Annual Report 2021

EUROPEAN CENTER FOR GEODYNAMICS AND SEISMOLOGY (ECGS)

ECGS, Fondation 19, rue Josy Welter L-7256 Walferdange Luxembourg
Tel : +352 33 14 87 31 Fax : +352 33 14 87 88 Email : info@ecgs.lu Web site : www.ecgs.lu
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- **Dr. Delphine Smittarello**, post-doctoral researcher, ECGS
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- **Dr. Nicolas d'Oreye**, geophysicist, National Museum of Natural History
- **Gilles Celli,** technical engineer, National Museum of Natural History

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INTRODUCTION

Similar to 2020, the COVID-19 pandemic still had a significant impact on the research activities carried out by ECGS in 2021. The related travel restrictions, sometimes weaker and sometimes stronger, made field trips or in-person conference attendances difficult to plan and, as a consequence, rather challenging endeavours. The pandemic also made it impossible to consider the organisation of a Journées Luxembourgeoises de Géodynamique (JLG) meeting. At the present stage, we hope that may welcome our colleagues again to the JLG here in Luxembourg in mid to late 2022.

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 three permanent scientists (Dr. Nicolas d'Oreye, Dr. Julien Barrière and Dr. Adrien Oth) and a post-doc scientist, Dr. Delphine Smittarello, who joined the team in June 2020, working on ground deformation studies using in particular remote sensing techniques.

The year 2021 was strongly marked by two main aspects: on one hand, we made major advances in the seismic network development and research in Luxembourg; on the other hand, Nyiragongo volcano in the Democratic Republic of the Congo erupted in May. Since we were strongly involved over that past 16 years in research activities on Nyiragongo (and the Kivu Rift region more generally) and massively contributed to improve the monitoring activities of the Goma Volcano Observatory (GVO), we were naturally strongly implicated in the follow-up of the volcanic crisis and subsequent scientific study of this eruption. The dense seismo-geodetic monitoring networks deployed over the years in the framework of several large research projects proved up to the challenge, allowing for real-time monitoring of the seismicity and deformations associated with the eruption, making the follow-up and scientific input to the decision makers (with a Be-Lux team present in Goma during the crisis) an undeniable success.

Unfortunately, besides this extraordinary scientific achievement and the in-depth analysis of the data from this eruption, we were forced to spend a very significant amount of time and energy during the remainder of 2021 on a less pleasant aspect of the eruption. Following the eruption, extremely grave and unfounded allegations were raised by the GVO union against the GVO management on one side, but also against our Belgo-Luxembourgian scientific consortium on the other. These defamatory allegations are rooted in various factors that we explain below and were relayed in the social media and international press, severely undermining the collaboration between our consortium and GVO. We responded in great detail to all these allegations and note that the Congolese authorities and GVO management, even though tardily, expressed their support to our consortium. Further details can be found in the dedicated section below.

We continued the implementation of the ECGS strategic paper, for which our 5-year funding plan was accepted by the Luxembourg government in 2019. In this context, we installed three additional seismic stations in Dudelange, Rumelange and near Ettelbruck, increasing the number of operational broadband seismic stations in the country to thirteen. We are also very pleased that in the 2022 government budget, the addition permanent position for a remote sensing scientist at ECGS was retained (this position should have been filled in 2021, but had been postponed by one year).

Besides the activities in the Kivu region and in Luxembourg, 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 seven articles in international peer-reviewed scientific journals in 2021, with four more currently under review, and (co-)authored 24 contributions at international conferences.

Besides ECGS internal budgets provided by the Luxembourg government, funding and support for the research activities in 2021 was obtained from the following sources:

- Belgian Science Policy (Belspo)
- Deutsches Zentrum für Luft- und Raumfahrt (DLR) and Canadian Space Agency (CSA) (support through free access to satellite images)

Seismology in Luxembourg and Abroad

❖ Seismological monitoring infrastructure operated by ECGS

Over the past years, ECGS has continuously developed 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 establishing and 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 section above, this year with particular focus on the 2021 Nyiragongo eruption). The interest in this region has been driven through a series of scientific research projects over the past 16 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.

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 current status of the monitoring networks operated by ECGS/Mnhn. The Kivu Rift Seismic and Geodetic Network (KivuSNet / KivuGNet) is operated in collaboration with local and international research partners and currently composed of 17 active broadband seismic stations, 16 GNSS stations and 2 infrasound arrays. 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).

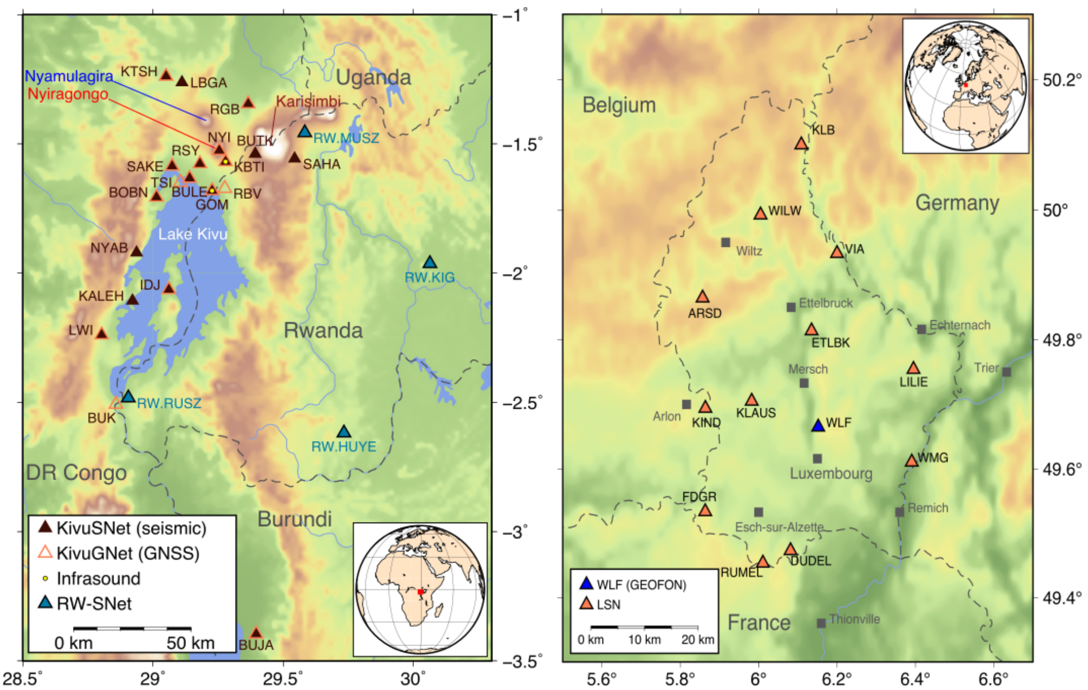

Figure 1: Current status of seismic, GNSS and infrasound monitoring infrastructure developed by ECGS in collaboration with its partners in the Kivu Rift region (left) and in the Grand-Duchy of Luxembourg (right).

We continued the development of the Luxembourg Seismic Network (LSN) in 2021, with three new broadband seismic stations installed: the stations at the *Centre National de l'Audiovisuel (CNA)* à Dudelange (code: DUDEL), the station at the *Musée national des Mines (MnM)* in Rumelange (code: RUMEL) and most recently in early 2022, following the site search and inspection in 2021, a station was installed near Ettelbrück (code: ETLBK). The station at the MnM was installed in collaboration with its staff and the *Inspection du Travail et des Mines (ITM, Service Mines, Minières & Carrières)* in order to test the applicability of such an installation for monitoring rockfall events in the affected gallery (see first test results below). In total, the LSN counts now 13 broadband seismic stations (Figure 1). Already in 2020, the two short-period stations installed already in the 1980ties in collaboration with the Royal Observatory of Belgium (ROB) in Kalborn and Vianden were both upgraded with modern broadband instrumentation acquired in the framework of ECGS's strategic paper investments.

All data 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). On the German side, we have real-time access to station RIVT close to Trier, while we provide data from our station WMG 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. As a final note, in November 2021, ECGS was contacted by the *Fonds de Logement* in the framework of the geothermal energy project for the site Neischmelz in Dudelange in order to provide a technical note on seismicity-related aspects. The drafting of this document will take place in the first months of 2022.

❖ A seismicity catalogue for Luxembourg

Here we compile seismic observations performed with the Luxembourgish national seismic network (international network code LU) during the past 4 years (November 2017 – November 2021). Some stations from the French networks FR and RD and Belgian stations (network BE) have been added to the ECGS automatic location routine XCloc (e.g., Barrière et al., 2019) in the course of recent years. As already highlighted in previous reports, this allows improving the location accuracy of regional seismic events outside the national network/territory.

Equipped with dense local seismic observations covering several years, we aim to provide a first accurate overview of potential tectonic seismicity occurring on the Luxembourgish territory. Among 1884 detected and located seismic events within a 400 x 400 km box centered around Luxembourg (see for instance the 2020 Annual Report for detailed location maps depicting the whole scanned area), 269 are located in Luxembourg or in its immediate vicinity (Figure 2). Previous analyses in the recent years reported a Luxembourgish seismic picture virtually completely dominated by anthropogenic seismic sources (quarry blasts), except for a few low-magnitude natural seismic events. Other network operator around the world use for instance daytime/nighttime distribution and event location for pre-flagging automatic seismic event locations (Allmann et al., 2008). In Figure 2, we plot the locations of these 269 seismic events and color each corresponding marker according to 4 attributes:

