Annual Report 2018

EUROPEAN CENTER FOR GEODYNAMICS AND SEISMOLOGY (ECGS)

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- **Dr. Julien Barrière**, geophysicist, ECGS (temporary research scientist)
- **Dr. Dominique Derauw**, remote sensing scientist, ECGS (visiting researcher on an FNR INTER Mobility research grant)

- **Dr. Nicolas d'Oreye**, geophysicist, National Museum of Natural History (permanent)

- **Prof. Dr-Ing. Manfred Bonatz,** geophysicist, Universität Bonn (D) (deceased on 2 December 2018)
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- **Gilles Celli,** technical engineer, National Museum of Natural History (permanent)

IN MEMORIAM: MANFRED BONATZ (1932 – 2018)

On 2 December 2018, Prof. Dr.-Ing. Manfred Bonatz passed away, aged 86. He was a professor emeritus for geodesy at the University of Bonn, Germany, and, together with Johnny Flick and Paul Melchior, one of the key personalities who shaped the European Center for Geodynamics and Seismology as it stands today.

Manfred Bonatz' key scientific interests focussed on gravimetric metrology and the scientific investigation of Earth tides. With these interests, he found a second scientific home in the Walferdange Underground Laboratory for Geodynamics, where he was actively involved in a vast range of research activates over the past five decades and carried out high-precision measurements until a few months prior to his death.

In 1971, he was among the founding fathers of the *Journées Luxembourgeoises de Géodynamiqu*e (JLG). The JLG started as an informal gathering of a group of passionate researchers, dedicated to the furthering of the understanding of Earth tides. From their very first edition, these meetings had a very special spirit and contributed to the reputation of Luxembourg as an Earth Science hub throughout the World. Manfred Bonatz, devoted with body and soul to the interdisciplinary vision of science, was the JLGs president for many years. On 25-27 March 2019, we will celebrate the 100th edition of the JLG, proving their extraordinary success, which is first and foremost Manfred Bonatz' merit.

Manfred Bonatz was a member of ECGS' board of administration for 30 years, right from its creation in 1988 until 2018, and a member of its scientific board from 1992 to 2011.

Manfred will be sorely missed at ECGS, not only for his outstanding contribution to the existence of our centre, but also and in particular for his kindness, stirring enthusiasm and wisdom.

INTRODUCTION

In 2018, the staff at ECGS remained stable following the 2016-2017 decline due to increasing difficulties in acquiring additional third-party funding for temporary scientific positions. As already explained in the 2016 Annual Report, ECGS has been very successful in acquiring third-party funding for research projects in the past years, in particular from the National Research Fund of Luxembourg (FNR), but due to large-scale modifications in the FNR grant schemes, the continuation of this successful acquisition of research grants is now not possible anymore.

In order to address this problematic situation and improve ECGS's ability to respond to enquires from Luxembourg administrations and the public, the two permanent scientists affiliated to ECGS and the ECGS Administrative Board developed a **strategic paper for the future development of ECGS**, of which the final version was discussed in a meeting on 5 October 2017 with Secretary of State for Culture, Mr. Guy Arendt. Following these reflections

and meeting, the required funds for the implementation of this strategic paper were included in the 2019 ECGS budget.

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 two permanent staff (Dr. Nicolas d'Oreye and Dr. Adrien Oth) and one temporary research scientist, Dr. Julien Barrière. Dr. Barrière is currently hired on a fixed-term contract by ECGS in order to develop the fundamental research results obtained in various research projects into an operational monitoring framework, both for the Virunga Volcanic Province and the Luxembourg case. Dr. Dominique Derauw from the Centre Spatial de Liège joined the team for a total duration of four months in 2018, in the framework of the FNR Inter Mobility research grant SMIPP.

A wide range of research activities was carried out at ECGS/Mnhn in 2018, which we present in detail below. The **dominant research topic in 2018 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 4 articles in international peer-reviewed scientific journals in 2018, with 1 more currently under review and 3 in the final steps of their preparation, and contributed to 30 conference abstracts. In addition to these articles and conference contributions, the final report of the GeoRisCA project (see 2017 report) was also published in 2018 (176 pages).

ECGS/Mnhn is heavily involved in a large 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 2018 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 – 30/11/2018)

Just like in 2017, the RESIST project is the key project worked on at ECGS/Mnhn in 2018, and involves 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 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 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 23), 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 March and October 2018. We installed a new permanent monitoring station at the summit of Nyiragongo volcano (3.500m asl). The station is equipped with a broad band seismometer, a geodetic GNSS receiver, an infrasound sensor and a video time lapse camera. Due to its exceptional situation, this station provides invaluable information about the volcanic activity and the status of the largest lava lake on Earth. This new station brings the Virunga monitoring network to a total of 17 broadband seismic, 16 GNSS and 4 infrasound stations telemetered in real time to Luxembourg and the Goma Volcano Observatory.

Given the high risk of destruction by lightening in that region, we redesigned and reinforced the lightning protections of the monitoring stations.

The **research activities** in 2018 focussed on two main subjects: 1) the seismic velocity structure of the Kivu region, which is an essential ingredient in order to better understand and characterize the seismic activity in the region, and; 2) the monitoring and characterization of the volcanic activity of Nyiragongo volcano, which represents a major threat for the city of Goma and surrounding agglomerations.

❖ Seismic velocity structure of the Kivu region

This work has been continuously updated since the main deployment of KivuSNet in October 2015. The results obtained in late 2018 regarding the seismic velocity structure of the region presented here below are expected to be published in 2019.

2-D ambient noise tomography

Using the full available dataset since 2012 (including data collected at former Goma Volcano Observatory (GVO) stations and the temporary experiment KIVU12, Figure 2), we investigated the seismic velocity structure in the region using a so-called ambient noise tomography (ANT), which allows to image changes in propagation velocities of seismic waves and hence provides information on the structure of the Earth's crust. A summary of the analysis is presented here below. It is based on 96 noise cross-correlation functions (NCFs, i.e. station pairs), automatically selected and satisfying constraints of high signal-to-noise ratio, minimum recording duration and consistent time lag.

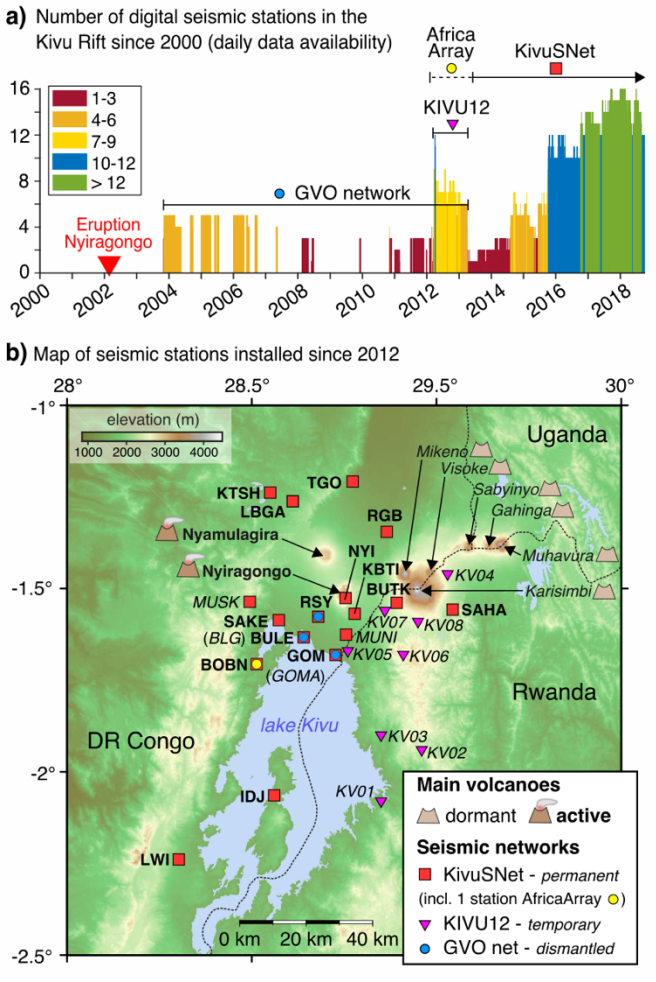

Figure 2: **a)** Timeline of daily data availability in the Kivu Rift region since 2000. The four different networks (GVO, KIVU12, AfricaArray, KivuSNet) deployed during this time period are indicated. **b)** Map of the seismic stations deployed in the Kivu Rift since 2012. An overview of the RESIST seismic (KivuSNet) and geodetic (KivuGNet) stations.

Using the tomography code FMST (Rawlinson & Sambridge, 2005) and after validating the result with standard resolution tests (spike test), we obtained a 2-D surface wave group velocity map in the microseismic period band (0.05-0.2 Hz), revealing new insights into the deep structural complexity of this volcanic region. The continuous strong tremor source from Nyiragongo's lava lake (Barrière et al., 2017, 2018) poses significant problems for investigating the 3-D case with good depth resolution. For the selected frequency range, we can expect that the depth of penetration of the surface waves could reach 15 to 20 km.

The result of the ANT notably reveals two significant patterns (Figure 3):

- The strongest "**low velocity zone**" with respect to surrounding medium is located below Nyamulagira and Nyiragongo and corresponds most likely to the **magmatic systems of both volcanoes**, which are undifferentiable at this scale.
- This low velocity zone extends to the south below Lake Kivu. This southern anomaly is of great interest because it could be related to a zone of preferential magmatic intrusion, as it corresponds to numerous aligned terrestrial and underwater volcanic cones. Wauthier et al. (2012) notably suggested that a deep dike intrusion following this pathway triggered the opening of an eruptive dike during the 2002 Nyiragongo eruption.

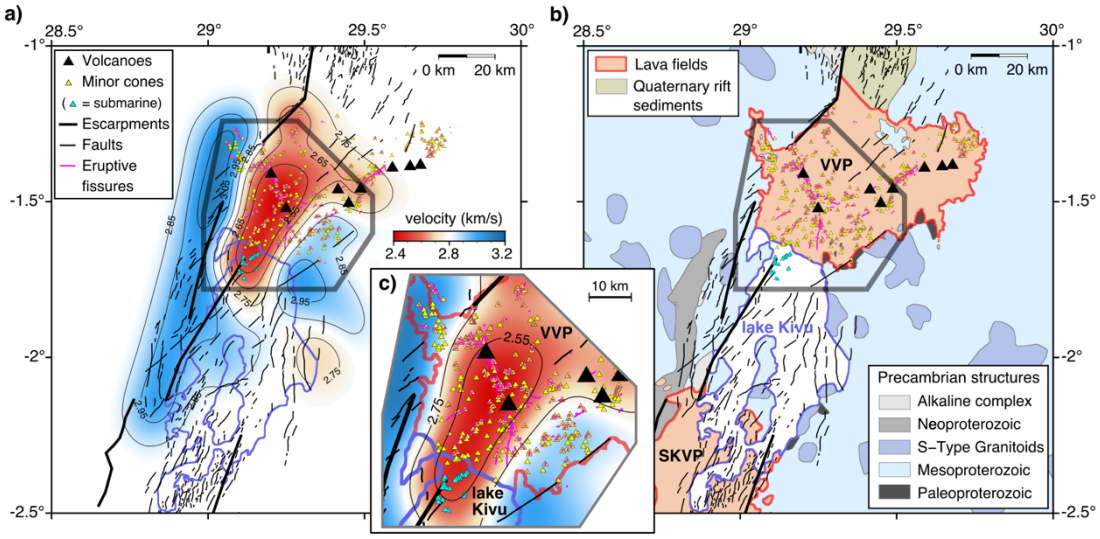

Figure 3: a) 2-D surface wave group velocity map in the microseismic period band (0.05-0.2 Hz). **b**) Geological map. The Confidence area of the inversion result (zoom in **c**) is plotted on each map and corresponds to the polygon delimited by grey lines. It is constrained by the ray paths coverage and the results of the spike resolution test.

