Annual Report 2023

EUROPEAN CENTER FOR GEODYNAMICS AND SEISMOLOGY (ECGS)

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- **Dr. Julien Barrière**, geophysicist, ECGS
- **Dr. Delphine Smittarello**, geophysicist, ECGS
- **Maxime Jaspard**, technical engineer, ECGS

- **Dr. Nicolas d'Oreye**, geophysicist, National Museum of Natural History
- **Gilles Celli,** technical engineer, National Museum of Natural History

- **Josué Subira,** PhD student, Liège University & Royal Museum for Central Africa (Belgium) / Goma Volcano Observatory (DR Congo), visit at ECGS from April to November 2023
- **Prof. emeritus Antoine Kies**, physicist

INTRODUCTION

ECGS collaborates intimately with the Geophysics/Astrophysics section of the National Museum of Natural History (Mnhn). The Earth Science research group of ECGS and the Mnhn is composed of four permanent scientists (Dr. Adrien Oth, Dr. Julien Barrière, Dr. Delphine Smittarello and Dr. Nicolas d'Oreye), two technical engineers (Gilles Celli and Maxime Jaspard) and one administrative assistant (Yannick Breh).

ECGS continued its work on the implementation of the 2019 – 2024 strategic paper. Due to parental leave of two of our staff members in the course of 2023 (and continuing in 2024), some of our activities could only pursued at reduced pace. Among other activities, we continued our work on the operation and development of the Luxembourg Seismological Network (LuxSNet), which is composed of 13 real-time broadband seismic stations at present. ECGS also contributed five broadband seismic stations for temporary deployment in the Large-N seismological experiment led by the GFZ German Research Centre for Geosciences in the Eifel, with the ensuing scientific collaborations currently under discussion. The deployment of the instruments in the Eifel was operational from September 2022 to August 2023, and ECGS also provides access to the entirety of the LuxSNet data for this time span in this context of this experiment. We also keep in constant development our tools for the automatic monitoring of ground deformation by satellite radar interferometry (AMSTer software). This allows for the systematic monitoring of several targets for studying volcanoes, tectonic, landslides and deformation of natural and anthropogenic origins (Luxembourg national territory, DR Congo, Chile-Argentina, Guadeloupe, Comores, La Réunion).

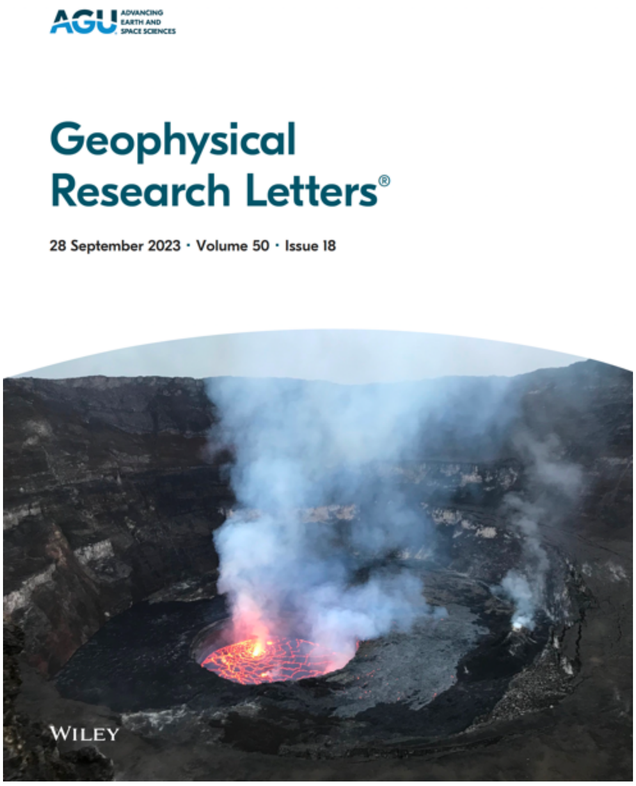


Figure 1: An ECGS study highlighted on the cover of GRL: Nyiragongo's lava lake, as photographed by Nicolas d'Oreye in March 2018 from the crater rim, showing the large lava lake (diameter of about 220 m) and the spatter cone on the right side. At that time, the crater depth (from the floor to its rim) was about 340 m. See also the article of Barrière et al. (doi: 10.1029/2023GL104664).

Notwithstanding the closure of collaboration with the Goma Volcano Observatory (GVO) in eastern DR Congo in 2022 (see previous annual reports for more information on these issues), the scientific research in this region still plays a major role in ECGS's activities and will do so also in the years to come. Over more than a decade, ECGS/Mnhn researchers have collected vast databases of ground-based and space-born data in the Kivu Rift region. As ECGS/Mnhn is not involved anymore in the acquisition of new ground-based data in this region since 1 July 2022, our researchers now fully focus on their research activities using the archived datasets rather than spending a lot of time to maintain this complex infrastructure operational. Obviously, the 2021 Nyiragongo eruption plays a key role in this research. The quality of the ECGS/Mnhn research is well demonstrated through our researchers' high-impact scientific publications, such as the 2022 *Nature* and *Nature Geoscience* articles (see 2022 report), or articles in other specialised highest-level research journals (e.g., *Geophysical Research Letters* published by the American Geophysical Union, see Figure 1).

Besides its work in Luxembourg and the Kivu region, ECGS/Mnhn was involved in a range of further research activities with strong international collaborations, which are the living proof of the wide recognition of its expertise. ECGS/Mnhn researchers published 9 articles in international peer-reviewed scientific journals and (co-)authored 18 contributions at international conferences in 2023.

RESEARCH ACTIVITIES

Seismological Research & Monitoring Activities

❖ Seismological monitoring infrastructure operated by ECGS

Over the past years, ECGS has continuously developed and maintained its **infrastructure for seismic, geodetic and infrasound monitoring and research**, with **key focus on two regions**:

1) The **Grand-Duchy of Luxembourg**. Here the focus lies on operating an adequately sized broadband seismic network for monitoring the seismic activity within and around Luxembourg's territory. The current status of the Luxembourg Seismological Network (LuxSNet) is shown in Figure 2, including the temporary stations deployed in the framework of the Large-N project in the Eifel coordinated by the GFZ German Research Centre for Geosciences in Potsdam;
2) The **Kivu region** in Central Africa (see also section below on the Kivu Rift region). The interest in this region has been driven through a series of scientific research projects over more than 17 years, and ECGS/Mnhn has become a key player in the scientific understanding and monitoring of the volcanic and seismic activity in this highly endangered region. However, the collaboration of ECGS/Mnhn with GVO and hence also the acquisition and/or transmission of any new data via ECGS/Mnhn infrastructure ended on 1 July 2022. The reasons for the closure of this collaboration were explained in detail in the 2022 Annual Report. At present we still support the Centre de Recherche en Sciences Naturelles (CRSN) in Lwiro (South Kivu) in the data acquisition of two seismic stations in the localities of Lwiro and Idjwi island, as this institution does not have the infrastructure available to take care of this acquisition by itself.

Luxembourg is a region of overall low seismic activity and hazard, as it is located well within the Eurasian Plate, far away from its boundaries. However, even though the Luxembourgish territory does not show significant present-day or historical seismicity, this is not the case for regions as close as 100 – 150 km from the Grand Duchy. For instance, the Roermond earthquake in 1992, which took place close to the border of the Netherlands and Germany and had a magnitude of 5.4, was also widely felt in Luxembourg. We will discuss the new scientific results of our monitoring activities in Luxembourg here below.

Starting in 2022, ECGS became also involved as a partner institution in a large-scale seismological experiment covering the **Eifel region** in western Germany, a project coordinated by the GFZ German Research Centre for Geosciences. The Eifel represents an intracontinental volcanic field, yet the magmatic system underlying this field is still not very well understood. Since 2013, episodic swarms of deep low-frequency earthquakes, typically related to fluid movements in the Earth's crust and upper mantle, have been recurrently observed in the East Eifel. In order to obtain new insights into this system, more than 350 seismic measurement stations have been installed in late 2022 and were operated for one year (dismantlement took place in August 2023), recording earthquakes as well as continuous ambient background noise. ECGS participates in this so-called Large-N seismic experiment by (1) providing five broadband stations for temporary deployment (Figure 2) as well as the data from the LuxSNet network and (2) through scientific contributions in the data analysis.

The LuxSNet network currently counts 13 broadband seismic stations (Figure 2), covering the entirety of the Grand-Duchy. The broadband stations currently installed in the Eifel for the Large-N experiment will be either integrated into the LuxSNet network (depending on site availability and requirements) or used for participating in further international experiments such as the Eifel experiment. LuxSNet is under continuous development, and we are always on the look-out for good monitoring sites in the different regions of Luxembourg.

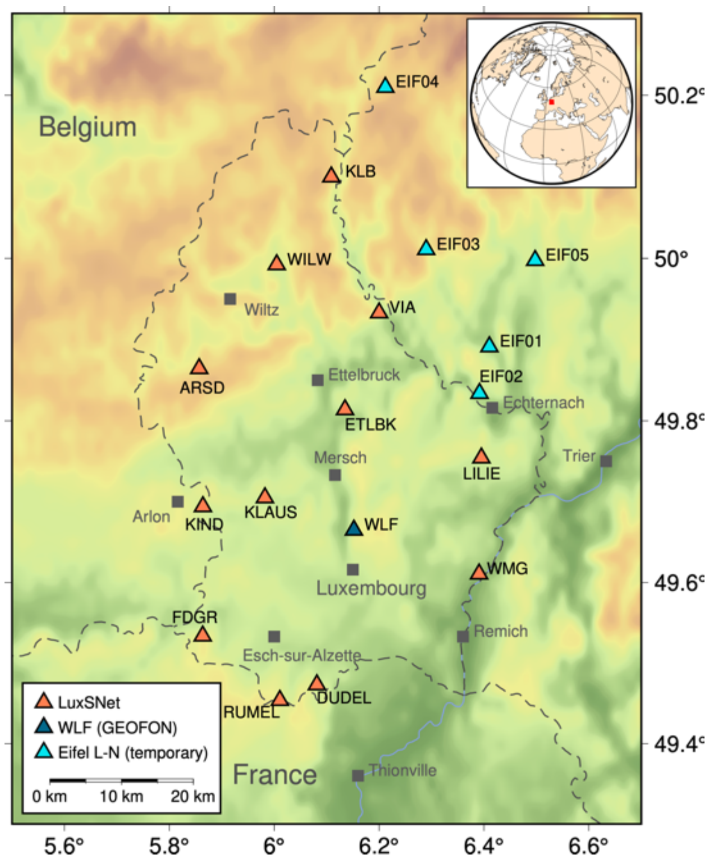


Figure 2: Current status of the Luxembourg Seismic Network (LuxSNet). The temporary stations EIF01 – EIF05 have been dismantled at the end of August 2023 after one year of operation.

All data (except those from the temporary station in the Eifel) are transmitted in real time to the ECGS office in Walferdange and evaluated with the real-time, automatic SeisComP software package developed by scientists at the GFZ German Research Centre for Geosciences and the company Gempa. Since 2018, ECGS shares seismic data of its broadband network with the ROB (a decades-long collaboration exists already for the seismic stations in Kalborn and Vianden) and the Erdbebendienst Südwest (Rheinland-Pfalz & Baden-Württemberg) and since 2022, data are also shared with the Bensberg Observatory of the University of Cologne, Germany.

On the German side, we have real-time access to station RIVT close to Trier as well as several stations from the Bensberg observatory towards the north of Luxembourg and towards Koblenz, while we provide data from our station WMG, KLB, VIA and WILW to the German colleagues. On the Belgian side, we receive access to stations DOU, HOU, RCHB and MEM, which are adding to our azimuthal coverage on the Belgian side. In turn, we provide our colleagues in Brussels with access to real-time data from our stations KIND and WILW. These collaborations show that the Luxembourg seismic data are also of interest to the monitoring agencies in our neighbouring countries and that the expertise of ECGS as Luxembourgish partner institution is recognized. Furthermore, we also make use of the openly available seismic data of the French ReNaSS network that are located in the vicinity of our borders.

Since 2020, ECGS assumes the role of National Data Centre in the framework of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), for which we were approached by the Ministry of Foreign Affairs in 2019 as potential scientific partner in the framework of a Benelux Memorandum of Understanding.

In December 2023, ECGS acquired licences for a set of commercial SeisComP modules from the German company Gempa in order to upgrade LuxSNet's detection and location capabilities. These modules will be installed and configured in early 2024 and their impact on ECGS's systems will be evaluated.

❖ Seismicity in Luxembourg

Based on the methodological framework detailed in previous reports, we continue to develop an accurate overview of tectonic seismicity occurring on the Luxembourgish territory following the progressive deployment of the national seismic network (Figures 2 & 3). The Luxembourgish seismic picture is almost fully dominated by anthropogenic sources (quarry blasts), but also depicts low-level tectonic activity in faulted areas. We recall below the 3 main active zones identified in the Gutland region:

- The south of Luxembourg close to Alzingen and Mondorf;
- The border with Germany between Grevenmacher and Echternach, mostly along the Moselle river;
- The Grünewald area, about 10 km to the East of the Walferdange Underground Laboratory and seismic station (WLF).

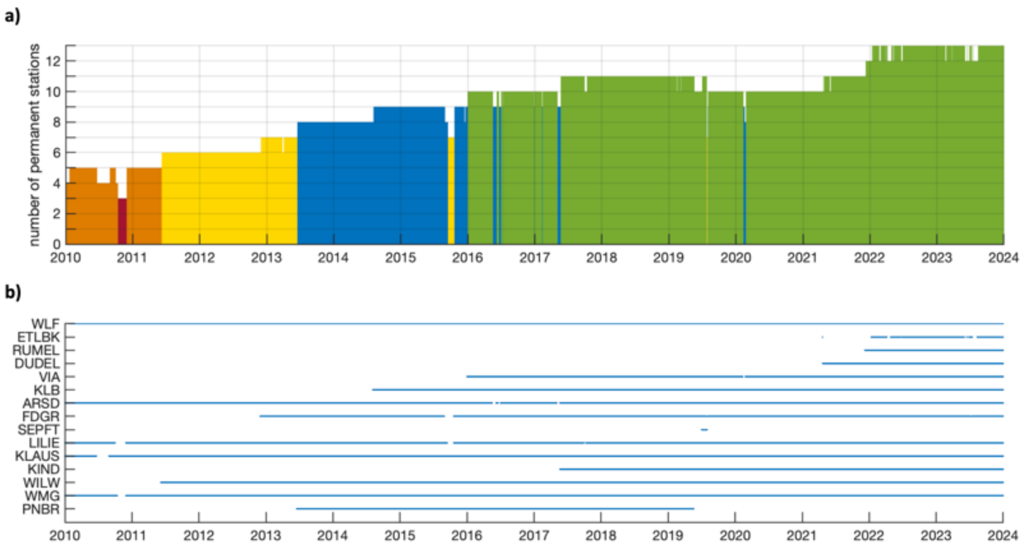


Figure 3: a) Timeline of data availability (number of operational permanent stations per day) for the Luxembourgish seismic network. **b)** Daily data availability per station (blue dots).

