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# "GEO-RISK IN CENTRAL AFRICA: INTEGRATING MULTI-HAZARDS AND VULNERABILITY TO SUPPORT RISK MANAGEMENT"

## «GEORISCA»

MICHELLIER C., DELVAUX D., DEWITTE O., D'OREYE N., HAVENITH H.-B., KERVYN M., POPPE S., SMETS B., TREFON T., WOLFF E., KERVYN F.

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***Natural risks in Central Africa***

# GEO-RISK IN CENTRAL AFRICA: INTEGRATING MULTI-HAZARDS AND VULNERABILITY TO SUPPORT RISK MANAGEMENT

## GEORISCA

**SD/RI/02A**


**Promotors**
**Dr. François Kervyn** (Royal Museum for Central Africa,
Leuvensesteenweg 13, B-3080 Tervuren)
**Dr Nicolas d'Oreye** (National Museum of Natural History of Luxembourg,
European Center for Geodynamics and Seismology
25 rue de Münster, L-2160 Luxembourg
**Dr. Hans-Balder Havenith** (Université de Liège,
Place du XX Août 7, B-4000 Liège)
**Dr. Matthieu Kervyn** (Vrije Universiteit Brussel,
Pleinlaan 2, B-1050 Brussel)
**Dr. Théodore Trefon** (Royal Museum for Central Africa,
Leuvensesteenweg 13, B-3080 Tervuren)
**Dr. Eléonore Wolff** (Université Libre de Bruxelles,
50 av. F. Roosevelt, 1050 Bruxelles)

**Authors**
Michellier C. (RMCA/ULB)
Delvaux D. (RMCA)
Dewitte O. (RMCA)
d'Oreye N. (ECGS/MNHN)
Havenith H.-B. (ULg)
Kervyn M. (VUB)
Poppe S. (VUB)
Smets B. (ECGS/MNHN, VUB)
Trefon T. (RMCA)
Wolff E. (ULB)
Kervyn F. (RMCA)

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Avenue Louise 231
Louizalaan 231
B-1050 Brussels
Belgium
Tel: +32 (0)2 238 34 11 – Fax: +32 (0)2 230 59 12
http://www.belspo.be

Contact person: Georges Jamart
+32 (0)2 238 36 90



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# ACRONYMS, ABBREVIATIONS AND UNITS

| | |
|---|---|
| ANAGEO | Analyse Géospatiale |
| CRSN | Centre de Recherche en Sciences Naturelles (RDC) |
| CSK | Cosmo Skymed |
| DEM | Digital Elevation Model |
| DRC | Democratic Republic of Congo |
| ECGS | European Centre for Geodynamics and Sismology |
| EWSA | Energy and Water Sanitation Authority |
| FS maps | Factor-of-Safety maps |
| GEM | Global Earthquake Model |
| GeoRisCA | Geo-Risk in Central Africa: integrating multi-hazards and vulnerability to support risk management |
| GIS | Geographic Information System |
| GVO | Goma Volcano Observatory (DRC) |
| IGEAT | Institut de Gestion de l'Environnement et d'Aménagement du Territoire |
| IRSAC | Institut de Recherche Scientifique en Afrique Centrale |
| INS-NK | Institut National de la Statistique – Nord Kivu |
| INS-SK | Institut National de la Statistique – Sud Kivu |
| ISP-Bukavu | Inst. Sup. Pédagogique de Bukavu (RDC) |
| MIDIMAR | Ministry of Disaster Management and Refugees (Rwanda) |
| ND | Newmark Displacements |
| NGO | Non Gouvernemental Organization |
| NMNH | National Museum of Natural History (Luxembourg) |
| OCHA | United Nations Office for the Coordination Humanitarian Affairs |
| PCA | Principal Component Analysis |
| RMCA | Royal Museum for Central Africa |
| UB | Université du Burundi |
| ULB | Université Libre de Bruxelles |
| ULg | Université de Liège |
| UNDP | United Nations Development Program |
| UNOPS | United Nations Office for Project Services |
| UOB | Université Officielle de Bukavu (DRC) |
| VUB | Vrije Universiteit Brussel |
| VVP | Virunga Volcanic Province |

# SUMMARY

The area around the lakes Kivu and Tanganyika is subject to various types of hazards that threaten the population densely distributed throughout the area. Earthquakes regularly affect the entire region and can be the source of major damage, both material and human. The Virunga volcanic chain, which stretches in the North Kivu province of the Democratic Republic of Congo (DRC) and in northern Rwanda, has two active volcanoes, Nyiragongo and Nyamulagira, which permanently threaten the urban population of Goma (DRC) and Gisenyi (Rwanda). Finally, landslides, which various processes can be sudden, are the source of the most frequent geological disasters that occur in this area. In addition, the region suffers from a low economic level and recurrent armed conflicts that further weaken the threatened population.

The GeoRisCA project (http://georisca.africamuseum.be), carried out under the SSD (SD/RI/02A) program of the Belgian Science Policy (Belspo), had the overall objective of meeting the need to study the risks of geological origin in the Lake Kivu region, to contribute to risk prevention at the regional and local levels.

The study was conducted at the regional scale (mainly for the study of seismic hazard) and also at the scale of two urban sites: Bukavu, capital of the province of South Kivu which has about 870,000 inhabitants, a city affected by frequent ground movements, and Goma, the capital of North Kivu Province, home to about 775,000 people under the threat of the lava flows of the Nyiragongo volcano, which last erupted in 2002.

To fill the lack of reliable data, many measuring instruments have been deployed and methodologies adapted to this particular context have been developed. Several databases were built during the project. The data formed the basis for the production of detailed maps, both for monitoring the evolution of the hazards, and for the population distribution and demographic characteristics. The final phase of the project was to spatially combine the vulnerability assessment and population density with the landslide susceptibility and lava flow probability analyzes developed by the GeoRisCA project experts.

The risk maps obtained are new tools for decision support; they have been officially delivered to local authorities in order to, on the one hand, strengthen disaster risk reduction policies and disaster prevention programs, and, on the other hand, allow the development of a new approach for land use planning. Finally, it is important to stress that this research could not have been achieved without a close partnership with scientific institutions and local authorities, and has significantly contributed to improving the interactions between these different stakeholders.

**Key words**: Geological Hazards, Landslides, Volcanism, Seism, Social Vulnerability, Natural Hazard, Democratic Republic of Congo, Rwanda, Burundi.

# 1. INTRODUCTION

Natural disasters are a major threat to the security of people and the sustainable development of many countries around the world. By definition, it corresponds to the "serious disruption of the functioning of a community or society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources" (UNISDR, 2009). In 2015, according to the international EM-DAT database (http://www.emdat.be), managed by the Center for research on the Epidemiology of Disasters (CRED-UCL), nearly 350 natural disasters occurred around the world, including a large majority in the so-called developing countries, thus further impeding their development. On the one hand, a natural disaster is triggered by a hazard that is a phenomenon of geophysical, meteorological, hydrological or climatological origin, which manifests itself by releasing a large amount of energy and can cause loss of live, injury or other health effects, damage to property, loss of livelihood and services, socio-economic disruption, or environmental damage (UNISDR, 2009). On the other hand, the extent of the impact of such a phenomenon depends on the exposed elements, also called 'stakes' (i.e. people, infrastructures, (eco-) systems, or other elements present in the risk areas and thus subject to potential losses (UNISDR, 2009)) and their characteristics controlling their specific vulnerability.

Numerous scientific studies or research-action programs evaluate and map natural hazards on a global scale (for example, André 2004, Comes et al., 2016, Dilley et al., 2005) As Bétard and Fort (2014) explain that such studies aim to compare the level of exposure and vulnerability of countries to natural hazards, and therefore to identify those who are most likely to generate loss of life and important economic impacts. Of all these studies, it appears that all the countries, in the North as in the South, are exposed to natural hazards, which are at the origin of major disasters, roughly in comparable number, type and intensity. On the other hand, the assessment of vulnerability to natural hazards reveals in all cases large North-South disparities, whatever the methodology used. Indeed, the impact of natural disasters, in terms of economic losses and human lives, appears to be much heavier in the so-called 'developing' countries. In other words, real inequalities in terms of natural risks exist between the North and the South, and remain above all conditioned by a lower level of development, which results in greater social vulnerability in developing countries (Bétard and Fort, 2014, Wisner et al., 2004).

By definition, vulnerability refers to the set of "characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard" (UNISDR, 2009). This definition proposed by UNISDR identifies vulnerability as the characteristics of the stake, independent of its exposure: it arises from various factors, be they physical, social, economic or environmental. For example, it may be poor construction of buildings, inadequate infrastructures' protection, fragility of people's livelihoods in the face of the impact of a disaster, lack of information and public awareness, low recognition of the need to implement preparedness measures, or contempt for environmental management (UNISDR, 2009). All these elements can be part of this concept that the scientific literature has both difficulty defining and quantifying. In addition, vulnerability varies significantly within a community and over time (UNISDR, 2009). Identifying and assessing this notion of vulnerability is complex, but has become crucial for an integrated risk assessment to reduce it.

In March 2015, the Third United Nations Conference on Disaster Risk Reduction was held in Sendai, Japan. The purpose of this conference was twofold: (1) to review the implementation of the Hyogo Framework for Action (HFA) defined at the previous Kobe (Hyogo, Japan) Conference on Disaster Reduction in January 2005; and (2) adopt a post-2015 disaster risk reduction framework. In 2005, the HFA was designed to give a new impetus, following the International Decade for Natural Disaster Reduction (1990-1999) and the International Strategy for Disaster Reduction developed in 1999. Five priorities were set by the Hyogo Framework for Action: (1) Ensure that disaster risk reduction is a national and local priority and that there is a strong institutional framework for carrying out the related activities; (2) Identify, assess and monitor disaster risk and strengthen early warning systems; (3) Use knowledge, innovations and education to build a culture of security and resilience at all levels; (4) Reduce the underlying risk factors; (5) Strengthen disaster preparedness so that it can effectively intervene at all levels when they occur.

It was during the period of implementation of the Hyogo Framework for Action that the Democratic Republic of Congo (DRC) actually initiated its disaster management and risk prevention policy. In the 1990s, it created a National Office of Emergency Preparedness, without simultaneously developing this service at the provincial level. Yet, the country has participated in UN-led policy discussions on Disaster Risk Reduction (DRR) taking part in successive meetings and conferences in Geneva, Hyogo, Sendai, Yaoundé, Cancun, etc. Since the conference of Sendai, the creation of disaster risk reduction platform is an international requirement. Under the leadership of the African Union, the 'Central Africa' platform was created within the Economic Community of Central African States (ECCAS) and was established in Libreville (Gabon). But at the national level, laxity, plurality of texts and actors, and lack of leadership have stalled the process.

It was not until the North and South Kivu were struck by disasters - respectively the volcanic eruption of Nyiragongo volcano in 2002 and the Bukavu earthquake in 2008 – that the provincial governments took action, respectively in 2003 and 2011. Thus were born the Civil Protections of North and South Kivu. Subsequently, seizing the opportunity presented by the decentralization - voted in 2006 -, the Eastern DRC provincial governments have recently promulgated decrees formally creating and organizing disaster risk reduction platforms. In 2015, the central level followed, but so far all this is still without legal basis. While Hyogo's first priority has struggled to set itself up, what about the other four priorities?
The DRC, and in particular the East of the country, has the disadvantage of having to implement this policy despite a challenging security, economic, political and social situation, characterized by a general lack of data. In the early 2010s, in terms of disaster risk reduction, tools for analysis and decision support are still deficiencies. It is in this context that the GeoRisCA project (Georisks in Central Africa, financing of the Belgian Science Policy, contract No. SD/RI/02A) was developed as a response to the second priority of the Hyogo Framework for Action: 'highlight, assess and monitor disaster risk'. This project was initiated in 2012, for a period of five years, while the Civil Protection of North and South Kivu were still in their infancy. The underlying desire of GeoRisCA was to strengthen the two existing structures by providing them with new decision support tools for risk management and disaster prevention. This project aimed both at the study of geological hazards, such as landslides, earthquakes and volcanic eruptions that regularly hit the region, as well as the assessment of the level of vulnerability and risk of targeted cities. Hazards of geological nature are not the only ones to affect the region (floods and storms are also frequent), but they are among the most regular (landslides) and the most striking (earthquakes and lava flows).

Based on the recognition of the need to strengthen disaster management and risk prevention structures, the central research question of the GeoRisCA project was:
How to evaluate geological hazards, as well as the vulnerability and risk of populations facing these phenomena in a context of data scarcity?

This central question was broken down into a series of specific questions:

- What are the type of hazards and disasters that have affected the studied region in the past years?
- In what cultural context are we trying to carry out this study? What is the influence of this cultural context on the perception of risks of geological origin?
- What are the types of major geological hazards encountered in the study area and what knowledge do we have of these phenomena?

- How can we apprehend and evaluate them better? And at which spatial scale?
- What types of infrastructure are threatened? How many individuals are potentially at risk of geological hazards? What are their socio-economic characteristics?
- How to assess the level of vulnerability and risk of the population in the face of geological hazards studied?
- What tools can we develop to contribute to risk management and how will they be used?

These questions could be addressed to all cities affected by natural hazards and suffering from a lack of quality information. They have already been addressed in other development contexts (eg Latin America, Asia; D'Ercole et al., 2009, Gaillard et al., 2001, Siagian et al., 2014, Thouret and D'Ercole, 1996), but very little in sub-Saharan Africa, much less in the DRC. We made the choice to develop this study in two cities in the DRC, specifically in Goma and Bukavu, respectively chief towns of the provinces of North and South Kivu.
The methodologies used were numerous and varied, depending on the scientific field considered. Some are based on qualitative research techniques; others use many quantitative data collections. Combining these has allowed us to achieve the results produced in the framework of GeoRisCA. We will detail them in the different parts of this report.

After a quick overview of some hazards that have struck the region in recent years, we will focus on the cultural characteristics of the studied environment, through the example of the city of Goma. It will give us an insight of how people perceive and react to natural risk they are facing.
Afterwards, we will present the results obtained during this project in relation to the different types of hazards studied: earthquakes analyzed at the scale regional, the volcanic hazard located around the city of Goma and the landslides that affect the shores of Lake Kivu, and in particular the city of Bujumbura and Bukavu. Faced with these hazards, the populations display a certain level of vulnerability that we have evaluated according to a methodology developed by Cutter et al. (2003) and today applied to various situations and spatial scales. This assessment was carried out through an inventory of existing quantitative and qualitative data, in order not only to determine the data available to present the current portrait of the cities studied and their population, but also to highlight the available data for the vulnerability assessment. . This inventory highlighted the scarcity of existing data and the need to collect our own data to carry out this study. This led us to focus on the vulnerability of populations and

the risk that they incur, without being able to analyse in detail at the vulnerability of infrastructures, which is just as crucial.

This project ended with the linking of the different results of our studies: the geological hazards that threaten the cities of Bukavu and Goma and the vulnerability of the population of these two cities. This enabled us to develop risk maps, decision support tools for Civil Protection. GeoRisCA has made a significant contribution to advancing research on hazard analysis and analysis, vulnerability and risk assessment for the region's populations. We conclude this report with recommendations, with a view to contribute to the implementation of disaster risk reduction policies in the provinces of North and South Kivu, and more broadly in the DRC.

# 2. METHODOLOGY AND RESULTS

## 2.1. Past hazards and disasters in the Lake Kivu region

The East African rift valley is a major tectonic feature that shapes Central Africa. It defines linear-shaped basins between highland ranges due to the action of geologic faults, and associated to earthquakes and volcanism. The region of interest, extending from the North Kivu province in Democratic Republic of the Congo (DRC) to North Burundi and East Rwanda, is centered on Lake Kivu and the Virunga Volcanic Province (VVP) in the center of the rift valley. A rare combination of several types of geohazards threatens this highly populated area, classified in seismic, volcanic and mass movement hazards.

At the regional scale, earthquakes are a real threat for this densely populated area. The Western branch of the East African rift is defined by a strong seismicity. This characteristic motivated the installation of the IRSAC (Institut pour la Recherche Scientifique en Afrique Centrale) seismic network, operated from the Lwiro scientific base on the Western shores of Lake Kivu between 1953 and 1963. A preliminary catalogue compiled by Herrinckx (1959) lists about 800 "felt seisms" between 1909 and 1954 in Congo, Rwanda and Burundi. The greatest historical known earthquakes in East Africa, in terms of magnitude, were recorded close to the studied region: M 7.3 in Western Tanzania between Lakes Rukwa and Tanganyika in 1910 (Ambraseys & Adams, 1992; Vittori et al., 1997); M 6.6 around Lake Tanganyika in 1960; M 7.0 in Kabalo (DRC) in 1992; M 6.8 near Kalemie (DRC) in 2005. Recent deadly earthquakes comprise the M 5.9 event that killed 38 people in Bukavu and Cyangugu in February 2008 (d'Oreye et al. 2010), the M 5.6 event in Katana in August 2016 (that killed at least 3 people) and the M 4.6 event in Cyangugu-Kamembe in September 2016 (that killed at least 6 people). An earthquake of similar magnitude (M 4.7) struck Burundi in February 2004. In the past, strong earthquakes did not cause many casualties as the region was much less populated than presently and there were few buildings other than traditional houses. The large number of fatalities caused by the moderate 2008 Bukavu earthquake (M 5.9) can be justified by a larger population at risk and by a higher proportion of modern buildings and houses that are vulnerable to earthquake shaking. This clearly illustrates the modern trend towards increasing exposure to the seismic risk. A new earthquake similar to the Rukwa 1910 earthquake (M 7.3) would be catastrophic. Seismic activity could also be the indirect cause of major disasters, as triggering factor for mass movement, and subsequent population migration in a highly sensitive political and ethnic context.

Several scientific investigations were performed in Virunga Volcanic Province during the 1950's and the 1970's and were mainly published in scientific reports or former Belgian scientific publications, nowadays not easily accessible. From the mid-1980's, only sparse

information on volcanic activity in the region exists. This is due to political unrests and subsequent limited access to the volcanoes. Among the 8 main volcanic edifices of the Virunga, two are very active: Nyiragongo and Nyamulagira. During the last eruption of the Nyamulagira in 2011-2012 (as during any of the eruptions at Nyamulagira), the lava flows seriously affected the surrounding ecosystem of the tropical primary forest. The Nyiragongo contains a (semi-) permanent ~200 m diametre lava lake, the largest on Earth. It threatens the city of Goma, located less than 15 km away directly. In January 2002, similarly to 1977, fissures opened on the southern flank of the volcano (Wauthier et al., 2010) and fast lava flows destroyed about 10 % of the city, killing ~ 150 persons, making 100.000 homeless and triggering a humanitarian crisis (Baxter and Ancia, 2002). It induced a long-term socio-economic impact. As Goma is the strategic economic centre for the Great Lake Region with a fast growing population, a similar event could cause an even larger disaster today. In addition, natural emanations of $CO_2$ in on-land depressions known as *mazuku* near Goma cause also a serious threat to the population and cattle.
Throughout the targeted region, landslides, defined as a wide variety of gravitationnal processes that result in the downward movement of slope-forming materials including rock, debris, soil, or a comnination of them (Hunger et al., 2014), are frequently observed (Moeyersons et al., 2004, 2010). A database of natural hazards for Central Africa developed by the RMCA in 2009 (Vandecasteele et al., 2009) showed that recorded landslides can have a climatic (rainfall) and/or seismic (and volcanic) origin. Moreover, Vandecasteele et al. (2009) suggested that a human-induced increase in the frequency and magnitude of these mass movements is observed in urban areas in Central Africa. In cities like Bujumbura, Uvira, and Bukavu both the rift escarpment and the lake limit urban expansion and population is forced to settle on unstable slopes affected by landslides.

Faced with these hazards, the population might react according to specific cultural believe which we are not necessarily aware of. An anthropological and sociological study is essential to understand the concerns and priorities of the population. This is essential to assess the vulnerability, the perception but also to understand why some of the efforts undertaken by external scientists for the benefit of the population are not always sustainable or even welcomed by these beneficiaries. The latter may have other priorities, crucial to take into account. Or they might not take us seriously because they have other beliefs to explain the disasters. This approach has been a major component in the development of the GeoRisCA project and the formulation of recommendations.

## 2.2. Focus on Goma: risk perception in a city of dangers and opportunities

Through this urban sociology of Goma based on twelve personal narratives we have highlighted the struggles, anxieties and hopes of ordinary people in this city of about 800,000 people. In-depth interviews with key informants, along with direct observation and literature review were the approach followed. The output of this study was published in a book entitled "Précarité et bien être à Goma (RDC)" edited by L'Harmattan in December 2016.

### CAST OF CHARACTERS AND THEIR SOCIAL UNIVERSES

Below is a brief introduction to the people with whom we have worked and their social universes. The aim is to let readers quickly identify the stories they may find most interesting or pertinent. The sequencing of the stories in the book is random: we decided not to decide on 'the' most coherent order because multiple ways of presenting them are possible. They could have been grouped by gender to emphasise the determination of woman to take charge of their destinies or by economic activities to highlight the dynamism of the informal sector. Some stories are focused solely on the city while others trace the relations between Goma and its hinterland. Some individuals in this collection, moreover, be they young or less young, are quite simply nicer or more sympathetic than others. Is Cerezo the *tshukudeur* more representative of Goma than Asumani the motorbike taxi driver or Doctor Chantal Sosole compared to Bernadette the market woman? Are some social universes really more symbolic than others? Probably not: all of them are little bits making up the social mosaic of Goma, contributing to how and why the city is the way it is today – and what it may become tomorrow. The stories can therefore be read in the order they appear but readers can also wander through them led on by their own curiosity.

Beans are part of the Goma identity. They are all over the city: in fields, in kitchen gardens and of course in pots simmering over smoky charcoal fires. Buying and selling them is a means for women like Bernadette Mpunga to sustain a modest lifestyle and achieve social recognition. The busy market where she has her stand is full of life and drama. Wife and mother by the time she was seventeen, she has been able to find peace of mind in Goma thanks to her hard work. Nevertheless, she remains wary of the 'malicious spirits' that could wreak havoc in her household and workplace. Humble, she considers herself part of the 'insignificant multitude'. While relating her story, Bernadette also describes administrative issues at the market, security problems in the Goma hinterland (where her husband buys beans wholesale) and transportation logistics.

Few households in the DRC have electricity and Goma is no exception (although low-capacity solar installations are increasingly visible on rooftops). The vast majority consequently relies on charcoal for cooking. The charcoal business is therefore an economic opportunity but one that comes with a high environmental impact, notably because most of Goma's charcoal comes from Africa's oldest nature reserve – the emblematic Virunga National Park. Exiled Hutu refugees from Rwanda (former *génocidaires* and their offspring) control much of its production and lucrative trade. Nguba Liboko who miraculously survived a cholera epidemic that wiped out his entire family on the Idjwi Island in Lake Kivu when he was a child, is a charcoal wholesaler. He was previously involved with partners in charcoal production and transport so knows the intricacies of the whole supply chain and with whom he has to negotiate along the way. After having survived skirmishes with Mayi-Mayi rebels and M23 troops, he says he thanks God for his relative good fortune.

The ingeniously designed *tshukudu* competes with the Nyiragongo volcano as the most emblematic symbol of Goma. The emergence of this handmade wooden scooter could be considered as an inventive popular response to transportation and employment needs but could also be considered as a reminder of underdevelopment in the Congo. Cerezo's narrative testifies to the dynamism, creativity and solidarity of the hundreds of *tshukudeurs* who have become indispensable to trolley building supplies, produce, furniture and other loads that in other cities would be hauled by lorry. Every few days Cerezo shuttles between his peri-urban farm and Goma with vegetables for a restaurant that caters to the city's middle class and expatriate aid community. His dream is to help his children become full-fledged city dwellers who can 'enjoy water from a tap' and other urban amenities. 'The city may modernise' he says, 'but the population will depend on my rudimentary *tshukudu* for years to come'.

Goma would not be Goma without the Nyiragongo volcano. Eruption is a permanent threat. The last two major eruptions (1977 and 2002) destroyed property and took lives. People that experienced an eruption never forget it. But there are some advantages too: indeed, the city is built largely with lava stones – mainly for house foundations and walls. Lava and volcanic ash, moreover, make for excellent fertile soil. Célestin and Mituga are two buddies who, with their simple steel tools and steel-like biceps, have learned to 'discipline' the lava into useful building blocks. Forlorn and poor, they have settled for their lot in life, saying: 'we have stopped dreaming about a better tomorrow'. Their joint narrative provides insightful information about the haves and haves not, house building and urban crawl in a context of urbanization without urban planning.

Goma is a rapidly changing city and a young one too. Approximately half of its inhabitants are less than eighteen years old. To understand the dynamics of change, therefore, listening to how the young express their expectations, determination and frustrations is unavoidable. Many youth are disoriented, having been broken by uncertainty, politics, conflict and family trauma. They have to grow up quickly. There is, however, in addition to those who complain of seeing little hope for the future, a category of gilded young adults. Clarisse Soki is one of them. With a degree from the University of Goma, she has a busy social life, a comfortable family home, a new car, plans for work and leisure and a sense of her own import and good fortune. While she is the first to admit that she was born under a lucky star, she also realises that her conveniences are petty and her self-satisfaction is illusory.

The health sector in Goma is confronted by a singular set of constraints resulting from regional violence and the stressful struggle to survive for a generally vulnerable population. It is a hybrid sector with ultramodern hospitals funded by foreign partners, a dilapidated public health delivery system, small private clinics and traditional healers. The pragmatic Doctor Chantal Sosole describes how patients 'shop around' depending on the type of care needed and how much money can be scraped together. Trust in Western medical science and belief in witchcraft are jumbled in her consultations with patients. Doctor Chantal reveals with empathy the defeats and suffering of her patients but also their victories and hopes. Her account of the worse day of her life as a doctor is powerful social commentary.

The population of eastern DRC has gone through one of the 21st century's worst social tragedies. Goma has become the principal hub for hundreds of humanitarian agencies and NGOs – but ones which are hampered by unrealistic mandates, poor coordination and sometimes, conflicting agendas. Their presence over the years has transformed the socio-economic condition of the city, through for example, employment of staff, the house and office rental market and indirect service provision. Eric Kyungu went from being a hotel bookkeeper to a humanitarian professional employed by the Red Cross. Eric is an active member of a Catholic congregation. His sardonic analysis of Goma's humanitarian 'business' is based upon sentiments of cynicism, altruism and opportunism.

Mathilde Musole is a surprizing businesswoman who has run the gauntlet of ups and downs personally and professionally in the city she sees as one of commercial opportunity. She can best be described as being energetic, enterprising and shrewd. In her description of life as both mother and father, cabaret owner and trader with Dubai, church-going social climber and loan shark, her story of contradiction and diversity resounds with her determination to take charge of her own destiny and provide for her offspring. From selling doughnuts on the street as a young mother to high-tech gadgets as an established trader today, her experience is firmly embedded in Goma's economic dynamism. She says that her own story, like that of Goma, is 'incomplete'.

The roar of the motor-bike taxi is one of Goma's characteristic sounds. This means of getting around, now widespread throughout the DRC, started in Goma as cheap Chinese and Indian motorbikes became available via east Africa. As the city became increasingly spread out, new transportation strategies emerged. The motor-bike taxi is cost-efficient for passengers and provides work for young men with relatively low entry costs. Asumani Birewa had to leave school young when his father died and then floated from job to job in his village in Masisi. He later settled in Goma hoping to find office work but that never happened. He eventually had the opportunity of becoming a motor-bike taxi driver, which he took: 'it was better than nothing'. He describes Goma through his experience with traffic police, passengers, fellow drivers and mechanics. His universe is the motorbike – for both work and leisure.

Insecurity in eastern Congo has created new needs for private security companies of which there are dozens in Goma today, catering to the protection of well-to-do Congolese and expatriate humanitarian and development workers. The companies recruit former soldiers and militia members – many of whom have blood on their hands, such as Papy Bahati. His story intertwines his experience as a drifter with the recent military history of the country. He tells his story according to military events that affected his life such as Laurent-Désiré Kabila's break with his Rwandan and Ugandan backers, battles in Kisangani, a 'mistaken' deportation to Rwanda and rebellion in South Kivu. He admits that his work as a private security agent is politically dubious but insists that 'having a clear conscience is a luxury for somebody like me', particularly in an unpredictable environment where 'it is cheaper to buy a Kalachnikov than a goat'. Papy is an eternal malcontent with a tormented spirit who sees himself as a predestined victim. Hazard, chance and accident – not justice – have defined his life.

Isabelle Michel is a Belgian agronomist who has spent most of her working life in the Congo, mainly as a coffee plantation manager for the past 25 years. As her plantation lies in the immediate Goma hinterland, she is an excellent source of information about how the city has evolved. The plantation's uninterrupted production is a surprising example of commercial resiliency in a conflict zone that requires maintaining good relations with a host of actors. She describes Goma's social, economic, spatial and security changes since she first discovered what has become her second home. Concerned with the well-being of the plantation's hundreds of workers and proud to participate in the 'noble enterprise' of getting coffee into our cups, this White European woman with a deep attachment to Congo and the Congolese admits that 'going to bed in Belgium without worrying about the volcano or being attacked is not hard to take sometimes'.

Even though most of Goma's economy is informal, there are also formal sector activities. Martin Mboma runs the provincial office of the Federation of Congolese Enterprise, whose mandate is to promote and facilitate private investment while also serving as a link between companies and government. His narrative helps us understand how the informal and formal sectors converge to make Goma a bustling city of opportunity. Martin offers an unexpected account of officialdom because even in the context of weak State structures, the Federation contributes to the economic dynamism of Goma. His advice to potential investors (from fruit juice prospectors to hotel developers) reflects his personal trajectory: 'only the paranoid survive – and only the really paranoid prosper'. His message is similar to those of many Goma residents: 'never underestimate the power of a relationship'.

