# Annual Report 2019

# 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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Researchers & technical staff affiliated to ECGS:

- **Dr. Adrien Oth**, geophysicist, ECGS
- **Dr. Julien Barrière**, geophysicist, ECGS
- **Dr. Dominique Derauw**, remote sensing scientist, ECGS
  (visiting researcher on an FNR INTER Mobility research grant)
- **Maxime Jaspard**, technical engineer, ECGS

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

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

# INTRODUCTION

The year 2019 was characterized by a **significant rise in permanent staff** of ECGS: Dr. Julien Barrière, a seismologist on a project-based temporary contract, could be hired on a permanent basis in July 2019, and Maxime Jaspard joined the ECGS team as a technical engineer in December 2019.

This substantial increase in permanent staff was possible thanks to the **positive decision of the Luxembourg government in relation to the strategic paper for the development at ECGS**, which was drafted by ECGS scientists and Administrative Board and submitted to the Ministry of Culture in 2017. This strategic paper aimed at addressing on one hand the increasing difficulties of ECGS to continue its successful history of third-party project funding acquisition, primarily due to large-scale modifications in the research grant schemes of the National Research Fund of Luxembourg (FNR), and on the other hand at improving ECGS's ability to adequately respond to inquiries from Luxembourg administrations and the public.

ECGS also saw a **major jubilee in 2019**: the 100$^{th}$ edition of the Journées Luxembourgeoises de Géodynamique (JLG) could be celebrated, along with the 30$^{th}$ anniversary of ECGS as an institution and the 60$^{th}$ anniversary of the establishment of the Walferdange Underground Laboratory for Geodynamics (WULG). Sadly, the last remaining founding father of the JLG, Prof. Dr. Manfred Bonatz, passed away in December 2018 and could thus not witness this joyful moment for ECGS anymore.

Besides this jubilee, ECGS also participated the **Science Festival** in November 2019, with a workshop on infrasound and seismic wave propagation and the location of events causing these waves.

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 now composed of three permanent scientists (Dr. Nicolas d'Oreye, Dr. Julien Barrière and Dr. Adrien Oth). Dr. Dominique Derauw from the Centre Spatial de Liège joined the team for a total duration of two months in 2019, in the framework of the FNR Inter Mobility research grant SMIPP.

A wide range of research activities was carried out at ECGS/Mnhn in 2019, which we present in detail below. As in 2018, the **dominant research topic in 2019 was given by the RESIST project**, providing the platform for the ECGS/Mnhn research on the Virunga volcanoes (Democratic Republic of the Congo). ECGS/Mnhn researchers published 3 articles in international peer-reviewed scientific journals in 2019, with 1 more currently in press, and contributed to 25 conference abstracts.

ECGS/Mnhn is heavily involved in a range of national and international collaborations (see research activities), which are the living proof of the wide recognition of its expertise. Besides the ECGS internal budgets provided by the Luxembourg government, funding and support for the research activities at ECGS/Mnhn in 2019 was obtained from the following sources:

- National Research Fund of Luxembourg (FNR)
- Belgian Science Policy (Belspo)
- EUR-OPA Major Hazards Agreement of the Council of Europe
- Deutsches Zentrum für Luft- und Raumfahrt (DLR) and Canadian Space Agency (CSA) (support through free access to satellite images)

## RESEARCH ACTIVITIES

# RESIST: REmote Sensing and In Situ Detection and Tracking of Geohazards
# BELSPO-FNR Project (1/12/2014 – 31/07/2019)

**Over the past years, the RESIST project has been the key project worked on at ECGS/Mnhn, involving all researchers and disciplines at ECGS.** The Kivu Rift region lies in the bordering region of the Democratic Republic of Congo and Rwanda. It is part of the Western branch of the East African Rift System and home to two of Africa's most active and dangerous volcanoes, Nyiragongo and Nyamulagira (Figure 1). The project RESIST aims at contributing to the understanding of the source mechanisms driving volcanic eruptions and landslides in the Kivu rift region by 1) filling the gap of knowledge on ground-based level through the installation of the densest seismic and infrasound network ever deployed in the region and first UV camera for $SO_2$ monitoring and 2) combining this information with innovative Earth observation (EO) approaches, using both archived data and new space-born acquisition possibilities in radar, optic, gas and precipitation monitoring. RESIST exploits ground-based instrument networks, field surveys and modern EO techniques (Split Band and MSBAS InSAR time-series, SO2 flux, TRMM) to study and characterize the changes in the monitored parameters that could/should be considered as significant in terms of volcanic and landslide processes. In the frame of RESIST, we search at gaining scientific insights into the mechanisms that lead to an eruption and what types of measurable phenomena and signals can be robustly considered as precursory information for eruptive activity.

**Figure 1**: Night view from Goma Volcano Observatory, DR Congo, of Nyiragongo and Nyamulagira lava lakes glowing and $SO_2$ plume. The city of Goma (1 Mo inhabitants) is visible in the foreground (photo N. d'Oreye).

The work performed within RESIST has both a seismological and a remote sensing-based component, which is why this project cannot be simply categorized as one or the other in this report. As such**, RESIST is an interdisciplinary effort**, encompassing all the different expertises available at ECGS/Mnhn and involving all the scientists at ECGS/Mnhn.

In the framework of the projects RESIST and MODUS (see page 20), we continued with the **maintenance** of the telemetered **seismic (KivuSNet) and GNSS (KivuGNet)** networks in DR Congo. In addition to the remote maintenance, two field missions were performed in June and October 2019. In the context of our well-known works and reputation in the region, the Rwanda Mines, Petroleum and Gas Board (RMB) resorted to our expertise for the design and installation of the National Seismic Network of Rwanda (4 new telemetered stations) and for the training of the local staff (see page 11). Without counting these 4 new stations, the KivuSnet infrastructure of the Virunga monitoring network comprises a total of 17 broadband seismic, 16 GNSS and 3 infrasound stations telemetered in real time to Luxembourg and the Goma Volcano Observatory.

The **research activities in the final year of RESIST** focussed on three main subjects, which are all inter-linked in order to better understand the volcanic mechanisms in the Virunga Volcanic Province: 1) the seismicity and outgassing characteristics of Nyiragongo volcano; 2) the seismic activity and crustal structure of the Kivu region in general, and 3) the usage of spaceborne synthetic aperture radar (SAR) data for measuring Nyiragongo's lava lake level.

## ❖ Seismicity and outgassing dynamics of Nyiragongo volcano

Active lava lakes at volcanoes can be regarded as open windows to their magmatic systems. The dynamics of such lakes may therefore provide decisive insights into deeper magmatic processes, potentially leading to fundamental theoretical implications and volcano monitoring improvements. Among the rare volcanoes on Earth hosting a persistent lava lake, Nyiragongo in D.R. Congo directly threatens a massive population of roughly 1 million inhabitants. In Barrière et al. (2019) we analysed close-range (i.e., summit) and distant (around 17 km) seismic measurements acquired at this African volcano between 2011 and 2018 in order to better understand the seismic signature of the lava lake activity and how it relates to the deeper volcanic processes. Both summit and distant seismic records contain a similar continuous tremor pattern attributable to the lava lake activity. Combining this information with time-lapse camera images and lava lake level measurements confirms the mechanism of gas pistoning at Nyiragongo, which is characterized by short-duration (a few minutes long) and meter-scale level variations during the period of observation. We also characterize the dominant periodicity of this shallow tremor signature of about a few tens of minutes. Because this marked periodic pattern varies during a significant one-month fluctuation of $SO_2$ emissions (estimated from space), we suggest that this particular seismic periodicity corresponds to the convective lake movement driven by the persistent degassing typical of active open-vent volcanoes (Figure 2).

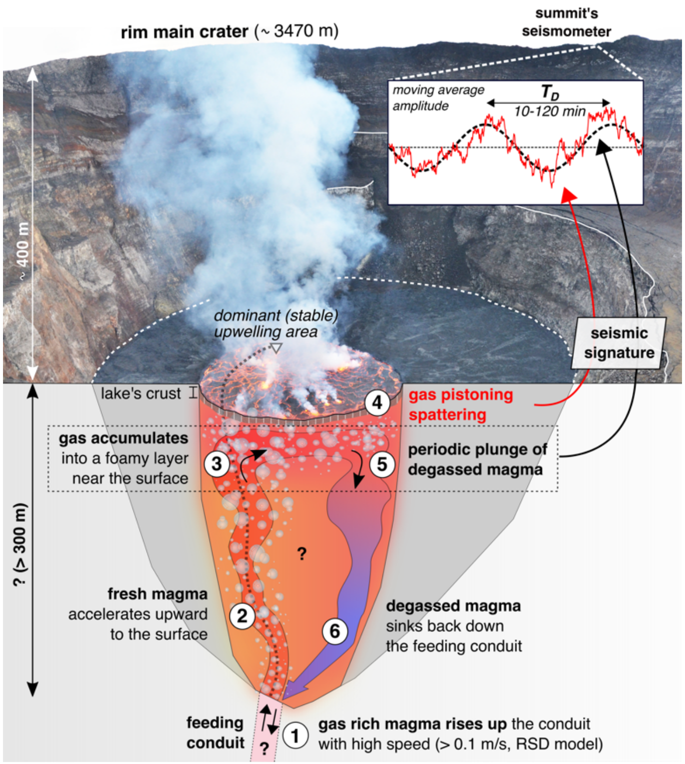


**Figure 2**: Conceptual model of convection and degassing mechanisms of the Nyiragongo lava lake system inferred from close-range seismic observations and space-based $SO_2$ estimates (steps 1 to 6, see text for more details). RSD model stands for "Rise Speed Dependent". For illustrative purpose, the seismometer is located on the northern part of the rim but the instrument has actually been deployed on the southern side in 2011 and 2018 (see Fig. 1b). The depth of the lava lake is estimated to be larger than 300 m since 2011 as inferred from observations of the crater morphology after the collapses of the crater in 1977 and 2002.

Finally, new seismic evidence reveals the effect of deep magmatic intrusion and consequent major pressure changes in the plumbing system, resulting in sudden and large drops of the lava lake level associated with strong degassing (Figure 3). Such transient episodes have similar characteristics to total lava lake drainage associated with flank eruptions already observed at this volcano in 1977 and 2002, or at Kīlauea volcano in 2018.

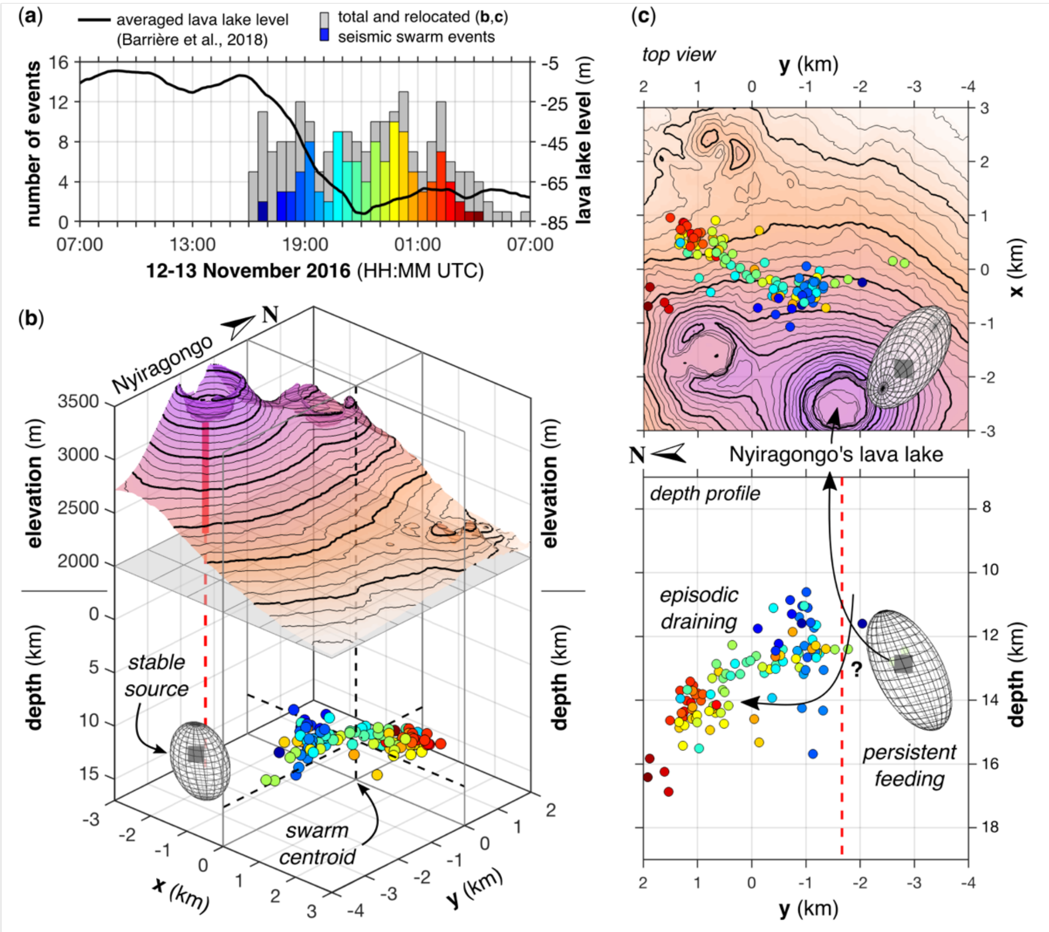


**Figure 3: a**) Number of events and lava lake level during the November 2016 swarm. Gray histogram corresponds to the total number of events detected beneath Nyiragongo and colored histogram correspond to events that can be adequately located. Each color is associated to a 30-min window. (**b**) 3D view of hypocenters of the swarm and master events, the latter being represented by its maximum likelihood – square gray marker – and its 68% confidence ellipsoid assuming errors following gaussian distribution. (**c**) Top view and depth profile from (b) illustrating the persistent feeding of the lava lake probably associated to the master event and its episodic drainage that occurs as the result of a magmatic intrusion associated with the seismic swarm. Considering a lava density of 2.5 $10^3$ kg/m$^3$ and neglecting the frictional pressure loss in the conduit, a lake level drop by 80 m such as the one observed in November 2016 corresponds to a magma-static pressure drop of about 2 MPa, the same order of magnitude as the overpressure within the 2002 eruptive dikes estimated by Wauthier et al. (2012).