1-D P- and S-wave velocity models

Simple one-dimensional (which means in this context only changing with depth) models of seismic velocity are of high importance for routine earthquake monitoring, because they are used for standard earthquake location procedures. While it would be desirable to have very detailed 3D velocity models for best possible earthquake location, such models are in most cases impossible to derive due to a lack of sufficient data coverage in most regions of the World. This is why 1D models play such an important role in observational seismology.

While the first stations in the Kivu region were already installed in 2012/2013, KivuSNet is fully operational with a sufficient station coverage since October 2015 (Oth et al., 2017; see Figure 2). In late 2018, KivuSNet contains 16 stations in the North Kivu-Virunga area. Relying on data from three years of continuous network operation between October 2015 and 2018, we recently derived new local 1-D P- and S-wave velocity models for this region using the inversion code VELEST (Kissling et al., 1994), which simultaneously solves for the earthquake locations and seismic velocity parameters that best explain the data. This work, which has been initiated in 2017 and previously restricted to P-wave velocity structure, is now mature enough to consider its publication in 2019 (Figure 4).

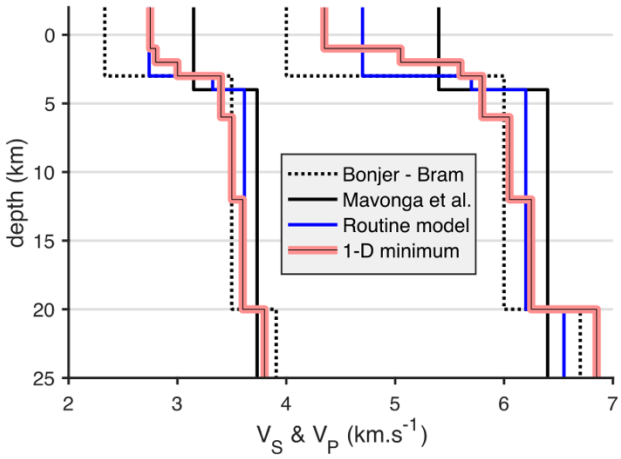

Figure 4: 1-D P and S-wave velocity models for the North Kivu/Virunga area. Former available models for the region (Bonjer-Bram, 1970-1975; Mavonga et al., 2010) are plotted for comparison (dashed and solid black lines, respectively). The initial routine model corresponds to the arithmetic mean of the above-mentioned models (blue) and the final 1-D models (so called 1-D "minimum") are plotted as a red line.

The set of 150 well-locatable earthquakes used for deriving these new 1D models can be referred as "reference events". In 2019, these reference events will be used for the final validation and error assessment of an automatic, "picking-free" cross-correlation based location procedure adapted to volcanic/tectonic events with low signal-to-noise ratio. This location technique developed at ECGS has been used for a couple of years as a routine monitoring procedure and was already described in previous reports (see also Barrière et al., 2017). Along with the seismological models (2-D ANT, 1-D P/S-waves velocity), this will allow for the publication of the first complete seismicity catalogue of several years for this region.

❖ Monitoring and characterization of Nyiragongo volcano

Nyiragongo volcano in North Kivu (D.R. Congo) is among the most active volcanoes in Africa and on Earth, with the presence of a persistent lava lake from at least 1928 to 1977 and since 2002. The persistent lava lake at Nyiragongo gives a unique opportunity to study the dynamics of the upper magmatic system of the volcano over long time scales. In particular, its monitoring offers a chance to detect pressure changes within the magmatic system and, thus, to better interpret periods of unrest at this volcano.

For this reason, a key focus of the RESIST project and the work carried out at ECGS/Mnhn over the past few years was set to the better understanding of this volcano's activity, and we summarize our key findings obtained during 2018 here below. These findings have been published in peer-reviewed international journals or are in preparation to be submitted.

A single-station seismo-acoustic approach for improved characterization of magma movements in the plumbing system

This work, partly presented in the 2017 report, has been finalized and published in 2018 (Barrière et al., 2018). High-resolution satellite SAR images allow to infer the lava lake level fluctuations by measuring the length of the SAR shadow cast by the edge of the bottom of the crater on the lava lake surface (Figure 5, see also dedicated next section below). Up to 72 estimations of the lava lake level are obtained with this technique between August 2016 and November 2017. Additionally, using co-located seismic and infrasound measurements at the closest station (KBTI, ~ 6 km from the crater, see Figure 3a), we detect numerous

highly similar long-period (LP) seismo-acoustic events (i.e., events with both seismic wave generation within the solid Earth and acoustic wave generation in the atmosphere) originating from the shallow lava lake spattering activity. Its continuous counterpart, a background shallow tremor source, was actually already identified across the KivuSNet network over long distances using a seismic interferometry technique (Barrière et al., 2017). A similar cross-correlation calculation between seismic and infrasound records allows to highlight the acoustic component of this shallow tremor.

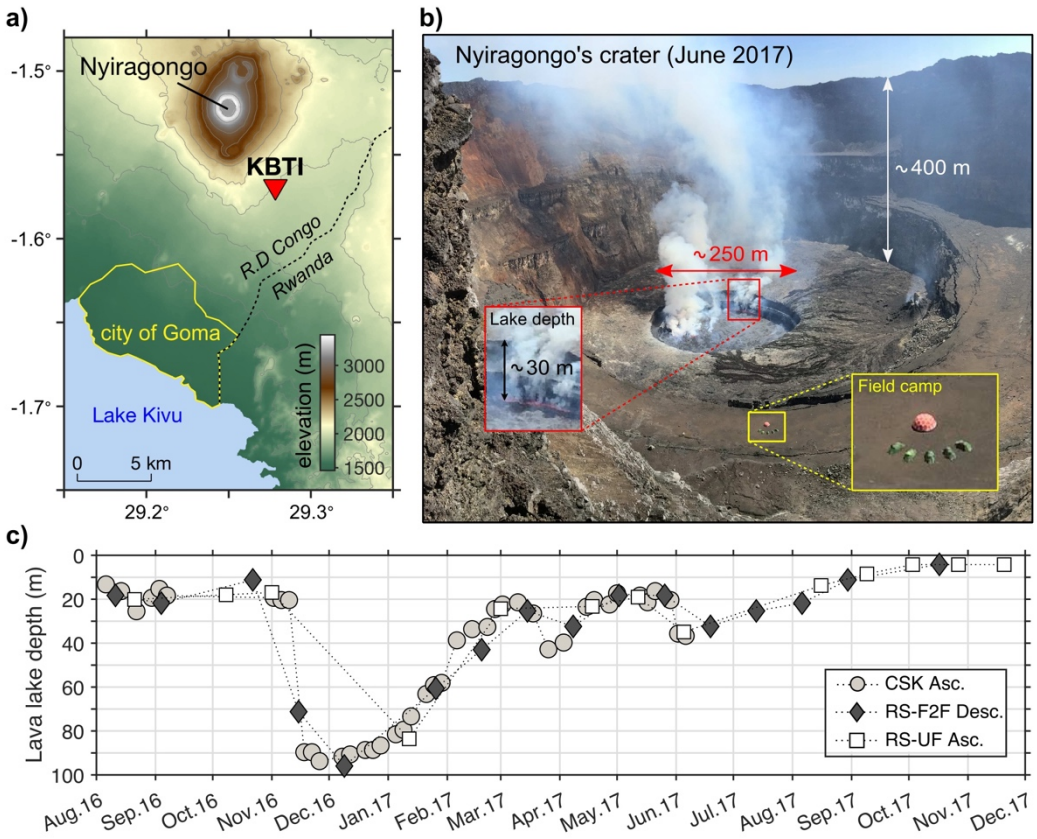

Figure 5: a) Map depicting Nyiragongo volcano, the city limits of Goma and the station KBTI equipped with a broadband seismometer and infrasound sensors. **b**) Picture of Nyiragongo's crater taken on 11 June 2017 (Nicolas d'Oreye). The zoom into the field camp (joint expedition with a BBC television team) allows to gauge the scale of the crater. The zoom into the lava lake depth corresponds to the height measured with the SAR technique. **c**) Estimated lava lake depth from SAR processing using CosmoSkyMed (CSK) and RADARSAT (RS-F2F and RS-UF) images. "Asc" and "Desc." refer to ascending and descending orbits, respectively.

The particularity of the present work is the use of SAR images for calibrating seismo-acoustic ground measurements with lava lake depth. Jointly analysed seismo-acoustic and SAR data reveal that slight changes in the spectral properties of the continuous cross-correlated low-frequency seismo-acoustic records (and not only the individual LP events) can be used to **track fluctuations of the lava lake level on a daily and hourly basis** after calibration (Figure 6a). In particular, we observe that major drops of the lava lake are a consequence of probable deep magma intrusion characterized by deep seismicity (Figure 6c), which induces changes in the shallow magmatic system.

This study highlights the potential to continuously monitor Nyiragongo's lava lake activity (and subsequent information about pressure changes within the magmatic system) using a single seismo-acoustic station located several kilometers from the vent.

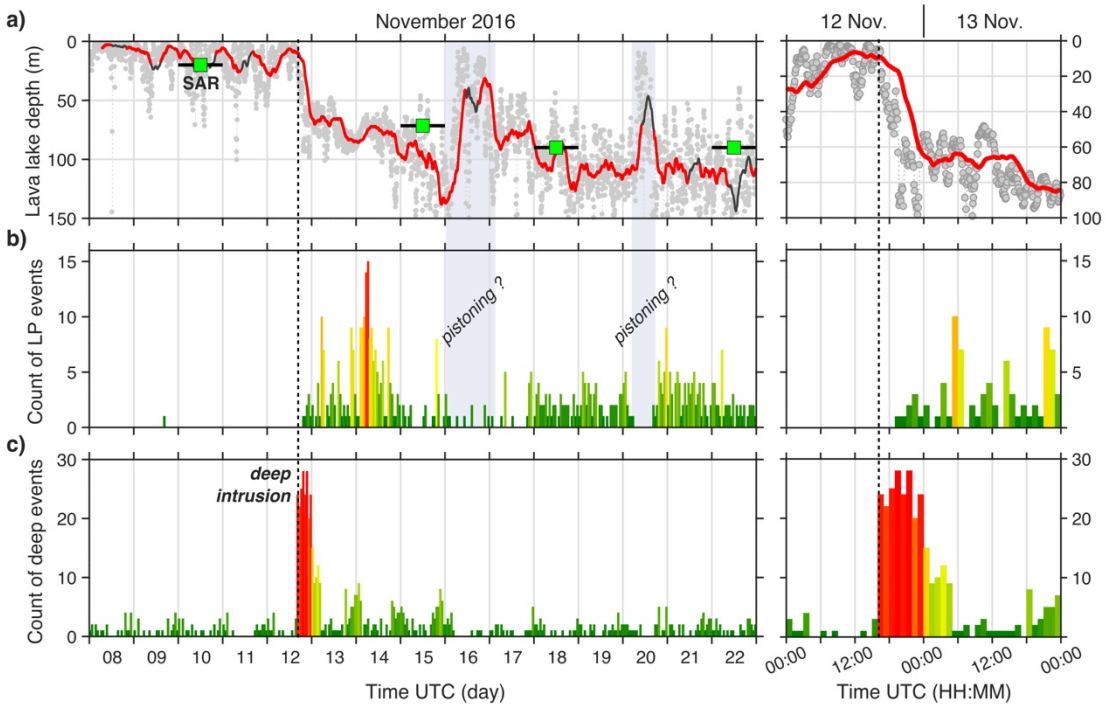

Figure 6: **a**) Hourly estimations of the lava lake depth during the main drop of the lava lake in November 2016 and detail is provided for 12–13 November 2016 (right panels). **b**) Hourly count of shallow LP events detected at KBTI and **c**) Hourly count of deep events at Nyiragongo (located deeper than 5 km b.s.l). The color (green to red) corresponds to the number of events per hour scaled for each type of events.

The processing approach defined here in order to retrieve consistent lava lake depth estimates could eventually be useful for other lava lake volcanoes when no close-range observations are possible. Telemetered near real-time information from the summit (e.g., seismometer, infrasound, SO2/thermal/visible cameras) would obviously be a great help, complementing these remote observations.