As already stated in previous reports, the ambiguity in determining rare low magnitude tectonic events among numerous quarry blasts can be strong due to, e.g., an origin time during daytime (when human activity is dominant), a source near quarries (numerous in our region), a badly constrained source depth, or site and path effects affecting the frequency content leading to similar waveforms. For this reason, the provided list of natural events occurring in Luxembourg could be marginally modified in light of potential new analyses and interpretations. To date, we have reported 9 low magnitude tectonic events (M_L < 2) between 1 January 2016 and 1 January 2023 in Luxembourg (i.e., of which hypocenters with uncertainties are located in Luxembourg). After review, an additional event in November 2019 near Walferdange is now characterized as tectonic (Figure 4). No seismic event can be flagged as tectonic earthquakes in Luxembourg neither during the first stage of station deployment (2010 – 2016), nor in 2023 after one round of review of the full catalog.

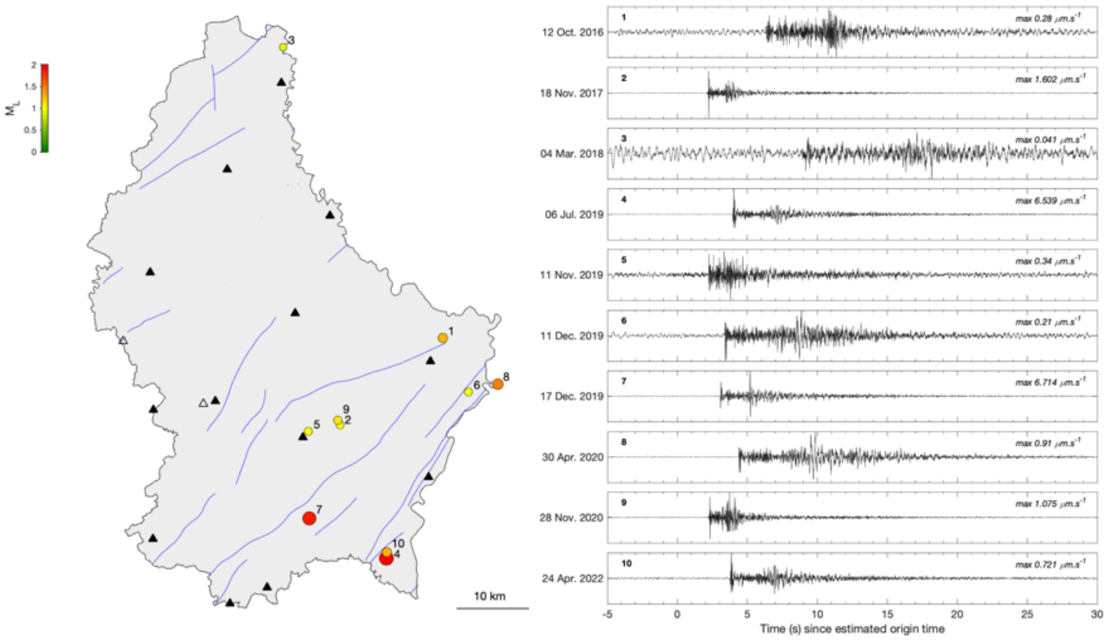


Figure 4: 10 earthquakes located in Luxembourg up to 1 January 2024. (Left) map of epicenters (size and color of the round markers are proportional to the magnitude M_L (computed using records from horizontal components, in contrast with magnitude M_{Lv} obtained from vertical component only). The main geological faults are depicted in blue (source: catalog.inspire.geoportail.lu). (Right) vertical component records at station WLF (Walferdange) for each earthquake (filtered above 2 Hz). Note that the amplitude of the seismic traces is normalized for each record. Operational permanent stations are depicted as black triangles and unfilled triangles represent dismantled stations at time of writing.

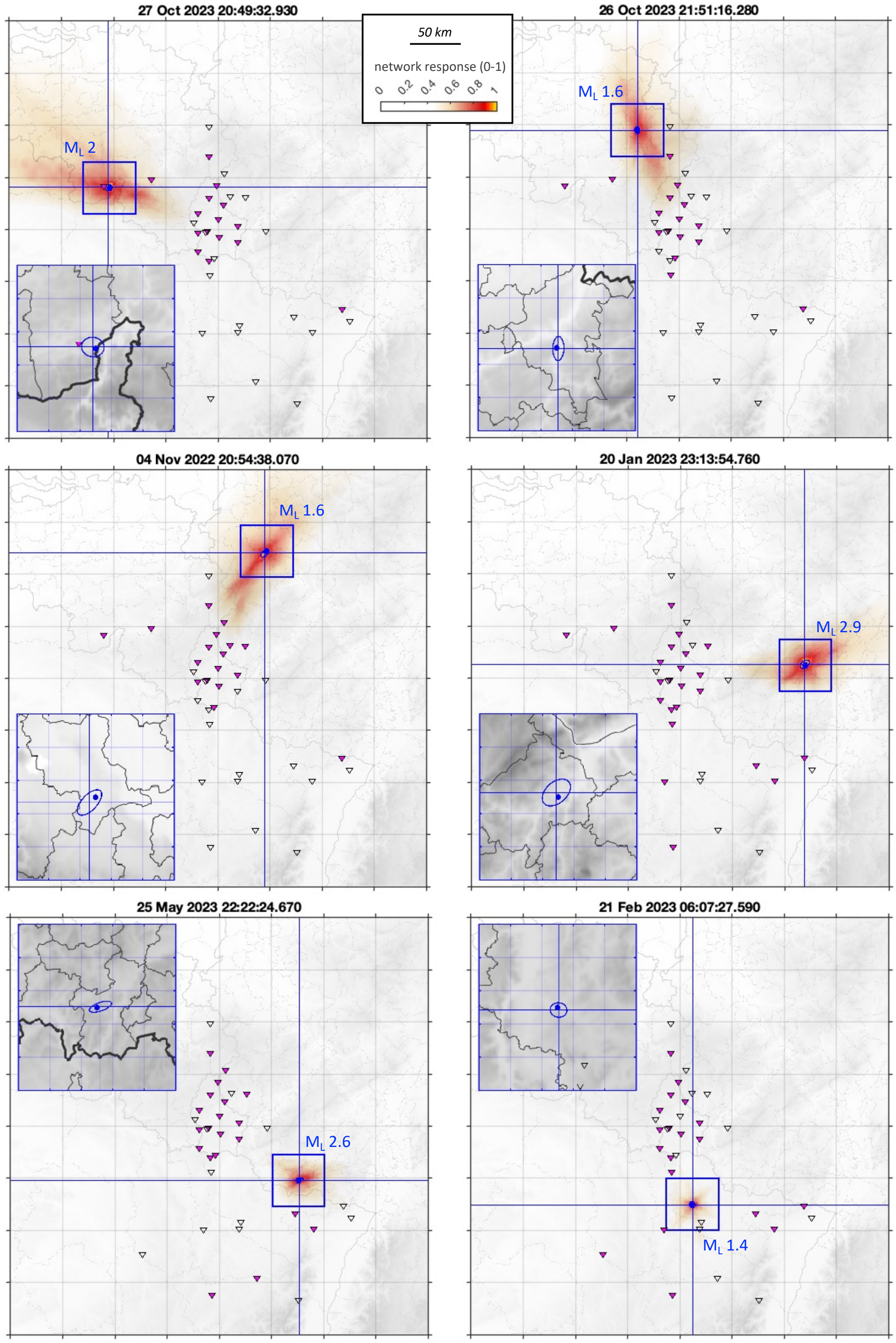


Figure 5: 6 seismic events located outside Luxembourg in 2022 and 2023 and detected by the Luxembourgish seismic network. Each map represents a location obtained with the grid-search, cross-correlation based location routine XCloc developed at ECGS. The color scale corresponds to the so-called "network response" obtained for each event, which can be understood as the location likelihood varying between 0 to 1 (the most probable location). The spatial distribution of the network response (i.e., the smearing of the colored red part) gives clues about the location uncertainty. For each panel, a zoom of 50x50 km around each solution (epicenter) is provided in inset, where only the maximum value of the network response (blue dot) and the 68% confidence ellipse (computed from values of the network response exceeding 0.9) are plotted. Note that the center of the ellipse and the maximum value are not necessarily co-located but a strong discrepancy should imply a large location error.

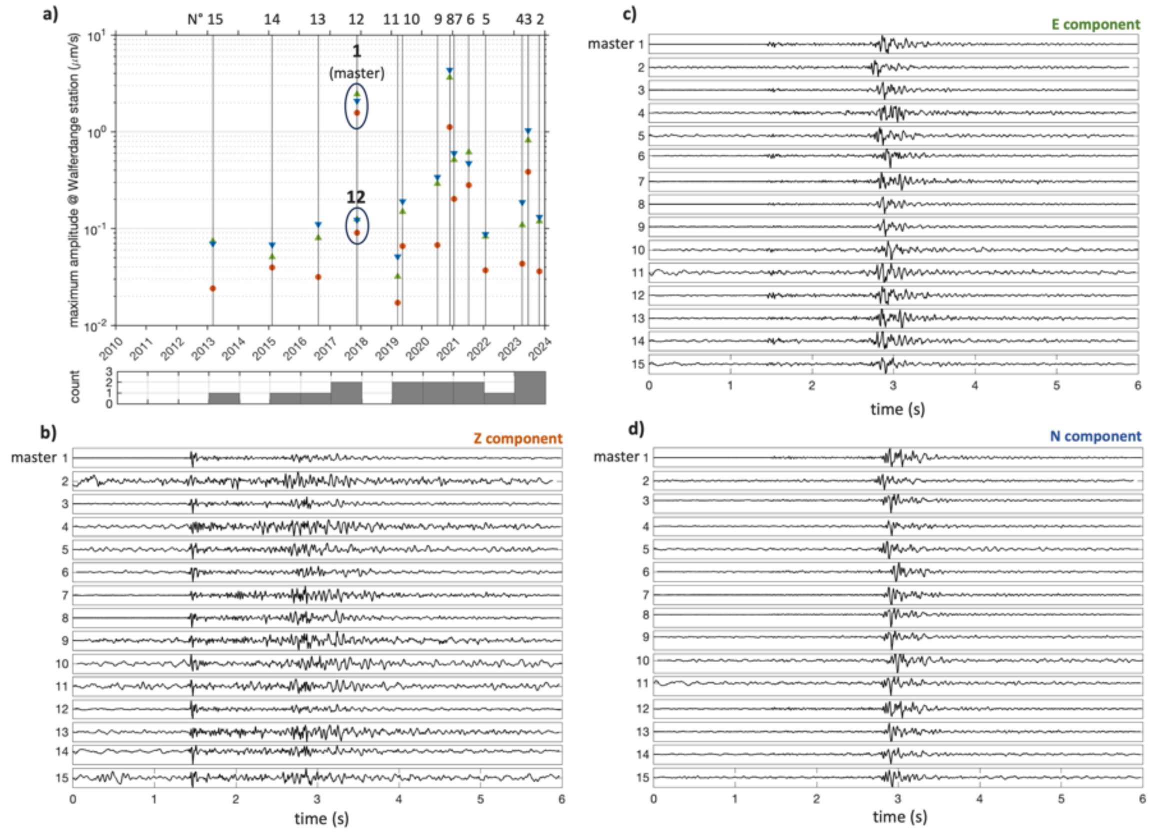


Figure 6: The Grünewald multiplet. **a)** Temporal distribution since 2010 with the maximum amplitude plotted on the y-axis (in µm/s, orange circle = vertical component, green triangle = east component, inverted blue triangle = north component). **b)**, **c)** and **d)** waveforms of detected events (high pass filtered above 5 Hz) extracted from Walferdange (WLF)'s records for vertical, east and north components, respectively. The event n°1 is the master event. The n°12 occurred the same day (November 18, 2017).

Obviously, we successfully detected/located earthquakes in nearby, more tectonically active regions around Luxembourg, notably thanks to additional seismic stations made available by our partner institutions and integrated into our routine analysis. This aspect is illustrated in Figure 5 with six seismic events located in 2022 and 2023 in different azimuth directions around Luxembourg.

We also report here a new analysis of the Grünewald multiplet, near Walferdange seismic station (WLF). Based on previous reports, this cluster encompasses seven similar microearthquakes detected thanks to a template matching method between 1 January 2010 and 1 January 2023. Only 2 events were detected across the national network and then successfully located (events n°2 and 10 in Figure 4). Similarly to our former approach, we used one of these two events (on November 18, 2017) as "master event" extracted from WLF's records. We tested several lengths and frequency filters for the master event to maximize our chance to detect a new event. By trial-and-error testing, we also evaluated the optimal threshold (normalized correlation coefficient) avoiding false detections yet still including the lowest magnitude events (i.e., having low signal-to-noise ratio). Finally, a 3-component template (1 vertical + 2 horizontals) of 6-sec long waveforms filtered between 5 and 25 Hz has been used for scanning the whole database since 2010. A perfect correlation would give a level of 3 (3 times 1) and an event is declared when the level exceeds 1.5 (with a minimum of 0.3 per component). Thanks to this new procedure, we have doubled the number of detected microearthquakes from this cluster (including three events detected in 2023). In Figure 6, we plot all 3-component records of the Grünewald multiplet and a timeline with the corresponding maximum amplitudes on the y-axis. It is noteworthy that most of events were detected in the past few years (2019-2023). As final step (not yet implemented), we could use all detected events, one after the other, as master event for a more exhaustive search.

❖ Seismological research in the Kivu Rift region

The research activities of ECGS/Mnhn carried out in the Kivu Rift region are outlined in more detail in a dedicated section further below (*The Kivu Rift region and the May 2021 Nyiragongo eruption*, page 10). A large component of this research has been seismological in nature, such as the seismo-acoustic analysis of the 2021 Nyiragongo eruption, the determination of a 1D velocity model for the region or the calibration of a local magnitude scale for better earthquake size characterisation.

❖ Various international seismological collaborations

▪ Uncertainties on earthquake source parameters based on the Community Stress Drop Validation Project

Back in 2021, a Technical Activity Group (TAG) has been set up in the framework of the *Southern California Earthquake Center (SCEC)*, addressing the need to better understand the large variability in earthquake source parameters observed across many studies, and to better gauge their physical and methodological origins in order to improve the usefulness of these parameters for ground motion prediction.

This TAG is based on the dataset of the 2019 Ridgecrest earthquake, on which A. Oth has co-authored a study in 2021 led by D. Bindi form the GFZ German Research Centre for Geosciences in Potsdam, Germany. In 2022 and 2023, the group of authors continued its work on the Ridgecrest dataset with a study designed to better understand the level of epistemic uncertainty affecting earthquake source parameter estimation due to the methodological choices of constraints made in the generalized inversion technique. As a result of this study, a set of two companion articles has been published in 2023 in *Seismological Research Letters*.

A. Oth will also serve as one of four guest editors for a special issue in *Bulletin of the Seismological Society of America* on improving measurements of earthquake source parameters.

▪ Design and Optimization of an Earthquake Early Warning System for the Lower Rhine Embayment

In the framework of the ROBUST project funded by the Bundesministerium für Bildung und Forschung (BMBF), the colleagues from the GFZ German Research Centre for Geosciences contacted A. Oth to participate in the seismic network optimisation efforts for earthquake early warning in the Lower Rhine Embayment. A manuscript on this study has been published in *Journal of Seismology*.