In conclusion, three important magmatic processes at Nyiragongo related to its lava lake activity are deciphered from the analysis of shallow (tremor) and deep (swarm) seismicity:

- **Continuous gas pistoning and spattering**: Small meter-scale lava lake level variations are seismically detected at long distance and correspond to a shallow degassing mechanism similar to the one inferred at the Halema'uma'u lava lake, i.e., gas pistoning and spattering (see Figure 2).

- **Periodic lake convection**: The dominant periodicity of the lava lake tremor tends to fluctuate between around 10 minutes to one hour in accordance with the long-term variations of $SO_2$ degassing. This pattern is thus interpreted as a proxy of the main convective movement and depends of the time-varying properties of the ascending gas-melt mixture from the shallow magma chamber. A potential link with fluctuations of the lake level has not been observed yet (see Figure 2).
- **Transient large lake level drops with strong degassing**: Major sudden decreases of the lake level such as reported in the literature (see Barrière et al., 2019, and references therein) are well explained by a pressure drop within the magmatic system due to deep magma intrusions (see Figure 3).

The multi-disciplinary datasets gathered in this study lead to a comprehensive conceptual model unravelling the outgassing dynamics at a lava lake system and highlight the benefits of monitoring the ambient seismic signal generated by lava lake activity in order to potentially connect surface processes with changing properties of the ascending gas-rich magma. Having a complete view of the underlying mechanisms responsible for major changes of lava lake activity also implies the analysis of magma movements at the level of deeper magma storage. Thanks to the identification of deep seismic swarms (> 10 km b.s.l.), sudden large drops of the lava lake level associated with a strong degassing are explained by major pressure changes in the magmatic reservoir due to lateral dyke intrusion at large depths.

## ❖ Seismic activity and crustal structure of the Kivu region

This work has been continuously updated since the main deployment of KivuSNet in October 2015 as part of the daily routine seismic monitoring (see Oth et al., 2017 and the previous reports). The publication of the main results in peer-reviewed journals (2D ambient noise tomography, 1D P- and S-wave velocity structure, local magnitude scale), which were initially expected in 2019, are postponed to 2020 for integrating several decisive improvements reached in the past year, including:

- The location of seismic events using new broadband data from additional stations installed around Lake Kivu in 2019 (Figure 4);
- The detailed analysis of the ambient seismic noise sources in the Kivu region highlighting the dominant source of microseisms originating from Indian Ocean and the role of Great Lakes (Kivu, Tanganyika) in generating noise above 0.5 Hz in accordance with daily/seasonality variations in wind patterns.

A "3D" (multiple 2D slices at several dominant periods) surface wave group velocity tomography of the area in the secondary microseisms band ~ 3.5-7.5 sec can be attempted thanks to updated data and new processing approaches, i.e., the calculation of Noise Cross-Correlation Functions (NCFs) using the "waveform preserving normalization" procedure by Groos et al. (2012) and the phase-weighted stacking of NCFs by Haned et al. (2016). As final processing step, promising results are also obtained with the use of a chirplet-based waveform decomposition technique for highlighting the fundamental mode of the Rayleigh wave group dispersion curves using the FAAD code developed in a previous project (FNR-BEDLOAD, see Barrière et al. 2015). This work is still in progress and is not detailed here.

## ❖ Measuring the Nyiragongo lava lake level using spaceborne synthetic aperture radar (SAR)

No continuous and reliable terrestrial observations of the lava lake are available from the rim of the Nyiragongo main crater; however, satellite data may be used to recover the lava lake level. To do this, we use a spaceborne Satellite Aperture Radar (SAR) technique. The principle is somewhat similar to measuring the shadow lengths from the Sun's illumination

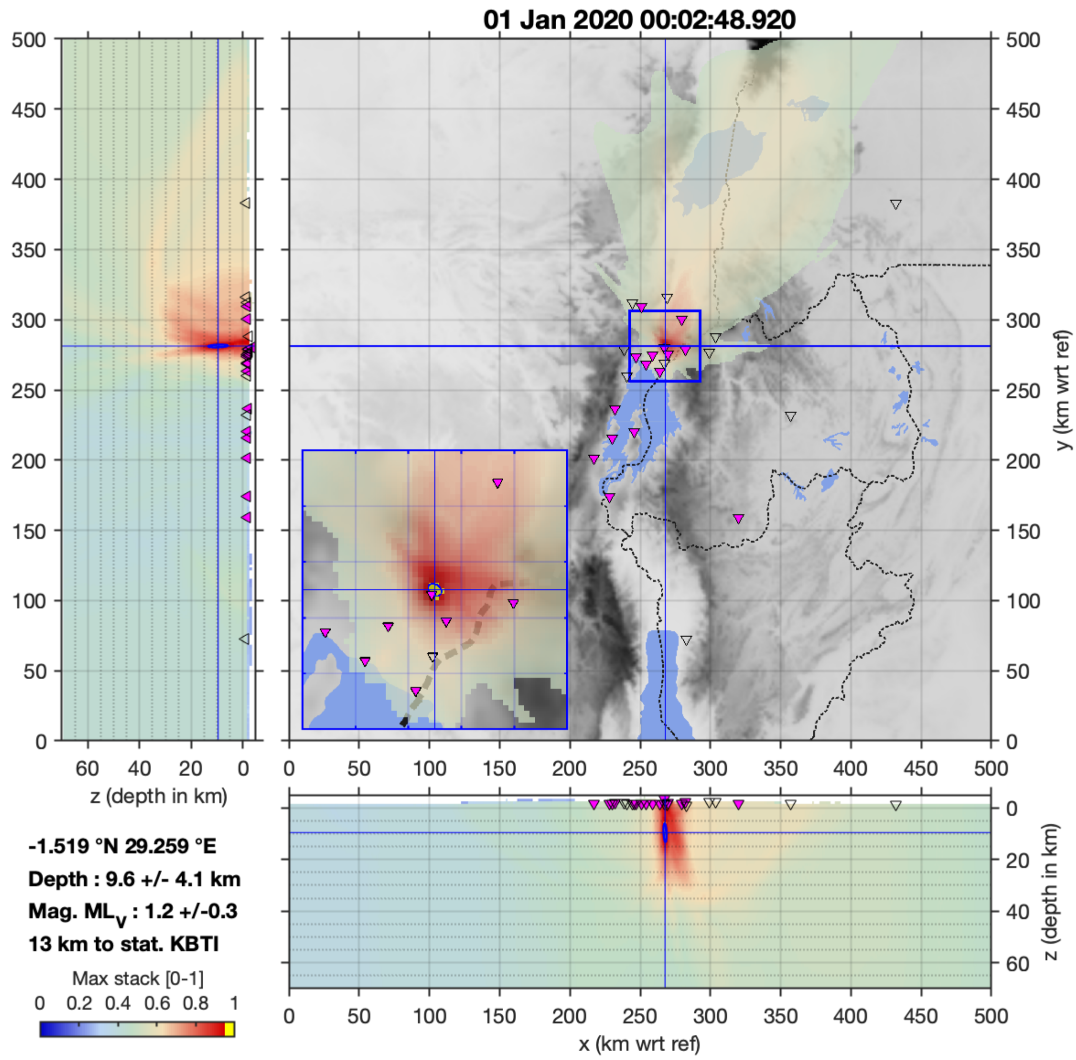


**Figure 4:** Example of output from the ECGS automatic location code applied to the Kivu region (the 1st detected event in 2020). The blue-to-red color scale corresponds to the normalized maximum likelihood location, which can be represented by an ellipsoid contouring the highest values (in yellow) above 95% (the 2D projected ellipses are plotted here). Data from 6 new stations installed in 2019 in collaboration with local partners have been incorporated into the routine. The seismic event located here correspond to a repetitive source beneath Nyiragongo volcano (see Figure 3).

on-site as done for instance at Erta' Ale, Ethiopia (Oppenheimer and Francis, 1997). The length of SAR shadow cast on the lava lake surface by the edge of the pit crater may be used to recover the lava lake level. It is important to note here that the SAR image does not respect the true geometry and correspond to a specific projection called slant range plane, thus requiring additional (but straightforward) geometric transformation in order to retrieve an estimate of the true lava lake depth. The idea of applying this method to Nyiragongo's lava lake has been initiated by Dr. N. d'Oreye, then developed in the last couple of years to an automatic method (see for instance the 2018 report). First results have been published in Barrière et al. (2018) for a joint analysis with seismo-acoustic signals generated by the lava lake activity. In 2019, the quality of the level estimates has been improved using a new denoising procedure based on the Split Bregman algorithm (Goldstein and Osher, 2009). An article focusing only on results obtained with this technique from 2006 to 2019 is in preparation. During this period, the morphology of the inner crater has changed a lot (Figure 5) and we aim to show in this paper how these changes are linked with the magmatic activity beneath the volcanic edifice, as already discussed in Barrière et al. (2018, 2019) for the large (~80 m) lava lake drop occurring in November 2016.

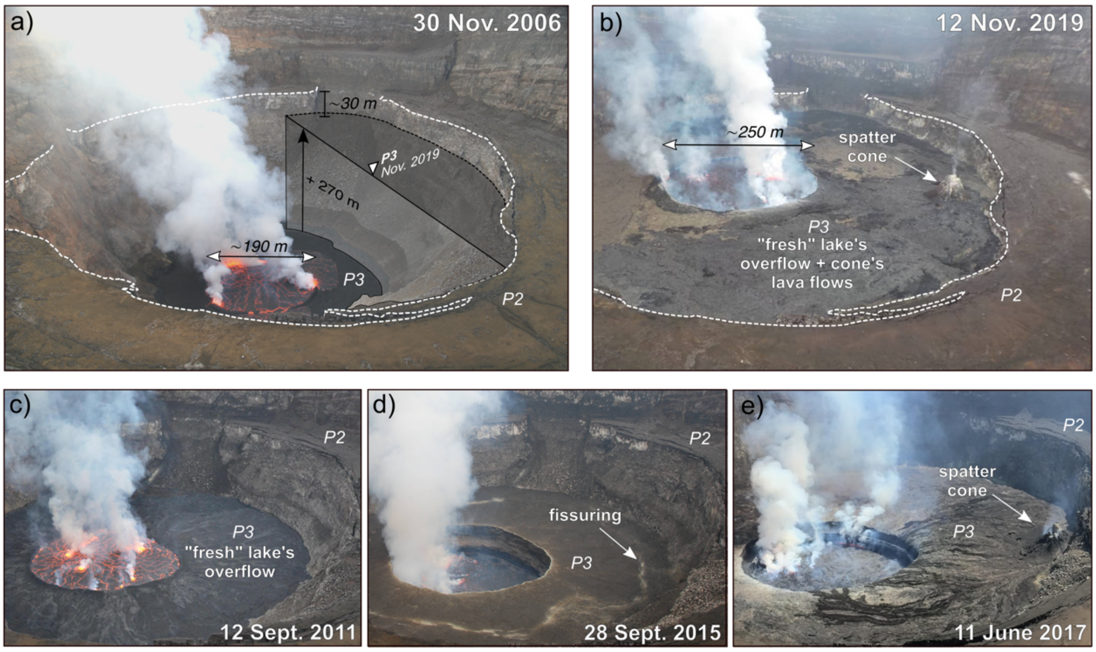


**Figure 5**: Pictures of Nyiragongo's lava lake spanning about 13 years time difference (2006-2019), which were taken from approximately the same position on the rim on the southern side (Photos courtesy of J. Durieux, B. Smets, D. Delvaux, N. d'Oreye, Thomas)

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**For further information on the RESIST project, please see also the websites [http://resist.africamuseum.be/](http://resist.africamuseum.be/) and [http://www.virunga-volcanoes.org/](http://www.virunga-volcanoes.org/).**

**Collaborators:** Royal Museum for Central Africa, Belgium (F. Kervyn, O. Dewitte, A. Nobile); Centre Spatial de Liège, Belgium (D. Derauw); Belgian Institute for Space Aeronomy, Belgium (N. Theys); NASA, USA (Dr D. Kirschbaum).

