BOOKLET PhD STUDENT CONGRESS

14, 15 & 16 JUNE 2023

Chambéry ~ Le-Bourget-du-Lac

ISTerre

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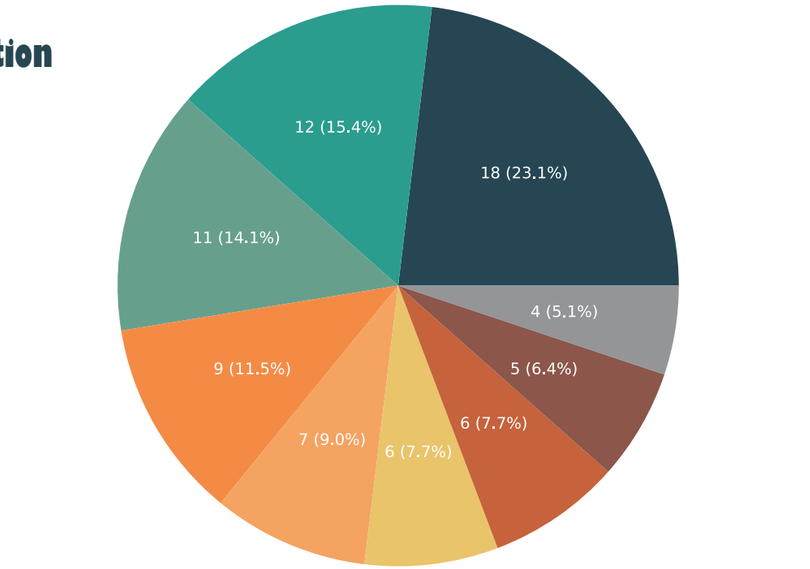
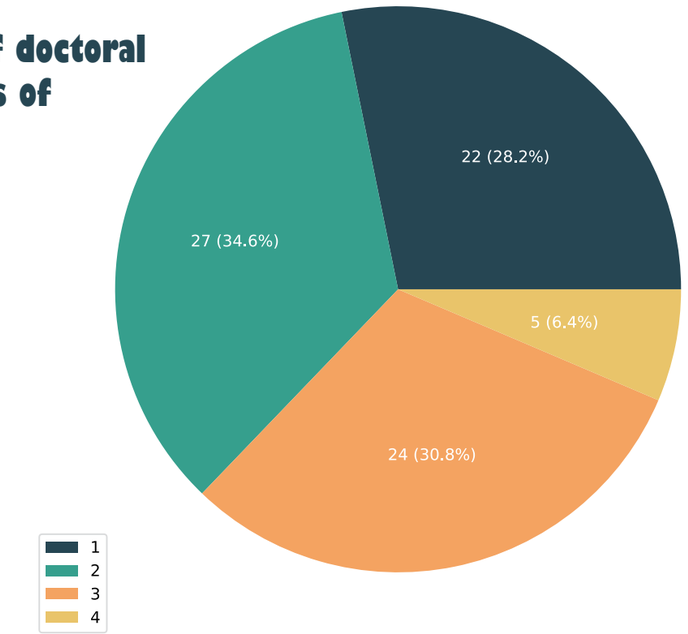


Distribution of doctoral students' years of thesis



PhD Students' Thesis Abstracts

This booklet is a compilation of the ISTerre PhD students' thesis abstract for the year 2023.
Its purpose is to have a state of advancement of the thesis ongoing at ISTerre laboratories and to keep a trace of every thesis subject done in the institute.
This document is made on the occasion of the PhD Congress of 2023 hold at ISTerre Chambéry, where some of the following subjects were presented. Each student is the authors of its thesis abstract and figure.

Mohamed Amine ABDELLAZIZ

Optimal Experimental Design for Full Waveform Inversion

Supervisors: Ludovic Métivier, Romain Brossier, Édouard Oudet (UGA/LJK)

Waves & structures

Optimal Experimental Design is a field related to finding the best experimental design for a specific purpose. In the context of geophysics it has been used to design seismic stations for the localization of earthquakesand to design acquisition geometries for seismic imaging. We consider the Full Waveform Inversion method.

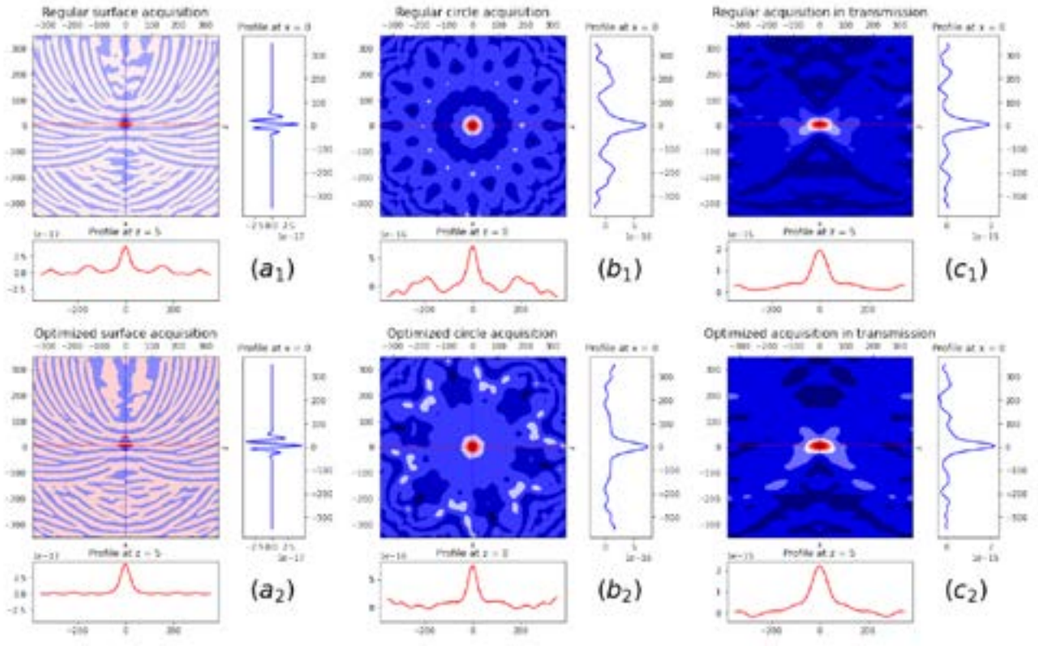
Most often the optimality criterion taken into account for the choice of a good acquisition design is based on the eigenvalue spectrum of the approximate Hessian. In this work we propose to use an alternative optimality criterion based on the wavenumber content of the gradient. The gradient can be computed as the zero-lag crosscorrelation between an adjoint wavefield and an incident wavefield. Under the planewave approximation we can estimate the wavenumber spectrum of the gradient. For an evenly spaced acquisition geometry we remark that those wavenumber points are not optimally distributed. We are interested in finding positions of sources and receivers for which these points are regularly and densely distributed in the wavenumber space.

In this work we propose a new optimality criterion for the design of acquisition geometries, which is based on the wavenumber spectrum of the gradient. We suppose an acquisition is composed of Ns sources and Nr receivers and where each source is fired with all the receivers, generating Ns × Nr wavenumbers. We are looking for the positions of sources and receivers that would optimize the distribution of wavenumbers. We are able to outline the envelope of the wavenumber cloud so this allows us to define the underlying problem as an instance of Centroidal Voronoi Tessellation and to propose a new energy function to minimize.

The preliminary results show that our optimization fulfills the criterion of optimal distribution of the wavenumbers and this has the consequence to produce gradients that are more focused at the position of the anomaly.

Mohamed Amine ABDELLAZIZ

Optimal Experimental Design for Full Waveform Inversion



The gradients for different types of acquisitioin the context of the reconstruction of a scattering point in a homogeneous medium, with profiles on the x and z-axis at the peak value. The first row are gradients associated to regular acquisitions and on the second are gradients associated to optimized acquisitions. The optimized acquisition geometries appear to provide gradients that are more focused on the anomaly compared to non-optimized acquisitions.

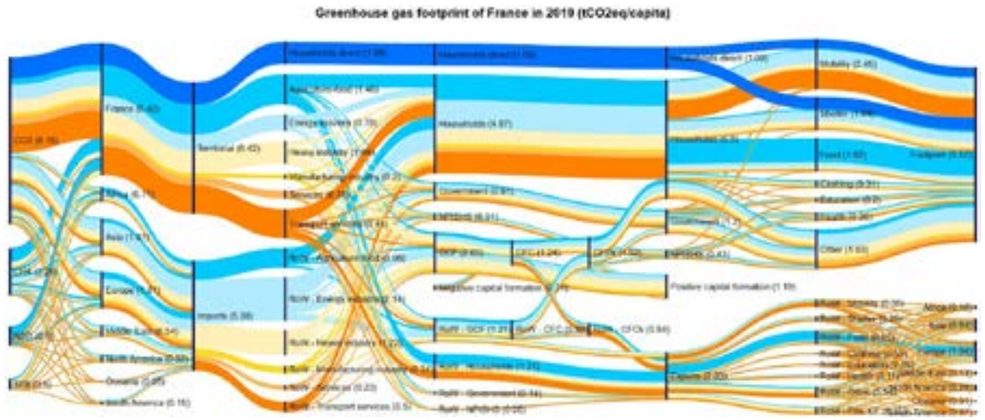
Baptiste ANDRIEU

Exploring energy dependencies - from raw materials to global health

Supervisor: Olivier Vidal

Mineralogy

The transition to a low carbon world requires building a new infrastructure for energy production, storage, transportation and use. As this new infrastructure is more intensive in raw materials than the existing infrastructure, the ability to achieve the energy transition is expected to be conditioned by the availability of a wide variety of metals in a context of growing demand from developing countries. The link between raw materials and energy is two-fold: raw materials are required to build the energy infrastructure but energy is also required to produce these raw materials and transform them into an infrastructure. To provide answers concerning the future availability of these resources, energy costs and environmental impacts of their production, ISTerre developed a dynamic model (DyMEMDS) able to transform the scenarios into energy production and consumption infrastructure, and then into raw material needs. It is used to estimate primary and recycled raw material requirements, energy consumption by sector, CO2 emissions and impacts on global warming and water consumption. During this PhD, I developed an approach to add flows of raw materials end energy in between the model's regions. I also worked on models to better understand the energy-economy-health nexus.



Example of flows in between regions: sankey diagram of the greenhouse gas footprint of France in 2019. Sankey diagrams for all years in between 1995 and 2019 for 49 world regions are available on the associated web application: https://sankey.theshiftproject.org/

Annet BAKEN

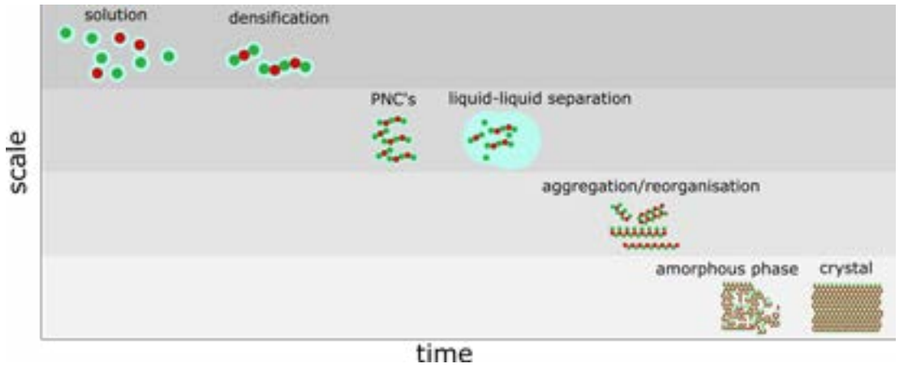
Understanding how green additives control crystallization at the nanoscale

Supervisors: Alexander van Driessche (Instituo Andaluz Ciencias de la Tierra & Laboratorio Estudios Cristalograficos), Alejandro Fernandez-Martinez, Marco Di Michiel (ESRF), Matthias Kellermeier (BASF)

Geochemistry

Additives – small amounts of (organic) molecules – are known to be able to control the outcome of a crystallization process, even when present in minor quantities [e.g. 1-3]. Outcomes of these additive-mineral interactions are ubiquitous. Examples vary from biomineralization processes, such as the formation of skeletons, to a vast amount of industries being depended on organic-based crystallization additives in order to produce materials with tailored properties (e.g. approximately $20 billion/year are spent on cement additives). But, despite the pivotal role of organic molecules in the formation of (crystalline) materials taking place in natural and industrial environments, surprisingly little is known about their modus operandi at the nanoscale during the early stages of nucleation and growth [1].
We aim to correlate the physicochemical properties of model organic molecules with their functionality during the crystallization process of portlandite and calcium carbonate. To achieve this, we employ in situ time-resolved Pair Distribution Function (PDF) analyses combined with potentiometric titration measurements, as well as complementary in situ Small-Angle X-ray Scattering (SAXS) experiments to monitor the mineralization process in the presence of different types of organic molecules. In particular, our newly devised method for PDF pushes the resolution limit of what has been previously achieved in mineral nucleation studies from diluted solution. Our results suggest that different additives act on different stages of the portlandite nucleation process. Our study will contribute to a better fundamental understanding of nucleation with and without additives and hence, serve as a step forward in biomineralization research as well as offer new insights for the development of sustainable crystallization additives in industry.

[1] Song and Cölfen. CrystEngComm. 13, 5, 2011.
[2] Verch et al. PCCP 13, 37, 2011.
[3] Nicoleau et al. Cem Concr Res. 124, 2019.



During the past twenty years several hypotheses have been proposed regarding nucleation mechanisms of minerals. These often involve complex multistep pathways, where each step takes place at a different time and scale. The goal of my PhD is to understand how additives act on these nucleation pathways.

Juliette BAS LORILLOT

Mineral reactivity and microbial diversity associated with water-basalt interactions under subsurface conditions

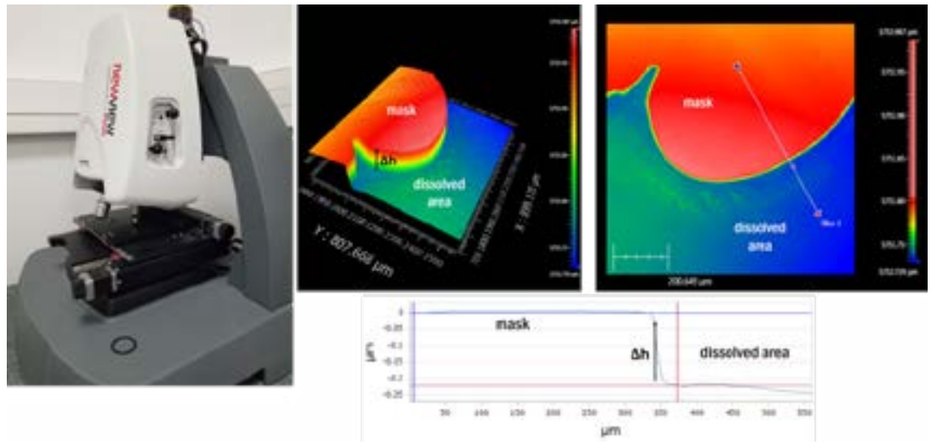
Supervisors: Damien Daval, Emmanuelle Gérard (IPGP)

Geochemistry

The purpose of my work is to assess the contribution of microorganisms to silicate weathering in basaltic subsurface environments. Although about 70% of microorganisms live in subsurface environments and have long been suspected to impact silicate weathering, the corresponding rates and mechanisms remain poorly constrained.

To study the microbial diversity in these environmental settings, field campaigns were carried out in Iceland targeting basaltic aquifers with contrasted physicochemical properties (22 boreholes with temperatures and pH ranging from 30 to 100°C and from 7 to 11). The biomass was collected by filtration using 0.22 µm filter. DNA was then extracted from the filters before Illumina MiSeq tag sequencing of the 16S rRNA-encoding gene. Preliminary results from bioinformatic analyses show that most of our samples are dominated by the phylum Nitrospirota, for the bacteria and the phylum Crenarchaeota for the archaea. To the first order, the pH seems to be one of the main factors shaping bacterial and archaeal diversity.

In parallel, dissolution experiments were conducted in a range of pH and temperature relevant to the targeted basaltic aquifers to characterize the abiotic reactivity of basaltic glass and olivine using non-invasive techniques such as vertical scanning interferometry. At these conditions, our preliminary results show that the reactivity of olivine is lower than expected whereas the reactivity of basaltic glass is consistent with the data in the literature. Such experiments will provide an abiotic silicate reactivity baseline for future experiments that will be conducted with microorganisms representative of the deep basaltic environments sampled during our field campaigns, and ultimately shed light on their contribution to silicate weathering rates.



Vertical scanning interferometer images of a basaltic glass sample after dissolution at pH 6 and 90°C, and the associated profile. The height difference between the masked and dissolved area is used to calculate dissolution rates.

Mustapha BENZIANE

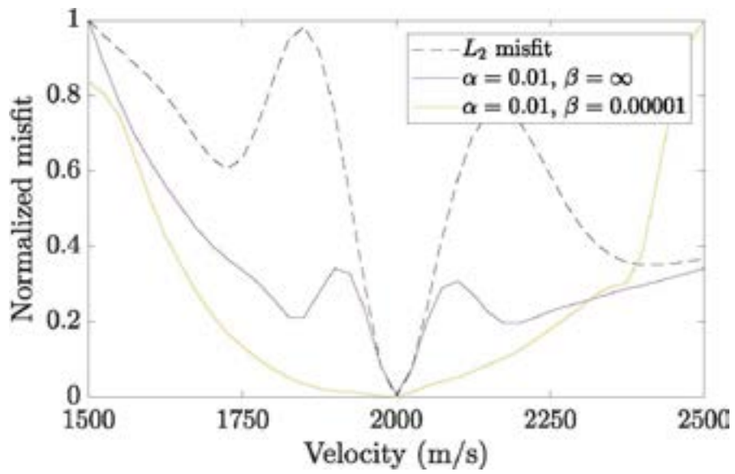
Receiver extension strategy using a time-dependent relocalization approach for time-domain FWI

Supervisors: Romain Brossier, Ludovic Métivier

Waves & structures

Full waveform inversion suffers from the cycle-skipping issue due to the non-linearity of the problem.

In this work, we devise a new extension strategy of the FWI misfit function, in which we introduce additional degrees of freedom to the receiver position, generating receivers positions corrections which are time-dependent. This allows the fit multiple arrivals in the observed and calculated data. Our extension strategy aims at eliminating the kinematic mismatch at earlier FWI iterations, when the model estimate is poor, and conventional FWI is prone to cycle-skipping. The FWI gradient is computed using the corrected receiver position, giving a correct model update. This is implemented using nested loops optimization strategy, the outer loop solves for the model parameters using a quasi-Newton strategy, while the inner loop solves for the optimal receiver position correction time profiles, using a simulated annealing method. We constrain the receiver position, and the receiver speed by introducing penalty terms to the FWI problem. A simple numerical experiment shows that a fit for two arrivals can be obtained, showing an improvement on the FWI gradient compared to conventional FWI and time-independent receiver extension. Lastly, we show the effect our strategy has on the convexity of the misfit function.



Misfit function values computed at the different first layer velocities (in a simple numerical experiment using a two layers model). The conventional least-squares misfit is shown in a dashed line. The misfit obtained using the time-independent and time dependent receiver extension strategies are shown in purple and yellow, respectively.

Dorian BIENVEIGNANT

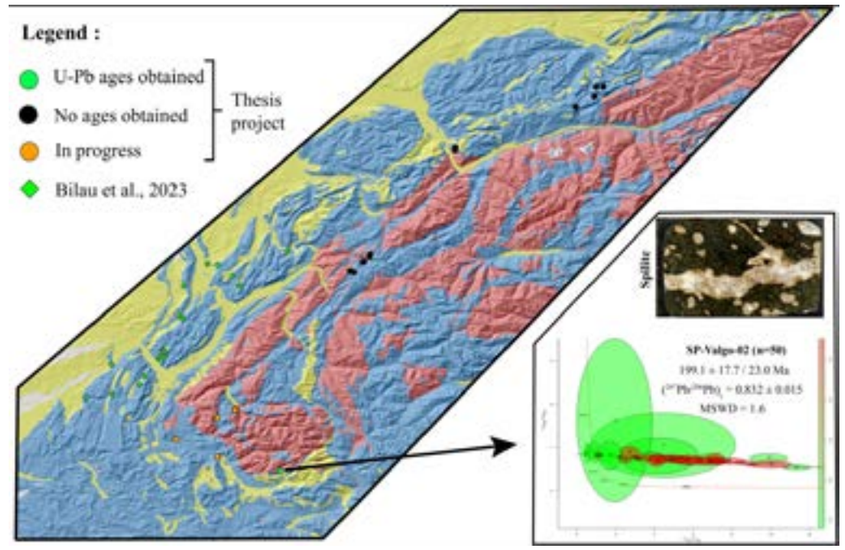
U-Pb dating of calcite : New perspectives for constraining (pre-)Alpine geodynamics

Supervisors: Matthias Bernet, Stéphane Schwartz

Tectonics, Reliefs, Basins

In recent years, calcite in situ U–Pb dating has emerged as a solution for absolute dating of deformation in sedimentary environments not accessible to conventional methods ([1], [2]). In the Western Alps, this method has been successfully applied to dating the structuring of the foreland (between 15 and 3 Ma ; i.e. [3] and [4]), thus constraining the latest stage of Alpine chain construction. Although calcite is a ubiquitous mineral in the peripheral basins of the chain, the challenge is quite different in the crystalline massifs where calcite does not seem favorable to this method's application due to low U/Pb in sampled calcite (see figure). Despite this difficulty, obtaining calcite U–Pb absolute age would enable to provide information on history of the past tectonic event in the W-Alps sector. With this in mind, the first part of my theisis project aims to test calcite's datability from different localities of the external/internal Crystalline Massifs and Subalpine Massifs of the Western Alps, in order to identify areas where this method could be applied.

Preliminary U–Pb isotope analyses of calcite veins in crystalline basement rocks shows the abundance of crystal domains dominated by common-Pb precluding precise and accurate dating. Nevertheless, dating of calcite vacuoles from spilites are one of the few samples where U/Pb is favourable and where the scatter of analysed calcite domains is sufficient enough. The age obtained provides information on the emplacement and weathering conditions of pre-Alpine volcanic rocks. By providing, for the first time, an absolute constraint on the stratigraphic sequence of the Triassic, this result extends the catalogue of datable geological objects and thus hence broadens the perspectives offered by this developing method.



Non-exhaustive compilation of published and ongoing U-Pb data on calcite in the Western Alps.

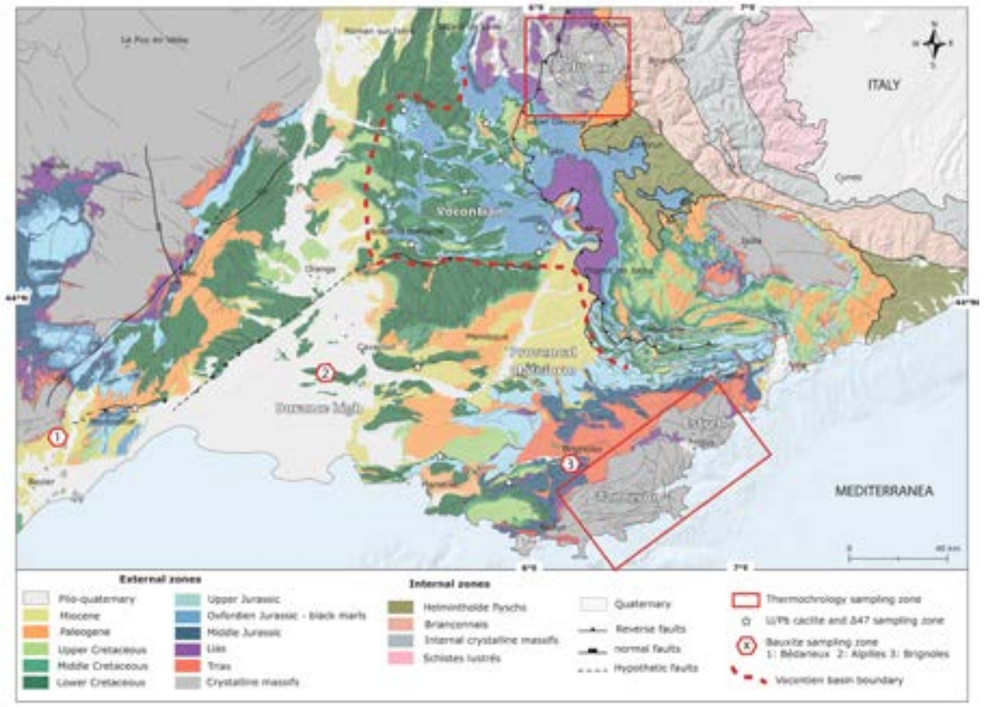
Louise BOSCHETTI

Orogenic evolution of the south Alps and SE France basin: Impact of Variscan, and Alpine rift structures

Supervisors: Frédéric Mouthereau (Univ. Paul Sabatier), Stéphane Schwartz, Yann Rolland (USMB)

Mineralogy

The impact of the pre-Alpine tectonic and thermal events on the mountain building and deep crustal structure of the basin of SE France is currently poorly understood. In particular, the temporal and tectonic setting of the pre-alpine phases remains to be clarified. The transition between the Mesozoic rifting and the beginning of the Cretaceous shortening, and paleogeography of the Vocontian in the complex plate framework between Europe, Iberia-Ebro and Adria must be established. The thesis project combines different geochronological approaches over SE France. New low-temperature dating will be carried out in the Pelvoux and Maures-Esterel massifs to constrain the pre-alpine thermal evolution of the Variscan basement. (U-Th)/He dating on hematite will be applied to the bauxites of Provence in order to link paleogeographic reconstruction of the Durancian uplift to tectonic and pre-Alpine paleo-topography. The thermal evolution of the Vocontian Basin will be constrained by U-Pb dating on fault-related calcites and the temperature of fluids associated with extension. These results, together with new crustal geophysical imagery from the AlpArray project, will provides new constraints on the still debated tectonic models and their impact on the structure and thermal evolution of the region.



Geological map and sample zones of the studied area.

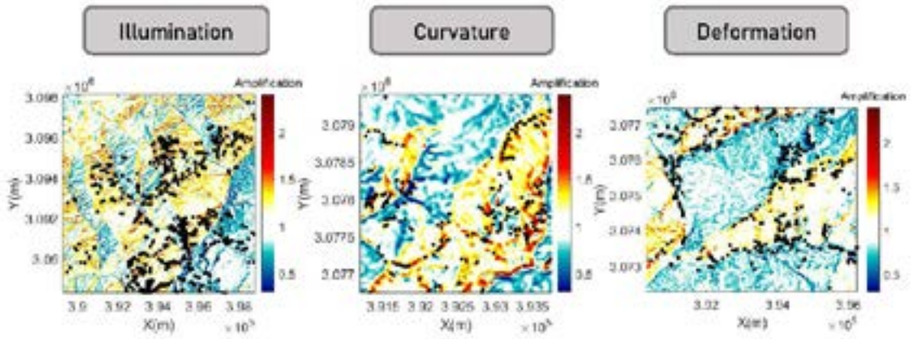
Aline BOU NASSIF

Strong earthquake ground motion in mountainous regions and induced landslides

Supervisors: Emeline Maufroy, Pascal Lacroix, Emmanuel Chaljub

Geophysics of seismic and gravity risks

Our study focuses on predicting ground motion amplification caused by surface topography during earthquakes, which is directly motivated by the high variability in damage distributions at fine spatial scales. Using a neural network analysis of data from 3D numerical simulation of seismic wave propagation, we developed the i-FSC proxy, a physics-based estimator of the topographic site effects in the near field. The proxy uses the S-wavelength, the topographic curvature, and a novel parameter called normalized illumination angle to quantify slope exposure to the incoming wavefield. It allows researchers to investigate amplification variations caused by a nearby seismic source, which is significant since the areas closest to the fault usually sustain the most damage. We used the proxy to investigate the correlation between seismic amplification and the spatial distribution co-seismic landslides triggered by the Gorkha 2015 earthquake. Results showed that at low frequencies, landslides tend to be concentrated on illuminated slopes facing away from the seismic source. At small scales, the landslides' location follows the amplification at high frequencies, mainly controlled by the curvature of the surface topography. Landslides were also concentrated at the interfaces between amplified and deamplified zones, indicating areas of the greatest slope deformation. The estimator shows potential in explaining co-seismic landslide distribution at local and regional scales, but we need to consider other key parameters such as slope steepness to better understand the physics behind it. Our initial findings, using the i-FSC proxy, enabled us to determine the threshold amplification levels that can trigger landslides for a given slope value. This was done at a regional scale and did not account for terrain geology, which remains to be investigated. Incorporating terrain geology into our analysis could provide additional insights into mechanisms governing landslides which helps develop more effective risk assessment and mitigation strategies.



Amplification maps predicted by the i-FSC proxy in different regions of the Gorkha study area showing the effects of seismic illumination, curvature, and deformation. Co-seismic landslide initiation points are represented with the black dots.

Mirko BRACALE

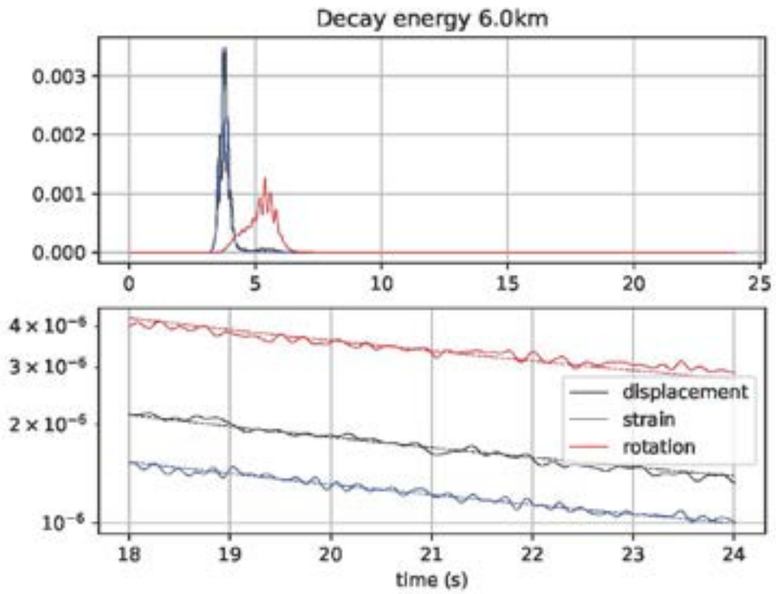
Effect of shallow heterogeneites on wavefield gradients measurements

Supervisors: CAMPILLO Michel, PEDERSEN Helle

Waves & structures

In recent years, the use of rotational sensors and DAS has become a topic of increasing interest within the seismological community because of their increasing sensitivity and cost-effectiveness. We performed several numerical simulations, using a suitably modified 3D-SEM code, to observe, in addition to wavefield itself, the normal strain and rotation as a direct output.

Our analysis focused on the sensitivity of wavefield gradients in two different contexts:
1. Homogeneous medium with shallow localized velocity changes
We analyzed two case studies, a first in which we considered a velocity anomaly, where the P-S velocity drops by 10% compared to the homogeneous medium, a second in which the velocity drops by 70%. We evaluated the sensitivity of these new observables in terms of phase shift and amplitude change, and observed a local effect of the wavefield gradients, which showed larger amplitude near the anomaly.
2. High scattering mediums
We conducted a preliminary study to verify that our simulations accurately represented the propagation properties of seismic waves in a scattering medium. We studied the mean free path, energy decay in the late coda, and the equipartition ratio as a function of time.



Energy decay in the late coda at 6km source to receiver distance. The medium has Laplacian correlated heterogeneities with 300m correlation length, the source is isotropic.

Margaux BUSCETTI

Development of multi-approach strategies in order to include site response in site-specific SHA for low to moderate seismic area

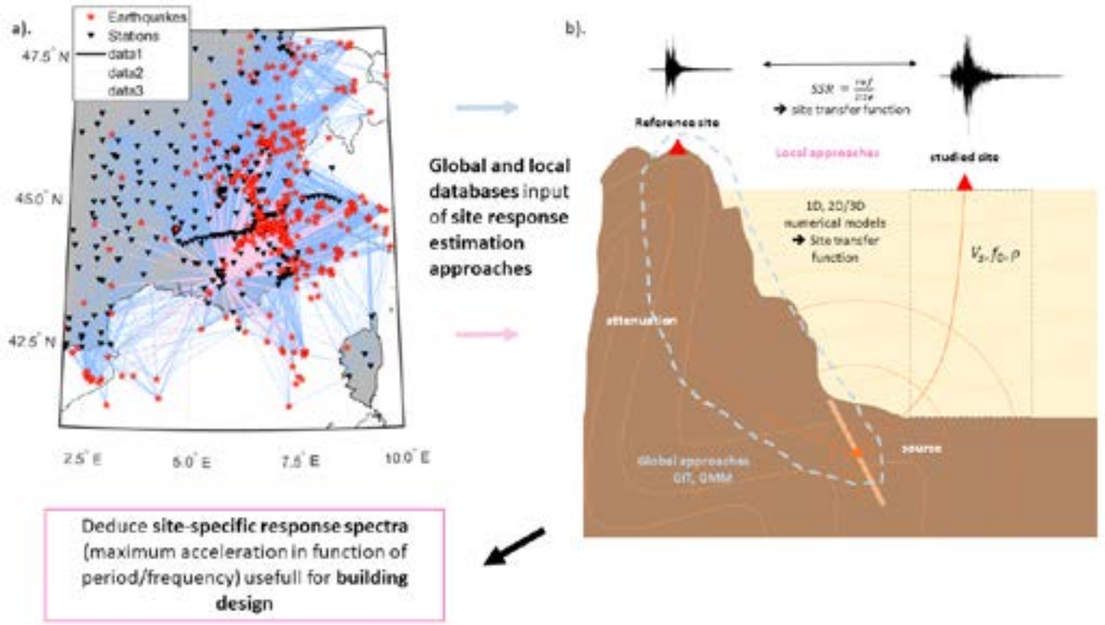
Supervisors: Fabrice Hollender, Vincent Perron (CEA)

Geophysics of seismic and gravity risks

One of the stake in Seismic Hazard Assessment is to integrate site effect, i.e the local spectral amplitude variations due to the specific characteristics of a site, to the acceleration expected at this site considering a certain seismic scenario deduced from a chosen Ground Motion Model (GMM). A wide range of GMMs exists, some of them could include site characteristics such as V_S30 or κ parameters, however the latter are not sufficient to take into account all of the site properties and complexity. Hence, the current steps are to estimate expected acceleration for the bedrock (first stiffer soil layer where the impedance contrast is significant) thank to a chosen GMMs, and convolve it to the site response computed with local empirical (SSR) or numerical (1D, 2D/3D modelling) approaches that estimate more accurately the site response. These approaches use local seismic recordings or significant amount of geophysical measures, to estimate the transfer function of the soil between the surface and the bedrock. Recently, global approaches of spectral decomposition such as Generalized Inversion Techniques (GIT) have also shown their reliability to assess the site response spectra for moderate to high seismic context. Similarly, the study of site-to-site residual (δS2S) in some GMMs, shown that it could contain a part of the site response. However, these two last global approaches have not been fully test for low to moderate seismic context as mainland France. Hence, the principal objectives of my PhD are (i) to compare the site response estimation of each approaches below by using a combination of global and local French databases, in order to assess the reliability and (ii) evaluate the epistemic uncertainty between and within each approaches. (iii) The final step is to develop methodologies to include these site response estimations in a Probabilistic Seismic Hazard Assessment study. The temporal site effect (phase variations) will be address too.