The study investigates the question as to how to best optimise the existing seismic network in the Lower Rhine embayment for earthquake early warning, pre-selecting a number of potential sites for additional stations and looking for the optimal station configuration using a genetic algorithm approach. In its essence, this work is based on the previous studies for Istanbul (Turkey) and Central Asia and makes use of the genetic algorithm codes developed by A. Oth for this purpose.

▪ Source parameters and scaling relationships of stress drop for shallow crustal earthquakes in Western Europe

This study is a collaboration between GFZ German Research Centre for Geosciences scientists, ECGS and the University of Liverpool. The study investigates the source characteristics of natural and induced earthquakes on a large scale throughout Western Europe, during the time period from January 1990 to May 2020. We show in this study that stress drops are generally higher in Southern Europe as compared to Northern Europe and discuss the scaling relationship of stress drop and magnitude.

A manuscript was submitted to Journal of Seismology in 2023 and has been accepted for publication.

The Kivu Rift Region & the May 2021 Nyiragongo Eruption

Figure 7: View of Nyiragongo summit crater taken on 21 May 2021, one day prior to its eruption.

On 22 May 2021, at around 16:30 UTC, without warning sign, began the third known eruption of Nyiragongo volcano since the end of the 19th Century. The first hours of this event were marked by great confusion and contradictory information concerning the location of the eruption (was it Nyamulagira or Nyiragongo volcano erupting?). Members of the Goma Volcano Observatory (GVO), civil protection and local authorities rapidly began to manage the crisis, assisted by the Belgo-Luxembourgian team of the Royal Museum for Central Africa (RMCA) and the ECGS/Mnhn, who worked with the GVO from 2005 to mid-2022.

Thanks to the seismic, GPS and infrasound monitoring networks that were perfectly operational and 3 additional temporary seismic stations deployed by ECGS/Mnhn in Rwanda during the crisis, the information obtained in real time as well as the numerous satellite data made it possible to follow the evolution of the situation with a quality and an accuracy never reached in the Virunga before, at the level of what is done for the best monitored volcanoes.

The real-time follow up of the volcanic crisis is described in detail in the 2021 annual report, and in 2022, we published among other a joint study of ground-based and space-born data in the journal *Nature*.

Here we therefore only present additional information on research works carried out in 2023.

❖ Local infrasound monitoring of lava eruptions at Nyiragongo volcano using urban and near-source stations

This work was published in 2023 in *Geophysical Research Letters*.

During eruptions, volcanoes produce air-pressure waves inaudible for the human ear called infrasound. Monitoring long-living lava effusion as observed at open-vent volcanoes needs close-range instruments (e.g., <15 km). Nyiragongo (Kivu rift region) towers above the cities of Goma (~1 million inhabitants) and Gisenyi (~200 000 inhabitants) and hosted the world's largest lava lake up to 2021, drained during its 3rd known flank eruption in May 2021.

Continuous tremor (i.e., a persistent pressure perturbation) is known to be associated with lava-lake activity (e.g., Barrière et al., 2018; Barrière et al., 2019). Detection of infrasound events with small aperture arrays (~20 m) for frequencies > 1 Hz are well noticed at station KBTI close to Nyiragongo, but hampered at station GOM due to urban noise and large distance (~17 km away from the crater) (see Barrière et al., 2023, and Figure 13 further below for the station locations). If a signal coming from Nyiragongo is recorded at different stations, the spacing between sensors by a minimum of 5.5 km (inter-station distance NYI-KBTI) allows exploring a wider frequency band than the single-station array approach down to 0.1 Hz (i.e., at least 1.5 infrasonic wavelengths between NYI and KBTI). Thus, we are looking for continuous signals originating from Nyiragongo's crater in a low frequency band (0.4-2 Hz) by cross-correlating signals recorded at each station. Cross-correlation Functions (CCFs) of successive 10-min segments are computed for the three station pairs (Figure 8). Clear single maxima (red color range in Figure 8b) are observed at positive and nearly constant time lags, which remarkably fit theoretical differential travel-times from a persistent signal generated at Nyiragongo's crater (solid black lines in Figure 8b).

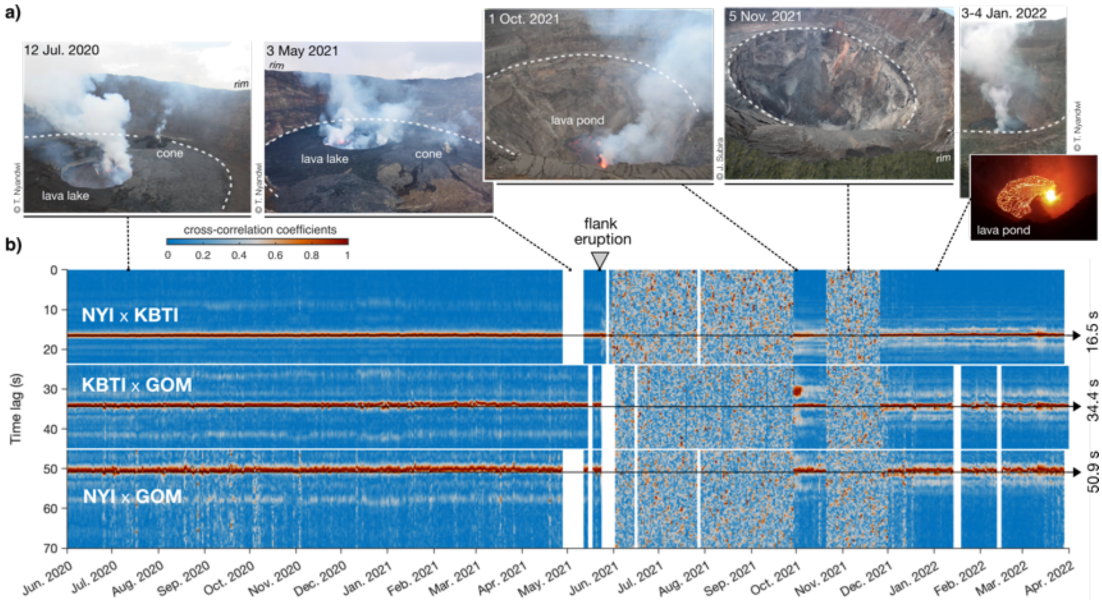


Figure 8: [Modified after Barrière et al., 2023]. **a)** Pictures of Nyiragongo's crater **b)** Normalized Hilbert envelopes of cross-correlation functions (CCFs) displayed in a plane "date versus time lag." Daily windows with less than 10% of calculated CCFs are ignored (blank parts). Only sections around the single maxima for each station pair are plotted. All single CCFs are scaled by their maximum (in red). Theoretical travel-times from a source at Nyiragongo are indicated by black lines.

It follows that Nyiragongo is a permanent emitter of infrasound that paused during few months after the 2021 flank eruption. With this approach, intra-crater lava eruptions (lava lake, spatter cone, lava pond) are successfully detected up to the Goma Volcano Observatory (GVO) in a dense urban area ~17 km away. The joint analysis with space-based observations (crater morphology, SO_2 emissions, thermal hotspots) over the period 2018–2022 helps decipher unrest at this volcano as illustrated in Figure 9.

Variations of infrasound amplitude linked with SO_2 emissions are both being related to high lava-lake levels and drops (see Barrière et al., 2022 for discussion about these drops due to repetitive deep magmatic intrusions). The lowest levels of infrasound amplitude at KBTI and the loss of correlation between stations (infrasound flag = 0) are observed when the crater was deep and empty after the May 2021 flank eruption (confirmed by rare pictures and satellite data). Both renewal of intra-crater activity on 28 September and 25 November 2021 are first identified in the infrasound records, further validated by thermal imagery despite cloudy conditions or by visual inspection at the summit by GVO.

On a daily monitoring aspect, the harsh field environment around Nyiragongo implies the need of an accessible and protected location for sensor deployment, which likely resides within the confines of the city (limited access to NYI and KBTI in 2023 due to civil war). Therefore, deploying another city-based station in Goma could be a strategy in the future to extract information through a unique pair of urban stations.

❖ Seismological models and seismicity patterns in the Kivu Rift and Virunga Volcanic Province

This work is performed in the framework of the PhD thesis by Mr. Josué Subira (affiliations: RMCA, Université de Liège, GVO). J. Subira visited ECGS for 8 months in 2023 (April – November), where he was mentored by Julien Barrière and Adrien Oth for completing the main part of his PhD thesis. An aspect of J. Subira's work was to continue his analysis of continuous seismic amplitude measurements in the Virunga volcanic province initiated in Subira et al. (2023) by focusing on Nyiragongo's 2021 eruption. Another important contribution is the development of a new velocity model for the Kivu rift region following the significant instrumental improvement between 2015 and 2022 in the framework of the KivuSNet (Oth et al., 2017). The main results are briefly described below.

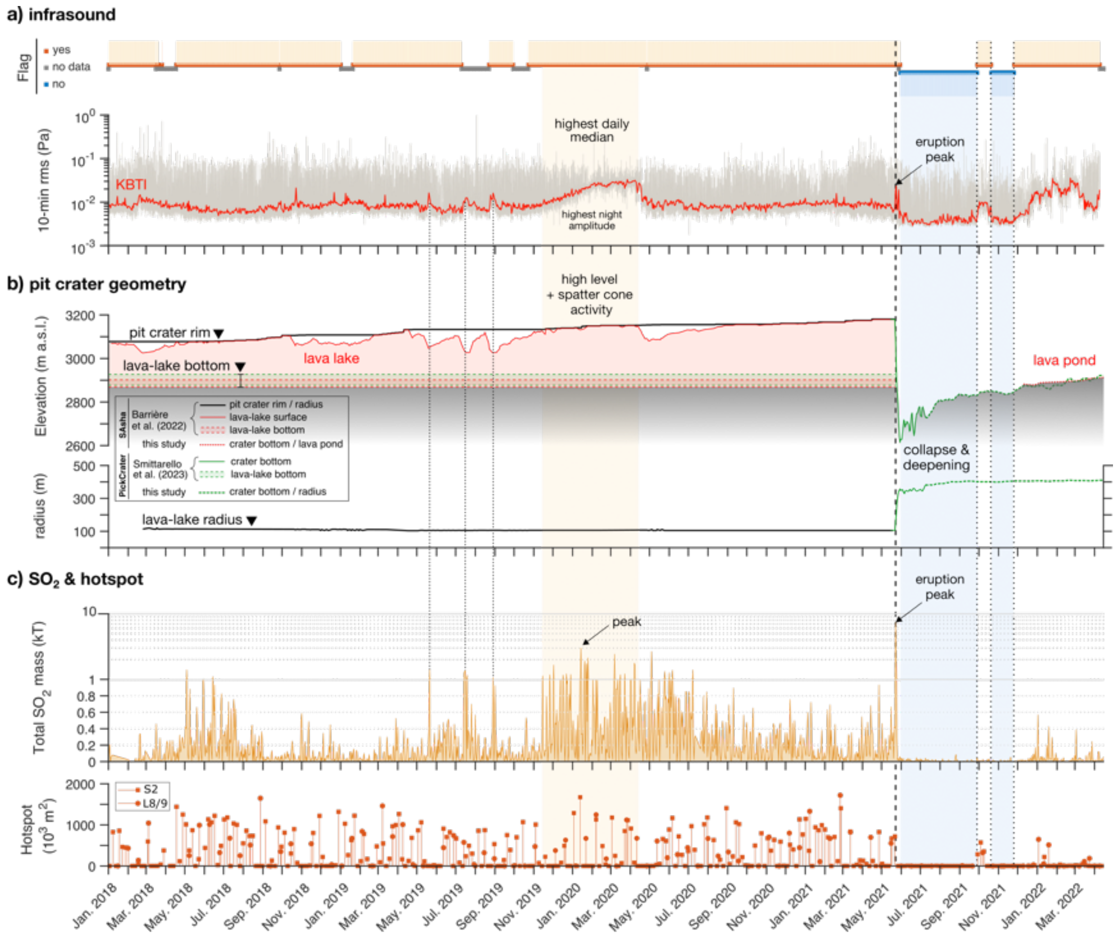


Figure 9: [Modified after Barrière et al., 2023]. **a)** Infrasound flag indicator for Nyiragongo's source derived from CCFs results (see left figure & article for details). Below, 10-min RMS amplitude at KBTI (gray) and moving daily median (red). **b)** Pit crater geometry (elevation and radius) using SAsha and PickCraterSAR methods (Barrière et al., 2022; Smittarello et al., 2023), including variations of the lava-lake level (in red). **c)** For Nyiragongo, space-based daily solutions for SO_2 emissions obtained from TROPOMI (Theys et al., 2019) and thermal hotspots (S2 stands for Sentinel-2, L8/9 for Landsat-8/9) using HOTMAP algorithm (Murphy et al., 2016)

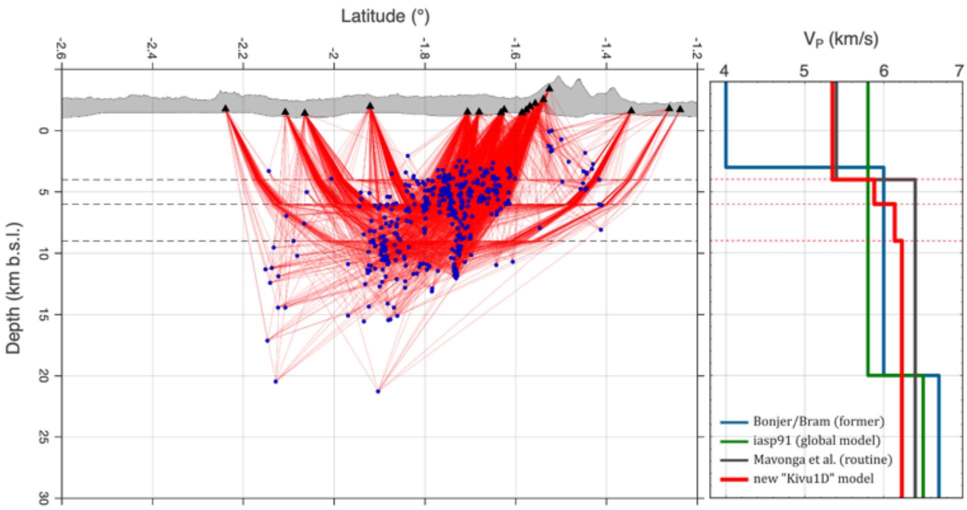


Figure 10: (Left) Depth distribution of events and seismic ray paths using the new 1D minimum model "Kivu1D". (Right) Final P-wave velocity model "Kivu 1D" (red) plotted against available velocity models for the region: The former Bonjer/Bram (1970/1975) model (blue), the iasp91 global reference model (green) and the routine model used at GVO (Mavonga et al., 2010) derived from receiver function analysis at two dismantled stations (dark gray).