An automatic processing method of SAR amplitude images for measuring long-term lava lake level changes

With this work, we aim to improve the SAR based method applied in Barrière et al. (2018) (see previous section and Figure 5c). A manuscript on this analysis is in preparation.

The topography of Nyiragongo's crater is characterized by the presence of three platforms, hereinafter called P1, P2 and P3. P1 and P2 are formed by slabs of solidified lava lake that remained after its drainage during former eruptions, while the deepest platform P3, created after the last eruption in January 2002, has evolved regularly due to the overflows of the lava lake, which inundate the crater thereby causing the floor to rise by up to several dozens of meters per year after solidification. We measure the rise of the crater floor and the lava lake level fluctuations from the module of hundreds of SAR images acquired by RADARSAT, COSMO-SkyMed, SENTINEL-1 and Envisat. The height changes are obtained from the length of the shadow cast by surrounding rims. We developed an automatic method for detecting illumination/shadow transitions using a grid-search strategy among an extensive dictionary of synthetics 1-D transects. Results are validated by comparison with high resolution DEMs obtained from UAV photogrammetry. Details about this method are not described here. Only results for the elevation of platform P3 and a few photos for the lava lake level are briefly presented below in Figure 7.

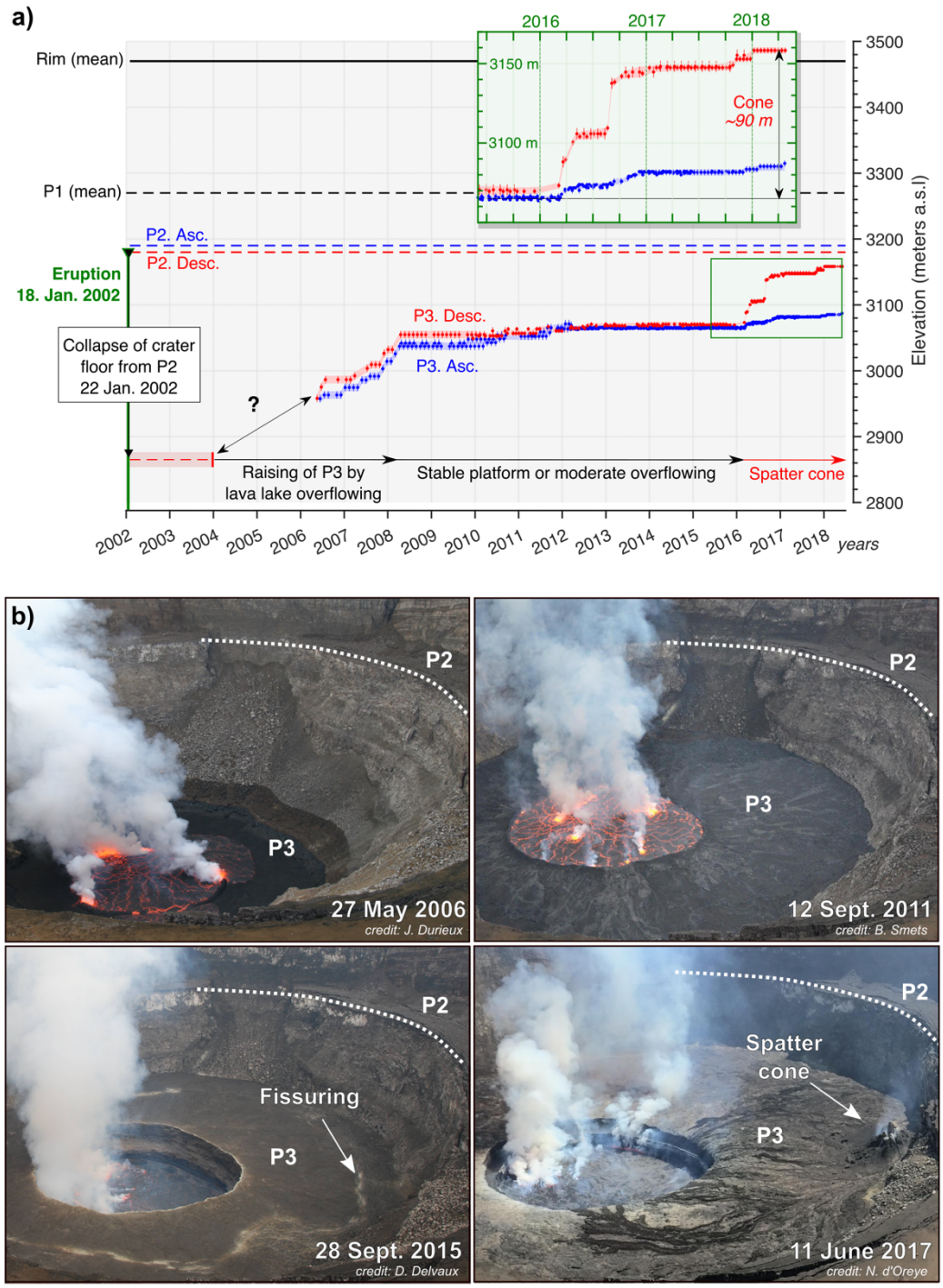

Figure 7: a) Elevation of the platform P3 since the first available satellite measurement (Envisat in late 2003). Asc (blue line) means "Ascending Orbit" (roughly the West side of the lava lake) and Desc. (red line) means "Descending" (East side, where a spatter cone has appeared in March 2016). **b**) 4 Pictures taken from the same location (main crater's rim) spanning May 2006 to June 0217. Note the various morphology of the platform P3 and the widening of the lava lake.

Our current work consists in comparing the obtained measures with other parameters (seismicity, degassing, ground deformation and visual observations). For instance, as already pointed out with the aforementioned seismo-acoustic approach, we inferred that observing lava lake level changes synchronous to deep intrusions revealed by the seismicity indicate major changes in the magmatic system (Figure 6). Comparing these lava lake level changes at Nyiragongo with the magmatic activity at neighbouring Nyamulagira volcano also suggests interactions between the two magmatic systems. Although this was suspected yet never observed before in the Virunga, it raises new questions about the mechanisms driving

these interactions. Indeed, petrological studies show that despite a distance as small as 13km, Nyiragongo and neighbouring Nyamulagira share no common magmatic sources, at least at crustal depth, and the distance is too large for possible influence by static stress transfer.

Multidisciplinary analysis of seismic, SO_2 and photogrammetry-based lava lake level measurements for an improved understanding of lava lake dynamics

This work, initiated in late 2017, aims at combining all available and relevant observations performed at the summit during the last few years (2011-2018) in order to deepen our understanding of the lava lake system. A manuscript is in preparation.

In particular, we aim to better understand the dynamics of Nyiragongo's lava lake, which has been understudied since the first geophysical expeditions in the sixties in comparison with other lava lake volcanoes (Kilauea, Erebus, Erta Ale). Although nowadays digital seismic measurements are of significant importance in the field of volcanology, none of these have yet been reported at Nyiragongo's summit in the literature. There is also no observational evidence for explaining the dynamics of the lava lake due to a lack of long-term and high-temporal resolution continuous geophysical datasets. In order to address this important question, we initiated a multi-disciplinary study combining the analysis of the lava lake's seismic signature with time-lapse camera images acquired during two days in September 2011 (Smets et al., 2016) and with long-term (9 months) daily space-based SO_2 estimates using the instrument TROPOMI deployed in 2017. In this work, we notably make the link between seismic data acquired in September 2011 with records obtained at similar locations several years later between March and November 2018.

This approach allows us to show that (1) small meter-scale lake level variations can be detected at long distance through its persistent seismic tremor signature (i.e., at least up to 17 km), (2) the shallow-rooted degassing mechanism is similar to the one inferred at Hawaii's Halema'uma'u lava lake (i.e. gas pistoning, Patrick et al., 2016) and (3) a range of seismic-amplitude cycles spanning few minutes to several tens of minutes characterizes the activity from the lake and the shallow plumbing system. We highlight a dominant lava lake seismic pattern connected to deep processes, which is periodic and fluctuates according to major long-term variations of SO_2 degassing (conceptual model in Figure 8).

We thus propose for the Nyiragongo shallow magmatic system a conceptual model including two competitive degassing sources responsible to the complex dynamics of its lava lake : shallow (gas pistoning and spattering at the upper level of the lava lake) and deep (periodic convection of magma batches into the lake controlled by the supply of fresh magma from the feeding conduit, i.e., the shallow magma reservoir). This final observation reflects the strong potential to continuously monitor the particular seismic signature of the lava lake in order to decipher changes in the magmatic regime.

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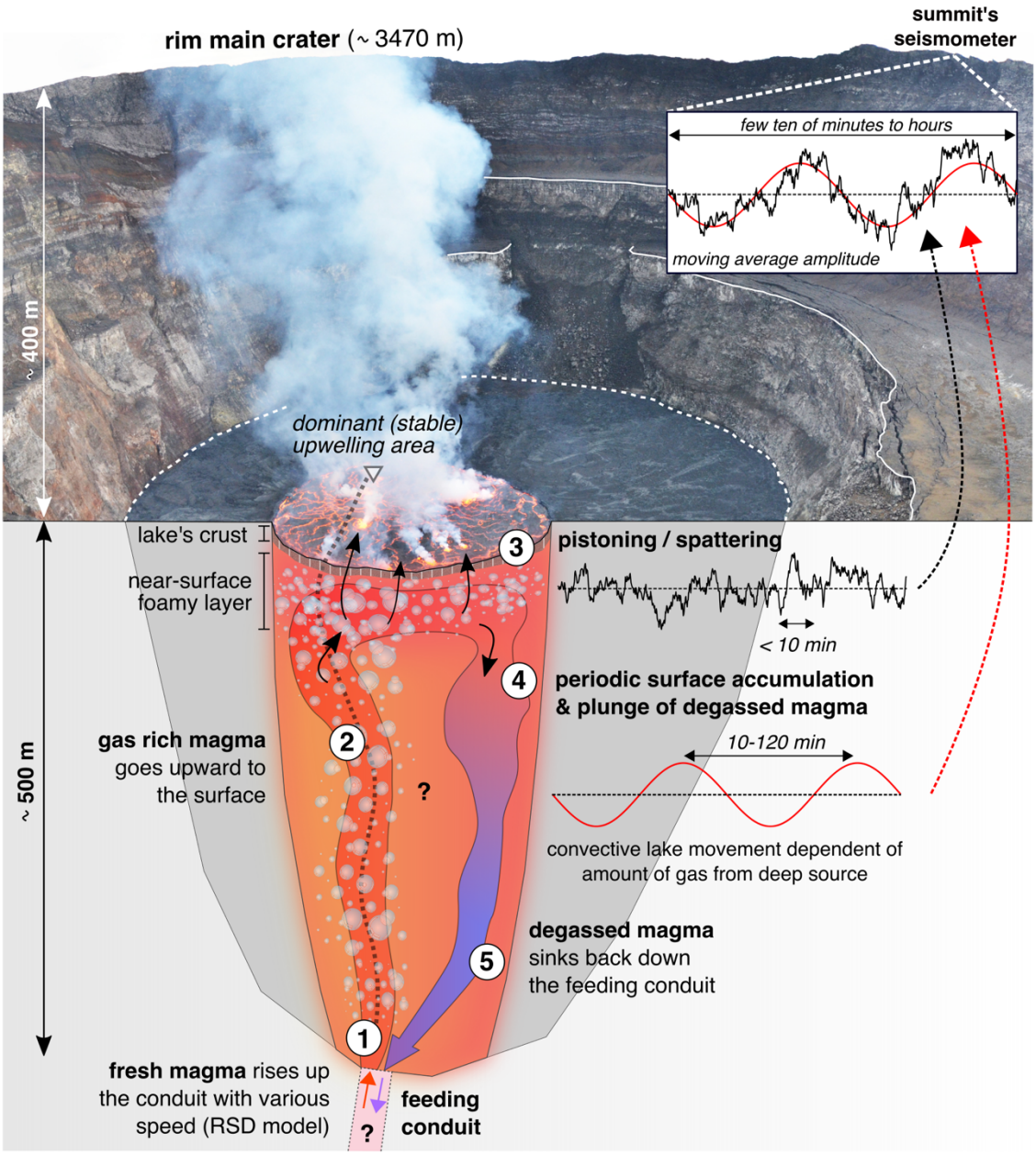

Figure 8: Conceptual model of convection and degassing mechanisms (steps 1 to 5) of the Nyiragongo lava lake system inferred from close-range seismic observations and space-based SO_2 estimates (TROPOMI sensor). RSD model stands for "Rise Speed Dependent" (e.g., Parfitt, 2004, Jour. Volc. Geo. Res.).