Margaux BUSCETTI

Development of multi-approach strategies in order to include site response in site-specific SHA for low to moderate seismic area



a). Global (RESIF French database, in blue) and local database (pink rays) used as input in b). empirical and numerical approaches to estimate site response (SSR, 1D/2D/3D modelling) or the three spectral ground motion component : source, attenuation including site response (GIT, GMM). All of these results are used to estimate Seismic Hazard Assessment, i.e response spectra of the site, in Deterministic or Probabilistic way.

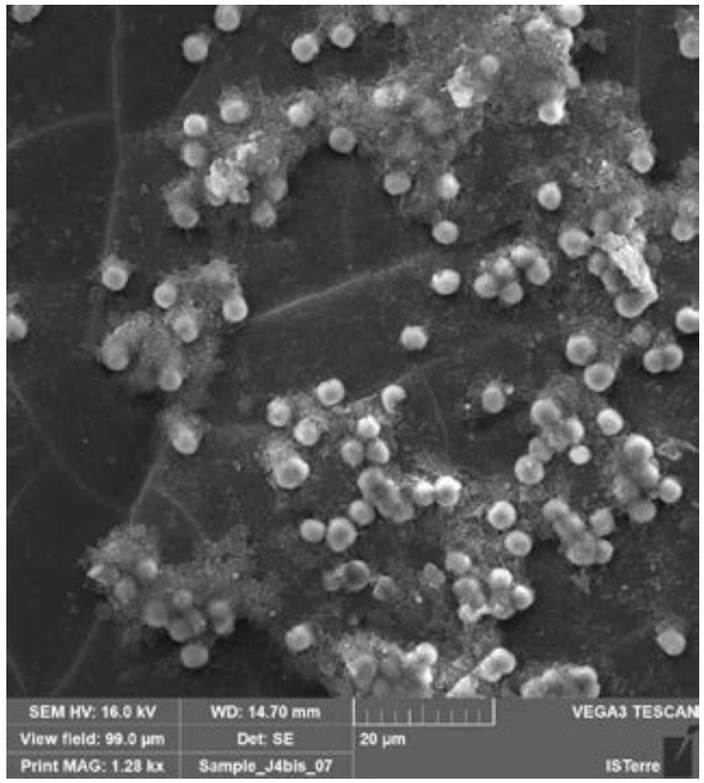
Benjamin CAGNON

A fundamental study of amorphous and crystalline silicate dissolution: contribution to the improvement of existing models

Supervisor: Damien Daval

Geochemistry

We investigated the dissolution of ISG in a solution with various concentrations of Si and Ca (from none to the saturation limit of amorphous silica and portlandite, respectively). The pH was adjusted initially to pH ≈10 according to the fluid composition at 90°C. CSH precipitation was expected in some experimental series, as well as amorphous silica and calcite. In order to simplify the thermodynamic calculations, CSH domain was divided into 3 sub-domains: CSH0.8, CSH1.2 and CSH1.6, where each number refers to the Ca/Si ratio in the structure of the CSH. The solution was analysed by ICP-AES in order to calculate the dissolution rate. It was then confirmed by either ToF-SIMS, VSI and FIB-TEM on the precipitates and/or the glass sample. SEM-EDX and IR was used to determine the composition of the precipitates.



SEM on the surface of the sample altered during 104 days in a solution saturated with silica and with a high initial introduction of calcium. We can observed on the ISG glass some precipitates that mix CSH and amorphous silica. The white balls are vaterite precipitates.

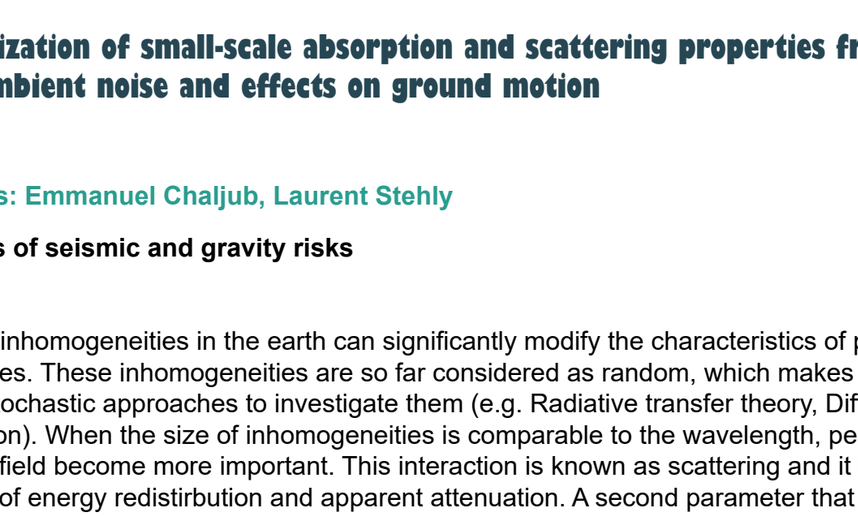
Malcon H. CELORIO MURILLO

Characterization of small-scale absorption and scattering properties from seismic ambient noise and effects on ground motion

Supervisors: Emmanuel Chaljub, Laurent Stehly

Geophysics of seismic and gravity risks

Small-scale inhomogeneities in the earth can significantly modify the characteristics of propagating seismic waves. These inhomogeneities are so far considered as random, which makes necessary the use of stochastic approaches to investigate them (e.g. Radiative transfer theory, Diffusion approximation). When the size of inhomogeneities is comparable to the wavelength, perturbations on the wavefield become more important. This interaction is known as scattering and it is the responsible of energy redistirbution and apparent attenuation. A second parameter that contributes to the amplitude decrease of seismic waves is the absorption, and it is defined as the dissipation of energy due to the conversion into heat. In this work we estimate scattering and absorption properties by using seismic ambient noise at Piton de la Fournaise volcano for frequencies ranging from 0.5 up to 4 Hz. In order to separate these two mechanisms we rely on the idea that the decrease of direct waves with distance is mainly a result of scattering, whereas the attenuation in the late coda is strongly controlled by absorption. As fitting procedure we use diverse techniques based on the multiple lapse time window analyses (MLTWA), as well as the so called Q_open method. Our results evidence that scattering is more dominant than absorption in the study area. However, this parameter is also less accurately constrained due to the difficulties to select the appropriate ballistic regime on time.



Fitting procedure for the estimation of scattering attenuation. (Top) Cross-correlation function (CCF) for a receiver couple with propagation distance of 8.1 km. The yellow rectangles indicate the length of search for the group velocity and the blue ones denote the reference window for the coda normalization. (Bottom) Comparison between the observed and modelled energy envelopes by using the best-fit parameters of scattering attenuation. The grey lines define the windows where the fitting procedure is performed.

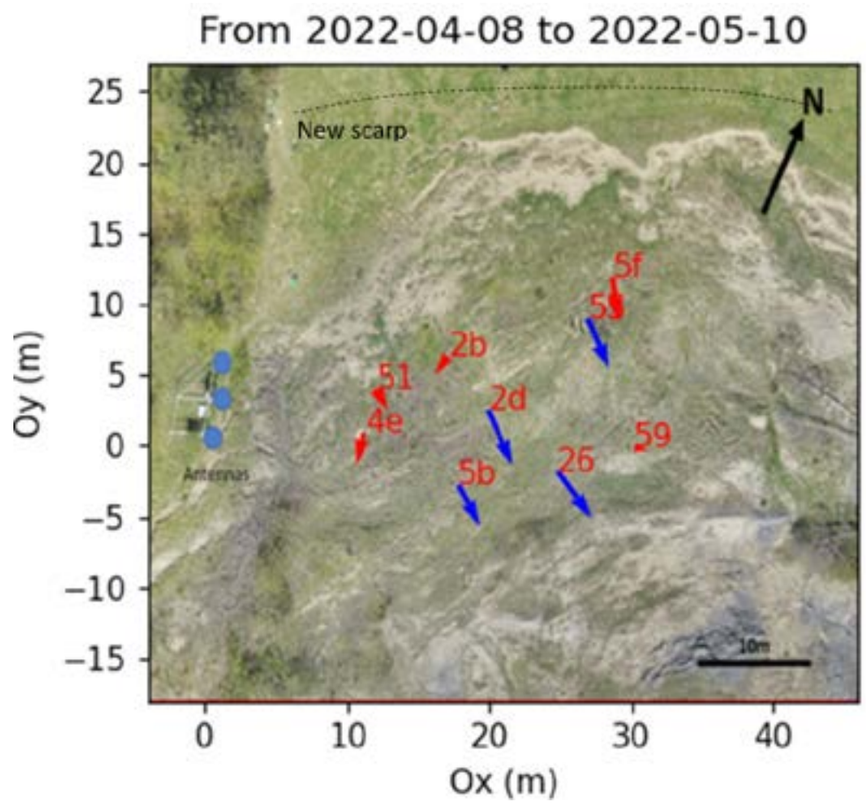
Arthur CHARLÉTY

RFID Landslide Monitoring

Supervisors: Laurent Baillet, Éric Larose

Fault mechanics

Monitoring landslides at a fine spatio-temporal scale is challenging, especially with the present of snow and vegetation in harsh terrain. RFID-based monitoring provides a way to monitor surface displacement at the centimeter scale, with a sub-hourly resolution. In this work, different approaches are presented in order to improve the quality and interpretability of RFID displacement results.



A field view of ground displacements, based on RFID results. Different clusters are highlighted, showing the different active blocks of the landslide.

Jacques CHARROY

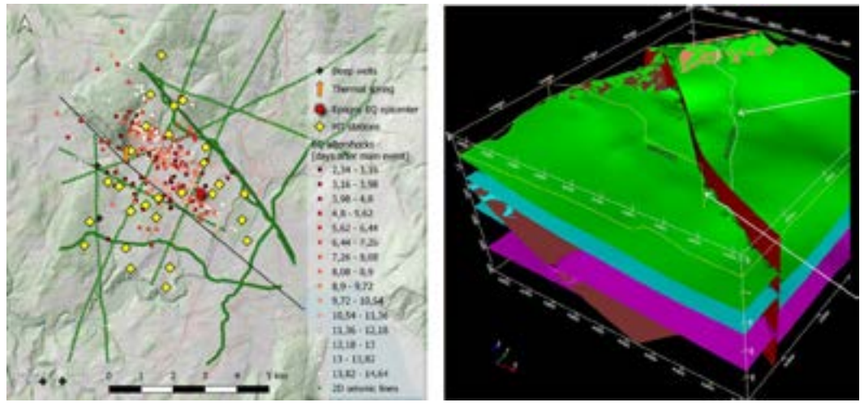
Resource and risk assessment for medium enthalpy geothermal energy by passive geophysical methods

Supervisors: Jean-Luc Got, Yan Yajing (USMB)

Geophysics of volcanoes & geothermal energy

Geothermal energy is an attractive renewable energy; however, its exploitation requires a sound knowledge of the nature, quality and boundaries of the reservoir to evaluate the resource potential and reduce the risk of induced seismicity. The purpose of this project is to use broad-band magnetotelluric (MT) data to investigate a medium-enthalpy geothermal zone in the region of Annecy, France. In this pre-alpine area, karstic limestones constitute a deep aquifer (up to ~2 km) intersected by the Vuache fault, an active strike-slip fault where a M5.3 earthquake occurred in 1996.
A data set of 27 MT sites was acquired, with generally all 5 components measured. Data quality was mostly satisfactory up to 3 Hz and sometimes up to 1 s. Major problems were related to the presence of electromagnetic noise in this urbanized region, mitigated by the careful use of advanced processing methods (FFMT). 1D MT models were produced and for the 3-D inversion required by the data (phase tensors, WAL, topography), we aim to undertake a joint inversion of induction vectors, phase tensors and off-diagonal impedances. This should allow us to obtain a suitable 3D model using the ModEM inversion code.
We aim at the integration of the obtained resistivity models with already existing results (seismic reflection, borehole information) into a 3D geological model, which will be used within re-inversion of the MT data by turning off the smoothing across interfaces detected by seismic reflection.

References:
(2) Weaver, J.T., Agarwal, A.K., Lilley, F.E.M. (2000). Characterisation of the magneto-telluric tensor in terms of its invariants. Geophysical Journal International 141, 321–336.
(3) Kelbert, A., Meqbel, N., Egbert, G.D., Kush, T. (2014). ModEM: A modular system for inversion of electromagnetic geophysical data, Computers and Geosciences 66, 440-53.



Map of the study area (left side) showing the 1996 Epagny EQ hypocenter and aftershocks, location of the seismogenic Vuache fault, MT stations acquired (yellow), thermal spring of Bromines, deep wells and 2D seismic lines (green) used to produce a geological model (right side).

Audrey CHOULI

Seismicity and deformation in subduction zones: from intermediate-depth intraslab earthquakes to shallow megathrust events

Supervisors: Anne Socquet, David Marsan, Sophie Giffard-Roisin

Seismic cycles and transient deformations

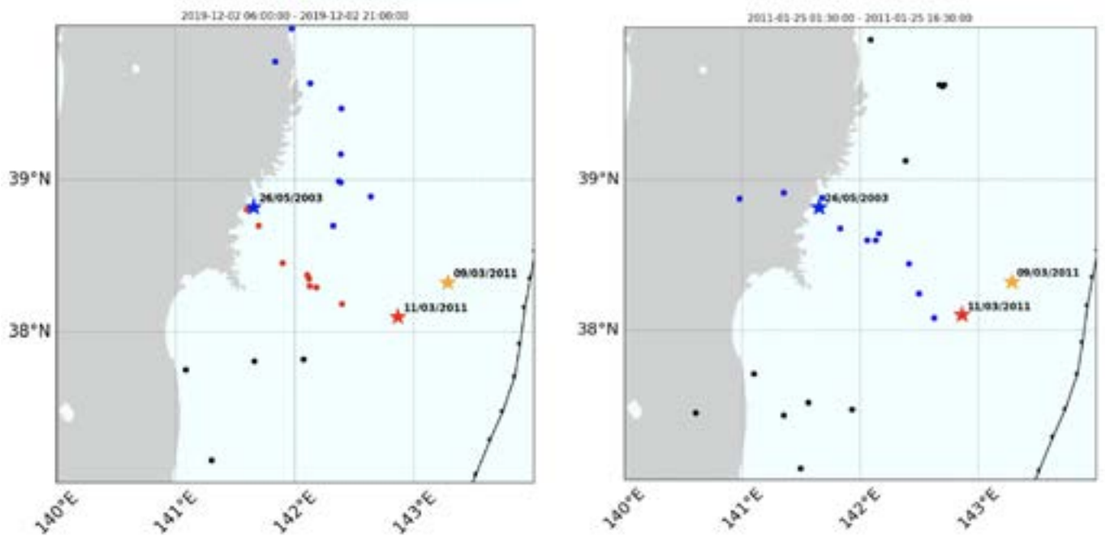
An increase of both shallow and intermediate-depth intraslab seismicity has been observed days to years before some great subduction earthquakes, sometimes accompanied by seismic spatial patterns forming along dip lineaments over some hours. These observations suggest that a link exists between these deep and shallow foreshocks, but it is still poorly understood and not characterized in a systematic manner. The aim of this study is to systematically and statistically identify the potential correlations between intermediate-depth and shallow seismicity, and to characterize their duration and spatial pattern.

For this purpose, we develop a statistical method based on cross-correlation to assess the relevance of deep-shallow interactions. We focus on the seismicity of the Japan and the Chile trench subduction zones, during the decades prior to the Tohoku-oki (Mw 9.0, 2011) and Iquique (Mw 8.2, 2014) earthquakes, respectively. The temporal correlation values between the deep and shallow events are calculated on various sliding-windows with durations from days to years, and then compared to the ones obtained using parts of seismicity catalogs far in space and therefore uncorrelated to evaluate their significance. In a second time, we also use DBScan to search seismic lineaments patterns linking intermediate-depth and shallow seismicity and check the evolution of the obtained clusters' parameters through time, especially before big events.

If the seismic spatial patterns are still under analysis, our study based on cross-correlation shows some windows with a strong link between shallow and intermediate depth events, sometimes on different timescales, including the months just before the two megathrusts. However, periods that don't precede great seismicity can present the same kind of interactions, indicating that the latter can't be used as precursors.

Audrey CHOULI

Seismicity and deformation in subduction zones: from intermediate-depth intraslab earthquakes to shallow megathrust events



Examples of seismic lineaments (in blue and red) found using DBScan, on a 15h long window scanning the Japan Meteorological Agency seismic catalog, in the area of the 2011/03/11 Mw 9 Tohoku megathrust (red star). The yellow star indicates the 2011/03/09 Mw 7.3 foreshock, and the blue star the 2003/05/26 Mw 7.1 intermediate-depth earthquake. Some seismic lineaments form a link between intermediate-depth and shallow large events.

Rajkumar CHOWDHURY

Physical and Chemical Characterization of Nannoconus, the main planktonic bio-producers of Early Cretaceous Oceans

Supervisors: Fabienne Giraud, Alejandro Fernandez-Martinez

Tectonics, Reliefs, Basins

The topic of my thesis is “The physical and chemical characterization of Nannoconus, the main planktonic bio-producers of the Early Cretaceous Oceans”. Geologically, the Early Cretaceous time period (~150-100 Ma) is marked by huge marine limestone deposition. These marine carbonates are composed for a major part by calcareous nannofossils (exoskeleton remains of calcifying planktonic algae). One group is dominant during this period: the Nannoconus; their calcareous exosleletons (5-30 µm) are made from interlocking arrangement of calcitic plates (~ 100 nm) spanned by a central canal. These skeletal remains are very massive (Mass ~ 300-1400 Pg) making Nannoconus the major bio-carbonate producers in the mentioned time period. This significant success for the marine calcifiers within a time period of (~) 50 Ma is very intriguing question to study. Nine major morphogroups have been recognized for Nannoconus. On the other hand, very little is known concerning their biological affinity, making it difficult for any interpretative results. My doctoral thesis lying in the cross-roads of Micropalaeontology and Geochemistry aims to combine the micro-scale physical and chemical characteristics of Nannoconus to answer the difficult yet interesting link between the successful calcification and the paleoceanographic conditions.

One part of my thesis deals with the interlocking arrangement of the calcitic plates of the exoskeleton of the Nannoconus. In this regard, the Ptychography X-ray computed tomography (PXCT) with synchrotron radiation was applied to get the finely resolved (~ 50nm) micro-structure. The experiment was performed at SWING beamline, the French synchrotron, SOLEIL. The analysis of the result led to reconstruct individual plate and then to the structural relation to the plates, hence the arrangement of the calcitic plates for different species of Nannoconus. These results are expected to combine with pre-known hypotheses of the 3-dimensional arrangement of the plates based on the SEM and the optical microscopy.
The other part of the doctoral thesis is the chemical characterization of the Nannoconus. For this we applied the micro-X-ray fluorescence technique with synchrotron radiation at the ID21 beamline, ESRF. The idea was to find about the distribution and quantification of different elements like Calcium, Magnesium and Strontitum in the Nannoconus through chemical mapping. The results are under process.
The variation of the micro-structural arrangement for different species with time, derived from the physical characterization will aid to the non-existing biological affinity of the Nannoconus. On the other hand, the chemical distribution of different elements (e.g., Magnesium) will help to find out the process of calcification. Combining all the results it will be possible to infer about the relation of the adaptation of Nannoconus with the changing paleoceanographic conditions.

Rajkumar CHOWDHURY

Physical and Chemical Characterization of Nannoconus, the main planktonic bio-producers of Early Cretaceous Oceans

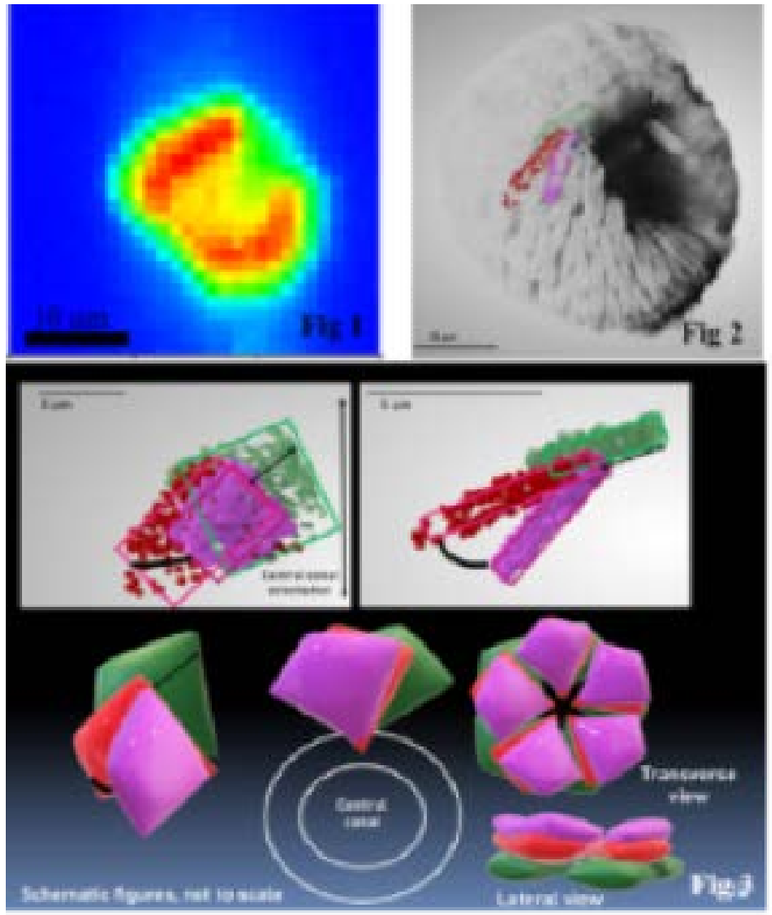


Fig 1: µ-XRF Map of Calcium on Nannoconus globulus.
Fig 2: Delineation of calcitic plates on Nannoconus globulus after the PXCT.
Fig 3: Partial reconstruction of the exoskeleton from the delineated plates of Nannoconus globulus.

Aleksandr CHUGUNOV

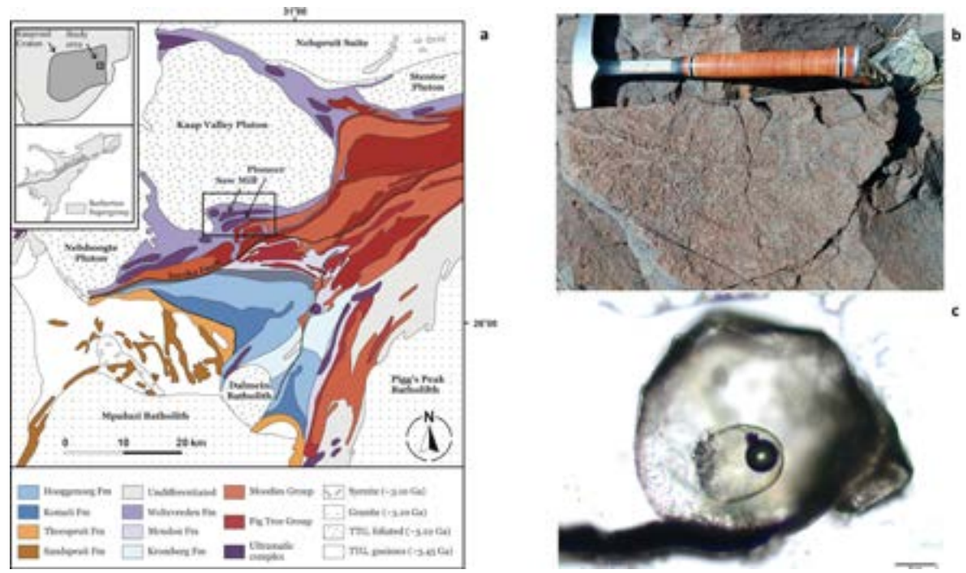
Evolution of Archean Earth Mantle Composition: The Evidence from Magmatism of Kaapvaal Craton

Supervisor: Alexandre Sobolev

Mineralogy and Environments

The goal om my PhD is to reconstruct the evolution of mantle composition in mobile and volatile elements and their isotopes during the 3.7-2.6 Ga of Earth history and to contribute to the understanding of the rate of crustal production and recycling in Archean eon.

Hadean recycling and subduction has been speculated for decades, and according to our data it started at least at 4.2 Ga, while mantle was already highly heterogeneous (but not the same geochemical composition as present mantle).
The main advantage of our approach is obtaining data from small melt inclusions from komatiites - ultra-mafic magmas, considered to be the most primitive mantle-derived rocks. The latter feature makes these komatiites the best candidate for representation of the mantle composition. Melt inclusions in komatiites were preserved and unaltered, trapped in olivine crystals for billions of years, saving valuable information about the ancient mantle composition. This information gives us a unique insight into the evolution of the mantle through time that is difficult to obtain using other methods, as most ancient rocks have undergone numerous alterations and have not retained any reliable initial data of their composition.



a. Geological map of the Barberton Greenstone Belt (South Africa), study areas are Saw Mill and Pioneer Complexes, Weltevreden Formation. b. Spinifex texture from the komatiite of the Barberton Greenstone Belt. c. Photo of the olivine-hosted melt inclusion from Saw Mill complex, size about 100 microns.

Machine learning applied to the detection and understanding of slow slip events

Supervisors: Anne Socquet, Sophie Giffard-Roisin

Seismic cycles and transient deformations

I work on an interdisciplinary thesis at the interface between geoscience and signal processing, computer science (and related fields). In my research, I develop machine learning techniques aimed at detecting and characterizing slow slip events in GNSS data.

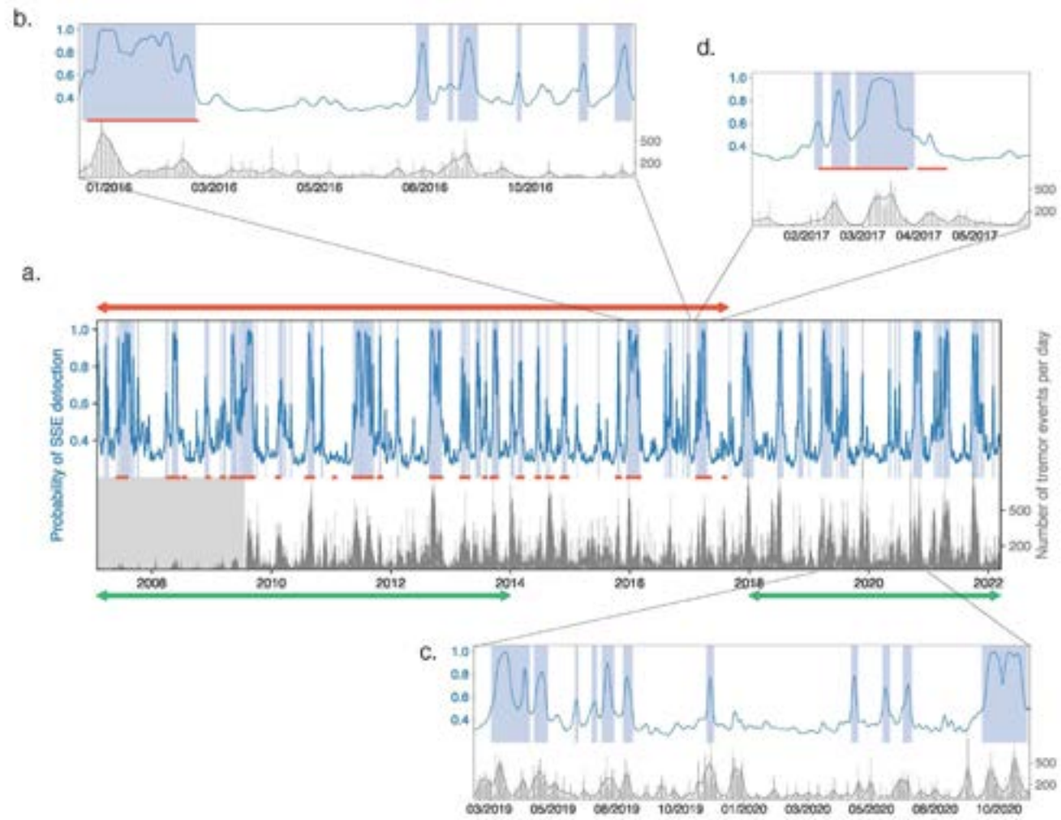
Like earthquakes, slow slip events originate from slip on faults and can have similar magnitude, thus significantly contributing to the release of stress on faults. More precise identification of slow slip events and the associated seismological signals is key to better understanding the mechanics of active faults and to better describing the role of seismic slip in the seismic cycle. Yet, our understanding of those phenomena is still hindered by our ability to systematically detect the full spectrum of slow slip events, including the smallest ones.

As a first step towards the characterization of slow deformation, I worked, during my first year of PhD, on the characterization of earthquakes by means of deep learning. As a main result, I showed that earthquakes in north Japan can be precisely characterized by taking into account spatial information (e.g., re-arranging GNSS time series as spatially-interpolated images) (Costantino et al., 2023). Then, I moved to the detection of slow slip events in GNSS time series in the Cascadia subduction zone. I first developed SSEgenerator, a method to generate ultra-realistic artificial GNSS time series, that I used to train SSEdetector, a combination of Convolutional and Transformer Neural Networks aimed at detecting slow slip events in real GNSS time series. As a result, SSEdetector detects 78 events in the period 2007-2022 that are in good accordance with previous detections (Michel et al., 2019) and show an excellent correlation with tremor episodes (Costantino et al., in review).

I am currently working on the characterization of slow slip events, i.e., the estimation of the event location and magnitude. I am analyzing different approaches both from the data and the methodological point of view. So far, image-based methods outperform time-series-based methods. As a third option, I am also making experiments on re-arranging GNSS data as a graph, to be used as input of Graph Neural Networks, to better exploit the geometry of the GNSS network.

Giuseppe COSTANTINO

Machine learning applied to the detection and understanding of slow slip events



Overview of the performance of SSEdetector on real raw GNSS time series. The blue curves show the probability of detecting a slow slip event (output by SSEdetector) in 60-day sliding windows centered on a given date. Grey bars represent the number of tremors per day, smoothed (gaussian smoothing, σ = 2 days) in the grey curve. Red horizontal segments represent the known events catalogued by Michel et al., 2019. The (a) panel shows the global performance of SSEdetector over 2007-2022. The red arrow indicates the time window analyzed by Michel et al., while the green arrows describe the two periods from which the synthetic training samples have been derived. The grey rectangle indicates the period which was not covered by the PNSN catalog. In this period, data from Ide, 2012 has been used. The (b), (c) and (d) panels show zooms on 2016-2017, 2019-2021 and 2017 (January to July), respectively. The figure has been taken from (Costantino et al., in review).

Charline COUDUN

The Cretaceous continental margins of the Demerara plateau

Supervisor: Christophe Basile

Tectonics, Reliefs, Basins

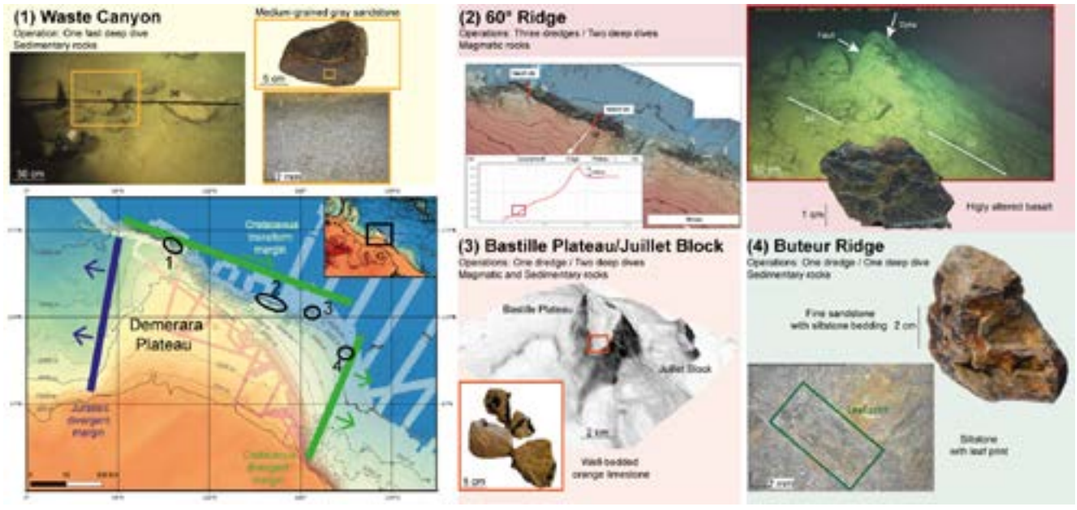
The Demerara plateau is a submarine bathymetric high, 230 km long and 170 km wide, located north of French Guiana and Suriname. It is bordered by oceanic domains of different ages: the Jurassic Central Atlantic domain and the Cretaceous Equatorial Atlantic domain. This two-stage evolution has segmented the Demerara Plateau into three margins: westward a Jurassic divergent margin, an eastern Cretaceous divergent margin and a northern Cretaceous transform margin. As a planar submarine relief extending the continental shelf, and bounded by a transform margin, the Demerara plateau is a typical Transform Marginal Plateau.

Since 2003, four oceanic cruises collected several types of data on the Demerara Plateau: mainly seismic profiles (vertical and wide angle), and dredges. Seismic profiles reveal the existence of a regional Albian age unconformity. The dredges recovered pre-Albian magmatic rocks and showed that the Jurassic margin was a magmatic divergent margin. It was supposed that its formation was related to hot spot activity, but the lack of samples did not allow to confirm this hypothesis. In early 2023, a new oceanic cruise called DIADEM took place. The aim of this cruise was to sample and observe the pre-albian units in order to verify the hot spot hypothesis and to bring new informations that would allow to reconstitute the unexplained vertical movements of the Demerara plateau.

