Annual Report 2022

EUROPEAN CENTER FOR GEODYNAMICS AND SEISMOLOGY (ECGS)

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- **Prof. emeritus Antoine Kies**, physicist

INTRODUCTION

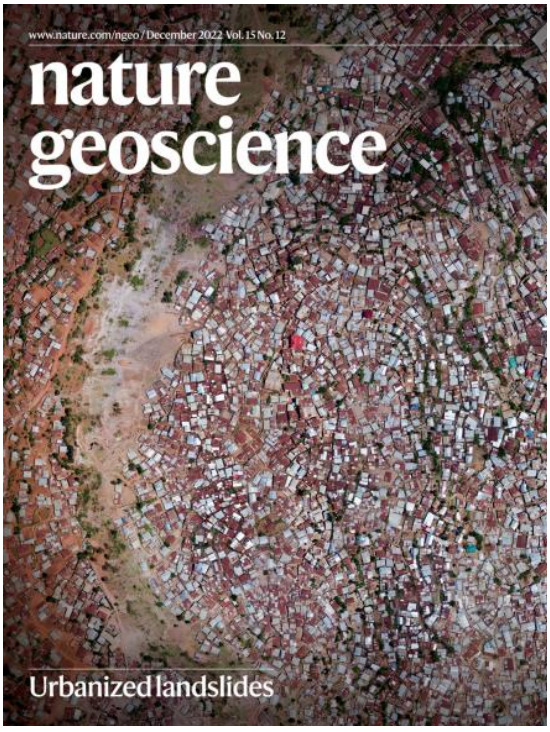
Over the course of 2022, the COVID-19 situation started to ease, with most travel restrictions being eventually eliminated. As a result, the scientific interaction on national and international level started to normalize. While a large number of meetings remained virtual (and will remain so for the foreseeable future), in-person conference attendance became possible again, and it was a great pleasure to be able to finally organize the 101st edition of the *Journées Luxembourgeoises de Géodynamique (JLG)* as an in-person meeting in Luxembourg again.

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). Dr. Smittarello joined the team in 2020 as a post-doc scientist and finally took over the remote scientist position made available in the framework of ECGS's strategic paper that is currently under implementation (2019 – 2024). Even though this position was granted with 1 ½ years delay as compared with the planning in the strategic paper, its implementation is overall very well on track.

The 2021 eruption of Nyiragongo volcano in eastern DR Congo still played a major role in ECGS's activity portfolio in 2022. The ECGS/Mnhn team is proud of its achievement of a *Nature* publication on the unfolding of and mechanisms driving the eruption, featured also on the cover of the *Nature* issue. This is certainly the key scientific highlight of the year, and the data collected over the past years in the Kivu region will of course still be the subject of intensive research in the coming years. ECGS/Mnhn also contributed to a *Nature Geoscience* article on urbanization feedbacks on landslide acceleration in the city of Bukavu.

In relation to the 2021 Nyiragongo eruption, ECGS/Mnhn however also definitely closed its collaboration with the Goma Volcano Observatory (GVO), effective on 1 July 2022. More details on the reasons for this decision are given in the following section here below.

In 2022, ECGS/Mnhn contributed its seismological expertise for two important case studies in Luxembourg. In late 2021, ECGS was solicited by the *Fonds de Logement* to provide its expertise on the current knowledge regarding induced seismicity from medium-depth geothermal projects. In response, ECGS provided a technical note at the end of February 2022.



In addition, in early May 2022, ECGS was contacted by a resident of the village of Rumelange regarding quarry blasts carried out at the quarry of the company Cimalux that could apparently be felt in his home. We provided this resident with information on quarry blasts detected and located by the Luxembourg Seismic Network (LuxSNet). Shortly after, a representative from Cimalux also contacted ECGS on this matter, asking whether an independent scientific assessment of the issue by ECGS would be possible. Since ECGS had installed a new broadband seismic station in the *Musée National des Mines* (MNM) in December 2021, in immediate vicinity to the quarry, an in-depth analysis of these data was carried out with respect to the ground motion levels measured from the Cimalux quarry blasts. We also carried out a short measurement campaign on the Cimalux premises with two additional seismometers for one week, capturing 4 blasts and allowing a more in-depth assessment, which we outline below.

Finally, ECGS contributed five broadband seismic stations for temporary deployment in the Large-N seismological experiment led by the GFZ German Research Centre for Geosciences, and will also be involved in a number of scientific studies that will follow in this framework.

These activities are particularly in-line with the aims of the ECGS strategic paper, putting ECGS's geoscientific expertise in the service of Luxembourg's society.

Besides its work in Luxembourg and the Kivu region, ECGS/Mnhn was involved in a range of further research activities with strong international collaborations (see research activities below), which are the living proof of the wide recognition of its expertise. ECGS/Mnhn researchers published 10 articles in international peer-reviewed scientific journals in 2022, with four more currently under review, and (co-)authored 26 contributions at international conferences.

CLOSURE OF COLLABORATION WITH GOMA VOLCANO OBSERVATORY (D.R. CONGO)

As foreshadowed by the situation following the Nyiragongo eruption in 2021, we have definitively ended our involvement in the DRC and ended our support and collaboration with GVO effective on 1 July 2022.

In response to the crisis that followed the 2021 eruption at Nyiragongo (see the 2021 annual report for details), the Be-Lux consortium, composed of researchers from the Royal Museum for Central Africa (RMCA) and ECGS/Mnhn, attempted to discuss with the director general of GVO and the responsible national authorities of DR Congo the possible continuation of the collaboration between GVO and the Be-Lux consortium. From the Be-Lux side, it was clear that such a continuation of the collaboration could only work if

1) it was actually desired by GVO staff, with whom the day-to-day work is carried out;
2) an unequivocal mandate for the Be-Lux consortium was agreed upon;
3) the necessary resources would be made available such that this mandate could be fulfilled;
4) the efforts from the different international partner institutions of GVO would be adequately coordinated to avoid duplications of existing infrastructures and unnecessary competition between the partners rather than working together for the benefit of GVO.

Several meetings and virtual discussion were held during the second half of 2021 and first half of 2022. On the invitation by the Congolese government, ECGS/Mnhn and RMCA scientists participated at the *1ère conférence Internationale sur la gestion des volcans des Virunga*[1], held in Goma from 19 to 21 March 2022. One of key aims of this conference was to clarify the collaborative framework of GVO and its historical and potential future international partners.

At this conference, while the GVO management committee and the national authorities expressed their interest in continuing the collaboration with the Be-Lux consortium, some representatives of GVO staff motivated by various and often unrelated reasons clearly expressed their wish to end

[1] Video recordings of the sessions of the conference can be found here: https://fr-fr.facebook.com/MinistereRsit/videos/1ère-conférence-internationale-sur-la-gestion-des-volcans-des-virunga-jour-3/707675787069117/?__so__=permalink&__rv__=related_videos

the collaboration. Evidently respecting the wishes of the GVO staff, the ECGS/Mnhn representatives announced their intent to end the collaboration with GVO, offering a generous transition period such that GVO could make arrangements with other international partners, who announced their desire to collaborate, and not to jeopardize the monitoring of the volcanoes.

The minister of research and technological innovation of DR Congo, Me José Mpanda, requested a meeting with the Be-Lux consortium in order to discuss the matter once more, which took place on 30 May 2022 at the premises of ECGS in Walferdange. At this meeting, Me Mpanda expressed his desire to continue the collaboration; however, this was not possible anymore for ECGS/Mnhn, since on one hand, it goes against the expressed wishes of GVO staff, and moreover, as announced since more than one year already, in absence of an official decision, ECGS/Mnhn had to urgently decide on the reallocation of its resources to other projects for the coming years. However, an extended transition period was requested by the Congolese authorities and agreed upon. It was agreed that a formal closure agreement would be signed to regulate this transition period, with the description of a number of milestones to be fulfilled by GVO staff on this way. It was also agreed that this closure agreement would need to be signed during the course of the month of June such that the transition period could be effectively started in a reasonably time frame.

Shortly after this meeting, ECGS/Mnhn provided the minister's cabinet with a draft agreement, to be discussed and amended if necessary. Unfortunately, no feedback whatsoever was received on this draft agreement until the date of its planned signature, that is 1 July 2022. In view of the fact that ECGS/Mnhn needed to take decisions on its resources' allocation and project participations for the remainder of 2022 and 2023, it was not possible to delay these decisions any further. As the Congolese authorities had been warned at the 30 May 2022 meeting, the collaboration with GVO was hence de facto officially closed on 1 July 2022, ending also all data acquisition and transmission via ECGS/Mnhn infrastructure.

As a consequence, we have started to take steps to repatriate all ECGS/Mnhn owned equipment that can be repatriated. This procedure will take time as 1) it is performed remotely and in accordance with local partners without endangering the monitoring of the Virunga volcanoes, and 2) it is performed in a particularly tense situation in that region affected by a renewed violence between armed groups.

The end of ECGS/Mnhn's implication in the Virunga also ended our implication in the Harissa project (see below), as agreed with the Royal Museum for Central Africa (RMCA). Note that this does not jeopardize our collaboration with RMCA and other partners with whom we will carry on some research on the Kivu region and Virunga volcanoes using for instance remote sensing techniques or archive data (seismic, GNSS, infrasound).

RESEARCH ACTIVITIES

Seismology in Luxembourg and Abroad

❖ 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;
2) The **Kivu region** in Central Africa (see also section below on the 2021 Nyiragongo eruption). The interest in this region has been driven through a series of scientific research projects over the past 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 are explained in detail in the previous section.

While the Kivu represents a highly active rifting region with both significant tectonic and volcano-related seismic activity, 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.

Figure 1 shows the status of the monitoring networks operated by ECGS/Mnhn. The Kivu Rift Seismic and Geodetic Network (KivuSNet / KivuGNet) has been operated in collaboration with local and international research partners and was composed of a total of 17 active broadband seismic stations, 16 GNSS stations and 2 infrasound arrays at the end of its lifetime. ECGS/Mnhn was also contracted by the Rwanda Mines, Petroleum and Gas Board (RMB) in 2019 to install the Rwanda National Seismic Network (RWSNet) as shown in Figure 1 (see 2019 Annual Report for more details).

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 will record earthquakes as well as continuous ambient background noise for about one year (Figure 2). ECGS participates in this so-called Large-N seismic experiment by (1) providing five broadband stations for temporary deployment (Figures 1 and 3) as well as the data from the LuxSNet network and (2) through scientific contributions in the data analysis.

The LuxSNet network counts 13 broadband seismic stations (Figure 1), covering the entirety of the Grand-Duchy. The broadband stations currently installed in the Eifel for the Large-N experiment will eventually 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.

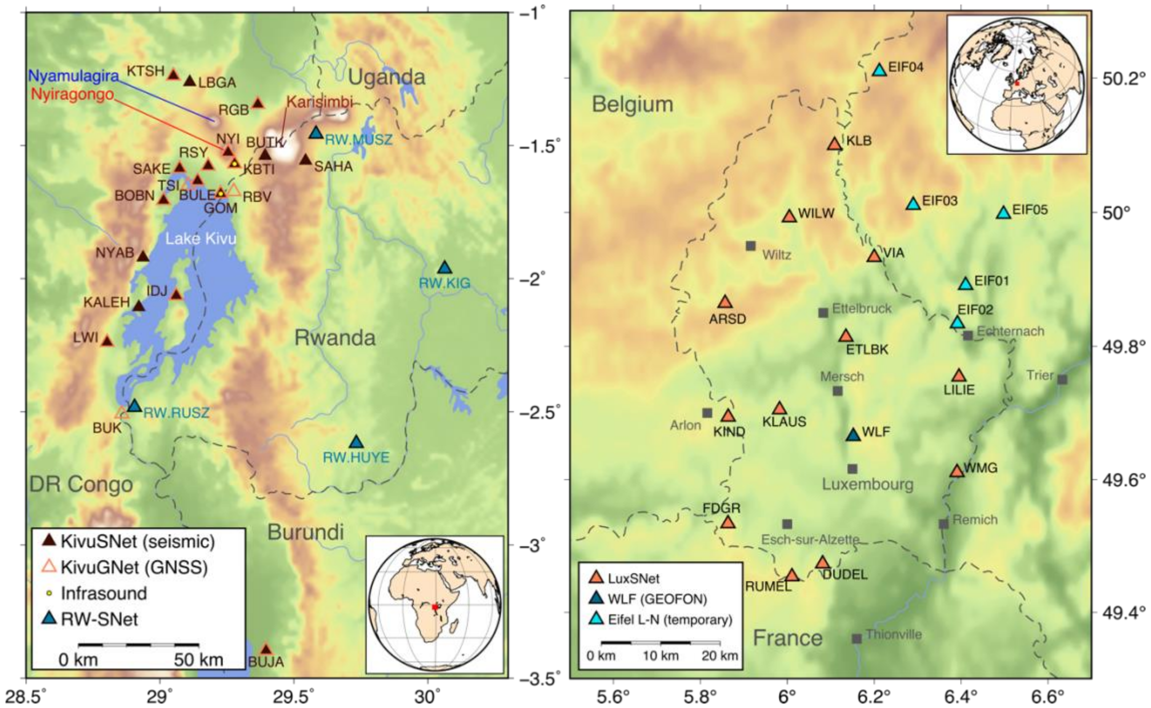


Figure 1: Status of seismic, GNSS and infrasound monitoring infrastructure developed by ECGS in collaboration with its partners in the Kivu Rift region (left) and in the Grand-Duchy of Luxembourg (right). Note that KivuSNet / KivuGNet operations have been terminated on 1 July 2022, as detailed in the previous section.

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.

❖ Technical note related to geothermal project “Neischmelz”

In the framework of the environmental impact assessment (*Etude des incidences sur l’environnement, EAE*) related to the authorization process of the geothermal drilling project on the site of *Neischmelz* in Dudelange, the *Fonds de Logement* and the consulting firm *Géoconseils* solicited ECGS in November 2021 in relation to the analysis of the seismic impact that will have to be addressed in the EAE.

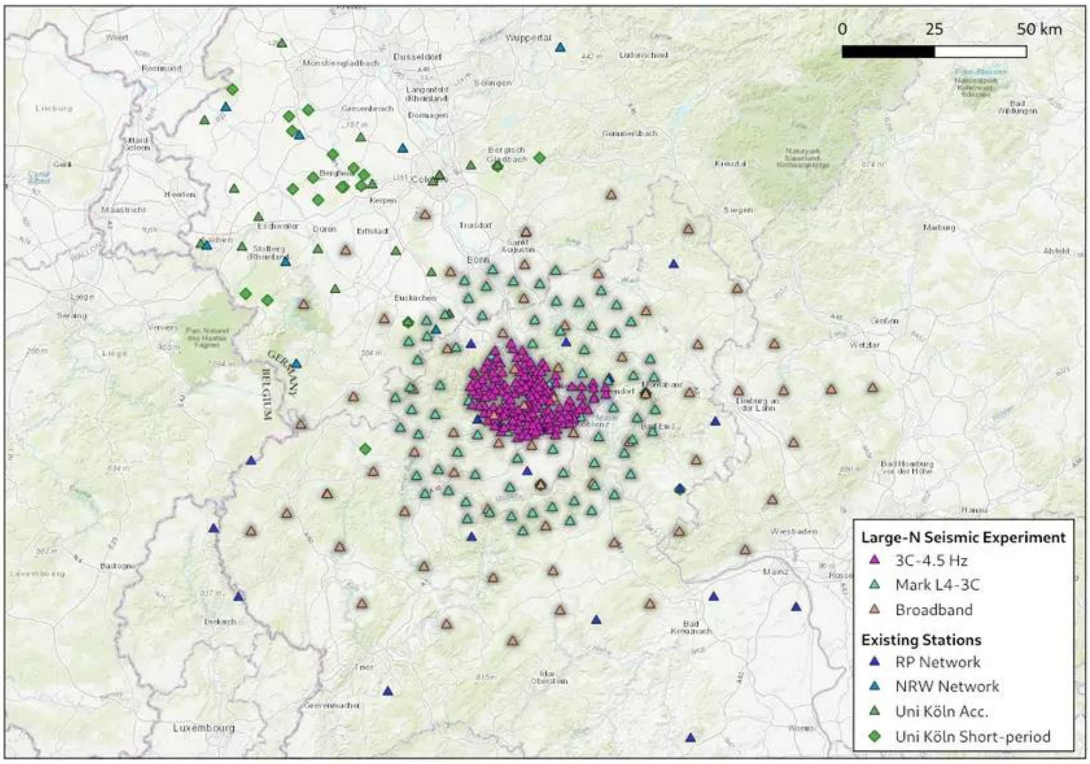


Figure 2: Planning sketch from the GFZ German Research Centre for Geosciences for the Eifel Large-N seismological experiment. This sketch can be found on the GFZ website[2] with further background information on the experiment and does not include all effectively occupied measurement sites.

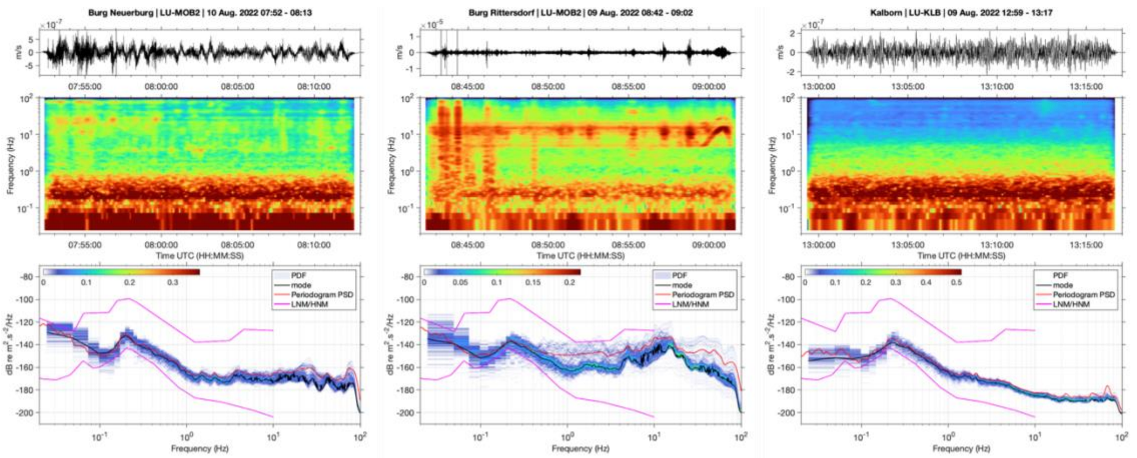
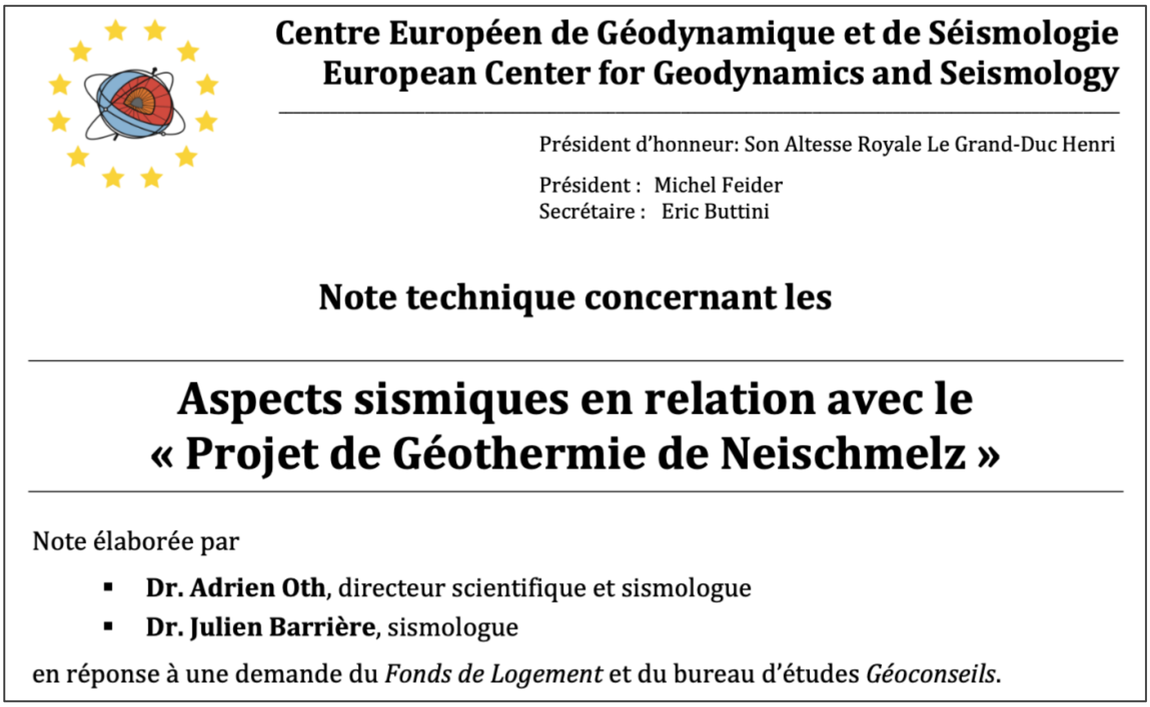


Figure 3: Test measurements taken at various potential station sites during the station scouting phase. Left: Burg Neuerburg (EIF03). Middle: Burg Rittersdorf (EIF05). Right: Reference station Kalborn (KLB) of the Luxembourg Seismic Network as a comparison. Top panels show recordings of the vertical component for a duration of about 15-20 min in each case, Middle panels the corresponding signal spectrograms and the bottom panels the power spectral densities. Low and High Noise Models (LNM/HNM) are shown for reference as magenta lines. The temporary station sites are generally noisier than the excellent station Kalborn, but provide a reasonable quality in particular at intermediate frequencies (0.1 – 5 Hz).