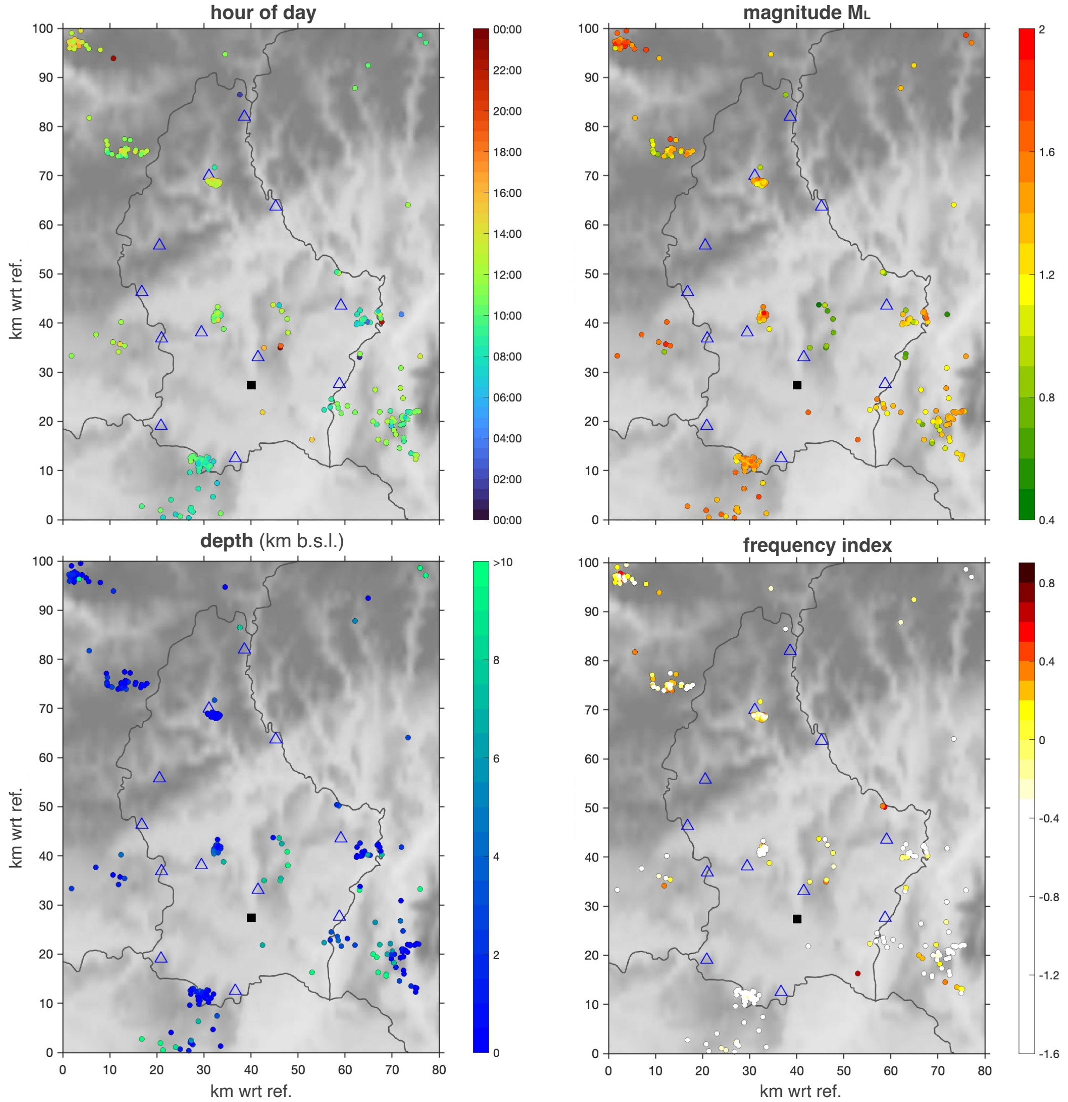

Figure 2: 269 seismic events located in Luxembourg and neighboring regions (80 x 100 km box) between 1 November 2017 and 1 November 2021. The four panels show the event epicenters color-coded with the origin time (hour of day, UTC), local magnitude (M_L), depth (km b.s.l.) and frequency index (dimensionless parameter conveying the average frequency content of the seismic event recorded at the stations).

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

The last of these is defined as (Matoza et al., 2014): $FI = \log_{10} (A_{upper}/A_{lower})$, where A_{upper} and A_{lower} are the mean spectral amplitude of the first P-wave arrival in a high and low frequency band, respectively (here we chose 1-4 Hz and 4-20 Hz, respectively).

We observe than most of events occur the morning, are of low M_L between 1 and 2, have a source at or close to the surface and generally have negative frequency index (low-frequency content dominates, as it is generally assumed for source mechanism of quarry blast, e.g., Keith et al., 2004). These are all blasts performed in the main quarries of the area. In Luxembourg (or near its borders), five quarries are especially active: close to Rumelange, Brouch, Wilwerwiltz, Remich and Wasserbillig.

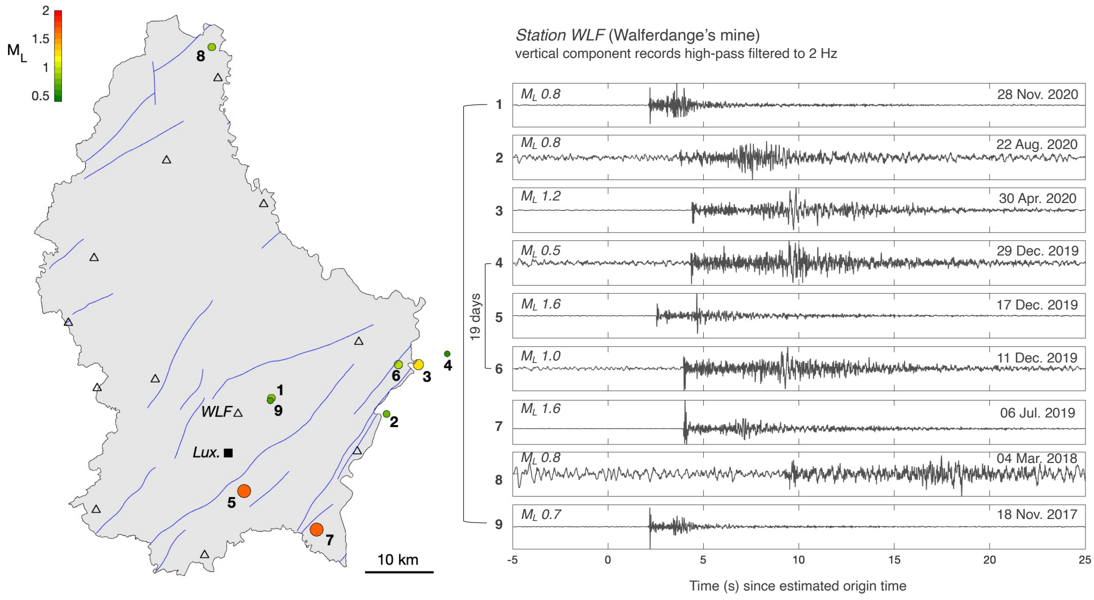

Figure 3: Nine earthquakes (M_L 0.5 – 1.6) located between November 2017 and November 2021. Left panel: map of epicenters (size and color of the round markers proportional to M_L). The main geological faults are depicted in blue (source: catalog.inspire.geoportail.lu). Right panel: vertical component records at station WLF for each event. Please note that the amplitude of the traces are normalized for each record.

For a few events, the differentiation between quarry blasts and natural earthquakes following these four parameters are not straightforward. Earthquakes occur also during daytime, the magnitude of both types of events are similar, the depth of the source can be badly constrained, site and path effects can affect the frequency content. More advanced comparison techniques could be employed but the automated discrimination between quarry blasts and earthquakes remains sometimes problematic (e.g., Allmann et al., 2008, using standard earthquake source models). We find that pre-classifying events using the above-mentioned attributes (hour of day, magnitude, depth, frequency index) in addition to the epicenter is a robust enough strategy for our purpose. We then perform an additional manual inspection for retrieving the natural earthquakes among the few remaining events that do not fit within identified clusters.

Nine such earthquakes are retrieved for the period November 2017 – November 2021 (Figure 3) and located at depth between 5 and 10 km b.s.l. (the smallest M_L 0.5 event n°4, outside the network, is estimated at about 2 km b.s.l. but this estimate should be considered with caution due to large uncertainties).

Despite this small number, we can identify three main zones, all in the Gutland (Southern) region:

- The two main events n°5 and n°7 (M_L ~1.6) are located in the south of Luxembourg (n°5 close to Alzingen and n°7 close to Mondorf).
- Four events (n° 2, 3, 4 and 6) along the Moselle river (boundary with Germany) from Grevenmacher to Wasserbillig.
- Two low-magnitude events n°1 and n°9 (M_L 0.7 & 0.8) in the Grünewald area, about 10 km to the East of the Walferdange underground laboratory.

Compared to the catalog of the Royal Observatory of Belgium providing robust and revised earthquakes location for the region, only the three largest events (n°3, 5 and 7) are reported, thus highlighting the benefit of deploying this dense national network for monitoring the seismicity on the Luxembourgish territory. We are particularly interested in these two last events n°1 and n°9 since they have highly similar waveforms and previous investigations (see 2019 Annual Report) revealed a potential cluster of repetitive events in the last decade. This type of event is generally called "multiplet", which can be defined following Moriya et al. (2003) as "a group of microseismic events with very similar waveforms, despite different origin times, and is likely

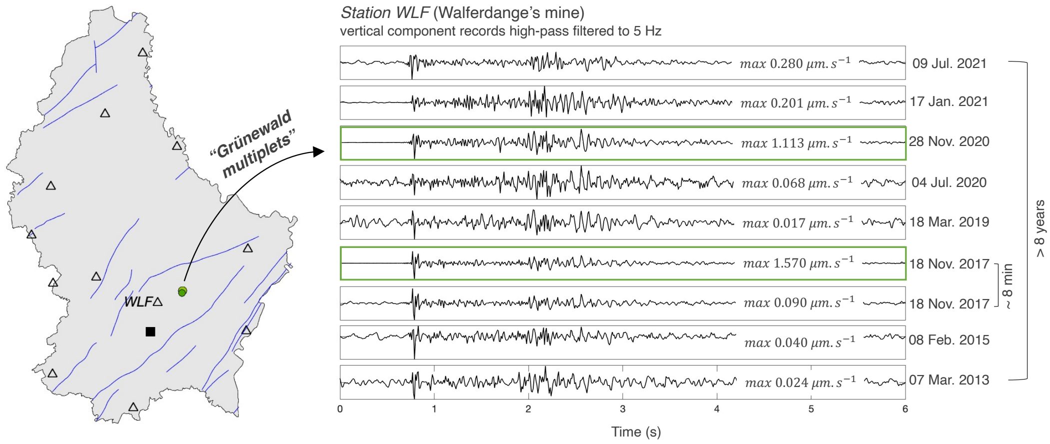

Figure 4: Nine earthquakes belonging to the cluster of "Grünewald multiplets". Earthquakes n°1 and n°9 from Figure 13 (29 November 2020 and 18 November 2017) are the only ones detected and locatable across the local network. Other microearthquakes are detected thanks to an automated detection algorithm (see text). The maximum absolute amplitude (ground velocity) for each event is indicated.

the expression of stress release on the same structure". Detecting such cluster of seismic events convey seismically activated structures.

As done by Barrière et al. (2017) for volcanic signals, we apply an automated detection technique called "template matching". With this method, we are able to scan the whole dataset available for one reference station (here station WLF). We use earthquake n°9 (Figure 3) as template (also called master event) in order to retrieve similar earthquakes. Earthquake n°1 (Figure 3), occurring almost three years later is well retrieved with this method, as well as several much smaller events (Figure 4). Nine earthquakes are detected in more than eight years of continuous recording. We note that the master M_L 0.8 event on 18 November 2017 was preceded by a similar but smaller seismic event about 8 min earlier.

❖ A broadband seismic station in the Musée National des Mines, Rumelange, for potential rockfall monitoring applications

In collaboration with the *ITM* and the *MnM*, on 9 December 2021, we installed a new telemetered broadband seismic station in the largest unsupported cavity of Luxembourg dug by humans, located in the underground mine of Rumelange close to its underground railway track (Figure 5). Some large fissures are visible on the roof yet this site only seems to experience rare rockfalls, which is a remarkable observation for such a large cavity according to the *ITM*. In a preliminary monitoring stage, the *ITM* placed tarps on the ground at some specific locations in order to detect new rockfalls. By the end of the year 2021, they contacted ECGS while looking for more advanced monitoring solutions. There is a dense literature addressing similar topics and our team already demonstrated the usefulness of seismic measurements for monitoring rock impacts by detecting the bedload transport of pebbles in a small Luxembourgish stream (Barrière et al., 2015). Our contribution is thus two folds:

- Testing a continuous, seismic monitoring using one broadband sensor deployed at the center of the cavity. The deployment of additional (short-period) sensors (for location purpose for instance) could be envisaged following first results and analyses (Figure 6), depending on available budgets.
- Using this remote site as a new permanent station for the national network if the seismic noise level in the frequency band of interest is low enough (Figure 7).

Before leaving the site on the installation day, we dropped a large rock at several intervals spaced by 10 m. This allows us to confirm some expected properties of rockfall signals recorded by the seismometer, i.e., a dominant high frequency content (>> 10 Hz) and a strong attenuation with distance. Nonetheless, distant impacts (at the beginning of the cavity, ~60 m away from the sensor) remain well detected by such a highly sensitive instrument (Figure 6).

Figure 5. Deployment on 9 December 2021 of an ECGS broadband seismic station in the largest unsupported cavity of the Rumelange mine (photo : G. Celli, Mnhn).