# Seismology

## ❖ Monitoring Infrastructure in Luxembourg and the Kivu region

Over the past few 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 also RESIST section above). The interest in this region has been driven through a series of scientific research projects over the past 15 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 (see RESIST section above).

While the Kivu region 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 scientific results of our monitoring activities in Luxembourg in the following section here below.

Figure 6 shows the current status of the monitoring networks that ECGS/Mnhn operate in collaboration with local and international research partners. At present, the Kivu Rift Seismic Network (**KivuSNet**) is composed of 17 broadband seismic stations, 16 GNSS stations and 3 infrasound arrays. The **Luxembourg Seismic Network** is currently composed of 8 broadband and 2 short-period seismic measurement stations.

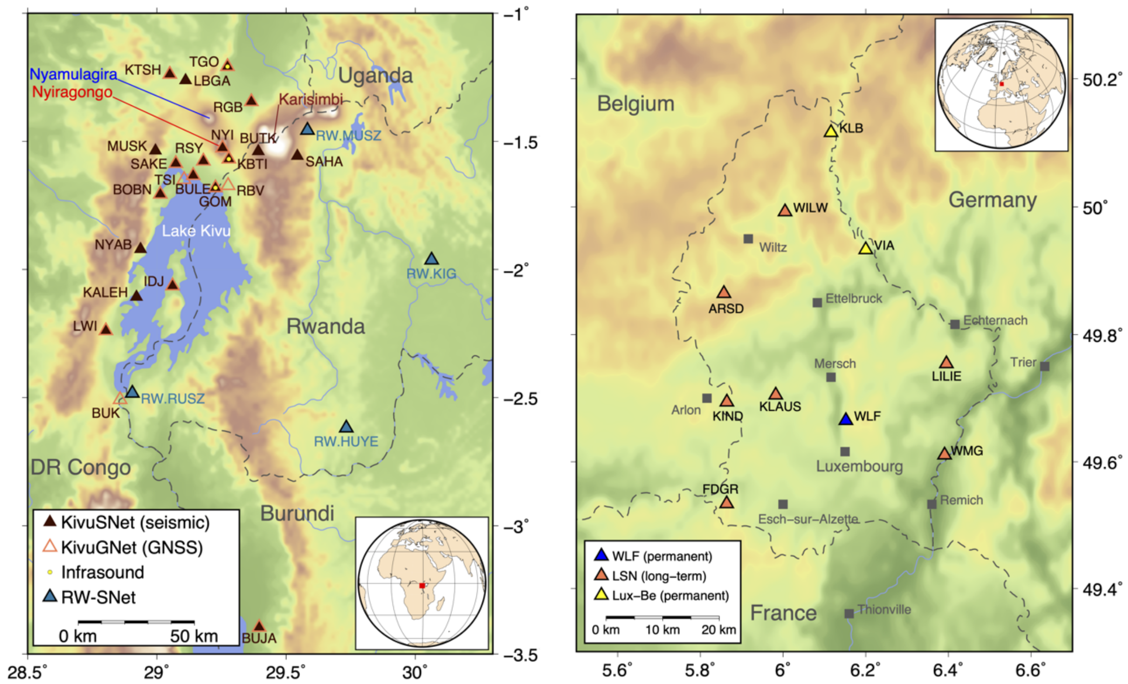


**Figure 6:** Current status of seismic, GNSS and infrasound monitoring infrastructure developed by ECGS in collaboration with its partners in the Kivu Rift region (left) and in the Grand-Duchy of Luxembourg (right).

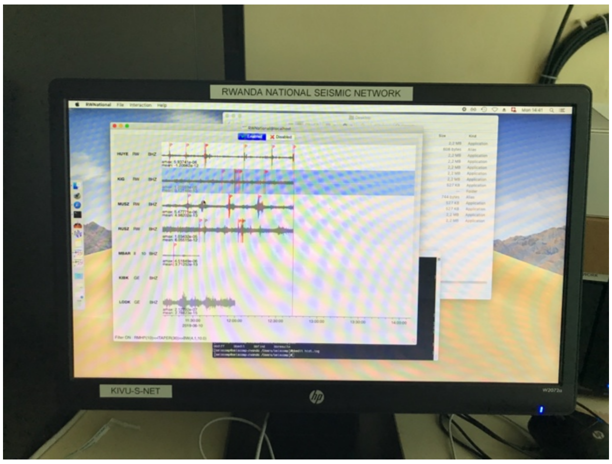


**Figure 7:** Left panel: Installation of a telemetered seismic station in Huye (Rwanda) for the Rwanda National Seismic Network. Top panel: Data are transmitted and analysed in real-time at the RMB facility in Kigali.

In the framework of the RESIST and MODUS projects, the ECGS/Mnhn team also designed and installed the **National Seismic Network of Rwanda**, which in an initial stage is composed of 4 permanent broadband seismic stations, telemetered in real-time to the central acquisition server located in the Rwanda Mines, Petroleum and Gas Board (RMB) premises in Kigali (Figure 6, left panel, blue triangles; Figure 7). We also carried out an intensive training session for the local staff.

In **Luxembourg**, ECGS has made it a priority over the past years to overcome the lack of seismic monitoring infrastructure that prevailed until recently, with only one broadband seismic station in the country, installed in the Walferdange Underground Laboratory for Geodynamics (WULG), and two short-period stations in Vianden and Kalborn. In order to be able to provide a reasonable level of seismic monitoring of the country and its surrounding regions, ECGS therefore operates an instrumentation programme to achieve an appropriate homogeneous, broadband seismic network throughout the country. A first part of this programme consisted of a temporary deployment of six stations that were installed in collaboration with the Karlsruhe Institute of Technology (KIT) beginning in December 2009 (LUXBB). Over the years, further stations were added step-by-step, leading to a first reasonable coverage of the country with modern seismic monitoring equipment.

In 2019, the remaining temporary KIT stations were replaced with ECGS-owned Guralp instruments with a long-term operation perspective. All data are transmitted in real-time to the ECGS office in Walferdange and evaluated with the real-time, automatic SeisComP3 software package developed by scientists at the GFZ German Research Centre for Geosciences (Figure 8). In 2019, ECGS acquired three more seismic stations for temporary and/or long-term deployments, and the acquisition of further three stations is planned in 2020 to enable ECGS scientists to carry out localized monitoring campaigns, for instance in the framework of subsurface operations where potential induced seismic events could be expected.

Since 2018, ECGS shares seismic data of its broadband network with the Royal Observatory of Belgium (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

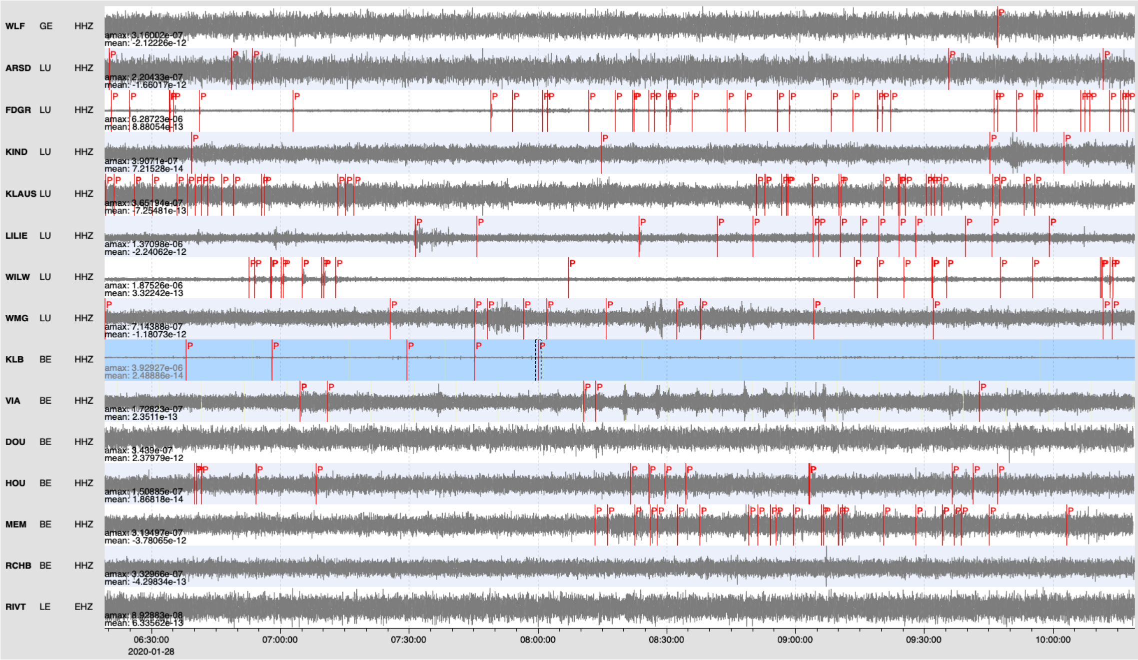

**Figure 8:** Example of real-time monitoring at ECGS, snapshot of SeisComP3 system from 28 January 2020 covering incoming seismic data of a 4h-long time window.

with access to real-time data from our stations KIND and WILW (see example records in Figure 8). These collaborations show that the Luxembourg seismic data are indeed also of interest to the monitoring agencies in our neighbouring countries and that the expertise of ECGS as Luxembourgish partner institution is recognized.

In 2019, ECGS was also contacted by the Ministry of Foreign Affairs as potential scientific partner in the framework of the Benelux Memorandum of Understanding relating to the collaboration among scientific institutions of the three countries in the framework of the **Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO)**. In this context, ECGS has launched the necessary steps in 2019 to become National Data Center (NDC) for Luxembourg and Dr. Adrien Oth participated in the CTBTO's Working Group B meeting in Vienna in September 2019.

**Collaborators:** Karlsruhe Institute of Technology, Germany; Royal Observatory of Belgium; Erdbebendienst Südwest, Germany.

## ❖ Seismological Monitoring Results & Research in Luxembourg

In 2019, we further pursued the development of the seismic monitoring of the Luxembourgish territory by combining high-quality, broadband seismic instrumentation with appropriate data processing and analysis. The main improvements with respect to the past year are:

- The addition of real-time data from 5 additional stations belonging to other networks into the processing chain in order to increase the confidence of the earthquake location procedure.
- The implementation of a picking-free, cross-correlation-based algorithm adapted to the detection and location of small earthquakes in Luxembourg and feeding this information into our SeisComp3 system, thus providing a complete solution for detecting, locating and archiving seismic events in real-time. For the moment, this result is achieved interfacing SeisComP3 and the computing platform where the

location program is running (Matlab). A more efficient alternative, which could be further envisaged, would be the development of a dedicated module for SeisComP3.

- The analysis of the ambient seismic noise properties in Luxembourg in order to gauge the feasibility of high-resolution (crustal images) surface wave tomography studies in the future.

We show in Figure 9 how the addition of several stations from neighbouring networks (Belgium, Germany) dramatically improves the location accuracy of nearby seismic events just outside the national network. The ellipse around each event (called the 2D error ellipse) represents the uncertainty of the location for the considered earthquake and is significantly reduced in regions where the station coverage has been improved (especially on the Belgian side). The addition of seismic stations also allows to improve the network detection threshold (234 events in one year against 194 in two years without using the additional stations).

As already observed from the previous analysis (Sept. 2016 – Sept. 2018, Figure 9, left panel), most of the seismicity in and around Luxembourg relates to human activity (quarry blasts). Nonetheless, the two most energetic events (local magnitude $M_L \sim 1.7$) for the past year (Oct. 2018 – Oct 2019, Figure 9, right panel) are tectonic earthquakes occurring at large depths (> 10-15 km). These events are numbered 2 and 3 in Figure 9 (right panel). Event 2 is located in an active seismic region (Belgian Ardennes), a few kilometres south of the city of Verviers, where one of the largest historical earthquakes known in Western Europe (M ~ 6-6.5, 18 Sept. 1692) took place, only about 50 km north of the Luxembourgish border. Event 2 has also been well detected by the Belgian seismic network leading to a manual location solution similar to the one we obtained. Event 3, however, is better constrained by our network because it is situated on the extreme South East of the Luxembourgish territory, highlighting the usefulness of the Luxembourg Seismic Network deployment, which can eventually help to improve our understanding of the background seismicity in this stable tectonic context.

