Annual Report 2020

EUROPEAN CENTER FOR GEODYNAMICS AND SEISMOLOGY (ECGS)

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Immatriculé au Registre de Commerce sous le nr G113 - Matricule 1988 6400 09099 - TVA Intracommunautaire LU 16035869

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INTRODUCTION

In 2020, the COVID-19 pandemic had a strong impact on the research activities carried out by ECGS. In particular, the related travel restrictions made any planned field trips impossible, including a major expedition to the Nyiragongo summit and crater that was originally planned to be carried out in the summer of 2020. In addition, regular network maintenance missions abroad had to be cancelled. Despite this challenging problem, ECGS managed to ensure the full operation of its seismic and geodetic measurement networks, both in Luxembourg and in the Kivu Rift region (Democratic Republic of the Congo).

The above-mentioned restrictions also meant that any international in-person conference participations had to be cancelled. While the ensuing trend for virtual meetings allows for some interaction with colleagues abroad, it is impossible to fully replace the personal contact for advancing collaborative projects. The pandemic also made it impossible to consider the organisation of a Journées Luxembourgeoises de Géodynamqique (JLG) meeting here in Luxembourg, and this will likely remain the case for the year 2021.

We continued the implementation of the ECGS strategic paper, for which our 5-year funding plan was accepted by the Luxembourg government in 2019. Seismic instrumentation has been acquired as planned and two of the existing seismic stations in Luxembourg, in Vianden and Kalborn, were already upgraded using this instrumentation in 2020. The search for further sites for the expansion of the Luxembourg Seismic Network is currently ongoing, even though somewhat more challenging than planned due to the pandemic. However, in the 2021 government budget, ECGS was unfortunately not granted the funding for an additional remote sensing scientist as planned in the strategic paper for 2021. This issue will significantly hamper the further implementation at least of part of the aims set out in the strategic paper, and we hope that this strongly needed additional position can be filled in 2022.

ECGS also joined the European Facilities for Earthquake Hazard and Risk (EFEHR) in 2020, which is a non-profit network of organisations and community resources aimed at advancing earthquake hazard and risk in the European-Mediterranean area.

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). In June 2020, Dr. Delphine Smittarello joined ECGS as a post-doctoral research scientist on a temporary contract, working on ground deformation studies using in particular remote sensing techniques.

ECGS/Mnhn was involved in a large range of research activities with strong national and international collaborations (see research activities below), which are the living proof of the wide recognition of its expertise. The dominant research topic involving all the internal synergies at ECGS was given by the study of the Virunga volcanoes and the Kivu Rift region. This work represents the natural continuation of more than a decade of scientific projects, which led among others to the deployment of one of the densest seismo-geodetic monitoring networks on the African continent. Besides this, another key focus point is the operation and further development of the Luxembourg Seismic Network. ECGS/Mnhn researchers published 4 articles in international peer-reviewed scientific journals in 2020, with 6 more currently under review.

Besides ECGS internal budgets provided by the Luxembourg government, funding and support for the research activities in 2020 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)

The Kivu Rift region: an extraordinary natural research laboratory

Over the past years, the RESIST project funded by Belspo and the FNR (see ECGS annual reports 2015 – 2019) has been the key project worked on at ECGS/Mnhn. 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 aimed at contributing to the under-standing 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, as well as the 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. In the frame of RESIST, we made significant progress in improving our understanding of the mechanisms that may lead to an eruption and what types of measurable phenomena and signals may 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).

While the RESIST project officially ended in 2019, ECGS/Mnhn remains deeply committed and involved to sustain the impressive research and monitoring infrastructure set up over the past decade as well as to continue to scientifically exploit the massive amounts of data acquired over the years, both ground- and space-based. These activities are carried out both in the framework of specific research projects (VERSUS, MODUS, HARISSA, see Remote Sensing section below, page 20) and within ECGS's general missions. In this context, all scientists at ECGS/Mnhn work together as an interdisciplinary team, encompassing all the different expertise available at ECGS/Mnhn, which is why we do not simply categorise it as purely seismological, remote sensing or ground deformation in this report.

In the framework of the VERSUS project, we initially focused on organizing an expedition to Nyiragongo's summit in mid-2020, which unfortunately had to be cancelled due to the COVID-19 pandemic. We therefore turned our primary attention to completing research using spaceborne SAR (Synthetic Aperture Radar) measurements for detecting magmatic pressure changes at Nyiragongo lava lake volcano. As indicated in the 2018 and 2019 reports, this work has been initiated several years ago by N. d'Oreye during the final stage of B. Smets' Ph.D. thesis at ECGS and the Royal Museum for Central Africa (RMCA) in Belgium, and developed in the last couple of years towards a promising semi-automatic method. The technique has been drastically improved during the past year and is now robust enough for publication in the peer-reviewed scientific literature (Barrière et al., in preparation). Despite the absence of recent field data at the summit (i.e., 2020 expedition cancelled), the complementary use of seismicity counts below Nyiragongo using the developed permanent seismic network in the region (KivuSNet, Oth et al., 2017) reinforces the understanding of the lava lake dynamics derived from this work. In addition, ongoing seismic studies focusing on the seismic monitoring in the Kivu region have been carried out in order to keep the results up to date and ready for new developments and analysis in 2021: seismic ambient noise properties, surface wave tomography and seismological velocity/magnitude models.

❖ Interpreting Nyiragongo's lava lake dynamics using spaceborne SAR measurements and seismicity

Nyiragongo is one of the rare lava lake volcanoes on Earth. Two flank eruptions in 1977 and 2002, resulting from dyke intrusions towards the surface, produced highly fluid lava flows from several km of fractures down to the heavily populated city of Goma (D.R. Congo). The inner crater, filled by fresh or cooled lava, collapsed both times due to the subsequent drainage of the crater's lava. Using a dense dataset of 1629 satellite radar images and the developed SAsha method (standing for SAR shadows) (Barrière et al., in prepation), we provide the first accurate time series of the lava lake and crater floor altitude measurements since the last 2002 eruption (Figure 2).

Converting these elevation measurements into extruded volume estimates using a 3D Digital Elevation Model (DEM) of the crater (not shown here), the elevation of the entire bottom platform (P3, see photos in Figure 2) has increased about 1.5 times more between 2002 and 2016 than between 2016 and 2020. However, taking into account the crater's conical shape, it appears that the amount of lava accumulated since the appearance of the spatter cone in early 2016 is about 1.75 times more important than the extruded volume between 2002 and 2016, i.e., ~35 million m^3 *vs.* ~20 million m^3 respectively. Similar to the lava lake volume, the alternance of plateaus and pulsatory growths is well noticeable for the period 2016-2020. Note however that the intracrateral accumulation rate observed since 2016 is similar to the 2006-2008 rate, i.e., about 10 million m^3/year, while it has been less than a million m^3/year since early 2020.

Figure 3 shows time series focusing on two connected processes occurring at different depths. Using information collected from the lava lake level and intracrateral volumes (Figure 3a, derived from Figure 2), we compute the daily magma budget inside Nyiragongo's crater since October 2015. Positive budgets (increase of the lake level and/or P3) are colored in blue, negative in red. We show that each large drop of the lava lake level is preceded by a significant positive magma budget. In other words, we highlight here a proxy for overpressure in the magmatic system prior to pressure drops, both detected from space-based measurements.

Comparing seismicity time series (Figure 3b) and crater topography changes indicates that the multiple pulse-like pressure variations result from changes in the deep feeding source of Nyiragongo, since several large seismic swarms are synchronous with the major drops of the lava lake level. Since then, each large lava lake drop associated to a seismic swarm conveys a similar mechanism. The seismic signature of the first large pressure drop in November 2016 has been studied in detail by Barrière et al. (2018) and Barrière et al. (2019) and is due to a magma intrusion at similar large depths as the repetitive events detected since the deployment of the network (magenta color in Figure 3b). This stable (non-destructive) seismic source at ~11-14 km b.s.l., most likely conveys the persistent feeding of the plumbing system at the level of the deep reservoir (Barrière et al., 2019). The overall seismicity ranges from 10 to 20 km b.s.l. and is of low magnitude (M_L ~0.5-1.5), which is typical for volcanic environments.

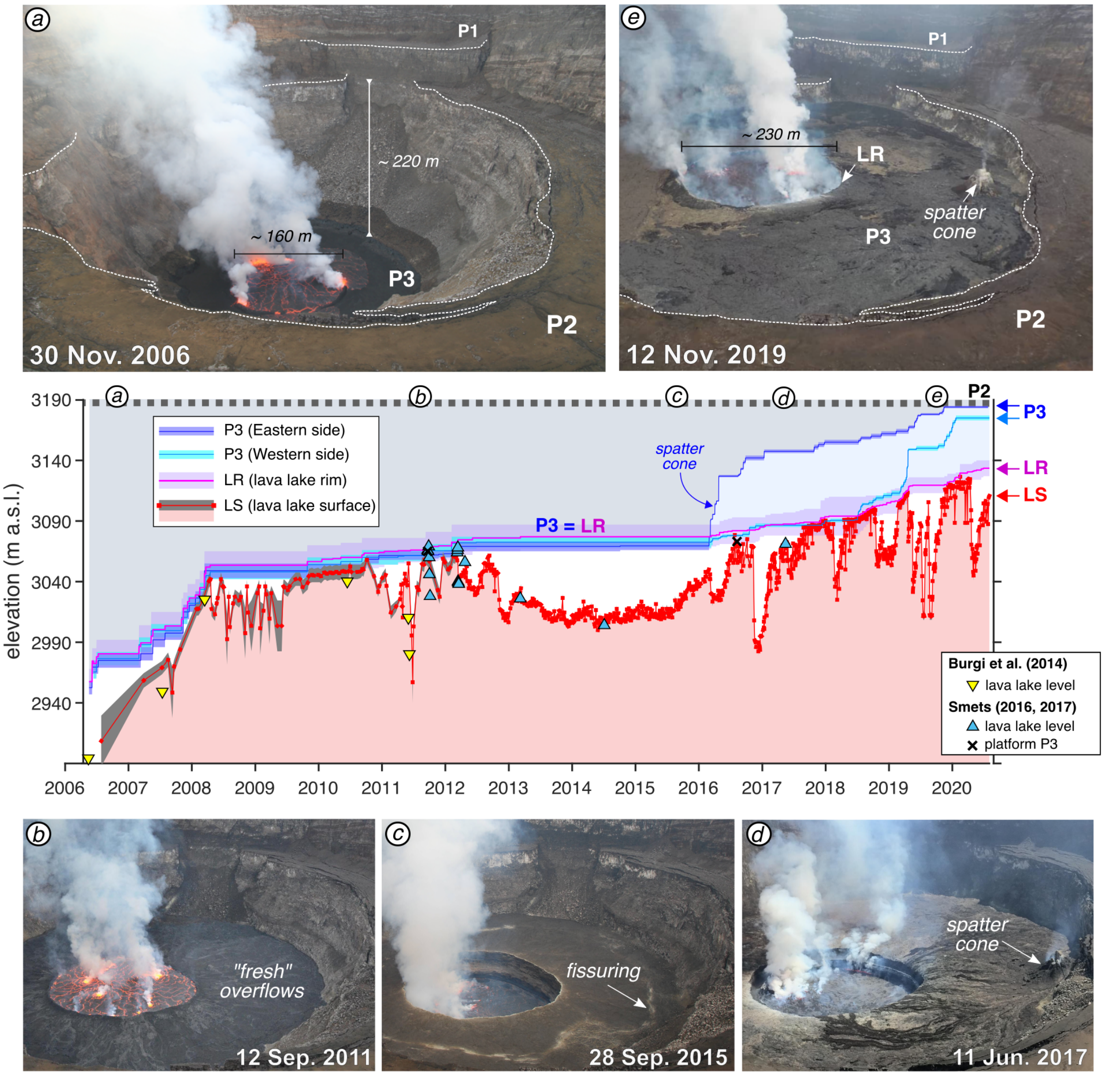

Figure 2. Topographic changes at Nyiragongo's crater: altitude of crater floor (*P3*), lava Lake Rim (*LR*) and lava Lake Surface (*LS*). These time series measured by SAR (see the main text) are illustrated with field pictures courtesy of J. Durieux (a), B. Smets (b), D. Delvaux (c), N. d'Oreye (d) and J. Subira (e). The shaded area around satellite measurements' curves corresponds to error margins. A constant, arbitrary uncertainty of 10 m to *LR* is added in order to take into account prominent spatter levees undetectable by the SAsha method and observed occasionally before 2013 around the lava lake. Lava lake and P3 levels from field measurements by Smets (2016, 2017 pers. comm.) are plotted with blue triangles and cross symbols, respectively, while estimates from Burgi et al. (2014) are plotted with yellow inverted triangles (note that 4 of 6 points from 2006 to 2010 have a coarse monthly temporal resolution).

