Study and Monitoring of the Virunga Volcanoes: Long-Term Involvement of Belgium and Grand-Duchy of Luxembourg

Etude et Surveillance des Volcans des Virunga: Implication Long-Terme de la Belgique et du Grand-Duché du Luxembourg

Studie en het Toezicht op de Virunga Vulkanen: Betrokkenheid op Lange Termijn van België en Groothertogdom Luxembourg

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Abstract:
Two of the most active African volcanoes, i.e., Nyiragongo and Nyamulagira, are located in the region of Goma (North Kivu, D.R. Congo). These volcanoes are of both scientific and societal importance, as they represent an ideal place to study volcanism associated with extensional setting, while they seriously threaten a densely populated region of ~1 million inhabitants. Since 2006, Belgian and Luxembourgian scientists have developed scientific activities ranging from fundamental and applied research to local capacity building and knowledge transfer, and aim to answer as best and fully as possible to the tackled environmental issue. The present article describes this long-term investment, including the followed strategy and its complexity due to the unstable socio-political context and the hostile natural environment. After 12 years of activities, the Belgian-Luxembourgian (BeLux) approach appears fruitful, but remains uncertain in terms of sustainability.

Résumé:

Deux des volcans les plus actifs d’Afrique, le Nyiragongo et le Nyamulagira, sont situés dans la région de Goma (Nord Kivu, R.D. Congo). Ces volcans sont d’une grande importance à la fois scientifique et sociétale, car ils représentent un endroit idéal pour étudier le volcanisme associé aux zones d’extension, tandis qu’ils sont aussi une menace sérieuse pour cette région densément peuplée (~1 million d’habitants). Depuis 2006, des scientifiques belges et luxembourgeois développent des activités scientifiques incluant des travaux de recherche fondamentale et appliquée, des actions de renforcement des capacités locales et de transfert de connaissances, et visant à répondre de manière la plus adéquate et complète possible à la problématique environnementale que représentent ces volcans. Le présent article décrit cet investissement à long-terme, dont la stratégie suivie et sa complexité liée au contexte socio-politique instable et l’environnement naturel hostile. Après 12 ans d’activité, l’approche belgo-luxembourgeoise (BeLux) apparaît fructueuse, mais reste incertaine au niveau de sa durabilité.

Samenvatting:
Twee van de meest actieve Afrikaanse vulkanen, Nyiragongo en Nyamulagira, bevinden zich in de regio van Goma (Noord-Kivu, D.R. Congo). Deze vulkanen zijn van zowel wetenschappelijk als maatschappelijk belang, omdat ze een ideale plek vormen om vulkanisme te bestuderen die verband houden met extensieve omgeving, terwijl ze de dichtbevolkte (~ 1 miljoen inwoners) Goma regio ernstig bedreigen. Sinds 2006 hebben Belgische en Luxemburgse wetenschappers wetenschappelijke activiteiten ontwikkeld, gaande van fundamenteel en toegepast onderzoek tot lokale capaciteitsopbouw en kennisoverdracht. Dit artikel beschrijft deze investering op lange termijn, met inbegrip van de gevolgde strategie en de complexiteit ervan als gevolg van de onstabiele sociaal-politieke context en de vijandige natuurlijke omgeving. Na 12 jaar van activiteiten lijkt de Belgisch-Luxemburgse (BeLux) aanpak vruchtbaar, maar blijft onzeker op het vlak van duurzaamheid.

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1. Introduction

The East African Rift System (EARS) is often mentioned as the modern archetype for rifting and continental break-up (Calais et al., 2006), showing the complex interaction between rift faults, magmatism and pre-existing structures of the basement. It is also a key place to study the relationship between alkaline volcanism, carbonatites, kimberlites, rifting and mantle plumes (Woolley, 2001). From the societal point of view, the EARS is a place particularly prone to risks associated with geological hazards (i.e., earthquakes, mass movements, volcanism). The vulnerability of the population to these hazards largely depends on the complex socio-economic context and is deepened by the political situation of the developing countries crossed by the EARS.