The first natural event (in contrast to human-induced) accurately located within the Luxembourgish territory with this new network was detected two years ago (18 Nov. 2017) close to Walferdange, with a focal depth around 10 km (numbered 1 in Figure 9, left panel). This seismic event of very low magnitude (<1) clearly illustrates the capability of this local network to monitor efficiently the micro-seismicity in this area. We decided to study this

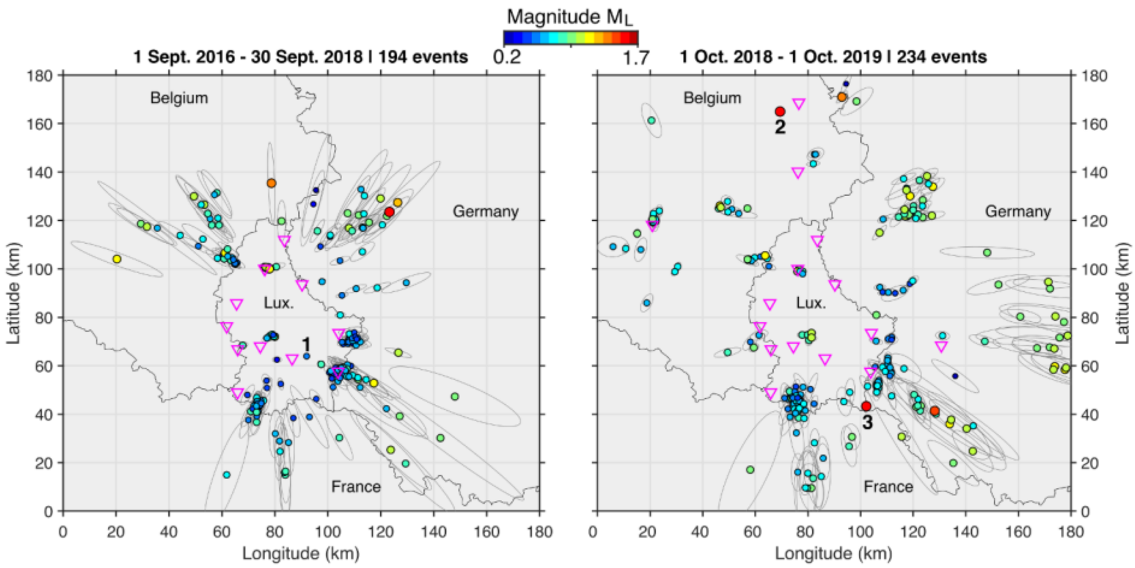


**Figure 9**: Local seismicity in and around Luxembourg with associated location errors (ellipses). Left panel: between 1 Sept. 2016 and 30 Sept. 2018; Right panel: between 1 Oct. 2018 and 1 Oct. 2019. The large majority of these seismic events are of human origin (quarry blasts) but some of them are clearly identified as tectonic earthquakes (e.g., event 1 on the left and events 2 and 3 on the right).

particular earthquake by applying a matched-filter technique in order to check if similar events occurred in the past in the same source region. This method is routinely employed at ECGS in the volcanic setting of the Virunga volcanoes in the Kivu region, where similar seismic source processes close to each other in space often repeat in time due to magma movements at depth (see Figure 3). Using the recordings of this earthquake at Walferdange as template (called thereafter master event, see Figure 10a), we can scan the entire available database at this station (roughly the past 10 years) for retrieving similar waveforms using a standard moving cross-correlation approach. This way we can retrieve similar past earthquakes not detectable and/or not locatable at that time due to an insufficient station coverage or a too low SNR (i.e., signal-to-noise ratio, indicating how the event emerges above the noise level).

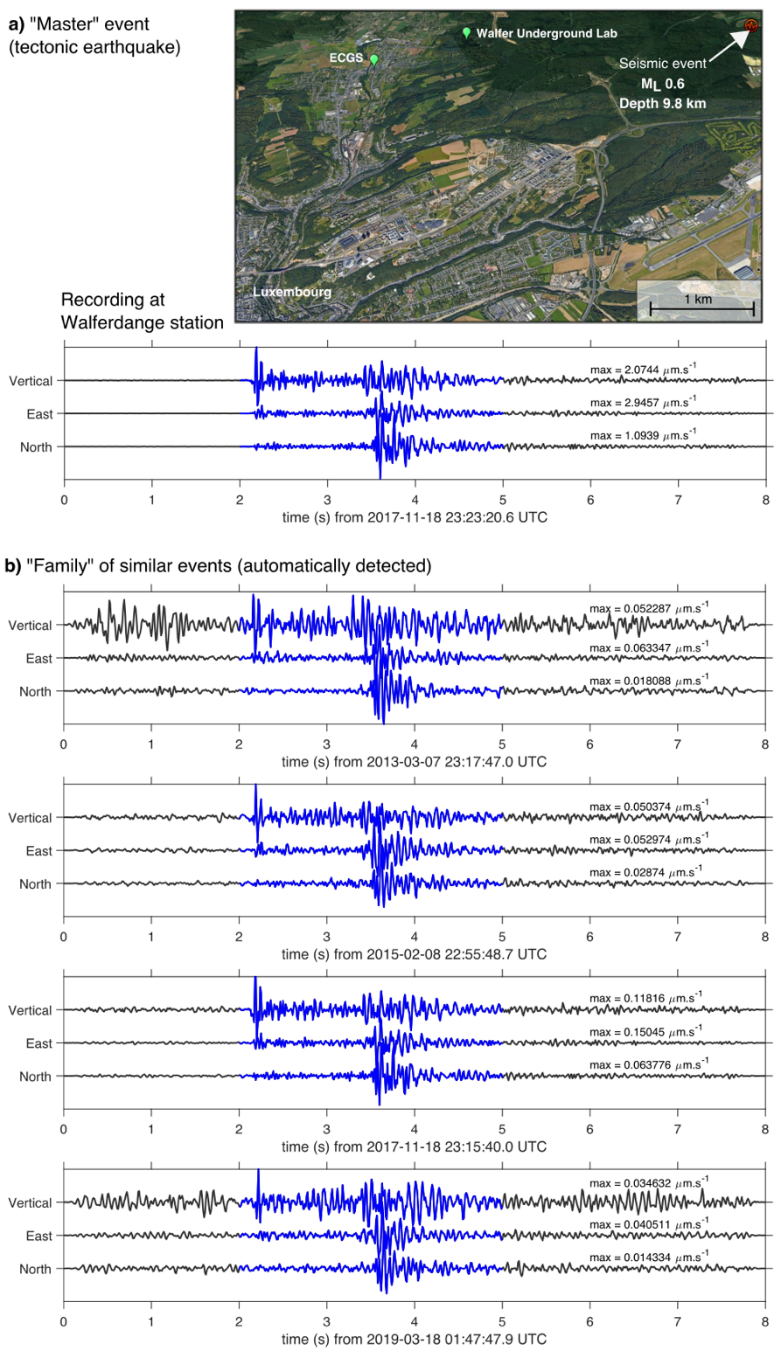


**Figure 10**: a) Map and 3-component records of the tectonic event occurring on 18 Nov. 2017 recorded at Walferdange station b) 4 highly similar events detected using a matched-filter technique. The maximum absolute amplitude is indicated above each trace. The waveforms highlighted in blue correspond to the 3-s event detected at the same closest station (Walferdange). Despite the very low amplitudes, the P-wave and S-wave arrivals are clearly visible for each event.

The dominant frequency content of the master event is relatively high (5-20Hz) and matching similar waveforms on the three seismic components (one vertical, two horizontals – North/East) would be only possible if highly similar source processes repeat in time. Using this technique, we have surprisingly detected a "family" of four other micro-earthquakes characterized by correlation coefficients higher than 0.66 for the three components (Figure 10b). These events occurred between March 2013 and March 2019 and have even smaller amplitudes than the main one (Figure 10a). As a first hypothesis about the source mechanism, this result could for instance suggest a seismic source linked to fluid-driven processes in a particular zone of weakness below this central region of Luxembourg (e.g., Audin et al., 2002 for the Vosges region). Interestingly, another natural earthquake of magnitude 1.8 was recently detected by the entire network and located in the same southern region of Luxembourg (near Alzingen-Hesperange, Figure 11) on 17 December 2019. This event has been taken significant note of in the Luxembourgish press (cf. for instance the press article from 18 December 2019, page 31) and shows that, even though rare and only of small magnitude, tectonically driven seismic activity within the Luxembourgish territory does exist.

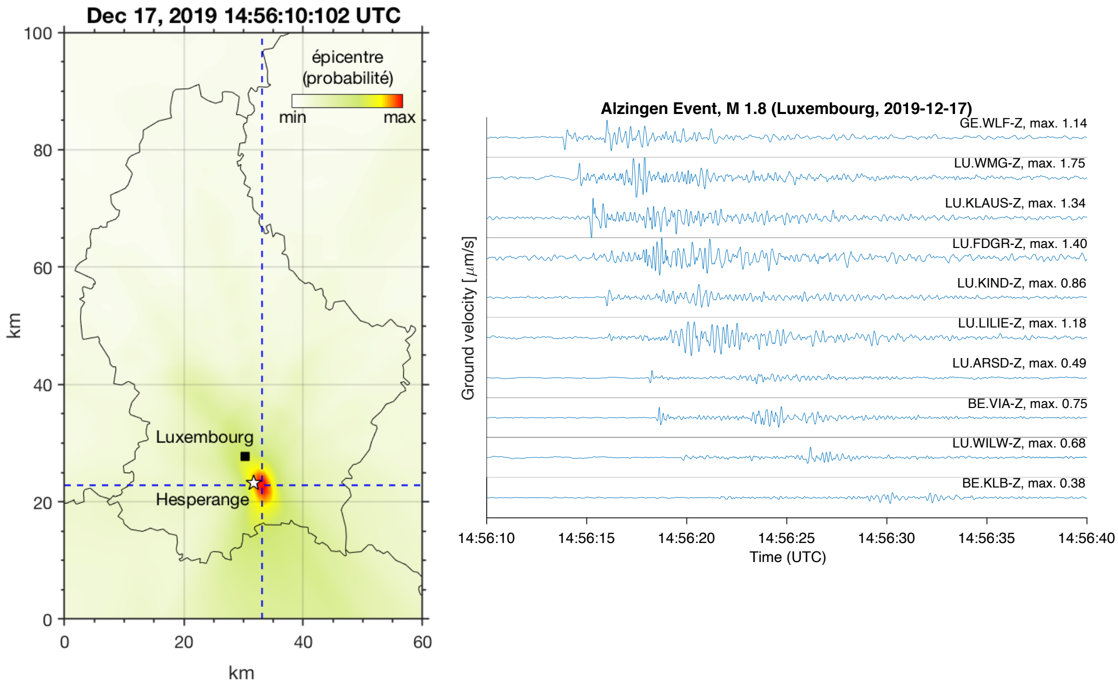


**Figure 11**: $M_L$ 1.8 Alzingen-Hesperange earthquake detected and located by the Luxembourg Seismic Network. Left panel: Location of event carried out at ECGS. Right panel: Vertical component seismic traces (time window of 30 seconds) observed at the 10 stations of the Luxembourg Seismic Network.

Finally, we calculated NCFs (see also RESIST section above, page 4) between all station pairs from the available continuous recordings between 1 Oct. 2018 and 1 Oct. 2019. Similar to the method applied in our studies for the Kivu region, the purpose here is to use the seismic signal continuously generated at the Earth's surface as a source of surface waves. The most powerful seismic noise source at low frequencies (< 1Hz) is called microseisms, basically consisting in a background tremor generated by water wave motions in oceans. Since the first applications (e.g., Shapiro et al., 2005 for Southern California), this method has proven to be very useful for imaging the Earth's crust, with no need for well-distributed seismicity as required for local earthquake tomography.

This *Surface Wave Tomography* (SWT) approach is thus an interesting technique for our low-seismicity region. We compute NCFs in the frequency band 0.05-0.2 Hz (at these frequencies, the surface waves can sample the uppermost 10-20 km of the crust and oceanic microseisms are the strongest). The NCFs between two stations consist in waveforms exhibiting maxima of correlation at time lags corresponding to the average surface wave speed between these two stations. If the station coverage is sufficiently dense, an image of the surface wave speed can be computed by combining all station pairs information. However, in case of a strongly directive source, biased travel time estimates can be obtained if station pairs do not align with the noise direction.

As a preliminary analysis using the set of available stations (Figure 12a), we check the directivity of noise sources (Figure 12b) and we plot the NCFs for interstation distances between 10 and 120 km (Figure 12c). As the calculation of cross-correlation between two signals, the maximum of NCFs can be obtained at positive or negative time lag depending on the station chosen as a reference. In the case of perfect omni-directional noise sources distribution, the NCFs should be symmetric around 0. In our case, the NCFs are asymmetric (the maximum is clearly identifiable on one side), a fact that implies a preferential directionality in the noise sources. Our results show that the seismic noise is oriented toward the North Sea because NCF maxima are obtained for station pairs alignment toward the North West. By selecting NCFs satisfying some selective criteria (e.g., minimum SNR, consistent time lag) we can plot NCFs showing reasonable moveouts of surface wave arrivals with a (global) best-fit of about 2.8 km/s for the surface wave group velocity (the red line in Figure 12c fitting the maximum of NCFs envelopes). These results are promising and will further encourage the deployment of additional stations in order to image the crust of this stable tectonic area with an unprecedented high-resolution (lower-resolution, large-scale SWT tomographies for entire Europe have already been published, e.g., Lu et al., 2018).