The location of an earthquake is the most fundamental seismological product and is at the core of any seismic monitoring operations. However, reliable estimates strongly depend, among other important factors like station coverage and quality of observations, on a ground velocity structure often poorly known. This is obviously the case for the Kivu Rift and Virunga Volcanic Province. From a selected dataset of well-recorded ~400 events, solving the coupled hypocenter-velocity inverse problem following Kissling et al. (1994) allows to get a suitable 1D (i.e., layered) local velocity model developed for improving hypocenter locations in the region, which is called a "minimum model" (Figure 10). Station correction terms (i.e., delays to subtract to the observed arrival times) are estimated in the inversion process to compensate for near-surface and large-scale heterogeneities in the crust not considered in the 1D solution. A complete seismic catalogue was relocated for the period 2015-2022 using this new velocity model and the XCloc location method developed at ECGS (e.g., Barrière et al., 2022). This period encompasses the 22 May 2021 Nyiragongo flank eruption and the subsequent 1-week, 25-km long dyke intrusion. The overall seismicity map can be divided into six spatial clusters: #1, #4, #5 and #6 dominated by tectonic seismicity related to rift dynamics, #2 and #3 corresponding to volcanic seismicity at Nyamulagira and Nyiragongo, respectively. Planned work for 2024 (concomitant with the final part of J. Subira's thesis) mainly includes the detailed analysis of the observed seismicity patterns as preliminary performed in Figures 11 and 12 and the publication of these results (both the velocity model and the full seismicity catalogue).

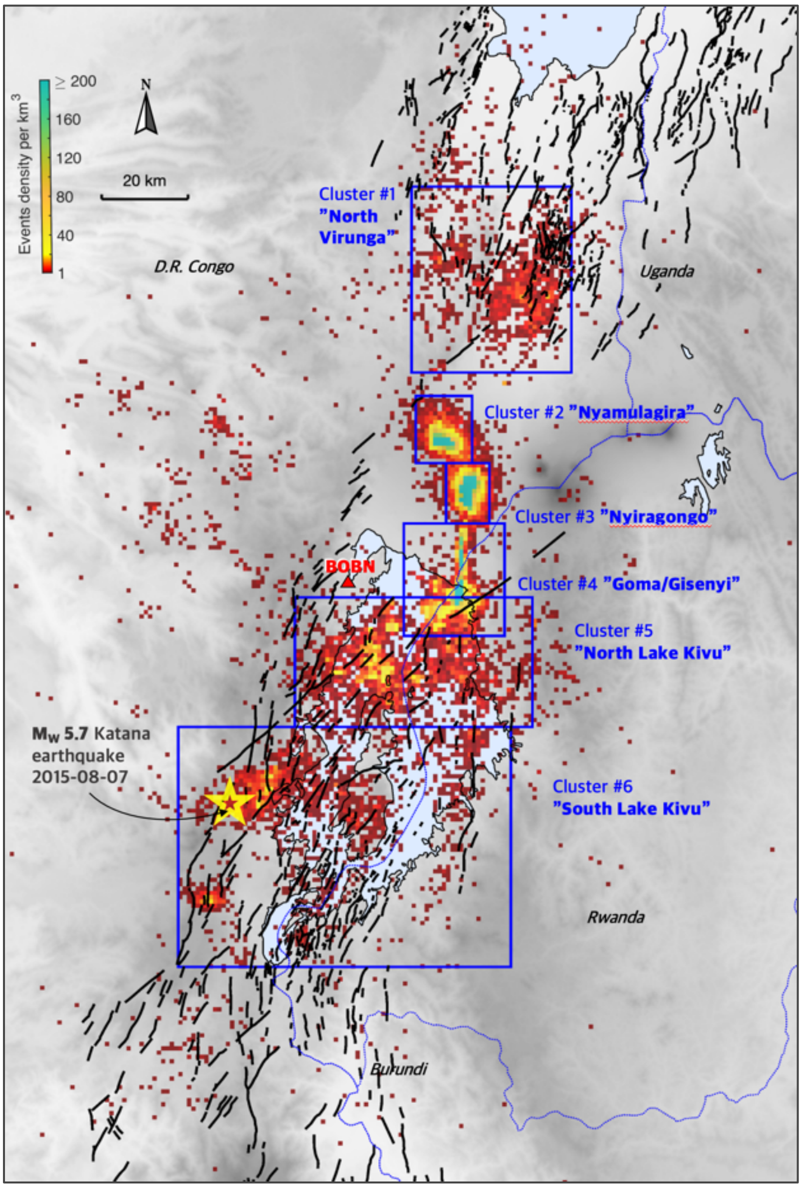


Figure 11: Seismic event density per km^3 between July 2015 and July 2022 (color scale red to green). The main fault lineaments are plotted as solid black lines (source: Smets et al., 2016). The dyke intrusion starting on 22

May 2021 is clearly visible in cluster #4.

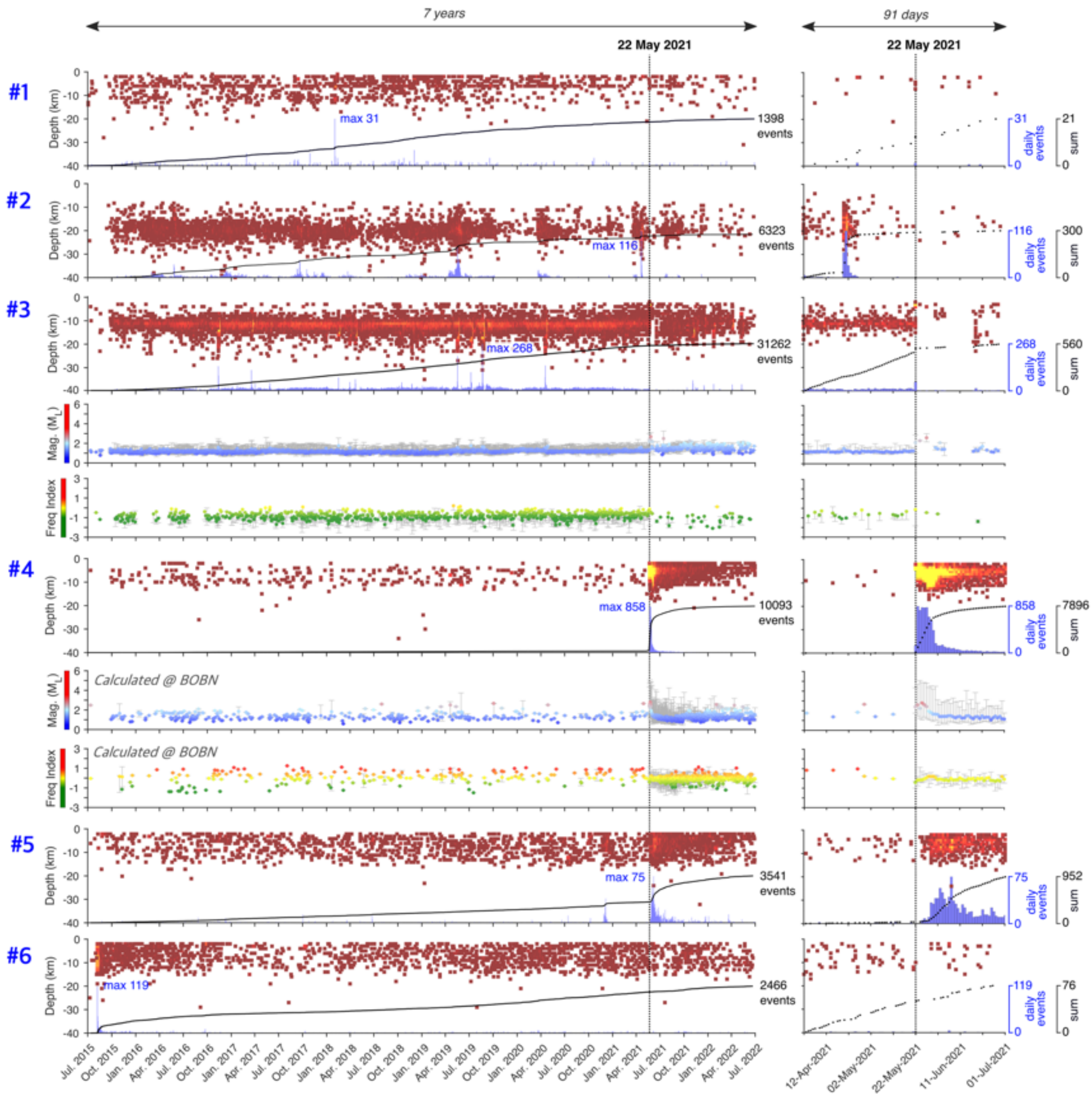


Figure 12: Daily event density per km³ plotted against the depth for the six clusters #1 to #6 (see Figure 11). The colour scale is the same as the one used for Figure 5. Count (blue histogram) and cumulative sum (black dots) are plotted in the same panels (see the y-scale on the right). For clusters #3 (Nyiragongo) and #4 (cities of Goma/Gisenyi + northern portion of lake Kivu), the timeseries of local magnitude and frequency index (FI, e.g., Matoza et al., 2014) are provided. Daily medians are indicated by coloured markers and error bars give the range from min to max values. The FI, calculated at station BOBN (see map), conveys the frequency content of event onset related to path/source, green to red for low (<4 Hz) to high (>4Hz).

❖ Calibration of a local magnitude scale for the Kivu Rift region

In order to adequately assess the size of an earthquake, the accurate estimation of its magnitude is of key importance. While a variety of different magnitude scales exist, for local to regional seismicity, the local magnitude M_L as originally defined by Richter in 1935 still is one of the most important quantitative measures of earthquake size. This magnitude scale is based on the measurements of amplitudes on Wood-Anderson (WA) mechanical seismographs (which nowadays are simulated using the data of modern instruments) and is defined by the following equation:

$$M_L = \log A(R) - \log A_0(R) + S,$$

where A is the maximum trace amplitude in mm and A_0 is an empirically determined attenuation correction term depending on the distance R and S is a station correction term.

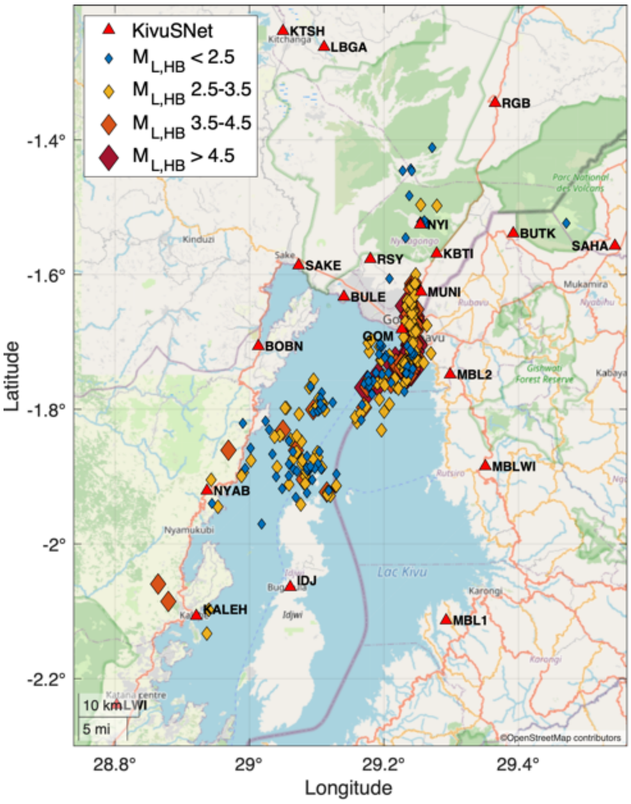


Figure 13: Epicentral map of earthquakes used in the M_L calibration study. Reg triangles depict the seismic stations, while the diamonds of different size and colors depict the earthquake epicenters.

If no region-specific attenuation correction function exists, it is common practice to use the A_0 function derived for southern California by Hutton and Boore in 1987. However, in tectonic regimes that may substantially differ from southern California, this can introduce significant errors and bias in the estimated M_L values. With the availability of the large dataset of local earthquake recordings in the Kivu region recorded by KivuSNet over the past years, it is possible to derive a regional correction function A_0 tailored to the Kivu area.

We use a total of 3586 earthquake records from 324 events recorded at 20 seismic stations (Figure 13) to calibrate an attenuation function A_0 for the Kivu region, using both non-parametric and parametric techniques (Figure 14). In particular, the database includes many earthquakes that occurred following the eruption of Nyirgongo volcano in May 2021.

We find that while there is significant difference between the calibrated functions and the Hutton and Boore (1987) curve, the M_L values estimated using the different curves are in good agreement with each other, with a slight underestimation of M_L by the Hutton and Boore (1987) relation as compared to the calibrated one for small earthquakes (Figure 15, left). Due to local geological conditions, the station correction terms S can be very large in some locations (Figure 15, right), reaching up to 0.5 magnitude units at station LBGA for instance.

This calibrated M_L scale will be used to recalculate the magnitudes of all earthquakes detected and located in the Kivu region with KivuSNet and used in the detailed study of the tectonic and volcanic seismicity patterns in this region.

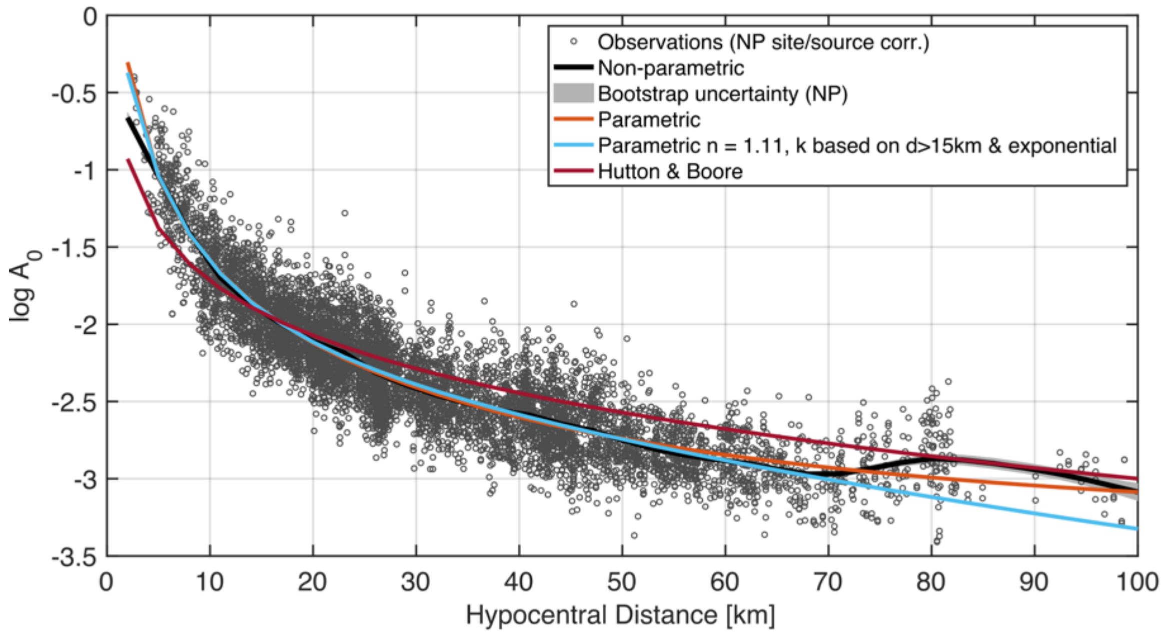
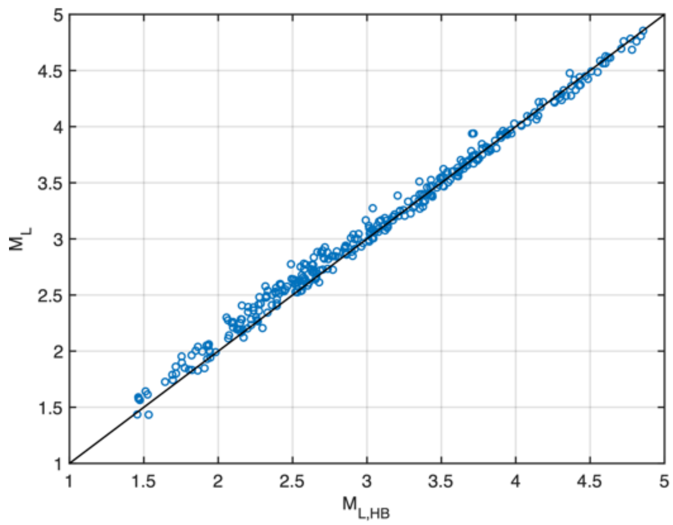
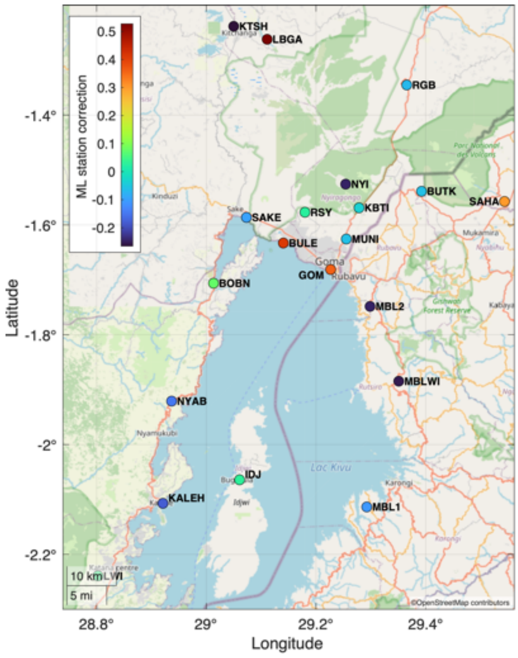


Figure 14: Earthquake WA amplitude observations (open dots) and various A0 curves calibrated to the data (see legend). Details on the underlying models can be found in a specific study report that is under preparation.