Paradoxically to the above-mentioned high scientific and societal importance, the study and understanding of the EARS and the associated natural hazards remain relatively limited. First field observations and scientific investigations started with the European explorations of the African continent, during the XIXth Century. But, the combination of poor field accessibility, limited local scientific capacities and missing infrastructures makes geological investigations complex. As highlighted by Kervyn et al. (2007), remote sensing offers to some extend a particularly relevant alternative, but it cannot replace field observations and measurements, as it rather represents a complementary set of techniques.

The Virunga Volcanic Province (VVP), in the western branch of the EARS, hosts two of the most active volcanoes of Africa, i.e., Nyiragongo and Nyamulagira (North Kivu, Democratic Republic of Congo), which are the most western volcanoes of the VVP, both currently hold an active lava lake; the Nyiragongo persistent lava lake being the largest on Earth, with a diameter of ~250 m. As Nyamulagira is located farther in the Virunga National Park, its lava flows rarely reach urbanized areas, but they regularly burn extensive vegetated surfaces of that protected area. In contrast, those from Nyiragongo are feared by the population living at foot of the volcano; this population being mostly concentrated in the city of Goma (775.806 +/- 115.284 inhabitants in 2015, according to the demographic survey conducted during the GeoRisCA project; http://georisca.africamuseum.be), located about 15 km south of the Nyiragongo main crater (Fig. 1). The Nyiragongo flank eruptions, in 1977 and 2002, indeed triggered humanitarian and socio-economic disasters, with tens of people killed and hundreds injured (Tazieff, 1977; Pottier, 1978; Cocheme and Vellutini, 1979; Allard et al., 2002; Baxter and Ancia, 2002; Tedesco et al., 2002; Michellier, 2017). In January 2002, the lava flows destroyed 10-13 % of Goma, leaving about 120,000 persons homeless and seriously affecting the regional economy (Allard et al., 2002; Baxter and Ancia, 2002; Tedesco et al., 2002).

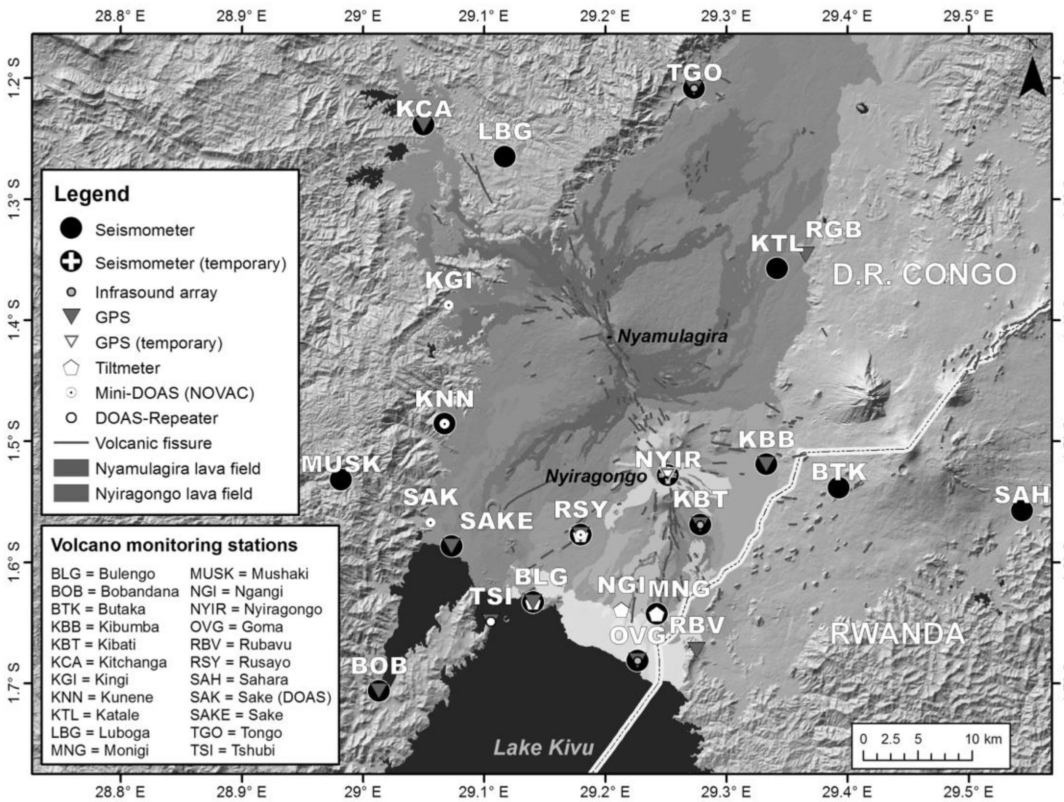

Figure 1: Map of Nyiragongo and Nyamulagira volcanoes with the distribution of the volcano monitoring networks maintained by the Goma Volcano Observatory (GVO), with the support of the international partners.

