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

by

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KEYWORDS. — East African Rift; Virunga; Nyiragongo; Nyamulagira; Geophysics; Remote Sensing; Natural Risks.

SUMMARY. — Two of the most active African volcanoes, *i.e.*, Nyiragongo and Nyamulagira, are located in the region of Goma (North Kivu, DR 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 about one 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 respond as best and fully as possible to the tackled environmental issues. The present paper deals with this long-term investment, including the strategy followed and its complexity due to the unstable socio-political context and the hostile natural environment. After twelve years of activities, the Belgian-Luxembourgian (BeLux) approach appears to be successful, but remains uncertain in terms of sustainability.

MOTS-CLÉS. — Rift est-africain; Virunga; Nyiragongo; Nyamulagira; Géophysique; Télédétection; Risques naturels.

RÉSUMÉ. — *Étude et surveillance des volcans des Virunga: implication à long terme de la Belgique et du grand-duché de Luxembourg.* — Deux des volcans les plus actifs d'Afrique, le Nyiragongo et le Nyamulagira, sont situés dans la région de Goma (Nord-Kivu, RD Congo). Ces volcans sont d'une grande importance à la fois scientifique et sociétale, car ils représentent l'endroit idéal pour étudier le volcanisme associé aux zones d'extension, tout en étant une menace sérieuse pour cette région densément peuplée (environ un million d'habitants). Depuis 2006, des scientifiques belges et luxembourgeois dévelop-

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pent des activités incluant des travaux de recherche fondamentale et appliquée, des actions de renforcement des capacités locales et de transfert de connaissances, visant à répondre de la 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 sociopolitique instable et à l'environnement naturel hostile. Après douze ans d'activité, l'approche belgo-luxembourgeoise (BeLux) apparaît fructueuse, mais reste incertaine en termes de durabilité.

Trefwoorden. — Oost-Afrikaanse rift; Virunga; Nyiragongo; Nyamulagira; Geofysica; Teledetectie; Natuurrampen.

Samenvatting. — *Studie en toezicht op de Virunga vulkanen: betrokkenheid op lange termijn van België en het Groothertogdom Luxemburg.* — Twee van de meest actieve Afrikaanse vulkanen, Nyiragongo en Nyamulagira, bevinden zich in de regio van Goma (Noord-Kivu, DR Congo). Deze vulkanen zijn van zowel wetenschappelijk als maatschappelijk belang, omdat ze een ideale plek vormen om vulkanisme te bestuderen en de daarmee gepaard gaande extensieve omgeving, terwijl ze de dichtbevolkte (ongeveer een 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 en die als doel hebben om op de best mogelijke manier de desbetreffende milieukwestie aan te pakken. Dit artikel beschrijft deze langetermijninvestering, met inbegrip van de gevolgde strategie en de complexiteit ervan als gevolg van de onstabiele sociaal-politieke context en de vijandige natuurlijke omgeving. Na twaalf jaar van activiteiten lijkt de Belgisch-Luxemburgse (BeLux) aanpak vruchtbaar, maar blijft hij onzeker op het vlak van duurzaamheid.

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 19th 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 extent 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 of them 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 the foot of the volcano, this population being mostly concentrated in the city of Goma (seven hundred and seventy-six thousand 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, triggered off humanitarian and socio-economic disasters, with tens of people killed and hundreds injured (Tazieff 1977, Pottier 1978, Cocheme & Vellutini 1979, Allard *et al.* 2002, Baxter & Ancia 2002, Tedesco *et al.* 2002, Michellier 2017). In January 2002, the lava flows destroyed 10-13 % of Goma, leaving about one hundred twenty thousand persons homeless and seriously affecting the regional economy (Allard *et al.* 2002, Baxter & Ancia 2002, Tedesco *et al.* 2002).

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 people, 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 interest 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) have 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 local expertise and the creation of tools, products and knowledge that contribute to improve the volcanic risk management.

In this paper, we provide a general description of the approach followed and methodologies developed by this Belgian-Luxembourgian (BeLux) team to address these challenging objectives. We also illustrate some key achievements in terms of fundamental research, volcano monitoring and risk assessment, made over the past twelve 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.