## MULTIPLE SOCIAL REALITIES

Common themes emerge whilst engaging with the people of Goma. It is obvious that security concerns and money worries are their main preoccupations, surpassing by far fear of volcanic eruption. People even say that they are used to the panache of the Nyiragongo, referred to as 'neighbour' or 'big brother'. Is volcanic activity, moreover, a natural risk or a supernatural one? The response is ambiguous in many minds because the last eruption took place on 17 January 2002 – a date permeated with connotation. The population of Goma is far from insensitive to the fact that the national hero Patrice Lumumba was killed on a 17 January (1961) and Laurent-Désiré Kabila on 16 January (2001).

The threat of militia fighters, common bandits and assassins is in everyone's discourse. All of these security problems were first sparked in the immediate aftermath of the Rwandan genocide. They exacerbated threats from predatory soldiers, an enduring legacy of the Mobutu dictatorship. The people of Goma appear cautious and suspicious because of these real threats which also help account for their general lack of light-heartedness. People undoubtedly have good reason to be afraid, but their fear needs to be nuanced. Martin Mboma, who describes his city of one of 'unanswered questions', provides a subtle twist: 'there will be victims, but there will be survivors too'.

Mathilde Musole has encapsulated what many of her friends and neighbours feel about household finances: 'you can't be happy without some financial security'. But before this can happen, many voices converge to say that you have to persevere, know how to adapt and learn quickly – in addition to being a little bit lucky. 'Wicked spirits, witchcraft and evil spells', according to Bernadette Mpunga, are forces to avoid in the fight against adversity. She therefore does whatever she can not to give her potential enemies reason to be jealous. The people of Goma rarely use the term 'resilience' but they have multiple expressions to express it: 'stick to it', 'get up when you have been knocked down', 'fend for yourself', 'do the impossible' and 'face up to reality', for example.

The importance of education is another common theme uppermost in people's discourse. While many people in Goma survive on the margins of the law, they pray to God for help in finding and keeping 'real' work. Education and a diploma 'help one stand above the others' and are perceived as being a key to open the door of recruitment. Similar to other parents who 'did not wear out the seat of his trousers on a school bench', Cerezo the tshukudeur has high hopes for his children to become 'educated city dwellers'. Doctor Chantal Sosole adds another perspective on education: 'insecurity, mobility and the general deterioration of State services has taken a heavy toll on children's education. It is a problem that contributes to our vulnerability'.

The role of the State is a frequently heard litany, particularly its abdication in safeguarding physical security. The population is also very sensitive to the State's ability to do harm in addition to the fact that 'State agents are so present but so useless'. Somewhat less obvious is the perception of a gap between the economic dynamism of the city and the absence of State services, pointing to the population's capacity to get things done through their own commercial and solidarity networks. Infrastructure deficiencies, as elsewhere throughout the country, are high on the list of complaints. 'The absence of running water is the big scandal of Goma' insists Isabelle Michel. Lack of electricity has serious implications on the Virunga National Park because Goma extracts charcoal from it.

The absence of a functioning State is a direct cause of the strong presence of humanitarian aid in Goma. Humanitarian agencies and NGOs have replaced the State – but at the same time handicap its ability to regain sovereignty. Consequently, 'humanitarian aid helps but destabilises at the same time'. While the dream of many skilled people, such as Clarisse Soki and Eric Kyungu, is to work in the sector, they realise that it also 'artificially dopes the economy' and that there will be a 'devastating void' when the humanitarians leave.

References to God and prayer, religion in general and other belief systems are omnipresent in people's stories. Trust and mistrust in Providence overlap. Papy Bahati looks to the Lord to reinforce his hope of improving his human condition and because 'God is the best defense to ward off adversity'. Looking back over the years, Martin Mboma does not waver in his conviction that 'it is only thanks to the Almighty that I have been able to avoid the traps destiny has laid for me'. After having narrowly escaped an ambush from M23 fighters, Liboto the charcoal trader 'glories the Eternal' for leaving him safe and sound. The Lord is undoubtedly a major force in the lives of the people of Goma but it is not because He traces their destinies that they do not accept to do the 'physically unthinkable and morally repugnant' to get ahead. The ambiguity between the belief that events are predestined and the will to take charge of one's existence is a striking sociological phenomenon in this city of 'false refuge' where 'life goes on but where the future remains uncertain'.

Starting with such an anthropological approach has provided the scientists team involved in GeoRisCA with another perception of the studied area. It was helpful to better understand the environment and communicate with the people, especially when assessing their vulnerability. But let's first focus on the hazards which were analysed in the project. The seismic hazard was studied and assessed at the regional scale of the Tanganyika and Kivu lakes.

## 2.3. Seismic hazard assessment: a regional approach

In this part of the project, a new seismic hazard assessment has been done for the Kivu rift region, on the basis of a new completed and revised seismic catalogue and an analysis of the seismotectonic setting of the region. The final product is a series of probabilistic seismic hazard maps expressed in Peak Ground Accelerations (PGA), in g. Additional intermediated products are the catalogues of historical seismicity, instrumental seismicity, earthquake focal mechanisms with their depth, thermal springs, shape files and bln files (for Surfer) of neotectonic fault network, a synthetic cross-border geological map, different seismotectonic maps and shape and bln files of the seismic zones defined for the seismic hazard assessment. The main results have been published in Delvaux et al. (2016), Smets et al. (2016) and Ganza et al. (*in press*).

### 2.3.1. Earthquake catalogue and the earthquake parametrisation

The starting point in probabilistic seismic hazard assessment is the construction of a seismic catalogue that is as long, complete and homogeneous as possible in order to better characterise the seismic activity of the studied region. In order to be credible and accepted by the scientific community, all steps of the compilation and choices made during this process need to be thoroughly described.

A new seismic catalogue was compiled from different sources, from publicly available catalogues and scientific literature. We used as a basis, the ISC (International Seismological Center) reviewed catalogue which holds data since 1970 and compiled them up to the end of 2015. It was completed by events from the CGS (Council for Geosciences) catalogue, NEIC (National Earthquake Information Center) and GSHAP (Global Seismic Hazard Assessment Project; Turyomurugyendo, 1996) which were not yet present in the ISC catalogue. For larger events, we preferred the data from detailed studies. Historical data were taken from the literature. For the period between 1956 and 1963, we added those events from the IRSAC local seismic network (managed at the Lwiro research center), which have been determined by at least 3 seismic stations.

In order to extend the time period covered by the catalogue, we determined new historical macroseismic events from records of felt seismic shocks reported at the meteorological stations during colonial times (Appendix C of Delvaux et al., 2016).

The resulting catalogue contains a total of 1068 events between 1888 and 2015, of which 1054 between 1931 and 2015 (85 years) will be further used in the homogenization process (Supplementary material 1 of Delvaux et al., 2016). After removal of duplicates, the different magnitudes have been homogenised to moment magnitude (Mw), using regression equations of Scordilis (2016) and Mavonga and

Durheim (2009). The dependent events (aftershocks and earthquakes related to volcanic activity) were then identified and removed. This was done primarily with the help of various publications on the subject.

The final catalogue of independent events was separated into four time-sliced sub-catalogues with different levels of completeness (Supplementary material 2 of Delvaux et al., 2016):

- **1931-1955**: 42 events with magnitude 4.2 to 6.2, mainly macroseismic
- **1956-1965**: 366 events with magnitude from 1.4 to 6.3, recorded mainly by the IRSAC local seismic network
- **1966-1989**: 172 events with magnitude from 4.2 to 5.7, recorded by regional seismic networks that were progressively setup in the neighboring regions
- **1990-2015**: 230 events with magnitude from 2.0 to 6.2, recorded by the modern world-wide seismic network

In addition, we compiled also the available earthquake focal mechanism solutions (focal planes and hypocentre depth) from published works and the Harvard Centroid Moment Tensor catalogue, obtained by waveform modelling (Appendix A of Delvaux et al., 2016).

### 2.3.2. Neotectonic and active faults study

A good knowledge of the geological setting and seismotectonic characteristics is also important in seismic hazard assessment. Unfortunately, for the Kivu rift region, geological and tectonic knowledge was fragmentary and therefore it was necessary to compile basic geological and fault maps as these did not existed in a suitable form.

As an additional sub-study, not planned in the research programme, we compiled a homogeneous and cross-border geological and tectonic map for the Kivu rift region which extends over Rwanda, Burundi, eastern D.R. Congo, Northwest Uganda and Southwest Tanzania, in the Mesoproterozoic Karagwe-Ankolean belt (general location in Figure 1). This compilation was done in a series of time-slices in order to image the long and complex past tectonic evolution of the region since the Paleoproterozoic.

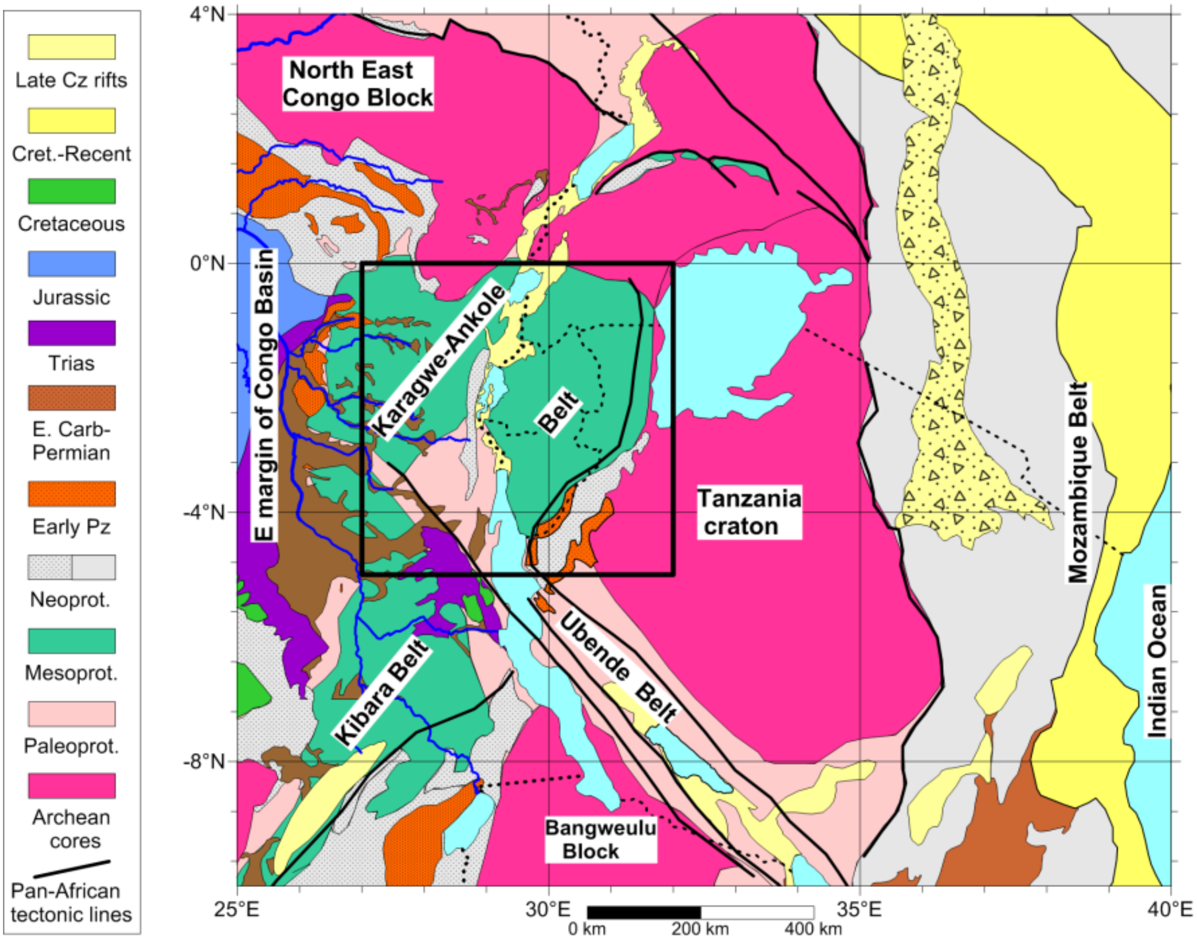



*Figure 1. Geological context of the Kivu rift region (area shown as rectangle) within the Mesoproterozoic Karagwe-Ankole belt between the Tanzania Craton, North-East Congo block, Ubende Paleoproterozoic belt and the Congo Basin. It is also located in the middle of the western branch of the East African Rift. It comprises Rwanda and Burundi and parts of Eastern Democratic Republic of Congo, Tanzania and Uganda (from Delvaux et al., 2016).*

In such a region, identifying active faults is not an easy task, due to strong weathering, the basaltic nature of part of the surface geology, steep reliefs with abundant slope instability and landslides, and the presence of water and sediments in the lake which mask or obliterate the tectonic morphology (Smets et al., 2016). In such conditions, we used the criteria defined by project IGCP 601 for the sismotectonic map (Meghraoui et al., 2016) and mapped instead neotectonic faults defined as faults activated during the last and still active tectonic stage, which is the Late Cenozoic rifting stage in this region.

With this definition in mind, we compiled the existing knowledge on neotectonic faults, using publications and MRAC databases. We updated this knowledge using remote sensing, with the processing and interpretation of digital elevation data. This was done using the SRTM elevation data at 90 m resolution for a regional approach and at 30 m resolution for detailed investigations. The compilation was extended outside the area affected by modern rifting activities. It evidenced that the Kivu rift basin was initially extending southwest into the Mwenga-Kamituga rift depression which appears now to be a failed rift branch (Fig. 1.2). We compared our compilation with several other fault maps available in the literature, some of which published in the course of this project (Wood et al., 2015; Smets et al., 2016).

Thermal springs (292) and hydrothermal travertine occurrences (13) were also compiled, mostly from literature data and the MRAC databases, with some additional own field observations. Since the work of Boutakoff (1933), they are considered indicators for the presence of active faults as they are generally related to fluid circulation in crustal faults down to a depth of several kilometers. Their large number, close relation with mapped faults and seismic epicenters make them good indicators for regions affected by active tectonic movements (Figure 2).

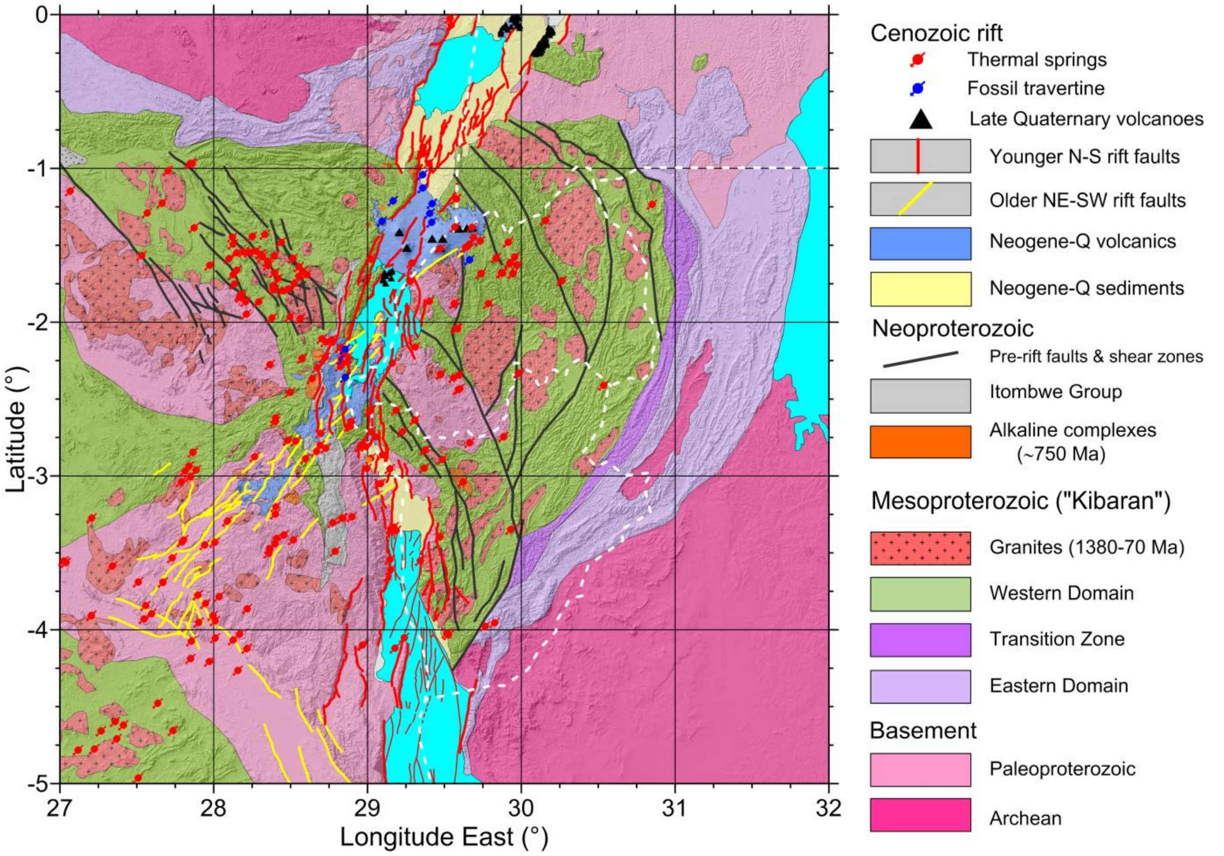



*Figure 2. Homogeneous cross-border synthetic geological map of the study region (background) with overprinted neotectonic features (neotectonic faults, late Quaternary volcanic centers, thermal springs and fossil hydrothermal travertine). Hill-shading from the SRTM DEM (90 m resolution) (from Delvaux et al., 2016).*

The mapped faults were all considered as neotectonic as they affect the morphology and control the architecture of the rift. They were classified in function of their origin and probable age of initiation. The oldest faults are considered indifferently as pre-rift, as their initiation appears to predate the development of the rift. Several different pre-rift fault systems exist, but the most significant in terms of seismic risk is the NW-trending strike-slip fault system that developed on the western side of Lake Kivu (Masisi region), probably during the Late Pan-African time (early Palaeozoic). It was mapped by Boutakoff (1939) and appear to control numerous hot thermal springs (Boutakoff (1933) and therefore considered as active. During the early stage of rift development (probably during the Late Miocene-Pliocene), a first system of rift faults developed in a general NE-SW to NNE-SSW trend controlling the early development of the Kivu rift system. At that time, the Kivu rift system was continuing south-westwards by the Mwenga-Kamituga rift basin, now less tectonically active. During the Quaternary, a new fault system of general N-S trend developed, probably due to the linkage of the current Kivu basin to the northern end of the Lake Tanganyika rift basin via the Rusizi accommodation zone. As a consequence, rifting ceased in the Mwenga-Kamituga basin which became a failed rift. Despite their age of initiation (pre-, early, or late rift), these three fault systems are currently active, as shown by their association with thermal springs and seismic epicentres.

Field investigation of potential active faults was performed in a few places. It was not possible to perform paleoseismic trenching due to lack of time and funding, but also because of the difficulty to find suitable trenching sites and the generally poor morphological expression of the neotectonic faults. Instead, the fault kinematics were investigated for a few faults by an assistant of the Université Officielle de Bukavu in the frame of the collaboration with project RGL_Georisk and under the supervision of the MRAC, with the aim of reconstructing the tectonic paleo-stress and comparing it with the current stress field deduced from earthquake focal mechanism (Ganza et al., *in press*).

The reactivation potential of the major fault systems was determined by the application of stress field determined from stress inversion of earthquake focal mechanisms using the Slip Tendency method which defines the ability of a fault to slip under a given stress field (Morris et al., 1996). The stress pattern over the Kivu region clearly suggests that the recent N-S faults of the active rift valley are in favorable orientation for being reactivated. The lateral variation of the stress trajectory on the western shoulder of the rift also suggests that the NE-trending normal faults of the Mwenga-Kamituga failed rift can also be reactivated, as the NW-trending (subvertical?) faults in the Masisi region.

### 2.3.3. Seismic hazard assessment

The seismic hazard assessment was performed using the probabilistic method, using the catalogue of known seismic activity. A deterministic approach is not possible in the Kivu Rift region due to the lack of knowledge of the paleosismic activity of the faults.

The probabilistic method for seismic hazard assessment involves the definition of seismic source zones for which the Gutenberg-Richter (G-R) laws needed for the seismic hazard assessment are considered as uniform. Important parameters related to these laws are Mc, the magnitude of completeness of the catalogue; Mmax, the maximum regional magnitude; lambda, the mean seismic activity rate; the a-value (intercept of the G-R linear fit); and the b-value (slope of the G-R fit, indicating the relative weight of large versus small events).

The definition of the seismic source zones was performed on the basis of the new geological and neotectonic maps as compiled above, taking into account the basement structure and the distribution of neotectonic faults, thermal springs and Quaternary volcanic centers as well as the seismic epicentres. A total of 7 zones have been determined (Figure 3). For the entire area and for each zone, the G-R parameters were determined by both the least square linear fit and maximum likelihood methods (program AUE, Kijko and Smit, 2012), assuming that earthquake magnitudes follow a double-truncated G-R cumulative magnitude-frequency distribution with a Poissonian model of earthquake occurrence and that the catalogue is complete above the magnitude threshold Mc. The results of the maximum likelihood and the G-R values obtained (Table 4 of Delvaux et al., 2016) are coherent with the tectonic setting of each zone (discussion in Delvaux et al., 2016).

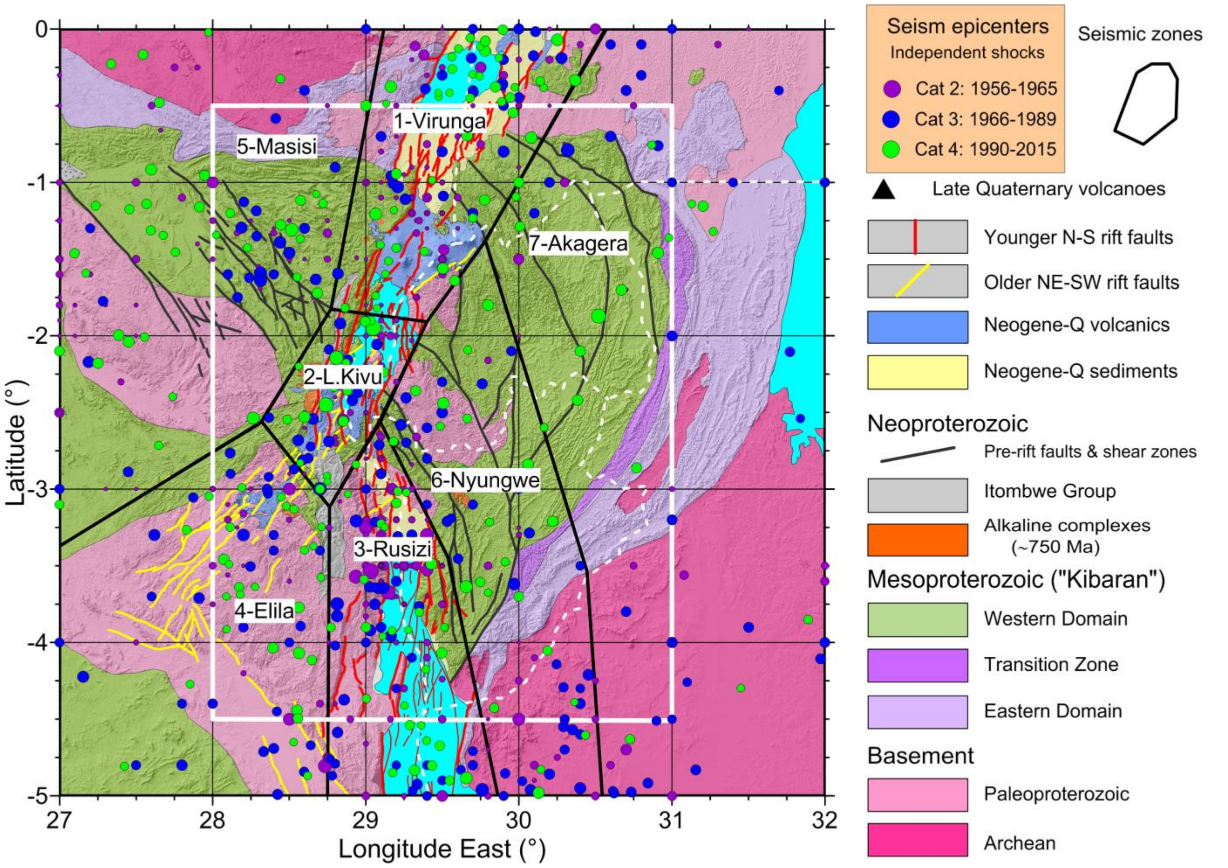
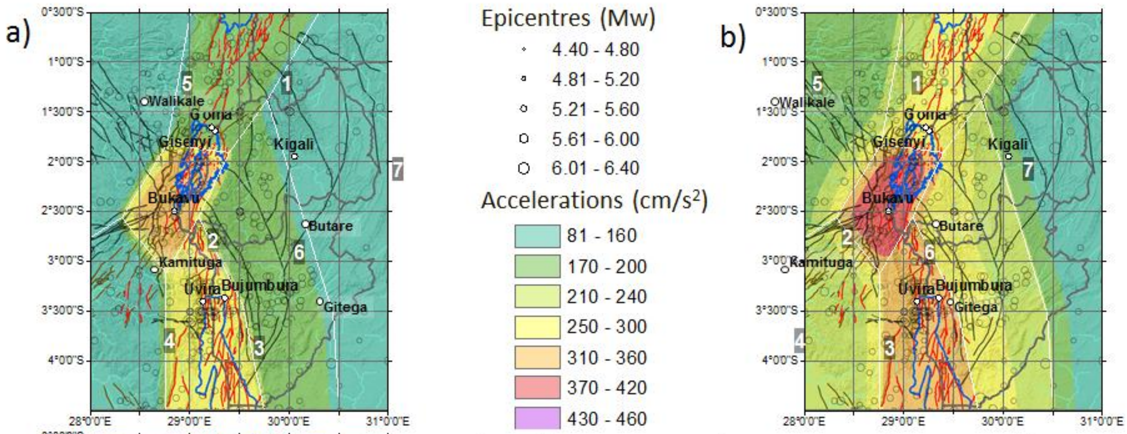
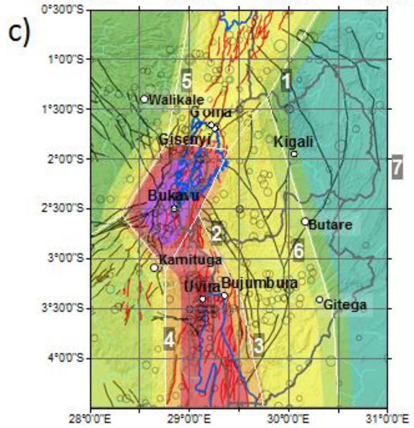



*Figure 3. Study region with outlines of the seven seismotectonic source zones defined for seismic hazard calculation (marked by black polygons, numbered), together with seismicity and fault map. Plotted on top of general geological map, with hill-shading from the SRTM DEM (30 m resolution). The white rectangle shows the area for which the seismic hazard was computed, taking into account also the seismic data from the surrounding area (from Delvaux et al., 2016).*

Another important parameter in the probabilistic method is the choice of the appropriate attenuation laws. It was not possible to derive new ground motion parametric equations for Central Africa due to the lack of local acceleration data for known earthquakes in the Kivu rift region. We used instead existing attenuation laws developed for the Kivu rift region (Mavonga, 2007), Uganda (Twesigomwe, 1997) and southern Africa (Jonathan, 1996).

With the G-R parameters for the 7 seismic source zones and those attenuation laws, we computed the probabilistic seismic hazard maps for the area with the CRISIS2012 software for probabilistic seismic hazard analysis of the bedrock. The three maps obtained (Figure 4) display different levels and patterns of peak ground acceleration (PGA) with the lowest PGA values for 475-year return period along the axis of the Western branch of the East African Rift with the attenuation law of Mavonga (0.17 – 0.32 g), intermediate values with the law of Twesigomwe (0.28 – 0.37 g).




d)

| Zone | Towns | Average PGA estimate – 475y (g) | Disaggreg. dominant Magnitude | Disaggreg. epicentral Dist. (km) |
|---|---|---|---|---|
| 1 | Goma, DRC<br>Gisenyi, Rwanda | 0.19, 0.28, 0.29 | 4.8, 4.8, 4.8 | 5, 9, 9 |
| 2 | Bukavu, DRC | 0.32, 0.37, 0.43 | 5.3, 5.5, 5.5 | 5, 9, 9 |
| 3 | Bujumbura, Bur.<br>Uvira, DRC | 0.26, 0.34, 0.37 | 5.0, 5.3, 5.5 | 5, 9, 9 |
| 4 | Kamituga, RDC | 0.13, 0.21, 0.21 | 4.6, 4.8, 4.8 | 5, 9, 9 |
| 5 | Walikale, RDC | 0.10, 0.18, 0.18 | 4.6, 4.8, 4.8 | 6, 9, 9 |
| 6 | Gitega, Burundi<br>Butare, Rwanda | 0.18, 0.25, 0.26 | 4.6, 4.9, 5.0 | 5, 9, 8 |
| 7 | Kigali, Rwanda | 0.15, 0.18, 0.18 | 4.5, 4.9, 5.0 | 5, 13, 13 |

*Figure 4. Seismic hazard assessment results for the central target area, for a 475-year return period in terms of Peak Ground Acceleration (PGA) on the bedrock: computation with the attenuation law of a): Mavonga (2007); b): Twesigomwe (1997); c): Jonathan (1996). On all maps are plotted also the main seismic shocks (circles with size according to magnitude), country borders, contour of Lake Kivu (in blue) and main cities. d) Averaged 475-year PGA estimate for cities in the target area with indication of the dominant magnitude-epicentral distance pair provided by the disaggregation charts: 3 values of Magnitude and epicentral distance, respectively, for each town, corresponding to results obtained for the 3 attenuation laws (from Delvaux et al., 2016).*

The obtained PGA values vary laterally in function of the tectonic setting, with the lowest value in the volcanically active Virunga – Rutshuru zone, highest in the currently non-volcanic parts of Lake Kivu, Rusizi valley and North Tanganyika rift zone, and intermediate in the regions flanking the axial rift zone. They are also significantly higher than the previous estimates by Midzi et al., 1999 (maximum: 0.24g) and Mavonga and Durrheim, 2009 (maximum: 0.15g). The higher PGA/acceleration values obtained in our study can be, at least partly, due to a finer seismic zonation and a longer duration of the dabase than in the previous studies, and possibly also due to a different computation method used.