In conclusion, Nyiragongo's open-vent crater is a remarkable source of information about the magmatic pressure changes. SAR amplitude images allow to infer a precise picture of these variations from space while adding seismic observations helps to better constrain their origins at depth. We emphasize here the importance of putting forward hypotheses supported by complementary observations. Ongoing research activities focus on analyzing additional information such as SO_2 emissions from TROPOMI and available, recent (2018-) acoustic/seismic records at Nyiragongo's summit and on its flank.

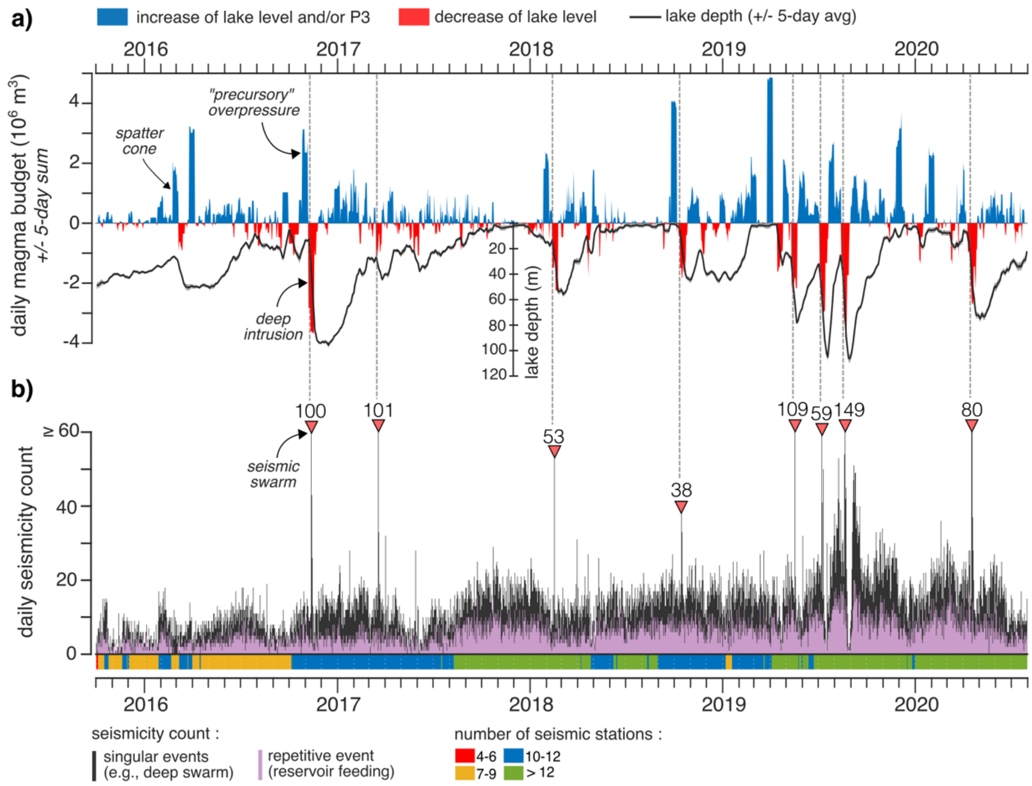

Figure 3. a) Daily magma budget (± 5-day sum) inside Nyiragongo's crater calculated since 1 October 2015, which is the date of the beginning of telemetered seismic network deployment (Oth et al., 2017). Blue and red histograms correspond to positive and negative budget, respectively. A negative magma budget only occurs during a drop of the lava lake level. The lake's surface depth (differential elevation between the lake rim and the lake surface) is also plotted as a black line. The strongest variations occur in 2016 and 2019. **b**) Daily count of repetitive seismic events from the same deep source (purple filling) and singular seismic events (black filling) (see the main text). The y-axis is truncated for visualization purposes. For each daily count, the number of available stations within 50 km around Nyiragongo is indicated by the color scale. This allows to check that the number of stations has no significant influence on the number of located events during the analyzed period of time. The number of available stations was lower before October 2016 (7-9) but short time periods with more stations (≥ 10) do not exhibit significantly seismicity rate differences (< 20 events/day).

❖ Seismic monitoring in the Kivu Rift region

Seismological models (P/S-wave velocity, local magnitude)

The development of the KivuSNet network (mainly since October 2015) led to an unprecedented knowledge of the seismicity patterns in this active tectonic region (e.g., Oth et al., 2017). Once a sufficient number of stations have a sufficiently long recording time, one can consider the development of new, more accurate seismological models for this area based on a catalog of selected events, which will be crucial for most further seismological applications (event location, local earthquake tomography, source parameters, etc.). Preliminary attempts have been presented in several international conferences over the last couple of years (e.g, IAVCEI Cities on Volcanoes 10, Naples – EGU General Assembly 2018, Vienna – SSA Annual Meeting 2018, Miami). These results, although highly promising, suffered from several limitations at that time, mainly:

- Too few well-locatable earthquakes within the Virunga Volcanic Province (typical volcanic seismicity, i.e., low signal-to-noise ratio, long-period events). A longer observational period is needed.

- Insufficient station coverage around Lake Kivu, thus not allowing for sufficient good quality observations of the numerous earthquakes in this area. More seismic stations were needed in this area.

The last two years have been game changing : 2 additional years of high-quality data (most stations have been fully operational); 2 additional stations have been installed in 2019 on the shore of Lake Kivu by the Goma Volcano Observatory (GVO) within the KivuSNet framework (same instrumentation, same acquisition system); 2 stations from the new Rwanda national seismic network (installed in 2019 by ECGS) help to close the critical azimuthal gap at the southern part of Lake Kivu and north-east of the volcanoes (Figure 4). Thousands of additional "good event candidates" have been detected. The process of phase-picking, which is an essential step, is time-consuming because this is a fully manual procedure. This work is in progress and starting to perform data inversion is envisaged in the course of 2021.

Seismic ambient noise properties

For similar reasons as mentioned above for the needed seismological models, the publication of the Surface Wave Tomography (SWT) of the Kivu region, already presented in international conferences, has been delayed in order to integrate new stations and improve the final resolution, notably for the Lake Kivu area. Moreover, the role of the Great Lakes (Kivu, Tanganyika) in generating low-frequency noise in accordance with daily/seasonality variations in wind patterns was already investigated (Barrière et al., 2019) but a more detailed analysis is required in order to gauge the potential effect in the frequency band of interest for the SWT (<0.5 Hz).

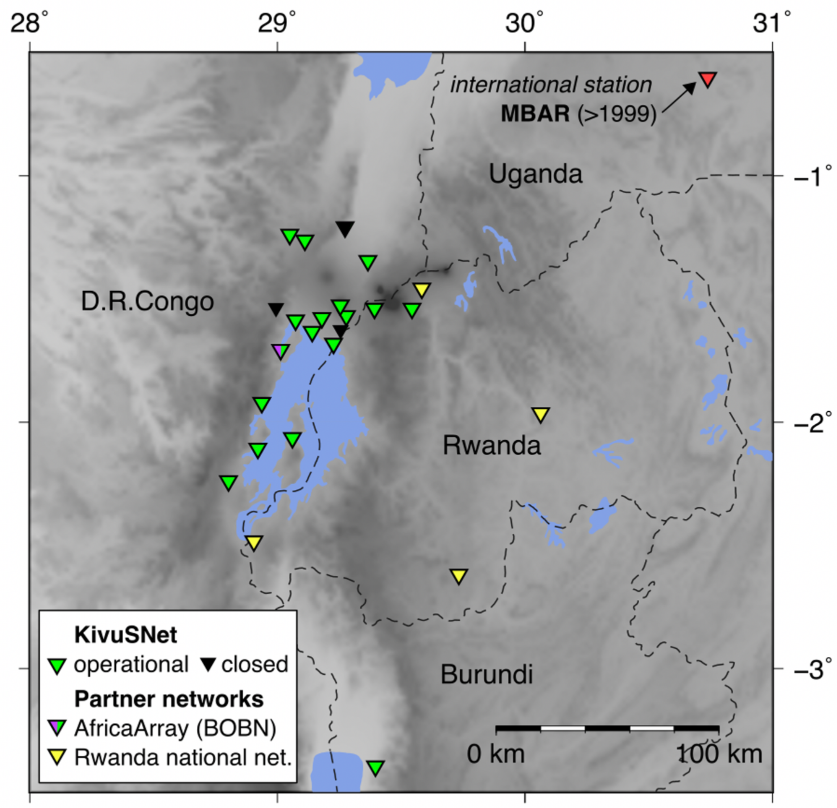

Figure 4. Seismic stations in the cross-borders region DR Congo/Rwanda/Burundi in early 2021, which have been deployed during the last decade by ECGS or partners (except the international station MBAR in Uganda).