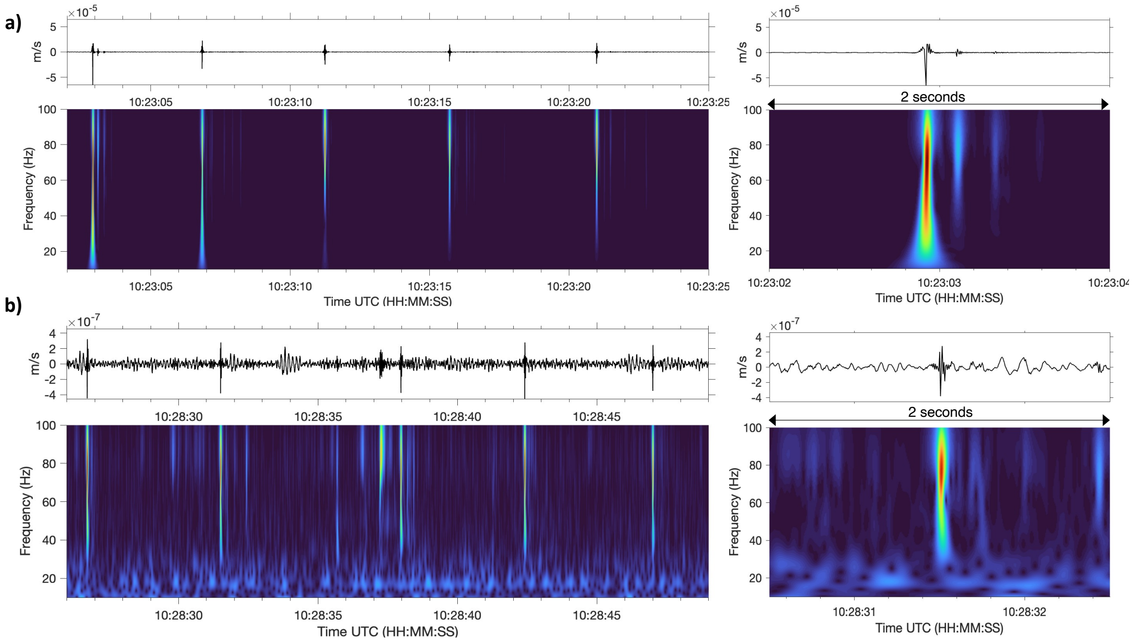

Figure 6. a) High-pass (> 10Hz) filtered seismograms of 23s duration and the corresponding normalized (min to max = blue to red) time-frequency transform (S-Transform) of 5 successive rockfalls from man's height about 5 m away from the sensor. A 2s zoom in the first impact is given on the right panel. As expected, the signal-to-noise ratio is excellent and the signal is very impulsive (with central frequency around 70 Hz). After the first large impact, up to 3 rebounds are clearly noticeable. b) same as in a) for 5 drops 60 m away from the sensor. The amplitude range of the seismic signal (m/s) is two orders of magnitude lower than in a). The 5 drops remain detectable but the SNR is poor since other disturbing arrivals (potentially caused by our presence at such high frequencies) can have about the same amplitude.

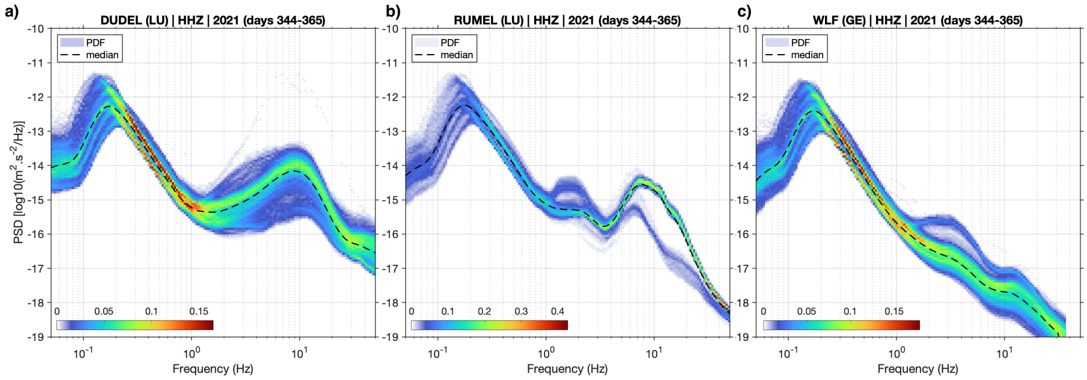

Figure 7. Probability Density Functions of PSDs (expressed in $m^2.s^{-2}/Hz$) for stations DUDEL (deployed in CNA's building, Dudelange, on 23 April 2021), RUMEL (Rumelange mine) and WLF (Walferdange mine) for the time period 10-31 December 2021. In comparison with WLF (the best site in Luxembourg for the whole frequency band of interest, 0.05 to 50 Hz), DUDEL and RUMEL show a rather good behavior in the low-frequency range (<1Hz). While DUDEL is highly affected by human activity above 1 Hz (a major drawback for locating regional/local earthquakes during daytime), RUMEL exhibits two distinct trends at high frequency: high-noise level due to discontinuous stationary noise (ventilation machinery) and the nearby quarry above the mine and low-noise level close to WLF's level when these sources of noise are reduced or shut down. Longer recording is needed in order to better gauge the site properties.

❖ Ambient noise tomography of Luxembourg and the Eifel volcanic field

The Eifel region is a large volcanic system in the middle of the European continent, close to Luxembourg (<100 km for the Western Eifel Volcanic Field - WEVF). From the Eifel teleseismic tomography experiment (eight months in 1997-1998, Ritter et al., 2001), a large mantle upwelling beneath the volcanic fields (down to 400 km depth) has been identified and further confirmed by receiver functions and teleseismic surface wave dispersion analyses (e.g., Mathar et al., 2006). A study in 2020 using dense geodetic observations led to the conclusion that the Eifel region experiences a pronounced uplift encompassing the neighbouring countries Netherlands, Belgium, Luxembourg and France, which is attributed to a buoyant mantle plume (Kreemer et al., 2020).

A detailed focus on the uppermost 30 km above the Moho has been missing until recently. However, a noteworthy recent seismological investigation (Hensch et al., 2019) showed the evidence of a deep magmatic recharge beneath the Laacher See Volcano in East Eifel between 2013 and 2018. Located at depth roughly between 40 and 10 km, low-frequency seismic swarms, which are typical of volcanic environment, convey the presence of magma movements and potential storage zones in the crust.

Our purpose here is to bring additional information on this shallow active magmatic system using Ambient Noise Tomography (ANT). Thanks to theoretical and technical developments over the two last decades, this approach has been increasingly popular for imaging Earth structure worldwide at different scales. We use here ambient noise data from archives of the 1997-1998 Eifel experiment and more recent (2019-2020) continuous broadband seismic record. The group velocity dispersion of Rayleigh waves is estimated between station pairs from Noise Cross-correlation Functions (NCF) covering the secondary microseismic frequency band, which allows to sample the uppermost 10-20 km of the crust. Our work includes a complete description of the ANT/NCF processing (e.g., directivity of the noise sources, sensitivity tests) in order to better constrain the velocity anomalies observed in the Eifel region and around. Because this work is under progress, we do not further detail the approach in the present report. Figures 8 and 9 provide first indications on the obtained results.

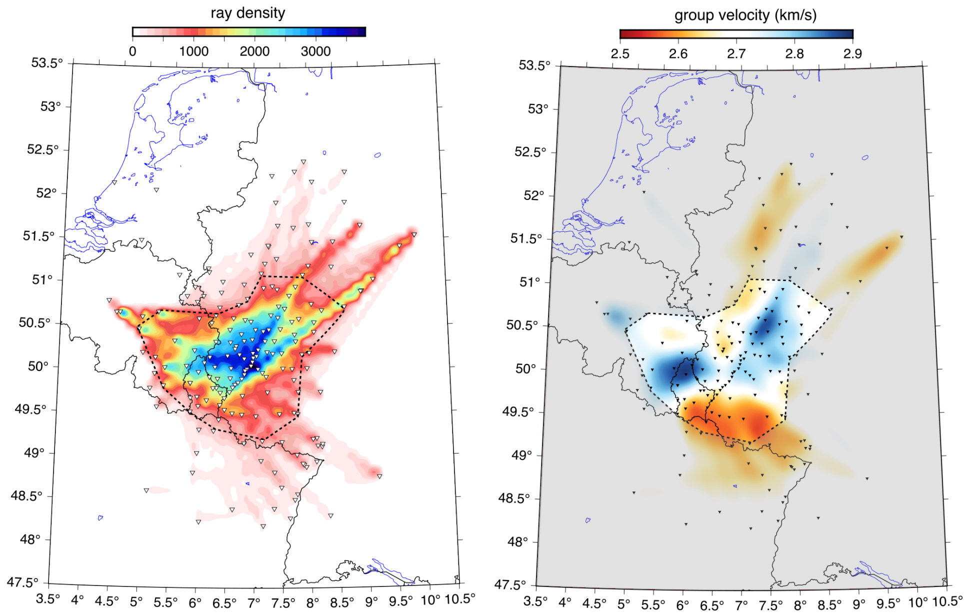

Figure 8. Left panel: ray density of selected paths between stations (inverted triangles). Right panel: 2D Rayleigh wave group velocity map at period T=5s obtained with the tomography code FMST (Rawlinson & Sambridge, 2005). The area with insufficient ray coverage (<10 % of the maximum density value) is masked while the polygon contoured with dashed lines is 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).

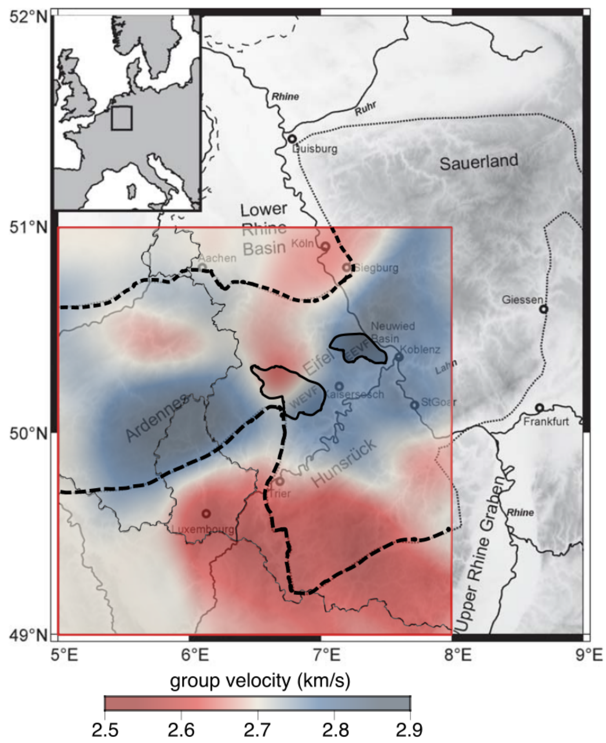

Figure 9. Preliminary comparison between the first obtained tomographic results (here for T=5s, sampling depth down to ~13 km) and the main surface geological features: the Rhenish Massif (black thick dashed line), the Quaternary volcanic fields WEVF (Western Eifel Volcanic Field) and EEVF (Eastern Eifel Volcanic Field). The North-South (Oesling-Gutland) geological boundary in Luxembourg is well retrieved through the positive (fast) and negative (low) anomalies (with respect to an average velocity of 2.7 km/s). Fastest velocities are encompassed within the Rhenish massif while some areas of lower velocities could convey local structural effect, including a part of WEVF (if larger than the minimum 2D spatial resolution > 10 km, sensitivity tests are not shown here). The figure is modified after Meyer and Stets (2007).

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❖ Various international seismological collaborations

In 2021, ECGS was involved in a series of international collaborations, which have led to peer-reviewed articles co-authored by ECGS scientists in high-impact journals.