Assessing local seismic hazards is the final part of the general seismic hazard assessment for a region. Since predicting local effects requires much more detailed information, this can only be done for some selected areas. We selected one profile crossing Bujumbura. Along this profile, 101 microseismic measurements (30 near two schools and 71 along the profile starting in the hills, crossing the city and finishing near the lake) have been completed during 2 weeks (through collaboration with local partners from the department of Physics, University of Burundi). In the eastern higher parts of Bujumbura site effects were identified in connection with colluvium or weathered bedrock material near the surface. In the Central and Western part, higher resonance frequencies and related amplification are probably related to the presence of fluvial and lake deposits that may reach a thickness of more than 10 m.
A more detailed analysis of the local seismic hazard situation of Bujumbura could, however, not be carried out due to the critical political situation that started in Burundi soon after our mission in summer 2014. Therefore, we recommend the cities of Bukavu (DRC) and Cyangugu (Rwanda) near the Kivu Lake for future local seismic hazard assessment, especially as the Kivu region had been impacted by damaging earthquakes during the last few years. Those two cities are likely to be located on amplifying sediments.

The second hazard type studied in details in the framework of the GeoRisCA project was the volcanic hazard in North Kivu province (DRC). The volcanic hazard is multifaceted, as we will explain in the following part of this report. The scientists involved in this study have deeply improved the knowledge and understanding of the various volcanic threats endangering the city of Goma.

## 2.4. First detailed study of volcanic hazards from Virunga volcanoes

For this part of the project, intensive and targeted field campaigns were conducted in the Virunga Volcanic Province (VVP) to collect geological and monitoring observations required to validate satellite images analyses and geomorphological interpretation, verify observations reported in the literature and collect samples to constrain eruption mechanism and lava flow rheological properties. Data collected was stored in secured places and backed up. Its quality was assessed for the analysis and interpretation of remote sensing monitoring results and lava lake variation analysis. In addition, fieldwork was performed for the installation, repair and maintenance of various monitoring instruments mentioned in the present report. These campaigns were always organised in collaboration with scientists from the Goma Volcano Observatory (GVO) with specific care given to transferring know-how and methods to enable local implementation.

### 2.4.1. Geomorphological analysis based on HR-DEM

#### METHODS

**Geographical Information System (GIS)**: A high-resolution (HR) Digital Elevation Model (DEM) was produced from TanDEM-X satellite data obtained by RMCA for the entire Virunga Volcanic Province (VVP) at a spatial resolution of 5 meter (Albino et al., 2015). In combination with published and unpublished geological and volcanological field maps, available at RMCA, and high-resolution satellite images (Pleiades, SPOT), this DEM was used as base to produce a volcano-structural map of the VVP in the form of a Geographic Information System (GIS) in the ArcGIS software. The GIS database contains all acquired DEMs, satellite images, scanned and georeferenced RMCA archive maps and point, line and polygon shapefile layers describing administrative and volcano-structural features (
Figure 5).

| | |
|---|---|
| DEMs (DEM, hillshade, slope) | - Shuttle Radar Topography Mission / SRTM (30 & 90 m)<br>- TanDEM-x (5 m) |
| Satellite imagery (multispectral/panchromatic) | - SPOT ( 5 m W-VVP; 10 m E-VVP; 2013), Landsat 5/7/8<br>- Pléiades ( 0.5 & 2 m; Nyamulagira & Nyiragongo; 2013)<br>- Ikonos (2008) |
| Administrative features | - National boundaries<br>- Roads<br>- Urban area |
| Tectonic Features (shapefiles) | - Tectonic faults<br>- Topographic lineaments<br>- Georeferenced scans of tectono-structural maps from literature & RMCA reports |
| Volcano-structural features (shapefiles) | - VVP volcanic subfields<br>- Large volcanoes (8) and small eruptive centers (>500)<br>- Volcanic crater rims<br>- Eruptive fissures<br>- Eruptive cones<br>- Volcanic cone base outlines (large and small)<br>- Lava flow outlines<br>- Mazuku locations<br>- Cones with phreatomagmatic nature<br>- Locations of samples with published geochemical data |

*Figure 5. Structure of the Geographical Information System (GIS) created for the Virunga Volcanic Province and employed in WP 2000.*

The volcanic subfields of the VVP are based on topographic escarpments or known boundaries of historic lava flows (Smets et al., 2010). Tectonic faults and topographic lineaments, eruptive fissures and the positions of small eruptive centres (cones, rings, maars) were mapped based on their well-known geomorphological characteristics on DEM-derived and satellite data. The morphological base of all volcanic cones was outlined automatically using NETVOLC (Euillades et al., 2013). Linear spectral mixture analysis was applied on Landsat TM and ALI scenes to characterise vegetation fraction on lava flows of different ages within Nyamulagira flow field (Li et al., 2015). Mapping of the historical lava flows combined with the TanDEM-X were used to re-assess the aerial coverage and volume of Nyamulagira and Nyiragongo lava flows (Albino et al., 2015, Smets et al., 2015).

**Morphological analysis**: Orientation analysis of the eruptive fissures was carried out by plotting their azimuths in stereoplots per VVP-subfield. Using the TanDEM-X DEM for the small cones, and the SRTM DEM (30 m resolution) for the 8 large volcanoes, a set of morphometric parameters was calculated for each cone using MORVOLC (Grosse et al., 2012). At last, SHAPEVOLC was used through a collaboration with Pierre Lahitte (Université Paris Sud), which resulted in the reconstruction of non-eroded volcano surfaces from the SRTM DEM (30 m), and estimates of volume of eroded rock for each of the six off-rift volcanic edifices. The calculated MORVOLC parameters of the small cones were used to contrast average cone shape between the different cone clusters in the VVP-subfields, as indicators of their erosion grade. The morphometric signature of the large volcanoes, notably their ellipticity and irregularity were compared qualitatively, in order to assess morphological age.

**A critical literature review** including colonial field reports available in the archives of the RMCA was carried out to summarise the known eruption history of Nyamulagira (Smets et al., 2015) and Nyiragongo volcanoes (Smets et al., in prep.) and the off-rift part of the Virunga, as a framework for interpreting Nyamulagira's and Nyiragongo's monitoring data and the morphometric dataset of W.P.2100.

## RESULTS

**The volcano-structural map** resulting from the integration of all GIS-mapped volcano-structural features (Figure 6) was presented on several international assemblies (e.g. Poppe et al., 2013). Besides the eight large volcanoes Nyamulagira, Nyiragongo, Mikeno, Karisimbi, Visoke, Sabinyo, Gahinga and Muhabura, > 600 small eruptive centres scattered around the province have been mapped. Dominant NNW-SSE orientations of eruptive fissures within the rift valley itself are attributed to the proximal interaction of Nyamulagira and Nyiragongo volcanoes, with subordinate N-S orientations at Nyiragongo (Smets et al., 2016). In the off-rift part of the VVP, fissures are oriented dominantly NE-SW, similar to the orientation of inherited structures in the Precambrian basement which underlies the VVP (Smets et al., 2016).

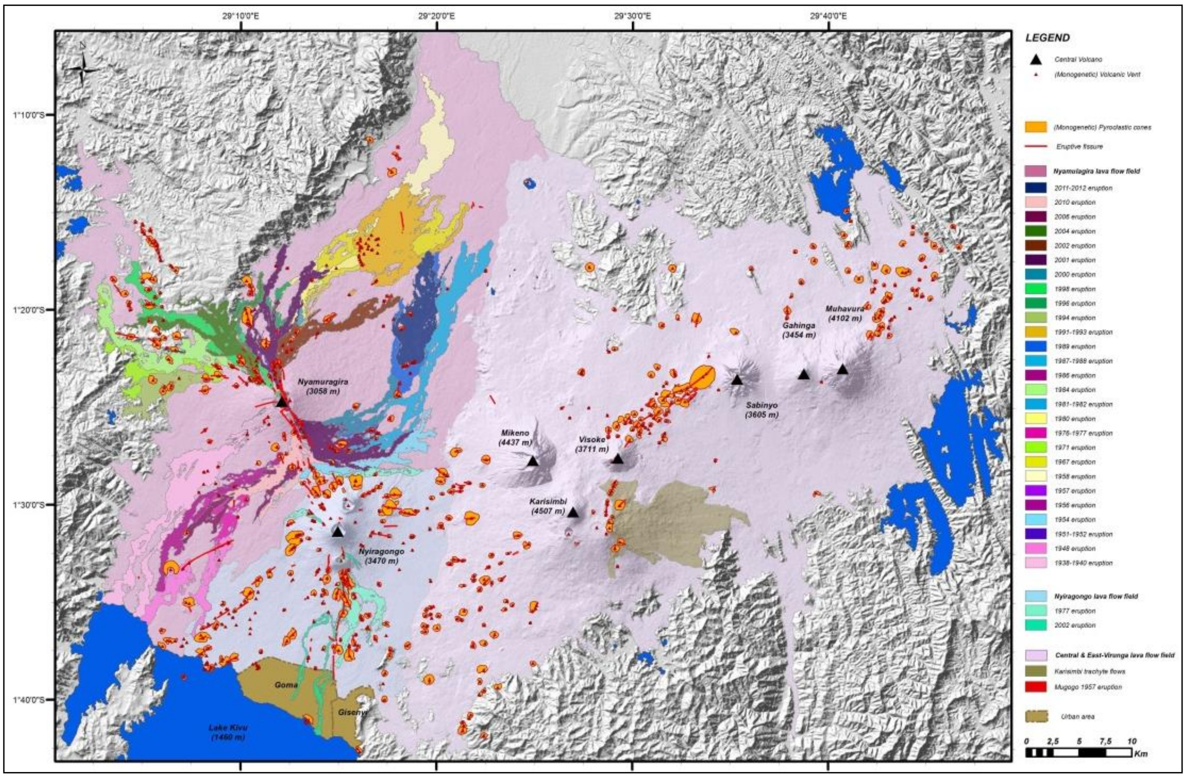



*Figure 6. Volcano-structural map of the Virunga Volcanic Province, based on post-colonial maps and reports, scientific publications and detailed analyses of high-resolution satellite imagery and topographic data (adapted from Poppe et al., 2013).*

**The historical eruptive history of Nyamulagira** was reconstructed thanks to the combination of archive literature and the new GIS database. Results show that erupted volumes poorly correlate with other eruption characteristics (Smets et al., 2015). On the other hand, the duration and location of eruptions allow the distinction of four eruption types: summit/upper-flank, classical flank, long-lived flank and atypical eruptions. The interpretation of these groups suggests that all Nyamulagira eruptions are related to the main crustal magmatic system, except for atypical ones (1904, 1912, 1991-1993), which seem directly related to a deeper magma reservoir. The 1938-1940 eruption, is also atypical, but is related to a caldera collapse and an important drainage of the upper magma plumbing system. The main edifice of Nyamulagira strongly influences the eruption location. No tectonic trigger of eruption is evidenced, but cone and eruptive fissure alignments suggest that rift structures also influence, in a lesser extent, the eruption location and duration. Data also suggest that major eruptions of Nyamulagira along structural axes close to Nyiragongo can induce a change in the eruptive activity of this neighbouring and hazardous volcano (Smets et al., 2015). In addition, the extraction of vegetation fraction for the Nyamulagira lava flows highlighted that vegetation recovery starts 10-15 years after emplacement and that 50% of the vegetation has recovered 40 years after emplacement. These spectral evolutions offer the potential to refine the age sequence and mapping of lava flows in poorly documented flow fields (Li et al. 2015).

For Nyiragongo, the variations of the **lava lakes and the two historical eruptions** were reconstructed based on literature. This review highlighted that the latest stage of eruptive activity is characterised by a succession of intracrateral eruptions and flank events that drained the uppermost magma conduits. Intracrateral eruptions are divided in two types: **persistent lava lake activity and ephemeral lava lake activity**. The drainage of the uppermost magmatic system during the 1977 and 2002 flank eruptions appeared as the consequence and not the cause of flank events. Field observations as well as seismic, petrological and geodetic results indeed indicate that these eruptions have an intimate link with deep magma intrusions and rift tectonics. As suggested by this interpretation, the volcanological mapping of the Nyiragongo lava field and the morphology and dimensions of the main volcanic edifice, there is no direct relationship between the mean elevation of the Nyiragongo lava lake and the imminence of a future flank eruption, as claimed in some publications. It is rather the intensity of eruptive lava lake activity and brutal changes in this activity, which provide such information (Smets et al., *in prep*).

**The morphometric characterisation** of the eight large Virunga volcanoes (MORVOLC and SHAPEVOLC) reveals three different groups of morphological age (Poppe et al., 2013, Lahitte et al., 2015): Nyiragongo and Nyamulagira are the recently active volcanoes with their slope profiles not affected by erosion, in contrast to Mikeno and Sabinyo volcanoes, which are the most eroded and thus inferred to be the oldest edifices in the VVP. Karisimbi, Visoke and Muhabura yield erosive grades intermediate between both end-members, while Gahinga appears surprisingly poorly eroded for a volcano without known historic eruption. Furthermore, the signature of a steep flank collapse scarp was clearly identified at Mikeno, while at Muhabura a similar signature in the morphometric slope profile revealed at least three minor scarps. Although this volcano has no clear signs of a previous catastrophic flank collapse, its morphometry clearly reveals the potential for flank failure in the future. The morphometric results are summarised in a manuscript in preparation for submission to the international scientific journal Geomorphology

The analysis of the **parasitic cone morphometry** show (i) that the cones of the Central and Eastern part of the VVP are not more degraded than Western ones, which suggest that these cones are not very old, and (ii) that the cones located in the Western rift shoulder are more degraded, which suggest that these cones might be the oldest of the VVP. We highlighted that the cones of the Nyamulagira volcanic field experience frequent cone burial by lava flows of Nyamulagira.

### 2.4.2. Paleo-volcanology at a scale of the Virunga Volcanic Province

#### METHOD

**The morpho-geology of Lake Kivu bathymetry** was analysed combining low resolution bathymetric datasets for the entire lake floor with high resolution bathymetry data acquired for the Northern basin of Lake Kivu (Ross et al., 2015, Smets et al., 2016). Identification of sub-lacustrine volcanic edifices and faults, confirmed by seismic profiles, and extrapolation of the on-land lithologies based on Lake Kivu floor morphology, provided a geological map of Lake Kivu, constraining the extent of the Virunga and South Kivu volcanic provinces.

**Identifying regional explosive volcanism** in the Virunga was the main focus of W.P.2200. Fieldwork concentrated on identifying indicators of explosive magma-water interaction along Lake Kivu's northern shoreline in and around Goma. During two field missions in 2013, volcanic deposits associated with small eruptive centres within 4 km of the Lake Kivu shoreline were described for geometry, texture and lithology, using widely accepted criteria (White & Houghton, 2006). Where deposits were inaccessible, observations were complemented with those of Denaeyer (1975) and Capaccioni et al. (2003). Qualitative observations of clast type and componentry of representative facies were performed on thin sections. Twelve paleosol samples and one gastropod shell collected from seven different horizons were dated through radiocarbon dating at Beta Analytic Inc. (Florida, USA) using Accelerator Mass Spectrometry. Paleosol samples were collected from the soils in the uppermost parts of the deposits immediately below overlying, more recent lava flows (Poppe et al., *in press*).

**A database of Virunga volcanic rock geochemistry** was constructed from all existing published literature, completed with post-colonial reports from the RMCA archives. The database contains whole-rock, glass and mineral major and minor element compositions, the sample/source locations of which are localised in a GIS shapefile. This database provides an unprecedented base for future petrological work on the VVP and is accessible from www.virunga-volcanoes.com through a request form. A BSc project (VUB), and submitted manuscript (Barette et al., *in press*) performed a Principal Component Analysis (PCA) and cluster analysis on whole rock major element compositions, in order to search for spatial patterns of geochemical composition of Virunga volcanics.

**A tephrochronological study** of Virunga tephra was initiated end of 2015 in collaboration with Dr. Christine Lane (Cambridge University, UK), with involvement of different scientific teams active in the Kivu area, *i.e.* C. Ebinger (University of Rochester, USA), C. Scholz (Syracuse University, USA), and M. Schmid and K.-A. Ross (EAWAG, Switzerland). Microprobe major and minor element analysis was performed in July and

October 2016 at Oxford University on tephra sampled from 1) subaerial phreatomagmatic cones along Lake Kivu's northern shore (GeoRisCA); 2) lake Kivu sediment cores (EAWAG, Switzerland; Syracuse University, USA; Zhang et al. 2014); 3) the summit crater lakes of Gahinga and Muhabura volcanoes (Dublin, Ireland; McGlynn et al. 2013); and 5) a pumice sample from the only explosive layer deposited at Karisimbi's summit caldera 'La Branca', (De Mulder, 1980; RMCA). Geochemical tephra layer fingerprinting, in combination with existing radiocarbon chronologies, will allow to integrate the scattered chronology into a VVP-wide geochronological framework of Holocene, ash-producing (*i.e.* explosive) volcanic eruptions, and to relate at least some of the tephra layers in the sedimentary record of Lake Kivu to their volcanic source, in the VVP or in nearby volcanic segments of the EARS. This effort was initiated in a late stage of GeoRisCA and results will only be available after an international publication foreseen for 2018.

## RESULTS

**The geological analysis of the Lake Kivu bathymetry** resulted in a mapping that covers the volcanically active area of the main lacustrine basin at an unprecedented resolution for Lake Kivu. New geomorphologic features identified on the lake floor can accurately describe related lake-floor processes for the first time. The late Pleistocene low-stand is observed at 425 m depth, and volcanic cones, tuff rings, and lava flows observed above this level indicate both subaerial and subaquatic volcanic activities during the Holocene. The geomorphologic analysis yields new implications on the geologic processes that have shaped Lake Kivu's basin, and the presence of young volcanic features can be linked to the possibility of a lake overturn (Ross et al., 2015).

**The phreatomagmatic deposits** along the northern shoreline of Lake Kivu provided a comprehensive Holocene radiocarbon chronology, concluding that:

1. Phreatomagmatic deposits from satellite eruptive centers of Nyiragongo and Nyamulagira volcanoes, along the Lake Kivu shoreline, can be subdivided into three types: tuff breccias from vent-clearing explosions; palagonitized tuffs and lapilli tuffs from water-rich phreatomagmatic eruptions; and coarse and fine lapilli tuffs from medium-wet to near-dry phreatomagmatic eruptions. A limited number of scoria and spatter cones formed by dry magmatic eruptions are also present.
2. At least 24 phreatomagmatic events constructed at least 15 phreatomagmatic tuff cones, rings and maars in the last ~12.2 k.a. within a 4 km distance from the current northern shoreline of Lake Kivu (Figure 7). Deposit characteristics suggest that dilute Pyroclastic Density Currents (PDC) and ash fallout repeatedly affected the major part of the presently urbanised area (>1.2 million inhabitants in 2015; Fig. 2.3).

3. Within the past 2,500 years at least five lava flow events occurred within the broader Goma area, two of which occurred in the past 500 years, and at least five phreatomagmatic eruptions with centennial to millennial recurrence rates, similar to the rate estimated from 24 tephra layers in Lake Kivu tephra record (Wood & Scholz, 2016).
4. We dated the occurrence of the Buyinga lava flow from Nyiragongo 1,000-800 years ago and it was preceded, by tens to a few hundred years, by the most recent phreatomagmatic phase of the Mt Goma cone complex. This demonstrates Mt. Goma was constructed relatively recently. Moreover, the Mt. Goma is contemporaneous with a lake stratification destabilization event in Lake Kivu identified by Ross et al. (2015), but does not represent causal evidence.

Poppe et al. (*in press*) and its' Supplementary Materials provide further detail and field observations. Thanks to the field campaigns and obtained results, with the involvement and field training of GVO scientists, explosive magma-water interaction, or phreatomagmatism, is now considered a likely eruption scenario in the most recent contingency plan of the city of Goma. To further improve the spatial and temporal susceptibility model for the phreatomagmatic hazard along Lake Kivu's northern shoreline, the established geochronological framework and lithofacies analysis should be extended, both in sub-aerial and sub-lacustrine environments, and detailed analysis of the Mt. Goma and Lac Vert eruption dynamics should be carried out using convential physical volcanology and petro-geochemical analysis.

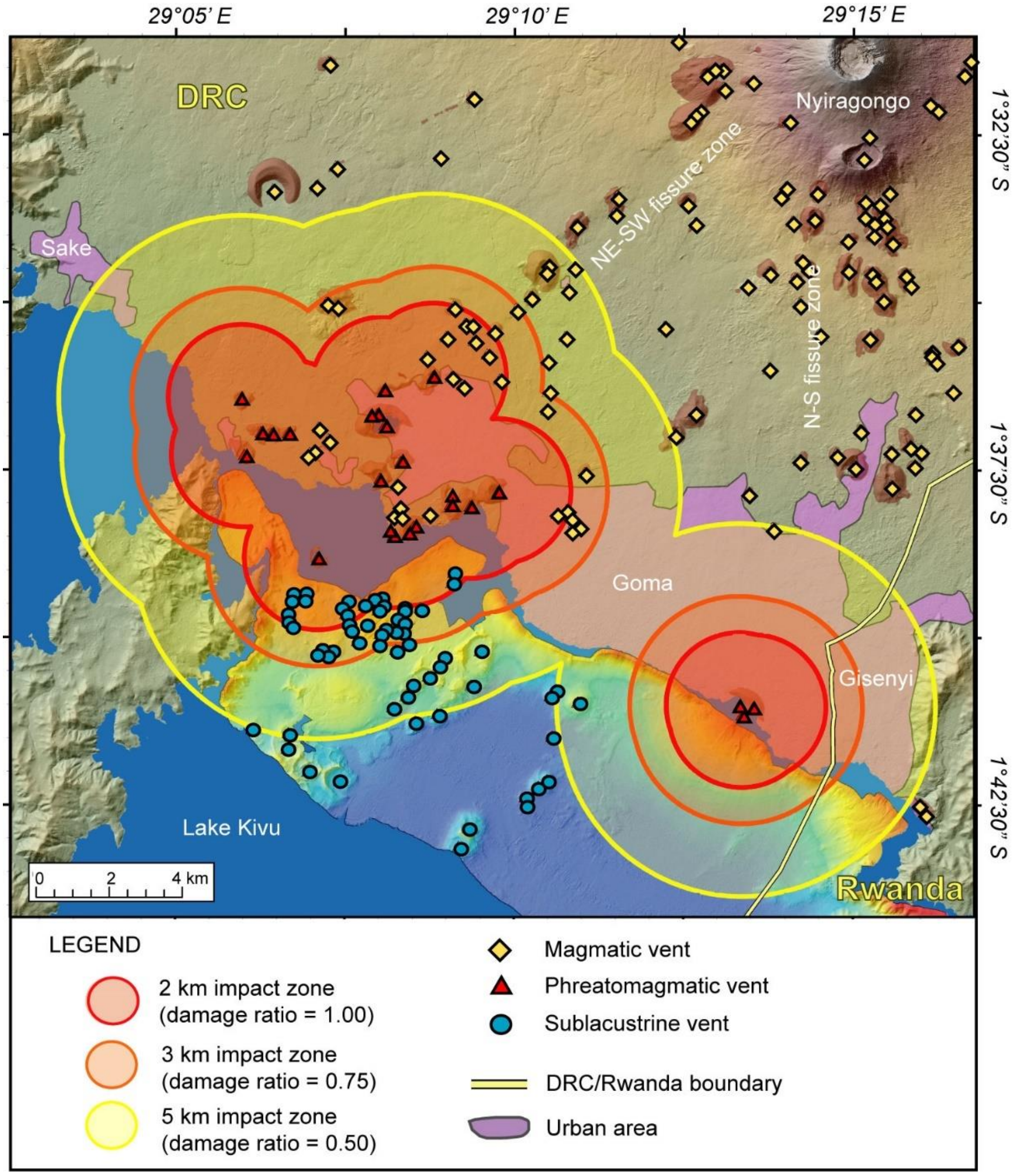



*Figure 7. Spatial extent of the area potentially impacted in the past ~12.2 k.a. by PDCs from past phreatomagmatic eruptive vents along Lake Kivu's northern shoreline. All subaerial phreatomagmatic vents are inferred to be of Holocene age, while the currently sublacustrine vents are assumed to have formed during periods of lower lake levels before ~12.2 k.a. (Ross et al., 2014). The impact and spatial extent of PDCs during a potential future phreatomagmatic eruption in the urban area would depend among others on the future vent location, eruption intensity and duration, and wind direction. The buffers represent areas of infrastructure damage ratios estimated by Deligne et al. (in rev.), based on dynamic pressures in the PDCs modeled for a 'worste-case' scenario in the analogue Auckland Volcanic Field, New Zealand (Brand et al., 2014). This map presents a qualitative estimation of the total area potentially impacted in the past by phreatomagmatic deposits from small eruptive centres, and should not be interpreted as a probabilistic hazard map. From Poppe et al.* (in press).

**The integrated database of existing geochemical analyses** includes a total of 908 entries with 716 whole rock geochemical analyses for the entire VVP and includes information about the localisation of the rock samples. A statistical analysis of the overall consistency of the database on subsets of geochemical analyses demonstrated that the database is consistent. The performed spatio-statistical study confirms previously observed geochemical gradients and provides new insights into the geochemical variability of eruptive products in the VVP (Barette et al., *in press*):

1. Products from volcanic vents related to the Nyamulagira and Nyiragongo volcanic systems are clearly separated based on their geochemistry despite their spatial overlap in the Bulengo area.
2. Two derived geochemical clusters correspond to less differentiated lavas that are representative of a deep magmatic source, as confirmed by earlier trace element and isotope studies on sample subsets (*e.g.*, Condomines et al., 2015). These more primitive compositions erupted across the entire VVP, at great distances of the main volcanic edifices, and preferentially along NE-SW volcanic alignments, interpreted as the trace at ground surface of deep crustal Precambrian structures reactivated by rifting processes. This is the case of the 1957 Mugogo eruption, which is the only historical eruption within the central part of the VVP and that was so far attributed to the magmatic system of Visoke volcano. These eruptions of primitive magma appear independent of crustal plumbing systems that feed the main volcanic edifices. Additional studies to better constrain their spatial and temporal occurrence are required to constrain the eruption hazard they may represent across the entire VVP in the future (Barette et al., *in press*).

### 2.4.3. Lava flow hazard analysis

#### METHOD

**Lava flow hazard simulation tool**: Existing lava flow simulation numerical models are not open-source or user-friendly. In the framework of GeoRisCA, a major effort was developed to integrate and improve some existing probabilistic and deterministic lava flow models by A. Feltz (MSc thesis, VUB) and by S. Mossoux (Ph.D. student, VUB) into a novel probabilistic numerical lava flow modelling tool, called Q-LavHA (QGIS Lava flow Hazard Assessment). The code is made freely available as a plugin with a user interface in the open-source geographical software QGIS. The tool offers three options to define the constraint on the simulated probabilistic lava flow length: a fixed maximum length, a waning probability at the lava flow front defined by a normal distribution function of lava flow lengths known for the studied volcano, and a thermo-rheological multi-parameter constraint based on the FLOWGO model (Harris & Rowland, 2001). The tool can be used for short-term or long-term hazard assessment by simulating respectively from a point (*i.e.* vent) or line (*i.e.* fissure), or by simulating from a Probability Density Function (PDF) map of vent opening susceptibility. The result in the latter case is then a probabilistic lava flow hazard map. The Q-LavHA code and applications are described in Mossoux et al. (2016).

**Lava flow hazard modelling of Nyamulagira/Nyiragongo**: Nyamulagira and Nyiragongo volcanoes represent a significant lava flow hazard to the urbanised area along the Northern shoreline of Lake Kivu. A lava flow hazard map for Nyamulagira and Nyiragongo volcanoes has been realised using Q-LavHA. Three input data are needed for the simulation of the lava flow hazard map: (1) a vent opening susceptibility PDF map, (2) a DEM, and (3) the calibration of Q-LavHA parameters based on past lava flows. A vent opening susceptibility map has been realised in ArcGIS by weighting the historic (*i.e.* the past ~120 years) and non-historic eruptive vents and fissures of Nyamulagira and Nyiragongo. An SRTM 90 m DEM was used as topographical basis, as higher resolutions for such large area result in level of details inappropriate for the scale of the produced map and require high computation capabilities. The model parameters for Nyamulagira were calibrated by systematically simulating recent lava flows of Nyamulagira (2004, 2006, 2010), both on steep slopes and the gently sloping lava plain (Peeters, 2015). The best-fit parameters for Nyiragongo were obtained from simulating the branches of the 2002 lava flow. Single lava flow simulations we ran on TanDEM–X DEM downsampled at 20 m, the SRTM 30m and 90 m DEM for comparison. The 2006 Nyamulagira flow is used as example in Mossoux et al. (2016). The best-fit parameter sets for each volcano were used to simulate from the age-weighted PDF maps a probabilistic lava flow inundation map (Table I), which represents the probability at which each pixel risks to be affected by a lava flow in the upcoming ~100 years. The map is provided with an explicatory notice in French and English to the Goma Volcano Observatory.

