Tutored Projects in the Geosciences: 2023-2024 edition

The idea behind the tutored project is for you to undertake a project that will take advantage of the skills that you gained over the course of the semester.

You select a topic among those listed below; each topic has been proposed by one or several professors who will follow your progress and guide you throughout, for example via weekly one hour-long meetings, or assisting you in running a number of laboratory sessions. Starting from the literature, your task is to address a scientific question by implementing a method or a suite of methods similar to those you got familiar with during the past few months.

We expect you to work by groups of 2 (working solo is also a possibility), and to hand in a report, that should respect the following structure:

1. Introduction – context of the study
2. Model and methods
3. Results
4. Discussion
5. Conclusion

The report should be no more than 12-page long. We will provide you with a LaTeX document class that you are encouraged (but not forced) to use. The deadline to hand in the report remains to be defined, but it will be around mid-January. An oral defense will follow. You should not spend more than 40 hours on this project.

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Contents

1 Seismic reflection imaging of magma bodies beneath Axial Volcano

Supervisor: Hélène Carton (carton@ipgp.fr)

Axial Volcano, located in the Eastern Pacific on the Juan de Fuca ridge at the intersection with the Cobb-Eickelberg seamount chain, is a very active underwater volcano with a history of recent documented eruptions. In 2019, it was the target of a large 3D multi-channel seismic experiment aiming to unravel the architecture of its underlying magma system. Preliminary data processing suggests that the flanks of the magma bodies can be imaged by seismic reflection and appear as steep boundaries, implying the presence of an impedance contrast whose nature is a topic of current research. The aim of the proposed project is to improve the imaging of these magma bodies including flank boundaries, i.e. enhancing their amplitude as well as their spatial continuity and depth extent, by investigating further two key parameters in the generation of the stacked images: the source-receiver offset range and the velocities used for stacking. To that end, focusing on a central strip within the 3D box, frequency-wavenumber filtering will be applied to remove the seafloor reflection and seafloor scattering, supergathers will be formed for visual inspection of the magma lens events before and after normal move-out correction, and a series of stacks of parallel inline sections will be formed. The student(s) will use seismic processing software Echos installed on Marine Geosciences workstations via remote access. An internship project focusing on the more sophisticated pre-stack depth imaging of these magma bodies, along with amplitude-versus-offset analysis to decipher melt/mush variations, will also be offered.

2 Seismic Detection and Characterization of Landslides and Rock Avalanches: Comparative Analysis Between Earth and Mars

Supervisor: Antoine Lucas (lucas@ipgp.fr)

Landslides and rock avalanches are significant geological events that can have a profound impact on the landscape. Detecting and characterizing these events is crucial for hazard assessment and planetary science. In recent years, there has been growing interest in using seismology as a tool for monitoring and understanding landslides and rock avalanches. This research project aims to explore the feasibility of seismic detection and characterization of these events and compare the results between Earth and Mars.

The objectives of this research project are as follows:

1. Use analytical solutions or conduct numerical simulations to model the force history applied by landslides and rock avalanches on the ground.
2. Generate synthetic seismograms using Python packages to simulate the seismic signals produced by these events
3. Conduct a sensitivity analysis to investigate how parameters like seismic network distance, geological characteristics, proximity to the seashore, and noise levels impact the detectability of these events
4. Compare the results obtained from Earth simulations to those from Mars, taking into account the differences in geological and environmental conditions.

We anticipate the following outcomes from this research project:

- Insights into the seismic signatures of landslides and rock avalanches under various conditions on Earth.
- A comparative analysis of seismic detectability between Earth and Mars.
- Recommendations for optimizing seismic monitoring strategies for landslide and rock avalanche hazard assessment.

3 The magnetisation of Mars

Supervisor: Vincent Lesur (lesur@ipgp.fr)

Questions remain open on the strength and direction of the magnetic field on Mars when the dynamo generating it was active. It is possible to partly answer these questions by assuming the Martian lithosphere magnetisation is aligned with the core field dominant direction at the time when the temperatures of the rocks fell below the Curie temperature. The magnetic field currently recorded at satellite altitude on Mars is essentially generated in the planet lithosphere. Magnetic field models derived from these data show a strong magnetisation of the rocks. Under the hypothesis that an isolated magnetic signal is associated with a magnetisation of the rocks that is constant in direction, it is possible to recover this direction and the intensity of the magnetisation. This tutored project will aim at identifying two isolated structures in a magnetic field model of Mars, and fit these signals with simple models of buried magnetized spheres.