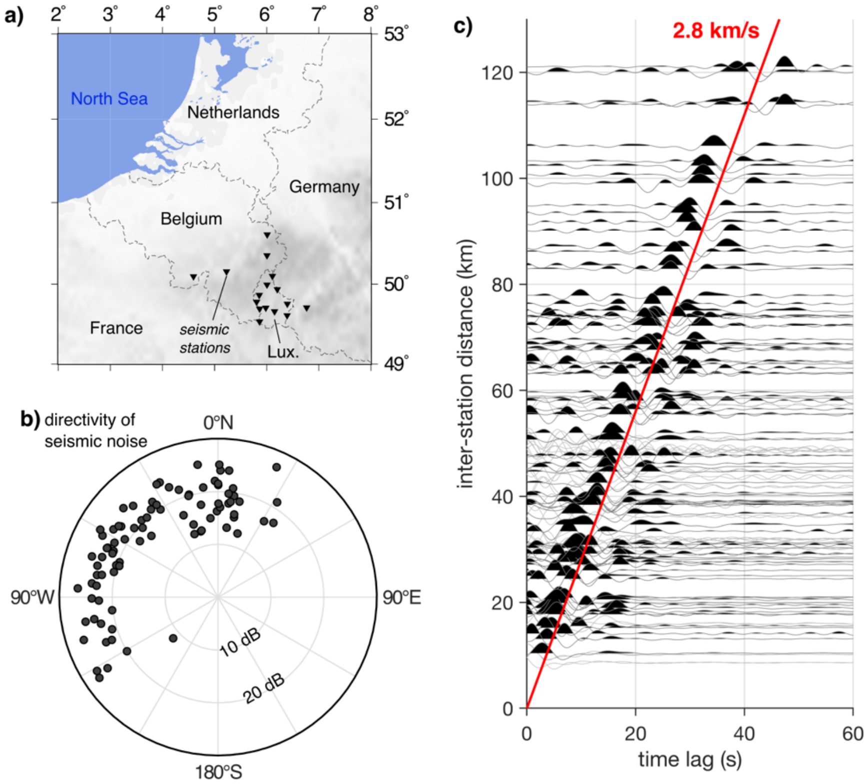


**Figure 12**: a) Map of seismic stations used for the calculation of NCFs. b) Each dot in the polar plot correspond to the preferential azimuth and SNR value (radial axis) of the NCFs displayed in c) Wiggle traces of the NCFs showing a moveout of surface wave arrivals corresponding to a group velocity of about 2.8 km/s.

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## ❖ Various seismological collaborations

In 2019, 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:

- **Moment and energy magnitudes: diversity of views on earthquake shaking potential and earthquake statistics**

  Dr. Oth contributed to a study led by Dr. Matteo Picozzi from the University of Naples This study deals with the problem of adequately characterizing the size of an earthquake and the relation with shaking potential of these measures. Typically, seismologists nowadays use the so-called moment magnitude to characterize the size of an earthquake. However, from a shaking potential perspective, the so-called energy magnitude is a more appropriate measure. The study investigates in particular the way that these two measures are linked with each other, which is non-trivial, and discusses the implications of the findings for the field of earthquake statistics, which plays a very important role in the typical procedures for seismic hazard assessment. An article presenting the results of this study has been published in *Geophysical Journal International* in 2019 (see Publications & Presentations section).

  **Collaborators:** University of Naples; GFZ German Research Centre for Geosciences; University of Genova; International Seismological Centre ISC, UK.

- **Nonparametric spectral modelling of source parameters, path attenuation and site effects from broadband waveforms of the Alborz earthquakes (2005-2017)**

  In this study, ground motion data from 312 earthquakes recorded at the Iranian national broadband seismic network in the Alborz region between 2005 and 2017 are analysed in order to evaluate earthquake source parameters, path attenuation and site amplification functions using the non-parametric generalized inversion technique (GIT). This is a region of particular interest in Iran since many devastating events occurred here in the past, such as the 1990 Rudbar-Tarom earthquake with a magnitude of 7.3, and several highly populated cities, including Tehran, are located in the Alborz region. Dr. Oth is involved in this work in view of his expertise on the subject of GIT inversions. This study has been published in the journal *Geophysical Journal International* in 2019 (see Publications & Presentations section).

  **Collaborators:** International Institute of Earthquake Engineering and Seismology, Iran; OGS Trieste, Italy.

- **Generalized Spectral Inversion Benchmark Exercise (GITEC)**

  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 relates 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 is 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 participate 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.

Following the first trial inversions in 2018, more refined inversions were carried out by the different groups on the three real test datasets from Italy, Japan and the French Alps. In particular, it was attempted to make the results as comparable as possible between the different groups by constraining specific seismic station responses to fixed site effects terms. The results were discussed at the second GITEC workshop which took again place in Cadarache in southern France in April 2019. Further collaborations were discussed during a visit of Dr. Fabrice Hollender, Dr. Paola Traversa, Dr. Dino Bindi and Hussein Shible at ECGS in September 2019.

**Collaborators:** CEA Cadarache, France; 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.

# Remote Sensing, Volcanology and Ground Deformation

## ❖ Running Projects and Objectives

In the context of the Remote Sensing & Ground Deformation studies carried out at ECGS/Mnhn in 2019, we were involved the following projects:

- **RESIST: REmote Sensing and In Situ detection and Tracking of geohazards**, 1/12/2014 - 31/07/2019 (Belspo and FNR)
- **MUZUBI: MUlti Zone phase Unwrapping using advanced Split Band Interferometry,** 1/12/2015 - 30/05/2019 (Belspo)
- **SMMIP: Split band assisted Multi-dimensional and Multi-zonal InSAR time series Processor,** 1/4/2017 - 29/2/2020 (FNR)
- **MODUS: A Multi-sensOr approach to characterize ground Displacements in Urban Sprawling contexts,** 1/12/2017 - 30/11/2020 (Belspo)
- **Hengill: Interaction of geothermal, tectonic, and magmatic processes in the Hengill area, SW-Iceland,** 1/1/2017 - 31/12/2020 (The Icelandic Research Fund)
- **RCM-AIT: The Development And Delivery Of On-Demand Radarsat Constellation Mission Ground Deformation Products Based On Advanced Insar Technology,** 1/1/2015 - 31/12/2020 (Canadian Space Agency)

In a nutshell, these projects aim at the following:

**RESIST** aims at contributing to the understanding of the source mechanisms driving volcanic eruptions and landslides in the Kivu rift region by 1) filling the gap of knowledge on ground-based level through the installation of the densest seismic and infrasound network ever deployed in the region and first UV camera for SO2 monitoring and 2) combining this information with innovative EO approaches, using both archived data and new space-born acquisition possibilities in radar, optic, gas and precipitation monitoring. The project exploits ground-based instrument networks, field surveys and modern EO techniques (Split Band and MSBAS InSAR time-series, SO2 flux, TRMM) to study and characterize the changes in the monitored parameters that could/should be considered as significant in terms of volcanic and landslide processes. In the frame of RESIST, we search at gaining scientific insights into the mechanisms that lead to an eruption and what types of measurable phenomena and signals can be robustly considered as precursory information for eruptive activity. **Since RESIST represents the key interdisciplinary project currently worked on at ECGS/Mnhn, a detailed report on the work carried out in in this project can be found in the dedicated section above on page 4.**

**MUZUBI** aims at developing a novel methodology to improve the phase unwrapping in SAR interferometry (InSAR) by combining SBInSAR processor with classical phase unwrapping procedure in order to get absolute phase measurement on all coherent zones. The innovative method to be developed here will be tested on two case studies in Argentina and DRC. Results will be compared with the results from a state-of-the-art method (MSBAS) currently used in the frame of a running project (RESIST) in order to assess and quantify the benefit of the proposed methodology.

**SMMIP** is an FNR-funded INTER mobility project and aims primarily at merging two highly innovative tools: MSBAS technique (developed by Dr. Sergey Samsonov during a post-doc stay at ECGS and aiming at producing multi-sensor and multi-temporal time series of ground deformation maps in horizontal and vertical components) and the Split Band Interferometry (SBInSAR) developed by Dr Derauw at the Centre Spatial de Liège (CSL). This second tool, through the exploitation of the multi-chromatic potential offered by the most recent SAR sensor, gives the possibility to solve the everlasting bottleneck of InSAR processing, which is the phase unwrapping by performing an absolute phase unwrapping on a point-by-point basis. Hence, in theory and coherence allowing, it would allow to extend the measurement zone to any non-contiguous unwrapped area, for feeding the MSBAS processing.

**MODUS** aims at combining 1) MSBAS deformation time series (using COSMO-SkyMED and Sentinel-1 satellites), 2) techniques using optical imageries (acquired with Pléiades and SPOT-6, SPOT-7 satellites) and 3) targeted ground-based stereo time-lapse photogrammetry, UAV, ground- based LiDAR and repeated DGPS measurement campaigns in order to study landslide processes and triggering mechanisms. The city of Bukavu (DR Congo, South Kivu) is chosen as experimental test site for comparing and integrating deformation monitoring by multiple sensors and techniques to assist in planning and risk management. This rapidly expanding city is set in a landslide-prone environment.

**Hengill** aims at studying interactions of geothermal, tectonic, and magmatic processes, with special focus on a region in Iceland where a new geothermal area will be taken into production. The study will focus on: a) Crustal deformation due to tectonic, geothermal, and magmatic processes; b) Natural and induced seismicity (fault activation by automatic, near-real-time, high-precision earthquake locations); c) Joint interpretation of deformation and seismic data with in-situ geothermal production parameters (pressure, temperature, production- and injection rates) and other available geological and geophysical observations through sophisticated numerical deformation and reservoir models.

**RCM-AIT** aims at developing a framework for automatic generation of standard and advanced deformation products based on Interferometric Synthetic Aperture Radar (InSAR) technology from RADARSAT Constellation Mission (RCM) Synthetic Aperture Radar data. We will utilize existing processing algorithms that are currently used for processing RADARSAT-2 data and adapt them to RCM specifications and develop novel advanced processing algorithms that will address large data sets.

**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).

Partners in these projects are

- Comahue National University, Argentina
- Royal Museum for Central Africa, Belgium
- Centre Spatial de Liège, Belgium
- Belgian Institute for Space Aeronomy, Belgium
- Natural Resources Canada, Canada
- Centre National de la Recherche Scientifique/Ecole et Obs. des Sciences de la Terre, France
- Univ. of Iceland, Iceland
- Icelandic Meteorological Office, Iceland
- Istituto per il Rilevamento Elettromagnetico dell'Ambiente IREA – CNR, Italy
- University of Leeds, UK
- NASA, USA
- European Space Agency (ESA)

- German Space Agency (DLR)
- Italian Space Agency (ASI)
- Japan Space Agency (JAXA)
- Canadian Space Agency (CSA)

## ❖ Results and achievements in 2019

### Monitoring networks

In the frame of RESIST and MODUS, we carried on the maintenance of the KivuGnet and KivuSnet telemetered networks in DR Congo. In addition to the remote maintenance, two missions were performed on the field in June and October 2019.

We also designed and installed the National Seismic Network of Rwanda (4 new telemetered seismic stations) and performed the training of the local staff (see page 11 above).

### Development of ground deformation monitoring tools by satellite

In the frame of MUZUBI, SMMIP, Hengill and RCM-AIT, we carried out the development of cutting-edge tools for satellite Radar interferometry (InSAR) processing based on the CSL InSAR Suite Software. Special tools for automated optimized mass processing (entitled **MasTer**: CSL InSAR Suite automated Mass processing Toolbox for Multidimensional time series) were further improved and new scripts were developed for optimization, validation, results plotting etc… The system now fully integrates with the Multidimensional Small Baseline Subset (**MSBAS**) tool and runs without human interaction to perform the systematic monitoring of the Virunga region. It is compliant with both Linux and Mac operating system.

The new version of **MSBAS** software (developed by Sergey Samsonov) able to compute full 3D displacements (when movements are expected to occur along the terrain slope) was finalized and published (Samsonov et al., in press). The processing was successfully tested on the Funu landslide area in Bukavu, South Kivu. Results are consistent with results from dGPS campaigns and from other 1D and 2D InSAR time series analysis.

Several mass processes using MasTer are routinely and automatically executed in Luxembourg. Thousands of interferograms are computed to monitor and study the volcanic activity in the Virunga Volcanic Province in Congo, the landslides in the highly populated city of Bukavu in South Kivu, (Figure 13) DRC and possible ground deformation in the Greater Region.