*Table I. Q-LavHA parameters used in the lava flow simulation.*

| | **Nyamulagira** | **Nyiragongo** |
|---|---|---|
| **Lava flow length**[1] | | |
| Mean (m) | 13180 | 5940 |
| Standard Deviation (m) | 6100 | 3150 |
| **Thickness parameters**[2] | | |
| $h_c$ | 3.5 | 1 |
| $h_p$ | 7 | 3 |
| **Distance between the vents (m)** | 450 | 450 |
| **Iterations** | 50 | 50 |
| **Minimum PDF value**[3] | 0.000005862 | 0.000005862 |

[1] The mean and standard deviation of the lava flow length was calculated based on the 1977 and 2002 lava flows of Nyiragongo, and the lava flows of Nyamulagira volcano from 1938 untill 2012.
[2] These parameters approach respectively the minimum and maximum lava flow thickness.
[2] This represents the lower 20% of the vent opening susceptibility map.

## RESULTS

**Nyiragongo 2002 lava flow** Q-LavHA simulations (Table II; Figure 8) show that the 2002 lava flow displayed a complex branching pattern, with overall high fit of the simulations with the actual flow outlines, resulting in slightly different best-fit simulation parameters for each branch. An average of all best-fit parameters could be used in a similar future lava flow crisis to produce a first-order short-term hazard assessment in Q-LavHA on a low-resolution DEM within minutes using the new vent location.

Figure 9 shows the **map of vent opening susceptibility** for the upcoming ~100 years, used as a base for the lava flow hazard map. **The lava flow hazard map** for the part of the rift valley containing Nyamulagira and Nyiragongo volcanoes is presented in Figure 10. In general, the lava flow hazard increases with increasing distance from Nyamulagira and Nyiragongo volcano, as multiple lava flow branches converge together. The outline of the 2002 lava flow of Nyiragongo and the 2001, 2002, 2004, 2006, 2010 and 2011 – 2012 lava flow of Nyamulagira demonstrate a good fit with moderate, high and very high lava flow hazard classes. High and very high lava flow hazard threatens parts of the densely populated city of Goma, the Bulengo area, the West and North of Nyamulagira area, the main road Goma- Rutshuru and to a lesser extent Sake. This map demonstrates that the Lac Vert – Bulengo area classifies among the areas yielding the highest hazard of lava flow inundation in the upcoming ~100 years, with significant implications for future spatial planning and risk mitigation strategies. With every future eruption of Nyamulagira or Nyiragongo, both the vent opening susceptibility map and the probabilistic lava flow inundation hazard map should be updated using a GIS software and Q-LavHA respectively, especially when new volcanic cones are formed in the flow fields and causing perturbation of the main drainage pattern.

*Table II. Best fit simulation parameters for the Nyiragongo 2002 eruption.*

| Simulated vent location | DEM | Hc | Hp | Max. Length (m) | Number of iterations | Thres-hold. | True posit. | True negat. | False negat. |
|---|---|---|---|---|---|---|---|---|---|
| NW flank Nyiragongo | TanDEM-X 20m | 0.4 | 1 | 3400 | 1500 | 0.5 | 0.47 | 0.46 | 0.07 |
| Shaheru crater | TanDEM-X 20m | 2.5 | 3 | 2700 | 1000 | 0.5 | 0.70 | 0.17 | 0.13 |
| South Shaheru – West | TanDEM-X 20m | 0.5 | 2 | 7000 | 1000 | 0.5 | 0.34 | 0.09 | 0.57 |
| South Shaheru – East | TanDEM-X 20m | 1 | 2 | 13000 | 1500 | 0.5 | 0.51 | 0.30 | 0.19 |
| Lemera - Mudjoga | TanDEM-X 20m | 1 | 3 | 11000 | 1500 | 0.5 | 0.34 | 0.55 | 0.11 |
| West Goma | SRTM 90m | 1 | 3 | 12000 | 1000 | 0.5 | | | |
| Goma | SRTM 90m | 2 | 4 | 8000 | 1500 | 0.5 | 0.41 | 0.52 | 0.07 |

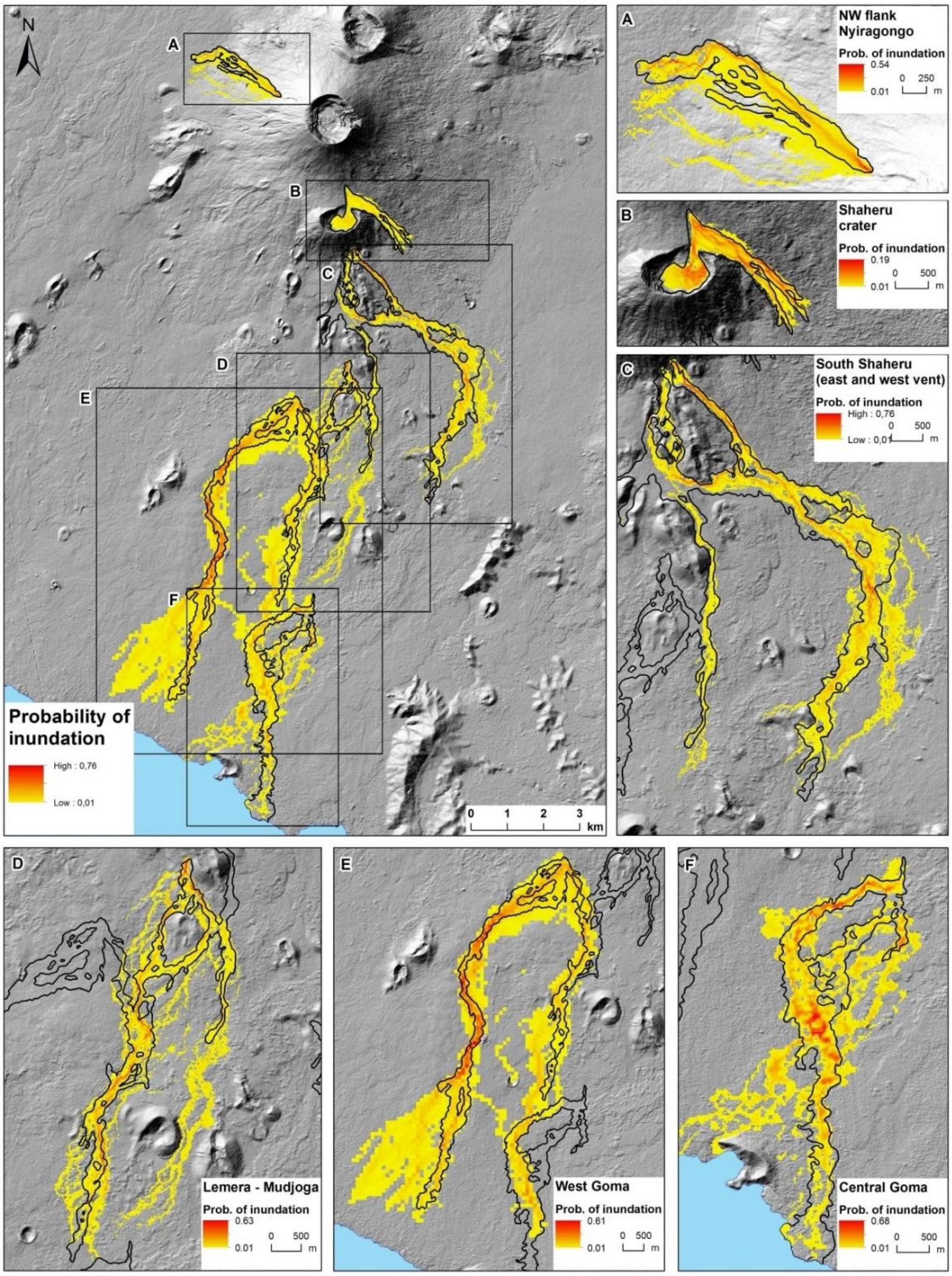



*Figure 8. Probabilistic best-fit Q-LavHA simulations of lava flow inundation probability for the branches of the 2002 lava flow of Nyiragongo. Background: TanDEM-X DEM hillshade image (Albino et al., 2015).*

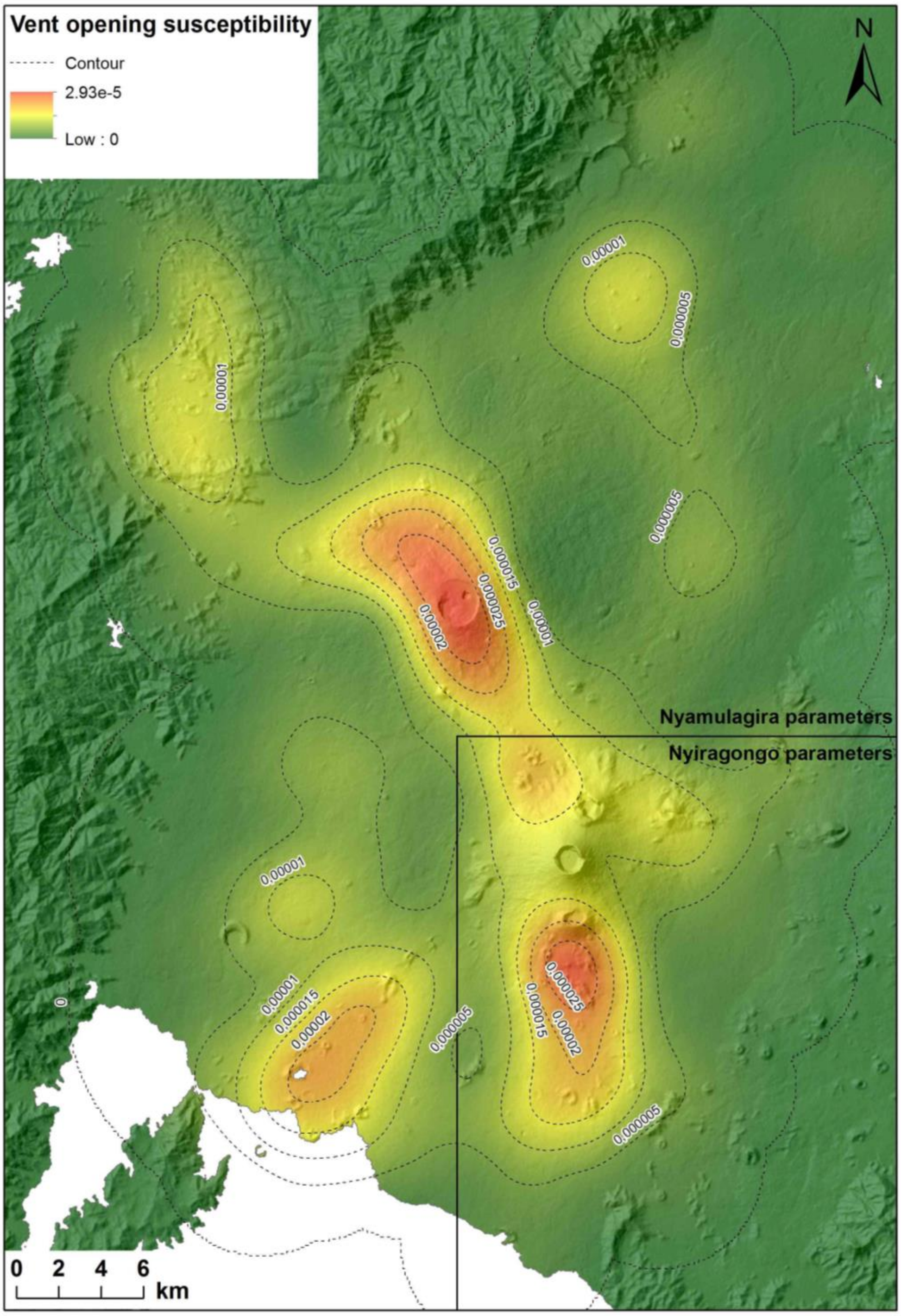



*Figure 9. Vent opening susceptibility map of the intra-rift part of the Virunga Volcanic Province for the upcoming ~100 years, produced in ArcGIS software, calculated from the positions of eruptive vents and fissures mapped from post-colonial reports, published literature and a morphological analysis of the TanDEM-X DEM hillshade image (in the background; Albino et al., 2015). Highest susceptibilities can be found along the NW-SE oriented rift zone of Nyamulagira and towards Nyiragongo, the southern flank of Nyiragongo, and the Rushayo – Lac Vert – Bulengo area to the West of Goma city, where Poppe et al.* (in press) *also demonstrated a high prevalence of Holocene phreatomagmatic eruptive centres and small-volume lava flows.*

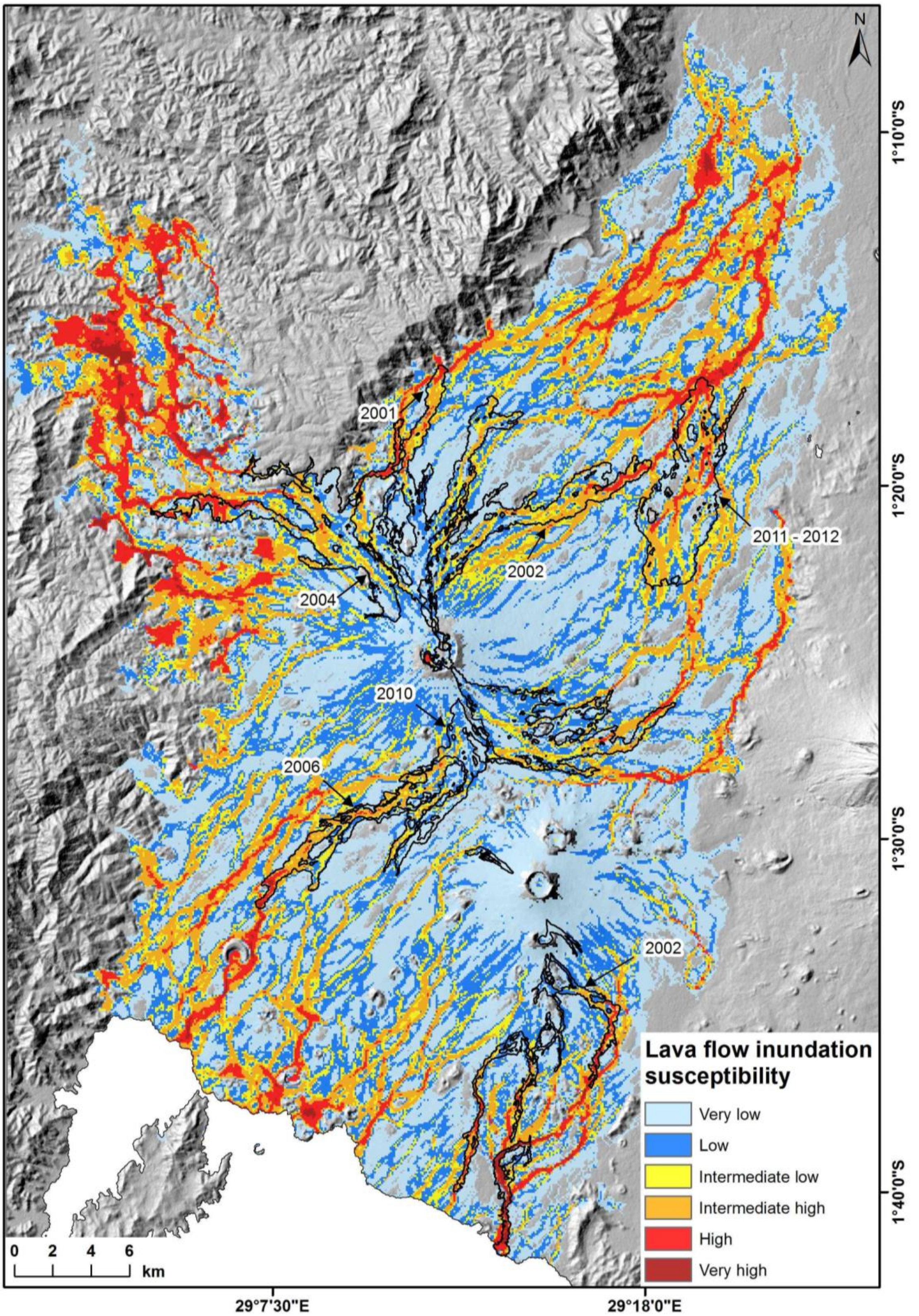



*Figure 10. Lava flow inundation susceptibility map of the intra-rift part of the Virunga Volcanic Province, displaying hazard for each pixel to be inundated by a lava flow in the upcoming ~100 years. Modeling was carried out in the Q-LavHA plug-in with the SRTM DEM at 90m resolution acquired in 2000 as a topographical base. The model input parameters for Nyamulagira and Nyiragongo as reported in Table 2.1. Good fits between the Nyamulagira 2001, 2004, 2006, 2010 and 2011-2012 flows and the Nyiragongo 2002 flows, and intermediate to high inundation*

*susceptibilities are shown. This map demonstrates several areas of high to very high susceptibility within the city of Goma and to its west, in the Lac Vert – Bulengo area and towards the smaller city of Saké. This map should not be reproduced without prior consent of the authors.*

### 2.4.4. Gas as a volcanic hazard: *Mazuku*

#### METHODS

$CO_2$ concentrations were measured in two Mazuku sites surrounded by habitations, in Goma ("Le Chalet" site) and Bulengo (Buhimba site), in order to study the dynamics of gas in these dangerous places. Measurements lasted 5 days (Nov. 2013) and 1.5 years (2012-2013) for the Buhimba and Le Chalet sites, respectively. These surveys were coupled with the measurement of meteorological parameters at both sites and radon fluxes at Le Chalet.

#### RESULTS

Results show that the evolution of radon concentrations at *Le Chalet* site is directly proportional to the evolution of $CO_2$ concentrations. Such correlation was expected, as $CO_2$ is the vector which transports radon towards the ground surface. Decorrelation between the two gases that could indicate stress change related to the magmatic/volcanic activity was not observed during the monitoring period. Results also show that concentrations close to the ground surface are less influenced by meteorological parameters. The first centimetres of air in the mazuku depression can always maintain a deadly concentration of $CO_2$. $CO_2$ concentration is higher during night-time and directly after rainfalls.

Preliminary results from the remote sensing and geomorphological analysis show that some mazuku, identified as such in the field, can be related to anomalous low NDVI values, closed topographic depressions, and the edges of lava flow fronts. This is however not the case for all identified mazuku, and most likely the spatial extent and temporal continuity of Mazuku activity play a major role in this observation.

### 2.4.5. Limnic eruption in Kabuno bay?

The **potential of limnic eruption in the Kabuno Bay** was investigated through data compilation and analytical modelling, in the framework a sub-contracting mission by Dr. F. Darchambeau (ULg). The water column of Kabuno Bay is characterised by a very stable chemocline (salinity, pH, temperature) at ~11 m deep irrespective of the sampling period (Borges et al., 2011). Deep waters of the bay are enriched in salts, $CO_2$ (Tietze, 1978; Tassi et al., 2009) and $CH_4$ (Borges et al., 2011, this study). Most likely, subaquatic springs are the source of the salts and $CO_2$ observed in deep waters. These subaquatic springs are an essential feature of the physics of the bay, as they are for the main basin of Lake Kivu (Schmid et al., 2005).

New observations of gas concentrations indicate that concentrations approach saturation at some depth in the Kabuno Bay. Particularly at 15 m depth the total gas pressure reaches 85% of hydrostatic pressure, which is relatively higher than in the main basin of Lake Kivu where, at maximum, saturation reached 56 % at 330 m in 2003 (Schmid et al., 2005). Nevertheless, the situation in Kabuno Bay contrasts in several ways with the one in the main basin of Lake Kivu. First, absolute gas concentrations and total gas volume are much lower in Kabuno Bay than in Lake Kivu (~2.9 $10^6$ $m^3$ and 360 $10^9$ $m^3$ at *Standard Temperatures and Pression*, respectively). Second, the near-saturating concentrations are shallower and closer to the main density gradient and the oxic zone in Kabuno Bay than in the main basin of the lake. Therefore, loss processes of accumulating gas such as diffusion and, for $CH_4$, oxidation is very active. While simultaneously the upwelling of the water column caused by the inflows at depth of ground waters uplifts the near-saturation zone, diffusion permanently transports gases upward to the mixing zone where they are then exchanged with the atmosphere (Borges et al., 2012, 2014), oxidized (Borges et al., 2011) and/or flushed out to the main basin of the lake.

Moreover, the water column of Kabuno Bay presents a highly stable density stratification (*i.e.* salty/heavier water at depth, underneath fresher/lighter water at the surface), which currently prevents the gases present in high concentrations in deep water from mixing upwards and is therefore crucial for safety. A hazard assessment demonstrated that the occurrence probability of a wind-induced mixing until near-saturation depth is null. Nevertheless, other powerful natural event (*i.e.* sub-lacustrine magmatic eruptions, earthquakes, hot lava flows from surrounding volcanoes, landslides along lake shores, etc.) could potentially initiate convective or advective transports of deep waters, followed by a disastrous gas outburst from Kabuno. Localization, magnitude and probability of such events were not evaluated during this study. Although the probability of such catastrophe is by nature rather limited, the possibility of a disastrous gas outburst cannot be completely ruled out.

Finally, the natural evolution of gas concentrations should be regularly measured and we recommend to regularly monitor gas concentrations as well as other parameters influencing water density and water column stratification (salinity and temperature) of Kabuno Bay. Such monitoring should be performed at 3-6 years' time interval.

### 2.4.6. Close Range Photogrammetry of the Nyiragongo crater to build 3D models

#### METHODS

A 3D dense point cloud of the Nyiragongo crater was produced by "Structure-from-Motion" (SfM) photogrammetry, using geotagged images acquired from a helicopter flight on 5th July 2014. This point cloud allowed the production of a **DEM and an orthophoto of Nyiragongo crater** with a resolution of 25 cm and 15 cm, respectively. According to the used geographic coordinates of the geotagged photographs, the relative accuracy of the geocoding is 16.8 m, *i.e.* 10.3 m, 10.9 m and 7.7 m, in X, Y and Z, respectively (Smets et al., *in press*).

There is no other georeferenced 3D model available to assess the absolute horizontal and vertical accuracy of the produced model of the Nyiragongo crater. However, using a SPOT-5 image (pixel resolution of 2.5 m) of the crater acquired in July 2009, we can assess its horizontal accuracy. For that, 10 control points were selected on the SPOT-5 image and their location compared on an orthophoto derived from the 3D model of the crater. As the SPOT-5 image was orthorectified using the SRTM-1 DEM (© NGA/NASA) and accurately georeferenced using a series of 24 ground control points acquired with a differential GPS in the urbanised areas surrounding the volcano, the accuracy of the control points selected on the SPOT-5 image is assumed to be of the order of the pixel size (*i.e.*, 2.5 m). The 10 control points revealed a rotation error in the geocoding, which is linked to the movement of the helicopter during the geotagged-image acquisition. This induces a large horizontal location error of maximum 45 m (Smets et al., *in press*). However, by comparing the horizontal distances between the selected control points (*i.e.* 90 baseline distances) measured on the SPOT-5 image and the orthophoto, a scaling error of maximum 2.9 % is detected, which is relatively good regarding the geocoding method applied here. As a consequence, the produced 3D model of the Nyiragongo main crater only provides a suitable reference for measuring distances and surface/volume changes (Smets et al., *in press*).

Additional image datasets of part of the crater on 28 September 2011, 23 April 2012, 8 March 2013 and 5 July 2014 were provided by D. Tedesco (University of Naples II, Italy). 3D point clouds were produced with these images and were co-registered on the georeferenced 3D point cloud using the Iterative Closest Point algorithm available in the CloudCompare software.

**RESULTS**

Thanks to these three 3D models of the Nyiragongo crater, a mean lava lake level decrease of 68 was estimated between September 2011 and July 2014. The long-term lava lake decrease observed between March 2012 and July 2014 was associated with the development of ring fissures on P3, around the lava lake pit, which were visually observed during fieldwork and on photographs. These ring fissures are interpreted as evidence of ground subsidence of P3 close to the pit. This subsidence is best illustrated by the difference between digital elevation models (DEM) derived from the 3D point clouds of the Nyiragongo crater produced using images acquired on 8 March 2013 and 5 July 2014, which are the most detailed and less noisy point clouds of the Nyiragongo crater produced with images acquired by helicopter. This ground deformation was also detected by SAR interferograms (Geirsson et al., *in press*.).

### 2.4.7. Study and monitoring of lava lake activity

**METHODS**

To study the Nyiragongo lava lake level, we developed a Stereographic Time-Lapse Camera (STLC) system to measure lava lake level variations. The STLC comprises two time-lapse cameras that synchronously take photographs of the lava lake. The main goal of this instrument is to regularly collect stereo-pairs of photographs, in order to create a time-series of 3D point clouds using SfM photogrammetry. The comparison of these 3D models can then be used to measure topographic changes related to the lava lake activity. To scale the produced 3D time-series, we used the georeferenced 3D model of the crater, the image-based alignment option of the PhotoScan Pro software and the Iterative Closest Point algorithm available in the CloudCompare software (Smets et al., *in press*).

Installed in September 2011 on P1, along the southern inner flank of the crater, the STLC system acquired a first dataset during 48 hours (18-20 September 2011), at a rate of one pair of images every 2 minutes, allowing the first measurements of gas piston cycles at the Nyiragongo lava lake with an unprecedented resolution of 0.5 to 1 m. Stereo-pairs of images were also acquired with the STLC system in September-November 2011 and March-May 2012, at a frequency of 4 image pairs per hour. Stereo-pairs allowing the measurements of the lava lake level using close-range photogrammetry are however limited to 33 pairs for the period from 26 September to 5 October 2011 and 20 pairs for the period from 10 March to 18 March 2012, as steam and outgassing from the lava lake prevented the visibility during other periods of data acquisition.

### RESULTS

Results from the 48h time series of September 2011 show that the lava lake exhibited metre-scale vertical gas piston cycles that commonly lasted a few tens of minutes. According to our observations and the resolution of measurements, gas piston cycles at Nyiragongo show similarities with those observed in Hawaii Additional investigations are however required to better constrain the relationship between those level variations and the dynamics of outgassing. These results were published by Smets et al. (*in press*).

These STLC data from the multi-week time series, together with field observations, revealed that the observed decrease of the lava lake level between 2012 and 2014 is not progressive and occurred through sporadic hour- to day-long variations. This observation of sporadic variations responsible of long-term lava lake level changes is confirmed by the innovative SAR technique to measure lava lake level changes. This technique uses high-resolution SAR amplitude images and consists of measuring, in the slant-range direction, the shadow induced by the vertical flanks of the lava lake's pit crater and, then, assessing the height different between the pit crater rim and the lava lake surface using simple trigonometry.

Using SAR measurements, we also produced the first accurate measurement of lava lake and Platform 3 level changes after the 2002 eruption of Nyiragongo, from May 2006 to February 2016. Results highlight the level increase of Platform 3, by lava lake overflowing up to 2008. This is followed by a progressive stabilization of the Platform 3 level. Starting from June 2011, large decametric variations of the lava lake level are measured and correlate with the results of the photogrammetric approach, validating the SAR technique for lava lake level measurement.

Results on the evolution of the lava lake level between 2011 and 2016 are partly found in the Ph.D. Thesis of B. Smets (Smets, 2016) and were presented at the AGU Fall Meeting in December 2015 and at the EGU General Assembly in April 2016. Their interpretation is still in progress.

## 2.4.8. Space borne InSAR techniques for ground deformation monitoring

### METHOD

The very large InSAR archive database started in 2005 was updated regularly with each SAR data (COSMOSkyMed, RadarSat, TerraSAR and TanDEM-X, ENVISAT, ERS, ALOS and Sentinel 1) made available to us through this project or additional projects (> 800 SAR images, which led to several thousands of interferograms). Conventional DInSAR mass processing and data mining tools were developed in the frame of previous projects (d'Oreye & Celli, 2010). The present project also benefits from outputs of other on-going

BELSPO funded projects (namely RESIST and MUZUBI) where our InSAR processing chain was updated to the use of CSL InSAR Suite software and to the most recent sensors. We performed mass processing DInSAR on active volcanoes and landslides in Bukavu (See Section 2.4) as well as conventional time series analysis point target (Persistent Scatterers) and Small Baseline Subset (SBAS) techniques (Hooper, 2008, Samsonov et al., 2010). We also used the MSBAS method, which is an advanced multidimensional time series analysis allowing the combination of multiple SAR data acquired with different acquisition parameters, such as azimuth and incidence angles, spatial resolution, wave-length or polarity, to retrieve vertical and horizontal displacement time series (Samsonov & d'Oreye, 2012, Samsonov et al., 2013). However, because the equatorial vegetation induced rapid decorrelation in the Virunga to build continuous small baseline subsets with appropriate temporal and spatial baselines, we used a newly developed version of the MSBAS method (Samsonov & d'Oreye, *submitted*, Samsonov et al., *submitted*). Indeed, the set of linear equations that comprises MSBAS is usually rank deficient and is solved in the least-square sense by applying the Singular Value Decomposition (SVD) and a Tikhonov regularization. In the new version of the MSBAS software, the regularization can be of order up to two. In case of the first and second order regularizations, the solution is found by least square fitting of data and by minimizing the first and second differences between consecutive in time deformation rates. This allows better estimation of the deformation velocity in the presence of small temporal gaps in small baseline subsets.

Software was developed to assist the analysis of deformation time series by performing outliers and trend changes detection (Arjona et al., *in prep*.). Deformation maps were modelled using analytical (Cervelli et al., 2001) or numerical method (3D numerical modelling based on boundary elements, Cayol & Cornet, 1997) to evaluate source(s) parameters.

Spaceborne data were complemented by ground-based measurements from the local permanent geodetic KivuGnet network (Geirsson et al., *in press*) and their analysis was assisted using results from the seismic KivuSNet network (Oth et al., 2016). KivuGNet and KivuSNet are both operated and maintained by NMNH/ECGS, RMCA and GVO.

Each of the thousands of deformation maps, coherence maps and SAR amplitude maps are stored on servers and readily available for use with any conventional GIS tool.