In order to do this, we used two complementary methods, dredges and manned deep underwater dives (Nautile) in four sites: the 60° Ridge, the Bastille Plateau and the Juillet Block, the Buteur Ridge and the Waste Canyon. At these sites the topography allows the Jurassic-Cretaceous rocks to the outcrop. Nearly 400 magmatic rocks and 100 sedimentary rocks were sampled. During my thesis, I will focus on the Cretaceous margins of the Demerara plateau by describing and analyzing the sedimentary samples at a macroscopic and microscopic scale, with X-Ray and with a Scanning Electron Microscope. I will then date sedimentary and magmatic samples (apatite and zircon fission tracks, biostratigraphy, U/Pb, Ar/Ar, Rb/S, Goethite, Magnetite…). In addition, the 38 hours video recording of each deep dive will be viewed in order to carry out the structural study and the log of the investigated outcrops.

Charline COUDUN

The Cretaceous continental margins of the Demerara plateau



The studied sites of the DIADEM oceanic cruise on the Demerara Plateau, offshore French Guiana (G) and Suriname (S). Pictures come from manned deep water dives (Nautile), samples from Nautile and dredges. S0 for stratification. 3D diagram is made using bathymetric data from DRADEM cruise, maps from DRADEM and older cruises, and worldwide datasets.

Léa COURTIAL-MANENT

Écroulements rocheux dans les parois de haute et moyenne montagne : quelles évolutions ? Quelle temporalité ? Quels risques ?

Supervisor: Jean-Louis Mugnier

Tectonics, Reliefs, Basins

Since the end of the 20th century, each decade has been warmer than the previous one. For instance, Europe has faced three major series of heat waves during the summers of 2003, 2015 and 2022. For the latter, the monthly temperature anomaly reached 3°C compared to the last 40 yr average and even the top of Europe, Mont Blanc (4808 m a.s.l.; French-Italian Alps) was momentarily affected by positive temperatures (up to 10°C). A consequence was the numerous rockfalls affecting the massif due to permafrost degradation.

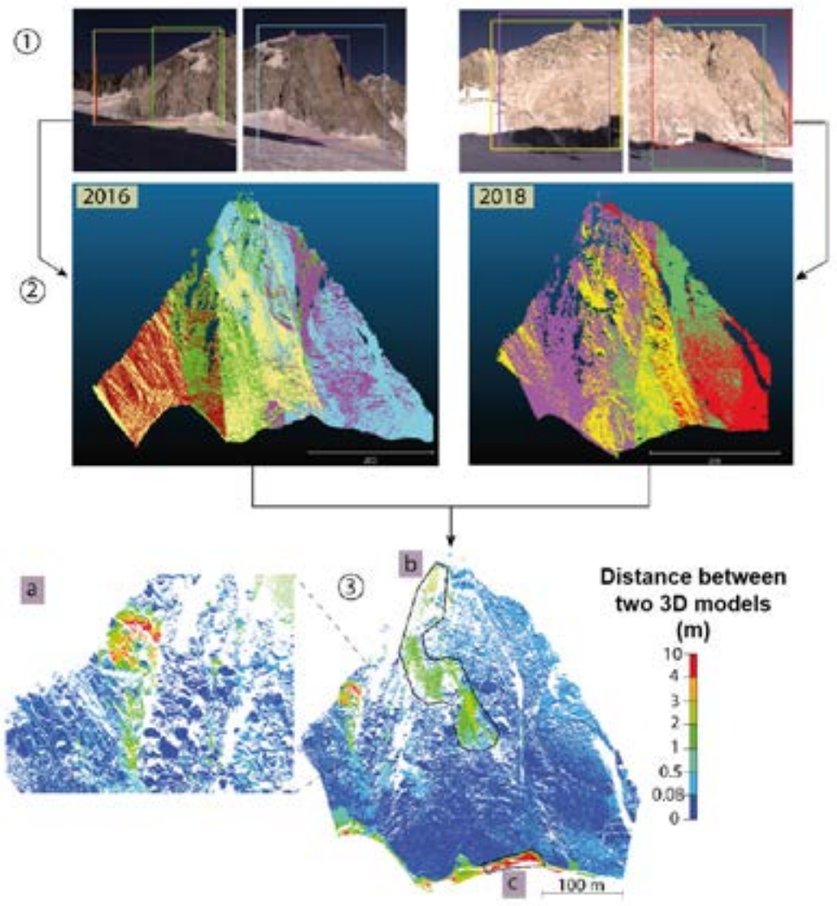
To quantify the morphological evolutions of steep rock slopes located in permafrost-affected areas in the current context of climate warming and induced permafrost degradation, we used terrestrial laser scanning over 17 years (2005-2022) on a series of rock walls of the Mont-Blanc massif. The data acquired results in one of the most extensive databases of high-Alpine rockfalls fed by 12 surveyed rock walls whose elevation is 2950-4600 m a.s.l. Overall, more than 110 high-resolution scans were acquired and ~400 rockfalls were registered, ranging from 0.2 ± 0.1 to 15,578 ± 188 m3. 40 events were > 100 m3 while 58 % of the rockfall volumes were < 10 m3.

These results show that the rockfall magnitude-frequency distribution follows a power law. The exponent b, which represents a frequently used variable to characterize spatiotemporal rockfall variations, ranges from -0.35 to -0.95 with a mean of -0.53 ± 0.19 (90 % confidence level). The depth of failure distribution follows a non-linear relation where 97 % of the scars < 5 m deep. Rockfalls mainly occur when the slope ranges from 60 to 75° (49 %) and for altitude in the range 3400-3700 m a.s.l (56 %). No clear pattern for the orientation of the rockwalls has been observed, although differences in sun exposure can play an important role within the same rockwall. Rock fractures also play a role as they determine a part of the frequency/volume relationship and enable water infiltration and heat convection (i.e., warming in depth).

Among the 12 surveyed rock walls, the eastern face of Tour Ronde (3440-3792 m a.s.l.), characterized by a mean annual rock surface temperature between -2 to 2°C, had in 2018 a total annual rockfall volume of more than twice the one of 2011, highlighting the recent and dramatic effects of permafrost degradation.

Léa COURTIAL-MANENT

Écroulements rocheux dans les parois de haute et moyenne montagne : quelles évolutions ? Quelle temporalité? Quels risques?



Different steps in processing the data acquired with the terrestrial laser scanner (TLS). 1) Alignment of the scenes for one year to create a 3D-point cloud of the whole area. 2) Alignment of the two complete point clouds to compare the years and observe the changes. a) Signal of one (or more) missing large block(s). b) Signal of the evolution of the glacier-snow cover. c) Signal of the evolution of the glacier height at the wall foot.

Interactions grande échelle pendant la séquence de séismes de subduction en Amérique du Sud

Supervisors: Anne Socquet, Mathilde Radiguet, Marie-Pierre Doin

Seismic cycles and transient deformations

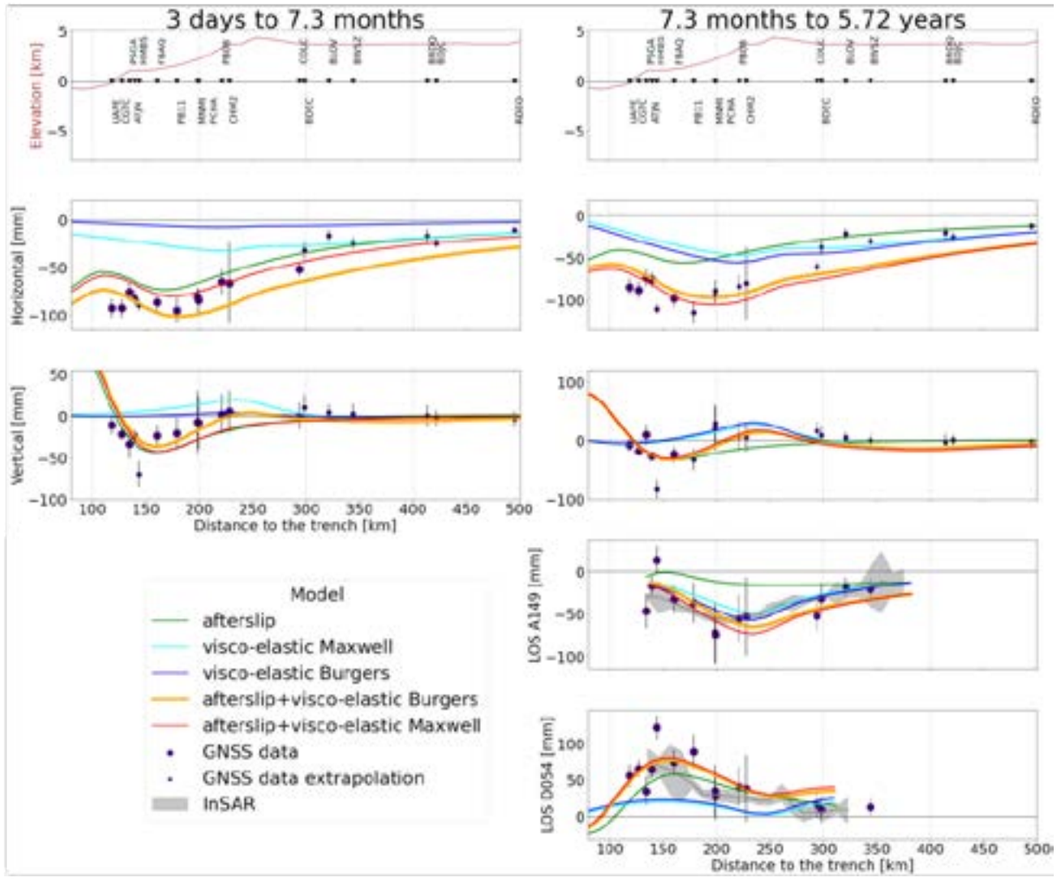
In the South American subduction zone, major earthquakes, thousands of kilometers apart, have occurred close in time (Maule 2010, Iquique 2014, Illapel 2015), and despite intriguing observations of surface velocity changes in distant regions, the mechanisms driving possible interactions between these events remain unclear. Viscoelastic relaxation is one phenomenon that can explain large-scale deformations, and modelling this process requires a good knowledge about the medium structure and the rheology.

Our dataset consists in 21 GNSS time series (processed with GipsyX) located in North Chile, Peru and Bolivia. The InSAR data consist in two Sentinel-1 time series (ascending and descending tracks) processed with the NSBAS chain, starting 7 months after the earthquake up to the end of 2019. We use a Finite Element Model (using the FEM software Pylith), firstly with a 2-dimensional model for the Iquique study, then extended it in 3D. Imposing a co-seismic slip on the interface, we investigate the relative contribution of afterslip and viscoelastic relaxation to explain the surface deformation. We vary the structure and the rheology of viscous zones and compare their impact on surface deformations, as well as the amplitude and location of the afterslip on the plate interface.

Our results reveal the necessity of a low viscosity area under the altiplano constrained by a long wavelength signal seen at long-term on the InSAR data, and confirmed by an uplift on the GNSS data. The location of this signal requires a rigid cold nose. We also show that a transient rheology with a lower viscosity at short term, using a Burgers rheology, is needed to fit the temporal evolution seen in GNSS. Tests on the viscosity with the 3D model highlight that the lower the viscosity, the more displacement is observed at large spatial scale. As it impacts a large area, relaxation in low viscosity zones could explain the far GNSS changes observations.

Juliette CRESSEAUX

Interactions grande échelle pendant la séquence de séismes de subduction en Amérique du Sud



Displacement perpendicular to the trench for the two processes: afterslip and visco-elastic on the short term and long term. The model displacements are compared with GNSS and InSAR data.

Djamilatou DABRE

Impact of gold mining on the contamination of aquatic ecosystems and populations in Burkina Faso and Guinea

Supervisors: Stéphane Guedron, Odile Bruneel (Hydrosciences Montpellier-Microbiology), Jacques Gardon (Hydrosciences Montpellier-epidemiology)

Geochemistry

Over the past decade, gold mining activities have developed intensively in West Africa. More and more disadvantaged populations are taking part in this lucrative activity, whose negative externalities on the environment and health are poorly assessed. Gold extraction processes and the chemicals used for its recovery lead to various and complex contaminations involving contaminants such as mercury (Hg), cyanide (CN) and also arsenic (As). These extractive activities can have a strong impact on the forest and aquatic environment through the remobilization of metals, but also on the populations working directly on the gold mining sites or downstream from the sites. The impact of these activities on the contamination of trophic chains and humans by these contaminants is poorly developed in Burkina Faso, but especially in Guinea where no study of this type is yet available. This project aims to understand the impact of mining activities on the contamination of surface waters and soils, food chains and populations of gold mining camps in Burkina Faso and Guinea where gold is the primary export product.

This research project aims first to establish a baseline of mercury, cyanide, and arsenic contamination of waters and food chains in two mining districts. Secondly, the study will focus on identifying the sources of pollution, the mechanisms and pathways of transfer of contaminants to the environment as well as those responsible for human exposure. This last point will allow to characterize the levels of impregnation of workers and people living near gold-mining sites, in order to evaluate the potential health impact.

The first sampling campaigns were conducted in Burkina Faso in November 2022 and the Kouroussa region in Upper Guinea in February-March 2023. Soil, surface and groundwater samples were taken in villages downstream of the mining sites. During this first sampling fieldwork, we observed an increased use of mercury by gold miners that could lead to environmental pollution and a real public health problem.

Djamilatou DABRE

Impact of gold mining on the contamination of aquatic ecosystems and populations in Burkina Faso and Guinea

1- Ore washing and environmental impact of gold mining
2- Amalgamation of gold and burning of amalgam
3- Human exposure on Hg vapor

Mathilde DEHUE

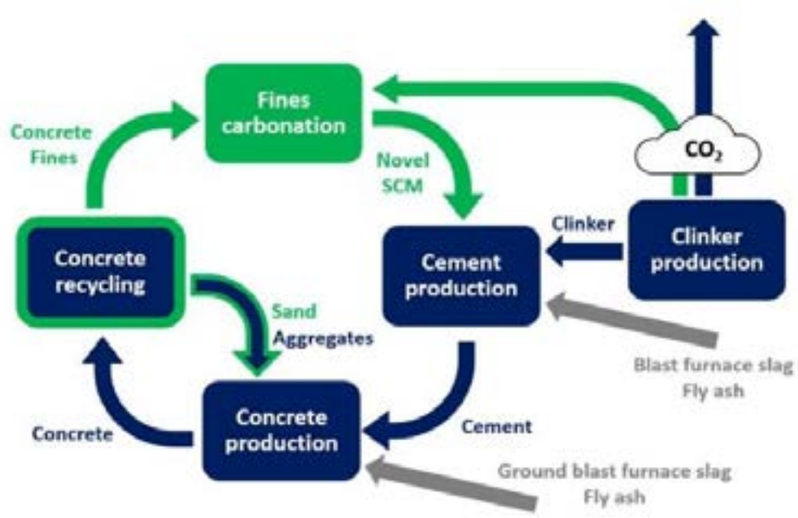
Reducing the carbon footprint of cement through the CO2 mineralization of recycled concrete

Supervisor: Alejandro Fernandez-Martinez

Geochemistry

The use of concrete has been growing continuously in the 20th and 21st century, leading to an increase of its environmental footprint. The current global warming crisis and the significant consumption of natural reserves have pushed the building industry to search for new and sustainable solutions. New breakthrough technologies for lowering the CO2 footprint include a circular utilization of demolished concrete. Recent developments have shown that most of the CO2 originally released by limestone calcination during clinker production can be sequestered by carbonation of the recycled cement paste. This technology, currently under development by the cement industry, consists in the carbonation of a part of recycled concrete in a humid/aqueous medium, leading to the formation of carbonate minerals and therefore to the permanent storage of the CO2 in solid form.

A successful deployment of this technology at large scale needs a good understanding and, eventually, a control of the CaCO3 polymorphism. The project of this thesis is to characterize the carbonation reactions using both laboratory and synchrotron X-ray scattering experiments. The effect that different ions from cement hydrates –e.g., silicate, aluminate, magnesium- and different organics used as modifiers of the hydration kinetics –e.g., gluconate, have on the calcium carbonate crystallization kinetics will be investigated in the framework of classic and non-classical theories of mineral formation.



Scheme of the production of the cement characterized by substantially lower CO2 emissions. The green color highlights improvements of the process compared to the current situation shown in blue. The gray color highlights the traditional supplementary cementitious materials input with uncertain future availability.

Bénédicte DONNIOL JOUVE

Seismic hazard assessment including GPS data

Supervisors: Céline Beauval, Anne Socquet

Seismic cycles and transient deformations

Most national and international seismic regulations require quantifying seismic hazard based on probabilistic seismic hazard assessment (PSHA) methods. The probabilities of exceeding ground-motion levels at sites of interest over a future time window are determined by combining a source model and a ground-motion model. Earthquake catalogs, merging instrumental and historical data, are usually used to establish earthquake recurrence models. Although these catalogs extend over several centuries, the observation time windows are often short with respect to the recurrence times of moderate-to-large events and in some regions the recurrence models can be weakly constrained.

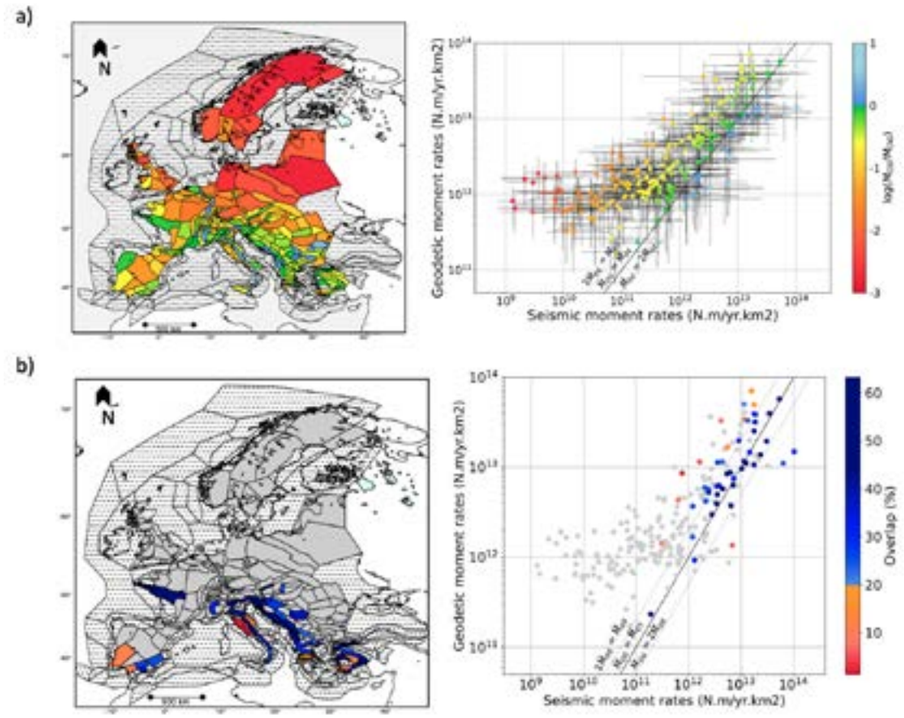
In the present work, we take advantage of two new studies conducted at the scale of Europe: the latest release of the probabilistic seismic hazard model for Europe (ESHM20, Danciu et al. 2021); and the strain rate maps computed by Piña-Valdés et al. (2022). Our objective is to test the compatibility between the ESHM20 model and the geodetic dataset from a moment comparison perspective.

We computed the seismic and geodetic moment distributions, as well as the overlap between them in polygons, called source zones, defined in ESHM20. We assume that an overlap higher than 20% indicates compatibility between the two models.

Our results show that in areas characterized by high activity, such as the Betics, the Apennines, the Dinarides, and the eastern Mediterranean, the moment rates derived by both methods are generally compatible. In these regions, the different spatial scales between geodesy and seismicity can trigger local incompatibility, but this effect can be neglected with the use of wider zones. However, areas characterized by low to moderate activity show different behavior. In the Fennoscandia source zones affected by GIA, the two models are not compatible. In the rest of intracontinental Europe, the compatibility between the two models depends on whether they are well-constrained or not.

Bénédicte DONNIOL JOUVE

Seismic hazard assessment including GPS data



Comparison between geodetic and seismic moment in Europe at the scale of the source zone.,
a) Geodetic VS seismic moment at the scale of the source zone,
b) Percentage of overlap between geodetic and seismic moment for the sources zones where at least 30 earthquakes are used to constrain the Gutenberg-Richter recurrence model.

Hugo DUTOIT

Exploration and modelling of natural hydrogen and helium sources and migration pathways

Supervisors: Frédéric Donzé, Laurent Truche

Mineralogy and Environments

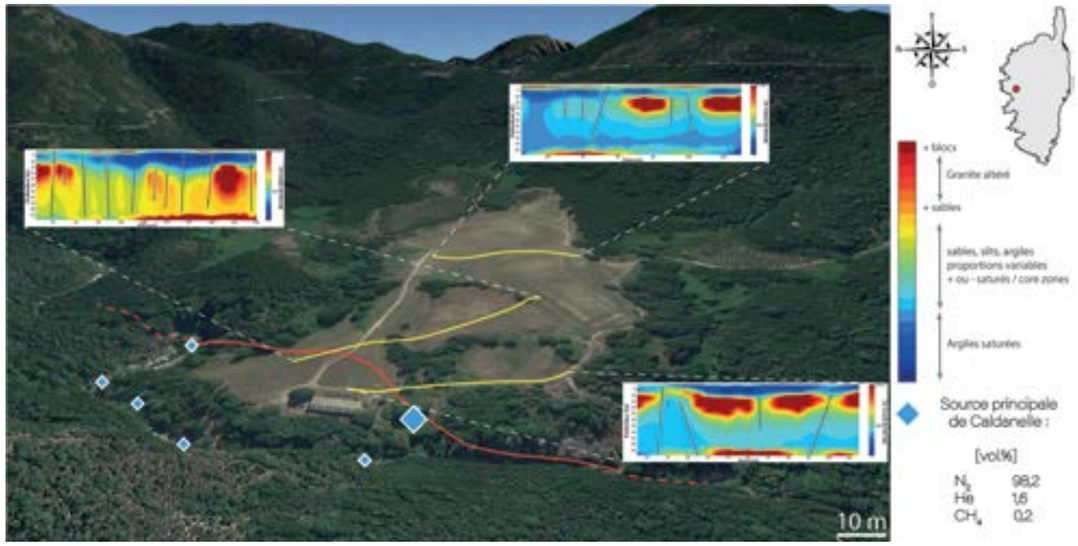
Most of the current He reserves originate from fortuitous discoveries, mainly made during oil and gas exploration in intra-cratonic sedimentary basins overlying Archean-Proterozoic crystalline bedrocks (3.8-0.54 Ga). As helium generation depends on U and Th α-decay, old geological provinces gather key ingredients for high He accumulations. However, numerous He-rich springs have also been documented in much younger rocks, like granites of post-Variscan age (320-250 Ma). These latter discoveries question the current exploration guidelines and require to revisit some of the long-standing paradigms that drive our reasonings.

Here, we investigate He migration along a major fault rooted in the Corso-Sardinian batholith (France). Two thermal springs, Caldanelle and Guagno-Les-Bains, show significant outgassing activity of crustal sourced He with concentration up to 1.6 vol% and flow rate of 3000 Nm3/ year. These two springs are calco-alkaline and low in Mg, and reflect little chemical basement variations. Beside He, the gas phase is dominated by N2 (≈98 vol%) and minor CH4. Calculated reservoir temperatures are approximately 130°C. Their surface water temperatures (35°C and 62°C respectively) and their age (9500 and 6000 years respectively) suggest a rapid upwelling without mixing with surficial aquifers. A multi-methods approach enabled us to detect the presence of a major fault between Caldanelle and Guagno as well several fracture sets, all of them draining the fluids, including He from a common reservoir to Caldanelle.

From these observations and measurements, we state that i) an efficient He production occurs at the early stage of radioactive decay, ii) the presence of a fault and a dense draining networks fractures drain the He, iii) the heat is above the closure temperature of minerals with respect to He retention, iv) there is a liquid-gas partitioning during the rapid fluid assent, v) there is an absence of high-CO2 flux diluting the resource but the low N2 flow rate acts as a carrier gas, and finally vi) a minimal diffusion leaks out of the drainage system, should be considered in addition to the U-Th concentrations and the age of the rocks. In that sense, young post-orogenic granites represent promising helium plays.

Hugo DUTOIT

Exploration and modelling of natural hydrogen and helium sources and migration pathways



Study area of Caldanelle thermal spring in Corsica. Gas bubbles containing crustal helium escape from the spring. The structural and geophysical study allowed to highlight a N30 fault direction (in red) draining the fluids. The yellow profiles correspond to the interpreted resistivity profiles.

Sarah EL KADRI

Probabilistic seismic hazard assessment for Lebanon

Supervisors: Céline Beauval, Yann Klinger (Institut de physique du globe de Paris)

Seismic cycles and transient deformations

We aim at estimating probabilistic seismic hazard levels for Lebanon, a country prone to a high seismic hazard since it is located along the Levant fault system (~5mm/year deformation). As a first step, we develop a source model that includes major faults in the area, with earthquake recurrence models for each fault based on the available geomorphology, paleoseismology and geodetic studies. This moment-balanced fault model is combined with a catalog-based smoothed-seismicity model to also forecast earthquakes off the main fault segments. Uncertainties are tracked and propagated up to the final hazard calculations to understand which parameters' uncertainties control hazard estimates. A set of seismic hazard maps at the scale of Lebanon is obtained, representative of uncertainties in the source model. As second step, another class of fault models is explored for application to the Levant fault system, algorithms that propose to include information on the segmentation of the faults, and permit that sub-fault segments freely break together, as in nature (SHERIF from Chartier et al. 2019; OpenSHA Fault System tool from Milner and Field 2021). These algorithms take into account more detailed information along the fault system. Again, uncertainties are tracked at the different steps required for building the source model, to understand the impact on hazard of the uncertainties associated to the input data, as well as the impact of the hypothesis and decisions that these algorithms require. We test the feasibility of such approaches for the Levant fault system, which is unevenly characterized along its 1000km length. We show how the hazard levels are modified within Lebanon if applying these methods, with respect to our previous hazard results relying on more classical fault models.

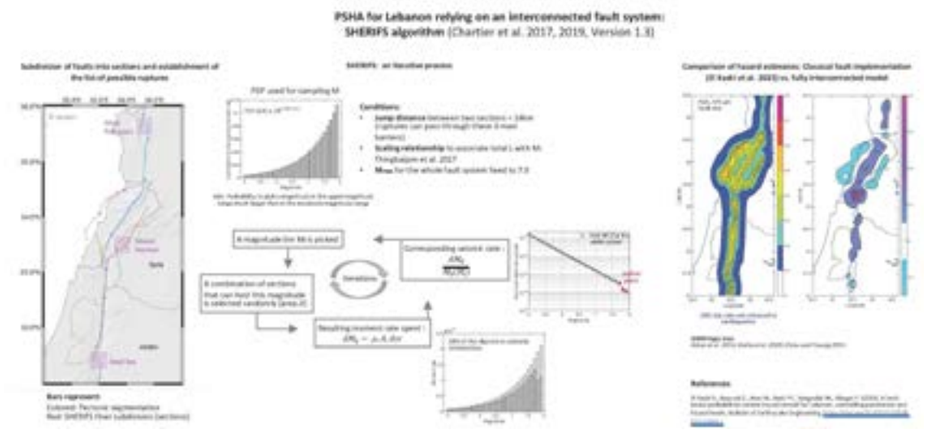


Figure is showing the steps used to relax fault segmentation by applying the SHERIFS algorithm. First step consist in sub-dividing the faults into sections with comparable lengths and establishing a list of possible ruptures. The second step represent the shape of the frequency-magnitude distribution chosen for the system and the PDF used to sample magnitudes in the iterative process shown in the diagram.
Finally hazard results for the PGA at 475 years of return period are shown based on rock sites.

Zaccaria EL YOUSFI

Diversity of transient slow slip along the Mexican subduction zone

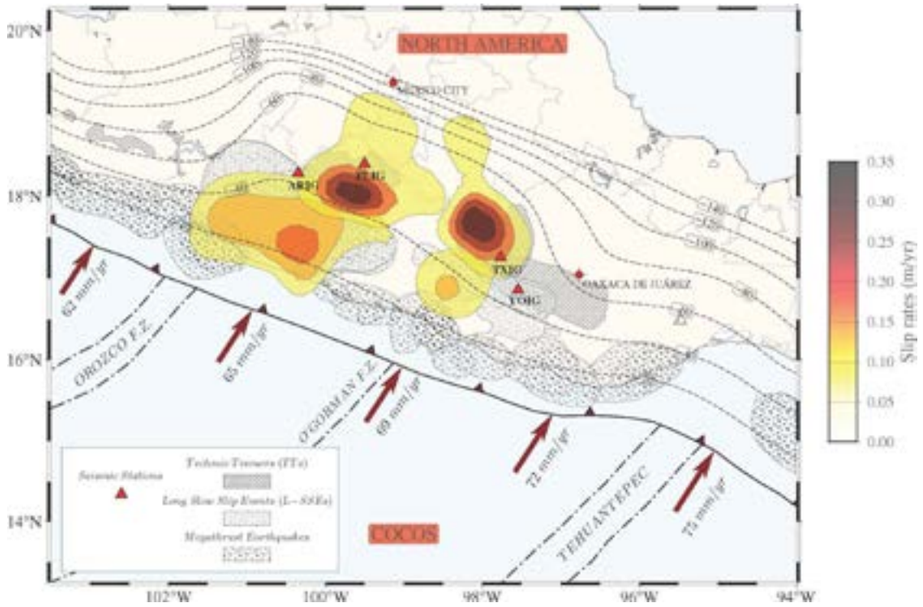
Supervisor: Mathilde Radiguet

Fault mechanics

In my work I study slow slip phenomena in the southern Mexican subduction sone. This area is characterized by a sub-horizontal slab, hosting recurrent slow slip events. These events can be of different sizes (up to magnitude 7.5) and they play a major role in the seismic cycle.

In this work we want to understand the dynamics and mechanics of these events with help of geodesy and seismology, as these events occur along with tectonic tremors.

Tremors show a complex dynamic of slow slip events. During tremors, large and long-lasting slow slips show an intermittent stress release behavior in the shallow part of the subduction, close to the trench (southern patches on the figure). While in periods between these large slow slips, small and short-lasting slow slips occur deeper in the subduction (northern patches on the figure).



Slip rates for large and small slow slip events. The shallow patches (close to the trench) correspond to slip rates for large, long-lasting slow slip events. The deeper patches (further from the trench) correspond slip rates to small and short-lasting slow slip events. The red triangles are seismic stations for which tremor catalogs are used in this work.

Fandy Adji FACHTONY

4D FWI with Reflection Oriented Workflow

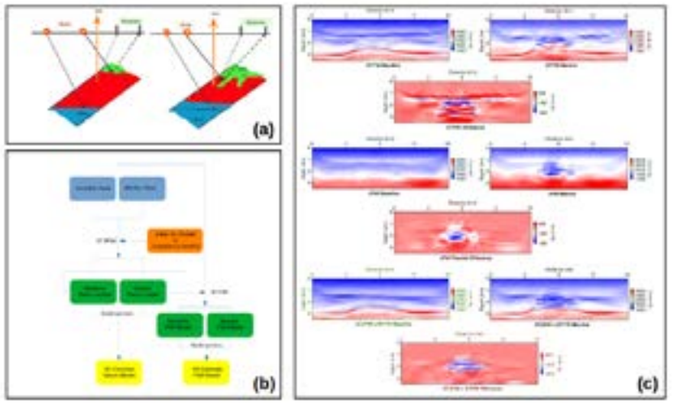
Supervisors: Romain Brossier, Ludovic Métivier

Waves & structures

Full waveform inversion (FWI) has become a standard tool for exploration seismic to deliver high resolution seismic images of the subsurface. When it comes to track the temporal evolution of the subsurface elastic properties, the use of FWI is still at a relatively experimental stage. The temporal evolution of the subsurface can be approximated by simple subtraction between two different models obtained by FWI, baseline and monitor respectively. However, a simple subtraction between two reconstructed FWI models suffers from artifacts due to the non-linearity and ill-posedness of the underlying inverse problem.

For most of time lapse applications, most of the available data sets are vintage seismic data which are mainly acquired with limited offset geometry. For FWI applications, limited offset implies the following limitation: the diving waves cannot sample the deep part of the model. Consequently, FWI is limited to high wavenumber perturbations (migration isochrone) at depth, which mainly contribute to the creation of interfaces rather than updating the background model. One possibility to circumvent this difficulty while relying on finite-frequency full waveform modeling approaches is to use Reflection oriented Waveform Inversion (RWI) which uses only the low wavenumber component to update the model beyond the depth sampled by diving waves (Xu et al., 2012).

In this work, we want to assess the interest of integrating the RWI workflow for 4D FWI in the context of short offset data. As for 4D strategy, we choose to utilize the simultaneous time lapse FWI (STFWI) proposed by (Maharramov et al., 2015) to enforce inversion coupling between data set. In a hierarchical manner, we combine the JFWI workflow with a simultaneous 4D approach which we call simultaneous time lapse JFWI (STJFWI) to infer reflection based 4D macromodel.



(a) Illustration of seismic time lapse problem.
(b) Reflection oriented workflow for 4D FWI problem.
(c) Synthetic comparison between standard 4D FWI method and reflection oriented FWI strategy.

Ilya FIRSOV

Constraints on the radial shear of the flow at the Earth's core surface

Supervisors: Nicolas Gillet, Dominique Jault, MANDEA Mioara (CNES)

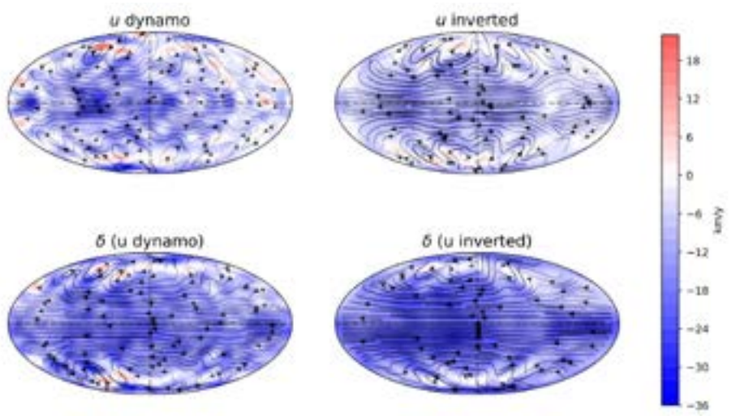
Geodynamo

The inversion of the rate of change of the magnetic field (or Secular Variation), using the radial induction equation to calculate the velocity of the core surface flow, has classically been performed with the use of the toroidal and poloidal representation of the horizontal part of the velocity at the CMB. There is room to use more information from physical conditions at the CMB, and thus to add new constraints on the velocity field during the inversion process.