The MasTer toolbox is used at several institutes (e.g. at the University of Luxembourg, the Geological Survey of Belgium, the Centre Spatial de Liège, the Roya Museum for Central Africa, the Geological Survey of Austria, the Universidad Mayor, Centro Hemera de observacion e la Tierra in Santiago, Chile, the Instituto de Investigación en Paleobiología y Geología - Universidad Nacional de Rio Negro - Argentina …).

### MasTer toolbox Summer School

In July 2019, we organized and taught a one-week summer school about the MasTer toolbox at ECGS in Walferdange (Figure 14). The number of participants was limited to 10 because of logistical constraints. Priority was given to research institutions from Luxembourg (Uni.lu and LIST) and Belgium (MRAC, VUB). Two more participants came from partner institutions in Iceland and Austria.

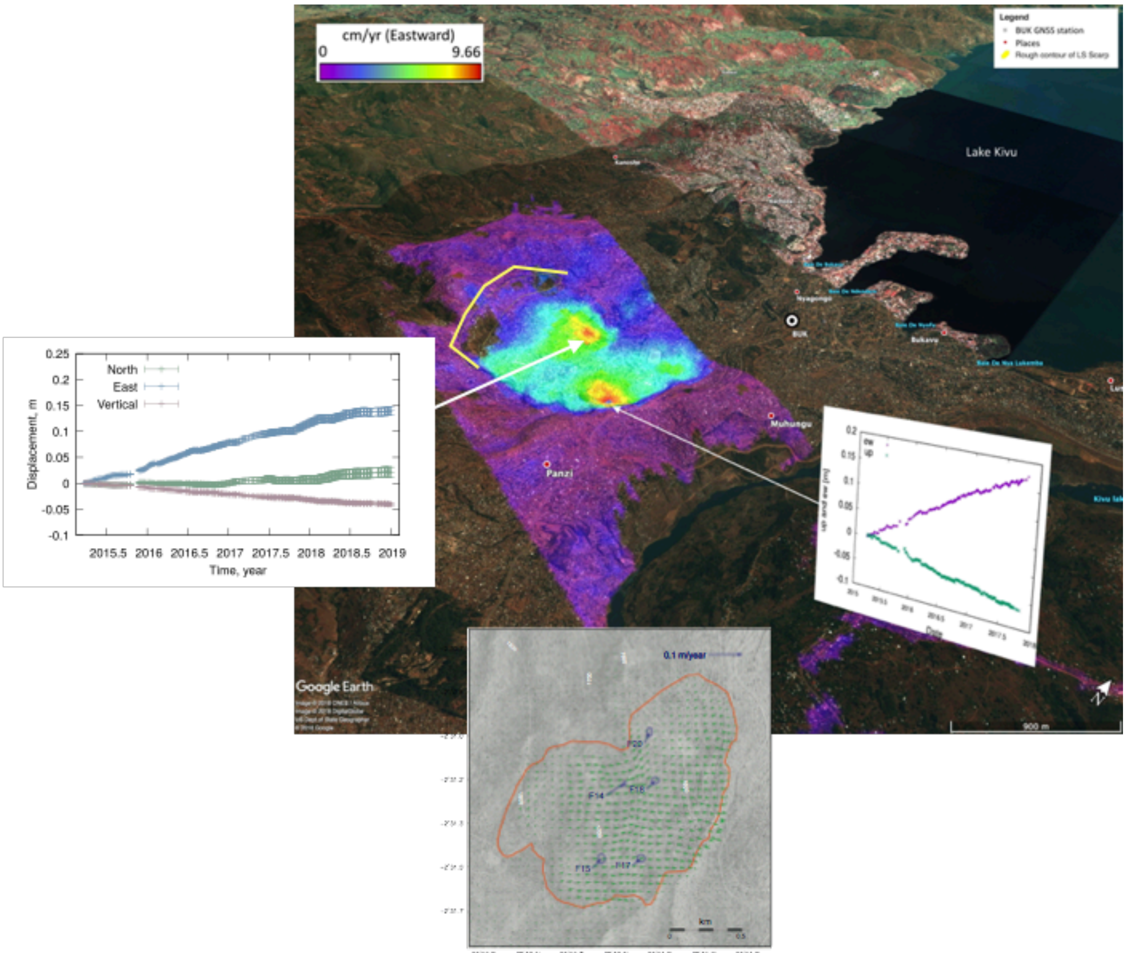


**Figure 13**: East-West velocity map of landslide ground displacement in Bukavu (South Kivu) wrapped on Google Earth image. **Right inset:** 2D vertical (green) and EW (purple) ground displacement time series measured for a pixel located in the southern part of the Funu landslide. **Left inset: 3D** vertical (red), EW (blue) and NS (green) ground displacement for a pixel located in the northern part of the landslide. **Bottom**: Horizontal deformation rate vectors computed with MSBAS-3D technique (green arrows) and deformation vectors measured from dGNSS campaigns. Landslide outline is in red (Samsonov et al. in press).

**Figure 14**: Participants to the MasTer summer school in Walferdange.

## Results for volcano monitoring

In addition to the ground deformation monitoring, MasTer toolbox is also used for monitoring depth changes and lava lake level variations within Nyiragongo and Nyamulagira craters. A fully automated procedure generates SAR amplitude image of each new ESA Sentinel-1 image acquired on the Virunga volcanoes (~every 2-6 days). Depths changes are measured from the SAR shadow cast by surrounding sub vertical structures such as the crater rims. These data are analyzed along with seismic, infrasound, geodetic and geochemical data.

In particular, these measures obtained in the Nyiragongo crater were analyzed along with close-range (i.e., summit) and distant (around 17 km) seismic measurements acquired at Nyiragongo volcano between 2011 and 2018 in order to better understand the seismic signature of the lava lake activity and how it relates to the deeper volcanic processes.

Both summit and distant seismic records contain a similar continuous tremor pattern attributable to the lava lake activity. Combining this information with time-lapse camera images and lava lake level measurements confirmed the mechanism of gas pistoning at Nyiragongo, which is characterized by short-duration (a few minutes long) and meter-scale level variations during the period of observation.

Analyzing the dominant periodicity of this shallow tremor signature along with fluctuation of $SO_2$ emissions (estimated from space), allowed suggesting that this particular seismic periodicity corresponds to the convective lake movement driven by the persistent degassing typical of active open-vent volcanoes.

Finally, new seismic evidence reveals the effect of deep magmatic intrusion and consequent major pressure changes in the plumbing system, resulting in sudden and large drops of the lava lake level associated with strong degassing. Such transient episodes of > 100m lava lake level drop, as observed 3 times in 2019, have similar characteristics to total lava lake drainage associated with flank eruptions already observed at this volcano in 1977 and 2002, or at Kilauea volcano in 2018. (see Barrière et al., 2019).

# Walferdange Undergound 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 2019, 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.

Given its exceptional quality, the WULG remains an exceptional measurement and test site for geophysical instrumentation in a highly stable environment since 1968. The University of Luxembourg carried out the maintenance of the superconducting gravimeter installed in the WULG since the beginning of the twenty-first century. From 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.

At present, radon 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 (changes in air circulation conditions, Earth Tides etc.).

It should be noted here that for several years now, issues regarding the stability of the entrance have been noticed and discussed among the administrations involved, with no final conclusion thus far on how to proceed to solve these issues. For this reason, access is currently restricted to ECGS/Mnhn staff for instrument maintenance purposes only, following strict security regulations.

## ❖ Radon measurements in the WULG during 2019

**Antoine Kies**

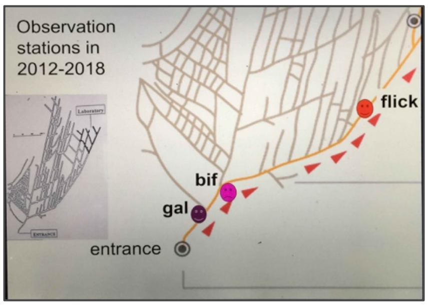


**Figure 15:** Radon observation sites in WULG.

Radon investigations continued in the Walferdange gypsum mine in 2019. Two radon monitors (Alphaguard) recorded radon in 'gal' and 'flick', while local temperatures were recorded at these places and in 'bif' (Figure 15). Meteo data are provided by MeteoLux.

2019 was characterized by an extreme hot summer that influenced dramatically the radon concentrations in the mine as documented below. Whereas the plastic shielding still closes all secondary galleries, some modifications have been made. The plastic was slightly opened at 'gal' in order to have a better primary response from the radon flux coming from this partly collapsed gallery. The position of the detector is roughly the same as before the plastic 'event', after which the detector had to be positioned in a non ideal place. The effect can be clearly seen on Figure 19.

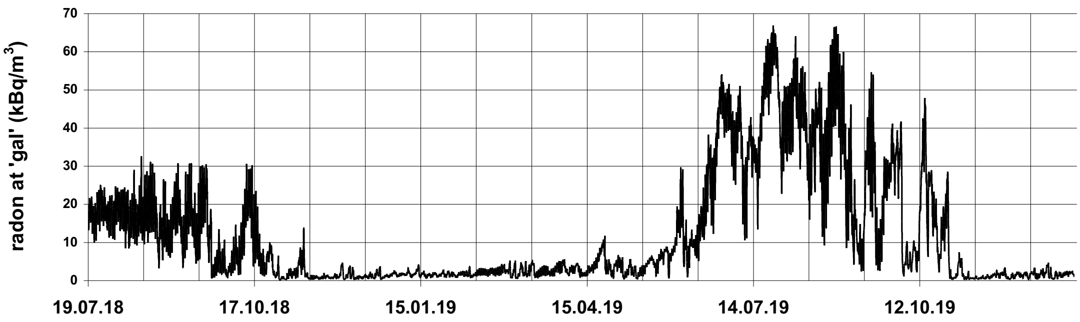


**Figure 16:** Radon concentrations at station 'gal' between July 2018 and January 2020.

Radon concentrations at 'gal' (Figure 16) are mainly influenced by external temperatures (extemp) that govern the direction of air circulating in the partly collapsed gallery, actually this air is the carrier of the radon atoms (Figures 17 & 18). If extemp>Tm (Tm = 10.5 °C mean mine temperature), air flows into the main gallery and to the mine interior, in the opposite no radon is carried to the mine. The influence of outside temperature is perfectly documented by the next two figures, the second being a close-up that shows the very sharp reaction of radon at 'bif' to short time temperature changes.

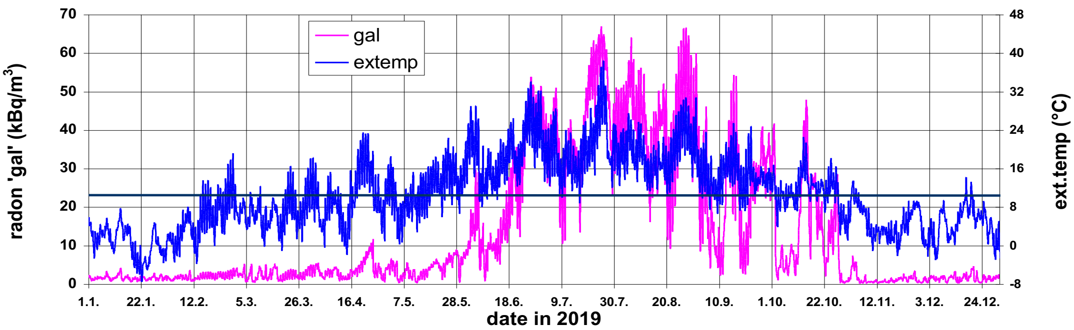


**Figure 17:** Comparison of temporal evolution of radon concentration at station 'gal' and external temperature measurements.

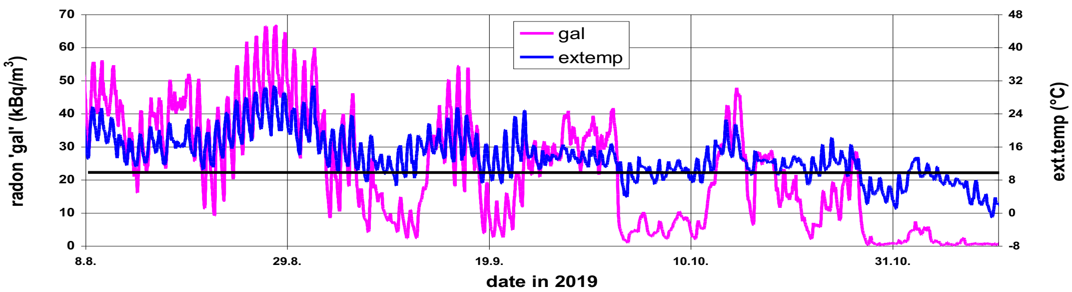


**Figure 18:** Close-up of Figure 20 for the time period August – October 2019.

Striking are the extremely high radon concentrations, over 60 kBq/m3, very difficult to explain. Part or radon entering the mine at 'gal' is distributed to the mine interior where it mixes with the radon produced in the mine (2.6 kBq/m3, also surprisingly high). A time delay is measured between the radon signal at 'gal' and at 'flick' (Figure 19). This gives the possibility to guess a mean velocity of air flow into the mine. Repetitive experiences with cigar smoke confirm this. It constitutes a strong prove of the ventilation of the mine, making a plastic shielding of lateral galleries obsolete. As shown in the next figures, the only effect of the plastic shielding is the high radon fluctuations at 'flick', proving an increased advection of fresh outside air, this is also the reason of higher local temperature variations. Note that due to the high temperatures lasting for several days, with high night temperatures, the highest ever measured radon concentrations in the mine interior were recorded in 2019.