4 Simulation of the viscosity of a cooling magma ocean

Supervisor: Charles Le Losq (lelosq@ipgp.fr)

Your task: Magma oceans on young planets play an important role on the formation of their atmosphere and mantle. Those phenomena actually may change the magma ocean composition,and, hence, its physical and chemical properties. This, ultimately, may affect processes such as the dynamics of convection of magma oceans. Here, I propose to couple the machine learning model *i-Melt* of melt properties with physical equations in order to explore how atmosphere condensation or melt crystallization influence the mobility of the magma through time.

How: We will use the greybox *i-Melt* model for melt properties and equations (Einstein-Roscoe, etc.) that allow taking into account the effect of crystals on melt viscosity. Different equations will be tested, and, depending on progress, we may try to include them in i-Melt.

Literature: Le Losq and Baldoni (2023) https://arxiv.org/abs/2304.12123

Prerequisites: Python programming.

5 Investigating the features of experimentally modified volcanic ash particles

Supervisors: Fidel Costa (costa@ipgp.fr) and Damià Benet (dbenet@ipgp.fr)

Identifying the different components in volcanic ash provides insights into the processes driving volcanic activity, and thus it is essential for hazard assessment. Traditionally, the classification of ash has relied on detailed particle examination and inferences by an expert researcher.

However, associating a set of characteristics with particular components is challenging and different observers have different interpretations of the particles' features. In this project, we will use a newly installed automated binocular system to collect images of ash particles that have been experimentally reacted in the lab to simulate the processes occurring during volcanic eruptions. We will attempt to correlate differences in image features with experimental variables in a quantitative manner and in this way partly benchmark the classifications and inferences made by expert researchers.

6 What did we learn from the Hayabusa2 sample return mission (from asteroid Ryugu) on the origin of the terrestrial planets?

Supervisor: Frédéric Moynier (moynier@ipgp.fr)

In 2020 the Hayabusa2 mission brought back over 5 g of samples from the carbonaceous asteroid Ryugu. In the last two years there have been many scientific studies of these samples. The project will consist in a bibliographic study of the results from the mission, including putting them in a general context on the Solar System formation.

7 Geodetic imaging of a network of interconnected reservoirs subject to magma influx

Supervisor: Raphaël Grandin (grandin@ipgp.fr)

Goal: Episodes of transient deformation, not connected to a recent eruption, have been reported on a number of volcanic systems (Yellowstone, Laguna del Maule, Campi Flegrei) (Delgado & Grandin, 2021; Le Mével et al, 2021; Amoruso & Crescentini, 2022). Implications in terms of volcanic hazard depend on the causative mechanism, which is often primarily interpreted as an influx of magmatic material in the system. When constrained by geodetic observations (GNSS, InSAR), inversions attempt to define (i) the best geometry of the reservoir, and (ii) the mass flux history feeding the reservoir. However, single-reservoir models may inadequately represent reality, as reservoirs likely consist in a network of individual sub-reservoirs, separated by regions where magmatic fluid circulation is restricted in conduits. Under the assumption of a multiplicity of connected reservoirs, a simplified description of (i) flow throw the conduits and (ii) deformation of the reservoirs, both quantities depending on the distribution of pressure within the system, allows for representing the global response of the system as a linear problem. The problem can then be casted in the framework of network theory, where reservoirs are represented by "nodes", and conduits are the "links" between them. Such a description should make it possible to efficiently invert for the pressure time history, or determine the optimal configuration of the system (number of sources, geometry, connectivity), using geodetic data.

Your task: (1) Define the set of governing equations for a generic network of N reservoirs, connected in 1D, 2D and 3D. (2) Make an analogy with network theory. (3) Build synthetic InSAR maps. (4) Discuss the domain of invertibility of the problem (in what regions of the parameters space can be expect the inverse problem to be well-posed?).

How: (1) Use Appendix A of Walver et al (2016) to define the equations for $N > 2$ reservoirs in a matrix form. (2) Use the networkx Python library to facilitate generation of a random synthetic reservoir (https://networkx.org). (3) Use Mogi equations to model the resulting synthetic deformation. (4) Compute many forward models and discuss the ability of geodetic data (GNSS, InSAR) to capture their main features.

Literature:

- Amoruso, A., & Crescentini, L. (2022). Clues of ongoing deep magma inflation at Campi Flegrei Caldera (Italy) from empirical orthogonal function analysis of SAR data. Remote Sensing, 14(22), 5698.
- Delgado, F., & Grandin, R. (2021). Dynamics of episodic magma injection and migration at Yellowstone Caldera: revisiting the 2004–2009 episode of caldera uplift with InSAR and GPS data. Journal of Geophysical Research: Solid Earth, 126(8), e2021JB022341.
- Le Mével, H., Córdova, L., Cardona, C., & Feigl, K. L. (2021). Unrest at the Laguna del Maule volcanic field 2005–2020: Renewed acceleration of deformation. Bulletin of Volcanology, 83(6), 39.
- Walwer, D., Ghil, M., & Calais, E. (2019). Oscillatory nature of the Okmok volcano's deformation. Earth and Planetary Science Letters, 506, 76-86

8 Sources analysis of the volcano tectonic earthquakes recorded in Mayotte

Supervisor: Lise Retailleau (retailleau@ipgp.fr). At IPGP from December 6 th , otherwise distant supervision.