We assume that the mantle is an insulator: no electrical currents can go through it, so there are no radial currents at the CMB, and the induced magnetic perturbation should attach to a potential field. Also, because there are no toroidal currents, the poloidal part of the magnetic field has to be continuous from the Earth's surface to the Earth's core. These constraints have been important for the discovery of interannual Magneto-Coriolis modes by Gerick et al. (2021).

Knowing the flow and magnetic field we can invert for the shear using boundary constraints equations. Using stress-free boundary condition at the Core surface, it is possible to estimate shear as being a priori equal to the flow. The estimation of radial derivative of the horizontal flow was done using the synthetic dynamo data. This allowed to verify first the inversion for the flow and then to check the difference in the estimation of the shear from either the surface flow directly extracted from the simulation or the flow inverted from the dynamo secular variation, plus geomagnetic data.

All the tests that have been done show high a correlation between the recovered shear and flow and, for synthetic path dynamos, we obtain a minimum misfit between the shear and flow when, as assumed, the shear is close to the flow.



Comparison between the flow (top) and shear (bottom) for synthetic experiment using 50%-Path dynamo. Shear calculated respectively from the surface flow directly extracted from the dynamo simulation (left) and the flow inverted from the dynamo secular variation (right). The color scale gives the amplitude of the phi component.

Thomas FRASSON

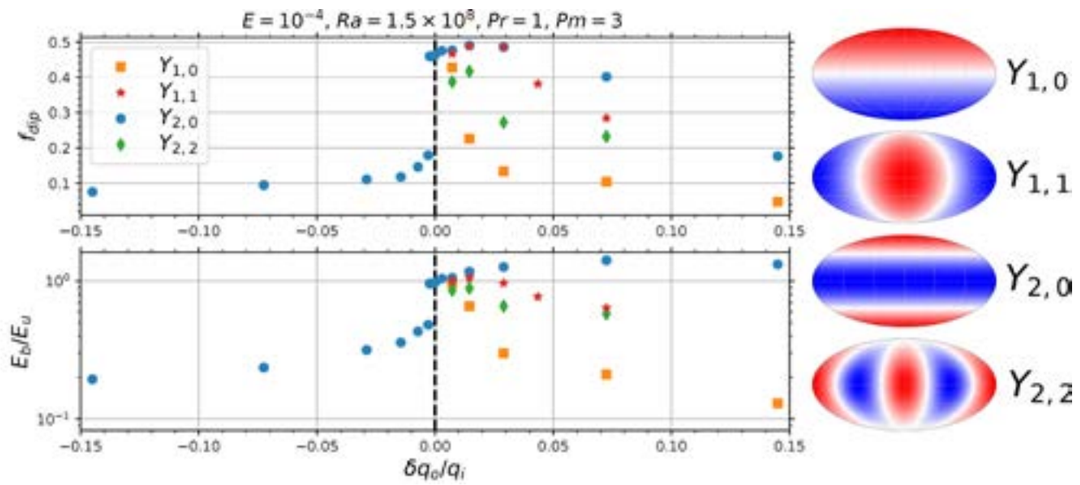
How does the mantle influence the magnetic reversals ?

Supervisor: Henri-Claude Nataf

Geodynamo

The chaotic reversals of the Earth's magnetic field have been reproduced since the first numerical geodynamo simulations. The question of the reversal frequency variations in the paleomagnetic record is, however, still open. The heat flux at the core-mantle boundary (CMB) is one of the simulation parameters influencing the reversal frequency of the magnetic field. Inside the Earth, the CMB heat flux is controlled by mantle convection, with possibly large lateral variations. This could thus be a significant parameter influencing the dynamo and explaining variations in the reversal frequency due to a coupling of the liquid core with a variable heat flux at the CMB.

The goal of this PhD is to study how the mantle convection affects the geodynamo and the magnetic field reversals through the CMB heat flux. For this purpose, we use the results of mantle convection models to obtain CMB heat flux maps. Those maps are obtained by computing a principal component analysis (PCA) of the CMB heat flux. We use two different models to compare a convection model driven by plate reconstructions and a convection model reproducing plate tectonics fully self-consistently. We then use geodynamo simulations to assess the effects of the PCA heat flux patterns and simpler geometries on the geodynamo. We are especially interested in the differences between polar cooling and equatorial cooling of the core. Our results show that cooling the core at low latitudes favours multipolar dynamos over dipolar dynamos. Going towards more realistic dynamo models allows for intermediate dynamos that are mostly dipolar while including reversals when an equatorial cooling of the core is applied.



Dipolar fraction of the magnetic field (top) and ratio of magnetic to kinetic energy (bottom) in geodynamo simulations using heterogeneous heat flux patterns as a function of the heterogeneity amplitude. The heat flux patterns are shown on the right. Polar and equatorial cooling of the core correspond both to the Y2,0 pattern with positive and negative amplitude respectively.

Nataliya GALINA

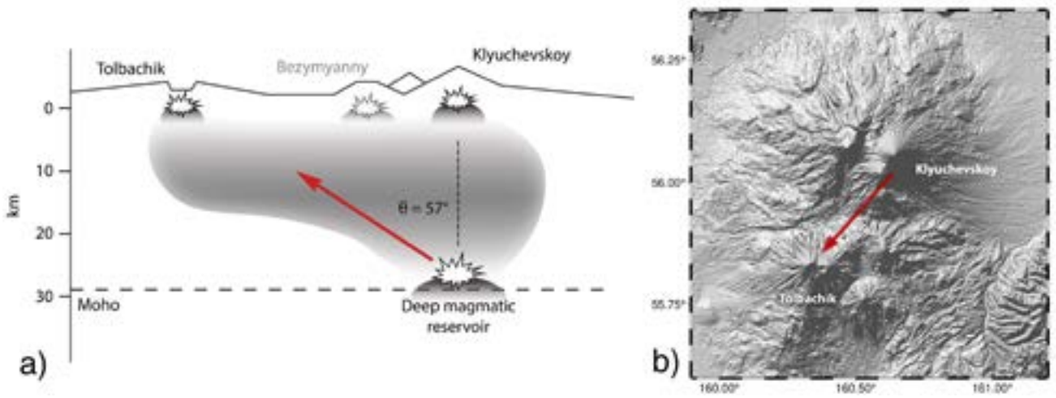
Study of deep long-period earthquakes beneath the Klyuchevskoy volcano group in Kamchatka, Russia

Supervisor: Nikolai Shapiro

Waves & structures

Seismicity is one of the main manifestations of volcanic activity. Seismic manifestations of volcanic activity, the so-called volcanic earthquakes, are very numerous and various. The observed seismic signals correspond to different types of volcanic seismicity occurring at different depths. Over time, it became obvious that these signals contain information about impending eruptions, the dynamics and state of magmatic systems. Timely detection of these signals and their comparison with various types of activity is the basis of seismological monitoring of volcanoes.

The work aims to study the physical mechanism of long-period earthquakes of the Klyuchevskoy volcano group, namely, earthquakes that occur at the crust–mantle boundary. It is believed that this type of seismicity can be used as precursors of eruptions, as it reflects the state of the magmatic system. It is assumed that the physical mechanism of the described earthquakes differs from the mechanism of ordinary tectonic events. To the present moment, the physical mechanism of these earthquakes is poorly understood. This thesis summarise the results of studying the described phenomenon using seismological data from the region investigated with different approaches (statistical analysis, machine learning, source inversion) to show the new interpretation of processes occurring in the magmatic system of the Klychevskoy volcano group.



Possible interpretation based on the obtained results: deep long period earthquakes is the result of an expanding sill in the vicinity of the deep magma chamber that pushes magma towards the Tolbachik volcano. A red arrow shows the vector direction of a traction force caused by magma movement. a) A cross-section along the Klyuchevskoy volcano group. b) A view from the top.

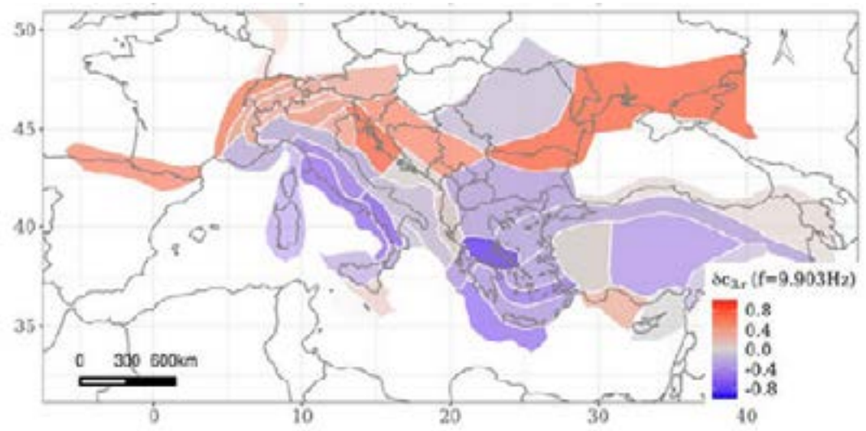
Pauline GEORGES

Regionalisation of ground motion models

Supervisors: Emmanuel Chaljub, Sreeram Reddy Kotha

Geophysics of seismic and gravity risks

Probabilistic seismic risk assessment is an estimate of probability of exceeding a specific level of social and economic consequences at a specific location in a specific duration of time due to earthquakes in its vicinity. Such probabilistic assessments are of great importance to decision making at national/international levels and development of resilient urban environments. The ground motion produced by earthquakes are modeled using the so-called Ground-Motion Models (GMMs). Several assumptions are made to simplify the very complex physics of the earthquake rupture dynamics, the seismic wave propagation, and the response of the surface geology to incoming seismic waves; from absence of data and of relevant physical parameters. Consequently, the simplified model predictions can be inaccurate and imprecise. This project aims at checking the relevance to apply the GMM's developed in area with abundant seismic data in others with poor data. Especially, it aims at characterizing the regionality of seismic ground motion. The first step consists in evaluating current regionalisation models used in ESHM20 and ESRM20, and refine them for use in a revision of existing regionally adaptable GMMs. The second step will explore new regionalisation parameters and models. The availability and applicability of regionalisation datasets, such as crustal velocity models, Mohorovicic boundary maps, 1Hz coda Q maps, seismic moment rate maps, stress-drop maps etc., will be evaluated for use with GMMs. The third step will aim at creating the next generation of regionalised GMMs. Based on outcomes of step 2, the new regionalisation models will be used to develop new regionalised GMMs for all of Europe Building upon the backbone-GMMs of European Seismic Hazard and Risk Maps 2020, (ESHM and ESRM20) this project aims to develop the next generation European GMMs.



c3,r variation across the 45 regions in ESM dataset for f = 10Hz. Blue polygons locate regions with anelastic attenuation faster than the pan-European average, red polygons locate regions with slower attenuation, and grey polygons are regions close to the average. Regions with fewer ground-motion observations, thereby larger epistemic error on c3,r , are more transparent and appear fainter.

Loïc GISSELBRECHT

Seismic site effects estimation using ambient noise recordings on a dense array

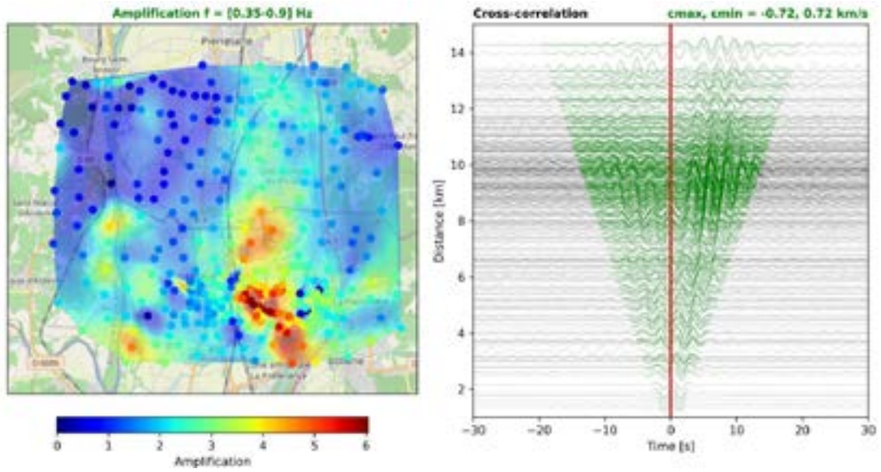
Supervisor: Pierre Boué

Waves & structures

Shallow sedimentary layers may be responsible for dramatic ground motion amplification and increase the duration of shaking when an earthquake occurs. These local modifications of ground motion are usually associated with site effects. Often associated with sedimentary basins, site effects are due to the impedance contrast at the interface between soft soil layers filling the basin and the bedrock. For site effects assessment, methods based on ambient noise might be of great interest in low-to-moderate seismicity regions.

In this thesis we evaluate the applicability of noise-based methods to assess site effects in the Tricastin region in the French Rhone Valley. This area is prone to generate complicated site effects associated with the valley's incised geometry and the strong lithological contrast between the sedimentary filling and the bedrock. We recorded ambient noise between February to March 2020 on a 400-sensors array. Previous studies have shown that important source effects might bias the resulting amplification factor of noise-based methods above 1 Hz. To attenuate these local source effects, we introduced a two-step workflow based on the spectral characteristics of the signal. Our workflow relies on a careful time window discrimination for removing strong transient signals and an automatic data selection through a clustering algorithm. By applying this method, we were able to remove strong anthropic transient signals at some sites and therefore improve the amplification assessment above 1 Hz through SSRn and SSRh. We also show that some sites are biased by permanent sources that remain an issue in quantifying the amplification at larger scale.

We currently explore new strategies based on interferometric methods to overcome the limitations of these approaches. By involving phase coherence, we expect the correlations to better filter uncoherent local sources and give better estimates of the amplification.



Amplification results extracted from deconvolutions computed between the rock reference station and the array for TT component at low frequency (0.35-0.9 Hz)

Elisabeth GLÜCK

Multi-scale high-resolution geophysical imaging of Krafla sub-volcanic system

Supervisors: Stéphane Garambois, Jean Vandemeulebrouck

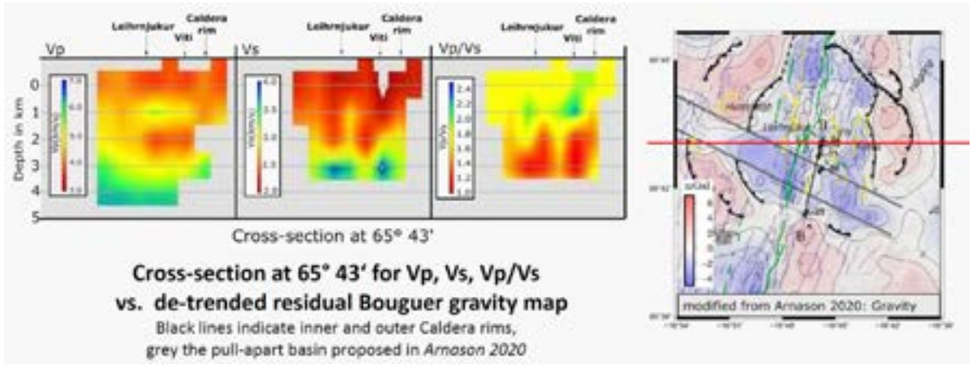
Waves & structures

The IMPROVE ITN project focuses its interdisciplinary approach on a better understanding of volcanic systems, partly with multiphysics imaging methods. One target of this project is Krafla, a volcano in northern Iceland, which erupted last with the Krafla fires in the 1970s and 80s. Also, in this period the national power company of Iceland (Landsvirkjun) built a geothermal powerplant inside the Krafla caldera, increasing the knowledge of the complex system through electro-magnetic and seismic imaging methods and seismological observations.

Nonetheless the high-resolution imaging of the magmatic system still poses a challenge just as the origins of the seismicity remain poorly understood.
Thus, a multi-physics experiment has been carried out in June and July 2022, which included an active 3D ERT experiment to image the first kilometre of the geothermal system, the densification of the already existing MT measurements and the installation of a dense seismic array of 100 3-C nodes deployed for 1 month. In addition, Landsvirkjun provided continuous seismic data acquired from 12 broadband 3-C stations over the last 9 years.

From this long-term broadband dataset, we selected 800 volcano-tectonic events, picked the first P- and S-wave onsets manually and inverted using a joint hypocentre-velocity tomography. This provides a new 3D P- and S-wave velocity model and refined locations of the seismicity. In a next step the picks of these 800 events will be used as reference picks for automatic detection and picking to analyse the whole 9-year dataset.
This updated earthquake catalogue will also cover a deflation and an inflation period of Krafla, yielding the opportunity to better investigate the seismicity properties in relation with geothermal industrial activity and long-term deformation of the volcano.

In the future, the dense seismic array will be used for high resolution imaging at the geothermal upflow-systems and jointly interpreted with the ERT and MT data.



Comparison of the first tomography results with other geophysical observations (in this example gravity)

High resolution 3D characterization of the Argentière glacier structure by waveform inversion.

Supervisors: Ludovic Métivier, Romain Brossier, Philippe Roux

Waves & structures

Glaciers represent almost 70% of the drinking water on Earth. A better understanding of their behavior and their mechanisms is therefore of crucial importance in the current context climate change.

For this purpose, a network of 98 3-component sensors was deployed on the Argentière glacier in the French Alps (RESOLVE project). This network recorded the displacements at the glacier surface for 1 month continuously during spring 2018, allowing the acquisition of an exceptional data set.

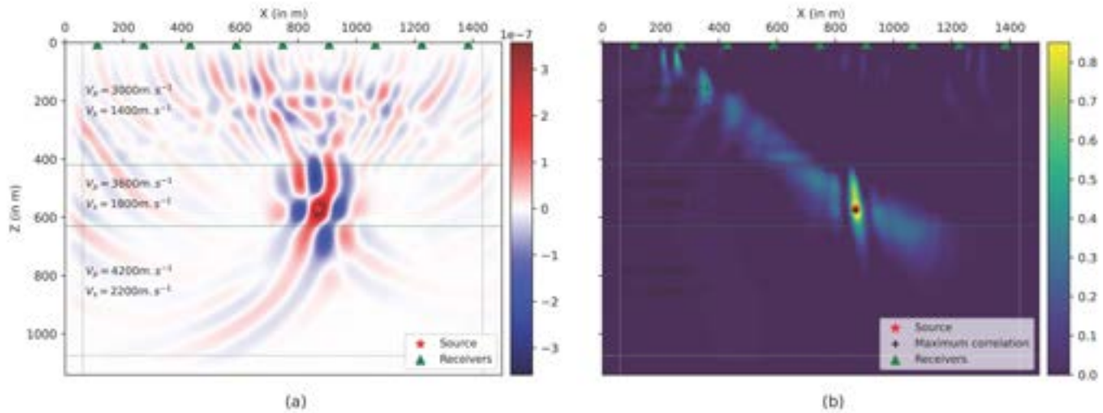
The objective of this project is the development of a joint inversion method based on the full waveform allowing the 3D reconstruction of the glacier structure, the location of the icequakes at the origin of the recorded signals as well as the description of their temporal mechanisms. A qualitative leap in model resolution and source location (icequake) is expected with the use of the full waveform compared to conventional methods based on surface wave dispersion curves and 1D propagation approximations.

The first step of the project consists in investigating different source location methods based on the concept of signal backpropagation. The data observed at each sensor is time-reversed and injected as a virtual source at the receiver positions in order to back-propagate the signal. Imaging conditions using the correlation between the different back-propagated fields (from the receivers separately) then make it possible to obtain a static image representing a spatial correlation map with a focal spot concentrated at the source. Indeed, the same icequake being at the origin of the recorded signals, the correlation of the back-propagated fields is high close to the spatial position of the source.

Preliminary localization results on 2D synthetic tests show that the correlation of back-propagated fields provides us with fairly precise information on the position of a point force source even in the case of propagation in an elastic medium made up of several homogeneous layers.

Arthur GRANGE

High resolution 3D characterization of the Argentière glacier structure by waveform inversion.



Synthetic example of a 2-point-force source location in a 2D elastic medium with increasing P and S wave velocities. (a) Back-propagated field from all receivers (green triangles) simultaneously at time t=0.75s (time-reversed) with focusing at the source position (red star). (b) Static image obtained from the correlations of back-propagated fields from each receiver separately. The focal spot at the source is clear, the maximum point correlation (black cross) is very close to the source.

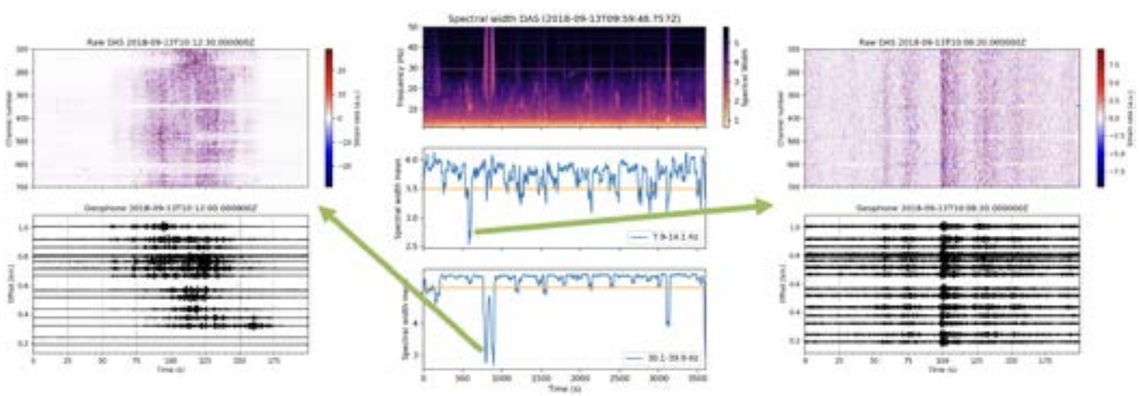
Julius GRIMM

Coherence-based methods for new instruments and heterogeneous datasets

Supervisors: Piero Poli, Cédric Schmelzbach (ETHZ)

Waves & structures

With the advent of large and heterogeneous datasets (e.g., Distributed Acoustic Sensing [DAS], dense arrays of nodes) it is possible to discover new, ‘hidden’ signals, besides earthquakes. These signals can directly inform us about the spatiotemporal evolution of elastic properties on a fault (e.g., processes occurring during earthquake nucleation, volcanic eruptions, etc.). In this project we will develop and apply coherence-based methods for new instruments and heterogeneous datasets, exploiting the different sensitivities of different sensors. This combination of technique and new data will be used to detect tiny and exotic signals (e.g., tremor-like, emergent) often escaping routine analysis. The coherence features will be used to obtain a global view of the wavefield, for a rapid identification of anomalous signals, and classification of large seismic datasets through clustering algorithms. During this project, different datasets will be explored, including DAS and dense array of nodes installed in volcanic areas, close to major seismogenic faults, and/or on glaciers.



Detection of seismic signals recorded on a fiber-optic cable deployed at Mount Etna, Italy. The top middle plot shows the spectral width computed for one hour of DAS data. Averaging in different frequency bands allows to easily detect transient seismic events. Examples of waveforms are shown both for DAS and collocated geophones.

Shan GRÉMION

Real-time InSAR and GNSS processing for magma source and magma propagation modelling aimed at volcano monitoring

Supervisors: Virginie Pinel, François Beauducel

Geophysics of volcanoes & geothermal energy

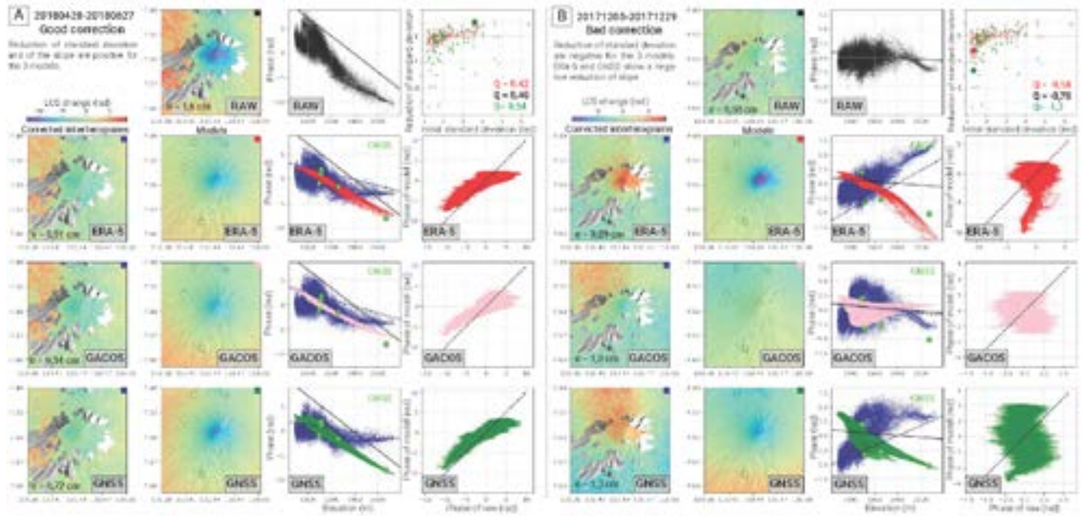
Merapi is a strato-volcano rising at 2900 m a.s.l, located on the South coast of Java island, Indonesia.

Only 30 km north to the city of Yogyakarta, it is considered one of the most dangerous dome building stratovolcanoes. Merapi is therefore routinely monitored by InSAR (Interferometric Synthetic Aperture Radar) to track ground deformation. To retrieve ground deformation from the full wave path, the delay due to the wave crossing the atmosphere needs to be corrected. In the case of Sentinel-1, interferograms are mostly biased by the tropospheric variations. Tropospheric variations are expected to be stronger in tropical regions and where topographic gradient is high, which is the case at Merapi. They can be estimated thanks to various methods, including global weather models (ERA-5 and GACOS), a linear model regarding topography, and GNSS (Global Navigation Satellite System) networks. Tropospheric delay maps are computed and used to correct interferograms.

We compare the performance of atmospheric corrections derived from global models ERA-5 and GACOS, and those derived from the local GNSS stations.
To this end, we choose to study a period between 2016-2018 during which no deformation occurred on the Merapi. We use three criteria to evaluate the performance: the reduction of the standard deviation, the reduction of the sill of the semi-variogram, and the slope reduction of the phase-elevation relation. Regarding the standard deviation reduction, we show that corrections with ERA-5 and GACOS are efficient on only half of the interferograms, and even less with GNSS. Moreover, we observe that at Merapi, the tropospheric delay is mostly stratified. Therefore, interferograms with a strong stratification are well corrected by atmospheric models, but interferograms that show low tropospheric variations are overcorrected by models. Our aim is to take advantage of the local GNSS to provide either GNSS tropospheric maps, either a criteria to select epochs that would need corrections or not.

Shan GRÉMION

Real-time InSAR and GNSS processing for magma source and magma propagation modelling aimed at volcano monitoring



Comparison of a good correction (A) and a bad correction (B) by tropospheric models. The level of atmospheric noise can reach up to 2.7 cm on a scale of 30 km (sill from semi-variograms). Good corrections reduce the level of tropospheric noise when the initial interferogram contains a large stratified signal, and inversely for bad corrections. It shows the quality of the the correction depends on the initial level of stratified atmospheric noise in the interferogram, as models mostly reflect the stratified part of the troposphere.

Caroline GUIDA

Characterizing the mechanisms controlling rhenium, selenium, and gadolinium sequestration under oxygen-depleted conditions

Supervisors: Laurent Charlet, Central Michigan University

Geochemistry

Trace elements are ubiquitous on Earth despite their low abundance. Some can either be micronutrients or toxic, while others display unique properties for industrial and medical applications. Finally, many trace elements are now listed as critical metals by the European Union. The biogeochemistry of trace elements in natural aquatic systems, where oxygen is absent, is influenced by a complex interaction of biological, chemical, and physical processes. Many processes governing the reactivity of certain trace elements remain unclear. The goal of my Ph.D. research project aims to fill this knowledge gap for three unique trace elements: Rhenium (Re), selenium (Se), and gadolinium (Gd). Rhenium is a metal and a recognized critical metal. It is mainly used in high-temperature superalloys to manufacture jet engine turbine blades and platinum-rhenium catalysts for the petrochemical industry. Rhenium has been used as a paleo-redox proxy to study ancient environments. Selenium, a metalloid, is a bioessential element at low concentrations but becomes toxic at high concentrations. Se is used in the metallurgic industry for producing electrolytic manganese as an additive in the steel manufacturing process and is a pollutant from coal mining and nuclear power plants. Gadolinium is a rare earth element and a critical metal too. It is an emerging contaminant because of its wide use as a contrast agent in magnetic resonance imaging (MRI).

The first focus of my Ph.D. project deals with investigating the interactions of Re, Se, and Gd with magnetite and pyrite under ferruginous and sulfidic conditions via an experimental approach. A second focus explores the geochemistry of these three elements in natural sedimentary systems. My thesis will consist of four chapters. The first chapter introduces why some trace elements have a better affinity for sulfur in anoxic environments through a literature review and an experimental study of the speciation of Re in sulfidic water. The second chapter presents new findings from a series of different adsorption and co-precipitation experiments to enhance the bonding of Se, Re, and Gd with magnetite and pyrite solids. The third chapter focuses on interpreting the geochemistry of Re, Se, and Gd in natural sediments buried under anoxic conditions. An array of complementary methods were used to characterize our experimental and natural samples: TEM, XRD, 57Fe Mössbauer spectrometry, XAFS spectroscopy, colorimetric analysis, ICP-MS, and MC-ICP-MS. Finally, the fourth chapter will discuss future research directions. Ultimately, my Ph.D. research will shed new light on the study of paleoenvironments, recycling of critical metals, mining processes, and nuclear waste management.

Molecular interaction of Se, Re and Gd in sulphidic and ferruginous environments.

Carlos HEREDIA AGUILAR

Multi-isotopic tracing of historical mining pollution in European environmental archives and their impact on populations

Supervisors: Alexandra Gourlan, Stéphane Guedron, Laurence Audin

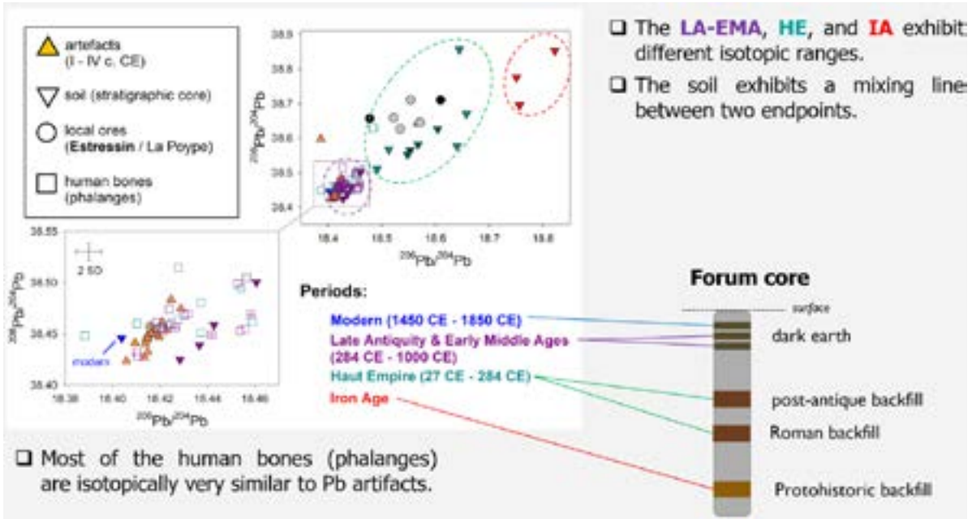
Geochemistry

Metallurgy is central to the development of ancient and modern societies. Lead, which started as a by-product during Antiquity, has boosted economic and sociocultural developments through the manufacturing of various tools, and urban pipework [1]. While elemental deposition rates of metals (such as Pb, Cu, Fe, or Hg) in sedimentary records have proven useful for quantifying the intensity of past metal emissions, few studies use their isotopic composition to identify the specific mining sources and the impact that these activities can have on human's health.

Here, we combined the elemental and isotopic composition of Pb of several lead artifacts (mainly pipes), ores, sedimentary archives, and human bones from the ancient city of Vienne (France) in order to i) trace de sources of mined ores that supplied the manufacturing demand of lead artifacts at Vienne (1st to 3rd century AD).

The lead isotopic composition of most of the artifacts differs from those of the local ores, suggesting a more distant source, like the Eifel region in Germany and the British Island. Our results also suggest that human exposure came mainly from water consumption and ore processing (particle inhalation).

These results improve our understanding of the Roman trade of lead and the impact of ore processing and casting during Antiquity.



Lead isotopic composition of artifacts (triangles), local ores (circles), human bones (squares), and soil from the stratigraphic core collected from the ancient Forum at Vienne (France).

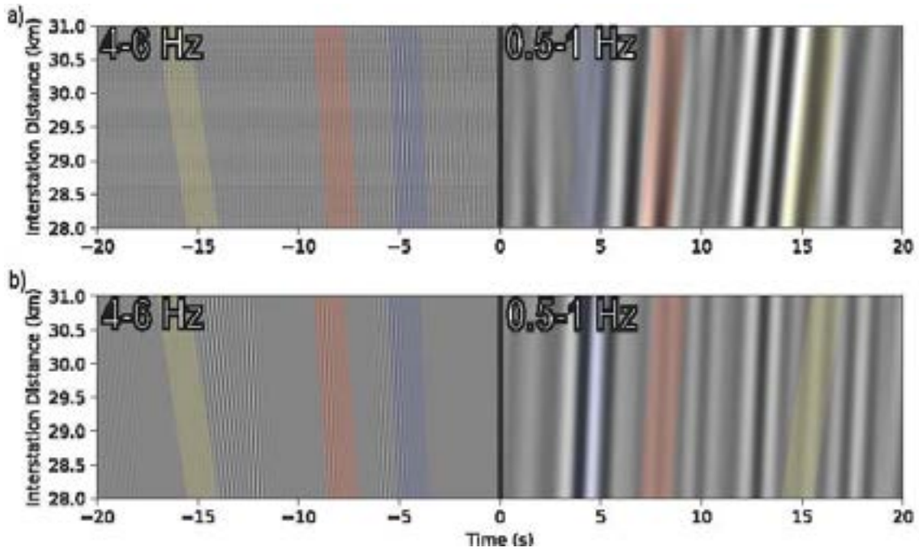
Quentin HIGUERET

Seismic study of the San Jacinto Fault dynamics using dense arrays

Supervisor: Florent Brenguier

Waves & structures

We use seismic interferometry to monitor seismic velocity changes within the San Jacinto fault in California. To infer those changes, we focus on using repetitive anthropogenic noise sources like freight trains and also wind driven ocean wave interaction that mainly produce body waves to gain more insight into the processes around the depth of the seismogenic zone. However, the Green function retrieval conditions are not fulfilled when using such localized noise sources because they are not homogeneous in space and time. Hence, it is essential to better understand the type of waveforms (interpretable P, S, or surface waves) we see in the correlation functions obtained when correlating these types of sources. This waveform information is closely related to the computation of sensitivity kernels that provide insights into how the earth's structure is linked with these waveforms, especially the sensitivity of these measurements to velocity variations at depth. We use 3D numerical simulations and adjoint methods to model noise correlations for any power-spectral density distribution of sources to assess these sensitivities. The modeling is done accurately, with no approximations, and without requiring any of the conditions needed for Green's function retrieval. Therefore, we can use the correlation waveforms as self-consistent observables, eliminating the need to invoke Green function retrieval between pairs of stations. By comparing synthetic and observed correlation functions on the San Jacinto fault in California, we validate our modeling approach and accurately assess the depth sensitivity of our monitoring observations.



a) Observed Causal and anti-causal stacked noise correlations between two dense array using distance-averaged bins.
b) Synthetic correlogram obtain through simulation considering only the P wave energy emitted by the noise source. The right panel displays the strong P wave generated by wind-driven ocean waves (0.5-1 Hz), while the left panel shows the powerful body wave arrival generated by a train as the noise source (4-6 Hz).