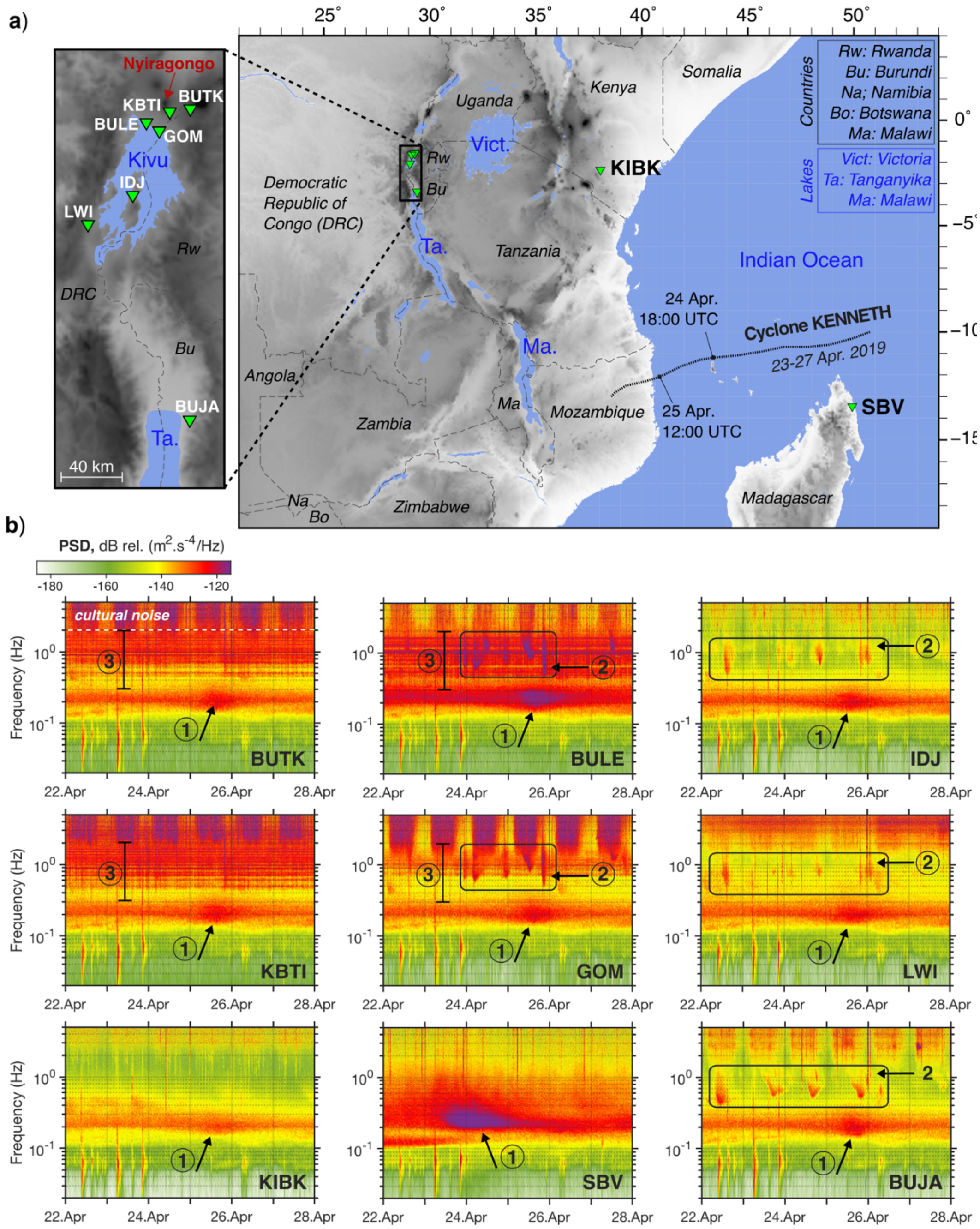

Figure 5. a) Geographical map of the East African Rift system (with a zoom into the Kivu/North Tanganyika basins) showing the selected seismic stations and the trajectory of the cyclone Kenneth (from ERCC - Emergency Response Coordination Centre, 2019) **b)** Spectrograms (Power Spectral Density – PSD) at stations in a) during the cyclone passage: (1) points out the oceanic microseism band, (2) is the intermittent lake microseism detected at stations on the shore of the Great Lakes (BUJA, LWI, IDJ, GOM, BULE), (3) corresponds to Nyiragongo's lava lake seismic tremor, which is continuously recorded anywhere in the Virunga Volcanic Province, as long as the lava lake will be active (Barrière et al., 2017).

The detection of such lake microseisms is by itself a significant result because it is relatively rare around the world (e.g., Xu et al., 2017), and characterized here for the first time in Africa.

An important aspect of this work is thus to better understand the dominant sources of noise useful for this passive tomography. Analyzing records from the station SBV (Madagascar) and KIBK (Kenya), two internationals stations from the GEOFON network (managed by the GFZ German Research Centre for Geosciences and also including station WLF in the

Walferdange Underground Laboratory) has been helpful to highlight the dominant source of microseisms originating from the Indian Ocean (Figure 5), e.g., the passage of the cyclone Kenneth (23-27 April 2019) hitting the coast of Mozambique, which was well recorded in the Kivu basin with a delay of about 1 day with regards to the station SBV in Madagascar. For publication purpose, this result will be integrated into a more comprehensive study about the seismic ambient noise in the Kivu Rift region, including the SWT.

❖ References

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Main collaborating institutions: Royal Museum for Central Africa (RMCA), Belgium; Goma Volcano Observatory, DR Congo; Centre Spatial de Liège, Belgium; Belgian Institute for Space Aeronomy, Belgium.

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/.

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 Kivu Rift 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 the Kivu Rift 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 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 active broadband seismic stations, 16 GNSS stations and 2 infrasound arrays (see also pages 8 & 22).

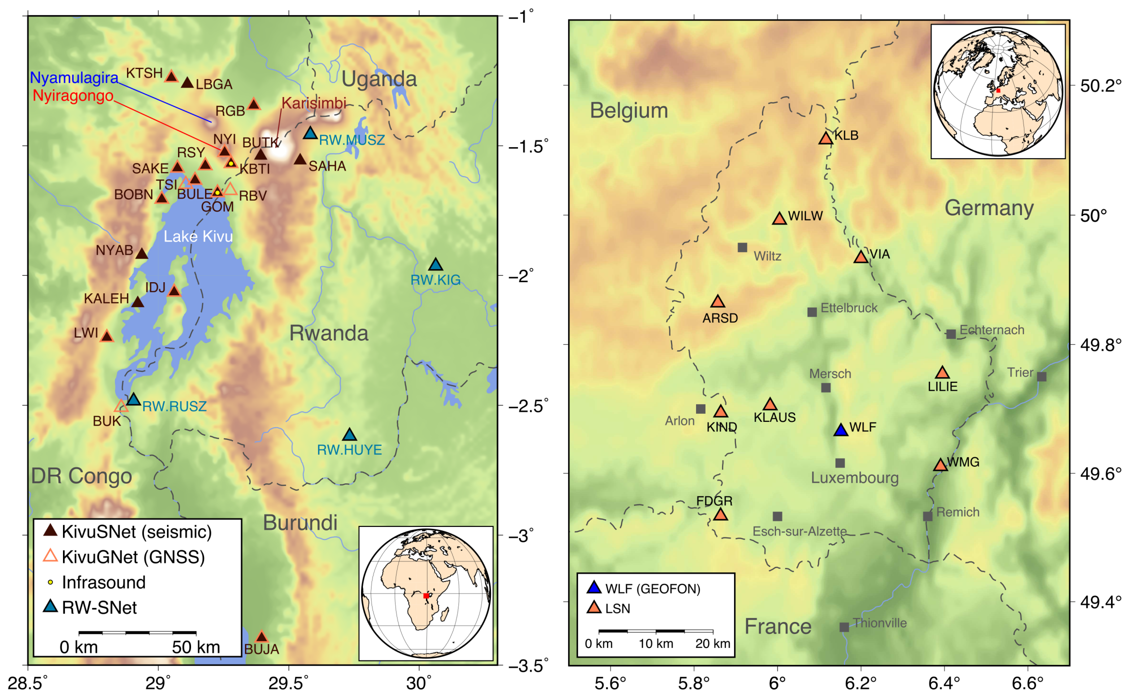

Figure 6: Current status of seismic, GNSS and infrasound monitoring infrastructure developed by ECGS in collaboration with its partners in the Kivu Rift region (left) and in the Grand-Duchy of Luxembourg (right).

In Luxembourg, ECGS has made it a priority over the past years to develop the **Luxembourg Seismic Network (LSN)** in order overcome the lack of seismic monitoring infrastructure that prevailed until recent years. In order to be able to provide a reasonable level of seismic monitoring of the country and its surrounding regions, ECGS 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.

The current status of the LSN is that it is composed of 10 broadband seismic stations (Figure 6). 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. In that context, 4 more stations have been acquired and await their installation. Due to the pandemic, the search for appropriate installation sites is currently more challenging than usual. We are presently in discussion with the Centre national de l'audiovisuel in Dudelange to potentially install a station in their basement in order to improve the seismic network in the southern part of the country.

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 indeed 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 also 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 as potential scientific partner in the framework of the Benelux Memorandum of Understanding in that context in 2019.

Collaborating institutions for seismic monitoring in Luxembourg: Karlsruhe Institute of Technology (KIT), Germany; Royal Observatory of Belgium; Erdbebendienst Südwest, Germany.

❖ Seismological Monitoring Results & Research in Luxembourg

Seismic ambient noise properties

We pursued the development of the seismic monitoring of the Luxembourgish territory by combining high-quality, broadband seismic instrumentation with appropriate data processing and analysis. In 2020, some stations from the French networks FR and RD have been added to the location routine XCloc (dedicated source-scanning algorithm developed at ECGS, see below). Together with several Belgian stations (network BE managed by the ROB), these additional stations improve the location accuracy of seismic events particularly outside the national network (code LU).

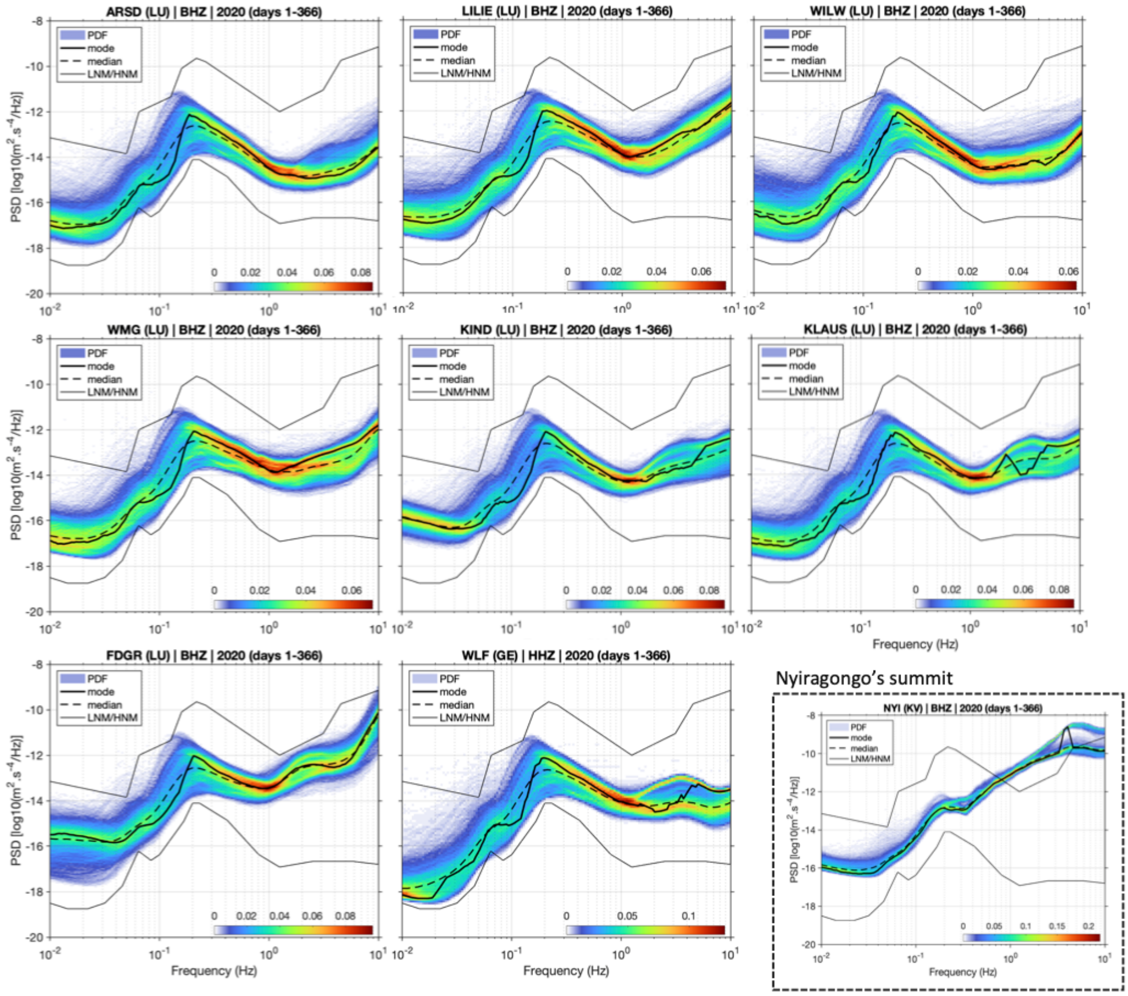

Figure 7. Examples for the seismic background noise level using power spectral density (PSD) analysis following McNamara and Buland (2004). The vertical component PSD Probability Density Function (PDF) estimates for the time period are shown. The plots cover the frequency range 0.01–10 Hz.