[2] https://www.gfz-potsdam.de/sektion/erdbeben-und-vulkanphysik/projekte/eifel-vulkanseismologisches-experiment



Centre Européen de Géodynamique et de Séismologie
European Center for Geodynamics and Seismology

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Note technique concernant les

Aspects sismiques en relation avec le « Projet de Géothermie de Neischmelz »

Note élaborée par

- **Dr. Adrien Oth**, directeur scientifique et sismologue
- **Dr. Julien Barrière**, sismologue

en réponse à une demande du *Fonds de Logement* et du bureau d'études *Géoconseils*.

Figure 4: Title page of the technical note provided to the *Fonds de Logement* and its consultancy company *Géoconseils* on 1 March 2022.

Specifically, following a meeting on 24 November 2021 where the details were discussed, ECGS was asked to write a technical note addressing the following aspects (email received by ECGS on December 1, 2021):

- The natural seismic activity of Luxembourg and the surrounding regions, followed by a presentation of the anthropogenic events measured by the national monitoring network;
- A description of the seismic measurement points currently available in the vicinity of Dudelange;
- A brief general state of knowledge on the seismicity induced by geothermal energy;
- Comments on the drilling project in Neischmelz on the basis of the geological cross-section, in the regional geological and seismo-tectonic context as it is currently known;
- Bibliographical data on seismic events measured and considered as induced by the realization or the exploitation of geothermal drillings in similar geological contexts, with the same mode of implementation (depth, absence of hydraulic fracturing, bedrock of sedimentary rocks under the solicited aquifer).

On 1 March 2022, ECGS provided the *Fonds de Logement* and *Géoconseils* with the requested technical note (copy was also addressed to the *Service Géologique des Ponts et Chaussées*) (Figure 4). The full technical note (in French) can be found in annex to this report.

❖ A study of quarry blast signals from the Cimalux quarry in Rumelange

In early May 2022, ECGS was first contacted by a resident of the town of Rumelange, directly located at the border between Luxembourg and France, in relation with recurring vibrations that apparently could be felt at the person's home. The resident also noted the presence of two quarries in the immediate vicinity (at about 2 km distance), of which at least one, exploited by the company Cimalux, regularly carries out quarry blasts in the framework of their operations.

As highlighted throughout the past years' annual reports, quarry blasts signals are indeed a common occurrence within the automatic detection and location procedures of the national seismic network LuxSNet. Some of these detected quarry blasts can without doubt also be associated with the quarries active in Rumelange, although it has at times been difficult to discriminate between the two near-by quarries due to a lack of locally installed seismic stations.

In December 2021, ECGS installed a broadband seismic station in the largest unsupported underground gallery of Luxembourg located in the *Musée National des Mines* (MNM) in Rumelange (Figure 5). This station (code RUMEL) was installed with the two-fold intention to (1) extend LuxSNet in southern Luxembourg and (2) test the potential of such a station for monitoring potential rockfalls within this cavity. However, it is by coincidence also located in the immediate vicinity of the Cimalux quarry and thus also provides high-confidence near-source recordings of blasts carried out in this quarry.

Not long after this initial contact by the resident of Rumelange, we were also contacted by a representative of the Cimalux company regarding this issue of these felt vibrations, with the request whether we could analyse the existing records of quarry blasts that we obtained until then at station RUMEL and whether we could also carry out a short-term experiment by installing some additional sensors for several blasts at the Cimalux quarry.

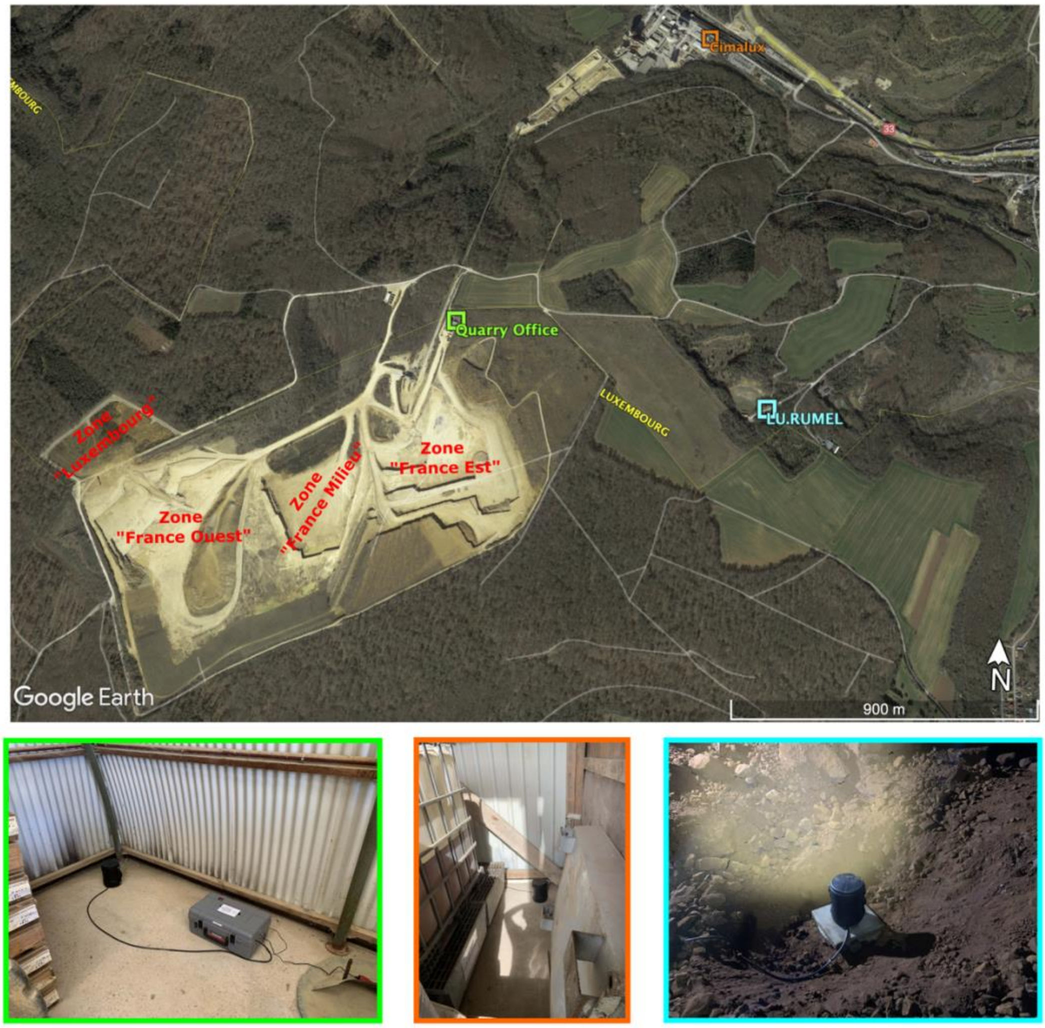

Figure 5: Situation plan of the Cimalux quarry in Rumelange (note that the largest extent of the quarry is located just across the French border) and the measurement sites considered in this study. RUMEL (light blue) denotes the permanent station of LuxSNet installed in a gallery of the *Musée National des Mines* (MNM, see also ECGS Annual Report of the year 2021). Two additional mobile stations were installed near the office of the quarry (green) and on the Cimalux main site (orange) in Rumelange. Photos of the corresponding installations are shown in the bottom row.

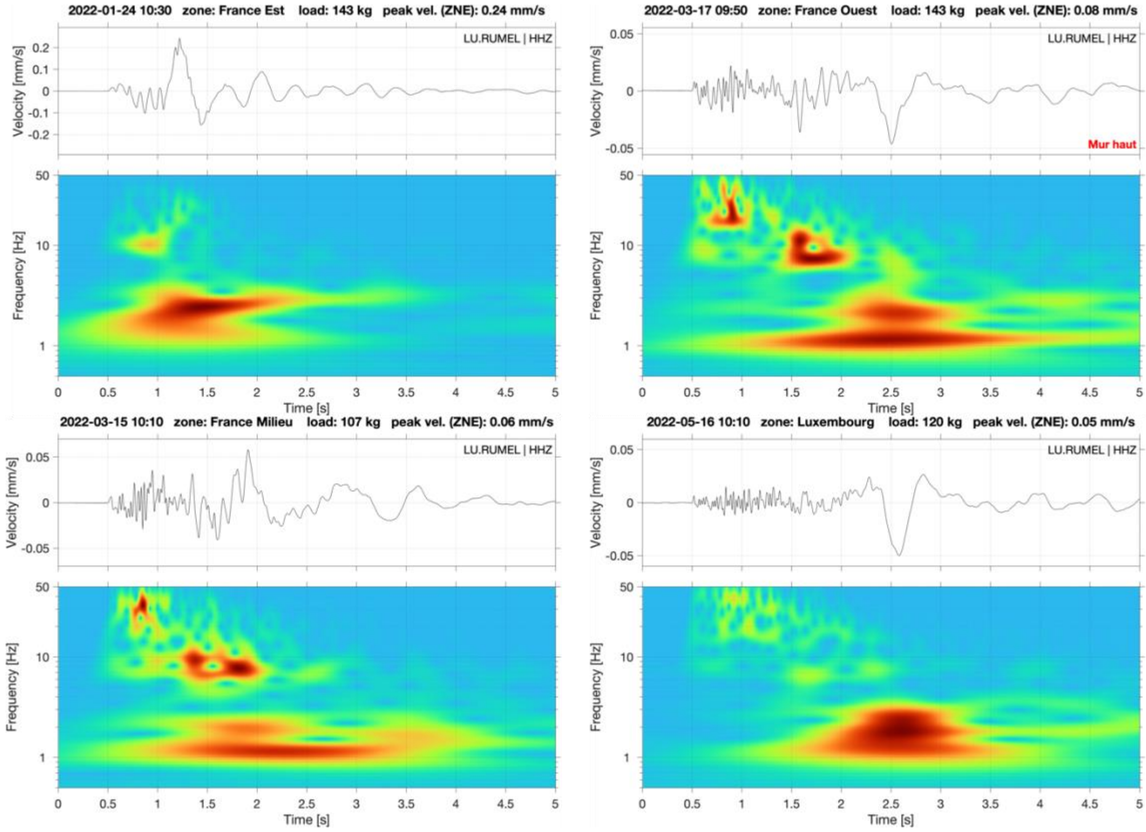

Figure 6: Vertical records (HHZ, 200 Hz sample rate, 5 seconds duration) and corresponding spectrograms for 4 quarry blasts recorded at station RUMEL in 2022.

In response to this request, ECGS analysed all quarry blasts signals from the Cimalux quarry recorded between the installation date of the RUMEL station in December 2021 and October 2022. To this end, Cimalux provided us with a detailed blast list. We also temporarily deployed two additional broadband stations for five days (22-27 August 2022) in order to record four well-defined blasts during this week on this three-sensor layout (Figure 5). A more extensive experiment involving further instruments was not possible at this time because all remaining non-deployed stations were in the course of preparation for the deployment in the framework of the Eifel Large-N experiment (see above) in early September.

The recordings of the quarry blasts were obtained at a sampling frequency of 200 Hz, allowing for an analysis of signals with frequency content up to 100 Hz. Figure 6 shows the vertical components recorded at station RUMEL of four such blasts carried out in the different operational zones (France Est; France Milieu; France Ouest; Luxembourg) of the quarry (roughly indicated in red in Figure 5). As can be expected, the near-source blast signals are generally characterized by significant high-frequency first arrivals (P-waves in frequency bands > 15 Hz) and dominant short-period surface wave components (between about 1 and 10 Hz). The generated wavefield tends to be complex, as is in particular witnessed for the blasts also recorded at the temporary stations in August 2022. Over the distance range of 1 to 2 km (distances between quarry and station RUMEL respectively the Cimalux headquarters), the signal characteristics can drastically change, with very short-period surface waves recorded on the nearest site to the blast (quarry office), likely related to spall effects. At the slightly more distant stations, longer-period surface wave components tend to become more relevant. Note also that station RUMEL is installed at a depth of about 80 m within the underground gallery.

Peak velocities measured at station RUMEL for 74 blasts from December 2021 to October 2022 show a maximum value of 0.46 mm/s (maximum of 3 components) (Figure 7). It becomes immediately clear that the blasts carried out in the zone “France Est” have by far the highest peak velocities, which is likely due to the fact that these blasts are simply the closest ones to the seismic

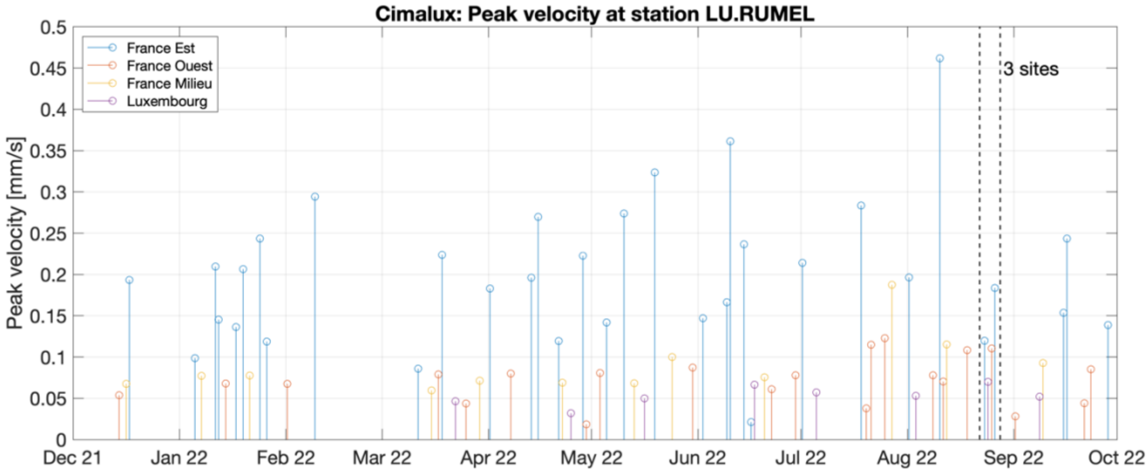

Figure 7: Peak velocities (3-component maximum) measured at station RUMEL for 74 quarry blasts in the Cimalux quarry from December 2021 to October 2022. Color-coding refers to the blasting zones as indicated in Figure 5.

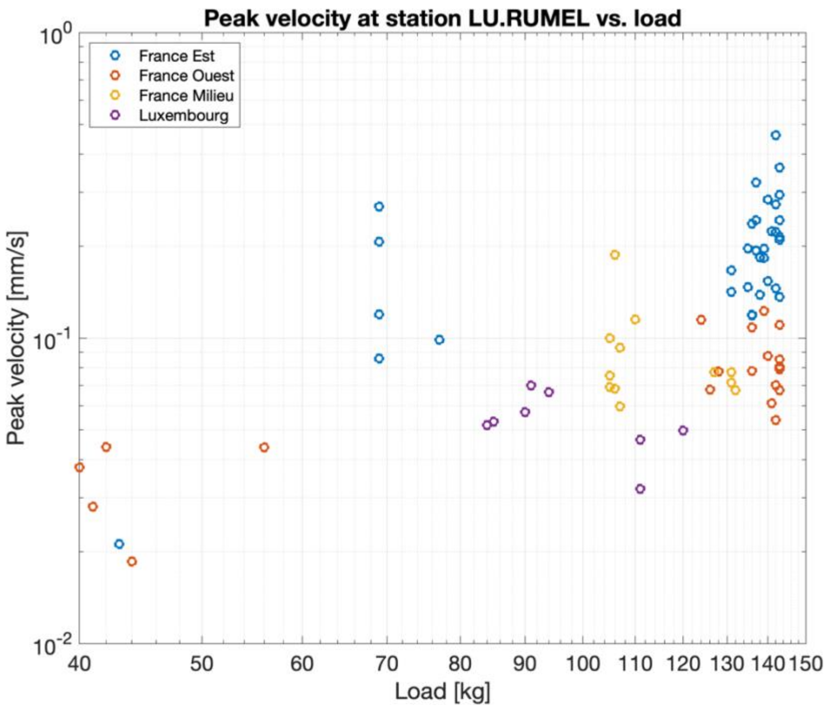

Figure 8: Peak velocity recorded at station RUMEL plotted versus the unitary load of the quarry blasts. Color-coding refers again to the blasting zone as indicated in Figure 5.

station. Figure 8 shows the peak velocities relative to the unitary load of the blasts as provided by Cimalux. While an overall correlation of peak velocity with load becomes apparent from this plot, within a given blasting zone, there is a large variability of peak velocities for similar loads, likely reflecting variations in blasting practices, quarry face orientations, locations within the quarry etc. (e.g., McLaughlin et al., 2004). Note that loads between 130 and 143 kg are very common because 143 kg represents the maximum allowed load. Again, the fact that peak velocities for similar loads are all higher for blasts in zone “France Est” as compared with “France Ouest” for instance clearly shows that distance to the blast is the dominant effect on the peak velocities as compared with the load.