Figure 15: Left: M_L as calibrated in this study compared with M_L calculated using the Hutton and Boore (1987) relationship ($M_{L,HB}$). Right: Station correction terms estimated using the parametric attenuation curve.





❖ Modelling the intermittent lava lake drops occurring between 2015 and 2021 at Nyiragongo volcano

We contributed to the work performed by D. Walwer (Penn. State University) and published in March 2023 in *Geophysical Research Letters*. Results obtained in Barrière et al. (2022) motivated the development of a fluid flow model explaining the mechanisms behind the main variations (drops) of Nyiragongo's lava lake (Figure 16). In accordance with the occurence of deep seismic swarms synchronous with major drops of the lava lake, Nyiragongo 2015–2021 successive lava lake level drops are modelled as the result of ~15 km deep lateral transport of magma. Nyiragongo's modelled central reservoir distributes the fluid up into the lava lake and laterally into a distal storage zone. Lava lake overflows exert top-down control on magma transport phenomena occurring in the deeper part of the plumbing system.

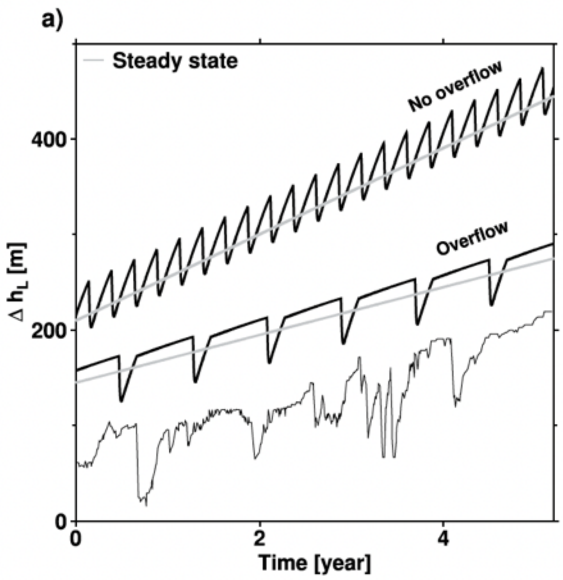


Figure 16: [Modified after Walwer et al., 2023]. Model results. (a) Simulated time series of lava lake level displaying successive rapid drops spaced by longer phase of increase (black lines) and the steady state evolution (gray line). Lava lake level drops are triggered by intermittent lateral magma transport. Top time series corresponds to a simulation without accounting for overflow while the middle time series accounts for overflows. For comparison the recorded lava lake level (Barrière et al., 2022) is displayed as the bottom time series.

❖ Nyiragongo crater collapse during the May 2021 eruption

In 2023, we continued the development of PickCraterSAR, a python toolbox that allows for the picking of features in SAR images of a volcano crater to determine its depth and other geometrical characteristics. We quantitatively analysed the collapse of Nyiragongo during the 2021 eruption and its following replenishment using SAR images (Figure 17). We also used PickCraterSAR to confirm the depth of the 2002 Nyiragongo crater collapse from SAR image archives. Those results have been published open access in *Journal of Geophysical Research* alongside with the codes of PickCaterSAR.

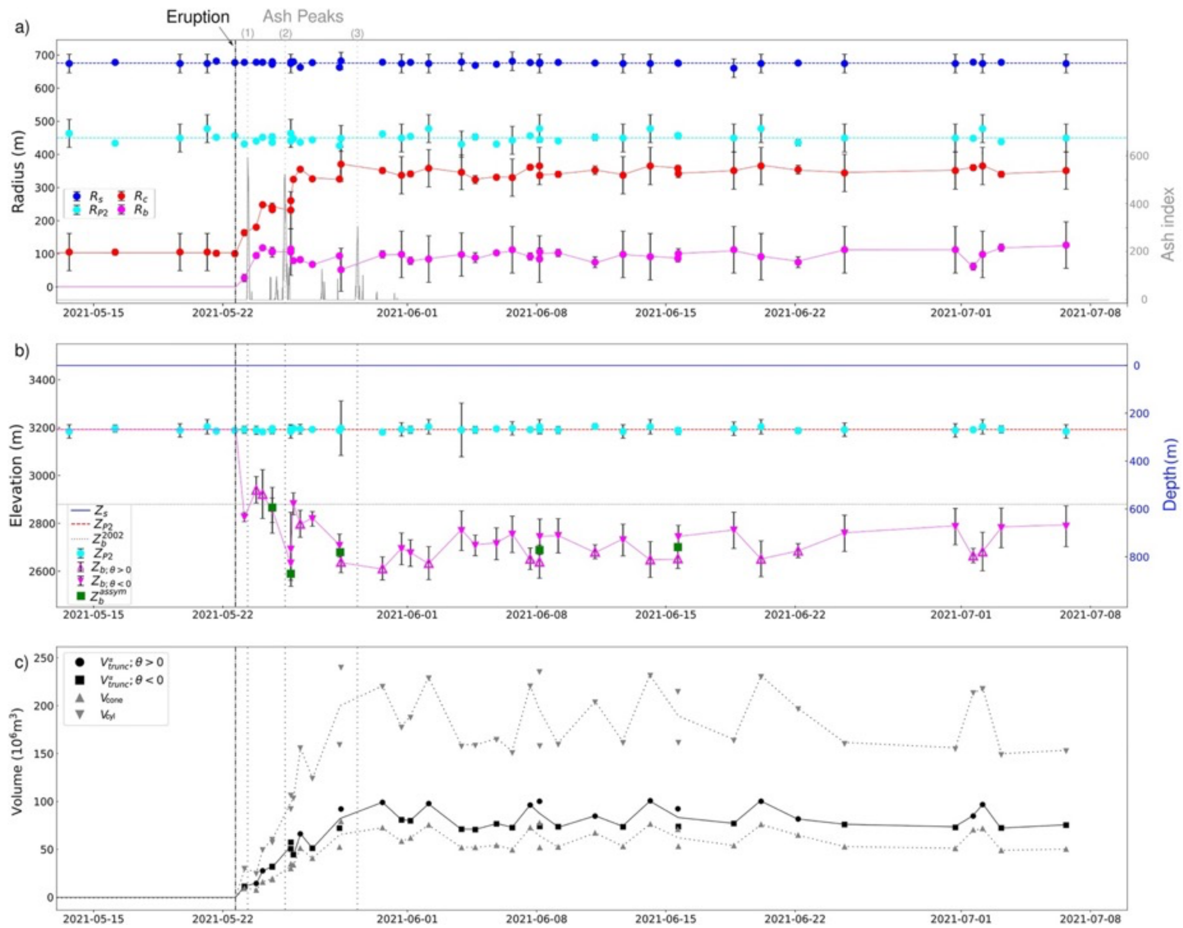


Figure 17: Time series of crater measures. Summit (dark blue), P2 (cyan), collapse crater (red) and bottom crater (magenta) radii (a) and elevation (b) time series obtained by manually picking four ellipses on each SAR image. Error bars in (a) represent 2, 3, 4, and 5 times the azimuth pixel spacing, respectively. Ash index computed using SEVIRI data spanning 13-05-2021 to 08-07-2021 from Smittarello et al. (2022) is shown in grey. Error bars in (b) on Z_{P2} represent 5 times the range pixel spacing. Error bars on Z_b are computed using Equation 7 from Smittarello et al. (2023). In panel (b), green squares mark values measured from both incidence angles, taking into account possible asymmetry of the crater. (c) Volume estimates derived from radius and elevation values for a truncated cone (black line). Square and dots are for measurements from negative and positive incidence angles, respectively. Minimum and maximum volume estimates corresponding to a cone (top grey triangles) and a cylinder (bottom grey cylinder), respectively, are also shown.

Remote Sensing, Volcanology and Ground Deformation

In 2023, we processed and carried on with the automatic monitoring of the ground deformation by satellite radar interferometry (InSAR time series) for the following target regions:

- Réunion Island (Le Piton de la Fournaise volcano and several landslides)
- Argentina and Chile (Domuyo/Laguna del Maule volcanic regions)
- Guadeloupe (La Soufrière volcano)
- Comores (Kathala volcano)
- Luxembourg national territory
- Virunga Volcanic Province

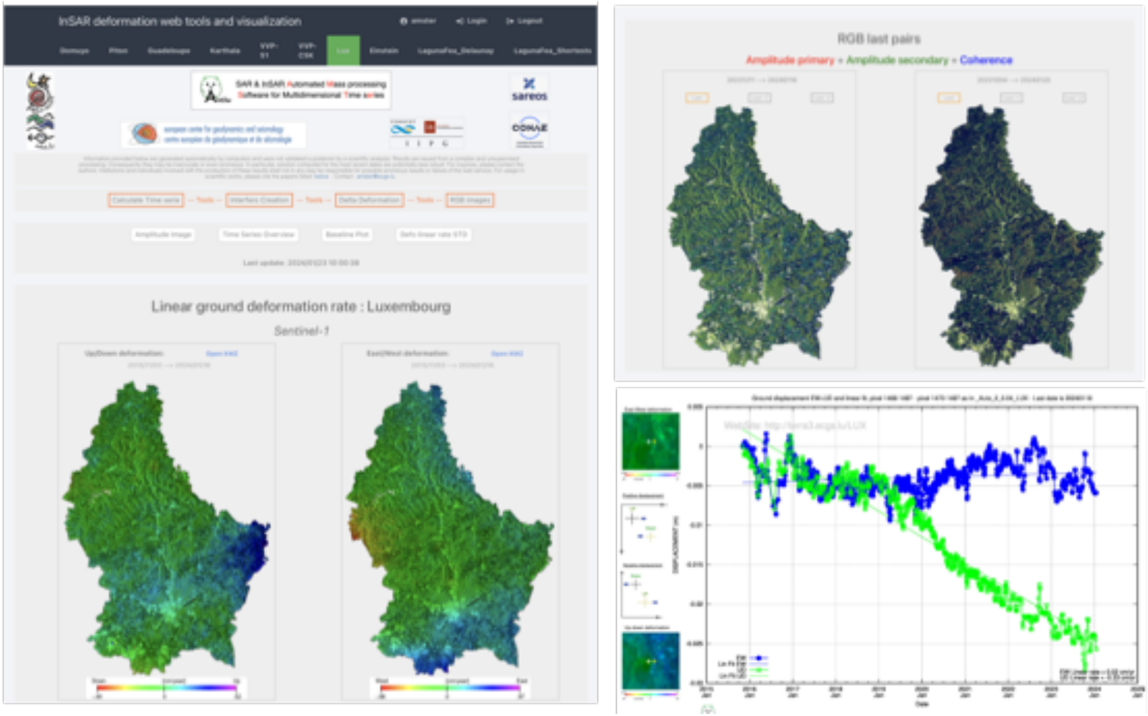


Figure 18: Example of results from the fully automatic InSAR ground deformation monitoring performed at ECGS using AMSTer software. Left panel (a) shows the web page where several targets are available (see the upper banner; note that access to some targets is password protected). The lowest part of that panel shows the Vertical and East-West linear velocity maps obtained on the Luxembourg national territory. Upper right panel (b) shows an example of RGB composition combining amplitudes and coherence maps (used e.g. to map ground cover changes). Lower right panel (c) shows an example of differential vertical (green) and East-West (blue) ground deformation time series between two pixels located near Consdorf. The time series starts at the beginning of the record (2015) up to the last image available at the time of writing the present report (January 16, 2024). It shows that the ground at that place is affected by a nearly linear subsidence of 4mm/year since January 2019, which represents nowadays a total of 2cm. More targets, tools and results are available at the web page (https://terra4.ecgs.lu). For more details, see the paragraph about the AMSTer tool below.

Besides this continuous data processing, we contributed to the following projects:

1. **NSF-Crater Floor: Modelling of crater floor deformation in relationship with lava lake activity,** 2020 – 2023 (NSF)

In a nutshell, the project aims at addressing the following question at two hazardous volcanoes hosting lava lakes (Nyiragongo and Nyamulagira, DRC): What is causing the deformation of their crater floors? Studies are performed in the frame of a PhD at Penn State University (USA) in collaboration with VUB and ECGS. Dense InSAR datasets are processed with the Multidimensional Small Baseline Subset (MSBAS) method and deformations are modelled using advanced numerical methods. The ground deformation of the crater floors is due to one - or a combination - of the following factors:

lava flow cooling and subsidence, pressure changes in a shallow reservoir, motion along caldera ring faults, and magma intrusion cooling and subsidence.

In 2023, the main results of the project were published in a paper entitled "*Modeling the Intermittent Lava Lake Drops Occurring Between 2015 and 2021 at Nyiragongo Volcano*" by Walwer, D., Wauthier, C., Barrière, J., Smittarello, D., Smets, B., & d'Oreye, N. was published in *Geophysical Research Letters*, *50*, e2022GL102365. https://doi.org/10.1029/2022GL102365 (see also page 16 & Figure 16).

It shows that between 2015 and 2021, Nyiragongo's lava lake level experienced a linear increase punctuated by fast intermittent drops. These drops occurred synchronously to seismic swarm at approximately 15 km below the surface and extending laterally NE from the volcano. To interpret these lava lake level patterns in terms of reservoirs pressure evolution within Nyiragongo, the study considers the following simplified plumbing system: a central reservoir is fed by a constant flux of magma, distributing the fluid up into the lava lake and laterally into a distal storage zone. Magma transport is driven by a pressure gradient between the magma storage bodies, accommodating influx and outflow of magma elastically, and the lava lake. Lateral transport at depth occurs through a hydraulic connection for which the flow resistance is coupled to the magma flux. When the right conditions are met, lateral magma transport occurs intermittently and triggers intermittent lava lake level drops matching the observations.