For further information on the RESIST project, please see also the websites http://resist.africamuseum.be/ and 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

❖ SeisMon: Seismic Monitoring Tools and Infrastructure in Luxembourg and DR Congo

ECGS operates two broadband seismic networks, one in the Virunga Volcanic Province (DR Congo, see also *RESIST* section above) and one covering the territory of Luxembourg. While the first of these networks is installed in a highly active rifting region with both significant tectonic and volcano-related seismic activity, Luxembourg is a region of 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.

Over the past few years, ECGS has made it a priority to overcome the lack of seismic monitoring infrastructure that prevailed in Luxembourg 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). Four of these stations are still running and provide continuous seismic data.

The SeisMon project inscribes into these efforts and intends to benefit from the fundamental research and data processing experience acquired within the RESIST project in order to set up an operational monitoring framework in the Virunga Volcanic Province, but also one such framework adapted to the Luxembourg context, using the seismic network available on our territory.

In 2018, nine broadband and two short-period seismic stations were operated by ECGS in Luxembourg (Figure 9). Four of these stations are temporary installations set up in collaboration with the Geophysical Institute of the Karlsruhe Institute of Technology (KIT). Three more seismic stations are planned and will require identification of appropriate land, agreement with the owner and installation in a secure, ideally purpose-build, seismic vault. 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 10).

An important aspect in 2018 was the establishment of data sharing routines with the Royal Observatory of Belgium and the Erdbebendienst Südwest (Rheinland-Pfalz & Baden-Württemberg) in Germany. On the German side, we now 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 (see example records in Figure 10). 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 clearly recognized.

Besides this data exchange and collaboration with monitoring agencies in our neighbouring countries, we have also been approached by colleagues at the University of Kaiserslautern

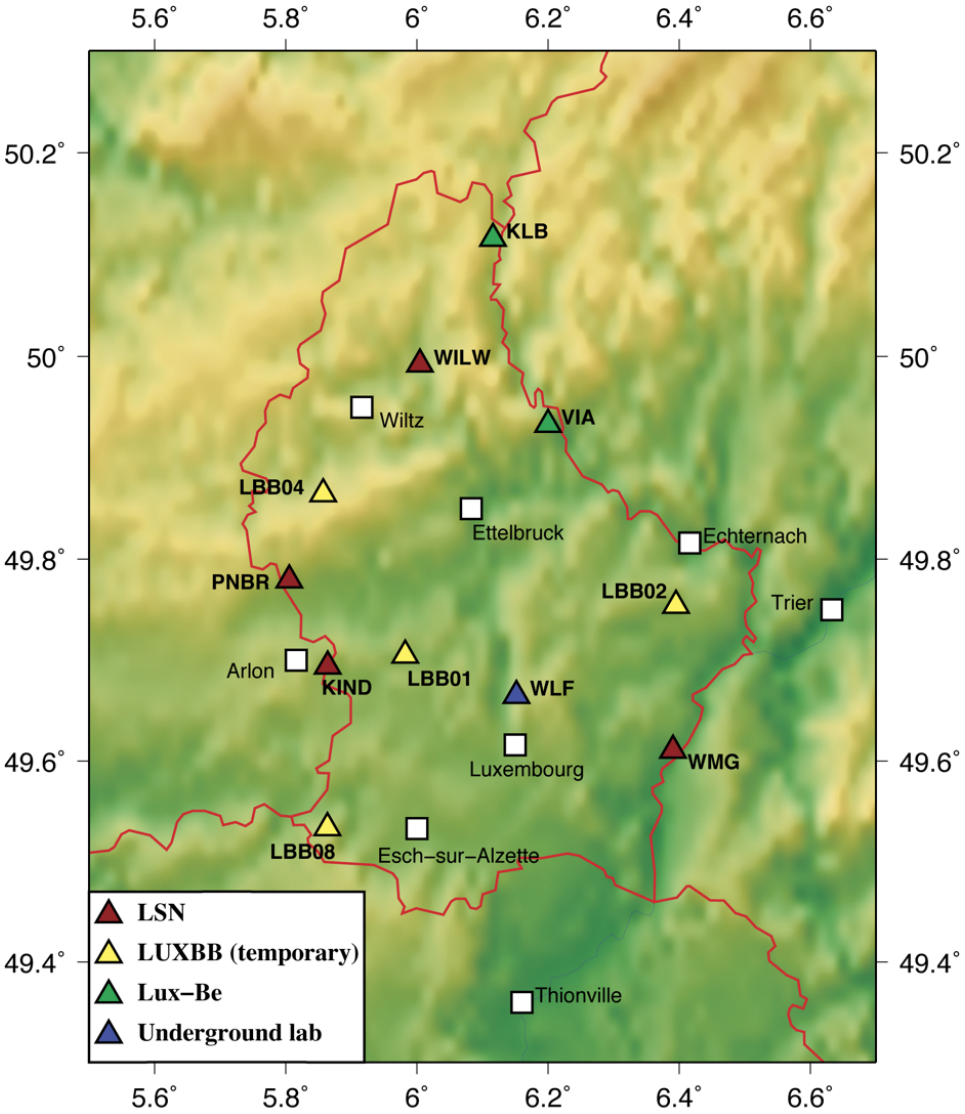

Figure 9: Map of the Grand Duchy of Luxembourg and the currently running 10 broadband seismic stations, five of which are temporary installations of instruments belonging to the KIT.

for a collaboration in the framework of a project proposal at the German Bundesministerium für Bildung und Forschung dealing with seismic hazard and risk estimation and reduction research in Rwanda. Our extensive and unrivalled expertise in seismic monitoring in the difficult conditions of the Kivu region as well as on its tectonic setting and seismicity characteristics acquired in the framework of the RESIST project are clearly recognized within the international scientific community.

Figure 11 shows a map of the seismic activity in and around Luxembourg as detected and located at ECGS over the past two years. This catalogue contains a total of 194 events with local magnitude estimations ranging about 0.2 to 2. The results presented in this map are based on an automatic detection procedure on the continuous seismic data streams using a kurtosis-based picking algorithm. Events were located when at least 5 potentially matching picks were found at 5 stations. Event location was carried out with a cross-correlation based algorithm developed in the framework of the RESIST project and refined during the past year. This algorithm carries out a grid search over a regular grid (1 km) of potential source locations and determines and, for each event, a map of location probability as well as one maximum likelihood epicentre (dots in Figure 11). However, it should be noted that for each individual event, the location uncertainties are large due to the low signal-to-noise ratio for such weak seismic events.

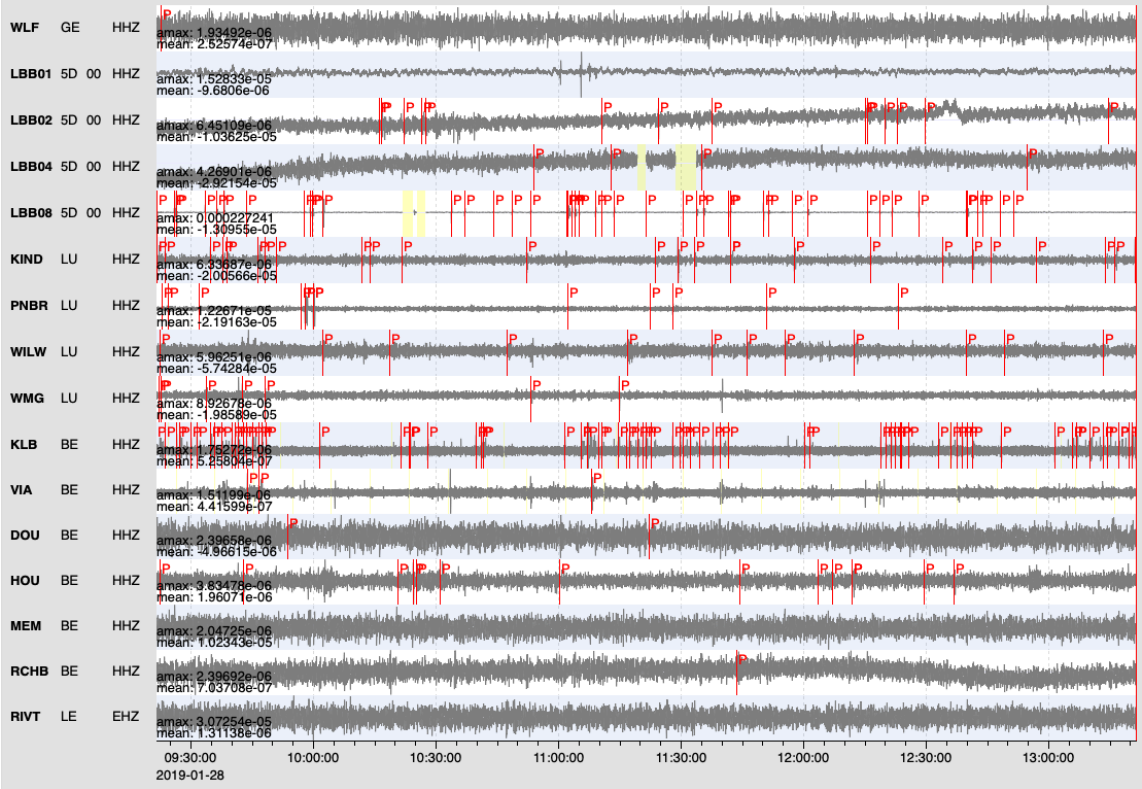

Figure 10: Example of real-time monitoring at ECGS, snapshot of SeisComP3 system from 28 January 2019 covering incoming seismic data of a 4h-long time window.

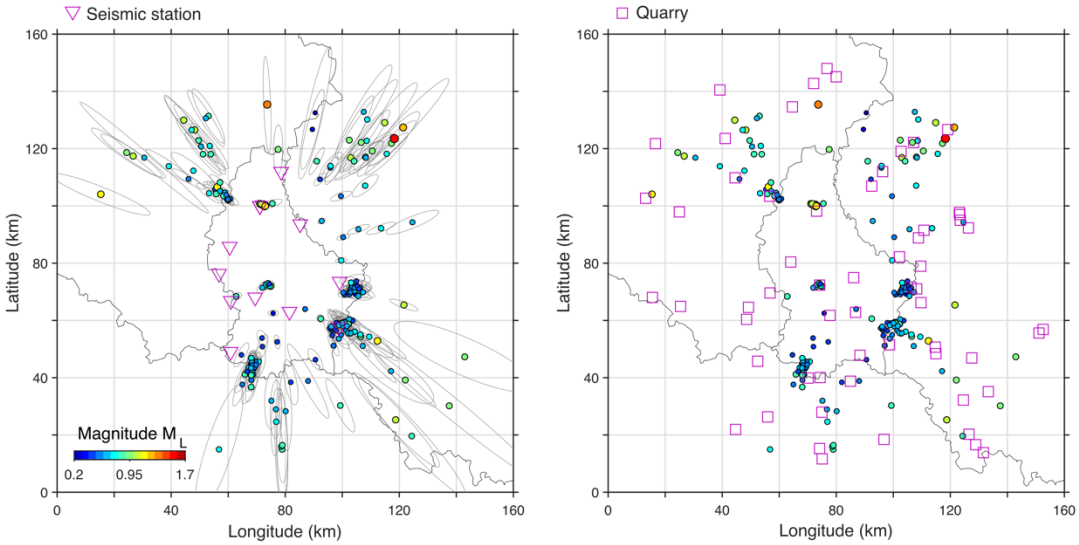

Figure 11: Map showing 194 local events detected and located by ECGS in and around the Luxembourgish territory over the past 2 years. Magnitude estimates are indicated with colour code as shown in left-hand plot. Ellipses on the left-hand plot indicate the location uncertainties of the events, and inverted triangles represent the locations of the seismic stations. Right-hand side: same set of seismic events in relation to known active quarries (indicated by violet squares).