For the four blasts recorded at the three different seismic stations during the week of 22-27 August 2022, the effect of distance becomes again very visible, with significantly larger amplitudes

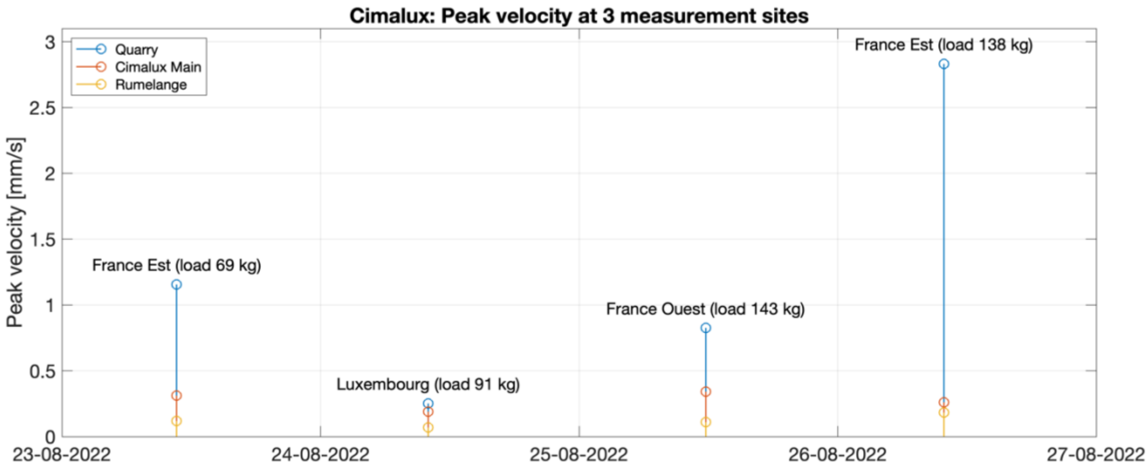

Figure 9: Peak velocities (3-component maximum) measured for the four test blasts carried out in the week of 22 to 27 August 2022. For these test blasts, two additional broadband stations were set up near the office at the quarry (blue) and on the Cimalux headquarter grounds in Rumelange (red), see also Figure 5. Station LU.RUMEL is denoted as "Rumelange" in the plot above (yellow).

measured at the quarry office location compared to station RUMEL and the main site of Cimalux in Rumelange (Figure 9). Note here again that station RUMEL is about 80 m underground, which may result in a missing free surface effect and hence reduced amplitudes as compared with a surface station.

The maximum measured peak velocity (maximum of 3 components) is 2.83 mm/s at the quarry office site for the 26 August 2022 blast in zone "France Est". Taking the vectorial sum of the 3 components would lead to a maximum peak velocity estimate of 3.82 mm/s. We analysed the recordings of the blasts in view of the constraints imposed by the French *Arrêté Ministeriel du 2 Septembre 1994*, which states that the *"quarry blasts must not be at the origin of vibrations susceptible to generate weighted particle velocities higher than 10 mm/s within near-by constructions, measured along the 3 axes of the construction"*. The weighted particle velocity limit is indicated in Figure 10 (right-hand side) as black line.

In order to graphically represent the frequency-dependence of peak velocity, we narrow-band filtered the traces along a set of frequencies equally spaced in log units. Figure 10 shows the analysis for the blast with the largest observed amplitudes (26 August 2022, zone "France Est"). It is evident that this limit function defined in the Arrêté was not surpassed for any of the recordings at any measurement station of the experiment. In conclusion, we can state that no evidently critical ground motion values were observed throughout the entire analysis.

Cimalux also provided us with the report of a recent measurement campaign carried out for a single blast in the zone "France Est" (8 July 2020) by the company Titanobel. The measurements in that report are in good agreement with our results, with a peak velocity measurement near the quarry office of 2.43 mm/s.

As a final note, Figure 11 shows the difference between the recordings of a small natural (tectonic) earthquake and the typical quarry blast signature. As expected, the tectonic earthquake shows typical impulsive P- and S-wave arrivals and no surface energy, in contrast to the quarry blast signal, which is dominated by short-period surface wave energy well visible throughout the entire LuxSNet network. Already these visual differences generally allow for a discrimination between tectonic earthquakes and quarry blasts, the latter being undesired signals from an earthquake monitoring perspective.

Reference:

McLaughlin, K. L., J. L. Bonner, and T. Barker (2004). Seismic source mechanisms for quarry blasts: modelling observed Rayleigh and Love wave radiation patterns from a Texas quarry, Geophys J Int, 156, 79–93.

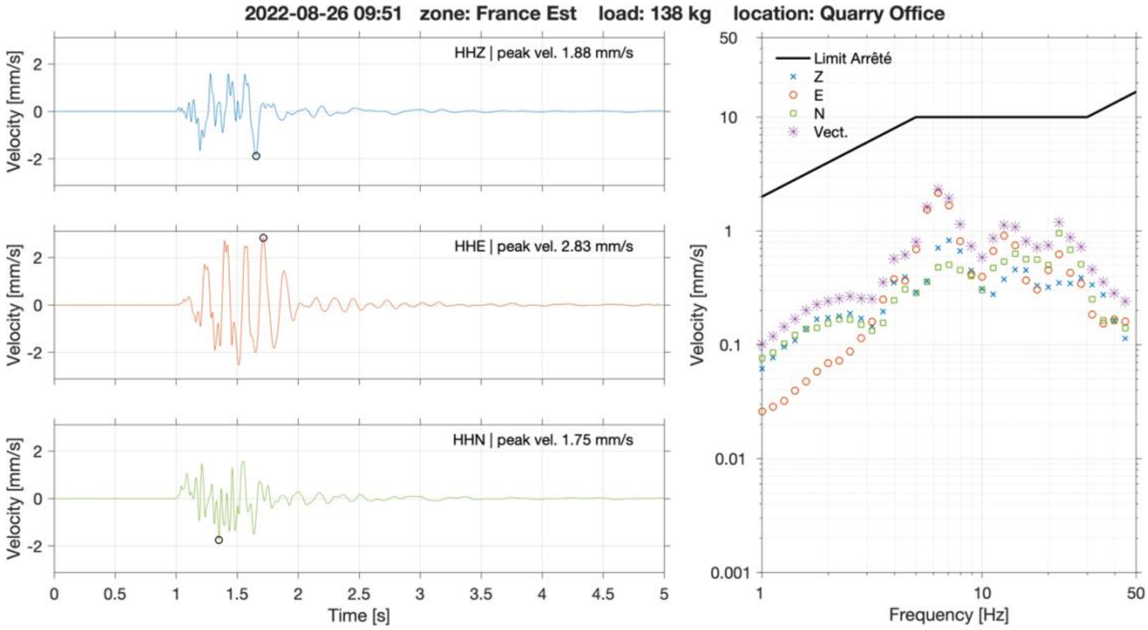

Figure 10: Left: 3-component recording of the blast with the largest measured peak velocity (2.83 mm/s, quarry office station) carried out on 26 August 2022 in the “France Est” zone of the quarry. Black circles indicate the time of the maximum ground velocity for each component. Right: Frequency-dependent analysis of ground velocities obtained through a narrow-band filtering procedure. The black line denotes the ground velocity limit set by the French *Arrêté Ministériel du 22 Septembre 1994*.

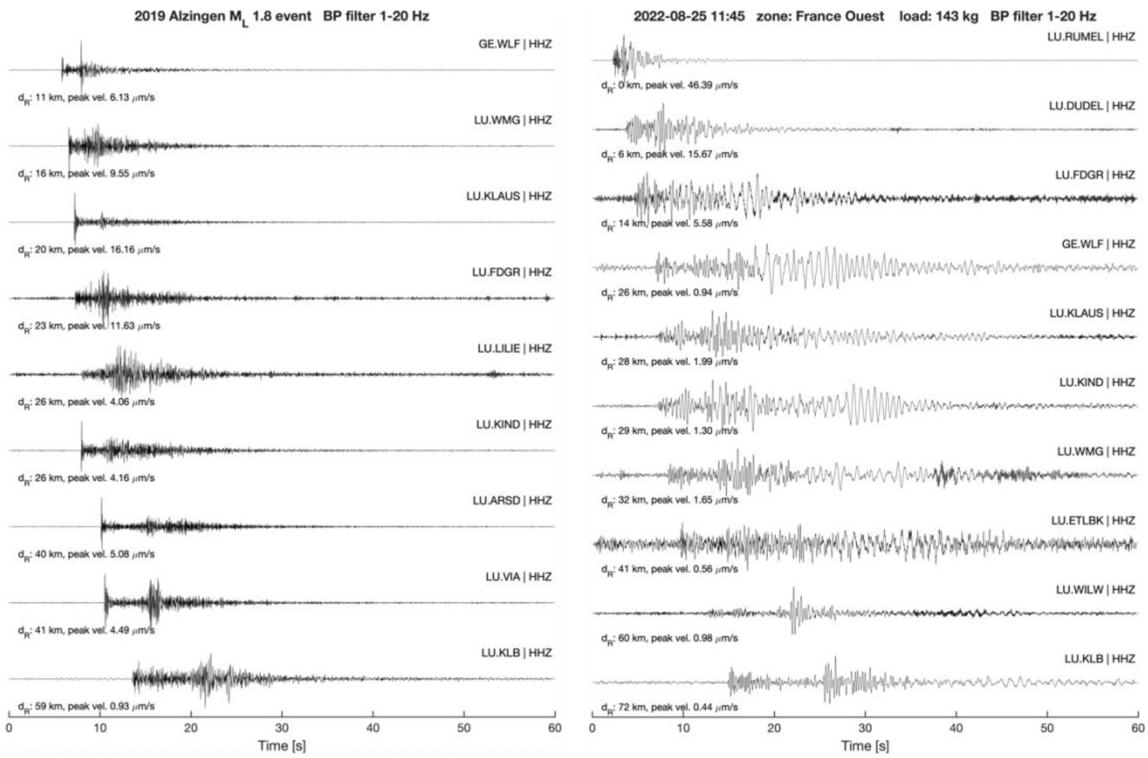

Figure 11: Comparative analysis of a small earthquake of tectonic origin (left, Alzingen event of 17 December 2019, magnitude M_L 1.8, depth 7 km) and the 25 August 2022 quarry blast carried out in zone “France Ouest” of the Cimalux quarry (right). Epicentral distances are given as values d_R for each vertical trace in the plots (for the Cimalux blast, since the exact coordinates of the blast could not be provided by Cimalux, we just measured the distance from station RUMEL). Note the very different characteristics of the waveforms, with strong dominance of surface waves in the quarry blast case.

❖ Seismicity in Luxembourg

Following the methodological framework detailed in the previous annual report (2021), we continue to develop the first accurate overview of tectonic seismicity occurring on the Luxembourgish territory. The Luxembourgish seismic picture is almost fully dominated by anthropogenic seismic sources (quarry blasts) but also depicts low-level tectonic activity in faulted areas. We used the automatic pre-classification of events of natural (i.e., tectonic) or anthropogenic (i.e., quarry blast) origin based on 4 attributes:

- origin time (hour of day, UTC),
- magnitude (local magnitude M_L),
- depth (km b.s.l.),
- frequency index (dimensionless metric conveying the average frequency content of the seismic event recorded at the stations).

We also recall below the 3 main active zones identified in the Gutland (Southern) region:

- The south of Luxembourg close to Alzingen and Mondorf;
- The Moselle river (border with Germany) from Grevenmacher to Wasserbillig;
- The Grünewald area, about 10 km to the East of Walferdange's mine/station (WLF).

An additional tectonic event located close to Mondorf occurred on 24 April 2022 (n°13 in Figure 12). Since 2016, 13 tectonic events have been clearly identified (Figure 12), of local magnitude (M_L) below 1.6, at depth generally constrained between 5 and 10 km. As already stated in previous reports, the automatic discrimination between natural (i.e., tectonic) and anthropogenic (i.e., quarry) events can sometimes be uncertain. Indeed, earthquakes occur also during daytime, the magnitudes of both type of events are similar, the depth of the source can be badly constrained, site and path effects can affect the frequency content. The most unfavorable situation for identifying low magnitude natural events is when they are located close to active quarries during daytime. This is notably the case for the group of events n°5,7,8,9,10 located close to Wasserbillig. On 30 April 2020, a M_L 1.2 event occurring at night was easily flagged as tectonic event. Two "new" events (n°8-9) of lower magnitude (M_L 0.9) occurring earlier the same day have been found

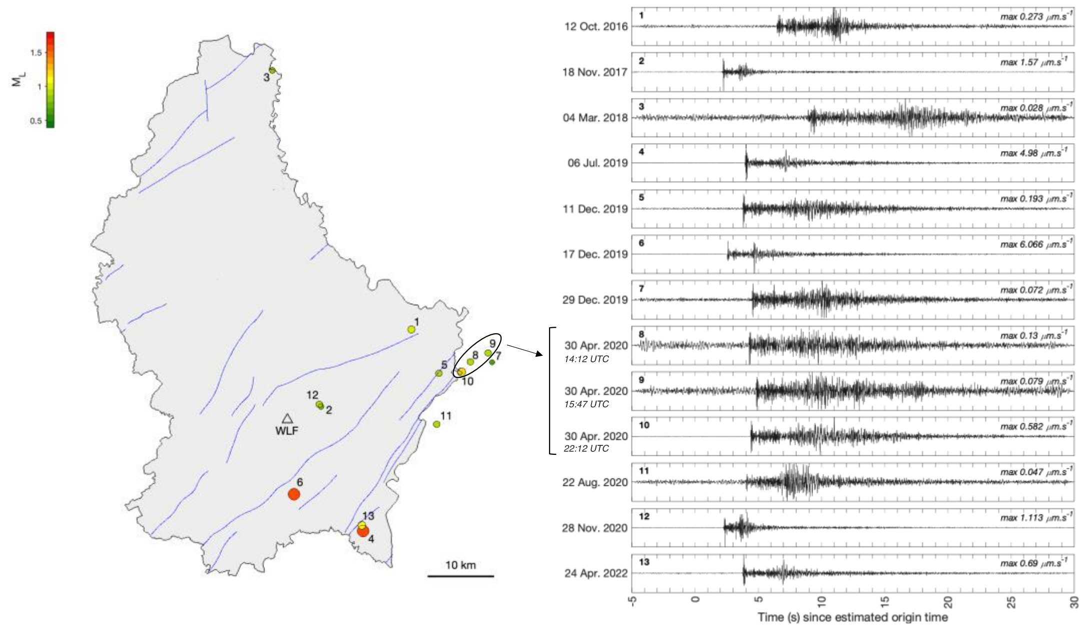

Figure 12: 13 earthquakes (Magnitude 0.5 – 1.6) located between Oct. 2016 and Dec. 2022. On left, map of epicenters (size and color of the round markers are proportional to the magnitude). The main geological faults are depicted in blue (source : catalog.inspire.geoportail.lu). On right, the vertical component records at station WLF (Walferdange) of each earthquake. Please note that amplitude of the seismic traces is normalized for each record.

thanks to a new manual inspection by comparing waveforms at available stations. The similarity of waveforms generally conveys a similar source region and mechanism. Finding some clusters of similar events (i.e., waveforms) would allow to identify active tectonic structures. This way, we can retrieve potential “multiplets”, as defined by Moriya et al. (2003) as *a group of microseismic events with very similar waveforms, despite different origin times, […] likely the expression of stress release on the same structure*.

A few years ago, we detected a cluster of microseismic events conveying seismically activated structures in the Grünewald area. Events n°2 and 12 are the only one located thanks to the network. Because very close in space and having highly similar waveforms, we looked for other similar events whose magnitude is too small for being detected/located across the national network. The method is an automated detection algorithm called “template matching”. The principle is to scan the whole database at one station (here the closest, WLF) with a master event (here n°2). A potential new event is found when the level of correlation between the master event and the scanned part of the continuous waveform exceeds a pre-defined threshold. 7 additional microearthquakes belonging to the “Grünewald multiplet” have been detected thanks to this method between 7 March 2013 and 9 July 2021 (see report 2021). We have updated the processing to December 2022 but no further events belonging to this cluster have been detected since then.

In addition to the Grünewald area, ongoing work (late 2022/early 2023) focusses on retrieving potential multiplets in other identified active areas:

- The Mondorf area where two highly similar earthquakes (of magnitude > 1) are spaced by about 3 years (n°4,13);
- The Wasserbillig area where several similar events have been already located (n°5,7,8,9,10).

In this regard, the Walferdange station (WLF) is a very interesting station because continuous records with high sampling rate (100 Hz today) have been available since 2010. This allows looking for clues on tectonic seismicity back to early 2010 using a dedicated single-station approach before the full deployment of the national network. We currently explore the possibility to go back to March 1994 when the first broadband station was deployed. The main drawback is that continuous data between 1994 and 2010 are only acquired with low sampling rate (20 Hz), thus hampering the detection of high-frequency low magnitude events.

❖ Ambient noise tomography on the Eifel and surrounding regions

Following the work initiated in 2021, we provided updated Rayleigh wave group velocity maps with a maximum depth of investigation of about 20 km (Figure 13). This initiative was notably motived by the few recent geophysical studies confirming a mantle upwelling beneath the Eifel volcanic fields (Kreemer et al., 2020, Dahm et al., 2021) and the detection of deep seismic events (10-40 km deep) conveying magmatic recharge beneath the Laacher See Volcano in East Eifel between 2013 and 2018 (Hensch et al., 2019).

These results rely on the use of data archives of the 1997-1998 Eifel experiment and more recent (2019-2020) seismic records from broadband and short-period sensors at regional scale. Some relevant geological structures are evidenced (i.e., Rhenish Massif) and we highlight a potential low velocity structure beneath the Eifel region, though the velocity contrast with the surrounding regions is small. As it stands with current available data, the lack of spatial resolution of such ambient noise tomography hampers to determine if there is a clear velocity anomaly attributed to a shallow active magmatic system in this region. Although not published yet, this preliminary work was presented at two conferences in 2022 (EGU and JLG). We will not further develop this topic since a scientific consortium (under the leadership of GFZ) deployed a new high-quality seismic experiment in late 2022 that should be able to answer this question with a much better precision (“Large-N experiment in the Eifel”). ECGS is involved in this effort and both results could be further compared for assessing the quality of ambient noise tomography maps derived from old data.