2. AMSTer: SAR & InSAR Automated Mass processing Software for Multidimensional Time series

AMSTer software is a rebranded and upgraded version of MasTer Toolbox (d'Oreye et al. 2021; Derauw et al. 2020; Smittarello et al. 2022; Smittarello et al. 2023).

In 2023, we made important developments and improvements. Moreover, all the source codes and scripts are now open and made available on a public GitHub repository:
https://github.com/AMSTerUsers/AMSTer_Distribution.

AMSTer is aiming at e.g.:

- processing automatically and incrementally a large number of interferometric pairs and feeding and running the MSBAS processor [Samsonov and d'Oreye, 2012, 2017; Samsonov et al., 2017, 2020] in order to obtain the desired 2D or 3D deformation maps and time series;
- performing individual differential interferograms (for deformation measurement or DEM creation purposes);
- creating time series of coherence or amplitude maps co-registered on a Global Primary (both in radar geometry or in geographic coordinates), e.g. for land use or geomorphological changes tracking.

AMSTer is able to process any type of SAR data (ERS1 & 2, EnviSAT, ALOS, ALOS2, RadarSAT, CosmoSkyMed, TerraSAR-X, TanDEM-X (incl. bistatic mode), Sentinel1 A & B (incl. SM mode), Kompsat5, PAZ, SAOCOM, ICEYE...). AMSTer Engine (a command line InSAR processor derived from the Centre Spatial de Liege (CSL) InSAR Suite (CIS) [Derauw, 1999; Derauw et al, 2019]) is optimized to fit the needs of the AMSTer Toolbox, which benefitted from some of its unique specificities.

AMSTer comes with a ~230 pages detailed manual in constant evolution to follow the developments of the software.

Moreover, the recent developments of AMSTer motivated in 2023 the following education and training activities:

- The organization of a 2nd *Summer School* dedicated to the software (see page 25);

- The organization of a *one-week training session* for a student from Laboratoire Magmas et Volcans (Alexis Hautecoeur; 30 Jan – 3 Feb, 2023);
- The organization of a *half-day training session* for a student from Uni.lu (Sona Salehian Ghamsari; 22 Aug. 2023);
- The organization of *videoconferences for remote support and training* (e.g. June 27 with Austrian colleague, August 7 with Belgian Colleague…).

The new developments also fuelled *new international collaborations or opportunitie*s:

- <u>With the Space Agency of Argentina (CONAE):</u> we started a systematic processing of SAOCOM images acquired over the Laguna Fea region (Argentina). Results from the monitoring, and comparison with the systematic processing of Sentinel-1 images avec the same region, are shared thanks to dedicated refurbished web page.
- <u>With Laboratoire Magmas et Volcans, Université Clermont Auvergne (France):</u> we carried out a systematic processing of Sentinel 1 images acquired over the Karthala volcano in Comores Island. The processing was complemented with results from the CosmoSkyMed images available over that region. The time series of deformation allowed, among others, to identify the source of deformation associated with the 2021 seismic crisis recorded on the volcano.

  These results were achieved in the frame of a Master Thesis (Alexis Hautecoeur) in collaboration with Valerie Cayol.
  - These results contributed to the INTERREG HATARI project led by the Institut de physique du globe de Paris and the Observatoire Volcanologique du Piton de la Fournaise (OVPF-IPGP) in La Réunion Island, in cooperation with the Centre National de Documentation et de Recherche Scientifique des Comores (CNDRS), the Observatoire Volcanologique du Karthala (OVK), the Université de La Réunion and the Cité du Volcan (Réunion des Musées Régionaux).
  - Preliminary results were presented at EGU in Vienna, at the "*1st rencontres EPOS-FR*", Saint-Jean-Cap-Ferrat (France) and *"1st Rencontre Scientifique Volcanologique",* Clermont-Ferrand (France).
- <u>With the Centre de Recherches Pétrographiques et Géochimiques (CRPG) from the University of Lorraine in Nancy, and with the ISTerre (Grenoble)</u>: we submitted a proposal to the "Programme National de Télédétection Spatiale" for a 2 years project named "MUVE: Suivi SAR multi-capteurs des processus de versant" aiming at *studying displacements along steep slopes in Nepal* using Sentinel-1, PAZ, TerraSARX SAR images and Pleaides, SPOT, Landsat-8, Sentinel-2 optical images. The positive funding decision for this project has been received at the beginning of 2024.
- <u>With the Centre de Recherches Pétrographiques et Géochimiques (CRPG) from the University of Lorraine in Nancy, the ISTerre (Grenoble), and the Centre Spatial de Liège (Belgium)</u>: we submitted a declaration of intent for a PRCI (Projet de Recherche Collaborative - International) proposal to the ANR (France) in the frame of a bilateral agreement with the FNR (Luxembourg) program. The proposed 4 years project named "SLIDE: Assessing the contribution of slow-moving landslides to erosion in the Himalayas" aims at studying the *contribution of slow-moving, deep-seated landslides in the denudation and evolution of mountain landscapes in Central Himalayas* using InSAR time series, optical imagery, GNSS, seismic and infrasound methods. Decision for receivability is expected at the beginning of 2024.
- <u>With the Université Jean Monnet, Saint Etienne (France) and the Centre Spatial de Liège (Belgium):</u> we submitted a short project to the Direction de la Recherche et de la Valorisation de l'Universté J. Monnet. The project with the Laboratoire de Géologie de Lyon aims at studying *inter-eruptive deformations at Piton de la Fournaise (Reunion Island)* using InSAR time series combining ALOS-2 and Sentinel-1 SAR images. The positive funding decision for this project has been received at the beginning of 2024.
- <u>With the Ecole et Observatoire des Sciences de la Terre (EOST) de Strasbourg (France):</u> we assist them in deploying AMSTer on HPC computer infrastructure for setting up an automatic processing chain for coherence tracking merging AMSTer and MicMac.

- Other projects opportunities are under study. For instance, we were approached by the European Space Agency (ESA) to study the feasibility of a project aiming at using ETAD correction files for improved Sentinel-1 range calculation. We were also approached to respond to ESA Digital Twin Earth call with the objective to deploy automatic processing chain for systematic, incremental, and multi-sensor monitoring of ground deformation, possibly coupling with optical and GNSS methods.

In parallel, we carry on with our systematic processing of InSAR ground deformation time series over several targets for volcano monitoring (e.g. on Comores Island, Guadeloupe Island, La Réunion Island, Domuyo, Laguna del Maule and Laguna Fea regions in Argentina and Chile, as well as Nyiragongo and Nyamulagira volcanic fields in the Virunga Volcanic Province in Democratic Republic of Congo), landslides and other deformations of anthropogenic and natural origins in Luxembourg etc...

The results from all these automatic incremental processing chains are available on a refurbished web page: https://terra4.ecgs.lu/ (see Figure 18).

3. GEOTROP: GEOmorphic hazards and compound events in a changing TROPical East Africa, 2022 – 2023 (BRAIN, BELSPO)

The project is led by RMCA and benefits from the collaboration with the Vrije Universiteit of Brussels (VUB), ECGS/Mnhn, the CNRS - Ecole et Observatoire des Sciences de la Terre (CNRS-EOST), University of Strasbourg and the Helmholtz Centre for Environmental Research (UFZ).

Landslides and flash floods are geomorphic hazards (GH) that often result from a combination of interacting processes across multiple spatial and temporal scales. GH events are linked to climate drivers (e.g., rainfall intensity) and land drivers (e.g., vegetation patterns). Land transformation such as deforestation has impacts on GH events and climate change will alter many drivers. The tropics are environments where GH are under-researched. In mountainous regions, high population densities with high societal vulnerability are common, frequently on the rise. GH events disproportionately impact these regions. In the future, the frequency and/or impacts of GH events will be more severe; not only due to, for example, climate change and deforestation, but also due to population growth and increased exposure to disasters.

GEOTROP aims to assess the role of land transformation and climate change on the occurrence of GH compound events in tropical East Africa, focusing on the western branch of the East African Rift. The specific objectives are:

- To develop an unprecedented spatio-temporal regional inventory of GH events;
- To understand the spatial distribution of the GH events in the landscape, and to assess the role of land transformation on their occurrence (location of GH events);
- To uncover the interplay of multiple land and climate drivers in triggering GH compound events (timing of GH events);
- To project the future evolution of GH compound events so that future hazard and risk hotspots can be identified.
- To strengthen capacities of African institutions involved in disaster risk reduction (DRR).

The kick off meeting took place by virtual meeting on 2 March 2023. The main results of the progresses made by Axel Deijns in the frame of that project were presented at the EGU 2023 meeting. Axel presented his methodology developed for regional multitemporal GH event detection, providing both location and (semi-accurate) timing of GH events without any prior knowledge on GH event occurrence. The methods are highly optimized in terms of computation time allowing to process large regions of interest, within a relative short time span.

Walferdange Underground Laboratory for Geodynamics (WULG)

The Underground Laboratory for Geodynamics in Walferdange, hosted in the former gypsum mine at 100m depth, remains an exceptional station for high quality seismic and geophysical measurements and tests.

Following the first seismic measurements obtained with three Sprengnether from 1973, the WULG was equipped with a Lennartz 3D short period seismometer in 1987 and a broad-band STS-2 GEOFON in 1994, providing us with more than 40 years of uninterrupted high-quality seismic observations. The data from the STS-2 very broadband seismometer are an important component of the national seismic network operated by ECGS as well as the global GEOFON seismic network operated by the GFZ German Research Centre for Geosciences.

The University of Luxembourg carries out the maintenance of the superconducting gravimeter installed in the WULG since the beginning of the twenty-first century. Between 2010 and 2018, Prof. Dr. Manfred Bonatz established and operated the Walferdange Geodynamical Laboratory (*GeoDynLab*) in a dedicated section of the WULG, operating various measurement devices for measuring gravity, rock dynamics (tilt), atmospheric pressure and chamber temperature for metrological investigations.

Given its outstanding quality, the WULG remains an exceptional measurement and test site for geophysical instrumentation in a highly stable environment since 1968. The interest in using the WULG as a high-quality test site for instrumentation is unbroken. Following a request in 2020, Mr. Bruno Pagliccia from the private company SeisBEE established in Luxembourg carried out instrumental performance studies for MEMS-based accelerometers in the WULG in collaboration with ECGS staff. In July 2022, the Luxembourg-based company FIRIS tested a new autonomous drone for carrying out 3D scans of underground structures in the WULG. In 2023, a request was addressed to ECGS/Mnhn by the University of Luxembourg PhD student Gabriel Garcia, SnT) for carrying out experiments in the WULG in order to test autonomous navigation algorithms for roboters in underground settings. These experiments are foreseen to be carried out in 2024.

Continuous radon (Rn) measurements in the Laboratory and the entrance gallery have also performed during the past decade. These data, along with the very long data base already acquired over the previous decades, allow for an assessment of the long-term evolution and the seasonal variations of Rn. It also allows monitoring transient signals or assessing gas transport into the underground environment and link them with external causes (e.g., changes in air circulation conditions). The two alphaguard radon detectors operated by ECGS collaborator A. Kies failed during the year 2023 (see short report below). A resumption of measurements might be possible in 2024.

For several years now, issues regarding the stability of the entrance have been noticed and discussed among the administrations and ministries involved (see previous reports). In order to advance on this subject, a meeting was held at the Ministry of Culture on 12 January 2021 (in hybrid mode). This meeting was attended by Minister for Culture Sam Tanson, the mayor of Walferdange, and representatives from the Ministry of Culture, the Commune de Walferdange, ECGS/Mnhn and the University of Luxembourg. At this occasion, mayor François Sauber presented the Commune's interest for the continued operation of the WULG as a scientific laboratory, but also as a site of historic and cultural heritage that should be, at least to some extent, open to the public.

After a meeting between representatives of the *Inspection du Travail et des Mines (ITM)* and ECGS/Mnhn in April 2021 and a short report by the *ITM* from July 2022 following a visit of the WULG, another follow-up meeting between ITM and ECGS/Mnhn representatives was held on 19 October 2022 to discuss the next steps. It was decided that the ITM carries out a number of additional studies, involving among other 3D scanning techniques in order to get a better overview of the situation in the mine. These works were carried out in early 2023. A follow-up meeting with ITM representatives is planned for early 2024.

No final conclusions on how to proceed have yet been reached. For this reason, access is currently still restricted to ECGS/Mnhn and Uni.lu staff for instruments operation and maintenance purposes only, following strict security regulations.

❖ Radon measurements in the WULG during 2023

Prof. em. Antoine Kies

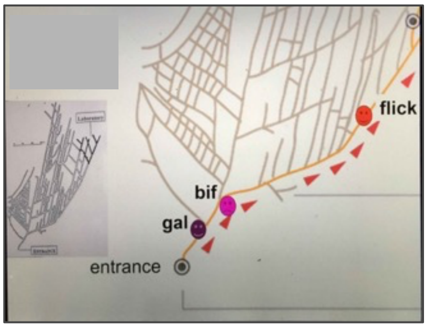


Figure 19: Radon observation sites in WULG.

We report from radon data recorded continuously in the mine at two locations (Figure 19):

- 'gal' endpoint of a collapsed lateral gallery close to the entrance, before the main bifurcation
- 'flick' in the main gallery close to 'Flick cellar'.

Furthermore, we rely on the meteorological data from MeteoLux.

Concerning radon concentrations, 2023 was a 'black' year as during 2023 the two alphaguard radon detectors failed. One of them worked continuously for 30 years, the other for 26 years, often in harsh environments such as caves (Moestroff) and mines all over Luxembourg, even in a slate mine in Belgium.

2023 had a rather cold spring, as shown in Figure 20. The external radon source at 'gal' started functioning only beginning of June, and at the end of June the radon level was about 10 Bq/m^3 lower than the value that could be expected (see previous years).

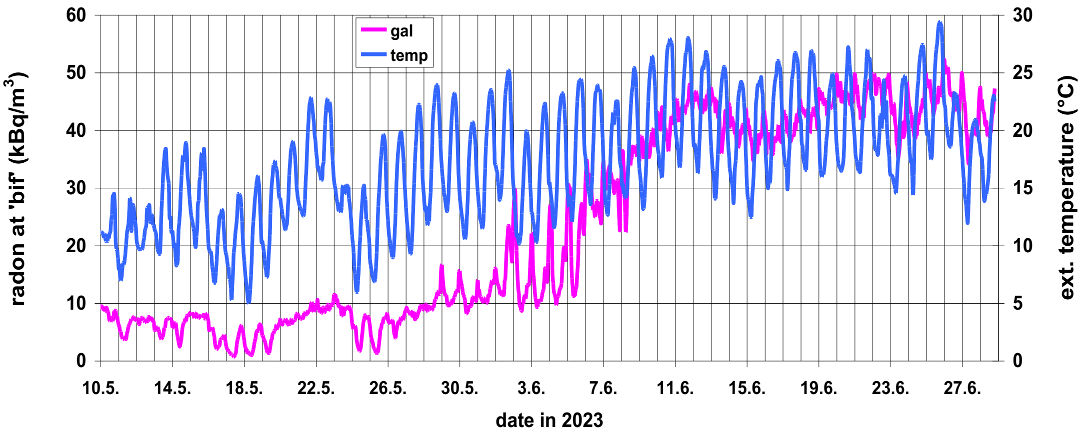


Figure 20: Radon concentration at 'gal' during from 10 May to 29 June 2023 (magenta line). Also shown is the external temperature (blue line).