Robin HINTZEN

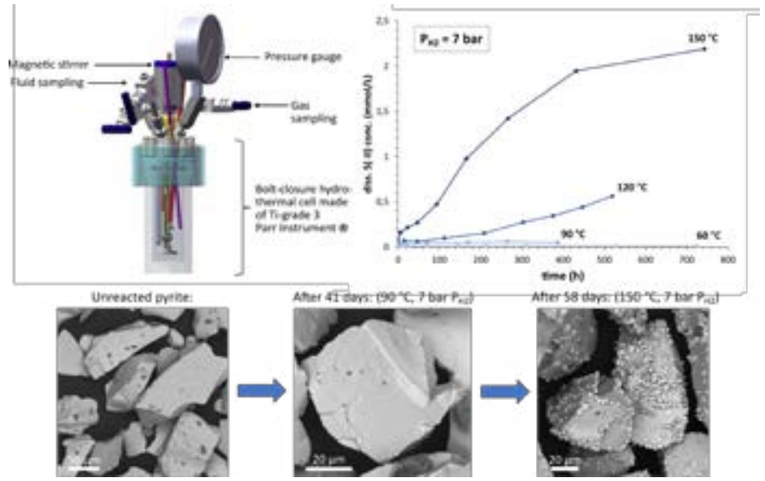
Abiotic reactivity of minerals at elevated H2 concentrations

Supervisors: Laurent Truche, Roland Hellmann

Mineralogy and Environments

H2 is a future energy storage medium, as excess energy from renewable sources can be used to produce green H2. Large-scale H2 storage in geologic subsurface environments (e.g. salt caverns, depleted natural gas fields, porous rock aquifers) is, therefore, anticipated as part of the energy transition. However, very few studies have investigated fluid-rock-H2 interactions at conditions relevant for underground storage (40-120 °C, PH2 up to 250 bar), including the production of H2S as a gaseous by-product phase (Truche et al. 2010, 2013).

To address these issues, the reaction kinetics of reductive pyrite dissolution at conditions relevant for underground H2 storage are currently being investigated at T = 60-150 °C and PH2 = 7 bar (70 bar Ar/10%-H2 gas mixture) in Ti-batch reactors, whereas other experiments at PH2 >> 7 bar (pure H2) are being performed in stainless steel batch reactors at 90 °C. The experiments are based on natural pyrite (50-100 µm) altered in 30 mmol/L NaCl solutions buffered to pH ≈ 8 by calcite. The temporal evolution of dissolved sulfide concentrations is determined using electrochemistry, photometry, and an SO42--derivative approach coupled to ICP-OES. After periods of 3-4 weeks approximate steady-state dissolved sulfide concentrations of 0.02-2.0 mmol/L at 60-150 °C have been measured, in addition to gaseous H2S production. SEM of post-mortem pyrite grains reveals the formation of authigenic pyrrhotite (Fig. 1). Experiments using pyrite bearing trace amounts of native sulfur (< 1 wt.%) correlate positively both with significantly faster initial sulfide release kinetics and higher total dissolved sulfide concentrations at the same T and PH2 conditions, suggesting that the reduction of native sulfur is another source for H2S.



Upper left: Continuously stirred batch reactor design applicable for in-situ fluid and gas sampling. Upper right: Measured dissolved S-II concentration (mmol/L) as a function of time (h) in experiments altering pyrite at different temperatures from 60-150 °C at 7 bar PH2. Bottom: BSE-SEM images illustrating increasing pyrite alteration stages by the growth of secondary pyrrhotite.

Nicolas JAISLE

Magma Oceans in Exoplanets

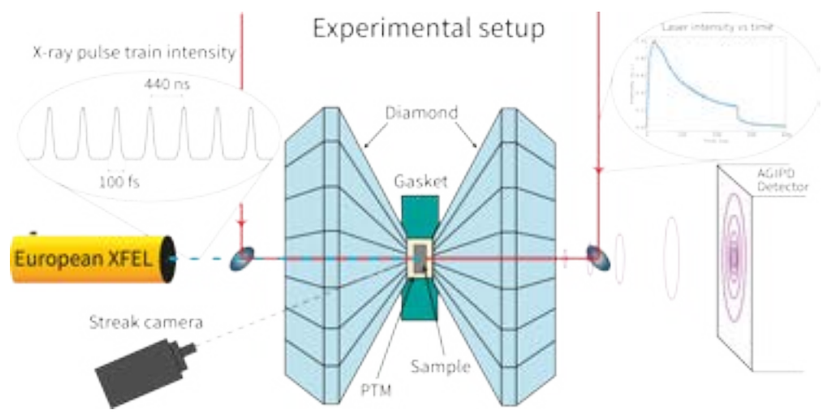
Supervisors: Guillaume Morard, David Cébron, Angelika Rosa (ESRF)

Geodynamo

The study of magma ocean crystallization and partial melting in the deep Earth is of prime interest to understand terrestrial planets evolution from early days up to late differentiated bodies. This understanding of planets mass distribution and chemical evolutionary pathway goes along with the determination of phase diagram and partial melting properties. In that context, we describe a combined experimental and numerical approach to study pure Fe and FeSiO alloys under high pressure and temperature.

A new fiber Laser Heating Diamond Anvil Cell (LH-DAC) setup, combined with MHz X-ray Diffraction (XRD) at the European X-ray Free Electron Laser (EuXFEL) was used to overcome possible issues within LH-DAC experiments when working with alloys. These potential biases, often designated as chemical migration, are mainly related to the temperature gradients (inherent to LH) within the sample. The presented setup is based on pulsed laser heating, which aims to limit the duration of huge temperature gradients within the sample.

To enhance experimental results, we present a Finite Element Model (FEM) reproducing experimental temperatures and pressures over the experiments µs time scales. A good agreement is found between experimental and numerical values by adjusting less constrained parameters as intensity, iron thermal conductivity and liquid KCl thermal conductivity. We use model outputs (by thermal stress corrected temperature maps) to reconcile Streak Optical Pyrometry (SOP) and XRD data by exploiting model capabilities to sound for temperature and pressure gradients. Moreover, models stress and strain calculations allow for thermal pressure determination over sample and pressure transmitting medium, crucial for accurate XRD interpretation.



Schematic (i.e. not at scale) representation of the whole setup employed at the European X-ray Free Electron Laser (EuXFEL) facility to achieve MHz X-ray Diffraction (XRD) in Laser-Heated Diamond Anvil Cell (LH-DAC). From left to right are schematized (i) the XFEL source, (ii) DAC, (iii) AGIPD XRD detector. Red lines coming onto the DAC from both sides represent the pulsed fiber laser heating. Turquoise dots on top of the laser coming from the EuXFEL source represent the X-ray pulses.

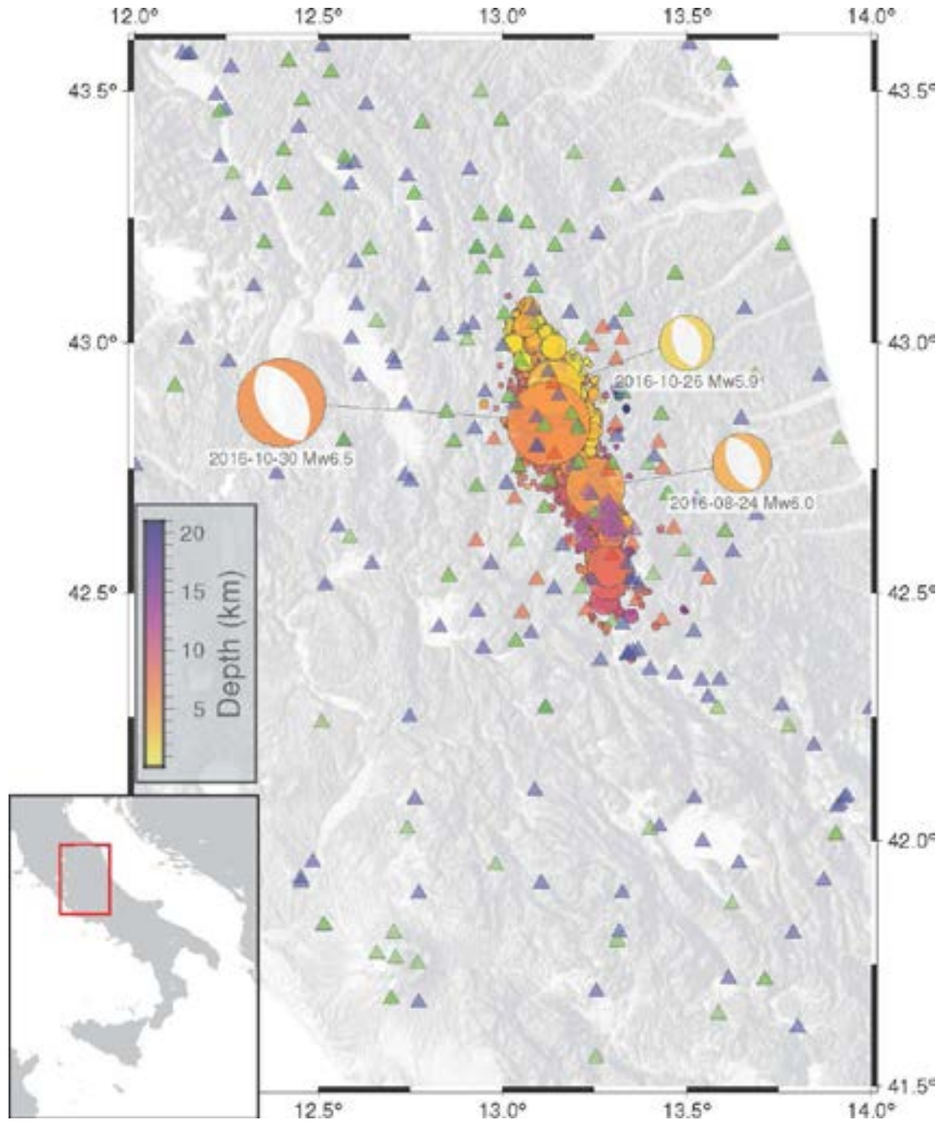
Spatial and temporal diversity of rupture characteristics and impact on ground-motion prediction for earthquake sequences

Supervisors: Mathieu Causse, Sreeram Reddy Kotha

Geophysics of seismic and gravity risks

The main idea of this thesis is to better quantify ground motions caused by earthquakes in the vicinity of a fault, including large earthquakes (mainshock), and their aftershocks, and investigate the underlying physical processes. To that end, we focus on the 2016 central Italy seismic sequences. Since near-fault ground motions caused by the mainshocks are highly sensitive to the rupture process, the kinematic source modelling of the Norcia mainshock is first performed using an innovative Bayesian inversion method. To achieve this goal, strong motions recorded at the near-field stations are used to provide high-resolution space-time evolution of the rupture propagation on the considered fault plane. This method avoids the complexity and uncertainty associated with using a velocity structure model and a numerical approach to compute Green's function by utilizing aftershocks occurring near the fault plane. These aftershocks provide the propagation path and site characteristics required for accurate modelling. Smaller aftershocks can damage the structures that have already been weakened by the preceding mainshock. Therefore, predicting ground-motion during a seismic sequence, including not only mainshocks but also the aftershocks, is a critical goal to seismic hazard and risk assessment. During a seismic sequence, it has been observed that after a large earthquake, the aftershock ground motions suddenly decrease and then gradually increase during the post-seismic period. This may be caused by modification of the Earth's crust during the mainshock rupture process by creating cracks in the fault vicinity, and during the wave propagation by perturbing the crustal medium beneath the ground surface. To begin, a Ground Motion Model (GMM) and a mixed-effects regression are then used to quantify the variability of ground motions and find out the physical processes behind. The mixed effect regression yields two residual models of between-event and within-event. The between-event temporal changes will be interpreted by stress drop. In contrast, the within-event residuals will reflect the potential variability of frequency-dependent site amplification.

Jafar KARASHI



This figure shows the spatial distribution of the seismic sequence along with the broad-band and strong-motion stations used in this study. The beach balls depict the three mainshocks, Amatrice (Mw 6.0), Norcia (Mw, 6.5), and Visso (Mw 5.9), characteristics.

Tatiana KARTSEVA

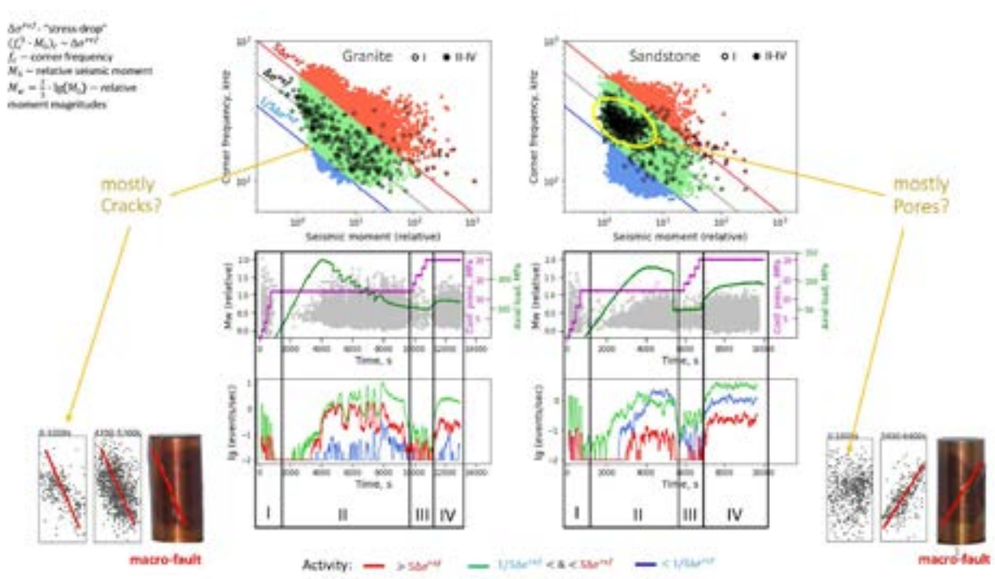
Coda-Based Estimation of Acoustic Emission Source Parameters

Supervisor: Nikolai Shapiro

Waves & structures

An approach that is aimed to enrich the catalogs of acoustic emission events recorded in laboratory experiments with such parameters as seismic moment and corner frequency was developed. Because of the difficulty of separation of direct waves in experiments performed on small samples, we use the coda waves that are composed of the reverberation of the acoustic field in the tested sample. After multiple reverberations, the resulting wavefield can be approximated as nearly homogeneously distributed over the sample and with signal amplitudes decaying exponentially in time (linearly in a logarithmic scale). Spectral ratio method is used to eliminate the unknown sensor and medium responses and to estimate main source parameters such as corner frequencies and relative seismic moments.

Two experiments with similar loading histories carried out on pseudo-triaxial test on two different samples – Voronezh granite and Berea sandstone. The dependence between source parameters close to the cubic that is frequently estimated for tectonic earthquakes was observed on the first stages of both experiments when confining pressure steps applied to the intact rock and therefore to the pre-existing inhomogeneties. After applying axial load changes in stress-drop is being observed: with higher stress-drops prevailing in granite and lower stress-drops in sandstone. Also there is a significant difference in Gutenberg-Richter relation in these two experimental conditions observed.



Main results showing the possibilities of coda-based method of source parameters estimations to enrich the picture of micro-fracturing

Charbel KAZZY

Evolution of the mantle source of komatiites through Proterozoic and Phanerozoic eons.

Supervisor: Alexandre Sobolev

Mineralogy and Environments

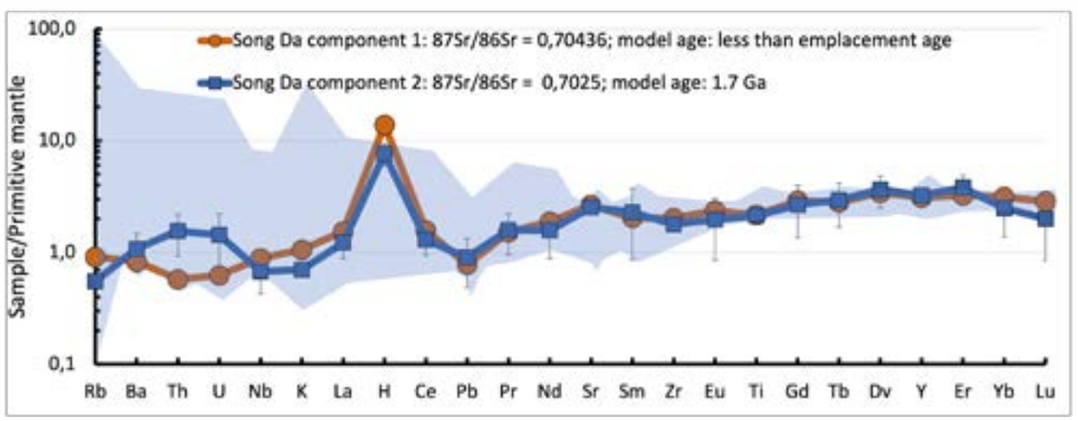
Studies of melt inclusions in Phanerozoic komatiites are crucial for understanding the evolution of mantle composition, as well as the rates of crustal production and recycling through time. The Permian (~260) Ma Song Da komatiites in Vietnam are among the few known occurrences of well-preserved Phanerozoic komatiites. Hanski et al. (2004) proposed that the Song Da lavas were derived from komatiitic primary magmas based on their bulk-rock composition, assuming that water content in these rocks was <0.03 wt.%. Despite continuous efforts to unravel their primary melt composition, concentrations of the volatile and mobile elements in the primary Song Da melt are still poorly constrained due to the widespread alteration and low-grade metamorphism of these rocks.

This study reports high precision EPMA, SIMS, and LA-ICP-MS melt inclusion data, suggesting that the primary melt of Song Da komatiites contained up to 0.9 wt.% H2O. Their original δD values were lower than −66‰, and the H2O/K2O ratio was ~37. Despite the elevated water content, we contend that these rocks were indeed derived from a komatiitic melt. Moreover, this study reports for the first time Sr isotope data for komatiite melt inclusions, recording a large range of 87Sr/86Sr from 0.7025 ± 0.001 to 0.7044 ± 0.0001 (2SE). Along with the trace element abundances, these data indicate the presence of two different components in melt inclusions. The first component is similar to mantle composition for isotopes and trace elements with some possible addition of small amount of radiogenic Sr, whereas the second component corresponds to the DM endmember with 1.7 Ga Rb-Sr model ages, but is too enriched in Th, U and Deuterium to plot on the mantle array. The uniformly high H2O/K2O ratios indicate a vast excess of water in both components and their sources compared to the BSE.

We propose that the trace-element depleted melt parental to the Song Da komatiites was derived from a mantle plume that passed through the partially molten mantle transition zone located between depths of 410 and 660 km. This plume entrained H2O from the hydrated transition zone, likely through the interstitial melt. This explains the high water content and depletion in deuterium recorded in the melt inclusions. The origin of these two components is still unknown.

Charbel KAZZY

Evolution of the mantle source of komatiites through Proterozoic and Phanerozoic eons.



The two endmember components are similar in terms of trace elements abundances from La to Lu (Figure above) and differ significantly in terms of Th, U, and Rb content. Both components are enriched in water. Component 2 has a 1.7 Ga Rb-Sr model age; it is significantly enriched in Th and U and depleted in Rb. Both components share the immobile element characteristics of bulk rocks. All data are recalculated using Al2O3 of 9.1 wt.% in the parental melt of MgO= 24 wt.%.

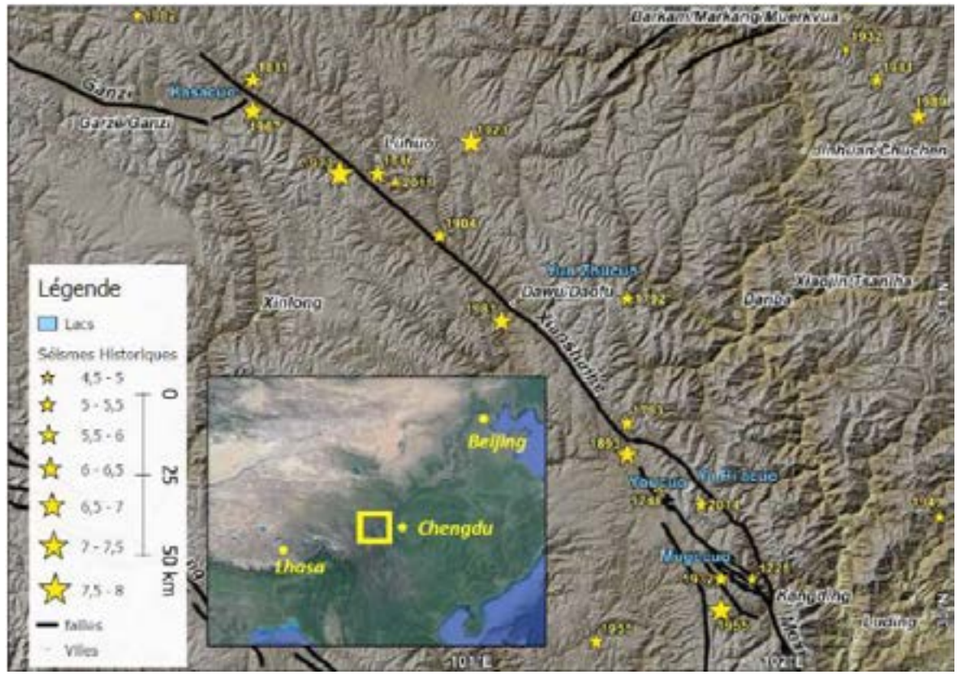
François LEMOT

Innovative multi-lake approach to study the seismic cycle in SE Tibet

Supervisor: Anne Replumaz

Tectonics, Reliefs, Basins

The Tibetan Plateau is traversed by major tectonic faults that are essential to study for determining seismic hazard and understanding the genesis of the plateau. However, fault activity has only been studied at either the geological timescale (>1 Ma) or the geodetic timescale (<20 years). To bridge this gap, my thesis focuses on using lake sedimentary archives to study fault activity at an intermediate timescale. By analyzing mass movement deposits generated by seismic shocks in sediment cores using sedimentology, geochemistry, and accurate dating methods, I aim to produce a catalog of Holocene seismicity for the Xianshuihe fault system in Southeast Tibet. Preliminary missions in fall 2021 and 2022 have already been conducted, resulting in the retrieval of 30 short cores covering 500 to 2 000 years from 8 lakes around the fault. Instantaneous deposits have been identified in all sections. Further fieldwork is planned for spring 2023 to retrieve longer cores from the most favorable sites to target an Holocene coverage.



Map of the sampled lakes with historical seismicity (National Geophysical Data Center / World Data Service (NGDC/WDS): NCEI/WDS Global Significant Earthquake Database. NOAA National Centers for Environmental Information. doi:10.7289/V5TD9V7K), major towns and relief from SRTM DEM (NASA/NGA).

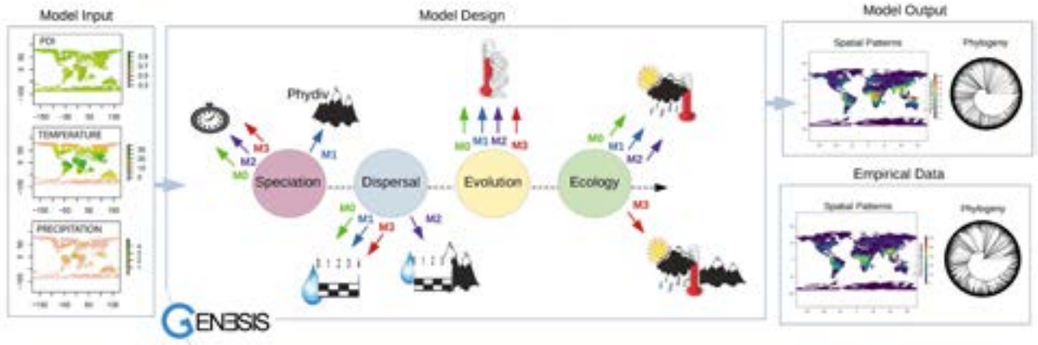
Manon LORCERY

Tectonic reshaping of the biosphere

Supervisor: Laurent Husson

Tectonics, Reliefs, Basins

Changes of physical environment, whether geological or climatic, is a major driver of biodiversity. However, the role of landscape complexity on biodiversity mechanisms remains incompletely understood. To test whether variation of physiography can explain the current richness pattern of biodiversity and understand the impact of landscape complexity evolution onto specific ecological rules, we simulated the diversification of terrestrial vertebrate taxa at global scale, over 150 Ma of geological and climatic change, using a spatially explicit eco-evolutionary simulation model. We designed four scenarios in which landscape complexity was implemented in ecological rules, with a null model (M0) dependent only on climatic factors, a model with speciation based on landscape complexity (M1), another scenario with species dispersal dependent on landscape complexity (M2) and finally a model with niche ecology dependent on abiotic factors with both climate and physiography (M3). Extracted phylogenies, present distributions and speciation events from the simulation will be thereafter compared to biotic empirical data.



Schematic representation of the model design, where biodiversity is modeled over macroevolutionary timescales on a dynamic gridded landscape using Gen3sis simulation engine.

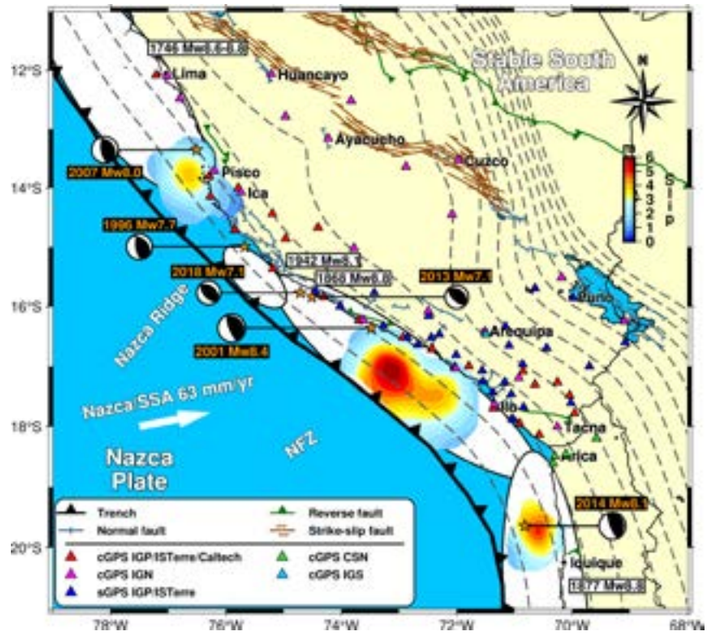
Bertrand LOVERY

Crustal Deformation Associated with the Seismic Cycle in the Central Andes from InSAR and GNSS Geodetic Time Series

Supervisors: Anne Socquet, Mohamed Chlieh, Marie-Pierre Doin, Mathilde Radiguet

Seismic cycles and transient deformations

Central Andes have been the theater of numerous megathrust earthquakes, like the one of Iquique in 2014 (Mw8.1), Pisco in 2007 (Mw8.0), or Arequipa in 2001 (Mw8.4). A deeper understanding of interseismic coupling distribution between tectonic plates and seismic cycle in this area is therefore a key issue in the frame of seismic hazard assessment. In this purpose, we can rely on geodetic data acquired by the dense GNSS networks that have been deployed, and on the Sentinel-1 InSAR acquisitions processed in the frame of the FLATSIM Andes project. Post-processing of these data and their joint inversion, by principal component analysis (PCAIM) and independent component analysis (ICAIM) will allow us to finely model interseismic coupling distribution along the subduction interface. From this model, we will carry out a moment budget analysis, in order to determine the maximum magnitude upcoming earthquake and its recurrence time. Finally, a significant part of the PhD will be dedicated to finite element modelling of the subduction zone, in order to determine rheological laws better suited to the various geological structures. This will enable taking into account complex visco-elasto-plastic behavior associated to megathrust events, as well as linking short-term and long-term crustal deformation.



Light gray ellipses indicate approximate rupture areas of major historical earthquakes since 1512 (Villegas et al., 2016). Rupture areas of the Mw8.1 2014 Iquique and Mw8.4 2001 Arequipa earthquakes have been modelled in this study. Mw8.0 2007 Pisco rupture is reported from Chlieh et al. (2011). Slab isodepth contours are reported every 20 km from Slab2 model (Hayes et al., 2018). Triangles show the location of GNSS stations used in this study.

Can we observe the North-Andean Sliver motion using InSAR time-series analysis?

Supervisors: Laurence Audin, Marie-Pierre Doin

Seismic cycles and transient deformations

In Northern Andes, oblique subduction of the Nazca plate below the South America Plate induces a northward motion of the North-Andean Sliver (NAS), at a rate of ~1 cm/yr with respect to Stable South America. In Ecuador in particular, the associated strain is mainly accommodated along the large Chingual-Cosanga-Puna-Pallatanga (CCPP) fault system, which hosted several magnitude 7+ earthquakes in the historical period. A recent study using block-modeling of GNSS data (P. Jarrin, PhD, 2021) raises important questions about the partitioning and the localization of the deformation both inside and at the limits of the North-Andean sliver. Therefore, we processed time-series of Sentinel-1 InSAR data, at a 120m resolution, in order to complement the existing geodetic dataset to resolve the low-rate crustal motions in this region.

Taking advantage of 6 to 8 years of Sentinel-1 archive using both ascending and descending tracks, we compute time-series of InSAR data for the whole Interandean region of Ecuador (~100 by 400 km), using the NSBAS processing chain (Doin et al., 2011). Because processing of InSAR data in this Equatorial region raises several challenges, such as low-coherence due to vegetation, ionospheric and tropospheric noise, and fading signals, we develop strategies to mitigate the noise terms. By using an optimized interferogram network, ECMWF-ERA5 weather model for tropospheric correction, improved weighting during multilooking using colinearity, and a temporal decomposition of the time-series, we produce the first InSAR velocity maps of the Ecuadorian Cordilleras.

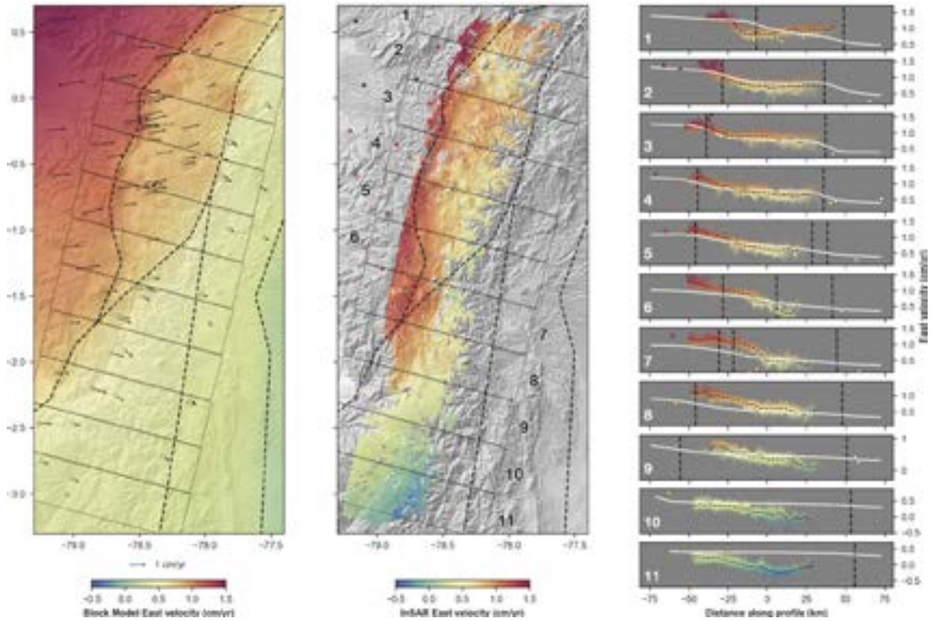
Analysis of GNSS time-series using PYACS (Nocquet, 2017) showed that this area is undergoing a strong post-seismic deformation due to the Pedernales megathrust earthquake (April 2016, Mw7.8). This post-seismic effect creates up to 5 mm/yr of East-West extension across the cordilleras and hides the long-term interseismic strain we are interested in. To deal with this issue, we first extract InSAR velocity starting from mid-2017, when the post-seismic deformation starts to be close to linear. We then reference the Sentinel-1 velocity maps to a 3-dimensional GNSS velocity field extracted on the same time-span, by removing a ramp. The RMS of the residuals after referencing is about 1.3-1.6 mm/yr. We then remove from the LOS velocity maps the interpolated North component of the GNSS field projected into LOS, therefore allowing to decompose the ascending + descending LOS velocities into East + Up velocities. Finally, we interpolate the difference between post-2017.6 and pre-2016 GNSS velocity fields, representing the deformation inherent to the (mostly linear) post-seismic phase of the Pedernales earthquake. We remove this deformation from the InSAR East + Up maps, in order to obtain equivalent interseismic velocity maps.

Léo MARCONATO

Can we observe the North-Andean Sliver motion using InSAR time-series analysis?

We compare the obtained velocity maps with the velocities predicted by the block model of Jarrin (2021), focusing on East component, where tectonic signal is dominant. We observe a good consistency between the two datasets at first order. Moreover, our results show strong deformation gradients which are not resolved by GNSS data. Also, the strongest gradients are not always located on the faults of the existing block model. Therefore, the next step will be to build an updated block model with updated limits and fed with our dense InSAR dataset.