## RESULTS

**Short-term deformations** associated to various eruptions at Nyiragongo and Nyamulagira were detected using DORIS, SARscape and CSL InSAR Suite and analyzed and modeled in detail. These results improved significantly our knowledge about the magmatic systems in the Virunga.

Wauthier et al. (2012) showed that **the 2002 eruption at Nyiragongo** was associated to a 40km long deep dike that extended below the Lake Kivu and that stopped 3 km below the surface. A shallower dike reached the surface along a 20 km long network of fractures and caused the drainage of Nyiragongo's lava lake. The low value of magma overpressure inferred in these dikes shows that the dike direction is probably not controlled by stresses but rather by a reduced tensile strength, inherited from previous rift intrusions. The lithostatic stresses indicate that magmatic activity is intense enough to relax tensional stresses associated with the rift extension.

Ground deformations associated to **Nyamulagira recent eruptions** (1996-2012) were also studied in detail and allowed to identify shallow (～3-4 km below the summit) and deep (～25 km) magma chambers and various dike intrusions (Wauthier et al., 2013, Wauthier et al. 2015a). The study of these eruptions shows that proximal eruptions are fed from the shallow reservoir through dikes while distal eruptions can be fed directly from the deep reservoir (Wauthier et al., 2015a). From a normal-stress change analysis, it is inferred that intrusions in 2010 could have encouraged the ascent of magma from a deeper reservoir and possibly resulting in the 2011–2012 intrusion. Repeated dike intrusions beneath Nyamulagira's SSE flank may also encourage intrusions beneath the nearby Nyiragongo volcano.

Based on InSAR studies of the January Nyiragongo 2002 eruption and the October 2002 **Kalehe Mw 6.2 earthquake** (the largest event recorded in the Kivu basin), a Coulomb stress analysis suggests that diking events, such as the 2002 Nyiragongo dike intrusion, could promote faulting on the Western border faults of the rift in the central part of Lake Kivu (Wauthier et al., 2015b). This shows that dike-induced stress changes can cause moderate to large-magnitude earthquakes on major border faults during continental rifting and suggests that dike intrusions play a major role in accommodating upper crustal extension in this part of the EARS, which is often considered as a magma-poor rift.

**The study of November 2011 eruption** at Nyamulagira volcano using TerraSAR-X add-on for Digital Elevation Measurement (TanDEM-X) data also allowed to compute several high resolution (5m) DEM. Their absolute vertical accuracy (1.6m) was obtained thanks to the comparison with GPS measurements acquired around Nyiragongo and Goma area. The difference between pre- and post-eruption high resolution DEMs provided the first accurate thickness map of lava flows emplaced during an eruption at Nyamulagira. Values range from 3 m along the margins up to 35 m in the middle. Re-evaluation of the volume of historical eruptions at Nyamulagira shows that the volume of the long-lived eruptions such as 2011-12 may be largely underestimated if they are based on the mapping of the flows multiplied by the 3m mean thickness used in the literature (Albino et al., 2015).

Ground deformations observed through DinSAR technique suggest that an intrusion that brought the magma from a source below the caldera to the eruptive vents located ~11 km ENE started about two days prior the lava outburst. Using analytical models, we tested different deformation sources: 2 dikes (one below the caldera and one aligned with the two eruptive vents), a deflating point source (below the caldera) plus one dike or a sill from the source to the vents, and the same deflating source with a sill that turns into a dike. Currently we are using InSAR time series to better understand the time evolution of the eruption and to identify the best source model. Furthermore, an unusual large patch of deformation of 20 km radius was also identified by InSAR and confirmed by GPS around Nyiragongo area during the eruption. This seemed related to a deep magma reservoir that feed the shallower eruptive source. Identified deformations are analyzed and compared with theoretical deformation (models) such as simple elastic analytical solutions (Mogi, 1958; Okada, 1985).

**Long-term deformations** in the Virunga have been detected through InSAR time series analysis (Wauthier, 2011; Samsonov & d'Oreye, 2012). These deformations related to pre-, co- or post-eruptive activity or other (un)related phenomena were studied by means of SBAS and PS time series method using STamPS software (Hooper, 2008) as well as with MSBAS (Samsonov & d'Oreye, 2012). Other deformations related to landslides were analyzed using time series methods (STamPS and MSBAS) in the Bukavu region.

While studying the **Nyamulagira 2010 eruption**, MSBAS allowed the first unambiguous detection of a long-term pre-eruptive deformation occurring before an eruption in the Virunga (Smets et al., 2014a). That deformation was correlated with changes in seismic and gas emission rates. However these changes were too small to be detected and interpreted alone as possible pre- eruptive signals. Although this requires deeper studies, it potentially represents a milestone in the contribution to hazard assessment in the Virunga.

Very local meter-scale ground deformations were detected inside the **crater of Nyiragongo** (out to ~200-300 m distance from the ~200 m-wide lava lake) using times series of high resolution and low look angle SAR data (RADARSAT-2 and TSX-TDX data). The SBAS time series method allowed characterizing the linear deformation of about 50 cm in 15 months, in the satellite line of sight. The deformation (both in amplitude and location) is confirmed by comparison with differences of photogrammetry-derived DEM models (Smets et al., *in press*). The deformation rate does not seem to be directly related to the lava lake level (see Task 2500), excluding mechanical (elastic) forcing as the responsible process. This leaves us to conclude that thermal contraction and mechanical compaction are driving the deformation of crater bottom (Geirsson et al., *in press*.).

Amplitude SAR data were also used to monitor the evolution of the collapse of the Nyamulagira crater, the emergence of a new lava lake in its pit crater (Smets et al., 2014b), to better define the time evolution of the 2011-2012 eruption, and to measure lava lake level variations in the crater of Nyiragongo.

Finally, a near-real time (1- day delay) **fully automatized GNSS processing** was set up using Bernese 5.2. The tool available in Luxembourg and Goma also assesses daily quality and station's health: observation time, number of observations and rejected data, number of cycle slips, multipath (environmental signal reflections), signal-noise ratio, uncertainties from processing results... The near-real time results using rapid orbits are seamlessly merged with results using final orbit products available with 1-3 week latency (Geirsson et al., *in press*). All results, including the station health and data quality graphs, are displayed on a password-protected webpage, which can be accessed by GeoRisCA partners. Comparison was performed with the analysis of the same dataset using GIPSY-OASIS. Both software show comparable short-term noise levels and long-term motion in the IGb08 reference frame. Kinematic analysis of low-latency (a few hours) data was implemented to run automatically since May 2016.

Analysis of **continuous GPS measurements** successfully completed the InSAR results by confirming co-eruptive deflations associated to 2010 and 2011-12 Nyamulagira eruptions but also revealing slow, fairly constant, weak though clear inter-eruptive inflation signals attributed to **on-going magma accumulation under the Nyamulagira-Nyiragongo volcanoes** (Geirsson et al., *in press*) that superimposes on plate motion across the Western – East Africa Rift. A combination of Kalman filtering and principal component analysis also allowed detecting a **pre-eruptive signal** that started 6 months prior the 2011 eruption at Nyamulagira. A Mogi point source at a depth >10 km can explain the displacement field suggesting a relatively deep source for the magma chamber that generated the inflationary signal (Ji et al., *in press*). GPS time series also revealed a small widespread deflation signal that seems to start approximately 3 days before the 2011-12 eruption broke the surface, accompanied by increased seismic activity, and additional local deformation signals from shallower sources. The most straight-forward interpretation of the InSAR and GPS signals is that magma started leaving the deeper parts of the magma plumbing system (the GNSS data are best fit by an ellipsoidal magma chamber at ~13 km depth) a couple days before the magma ruptured the surface (Nobile et al., in prep.).

Finally, as explained in the next section, landslides constitute another type of hazard threatening the region of Bujumbura (Burundi), Bukavu (DRC), and the area around the lake Kivu. Various processes have been identified and studied, in order to improve forecasting such catastrophic events.

## 2.5. Mass movement hazard: local and regional scale studies

Before the start of the project, Belgian, and also international landslide research in the GeoRisCA study area was limited to a few case studies targeting urban areas of Bukavu, Uvira and Bujumbura (*e.g.* Moeyersons et al., 2004; 2010). Those studies described mainly basic processes observed in the field. The scarcity of landslide investigation in the region was confirmed through a thorough literature review on landslide research in the tropics (Maes et al., 2017). In this review, we highlighted the need for landslide research in the region considering the high density of the population potentially at risk.

From a first regional visual analysis using Google Earth (easy to use; availability of high resolution images over large parts of the region, 3D morphology) we obtained a broad picture of the landslide context at the regional level and draw preliminary conclusions:

- Landslides are identified in many other places outside the urban areas.
- When a landslide is recent, visual detection is easier as vegetation is disturbed; sometimes, vegetation can even be absent. However such a situation is not frequent as vegetation regrowth is rapid in tropical environments.
- Most landslides are geomorphological historical features. In a geomorphological historical inventory, the age of the landslide is not differentiated. What often remains in the geomorphic record, or what we see in the landscape today, is probably a small percentage of the landslides that have occurred over the last (tens, hundreds or thousands of) years. Historical inventories can be the sum of many landslide events that have occurred over time.
- The vast majority of landslides are covered by vegetation; in most of the cases their land use/land cover characteristics is similar to those of the stable slopes. In addition, for the oldest landslides, their morphology can be partly reshaped by erosion.

The age of many landslides and the fact that most landslides are vegetated had strong implications in the realisation of the project:

- Rapid vegetation regrowth makes an automatic identification and delineation of landslides from optical remote sensing impossible. Visual analysis of remote sensing product is therefore the only way to compile a regional landslide inventory. Field validation is also needed.
- Landslide visual identification is less straightforward and therefore much more time consuming when features are vegetated than what is expected when recent event-based landslides are to be mapped. The situation worsens where the morphology is reshaped by erosion and weathering.
- In an event inventory, the date of landslides is known and corresponds to the date (or period) of the triggering event. The landslide trigger in this region can be a rainfall or an earthquake, sometimes combined. However, for most landslides that we mapped

the timing is unknown, which makes it more challenging to assess the triggering mechanism of the events.

These observations allowed us to better design the landslide hazard assessment to target different spatial and temporal scales. We will first present the results at regional scales (sections 2.4.1 & 2). Then we will focus on two local areas (sections 2.4.3 & 4) whose selection is driven from the results obtained at the regional level.

### 2.5.1. Regional landslide inventory – description of the processes at play

#### METHOD

Table III shows the various ancillary data used for the regional inventory:

- For the visual analysis and the geomorphologic detection and mapping of the landslides we used Google Earth images. It offers for most of the investigated region a harmonised cover of high-resolution images (often multi-temporal). Building-up of such a large cover would not have been possible through the acquisition and processing of new high resolution images within the time frame and budget line of the project. Since the visual identification for historical and multi-temporal inventories is time consuming, it was decided to restrict the focus on a target region that covers an extent smaller than the whole GeoRisCA area but that still includes the major urban centres, the rift flanks and the Ruzizi River (*i.e.* regions were potential risk is known to be high). It was also decided to consider only landslide features where detection is not questioned.
- To complete the regional inventory, information was also collected though archive sources (articles, governmental and non-governmental reports, Internet sources); the methodology is described in a similar research we did in the Rwenzori Mountains (Jacobs et al., 2016).
- Aware of the possible limitations related to the use of Google Earth due to poor topographic resolution, a specific focus was put on the rift flanks West of Lake Kivu. For this region, we used a high-resolution Digital Elevation Model (DEM) that was produced at a spatial resolution of 5 meters from TanDEM-X satellite data obtained by RMCA (Albino et al. 2015). This DEM (also used in WP 2000) is built from images between 2011 and 2012.
- 14 field campaigns carefully targeting representative areas were performed to validate the inventory.

*Table III. Ancillary data used for the regional landslide inventory, the regional susceptibility assessment, the landslide inventory in the rift flanks West of Lake Kivu, the landslide inventory, geophysical analysis and numerical modelling in Bujumbura; and the landslide inventory, hazard assessment and kinematics analysis in Bukavu.*

| | Year | Regional inv. | Regional susc. | Lake Kivu | Bujumbura | Bukavu | Origin |
|---|---|---|---|---|---|---|---|
| **Aerial Photographs** | 1950s - 1960 | | | | ■ | ■ | C |
| | 1970s | | | | ■ | ■ | C |
| **Archives** | last 15 years | ■ | | ■ | ■ | ■ | O |
| **Recent field campaigns and photos** | 2013 -2016 | ■ | | ■ | ■ | ■ | R |
| **Satellite images** | | | | | | | |
| Pléiades images (1) | 2010s | | | | D | D | R |
| Radar images (2, 3, 4) | 2010s | | | | | D | R |
| Google Earth images | 1980 -2000s | D | | D | D | D | O |
| **Orthophotos** | 2014 | | | | D | | O |
| **Topography (DEM)** | | | | | | | |
| 5 m resolution TanDEM-X (4) | 2015 | D | | D | | D | R |
| 10 m resolution | 2011 | | | | D | | O |
| 30 m resolution SRTM | | D | D | | | | O |
| **Natural environemt** | | | | | | | |
| Land cover | 2010s | | D | | | | O |
| Lithology (1) | 2016 | | D | D | | | R |
| Lava flow maps (1,3) | 2015 | | D | | | | R |
| Seismic catalogue | 2016 | | D | | | | R |
| Seimicity maps (1) | 2016 | | D | | | | R |
| Soil map, national (5) | 2016 | | | | D | | R |
| Soil map, regional | 2013 | | D | D | | | O |
| **Society** | | | | | | | |
| Administrative maps (1) | 2014 | | | | | D | R |

**D** = in digital format at RMCA; **C** = RMCA collection; **R** = RMCA research outputs ; **O** = other origin

1 = GeoRisCA (BELSPO-SDD, 2012-2016); 2 = RESIST (BELSPO-STEREOIII, 2014-2019); 3 = GORISK (BELSPO-STEREOII, 2007-2010); 4 = VI-X (BELSPO-STEREOII, 2012-2014); 5 = Carte pédologique du Burundi (BTC Project)

## RESULTS

From Google Earth, a regional historical inventory of 1780 landslides (hereafter called “regional inventory”) was compiled in a harmonised way at the regional scale (Figure 11). The most recent Google Earth images used in the inventory are from June 2014. The landslides are diverse in size (up to 2 km²), shape, processes, and time of occurrence. They appear in various environments (urban areas, rural areas, forested natural parks). For the landslides of unknown timing (the majority of them), the triggering conditions can be inferred in some cases (e.g. earthquake-triggered when distributed along major fault systems) (Maki Mateso and Dewitte, 2014; Dewitte et al., in prep.). Distinction between shallow and deep-seated landslides (*i.e.* landslides with a depth respectively < or > 5m) is important since the occurrence of shallow movements is much more sensitive to surficial environmental conditions (*e.g.* land use/land cover and its changes) and rainfall conditions. With Google Earth this distinction is not always straightforward due to the low topographic resolution of the data. The inventory does not include the landslides that are linked to quarrying and mining activities.

For the recent landslides that have occurred over the last 10 years (Google Earth cover), *i.e.* those where changes (*e.g.*, vegetation disruption) are observed between two satellite images, rainfall-triggering conditions explain their occurrence. Apart from a magnitude 5.6-5.8 earthquake that occurred 7th August 2015 (where only few new small shallow landslides were observed in the field), no earthquake with magnitude large enough to trigger landslides was recorded in the region during that period (see WP1; Delvaux et al., 2016). This link to rainfall conditions was further confirmed via archive analysis. Here we compiled an inventory of more than 100 dated landslides (all in the last 15 years) that shows that the vast majority can be linked to climatic parameters (Monsieurs et al., *in press; to be submitted*).

From the regional inventory alone, there were 670 landslides mapped in the focus area of the rift flanks West of lake Kivu (Maki Mateso and Dewitte, 2014). The maximum landslide size is 2 km². The use of the 5 m 2011-2012 DEM has enabled us:

- to make the distinction between shallow and deep-seated landslides (for the pre-2012 features);
- to show that, except for recent (partially) non-vegetated landslides, the large majority of the features mapped with the sole use of Google Earth are deep-seated landslides (in total 600);
- to verify that deep-seated landslides identified with the sole use of Google Earth are correctly delimited according to their topographic signature;
- to identify more than 300 additional deep-seated landslides. The higher topographic resolution was efficient to delimit not only smaller occurrences but also larger ones (now several mapped landslides are ~ 4 km²).
- to better differentiate landslides with flow patterns;
- to better understand landslide distribution according to topographic and lithologic context.

In addition, for the Kivu Rift flanks, Google Earth images from June 2014 to February 2016 (new images since the compilation of the regional inventory) allowed to map more than 1200 new landslides linked to the fatal heavy rains of October 2014 (Maki Mateso and Dewitte, 2014). These landslides are mostly shallow flowing features (validated in the field). In total the Kivu inventory contains 2152 landslides. Figure 11 shows distributions patterns that can be linked to climate triggers (clusters of shallow landslides) and suggests earthquake (seismic) controls in some places (Dewitte et al., in prep.).

Bukavu and Bujumbura are the two populated places most affected by landslides. The patterns are however different between the two places. In Bukavu, landslides are present in the urban and populated area in itself, creating disturbance immediately on site. In Bujumbura, landslides extents mostly on the steep mountain slopes at the outskirt of the city. Their impact is indirect. Through cascading effect they can create dams on the rivers flowing to the city, which, when they break, cause (very often deadly) flash-floods.

Both regional and Kivu inventories were validated in the field during 14 field missions in 2013, 2014, 2015 and 2016 (Figure 12). Field validation sites were selected so that most representative environments were visited in the three counties. The on-site visit at 250 landslides allowed to better identify the environmental settings (geology, pedology, geomorphology, vegetation), which helped improving processes understanding (Dewitte et al., *in prep*.; Draidia et al., *in prep*.). This was further completed with the mineralogical and geotechnical analyses of 50 rock and soil samples taken in stable and instable slope contexts in Rwanda and Burundi. This enabled us to highlight the role of weathering in the occurrence of some landslides (Draidia et al., *in prep*.). Weathering is also a factor that can be used to explain the presence of many deep-seated landslides in the South-Kivu Volcanic Province (Miocene - Pliocene) and the absence of such landslides in the Virunga Volcanic Province that consists of much more recent lithology (Holocene) (Figure 12).

From field validation, we confirmed the high success rate of landslide identification through Google Earth (Dewitte et al., *in prep*.; Draidia et al., *in prep*.). We also show that, even with the 5m DEM, the number of delimited landslides is still below the reality in the field. However, the frequency-area distribution analysis (Malamud et al., 2004) shows that the two regional inventories are unbiased and “complete” in terms of landslide area distribution (Dewitte et al., *in prep*.).

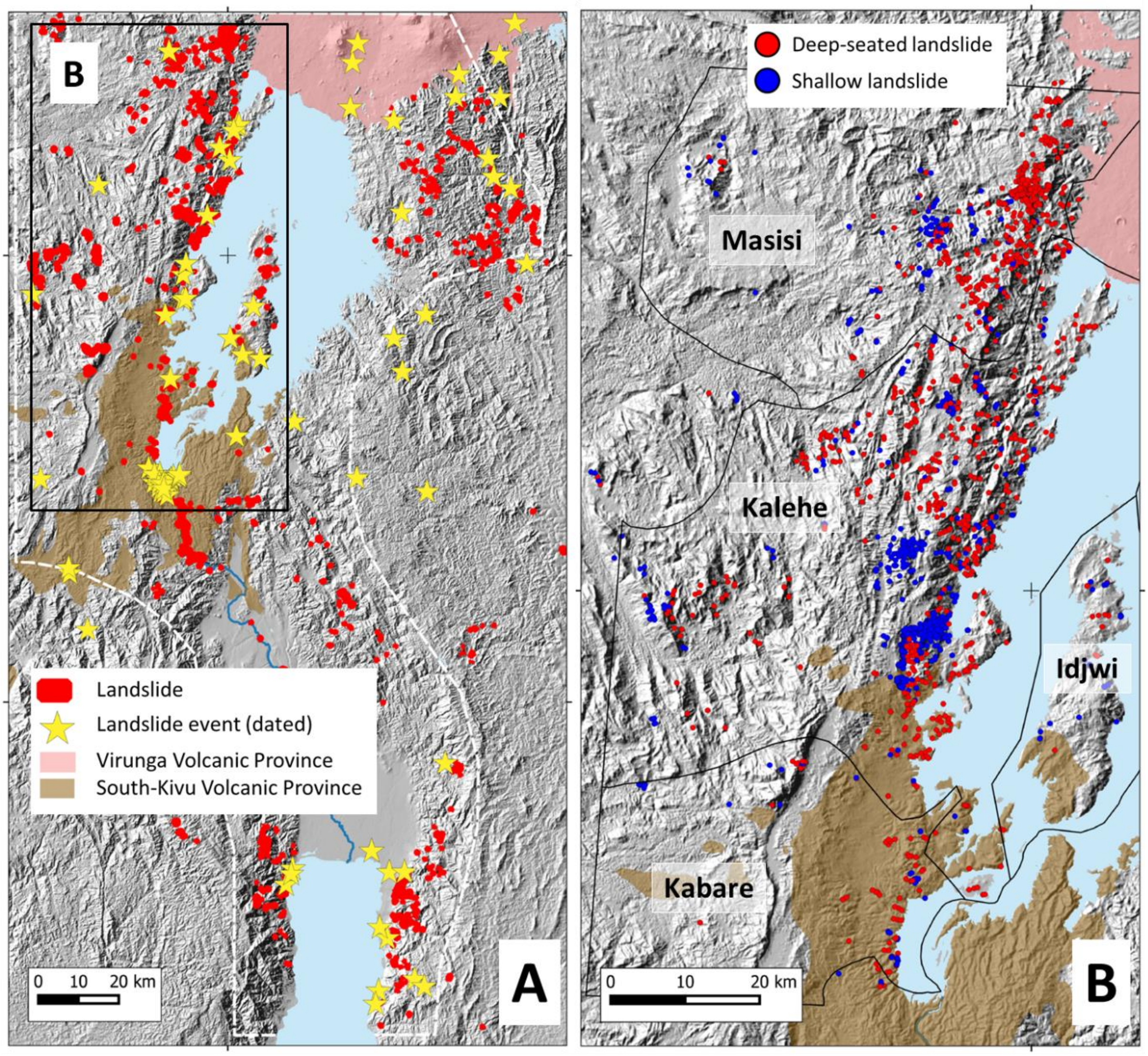



*Figure 11. (A) Regional landslide inventory compiled from Google Earth images. Yellow stars indicate dated landslide events. White dashed line delimits the target area. (B) Landslide inventory compiled with the combined use of Google Earth images and 5 m spatial resolution TanDEM-X data in the rift flanks West of Lake Kivu. Outside, little was checked.*

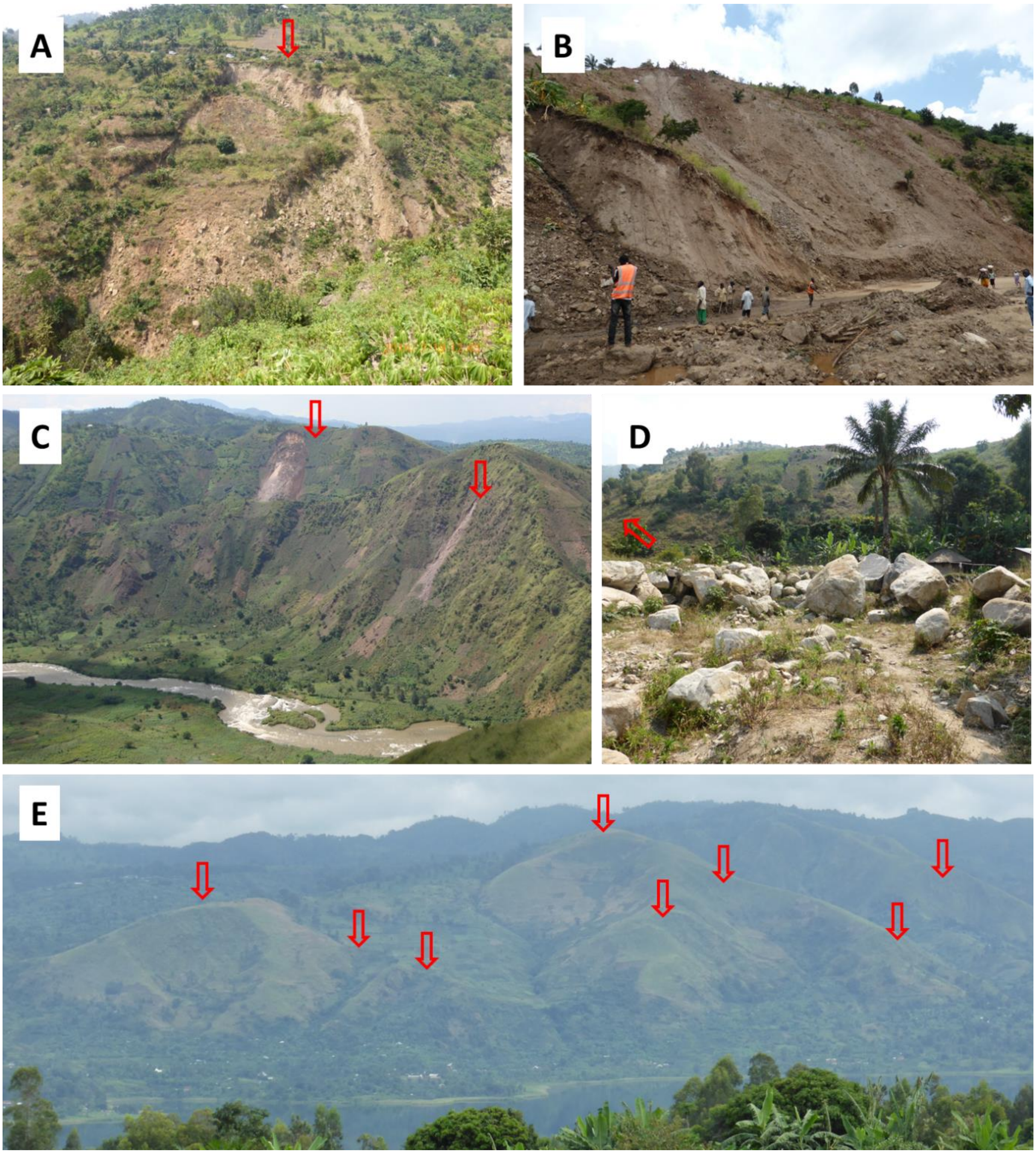



*Figure 12. Examples of landslide types (terminology after Hungr et al., 2014). Red arrows point to landslide heads. (A) Deep-seated rotational slide along National Road 1, Bujumbura, Burundi. Landslide was triggered 09 February 2014 after a heavy rainfall. Photo taken in July 2014. (B) Reactivation of the foot of a large slide-earthflow damaging National Road 3 along Lake Tanganyika, South of Bujumbura. This event occurred during the 2013-2014 wet season. Photo taken in March 2014. (C) Debris slides and debris avalanches in Rwanda that occurred during 2012-2013 wet season along the Ruzizi River. Photo taken from DRC in May 2013. (D) Debris flow that occurred 25 October 2014 along Lake Kivu after a heavy rainfall event (Rambira, DRC). Photo taken in July 2015. (E) Large deep-seated rock slides of probable seismic origin that extent along a fault scarp along Lake Kivu (South of Kalehe). Photo taken in May 2016.*

### 2.5.2. Regional susceptibility assessment – quantification of the process understanding

#### METHOD

To quantify the role of environmental factors (controlling and triggering) on landslide occurrence at the regional level, we rely on both the regional landslide inventory (that was proved to be reliable, Figure 11) and ancillary data that are available uniformly for the whole region, some being outputs from WP1000 (Table 3.1).

With regards to the rather coarse spatial resolution of most of these data, we have used two susceptibility modelling approaches that have proved to be efficient also at a small-scale level:

- The first approach is a data-driven method that utilises a frequency ratio methodology (see description in Lee and Pradhan, 2007) which considers each environmental factor individually (*e.g.*, slope), and classifies values into a set of defined bins (*e.g.*, <5°, 5-10°, 10-15°, etc.). A frequency ratio value is calculated for each bin as the percentage of landslide pixels in each bin divided by the percentage of pixels within the study area having the same bin values. The frequency ratio values are calculated for each environmental factors and their multiplication on a pixel-by-pixel basis gives the susceptibility estimate (Havenith et al., 2015).
- The second approach is a process-based method that uses the mapping of the Factor of Safety and of the Newmark Displacements (ND) applying the method by Jibson et al. (2000) to map the susceptibility to seismically triggered landslides. For the Factor of Safety map, we needed to compile geomechanical information for all main lithologies (see Table 3.1). From the Factor of Safety map, the critical acceleration map was computed. The Arias Intensity (produced as a result of WP1; Delvaux et al., 2016) and the Critical Acceleration maps combined allowed us to estimate the ND.

#### RESULTS

Figure 13 shows the most relevant model outputs obtained with each approach at the pixel resolution of 30m (use of SRTM topographic data). The data-driven model combines a selection of various environmental factors that were derived from the ancillary data (Table 3.1). As it is built from the landslide regional inventory, the model highlights factors that explain the occurrence of deep-seated processes. It highlights the role of slope gradient, slope aspect, lithology, land use, distance to drainage network and distance to fault systems as explaining factors for the landslide occurrence at the regional scale. More details on the explicit role of these factors can be found in Maki Mateso and Dewitte (2014) and Dewitte et al. (in prep.).

The susceptibility pattern highlights the region of Bukavu (and the role of the lithologic control linked the lavas of the South-Kivu Volcanic Province), and the southern part of the rift flanks West of Lake Kivu as highly susceptible (also confirmed by the inventory and field work). However, despite the fact that the measured success rate of the model is rather good with regards to the drawback of such a regional approach with limited spatial data (*i.e.* 20% of the landslides fall within the 10 % of highest susceptibility), it is important to keep it mind that this first regional assessment needs to be taken with the highest care. For example, the regions of the Masisi Territory and Bujumbura, known to be landslide-prone, are not highlighted at all (Maki Mateso and Dewitte, 2014; Nibigira et al., 2015).