Goal: The seismic activity linked to Mayotte's volcanic system is still active. In particular, the proximal cluster (closest to Mayotte), shows a complex and still obscure system. Its understanding is crucial as it presents risks for future activity. The structure of the seismic activity can be informed by the determination of source mechanism.

Your task: To develop a methodology to study the mechanism of the volcano-tectonic earthquake sources.

How: Develop a code to determine the polarity of the P waves to improve the mechanism knowledge of the sources. The project will make use of a catalog built using both land seismometers and ocean bottom seismometers.

Literature: Retailleau et al. (2022 a, b)

- Retailleau Lise, Saurel Jean-Marie, Zhu Weiqiang, Satriano Claudio, Beroza Gregory, Issartel Simon, Boissier Patrice, Team Ovpf. A Wrapper to Use a Machine-Learning-Based Algorithm for Earthquake Monitoring. Seismological Research Letters, Seismological Society of America, 16 février 2022, 93.

- Retailleau Lise, Saurel Jean-Marie, Laporte Marine, Lavayssière Aude, Ferrazzini Valérie, Zhu Weiqiang, Beroza Gregory, Satriano Claudio, Komorowski Jean-Christophe, Team Ovpf. Automatic detection for a comprehensive view of Mayotte seismicity. Comptes Rendus. Géoscience, Académie des sciences (Paris), 2022, 354.

9 Seismology of Comet: Investigation of Normal Mode Detection for Future Comet Sample Return Mission

Supervisors: Taichi Kawamura (kawamura@ipgp.fr), Philippe Lognonné (lognonne@ipgp.fr)

Goal: The goal of the mission is to evaluate the seismic signal excited on a comet with an artificial impact and discuss the detectability. Comets are regarded as one of the most primitive bodies in the solar system and they are the key to understand how the planets formed in our solar system. To understand better the origin and the formation of comets, we would like to probe the internal structure using seismology. Japanese Space Agency JAXA is now planning a sample return mission from the comet and seismometer is listed as a candidate payload. We would like to evaluate the detectability of seismic signal on the comets to study how the seismometer will be useful for the future mission.

Your task: You would be asked to use the existing code and calculate synthetic seismic signal on a comet. You should refer to previous studies discussing internal structure of comet and define a reference model (or several reference models) that will be used to calculate the seismic signal. Once you obtained the seismic signal, you will need to compare this with different sensitivity curve of seismometers to discuss the detectability. It would be also important to test different methods, such as signal stacking, to further discuss the detectability.

How: We will use MINEOS to model the seismic signal (e.g. Masters et al., 2014, Lognonné & Clévédé CIDER package). This is a well-established code which uses normal mode summation to calculate synthetic seismic signal, which is available also with example for computing seismograms of planets.

For the internal structure of comets, we will refer to past studies such as Knapmeyer et al., (2018) or Blum et al. (2022). For the seismic source we will assume an artificial impact as in the case of Hayabusa 2 SCI (Arakawa et al., 2020; Nishiyama et al., 2021). Once the seismic signal is obtained, we will perform spectral analyses to discuss the detectability as well as seismic shacking, e.g. seismic waves accelerations larger than local g.

Literature:

- Mineos User Manual; Masters et al., 2014 https://geodynamics.org/resources/1753/download/mineos-manual-1.0.2.pdf

- CIDER package : `https://www.dropbox.com/scl/fo/iaxz7x79fomqdb1zmrxhr/h?rlkey=rha1ayb1baj4d3f amp;dl=0`

- Knapmeyer et al., 2018; https://doi.org/10.1016/j.icarus.2017.12.002

- Blum et al., 2022 Universe 2022, 8(7), 381; https://doi.org/10.3390/universe8070381

- Arakawa et al., 2020 ; Science, 2020, 368 (6486), pp.67-71. https://doi.org/10.1126/science.aaz1701.

- Nishiyama et al., 2021 https://doi.org/10.1029/2020JE006594

- A. J. Ball, Philippe Lognonné, Karsten Seiferlin, Tilman Spohn, John C. Zarnecki, Lander and Penetrator Science for NEO Mitigation Studies, chapter 13, in Belton, M.J.S., Yeomans, D.K., Morgan, T.H. (editors), Mitigation of Hazardous Impacts due to Asteroids and Comets, Cambridge University Press, ISBN: 0521827647, 2003.