- **Stress drop derived from spectral analysis considering the hypocentral depth in the attenuation model: application to the Ridgecrest region, California**

  In 2020, D. Bindi from the GFZ German Research Centre for Geosciences in Potsdam, Germany, contacted A. Oth to become involved in a study on the depth-dependence of stress drop estimates by spectral decomposition using the Ridgecrest earthquake sequence in California as an example study region. This work was published in 2021 in the Bulletin of the Seismological Society of America (see Publications section below).

  The study investigates the impact of considering a depth-dependent attenuation model on source parameters assessed through a spectral decomposition. Fourier spectra of S-waves are analysed for about 1900 earthquakes with magnitude above 2.5 recorded in the Ridgecrest region, Southern California. Two different parametrizations of the attenuation term are implemented in the spectral decomposition, either as function of the hypocentral distance alone or as function of both epicentral distance and depth. These parameterisations lead to different attenuation estimates and these differences are transferred to the source spectra and, in turn, to the source parameters. In particular, stress drops for events deeper than 7 km are, on average, almost double when depth is introduced explicitly in the attenuation model.

- **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 is currently in preparation and is planned to be submitted in early 2022.

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 carried out by Oth et al. and Stankiewicz et al. 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. A manuscript on this study is currently in preparation and is planned to be submitted in early 2022.

  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.

- **GITEC: A benchmark for Generalized Spectral Inversion Technique**

  Already in 2018, ECGS became involved in the so-called GITEC benchmark exercise, led by Dr. Fabrice Hollender from the Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA) in Cadarache, France. This benchmark exercise related to a subject of great expertise at ECGS, i.e. the generalized spectral inversion for earthquake ground motion characterization.

  A range of different methods and approaches to this technique exist in the literature, and although this inversion approach is widely used by various research groups throughout the World for earthquake ground motion studies (earthquake source physics, site effects on ground motions, or also seismic attenuation studies of the Earth's crust), there are many methodological assumptions that need to be made when running such inversions, leading to large variations in the results for same datasets by different research groups and inconsistencies in the interpretations.

  The aim of the GITEC exercise was to use a set of synthetic and real dataset examples in order to put the different approaches and existing codes to the test and compare the outcomes of the data processing and inversions in the most objective way possible. Scientists from several world-renowned institutions participated in this exercise, such as the GFZ German Research Centre for Geosciences, Germany; the University of Kobe, Japan; the University of Liverpool, UK; Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Italy; CICESE, Mexico; University of Thessaloniki, Greece; and Electricité de France.

  The consortium involved in the exercise wrote an article on the GITEC study during the course of 2021, which was finally accepted for publication in the Bulletin of the Seismological Society of America.

The May 2021 Nyiragongo Eruption

Figure 10: 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.

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 (Figure 11), 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.

❖ Unfolding of the eruption and scientific follow-up

A retrospective analysis of the seismic and acoustic data recorded by the KivuSNet network stations NYI and KBTI (Figure 12, see also Figure 11 for their locations) allows for an in-depth study of the beginning of this eruption. At around 15:57 UTC, first high-frequency ground motion signals can be seen at the summit station NYI, masking the well-known continuous seismo-acoustic tremor signature that could usually be observed there. At around 16:15, the first earthquakes located at shallow depth beneath the edifice of Nyiragongo could be detected and located across the local network. From 16:35 onwards, the acoustic level on the infrasound sensors increased noticeably, with a coherent source that could be attributed to Nyiragongo. These acoustic signals culminated in bursts of continuous signals between 16:46 and 16:56, which roughly coincides with the first visual observations of lava outflows.

The volcanic crisis continued for several days with numerous earthquakes (Figures 13 and 14) and intense fracturing observed in the cities of Goma (DRC) and Gisenyi (Rwanda). This activity was caused by the southward progression of a 25km long magma injection under the agglomerations of Goma and Gisenyi, then under the gas-laden Lake Kivu. This dyke progression was also clearly visible in the GNSS data from KivuGNet (Figure 14) and in the co-eruptive interferograms from InSAR analysis (Figure 15). It kept the concern at a very high level during 10 more days, especially because the magma progressed at very shallow depth (<500m) below the surface. While the progression could be followed nearly minute by minute, it was impossible to anticipate if it would

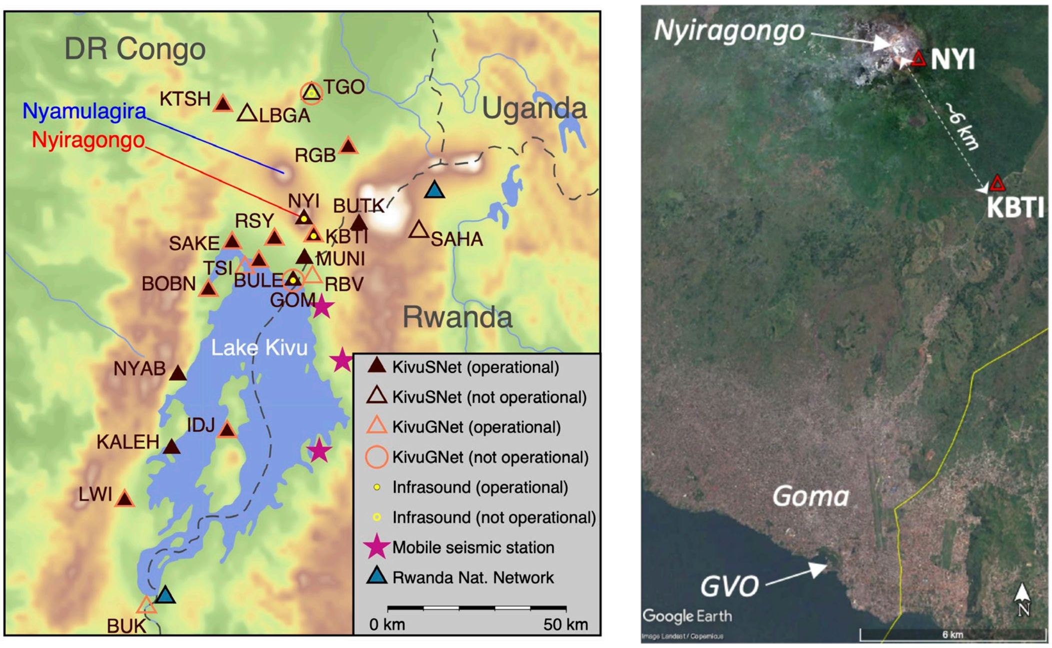

Figure 11: Left panel: Seismic and geodetic stations from KivuSNet and KivuGnet (see also Seismology section below) operating at the time of the eruption. Including stations from the Rwanda National Seismic Network and the mobile stations deployed by ECGS/Mnhn, a total of up to 23 stations was available during the volcanic crisis. Up to 13 GNSS stations from KivuGNet were available. More detailed information on station availability can be found in the report *Nyiragongo 2021 eruption: The Failure of a Success* (see Publications section below). Right panel: Two nearest stations to the volcanic edifice, i.e., station NYI on the rim of the summit crater and station KBTI about 6 km to the SW of the summit crater. Station NYI is equipped with a seismic and an infrasound sensor, while station KBTI is equipped with a seismic sensor, an infrasound array and a GNSS sensor.

suddenly move upward to the surface and produce devastating lava flows directly within the city centres of Goma and Gisenyi, or reach the surface below the Lake Kivu and trigger a phreato-magmatic eruption or a limnic eruption of Lake Kivu. Fortunately, the dyke was arrested against a geological fault while the magma feeding diminished, without creating any of these catastrophic scenarios. Nevertheless, the absence of precursory signals 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 the scientist's vision of the eruptions at that type of volcano, calling for revising the way to prepare for these events.

The eruption killed at least 31 and left 6.000 people homeless while lava flows entered the highly populated city of Goma. That effusive part lasted only 6 hours. A manuscript describing the eruption as well as the subsequent dyke intrusion in detail was prepared in 2021 and submitted early in 2022 (Smittarello et al., under review).

❖ Defamatory accusations by GVO staff and their consequences

While one can doubtlessly say that the monitoring and follow-up of the 2021 Nyiragongo eruption was a major scientific success internationally recognized, unfortunately, the subject that received by far the most, if not exclusive, attention from the media and social networks was the fact that extremely serious unfounded allegations and lies against the GVO management and our Be-Lux consortium were raised by a GVO union representative. The ensuing bashing campaign fuelled by the social networks culminated in a news article[1] published in the renowned *Science* Magazine. Following our response to *Science*, another letter of the GVO union was launched, reiterating on the false accusations of the first letter.

[1] https://www.science.org/content/article/european-data-monopoly-hurt-forecasts-deadly-eruption-congolese-researchers-charge

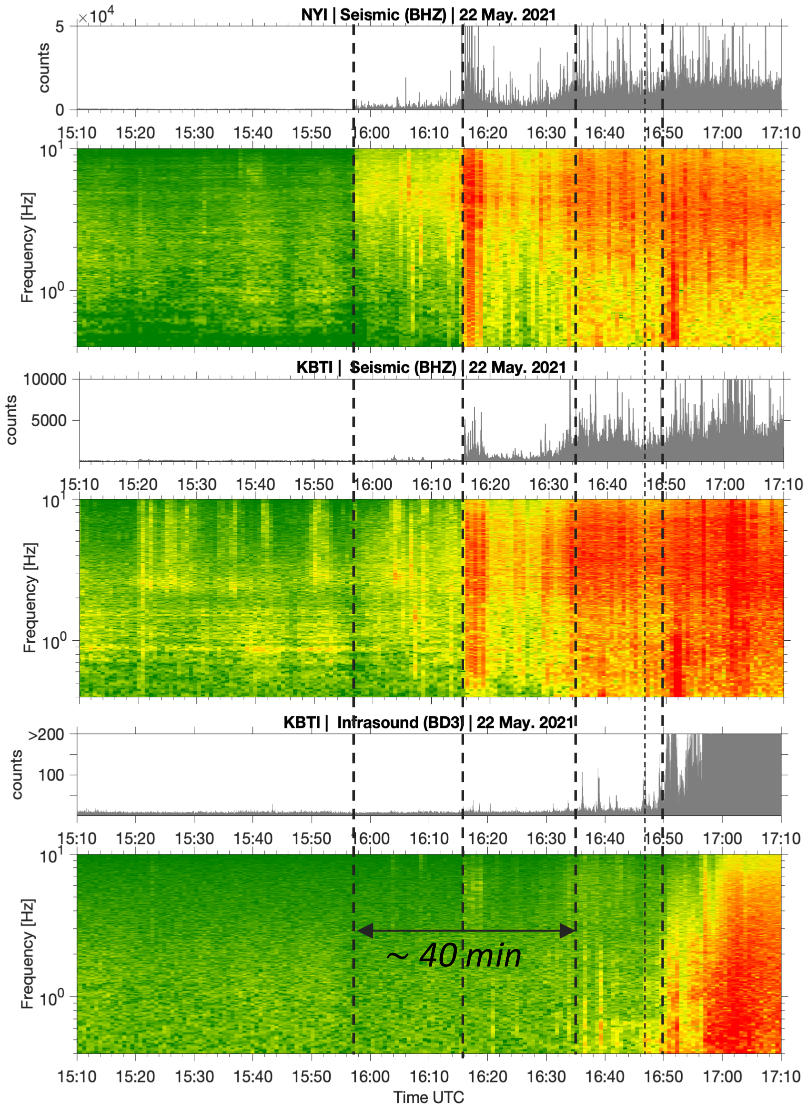

Figure 12: Raw seismic amplitudes and spectrograms of vertical seismic and infrasound channels at stations NYI and KBTI (see Figure 11). Top panels: Vertical seismic channel at station NYI. Middle panels: Vertical seismic channel at station KBTI. Bottom panels: Infrasound channel at station KBTI. The vertical dashed lines indicate onset times for different signals (see text). Note that the very first seismic signals at station NYI appear only ~40 min prior to the first visual accounts of lava outbursts.