In addition to the lava flow hazard, both Nyiragongo and Nyamulagira emit SO_2-rich acidic gas plumes. These gas plumes cause air and water pollution and have health and environmental consequences (Vaselli et al., 2010; van Overbeke et al., 2010; Cuoco et al., 2013; Balagizi et al., 2017). Another related hazard associated with the Virunga volcanoes is the presence of "Mazuku", those areas of diffuse CO_2 degassing, where the gas concentrates to lethal levels, frequently killing unaware people along the northern shoreline of Lake Kivu (Verschuren, 1965; Vaselli et al., 2004; Smets et al., 2010).

All these volcanic hazards, which threaten a population roughly estimated to one million persons, are located in a region recurrently affected by periods of political instability and armed conflicts since the 1990s. In such context, the population constantly suffers from extreme poverty, poor education, different kinds of violence, deliquescent infrastructures, slow socio-economic development and recurrent health issues. These difficulties consequently place the volcanic threats far from their main priorities.

Because of the major scientific and societal interests in studying such a very active volcanic zone, the Royal Museum for Central Africa (RMCA, Belgium), the National Museum of Natural History (NMNH, Luxembourg) and the European Center for Geodynamics and Seismology (ECGS, Luxembourg) developed, since 2006, scientific activities in the Virunga Volcanic Province (VVP) with the long-term perspective of providing answers to the existing volcanic risk issues, through scientific research activities, the development of the local expertise and the creation of tools, products and knowledge that contribute to improve the volcanic risk management.

In this work, we provide a general description of the followed approach and methodologies developed by this BeLux team to address these challenging objectives. We also illustrate some key achievements in terms of fundamental research, volcano monitoring and risk assessment, made during these past 12 years of scientific implication. The references to the related publications are provided to allow the reader to go into the details on these key results.

2. Long-term policy and applied methodologies

In the following section, we explain the general approach followed by the BeLux scientific team (Section 2.1) and describe the importance given to the remote sensing approach (Section 2.2), the local expertise (Section 2.3), the role of each partners in the study and monitoring of the Virunga volcanoes (Section 2.4) and the need to sustain the developed initiatives in the frame of time-limited research projects (Section 2.5).

2.1 General approach

Environmental systems, including those exposed to natural hazards, are very complex. Despite extensive research activities during the last decades, our understanding of these systems remains relatively limited. In such a context, geoscientists play a key role in addressing the growing environmental issues that the society has to face. They use to deal with different time scales (i.e., human versus geological time scale), which are important to accurately assess both short- and long-term natural hazards. Human scientists, on their side, are studying how humans are affected and interact with the environmental issues. Together, geoscientists and human scientists can better assess and characterize the risks associated with natural hazards, using different types, quantity and quality of data and information. This way of tackling the environmental issues is the one followed by the BeLux scientific team.

In the specific case of Nyiragongo and Nyamulagira volcanoes, the BeLux scientists are indeed tackling the volcanic risk issues through different types of actions, which contribute to improve, as best and as fully as possible, the volcanic risk management in North Kivu.
The approach is multifold and consist in:

- Increasing the scientific knowledge about the volcanoes, their geologic context and the underlying processes, the related volcanic hazards and their impacts, and the vulnerability of the population facing these volcanic hazards;
- Improving the monitoring of volcanoes with complementary classical and innovative space- and ground-based techniques;
- Increasing the existing local expertise in performing scientific research, volcano monitoring and hazard/vulnerability/risk assessments;
- Developing new and adapted tools, products and knowledge to improve the volcanic risk management.

In practice, the implementation in the VVP of each of these activities is complicated by a wide range of reasons related to the socio-economic and political context, the availability of basic infrastructures (i.e., power supply, internet access, roads, etc.) and the hostile natural environment (e.g., fast-growing and dense vegetation, humidity, frequent lightning strikes, acidic volcanic gases, fauna, etc.). As a consequence, research activities require a lot of time, energy, diplomacy, creativity and suitable funding to be developed. Moreover, most of the time, classical techniques to study and monitor volcanoes are found inappropriate or need to be first iteratively adapted to the local context before being operational.