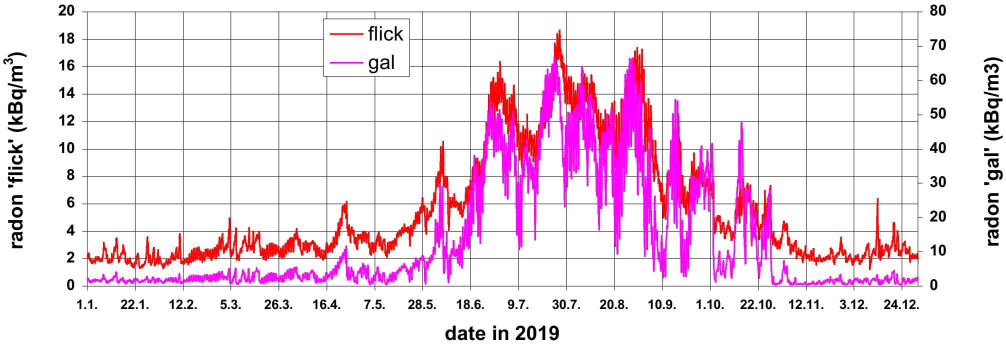


**Figure 19:** Close-up of Figure 20 for the time period August – October 2019.

On several occasions, during the downloading process, $CO_2$ measurements were done in different locations in the mine, including the geophysical laboratory and the closed galleries. No significant differences were noted. Concentrations oscillated between 1000 and 1350 ppm, similar to concentrations in the morning in a bedroom with closed windows.

The author wants to express his thanks to MeteoLux (climatology) and especially Dr. Joerg Bareiss for the meteo data and to the Museum of Natural History for the possibility to do research in the mine of Walferdange.

## 100TH JOURNEES LUXEMBOURGEOISES DE GEODYNAMIQUE

The Journées Luxembourgeoises de Géodynamique (JLG) organized by ECGS from 25 to 27 March 2019 marked a very special jubilee: this was the 100th edition of the JLG, and at this occasion, we celebrated at the same time the 30th anniversary of ECGS (created 1988) and the 60th anniversary of the Walferdange Underground Laboratory for Geodynamics (WULG).

In order to celebrate this special occasion, ECGS organized the 100th JLG composed of three parts: on the first day (25 March 2019), an academic session was organized. The second day (26 March 2019) was dedicated to the advances on the scientific research related to the Virunga Volcanoes and the Kivu Rift region in Eastern Democratic Republic of the Congo, which is one of the key research topics at ECGS in the framework of the RESIST project. The 100th JLG provided the platform for the final meeting of the project, which ended in July 2019. Finally, the third day (27 March 2019) was dedicated to the developments in ground motion modelling in Europe for the 2020 European seismic hazard model, a model under development within the H2020 project SERA.

Sadly, JLG president Prof. Dr. Manfred Bonatz, a highly esteemed colleague and friend, passed away shortly prior to the meeting in December 2018. The 100th JLG are dedicated to his memory and showcased the wide range of research expertise held at ECGS as well as its rooting within the international community. It also is an excellent example for the extraordinary value of the JLG: an informal type of meeting acting as an excellent platform for exchange among researchers and advancement in important topics in the Earth Sciences.

Séance Académique

à l'occasion de la Célébration

de la 100e Edition des Journées Luxembourgeoises de Géodynamique

du 60e Anniversaire de la création du Laboratoire Souterrain de Géodynamique à Walferdange

et du 30e Anniversaire de la création du Centre Européen de Géodynamique et de Séismologie (CEGS)

25 mars 2019

Programme

Ouverture musicale Wilhelmus

Mot de bienvenue
*Michel Feider, Président du Conseil d'Administration du CEGS*

Un demi-siècle de Sciences de la Terre au Luxembourg
*Nicolas d'Oreye, Géophysicien, Musée national d'histoire naturelle et CEGS*

Intermède musical Alphonse Hasselmans : La source Op.44

Le Centre Européen de Géodynamique et de Séismologie vu du Conseil de l'Europe
*Jean-Pierre Massué, Ancien Secrétaire Exécutif de l'Accord EUR-OPA Risques Majeures du Conseil de l'Europe*

Intermède musical Domenico Scarlatti : Sonata K27

Les catastrophes naturelles : un défi pour les Sciences de la Terre
*Adrien Oth, Géophysicien, Directeur Scientifique du CEGS*

Intermède musical Claude Debussy : Première Arabesque

Les Programmes d'Observation de la Terre de l'ESA & le Programme Copernicus
*Pierre Potin, Chef de Mission Sentinelle 1, ESA – European Space Agency*

Allocution de Mme la Ministre de la Culture
*Sam Tanson, Ministre de la Culture*

Mot de Clôture
*Michel Feider, Président du Conseil d'Administration du CEGS*

Clôture musicale Domenico Scarlatti : Sonata K208

Encadrement musical par Catherine Beynon,
Harpiste solo de l'Orchestre Philharmonique du Luxembourg

**Figure 20**: Programme of the academic session of 25 March 2019 organised on the occasion of the 100th edition of the JLG, the 60th anniversary of the WULG and the 30th anniversary of ECGS.

### Day 1: Academic session & celebration dinner

The 100th JLG started with an academic session on 25 March 2019. The programme (Figure 20) started with a welcome speech by ECGS president, Dr. Michel Feider, followed by three speeches guiding through the history of Earth Sciences in Luxembourg in general and ECGS in particular (Dr. Nicolas d'Oreye), the rooting of ECGS within the framework of the EUR-OPA Major Hazards Agreement of the Council of Europe (Mr. Jean-Pierre Massué) and scientific research activities and perspectives for the future of ECGS (Dr. Adrien Oth).

These speeches were followed by a key note lecture regarding the Earth observation programmes of the European Space Agency (ESA) given my Dr. Pierre Potin, mission manager of Sentinel-1 at ESA, and an address of Ms. Sam Tanson, Minister of Culture, before the session was closed by ECGS president Dr. Feider. Musical interludes were presented by harp solist Ms. Catherine Beynon.

ECGS was honoured with the presence of HRH Grand Duke Henri, who also holds ECGS's honorary presidency, and Minister of Culture Ms. Sam Tanson (Figure 21). The academic session was attended by 80 invitees, among which members of the civil society (e.g., mayor and échevins of the Commune de Walferdange), past and current collaborators as well as representatives from partner and funding institutions, members of the administrative and scientific boards throughout ECGS's history, etc.

The academic session was followed by a reception and a celebration dinner.

### Day 2: Research advances in the RESIST project

The aim of the second day of the 100th JLG was, as a follow-up of the 2017 meeting, to provide a platform for the discussion of the recent advances within the RESIST project (page 4). The 100th JLG also marked the final meeting of this project, which finalised at the end of July 2019. The meeting was structured in four oral and one poster session dedicated to the subjects of volcano-tectonic deformation measurements through satellite and ground-based approaches and their methodological developments, volcanic $SO_2$ emission measurements

**Figure 21**: Left: Members of the ECGS Administrative Board with HRH Grand Duke Henri (middle front row) and Minister for Culture Sam Tanson (right front row). Right: Dr. Nicolas d'Oreye presents a gift by ECGS to HRH Grand Duke Henri, composed of a piece of a volcanic bomb originating from Nyiragongo volcano in Eastern Democratic Republic of the Congo.

using space-based and ground data, the lava lake of Nyiragongo volcano, landslide characteristics and triggering in the Kivu region as well as the volcanic and tectonic seismicity characteristics of the area.

Overall 17 oral and 8 poster presentations were given. Ample time was, as always at the JLG, foreseen for the discussion of scientific and practical issues that arose during the RESIST project implementation and how to best possibly valorise the RESIST results for current and future research and monitoring activities in the Kivu Rift region.

**Day 3: Ground motion modelling in Europe for the 2020 European Seismic Hazard Model**

The target of the third day of the 100th edition of the JLG was to discuss with the community of experts in the field of seismic hazard assessment in Europe the ground motion models proposed to be used in the implementation of the 2020 European Seismic Hazard Model, developed in the framework of the European H2020 project SERA (*Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe*).

25 scientists from all over Europe participated in this meeting, and the agenda was composed of four keynote presentations covering the 2020 European Seismic Hazard Model from a project agenda point of view, the backbone logic tree approach, the development of a backbone model for shallow crustal seismicity and the proposed structure of the logic tree and strategies for calibration and testing.

This session was then followed by a round table discussion and a series of short presentations on the lessons learned from recent ground motion model development efforts in various European countries.

**Figure 22**: Participants of the Day 3 JLG session on ground motion modelling in Europe.

## SCIENCE FESTIVAL 2019

ECGS participated in the 2019 Science Festival (7-10 November 2019), organised by the National Museum for Natural History (Mnhn) in collaboration with the Luxembourg National Research Fund (FNR). The workshop set up by ECGS was entitled *ShakeLab: Make your Quake*!

The key idea of the workshop was to explain to school children and the general public how seismic and acoustic (more specifically, infrasound) waves propagate through the Earth and Atmosphere, and how they can be used to locate seismic events and their utility in the volcano research and monitoring activities of ECGS. To this end, ECGS acquired four Raspberry Shake& Boom instruments, composed of a vertical short-period seismometer and an infrasound sensor, and demonstrated the concepts of wave propagation and travel time to the visitors by showing the acoustic wave propagation from an infrasound source (e.g., opening/closing a window or a door) in the premises of the Science Festival and Abbaye Neumünster.

The stand of ECGS also featured a visualisation of its real-time seismic acquisition and processing system, the display of several instruments, a photo slideshow and a set of posters used for providing explanations on the concepts required for the understanding of the workshop.

A total of 11 school classes (pupils aged 12-15 years) had registered for the workshop, and the workshop was also a great success among the general public visiting the Science Festival over the two weekend days (9-10 November).

**Figure 23**: Overview of the ECGS stand at the 2019 Science Festival.

**Figure 24**: Dr. Julien Barrière explaining the principles of seismic wave propagation to a school class.

## OTHER OUTREACH ACTIVITIES

- **Eldoradio Reportage "**Nogefrot: Gouf et scho gréisser Äerdbiewen hei zu Lëtzebuerg?", 24 January 2019, featuring A. Oth

  Weblink: http://www.eldo.lu/radio/reportagen/88980.html

- **RTL am Gespréich: Dr. Adrien Oth**, 19 June 2019, featuring A. Oth

  Weblink: https://www.rtl.lu/radio/am-gespreich/a/1364700.html

- **Article in Lëtzebueger Journal**, "Reinhören in die Erdkruste", 15 September 2019, featuring A. Oth

  Weblink: https://www.journal.lu/top-navigation/article/reinhoeren-in-die-erdkruste/?L=0&cHash=f93ba6f31d362d010f0a6672a8bfa234

- **Article in Luxemburger Wort**, "Le Luxembourg victime d'un séisme «très rare»", 18 December 2019, featuring A. Oth

  Weblink: https://www.wort.lu/fr/luxembourg/le-luxembourg-victime-d-un-seisme-tres-rare-5dfa0d59da2cc1784e3524c1

- Maintenance of a **web site** dedicated to the monitoring activities and studies of the **Virunga volcanoes**: www.virunga-volcanoes.org

# PUBLICATIONS & PRESENTATIONS

## ❖ Peer-reviewed Journal Publications and Proceedings

### Published

**Barrière, J.**, **N. d'Oreye**, **A. Oth**, N. Theys, N. Mashagiro, J. Subira, F. Kervyn and B. Smets (2019). Seismicity and outgassing dynamics of Nyiragongo volcano. *Earth Planet. Sci. Lett.*, 528, 115821, doi: 10.1016/j.epsl.2019.115821.

Ahmadzadeh, S., S. Parolai, G. Javan-Doloei and **A. Oth** (2019). Non-parametric spectral modelling of source parameters, path attenuation and site effects from broadband waveforms of the Alborz earthquakes (2005-2017). *Geophys. J. Int.*., 219(3), 1514-1531, doi: 10.1093/gji/ggz377.

Picozzi, M., D. Bindi, D. Spallarossa, **A. Oth**, D. Di Giacomo and A. Zollo (2019). Moment and energy magnitudes: diversity of views on earthquake shaking potential and earthquake statistics. *Geophys. J. Int.*, 216, 1245-1259, doi: 10.1093/gji/ggy488.

### In press

Samsonov, S., A Dille, O. Dewitte, F. Kervyn and **N. d'Oreye** (2019). Satellite interferometry for mapping surface deformation time series in one, two and three dimensions. *Eng. Geol.* (in press).