The performance of the current Luxembourgish stations has been re-evaluated using the records of the whole year 2020 by computing Probability Density Functions (PDF) of Power Spectral Density (PSD) following the processing procedure by McNamara and Buland (2004) (Figure 7). This kind of evaluation is for instance important to assess the sensitivity of the network to the diurnal anthropogenic activity, which is typical for industrialized countries and dominates the seismic noise environment in a frequency band also exploited to detect and locate low magnitude local/regional earthquakes (> 1 Hz). In contrast, other applications (e.g., teleseismic events, ambient noise tomography) focus on the quality of long-period records (>> 1 s).

Except station FDGR, which depicts highly noisy records for frequencies > 1 Hz, all other stations exhibit reasonable noise floors at high frequency, between the global Low-Noise and High-Noise models (Petersen et al., 1993). The same remark applies to the longer period components. PSD levels at the Walferdange station (WLF, GEOFON - GE – network) are remarkably low in this low frequency band (> 10 s), which conveys the outstanding quality of the mine's site (bedrock basement). For all stations, diurnal and seasonal variations are well noticeable through the broadening of the final PDF calculated for 1 year. For comparison, we plot the same calculation for the particular seismic station deployed at the summit of Nyiragongo volcano in the Democratic Republic of Congo (bottom right corner in Figure 7). The sharper PDF for the whole frequency band (0.01 – 10 Hz) is due to the specific location of the seismometer (high altitude and near the equator, i.e., low temperature gradient) and the absence of human activity nearby. The microseism peak (0.2 Hz) is also lower than the level retrieved in Luxembourg, probably reflecting the fact that the station is located well in Africa's continental interior at larger distance from the closest Ocean (Oth et al., 2017, see also Figure 4). Note that PSD levels above 0.2 Hz significantly increase and exceed the High-Noise model for frequencies higher than 0.8 Hz. In this specific case, this noise is not "unwanted" since it reflects the continuous activity of Nyiragongo's lava lake (see also Kivu Rift section above).

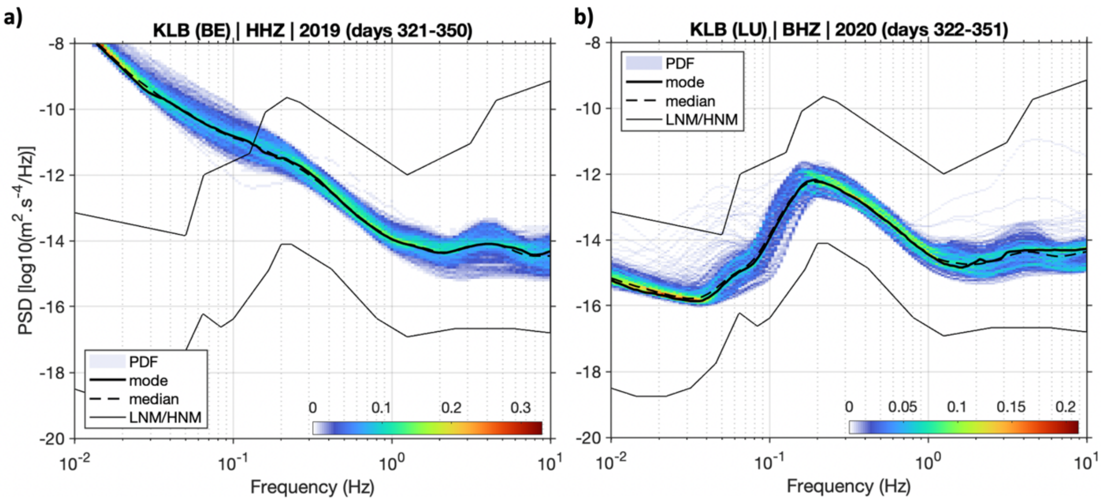

Figure 8. PSDs for KLB station for the intervals 17 Nov.-16 Dec. 2019 and 2020. The recording of low-frequency components (<0.2 Hz) has been clearly improved since the change of instrumentation.

Finally, as mentioned above, we replaced the seismic equipment at stations VIA (Vianden castle) and KLB (Kalborn, private property). They were formerly equipped with Lennartz-5s (short-period) seismometers and have been replaced by Nanometrics Trillium Compact 20s broadband sensors, as well as been integrated in the Luxembourgish network code LU. Figure 8 gives an example of 30-day PSDs in 2019 (Lennartz-5s) and in 2020 (Trillium Compact 20s) between 17 November and 16 December at KLB station. The advantage of using the new broadband seismometer for frequencies < 0.2 Hz is obvious. The noise level at high frequency is logically nearly identical between both 2019 and 2020 records.

2020 Seismicity maps

In order to get an overview of the seismicity in 2020 recorded by the Luxembourgish seismic network, we show below several maps which are selected from the outputs of the automatic location code XCloc developed at ECGS. By default, the code locates any potential events with few constraints about the quality of the solution in order to find as many events as possible, followed by a discrimination procedure to remove false events.

Figure 9 shows the map with all reliable events in and around Luxembourg in 2020. In total, 121 events have been successfully detected and located. The vast majority of these events are of human origin, i.e., mostly quarry blasts. Typical sites are the quarries in Mesenich at the German border, the quarry in Ottange at the French border or the quarry in Consthum. Only two events of clearly tectonic origin within Luxembourg or close to the German border could be detected in 2020 (Figure 9). Noteworthy is event number 2, because it belongs to a cluster of 5 repetitive small earthquakes observed previously not far away from Walferdange.

The automatic discrimination of real events is not detailed here as it is a very technical subject. However, an example illustrating how false events that are eliminated look like is given in Figure 10. Here the left example shows a false event with massive location uncertainties, while on the right the location accuracy of the tectonic event 2 in Figure 9 is demonstrated.

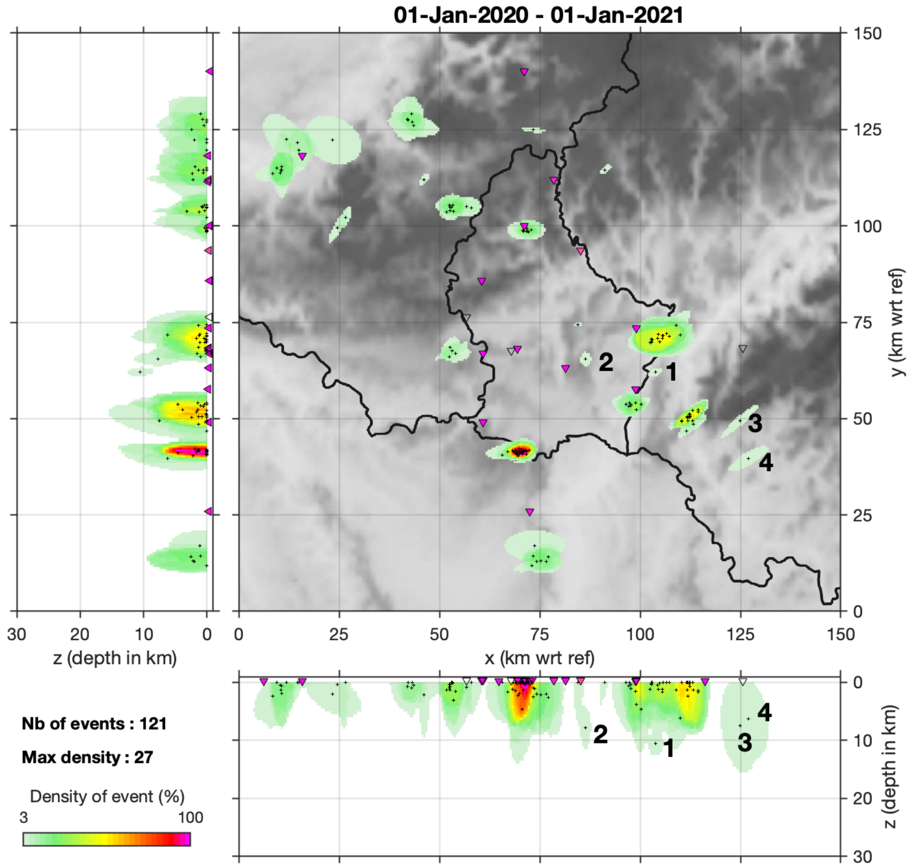

Figure 9. Local seismicity in and around Luxembourg with associated location errors (ellipses) between 1 Jan. 2020 and 1 Jan. 2021. Despite some restrictive selection criteria, some significant uncertainties about the location (> 10 km) can still occur, especially for the depth attribute. Indeed, a vast majority of these seismic events are of human origin (quarry blasts, source at the surface). 2 of them are clearly identified as tectonic earthquakes in or very close to Luxembourg borders (1 and 2, see Fig. 10). Events 3 and 4 are also tectonic ones (ML_V about 1-1.5, on 2 and 5 May, respectively).

In addition to seismic events within or near-by the Luxembourg territory, the seismic network also allows us to detect and locate regional earthquakes, together with international stations around us (Figure 11). The examples shown are two regional events in Germany (Lower Rhine Embayment and the Eifel) as well as two induced earthquakes at a geothermal site in Soultz-sous-Forêts in France.

Finally, we show the results of a 1-month internship study at ECGS by geophysics bachelor student Thea Lepage from the Karlsruhe Institute of Technology (KIT). She focussed on evaluating the feasibility to determine the focal mechanism solution for several small earthquakes in Luxembourg and the Kivu Rift region. In Figure 12, she analysed the 6 July 2019 Schengen event which was clearly of tectonic origin. We found that this event, considering all associated uncertainties, could well be characterized as a normal faulting event.