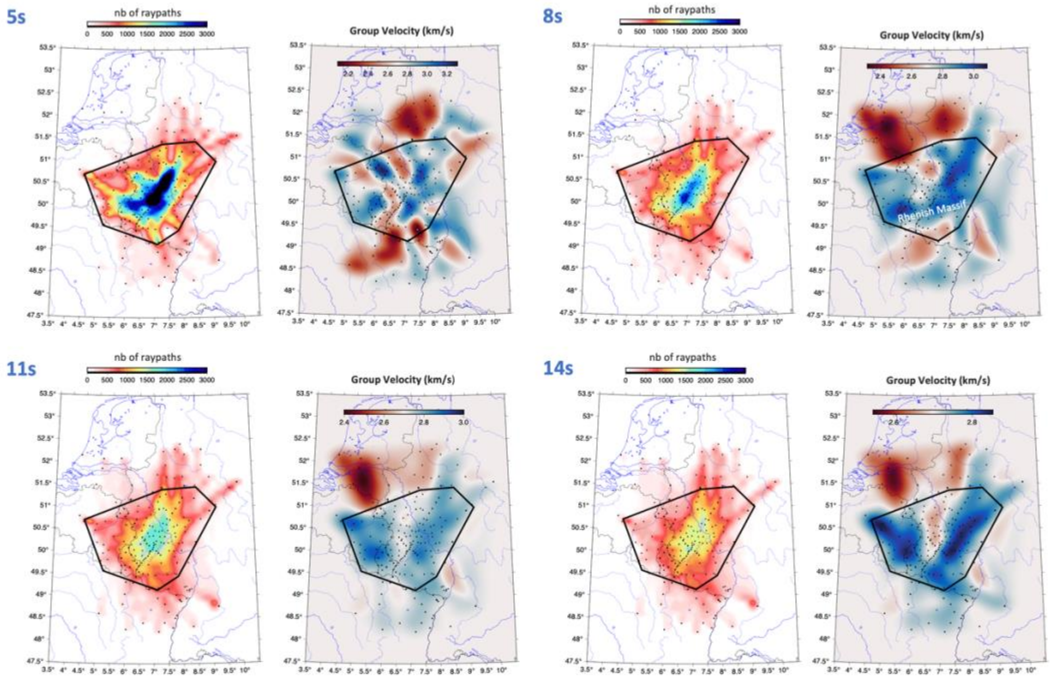

Figure 13: Left panel: ray density of selected paths between stations (black markers). Right panel: 2D Rayleigh wave group velocity maps at period T=5, 8, 11, 14s obtained with the tomography code FMST (Rawlinson & Sambridge, 2005). This corresponds to maximum depth of investigation of about 7, 11, 15 and 19 km, respectively, using the rule of thumb "depth=wavelength/2" (Haney and Tsai, 2017) and an average velocity of 2.7 km/s. The polygon contoured with black lines is roughly the region that can be appropriately imaged (encompassing the whole Luxembourgish territory, the Ardennes in Belgium, the Hunsrück upland and the Eifel volcanic field in Germany).

An interesting outcome of this work with archive data concerns the chosen processing. Because of uneven data quality, particular attention was given to the retrieval of meaningful Noise Cross-correlation Functions (NCFs), and thus reliable velocity information between station pairs. We tested several strategies (Figure 14):

- Linear Stacking LS (Bensen et al., 2007),
- Linear Stacking with additional selection based on RMS criterion LS_{RMS} (Xie et al., 2020),
- Time-Frequency Phase-Weighted Stacking tf-PWS (Schimmel and Gallard, 2007).

We ultimately proposed a new approach (*tf-PWS*$_{RMS}$), which is a combination of the *LS*$_{RMS}$ and *tf-PWS* approaches. We think that this procedure can help to extract NCFs with better signal-to-noise ratio and we will further test this processing approach on other datasets (e.g., KivuSNet). *tf-PWS* and *tf-PWS*$_{RMS}$ give similar results but, overall, spurious arrivals that do not correspond to ballistic arrivals of Rayleigh waves are more efficiently eliminated with *tf-PWS*$_{RMS}$ (at |time lag| < 50 s for both station pairs in Figure 14b).

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Moriya, H., H. Niitsuma, R. Baria (2003). Multiplet-Clustering Analysis Reveals Structural Details within the Seismic Cloud at the Soultz Geothermal Field, France. Bull. Seismol. Soc. Am, 93, 1606–1620.

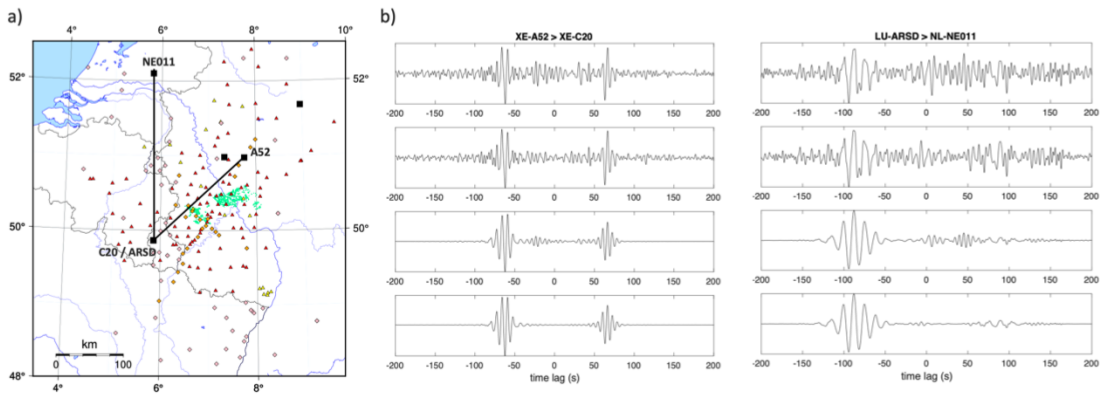


Figure 14: **a)** Map of available stations used for the ambient noise tomography (each color and marker style correspond to a particular network and period of availability). Stations C20, ARSD, NE011 and A52 are depicted as big black squares. Stations C20 and ARSD are almost co-located but C20 is a temporary station deployed in 1997-1998 and ARSD is a permanent station from the Luxembourgish network (2009-). **b)** NCFs obtained from stations pairs A52-C20 (1997-1998) and ARSD-NE011 (2019-2020). From top to bottom, 4 different processing (stacking) methods are applied: LS, LS_{RMS}, tf-PWS, tf-PWS_{RMS} (see text for details).

Rawlinson, N. and M. Sambridge (2005): The Fast Marching Method: An Effective Tool for Tomographic Imaging and Tracking Multiple Phases in Complex Layered Media, Exploration Geophysics, 36:4, 341-350.

Schimmel, M., and J. Gallart (2007). Frequency-dependent phase coherence for noise suppression in seismic array data. J. Geophys. Res., 112, B04303.

Xie, J., Y. Yang and Y. Luo (2020). Improving cross-correlations of ambient noise using an rms-ratio selection stacking method. Geophys. J. Int., 222, 989–1002.

❖ Various international seismological collaborations

In 2022, ECGS was involved in a series of international collaborations on seismological research, which have led to peer-reviewed articles co-authored by ECGS scientists in high-impact journals.

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

  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 that paper, we focussed on the specific impact of accounting for earthquake depth in the non-parametric generalized inversion technique.

  In 2022, the group of authors of the 2021 article 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 written and recently submitted to *Seismological Research Letters*.

- **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 accepted for publication in *Journal of Seismology* and is currently in press.

  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. This study uses for the first time with this optimisation approach a hazard-consistent seismic catalogue for calculating the necessary synthetic ground motion time histories.

- **The limitations of direct spectral estimation of source parameters for minor and micro earthquakes**

  This is a study carried out as a collaboration between S. Parolai, Director of the Seismology Section of the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS, Italy) and A. Oth. An article presenting the results of the study has been published in 2022 in the *Bulletin of the Seismological Society of America*.

  The study investigates the impact of parameter trade-offs when calculating earthquake source parameters for minor and micro events using direct spectral estimation. While it is generally known that the parameters corner frequency, seismic moment and Q (or kappa) trade off, a systematic evaluation of this trade-off in particular for very small seismic events and the consequences for the reliability of the obtained results using this approach has not yet been undertaken, and is the aim of this study.

New Insights on the May 2021 Nyiragongo Eruption

Figure 15: 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 RMCA and the ECGS/Mnhn, who work with the GVO since 2005.

On the advice of the Be-Lux consortium, a group of experts covering all relevant scientific fields was set up. In the end, about 30 experts from a dozen countries contributed to this group which met daily by Zoom from May 26 onwards to assist GVO in the follow-up of this eruption. A team of RMCA and ECGS/Mnhn travelled to Goma from May 29 to June 12 to assist GVO in follow-up of this crisis.

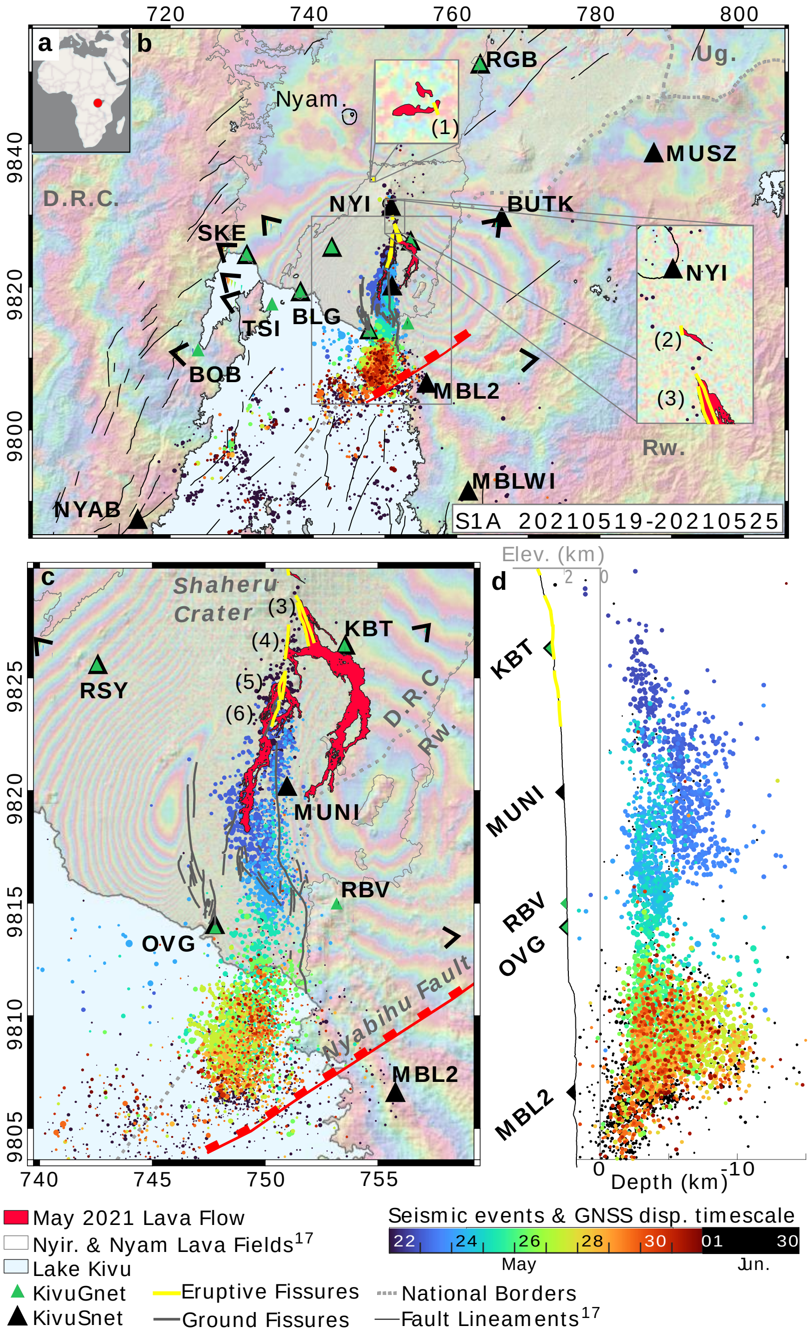


Figure 16 *(Smittarello et al., 2022, Nature)*: Co-eruptive geodetic signals and seismicity. (a) Situation map. (b and c) Sentinel-1 20210519-20210531 ascending interferogram overlaid with automatic earthquakes locations and GNSS displacements over time (blue to black coloured with time from from the onset of the eruption), eruptive fissures (yellow lines 1 to 6, from North to South), ground fissures detected from interferogram discontinuities (grey lines), lava flows (red area) and seismic and GNSS stations from KivuSNet[18] and KivuGNet[25] available during the crisis (black and green triangles respectively). D.R.C - Democratic Republic of Congo; Nyam. – Nyamulagira; Rw. - Rwanda; Ug. - Uganda. (d) North-South transect of hypocentral depth (same symbols as in b and c). Coordinates are given in kilometres in the WGS 1984 UTM (Zone 35S) system.

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. Here we therefore only present additional information on research works carried out in 2022.

❖ Joint study of ground-based and space-born data published in *Nature*

The joint analysis of ground based (seismic, GNSS) and space borne (SAR, Multispectral) data allowed us to unravel the physical mechanism of the May 2021 eruption. This study has been published in a paper by Smittarello et al. (2022) in *Nature*, where all the details of the study can be found.

To summarize, the analysis shows that a structural failure of the Nyiragongo edifice produced a ~6 hours long fissure effusion whose deadly lava flows threatened about 1 million inhabitants living in the cities of Goma (DR Congo) and Gisenyi (Rwanda). At least 220 people died or went missing, and the eruption left 6.000 households homeless while lava flows entered the city of Goma. The flank eruption started without any alarming precursory unrest having been reported, which highlights the difficulty to monitor permanently erupting volcanoes such as Nyiragongo.

After about 6 hours, the eruption stopped, yet the volcanic crisis continued for several days with numerous earthquakes (Figure 16) and intense fracturing observed in Goma and Gisenyi. This activity was caused by the southward progression of a shallow dike from the Nyiragongo edifice to beneath Goma and Gisenyi city centers, then below the northern part of Lake Kivu (Figure 16 and 17). It finally stopped in front of a regional inherited structure called the Nyabihu fault and reactivated micro-tectonic seismicity in the whole Lake Kivu area.

The absence of precursory signals (Figure 18), which was due to the fact that the eruption was caused by a structural failure of the edifice rather than a volcano-tectonic origin like the two former eruptions (1977 and 2002), shook up the classical scientific view of the eruptions at that type of volcano, calling for revising the way to prepare for these events.

Further work on the 2021 Nyiragongo eruption includes the development of a new method for estimating the collapse crater area and depth (see section below, pages 25-28).

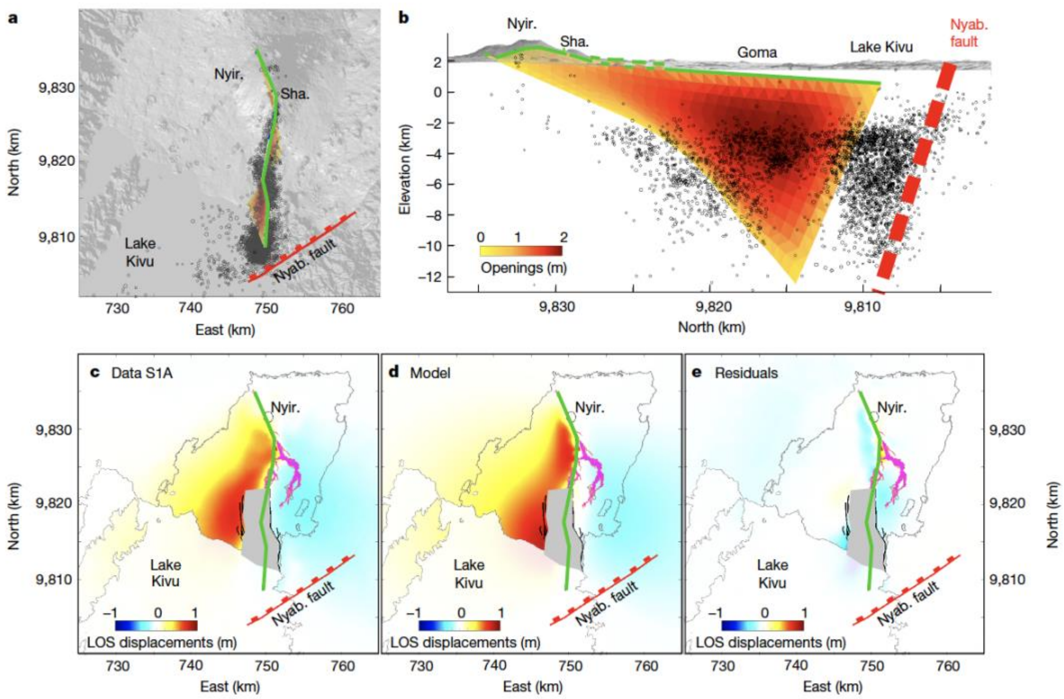


Figure 17 *(Smittarello et al., 2022, Nature)*: Inversion results for dike geometry. (a)(b) Best results of dike geometry inverted from four interferograms spanning the eruption overlaid with seismicity between 22 and 31 May in a map view (a) and along a north–south cross section (b) (see also Extended Data Fig. 1). Colours represent the dike opening (0–2.5 m). Sha., Shaheru Crater. (c) Displacement map observed in satellite line of sight (LOS) from the S1 interferogram shown in Fig. 1. d, Modelled displacement in LOS. (e) Residuals. In c–e, the lava flows are mapped in pink. Inelastic deformation within the graben is masked in grey. Black and green lines represent ground fissures and the dike top trace, respectively. The dike top trace is connected

to eruptive fractures (b). Nyabihu Fault is marked in red. Its 72.5° dip is estimated from seismic profiles45. Coordinates are given in kilometres in the WGS 1984 UTM (Zone 35S) system.

❖ Infrasonic noise from lava eruptions at Nyiragongo volcano, D.R. Congo

During eruptions, volcanoes produce air-pressure waves inaudible for the human ear called infrasound, which are very helpful for detecting early signs of magma at the surface. Compared to violent ash-rich explosions, recording more subtle atmospheric disturbances from effusive eruptions remains a practical challenge. Wind and human activity are other powerful sources of unwanted infrasound noise, potentially masking volcanic sources. At Nyiragongo volcano (D.R. Congo), close to a one-million urban area, the drainage of the world's largest lava lake concomitant with short-duration lava flows on its flank and the renewal of an effusive eruption within its crater a few months later were a series of major volcanic events in 2021, all monitored with infrasound sensors. These events resulted in remarkable local recordings of eruptive infrasound from rural and city-based stations and have significant implication for optimizing future monitoring efforts in a harsh field environment. First, we explore these records for characterizing the temporal and spatial evolution of the flank eruption on 22 May 2021 (Figure 19). In a second step, we show evidence of the infrasonic rumbling of a nascent lava lake starting a few months later detected up to the volcano observatory facilities in Goma city center about 17 km from Nyiragongo's crater. This particular result was presented at the "Cities On Volcanoes" conference in June 2022 and is part of an article in preparation. We detail below some characteristics of the infrasound record during the flank eruption.