10 Seismology of Enceladus: Investigation of seismic signal and its detectability

Supervisors: Philippe Lognonné (lognonne@ipgp.fr), Taichi Kawamura (kawamura@ipgp.fr)

Goal: The goal of the mission is to evaluate the seismic signal excited on Enceladus and discuss the detectability. Enceladus is an icy satellite of Saturn known to have inner ocean and some activities such as plumes. It is one of the key targets for future space missions in terms of planetary science and astrobiology. We would like to calculate synthetic seismic signals on Enceladus to study how much we can constrain the internal structure with seismology.

Your task: You would be asked to use the existing code and calculate synthetic seismic signal on Enceladus. You should refer to previous studies discussing internal structure of Enceladus and define several reference models that will be used to calculate the seismic signal. Using different models, you should discuss how the different internal structure will affect the seismic signal and investigate if we can distinguish this with existing instruments or instruments in development. In that study, you will perform parametric analysis related to the ice-crust thickness, and will try to estimate the tidal seismicity based on scaling law with tidal moon activity.

How:

You will use MINEOS to model the seismic signal (e.g. Masters et al., 2014, Lognonné & Clévédé CIDER package).. This is a well-established code which uses normal mode summation to calculate synthetic seismic signal. For the internal structure of Enceladus, you will use PlanetProfile, which is an open source code which calculate internal structure of different icy satellites with thermodynamic and geodesic constraints (https://github.com/vancesteven/PlanetProfile).

Literature:

- Mineos User Manual; Masters et al., 2014 https://geodynamics.org/resources/1753/download/mineos-manual-1.0.2.pdf
- CIDER package : `https://www.dropbox.com/scl/fo/iaxz7x79fomqdb1zmrxhr/h?rlkey=rha1ayb1baj4d3f` `amp;dl=0`
- Vance,S. D., et al (2018). Geophysical investigations of habitability in ice-covered ocean worlds. Journal of Geophysical Research: Planets, 123, 180–205. https://doi.org/10.1002/2017JE005341
- Angela G Marusiak et al 2021 Planet. Sci. J. 2 150 https://doi.org/10.3847/PSJ/ac1272
- Stähler et al. (2018), https://doi.org/10.1002/2017JE00533
- Panning, M. P., Stähler, S. C., Huang, H.-H., Vance, S. D., Kedar, S., Tsai, V. C., Pike, W. T., & Lorenz, R. D. (2018). Expected seismicity and the seismic noise environment of Europa. Journal of Geophysical Research: Planets, 123, 163–179. https://doi.org/10.1002/2017JE005332
- Kawamura, T., P. Lognonné, Y. Nishikawa, and S. Tanaka, Evaluation of deep moonquake source parameters: Implication for fault characteristics and thermal state, J. Geophys. Res. Planets, 122, 1487–1504, https://doi.org/10.1002/2016JE005147, 2017.

11 Measuring the recharge of a confined aquifer system following a flood event from surface elevation change

Supervisor: Manon Dalaison (dalaison@ipgp.fr)

Background: During a flood, precipitation and surface water that infiltrates are sources of water for aquifer recharge. You will focus on confined aquifer in which water under pressure holds the above layers to a certain height. When pore pressure increases within a confined aquifer, the aquifer skeleton expands resulting in surface uplift, which can be measured using various geodetic techniques (GPS, InSAR. . .). Vertically, the transfert will depend on the hydrogeologic properties of the aquifer material and its overburden. Horizontally, the pressure wave will travel through the porous aquifer with a speed that will depend on its diffusivity, while water transport is a function of the ratio of hydraulic conductivity to aquifer porosity. What is the expected surface uplift related to groundwater recharge after a flood event in a simple configuration and what is the expected time delay? You will study the big picture and extract orders of magnitude as well as assess the role of key parameters like volume change, compressibility, diffusivity or conductivity within a natural range of conditions.

Task: First, the challenge is to define the complex natural problem in simple terms with a reference scenario and geometry. Then, the idea is to code two simple one-dimensional models of diffusion through a porous medium and of ground deformation response to pressure change. The analysis of the sensitivity to parameters will feed a discussion on the detectability of such flood aquifer recharge from geodetic data.

Prerequisite: Python coding, notions of mechanics of continuous medium

References :

- Nimmo, J., Stonestrom, D. A. and Healy, R. W. Aquifers: Recharge Encyclopaedia of Water Science, 2008, https://wwwrcamnl.wr.usgs.gov/uzf/abs_pubs/papers/nimmo.03.encyc.aquiferrecharge.ehs.pdf

- Brown, M. R., Ge, S., & Screaton, E. (2022). A Simple Relation to Constrain Groundwater Models Using Surface Deformation. Groundwater, 60(3), 410-417. https://doi.org/10.1111/gwat.13148

(And a number of other references I will provide to have reference values for hydrogeologic parameters.)