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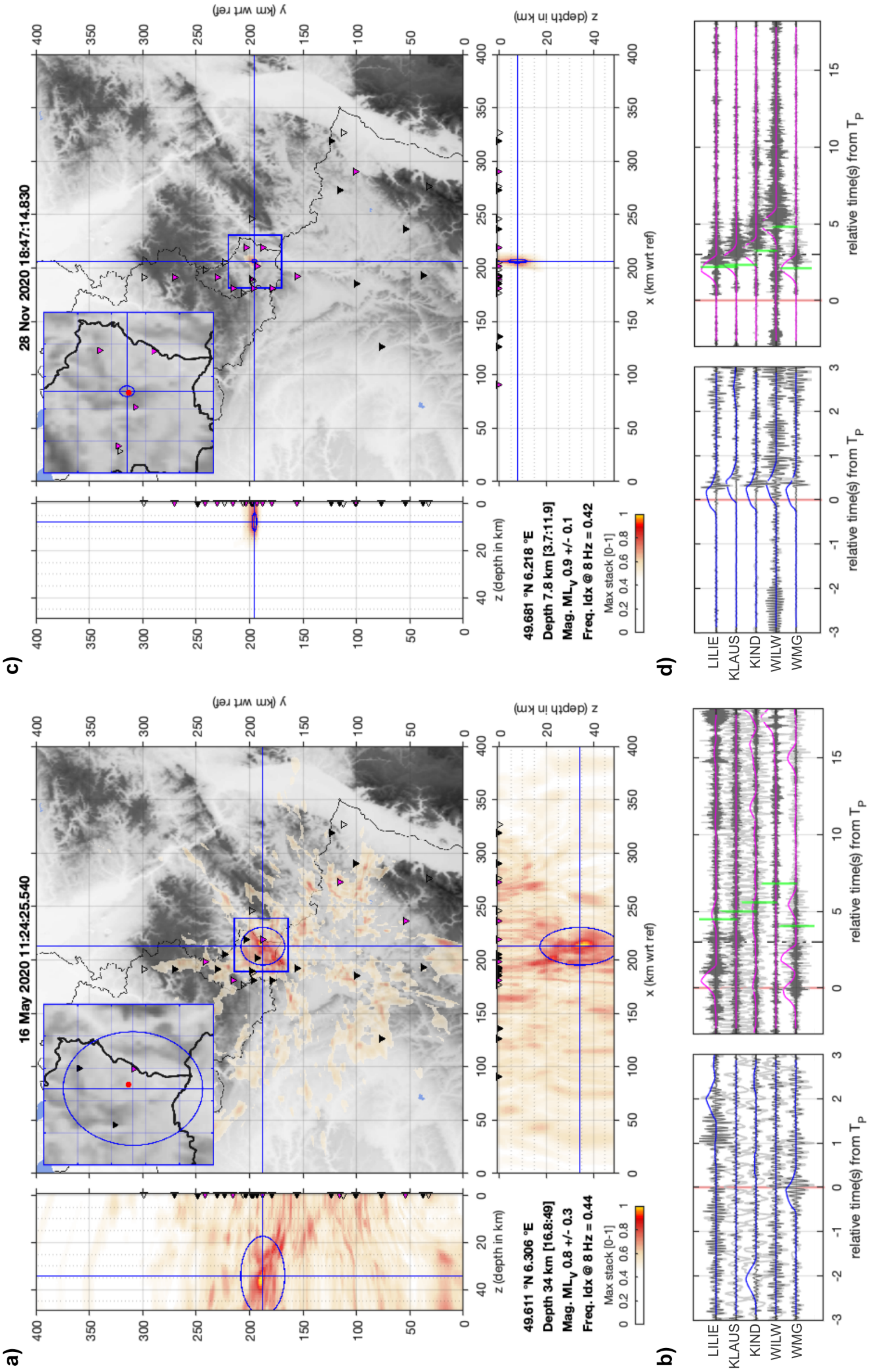

Figure 10. Examples of "bad" and "good" automatic event locations for two close epicentral solutions in Luxembourg. **a)** "false event" automatically located because a local maximum has been considered as plausible. Selection criteria are adjusted for eliminating such kind of "event" from the catalogue. **b)** Corresponding vertical seismic traces (2 colors per station corresponding to 2 different filtering into the interval [1-20] Hz) for 5 seismic stations in Luxembourg (blue = P-wave kurtosis; pink = S-wave envelope). All traces are shifted accordingly to T_P, which are the theoretical arrival times for P-wave corresponding to the best location in a). **c)** and **d)** Same as in a) and b) for a real tectonic event (Figure 9b).

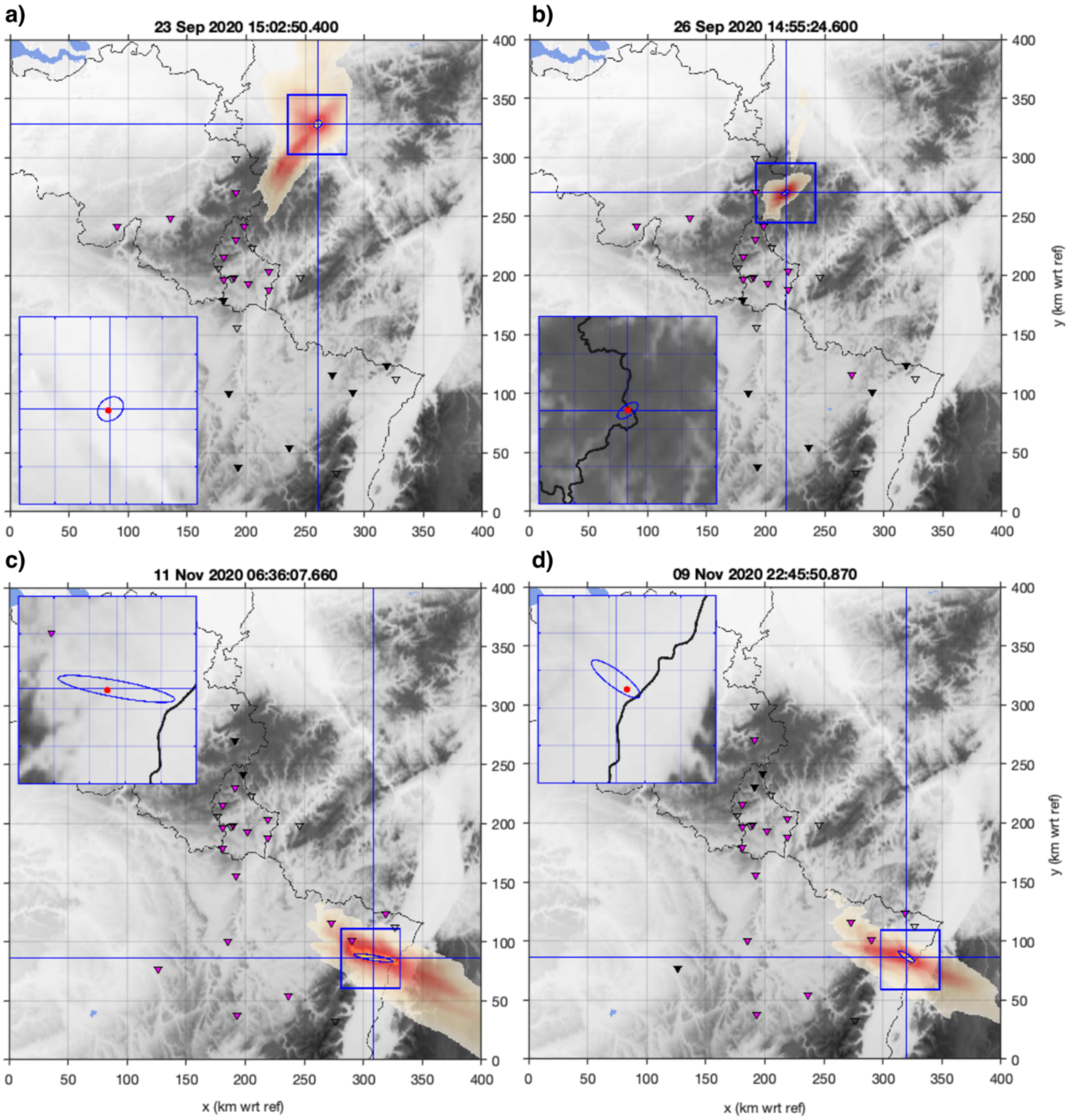

Figure 11. 2 examples of regional tectonic events: **a**) Local magnitude ML_V 2.1, depth [4-11] km, **b**) ML_V 1.6, depth [18-22] km. 2 induced events at geothermal site in France are shown in **c**) ML_V 2.2, depth [0-5] km, and **d**) ML_V 1.6, depth [0-5] km. The detection/location of these 2 last events benefits from the additional stations in France added to the location routine but are also well recorded at Luxembourgish stations.

❖ Various seismological collaborations

In 2020, 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.

- **Global quieting of high-frequency seismic noise due to COVID-19 pandemic lockdown measures**

  A. Oth contributed to a high-profile study led by T. Lecocq from the Royal Observatory of Belgium, which was published in the prestigious journal *Science* (see Publications section). A group of 76 authors from 66 institutions in 27 countries

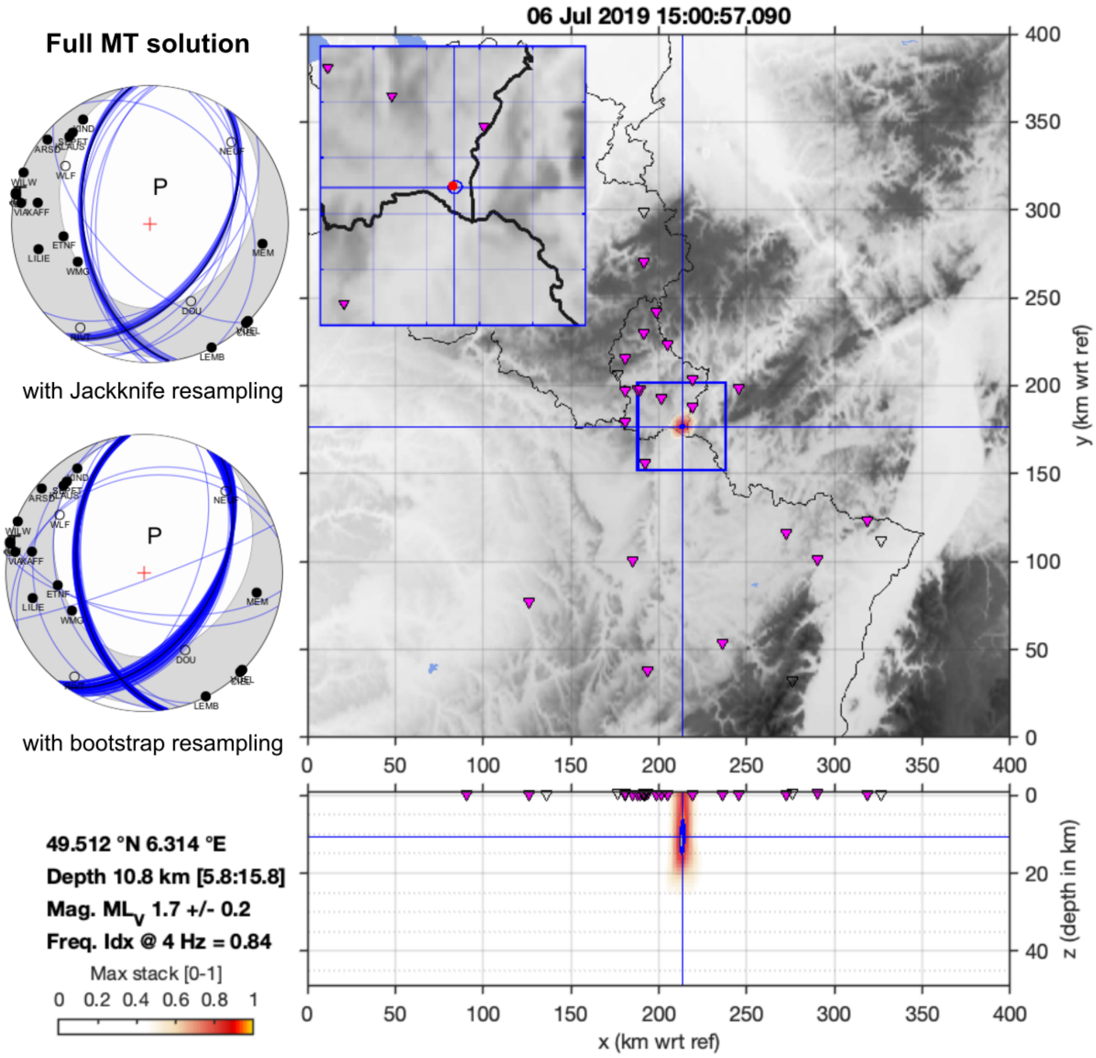

Figure 12. Moment Tensor inversion of the "2019 Schengen's tectonic event" (1-month intership of T. Lepage at ECGS, March 2020) using the HybridMT package (Kwiatek et al., 2016) and first P-wave amplitudes. The best solution with uncertainty gauged by resampling tests supports a normal fault type.

shows in this publication how the lockdown measures to combat the first wave of COVID-19 around the World led to a reduction in seismic noise levels of up to 50% in early to mid 2020.