The Newmark Displacement (ND) model (Figure 13) also highlights the rift flanks West of Lake Kivu. However, in general the pattern is quite different from the data-driven model. For example, the region of Bukavu in itself is less susceptible according to ND, indicating that weathering of lava lithology could be more important than seismic activity for the occurrence of deep-seated landslides in this area. The differences between the two models could be explained by the fact that the data-driven approach relies on a historical inventory where landslides from seismic or climatic origin are undifferentiated.

The places where ND is greater than 10cm cover an area of about 35%. This area contains 40% of the landslide depletion zone, meaning that the density of the landslide occurrences in this area is not really higher. However, the total cumulative area covered by those landslides represented 65% of the total area covered by the entire landslide inventory. The largest landslides are concentrated in the highest ND value areas; therefore seismicity could be considered as the main cause of those large mass movements. However, this requires further investigating. For example, the ND model shows the mountain region south of Bukavu as a susceptible area, but there is currently no landslide inventory for this area.

Both regional models presented here are first assessments and enable us to better understand some processes at play but they require further development in order to improve their reliability.

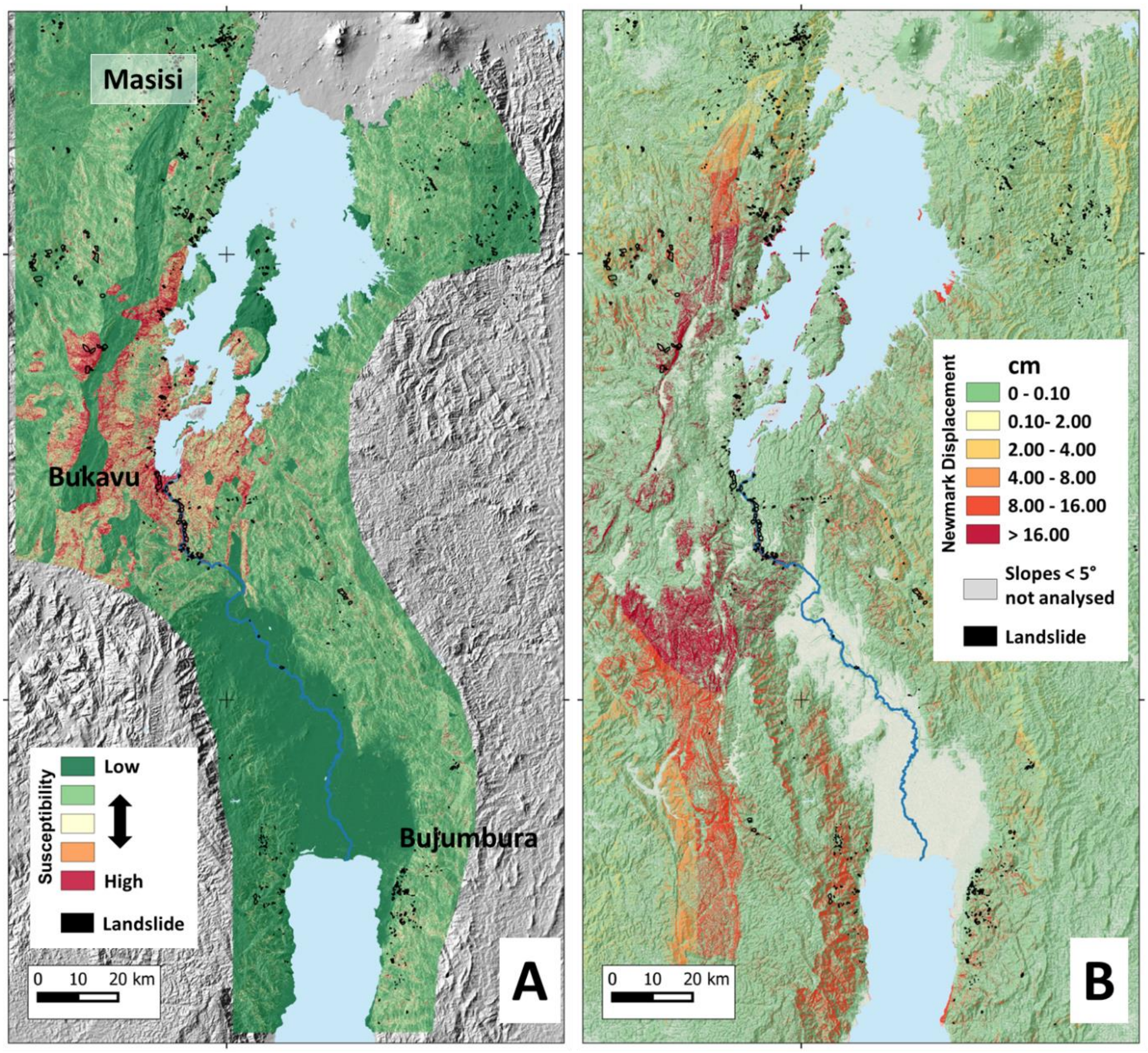



*Figure 13. (A) Data-driven model. Susceptibility assessment was restricted to the zones where landslides were inventoried (see Figure 11 (A)). Landslide susceptibility values are presented in five classes. (B) Newmark Displacement (ND) assessment based on the Factor of Safety map for average static conditions (thickness of 10 m of sliding layer, 50% water-saturated) and the Arias Intensity map computed for a 475-year return period (product of WP1). ND values range from 0 cm to 19.6 cm.*

### 2.5.3. Focus on Bujumbura – detailed landslide investigation and numerical modelling in the context of cascading events at the border of a city

Even though Bujumbura was not highlighted as a high landslide susceptibility location in our regional quantitative assessments (Figure 13), field evidence and visual inventory clearly attest of the opposite. Most landslides are actually located outside the city on the steep slopes along the rivers flowing towards the populated urban areas. The highest landslide threat is indirect, linked to river damming. When a dams breaks, it can trigger lake outbursts and massive floods downstream. Such an event happened in February 2014 after an intense thunderstorm, causing more than 100 fatalities in few hours (Monsieurs et al., *to be submitted*)

## METHOD

The first step was to complete and update the regional inventory. This enabled us to better understand slope deformation processes and to identify the landslides that were the most active over the last few years and that could present the highest threat in a near future. We then studied some of them by geophysical methods (microseismic zonation, electric resistivity). This helped collect structural information that was required for numerical modelling (we used the UDEC software, ITASCA). The geomorphological mapping was done from the regional inventory and combined with more recent Google Earth images, intense field survey and analysis of high resolution satellite-derived products (Table 3.1).

## RESULTS

Geomorphological mapping and slope stability assessment were carried out for several tens of landslides. For the investigated sites (with recent (re)activation), we reconstructed the sliding history. We estimated that a very high risk (comparing all studied sites) is related to a reactivation of the so-called "Bananatree landslide", as it is one of the largest and most active landslide in the vicinity of Bujumbura and it has proven to have dammed Kanyosha River in the past (lake sediments were found upstream of the landslide), which most likely had been at the origin of lake outbursts with massive floods downstream. We therefore focused geophysical investigations on that landslide; related results were used as inputs for numerical back-analyses and predictive simulations to identify the original trigger mechanisms. Two additional landslides were also studied by geophysical methods. The main results for the Bananatree landslide are shown in Figure 14. More information on this landslide as well has on the other investigated sites can be found in Draidia et al. (*in prep*.).

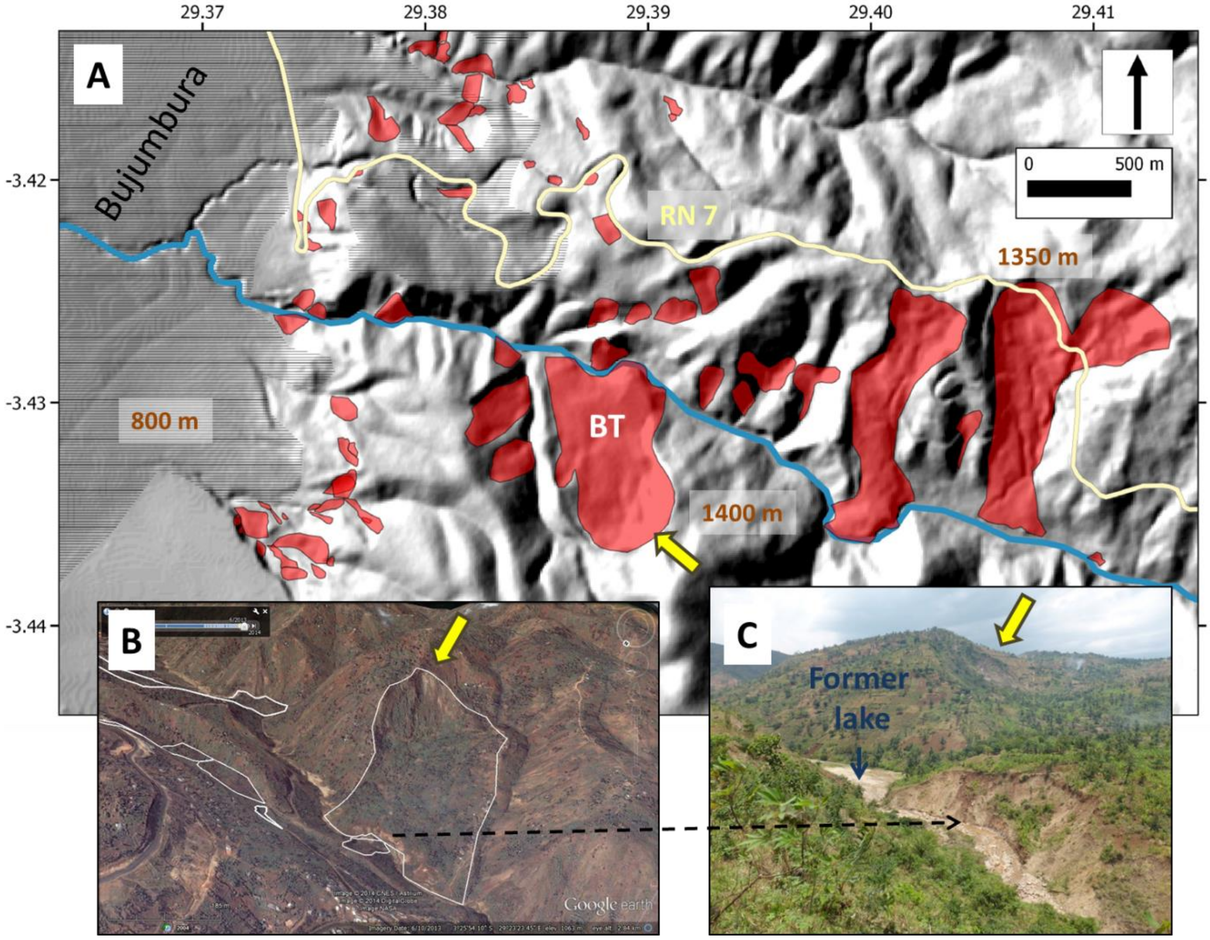



*Figure 14. Landslides along the Kanyosha river valley and National Road RN7 with location of the so-called "Banatree landslide" (BT); an active deep-seated slide-earthflow. The yellow arrows indicate the head scarp.*

Electrical and microseismic measurements (HV) show a rather heterogeneous distribution of conductive and resistive, hard and soft materials, which highlight the presence of multiple sliding surfaces that contribute to instability (Figure 15 and Figure 16).

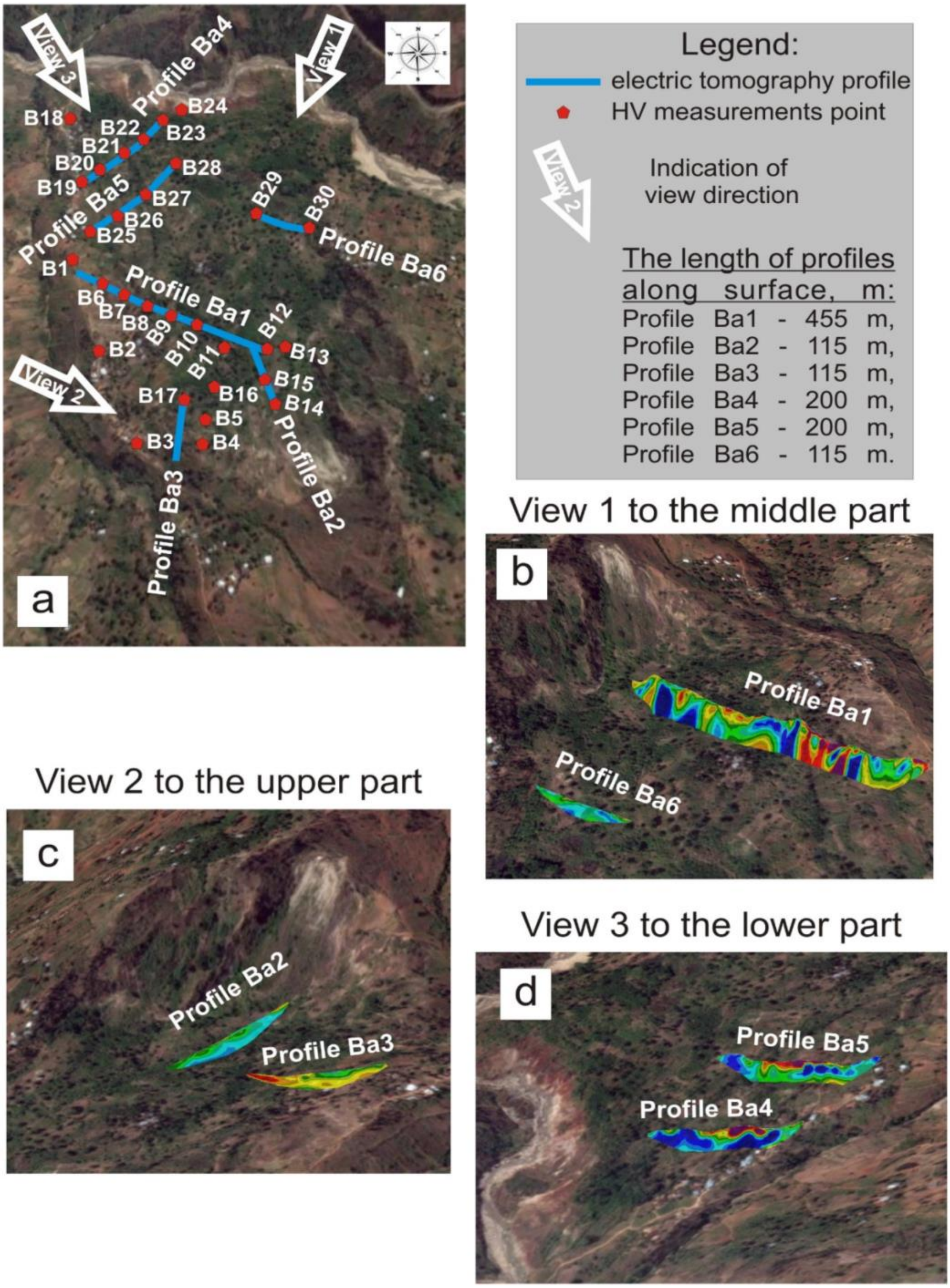



*Figure 15. Electrical tomography profiles on Bananatree landslide showing a heterogeneous distribution of high and low resistivity materials (resistivities shown by colours range from blue ~5 Ohm.m to red ~1000 Ohm.m).*

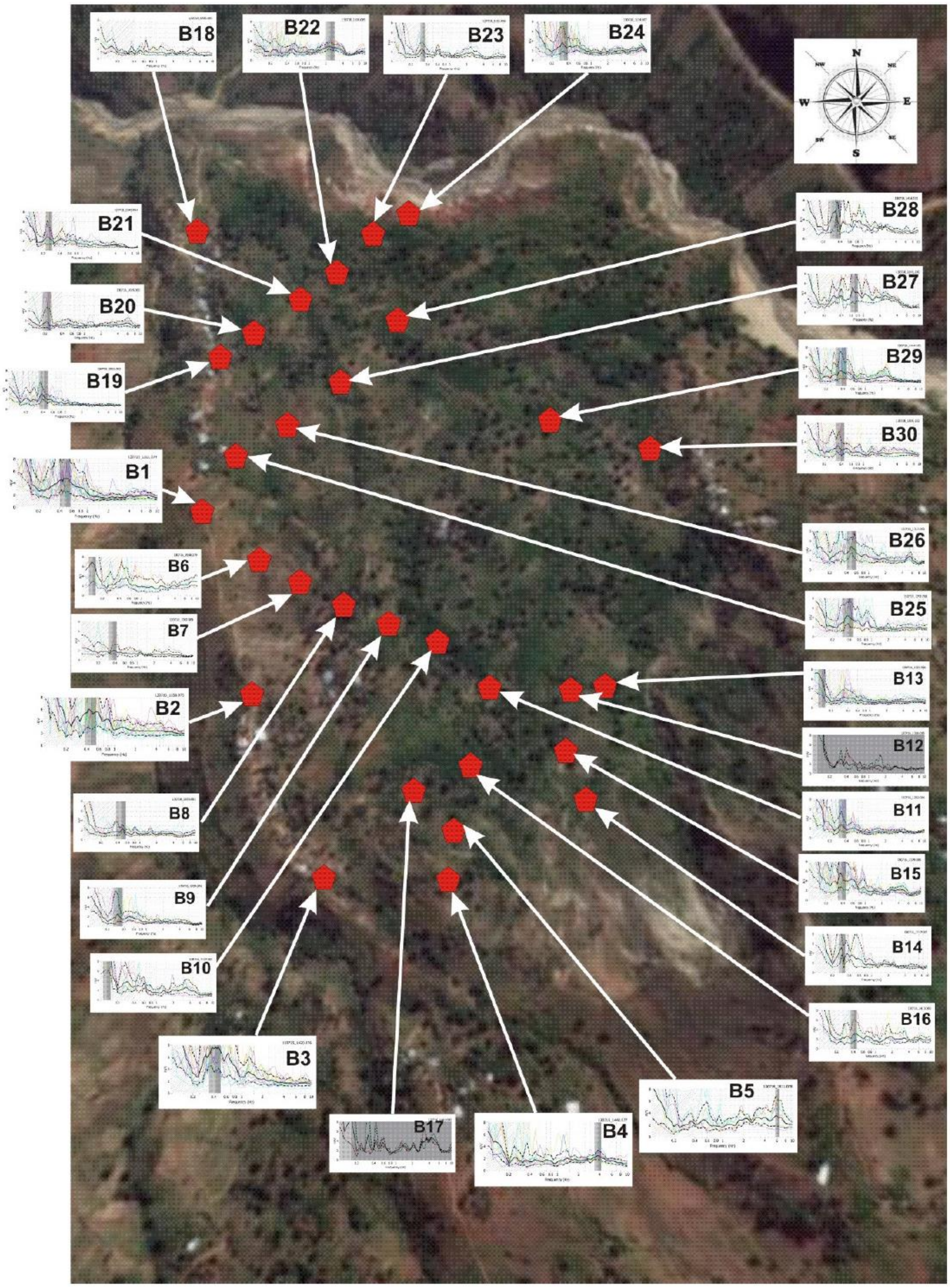



*Figure 16. H/V ambient noise (microseismic) spectra obtained for the different measurement points on the Bananatree landslide. Most indicate an amplification at around 0.7-1 Hz that would correspond to a thickness of sliding material of about 50m (considering a shear wave velocity, Vs, of the bulk clay material of 180 m/s).*

We compiled a geological section of the landslide from the data above. The complex structure of the landslide was taken into consideration when back-analysing the slope failure phenomena. First, we reconstructed the pre-sliding topography (taking into consideration the volume of failed material as estimated from the results of the geophysical surveys). This pre-sliding model was used as input for the numerical model.

Multiple simulations were run to identify the original trigger of the landslide. The modified parameters concern the uncertain values of plastic properties, the level of groundwater in the massive and the possible seismic input. One result with modelled 80 m of displacement and large subsidence in the upper landslide area (as observed in reality) is shown in Figure 17. This effect could be modelled for a seismic triggering with 0.2g peak ground acceleration input (see right part in Figure 17). Non-seismic displacements (event those modelled for fully saturated ground) were generally one to two orders of magnitudes smaller than this displacement of 80m, which favours the hypothesis of an initial seismic trigger.

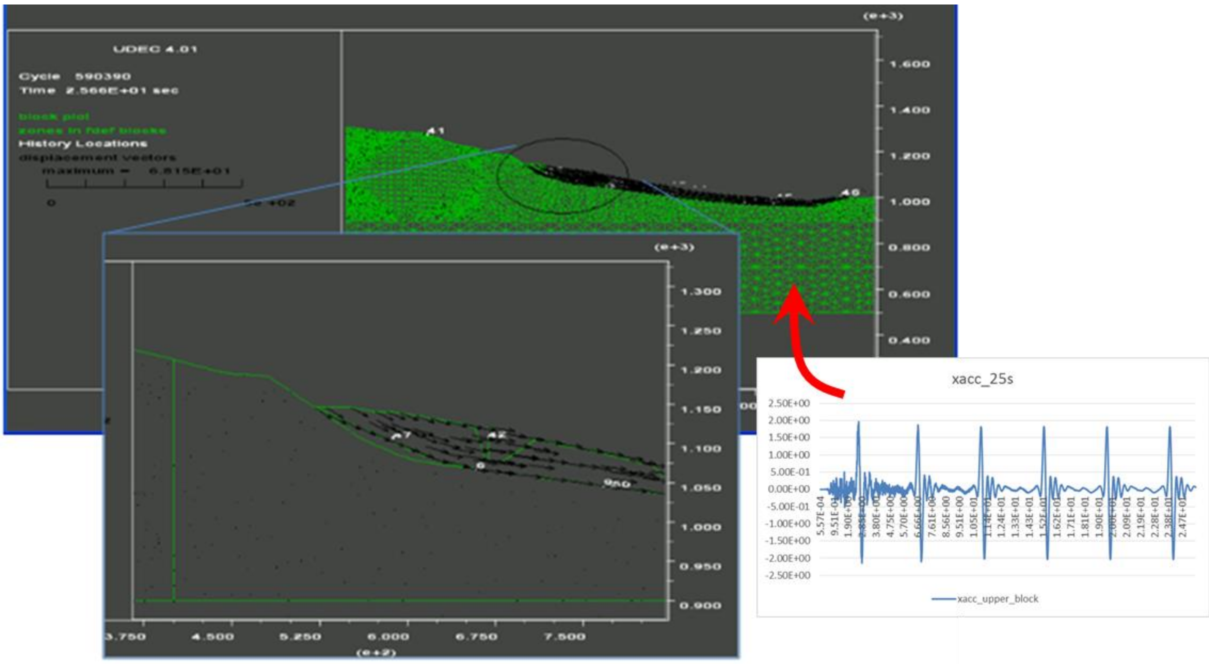



*Figure 17. Example of scenario simulations with 0.2 g peak ground acceleration input (6 Ricker wavelets, right part). Zoom on the upper landslide zone where the largest deformation occurred is shown in lower left corner.*

In addition, we developed predictive simulations starting with the present-day situation of the landslide. Those predictive simulations showed that for severe (but not for extreme) seismic (up to 0.3 g input) and climatic conditions (100% water saturation) not more than 1m of displacement would occur. However, those simulations exclude the effect of river erosion that could not be simulated with the available software. Severe seismic and climatic conditions combined with river erosion (which would be active in the same time as the severe climatic conditions; and is also currently increased to riverbed material quarrying) might therefore result in a full reactivation of the landslide, with consequential damming of the river. Water accumulation upstream would then be at the origin of a high flooding risk downstream.

### 2.5.4. Focus on Bukavu – geomorphological hazard assessment and landslide kinematics in a highly populated urban context

#### METHOD

Landslides are present in many places in Bukavu and the processes at play are various. Assessing the true hazard (location "where", time "when" and frequency "how often", and intensity "how large") remains challenging, especially in an urban context where the role of anthropogenic activities is supposed. In the case of Bukavu, such assessment is even more challenging as there is no existing information on the history of the landslides and data on lithology, hydrology and soil characteristics is of very poor quality. In such a context, landslide hazard can be assessed only through qualitative inventory-based and knowledge-driven methods. Here we chose to adapt the geomorphological approach developed by Cardinali and al. (2002). This qualitative methodology is not straightforward and requires experienced geomorphologists trained in the recognition and analysis of slope processes. The potential role of anthropogenic activities can be considered in such an assessment.

The core of the geomorphological approach is a historical multi-temporal landslide inventory. In order to do so, we have used various data (Table 3.1), archive analysis and intense field work that allowed us to reconstruct several decades of landslide history. Changes in the distribution and pattern of landslides enable us to then infer the possible evolution of slopes, the most probable type of failures, and their expected frequency of occurrence and intensity. This information is used to evaluate landslide hazard.

In addition to the geomorphological hazard assessment, it is important to quantify the current kinematics of the deformation. We used two approaches here. For the entire urban area, we have used space-borne InSAR techniques (Table 3.1) (data acquisition and processing chain benefited directly from another BELSPO funded project called "RESIST"). Details on the InSAR processing are given in Section 2.3.8. For specific landslides, we used multi-temporal DGPS.

#### RESULTS

Thanks to the combined use of historical aerial photos (1959), recent satellite images and intense fieldwork, we built a multi-temporal historical inventory for a period of 60 years (Figure 18 (B)). A total of 151 landslides were mapped (Figure 19). Their cumulative areas cover ~30% of the urban territory. Several processes are identified. Differentiation was done between sliding (rotational and planar) and rock fall processes. Landslides can be shallow (< 5m) or deep-seated. Gully systems related to landslides were also inventoried (Balegamire et al., *in press*; Kulimushi Matabaro et al., *in press*; Mugaruka Bibentyo et al., *in press*). Relative landslide age was estimated for three categories (recent, old, and very old). Recent landslides include features morphologically fresh on the aerial photographs of 1959, or new landslides or reactivations of pre-existing landslides in the more recent photos or images, or checked by field mapping and archive. Old landslides show a clear morphology without erosion features on the aerial photographs of 1959. Very old landslides show a morphology that is at least partly dismantled by erosion, sometimes heavily (age classification based on Cardinali et al., 2002). The oldest landslides are at least 10,000 years old with regards to their distribution in relation to the Holocene highstands of Lake Kivu and the characteristics of soils and debris deposits in the displaced structures (Dewitte et al., *to be submitted*). Most large deep-seated landslides are old or very old features. Shallow landslides are all recent (it is assumed that older features are no longer identifiable). Gully systems are all considered as recent. Interactions with recent and rather small instabilities were also highlighted.

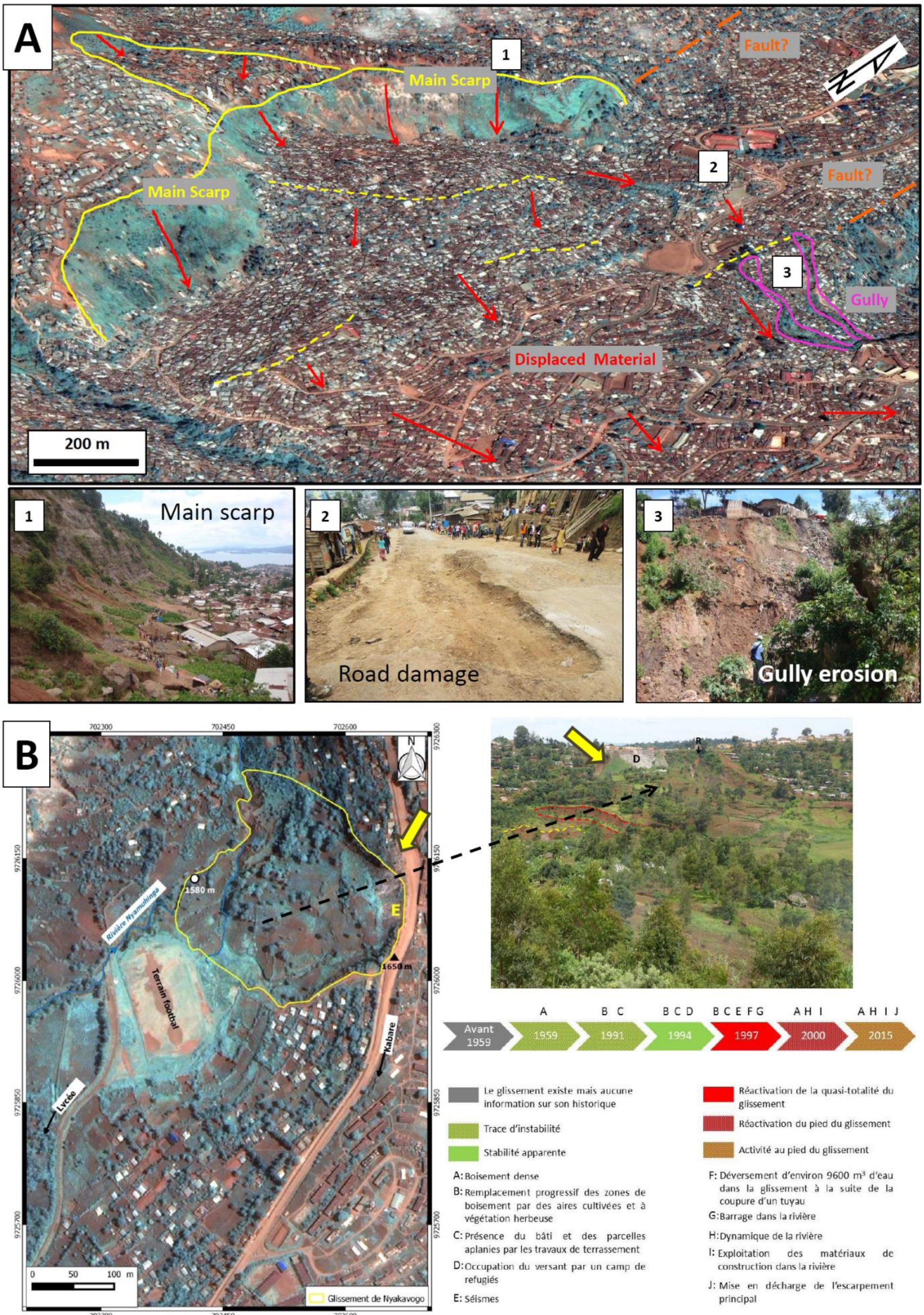



*Figure 18. Examples of two large active landsides in Bukavu. (A). Structure and processes at play in the Funu landslide (see complementary info in Figure 20). TanDEM-X topography is combined*

*to a 2013 Pléiades image for the visualization. (B) 60 years of history of the Nyakavogo landslide, with highlight to the interplay between natural and anthropogenic factors (Mugaruka Bibentyo et al.,* in press*). Yellow arrows indicate the head scarp.*

Large deep-seated landslides are the most prominent mass movements in Bukavu. The largest one (called "Funu" landslide) covers an area of ~1.5km² (Figure 18 (A)). This landslide is particularly interesting as it lies in a very populated area and it is the location of various active gravitational processes (Balegamire et al., *in press*; Dewitte et al., *submitted*). The frequency-area distribution analysis shows that the inventory for Bukavu is not complete for the smallest landslides. This biased distribution has already been observed for other historical inventories. This is most probably due to the fact that the smallest features are less indentifiable and easily eroded, especially in areas with such a strong anthropogenic impact (Dewitte et al., *to be submitted*).