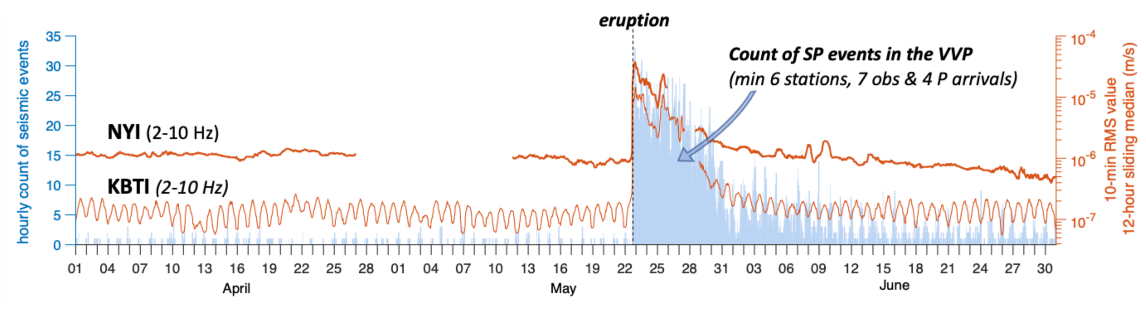

Figure 13: Hourly count of volcano-tectonic earthquakes in the Virunga region (blue). Note the very sudden onset of seismic activity at the time of the eruption, indicating that no precursory increase in seismicity was present prior to the eruption. Orange lines show 12h moving averages of the seismic amplitudes at stations NYI and KBTI, also showing no anomalies prior to the eruption. Note the diurnal variation in network sensitivity due to anthropogenic noise visible prior to the eruption and in the amplitudes at KBTI station (higher amplitudes and more detected events during night time).

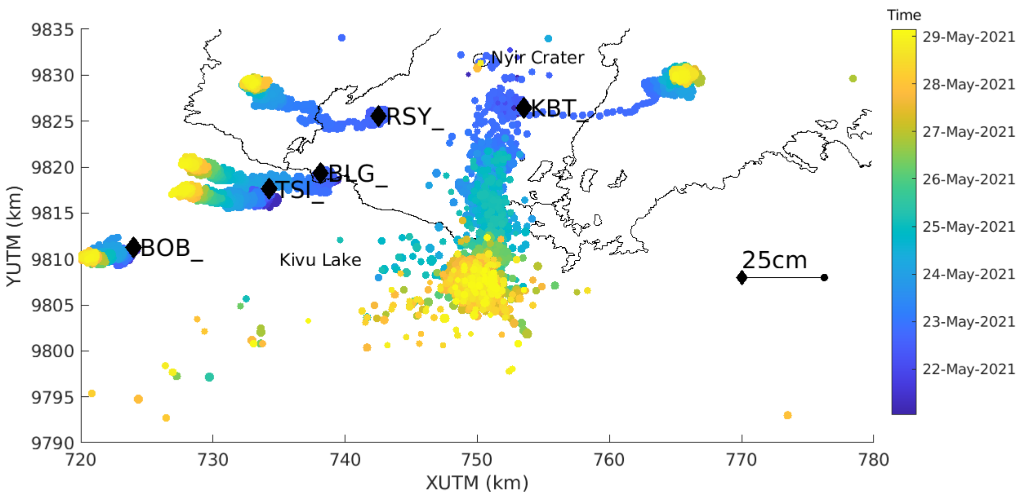

Figure 14: Migration of seismicity during the dyke intrusion from North to South from the beginning of the eruption on 22 May until 29 May (color-coding), when the dyke stopped its southward progression underneath Lake Kivu. In addition, the movement with time of the GNSS stations BOB, TSI, BLG, RSY and KBT is shown with the same color-coding, clearly visualizing the EW opening caused by the dyke intrusion.

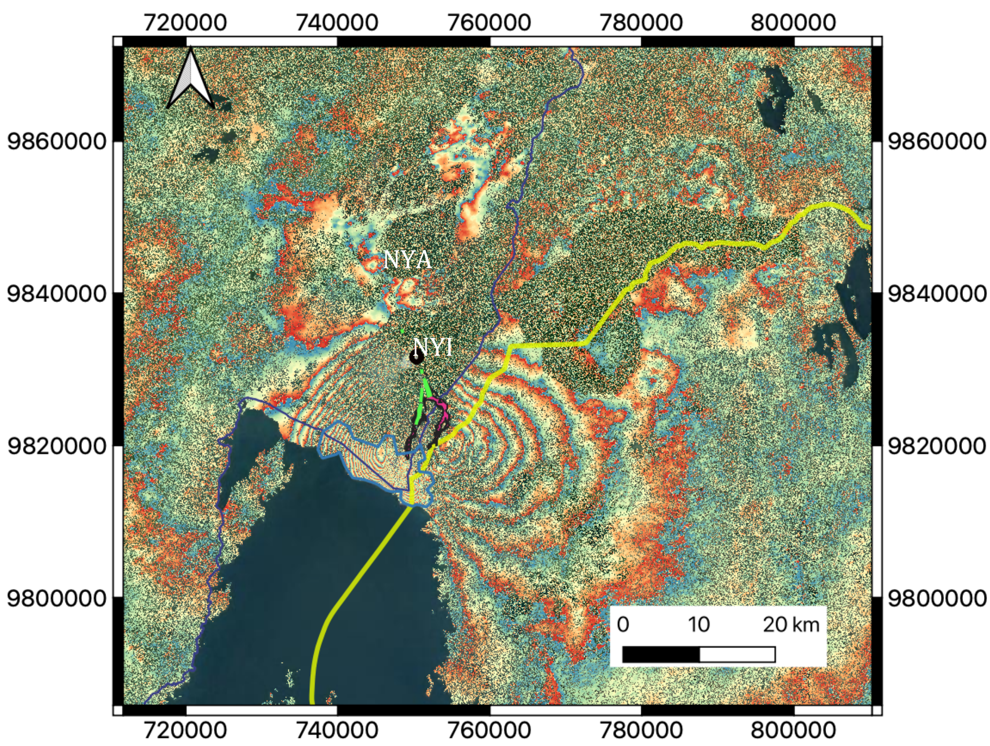

Figure 15: Co-eruptive deformation at Nyiragongo volcano measured with Sentinel 1 interferogram using images acquired on 2021-05-19 and 2021-05-25 along Ascending orbits 174 (wrapped on Google Earth image). The interferogram was computed with MasTer toolbox (d'Oreye et al., 2021). Each color cycle represents a displacement of 3cm in the satellite line of sight. The border between DRC (left) and Rwanda (right) is shown in yellow, eruptive fractures in green, 2021 lava flows in pink, Goma (DRC) and Gisenyi (Rwanda) cities contour in light blue, main roads in dark blue. The black circle marks the contour of Nyiragongo (NYI) volcano. Nyamulagira volcano is marked by NYA. The deformed region extends over more than 15.000 km^2. The ground uplifted more than 2 meters and spread by about 2.5 meters at its maximum. Numerical models and inversions allow to determine that these deformations were caused by a 25 km long dyke oriented in north-south direction, extending from north of Nyiragongo up to below the Lake Kivu. The tip of the dyke was less than 500m below the cities of Goma and Gisenyi and Lake Kivu.

Among several other accusations against the GVO management board and local authorities, these letters from the GVO union, in short, describe our consortium as a group of colonial scientists preventing the development of GVO's monitoring and research capabilities, and include a vast plethora of wild accusations. As the Be-Lux consortium, we responded in great detail to each and every of these accusations in the report *The Nyiragongo 2021 eruption: the failure of a success*[2], available online in the News section of the GeoRiskA via the link provided in footnote. This document contains our responses to the accusations, supported by facts and evidences, and all the accusation letters in annexes. We therefore do not discuss any further this unpleasant matter, but refer the interested reader to this document for more details on these issues.

While it may seem that these accusations surface out of nowhere, they have to be seen in a doubtlessly difficult national (political, economic, security) and local (internal conflicts among GVO staff, monetary motifs, ethnic rivalries etc) context, often putting international collaborators between the hammer and the anvil. There was nothing really new in these difficulties, but the eruption offered unprecedented visibility to all kinds of messages, quickly relayed by social media and subject to all kinds of amalgams.

Naturally, despite the (unfortunately late) support from the Congolese authorities, these accusations and defamation severely undermined our relationship with GVO. As a consequence, our Be-Lux consortium chose to temporarily limit the collaboration to the minimum level required to maintain the fundamental monitoring capabilities of GVO (i.e., data transmission and remote maintenance of the acquisition server) until we receive the necessary clarifications from the Congolese side (what type of collaboration is desired?) and the definition of an adequate formal framework for the future collaboration with GVO. This was already the topic of several discussions[3] and will be further discussed at the occasion of an International Conference planned in Goma early in 2022, assisted by the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), who stepped in to facilitate the necessary discussions on an international level.

We would like to note at this point that despite their evident unpleasant nature, these issues do of course not hamper our scientific research activities.

❖ Nyiragongo's intracrateral eruption dynamics from 2002 to 2021

Nyiragongo is one of the rare volcanoes on Earth hosting a lava lake. However, the understanding of its plumbing and lava lake systems remains limited, with, until recently, only sporadic or time-limited historical observations and measurements (Figure 16). Combining dense accurate lava lake and crater floor level measurements based on 1703 satellite radar images and topographic reconstructions using photogrammetry, we obtain the first reliable picture and time evolution of intracrateral erupted lava volumes between the two last flank eruptions in January 2002 and May 2021. The filling of the crater by lava initiated in 2002 and continued up to May 2021 through successive but irregular pulsatory episodes of lava lake overflows. Numerous drops of the lake level also punctuated this long-term pressure build up. The joint analysis with seismic records available since 2015 revealed that the largest lava lake drops are synchronous to seismic swarms associated with deep magma intrusions. In contrast, the absence of seismicity during the appearance of a spatter cone in the summit crater in 2016 indicates that this cone was most likely shallowly connected to the lava lake system. An increase of extrusion rate within the crater was generally, but not systematically, observed during the months preceding major drops of the lava lake level between 2016 and 2020, as well as before the last 2021 flank eruption. This first long-term timeseries of Nyiragongo's crater topography changes between two hazardous flank eruptions might further help to better decipher Nyiragongo's past and future behavior using multi-parameter observations.

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[2] https://georiska.africamuseum.be/en/news/ResponseToAccusations

[3] Including a meeting with the Congolese Minister for Research in Brussels and a visit of GVO's director general and the chief of staff (directeur de cabinet) of the Minister at the premises of ECGS/Mnhn in Walferdange in September 2021, who both confirmed their support to our consortium and expressed their wish for us to carry on with the support to GVO.

This work was carried out to a large extent already in 2020, but had to be taken back after submission in light of the 2021 Nyiragongo eruption in order to include data reaching up to the eruption into the paper. This article manuscript thus provides the most complete and densest possible scientific analysis of Nyiragongo's intracrateral eruption dynamics between the two flank eruptions of 2002 and 2021. The manuscript was re-submitted in December 2021 and is currently under review in Journal of Geophysical Research.