On 22 May 2021, the third known flank eruption in Nyiragongo's history followed the patterns of the two previous ones in 1977 and 2022: the draining of the long-lived lava lake within the crater was accompanied by lava flows from several eruptive fissures on its southern flank toward

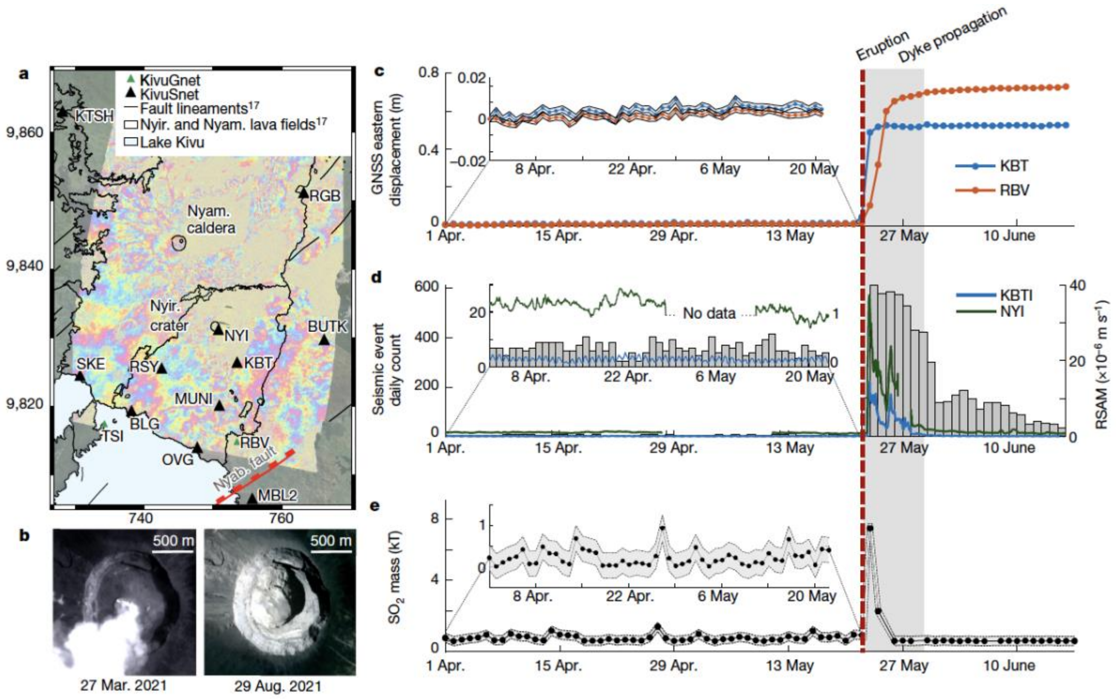


Figure 18 *(Smittarello et al., 2022, Nature)*: Absence of precursory signals. (a) COSMO-SkyMed (CSK) interferogram from 21 May 2021 at 15:37 UTC to 22 May 2021 at 15:37 UTC showing no obvious deformation less than 1 h before the eruption starts. Coordinates are given in kilometres in the WGS 1984 UTM (Zone 35S) system. (b) PlanetScope46 image comparison of Nyiragongo Crater between 27 March 2021 and 9 August 2021. (c) Daily eastern displacements recorded at KBT (blue) and RBV (orange) permanent GNSS stations (see location on map a) from 1 April 2021 to 30 June 2021. Error bounds represent 2 standard errors. (d) Daily count of seismic events automatically detected and located (fulfilling selection criteria defined in the Methods) from 1 April 2021 to 30 June 2021 and 12-h moving median of real-time seismic amplitude measurement (RSAM) filtered between 2 Hz and 10 Hz at NYI (green) and KBTI (blue) permanent seismic stations. Note that the KBTI station is co-located with the KBT GNSS station. (e) SO_2

mass automatic detection from TROPOMI over the Virunga region. Error bounds represent 2 standard errors.

Goma. KBTI station is equipped with three close sensors, which were all functional during the flank eruption. This is the minimal configuration for retrieving the direction of arrival (DOA) and apparent velocity (V_{app}) of coherent waves passing through the three-element array using standard beamforming analysis. Lava fountaining and lava flows were first reported west of KBTI, corresponding to the main eruptive fissures mapped afterwards. According to abnormal infrasound signals, the eruptive sequence began at the sunset on 22 May around 16:50 UTC (local time minus 2 hours) and lasted ~6 hours.

We provide in Figure 19 a more detailed understanding of the flank eruption thanks to array processing. Lava flows are color coded according to all possible DOA from the eruptive fissures to the west (named *F1* to *F4*) between 0° (north) and -180° (south). Intra-crater activity (named *C*) corresponds to DOA colored in black. In the specific timeframe of the eruption, we apply a grid-search strategy for finding the DOA of direct waves, which is best suited to three-element small aperture array than beamforming (Yamakawa et al., 2018). Potential sources (crater, eruptive fissures) are in line-of-sight with the station with low incident angles (<15°) and at distance greater than two infrasonic wavelengths (> 1 km) at 1 Hz. We can thus assume sub-horizontally plane wave propagation to the array with apparent velocity close to the group velocity (i.e., V_{app} ~340 m/s). Arrivals from the main crater may cover an angle aperture up to 16°, which overlap potential sources from the most elevated fissure *F1*. The chronology of the eruption is easily deduced from the observed variation of DOA (Figure 19).

Reference:

Yamakawa, K., M. Ichihara, K. Ishii, H. Aoyama, T. Nishimura and M. Ripepe (2018). Azimuth Estimations from a small aperture infrasonic array: test observations at Stromboli volcano. Geophys. Res. Lett., 45, 8931-8938, doi: 10.1029/2018GL078851.

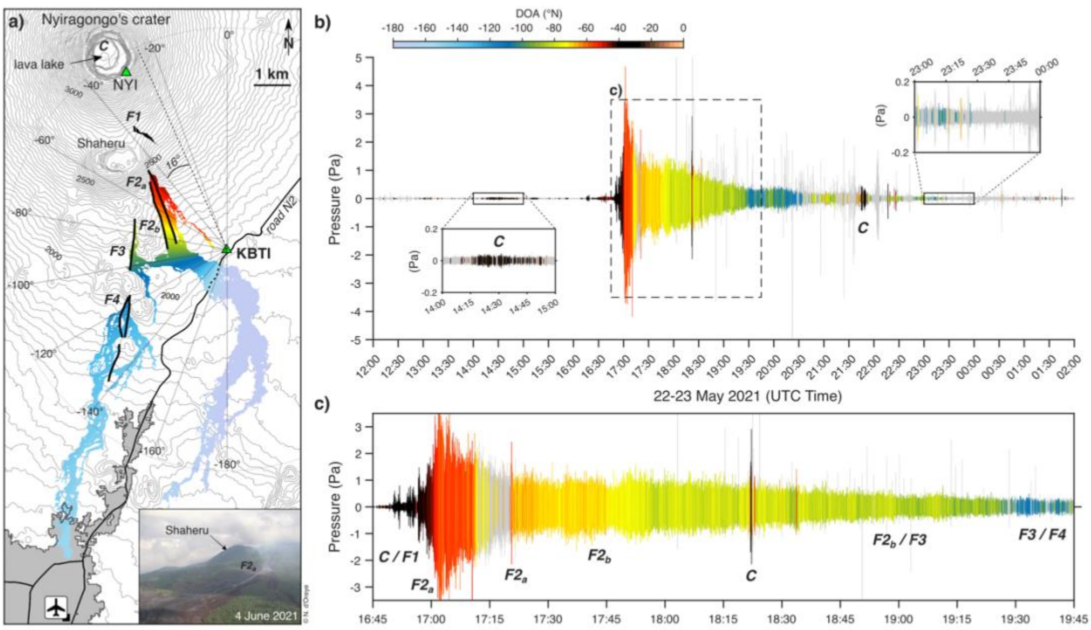


Figure 19: a) Map of eruptive fissures and lava flows (colored according to DOA at KBTI) during the May 2021 flank eruption. Contour levels are expressed in m a.s.l. The gray area correspond to the urban environment (north of Goma) and the thick black lines are the main roads. A picture taken from helicopter on 4 June 2021 (13 days after the eruption) showing the Mount Shaheru and the main fissure F2a is also depicted. b,c) Infrasound signal recorded at one element of the KBTI array. After processing, the meaningful part of the recording related to the eruptive signals than can associated to DOA are colored with the same color code than in Figure 19a.

Remote Sensing, Volcanology and Ground Deformation

❖ Running projects and objectives

In the context of the Remote Sensing & Ground Deformation research carried out at ECGS/Mnhn in 2022, we were involved the following projects:

- **VERSUS: Open-Vent Volcano Remote Sensing Monitoring Using Spaceborne Imaging,** 01/07/2019 - 31/12/2021 (Belspo)
- **HARISSA: Natural hazards, risks and society in Africa: developing knowledge and capacities,** 01/05/2019 - 30/04/2023 (Direction Générale de la Coopération au Développement, Belgium)
- **ECTIC : Environmental Changes Tracking using ICEYE Constellation,** 2020 - 2022 (ESA, Belspo)
- **NSF-Crater-Floor: Modeling of crater floor deformation in relationship with lava lake activity,** 2020 - 2023 (NSF, USA)
- **GERMANE: Ground Deformation from Meteorological, Seismic and Anthropogenic Changes Analysed by Remote Sensing, Geomatic Experiments and Extended Reality** (ESA)

In a nutshell, these projects aim at the following:

VERSUS aims at getting insights into the dynamics of persistent lava lakes and the underlying magmatic processes, from the complementary use of UV, visible, IR and radar satellite imagery coming from the most recent generations of satellites and sensors. It uses state-of-the-art volcano remote sensing techniques and applies them to the most recent satellite imagery (Sentinel-1, Sentinel-2 MSI, Sentinel-3 SLSTR, Sentinel-5P TROPOMI, Suomi NPP VIIRS, Landsat 8 OLI, PlanetScope and COSMO-SkyMed), in order to complement classical geophysical ground-based monitoring techniques and improve our understanding of volcanic and crustal magmatic processes. Classical and pre-eruptive (i.e., before a flank eruption) lava lake activity will be studied thanks to the selection of two case studies that ensure the availability of ground-based monitoring data as complement or validation sources: Kilauea volcano (Hawaii, USA) and the active Virunga volcanoes (D.R. Congo).

HARISSA is a 5 years project between RMCA and the Belgian Development Cooperation aiming at 1) supporting local training and education at the level of PhD's and Masters, 2) supporting local actors in the risk management domain, 3) supporting/developing natural risks awareness and 4) sustainability of former achievements (local monitoring networks, analysis tools..). Local partners are: Centre de Recherche en Sciences Naturelles de Lwiro (CRSN, DRC), Mbarara University of Sciences and Technology (MUST, Ouganda), Institut Géographique du Congo (IGC-KIN, DRC), Observatoire Volcanologique de Goma (OVG, DRC), Protection Civile du Sud-Kivu, (PC-SK, DRC), Université Officielle de Bukavu (UOB, DRC), Protection Civile du Nord-Kivu (PC-NK, DRC), Université de Goma (UNIGOM, DRC), Université du Burundi (UB, Burindi) and Institut Géographique du Congo – Goma (IGC-NK, DRC).

ECTIC aims at testing ICEYE SAR imagery targeting two main applications: 1) the aptitude of ICEYE SAR products for height change detection by tracking SAR shadow changes through time series, 2) the aptitude of ICEYE products in vessel detection and deforestation detection. Aside of the ESA project that makes the image freely available, the project was supported in 2021 by a 6 months BELSPO share-cost project.

NSF-Crater Floor 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 will be 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.

GERMANE is a project which intend to analyse ground deformation hazards induced by meteorological changes and seismotectonic conditions in eastern Belgium, western Germany and the south-eastern Netherlands. Thus, its outcomes should also be of interest for the ongoing Interreg project Einstein Telescope EMR Site & Technology (E-TEST). Focus is on the differentiation of weather-induced and seismotectonically influenced Earth surface processes in the E-Test area where human-induced groundwater level changes are also observed. Note that we are not officially (funded) member of that project, though we collaborate by providing the data processing and assisting to their interpretation.

The main partners of ECGS/Mnhn in these projects are:

- Royal Museum for Central Africa (RMCA), Belgium
- Laboratorio de Estudio y Seguimiento de Volcanes Activos, Instituto de Investigación en Paleobiología y Geología, Universidad Nacional de Rio Negro, Argentina
- Centre Spatial de Liège (CSL), Belgium
- Royal Belgian Institute for Space Aeronomy (BISA), Belgium
- Natural Ressources Canada (NRC), Canada
- Univ. of Iceland (UI), Iceland
- Icelandic Meteorological Office (IMO), Iceland
- Penn State University (PSU), USA
- Vrije Universiteit van Brussel (VUB), Belgium
- Observatoire du Piton de la Fournaise (OPF), Ile de la Réunion, France
- European Space Agency (ESA)
- German Space Agency (DLR)
- Italian Space Agency (ASI)
- Japan Space Agency (JAXA)
- Canadian Space Agency (CSA)

❖ Project achievements in 2022

The SaSHA method, using SAR shadows cast by subvertical structures to measure the height of these structures, was successfully applied to measure the lava lake level and crater depth of Nyiragongo. The time series was automatically updated as soon as new SENTINEL-1 and CSK images were made available. The complete data set of SENTINEL-1 and COSMO-SkyMed images was complemented with ENVISAT and RADARSAT SAR archives (1703 SAR images in total). The whole time series, which was analysed along with high resolution photogrammetric DEM, allowed to study the inter-eruptive activity at Nyiragongo, from 2003 to 2021 (Figure 20).

The processing of the SAR images was performed with the MasTer Toolbox (Derauw et al. 2020, d'Oreye et al. 2021). The method and the main results were published in a paper by Barrière et al. (2022) in the Journal of Geophysical Research. The main findings can be summarized as follow:

- Both photogrammetry and SAR-based methods show that the depth of the crater after its drainage during the 2002 eruption was ∼590 m. This strongly contrasts with some values encountered in the literature (e.g., 945 m estimated by Tedesco et al., 2007). This of course has an important impact on models based on estimation of lava accumulated within the crater during the inter-eruptive activity.

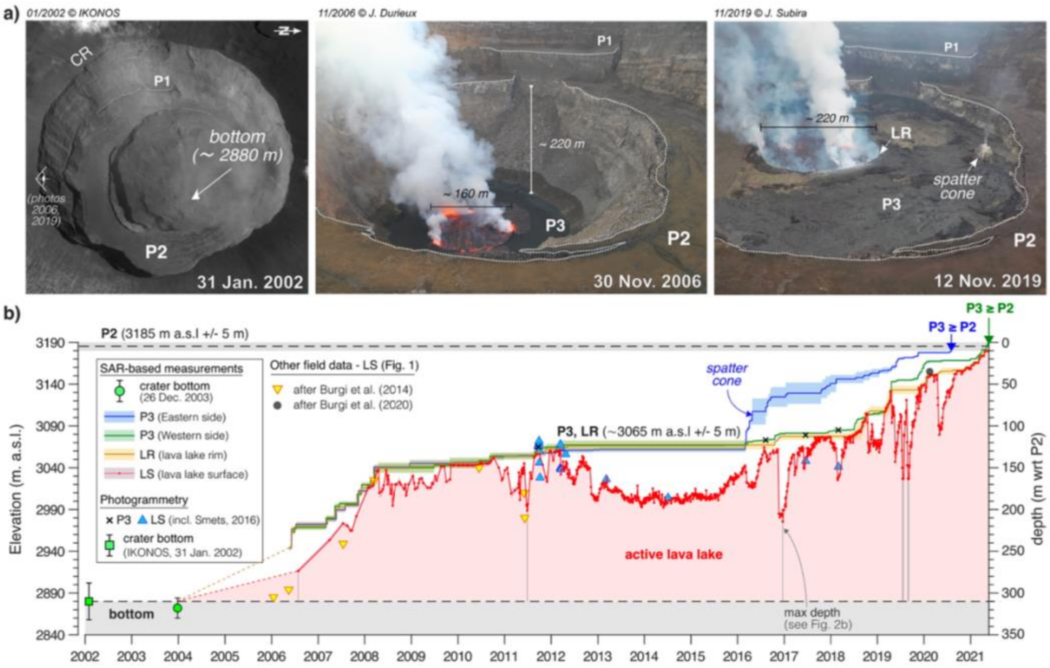


Figure 20 *(Barrière et al., 2022, JGR)*: (a) A single IKONOS image acquired on January 31, 2002, 9 days after the crater collapse, and 14 days after the flank eruption. Two pictures of Nyiragongo's inner crater over a span of 13 years, on November 30, 2006 (courtesy of J. Durieux) and November 12, 2019. (b) Topographic changes at Nyiragongo's crater: altitude of crater floor (P3), lava Lake Rim (LR), and lava Lake Surface (LS). Shaded area around satellite measurements' curves corresponds to error margins. Photogrammetry-based lava lake and level measurements (Smets, 2016; Barrière et al. 2022) are plotted with blue triangles and cross symbols, respectively. The elevations of the crater bottom estimated on January 31, 2002 and December 26, 2003 are depicted as round and square green markers with error bars, respectively. Estimates from Burgi et al. (2014, 2020) are plotted with yellow inverted triangles and a black round marker.

- The filling of the crater by lava, initiated in 2002 and continued up to May 2021, is seen as evidence of a long-term pressure build-up of the magmatic system. This filling occurs through irregular pulsatory episodes of rising lava lake level, some of which overflow and solidify on the surrounding crater floor. Pauses of stable molten lava lake level and sudden numerous level drops also marked the summit's eruptive activity.
- The joint analysis with seismic records available since 2015 revealed that the largest lava lake drops are synchronous with seismic swarms associated with deep magma intrusions, generally preceded by an increase of extrusion rate within the crater.
- The appearance of a spatter cone in the summit crater in 2016, most likely superficially branched to the lava lake, was a clear marker of the change in eruption dynamics.
- The lava accumulation rate within the crater from 2016 to the 2021 eruption was similar to the accumulation rate measured in 2007-2008 (Figure 21).

The lava lake was, however, drained during the May 2021 eruption and the crater partly collapsed (Smittarello et al. 2022). It became so deep that the bottom appeared in the layover region of the SAR images, preventing the use of the SaSHA method (Barrière et al. 2022). As a result, a new method was developed for estimating the collapse crater area and depth, assuming an idealized circular shape of the summit caldera rim (blue circle/ellipse in Figure 22) and crater edge (red circle/ellipse in Figure 22). The semi-axes of the ellipses, and the location of the crater edge, center and bottom, were all determined manually with an in-house interactive picking tool and the corresponding values are used to derive the crater area and depth according to simple trigonometry (Figure 22). The method was applied on 41 SAR images acquired by 7 different satellites

(SENTINEL-1, COSMO- SkyMed, SAOCOM, TERRASAR-X, ICEYE[3], CAPELLA and RCM) to measure the evolution of the crater during the 2021 Nyiragongo volcanic crisis (results and method will be described in a paper in preparation). The analysis of these data along with several other ground based and space borne data allowed us to unravel the mechanism of the May 2021 eruption (Smittarello et al. 2022) (section above, page 19).

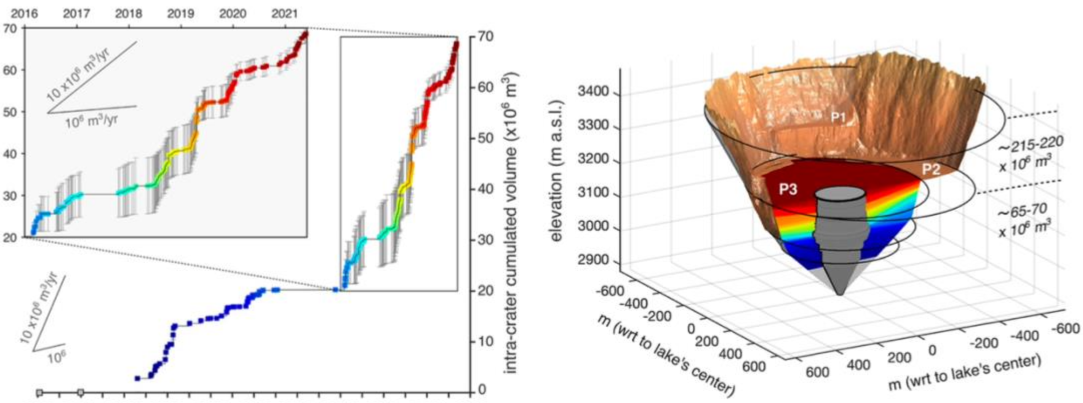


Figure 21 (*Barrière et al. 2022, JGR*): Left: Time series of the total intra-crater accumulated volume (including the lava lake). Error bars correspond to the uncertainty about the volume accumulated between the western and the eastern sides of the crater, which are large between 2016 and 2019 since only the highest section of the cone is illuminated on the eastern side. Right: Filling of Nyiragongo crater by lava (same colour code as left panel) from 2002 eruption until March 2021, plotted on DEM cross-section obtained from UAV-based photogrammetry model taken on August 8, 2016 (brown surface).