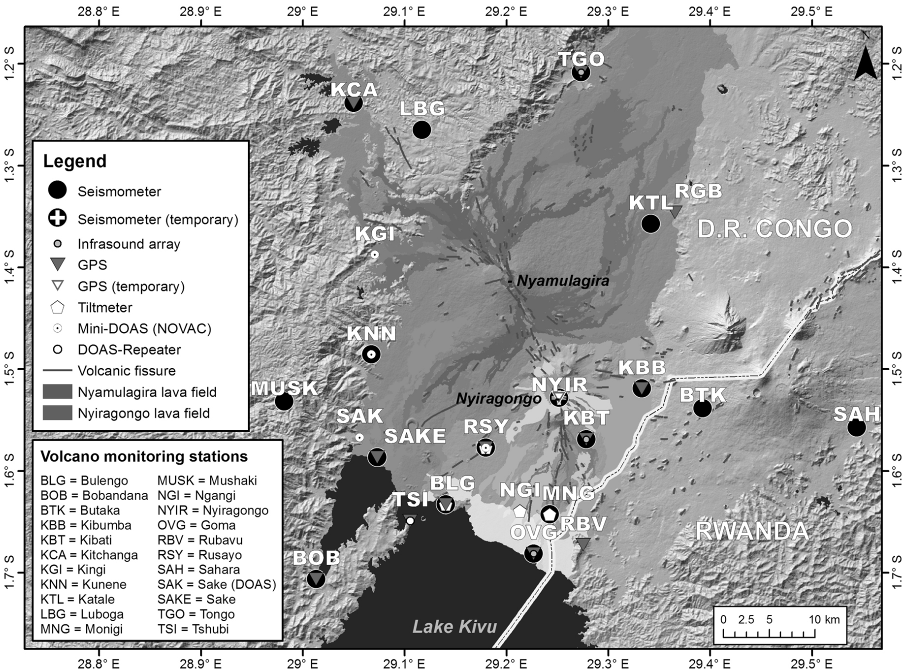

Fig. 1. — Map of Nyiragongo and Nyamulagira volcanoes with the distribution of volcano monitoring networks maintained by the Goma Volcano Observatory (GVO), with the support of international partners.

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 partner in the study and monitoring of the Virunga volcanoes (section 2.4) and the need to sustain the initiatives developed 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 over the last few decades, our understanding of these systems remains relatively limited. In such a context, geoscientists play a key role in addressing the growing environmental issues the society has to face. They are used to dealing 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, for their part, study 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 in fact tackling the volcanic risk issues through different types of action, which contribute to improve, as best and as fully as possible, the volcanic risk management in North Kivu.

The approach is multifold and consists 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 assessment;
- 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 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 study area, none of these data exist, at least with sufficient quality, completeness, or homogeneity required for such assessment. Researchers working on the vulnerability and risk aspects had to fully create these data sets from scratch, including the delimitation of administrative boundaries, by intensive field work 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. In fact, optical satellite remote sensing is often of limited use because of frequent cloud cover, and Synthetic Aperture Radar (SAR), which makes this problem easier to circumvent and the ground surface to see through cloud cover, is of limited use for SAR interferometry (InSAR) due to the loss of coherence created by tropical vegetation, which restricts the observations and measurements to areas with non-changing land cover. Hence, the limitations encountered have to be compensated by field or airborne techniques, or innovative processing solutions must be found to partly reduce them.

The best example of adaptation allowing scientists to make use of the "conventional" techniques is the development of a new dense InSAR time-series technique (*i.e.*, MSBAS; Samsonov & d'Oreye 2012), by which images from different orbits and satellites can be mixed 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 due to weather conditions (Smets *et al.* 2014).

InSAR remote sensing plays a key role in 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 have improved our knowledge on eruption mechanisms in extensional setting. They have also contributed to 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 varies over time.

2.3. Importance of Local Expertise

Developing knowledge in that specific environment cannot be genuinely envisaged without contributing to the growth of local expertise. Scientists from local research institutions are suffering from years of political instability, budget cuts, and are victims of the poor quality of academic formation. Training of researchers involved in the implemented modern surveys and monitoring techniques is therefore required in parallel to the research activities *stricto sensu*. Their involvement in interpretation processes also makes them aware of 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 scientific results and their impact on sustainable development. Moreover, training not only deals with the way the geological or population data are collected, but also concerns the ability of political authorities to properly access and understand the scientific message so that they have the capacity to take the most appropriate decisions. For this reason, it is essential that scientists consider learning from all the stakeholders and constantly maintaining the dialogue with them.