Hazard linked to the occurrence of new large deep-seated landslides cannot be assessed in this specific case due a scarcity of reliable data on the environmental factors controlling their occurrence. Numerical modelling requires very high amount of local information that is not available (lithology, hydrology and soil characteristics a.o.) and regional statistical assessment relies on comprehensive and very detailed regional inventories as well as accurate environmental data that are impossible to obtain at this stage of the research. In addition, age estimation of the occurrence of some of the largest landslides refers to periods at the beginning of the Holocene where climatic and seismic conditions were probably different (Dewitte et al., *to be submitted*).

Therefore, based on the inventory, we propose hazard scenarii that coincide with today's environment (Dewitte et al., *to be submitted*). Considering the age, the frequency, and the intensity of the landslides, four hazard scenarii are proposed. These scenarii are based on hazard zoning, which is the subdivision of the terrain into zones that are characterised by the temporal probability of occurrence of a type of landslides of a particular intensity within a given period of time. Hazard assessment was achieved for:

- Reactivation of deep-seated landslides: these could be the most damaging processes, impacting on both infrastructures and population. However their frequency is rather low.
- Occurrence of new small shallow landslides: they occur every year. Their exact location is impossible to predict in such an urban context. Their impact can be very limited spatially and their damages to infrastructure are rather small compared to the consequences of large landslide reactivation. However they can still injure people, and sometimes be fatal.

- Rockfalls: their spatial location is well constrained, mostly on the main scarp of the Funu landslide. They occur every year and can be of a variety of sizes.
- Current dynamics of existing landslides: on a regular basis, movements within existing landslides are the most damaging processes on the infrastructure; they occur in many places and can be continuous. Their occurrence is due to the presence of loose material and destructed rocks in the slipped masses, which favour processes such as compaction and subsurface erosion that, in turn, affect slope instability.

Based on these assessments, we produced four hazard maps that indicate the zones where landslides may occur as well as the runout zones (Figure 19) (Dewitte et al., *to be submitted*). Rockfall hazard concerns a very small portion of the urban territory. The other three hazards are much more widespread. For these three scenarios, the hazard is the highest in about 5 to 10% of the urban territory. The maps are presented in four classes. They present information that can be easily used for further risk analysis and/or urban planning purposes.

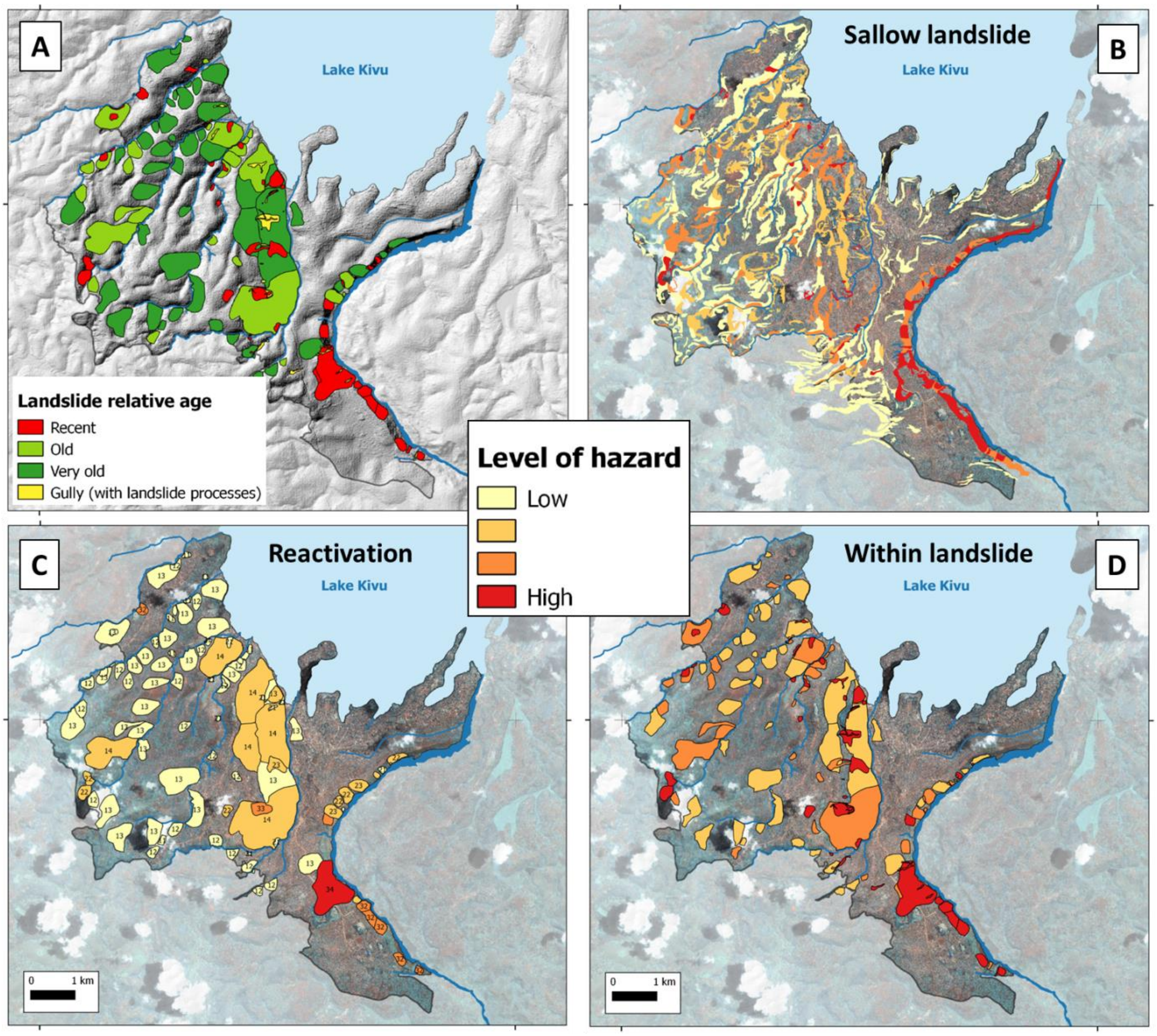



*Figure 19. (A) Multi-temporal landslide inventory that is the basis for the geomorphological landslide hazard assessment. (B) Hazard for the occurrence of small shallow landslides. (C) Hazard for the reactivation of large deep-seated landslides. (D) Hazard linked to current landslide dynamics,* i.e. *displacements within existing landslides.*

The kinematics of the deformations of several landslides was quantified with the use of 80 COSMOSkyMed InSAR images, acquired between March 2015 and June 2016 with a mean revisiting time of 8 days in both ascending and descending orbits. We produced and compared displacement-rate maps and ground deformation time series derived from two techniques: Permanent Scatter (PS) and Small Baseline Subset (SBAS) techniques. Movements with a velocity >5cm/yr with reference to the Line of Sight are detected in the Funu landslide. Results show that the landslide is divided into blocks that move with different velocities, which is consistent with field observations and reflects the relative age of landslides (Figure 20). Despite a short revisiting time offered by CSK constellation, we lose the coherence within the fastest moving regions of the landslide.

DGPS measurements (9 campaigns), taken at 21 benchmark points in the area of Funu landslide during the same period, enables us to validate the results and identify first seasonality effects. Similar ground deformation rates are found for the period 2002-2008 using Envisat ASAR images. Furthermore, comparison with rainfall monitoring data acquired on-site and derived rainfall satellite products (TRMM and GPM) will help us understanding the influence of water and the seasonality in the sliding mechanisms. More details on the kinematics analysis and the rainfall characterisation can be found in Nobile et al. (*in prep.*).

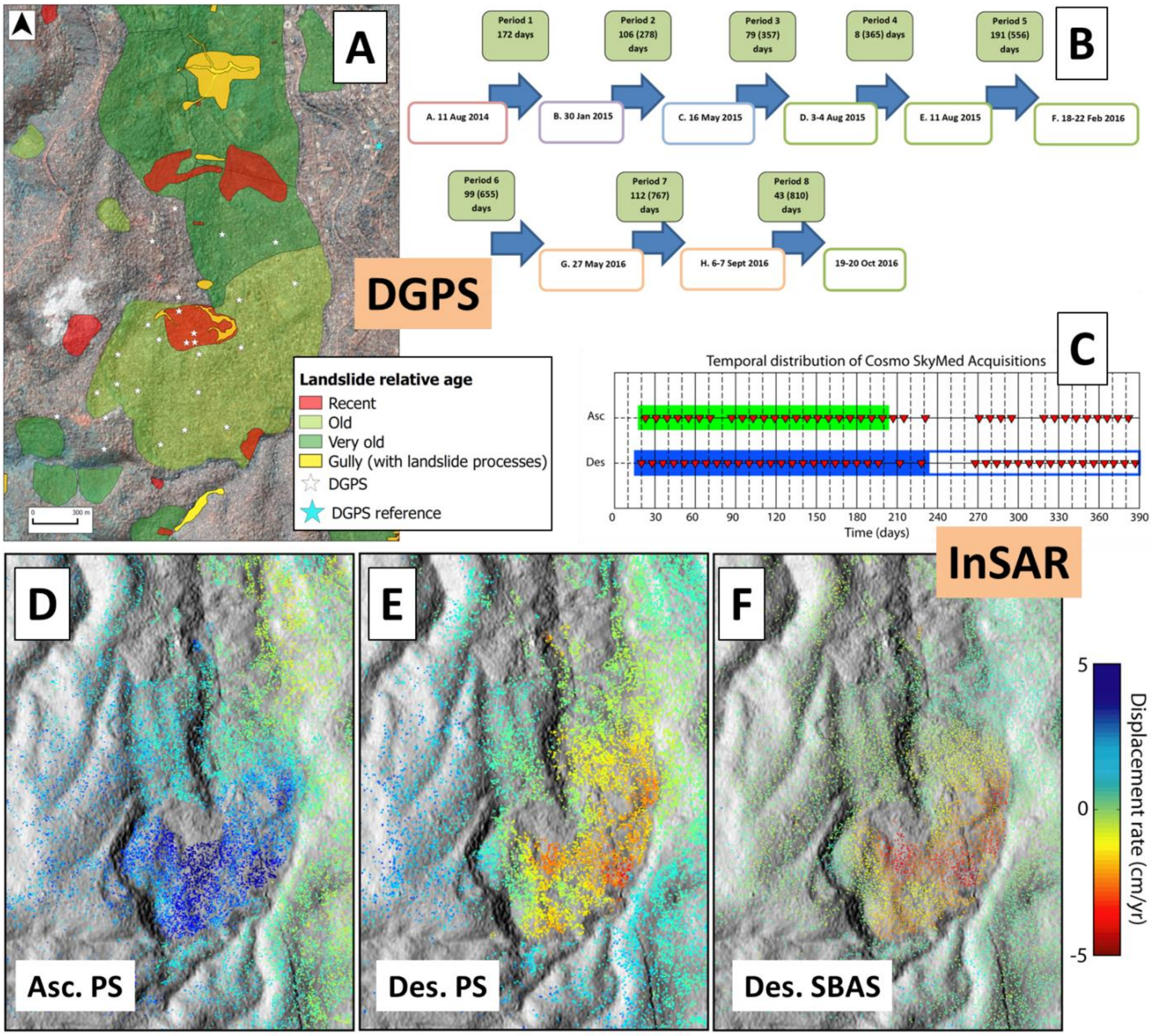



*Figure 20. DGPS measurements and InSAR displacements with a focus on the Funu landslide.(A) Landslide relative ages (see Figure 18) and the DGPS network (white stars). (B) DGPS campaigns. (C) COSMOSkyMed acquisitions. (D) Ascending PS InSAR. (E) Descending PS InSAR. (F) Descending SBAS InSAR. Ascending data shows a movement away from the satellite and descending data show a movement towards the satellite. The real movement is towards the East.*

Besides studying in detail the various geological hazards affecting the lake Kivu basin, it was crucial to assess the vulnerability of the population living under these threats in order to contribute to the georisk assessment.

## 2.6. Vulnerability assessment: a major component of the risk assessement

### 2.6.1. Regional vulnerability analysis

One of the main objectives of the project was to conduct the vulnerability assessment at a regional scale taking into account all the data gathered in the context of the project. The planned methodology was based on the existing (socio-economic and spatial) data available at a regional scale. During the field campaigns of in May 2013 and April 2015, existing data for the South and North Kivu provinces were collected thanks to the representatives of national institutions, as well as local and international NGO's and scientists. However, the little gathered socio-economics data were too agglomerated and not sufficient to develop a vulnerability index at a regional scale.

Data collection through the Internet (open-source data) was then launched. A Congolese student completed a master thesis at the University of Liège in "Risk management and disasters" on this topic (Baligamire, 2016). The conclusion of this study was that apart from the level-3 administrative boundaries and the WorldPop data giving the population density at a 1-km² scale for the three countries of interest, no socio-economic data was uniformly available for the studied region.

Finally, at this stage, the choice was made to consider the vulnerability only through the exposure, *i.e.* the population distribution in the studied region. In other words at the regional scale, the most vulnerable areas were identified as the most populated areas.

### 2.6.2. From the literature to the field, defining the vulnerability factors

#### METHOD

Gathering and summarizing the vulnerability literature aimed at better defining the GeoRisCA framework, as well as the type of approach to adopt, develop and adapt to the context of GeoRisCA.

The methodology adopted for this task was a systematic research through the *Web of Science* and other specialised publications websites and books. This activity was an on-going process, throughout the project, *i.e.* new scientific papers were constantly added to this state-of-the-art collection.

After this extensive review of the scientific literature, we crossed this approach with a Delphi survey. It is a structured communication technique, developed as an interactive method, which relies on a panel of experts. In our survey, the experts answered questionnaires in two rounds. After each round, we provided an anonymous summary of the experts' forecasts from the previous round. Experts were then encouraged to revise

their earlier answers in light of the replies of other members of their panel; finally, the group converged towards a consensus.
The objective of these two combined approaches was to identify the parameters defining vulnerability as well as an appropriate methodology which could be implemented for the vulnerability and risk assessment at a local scale.

## RESULTS

In the Global Assessment Report (GAR 2015) glossary, based on the advice of hundreds of experts in the field, "disaster risk is considered to be a function of hazard, exposure and vulnerability" (UNISDR, 2015). “Exposed elements” or “exposure” correspond to “people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses” (UNISDR, 2009). In the scientific literature, some authors tend to confuse 'vulnerability' and 'exposed elements' (Biass et al., 2013, Künzler et al., 2012; Barette, 2017, Leone and Vinet, 2006). The exposed elements are characterized by their exposure, in the sense that they are defined by their location. Consequently, their exposure to a potential hazard will arise directly from this distribution. This means that the exposed elements are considered separately from their vulnerability. The equation of risk assessment, used in this project, includes therefore three parameters (Figure 21; Leone et al., 2010, Varnes, 1984), two of which we will explain here in detail, 'exposed elements' and 'vulnerability'

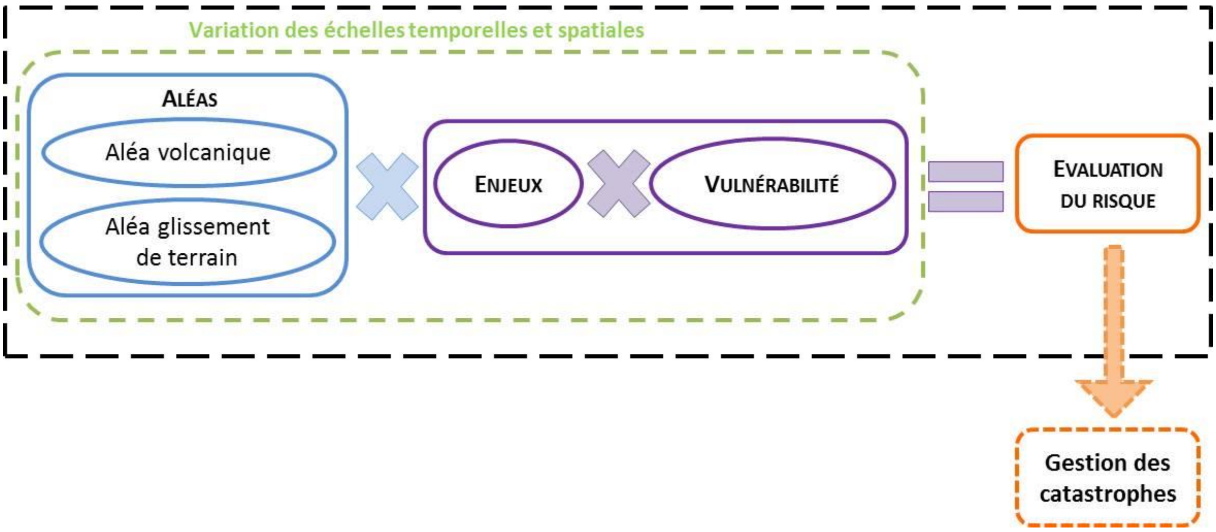



*Figure 21. Conceptual model used in this research and based on Wisner et al. (2004)*

Until a few years ago, research was influenced by the primacy of the study of the hazard, *i.e.* the natural phenomenon that generates a potential threat to people and property in a defined area and period (D'Ercole and Metzger, 2005, Veyret and Reghezza, 2006; Thouret, 2002). As explained by Veyret and Reghezza (2006), the reduction of disasters involved an action on the physical process (Cutter, 1994). The response to the risk was mainly provided in the form of physical protection (dike to fight against floods, retaining walls to fight landslides, etc.) of the population, which was in return only considered as a victim (D'Ercole and Metzger 2005, Veyret and Reghezza 2006). However, according to Veyret and Reghezza (2006), which refers to the work of Burton et al. (1993), numerous examples show that hazards of identical intensity can have very different consequences, depending on the time and the population considered.

Since the turn of the millennium, risk assessment has been geared towards greater consideration of societal aspects (D'Ercole and Metzger 2005, Pigeon 2002, Turner et al., 2003, Veyret and Reghezza 2006; Wisner et al., 2004). D'Ercole and Metzger (2005) even situate this tendency to reject the primacy of the hazard in the early 1990s. It was initially a question of assessing the impact of the hazard on assets, in terms of damage (Veyret and Reghezza, 2006). Then, little by little, it is not only the exposure of the stake that was considered, but also its own fragility and its ability to recover (Leone et al., 2010, Veyret and Reghezza, 2006). Several studies stand out quickly by highlighting vulnerability in their risk analysis (D'Ercole and Pigeon 1999, Thouret and D'Ercole 1996). An in-depth analysis of hazards, through their magnitude, frequency, duration, mechanism and intensity, remains crucial to better understand the dangers that the population faces. But, as explained by Wisner et al. (2004), such knowledge, although necessary, is far from sufficient to calculate the actual level of risk. Vulnerability analysis has become just as crucial as natural phenomena (Cutter et al., 2003, D'Ercole and Pigeon, 1999, Dauphine, 2003, Dollfus and D'Ercole, 1996, Leone and Lesales, 2009; Wisner et al., 2004). And for some authors, even more.

The concept of vulnerability has now become an essential component in risk assessment (Leone et al., 2010). Becerra (2012), supported by other authors, points out that vulnerability is a polysemic, multiscale and multidimensional concept (Barroca et al., 2013, Becerra 2012, Birkmann 2006, Leone 2007). As a result, many definitions of vulnerability have emerged in the past 30 years. They are influenced by different schools of thoughts, research traditions, and the different disciplines involved in its evaluation (Barroca et al., 2013, Becerra 2012, Birkmann 2006, Donze 2012, Lei et al. 2014, Thywissen, 2006, Veyret and Reghezza, 2006). In their literature review, Thywissen (2006) and Birkmann (2006) both identify over 30 different definitions of vulnerability; Birkmann (2006) also identifies mainly three schools of thoughts from which emerged the concept of vulnerability: one focusing on research on development and poverty, another studying the reduction of hazards and disaster risks and finally a third on change climate change, each studying vulnerability according to the specificity of its angle of approach (Birkmann, 2006). From this come more than a dozen conceptual models, all of which bring a specific added value to the analysis of vulnerability (Barroca et al., 2013, Becerra, 2012, Birkmann, 2006). There is no scientific consensus about the definition of vulnerability, or the underlying conceptual models, or the factors that influence it (Hinkel, 2011, Künzler et al., 2012).

According to Léone et al. (2010), the generic definition the most shared and appropriate to risk analyzes is that the vulnerability is "a propensity for damage or dysfunction of various exposed elements (goods, people, activities, functions, environment, systems) of a given territory and society" (Adger 2006; Cutter et al. 2003; D'Ercole and Pigeon 1999; Dauphine and Provitolo 2013; Dollfus and D'Ercole 1996; al., 2010; Leone and Lesales, 2009; Wisner et al., 2004). In other words, vulnerability characterizes the elements exposed directly or indirectly to the hazard, reflecting their own fragility.

Multiple and complex interpretations of vulnerability have led some authors to divide it into several dimensions: social, economic, environmental, institutional, physical, and so on (Birkmann, 2006; Cutter et al., 2003; Renaud et al., 2013). Some authors such as Brooks (2003) delineate essentially two types of vulnerabilities: social vulnerability, which takes into account criteria such as poverty, social inequality, health, access to resources and social status - which tend to increase or reduce the vulnerability of communities and individuals - and physical (or biophysical) vulnerability, which corresponds to the impacts caused by a natural disaster and is often seen as the cost of damage to a system (Brooks et al., 2005). Finally, the concept of vulnerability has largely evolved into a less analytic and passive approach (Birkmann 2006, Birkmann et al., 2013, D'Ercole et al., 2012). For example, in an area subject to volcanic risk, the assessment of physical vulnerability (*i.e.* vulnerability of buildings) is an important step in risk assessment, but it is not exclusive. The social dimension of vulnerability is the one which is generally assessed in the literature and which has been our focus in this project (Cutter et al., 2003, Hinkel, 2011). Indeed, the assessment of social vulnerability (*i.e.* the vulnerability of the population and of exposed households) is today recognized as essential for understanding the risks associated with natural hazards and for developing effective response capacities (Wisner et al., 2004).

Although the scientific literature review contributed to highlight the major vulnerability factors (population, education, economic status), we arrived at the conclusion that a more local definition of vulnerability would really improve our approach. That result was an important output of the AVCoR-2013 conference (cf. *4. Dissemination and valorisation*), in margin of which we organised a “vulnerability and risk” focused meeting. Then a Delphi survey contributed to identify the factors to take into account and the adequate methodology.

Experts were asked about several points related to the population vulnerability to geological hazards in Central Africa. The first one was: *what varieties of factors should be* *considered in assessing the vulnerability of a population?* The experts' responses suggest a classification of vulnerability parameters into intrinsic or internal parameters and risk or external parameters. The intrinsic factors include several sub categories:

- Demographic parameters: age will influence vulnerability, in that young children and the elderly will be classified in the categories of the population identified as the most vulnerable;
- Economic parameters: all the elements that contribute to exacerbating poverty contribute to increasing the level of vulnerability of individuals and households;
- Social parameters: the level of education will influence the degree of vulnerability of the individual and by extension of the household; the displaced or recently settled population will be more vulnerable than a population that has always lived in the same environment;
- Cultural parameters: this brings together the factors of language and religious practices that could contribute to a worsening of the vulnerability of the population.

Regarding risk or external factors, four aspects were highlighted as essential in the assessment of vulnerability:

- Parameters of risks perception;
- Parameters of exposure to hazards and susceptibility to assignment: some experts take into account these parameters as an integral part of the vulnerability; others see it as the parameter representing the hazard that can lead to loss of life and vital goods for the survival of the population;
- Accessibility-related parameters: accessing or leaving a community / neighborhood in the event of a crisis;
- Parameters related to the quality of the preventive system and crisis management: this includes the existence of institutions in charge of crisis management, as well as prevention policies and their effectiveness.

The local context is identified by many experts as being more appropriate to study than the national or international context, although they can of course influence local vulnerability. Several experts consider that taking into account the local context involves elements directly related to risk, such as disaster risk reduction policies. Some experts emphasize the need to take into account the dynamic factors of the region, such as urbanization, political instability, population displacements, the feeling of land ownership, the border; as well as cultural and religious factors that characterize the study area. However, the data regarding population and habitat type were clearly identified by experts as factors influencing vulnerability. In terms of the data to be collected, they correspond to those frequently indicated in the literature: age of the population, number of persons per household, level of income, type of materials and age of construction, level of education, etc. Several experts referred to population density as a minimum for vulnerability assessment. But in our study context, even this information is not available.

Besides, three methodological orientations stand out in the experts' responses:

- A satellite approach: using remote sensing is a possible means of assessing vulnerability, if crossed with information obtained from other sources, and, above all, through field work;
- The population survey and field observation approach: an assessment of vulnerability can be envisaged using, on one hand, the testimony of the population, and on the other hand, field surveys allowing the characterization of neighborhoods in terms of population density, income level, etc. (socio-economic characteristics);
- Working in connection with the institutions and their Congolese representatives is essential. One expert highlights the research work already carried out in local institutions that has remained unexploited to this day.

Finally, the link between the results of this Delphi survey and this study was then established both in terms of the choice of variables and the development of an appropriate methodology. We have taken into account the methodological suggestions of the experts and crossed the approaches. Following a detailed visual analysis of the satellite images of the urban areas studied, we have located the population of the cities studied, as exposed elements, and determined the densities by morphologically homogeneous zone. We have taken into account the internal and external factors suggested in the construction of our socio-economic survey questionnaire. However, some elements were more difficult to integrate, such as scale variations, security issue and political conditions in the region, complex cultural and religious elements, the presence of humanitarian NGOs and disaster risk reduction programs under development.

### 2.6.3. Existing data collection

#### METHODS

Following the workshop organised in September 2012 between the GeoRisCA team and all the stakeholders of the region, an important network of contacts was created around the project. It was therefore essential to maintain and develop this network in order to slowly gain the trust of the various stakeholders and gain access to local data and information. The choice was made to first collaborate with local scientists and the institutions in charge of disasters management and risk prevention through the vulnerability assessment at the local scale.

After defining the vulnerability assessment methodology, the availability and reliability of data was analysed.

#### RESULTS

**Bukavu and Goma**

Valuable geodata availability is one of the major challenges for the development of the region. Neither harmonised nor systematic data acquisition and archiving policy exists and uncoordinated initiatives generally remain isolated from each other.

The inventory of existing data highlighted that very little is available at an appropriate scale for the cities of Bukavu and Goma. The local office of the National Institute of Statistics regularly collects socio-economic data, but the process might not be rigorous enough for our purpose and the scale is often limited to parts of the municipalities (3 in Bukavu, 2 in Goma). New provincial offices of the *Institut Géographique du Congo* (IGC) exist in Goma and Bukavu. However, being recently created, there is no on-going project yet and hence, no geographic data is available so far. Other local institutions rarely own computers to record data; where information is available, it is always on paper format, and not very complete. Finally, international institutions (*e.g.* UN agencies, NGOs) based in Bukavu also have data, but either to an excessively large scale, or not validated. The vulnerability assessment in Bukavu and Goma therefore first required intensive mapping processes based on satellite data and fieldwork at the districts scale. Fieldwork was also required for the collection of socio-economic data.

**Rwanda**

The situation in Rwanda contrasts with neighboring countries. Indeed, the country has invested heavily in geodata collection. As a result, GIS data is available up to the scale of the plot. The networks (roads, electricity, water) and infrastructures have already been digitalised. Various and recent socio-economic data was collected during the 2012 census.

Unfortunately, it was not possible to gain access to the raw format of this data (only global statistics were available and therefore not useful in our research). Indeed, although visited institutions (Rwanda National Institute for Statistcs, Environmental board, Urban and habitat offices, MIDIMAR, etc.) positively welcomed GeoRisCA, no action was taken to build a partnership or data exchanges. Furthermore, despite being verbally agreed with MIDIMAR, the collaboration remained ineffective.

Despite the fact that (1) a large quantity of data, at a very precise scale, was available for this country, and (2) we had six meetings with MIDIMAR who promised to provide us with the required information for vulnerability assessment in the Western province, no data was obtained from them.

Finally, due to the highly time consuming fieldwork organised in DRC which did not leave any time for data collection in Rwanda, combined with the fact that 2012 census data were not accessible, even with the help of our Rwandan partner, MIDIMAR, the Western province of Rwanda was not excluded from the scope of our vulnerability assessment study.