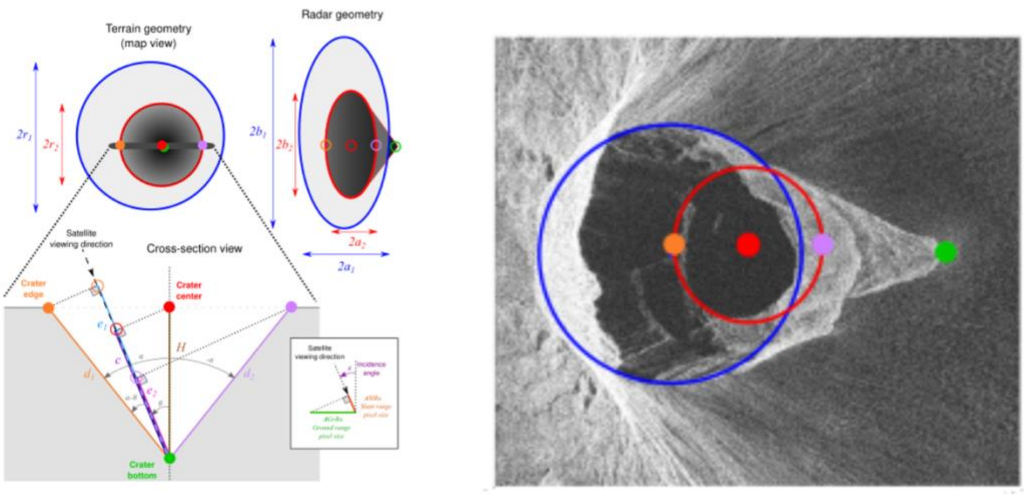


Figure 22: Left: SAR trigonometry to measure the crater depth on SAR images based on the position of the crater centre and crater shape as seen in radar geometry assuming a symmetrical conical shape (Smittarello et al., in prep.). Right: example of SAR amplitude image taken on May 28 2021 (ICEYE satellite) showing the collapsed crater and its bottom imaged in the layover region. Coloured features are used to measure the depth following the trigonometry shown in the left panel.

[3] The processing of the ICEYE data required the development of a specific software to read these data. That data reader was developed by Dominique Derauw in the frame of the ECTIC project and integrated and tested in the MasTer toolbox developed at ECGS.

The lava lake level and the crater ground level time series also allowed to build an analytical model able to explain and reproduce (at least at a first order) some of the main characteristics of the lava lake level behaviour (Walwer et al. submitted), that is a linear rise of the lava lake level sporadically interrupted by sudden drops followed by slow recoveries. The model also highlights an interesting mechanism of top-down control that the lava lake has onto the deeper part of the plumbing system. The simplified model considers a central reservoir fed by a constant flux of magma that distributes 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.

More SAR images acquired over Nyamulagira crater (SENTINEL-1 and COSMO-SkyMed) were also prepared automatically using the MasTer Toolbox. However, they were not processed using the SaSHA method. Indeed, the crater shape and depth at Nyamulagira is often too deep to be measured automatically. The same method as the one used for the Nyiragongo crater during the 2021 volcanic crisis was used to manually analyse 1418 images (319 ascending CSK, 603 CSK descending, 306 S1 ascending and 190 S1 descending) and produce a first draft time series that need to be further verified, cross-checked and analysed along with other ground-based and space-born data.

❖ Further development of the MasTer SAR and InSAR tools

In the frame of these several research projects, we carried out the development of our home-made InSAR time series toolbox (**MasTer: InSAR Mass processing Toolbox for Multidimensional time series**). MasTer is able to automatically download SAR data, select the appropriate interferometric pairs, perform the interferometric mass processing, compute the geocoded deformation maps, invert and display the velocity maps and the 2D time series on a web page updated incrementally as soon as a new image is made available. MasTer also allows the production of time series of coherences or SAR amplitude images, which can be used e.g., for land use monitoring or geomorphological changes detection.

Among others, MasTer benefitted from the following main improvements:

- Development of a recursive unwrapping module, which was mandatory to properly unwrap the huge deformation gradients observed during the 2021 eruption at Nyiragongo.
- Development of an optimization module for selecting the compatible InSAR pairs. The method was published in a paper by Smittarello et al. (2022) in Journal of Geophysical Research.
- The additional capability to process ICEYE data the same way as any other sensor in the processing chain.
- The development of an automated installer (compatible with Linux and Mac).
- The ability to convert any DEM provided in Geotiff or Envi format that would be referenced to the geoid in the specific format expected by MasTer and referenced to the ellipsoid.
- The distribution of all the necessary material (documentation, installer, scripts, MSBAS source code, and MasTer Engine binaries) through a single GitHub account accessible upon request to the authors.
- Further improvements of the manual (including for the installation and setup of the web page).

This, and several other minor improvements represented 340 new contributions to the development GitHub account and 37 modifications of the MasTer Engine. These last modifications were performed by Dominique Derauw (Univ. Rio Negro, Argentina) and are mostly aiming at improving the creation of DEM, the geocoding and several additions or improvements in the data readers.

In 2022, MasTer was routinely used for the fully automatic processing (from image download up to the creation of ground deformation time series and maps, and displaying the results on interactive web page) in the following regions:

- The Virunga Volcanic Province (Nyiragongo and Nyamulagira volcanoes)
- The Argentina-Chile border (Laguna del Maule and Domuyo volcanic regions)
- The La Réunion Island (Piton de la Fournaise volcano and 3 main landslide regions in the North of the island)
- The Comores Island (Karthala volcano)
- The Guadeloupe Island (La Soufrière volcano)

Additional processing (without automatic updates) was also performed on demand for several applications such as landslides monitoring (e.g., in South Kivu), ground subsidence related to permafrost changes (Mongolia), seismic crisis (Chambon-sur-Lac, France) or geological stability (Belgian-NL-German border). Some of these results were used in published paper (Dille et al. 2022, Deijns et al. 2022), while others are in preparation.

End of 2022, thanks to a new storage server, we also started to complete the reprocessing of the whole data base (from raw data reading to time series inversion) in order to benefit from the recent improvements and obtain the most accurate results. This will include the reprocessing of the Greater Region that was on hold due to storage shortage.

Figure 23 shows 20 years of ground deformation at Nyamulagira volcano (DRC), illustrating the unique capability of MasTer to produce very long ground deformation time series (regardless of the satellite's life time) combining ~2.000 SAR images of all data types (regardless of the satellite's ground resolution, polarization, frequency band…).

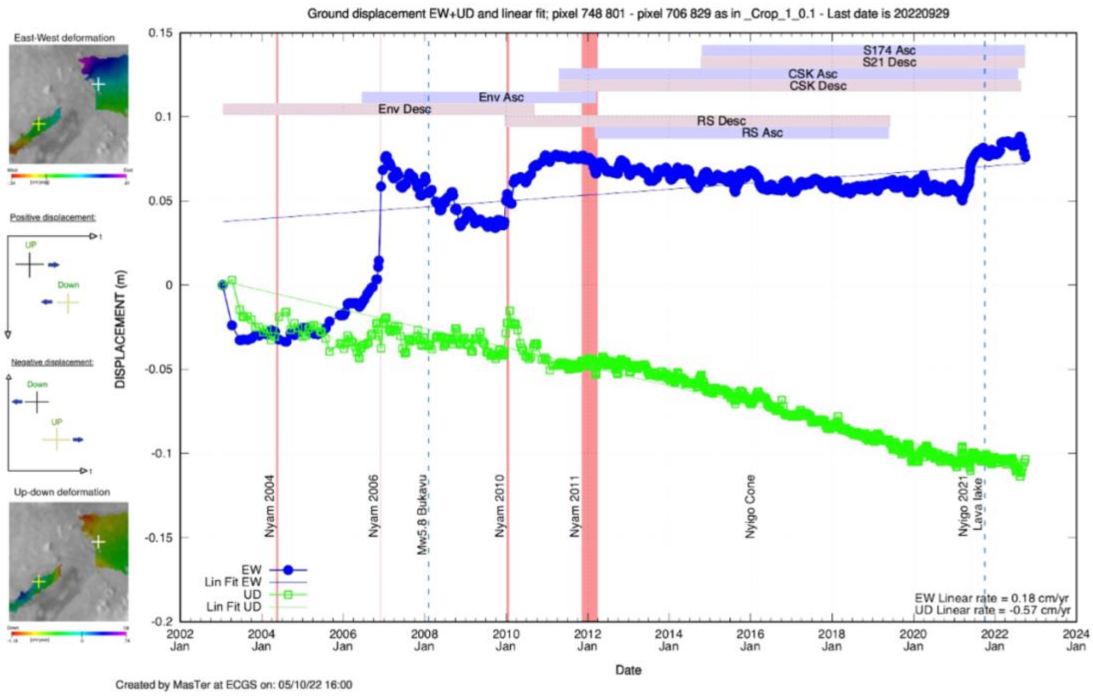


Figure 23: Example of double difference ground deformation measured with MasTer Toolbox in vertical (green) and East-West (Blue) components from 2003 to October 29 2022 based on ~2.000 images (ENVISAT, RADARSAT, COSMO-SkyMed, SENTINEL-1) used to produce ~13.000 interferograms. The deformation curves show the relative displacement between two pixels located on the flank of the Nyamulagira volcano (see their location as white and yellow crosses in the insets on the left. Upper and Lower insets show respectively the EW and Vertical mean linear velocity wrapped on DEM; decorrelated areas due to equatorial vegetation were masked). Direction of displacement is explained by the sketches on the left (e.g., a negative sign on the green curve means that the white cross goes downward compared to the

yellow cross). Vertical red lines mark the timing of the eruptions at Nyamulagira and Nyiragongo. Red and Blue shaded rectangles on the top of the plot indicate the satellites used to compute the time series.

Process. chain	(InSAR processor)	All sat. inc. S1 SM	Combine sat.	Atmo corr	S1 WS stitching	automatic	Parrallelized	Pair selec. optim.	Ampli-Coh TS	Incremental	Auto-eval.	Free	Web - GIS	PS	SBAS	2/3 D	Enh. Spect. D.	Coh Threshold	Gap proof	Coh. Proxy	Ref
MasTer	(MasTer Engine)	V	V	X	V	V	V	V	V	V	V	V	V	X	V	V	X	V	V	V	(Derauw et al. 2020) (d'Oreye et al. 2021)
LiCSBAS	(Gamma)	?	X	V	?	V	?	3	X	V	V	V (X)	V	X	V	X	V	V	Lin	X	(Morishita et al. 2020) (lazecky et al. in prep.)
MOUNTS	(SNAP)	X	X	X	X	V	X	X	V	V	V	V	V	X	X	X	?	X	X	X	(Valade et al. 2019)
SARVIEWS	(Gamma)	X (V)	X	V	V	V	?	1	V	X	?	? (X)	V	X	X	X	?	X	X	X	(Meyer et al. 2019)
OSARIS	(GMTSAR)	X (V)	X	V	V	V	V	1	V	V	V	V	V	X	X (V)	X	V	V	X	X	(Loibl et al. 2019) (Sandwell et al. 2016)
MTInSAR	(PSIG @ CTTC)	X (V)	X	Filt	?	V	?	V	?	X	?	X	?	X	V	V	?	?	?	X	(Palama et al. 2022) (Devanthéry et al. 2014)
SNAP-StaMPS	(SNAP)	X	X	V	V	V	?	X	X	X	?	V	?	V	X	1D	V	X	X	X	(Delgado Blasco et al. 2019) (Foumelos et al. 2018)
P-SBAS / GEP		X	X	V	X	V	V	3	X	X	?	?	V	X	V	V	V	X	?	X	(Cigna & tapete, 2021) (De Luca et al. 2018)
FLATSIM-NSBAS	(ROI_PAC)	X(V)	X	V	X	V	V	V	C	?	V	?	V	X	V	X	V	X	?	X	(Thollard et al., 2021) (Doin et al. 2012)
MintPy	(ROI_PAC, ISCE, GAM.)	V	X	V	V	?	V	V	X	?	V	V	X	X	V	X	?	V	?	X	(Yunjun et al. 2019)
SqueeSAR®	(ALTAMIRA)	X	X	?	?	V	V	?	?	V	?	X	?	V	X	V	?	?	?	?	(Raspini et al. 2018) (Bischoff et al. 2020)

Table 1: Comparison of illustrative MasTer capabilities with some other InSAR mass processing chain.

The comprehensive capabilities of MasTer and its agility, universality and automation capabilities (see table 1 for tentative – unexhaustive- comparison with other processing chains), make it very interesting for the InSAR community, as attested by the invitation for a keynote presentation at the "MDIS-2022 / Deformation Measurements by Earth Observation Techniques" meeting.

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. In 2020, the data from the STS-2 very broadband seismometer were again 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.

Continuous radon (Rn) measurements in the Laboratory and the entrance gallery are also performed. These data, along with the very long data base already acquired over the previous decades, allow for a continuous monitoring 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).

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. The ITM proposed to carry 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 will be carried out in early 2023.

As a result, so far, 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 2022

Prof. em. Antoine Kies

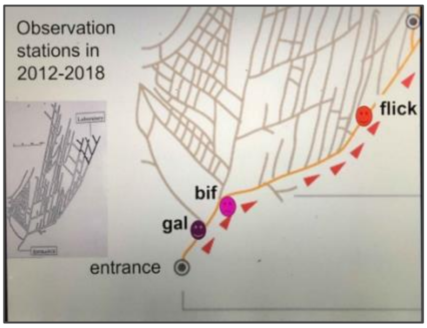


Figure 24: Radon observation sites in WULG.

We report from radon data recorded continuously in the mine at two locations (Figure 24):

- '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, 2022 was, after 2021, again an exceptional year: Since 1992 we measure radon in the mine and

- radon levels were never as low as over the summer 2021,
- whereas they were never as high as in 2022.

Figure 25 shows summer radon mine levels in 2022 twice the level of 2021. For the explanation of the low radon levels in 2021 please refer to the 2021 report.

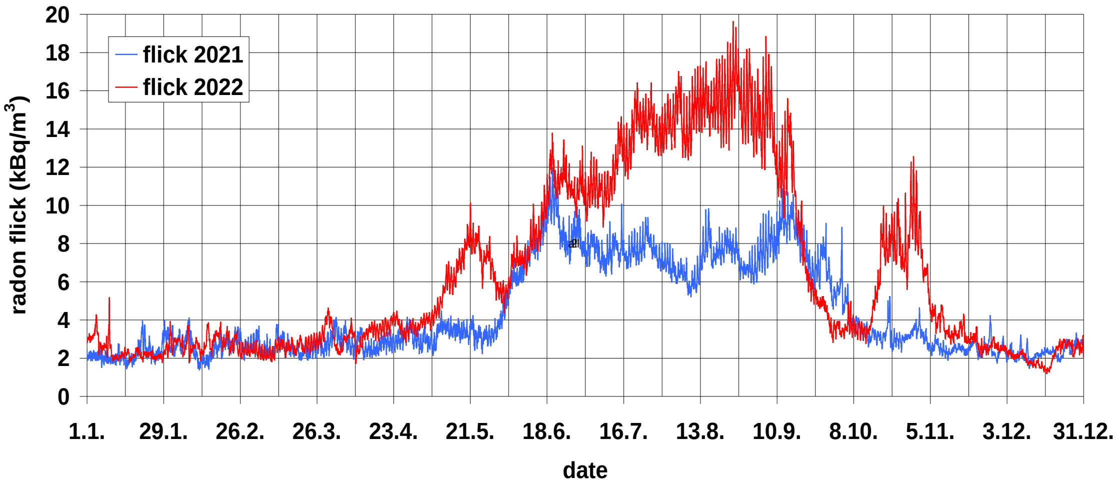


Figure 25: Radon concentration at 'flick' during the years 2021 and 2022.

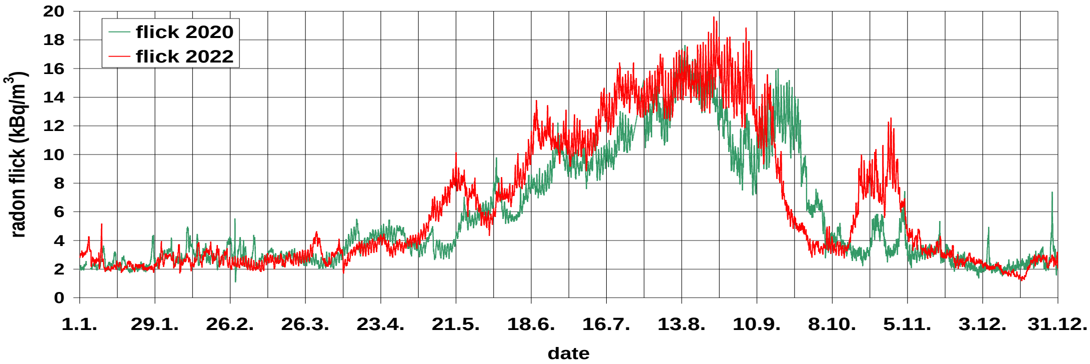


Figure 26: Comparison of radon concentrations at 'flick' over the years 2020 and 2022. Note their similarity and typical behaviour for hot summers.

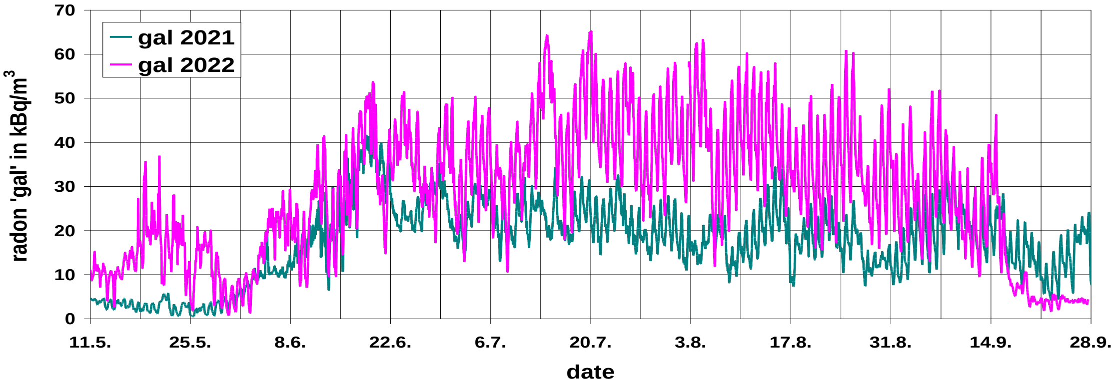


Figure 27: Radon concentration at 'gal' over the years 2021 and 2022.

Let us remind some Walferdange mine basics as noted over the past years: without mine air movements, the temperature in the mine is stable, slightly above 10 °C (blue lines in Figures 28 and 29). Radon measured in the air of the mine, at station 'flick' has two contributions: one stable contribution (around 2.5 kBq/m^3) due to radon supplied continuously by the rocks of the mine and one variable resulting from the radon transported by air movement from 'gal' into the mine.