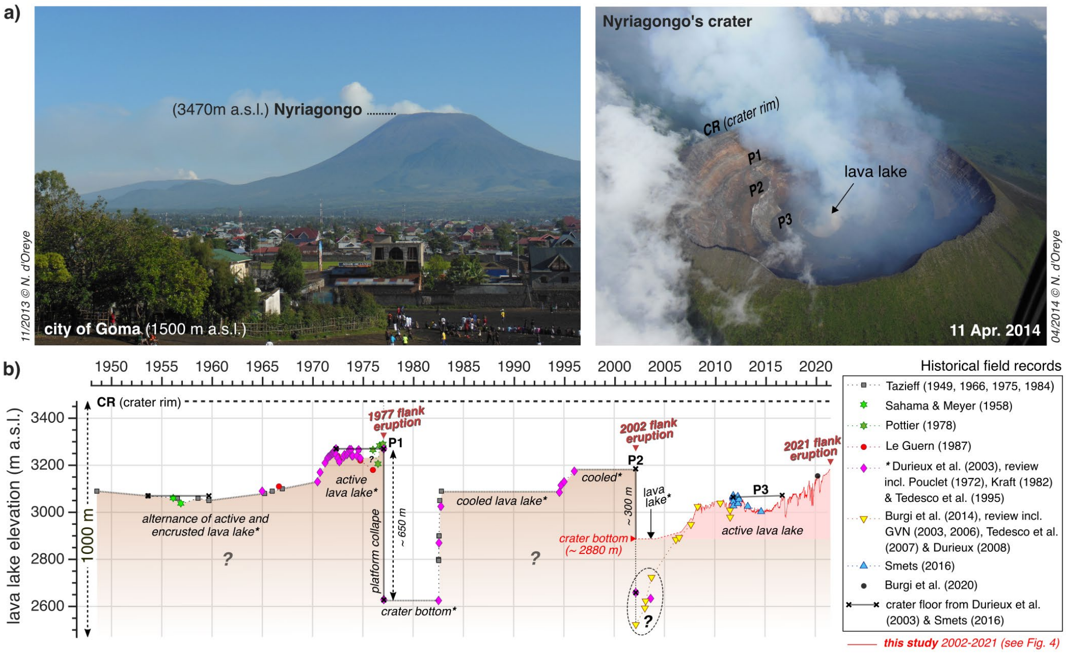

Figure 16: a) Picture of Nyiragongo taken from the Goma Volcano Observatory (GVO) on November 2013. The active volcano Nyamulagira (D.R. Congo, ~3052 m a.s.l.) is also visible at the background. The orientation of this picture is roughly South to North. An aerial view of Nyiragongo's crater on April 2014 is depicted on the right. b) Lava lake elevation (in m a.s.l.) from historical field records and recent expeditions (1948-2020) and from the continuous estimates obtained in the present study (red line). Details about the references before 2016 can be found in Smets (2016). Comments marked by an asterisk come from the review paper by Durieux et al. (2003). The new estimate of the crater floor after the 2002 eruption (~2880 m a.s.l.) is taken into account. Batches of former crater floor left after the 1977 eruption are named *P*1 platform (~3270 m a.s.l), while batches of level reached prior to the 2002 eruption are named *P*2 platform (~3190 m a.s.l). *P*3 platform is the crater floor hosting the lava lake.

For further information on our work in the Kivu Rift region, please see also the websites http://resist.africamuseum.be/ and http://www.virunga-volcanoes.org/.

Further details on the 2021 Nyiragongo eruption can also be found on the website of GeoRiskA: https://georiska.africamuseum.be/en/news/nyiragongo_eruption.

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 2021, 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 - 2021 (ESA, Belspo)
- **NSF-Crater-Floor: Modeling of crater floor deformation in relationship with lava lake activity,** 2020 - 2023 (NSF, USA)

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 apply 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 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 will be 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 modeled 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.

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)

In the framework of HARISSA, VERSUS and MODUS, we carried on with the **maintenance of the KivuGnet and KivuSnet** telemetered networks in DR Congo. Data are automatically processed and displayed on password protected web pages. Despite the travel restrictions imposed by the COVID pandemic, enough spare parts left at Goma Volcano Observatory (GVO) helped to solve most of the problems remotely.

❖ Development of ground motion deformation monitoring tools by satellite

In the frame of several research projects, we carried on 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.

The toolbox was enriched with several new scripts to perform various tasks answering specific needs from the various projects and 40 new pages were added to the manual to explain these new features. Description of MasTer toolbox was published in a peer reviewed paper (d'Oreye et al., 2021).

The MSBAS time series inversion optimization tools based on a coherence proxy to guide the interferometric pair selection (developed by Delphine Smittarello, ECGS) was presented in a manuscript currently under review (Smittarello et al., under review).

The MasTer software is still routinely used at ECGS to perform automatic monitoring of several targets using ESA Sentinel-1 data, i.e. for volcano monitoring in the Virunga Volcanic Province in DRC, anthropogenic deformation in the Greater Region, landslides and volcanic activity in the Réunion Island and volcano monitoring in the Domuyo/Laguna del Maule volcanic region in Chile and Argentina. SAR amplitude time series using Sentinel-1 images are also routinely used to monitor the geomorphological changes in the crater of the Nyiragongo and Nyamulagira volcanoes in DRC and Kilauea volcano in Hawaii. This method, named SASha, was presented in a paper currently under review (Barrière et al., under review).

New additional automatic procedures were set up using CosmoSkyMed data provided by ASI (Italian Space Agency) and applied to monitor the ground deformation monitoring in the Virunga and the geomorphological changes at Nyiragongo and Nyamulagira volcanoes.

The tool was also used to contribute to additional non funded collaborations such as landslides studies in South Kivu (Dille et al., 2021), monitoring the ground stability in the region of the possible installation of the future Einstein gravitational telescope (border region between Belgium, Netherlands and Germany), or Wallonia region in Belgium between Genappe and Waremme.

The remote sensing and ground deformation monitoring tools developed at ECGS/Mnhn also played a key role in the **follow-up of the 2021 Nyiragongo eruption**, for which we refer the reader to the dedicated section above.

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 carried 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 addition, radon (Rn) and various other gas and ultra-high-resolution temperature monitoring in the Laboratory and all along the entrance galleries are 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 also previous reports). In order to advance on this subject, a meeting was held at the premises of 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.

As a follow-up of this meeting, representatives from the *Inspection du Travail et des Mines (ITM)* visited ECGS/Mnhn and the WULG on 21 April 2021 in order to discuss the modalities on how to advance on the security issues of the mine and the requirements to be fulfilled. Following this meeting, the ITM was also provided with plans and photos of the mine by Mr. Robert Colbach from the *Service géologique*.

Since these meetings, however, 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 2021

Prof. em. Antoine Kies

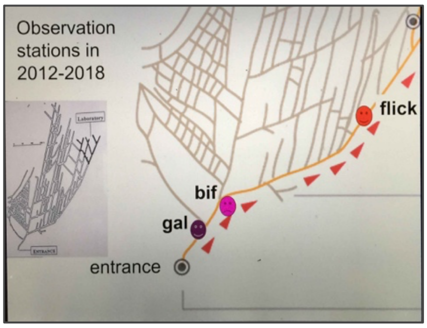

Figure 17: Radon observation sites in WULG.

We report from radon and temperature data recorded continuously in the mine at two locations:

- 'gal' endpoint of the lateral gallery situated before the main bifurcation
- 'flick' in the main gallery close to 'Flick cellar'.

Furthermore, we rely on the meteorological data kindly provided by Dr. Joerg Bareiss from MeteoLux.

With respect to the radon concentrations, 2021 was an exceptional year. Throughout all the years since 1992 that we measure radon concentrations in the WULG, the radon levels were never so low over the summer.

In this context, we need to recall some basic characteristics of the mine. The temperature inside the mine is stable, slightly above 10 °C. Radon measured in the air of the mine at the measurement site 'flick' has two contributions: one stable contribution (around 2.4 kBq/m^3) due to radon supplied continuously by the rocks of the mine and one contribution through radon transported by air movement from 'gal' into the mine. Radon at 'gal' is highly influenced by the external temperatures that dictate air movements in the partly collapsed lateral gallery ending at the gal measurement point. The higher the outside temperature ranges above the mine temperature of about 10 °C, the more radon-charged air reaches the 'gal' point and enters the mine interior. At outside temperatures below 10°C, the direction of air movements in the source gallery is reversed; no radon enters the mine at the 'gal' point.

Figure 18 shows yearly radon concentrations and atmospheric pressure. There is limited influence of air pressure on radon concentrations. Low air pressures facilitate radon to leave the rocks whereas high pressures slightly inhibit this process.

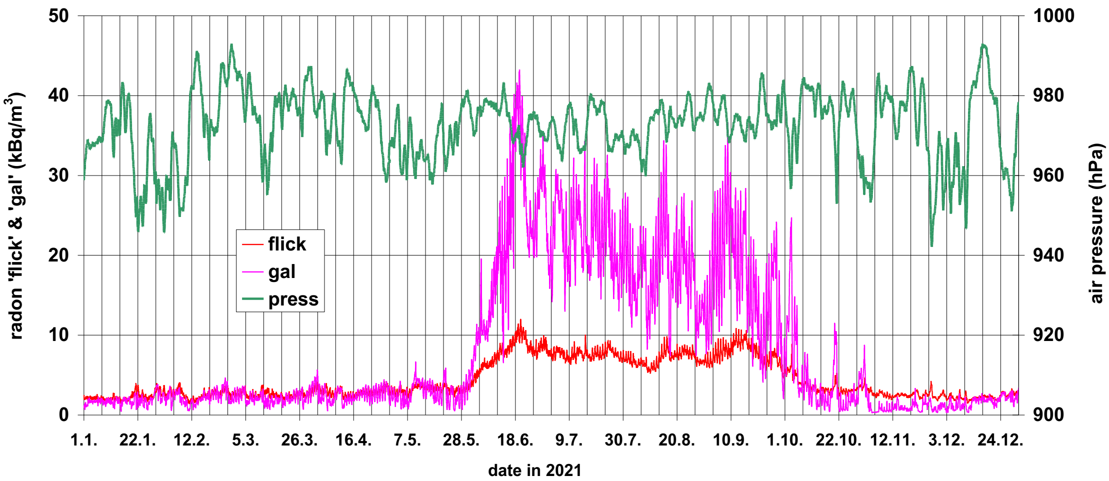

Figure 18: Radon concentration at 'flick' and 'gal' are slightly influenced by atmospheric pressure.

Radon concentrations are low in the cold seasons, where radon from local production remains in the mine. At 'gal' they are below the mine levels. In 2021 mine radon levels reached 10 kBq/m^3 only once, in June, and not in the summer months, very unusual. In 2020 they went up to 16 Bq/m^3.

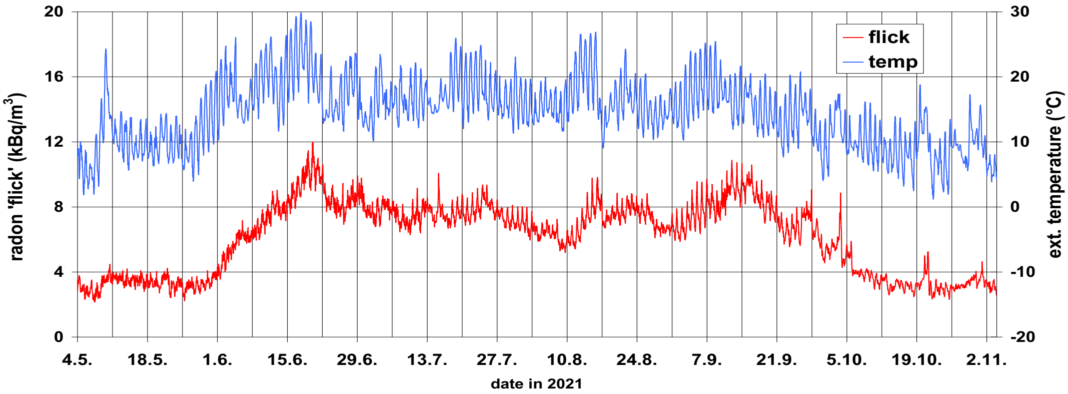

Figure 19: Radon measurements at 'flick' and outside temperature.