These adaptations are of two kinds. On the one hand, they can be technical. They mostly concern the communication with monitoring stations, the data transfer and storage, the protection of instruments against lightning strikes, acidic gases, magnetic dust, rodents, looting and sabotage, and the choice of safe locations for the monitoring instruments. On the other hand, they can be at the level of the level of the methodology selected by the scientist to obtain the required observations and measurements

An example of this second type of adaptation is the methodology developed to assess the vulnerability of the population in eastern Congo. Scientists classically use population-related data such as census and socio-economic data. In the studied area, none of these data exist, at least with sufficient quality, completeness, or homogeneity required for such assessment. Researchers working on the vulnerability and risks aspects had to fully create these datasets from scratch, including the delimitation of administrative boundaries, by intense field works and household surveys.

2.2 The key role of adapted remote sensing techniques

This need of methodological adaptation is also well illustrated with the use of satellite remote sensing in the VVP. Indeed, optical satellite remote sensing is often of limited use because of the frequent cloud cover, and Synthetic Aperture Radar (SAR), which allows circumventing this problem and seeing the ground surface through the clouds, is of limited use for SAR interferometry (InSAR) due to the loss of coherence created by the tropical vegetation, which restrict the observations and measurements to areas with non-changing land cover. Hence, the encountered limitations have to be either compensated by field or airborne techniques, or innovative processing solutions must be found to partly reduce them.

The best example of adaptation allowing the scientists to make use of the "conventional" techniques is the development of a new dense InSAR time-series technique (i.e., MSBAS; Samsonov and d'Oreye, 2012), which allows mixing images from different orbits and satellites in order to compensate the spatial limitations by a better temporal coverage.

Remote sensing can also compensate field limitations. During the January 2010 eruption of Nyamulagira, for example, radar imagery helped locate the eruptive sites and allowed the detection of lava flows in the summit caldera, while field observations by helicopter were made difficult by the weather conditions (Smets et al., 2014).

InSAR remote sensing plays a key role for the monitoring of the Virunga volcanoes. The detection and monitoring by satellite of ground deformations related to the 2002 eruption at Nyiragongo (Wauthier et al., 2012) provided the first detailed information about the volcanic structure and related mechanisms, while state-of-the-art ground-based geodetic measurements were not available yet. These remote sensing studies improved our knowledge on eruption mechanisms in extensional setting. They also allowed determining how the monitoring techniques and infrastructures should be further developed and adapted, taking into account the combined advantage of ground- and space-borne methods and the fact that field accessibility is generally very limited and may vary through time.

2.3 Importance of the local expertise

Developing knowledge in that specific environment cannot be genuinely envisaged without contributing to the growth of the local expertise. Scientists from local research institutions are suffering from years of political instability, budget cuts, and are victims of poor quality of academic formation. Training of the involved researchers to the implemented modern surveys and monitoring techniques is therefore required in parallel to the research activities *sensu stricto*. Their involvement in interpretation processes also make them aware about the importance of maintaining the monitoring equipment and having continuous data acquisitions.

Whereas such approach appears to be rarely applied, we consider that aspect as a pillar for the local appropriation of the developed techniques and the assimilation of the scientific results and their impact on sustainable development. Moreover, training not only addresses the way the geological or population data are collected, but also concerns the ability of the political authorities to properly access and understand the scientific message so that they have the capacity to take the most appropriate decisions. For that reason, it is essential that scientists consider learning from all the stakeholders and constantly maintaining the dialog with them.