In Figure 27 the summer radon levels at 'gal' are shown for the summer period in 2021 and 2022. In 2022 the radon source was twice more important compared to 2021, and thus also the amount of radon transported into the mine.

The radon concentration at 'gal' is highly influenced by the external temperature that dictates air movements in the partly collapsed lateral gallery ending at the 'gal' point. The more the outside temperature exceeds the critical value of 10 °C, the more radon charged air reaches the 'gal' point and enters the mine interior. At temperatures near and below 10°C, the direction of air movements in the source gallery is stopped and reversed; no radon enters the mine at 'gal' and eventually radon-free air reaches 'gal' from the entrance.

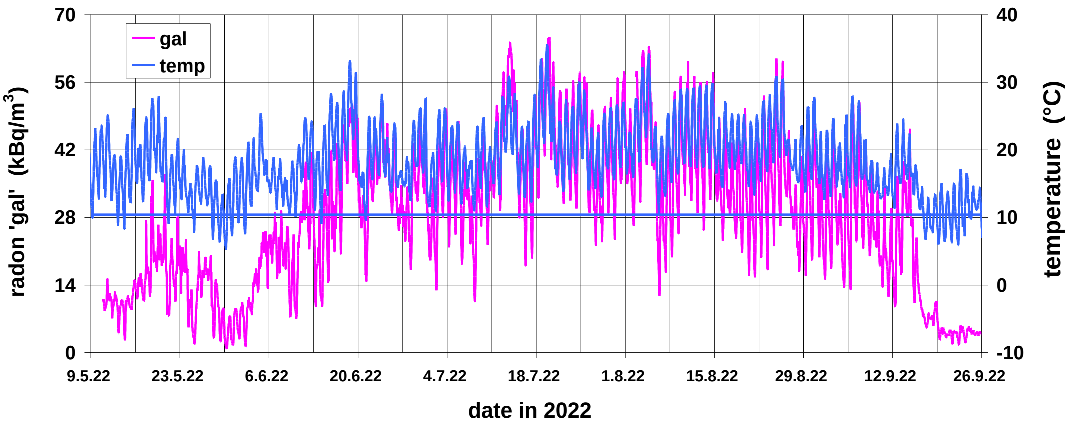


Figure 28: Radon concentration at 'gal' and outside temperature.

Figure 28 shows the interplay between atmospheric temperature and radon levels measured at the 'gal' point for the hottest part of the summer 2022. The higher the outside-inside temperature gap, the more radon levels increase, especially during the night. Atmospheric temperature and radon vary in phase.

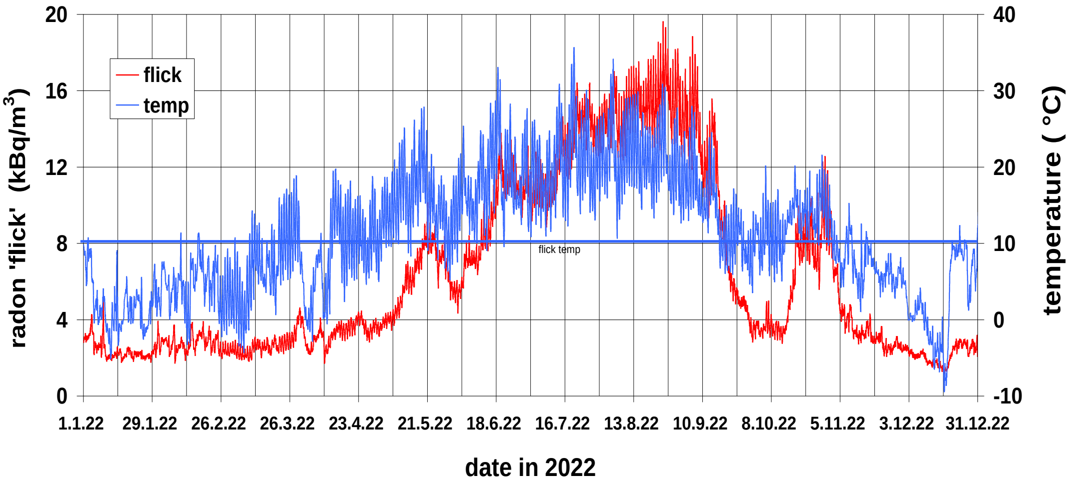
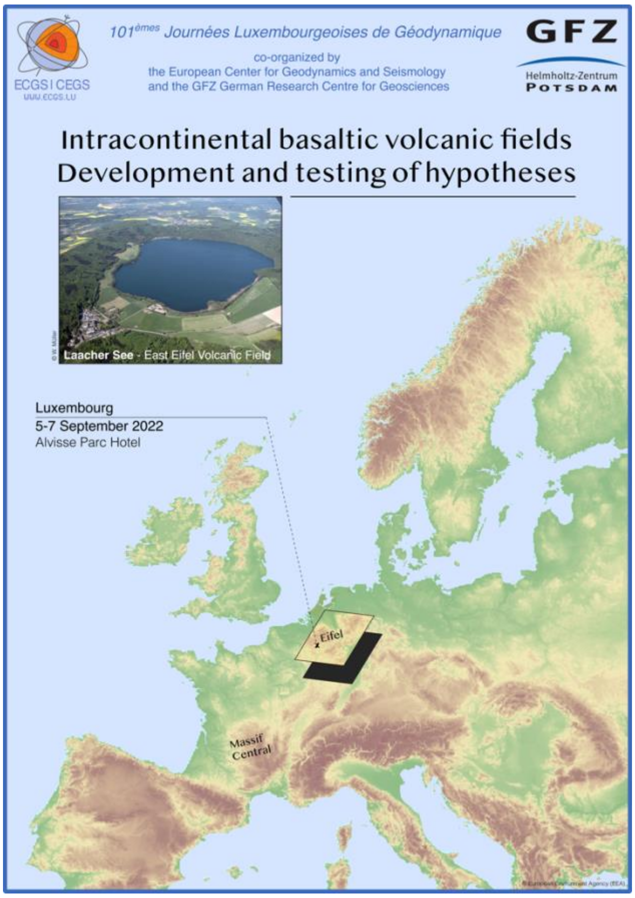


Figure 29: Radon concentration at 'flick' and outside temperature.

Figure 29 shows the radon concentration within the mine ('flick') and atmospheric temperature. The continuous high temperatures over a long time span induce the high radon concentrations in the mine. The rapid drop of temperature to values around the mine temperature in mid-September stops all radon supply and radon levels become low before being reactivated during the 'Indian Summer' with temperatures well above 10 °C.

The author thanks Dr. Joerg Bareiss MeteoLux and for the meteorological data. He also expresses his gratitude to the organisation in charge of the Walferdange former gypsum mine, for the permission to carry out the measurements in the mine.

101st JOURNEES LUXEMBOURGEOISES DE GEODYNAMIQUE



After a 2-years break imposed by the Covid-19 pandemic, ECGS could finally organise the 101st edition of its meeting series *Journées Luxembourgeoises de Géodynamique* (JLG), held from 5-7 September 2022 in Luxembourg. The JLG serve as a platform for scientists throughout the various disciplines of the Earth Sciences to meet and discuss in a rather informal setting in order to foster international collaboration.

This 101st edition of the JLG was dedicated to the subject of **Intra-continental basaltic volcanic fields** and was co-organised between the GFZ German Research Centre for Geosciences and ECGS. In western Europe, two such significant volcanic systems, the Eifel Volcanic Field (EVF) in Germany and the Massif Central in France, are presently considered active, although none of them has erupted in historical times. In particular in the EVF, signs of unrest such as earthquakes typical for volcanic environments and significant surface uplift have been detected in recent years. These observations raise important questions on the underlying processes and potential consequences, highlighting the need for an in-depth study of these systems.

The 101st JLG meeting placed itself in the context of the major scientific initiative led by the MAARE[4] consortium in Germany. While the focus region of the meeting was therefore naturally the near-by Eifel Volcanic Field (EVF), the meeting aimed at fostering a holistic view on this type of volcanic systems in general, including all relevant disciplines such as geophysics, volcanology, geodesy, geochemistry, geochronology, geology, petrology, etc.

Conveners

- Prof. Dr. Torsten Dahm, GFZ
- Dr. Adrien Oth, ECGS
- Dr. Christoph Sens-Schönfelder, GFZ
- Dr. Julien Barrière, ECGS
- Prof. Dr. Axel Schmitt, U. Heidelberg

Local Organizing Committee

- Dr. Adrien Oth
- Marie-Jo Maciel
- Corine Galassi
- Dr. Julien Barrière
- Dr. Delphine Smittarello
- Gilles Celli

[4] https://www.uni-potsdam.de/de/maare/index

The 101st JLG gathered 42 participants from 7 countries at the Alvisse Parc Hotel in Luxembourg to discuss these questions and the ways forward in the study of these systems, including 26 oral and 8 poster presentations, with a keynote lecture from G. De Natale on *"The Campi Flegrei Deep Drilling Project: Advancing volcanological research despite fake news of an apocalypse"*. The meeting was followed by the first deployment wave of the temporary seismological stations in the Eifel in the framework of the Large-N seismological experiment[5] led by the GFZ (see for instance), to which ECGS contributes 5 broadband stations.

More information and the full scientific programme can still be found on the website[6] of the meeting.

101st JLG programme in a nutshell

Sunday 4.9: Arrival of participants, "ice breaker"

Monday 5.9: **Research questions on the Eifel and basaltic volcanic fields in general**

- Welcome by GFZ/ECGS representatives
- State and evolution of transcrustal magmatic reservoirs at different depths
- Migration of magmatic fluids and triggering of reservoir unrest
- Spatio-temporal control of volcanism in low-flux systems
- Multi-scale monitoring of volcanic fields and precursory signals

Tuesday 6.9: **Ideas – Experimental approach and research visions**

- Joining forces between disciplines: geophysics, geochemistry, volcanology and more
- Eifel Large-N experiment: methods, data and aims
- Discussion on proposal ideas
- Think tank working groups A-C
    a) SWOT of an ICDP drilling project / workshop proposal – go or not-to-go?
    b) Large-N Seismology: maximal output with minimal funds – how to reach?
    c) A distributed, integrated Eifel Volcano Observatory – how to construct?

Wednesday 7.9: **Conclude**

- Report and plenary discussion of outcomes from working groups
- Keynote lecture by G. De Natale: *The Campi Flegrei Deep Drilling Project: Advancing volcanological research despite fake news of an apocalypse*

[5] https://www.gfz-potsdam.de/sektion/erdbeben-und-vulkanphysik/projekte/eifel-vulkanseismologisches-experiment
[6] https://www.ecgs.lu/101st-jlg/

OUTREACH ACTIVITIES & MEDIA COVERAGE

General outreach activities

- School class visit in Lycée Ermesinde Mersch (classe 6C2) by A. Oth, discussing about earthquakes and volcanoes (1 March 2022).
- RTL Radio Feature Interview: *Ennerschätze mir d'Gefor vu Vulkaner?* featuring A. Oth (22 August 2022), https://www.rtl.lu/radio/feature/s/4093277.html.
- RTL Radio Reportage: *Nei Insel entdeckt bei Tonga am Pazifik* featuring A. Oth (3 October 2022), https://www.rtl.lu/radio/reportage/s/4145071.html.

Nature paper on the 2021 Nyiragongo eruption

On the invitation of Nature Portfolio Earth and Environment, we published a **web story** in their category *Behind the paper* to provide more insights to the reader on the context leading to the Nature paper. This webstory can be found here:

https://earthenvironmentcommunity.nature.com/posts/volcanic-precursors-and-eruptions

The nature paper was also **accompanied by a News and Views article** by Emily K. Montgomery-Brown from the Unites States Geological Survey to be found here:

https://www.nature.com/articles/d41586-022-02347-x?utm_medium=Social&utm_campaign=nature&utm_source=Twitter#Echobox=1661964136

Media coverage of the Nature paper including interviews (mostly with lead author D. Smittarello) was very extensive, with a large number of news articles around the World. Here we just list the most noteworthy ones.

- National Geographic: to be published
- Axios: https://www.axios.com/2022/09/01/volcano-eruption-warnings-signs-explained
- Science News: https://www.sciencenews.org/article/volcano-eruption-deadly-warning-nyiragong-congo
- New York Times: https://www.nytimes.com/2022/09/02/science/nyiragongo-volcano-eruption.html?smid=nytcore-ios-share&referringSource=articleShare
- CNRS INSU: https://www.insu.cnrs.fr/fr/cnrsinfo/une-eruption-volcanique-sans-precurseurs-clairs-ca-peut-se-produire
- Spektrum der Wissenschaft: https://www.spektrum.de/news/vulkan-warum-der-nyiragongo-ohne-vorwarnung-lava-spuckte/2053137
- Frankfurter Allgemeine Zeitung: https://www.faz.net/aktuell/wissen/erde-klima/ostafrika-vulkan-nyiragongo-wurde-zur-katastrophe-ohne-vorwarnung-18294596.html
- Smithsonian Magazine: https://www.smithsonianmag.com/smart-news/how-a-volcanic-eruption-caught-seismologists-by-surprise-180980704/
- Science.lu: https://science.lu/de/geowissenschaften/luxemburger-forscher-federfuehrend-bei-wichtiger-vulkan-studie
- La Libre Afrique: https://afrique.lalibre.be/72264/rdc-leruption-du-volcan-nyiragongo-ne-pouvait-etre-predite/
- Mediacongo.net: https://www.mediacongo.net/article-actualite-109987_l_eruption_du_volcan_nyiragongo_ne_pouvait_etre_predite.html

The publications of Barrière et al. (2022) (see publication list below) was featured as an **EOS Editors Highlight** by the American Geophysical Union, which can be found here:

https://eos.org/editor-highlights/tracking-lava-lake-levels-at-an-african-volcano-from-space

PUBLICATIONS & PRESENTATIONS

❖ Peer-reviewed Journal Publications

Published & in press

Barrière, J., **N. d'Oreye**, B. Smets, **A. Oth**, L. Delhaye, J. Subira, N. Mashagiro, D. Derauw, **D. Smittarello**, A. M. Syavulisembo and F. Kervyn (2022). Intra-crater eruption dynamics at Nyiragongo (D.R. Congo), 2002–2021, *J. Geophys. Res. Solid Earth*, 127(4), e2021JB023858, doi: 10.1029/2021jb023858.

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.

Deijns A., O. Dewitte, W. Thiery, **N. d'Oreye**, J.-P. Malet and F. Kervyn (2022). Timing landslide and flash flood events from SAR satellite: a regionally applicable methodology illustrated in African cloud-covered tropical environments. *Nat. Hazards Earth Sci. Sci.*, 22, 3679-3700, doi: 10.5194/nhess-22-3679-2022.

Dille, A., O. Dewitte, A. Handwerger, **N. d'Oreye**, D. Derauw, G. Ganza Bamulezi, G. Ilombe Mawe, C. Michellier, J. Moeyersons, E. Monsieurs, T. Mugaruka Bibentyo, S. Samsonov, B. Smets, M. Kervyn and F. Kervyn (2022). Acceleration of a large deep-seated tropical landslide due to urbanisation feedbacks. *Nature Geoscience*, 15, 1048-1055, doi: 10.1038/s41561-022-01073-3.

Najdahmadi, B., M. Pilz, D. Bindi, H.N.T. Razafindrakoto, **A. Oth** and F. Cotton (2022). Hazard-consistent optimization of seismic networks for earthquake early warning – the case of the Lower Rhine Embayment (western Germany). *J. Seismol.*, in press.

Parolai, S. and **A. Oth** (2022). On the Limitations of Spectral Source Parameter Estimation for Minor and Microearthquakes, *Bull. Seismol. Soc. Am.*, 112(5), 2364-2375, doi: 10.1785/0120220050.

Pinel, V., S. Furst, F. Maccaferri and **D. Smittarello** (2022). Buoyancy Versus Local Stress Field Control on the Velocity of Magma Propagation: Insight from Analog and Numerical Modelling. *Front. Earth Sci*, 10, 838318, doi: 10.3389/feart.2022.838318.

Shible, H., F. Hollender, D. Bindi, P. Traversa, **A. Oth**, B. Edwards, P. Klin, H. Kawase, I. Grendas, R. Castro, N. Theodoulidis and P. Gueguen (2022). GITEC: A Generalized Inversion Technique Benchmark, *Bull. Seismol. Soc. Am.*, 112(2), 850–877, doi: 10.1785/0120210242.

Smittarello, D., **N. d'Oreye**, **M. Jaspard**, D. Derauw and S. Samsonov. Pair Selection Optimization for InSAR Time Series Processing. *J. Geophys. Res.*, 127(3), e2021JB022825, doi: 10.1029/2021JB022825.

Smittarello, D., B. Smets, **J. Barrière**, C. Michellier, **A. Oth**, T. Shreve, R. Grandin, N. Theys, H. Brenot, V. Cayol, P. Allard, C. Caudron, O. Chevrel, F. Darchambeau, P. de Buyl, L. Delhaye, D. Derauw, G. Ganci, H. Geirsson, E. Kamate Kaleghetso, J. Kambale Makundi, I. Kambale Nguomoja, C. Kasereka Mahinda, M. Kervyn, C. Kimanuka Ruriho, H. Le Mével, S. Molendijk, O. Namur, S. Poppe, M. Schmid, J. Subira, C. Wauthier, M. Yalire, **N. d'Oreye**, F. Kervyn and A. Syavulisembo Muhindo (2022). Precursor-free eruption triggered by edifice rupture at Nyiragongo volcano. *Nature*, 609, 83-88, doi: 10.1038/s41586-022-05047-8.

Under review

Bindi, D., D. Spallarossa, M. Picozzi, **A. Oth**, P. Morasca and K. Mayeda. The Community Stress Drop Validation Study: Part I: Source, propagation and site decomposition of Fourier spectra. *Seismol. Res. Lett.*, under review.

Bindi, D., D. Spallarossa, M. Picozzi, **A. Oth**, P. Morasca and K. Mayeda. The Community Stress Drop Validation Study: Part II: Uncertainties of source parameters and stress drop. *Seismol. Res. Lett.*, under review.

Subira, J., **J. Barrière**, C. Caudron, A. Hubert-Ferrari, **A. Oth**, B. Smets, **N. d'Oreye** and F. Kervyn. Detecting sources of shallow tremor at neighboring volcanoes in the Virunga Volcanic Province using seismic amplitude ratio analysis (SARA). *Bull. Volc.*, under review for special issue "Open-Vent Volcanoes".

Walwer, D., C. Wauthier, **J. Barrière**, **D. Smittarello**, B. Smets and **N. d'Oreye**. Modeling the intermittent lava lake drops occurring between 2015 and 2021 at Nyiragongo volcano. Geophys. Res. Lett., under review.

❖ Technical Note

Oth, A. and **J. Barrière** (2022). Note technique concernant les "Aspects sismiques en relation avec le projet de Géothermie de Neischmelz », en réponse à une demande du Fonds de Logement et du bureau d'études Géoconseils, March 2022, 15 p.