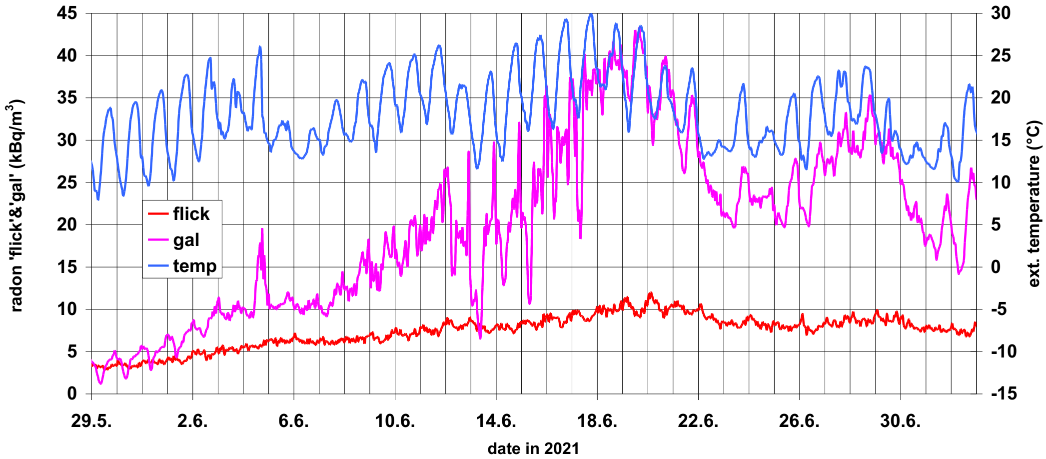

Figure 20: Close-up of Figure 19 for the time period of 29 May to 3 July 2021, including also measurement point 'gal'.

Figure 19 shows radon at 'flick' and 'gal' and outside temperature for the summer months. Only once the maximum daily temperature reached 30 °C. In Figure 20 a close-up view of the month of June illustrates why in 2021 radon levels did not build up as in the years before.

Rising ambient temperatures, also at night, increase radon concentrations at 'gal', radon charged air can mix with the mine air. This ended on 18 June. Especially low night temperatures, approaching 10°C after 26 June, lowered the radon levels at 'gal' and hence limited the transport of radon into the mine. Besides this situation, one has to take into account the decay time of radon (T = 3.8 days). Similar situations continued the next months and radon concentrations could never built up to their usual levels.

Finally, we report of an interesting finding: during visits to the mine (collecting the data), air movements are usually checked with cigar smoke, a very unhealthy but convenient method. Before the plastic shielding of side galleries as discussed in previous reports, the main airflow in the mine was documented by us along the main gallery leading to the geophysical laboratory, diverging into the last lateral gallery anterior to the separation wall, distributing air into the maze of galleries. The outflow of these air movements was primarily located at the main bifurcation, location 'bif' (Figure 17). This was/is the cause why the whole mine had/has good air quality proven also by uniform radon concentrations. Fortunately, this air movement still exists despite the closure of all lateral galleries with plastic sheets. Two laboratories for gravimeters were built in two of the side galleries, but there exists a lateral space between the rocks and the laboratory walls. A very strong air inflow from the main gallery into the mine interior always exists here. At location 'bif', though a hole in the plastic shielding, there is a strong inflow of air into the main gallery, closing the circle.

OUTREACH ACTIVITIES

- **Radio 100,7 Interviews on the Nyiragongo eruption**, 1 June 2021 and 17 June 2021, featuring A. Oth (1 June) and N. d'Oreye (17 June)
- **RTL De Magazin Interview** regarding the seismic noise characteristics in Luxembourg during the Covid 19 lockdown in 2020, 21 June 2021, featuring A. Oth
Weblink: https://5minutes.rtl.lu/actu/frontieres/a/1535442.html
- **"L'Eruption du Nyiragongo"**, L'Eventail Magazine, 1 September 2021, pp 32-35, featuring N. d'Oreye
- Several interviews in the international press regarding the Nyiragongo eruption
- Development of an easy-to-use real-time visualization system of seismic records based on Raspberry Shake instruments for educational purposes in DR Congo (CIRRINa, Centre d'Information et de Recherche sur les Risques d'Origine Naturelle, Université de Bukavu), J. Barrière and G. Celli
- Maintenance of a **web site** dedicated to the monitoring activities and studies of the **Virunga volcanoes**: www.virunga-volcanoes.org
- Contributions to the **web site of the Georiska research group** for the follow-up of the volcanic crisis at Nyiragongo in May 2021:
Weblink: https://georiska.africamuseum.be/fr/news/nyiragongo_eruption

PUBLICATIONS & PRESENTATIONS

❖ Peer-reviewed Journal Publications and Proceedings

Published & in press

Bindi, D., H. N. T. Razafindrakoto, M. Picozzi and **A. Oth** (2021). Stress Drop Derived from Spectral Analysis Considering the Hypocentral Depth in the Attenuation Model: Application to the Ridgecrest Region, California. *Bull. Seismol. Soc. Am.*, 111, 3175–3188.

Dille A., F. Kervyn, A. Handwerger, **N. d'Oreye**, D. Derauw, T. Mugaruka Bibentyo, S. Samsonov, J.-P. Malet, M. Kervyn and O. Dewitte (2021). When image correlation is needed: unravelling the complex dynamics of a slow-moving landslide in the tropics with dense radar and optical time series *Remote Sensing of Environment,* 258, 112402.

d'Oreye, N., D. Derauw, S. Samsonov, **M. Jaspard** and **D. Smittarello** (2021). MasTer: a full automatic multi-satellite InSAR mass processing tool for rapid incremental 2D ground deformation time series. *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2021*, Brussels.

Shible, H. F. Hollender, D. Bindi, P. Traversa, **A. Oth**, B. Edwards, P. Klin, H. Kawase, I. Grendas, R. R. Castro, N. Theodoulidis and P. Gueguen (2021). GITEC: A Generalized Inversion Technique Benchmark. *Bull. Seismol. Soc. Am.*, in press.

Shreve, T., R. Grandin, **D. Smittarello**, V. Cayol, V. Pinel, M. Boichu and Y. Morishita (2021). What triggers caldera ring-fault subsidence at Ambrym volcano? Insights from the 2015 dike intrusion and eruption. *J. Geophys. Res.*, e2020JB020277.

Smittarello, D., V. Pinel, F. Maccaferri, S. Furst, E. Rivalta and V. Cayol (2021). Characterizing the physical properties of gelatin, a classic analog for the brittle elastic crust, insight from numerical modeling. *Tectonophysics*, 812, 228901.

Theys, N., H. Brenot, I. De Smedt, C. Lerot, P. Hedelt, D. Loyola, J. Vlietinck, H. Yu, B. Smets, F. Kervyn, **J. Barrière**, **N. d'Oreye** and M. Van Roozendael (2021). Global Monitoring of volcanic SO2 Degassing using Sentinel-5 precursor Tropomi. *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2021*, Brussels.

Under review

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. On the origins of intracrateral eruption dynamics at Nyiragongo volcano (D.R. Congo) in the period 2002-2021, *J. Geophys. Res.*, under review.

Dille, A., O. Dewitte, A. Handwerger, D. Derauw, **N. d'Oreye**, J. Moeyersons, E. Monsieurs, T. Mugaruka Bibentyo, S. Samsonov, B. Smets, M. Kervyn and F. Kervyn. Urban growth and the dynamics of a large deep-seated landslide in the tropics. *Nature Geoscience*, under review.

Smittarello, D., **N. d'Oreye**, **M. Jaspard**, D. Derauw and S. Samsonov. Pair Selection Optimization for InSAR Time Series Processing. *J. Geophys. Res.*, under review.

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. Precursor-free eruption and lateral dike migration triggered by edifice rupture at Nyiragongo volcano. *Nature*, under consideration.

❖ Reports

Kervyn, F., **N. d'Oreye**, **A. Oth** and **J. Barrière** (2021). *The Nyiragongo 2021 eruption: the Failure of a Success*, 29 pp. Report in response to unfounded and defamatory allegations against the GVO management committee and the Belgo-Luxembourgian consortium (RMCA and ECGS/Mnhn) after the 2021 Nyiragongo eruption.

Weblink: https://georiska.africamuseum.be/sites/default/files/media/2_NEWS/2109_ResponseAccusation/Failure%20of%20a%20success_ExecSum&Doc&Annex-EN.pdf

❖ Conference Presentations and Abstracts

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 (2021). On the origins of intracrateral eruption dynamics at Nyiragongo volcano in the period 2002-2021. *AGU Fall Meeting 2021, New Orleans & Online, 13-17 Dec 2021.*

F. Kervyn, O. Dewitte, W. Thiery, **N. d'Oreye** and J.-P. Malet (2021). Landslide and Flash Flood Timing from Satellite Radar Imagery in the Western Branch of the East African Rift. *AGU Fall Meeting 2021, New Orleans & Online, 13-17 Dec 2021.*

Deijns, A., F. Kervyn, O. Dewitte, W. Thiery, J.-P. Malet and **N. d'Oreye** (2021). A multi-sensor satellite method to spatial and temporal detection of landslides and flash floods in cloud-covered tropical environments: the western branch of the East African Rift. *EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-8909.*

Deijns, A., O. Dewitte, W. Thiery, J.-P. Malet, **N. d'Oreye** and F. Kervyn (2021). Landslide and flash flood timing from satellite radar imagery in the western branch of the East African Rift. *7th International Geologica Belgica Meeting, 15-17 September 2021 – AfricaMuseum Tervuren (Belgium).*

Delhaye, L., **J. Barrière**, **N. d'Oreye**, F. Kervyn, **A. Oth** and B. Smets (2021). Application of Photogrammetry in Earth Sciences: Case Study of Lava Accumulation and Ground Deformation in an Active Volcanic Crater. *7th International Geologica Belgica Meeting, 15-17 September 2021 – AfricaMuseum Tervuren (Belgium).*

Dille, A., F. Kervyn, A. Handwerger, **N. d'Oreye,** D. Derauw, T. Mugaruka Bibentyo, S. Samsonov, J.-P. Malet, M. Kervyn and O. Dewitte (2021). When image correlation is needed: combining very dense radar-amplitude and optical times series for unravelling the complex dynamics of a not so slow slow-moving landslide in the tropics. *EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-10627.*

d'Oreye, N., D. Derauw, **D. Smittarello**, S. Samsonov and **M. Jaspard** (2021). MasTer: A Full Automatic Multi-Satellite InSAR Mass Processing Tool for Rapid Incremental 2D Ground Deformation Time Series. *AGU Fall Meeting 2021, New Orleans & Online, 13-17 Dec 2021.*

d'Oreye, N., D. Derauw, S. Samsonov, **M. Jaspard** and **D. Smittarello** (2021). MasTer: A Full Automatic Multi-Satellite InSAR Mass Processing Tool for Rapid Incremental 2D Ground Deformation Time Series. *International Geoscience and Remote Sensing Symposium, July 12-16 (IGARSS2021), Brussels (Belgium) – Virtual conference*.

Kervyn F. et al. (2021). Natural hazards and associated risks in central Africa: a holistic approach. *6th Journées Scientifiques du Centre de Recherche Géologique et Minière (CRGM) sur le theme "Les Risques Naturels : Leur connaissance, impact environnemental et societal en RD. Congo", 28-29 Oct 2021, Kinshasa (RDC).*

Kervyn, F., A. Muhindo Syavulisembo, **J. Barrière**, **N. d'Oreye**, B. Mafuko, J. Makundi, C. Michellier, B. Smets and J. Subira (2021). The long way towards volcanic risk reduction in the Kivu region (DRC-Rwanda border). Sharing experience of an international collaboration. *9th UNESCO's 'Geoheritage for Geohazard Resilience Program' webinar, 5 May 2021*, On-line (http://www.geopoderes.com/webinar_09/).

Najdahmadi, B., M. Pilz, . Bindi, H. N. T. Razafindrakoto, **A. Oth** and F. Cotton (2021). ROBUST, an earthquake early warning system in the Lower Rhine Embayment, Germany. Second International Conference on Natural Hazards and Risks in a Changing World, 5-6 October, Potsdam, Germany.