## ❖ Conference Presentations, Proceedings and Abstracts

**Barrière**, **J.**, **Oth, A.** and the **RESIST team** (2019). Case studies of integrated space-ground monitoring of volcanic activity in the Virunga volcanic province. *100th Journées Luxembourgeoises de Géodynamique, 25-27 March 2019, Luxembourg.*

**Barrière, J.**, **A. Oth**, **N. d'Oreye**, N. Theys and F. Kervyn (2019). Two recent case studies of integrated space-ground monitoring of volcanic activity in the Virunga volcanic province, D.R. Congo. *ESA Living Planet Symposium, 13-17 May 2019, Milan, Italy.*

**Barrière**, **J. A. Oth**, B. Smets, **N. d'Oreye**, N. Theys, N. Mashagiro, J. Subira and F. Kervyn (2019). The outgassing dynamics of Nyiragongo volcano. *27th General Assembly of the International Union of Geodesy and Geophysics, 8-18 July 2019, Montreal, Canada.*

Brenot, H., N. Theys, M. Van Roozendael, C. Fayt, J. Gliß, K. Stebel, B. Smets, **N. d'Oreye**, **J. Barrière**, M. Yalire, A. Minani, M. Syauswa, S. Arellano and F. Kervyn (2019). The RESIST project: SO2 changes from the ground using UV instruments. *100th Journées Luxembourgeoises de Géodynamique, 25-27 March 2019, Luxembourg.*

Brenot, H., N. Theys, M. Van Roozendael, C. Fayt, J. Gliss, K. Stebel, B. Smets, **J. Barrière**, **N. d'Oreye**, M. Yalire, A. Minani, M. Syauswa, S. Arellano and F. Kervyn (2019). Investigation of cyclic relation between Nyiragongo $SO_2$ fluxes and its lava lake height. *European Geosciences Union General Assembly 2019, 7-12 April 2019, Vienna, Austria.*

Cayol, V., C. Wauthier, **N. d'Oreye,** F. Kervyn, M. Tridon, J.-L. Froger and Y. Fukushima (2019). Assets of determining stress changes from InSAR displacement at Kivu and Reunion. *100th Journées Luxembourgeoises de Géodynamique, 25-27 March 2019, Luxembourg.*

**Derauw, D.**, L. Libert, Q. Glaude, C. Barbier, A. Orban, F. Kervyn, S. Samsonov and **N. d'Oreye** (2019). The CSL InSAR Suite processor: specificities of a command line InSAR processing software specifically adapted for automated time series processing. *Belgian Earth Observation Day 2019, 30 January 2019, Beersel, Belgium.*

**Derauw, D.**, L. Libert, C. Barbier, A. Orban, F. Kervyn, S. Samsonov and **N. d'Oreye** (2019). The CSL InSAR Suite processor: specificities of a command line InSAR processing software specifically adapted for automated time series processing. *ESA Living Planet Symposium, 13-17 May 2019, Milan, Italy.*

**Derauw, D.**, **N. d'Oreye** and A. Caselli (2019). Multidimensional Small BAseline Subset (MSBAS): una técnica para monitorear la deformación de volcanes activos. *1 Congreso ALVO (Volcanologia en y para Latinoamerica), 3-7 November 2019, Antofagasta, Chile.*

Dille, A., O. Dewitte, **D. Derauw**, L. Libert, B. Smets, E. Monsieurs, M. Kervyn, **N. d'Oreye** and F. Kervyn (2019). Kinematics of deep-seated landslides in a tropical urban environment: insight from combined analysis of long InSAR time series and ground-based measurements. *ESA Living Planet Symposium, 13-17 May 2019, Milan, Italy.*

**d'Oreye**, **N., J. Barrière**, **D. Derauw**, H. Geirsson, B. Smets, **A. Oth**, S. Samsonov and F. Kervyn (2019). Pressure changes in volcanic systems and volcanic interactions in the Virunga Volcanic Province inferred from lava lake measurements. *European Geosciences Union General Assembly 2019, 7-12 April 2019, Vienna, Austria.*

**d'Oreye, N.** (2019). Un demi siècle de Sciences de la Terre au Luxembourg. *Séance Académique, 100th Journées Luxembourgeoises de Géodynamique, 25-27 March 2019, Luxembourg.*

**d'Oreye, N.** and the **RESIST team** (2019). The RESIST project: Pre-eruptive signals revealed by very long MSBAS time series (2003-2019) of ground displacement in the Virunga. *100th Journées Luxembourgeoises de Géodynamique, 25-27 March 2019, Luxembourg.*

**d'Oreye, N., D. Derauw**, L. Libert, S. Samsonov, A. Dille, A. Nobile, E. Monsieiurs, O. Dewitte and F. Kervyn (2019). Automatization of InSAR mass processing using CSL InSAR Suite (CIS) software for Multidimensional Small Baseline Subset (MSBAS) analysis: example combining Sentinel-1 and Cosmo-SkyMed SAR data for landslides monitoring in South Kivu, DR Congo. *ESA Living Planet Symposium, 13-17 May 2019, Milan, Italy.*

**d'Oreye**, **N., J. Barrière**, **D. Derauw**, H. Geirsson, B. Smets, **A. Oth**, S. Samsonov and F. Kervyn (2019). SAR shadows for measuring height changes: Application for monitoring pressure changes in volcanic systems in the Virunga Volcanic Province. *ESA Living Planet Symposium, 13-17 May 2019, Milan, Italy.*

Geirsson, H., **N. d'Oreye**, A. Nobile, B. Smets and F. Kervyn (2019). Deformation of tectonic and volcanic origin in the greater Kivu region. *100th Journées Luxembourgeoises de Géodynamique, 25-27 March 2019, Luxembourg.*

Nobile, A., B. Smets, J. Subira, H. Geirsson, N. Theys, **N. d'Oreye** and F. Kervyn (2019). A multi-technique investigation of the 2011-2012 Nyamulagira eruption. *100th Journées Luxembourgeoises de Géodynamique, 25-27 March 2019, Luxembourg.*

**Oth, A.** (2019). Natural disasters: A challenge for Earth Sciences. *Séance Académique, 100th Journées Luxembourgeoises de Géodynamique, 25-27 March 2019, Luxembourg.*

**Oth, A.**, **J. Barrière** and the **RESIST team** (2019). The Kivu Seismological Network (KivuSNet) through the course of the RESIST project: network development, performance and fundamental seismological models. *100th Journées Luxembourgeoises de Géodynamique, 25-27 March 2019, Luxembourg.*

Picozzi, M., D. Bindi, D. Spallarossa, **A. Oth**, D. Di Giacomo and A. Zollo (2019). Moment and energy magnitudes: diversity of views on earthquake shaking potential and earthquake statistics. *Abstract, American Geophysical Union Fall Meeting, 9-13 December 2019, San Francisco, USA.*

Samsonov, S., **N. d'Oreye**, A. Dille, E. Monsieurs and O. Dewitte (2019). A MSBAS3DT software for computing 3D displacements along the surface tangent plane from ascending and descending DInSAR datasets. Case study: landslide in Bukavu, South Kivu, DR Congo. *ESA Living Planet Symposium, 13-17 May 2019, Milan, Italy.*

Samsonov, S. and **N. d'Oreye** (2019). Monitoring ground deformation with satellite radar in one, two and three dimensions. *Advanced SAR Workshop, October 1-3 2019, Saint-Hubert, Quebec, Canada*.

Smets, B., C. Wauthier, A. Dille, R. Paris, D. Samyn, **N. d'Oreye** and F. Kervyn (2019). Ground deformation and topographic change measurements in active volcanic craters using UAS-based SfM-MVS photogrammetry. *100th Journées Luxembourgeoises de Géodynamique, 25-27 March 2019, Luxembourg.*

Smets, B., C. Wauthier, A. Dille, R. Paris, D. Samyn, **N. d'Oreye**, and F. Kervyn (2019). Ground deformation and lava accumulation measurements in volcanic craters using UAS image acquisitions and 4D photogrammetry. *European Geosciences Union General Assembly 2019, 7-12 April 2019, Vienna, Austria.*

Theys, N., **J. Barrière**, **A. Oth**, **N. d'Oreye**, H. Brenot, M. Van Roozendael and F. Kervyn (2019). Sulfur dioxide retrievals from space (OMI and TROPOMI) combined with in-situ data at active volcanoes in North Kivu region. *ESA Living Planet Symposium, 13-17 May 2019, Milan, Italy.*

# MEETING ATTENDANCE, FIELD MISSIONS, WORK VISITS

## Adrien Oth

- 100th Journées Luxembourgeoises de Géodynamique (JLG), Luxembourg, 25-27 March
- 2nd GITEC Generalized Inversion Benchmark Group Meeting, Cadarache, France, 3-4 April
- BMBF (Bundesministerium for Bildung und Forschung) reviewer panel meeting, Berlin, Germany, 16-17 May
- Field mission and Rwanda National Seismic Network deployment assistance, Rwanda, 27 May – 8 June
- European Seismic Hazard Model Review Meeting, Potsdam, Germany, 12-13 June
- Participation in the WG-B meeting of the Comprehensive Test Ban Treaty Organisation (CTBTO), Vienna, 26-28 September
- Participation in EFEHR consortium establishment meeting (via Skype), Zurich, 2 October
- Workshop on earthquake source physics collaborations, OGS Trieste, 3-4 December
- Work visits & Visitors at ECGS:
    - Visit of Ministry of Foreign Affairs representative (Mr. Christian Steinbach) in the framework of CTBTO activites (7 May)
    - Visit of GITEC participants F. Hollender, H. Shible, P. Traversa and D. Bindi at ECGS (9-10 September)
    - Visit PhD student Eugène Ndenzako from Burundi (8-21 September)

## Nicolas d'Oreye

- 100th Journées Luxembourgeoises de Géodynamique (JLG), Luxembourg, 25-27 March
- European Geosciences Union General Assembly, Vienna, Austria, 7-12 April
- ESA Living Planet Symposium, Milan, Italy, 12-17 May 2019
- Field mission to Rwanda and D.R. Congo, Rwanda National Seismic Network deployment assistance, 1-10 June
- Summer school in InSAR (CIS and MasTer training), Walferdange, 22-26 July
- Field mission to D.R. Congo (Goma) & Rwanda (Kigali), 18-24 October
- Participation in Science Festival 2019, 7-10 November
- Belgian Earth Observation Day 2019, Kluisbergen, Belgium, 28 November
- Work visits & Visitors at ECGS:
    - Work visit at MRAC in RESIST project context (21 January)
    - Work visit at MRAC in dGPS training context (28 January)
    - Work visit at Centre Spatial de Liège in MUZUBI project context (6 February)
    - Work visit of Dr. B Smets (MRAC) at ECGS for training on CIS MaSter toolbox (18-22 March)
    - Visit of Ministry of Foreign Affairs representative (Mr. Christian Steinbach) at ECGS in the framework of CTBTO activites (7 May)
    - Visit of Prof. Norman Teferele (Uni.lu) at ECGS for discussing future collaborations (7 May)
    - Work visit at MRAC in MODUS project context (28 May)
    - Work visit of Quentin Glaude (Centre Spatial de Liège) at ECGS (24 July)
    - Project stay in context of SMIPP project of D. Derauw (1 June – 31 July)
    - Work visit at MRAC in VERSUS project context (29 November)

## Julien Barrière

- 100th Journées Luxembourgeoises de Géodynamique (JLG), Luxembourg, 25-27 March
- Field mission and Rwanda National Seismic Network deployment assistance, Rwanda, 27 May – 8 June
- 27th General Assembly of the Internation Union of Geodesy and Geophysics, Montreal, Canada, 8-18 July
- Participation in Science Festival 2019, 7-10 November

# 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)
- **Editor** of *Pure and Applied Geophysics* (December 2014 – November 2019)
- **Reviewer** (proposals & papers) for *Bundesminsterium für Bildung und Forschung (BMBF), Bulletin of the Seismological Society of America, Journal of Geophysical Research*
- **Member** of American Geophysical Union, Seismological Society of America, European Geosciences Union, Deutsche Geophysikalische Gesellschaft

## 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** (proposals & papers) for *Lake Kivu Monitoring Programme, ESA, J. African Eart Sci., Geophys. Res. Lett., Remote Sensing*
- **Scientific Committee Member** for ESA Fringe Workshop
- **Scientific Committee Member** for ESA Living Planet Workshop
- **Session convener** at EGU General Assembly and ESA Living Planet Worksop
- **Member** of American Geophysical Union, European Geosciences Union & Academy of Sciences Luxembourg

## Julien Barrière

- **Mentorships & Supervision**
    - Josué Subira (planning of PhD programme starting in 2020)
    - Eugène Ndenzako (PhD student, University of Burundi, committee member)
- **Reviewer** for *Journal of Geophysical Research, Tectonophysics*
- **Member** of American Geophysical Union and European Geosciences Union