2.4 From the study to the monitoring: a subtle and critical boundary

The questions about the limit between volcano study and volcano monitoring and the involvement of the BeLux team in the real-time/everyday volcano monitoring come up recurrently to consortium. The answer is actually subtle and sensitive. The data required by the scientists to study the volcanoes through their recent eruptive activity are indeed essentially the same as those required for volcano monitoring. However, the way these data are collected (i.e., the need or not of a real-time transmission), processed and analyzed makes the difference. On the one hand, it is obvious that the scientists from the Goma Volcano Observatory (GVO) have the clear institutional mandate to ensure the monitoring activity of Nyiragongo and Nyamulagira volcanoes, whereas international partners from Belgium and Luxemburg are focused on research and expertise sharing. On the other hand, in practice, BeLux scientists are closely collaborating with the Congolese scientists of the GVO to help them maintain the instrument network and interpret the scientific data. The architecture of the relevant monitoring networks of scientific instruments has been designed to ensure that both sides have access to the exactly same datasets, in real time. This allows “e-discussions” of the observations between the scientific partners and provides the GVO with more information on the volcanic activity, which improve its communication with the Civil Protection and the local government in terms of hazard assessment and management. Another advantage of the real-time transmission is the possibility to immediately and remotely detect any problem or failure in the monitoring system, allowing rapid response and, hence, minimizing the loss of data. In conclusion, if the mandates are different and identified for each group, the local and BeLux scientists actually contribute, directly or indirectly, to both mandates.

2.5 From the project time frame to the sustainable use of the results

As a result of the specific context and its complexity, the cost/result ratio is drastically higher than for similar works performed in more developed countries. The mandatory long-term vision has an impact on the architecture, time frame, and costs and budget schemes of the project. This often contrasts with the project-based funding generally observed in classical scientific research projects, for two main reasons. Firstly, developing high-quality monitoring takes time and the volcanic activity occurs at different time scales. Hence, it is difficult to study active volcanoes within a single 2-4-year-long project. Secondly, studying active volcanoes and assessing their respective hazards and risks cover different disciplines and require different types of action. Therefore, it is, for example, hard to explain the relevance of some logistical costs of equipment maintenance or replacement, or the necessity to support intense training courses, with funding initially dedicated to fundamental research, and *vice versa*. It is also hard to justify the time-consuming, but mandatory, diplomatic tasks of maintaining in the long-term the network of contacts with all the stakeholders, whose the turn-over is rapid and, of course, independent of the research project’s time frame. Similarly, it is difficult to maintain monitoring facilities, tools, and protocols developed in the frame of a specific time-limited project, beyond the end of that project. In that perspective and although the respective roles of the scientists and the cooperation agencies are generally well defined, the setup of a collaborative coordinated support to guarantee a sustainable high-quality volcano monitoring structure has not been reached so far.

To summarize, the various types of activity that are performed range from pure fundamental research (understanding natural processes, methodological developments) to applied activities (volcano monitoring), or the setup of training course sessions. Up to now, the financial support was obtained from the Belgian Science Policy Office (BELSPO), the Luxembourgian "Fond National de la Recherche" (FNR) and the Belgian Development Cooperation agency, through isolated yet complementary actions. However, the monitoring of Nyiragongo and Nyamulagira and its local appropriation shouldn't solely rely on research and Belgian cooperation funding, and the time has come today to share that responsibility with all the actors, including the government of the DRC, each of them contributing to a common objective, which is the mitigation of the volcanic risk for the population.

3. Key results

3.1 Understanding volcanic processes and associated risks

In term of fundamental research, great advances have been made in the Virunga region to understand the volcanic processes, and contextualize some concepts of risk assessment. The study of the known eruption history highlighted, for example, that the gravitational stress field of a main volcanic edifice can be a stronger influencing factor than rift faults for the location of flank eruptions (Smets et al., 2015). Ground deformation modelling also suggested that magmatic intrusions actively participate to the rift extension (Wauthier et al., 2012) and that large intrusions may also trigger tectonic earthquakes (Wauthier et al., 2015). On a more conceptual aspect and as mentioned in Section 2.1, Michellier et al. (2016) highlighted the importance of adapting the definition of vulnerability to the local context based on data availability and reliability, and developing specific methodologies to collect additional data in the studied area.

3.2 Monitoring the volcanic activity

Important steps have been made for volcano monitoring in the VVP, using both ground- and space-based techniques. Thanks to the new InSAR time-series technique developed by Samsonov and d'Oreye (2012), ground deformation precursors were, *a posteriori*, detected up to three weeks prior to the onset of the January 2010 eruption of Nyamulagira, while classical seismic precursors appeared two hours before the eruption (Smets et al., 2014). This observation offers new perspectives for the early detection of upcoming eruptions in the VVP, as ground deformation also provides information on the location of the future eruptive site(s). The 2010 eruption of Nyamulagira also highlighted the importance of a multidisciplinary monitoring of volcanoes, as both precursors and eruption stages were translated by changes in seismic, geodetic, gas and thermal data.