Najdahmadi, B., M. Pilz, . Bindi, H. N. T. Razafindrakoto, **A. Oth** and F. Cotton (2021). ROBUST, an earthquake early warning system in the Lower Rhine Embayment, Germany. European Seismological Commission, 19-24 September 2021, virtual.

Najdahmadi, B., M. Pilz, . Bindi, H. N. T. Razafindrakoto, **A. Oth** and F. Cotton (2021). ROBUST, an earthquake early warning system in the Lower Rhine Embayment, Germany. *EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-7997.*

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**) (2021). The Be-Lux contribution to the real time tracking of the 2021 Nyiragongo eruptive crisis. *4th IAVCEI Webinar, 29 Oct 2021, online (https://www.iavceivolcano.org/media-gallery/webinars/ - requires IAVCEI membership).*

Oth, A., **N. d'Oreye**, **J. Barrière, D. Smittarello** (2021). ECGS Research Activities. *Seminar at the occasion of the visit of a Congolese delegation at ECGS (General Director of the Goma Volcano Observatory and Ministry of Research's chief of staff – Directeur de Cabinet), 28 Sept 2021, Walferdange, Luxembourg.*

Smets, B., **J. Barrière**, C. Caudron, V. Cayol, **N. d'Oreye**, L. Delhaye, R. Grandin, E. Kamathe Kaleghetso, S. Molendijk, A. Muhindo Syavulisembo, C. Kasereka Mahinda, O. Namur, **A. Oth**, S. Poppe, **D. Smittarello**, J. Subira, N. Theys, C. Wauthier and F. Kervyn (2021). Magma reservoir failure at open-vent volcanoes: lessons learned from Nyiragongo volcano, Democratic Republic of Congo. *AGU Fall Meeting 2021, New Orleans & Oline, 13-17 Dec 2021.*

Smets, B., **J. Barrière**, C. Caudron, V. Cayol, O. Chevrel, **N. d'Oreye**, F. Darchambeau, L. Delhaye, D. Derauw, H. Geirsson, R. Grandin, E. Kamate Kaleghetso, C. Kasereka Mahinda, M. Kervyn, C. Michellier, S. Molendijk, A. Muhindo Syavulisembo, O. Namur, **A. Oth**, S. Poppe, S. Samsonov, **D. Smittarello**, J. Subira, N. Theys, C. Wauthier, T. Zwiener, F. Kervyn (2021). The May 2021 Flank Eruption of Nyiragongo Volcano, Democratic Republic of Congo. *7th International Geologica Belgica Meeting, 15-17 September 2021 – AfricaMuseum Tervuren (Belgium).*

Smets, B., **J. Barrière**, O. Dewitte, A. Deijns, L. Delhaye, A. Depicker, A. Dille, **N. d'Oreye**, N. Theys, T. Zwiener and F. Kervyn (2021). Remote Sensing of Geohazards in Central Africa. *7th International Geologica Belgica Meeting, 15-17 September 2021 – AfricaMuseum Tervuren (Belgium).*

Smittarello, D., **J. Barrière**, **N. d'Oreye**, B. Smets, **A. Oth**, T. Shreve, J. Subira, B. Mafuko Nyandwi, V. Cayol, R. Grandin, C. Wauthier, D. Derauw, H. Geirsson, N. Theys, F. Darchambeau, S. Poppe, P. Allard, C. Caudron, P. Lesage, S. Samsonov, L. Delhaye, O. Chevrel and N. Mashagiro (2021). Propagation and arrest of the May 2021 lateral dike intrusion at Nyiragongo (D.R. Congo). *AGU Fall Meeting 2021, New Orleans & Online, 13-17 Dec 2021, https://www.essoar.org/doi/10.1002/essoar.10509249.1.*

Smittarello, D., **N. d'Oreye**, D. Derauw, S. Samsonov and **M. Jaspard** (2021). A New Optimisation Tool for Automatic InSAR Time Series Processing with MasTer. *EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-410.*

Smittarello, D. (2021). InSAR contributions to the temporal monitoring of deformation and its applications to volcanic context, Seminar, IPGP (5 March 2021).

Smittarello, D. (2021). Apports des images SAR pour le suivi temporel de la déformation et applications en contexte volcanique, Seminar, Kermap (26 November 2021).

Theys, N., H. Brenot, I. De Smedt, C. Lerot, P. Hedelt, D. Loyola, J. Vlietinck, H. Yu, B. Smets, F. Kervyn, **J. Barrière**, **A. Oth**, **N. d'Oreye** and M. Van Roozendael (2021). Global Monitoring of Volcanic SO2 Degassing using Sentinel-5 Precursor Tropomi. *International Geoscience and Remote Sensing Symposium, July 12-16 (IGARSS2021), Brussels (Belgium) – Virtual conference*.

Yen, M.-H., D. Bindi, R. Zaccarelli, **A. Oth** and F. Cotton (2021). Scaling relationships and spatial variability of source parameters in central-southern Europe. European Seismological Commission, 19-24 September 2021, virtual.

MEETING ATTENDANCE, FIELD MISSIONS, WORK VISITS

Due to the COVID-19 pandemic, major conferences were generally online meetings also in 2021. The pandemic also resulted in the fact that very few, in-person work visits were possible. Most work meetings took place virtually, which will not be listed here due to their very large number.

Adrien Oth

- 7th International Geologica Belgica Meeting, Brussels (Belgium), 17-19 September
- 37th General Assembly of the European Seismological Commission, 19-24 September
- IAVCEI Webinar "Nyiragongo 2021 eruption", 29 October
- Southern California Earthquake Center (SCEC) Community Workshop: Stress Drop Validation, online, 4 November
- Several virtual meetings for planning of the 2022 Eifel Large-N array experiment, initiated by the GFZ German Research Centre for Geosciences, Germany.
- Work visits & visitors at ECGS:
  - Meeting regarding the WULG at Ministry of Culture, Luxembourg (12 January)
  - Online meeting with VDAP (Volcano Disaster Assistance Program, USGS), GVO and RMCA about the future of geophysical monitoring capabilities at GVO (14 April)
  - Meeting with ITM regarding the WULG at ECGS (21 April)
  - Visit of PhD student Josué Subira at ECGS (7-25 June 2021)
  - Visit of GVO's Director General Dr. Adalbert Muhindo and the Chief of Staff (Directeur de cabinet) of the DR Congo Minstry of Research at ECGS (28 September)

Nicolas d'Oreye

- Field mission to DR Congo and Rwanda for the follow-up of the 2021 Nyiragongo eruption, 28 May - 12 June
- International Geoscience and Remote Sensing Symposium (IGARSS2021), Brussels (Belgium), 12-16 July
- IAVCEI Webinar "Nyiragongo 2021 eruption", 29 October
- American Geophysical Union (AGU) Fall Meeting, New Orleans (USA) & online, 13-17 December
- Work visits & visitors at ECGS:
    - Meeting regarding the WULG at Ministry of Culture, Luxembourg (12 January)
    - Online meeting with VDAP (Volcano Disaster Assistance Program, USGS), GVO and RMCA about the future of geophysical monitoring capabilities at GVO (14 April)
    - Meeting with ITM regarding the WULG at ECGS (21 April)
    - Scientific Committee meeting of VERSUS project, RMCA, Brussels (21 January)
    - Meeting with the Congolese Minster for Research and GVO's Director General, RMCA, Brussels (22 September)
    - Meeting with ITM (at ITM's building) regarding Rumelange's mine and rockfall monitoring applications (27 September)
    - Visit of Dr. Dominique Derauw at ECGS (19-20 May)
    - Visit of GVO's Director General Dr. Adalbert Muhindo and the Chief of Staff (Directeur de cabinet) of the DR Congo Minstry of Research at ECGS (28 September)

Julien Barrière

- 7th International Geologica Belgica Meeting, Brussels (Belgium), 17-19 September
- 37th General Assembly of the European Seismological Commission, 19-24 September
- IAVCEI Webinar "Nyiragongo 2021 eruption", 29 October 2021
- American Geophysical Union (AGU) Fall Meeting, New Orleans (USA) & online, 13-17 December
- Work visits & visitors at ECGS:
    - Scientific committee meeting of VERSUS project, RMCA, Brussels (21 January)
    - Online meeting with VDAP (Volcano Disaster Assistance Program, USGS), GVO and RMCA about the future of geophysical monitoring capabilities at GVO (14 April)
    - Visit of PhD student Josué Subira at ECGS (7-25 June 2021)
    - Meeting with ITM (at ITM's building) regarding Rumelange's mine and rockfall monitoring applications (27 September)
    - Visit of GVO's Director General Dr. Adalbert Muhindo and the Chief of Staff (Directeur de cabinet) of the DR Congo Minstry of Research at ECGS (28 September)

Delphine Smittarello

- European Geosciences Union (EGU) General Assembly, virtual, 19-30 April
- IAVCEI Webinar "Nyiragongo 2021 eruption", 29 October 2021
- American Geophysical Union (AGU) Fall Meeting, New Orleans (USA) & online, 13-17 December
- Work visits & visitors at ECGS:
    - Visit of GVO's Director General Dr. Adalbert Muhindo and the Chief of Staff (Directeur de cabinet) of the DR Congo Minstry of Research at ECGS (28 September)

SCIENTIFIC COMMUNITY SERVICE

Adrien Oth

- 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 Institutt (KNMI)**, Netherlands
- Member of **Science Advisory Board** of the **Central Asian Institute for Applied Geosciences** (CAIAG), Kyrgyz Republic
- **Member** of American Geophysical Union, Seismological Society of America, European Geosciences Union, Deutsche Geophysikalische Gesellschaft
- **Resolutions Committee Member** at 37th General Assembly of the ESC
- **Session Convener** at 7th International Geologica Belgica Meeting
- **Mentorships & Supervision**
    - Support to PhD thesis performed by Josué Subira (RMCA, GVO)

Nicolas d'Oreye

- **Guest Editor** of special issue of Journal of African Earth Science on *Active Volcanism and Continental Rifting*
- **Guest Editor** of special issue of Remote Sensing on *InSAR for Earth Observation*
- 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 *IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2021, Brussels*
- **Scientific Committee Member** for ESA Fringe Workshop
- **Scientific Committee Member** for ESA Living Planet Workshop
- **Scientific Committee Member** for IEEE International Geoscience and Remote Sensing Symposioum (IGARSS)
- **Member** of American Geophysical Union, European Geosciences Union, IAVCEI & Academy of Sciences Luxembourg
- **Mentorships & Supervision**
    - Post-doc supervision for Dr. Delphine Smittarello
    - Support to PhD thesis performed by Axel Deijns (RMCA) and Josué Subira (RMCA, GVO)

Julien Barrière

- **Reviewer** for *Water Resources Research*, *Journal of Volcanology and Geothermal Research, Earth Planets Space*
- **Member** of American Geophysical Union, European Geosciences Union & IAVCEI
- **Mentorships & Supervision**
    - Co-supervision of the PhD thesis "*Détection des événements naturels (glissements de terrain, inondations et effondrements associés, séismes) à l'aide des signaux infrasons et sismiques au Burundi*" of Eugène Ndenzako (Univ. Liège & Burundi) started in 2019

- Co-supervision of the PhD thesis "*Développement d'une chaîne de traitement automatique en temps-réel pour la détection, la classification et la localisation des signaux séismo-volcaniques dans la province des Virunga (RD Congo)*" of Josué Subira (Univ. Liège, MRAC & GVO), started in 2020 (project HARISSA/Belspo)

Delphine Smittarello

- **Reviewer** for *Frontiers in Earth Science, Remote Sensing, Journal of Geophysical Research: Solid Earth*
- **Member** of American Geophysical Union and European Geosciences Union