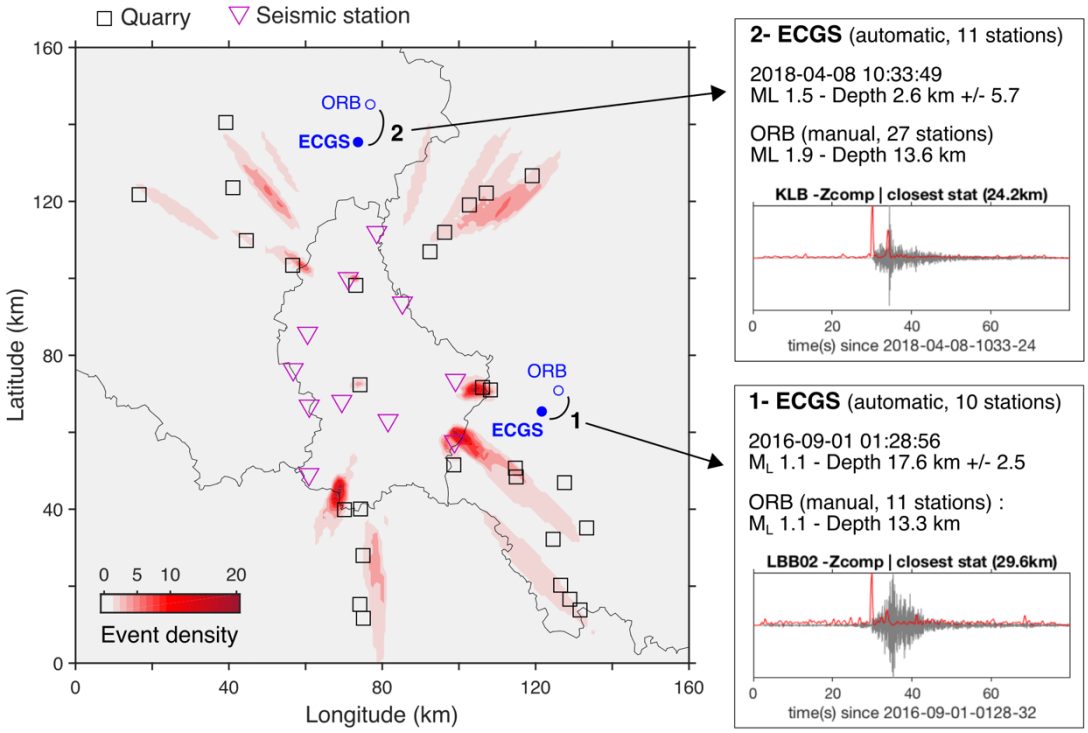

Figure 12: Seismicity density map of Luxembourg and surroundings obtained by stacking the individual probability map for all events. The map also contains two examples of tectonic earthquakes not far from the Luxembourgish border, with location comparison with the solution of the Royal Observatory of Belgium. Right-hand insets show example recordings from stations in Luxembourg together with the kurtosis functions used for automatic detection (red lines).

Most of the events detected and located by our algorithm have characteristics of quarry blasts, and their locations generally agree with known active quarries. However, the individual event locations have significant uncertainties, and one way to better image repeating seismic events (i.e., events originating from the same source, which is the case for quarry blasts) is to stack (i.e., to sum) all individual event location probability maps. This way, locations of recurring seismic events will be highlighted, while randomly occurring events will be downweighed.

Figure 12 shows the result of this process. For each event, the location probability map is normalized to the interval [0 1], and the colour code in Figure 12 simply shows the value of the sum of all location probability values at each grid point for all events. The map in Figure 12 clearly delineates the regions where active quarries are located, such as in Brouch near Mersch (Carrières Feidt), or the quarry in Mesenich (Germany).

As already described in the annual report last year, the observable seismic activity on the Luxembourg territory can therefore be largely associated with anthropogenic activities. Nonetheless, some clearly tectonic seismic events also occur, such as the example magnitude 0.6 event depicted in Figure 13. This event is very interesting: it occurred very close to a known active quarry on Senningerberg, and as such could have been simply associated to this anthropogenic activity. However, the event was very well located by ECGS's network, and the obtained depth estimate is remarkably well-constrained to a depth of nearly 10 km. Furthermore, the waveforms of the event look like a typical small earthquake. Thus, this event is most likely of natural, tectonic origin. This event shows that our seismic network is able to record very small earthquakes on the national scale and that that small events occur, even though rarely, on Luxembourgish territory.

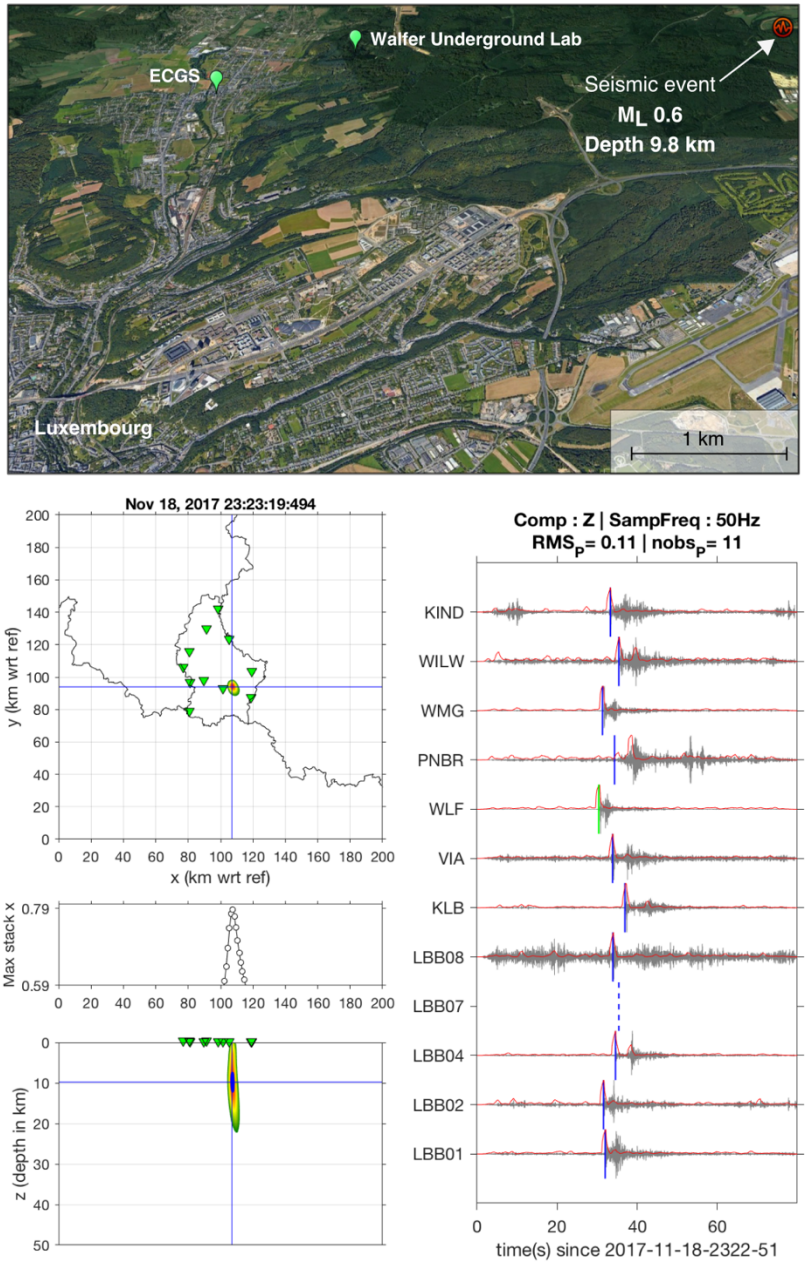

Figure 13: Example of very small tectonic event well located within Luxembourg territory at an estimated depth of 10 km. See text for further details.

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

❖ 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.

In 2018, first trial inversions were carried out by the different groups on three real test datasets: one from Italy, one from Japan and one from the French Alps. In addition, a first synthetic dataset was processed by the participants. The results of these inversions were discussed at the first GITEC workshop which took place in Cadarache in southern France in December 2018. The work of this group of experts continues in 2019.

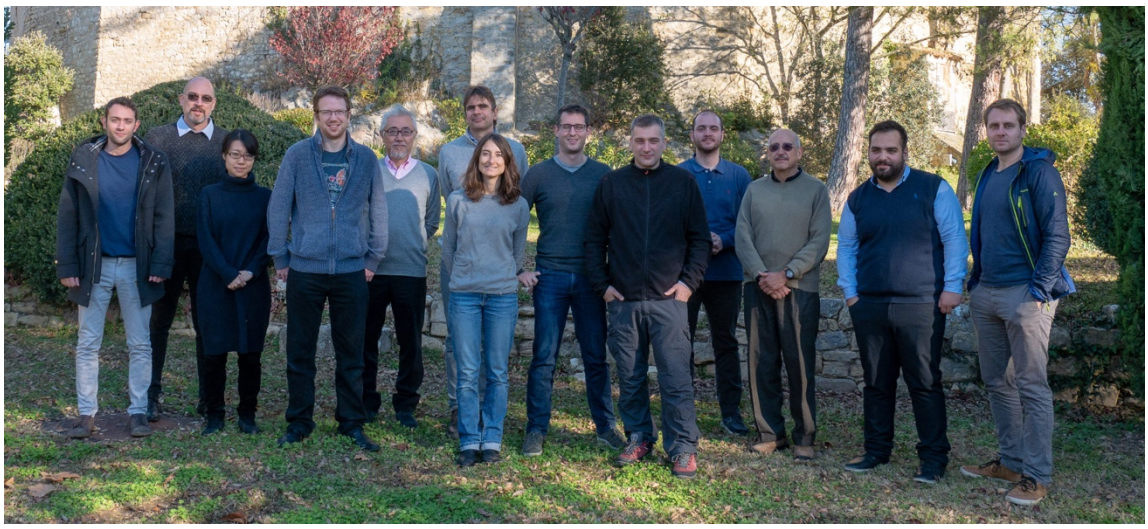

Figure 14: GITEC group photo at workshop in Cadarache, France, 5-6 December 2018.

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.

❖ Various seismological collaborations

In 2018, ECGS was involved in a series of international collaborations, all of which have led to high-impact peer-reviewed journal articles co-authored by ECGS scientists:

- **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 2018 (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 is currently in review in the journal *Geophysical Journal International* (see Publications & Presentations section).

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

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 2018, we were involved the following projects:

- **RESIST: REmote Sensing and In Situ detection and Tracking of geohazards**, 1/12/2014 - 30/11/2018 (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 6.**

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.

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
  European Center for Geodynamics and Seismology, Luxembourg
- Nat. Museum of Natural Hist. (Mnhn), Luxembourg
- 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 2018

Monitoring networks

Please see RESIST section on page 6.

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 CSL InSAR Suite Software. Special tools for automated optimized mass processing (entitled **CIS-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… Automatic integration with the Multidimensional Small Baseline Subset (MSBAS) tool was further improved. These toolboxes are now compliant for both Linux and Mac operating system. Manuals are under development.

A first beta version of CIS-MasTer is ready for distribution and was installed e.g. at the Geological Survey of Belgium, the Centre Spatial de Liège, the Roya Museum for Central Africa or the Universidad Mayor, Centro Hemera de observacion e la Tierra in Santiago, Chile.

An upgraded version of MSBAS software (under development by Sergey Samsonov for computing full 3D displacements when movements are expected to occur along the terrain slope) was tested in Luxembourg.

Several mass processes were and/or are currently executed in Luxembourg on a new Linux server. 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, DRC.