References:
Doin, M.-P., Guillaso, S., Jolivet, R., Lasserre, C., Lodge, F., Ducret, G. & Grandin, R., 2011. Presentation of the small baseline NSBAS proc. chain on a case ex.: The Etna deform. monitoring from 2003 to 2010 using Envisat data, At the Proc. of the Fringe symposium, ESA SP-697.
Jarrin, P., 2021. Cinématique actuelle dans les Andes du Nord par GPS, Sciences de la Terre, Sorbonne Université.
Nocquet, J. M. (2017). PYACS: a set of Python tools for GPS analysis and tectonic modelling. In Colloque G2.



Comparison of block model predictions with InSAR observations. Left: East velocity map from the block model by Jarrin (2021), together with the GNSS velocity field used to build the model (pre-2016 time-span; color of dots represents East velocity). Center: East velocity map produced from InSAR in this study, together with the GNSS East velocities. Right: profiles of block model (white line), InSAR (point cloud) and GNSS (dots) velocities. Faults of the block model are shown in dashed black lines.

Kristina MATRAKU

Quantification and modelling of current tectonics of Albania

Supervisor: François Jouanne

Seismic cycles and transient deformations

The present tectonics of Albania is characterised by significant seismicity as evidenced by the occurrence of 7 earthquakes with magnitudes Ms exceeding 6 in the last century and known historical seismicity over 25 centuries with catastrophic events affecting the city of Dyrachium-Durres on 10 occasions. The geodetic investigations have allowed the measurement of shortening across Outer Albania, with a NE-SW shortening rate of 3-4 mm/yr (Jouanne et al. 2012; D'Agostino et al. 2020) in Northern Albania and 4.9 mm/yr in Southern Albania (Jouanne et al. 2012). This spatial variation expresses a clockwise rotation of Albania and north-western Greece. The rate of shortening increases to 8.9 mm/yr (NE- SW) according to Valkaniotis et al. 2020 in the Epirus region (NW Greece), while an east-west extension of 2-3 mm/yr affects the inner Albanians. The aim of my research is to produce a velocity field from 20 years of GNSS measurements on permanent and episodic networks. These data will permit to analyse of (1) the importance of the deformation along the transverse faults that cross the Albanides such as the Elbasan-Diber-Skopje fault affected by the Skopje 1963 M6.9 earthquake, (2) the mechanism of extension of the Inner Albanides (Rollback of the Adriatic slab) + the deformation of the Outer Albanides (Rollback of the Hellenic subduction?).

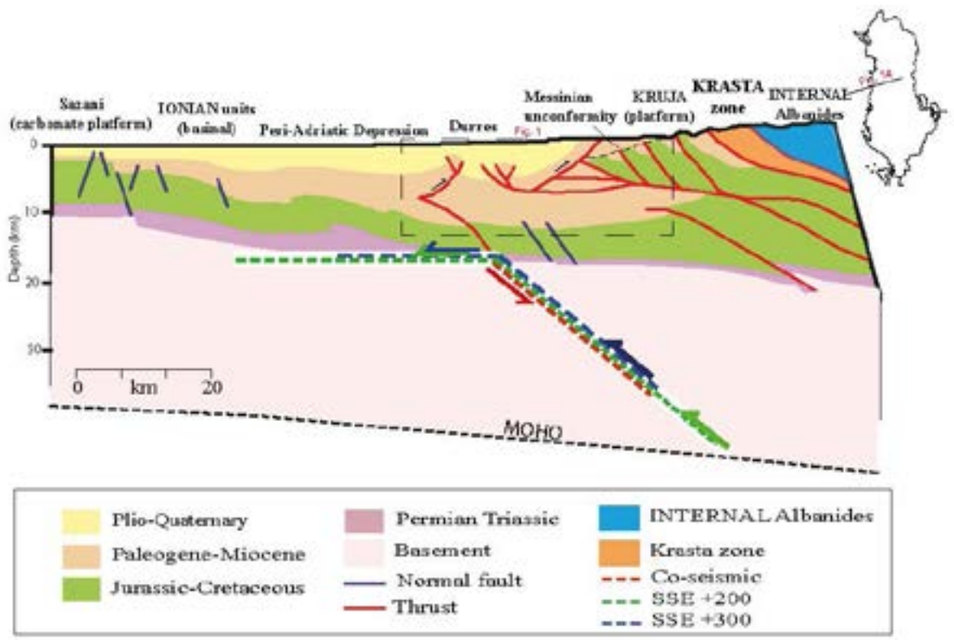
The first half of the work focused on the Mw6.4 earthquake of 26 November 2019 near Durres. Outer Albanides experienced a seismic sequence starting on 21 September 2019, with an Mw 5.6 earthquake, considered a foreshock, and culminated with the mainshock on 26 November 2019, followed by a paramount aftershock activity. We propose a model for the co-seismic slip distribution using InSAR, permanent, and campaign GNSS measurements. We tested two hypotheses: an earthquake on a thrust plane with the direction N160° and along with a back thrust. By varying the depth and dip angle for the first hypothesis and only the dip angle for the second hypothesis, we concluded the optimal solution is a blind thrust at a 15-km depth dipping eastward 40°, a maximum slip of 1.4 m, and an Mw 6.38. A GNSS time series obtained after 2020 shows two slow slip events (SSEs): the first one is 200 days after the mainshock up to 26 days, and the second one is 300 days after the mainshock up to 28 days. We tested three hypotheses: SSE along the basement thrust where the mainshock has been localized, SSE along the flat formed by the detachment layer of the cover, and SSE along these two faults. We concluded that SSE occurred along the detachment layer or along the two faults.

Kristina MATRAKU

Quantification and modelling of current tectonics of Albania

Supervisor: François Jouanne

Seismic cycles and transient deformations



(from Telfoni et al. (2021), modified). The white line represents our optimal model for co-seismic slip, SSEs +200 and +300 slip distribution. The fault model for co-seismic slip is a thrust fault with a 25-km width (red dashed line); the maximum co-seismic slip is located around Durrës (red arrow). The SSEs for +200 days occurred along the upper flat and basement thrust (green dashed line) with a larger width than the co-seismic slip (green arrows). The SSEs for +300 days occurred on the upper flat corresponding with the detachment layer of Outer Albanides (blue dashed line) with maximum slip occurrence around Durrës city (blue arrow).

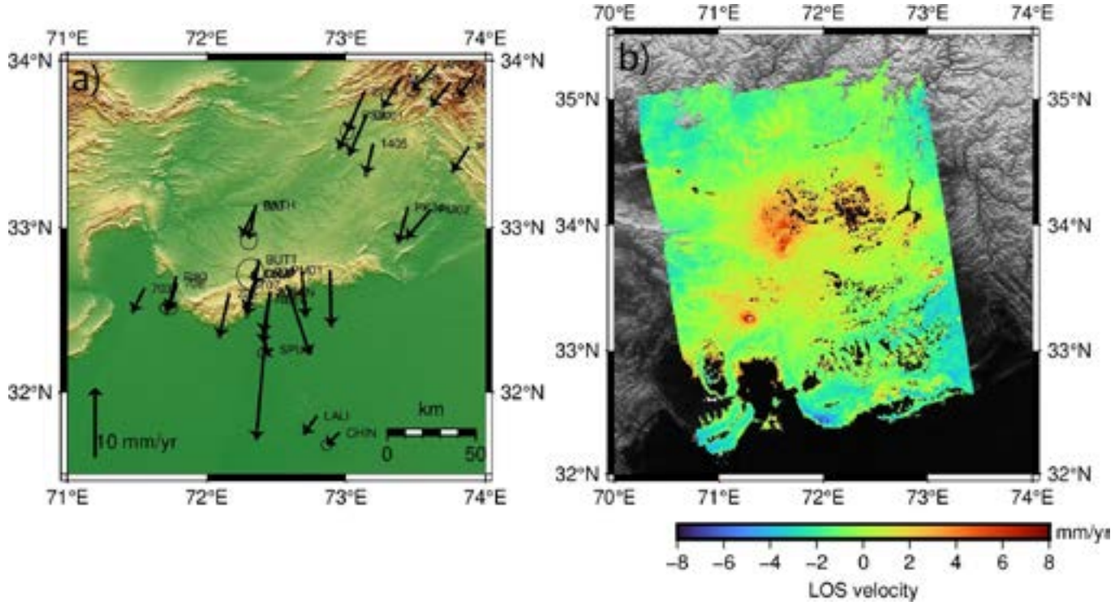
Pauline MEYER

Active tectonics of the northwestern edge of the Indian plate: observation and modelling

Supervisor: François Jouanne

Seismic cycles and transient deformations

The northwestern boundary of the Indian plate is very quickly deformed area at the edge of the India-Asia collision zone. In particular, we observe deformations resulting from the existence of salts levels forming excellent detachment levels associated to diapirism (Salt Ranges and Kohat) and from the presence of a hot continental crust that is creeping and giving rise to a crustal dome, the Nanga Parbat. The objective of this thesis is to better understand the different mechanisms that control the deformation in this area. To answer these questions, the first step is to determine the global cinematics of this region by refining our knowledge of the current deformation with new GNSS measurements and by using the INSAR method. The second step of this thesis is to model the deformation of the Salt and the Nanga Parbat both analogically and numerically. The purpose is to better understand the role of the salt layer in the deformation and the rheological control of the ductile continental crust in the uplift of the Nanga Parbat. The modeling of Nanga Parbat will also raise the question of the influence of the erosion in the development of this formation since the Indus valley is located nearby.



a) Horizontal GPS velocities over the Salt Range and the Potwar Plateau with reference taken as India fixed plate ; b) Map of linear LOS velocities in mm/yr obtained from InSAR using the ascending track 173 over the Salt Range region.

Nour MIKHAEL

Monitoring Crustal Velocity Variations

Supervisors: Piero Poli, Stéphane Garambois

Waves & structures

Temporal seismic velocity variations (dv/v) in the Earth's crust are associated with perturbations in the poro-elastic properties of the crustal material. Continuous noise-based monitoring of dv/v in the Earth's crust could reveal crucial information about some of its dynamic processes. We aim to gain new insights into the physics of earthquake cycles along with transient tectonic deformations and shed new light into the depth dependent rheology of the crust through the exploit of temporal dv/v.

The research is centered on continuous seismic data analysis for the estimation of dv/v. With these measurements we aspire to study the slow and fast deformation episodes taking place in Italy. We focus on two sub regions of the Apennines, the northern and the central Apennines. The latter exhibits seismic activity belonging to the classic mainshock-aftershock pattern. Whereas the former displays a swarm like seismicity lasting from hours to months without a clear mainshock. We perform dv/v measurements on seismic noise autocorrelations over a period of 14 years. We investigate 3 frequency bands and 15 different coda windows using the stretching and the wavelet transform approach with daily resolution.

In the northern Apennines, after decomposing our dv/v into tectonic and non-tectonic (thermoelastic and rain induced changes) components, we find a velocity drop (0.035%) coinciding with the seismic swarm. Our observations and the deduced strain sensitivity of roughly 1000 suggest a non-linear crustal behavior and that the triggering of the swarm is mainly caused by an aseismic slip enhanced by the presence of fluids at seismogenic depth.

In the central Apennines, we track dv/v associated with the L'Aquila earthquake and the Amatrice-Visso-Norcia sequence. Through a non-linear curve fitting we retrieve quantitative parameters that can lead to the characterization of both events as well as their associated crustal behaviors.

Nour MIKHAEL

Monitoring Crustal Velocity Variations

(a) Map of the northern Apennines showing the spatial distribution of the seismic swarm. Black triangles refer to seismic stations and blue inverted triangles refer to GPS stations. The ATF (right) and the GF (left) are shown in red. (b) Relative dv/v measurements (black) and synthetic models (green). (c) Residual tectonic dv/v and its standard variation. (d) Relative distance evolution between the two GPS stations localized at opposite sides from the GF in gray and daily seismicity rate in red.

Shoaib Ayjaz MOHAMMED

Metamaterials on the geophysical scale: from forests to wind farms to cities

Supervisor: Philippe Roux

Waves & structures

Inspired by anomalous wave propagation through elastic metamaterials and metasurfaces at various scales, this thesis aims at understanding the propagation of seismic waves in a setting with dense arrangement of (a) trees, (b) wind turbines and (c) buildings, which act like resonators. The interaction of surface waves with such a cluster of resonators arranged at sub-wavelength scale and well coupled to the ground through their roots/foundations, can lead to forbidden frequency bands within a forest, wind farm or a city. These surface resonators are characterized by both flexural and longitudinal resonances. In this thesis, focus is placed only on the flexural resonances which are dominant in the low frequency regime.

Current effort towards this thesis concerns the azimuthal anisotropy of surface waves in a dense forest. Continuous ambient noise recorded from a 31x31 1C square array with a dense 4m spacing is analyzed. The phase velocity of Rayleigh waves as a function of azimuth obtained from beamforming analysis, shows a cos2θ variation with a 45 degree fast direction. This observation is consistent over a wide frequency range of 7-40 Hz with varying mean phase velocity and degree of anisotropy. The mean anisotropy of Rayleigh waves is 13%, which is relatively high. This observation could suggest the possible orientation of cracks and the crack density distribution in the subsurface, but may not be directly related to the tree resonances or the tree roots. We also attempt to derive the Love wave azimuthal anisotropy from ambient noise data recorded by another 10x10 3C square array with a 4m spacing. The combined results from Rayleigh and Love wave analysis can help in understanding the physical origin of the observed anisotropy.

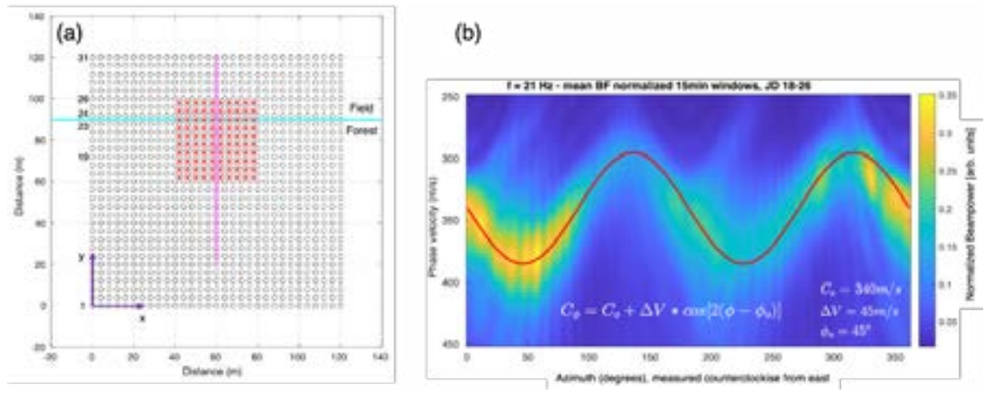


Figure (a) shows the dense square array of 1C (black circles) and 3C (red/magenta crosses) geophones deployed during the METAFORET experiment at the boundary of a forest and a canola field in the Landes region of France, October 2016.
Figure (b) is the average beamforming output for the vertical component at f = 21Hz. The color shows the normalized beam power for 15-min windows averaged over a period of 9 days and nights.

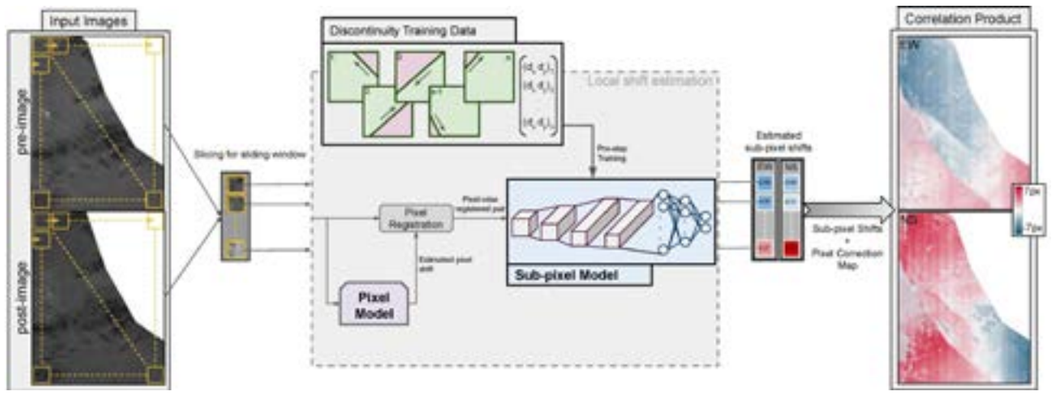
Tristan MONTAGNON

Optical Satellite Image Sub-pixel Registration byDeep Learning: Application to Earthquake GroundDeformation Estimation

Supervisors: James Hollingsworth, Erwan Pathier, Sophie Giffard-Roisin, Mauro Dalla Mura (Gipsa Lab)

Seismic cycles and transient deformations

Image correlation constitutes a highly effective non-contact method for assessing horizontal ground displacements associated with seismic events. This analytical approach enables the identification of the causal factors and mechanisms underlying such occurrences. By employing sub-pixel correlation algorithms, one can obtain displacement fields by comparing satellite imagery acquired before and after the event. However, this computation may be biased by different types of sources of noise, or when dealing with geometries like ruptures, which are often areas of most interest for geodesists. Our work is to develop an innovative deep learning method to perform correlation on optical satellite images for the retrieval of ground displacement. From the generation of a realistic simulated database based specifically built to deal with noise and discontinuities on Landsat-8 satellite image pairs with added simulated sub-pixel shifts, we developed a Convolutional Neural Network (CNN) able to retrieve sub-pixel displacements. The comparison to state-of-the-art correlation methods shows our pipeline is able to mitigate the bias around fault, and qualitative application on the 2019 Ridgecrest case proves the capability of our model to present realistic results on real data.



From left to right : A pair of input images (pre and post) are acquired on two different dates. The local sub-pixel displacement between the two images is retrieved using a sub-pixel model; displacements given in the row (North-South) and column (East-West) direction. Our model is trained with data containing discontinuities.

Rémy MONVILLE

Topographic coupling and wave dynamics in planetary cores

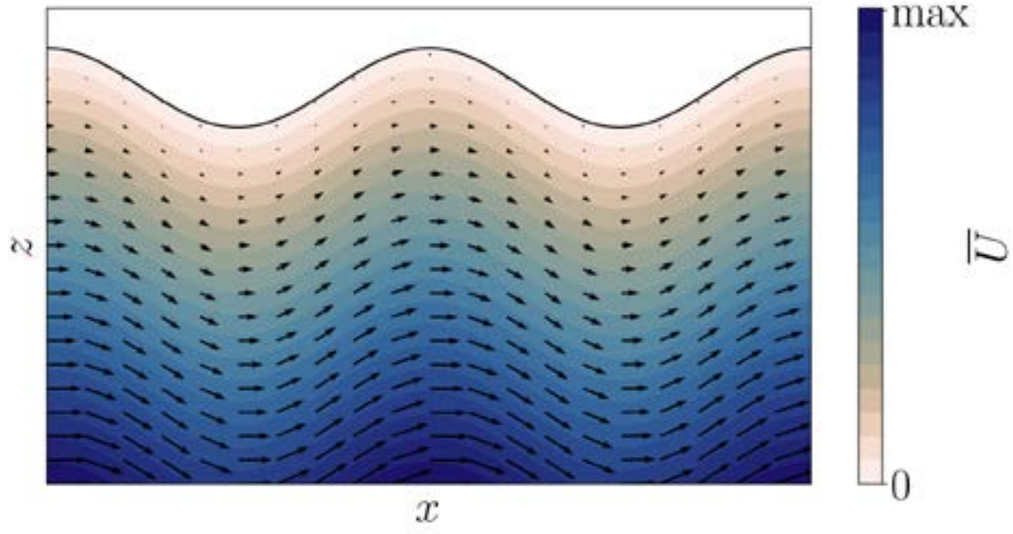
Supervisors: David Cébron, Dominique Jault

Geodynamo

The accurate tracking of the Earth rotation allows us to constrain the coupling between the liquid core and the mantle. However, despite well-constrained values, the coupling mechanisms are still disputed. These couplings are not straightforward to calculate and can originate from pressure, gravity, viscous, or electromagnetic forces.

Studies have therefore studied whether these observations can be due to the laminar dynamics of a stratified fluid layer, below a bumpy Core-Mantle boundary (CMB). Investigating the stress generated by the flows in this thin layer, they concluded that they could explain the observed Earth length-of-day variations (Jault, 2020; Glane, 2018) or the dissipation of the annual nutation (Buffett, 2010). However, these conclusions rely on leading order perturbative calculations, sometimes applied beyond their range of validity e.g. by using too high topographies, in addition to having been performed under multiple assumptions.

Our code, based on plane-wave perturbations in a local reference frame, allows us to estimate the torque at the CMB using mixed high-precision symbolic calculations. We calculate «higher-order» solutions that go beyond the forced-wave linear regime. With this new method, we explore a wide range of parameters and boundary conditions for arbitrary topography shapes. We also consider the spherical geometry, via spatial integration, which includes the lateral variations of the magnetic field and of the orientation of the rotation vector.



Viscous magnetic flow below a sinusoidal topography.

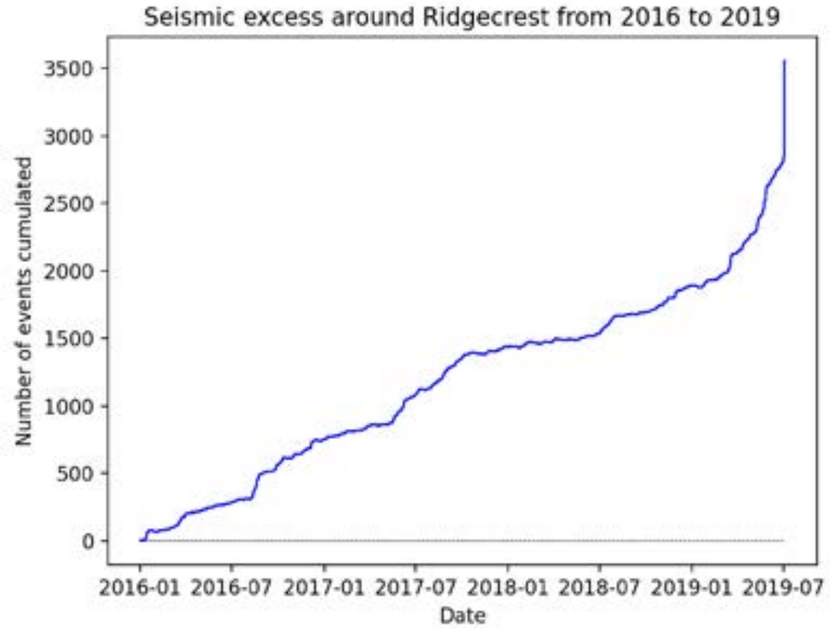
Sarah MOUAOUED

Classification de données sismiques continues

Supervisor: Michel Campillo

Waves & structures

On a dans un premier temps téléchargé 300 jours puis 3 ans de données à la station SRT pour la seule composante verticale. A l'aide d'une stratégie en apprentissage profond non supervisée, proposé par Seydoux et al. (2020) on a définie des caractéristiques plus stables des formes d'onde afin de classifier les fenêtres de temps dans des familles en fonction de leur origines physique. On a ainsi pu identifier les fenêtres correspondant aux séismes, soit sur faille ou diffus ; et des fenêtres de bruit comme du bruit antropique se produisant la journée ou des bruits ambients ou océnanique. A partir d'un catalogue bien fournit on montre que la classification sépare les événements en fonction de la contribution des sources mais aussi que certains séismes loin de la station et de faible magnitude sont parfois classifiés dans des familles de bruit. Une même analyse sur 3 ans de données révèle les mêmes groupes de signaux mais cette fois-ci, on distingue en plus qu'ils se produisent de manière saisonnière et cela permet d'avantage d'expliquer la répartition des familles de bruit. Enfin, à l'aide du catalogue on montre qu'il existe une zone au Nord-Ouest de la faille où l'activité sismique augmente quelques mois avant le séisme. On télécharge donc 10 ans de données à la station B918 proche de cette zone pour vérifier si l'on retrouve cette évolution avec notre stratégie, dans un groupe de signaux.



Différence entre le nombre cumulé d'événements de 2016 à Juillet 2019 (jour avant le début du séisme le 4 juillet 2019) et sa moyenne; représentant l'excès de sismicité avant le séisme. On observe une augmentation significative environs 3 mois avant le séisme.

Naomi NITSCHKE

Rehabilitation of gold mining sites in French Guyana : Stabilisation and fate of natural and anthropogenic Hg and Pb

Supervisors: Stéphane Guedron, HELLAL Jennifer (BRGM)

Geochemistry

French Guiana is experiencing a new rush in artisanal and small-scale gold mining (ASGM). Both legal and illegal mining activities have an impact on mercury (Hg) fluxes to rivers as they involve deforestation and soil reworking for the extraction of gold in naturally Hg rich soils. In contrast to illegal ASGM, legal mines extract gold without Hg addition.
The impact of legal mines is however not fully characterised, as their remote location makes continuous monitoring challenging, the exact nature of the geogenic background is poorly characterized and these sites are often impacted by Hg contamination inherited from former ASGM activities.

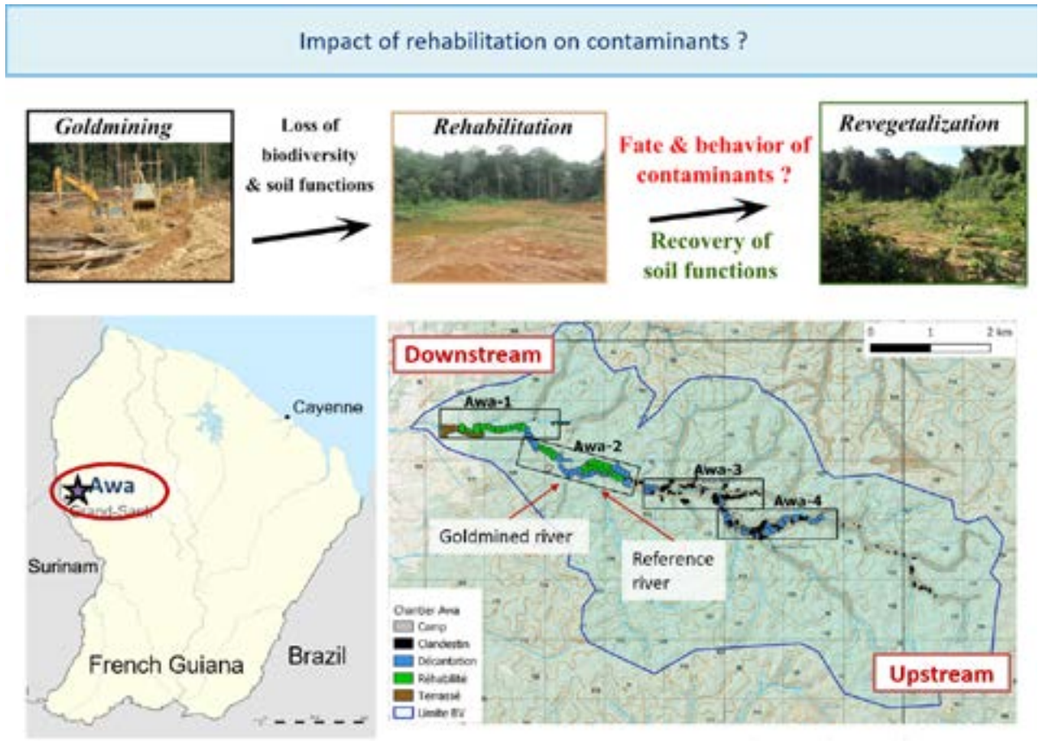
In this study, we monitored Hg species and trace metal (Pb, As, Cd…) levels and fluxes during 1.5 years, upstream and downstream of a legal gold mining site after exploitation and during revegetation. The combination of continuous monitoring of water flow and turbidity, with discrete sampling during flood events allowed a high resolution (time step of 1h) chronicle of trace metal fluxes. Sources of contaminants to the river were identified through the characterisation of ecosystem compartments (pristine and mining soil, stream, rain and pore-water, mining ponds). This enables a better understanding of background levels and enrichment factors of contaminants in a natural and mine impacted Amazonian tropical system.

Results showed that for major contaminants (Hg, Pb, As), more than 80% of the element is in the particulate fraction. During flood events, erosion of the mining flat is the major source of particulate Hg, as Hg concentrations almost double downstream of the flat compared to upstream. However, other contaminants including methylmercury, Pb and As are not impacted by the mining flat as their concentrations remain constant.

The comparison of soil erosion and contaminant fluxes between rehabilitated and bare soils revealed that erosion was 10 times lower on rehabilitated soils, demonstrating that revegetation efficiently decreases the amount of particulate contaminants transported to the river system. These results highlight that the rehabilitation step must be accomplished shortly after exploitation to limit contaminant fluxes to the hydrosystems and favour revegetation.

Naomi NITSCHKE

Rehabilitation of gold mining sites in French Guyana : Stabilisation and fate of natural and anthropogenic Hg and Pb



Study site of the gold mine in French Guiana to follow Hg and other contaminant fluxes.

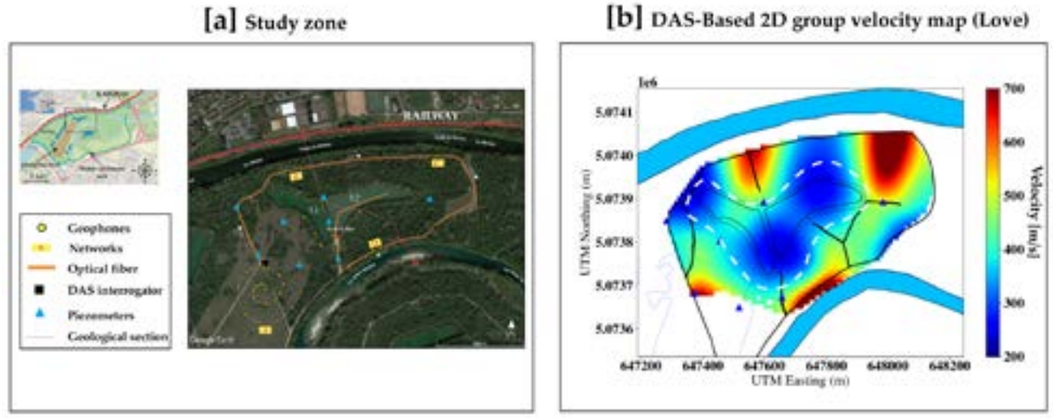
Destin NZIENGUI BÂ

DAS (Distributed Acoustic Sensing) measurements in seismology: methodological developments and experiments

Supervisor: Olivier Coutant

Waves & structures

Distributed acoustic sensing (DAS) is a new, relatively inexpensive technology that is rapidly demonstrating its promise for recording seismic signals in a wide range of research. In this thesis project, we focus on applications in the field of near-surface geophysics. We are interested in this second main project at the monitoring of an aquifer using passive seismic interferometry and DAS. We deployed 3km of optical fiber and a dense array of 50 3C geophones on the groundwater exploitation field of Crépieux-Charmy (Lyon, France). We successfully performed a DAS-based surface waves tomography (velocity and velocity variations). These models are intended to contribute to a better understanding of water exchanges in the aquifer.



[a] Study zone: groundwater exploitation field of Crépieux-Charmy (basins 5.1 & 5.2) [b] DAS-based 2D love wave group velocity map.

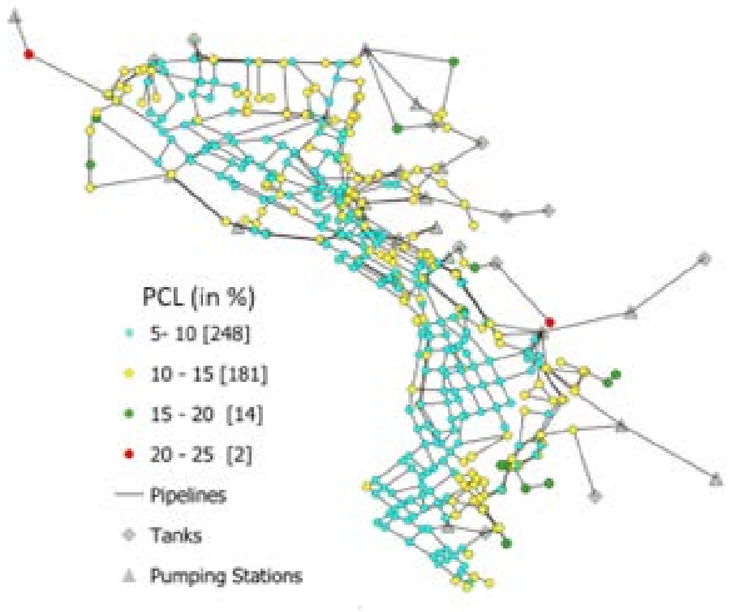
Astha POUDEL

Systemic Vulnerability and Risk Assessment of Interdependent Critical Infrastructures at Urban Scale

Supervisor: Philippe Guéguen

Waves & structures

Critical infrastructures, whose components are interconnected and behave as a system, are vital for the functioning of society. The synergies between the components of the various systems might exacerbate the total losses at the urban scale after an earthquake event. However, the seismic risk assessment of infrastructures at system level is still limited due to the underlying complexities, paucity and heterogeneity of data and methods, and lack of comprehensive computation tool. This study proposes a thorough approach for systemic risk assessment of infrastructure systems built upon strength of previous studies, and subsequently implementing it to a widely used open-source tool for global usage. This is applied to assess the performance of the test bed of the water supply system of Thessaloniki considering the scenario as well as event-based probabilistic approach. This study provides an insight to policy makers, system operators and civil protection to identify the overall performance of service from infrastructures at urban as well as local scale for better mitigation and recovery plan.



Partial connectivity loss (PCL) of each demand node of water supply system of Thessaloniki considering scenario based analysis.

Árpád PUSZTAI

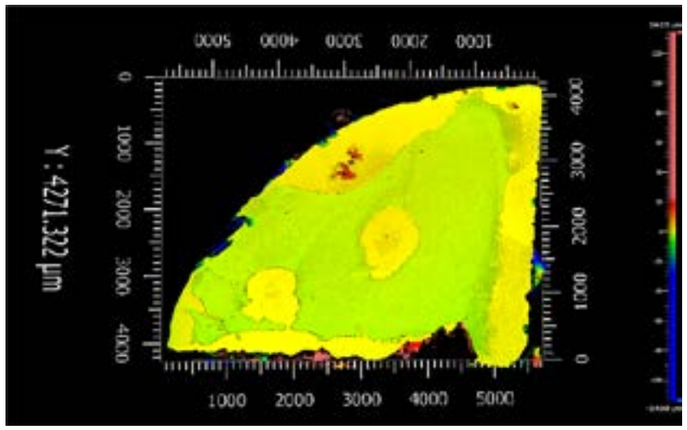
Microbial diversity and mineral reactivity in soils developed on basaltic bedrocks

Supervisor: Damien Daval

Geochemistry

The weathering of calcium and magnesium silicates plays a significant role in the long-term carbon cycle, by initiating the formation of carbonate rock and providing important nutrients for surface ecosystems. Basaltic glass, one of the most reactive and abundant silicate phases, has been extensively studied in laboratories for its dissolution rates and kinetics under varying pH, temperature, and solution compositions. However, laboratory measurements made on freshly ground powders and surface area conversions relying mainly on BET are not necessarily suitable for scaling with dissolution rates. Additionally, only considering surface alteration layers and potential biotic enhancements fails to explain weathering rates measured in natural settings.