By analysing months-to-years long datasets from over 300 seismic stations around the world, the study was able to show the seismic noise reduced in many countries and regions, making it possible to visualise the resulting "wave" moving through China, then to Italy, and around the rest of the world. The seismic lockdown sees the total effect of physical/social distancing measures, reduced economic and industrial activity and drops in tourism and travel. The 2020 seismic noise quiet period is the longest and most prominent global anthropogenic seismic noise reduction on record.

- **Ground-motion attenuation, stress drop and directivity of induced events in the Groningen gas field by spectral inversion of borehole records**

  Production-induced earthquakes in the Groningen gas field were analysed in this study in which A. Oth collaborated with the lead author G. Ameri and other co-author C. Martin from the company SEISTER, published *in the Bulletin of the Seismological Society of America.*

These events caused damage to buildings and concerns for the population, the gas-field owner and the local and national authorities and institutions. The largest event (M_L=3.6) occurred in 2012 near Huizinge and despite the subsequent decision of the Dutch government to reduce the gas production in the following years, similar magnitude events occurred in 2018 and 2019 (M_L=3.4). Thanks to the improvement of the local seismic networks in the last years, recent events provide a large number of recordings and an unprecedented opportunity to study the characteristics of induced earthquakes in the Groningen gas field and related ground motions.

In the study, S-wave Fourier amplitude spectra recorded by the 200 meters depth borehole sensors of the G network from 2015 to 2019 were exploited to derive source and attenuation parameters for ML≥2 induced earthquakes.

The analysis reveals that about half of the events clearly show rupture directivity and provides clear and first evidence of frequency-dependent directivity effects in induced earthquakes. The estimated rupture direction shows a remarkably good agreement with orientation of pre-existing faults in the reservoir. The results confirm that rupture directivity is still an important factor for small magnitude induced events, affecting the amplitude of recorded short-period response spectral amplitudes and causing relevant spatial ground-motion variability.

- **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 is in its final stages and will be submitted for publication in 2021.

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.

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 2020, we were involved the following projects:

- **SMMIP: Split band assisted Multi-dimensional and Multi-zonal InSAR time series Processor,** 01/04/2017 - 29/02/2020 (FNR)
- **VERSUS: Open-Vent Volcano Remote Sensing Monitoring Using Spaceborne Imaging,** 01/07/2019 - 31/12/2021 (Belspo)
- **MODUS: A Multi-sensOr approach to characterize ground Displacements in Urban Sprawling contexts,** 01/12/2017 - 30/11/2020 (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)
- **Hengill: Interaction of geothermal, tectonic, and magmatic processes in the Hengill area, SW-Iceland,** 01/01/2017 - 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)

For each of these projects, a short description of the objectives is given below:

SMMIP aims first at merging two highly innovative tools: MSBAS technique (developed by S. 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 D. 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.

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).

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.

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 Univiversity (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.

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.

Partners in these projects are

- Comahue National University, Argentina
- Royal Museum for Central Africa, Belgium
- Centre Spatial de Liège, Belgium

- Royal Belgian Institute for Space Aeronomy (BISA), Belgium
- Natural Resources Canada, Canada
- Univ. of Iceland, Iceland
- Icelandic Meteorological Office, Iceland
- Vrije Universiteit van Brussel (VUB), Belgium
- University of Leeds, UK
- 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)

❖ Results and achievements in 2020

Monitoring networks

In the frame of HARISSA, VERSUS and MODUS, we carried on the maintenance of the KivuGnet and KivuSnet telemetered networks in DR Congo. Data are automatically processed and displayed on password protected web pages.

Due to the COVID-19 pandemic, all the field missions were cancelled. Fortunately, we had stored enough spare parts at Goma Volcano Observatory (GVO) and so far, GVO staff succeeded to solve most of the problems with these parts and our remote help. Nonetheless, would the situation persist for much longer time, the situation will become critical as some spare parts may be missing.

At the time of reporting, 13 out of the 16 GNSS stations of the KivuGnet are operating and analyzed in real-time and results are displayed on a password protected web page. The 3 missing stations were stopped for different reasons: one was dismantled because of the dismantling of the MONUSCO military base where it was hosted, another was removed after the theft of its solar power supply, and the last one was destroyed by lightening. This last one, located at the summit of Nyiragongo volcano, was supposed to be replaced at the occasion of a field campaign planned to Nyiragongo in June-July 2020 in the frame of the VERSUS project, but that mission was cancelled due to the pandemic.

Similarly, 17 out of the 18 seismic stations of the KivuSnet are operational and analyzed in real time (see Seismology section above). The missing station was collocated with the GNSS station in the same MONUSCO base that was abandoned by the United Nation army. Note that another station is recording seismic data on-site but we lost remote access after a thunderstorm that destroyed its Ethernet port, as confirmed by GVO staff.

For some of the KivuGnet and KivuSnet stations that are installed in Rwanda, the real time data transmission is momentarily suspended for administrative reasons. We work with local partners and the local phone company to sort these issues out.

Development of ground deformation monitoring tools by satellite

In the frame of SMMIP, VERSUS, MODUS, Hengill and RCM-AIT, we carried out the development of our home made InSAR time series toolbox (**MasTer: InSAR Mass processing Toolbox for Multidimensional time series**). The toolbox was enriched with several new scripts to perform various tasks answering specific needs from the various projects. New tools (developed by Maxime Jaspard, ECGS) were also created to automatically display the results on dedicated web pages (Figure 13).

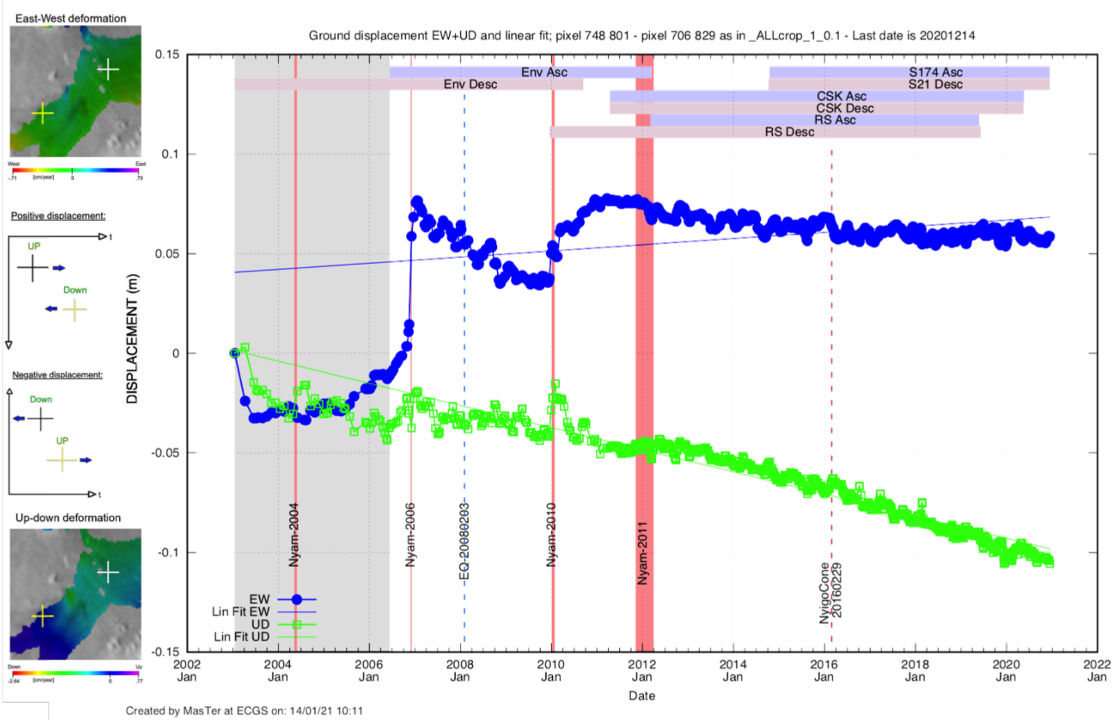

Figure 13: Example of automatic time series of ground deformation obtained by MasTer and displayed on dedicated web page. Double difference of Vertical (green) and EW (blue) ground deformation (in m) between 2 pixels located on the flank of Nyamulagira volcano (see crosses on the velocity maps wrapped on the DEM in insets). Direction of displacement of one pixel with respect to the other is explained with the two graphs on the left. Red and grey vertical rectangles illustrate eruption durations and period of asymmetric SAR geometry (Ascending vs Descending), respectively. Blue and light red horizontal rectangles highlight the epoch covered with each satellite along Ascending and Descending orbits respectively. The time series combines data acquired by 4 satellites (ENVISAT, COSMOSKYMED, RADARSAT, SENTINEL1) in 13 different geometries spanning 2003-2021.

Recent methodological improvement developed by the new post doc at ECGS (Delphine Smittarello) consists in the computation of a coherence proxy to guide the pair selection optimization balancing the use of each image as primary and secondary image during the differential interferometric (DInSAR) processing. This improves the signal-to-noise ratio by reducing the influence of DEM errors and atmospheric noise. It also reduces the total number of computed interferograms by up to 75%, which as a consequence also reduces the computation time and raw-memory and storage requirements (Smittarello et al., in preparation) (Figure 14).

MasTer is now optimized 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 MasTer toolbox was presented in a paper published in Journal of South American Earth Sciences. Another paper presenting the tool was recently submitted for an invited session at IGARSS workshop in 2021 (see list of publications).

The software and a detailed manual (>120 pages) are now available upon request.