2.4. From Study to 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 the consortium. The answer is actually subtle and sensitive. The data required by scientists to study the volcanoes through their recent eruptive activity are in fact 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 analysed makes the difference. On the one hand, it is obvious that scientists from the Goma Volcano Observatory (GVO) have a clear institutional mandate to ensure the monitoring activity of Nyiragongo and Nyamulagira volcanoes, whereas international partners from Belgium and Luxembourg focus on research and expertise sharing. On the other hand, in practice, BeLux scientists closely collaborate 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 exactly the same data sets, in real time. This allows “e-discussions” of the observations between scientific partners and provides the GVO with more information on volcanic activity, improving its communication with the civil protection and the local government in terms of hazard assessment and management. Another advantage of real-time transmission is the possibility of immediately and remotely detecting any problem or failure in the monitoring system, allowing rapid response and, hence, minimizing data loss. 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 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 cost 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. First, developing high-quality monitoring takes time and volcanic activity occurs at different time scales. Hence, it is difficult to study active volcanoes within a single two-four-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 intensive 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 turnover 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 as part of a specific time-limited project, beyond the end of it. In this perspective and although the respective roles of scientists and cooperation agencies are generally well defined, the set-up of a collaborative coordinated support to guarantee a sustainable high-quality volcano monitoring structure has not been reached so far.

To sum up, the various types of activity performed range from pure fundamental research (understanding natural processes, methodological developments) to applied activities (volcano monitoring), or the set-up of training course sessions. Up to now, financial support has been obtained from the Belgian Science Policy Office (BELSPO), the Luxembourgian *Fonds 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 should not solely rely on research and Belgian cooperation funding, and the time has come today to share that responsibility with all the actors, including the DRC government, each of them contributing to a common objective, which is the mitigation of volcanic risk for the population.

3. Key Results

3.1. Understanding Volcanic Processes and Associated Risks

In terms 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 eruption history has 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 has also suggested that magmatic intrusions actively participate in 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 of developing specific methodologies to collect additional data in the study 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 & 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 resulted in 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 (see 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 fifteen permanent broadband seismic stations and geodetic GNSS stations, are among the densest ones in Africa. The data recorded 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). Broadband seismometers and infrasound arrays offer a new window on the volcanic processes involved in the VVP, showing a better and accurate distribution of seismic activity. Seismic data show, for example, variations related to the lava lake outgassing activity (Barrière *et al.* 2017). From 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 stereophotogrammetric 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 volcanic activity are in fact crucial for Nyiragongo, as persistent lava lake activity may bring about pressure and volume changes in the upper magma plumbing system (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 experienced with such kind of instruments. If the GVO has gained a large autonomy in managing the developed instrument networks, they are still dependent on the BeLux partners for the replacement of spare parts and the improvement of networks, by lack of local budget 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 as part 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, population vulnerability, 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 tools and maps produced are now being implemented 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 is 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 the 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 three-year programme focused on the training of twenty-five students in various fields related to geological risks. In parallel, two training sessions of ten to fifteen days in seismology and geodesy were organized by the BeLux team, in September 2015 and October 2016, as part 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 brought together scientists from Africa, Europe and North America to share and discuss various topics related to the evolution of the East African rift. These events aimed at stimulating exchanges between scientists, building potential national and international collaborations, and providing specific training courses to the participants. In 2013, the AVCoR conference also focused on fostering interactions between scientists and local stakeholders implied in hazard assessment and risk management. In this second edition, a three-day training session for thirty 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. Is this Long-term Investment Worth it in Terms of Research Output?

Knowing that twelve 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 as far as scientific production is concerned.