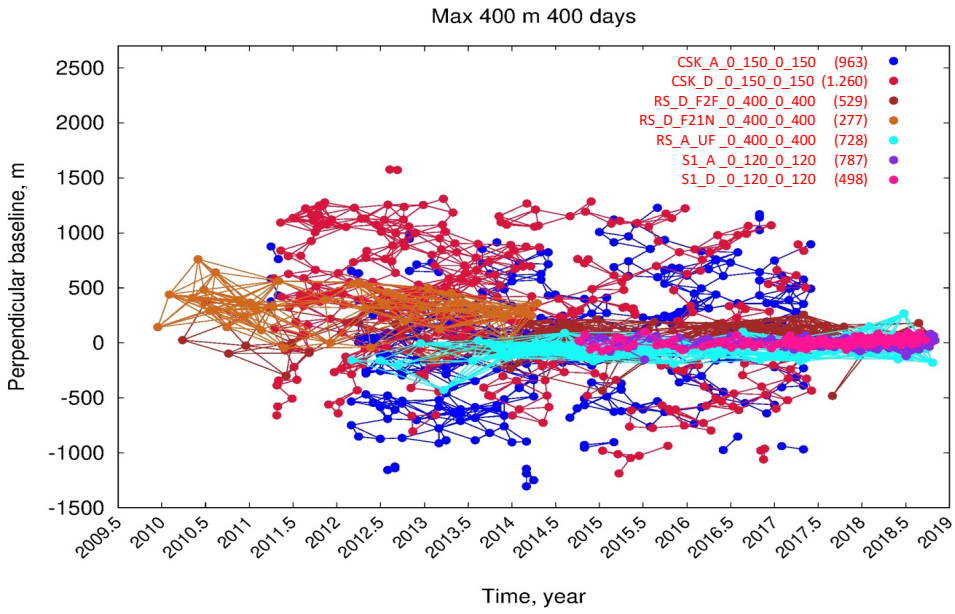

Figure 15: Baselines plot of the 5.042 interferograms computed by combining 992 SAR images acquired by 3 satellites. These interferograms are used to perform MSBAS studies over the Virunga Volcanic Province using CIS-MasTer. The legend shows the color code for each satellite (CosmoSKyMed, RadarSat or Sentinel 1), the orbit (Ascending in blueish colors or Descending in reddish colors), the maximum spatial and temporal baselines and the number of pairs. A total 992 SAR images are used.

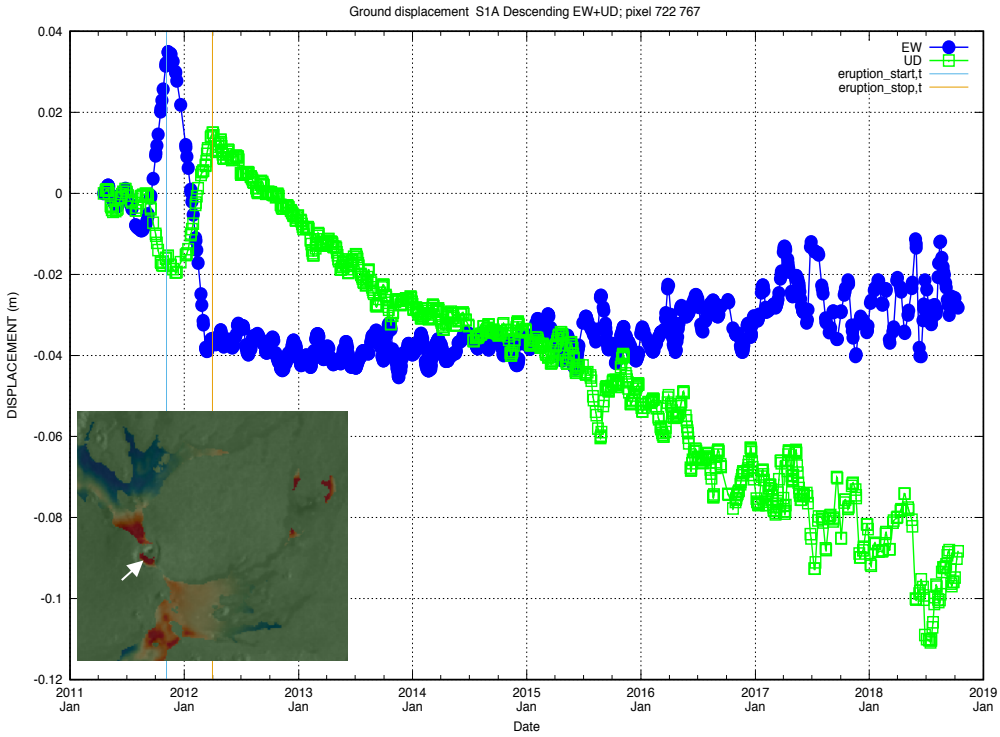

Figure 16: Example of MSBAS time series of ground deformation in East-West (blue) and vertical (green) directions for a pixel located within the crater of Nyamulagira (see white arrow in inset), from 2011 to 2018 (992 points). Beginning and end (estimated) of distal 2011-2012 eruption at Nyamulagira are marked in blue and red vertical lines respectively. Clear pre-eruptive deformation and co-eruptive ground deformation are visible. Subsidence started after the end of eruption at a linear rate till end of 2013, then slowed down till early 2015 then accelerated again till now.

An automated procedure was set up to generate a SAR amplitude image of each new ESA Sentinel 1 image acquired on the Virunga volcanoes (~one new image every 2-6 days) and animated gifs are automatically updated to monitor Nyiragongo and Nyamulagira craters.

Similar animated gifs in false color are automatically updated using Sentinel 2 multispectral images to monitor Nyiragongo and Nyamulagira craters (1 new image every 5 day).

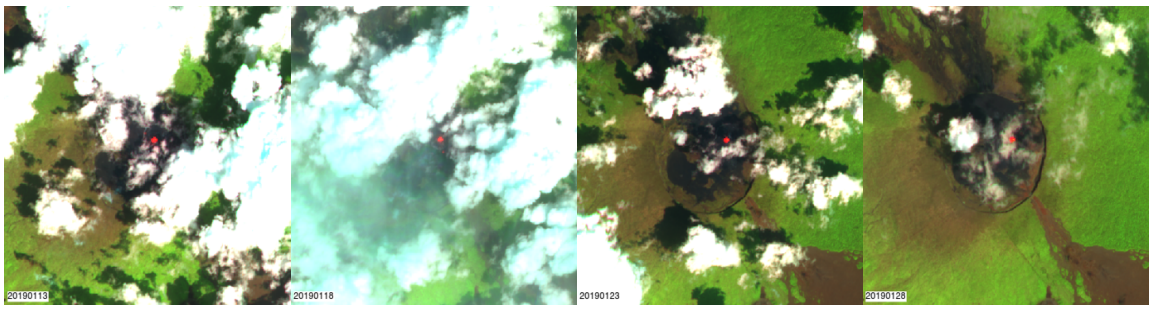

Figure 17: Example of last 4 Sentinel-2 multispectral images in false colour acquired over Nyamulagira volcano (from 20190113 to 20190128), showing that a lava lake is active in Nyamulagira (see red zone in the crater).

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 2018, these data 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.

In 2018, the work in the Walferdange Geodynamical Laboratory (*GeoDynLab*), established by Prof. Dr. Manfred Bonatz within a dedicated chamber of the WULG, has been continued. *GeoDynLab* was used for multifarious metrological investigations and local geodynamical research. The deployed measurement devices include high definition sensors for measuring gravity, rock dynamics (tilt), atmospheric pressure, as well as the chamber temperature.

Unfortunately, this report cannot summarize the results obtained from *GeoDynLab* during the course of 2018, since Prof. Dr. Manfred Bonatz passed away in December 2018.

In addition to the measurements in *GeoDynLab*, radon and various other gas and ultra-high-resolution temperature monitoring in the Laboratory and all along the entrance galleries was 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.).

❖ Radon measurements in the WULG during 2018

Antoine Kies

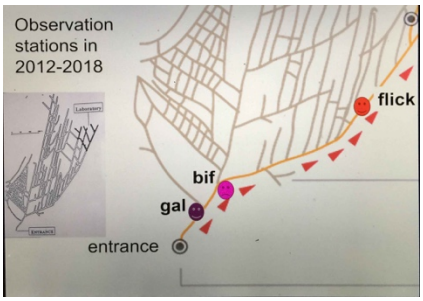

Figure 18: Radon observation sites in WULG.

The radon investigations from the past years (see previous annual reports) were continued in 2018. Two radon monitors (Alphaguard) recorded radon in 'gal' and 'flick', local temperatures were recorded at these places. Meteorological data were provided by MeteoLux.

Our model for the radon concentration was confirmed. This model stipulates that in the mine interior (represented by 'flick'), the measured radon has two origins: *supported radon* (some 2.4 kBq/m^3) produced within the mine and *unsupported radon* (up to 14 kBq/m^3) directed into the mine, originating from a partly collapsed gallery joining the entrance way at 'gal'. Whereas the first contribution is rather stable, the other contribution adding radon to the galleries is absent or very limited in winter, but acts actively in summer, with a strong dependency on environmental temperature changes.

We can thus summarize the two contributions as:

mine radon = supported radon + unsupported radon, and

unsupported radon = mine radon – supported radon (2.4 kBq/m³).

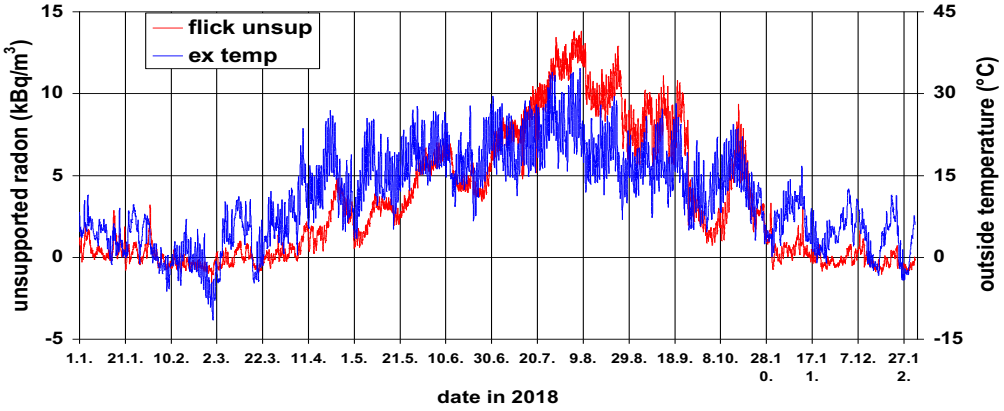

Figure 19: Unsupported radon at station 'flick' (red curve) and outside temperature (blue curve) for the year 2018.

Figure 19 shows the unsupported radon and outside temperature for 2018. External temperature variations are mostly responsible for the radon pattern inside the mine.

Last years' report discussed the 'plastic attack' to the mine from 2015, i.e. the closure of the side galleries by plastic sheets. The negative values of unsupported radon at 'flick' measurement station (Figure 20) are a consequence of this operation. Air from the exterior, with low radon concentrations, reaches 'gal' and lowers the radon concentrations. Before this closure of the side galleries, no negative unsupported radon values were observed at station 'flick'.

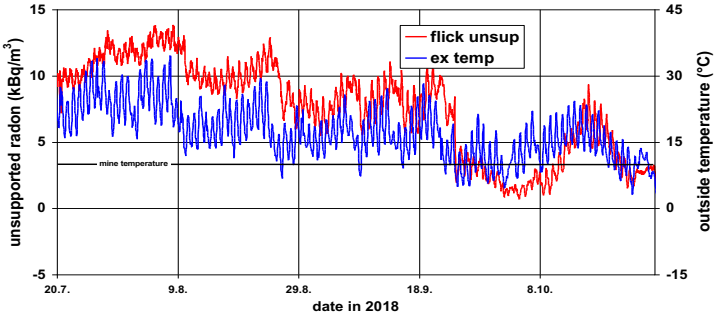

Figure 20: Unsupported radon at station 'flick' and outside temperature for the summer period of 2018, highlighting that the summer period shows very high daily variations of radon at 'flick', which is a direct consequence of the plastic shielding.