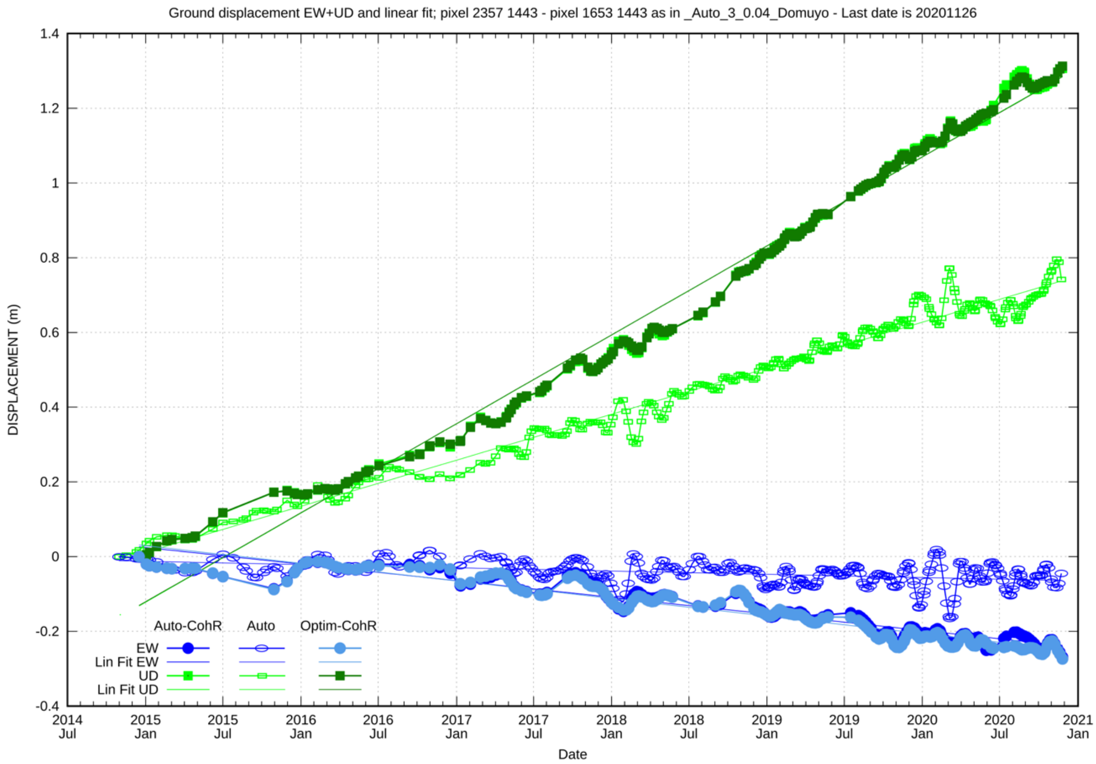

Figure 14: Example of optimization of MasTer processing using coherence proxy to guide the pair selection optimization. Vertical (Green) and horizontal EW (Blue) differential deformation measured at Laguna del Maule volcanic region (Chile) between the center of the deforming zone and a pixel located 50 km to the west. MasTer automatic processing rejects interferograms affected by seasonal decorrelation (Auto-CohR, filled symbols). Neglecting decorrelation during austral winter underestimates the displacement by several tens of % (Auto; open symbols). Pair selection optimization reduces the noise and speeds up the computation by up to 75% (Optim-CohR; filled symbols).

A one-week training course (restricted to 3 participants for sanitary reasons) was organized at Walferdange from 28 September to 2 October 2020. We also carry on the remote support for several users in Argentina, Chile, Austria, Belgium, etc... A webinar took place on 14 October 2020 to explain the MasTer toolbox to Goma Volcano Observatory staff and share with them the automatic processing and results for the volcanoes.

The MasTer software is now routinely used at ECGS to perform automatic monitoring of several targets. In addition to the processing performed for several years at ECGS targeting the Virunga Volcanic Province and South Kivu basin (DRC, Rwanda, Uganda and Burundi region), the Greater Region (Luxembourg, South of Belgium, North France and West of Germany) and the Chile-Argentina border region (Laguna del Maule and Domuyo volcanoes), we started in 2020 the systematic monitoring of Réunion Island (for monitoring the Piton de la Fournaise volcano and several landslides in the North of the island) and Hawaii (for studies on Kilauea volcano's lava lake).

At the time of writing, this represents several thousand of satellite SAR images acquired by various satellites (ERS, ENVISAT, ALOS, TSX, TDX, SAOCOM, KOMPSAT, RADARSAT, COSMOSKYMED, SENTINEL, ICEYE) and several tens of thousands of interferograms.

Note that ECGS has now premium access to Sentinel 1 data from the LSA Data Center (Luxembourg Space Agency), which allows ultra-rapid data download.

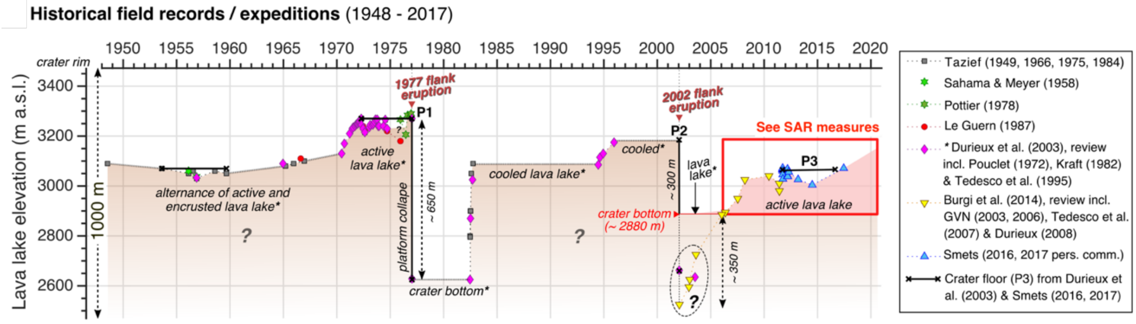

Figure 15: Lava lake elevation (in m a.s.l.) from historical field records and recent expeditions (1948-2017). Comments marked by an asterisk come from the review paper by Durieux et al. (2003). Note the new estimate of the crater floor after the 2002 eruption (~2880 m a.s.l.) obtained from SAR and photogrammetry). Batches of former crater floor left after the 1977 eruption are named P1 platform (~3270 m a.s.l), while batches of level reached prior to the 2002 eruption are named P2 platform (~3190 m a.s.l). P3 platform is the crater floor hosting the lava lake (Barrière et al., in preparation).

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.

Given its exceptional 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. We recently received a request from Mr. Bruno Pagliccia from the private company SeisBEE established in Luxembourg to carry out instrumental performance studies for MEMS-based accelerometers in the WULG, through comparison with the STS-2 GEOFON station installed there. Moreover, Dr. Valentin Gravirov from the Russian Academy of Sciences contacted us in view of potentially testing a precision temperature observation system in the WULG.

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.

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 that for several years now, issues regarding the stability of the entrance have been noticed and discussed among the administrations and ministries involved. Thus far, no final conclusion on how to proceed in view of these issues has 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 2020

Antoine Kies

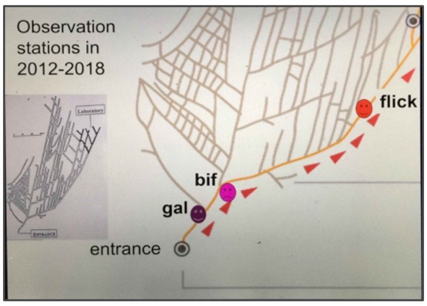

Figure 16: Radon observation sites in WULG.

Radon investigations continued in the Walferdange gypsum mine in 2020. Two radon monitors (Alphaguard) recorded radon in 'gal' and 'flick', while local temperatures were recorded at these places and in 'bif' (Figure 16). Meteo data are provided by MeteoLux.

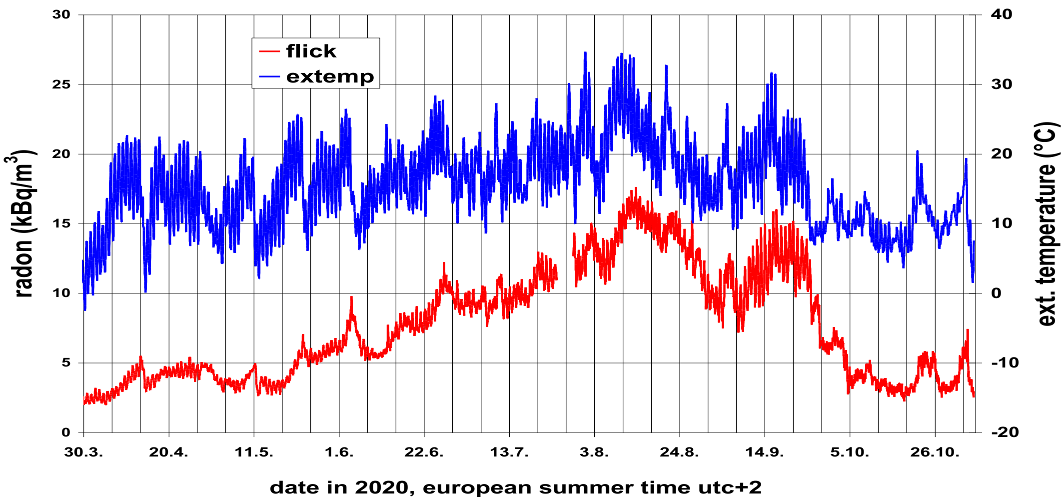

Figure 17: Radon concentration at station 'flick' and outside temperature (April-October 2020).

Concerning radon, the Walferdange former gypsum mine is exceptional and unique. The temperature-induced behavior depicted in Figure 17, i.e. radon summer highs and winter lows, is well known for mines and caves, with limited air circulation in summer and high ventilation rates in winter that depress indoor radon concentrations. However, here this classical model does not fit. Rather, the origin of the summer high is given by a changing radon source situated close to the entrance, the 'gal' location. The critical temperature for the changing radon levels is 10.5°C, the nearly constant mine temperature. The more the outside temperature exceeds 10°C, the more radon accumulates in mine air. Below 10°C radon rapidly decreases, to a lowest value of 2.4 kBq/m^3. in winter.

Figure 18 shows a detail of Figure 17. Radon and temperature seem to be opposite in phase. For the explanation of this strange observation, one has to look at the influence of environmental temperature on radon at 'gal'. At 'gal', one observes very high fluctuations of radon, between zero and 70 kBq/m^3 (Figure 19). There is a slight shift between external temperature and radon, which is expected as external temperature influences the air movement carrying radon. We rely on hourly data, i.e., the mean of the last hour for temperature and accumulated radon for the last hour. Here the influence of the critical temperature of 10°C is much more pronounced: above 10°C, radon charged air moves out of a fracture system into the gallery, below 10°C the air circulation is reversed and fresh outside air enters the fracture system.

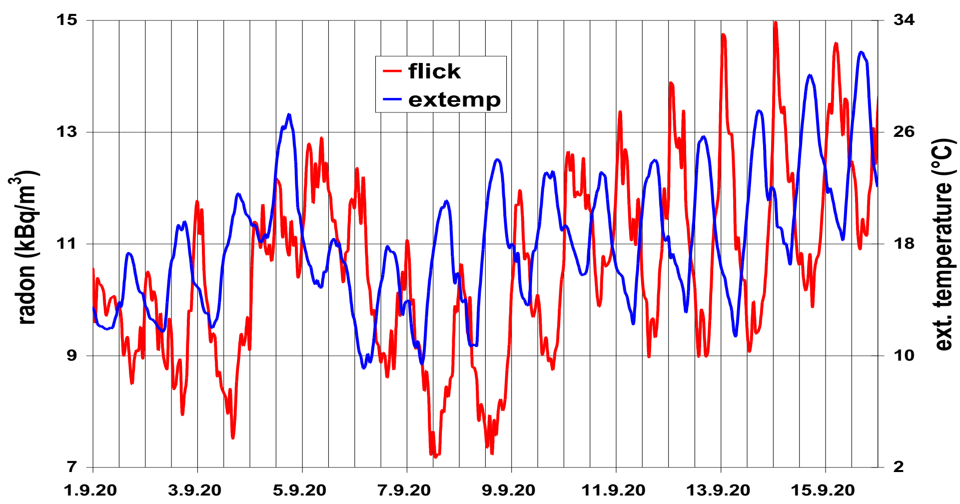

Figure 18: Comparison of temporal evolution of radon concentration at station 'gal' and external temperature measurements.