To address this gap, this study examined the dissolution of basaltic glass using monoliths with controlled initial surface properties. An approach based on surface sensitive techniques, including vertical scanning interferometry (VSI) and atomic force microscopy (AFM), enabled accurate scaling of the weathering rates to geometric surface area. In-depth investigations of the resulting surfaces unraveled signatures of weathering processes associated with various dissolution conditions. In parallel, similar samples were introduced in soil columns cored from Réunion Island to shed light on factors controlling basaltic glass dissolution in more complex environment. The effect of the colonization of glass surfaces by microbial communities inhabiting soils developed on basaltic substrates was thereby quantified. This study will help adjusting previous findings of basaltic glass dissolution in a three-dimensional domain of temperature, solution content, and substrate age. The use of reaction environments with contrasting levels of complexity will help bridging the gap between laboratory experiments and field measurements and will aid the exploration of biotic impacts on weathering.



A Vertical Scanning Interferometer image of basaltic glass in mild acidic conditions. contrasting the areas exposed and areas masked on the topological profile.

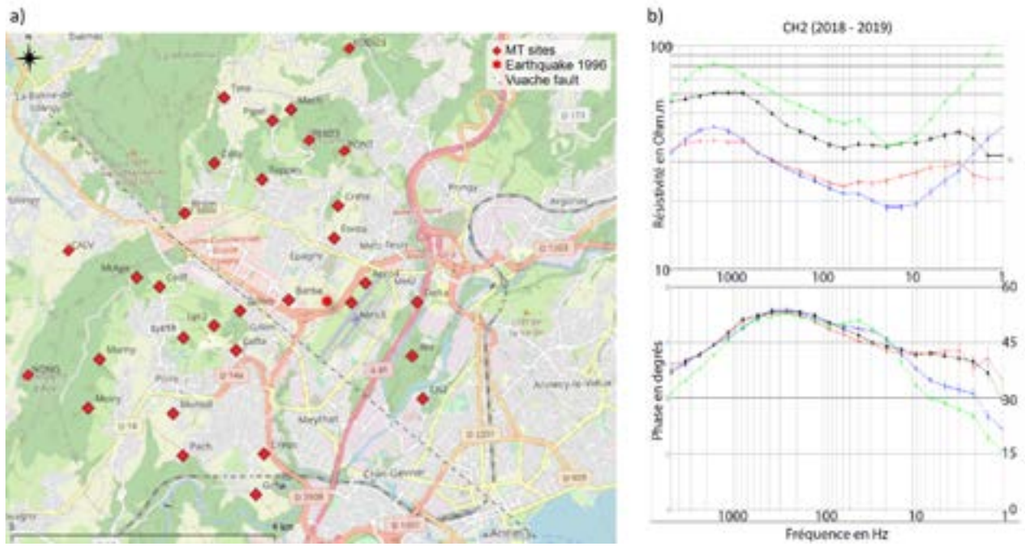
Camila Celeste RIBA PEREYRA

Magneto-tellurics for investigating fractured geothermal reservoirs

Supervisors: Jean-Luc Got, Svetlana Byrdina

Geophysics of volcanoes & geothermal energy

The Magnetotelluric (MT) method can be a powerful tool to characterize the geological structures and reservoirs underground, from 50m up to 500km. It measures the variations caused by solar activity in the natural electromagnetic signal, which has a minimum amplitude signal between 10 and 0.1Hz, area known as the dead band. Furthermore, MT is sensible to anthropic noise and the increment of urbanized areas decreases the potential places to acquire data. Due to this, the objective of this PhD is to improve the signal-to-noise ratio of the MT data to obtain better quality data in the dead band. We are currently working with FFMT (Hering and Junge, 2020), a processing method that uses remote reference stations, multicomponent analysis (eigenvalues/ eigenvectors analysis) and a noise model to process data before the inversion. The data that is being used correspond to measurements from the Annecy region. In this area a geothermal reservoir is suspected at about 2km depth, in the Tithonian karstic limestones. It corresponds to the frequency band 0.2 to 5Hz, inside the dead band. This reservoir is crossed by the active Vuache fault (M5.3 in 1996, with several hundreds of aftershocks), which is expected to be fractured. Our aim is to improve the resistivity processing and results by using very long time series, to improve (1) the resolution of the resistivity inversion at depth, and (2) the interpretation of the resistivity tensor in terms of anisotropy. We will relate this anisotropy to the medium anisotropy, eventually due to fracturing.



a) Map of Annecy with the MT sites recorded during 2018 – 2023 and the trace of the Vuache fault.
b) Apparent resistivity and phase curves of the CH2 site: Red and blue curves correspond to the data acquired in 2018, and the black and green for the data from 2019 (Got et al. 2021).

Aurélien RIGOTTI

Investigating the rheology of the Marginal Ice Zone through DEM simulations of a dry frictional 2D granular material

Supervisor: Jérôme Weiss

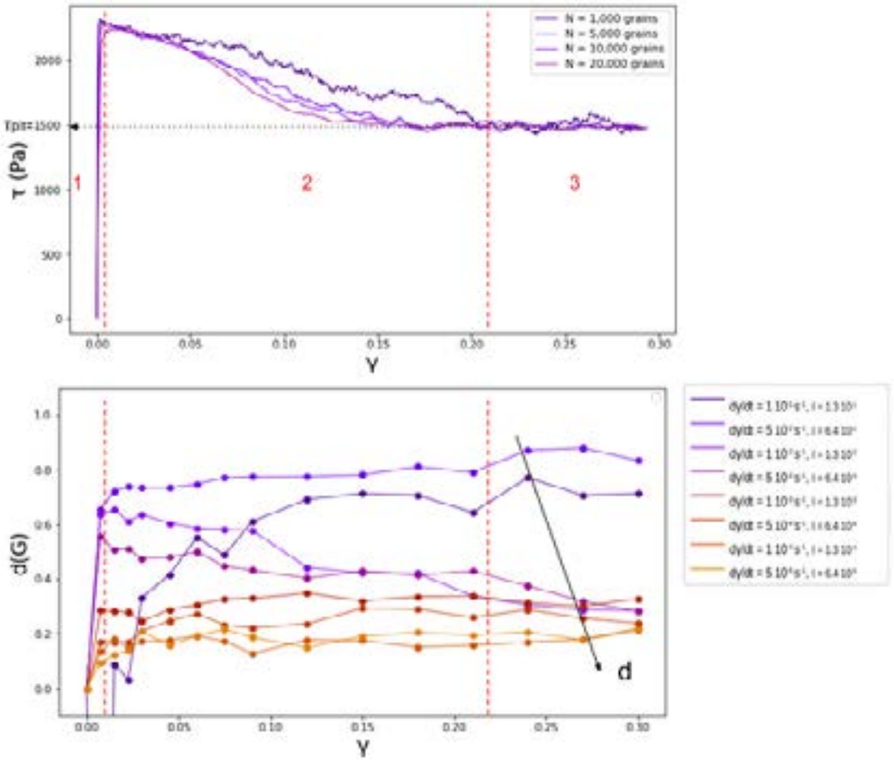
Fault mechanics

Sea ice can be assimilated to both an elastic-brittle solid, where it's concentration is high and its mechanical behaviour is dominated by fracturing processes, or as a granular material, in zones of lower concentration such as the MIZ, where the behaviour is dominated by collision and friction between individual floes. In this later state, it can either behave like a viscous fluid at low packing fraction (i.e., concentration) or like a solid at critically high packing fractions. The transition in its behavior between the low and critically high packing fraction limit is reminiscent of a "jamming transition".

In sea ice, the strain experienced at the local (micro) scale has a significant influence over the deformations patterns that emerge at much larger (macro) scales. With this idea in mind, this study aims at improving the current grid-scale (mesoscale) parameterisations of sea ice strength in continuum, sea ice models used for short and long-term predictions in the Arctic and Antarctic, by formulating a coupling between the mesoscale ice-strength parameters (apparent viscosity and elastic modulus) to the state (packing fraction, level of damage, floe size distribution) of the granular sea ice cover in the closed-packed limit. To do so, a DEM (molecular dynamics model, LAMMPS) code is used to compute the apparent level of damage, viscosity and elastic modulii at the scale of an idealised, frictional granular assembly of ice floes and to establish its dépendance on the applied shear rate, the friction coefficient and, eventually, its granular concentration.

Aurélien RIGOTTI

Investigating the rheology of the Marginal Ice Zone through DEM simulations of a dry frictional 2D granular material



Shear stress versus shear strain curve for size study of the sample. Granular system are highly sensitive to size effect, to determine the right size of sample in order to minimise boundary effect, simulations were run for 1000 grains, 5000 grains, 10 000 grains and 20 000 grains. A shear strain of 5E-5 s^-1 with 5 kPa of pressure are imposed. First a linear elastic response is observe (1), then a transitional regime with stress softening (2), finally a fluid like regime appears, characterise by the saturation of the shear stress (3). Bellow an example of quantification of damage is presented, for a 1000 grains size system (33 x33 grains). Shear rate have a direct effect on the residual damage measure in the system.

Pauline RISCHETTE

Optimization of seismic motion recordings in free field for a better estimation of the seismic hazard

Supervisors: Fabrice Hollender, Paola Traversa (EDF), Emeline Maufroy

Geophysics of seismic and gravity risks

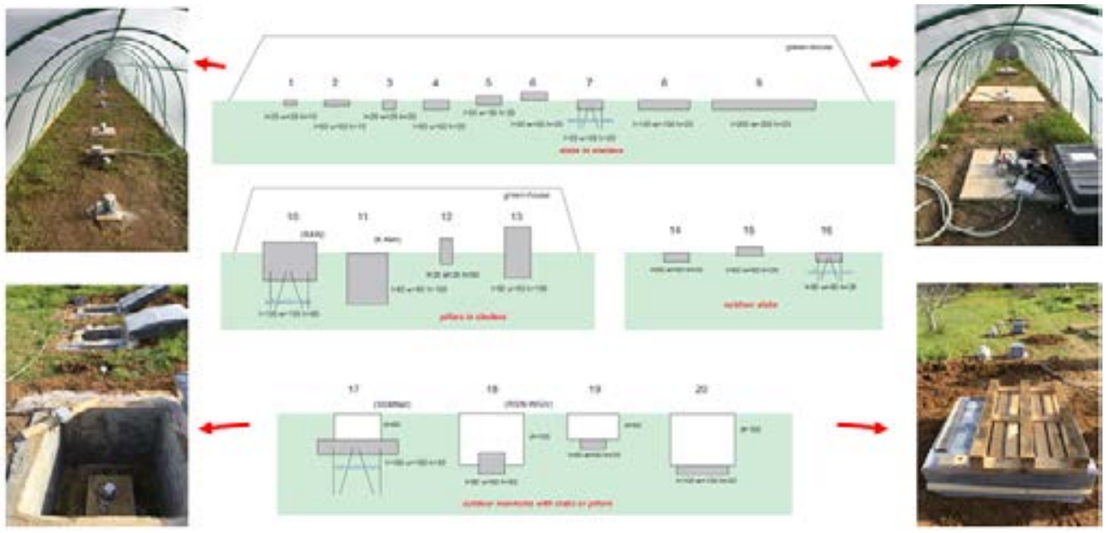
Recording ground motions is essential to estimate the seismic hazard. Current ground motion databases rarely provide information about the station housing and sensor installation conditions. Then developers make the assumption that ground motion is referred to the “Free-field” condition, i.e. at the natural surface of the ground, without disturbances due to buildings or neighbouring structures. Nevertheless, the analysis of seismological networks has highlighted many installation and sensor coupling configurations coexist. Recent studies have shown that the installation conditions of seismological stations can have a significant impact on the recorded motion, compared to true free-field measurements. Similarly, the topography condition on which the station is installed also impact measurements at high frequency.

The main objectives of this thesis are to identify the different possible disturbances, to define ideal station installation configurations, producing ground motion recordings as close as possible to the free-field condition, and finally to propose corrections. In order to do this, an empirical approach will be followed, aimed at studying:
- The effect of soil-structure interaction will be studied thanks to the comparison of pairs of sensors installed inside buildings and in free-field. The experiment will be carried out at selected reference Greek stations. To understand sensitivities and dependencies, soil-structure interaction numerical computations will be performed and compared;
- The effect of sensor couplings will be studied with the ArgoSlab experiment, set up on Kefalonia island, where seismometers have been installed on concrete slabs or on seismic pillars of different size and shape, outdoor or sheltered, and compared to free-field recordings;
- The effect of the topography at the metric scale will be studied with the ArgoScarp experiment, implemented on Krani hill (Greece).

Finally, a work of enhancement of existing databases will be conducted by optimizing the metadata and the statistical analysis of these installation effects. This work will allow to make an inventory of the installation and site conditions of the stations of the European network and of the French permanent accelerometric and broadband networks, and to characterize their effect on the seismic motion.

Pauline RISCHETTE

Optimization of seismic motion recordings in free field for a better estimation of the seismic hazard



Cross section and photos of the different coupling means studied with the ArgoSlab experiment: concrete slabs of diffrent sizes, seismic pillars, manholes. This experiment has been implement on the Island of Kefalonia, in Greece. This is one of the three types of effects studied in this PhD.

Diksha SAINI

Redox Reactivity of Selenium in Environmental Geomedia

Supervisor: Alejandro Fernandez-Martinez

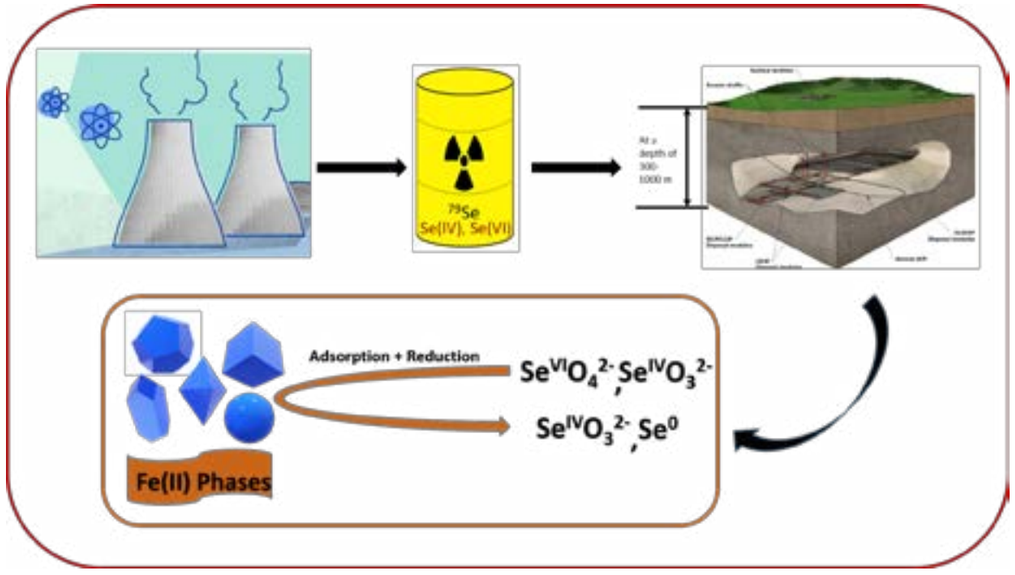
Geochemistry

79Se with a half-life of 3.27 × 105 y [1] is presently considered as a key mobile radionuclide for the disposal of spent fuel and high-level waste [2]. The solubility of selenium (Se) is largely controlled by its oxidation state, and hence depends on the redox conditions present in soils, sediments, bedrock and aquifers. The −II, −I, and 0 oxidation states are commonly predominant in “reducing” anoxic environments, while the +IV and +VI states predominate in more “oxidizing” environments [2]. The interactions with Fe(II) and S(–II)-bearing redox-active solids- mediate the oxido-reduction kinetics of Se oxyanions, playing an important role in the control of Se speciation [3]. Regarding Se(VI), it was found to be metastable (far from thermodynamic equilibrium) and potentially selenium could coexist in different oxidation states in the Callovo-Oxfordian pore waters [4]. The reduction of Se(VI) by magnetite, much slower than for Se(IV), include different steps (adsorption, reduction to Se(IV), and further reduction to less soluble Se phases: Se0(s), FeSe2(s), FeSe(s)), each of them imposing a kinetic barrier for the whole reduction process. At present it is not clear whether the Se(VI) initial adsorption or its reduction to Se(IV) are concomitant or not, and extra work needs to be done in this direction to establish the reduction pathway. Furthermore, little is known about the potential competition with ubiquitous ions in porewater such as carbonate or sulfate and especially about their capability to limit the contact of selenate molecules with the Fe(II)-bearing solids, and thus to inhibit the electron transfer.

The redox reactions Se(VI) with magnetite and pyrite under neutral pH conditions will be deciphered at both macroscopic and molecular levels by combining batch sorption studies and advanced spectroscopic techniques (XAS, XPS). In addition, the influence of sulfate ions will be investigated.

Diksha SAINI

Redox Reactivity of Selenium in Environmental Geomedia



Production of electricity by nuclear power plants inevitably generates radioactive waste. As many other countries, the French agency for the management of the nuclear waste is working on the development of an underground repository for the high-level and long-lived radioactive waste. The principle of such a concept is to provide a multi-barrier system with several matrixes to avoid the release of the radioactive waste through the biosphere for very long time scales (up to hundred thousand of years). Long-term safety assessments require a characterization at both macroscopic and molecular level of the different processes (retention, reduction, surface precipitation, etc.) that can take place onto the involved solid surfaces and the considered radioactive pollutants. Among them, the 79Se isotope (3.27 × 105 years half-life time) is considered as one of the main radionuclides contributing to the dose-to-man after final disposal. Though it has been shown that Se(IV) can be reduced by Fe(II)-bearing solids such as magnetite (a common corrosion product of steel canisters) and pyrite (a common Fe(II)-solid in the Cox formation.

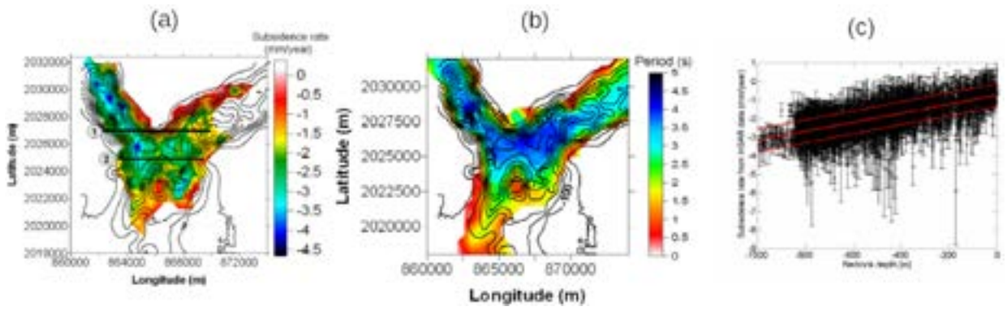
Valentin SCHINDELHOLZ

SAtellite imagery strategies for earthquake strong-motion prediction and SHAkemap generation

Supervisors: Cécile Cornou, Emeline Maufroy

Geophysics of seismic and gravity risks

Although shakemaps are of great interest for large-magnitude earthquakes where the ground motion is mainly controlled by the rupture on the fault, their relevance for moderate-size events is still questionable. So far, the implemented ground-motion prediction does not have the necessary spatial resolution to account for the real impact of the earthquake, because shakemaps use only first-order parameters that are not relevant for the fine city or building scales. This results in their poor efficiency in areas close to moderate earthquakes and/or located on deep sedimentary layers prone to complex site effects. This project aims at improving the reliability and the spatial resolution of the shakemaps and developing damage maps to predict the impact of an earthquake anywhere, including in complex geological environments and in the lack of seismological data. Our methodology is targeted on rapid and low-cost estimates, but still keeping track of physics-based approaches. We take advantage of satellite imagery in France to develop an innovative method for retrieving sediment thicknesses and predicting sediment resonance periods based on the mapping of subsidence rates in alluvial and urbanised valleys from InSAR data. The collected parameters are compared to observations: earthquake recordings from French seismic stations, from low-cost seismometers hosted by citizens, contemporary and historical macroseismic intensities. The comparison is performed by artificial intelligence to develop a new estimator of the aggravation of the ground motion at fine scale in sedimentary valleys and their periphery. The combination of the high-resolution shakemaps with an innovative damage prediction model will allow to get the damage maps at building scale.



Subsidence rate inferred from InSAR data in the Grenoble basin (a), map of resonance period T0 obtained by seismological H/V measurements (b) and (c) subsidence rate as a function of the bedrock depth derived from gravimetric measurements (from Michel et al. 2010, poster contribution to SSA 2010). The black contour lines on the maps represent the depth of the sedimentary basin.

3D modeling of the Tehran sedimentary basin: impact on seismic risk assessment

Supervisors: Bertrand Guillier, Cécile Cornou, Ebrahim Haghshenas (IIEES)

Geophysics of seismic and gravity risks

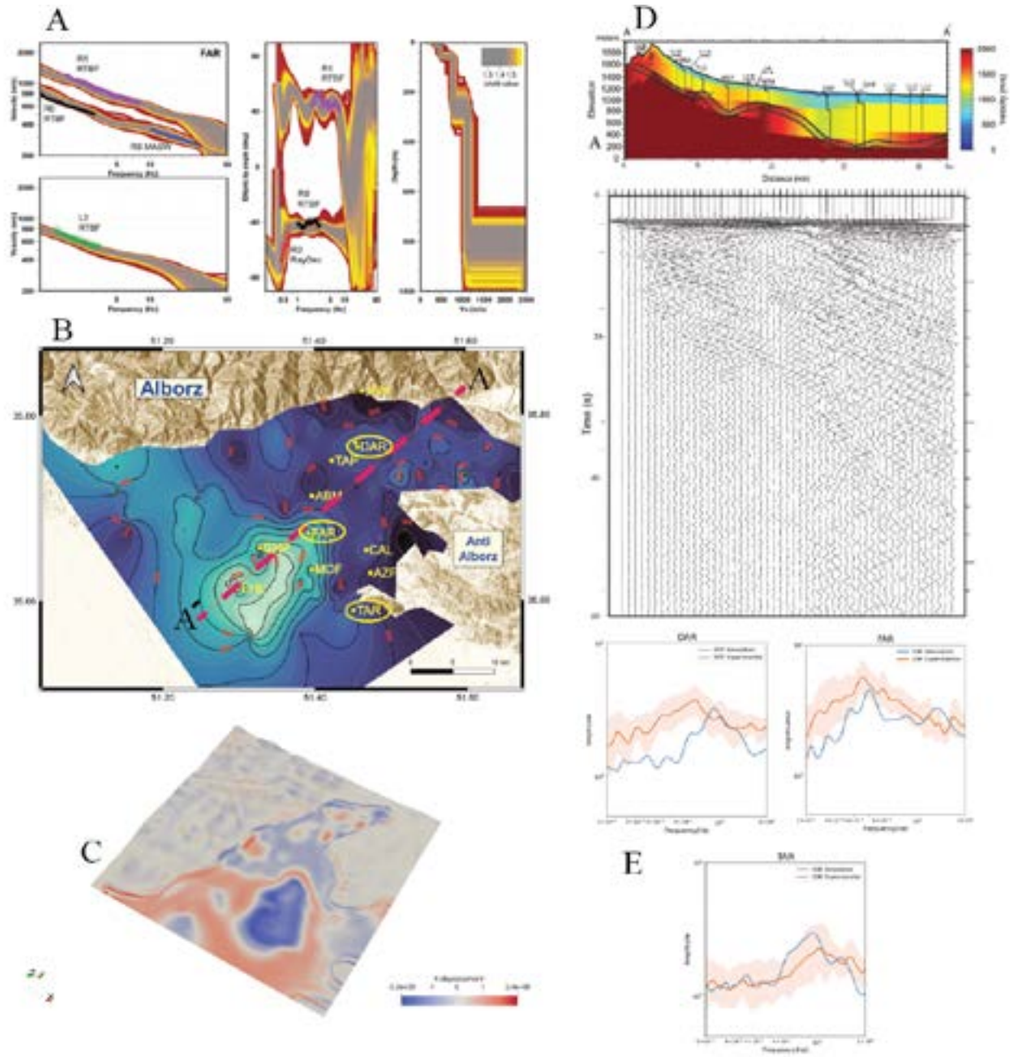
Tehran urban area serves as the main hub for economic and social activities in Iran. The city is located on a sedimentary basin including faults and folds, and thus it is vulnerable to large site effects. Analysis of earthquakes recorded by a temporary seismological network has approved a large amplification of seismic ground motion (about 4 to 8) over a broad frequency range. In order to better understand and predict the effects of the geometry and mechanical properties on surface ground motions, we developed a 3D shear-wave velocity model of Tehran by integrating extensive geophysical surveys including almost 600 single station measurements and 33 ambient vibrations arrays, with geotechnical and geological data. This 3D model shows that the bedrock depth varies between 100 and 900 meters with a general increasing depth from N-NE toward the S-SW. Also, there are two main velocity layers in the basin. A surface layer, which drops from 950 m/s to 600 m/s from NE to SW and a deeper layer with Vs up to 1300 m/s.

We then used the open-source spectral-element code, EfiSpec3D (DeMartin et al., 2013), to simulate ground motion by this new sedimentary basin model at the defined 50*50 kilometers tilted square simulation block up to the maximum target frequency of 2 Hz. The source time function is a 2-Hz lowpass filtered Dirac impulse injected from the defined z-plane at 5 km depth.

The results reveal a good correlation between real and simulated earthquake ground motion by the comparison between experimental and synthetic standard spectral ratios (SSR). The results also reproduced the experimental H/V frequency peaks over the basin relatively well and suggest that 3D geometry always should be considered for an accurate estimation of realistic basin response.

Saeid SOLTANI

3D modeling of the Tehran sedimentary basin: impact on seismic risk assessment



A: An example of an inversion process (for station FAR) to obtain 1D shear wave velocity; B: A 3D bedrock depth map of Tehran retrieved by combining all geophysical results. C: Snapshot of the X-displacement component 5 seconds after injection of the source in 3D simulation D: Simulated displacement time series along AA' cross section representing multidimensional effect; E: comparison between the simulated amplification function (SSR) and the experimental SSR for three selected stations.

Comparative microscopic signatures of microbial and abiotic alteration of minerals

Supervisors: Damien Daval, Karim Benzerara (IMPMC, Paris)

Geochemistry

The unequivocal determination of biosignatures based on the microtopography of naturally weathered mineral samples has been inconclusive. For instance, Fisk et al. showed that etching features and microchannels similar in 'size, shape, and distribution' to those found in naturally weathered basaltic glasses and attributed to the activity of microorganisms, can also be produced through fully abiotic dissolution experiments[1]. However, solely relying on qualitative comparisons of the microtopography can mask some of its potential in differentiating between those processes. In the framework of my PhD project, we developed a statistical characterization (involving power spectral density and semi-variogram) of the steady-state surface roughness resulting from dissolution as a tool to quantitatively differentiate between biotically and abiotically weathered mineral surfaces, based on surface topography data acquired with vertical scanning interferometry (VSI). First, we conducted flow-through dissolution experiments with calcite samples reacting abiotically at different degrees of undersaturation, Ω. We showed that the steady-state surface roughness resulting from dissolution can serve as a proxy for the reaction conditions. The Ω-roughness relationship derived from experimental observations was explored through kinetic Monte Carlo (kMC) and Ising modeling of mineral dissolution, attempting to identify the atomic scale factors that might play a role in determining the trend detected. We then performed the corresponding biotic experiments by covering the calcite surface subject to dissolution with a biofilm of Chroococcidiopsis thermalis PCC 7203 cells. Our preliminary results suggested that, at $\Omega \leq 0.3$, the presence of a biofilm on the dissolving calcite substrate produces surface features that can be unambiguously captured by our statistical characterization. Overall, my research aims at providing an additional, independent tool for detecting true Life traces in the rock records of Earth and potentially other planets.

[1] Fisk, M. R.; Crovisier, J.-L.; Honnorez, J., Experimental abiotic alteration of igneous and manufactured glasses. Comptes Rendus Geoscience 2013, 345 (4), 176-184, https://doi.org/10.1016/j.crte.2013.02.001.

Luca STIGLIANO

Comparative microscopic signatures of microbial and abiotic alteration of minerals

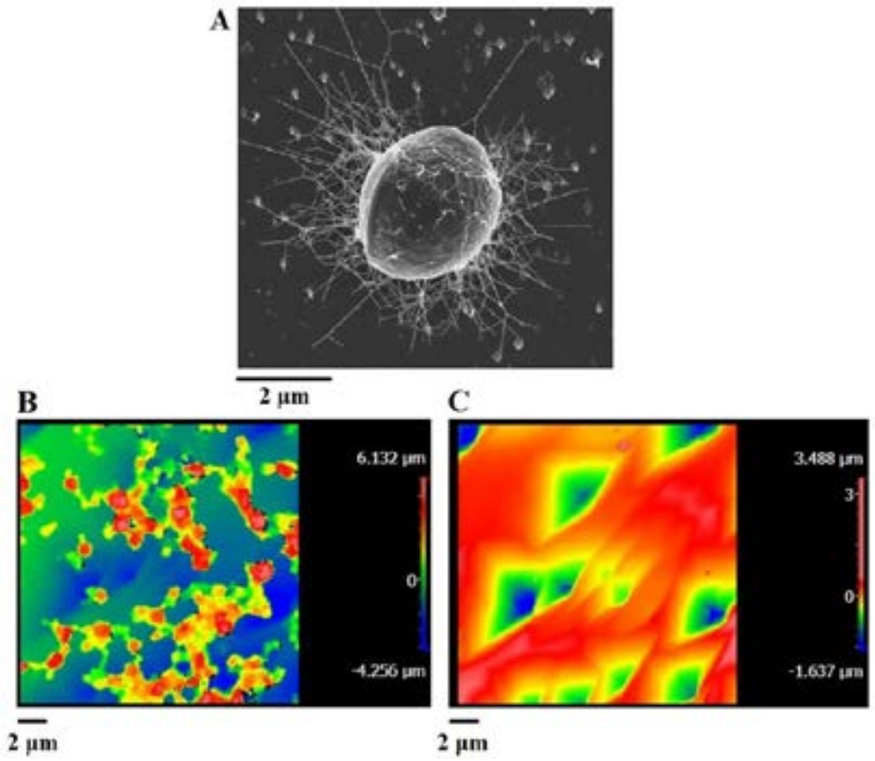


Figure 1 A) SEM image showing adhesion of a single cell of PCC 7203 to a calcite substrate. B+C) VSI images of a bio-weathered calcite surface before (B) and after (C) physical removal of the cells.

Anna THEUREL

Effect of crystallization on eruptive dynamics for silicic magmas

Supervisors: Alain Burgisser, Marielle Collombet, Caroline Martel (ISTO)

Geophysics of volcanoes & geothermal energy

Volcanic eruption mode is directly related to the capacity of the magma to lose its gases. One efficient way to do so is to create gas pathways through the magmatic column by merging bubbles along the framework-like crystalline structure of the magma.

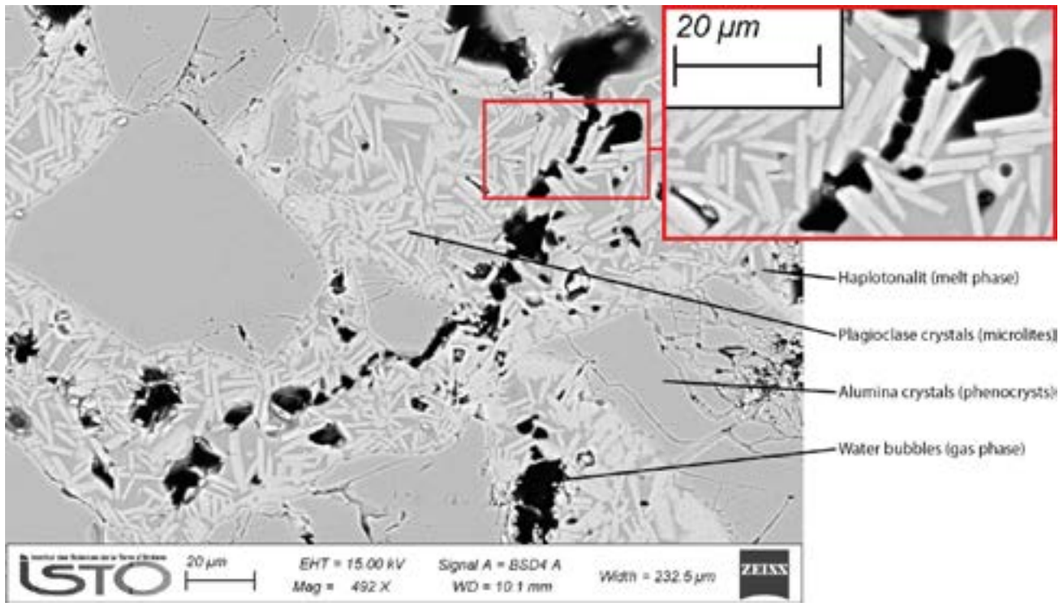
This PhD is focusing on that phenomenon called Coalescence. Intensive coalescence will further lead to channelization and gas permeability through the conduit. We propose to constrain experimentally the extreme conditions under which coalescence will happen in silicic high-crystallinity magmas without external deformation with special regard for crystal content and size, gas content, and time at final rest state. We produce synthetic magma samples that undergo time-series decompression experiments in internally-heated autoclave in order to compare and highlight the different time-related bubble behaviors.

Preliminary results suggest the strong influence of dwelling time at final pressure. When quenched directly after decompression, bubbles are small, numerous, and dispersed; early-stage coalescence is visible but not well-established enough to create gas permeability. When dwelling time is long (average 48h), we observe big bubbles with a more spherical shape or widely spread connections. In both cases, no sample showed gas permeability. For an intermediate dwelling time at final pressure of 1h30, coalescence is more developed and gas pathways can extend to the whole. When permeable, these samples present gas permeability of about 10-14 m/s² at 10% bulk porosity for a bulk crystal content of 70 vol%.