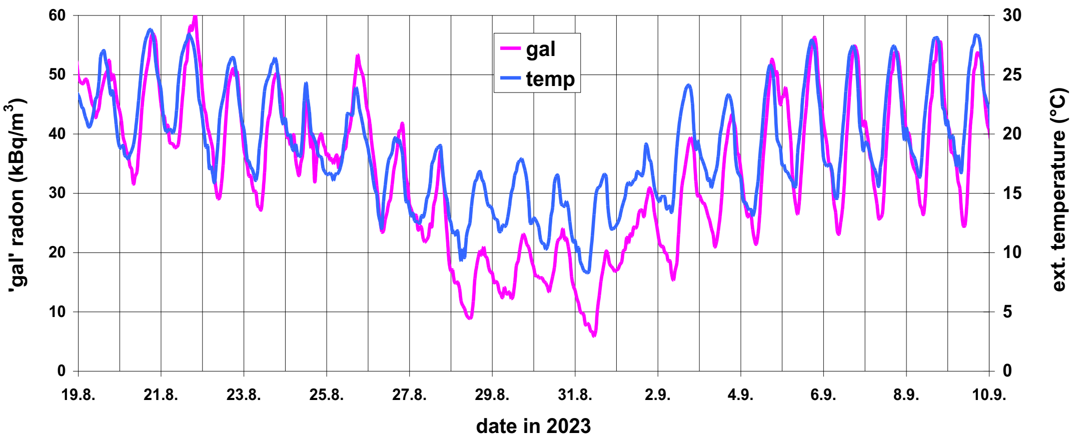


Figure 21: Radon concentration at 'gal' from end-August to beginning of September 2023 (magenta line). Also shown is the external temperature (blue line).

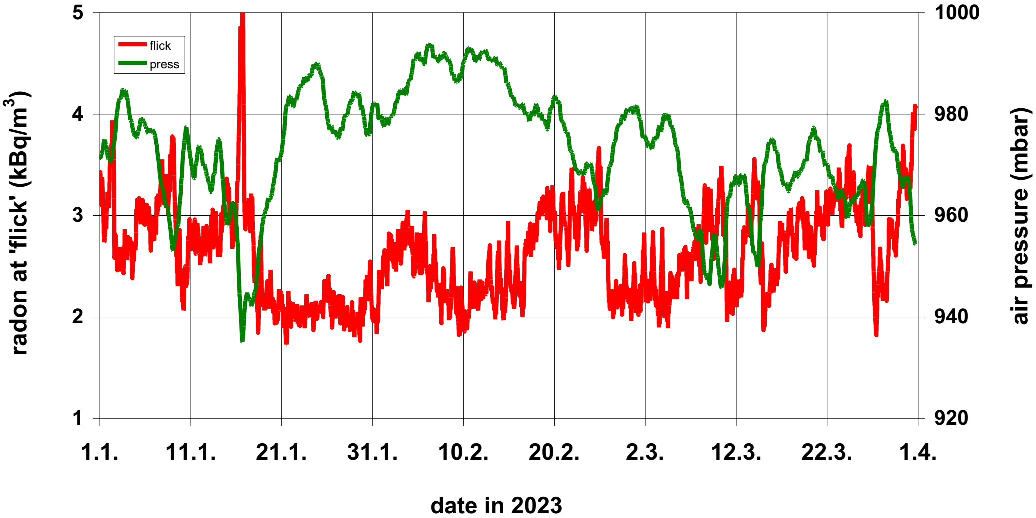


Figure 22: Radon concentration at 'flick' from 1 January to 1 April 2023 (red line). Also shown is the air pressure in mbar (green line).

Figure 21 documents again the very high influence of external temperature on 'gal' radon and consequently on the radon in the mine. It also shows the importance of low night temperatures from end-August to beginning of September, approaching and even going below 10 °C (mine temperature).

Finally we show in Figure 22 that, when the high influence on mine radon by the 'gal' source is suppressed, it is possible to document the influence of atmospheric pressure on radon in the mine: the rapid decrease of atmospheric pressure enables radon to leave the rocks, while radon is blocked by increasing pressures.

We hope that in 2024 we can continue our measurements; one has to keep in mind that the most important aim of our study tis o detect any major changes in the structures of the mine, especially close to the hill side. Radon is a very sensible tracer for slides, soil and rock movements. Our study so far proves that there is no communication between the mine and the exterior except at the main entrance.

2nd SUMMER SCHOOL IN INSAR, TIME SERIES PROCESSING AND DEFORMATION MODELLING

The European Center for Geodynamics and Seismology organised the 2nd **Summer School in InSAR, time series processing and deformation modelling** entitled **“If you need InSAR... MasTer it!"** in the Chamber of Commerce in Luxembourg, from May 22 to 26 2023.

The full week intensive training session targeted PhD candidates, postdocs or scientists involved in SAR/InSAR processing who wanted to learn the **MasTer Toolbox** (an automatic InSAR and ground deformation time series processing software) and **DefVolc** (a 3D inverse modelling software).

Twenty participants from Luxembourg (1), Belgium (5), France (5), Austria (1), Germany (1), Hong Kong (1), Japan (3), Spain (2), Sweden (1) attended the event.

MasTer Toolbox – now renamed AMSTer Software – is a tool dedicated to the processing of Synthetic Aperture Radar (SAR) images. It is mostly designed to allow optimized mass processing of SAR interferometry (InSAR) and the production of 2/3D ground deformation time series. It can also be used to produce Digital Elevation Models (DEM), coherence maps and amplitude images time series e.g. for land cover or geomorphological changes, flood mapping etc.

It is made of three components: an InSAR command line processor (the MasTerEngine), the MSBAS processor (for the computation of 2/3D time series of ground deformation) and a bunch of shell scripts for automatising all tasks, from data downloading to updated displacement maps and time series and possible automatic display on a dedicated webpage.

AMSTer is able to process nearly all the SAR sensors currently available (ERS1 & 2, EnviSAT, ALOS, ALOS2, RadarSAT, CosmoSkyMed, TerraSAR-X, TanDEM-X – incl. bistatic and pursuit mode, Sentinel1 A & B, Kompsat5, PAZ, SAOCOM, ICEYE...). The Multidimensional Small BAseline Subset (MSBAS) time series software allows inverting simultaneously several interferometric SAR time series acquired along different acquisition modes, including different sensors, SAR wavelengths, incidence angles, polarization etc., to solve for horizontal and vertical component of the ground displacement.

For more information about the software, see e.g. Smittarello et al. (2022) and Derauw et al. (2020).
To see an example of AMSTer results, visit https://terra4.ecgs.lu/defo-domuyo/index.php.
To access the software, visit https://github.com/AMSTerUsers/AMSTer_Distribution.

DefVolc is a software for inverse modeling of volcano displacement data (InSAR, GNSS), whether the sources of displacement are fracture (fluid filled fracture or faults) or massive reservoirs. DefVolc is based on a 3D Boundary element method for elastic media combined with inversions, based on near-neighborhood inversion algorithms. Topographies are considered as well as interactions between sources. Boundary conditions are stress changes.

Defvolc consist of a pre- and post-processor. Inversions can be run on demand on the University Clermont-Auvergne Clusters. Defvolc manuals and compiled programs are available to registered users on the web site www.opgc.fr/defvolc/. Users can register with the project code "anonymous".

Speakers:

- Nicolas d'Oreye (ndo@ecgs.lu)
- Dominique Derauw (dderauw@uliege.be)
- Delphine Smittarello (delphine.smittarello@ecgs.lu)
- Sergey Samsonov (sergey.samsonov@NRCan-RNCan.gc.ca)
- Maxime Jaspard (maxime@ecgs.lu)
- Valérie Cayol (valerie.cayol@uca.fr)

With the help of:

- Gilles Celli (gilles.celli@ecgs.lu)
- Marie-Jo Maciel (marie-jo.maciel@ecgs.lu)

Participants:

- Fabien Albino (fabien.albino@univ-grenoble-alpes.fr)
- Atefe Choopani (achoopani@naturalsciences.be)
- Pierre-Yves Declercq (pydeclercq@naturalsciences.be)
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- Jean-Luc Froger (jean.luc.froger@univ-st-etienne.fr)
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- Sofie Rolain (Sofie.Rolain@vub.be)
- Benoît Smets (benoit.smets@africamuseum.be)
- Filippo Vecchiotti (Filippo.Vecchiotti@geosphere.at)
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- Micaela Colavita (colavita.micaela.q6@dc.tohoku.ac.jp)

Programme

Monday 22 May

10h00 – 12h00	Registration / installation	
12h00-13h30	Lunch	
13h30 – 14h00	Welcome	N. d'Oreye
14h00 – 15h00	Introduction to InSAR	D. Derauw
15h00 – 16h00	Check installations MasTer	All
16h00 – 16h30	Coffee Break	
16h30 – 18h00	MasTer Engine	D. Derauw
18h00 – 18h30	Check installations DefVolc	All
19h00	Hotel Check-in Dinner: participant's choice	

Tuesday 23 May

8h15	Departure from hotel	
8h45-10h00	MasTer Toolbox structure	N. d'Oreye
10h00-10h30	Coffee Break	
10h30 – 12h30	DInSAR processing Exercise 1	N. d'Oreye
12h30-13h30	Lunch	
13h30 – 14h30	Mass Processing Exercise 2	N. d'Oreye
14h30 – 16h00	MSBAS	S. Samsonov
16h00 – 16h30	Coffee Break	
16h30 – 17h30	MSBAS with MasTer Exercise 3	N. d'Oreye
17h30 – 18h00	MSBAS 3D	S. Samsonov
18h00 – 18h30	Amplitude time series	N. d'Oreye
20h00	Ice braking dinner at hotel	

Wednesday 24 May

8h15	Departure from hotel	
8h45-10h00	Optimized pair selection	D. Smittarello
10h00-10h30	Coffee Break	
10h30 – 11h30	Automatization with cron jobs	N. d'Oreye
11h30 – 12h30	Time series plots	N. d'Oreye
12h30-13h30	Lunch	
13h30 – 14h30	Web page – example	M. Jaspard
14h30 – 15h30	Web page – how to	M. Jaspard
15h30 – 16h00	Coffee Break	
16h00 – 16h30	Data manipulation with QGIS	N. d'Oreye
16h30 – 17h30	Scripts for everything….	N. d'Oreye
17h30 – 18h30	Exercise 4 with participant's data	All
	Dinner: participant's choice	

Thursday 25 May

8h15	Departure from hotel	
8h45-10h00	Exercise 5 with participant's data	All
10h00-10h30	Coffee Break	

10h30 – 12h30	Exercise 6 with participant's data	All
12h30-13h30	Lunch	
13h30 – 14h30	DefVolc	V. Cayol
14h30 – 15h30	DefVolc	V. Cayol
15h30 – 16h00	Coffee Break	
16h00 – 17h00	DefVolc	V. Cayol
17h00 – 18h00	DefVolc	V. Cayol
18h80 – 18h30	DefVolc	V. Cayol
	Dinner: participant's choice	

Friday 26 May

8h15	Departure from hotel	
8h45-10h00	DefVolc	V. Cayol
10h00-10h30	Coffee Break	
10h30 – 12h15	DefVolc	V. Cayol
12h15 – 13h00	Closure	N. d'Oreye
12h30-13h30	Lunch	

- Essentiel.lu: *Séismes en Turquie et en Syrie – Les secousses perçues au Luxembourg*, featuring A. Oth (6 February 2023), https://www.lessentiel.lu/fr/story/les-secousses-percues-au-luxembourg-458431061207
- Virgule.lu: *Le Luxembourg peut-il être frappé par un séisme?* featuring A. Oth (7 February 2023), https://www.virgule.lu/luxembourg/seisme-en-turquie-le-luxembourg-peut-il-etre-frappe/1065714.html
- RTL Luxembourg: *Mir hun nogefrot: Kéint en Äerdbiewen Lëtzebuerg zum wackele bréngen?* featuring A. Oth (8 February 2023) (also in French and English), https://www.rtl.lu/news/national/a/2027666.html
- Wort.lu: *Kann Luxemburg von einem Erdbeben erschüttert werden?* featuring A. Oth (9 February 2023), https://www.wort.lu/luxemburg/kann-luxemburg-von-einem-erdbeben-erschuettert-werden/1192470.html
- Tageblatt (print): *Auf der sicheren Seite – Auch in Luxemburg hält man Erdbeben fest im Blick*, featuring A. Oth (11/12 February 2023)
- Public talk at National Museum of Natural History on the 2021 Nyiragongo eruption, N. d'Oreye (11 March 2023)
- Presentation of ECGS research and activites at the *European School Luxembourg*, D. Smittarello & J. Barrière (24 March 2023)
- Support as expert for a school project of a pupil from *Eis Schoul*, A. Oth (May 2023)
- Essentiel.lu: *Un séisme a-t-il frappé le sud du Luxembourg mercredi matin?* featuring A. Oth (31 August 2023), https://www.lessentiel.lu/fr/story/a-9h42-un-seisme-a-t-il-frappe-le-sud-du-luxembourg-mercredi-matin-483383478513

Honours

- Award of *Chevalier de l'Ordre National de la Couronne de Chêne* to N. d'Oreye, received from S. Tanson (Minister of Culture), 20 June 2023

PUBLICATIONS & PRESENTATIONS

❖ Peer-reviewed Journal Publications

Published & in Press

Barrière, J., **A. Oth**, **N. d'Oreye**, J. Subira, **D. Smittarello**, H. Brenot, N. Theys and B. Smets (2023). Local Infrasound Monitoring of Lava Eruptions at Nyiragongo Volcano (D.R. Congo) Using Urban and Near-Source Stations, *Geophys. Res. Lett.*, 50(18), e2023GL104664, doi: 10.1029/2023gl104664.

Bindi, D., D. Spallarossa, M. Picozzi, **A. Oth**, P. Morasca, and K. Mayeda, (2023). The Community Stress-Drop Validation Study—Part I: Source, Propagation, and Site Decomposition of Fourier Spectra, *Seism. Res. Lett.*, 94(4), 1980–1991, doi: 10.1785/0220230019.

Bindi, D., D. Spallarossa, M. Picozzi, **A. Oth**, P. Morasca, and K. Mayeda (2023). The Community Stress-Drop Validation Study—Part II: Uncertainties of the Source Parameters and Stress Drop Analysis, *Seism. Res. Lett.*, 94(4), 1992–2002, doi: 10.1785/0220230020.

Davis, T., E. Rivalta, **D. Smittarello** and R. Katz (2023). Ascent rates of 3D fractures driven by a finite batch of buoyant fluid. Journal of Fluid Mechanics, 954, A12. doi:10.1017/jfm.2022.986.

Najdahmadi, B., M. Pilz, D. Bindi, H. N. T. Razafindrakoto, **A. Oth**, and F. Cotton (2023). Hazard-informed optimization of seismic networks for earthquake early warning—the case of the Lower Rhine Embayment (western Germany), *J. Seismol.*, 27(2), 261–277, doi: 10.1007/s10950-023-10133-z.