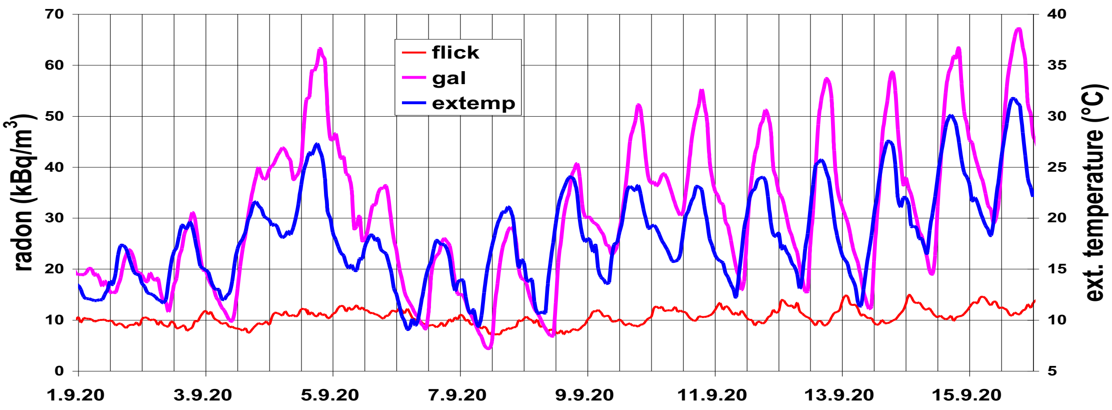

Figure 19: Close-up of Figure 20 for the time period August – October 2019.

From 'gal' to the 'flick' measuring station, air carrying radon takes half a day, which explains the apparent anticorrelation mentioned previously. One interesting feature in Figure 19 is the high radon peak on 4 September 2020. After days of poor ventilation of the fracture system, an increase of temperature activates the air circulation, thus flushing the accumulated radon out of the fractures into the gallery.

OUTREACH ACTIVITIES

- **RTL 5minutes "**Un volcan est-il en train de se réveiller au portes du Luxembourg?", 17 juin 2020, featuring A. Oth

  Weblink: https://5minutes.rtl.lu/actu/frontieres/a/1535442.html

- **ESA Success Story**, "Copernicus Sentinel-1 used to better understand active volcanic areas and landslide mechanisms",23 July 2020, featuring N. d'Oreye

  Weblink: https://sentinel.esa.int/web/sentinel/-/copernicus-sentinel-1-used-to-better-understand-active-volcanic-areas-and-landslide-mechanisms

- **Article on Science.lu (FNR)**, "Sound of silence: COVID-19 Lockdown brachte Ruhe in den Erdboden", 21 August 2020, featuring A. Oth

  Weblink: https://science.lu/de/geowissenschaften/sound-silence-covid-19-lockdown-brachte-ruhe-den-erdboden

- **RTL Radio Sujet**, "Ärdbiewen ! Firwaat ginn et do Plazen a Risk?", 10 November 2020, featuring A. Oth

  Weblink: https://www.rtl.lu/radio/feature/s/3317569.html

- 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

Ameri, G., C. Martin and **A. Oth** (2020). Ground-motion attenuation, stress drop and directivity of induced events in the Groningen gas field by spectral inversion of borehole records. *Bull. Seismol. Soc. Am.*, 110(5), 2077-2094, doi: 10.1785/ 0120200149.

Derauw D., **N. d'Oreye**, **M. Jaspard**, A. Caselli and S. Samsonov (2020). Ongoing automated Ground Deformation monitoring of Domuyo – Laguna del Maule area (Argentina) using Sentinel-1 MSBAS time series: Methodology description and first observations for the period 2015 – 2020. *J. South Am. Earth Sc.*, 104, 102850, doi: 10.1016/j.jsames.2020.102850.

Lecocq, T., S. Hicks, K. Van Noten, K. van Wijk, P. Koelemeijer, R.S.M. de Plaen, F. Massin, G. Hillers, R. Anthony, M.-T. Apoloner, M. Arroyo-Solórzano, J.D. Assink, P. Büyükokpinar, A. Cannata, F. Cannavo, S. Carrasco, C. Caudron, E.J. Chaves, D.G. Cornwell, D. Craig, O.F.C. den Ouden, J. Diaz, S. Donner, C.P. Evangelidis, L. Evers, B. Fauville, G.A. Fernandez, D. Giannopoulos, S.J. Gibbons, T. Girona, B. Grecu, M. Grunberg, G. Hetényi, A. Horleston, A. Inza, J.C.E. Irving, M. Jamalreyhani, A. Kafka, M.R. Koymans, C. Labedz, E. Larose, N.J. Lindsey, M. McKinnon, T. Megies, M.S. Miller, W. Minarik, L. Moresi, V.H.Márquez-Ramírez, M. Möllhoff, I. Nesbitt, S. Niyogi, J. Ojeda, **A. Oth**, S. Proud, J. Pulli, L. Retailleau, A.E. Rintamäki, C. Satriano, M.K. Savage, S. Shani-Kadmiel, R. Sleeman, E. Sokos, K. Stammler, A.E. Scott, S. Subedi, M.B. Sørensen, T. Taira, M. Tapia, F. Turhan, B. van der Pluijm, M. Vanstone, J. Vergne, T.A.T. Vuorinen, T. Warren, J. Wassermann and H. Xiao (2020). Global quieting of high frequency seismic noise due to COVID-19 pandemic lockdown measures. *Science*, 369(6509), 1338-1343, doi: 10.1126/science.abd2438.

Samsonov, S., A Dille, O. Dewitte, F. Kervyn and **N. d'Oreye** (2020). Satellite interferometry for mapping surface deformation time series in one, two and three dimensions. *Eng. Geol.*, 266, 105471, doi: 10.1016/j.enggeo.2019.105471.

Under review

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. *Proc. IGARSS 2021 - 2021 IEEE International Geoscience and Remote Sensing Symposium*, under review.

Dille, A., O. Dewitte, A. Handwerger, **N. d'Oreye**, D. Derauw, G. Ganza, G. Ilombe, C. Michellier, J. Moeyersons, E. Monsieurs, T. Bibentyo, S. Samsonov, B. Smets, M. Kervyn and F. Kervyn (2021). Urban growth and the dynamics of a large deep-seated landslide in the tropics. *Nature Geoscience*, under review.

Dille, A., F. Kervyn, O. Dewitte, A. Handwerger, **N. d'Oreye**, D. Derauw, T. 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*, under review.

Shreve, T., R. Grandin, **D. Smittarello**, V. Cayol, V. Pinel and Y. Morishita (2021). What triggers caldera ring-fault subsidence at Ambrym volcano ? Insights from the 2015 dike intrusion and eruption. *Journal of Geophysical Research: Solid Earth*, under review.

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*, under review.

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 so_2 degassing using sentinel-5 precursor tropomi. *Proc. IGARSS 2021 - 2021 IEEE International Geoscience and Remote Sensing Symposium*, under review.

❖ Conference Presentations, Proceedings and Abstracts

Due to the COVID-19 pandemic, all major conferences were either cancelled or switched to fully online meetings. As a result, participation at conferences/meetings was severely reduced in 2020.

Barrière, J., **A. Oth**, **N. d'Oreye** et al. (2020). An overview of lessons learnt from the deployement of KivuSNet (2015-), a cross-border seismic network in Central Africa. *Invited talk to INOGS seminar (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Italy), June 12 2020, Online*.

d'Oreye, N., D. Derauw and S. Samsonov (2020). MasTer: an automated InSAR Mass processing Toolbox for Multidimensional time series. *Abstract, VAPOUR (AdVanced Asymmetry TroPOspheric ProdUcts for MeteoRology from GNSS and SAR observations)" workshop, January 25-26 2020, Luxembourg.*

Derauw, D. and **N. d'Oreye** (2020**).** An independent tool for split band SAR interferometry and ionospheric mapping. *Abstract, VAPOUR (AdVanced Asymmetry TroPOspheric ProdUcts for MeteoRology from GNSS and SAR observations)" workshop, January 25-26 2020, Luxembourg.*

Dille, A., O. Dewitte, A. Handwerger, D. Derauw, **N. d'Oreye**, E. Monsieurs, S. Samsonov, B. Smets, M. Kervyn and F. Kervyn (2020). Urban growth changes the pulse of a large deep-seated landslide. *EGU General Assembly Conference, Abstracts 17805, 4-8 May 2020, Online.*

Dille, A., et al. (including **N. d'Oreye**) (2020). MODUS: A multi-sensor approach to unravel natural and anthropogenic controls on landslides dynamics in the tropics. *Abstract, Belgian Earth Observation Day (BEODAY), November 24 2020, Online.*

Smets, B., J. Subira, A. Dille, N. Theys, F. Broekmans, A. Nobile, **N. d'Oreye** and F. Kervyn (2020). Study of the 2012-2020 pit crater evolution in the summit caldera of Nyamulagira volcano using multiple satellite sensors and UAS-based photogrammetry. *EGU General Assembly Conference, Abstracts 19354, 4-8 May 2020, Online.*

MEETING ATTENDANCE, FIELD MISSIONS, WORK VISITS

Due to the COVID-19 pandemic, all major conferences were either cancelled or switched to fully online meetings. As a result, participation at conferences/meetings was severely reduced in 2020. The pandemic also resulted in the fact that very few, if any, in-person work visits were possible. Most of the work meetings took place virtually, which will not be listed here due to the very large number of these meetings.

Adrien Oth

- Work visits & Visitors at ECGS:
  - Visit of representatives of the Service Géologique des Ponts et Chaussées (R. Colbach), ITM (Y. Melcher, D. Eackhaut, G. Schmit) and Ministry of the Interior (P. Henrotte) at ECGS to discuss seismic hazard in Luxembourg, also in the context of Seveso sites (4 February)
  - Visit at Fonds du Logement site “NeiSchmelz” in Dudelange to discuss potential hosting of seismic station, together with R . Colbach from the “Service Géologique des Ponts et Chaussées” (13 March)

Nicolas d’Oreye

- Organisation of course “CIS-MasTer: CSL InSAR Suite automated Mass Processing Toolbox for Multidimensional time series”, Walferdange, Luxembourg, 28 September – 2 October
- Online Webinar for Goma Volcano Observatory staff (Democratic Republic of the Congo): “MasTer, un outil SAR/InSAR pour time series: application automatisée pour la surveillance des Virunga”, 14 October
- Work visits & Visitors at ECGS:
  - Meeting at ECAM (Brussels) to set up a project using artificial intelligence (AI) to assist InSAR data analysis (6 February)
  - Work visit at MRAC for MODUS project at MRAC and PhD defense of Elise Monsieurs (11 February)

Julien Barrière

- Online invited presentation in INOGS seminar: “*An overview of lessons learnt from the deployement of KivuSNet (2015-), a cross-border seismic network in Central Africa*.” (12 June)

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
- **Reviewer** for *Bulletin of Seismological Society of America, Journal of Seismology, Seismological Research Letters, Geophysical Journal International*

- **External Evaluator** for assistant professor application at Hebrew University of Jerusalem, Israel
- **Member** of American Geophysical Union, Seismological Society of America, European Geosciences Union, Deutsche Geophysikalische Gesellschaft
- **Mentorships & Supervision**
    - Co-supervision of the 1-month internship "*Focal Mechanisms of small earthquakes in Luxembourg and D.R. Congo*" of Thea Lepage, Bachelor student at Karlsruhe Institute of Technology (KIT)

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 *Bulletin of Volcanology, Geosciences, Geophysical Research Letters, Remote Sensing, Journal of African Earth Sciences*
- **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 & Academy of Sciences Luxembourg

Julien Barrière

- **Reviewer** for *Water Resources Research*, *Journal of Volcanology and Geothermal Research, Earth Planets Space*
- **Member** of American Geophysical Union and European Geosciences Union
- **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)
    - Co-supervision of the 1-month internship "*Focal Mechanisms of small earthquakes in Luxembourg and D.R. Congo*" of Thea Lepage, Bachelor student at Karlsruhe Institute of Technology (KIT)