Such permeability is unprecedented under such experimental conditions and suggests amongst else the influence of time-related bubble evolution. Unlike previously thought, we also show that optimal crystal content is necessary but not sufficient to create gas permeability and if optimal dwelling time is constrained properly, channelization can occur at even lower gas content than those demonstrated to date.

Anna THEUREL

Effect of crystallization on eruptive dynamics for silicic magmas



SEM image of a sample quenched directly after decompression. We observe the pre-coalescence state where bubbles are gathered along plagioclase crystals and about to merge into channels. In the close-up view, we see three bubbles only separated by a film of melt thinner than 1 µm indicating that the shot has been taken right before coalescence of these bubbles.

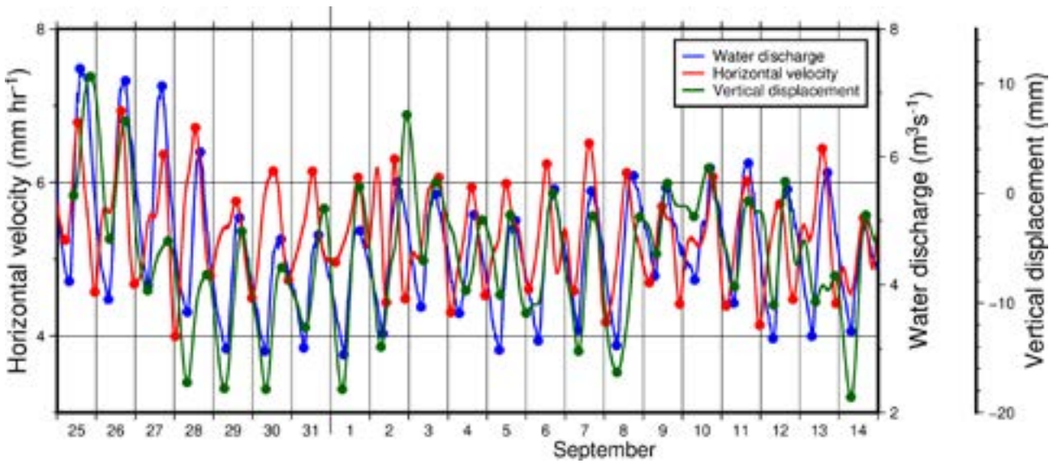
Anuar TOGAIBEKOV

The mechanism of glacier basal sliding characterized by high frequency GNSS measurements and the comparison with other geophysic

Supervisor: Andrea Walpersdorf

Seismic cycles and transient deformations

The motion of glaciers with a temperate base is highly variable in time and space, mainly as a result of glacier basal sliding being strongly modulated by subglacial hydrology. Although transient friction laws have recently been established in order to predict short-term sliding velocity changes in response to water input changes, yet little observations enable fully constraining these laws. Here we investigate short-term changes in glacier dynamics induced by transient rainwater input on the Glacier d'Argentière (French Alps) using up to 13 permanent GPS stations. We observe strong surface acceleration events materialized by maximum downglacier velocities on the order of 2 to 3 times background velocities and associated with significant glacier surface uplift of 0.03 m to 0.1 m. We demonstrate that uplift strikingly coincides with water discharge. In contrast, horizontal speed-up occurs over a timescale shorter than discharge and uplift changes, with a maximum occurring concomitantly with maximum water pressure but prior to maximum discharge or uplift. Our findings suggest that transient acceleration and uplift of the glacier are not necessarily modulated by the same mechanism. We also observe that the horizontal speed-ups propagate downglacier at migrating speeds of 0.04 m s-1 to 0.13 m s-1, suggesting an underlying migration of subglacial water flows through the inefficient, distributed system. We demonstrate that the temporal relationship between water discharge, water pressure, and three-dimensional glacier motions are complex and cannot be directly interpreted by changes in the subglacial water pressure through cavity formation and water storage.



Diurnal variations in ice surface horizontal velocity (red), vertical displacement (green), and water discharge (blue)

Lisa TOMASETTO

Microseism Correlation Functions as a New Dataset for Deep Earth Imaging

Supervisors: Pierre Boué, Laurent Stehly

Waves & structures

Ambient noise spectra show two peaks in amplitude between 3 and 10 seconds of period. The first peak at 7s arise from the interaction of two wave trains travelling in opposite directions, called the double frequency microseisms. The second peak at 14 s is due to the interaction between waves and the coastal seafloor, called the single frequency microseisms. Ambient noise correlation of two seismic stations computed in the 3 – 10 seconds of periods are dominated by Rayleigh waves however at greater distances body waves emerge. The double frequency generated body waves carry information about the inner structures of Earth they travel into, and could be used in addition to the usual earthquakes.

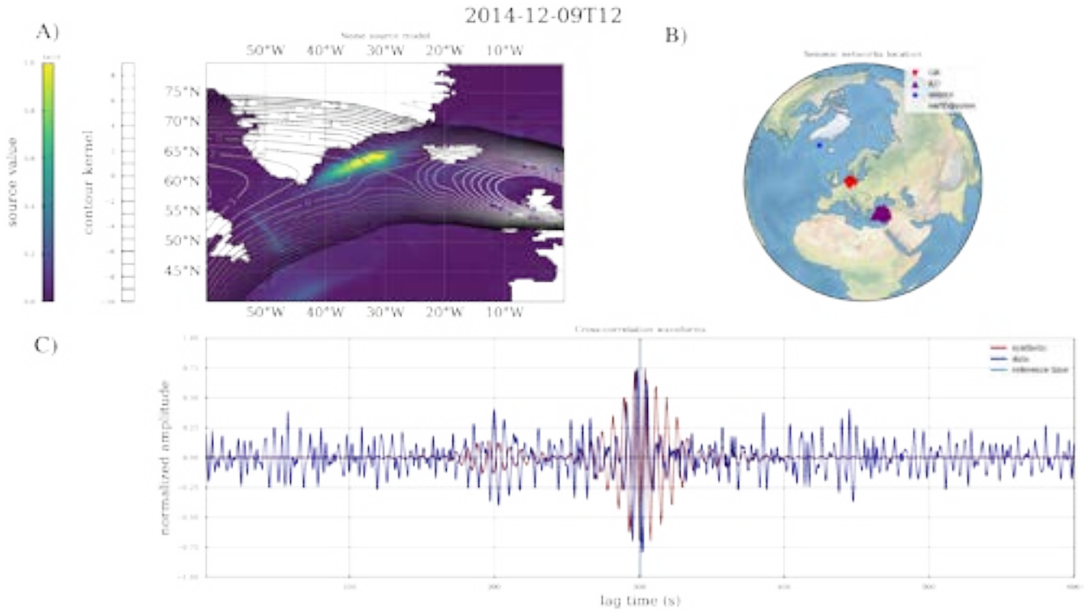
A catalog of double frequency microseismic events has been computed using the ocean wave model WAVEWATCHIII (WW3). Using the centroid position of a microseismic source an opportune pair selection is used for cross-correlation. This selection avoids the uncertainties on the source for classic blind correlations. 24 hours of data is correlated using the phase weighted stack method and filtered between 3s and 10s.
The emergence of P waves retrieved from PP-P interference seems to depend on the source behavior. An equivalent vertical force of 1010 N seems to be a threshold value for emergence. Among many parameters, assessing the source extent and time variations is key to interpret the measured travel times.

A dozen events per year are energetic enough to highlight deep body waves with seismic interferometry. The double frequency sources present a seasonal variation between northern and southern hemisphere and redundant localizations. This could be used to stack smaller amplitudes events occurring at the same place each year.

In conclusion, deep body waves can be retrieved from the opportune station pairs cross-correlation of a single source. Focus on time and spatial variations is needed to better interpret the measured travel time.

Lisa TOMASETTO

Microseism Correlation Functions as a New Dataset for Deep Earth Imaging



Comparison between synthetic and data cross-correlations between networks GR and KO on the 9th of December 2014 during storm Alexandra. A) Seismic noise source of P waves near the south of Greenland from WW3 model. The contour lines represents the source gradient in time for PP-P interference. B) Networks GR and KO, source and possibly earthquake locations. C) Cross-correlation stacks comparison between real data and synthetics computed using the oceanographic modelled noise sources.

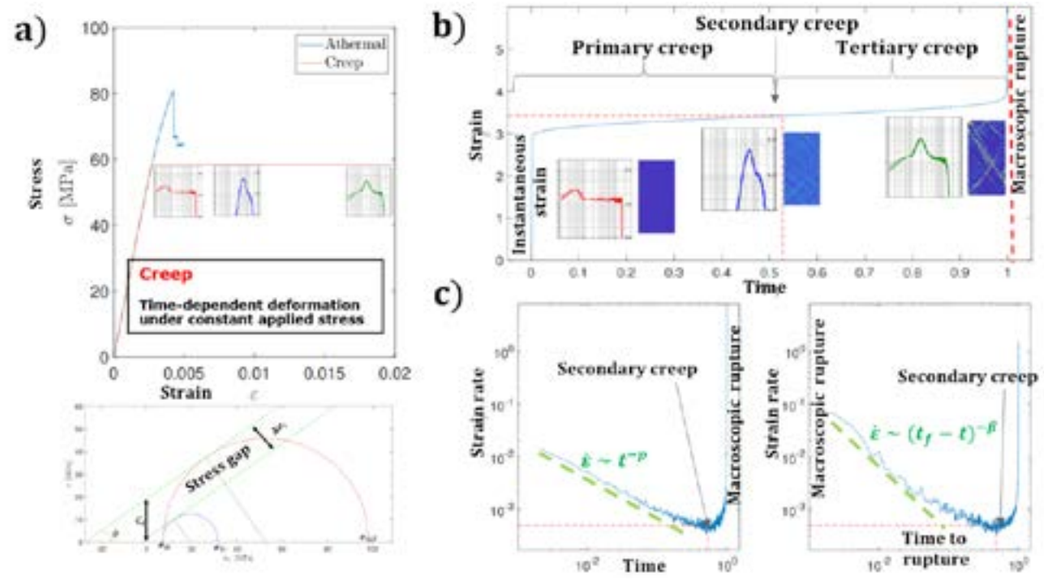
Juan Carlos VERANO ESPITIA

Statistical physics of creep rupture of heterogeneous materials

Supervisor: Jérôme Weiss

Fault mechanics

Understanding how materials deform, damage and approach failure is of relevant importance for engineering. Nevertheless, in classical mechanics and engineering literature, creep failure is described by empirical approaches. Therefore, in this project, the objective is to track the progressive damage in different heterogeneous materials during creep loading using various monitoring tools, and to introduce statistical physics theory to interpret this damage evolution and subsequently predict failure.



a) Strain-Stress curves representing creep behaviour and rupture without any thermal activation. Evolution of the stress gap for different strain values according to the Mohr-Coulomb criterion. b) Time - Strain curve and representation of the different stages during the creep behaviour and the evolution of the stress gap. c) Time-Strain rate and Time to rupture-Strain rate curves.

François VERZIER

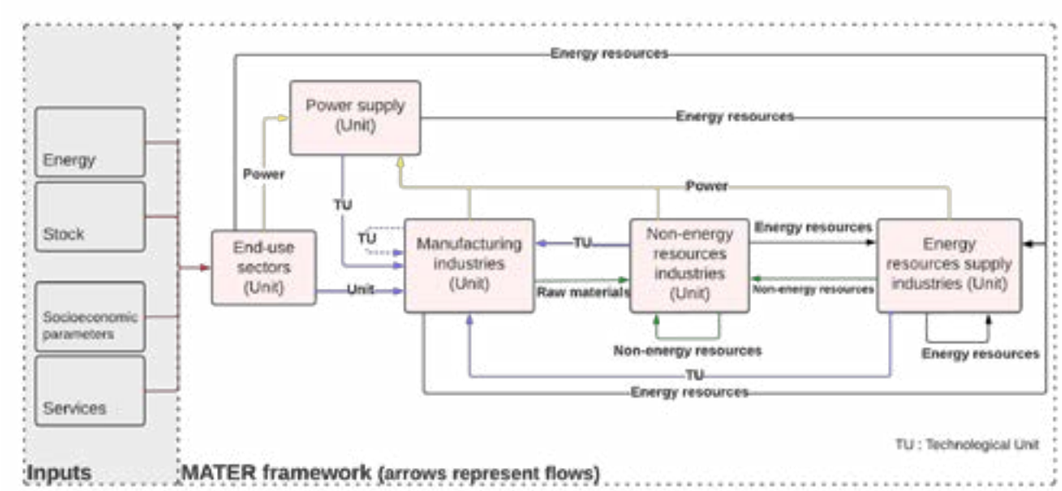
Multiregional assessment of technologies, energy and resources

Supervisor: Olivier Vidal

Mineralogy and Environments

I am working on a multiregional bottom-up dynamic model of the society to evaluate the energy transition scenarios through the lens of physical indicators such as energy consumption, material consumption and impacts emissions.

The model assess the energy-raw material nexus and endogenize the industrial energy needs for a better understanding of the physical links and feedbacks between the sectors of the society.



A simplified general framework of the MATER model.
It represents the flows of energy and materials between the different sectors. We can see that the inputs of the model are the end-use sectors infrastructures (passenger transport, buildings, food, textile, ...) and that the industrial and power supply infrastructures are outputs as well as energy and materials consumption.

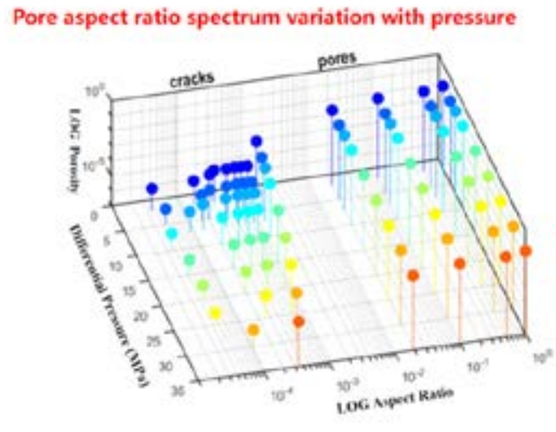
Heming WANG

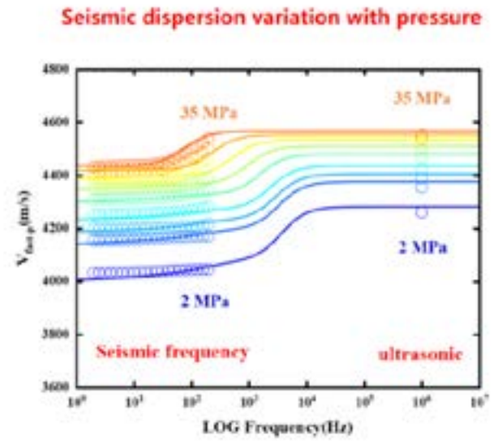
Using the multi-crack elastic wave theory to invert the micro-pore structure and its application on serpentinite

Supervisors: Mai-Linh Doan, Anne-Line Auzende, Stéphane Schwartz, Xiao-Ming Tang, (China University of Petroleum /East China)

Fault mechanics

I am working on the rock physical theory to link the micro structure to the seismic wave dispersion, I focus on the serpentinite seismic properties and mineralogy currently.





pore structure evolution → dispersion change

Relationship of seismic dispersion with pore structure

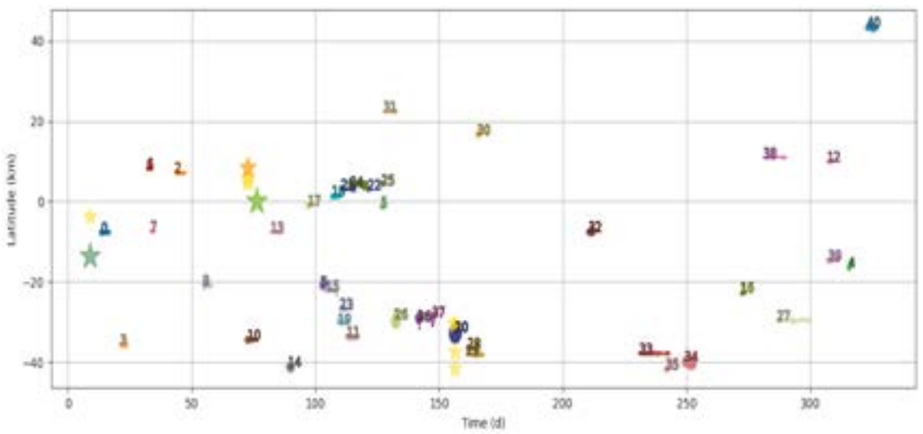
Louise XIANG

Analysis of the 2016 Central Italy earthquake sequence by using a refined earthquake catalog

Supervisor: David Marsan

Seismic cycles and transient deformations

The 2016 Central Italy seismic sequence occurred within an area dominated by normal-fault systems present along the Apennines. The sequence began with the Mw 6.0 Amatrice event on the 24 August 2016, followed by the Mw 5.9 Visso event on the 26 October 2016 and then, two days later, the Mw 6.5 Norcia event. In this study, we aim at modeling the seismicity of this complex earthquake sequence in order to determine the location of highly-pressurized fluids under the studied area through swarms occurring during the sequence. To do so, we take advantage of a high-resolution earthquake catalog based on arrival times derived using a deep-neural-network-based picker. As a first step, we apply a density-based clustering algorithm (DBSCAN) to group earthquakes into dense clusters. The majority of the resulting clusters highlight distinct fault planes which indicates an activation of a complex fault network. We further define a 4-dimensional seismicity model based on the « Epidemic-Type-Aftershock- Sequence » (ETAS) model, that we modified to include an earthquake detection probability, as required by the continuous change of completeness magnitude. This allow us to compute the seismicity rate of the DBSCAN clusters. Swarms are then deduced based on the ratio between observed and modeled seismicity rates. We finally analyze how the swarms occur, in relation with the development of the seismic sequence.



Spatio-temporal distribution of swarms in Amatrice-Visso-Norcia seismic sequence. Each warm is represented by a specific color with its name associated. There are in total 41 swarms. Amatrice, Visso and Norcia mainshocks are respectively indicated by a blue, orange and green star. All earthquakes beside mainshocks with a magnitude m ≥ 5 are showed in gold stars. We can observe that swarms are highly concentrate between 100 and 150 days and close to Norcia hypocenter in latitude.

Alexander YATES

Monitoring explosive activity at three volcanoes using seismic noise interferometry

Supervisors: Corentin Caudron (Université Libre de Bruxelles), Philippe Lesage, Aurélien Mordret, Virginie Pinel

Geophysics of volcanoes & geothermal energy

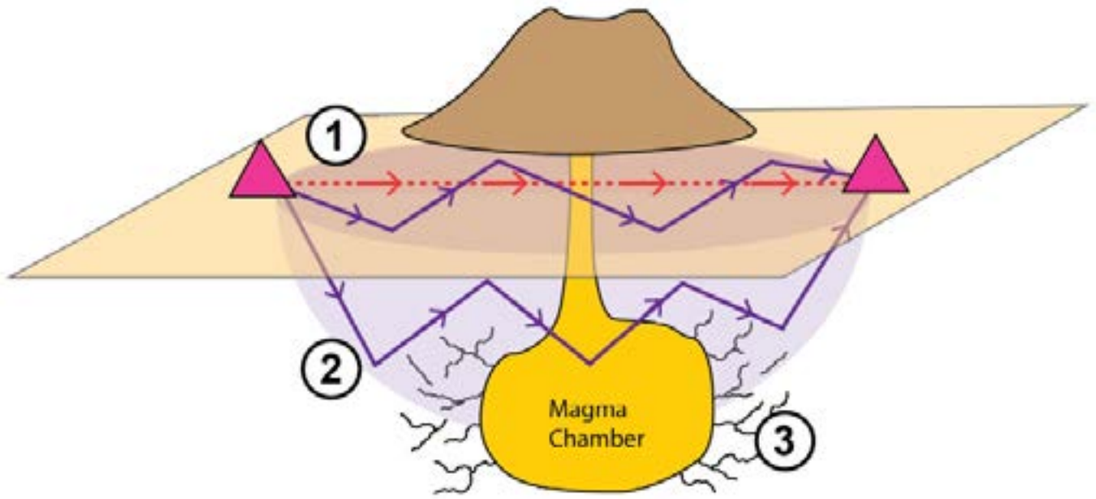
Seismic noise interferometry is becoming an increasingly popular technique for monitoring volcanoes. By cross-correlating continuously recorded ambient noise, we can recover changes in seismic velocity that reflect the evolving behavior of volcanic systems. Explosive activity, in particular, remains challenging to monitor, where the associated volcanic processes are often complex.

This work aims to better understand the potential to use seismic interferometry to monitor explosive activity. We target multiple volcanoes, including Mount Ruapehu (New Zealand), Stromboli (Italy), and Grímsvötn (Iceland). We apply various techniques to develop a suitable processing scheme at each volcano, including network covariance matrix analysis to identify key features of the seismic wavefield and hierarchical clustering of cross-correlation functions based on waveform similarity. The latter approach can identify structure in seismic interferometry datasets that aids both decision making in processing and the interpretation of results.

Seismic velocity changes from all studied volcanoes highlight the importance of accounting for environmental processes. At Mount Ruapehu, we observe velocity changes on the order of 1% associated with snow-loading. Similarly, while monitoring in real-time during recent unrest (starting March 2022), stations closer to the volcano were found to be more sensitive to environmental processes. At Stromboli, we model seasonal changes as due to fluid pressure changes following rainfall. After subtracting the seasonal component, we identify anomalous velocity changes in the months prior to major paroxysms in 2019, with opposite trends at different frequencies. This likely reflects a different response of seismic velocities at different depths. These results are encouraging towards the use of seismic interferometry to monitor explosive activity, though also highlight the need to account for non-volcanic processes.

Alexander YATES

Monitoring explosive activity at three volcanoes using seismic noise interferometry



Monitoring velocity changes at volcanoes using ambient seismic interferometry. (1) Seismic noise passes between sensors via direct and scattered paths. (2) The velocities of this seismic energy are sensitive to changes at depth, thus repeated measurements of travel time can be used to sample the sub-surface. (3) Changes in the pressure state of the volcano, or changes in fluid content, can be detected through variations in seismic velocity.

Eliane YOUSSEF

Modeling of the seismic movement in Beirut coupling spatial variability of the subsoil structure and variability of the incident

Supervisors: Cécile Cornou, Tamara Al-Bittar (Lebanese University, Faculty of Engineering)

Geophysics of seismic and gravity risks

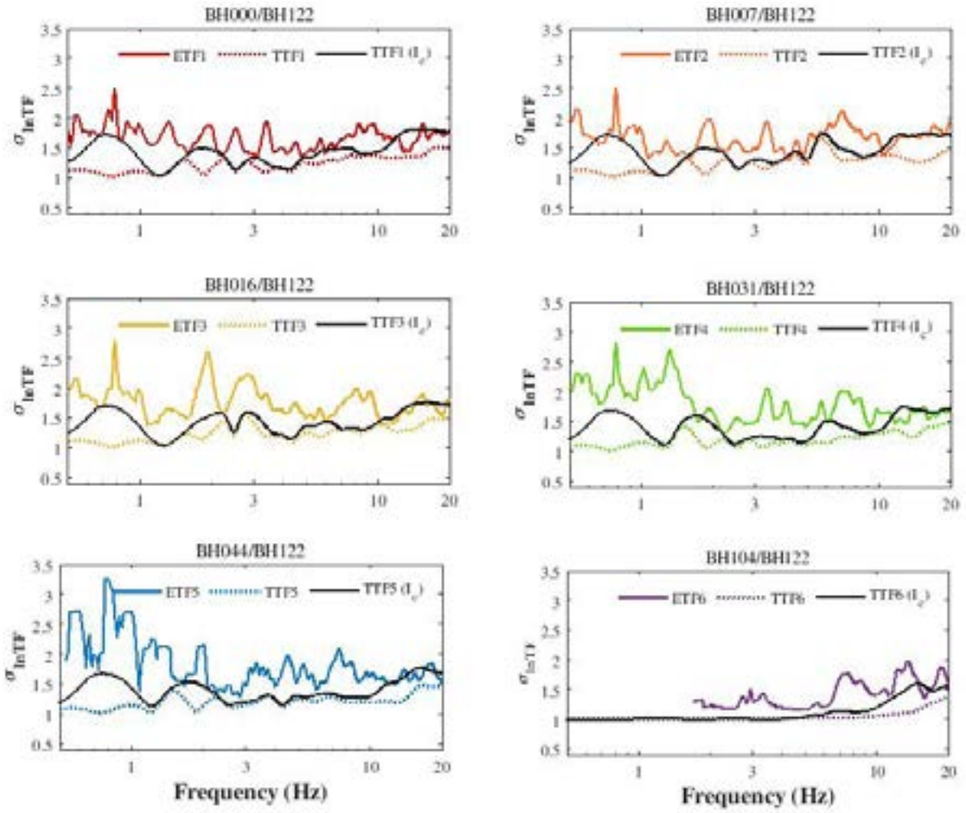
Recent studies in earthquake engineering proved the inability of 1-dimensional (1D) ground response analyses (GRAs) to exactly replicate the recorded ground motion at borehole array sites. The gap between observed and simulated ground motion exists due to simplifications in the 1D wave propagation and in the description of local soil conditions. Uncertainties in the description of dynamic site conditions include the characterization of the shear-wave velocity (Vs), the attenuation structure and non-linear soil behavior. Uncertainties in Vs are manifested through multiple-scale spatial heterogeneities caused by natural geological phenomena. Accounting for small-scale heterogeneities in Vs profiles is important for site response prediction at geotechnical and sedimentary scales and for site-specific probabilistic hazard assessment.

In our work, we propose a Vs randomization approach to propagate the small-scale Vs heterogeneities into samples of Vs profiles within a non-stationary probabilistic framework. Samples of VS profiles can be then used to perform 1D-GRA. The proposed randomization approach was first calibrated at three European sites with different subsurface conditions. The results provided by this application strongly demonstrate that randomized Vs profiles succeed in reproducing the observed spatial variability in Vs structure. Vs profiles were competent in replicating the experimentally-measured site signatures such as dispersion curves, site amplification and fundamental site resonance frequency.

For further validation purposes, the proposed approach was successful in reproducing most of the observed seismic site response variability at two instrumented downhole array sites: Treasure Island (California) soft soil and Cadarache (South-East France) outcrop rock sites. Based on the results of this application, the implementation of the Vs randomization approach in 1D-GRA yields a promising straightforward method to account for the spatial variability of Vs.

Eliane YOUSSEF

Modeling of the seismic movement in Beirut coupling spatial variability of the subsoil structure and variability of the incident



Site response variability (σlnTF) for empirical (ETF) and theoretical (TTF) transfer functions computed between pairs of sensors at Treasure Island downhole array. σlnETF are shown in continuous colored lines, σlnTTF in dotted colored lines for TTFs computed assuming vertically incident S-wave (Ic 0°) and black lines for TTFs assuming varying S-wave incidence angles (Ic 0-40°).

Hooshmand ZANDI

Inversion of seismic waveforms and deep learning to study sea ice dynamics

Supervisors: Ludovic Moreau, Ludovic Métivier, Romain Brossier

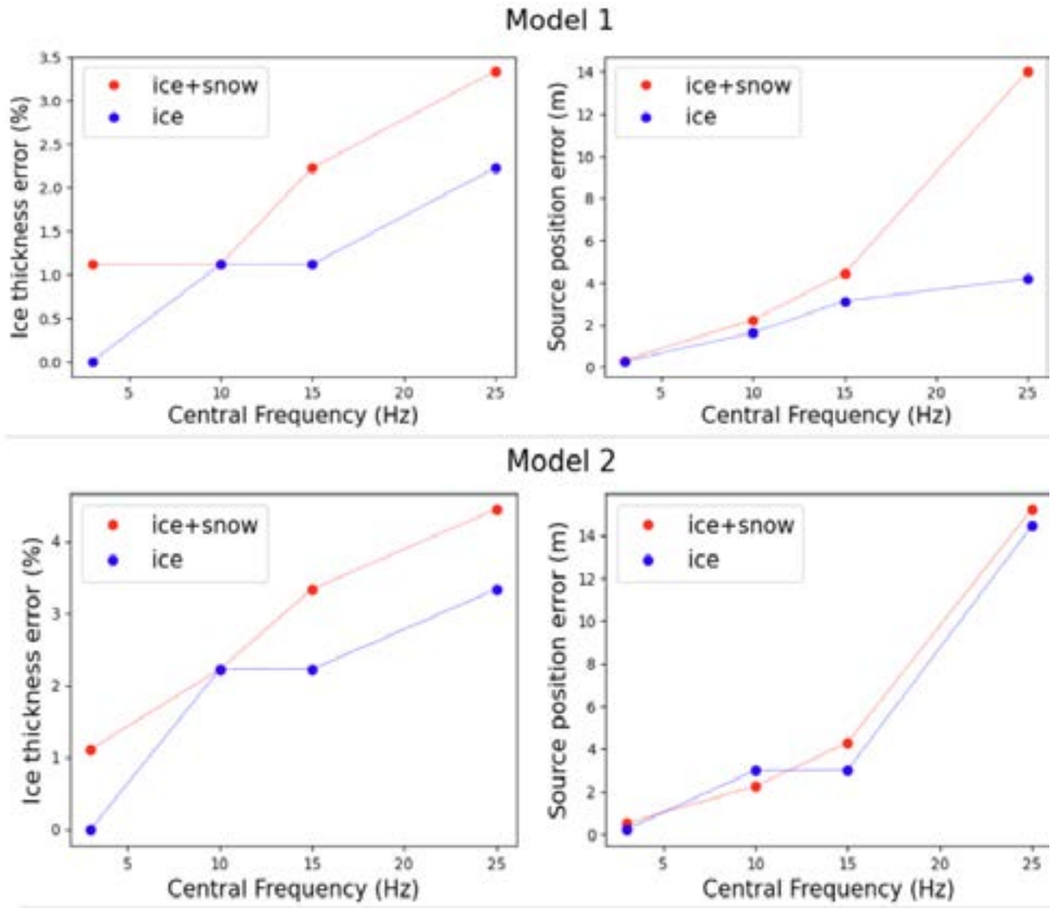
Waves & structures

Inversion methods in the previous studies used for deriving the ice thickness and mechanical properties are based on these analytical models. Since these analytical approaches do not take into account inhomogeneities (e.g., an overlying snow layer) and also have been developed for low frequencies, we expect the high frequency content and the presence of a snow layer to lead to under- or over-estimations in ice parameters, including ice thickness and source location. To evaluate these limitations, 2D forward modeling of elastic wave propagation using spectral element method is performed. Using this numerical method, an overlying snow layer and sources with high frequency content are taken into account. First, simulations using spectral element method are compared to forward modeling using analytical models. Then, using a new inversion scheme, in which the observed data are simulations using the numerical method and synthetic data are forward modeling using the analytical models, the limitations of the analytical approaches in the estimation of ice thickness and source location are evaluated.

The results show that, when using analytical models for forward modeling, the high frequency content and the presence of a snow layer on top of the ice lead to the under-estimation of ice thickness and source location.

Hooshmand ZANDI

Inversion of seismic waveforms and deep learning to study sea ice dynamics



Errors associated to the estimation of ice thickness and source location when using analytical models (Model 1 (Stein et al, 1998) and Model 2 (Squire et al, 1996)) of wave propagation for building synthetic data. Observed data are simulations using spectral element method for ice and ice-snow systems using sources with different central frequencies.

Sources: 1) https://doi.org/10.1029/98JC01269 2) https://doi.org/10.1007/978-94-009-1649-4

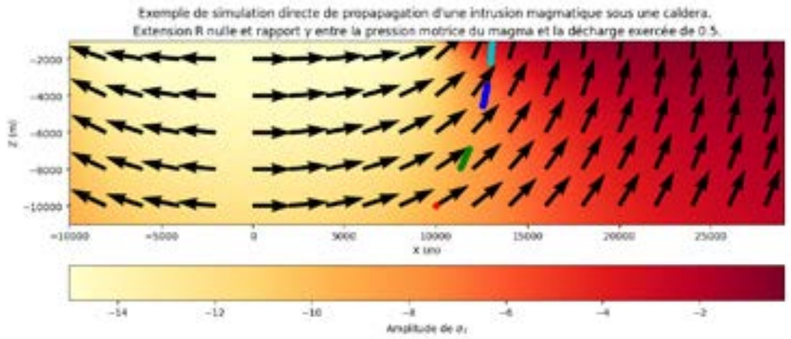
Léa ZUCCALI

Vers une prédiction de la position et du moment de l'ouverture d'une fissure éruptive par assimilation de données

Supervisor: Virginie Pinel

Geophysics of volcanoes & geothermal energy

Dans une perspective d'évaluation des risques volcaniques, il est fondamental de pouvoir savoir, à l'avance, si le magma qui a commencé à se propager à partir d'une zone de stockage, atteindra la surface, où et quand. La phase de propagation est généralement rapide, de quelques heures à quelques mois, mais elle induit des signaux de sismicité et de déformation qui sont enregistrés par des capteurs continus (GNSS) et des données InSAR. Par ailleurs, des modèles numériques dynamiques permettent de calculer la trajectoire et la vitesse de propagation du magma en fonction des propriétés physiques du magma, de la croûte et des conditions initiales.
L'assimilation de données est une méthode qui combine un modèle dynamique avec des observations actuelles et passées basées sur des statistiques d'erreur et qui prédit l'état futur du système observé. Cette méthode est donc un outil approprié pour répondre au besoin de pouvoir prédire la position et le moment d'une éruption en volcanologie.
Le filtre particulaire se distingue en particulier par sa grande capacité à traiter des modèles non linéaires et des statistiques d'erreur non gaussiennes. Cette méthode est basée sur une représentation de la densité de probabilité du modèle dynamique par un ensemble discret d'états du modèle (les particules) et s'appuie sur le théorème de Bayes.
Dans un premier temps nous mettrons en œuvre le filtre particulaire avec un modèle physique simple, en deux dimensions, des trajectoires empruntées par le magma, dans le cas d'une caldera, en contexte extensif. Les paramètres d'entrées seront la position initiale du magma, sa viscosité, sa surpression motrice, le volume injecté, la rigidité de la croûte ainsi que le champ de contrainte local. Le déplacement induit en surface sera calculé via un modèle de dislocation d'Okada. Les données utilisées seront d'abord des données de simulation synthétique, puis des données réelles issues d'observations du Piton de la Fournaise.



Exemple de simulation directe de propagation d'une intrusion magmatique sous une caldera.
Les flèches noires représentent le champs de contrainte du milieu, l'ensemble de points rouge la position initiale du magma, l'ensemble de points bleu ciel représente la position finale de la remontée magmatique, les ensembles bleu foncé et vert représentent des positions intermédiaires.

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