajectory model. The InSAR data consist in two Sentinel-1 time series (ascending and descending tracks) processed with the NSBAS chain, they include 514 and 1144 interferograms for the ascending and descending tracks respectively, starting 7 months after the earthquake up to the end of 2019. In the model we impose a co-seismic displacement on the plate interface, after checking that it fits the co-seismic displacements observed at the surface, we explore the influence of the structure and the rheology on the visco-elastic response. We then impose a time dependent afterslip sliding on the fault which we explore the parameters. The combination of these two models allows to constrain our model (structure, rheology and afterslip).

Our tests reveal that the viscosity in the continental and the oceanic mantle both have an impact on the displacement produced at the surface. The difference between these viscosities controls the movements allowed at depth. The crust thickness and the presence of a cold nose have a clear impact on the wavelength and the location of the maximum of amplitude, respectively. The uplift from 200 to 300 km from the trench shows the necessity of the visco-elastic process.
The afterslip is the major contribution at short term. The dip of the slab where the afterslip occurs controls the ratio of amplitude between near field and far field. The depth of the afterslip is control by the location of the maximum of amplitude on all the components. At longer term, this process explains the near field subsidence observed.
The temporal evolutions help to distinguish between the afterslip and visco-elastic and to explore the characterizing time of the visco-elastic relaxation. The short term clearly shows an afterslip decreasing. This one becomes no more sufficient at longer time requiring visco-elastic process.
We pointing out that these is a trade-off between the contribution of afterslip and visco-elastic relaxation.

The used of two times scale helps to separate the two processes. On the long-time period, both processes influence the surface displacements, however, the visco-elastic is preponderant on the ascending InSAR track and the afterslip on the descending one. The used of several datasets allows to strongly constrain the model and reduce the range of plausible models.

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