From a ground-based perspective, geodetic, broadband seismic and infrasound networks have been developed around Nyiragongo and Nyamulagira (Fig. 1; Geirsson et al., 2017; Oth et al., 2016). Installed instruments are restricted to safe places guarded by sentinels or into military camps of the United Nations. As a consequence, their distribution is not always ideal from a scientific or monitoring point of view, but efforts have been made to continuously develop the networks to efficiently cover the active volcanic zone. Today, these networks, composed of more than 15 permanent broadband seismic stations and geodetic GNSS stations, are among the densest of Africa. The recorded data are stored locally, and transferred in real-time to both Goma and Luxembourg. GNSS data provide complementary information on ground deformation monitored by InSAR, which helps detect and model the magmatic source(s) of eruptive events, and better interpret movements related to the volcano-tectonic activity (Smets et al., 2014; Geirsson et al., 2016; Ji et al., 2016). The broadband seismometers and infrasound arrays offer a new window on the volcanic processes involved in the VVP, showing a better and accurate distribution of the seismic activity. Seismic data show for example variations related to the lava lake outgassing activity (Barrière et al., 2017). On a short-term perspective, seismic data will also allow calculating a better local velocity model, which will improve the location of seismic events beneath the active volcanoes. In addition, ground-based stereo-photogrammetric and space-based SAR techniques have been tested on Nyiragongo to measure and monitor the vertical variations of the lava lake level (Smets et al., 2016; Smets, 2016). These direct measurements of the volcanic activity are indeed crucial for Nyiragongo, as persistent lava lake activity may translate pressure and volume changes in the upper magma plumbing system (e.g., Patrick et al. 2015). Hopefully, these tests might lead, in the future, to the development of a permanent camera monitoring system.

The daily maintenance of the ground-based monitoring instruments is managed by the GVO staff, which is totally able to manage the common technical issues encountered with such kind of instruments. If the GVO has gain a large autonomy in managing the developed instrument networks, they are still dependent of the BeLux partners for the replacement of spare parts and the improvement of the networks, by lack of local budgets for that.

3.3 Creating databases and deliverables

Downstream of these activities, the BeLux scientific team has also produced geodatabases, maps and tools that aim to improve the volcanic risk assessment and help decision making by the local stakeholders. First maps and impact assessment were performed in the framework of the early GORISK project (2007-2010; http://www.ecgs.lu/gorisk/projects/the-gorisk-project/), but major advances have been made recently, thanks to the multidisciplinary GeoRisCA project (2012-2017; http://georisca.africamuseum.be/), through the creation of several thematic maps (geology, vulnerability of the population, population density, volcanic hazards and risks), and the development of a lava flow simulation model working within the open-source QGIS software (Mossoux et al., 2016). A web platform has also been created to visualize the spatially integrated monitoring data on the same timeline (Fulgen, 2016). The produced tools and maps are now under implementation at the GVO, the Geographic Institute of Congo (IGC) and the Civil Protection of Goma, to improve urban and contingency planning in the Goma region.

3.4 Training and cooperation

As far as training is concerned, researchers from local partner institutions are always associated with field operations during which dedicated training are given on, e.g., instrument installation, maintenance and repair, data collection, data processing and interpretation. Interested and motivated researchers are also implied in the research work and, whenever an opportunity arises, they get support when they apply for academic training in Europe and Africa. When these researchers are granted, they also receive support from the BeLux group or its partners, through the supervision of their master or PhD research. In addition, the RMCA organized, with the funding of the Belgium Cooperation agency, the RGL-GEORISK project (2013-2016), a 3-year program focused on the training of 25 students in various fields related to geological risks. In parallel, two training sessions of 10 to 15 days in seismology and geodesy were organized by the BeLux team, in September 2015 and October 2016, in the frame of the RESIST (http://resist.africamuseum.be/) and GeoRisCA (http://georisca.africamuseum.be) research projects. These training sessions were followed by a dozen of young scientists from the Democratic Republic of Congo, Rwanda and Burundi. Finally, two conferences focused on "Active Volcanism and Continental Rifting" (AVCoR) were organized in November 2007 in Luxembourg, and in November 2013 in Gisenyi (Rwanda). These conferences allowed gathering scientists from Africa, Europe and North America to share and discuss about various topics related to the evolution of the East African rift. These events aimed to stimulate exchanges between scientists, trigger potential national and international collaborations, and provide specific training courses to the participants. In 2013, the AVCoR conference was also focused on fostering interactions between scientists and local stakeholders implied in hazard assessment and risk management. In this second edition, a 3-day training session for 30 participants was given by the Institute of EARTH Sciences *Jaume Almera* (Madrid, Spain), on the use of the VORIS (Felpeto et al., 2007) and HASSET (Sobradelo et al., 2014) tools for both short- and long-term volcanic hazard assessment.