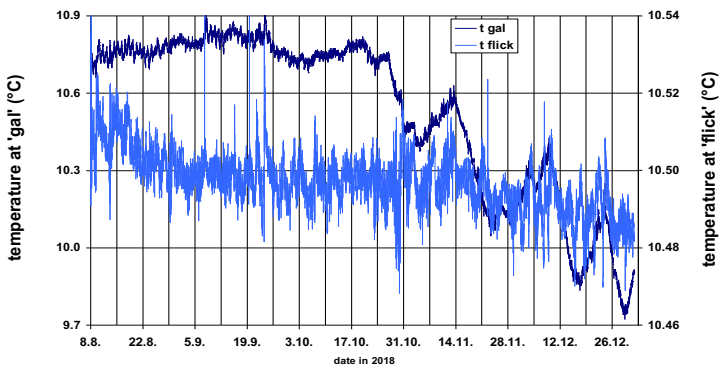

Figure 21: Temperature variations recorded at stations 'gal' and 'flick' for the second half of 2018. As long as minimum outside temperatures are above the mine temperature, the temperatures at 'gal' are constantly 'high'. They decrease as soon as night temperatures get below 10 °C. Alarming are the elevated temperature variations at station 'flick'.

PUBLICATIONS & PRESENTATIONS

❖ Peer-reviewed Journal Publications and Proceedings

Published

Barrière, J., **N. d'Oreye**, **A. Oth**, H. Geirsson, N. Mashagiro, J. Johnson, B. Smets, S. V. Samsonov and F. Kervyn (2018). Single-station seismo-acoustic monitoring of Nyiragongo's lava lake activity (D.R. Congo). *Front. Earth Sci.*, 6:82, doi: 10.3389/feart.2018.00082.

Nobile, A., A. Dille, E. Monsieurs, J. Basimike, T.B. Mugaruka, **N. d'Oreye**, F. Kervyn F. and O. Dewitte (2018). Multi-temporal DInSAR to characterise landslide ground deformations ina tropical urban environment: focus on Bukavu (DR Congo). *Remote Sensing,* 10(4)*,* Special issue "Radar Interferometry for Geohazards"*,* doi: 10.3390/rs10040626.

Picozzi, M., D. Bindi, D. Spallarossa, **A. Oth**, D. Di Giacomo and A. Zollo (2018). Moment and energy magnitudes: diversity of views on earthquake shaking potential and earthquake statistics. *Geophys. J. Int.*, in press*.*

Wauthier, C., B. Smets, A. Hooper, F. Kervyn, **N. d'Oreye** (2018). Identification of subsiding areas undergoing significant magmatic carbon dioxide degassing, along the northern shore of Lake Kivu, East African Rift. *J. Volc. Geotherm. Res.*, 363, 40-49, doi : 10.1016/j.jvolgeores.2018.08.018

Under review & in preparation

Ahmadzadeh, S., G. Javan-Doloei, S. Parolai, and **A. Oth** (2018). Non-parametric spectral modelling of source parameters, path attenuation and site effects from broadband waveforms of the Alborz earthquakes (2005-2017). *Geophys. J. Int.*, under review.

d'Oreye, N., **J. Barrière**, **D. Derauw**, H. Geirsson, and B. Smets (2019). Lava lake level changes measured by time series of SAR amplitude : a proxy for pressure changes in the magmatic system, *in preparation*.

Barrière, J., **A. Oth**, B. Smets, **N. d'Oreye**, N. Theys, N. Mashagiro, J. Subira and F. Kervyn. (2019). Competitive shallow and deep degassing regimes controlling Nyiragongo's lava lake dynamics, *in preparation*.

Barrière, J., **A. Oth**, **N. d'Oreye**, G. Mavonga and F. Kervyn (2019). Fundamental seismological models and seismicity catalogues (2015-2018) for the Virunga Volcanic Province (D.R. Congo, Rwanda), *in preparation*.

❖ Conference Presentations, Proceedings and Abstracts

Barrière, J., **N. d'Oreye**, **A. Oth**, H. Geirsson, N. Mashagiro, J.B. Johnson, B. Smets and F. Kervyn (2018). Monitoring Nyiragongo's lava lake activity (D.R. Congo) using seismic, infrasound and SAR measurements, *Abstract, Seismological Society of America (SSA) Annual Meeting, 14-17 May 2018, Miami, USA.*

Barrière, J., **N. d'Oreye**, **A. Oth**, G. Geirsson, N. Mashagiro, J.B. Johnson, B. Smets and F. Kervyn (2018). Single-station seismo-acoustic monitoring of Nyiragongo's lava lake activity (D.R. Congo) *Abstract, Cities on Volcanoes 10, 3-7 September 2018, Naples, Italy.*

Barrière, J., **N. d'Oreye**, **A. Oth**, H. Geirsson, N. Mashagiro, J.B. Johnson, B. Smets and F. Kervyn (2018). Monitoring Nyiragongo's lava lake activity (D.R. Congo) using seismic, infrasound and SAR measurements. *Abstract, General Assembly of the European Seismological Commission 2018, September 2-7 2018, Valetta, Malta.*

Brenot, H., N. Theys, M. Van Roozendael, J. Gliss, K. Stebel, **N. d'Oreye**, A. Minani and M. Yalire (2018). Monitoring of the SO2 emissions from Nyiragongo volcano using UV camera imaging and spectroscopy during 10 days in June 2017 *Abstract, European Geosciences Union General Assembly 2018, April 7-12 2018.*

d'Oreye, N., **J. Barrière**, **D. Derauw**, H. Geirsson, B. Smets, **A. Oth**, S. Samsonov and F. Kervyn (2018). Lava lake level changes measured by times series of SAR amplitude: a proxy for pressure changes in the magmatic system at active volcanoes *Abstract, Cities on Volcanoes 10, 3-7 September 2018, Naples, Italy.*

d'Oreye, N., **D. Derauw**, H. Geirsson, B. Smets, S. Samsonov, **J. Barrière**, **A. Oth**, N. Theys, C. Kassereka, L. Libert, A. Nobile and F. Kervyn (2018). Recent activity in Nyiragongo active crater, Democratic Republic of Congo – remote sensing and in-situ measurements *Abstract, Grande Conférence sur la Géologie du Congo, October 24-25 2018, Kinshasa, Democratic Republic of Congo.*

d'Oreye, N., **D. Derauw**, S. Samsonov, A. Dille, A. Nobile, L. Libert, E. Monsieurs and F. Kervyn (2018). Combined use of Sentinel-1 and Cosmo-SkyMed SAR data for multi-dimensional detection and monitoring of landslides in South Kivu, DR Congo. *Abstract, Grande Conférence sur la Géologie du Congo, October 24-25 2018, Kinshasa, Democratic Republic of Congo.*

d'Oreye, N., **D. Derauw**, S. Samsonov, A. Dille, A. Nobile, L. Libert, E. Monsieurs and F. Kervyn (2018). Combined used of Sentinel-1 and CosmoSkyMed SAR data for multi-dimensional detection and monitoring of landslides in South Kivu, DR Congo *Abstract, Luxembourg Earth Observation and Integrated Applications Day, April 19th 2018, Mondorf, Luxembourg.*

d'Oreye, N., **D. Derauw**, L. Libert, S. Samsonov, A. Dille, A. Nobile, E. Monsieurs and F. Kervyn (2018). Automated InSAR mass processing using CSL InSAR Suite (CIS) software for Multidimensional Small Baseline Subset (MSBAS) analysis: exemple using Sentinel-1 and Cosmo-SkyMed SAR data for the detection and monitoring of landslides in South Kivu, DR Congo, *Abstract, 13 November 2018, Belgian Earth Observation Day 2018 2.0, Barvaux Condroz, Belgium.*

Derauw, D., **N. d'Oreye**, S. Samsonov, F. Kervyn, L. Libert and A. Orban (2018). Development of an integrated and automated tool for InSAR time series processing and near real time displacements monitoring. *Abstract, Cities on Volcanoes 10, 3-7 September 2018, Naples, Italy.*

Derauw, D., M. Kirkove, L. Libert, A. Orban and **N. d'Oreye** (2018). Split-Band SAR and Split Band InSAR principle and applications *Abstract, Luxembourg Earth Observation and Integrated Applications Day, April 19th 2018, Mondorf, Luxembourg.*

Dille, A. et al. (2018). MODUS: A Multi-sensOr approach to characterize ground Displacements in Urban Sprawling contexts *Abstract, 30 January 2018, Belgian Earth Observation Day 2018, Beersel, Belgium.*

Kervyn, F., **N. d'Oreye**, K. Karume, B. Smets and C. Michellier (2018). Development of an efficient monitoring infrastructure at Nyiragongo volcano (DR Congo). The challenge of capitalizing on 13 years of experience on hazard and risk assessment. *Abstract, Cities on Volcanoes 10, 3-7 September 2018, Naples, Italy.*

Kervyn, F., **N. d'Oreye**, O. Dewitte, B. Smets et al. (2018). Framework of research in the Kivu rift Basin context (Central Africa – Great Lakes Region) *Abstract, Grande Conférence sur la Géologie du Congo, October 24-25 2018, Kinshasa, Democratic Republic of Congo.*

Kervyn, F. **et al.** (2018). RESIST: Remote Sensing and In Situ Detection and Tracking of Geohazards: 4 years of landslides and volcanoes studies in the Kivu Basin. *Abstract, 13 November 2018, Belgian Earth Observation Day 2018 2.0, Barvaux Condroz, Belgium.*

Geirsson, H., **N. d'Oreye**, F. Albino, B. Smets and F. Kervyn (2018). Volcano-tectonic deformation in the Kivu Region, Central Africa, observed by continuous GNSS observations of the Kivu Geodetic Network (KivuGNet) and InSAR time series analysis. *Abstract, Cities on Volcanoes 10, 3-7 September 2018, Naples, Italy.*

Geirsson, H., **N. d'Oreye**, A. Nobile, B. Smets, N. Mashagiro and F. Kervyn (2018). Volcano-tectonic deformation in the Kivu Region, Central Africa, observed by continuous GNSS observations of the Kivu Geodetic Network (KivuGNet) and InSAR time series analysis *Abstract, Grande Conférence sur la Géologie du Congo, October 24-25 2018, Kinshasa, Democratic Republic of Congo.*

Johnson, J.B., L.M. Watson, K. Kim, J.L. Palma, J.F. Anderson, E.M. Dunham, **N. d'Oreye**, **J. Barrière**, B. Smets, F. Kervyn, **A. Oth**, N. Turner, B. Houghton, A. Cannata, L. Spina, D. Morgavi, M.C. Ruiz, H.D. Ortiz, P. Ramon, G. Viracucha, M. Almeida (2018). Decoupling the volcano Infrasound source from the crater acoustic response *Abstract, Cities on Volcanoes 10, 3-7 September 2018, Naples, Italy.*

Libert, L., **D. Derauw**, **N. d'Oreye**, A. Orban and C. Barbier (2018). On the characterization of frequency-persistent scatterers in Split-Band Interferometry *Abstract, International Geoscience and Remote Sensing Symposium (IGARSS 2018), July 22-27 2018, Valencia, Spain.*

Nobile, A., H. Geirsson, B. Smets, J. Subira, **N. d'Oreye** and F. Kervyn (2018). InSAR and GPS ground deformation along the Kivu segment of the East African Rift during the 2011-2012 Nyamulagira eruption *Abstract, European Geosciences Union General Assembly 2018, April 7-12 2018.*

Oth, A., **J. Barrière**, **N. d'Oreye**, G. Mavonga and F. Kervyn (2018). The broadband seismic network KivuSNet in the Virunga Volcanic Province (D.R. Congo): seismicity catalogues and new fundamental seismological models *Abstract, Cities on Volcanoes 10, 3-7 September 2018, Naples, Italy.*