Smittarello, D., R. Grandin, **M. Jaspard**, D. Derauw, **N. d'Oreye**, T. Shreve, M. Debret, N. Theys, and H. Brenot (2023). Nyiragongo Crater Collapses Measured by Multi-Sensor SAR Amplitude Time Series, J. *Geophys. Res.: Solid Earth*, 128(10), doi: 10.1029/2023jb026683.

Subira, J., **J. Barrière**, C. Caudron, A. Hubert-Ferrari, **A. Oth**, B. Smets, **N. d'Oreye**, and F. Kervyn (2023). Detecting sources of shallow tremor at neighboring volcanoes in the Virunga Volcanic Province using seismic amplitude ratio analysis (SARA), *Bull. Volcanol.,* 85(5), 27, doi: 10.1007/s00445-023-01640-5.

Walwer, D., C. Wauthier, **J. Barrière**, **D. Smittarello**, B. Smets and **N. d'Oreye** (2023). Modeling the Intermittent Lava Lake Drops Occurring Between 2015 and 2021 at Nyiragongo Volcano. *Geophys. Res. Lett.*, 50(8), e2022GL102365, doi: 10.1029/2022gl102365.

Yen, M.-H., D. Bindi, **A. Oth**, B. Edwards, R. Zaccarelli and F. Cotton (2023). Source parameters and scaling relationships of stress drop for shallow crustal earthquakes in Western Europe. *Accepted for publication, J. Seismol.*

❖ Conference Presentations and Abstracts

Barrière, J., **A. Oth**, **N. d'Oreye**, J. Subira, **D. Smittarello**, H. Brenot, N. Theys and B. Smets (2023). Local infrasound monitoring of lavav eruptions at Nyiragongo volcano (D.R. Congo) using urban and near-source stations. *AGU Fall Meeting 2023, San Francisco, 11-15-17 December 2023 (Poster).*

Barrière, J., **A. Oth**, J. Subira, B. Smets, and **N. d'Oreye** (2023). Infrasonic noise from lava eruptions at Nyiragongo volcano, D.R. Congo. *Seismological Society of America (SSA) Annual Meeting, 17-20 April 2023, San Juan, Puerto Rico.*

Barrière, J., **A. Oth**, J. Subira, B. Smets, and **N. d'Oreye** (2023). Infrasonic noise from lava eruptions at Nyiragongo volcano, D.R. Congo. *IUGG General Assembly, 11-20 July 2023, Berlin, Germany.*

Bindi, D., D. Spallarossa, M. Picozzi, **A. Oth**, P. Morasca and K. Mayeda (2023). Assessing Epistemic Uncertainty of earthquake source parameters: a within-approach contribution to the SCEC Community Stress Drop Validation Study. *AGU Fall Meeting 2023, San Francisco, 11-15-17 December 2023.*

d'Oreye, N., D. Derauw, **D. Smittarello**, S. Samsonov, **M. Jaspard** and **G. Celli** (2023). MasTer: ("Mass processing Toolbox for Multidimensional time series"), un outils satellitaire développé

au Luxembourg pour les mesures de déformations du sol. *Réunion des Collaborateurs Scientifiques du Musée national d'histoire naturelle, 11 March 2023, Luxembourg.*

d'Oreye N., **D. Smittarello**, **J. Barrière**, **A. Oth**, F. Kervyn and B. Smets, B (2023). Prepared for a precursor-free eruption? The case of Mount Nyiragongo. *Seminar Université de Lorraine, 19 January 2023, Nancy, France.*

d'Oreye N., **D. Smittarello**, **J. Barrière**, **A. Oth**, F. Kervyn and B. Smets, B (2023). Prepared for a precursor-free eruption? The case of Mount Nyiragongo. *Conférence au Musée national d'histoire naturelle, 20 March 2023, Luxembourg.*

Dahm, T., C. Sens-Schönfelder, C. Milkereit, M. Isken, S. Cesca, X. Yuan, F. Tilmann, M. Pilz, F. Cotton, H. Woith, M. Hensch, B. Schmidt, B. Knapmeyer-Endrun, T. Meier, F. Eckel, L. de Siena, M. van Camp, Th. Lecocq, **A. Oth** and Z. Deng (2023). A large-N passive seismological experiment to unravel the structure and activity of the transcrustal magma system of the Eifel Volcanic Field. *European Geosciences Union General Assembly 2023, Vienna, Austria, 23–28 April 2023, EGU23-2590, https://doi.org/10.5194/egusphere-egu23-2590*.

Dahm, T., M. Isken, C. Milkereit, C. Sens-Schönfelder and the Eifel Large-N group (including **A. Oth** and **J. Barrière**) (2023). Eifel Large-N Experiment: Understanding Magmatic Processes beneath Volcanic Fields. *AG Seismologie, 25-28 September 2024, Freiburg, Germany*.

Di Muro, A., H. Toiwilou, V. Ferrazzini, B. Smets, H. Soule, J.-L. Froger, S. Poppe, B. Benard, M. Liuzzo, V. Cayol, S. Bafakhi, L. Retailleau, F. Lauret, M. Magne, C. Brunet, T. Lecocq, C. Caudron, **N. d'Oreye**, **D. Smittarello**, F. Lötter and the Interreg Project Hatari Team members (2023). Managing the progressive awakening of Karthala volcano (Comoros Archipelago) after 14 years of quiescence: lessons learned from a long phase (2021-2023) of unrest. *European Geosciences Union General Assembly 2023, Vienna, Austria, 23–28 April 2023, EGU23-8962, https://doi.org/10.5194/egusphere-egu23-8962.*

Hautecoeur, A., V. Cayol, J.-L. Froger, **D. Smittarello** and **N. d'Oreye** (2023). InSAR time series analysis of the 2021-2022 unrest phase of the Karthala volcano (Grande Comore). *1ères rencontres EPOS-FR, 7-10 November 2023, Saint-Jean-Cap-Ferrat, France.*

Hautecoeur, A., V. Cayol, J.-L. Froger, **N. d'Oreye** and **D. Smittarello** (2023). Analyse InSAR en séries temporelles de la crise 2021-2022 au volcan Karthala, Grande Comore. *1ère Rencontre Scientifique Volcanologique, , 10-20 October, 2023, Laboratoire Magma et Volcan, Clermont-Ferrand, France.*

Hopquin, C., **D. Smittarello**, E. Gayer, L. Michon, and A. Lucas (2023). Dynamics and controls of the Grand Eboulis landslide measured by remote sensing (Rivière des Pluies, Réunion Island). *OZCAR Summer School, Aubure (France).*

Oth, A. and **J. Barrière** (2023). A short overview of ECGS's networks and activities. *Rhine-Meuse-Schelde (RMS) seismological meeting, 28 March 2023, Royal Observatory of Belgium.*

Parolai, S. and **A. Oth** (2023). On the limitations of spectral source parameter estimation for minor and microearthquakes. *Seismological Society of America (SSA) Annual Meeting, 17-20 April 2023, San Juan, Puerto Rico.*

Yen, M.-H., D. Bindi, B. Edwards, **A. Oth**, R. Zaccarelli and F. Cotton (2023). Scaling relations and variability of source parameters for shallow crustal earthquakes in Europe. . *IUGG General Assembly, 11-20 July 2023, Berlin, Germany.*

Smets B., L. Delhaye, **J. Barrière**, **N. d'Oreye** and F. Kervyn (2023). Topographic evolution of Nyiragongo's main crater from 2002 to 2021 using Structure-from-Motion (SfM) photogrammetry. *IAVCEI 2023 Scientific Assembly, 30 January- 3 February 2023, Rotorua, New Zealand.*

Subira, J., **J. Barrière**, C. Caudron, **A. Oth**, **N. d'Oreye**, A. Hubert-Ferrari and F. Kervyn (2023). Seismological models and seismicity patterns in the Kivu Rift and Virunga Volcanic Province (D.R. Congo). *AGU Fall Meeting 2023, San Francisco, 11-15-17 December 2023 (Poster).*

MEETING ATTENDANCE & WORK VISITS

Adrien Oth

- Rhine-Meuse-Schelde (RMS) Seismological Meeting, Brussels, Belgium (28 March)
- Annual Meeting of the Seismological Society of America (SSA), San Juan, Puerto Rico (17-20 April)
- ESC Pre-Conference Site Visit for ESC GA 2024, Corfu, Greece (21-23 May)
- 28th General Assembly of the International Union of Geodesy and Geophysics (IUGG), Berlin, Germany (11-20 July)
- EPOS Seismology Workshop on Next-Generation Open Seismological Dara Sharing for Science and Society, Podgorica, Montenegro (9-11 October)
- EMSC Executive Council and General Assembly, Podgorica, Montenegro (10 October)
- KNMI Supervisory Board Meeting, De Bilt, The Netherlands (24-25 October)
- ICDP-Eifel Workshop: Follow the CO2 – Drilling into an actively degassing intraplate volcano underlain by a silicate-carbonatitic intrusion (4-5 December)
- Work visits & visitors at ECGS, virtual meetings:
  - Visit of Annabelle Dullin from the Luxembourg Permanent Mission in Vienna at ECGS regarding CTBTO (3 April)
  - Visit of student form “Eis Schoul” at ECGS for her project on earthquakes (26 May)
  - Visit of engineering seismology PhD student Luis Munoz Heinen (8 November)
  - Meeting with Gabriel Garcia, PhD student at Uni.lu, regarding a potential robotics experiment in the WULG (13 December)
  - Station Maintenances and Retrieval in the Eifel region (6 June, 24 August)
  - Virtual ESC ExeCom Meetings (8 June, 7 July, 1 September, 27 October)
  - Virtual Associate Editor meetings of Seismological Society of America (12 January, 25 July, 8 September and 14 November)
  - Virtual ORFEUS Board of Directors Meetings (8 February, 14 July, 24 November)
  - Virtual EPOS TCS Seismology Meetings (9 February, 11 December)
  - Virtual EFEHR Consortium Meetings (1 June)
  - Virtual SCEC Stress Drop Validation Study Meeting (26 January)
  - Regular Eifel Large-N Array Virtual Meetings (22 February, 17 May)

Nicolas d’Oreye

- BeoDay 2023, Floreffe, Belgium (9 March)
- Réunion des collaborateurs scientifiques du Musée national d’histoire naturelle (Mnhn), Luxembourg (11 March)
- Conference for HATARI project termination (virtual) (10-11 July)
- Work visits & visitors at ECGS, virtual meetings:
  - Working session on AMSTer tools and presentation of a seminar about 2021 Nyiragongo eruption at Université de Lorraine (Nancy) (19 January)
  - Internship of Alexis Hautecoeur at ECGS in the frame of a master thesis at Laboratoire Magmas et Volcans (30 January – 3 February)
  - Working session with D. Derauw (27-28 March)
  - Working session on AMSTer tools at Université de Lorraine (Nancy) (28 March)
  - AMSTer training session for Sona Salehian Ghamsari (University of Luxembourg) (22 August 2023)
  - Meeting with Gabriel Garcia, PhD student at Uni.lu, regarding a potential robotics experiment in the WULG (13 December)
  - Virtual meetings for the ongoing research activities at Karthala volcano (Comores Island) (9 January, 22 February, 22 March, 7 April, 29 June, 10 July)
  - Virtual meeting regarding institutional review of Goma Volcano Observatory (7 February)
  - Virtual meeting for the GEOTROP project (2 March)
  - Virtual meeting of Bastien Wirtz’s thesis committee (11 July)

    - Virtual meeting with ESA representative PH. Bally about ETAD project (19 September)
    - Virtual meeting for ANR project preparation with Université of Lorraine and ISTerre Grenoble (12 October)
    - Virtual meeting with F. Vecchiotti (Geological Survey of Austria) about AMSTer software (27 June)
    - Virtual meeting with B. Smets (RMCA, Belgium) about AMSTer software (7 August)

Julien Barrière

- Rhine-Meuse-Schelde (RMS) Seismological Meeting, Brussels, Belgium (28 March)
- Thesis defence of Blaise Mafuko, Goma University and RMCA, Tervuren, Belgium (12 October)
- American Geophysical Union (AGU) Fall Meeting 2023, San Francisco, USA (11-15 December)

Delphine Smittarello

- Several work visits at LMV (Clermont-Ferrand) and IGN (Paris).

SCIENTIFIC COMMUNITY SERVICE

Adrien Oth

- European Seismological Commission (ESC) **Secretary General** (2022 – present)
- European Seismological Commission (ESC) **Titular Member** for Luxembourg
- **ESC Representative** in EPOS TCS Seismology, ORFEURS Board of Directors, EMSC Executive Council, EFEHR
- **ECGS Representative in EFEHR consortium**
- International Association of Seismology and Physics of the Earth's Interior (IASPEI) **National Correspondent** for Luxembourg
- **Associate Editor** of *Bulletin of the Seismological Society of America* (November 2017 – present)
- Member of the **Supervisory Board** of the **Koninklijk Nederlands Meteorologisch Institutt (KNMI)**, Netherlands
- Member of **Science Advisory Board** of the **Central Asian Institute for Applied Geosciences** (CAIAG), Kyrgyz Republic
- **Reviewer** for *Bulletin of Earthquake Engineering, Journal of Geophysical Research – Solid Earth, Sensors*
- **Member** of Seismological Society of America, Deutsche Geophysikalische Gesellschaft (DGG)
- **Mentorships & Supervision**
    - Support to PhD thesis performed by Josué Subira (Univ. Liège, MRAC & GVO)

Nicolas d'Oreye

- International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) **National Correspondent** for Luxembourg
- IAVCEI Board member of the Volcano Geodesy Commission
- **Scientific Committee Member** for *ESA Fringe workshop*
- **Scientific Committee Member** for French "Service National d'Observation (SNO) ISDeform"
- **Member** of American Geophysical Union, European Geosciences Union, IAVCEI & Academy of Sciences Luxembourg

- **Mentorships & Supervision**
  - Support to PhD thesis performed by Axel Deijns (RMCA) and Josué Subira (RMCA, GVO)
  - Support to master thesis performed by Alexis Hautecoeur at Laboratoire Magmas et Volcans (Université Clermont Auvergne)
  - Support to master thesis of Florian Leder at Université de Lorraine (Nancy)

Julien Barrière

- **Reviewer** for *J. Volc. Geotherm. Res.*, *EPS (Earth, Planets, Space)*, *Volcanica*, *Sensors*
- **Member** of American Geophysical Union, European Geosciences Union & IAVCEI
- **Mentorships & Supervision**
  - Co-supervision of the PhD thesis "*Seismicity analysis and seismological models in the Virunga Volcanic Province and Kivu rift region, DR Congo*" of Josué Subira (Univ. Liège, MRAC & GVO), started in 2020 (project HARISSA/Belspo)

Delphine Smittarello

- **Reviewer** for *J. Volc. Geotherm. Res., J. Geophys. Res.: Solid Earth*
- **Member** of European Geosciences Union, IAVCEI
- **Mentorships & Supervision**
  - Co-supervision of the MasTer Thesis of Alexis Hautecoeur (Student at UCA, Clermont-Ferrand) defended in June 2023.
  - Co-supervision of the MasTer Thesis of Pierre Papelard (Student at Sorbonne Université) defended in October 2023.
  - Co-supervision of the Master thesis of Greta Bellagamba (Master thesis at INGV Bologna) defended in May 2023.