4. Does this long-term investment worth it in terms of research output?

Knowing that 12 years of scientific activities were performed by Belgium and Luxembourg on Nyiragongo and Nyamulagira, it is interesting to question the benefits of such a long-term investment in terms of scientific production.

Since 2006, the scientific knowledge on the two active volcanoes of the VVP has been improved significantly. In the recent years, specific efforts were concentrated on the development of ground-based and space-borne techniques. The telemetered seismic and GNSS networks are paving the ways of exciting discoveries while we are entering in a new era of Earth Observation, with the development of new and various sensors and the creation of satellite constellations, offering multi-scale time series on the studied changing surface. Besides, unpublished works excavated from the RMCA archives have been analyzed to produce the most accurate baseline of physical observations on the two volcanoes (e.g., Smets et al, 2015; Smets, 2016).

Since 2012, the number of scientific publications started increasing to reach competitive levels (Fig. 2). The various sets of collected data and the installed instrument networks indeed boosted the scientific research and the collaboration with other scientists. It is worth underlying that the influence of the AVCoR meetings was different in 2007 and 2013. The first edition of the conference initiated the production of both a high number of conference abstracts in 2007 and a first set of peer-reviewed articles in 2010. The second edition was mostly marked by a higher number of conference abstracts and did no not modify the increasing rate of peer-reviewed publications observed since 2013. (Fig. 2). These observations highlight the gained maturity in the different scientific activities between the two meeting events.

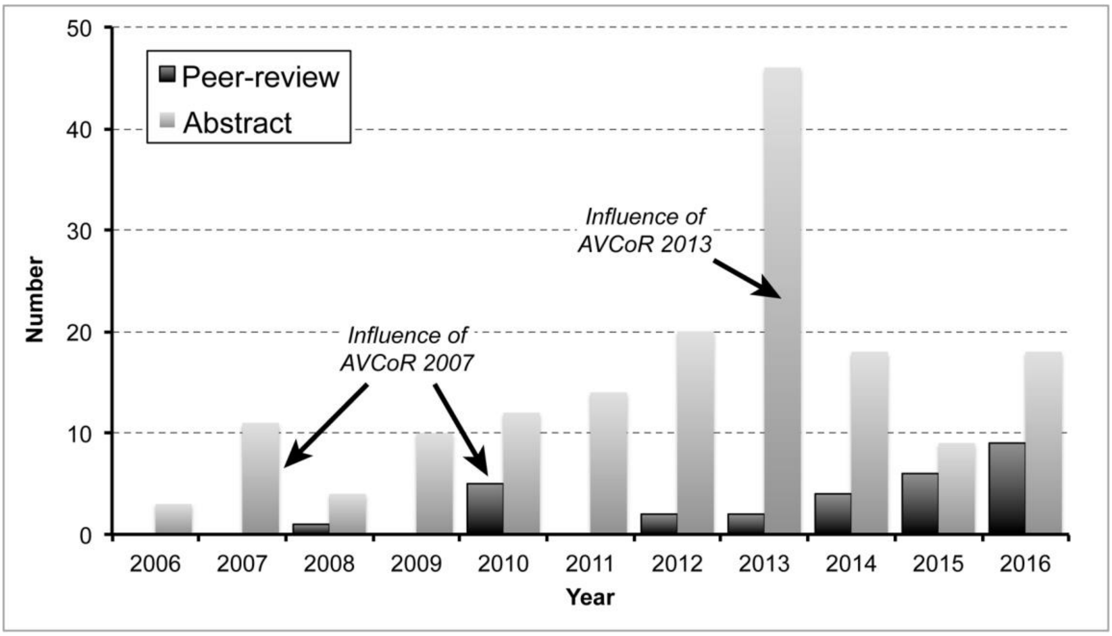

Figure 2: Evolution between 2006 and 2016 of the number of peer-reviewed publications and conference abstracts produced by the scientists of the RMCA, NMNH and ECGS, on the Virunga volcanoes. All publications that imply a working collaboration with the local Congolese partners include these partners as co-authors.