Oth, A., **J. Barrière**, **N. d'Oreye**, G. Mavonga and F. Kervyn (2018). The broadband seismic network KivuSNet in the Virunga Volcanic Province (Democratic Republic of the Congo): seismicity catalogues and fundamental seismological models after more than 2 years of continuous operation *Abstract, European Geosciences Union General Assembly 2018, April 7-12 2018.*

Oth, A., **J. Barrière**, **N. d'Oreye**, G. Mavonga and F. Kervyn (2018). The broadband seismic network KivuSNet in the Virunga Volcanic Province (D.R. Congo): seismicity catalogues and new fundamental seismological models *Abstract, Seismological Society of America (SSA) Annual Meeting, 14-17 May 2018, Miami, USA.*

Oth, A., **J. Barrière**, **N. d'Oreye**, G. Mavonga and F. Kervyn (2018). The broadband seismic network KivuSNet in the Virunga Volcanic Province (Democratic Republic of the Congo): seismicity catalogues and fundamental seismological models after more than 2 years of continuous operation *Abstract, General Assembly of the European Seismological Commission 2018, September 2-7 2018, Valetta, Malta.*

Oth, A., **J. Barrière**, **N. d'Oreye**, G. Mavonga and F. Kervyn(2018). The broadband seismic network KivuSNet in the Virunga Volcanic Province (Democratic Republic of the Congo). *Abstract, Grande Conférence sur la Géologie du Congo, October 24-25 2018, Kinshasa, Democratic Republic of Congo.*

Oth, A., **J. Barrière**, **N. d'Oreye**, N. Mashagiro, J. Subira, B. Smets, and F. Kervyn (2018).The broadband seismic network KivuSNet in the Virunga Volcanic Province (D.R. Congo) developed in the context of the RESIST project. *15 June 2018: Seminar at ISTerre, Univ. Savoie Mont-Blanc, Bourget-du-Lac, France.*

Smets, B., C. Wauthier, A. Dille, R. Paris, D. Samyn, **N. d'Oreye** and F. Kervyn (2018). Monitoring ground deformation and lava accumulation in volcanic craters using UAS image acquisitions and 4D photogrammetry *Abstract, AGU 10-14 December 2018, San Francisco, California, USA.*

Smets, B., M. Syavulisembo, C. Michellier, **N. d'Oreye** and F. Kervyn (2018). Drone-based acquisition and SfM-MVS Photogrammetry as revolutions to study volcanoes and map the related hazards in complex tropical environment *Abstract, European Geosciences Union General Assembly 2018, April 7-12 2018.*

Smets, B., L. Steyaert, C. Michellier, A.M. Syavulisembo, G. Mungunga, **J. Barrière**, **N. d'Oreye** and F. Kervyn (2018). Significant improvements provided by SfM-MVS photogrammetry for the study of active volcanism and related hazards and risks in the Virunga Volcanic Province *Abstract, 6th Int. Geologica Belgica Meeting, 12-14 September 2018,* Leuven, Belgium.

Smets, B., C. Michellier, A.M. Syavulisembo, G. Munganga, **N. d'Oreye**, F. Kervyn (2018). Very high-resolution imaging of the city of Goma (North Kivu, D.R. Congo) using SfM-MVS Photogrammetry *Abstract, International Geoscience and Remote Sensing Symposium (IGARSS 2018), July 22-27 2018, Valencia, Spain.*

MEETING ATTENDANCE, FIELD MISSIONS, WORK VISITS

Adrien Oth

- Seismology of the Americas, SSA & LASC Joint Meeting, Miami, USA, 14-17 May
- Seminar talk at ISTerre Chambéry, France, 14-15 June
- European Seismological Commission (ESC) General Assembly 2017 General Assembly, Kobe, Japan, 2-7 September
- BMBF (Bundesministerium for Bildung unf Forschung) reviewer panel meeting, Berlin, Germany, 25-26 October
- EUR-OPA Major Hazards Agreement Meeting of Directors, Zagreb, Croatia, 6-7 November
- 1st GITEC Generalized Inversion Benchmark Group Meeting, Cadarache, France, 5-6 December
- Work visits & Visitors at ECGS:
    - Visit of student L. Munoz (University College London) at ECGS, 3 April
    - Work visit of T. Camelbeeck & T. Lecocq (Royal Observatory of Belgium) at ECGS, 23 April
    - RESIST Steering Committee Meeting, ECGS, 25-26 April
    - Visit of Dr. Kevin Mayeda (University of California, Berkeley), 11 June
    - Visit at University of Kaiserslautern for potential project InnoRisk, 16 November

Nicolas d'Oreye

- Belgian Earth Observation Day 2018, Beersel, Belgium, 30 January
- Field mission to D.R. Congo (Goma) & Rwanda (Kigali/Gisenyi), 24 February - 8 March
- Luxembourg Earth Observation and Integrated Applications Day, Mondorf, Luxembourg, 19 April
- Cities on Volcanoes 10, Napoli, Italy, 2-7 September
- Field mission to D.R. Congo (Goma) & Rwanda (Kigali/Gisenyi), 6-12 October
- Belgian Earth Observation Day 2018 2.0, Barvaux, Belgium, 13 November
- Work visits & Visitors at ECGS:
    - Visit at Service Géologique de Belgique for installation of MSBAS and mass processing chain, 2 February
    - Work visits at Musée Royal d'Afrique Centrale (MRAC), Belgium, 20 February, 13 June, 25 June, 17 September, 21 September
    - Project stay in context of SMIPP project of D. Derauw, 15 March – 15 July
    - "Stage découverte" of student Elas Blond-Hanten (2e BC SportLycée), 19-23 March
    - Work visit of B. Smets (MRAC) at ECGS, 18 April
    - Work visit of T. Camelbeeck (Royal Observatory of Belgium) at ECGS, 23 April
    - RESIST Steering Committee Meeting, ECGS, 25-26 April
    - Work visit at Centre Spatial de Liège for projects SMIPP and MUZUBI and PhD supervision of L. Libert, 18 June
    - Work visit of A. Dille (MRAC) at ECGS in frame of RESIST project, 6-17 August
    - Master thesis defense of J. Subira, Université de Liège, 10 September
    - Work visit of S. Samsonov (NRCan) for development of MSBAS 3D, 9-17 November
    - Jury membership at PhD defense of L. Libert, Université de Liège, Belgium, 21 November
    - Work visit of D. Derauw (Centre Spatial de Liège), 3-4 December

Julien Barrière

- Cities on Volcanoes 10, Napoli, Italy, 2-7 September
- Seminar talk at ISTerre Chambéry, France, 14-15 June
- Work visits & Visitors at ECGS:
  - RESIST Steering Committee Meeting, ECGS, 25-26 April
  - Master thesis defense of J. Subira, Université de Liège, 10 September
  - Work visit of T. Camelbeeck & T. Lecocq (Royal Observatory of Belgium) at ECGS, 23 April

HONOURS, MENTORSHIPS & SCIENTIFIC COMMUNITY SERVICE

Adrien Oth

- **Executive Committee Member** of European Seismological Commission (ESC)
- European Seismological Commission (ESC) **Titular Member** for Luxembourg
- International Association of Seismology and Physics of the Earth's Interior (IASPEI) **National Correspondent** for Luxembourg
- Member of the **Management Committee of COST Action ES1401**
- **Associate Editor** of *Bulletin of the Seismological Society of America* (November 2017 – present)
- **Editor** of *Pure and Applied Geophysics* (December 2014 – present)
- **Mentorships**
  - Josué Subira (Master student, Université de Liège)
- **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*
- **Mentorships**
  - Ludivine Libert (PhD student, Université de Liège, RESIST project)
  - Josué Subira (Master student, Université de Liège)
- 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 *European Space Agency, Journal of African Earth Sciences, Lake Kivu Monitoring Programme, Geophy. Res. Lett., Remote Sensing*
- **Member** of American Geophysical Union
- **Member** of European Geosciences Union
- **Member** of Academy of Sciences of Luxembourg

Julien Barrière

- **Member** of American Geophysical Union and European Geosciences Union
- **Mentorships**
  - Josué Subira (Master student, Université de Liège)

OUTREACH ACTIVITIES

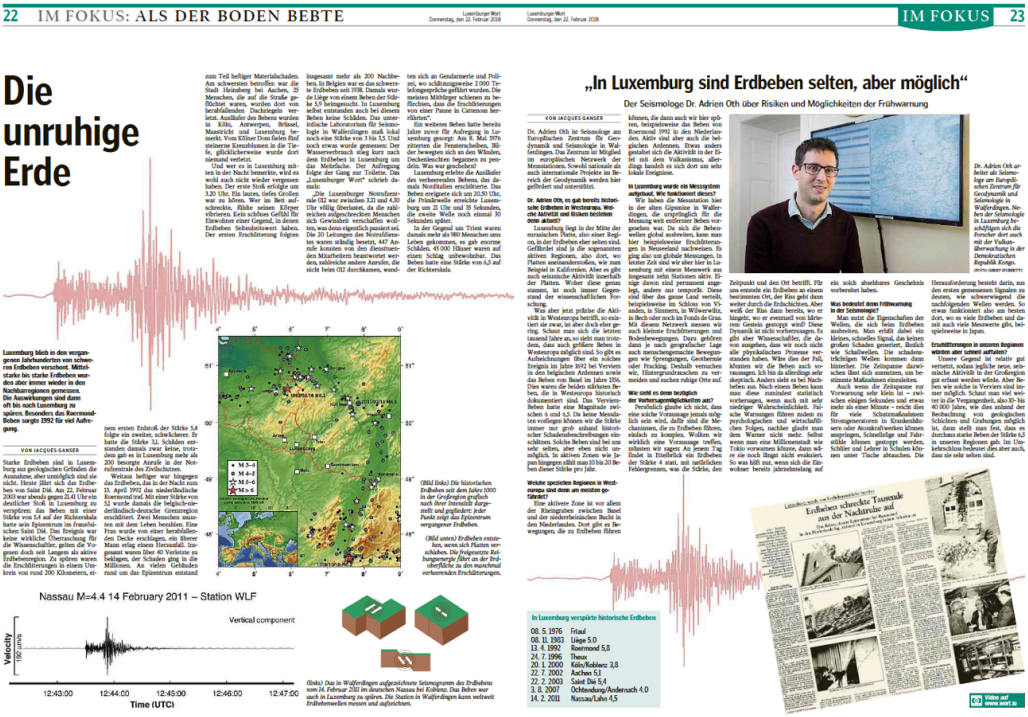

Figure 22: Article in “Luxemburger Wort”, 22 February 2018.

- **Article in “Luxemburger Wort”**, 22 February 2018, titled “Als der Boden bebte“, including interview with A. Oth.
- **Article in “Pannewippchen”** (n 123/2018) “Fuerschung am Natur Musée, Geophysik“ featuring N. d’Oreye.
- Participation with scientists from Royal Museum for Central Africa in a documentary by PBS “**Volcano on Fire, Season 45, episode 10: Climb into the Crater of Nyiragongo”** broadcasted in the USA on television channel NOVA on 19 September 2018.

  See video here:
  https://rutube.ru/video/8a03c8b546296a2e6da5a28521af0362/?ref=search
- Participation with scientists from Royal Museum for Central Africa in a documentary by PBS France Télévision “**Nyiragongo, voyage au coeur du volcan**” broadcasted on the French TV channel “La 5” on 20 September 2018.

  See video here: https://www.dailymotion.com/video/x6u0268

  These two documentaries represent a complement to the two episodes of “**Expedition Volcano**”, which were broadcasted by the BBC in 2017.

  See episode one here: https://www.youtube.com/watch?v=Djn-Ph4zetA

  An international version will follow.
- Contribution of N. d’Oreye to the artistic performance “**The Liquid Earth”** by Caecilia Tripp (images et videos of Nyiragongo volcano and transformation of seismic waves into the audible range). Vernissage 15 March 2018, Annexes du château de Bourglinster, Luxembourg.
- Publication of an article titled “Sentinel data support study of volcanoes and landslides in Africa” on website of ESA in the column “**Sentinel success story”.**
- Maintenance of a web site dedicated to the monitoring activities and studies of the Virunga volcanoes: www.virunga-volcanoes.org