❖ Conference Presentations and Abstracts

Barrière, J. and **A. Oth** (2022). Imaging the uppermost layers of the Eifel volcanic system (Germany) using ambient microseismic noise. *European Geosciences Union General Assembly 2019, 23-27 May 2022, Vienna, Austria.*

Barrière, J. and **A. Oth** (2022). Ambient noise tomography of the Eifel and surrounding regions using current available data. *101th Journées Luxembourgeoises de Géodynamique, 5-7 September 2022, Luxembourg.*

Barrière, J., **N. d'Oreye**, B. Smets, **A. Oth**, L. Delhaye, J. Subira, N. Mashagiro, D. Derauw, **D. Smittarello**, A. Muhindo Syavulisembo and F. Kervyn (2022). On the origins of intracrateral eruption dynamics at Nyiragongo volcano in the period 2002-2021. *Cities on Volcanoes 11, 12-17 June 2022, Heraklion (Crete), Greece.*

Barrière, J. **A. Oth**, J. Subira and **N. d'Oreye** (2022). The renewal of a lava lake activity inside Nyiragongo's crater after the 2021 flank eruption as heard by nearby acoustic and seismic sensors. *Cities on Volcanoes 11, 12-17 June 2022, Heraklion (Crete), Greece.*

d'Oreye, N., D. Derauw, **D. Smittarello**, S. Samsonov, **M. Jaspard** and **G. Celli** (2022). Automatic Multi-Satellite and Incremental InSAR Mass Processing chain for ground deformation time series: the MasTer Toolbox. Abstract (Invited keynote). *MDIS 2022: Deformation Measurements by Earth Observation Techniques, Ax-Les-Thermes, 10-12 October 2022, France.*

d'Oreye, N., for the Be-Lux consortium (F. Kervyn, B. Smets, C. Michellier, N. Theys, H. Brenot, **N. d'Oreye**, **A. Oth**, **J. Barrière**, **D. Smittarello**) (2022). Contribution du groupe Be-Lux aux moyens de surveillance sismique et géodésique du Nyiragongo. *1ère Conférence Internationale sur la gestion des volcans de Virunga, 19-21 March 2022, Goma, D.R. Congo (in french).*

Dahm. T., C. Milkereit, M. Isken, S. Cesca, X. Yuan, C. Sens-Schönfelder, F. Tilmann, M. Pilz, F. Cotton, H. Woith, M. Hensch, B. Schmidt, B. Endrun-Knapmeyer, T. Meier, L. de Siena, M. van Camp and **A. Oth** (2022). Ein seismologisches Großexperiment zur Untersuchung magmatischer Prozesse unter der Eifel. *82. Jahrestagung der DGG, virtuel.*

Deijns, A., O. Dewitte, W. Thiery, **N. d'Oreye**, J.-P. Malet, and F. Kervyn (2022). Timing landslide and flash flood events from radar satellite. *European Geosciences Union General Assembly 2022, 23-27 May 2022, Vienna, Austria.*

Hopquin, C., **Smittarello, D.**, Gayer, E., Michon, L., Lucas, A., Dynamics and controls of the Grand Éboulis landslide (La Réunion island) measured by radar interferometry. *MDIS 2022: Deformation Measurements by Earth Observation Techniques, Ax-Les-Thermes, 10-12 October 2022, France.*

Kervyn, F., for the Be-Lux consortium (F. Kervyn, B. Smets, C. Michellier, N. Theys, H. Brenot, **N. d'Oreye**, **A. Oth**, **J. Barrière**, **D. Smittarello**) (2022). Leçons tirées par le groupe Be-Lux du déroulement et du suivi de l'éruption volcanique du Nyiragongo de mai 2021. *1ère Conférence Internationale sur la gestion des volcans de Virunga, 19-21 March 2022, Goma, D.R. Congo (in french).*

Muhindo Syavulisembo, A., F. Kervyn, **N. d'Oreye**, **J. Barrière**, C. Michellier, **A. Oth**, B. Smets and **D. Smittarello** (2022). The challenging crisis management during the Nyiragongo 22nd May 2021 eruption (D. R. Congo). *Cities on Volcanoes 11, 12-17 June 2022, Heraklion (Crete), Greece.*

Oth A., for the Be-Lux consortium (F. Kervyn, B. Smets, C. Michellier, N. Theys, H. Brenot, **N. d'Oreye**, **A. Oth**, **J. Barrière**, **D. Smittarello**) (2022). Contribution du groupe Be-Lux au suivi de l'éruption de mai 2021. *1ère Conférence Internationale sur la gestion des volcans de Virunga, 19-21 March 2022, Goma, D.R. Congo (in french).*

Schlögel, R., N. **d'Oreye**, A. Orban, D. Derauw, H.-B. Havenith and R. Hanssen (2022). Investigating ground deformation with InSAR methods in the Euregio Meuse-Rhine transborder region'. Abstract. *ESA Living Planet Symposium 2022, Bonn, Germany*.

Schlögel, R. et al. (2022). SAR interferometry techniques to measure Earth surface displacements in the Euregio Meuse-Rhine region. *GRSG Annual Conference & AGM 2022: Orbit to Outcrop. University of Twente, NL, 11–14 December 2022, The Netherlands.*

Smets, B., **J. Barrière**, **N. d'Oreye**, L. Delhaye, **A. Oth**, J. Subira, N. Mashagiro, D. Derauw, **D. Smittarello**, A. Syavulsembo Muhindo and F. Kervyn (2022). Evolution of Nyiragongo's main crater from 2022 to 2021 using photogrammetry and SAR-shadow measurements. *Mesure de la Déformation par Imagerie Satellite (MDIS), 10-12 October 2022, Ax-les-Thermes, France.*

Smets, B. for the Be-Lux consortium (F. Kervyn, B. Smets, C. Michellier, N. Theys, H. Brenot, **N. d'Oreye**, **A. Oth**, **J. Barrière**, **D. Smittarello**) (2022). Histoire éruptive de la chaîne volcanique des Virunga. *Abstract. 1ère Conférence Internationale sur la gestion des volcans de Virunga, 19-21 March 2022, Goma, D.R. Congo (in french).*

Smittarello, D., **J. Barrière**, **N. d'Oreye**, B. Smets, **A. Oth**, C. Michellier, T. Shreve, R. Grandin, V. Cayol, C. Wauthier, D. Derauw, H. Geirsson, N. Theys, H. Brenot, A. Syavulisembo Muhindo and F. Kervyn (2022). Structural failure and shallow dike intrusion at Nyiragongo volcano (D.R. Congo). *European Geosciences Union General Assembly 2022, 23-27 May 2022, Vienna, Austria.*

Smittarello, D., B. Smets, **J. Barrière**, **A. Oth**, C. Michellier, T. Shreve, R. Grandin, V. Cayol, N. Theys, H. Brenot, H. Gerisson, D. Derauw, O. Namur, M. Sander Moendijk, M. Ephrem Kamate Kaleghetso, M. Schmid, **N. d'Oreye**, F. Kervyn and A. Syavulisembo Muhindo (2022). Challenges from structural failure and shallow dike intrusion at Nyiragongo. *Cities on Volcanoes 11, 12-17 June 2022, Heraklion (Crete), Greece.*

Smittarello, D., **J. Barrière**, B. Smets, **A. Oth**, T. Shreve, V. Cayol, R. Grandin, C. Wauthier, D. Derauw, H. Geirsson, N. Theys, H. Brenot, C. Michellier, J.-L. Froger, A. Syavulisembo Muhindo, **N. d'Oreye** and F. Kervyn (2022). Propagation and arrest of the dike during the May 2021 eruption of Nyiragongo volcano. *Cities on Volcanoes 11, 12-17 June 2022, Heraklion (Crete), Greece.*

Smittarello, D., **J. Barrière**, **N. d'Oreye**, B. Smets, **A. Oth**, C. Michellier, V. Cayol, T. Shreve, R. Grandin, C. Wauthier, D. Derauw, H. Geirsson, N. Theys, H. Brenot, O. Namur, S. Molendijk, E. Kamate Kaleghetso , A. Muhindo, and F. Kervyn (2022). A multidisciplinary study of the May 2021 Nyiragongo Eruption. *101th Journées Luxembourgeoises de Géodynamique, 5-7 September 2022, Luxembourg.*

Smittarello, D., **N. d'Oreye**, R. Grandin, V. Cayol, B. Smets, **J. Barrière**, T. Shreve, D. Derauw, J.-L. Froger, H. Geirsson, C. Wauthier, N. Theys, H. Brenot, C. Michellier, **A. Oth**, A. Muhindo Syavulisembo, and F. Kervyn (2022). An unpredictable eruption ? The mechanism behind the Nyiragongo 2021 eruption. *G2, November 2022, Grenoble, France*.

Smittarello, D., T. Shreve, R. Grandin, V. Cayol, D. Derauw, C. Wauthier, J.-L. Froger, B. Smets, **J. Barrière**, **A. Oth**, C. Michellier, H. Geirsson, N. Theys, H. Brenot, **N. d'Oreye**, A.

Muhindo, and F. Kervyn (2022). What did we learn from SAR data during the May 2021 Nyiragongo eruption ? Abstract. *MDIS 2022: Deformation Measurements by Earth Observation Techniques, Ax-Les-Thermes, 10-12 October 2022, France.*

Subira, J., **J. Barrière**, C. Caudron, A. Hubert-Ferrari, **A. Oth**, B. Smets, **N. d'Oreye** and F. Kervyn (2022). Detecting sources of shallow tremor at neighboring volcanoes in the Virunga Volcanic Province using seismic amplitude ratio analysis (SARA). *Cities on Volcanoes 11, 12-17 June 2022, Heraklion (Crete), Greece (Poster).*

Theys N., H. Brenot, M. Van Roozendae, B. Smets, F. Kervyn, **N. d'Oreye**, **J. Barrière**, **A. Oth**, **D. Smittarello**, P. de Buyl, N. Clerbaux and L. Clarisse (2022). Approche spatiale pour le suivi des émissions de gaz et aérosols volcaniques des volcans actifs des Virunga. *1ère Conférence Internationale sur la gestion des volcans de Virunga, 19-21 March 2022, Goma, D.R. Congo (in french).*

Yen, M.-H., D. Bindi, R. Zaccarelli, **A. Oth**, B. Edwards and F. Cotton (2022). Source parameter scaling relationship in central-southern Europe. *European Geosciences Union General Assembly 2019, 23-27 May 2022, Vienna, Austria (Poster).*

Yen, M.-H., D. Bindi, R. Zaccarelli, **A. Oth**, B. Edwards and F. Cotton (2022). Source parameter determination using a spectral decomposition approach in central-southern Europe. *Third European Conference on Earthquake Engineering and Seismology (3rd ECEES), Bucharest, Romania (Poster).*

MEETING ATTENDANCE & WORK VISITS

With the gradual relaxation of the COVID-19 pandemic measures throughout Europe and around the World, in-person conferences and meetings started to resume during the course of 2022. While many work meetings still take place virtually and some will certainly continue to do so in the future, in-person meetings are crucial to boost the scientific discussion and collaboration, and the 101st JLG meeting held in Luxembourg (see page 35) provides an excellent example.

Adrien Oth

- 1ère Conférence Internationale sur les Volcans des Virunga, Goma, DR Congo, 19-21 March
- 101st Journées Luxembourgeoises de Géodynamique: Intracontinental basaltic volcanic fields, Luxembourg, 5-7 September
- 3rd European Conference on Earthquake Engineering and Seismology, Bucharest, Romania, 4-9 September
- KNMI Supervisory Board Meeting, De Bilt, The Netherlands, 26-27 October
- Permanent Correspondent and Specialized Centres Directors Meeting of the EUR-OPA Major Hazards agreement of the Council of Europe (17-18 November)
- Work visits & visitors at ECGS:
    - Working session in preparation of the 1st International Conference in Goma related to the 2021 Nyiragongo eruption, RMCA, Brussels (11 March)
    - Visit of the Congolese Minister of Research, his first counsellor, the General Director of Goma Volcano Observatory (GVO) and ECGS to discuss the end of collaboration with GVO (30 May)
    - Station Location Scouting in the Eifel region (9-11 August)
    - Station Installation in the Eifel region (12 and 14 September)
    - Meeting with ITM regarding the WULG at ECGS (19 October)
    - Meeting with Cimalux representative for explaining results of quarry blast study (9 November)
    - Virtual meeting with RMCA, ECGS, MNHN and representatives of Belgian Ambassy in DRC and Belgian Science Policy to discuss the future of the collaboration with Goma Volcano Observatory and other partners (27 January)

- Virtual Associate Editor meetings of Seismological Society of America (31 January and 17 November)
- Virtual Permanent Correspondent and Specialized Centres Directors Meeting of the EUR-OPA Major Hazards agreement of the Council of Europe (10-11 February)
- Virtual meeting with ECGS, MNHN and RMCA in preparation of the 1st International Conference in Goma about the 2021 eruption of Nyiragongo (18 February, 2, 4 and 8 March)
- Virtual Participation in hybrid meeting of the KNMI Supervisory Board (25 May)
- Virtual SCEC Stress Drop Validation Study Meeting (16 June)
- Virtual meeting organized by Prof. P. Allard (president of IAVCEI) with former and potential futures collaborators with Goma Volcano Observatory (29 June)
- Virtual SCEC Stress Drop Validation Study Meeting (26 July)
- Virtual SCEC Stress Drop Validation Study Meeting (6 October)
- Virtual ESC ExeCom Meeting (6 December)
- Regular virtual meetings on the Eifel Large-N Array project led by the GFZ German Research Centre for Geosciences (in general every first Wednesday of each month)

Nicolas d'Oreye

- 1ère Conférence Internationale sur les Volcans des Virunga, Goma, DR Congo, 19-21 March
- 101st Journées Luxembourgeoises de Géodynamique: Intracontinental basaltic volcanic fields, Luxembourg, 5-7 September
- MDIS 2022: Deformation Measurements by Earth Observation Techniques, ,Ax-Les-Thermes, France, 10-12 October
- Work visits & visitors at ECGS:
  - Working session in preparation of the 1st International Conference in Goma related to the 2021 Nyiragongo eruption, RMCA, Brussels (11 March)
  - Visit of the Congolese Minister of Research, his first counsellor, the General Director of Goma Volcano Observatory (GVO) and ECGS to discuss the end of collaboration with GVO (30 May)
  - Closing meeting of the Versus project, RMCA, Brussels (30 June)
  - Meeting of the Scientific Committee of the French Service National d'Observation (SNO) ISDeform, Ax-Les-Thermes, France (12-13 October)
  - Virtual meeting with RMCA, ECGS, MNHN and representatives of Belgian Ambassy in DRC and Belgian Science Policy to discuss the future of the collaboration with Goma Volcano Observatory and other partners (27 January)
  - Virtual meeting with F. Albino in the view of a participation to the scientific Committee of ISDEFORM (10 February)
  - Virtual meeting of the scientific Committee of ISDEFORM (3 June)
  - Virtual meeting with ECGS, MNHN and RMCA in preparation of the 1st International Conference in Goma about the 2021 eruption of Nyiragongo (18 February, 2, 4 and 8 March)
  - Virtual meeting with Romy Schlögel for the GERMANE project (monitoring of the possible installation site of the Einstein telescope using InSAR time series) (16 May and 14 September)
  - Virtual meeting organized by Prof. P. Allard (president of IAVCEI) with former and potential futures collaborators with Goma Volcano Observatory (29 June)
  - Virtual meeting with BELSPO and Dominique Derauw (CSL & Universidad Nacional de Rio-Negro-Conicet) about Master software (8 July)
  - Virtual meeting with F.Vecchiotti (Geological Survey of Austria) about Master software (13 September

- Virtual meeting with ECGS, MNHN and J.L. Froger (Laboratoire Magmas et Volcans, Université Clermont Auvergne) about the recursive unwrapping of interferograms (27 October)
- Virtual meeting with ECGS, MNHN and D. Walwer (Pennsylvania State University, USA) about the NSF-Crater Floor project (3 and 13 November)

Julien Barrière

- European Geosciences Union (EGU) General Assembly, 23-27 April
- Cities on Volcanoes 11, Heraklion (Crete), Greece, 12-17 June
- 101st Journées Luxembourgeoises de Géodynamique: Intracontinental basaltic volcanic fields, Luxembourg, 5-7 September
- Work visits & visitors at ECGS:
    - Visit of the Congolese Minister of Research, his first counsellor, the General Director of Goma Volcano Observatory (GVO) and ECGS to discuss the end of collaboration with GVO (30 May)
    - Virtual meeting with ECGS, MNHN and RMCA in preparation of the 1st International Conference in Goma about the 2021 eruption of Nyiragongo (18 February, 2, 4 and 8 March)
    - Virtual meeting organized by Prof. P. Allard (president of IAVCEI) with former and potential futures collaborators with Goma Volcano Observatory (29 June)

Delphine Smittarello

- European Geosciences Union (EGU) General Assembly, 23-27 April
- Cities on Volcanoes 11, Heraklion (Crete), Greece, 12-17 June
- 101st Journées Luxembourgeoises de Géodynamique: Intracontinental basaltic volcanic fields, Luxembourg, 5-7 September
- MDIS 2022: Deformation Measurements by Earth Observation Techniques, ,Ax-Les-Thermes, France, 10-12 October
- Colloque du G2 2022: "Géodésie, Géophysique et Montagne", Grenoble, France, 8-10 November
- Work visits & visitors at ECGS:
    - Seminar at ISTerre, Chambéry, France (28-30 September)
    - Several work visits to IPGP, Paris, France
    - Virtual meeting with ECGS, MNHN and RMCA in preparation of the 1st International Conference in Goma about the 2021 eruption of Nyiragongo (18 February, 2, 4 and 8 March)
    - Virtual meeting organized by Prof. P. Allard (president of IAVCEI) with former and potential futures collaborators with Goma Volcano Observatory (29 June)

SCIENTIFIC COMMUNITY SERVICE

Adrien Oth

- European Seismological Commission (ESC) **Secretary General** (2022 – present)
- European Seismological Commission (ESC) **Titular Member** for Luxembourg
- 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 Instituut (KNMI)**, Netherlands

- Member of **Science Advisory Board** of the **Central Asian Institute for Applied Geosciences** (CAIAG), Kyrgyz Republic
- **Session Convener** at 3rd European Conference on Earthquake Engineering and Seismology (3ECEES)
- **Reviewer** for *Geophysical Journal International*
- **Member** of Seismological Society of America, IAVCEI, 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
- **Reviewer** for *Centre National de la recherche scientifique (CNRS), France*
- **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)
    - Co-supervision of internship in the framework of a Master thesis at Institut de Physique du Globe de Paris (IPGP): Coline Hopquin, 14-24 February 2022
    - Co-supervision of internship of undergraduate student Marina Debret, 2nd year in Engineering School in Geophysics at EOST Strasbourg, 27 July – 5 August 2022

Julien Barrière

- **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 *Remote Sensing, J. Volc. Geotherm. Res., J. Geophys. Res.: Solid Earth, Comptes rendus Geosciences, SYSTER*
- **Member** of American Geophysical Union, European Geosciences Union, IAVCEI
- **Mentorships & Supervision**
    - Co-supervision of internship in the framework of a Master thesis at Institut de Physique du Globe de Paris (IPGP): Coline Hopquin, 14-24 February 2022
    - Co-supervision of internship of undergraduate student Marina Debret, 2nd year in Engineering School in Geophysics at EOST Strasbourg, 27 July – 5 August 2022
    - Co-supervision of master thesis at INGV Bologna started in October 2022: Greta Bellagamba