Hence, the major outputs from the BeLux research activities are the multidisciplinary expertise and knowledge in the studied area, the collections of various datasets (ground- and space-based data, GIS data, field data, literature, etc.), the methodological development in remote sensing, instrumentation and data collection, and the production of tools for risk management. If the number of scientific peer-reviewed articles has only reached competitive levels in the past few years, the current state of the followed approach seems to promise better publication rates for the coming years and the development of additional fruitful projects and collaborations.

From the local perspective, the Congolese scientists also increased their publication rate thanks to the installed instrument networks and the training programs developed with the BeLux scientists. As an example, in 2017, a tome of the journal Geo-Eco-Trop (http://www.geoecotrop.be), which represents 10 publications led by Congolese scientists, was dedicated to the research results obtained during a training program provided by a project funded by the Belgian Cooperation (RGL_GEORISK Project, Frame Agreement RMCA-DGD Programme). Such a result shows that the local scientists have gained research skills in parallel to those they have gained in volcano monitoring and instrument maintenance.

In terms of scientific outputs for the local authorities, the hazard, risk and thematic maps produced during the last 3 years are now exploited by the Civil Protection of North Kivu for the development of a regional contingency plan between the

Democratic Republic of Congo and the Republic of Rwanda. The same maps will be used during the revision of the existing Congolese contingency plan of the city of Goma.

5. Conclusions and perspectives

By developing projects ranging from fundamental research to capacity building, the Belgian-Luxembourgian scientific team has built an efficient framework to address the issue that Nyiragongo and Nyamulagira volcanoes represent for the local population, while results from fundamental research also help to tackle key scientific questions about volcanism in extensional setting. The gained scientific knowledge and developed monitoring techniques are used by the GVO and its collaborators to interpret the evolution of the volcanic activity. The number of Congolese scientists with technical skills for the maintenance of the instruments or with MSc and PhD degrees is constantly increasing, and local scientists have also gain skills as independent scientific researchers. Moreover, since 2018, the local stakeholders, including the Civil Protection of North Kivu, have start exploiting the developed maps and tools to improve urban and contingency planning, as well as risk prevention programs.

However, strong limitations threaten the sustainability of this kind of successful approach. Tackling natural risk issue in a tropical, socio-politically unstable environment is indeed very challenging. It requires time to develop the local collaborations, the multidisciplinary and adapted methodologies to answer the targeted issue, and to train a minimum number of persons to cover all aspects of the developed activities. It also requires different types of funding to support at the same time fundamental and applied research, instrument maintenance, data acquisition and management, teaching and training activities, and actions of dissemination of information. The Belgian and Luxembourgian scientists consequently struggle to combine different types of funding, increase the number of collaborators, and transfer as many skills and tools as possible to the local partners. Hence, the strategy is successful as, after 12 years of investment, results are met from research output and local capacity building to volcano monitoring and risk management. Although this strategy has required a lot of time, energy and inventiveness to succeed, we strongly believe it worth it to answer such environmental issues.

Because the competition to get funded for research has strongly increased, especially these past 10 years, and because science funding commonly prioritizes research having a high visibility and a short-term return on investment, it is difficult to maintain such diversified scientific activities focused on a local challenging working area, which require a significant manpower and the maintenance of several existing routine tasks. The time has come to find an appropriate balance between the funding of purely research activities and those dedicated to operations and maintenance of the monitoring structure. The successive research projects have contributed to the setup of mature and operational monitoring tools that must be taken over and capitalized by other relevant mechanisms. This would allow concentrating funding on the development of new research and therefore pursue the optimization of risk reduction processes. That challenge requires the ears and attention of all the stakeholders who must understand the risks to see years of efforts ruined in a very short delay.

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