Since 2006, the scientific knowledge on the two active volcanoes of the VVP has significantly improved. In recent years, specific efforts concentrated on the development of ground-based and space-borne techniques. The telemetered seismic and GNSS networks are paving the way for exciting discoveries while we are entering a new era of earth observation with the development of new and various sensors and the creation of satellite constellations, offering multiscale time series on the changing surface studied. Besides, unpublished works unearthed from the RMCA archives have been analysed to produce the most accurate baseline of physical observations on the two volcanoes (Smets *et al.* 2015, Smets 2016).

Since 2012, the number of scientific publications has started increasing to reach competitive levels (fig. 2). The various sets of collected data and the installed instrument networks have really boosted scientific research and the collaboration with other scientists. It is worth underlining 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 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 not modify the increasing rate of peer-reviewed publications observed since 2013 (fig. 2). These observations highlight the maturity gained in the different scientific activities between the two meeting events.

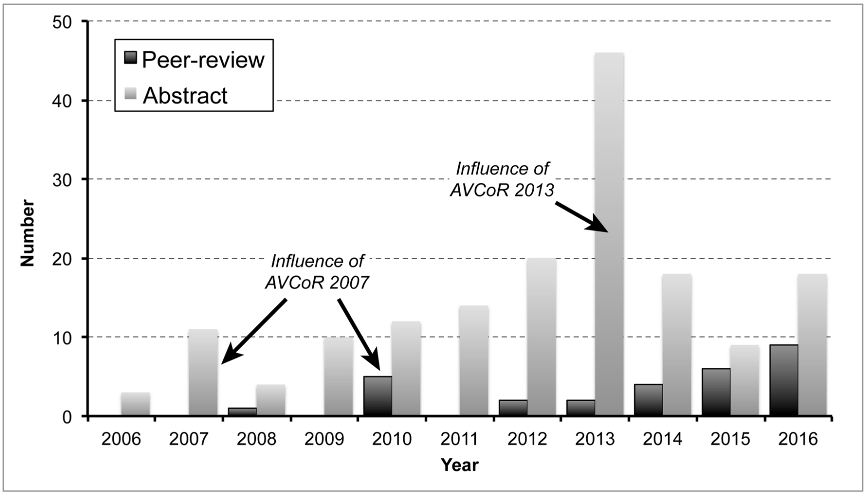

Fig. 2. — Evolution between 2006 and 2016 of the number of peer-reviewed publications and conference abstracts produced by the scientists of the RMCA, NMNH and ECGS on the Virunga volcanoes. All publications implying a working collaboration with the local Congolese partners include these partners as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

Hence, the major outputs from the BeLux research activities are the multidisciplinary expertise and knowledge in the study area, the collection of various data sets (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 only reached competitive levels over the past few years, the current state of the approach followed seems to promise better publication rates for the coming years and the development of additional fruitful projects and collaborations.

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

In terms of scientific output for the local authorities, the hazard, risk and thematic maps produced over the last three years are now being 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 set up an efficient framework to address the issue of Nyiragongo and Nyamulagira volcanoes for the local population, while results from fundamental research also help to tackle key scientific questions about volcanism in extensional setting. The scientific knowledge gained and monitoring techniques developed are used by the GVO and its collaborators to interpret the evolution of 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 gained skills as independent scientific researchers. Moreover, since 2018, the local stakeholders, including the civil protection of North Kivu, have started exploiting the maps and tools developed to improve urban and contingency planning, as well as risk prevention programmes.

However, strong limitations threaten the sustainability of this kind of successful approach. Tackling natural risk issues in a tropical, socio-politically unstable environment is very challenging indeed. It takes time to develop local collaborations, multidisciplinary and adapted methodologies to address the targeted issues, and to train a minimum number of persons to cover all aspects of the activities developed. 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 dissemination of information actions. Belgian and Luxembourgian scientists consequently fight to combine different types of funding, increase the number of collaborators, and transfer as many skills and tools as possible to the local partners. But the strategy is successful as, after twelve years of investment, results are met from research output and local capacity building to volcano monitoring and risk management. Although this strategy has taken a lot of time, energy and inventiveness to succeed, we strongly believe that such environmental issues are worth tackling.

Because the competition to get research funds has strongly increased, especially over the past ten years, and because science funding commonly prioritizes research with 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 setting up mature and operational monitoring tools, which 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. This challenge requires the ear and attention of all the stakeholders who must understand the risk to see years of efforts ruined in a very short delay.

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