### 2.6.4. Mapping and demographic households surveys: baseline data collection in Bukavu and Goma

#### METHODS

**BUKAVU AND GOMA WERE CHOSEN AS LOCAL STUDY SITES** (Figure 22 and Figure 23), because these cities are the highest populated areas in the studied region; in addition, existing hazards are real threats for the population; and finally, strong partnerships were already in existence with the local scientists from these two areas.

*Figure 22. The city of Goma at the foot of the Nyiragongo volcano*

*Figure 23. The city of Bukavu at risk from multiple landslides*

**LAND USE/LAND COVER AS WELL AS URBAN GROWTH** were analysed for Bukavu and Goma cities, using remote sensing data (Landsat satellite images from 1984 to 2013). Most of the urban growth took place during the past three decades. Urban and non-urban areas were classified according to two different methodologies applied to satellite images: the first was based on pixels analysis and the other was an object-based approach.

On the one hand, the *pixels method* was easy to develop and led to interesting results in Bukavu, showing that the city clearly growths southward. On the contrary, the resolution of the Landsat satellite images gave no result with this method applied to Goma: lava (and identification of lava field) not only characterises the ground surface, but is also widely used as building material, which make the spectral discrimination between ground and houses generally impossible.

On the other hand, the *object-based method* gave interesting results for both cities. This method was applied in the eCognition software according to the technique of rules set defined by an expert. The aim was to develop a set of rules using spectral, textural and shape characteristics to identify urban areas in non-urban areas.

For the Goma area, a major obstacle was the confusion between urban areas and lava flows. The legend has been reviewed in 5 classes to limit confusion: urban, vegetation, water, bare soils (including lava) and clouds. Given the changes in the peri-urban and intra-urban environment in the period of study, due in particular to the 2002 eruption, the thresholds set in the rules were modified for the treatment of each image and some rules were added (for example to classify a fresh lava flow that corresponds to a type of bare soil not present in previous images). The changes in band numbering and spatial resolution due to the variety of sensors have also required some adjustments to the rules. In view of the large presence of lavas in Goma, the soil composition indices were very useful:

- Soil index composition = (SWIR1-NIR) / (SWIR1 + NIR)

- Ferrous silicates = SWIR2 / SWIR1

Moreover, Principal Component Analyses (PCA) were performed on the images of each year and the components were included in the classification in case they differentiated interesting elements: according to the years, some put forward urban areas or certain types of lava.

Despite the cities' growth and the well-known boundaries of each district of Bukavu and Goma, no administrative limits were available in numerical format. With the help of the local authorities, intensive field work using GPS and the expertise of hundreds of local people, either from the official institutions or from the surveyed areas, **ADMINISTRATIVE BOUNDARIES WERE DRAWN** (Figure 24).

*Figure 24. Drawing of the administrative limits of (A) Bukavu and (B) Goma, respectively, with the help of the local authority representatives and the colleagues from INS-SK, ISP-Bukavu and GVO.*

Besides, as explained above, sources of second hand data were scarce and of limited quality. To cope with this, we have used a **METHODOLOGY COMBINING REMOTE SENSING AND FIELD SURVEY**. We had two distinct objectives: to count of the population of the studied cities, and to collect information on the main socio-economic characteristics of their population. To achieve these goals, we combined the visual analysis of very high-resolution satellite images (VHR) with a field survey of a sample of households stratified by commune. Precisely, from multispectral Pléiades satellite images refined to 0.5m resolution thanks to the panchromatic image (dating from July 2013 for Bukavu, and September and October 2014 for Goma) and covering the whole urban area, we performed a visual analysis of the density of land use. On the basis of satellite imagery, our field knowledge and a validation carried out by our geographers colleagues from ISP and INS, the first step was to delineate the zones corresponding to collective habitat spaces or uninhabited spaces, identified to be counted separately in the field survey (university campuses, football fields, schools, military camps, cemeteries, parishes, administrations, businesses, etc.). Using QGIS software, we visually delineated these 'excluded zones' (EZ) on the THR satellite image. Maps of the city in A0 format were then printed and reworked manually and digitally to produce a map file listing all the EZ in the city.

The next step was to delineate homogeneous areas across the urban space from the point of view of their structure and building density (Figure 25). In other words, it was necessary to visually identify areas in which buildings had not only a similar size, but also a regular trellis. As for the EZs, we worked in a GIS on the city's THR satellite image to plot homogeneous 'morphological zones' (MZ). This decisive step in our methodology - the delineation of the MZs - is based on a visual interpretation. This mode of interpretation could be questioned because it is particularly subjective due to the complexity and variability of visual perception.

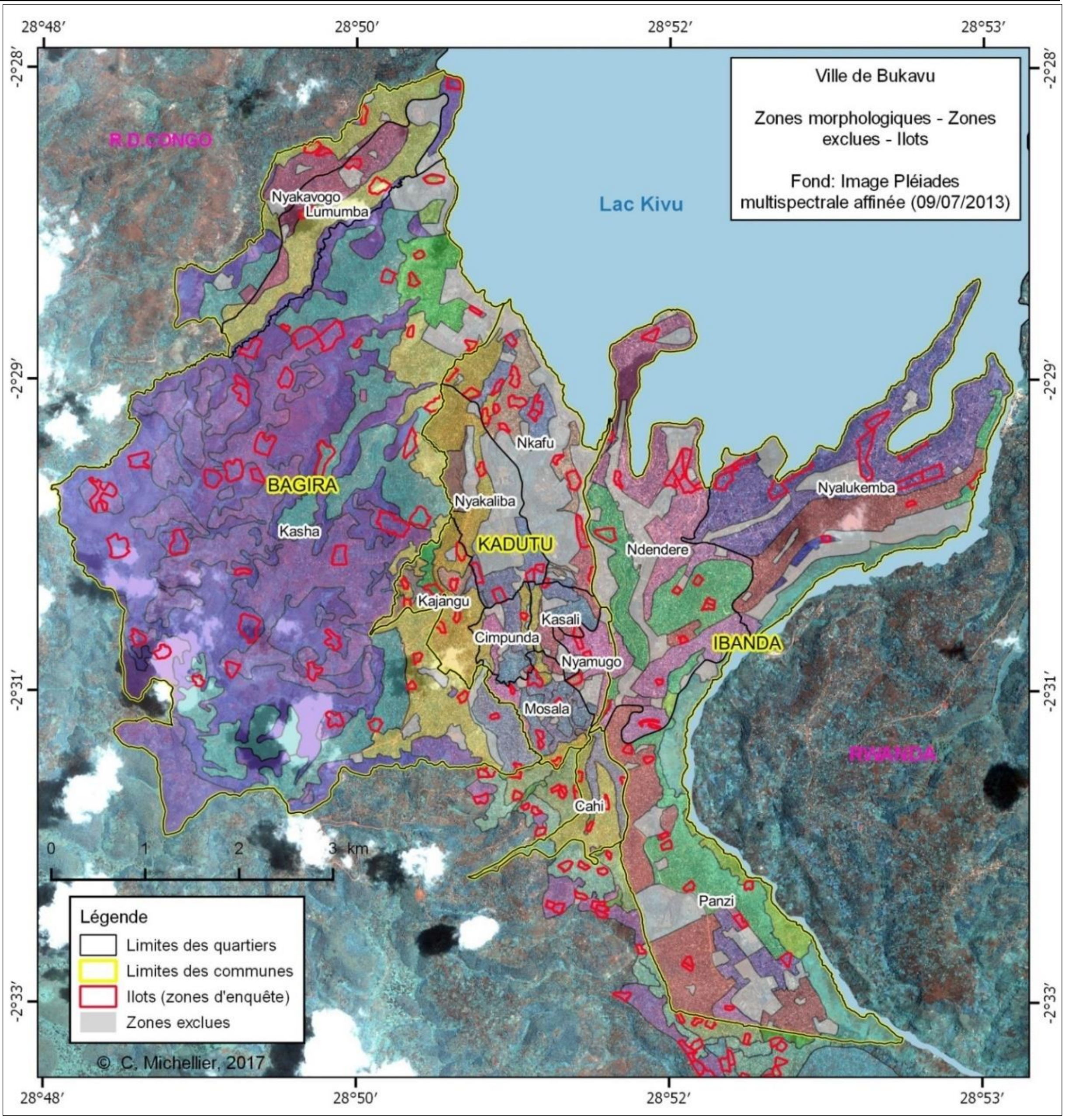



*Figure 25. Example of Bukavu cut in morphological zones with plots delimited as sampling areas for the household survey.*

In Bukavu, as in Goma, we considered the communes (first administrative level) as the basic unit of our survey. However, in order to **ACQUIRE DATA ON THE ENTIRE URBAN AREA OF THESE TWO CITIES**, we have defined for each of them an area outside the administrative boundaries, but where building density was close to that of the urban districts located near. These areas are called 'Annex' in Bukavu and 'Nyiragongo' in Goma, and are identified in our study as commune in our study.

The basic pattern was provided for nine different types of MZ. Visual interpretation was carried out commune by commune. Therefore, one type of MZ in a certain commune

was not exactly identical to the same type of MZ in another commune. But to make a relative ranking within each commune has enabled us to develop a classification of greater precision. We thus created several morphological zones in each of the communes of the two cities (Appendix 5). Each of them was divided into several tens of polygons identified by a code of MZ. Several polygons, even spatially non-contiguous, were assigned to the same MZ.
The size of our sample was fixed at 40 'plots' per commune, to be statistically representative. A 'plot' is a space encompassing several households, delineated on the basis of linear urban elements visible on the image, such as roads, gullies, rivers, etc.. The use of the VHR satellite images has the advantage of providing all the elements required for a rapid sampling plan. The 40 'plots' to be surveyed in each commune were distributed randomly and proportionally to the area of each MZ. In other words, if a MZ covers 50% of the commune, then 20 plots will be distributed randomly on its surface. Using the appropriate QGIS function, we distributed 40 points in each of the communes at random and in proportion to the area of each MZ. These points represented the origin (i.e. one of the angles) of each plot to be surveyed. From the VHR satellite image, we then manually delimited the plots, at a scale of 1/1,500 in a GIS. In a city in a developed country, a plot could be defined as a block. In Bukavu and Goma, their delimitation was made on the basis of roads, gullies, rivers, etc. This methodology, however, shows its limitations in a semi-urban environment: when the elements which serve in principle as borders to the plots are not easy to determine, or are less visible than an urban block. This was the case in semi-rural areas, such as Kasha in Bukavu and Lac Vert in Goma, because the roads were not always very visible on the VHR satellite image. This can have consequences for the surveyed area and the enumerated population; population densities are therefore not as rigorously defined as those obtained in urban areas. However, this limitation does not question the quality of the results obtained by this methodology. Infrastructures quality measurement and networks identification using exclusively remote sensing was not possible in Bukavu due to the complexity of the city, and not easy in Goma. Although we collected some data, additional detailed fieldwork would provide more precise information regarding these networks (road, power and water supply).

Population density and socio-economic data collection campaigns were conducted firstly in Bukavu in 2014, and then in Goma in 2015. It has required a few months of preparation (March to June 2014; February to April 2015). The main step was to develop a questionnaire which would enable us to get the appropriate demographic baseline data and more specific information on the past disasters experience and risk perception of the population. Each survey also required some specific material, such as GPS, batteries, questionnaire copies, field maps, etc.. Two local supervisors - a representative of ISP-Bukavu, and a representative of the INS - were responsible for obtaining the required permits from the mayors of Bukavu and Goma, who themselves informed the mayors of each commune in their city. After training a team of 10 surveyors, during which the objective of the study were explained in detail, the questionnaire was translated into Swahili to limit language mistakes, and a field survey testing, the survey itself was conducted in Bukavu in July and August 2014, and in Goma in May and June 2015 (Fig. 4.5 and 4.6). Surveyors, coached by the two supervisors, circulated throughout each urban area in order to achieve the population count in the plots. Then, in each plot, 10 households were randomly selected to be part of the demographic survey.

Our final sample in Bukavu was 179 plots, and in Goma 130 plots (of which 15 were uninhabited). The surveyors visited each of the identified plots. The principle of this survey was to make a systematic survey of all households living in the plot. For each of the 309 selected plots, a pair of field maps describing the plot was produced from the VHR satellite images, printed in black and white and inserted into the survey equipment:

- the first map, on a small scale, made it possible to observe the plot in its direct environment and to identify remarkable points located nearby;
- the second map was an enlarged and more detailed view of the plot to survey; this map allowed surveyors to number each house and avoid double counting.

The objective of the **first part of the survey** was a **COUNT OF HOUSEHOLDS AND INDIVIDUALS** living in each household. After introducing himself to the head of the household, or his wife / husband, to explain the framework and purpose of the study, one of the interviewers was asking the central question of their visit: "How many people count this household?" Once all the information about a household collected, the interviewers moved on to the next household, and so on until they had covered the entire plot. In total, we counted nearly 44,000 people in Bukavu (belonging to 6,582 households) and more than 27,000 people in Goma (4,511 households) (Table IV). It is from this data that we then estimated the number of households and individuals of the two studied cities. The analysis of our survey data enabled us not only to compare our population numbers with those presented by the authorities and the *Division provinciale de la Santé*, but also to calculate the population density at the scale of the MZ in each city. To our knowledge, this information had never been established at this scale for these cities. Combined with our survey data, we have calculated the population densities and established the maps that we present below. This layer of information is essential for risk assessment, since it materializes the exposed population.

*Table IV. Number of plots, individuals and households counted in the GeoRisCA survey*

| CITY | Commune | Total number of plots | Total number of counted households | Total number of counted individuals |
|---|---|---|---|---|
| BUKAVU | Bagira | 55 | 1.446 | 9.636 |
| | Ibanda | 42 | 1.656 | 11.461 |
| | Kadutu | 40 | 2.283 | 14.943 |
| | Annexe | 42 | 1.197 | 7.891 |
| | **TOTAL** | 179 | 6.582 | 43.931 |
| GOMA | Goma | 42 | 1.060 | 6.440 |
| | Karisimbi | 44[106] | 2.414 | 14.322 |
| | Nyiragongo | 29 | 1.037 | 6.309 |
| | **TOTAL** | 115 | 4.511 | 27.071 |
| **GRAND TOTAL** | | **294** | **11.093** | **71.002** |

In addition to the population census, we used the morphological zones to develop the **second part of the field survey**, which has enabled us to acquire **SOCIO-ECONOMIC DATA RELATING TO THE SURVEYED INDIVIDUALS AND HOUSEHOLDS** (Figure 26).

*Figure 26. (A) Interview and (B) team briefing in the framework of the household demographic survey, in Bukavu and Goma respectively.*

Based on a questionnaire developed for a socio-economic study of the population of Lubumbashi, and validated by the supervisors of our survey, we collected data over the following aspects:

- The first page (part A) is devoted to the precise identification of the household surveyed: this page is completed from the beginning of the interview; there is also a part of the page dedicated to the overall household structure, which can be filled after the interview; each interviewer must also indicate the location and timing information at the beginning or end of the interview.

- The following two pages (part B) constitute the individual questionnaire on demographic and socio-economic aspects. It consists of questions (presented in columns) for which the interviewer takes the answers in the horizontal direction, at the rate of one line for each member of the household. A questionnaire is planned for a maximum of ten people; if the household includes more individuals, the interviewer continues with a second questionnaire.
- The fourth page (part C) deals with threats facing the household. And more particularly its experience in the face of geological hazards. This part concerns the whole household.
- The fifth page (Part D) describes the description of habitat and equipment in the household.
- On the last page, any questions from the interviewee or comments from the interviewer may be provided in a box provided for this purpose.

For this phase, all households counted in the plot were not systematically surveyed: only 10 randomly selected households answer socio-economic questions. Once the 10 households to be investigated identified, each surveyor travelled to the plot using the field maps. After introducing himself and explaining the objectives of the survey, the surveyor then asked the head of household or his representative if he wished to participate in this survey, and if so, he began the interview. Once the 10 questionnaires completed, the surveyor moved on to another plot.

In total (Table V), we were able to investigate nearly 11,000 people in Bukavu (belonging to 1,614 households) and nearly 6,500 people in Goma (1,060 households). It is from that data that we then characterized the population of the two cities studied, through the socio-economic variables collected.

*Table V. Number of plots, individuals and households surveyed to collect socio-economic data*

| **CITY** | Commune | Total number of plots | Total number of surveyed households | Total number of surveyed individuals |
|---|---|---|---|---|
| **BUKAVU** | Bagira | 55 | 487 | 3.154 |
| | Ibanda | 42 | 414 | 2.810 |
| | Kadutu | 40 | 398 | 2.542 |
| | Annexe | 42 | 395 | 2.370 |
| | **TOTAL** | 179 | 1.614 | 10.876 |
| **GOMA** | Goma | 42 | 364 | 2.329 |
| | Karisimbi | 44 | 400 | 2.412 |
| | Nyiragongo | 29 | 296 | 1.731 |
| | **TOTAL** | 115 | 1.060 | 6.472 |
| **GRAND TOTAL** | | **294** | **2.674** | **17.348** |

The **DATA ENCODING** took place between October 2014 and February 2015 and between August and October 2015. A web form accessible through the GeoRisCA website using a login and password was created to facilitate this task. Then, between March and June 2015, a student (geographer) from Ghent University completed the first phase of the Bukavu data analysis using excel and Access software. A more detailed analysis of the demographic data was produced beginning of 2016 for both cities (partly automatized) with the help from VUB students. It was followed by the social vulnerability assessment analysis and mapping conducted between July and October 2016.

## RESULTS

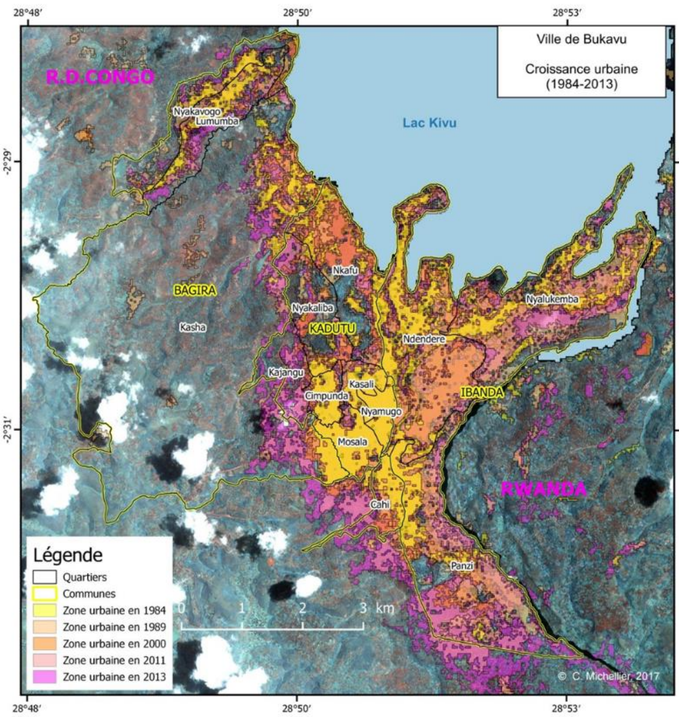
For each surveyed city, **A GIS WAS CREATED**, combining:

- the little existing data collected in various national and international institutions;
- several satellite images at various resolution scales (Landsat, Pléiades, SPOT 5);
- urban growth paths over the last 30 years;
- administrative boundaries at the communes and districts scales;
- morphological homogenous areas defined according to the buildings density;
- sampling plots visited during the demographic households surveys.

This GIS constitute one of the major outputs, as it compiles several types of information and it will be the visual interface of vulnerability and risk assessment.

**ANALYSES OF THE URBAN GROWTH** recorded on satellite images over the past 30 years allow highlighting spatial direction of each city development (Figure 27). The urban area of **Goma** is expanding towards the west, in direction of Sake, and also towards the North, along the border with Rwanda. Moreover, the city appears to be more and more constrained by the physical limitations: the lake to the South, the Virunga National Park to the West and North, and the Rwandese border to the East.

We observe the growth of **Goma** towards the West, where areas at risk of mazuku (*i.e.* local areas where $CO_2$ is accumulated up to lethal level) are located. This spatial analysis has also showed that the areas affected by the lava flow of the 2002 eruption of Nyiragongo had already been recolonised only five years later. This observation raises some concern, knowing the high probability that the next eruption could produce lava flow in the same area. Urban development is becoming an urgent matter for the authorities, taking into account the danger represented by the Nyiragongo volcano.



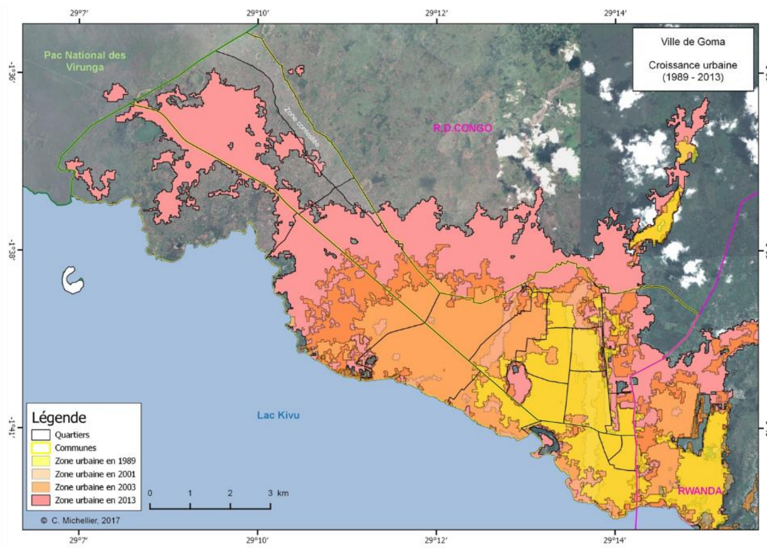




*Figure 27. Map of the urban growth of (A) Bukavu and (B) Goma*

In **Bukavu**, the urban area is expanding to the South. A secondary city center is developing around the Panzi hospital, so that distances do not become excessive. The densification of the habitat (of the increase of number of houses per km²) is also a huge problem in Bukavu: the parcels sometimes do not exceed 9m² for a family of five people. If this phenomenon is also observed in areas concerned by landslides, then the number of individuals at risk is becoming higher and higher. Urban growth is therefore a crucial parameter both for urban planning, and for the assessment of impact of future hazards.

A relevant results is the **DEVELOPMENT AND THE PUBLICATION OF 17 ADMINISTRATIVE MAPS OF BUKAVU** (whole city (Figure 28), each 3 communes and 14 districts), and **19 MAPS FOR GOMA** (whole city and 18 districts). It is an important output of GeoRisCA, as it represents baseline information which was so far not available for the authorities. These maps were officially delivered to the mayors of both cities, as well as to the *bourgmestres* and districts' chiefs in January 2015 and December 2016.

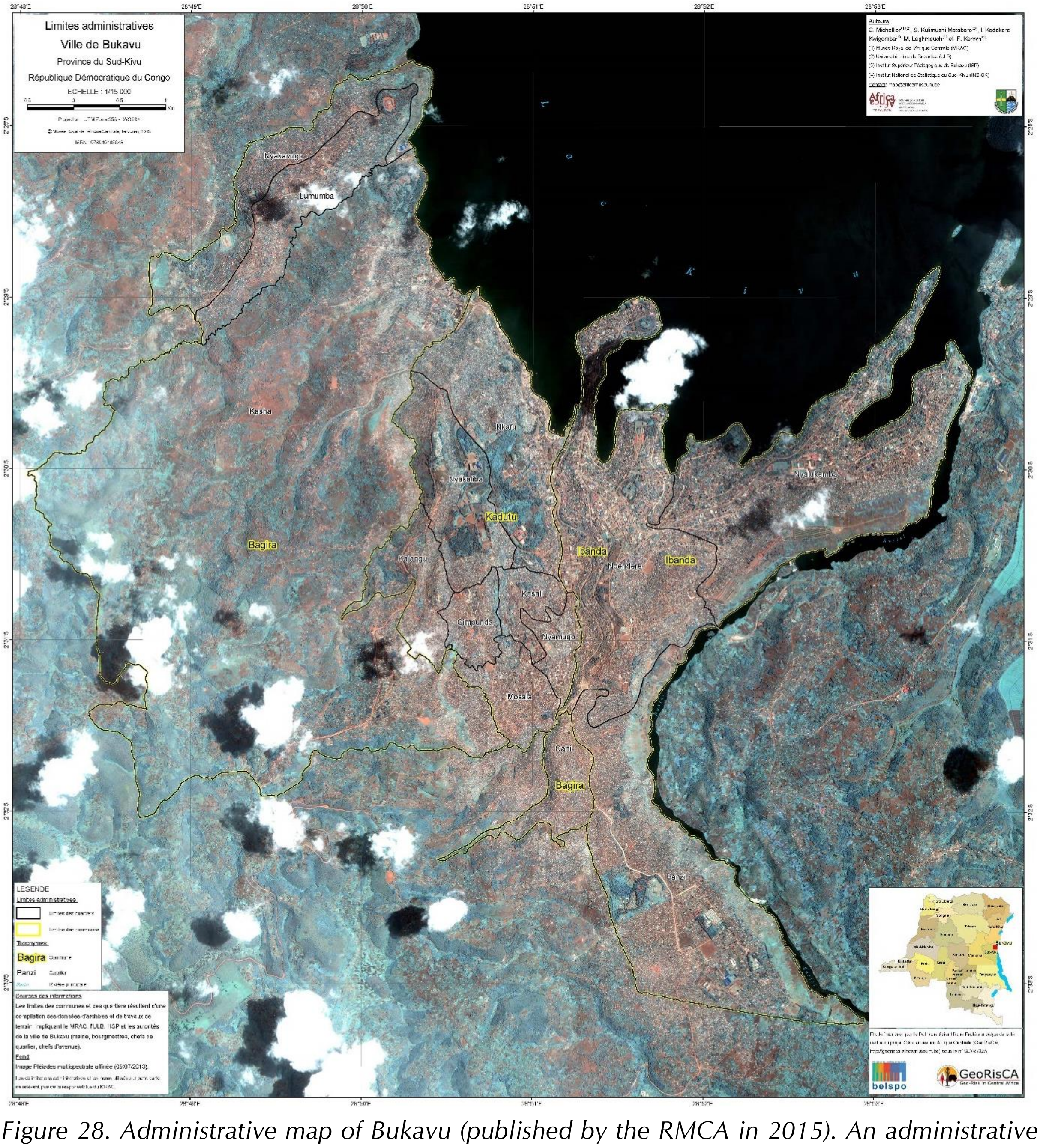



*Figure 28. Administrative map of Bukavu (published by the RMCA in 2015). An administrative map of Goma was also produced and published in 2016.*

Based on the field survey, a major output of the GeoRisCA project was the **POPULATION ESTIMATES CALCULATED FOR BUKAVU AND GOMA**, and compared to the official numbers given by the Authorities and the Provincial Ministry of Health (Table VI and Table VII).

In **Bukavu**, the total number of people calculated for the year 2014 is 870,589 (+/- 69,618) inhabitants. The most populated commune is Ibanda (361,485 inhabitants), followed by Bagira and Kadutu, which has the smallest area of the three communes. Historically, Ibanda is the commune from which the city of Bukavu was born, and also the one that supports the demographic growth of Bukavu towards the south. It is interesting to note that the population size obtained from our survey for the whole urban area of Bukavu (*i.e.* including *Annexe*) is within the range of those of the Provincial Ministry of Health - lower - and those of the administration - higher. Moreover, the two official figures are also within the margin of error of the figures calculated from our survey. However, this is not the case for Ibanda, where our survey seems to have overestimated the number of inhabitants living in this municipality. In addition, some very significant differences can be highlighted: the assessment of the Bagira population by the Provincial Ministry of Health seems overestimated given the semi-rural character of this municipality. The results are even more disparate in Kadutu: this reflects the difficulties of making a reliable count of the population in a commune where the density may be very high, whatever the method.

*Table VI. Population count in Bukavu in 2014*

| **Communes** | Population estimates (GeoRisCA, 2014) | Official numbers (Administration, 2014) | Official numbers (Prov. Min. Health, 2014) |
|---|---|---|---|
| *Annexe* | *72.011 (± 5.544)* | | |
| **Bagira** | 246.454 (± 29.572) | 221.307 | 400.575 |
| **Ibanda** | 361.485 (± 24.784) | 316.601 | 326.634 |
| **Kadutu** | 190.639 (± 9.718) | 377.883 | 123.337 |
| **BUKAVU** | **870.589 (± 69.618)** | **915.791** | **850.546** |

In **Goma**, the total population was estimated to 775,806 (+/- 115,284) individuals in 2015. While their areas are almost equivalent, the Karisimbi commune has more than twice the population of Goma commune. More than 487,000 people live in Karisimbi, while only 193,000 live in Goma. Karisimbi is a very dynamic commune: it is in its limits that the economic heart of Goma's life is located, on the Murara and Virunga districts. The districts Les Volcans, Katindo and Himbi are not intensely subject to a fragmentation of their plots, as can be observed in other parts of the city. On the other hand, Karisimbi shows a strong demographic growth and tends to overflow towards the north in the *chefferie* of Bukumu. The comparison of our results with the figures of the administration and the Provincial Ministry of Health leads us to the same conclusion as in Bukavu: the population figures of the whole urban area, including Nyiragongo, are between those of the Provincial Ministry of Health - less high - and those of the administration - higher; and the two official numbers are also within the bounds of the calculated uncertainty. Here again, the commune of Goma is an exception: our survey has a lower population size than those obtained via the other two methods, which suggests an underestimation of the evaluation of the population in this commune. In Karisimbi, the population counted by the administration seems to be much larger than the numbers obtained via the two other approaches, which is perhaps linked to the vagueness concerning the northern limit of the city, and therefore of this commune, with the *chefferie* of Bukumu.

*Table VII. Population count in Goma in 2015*

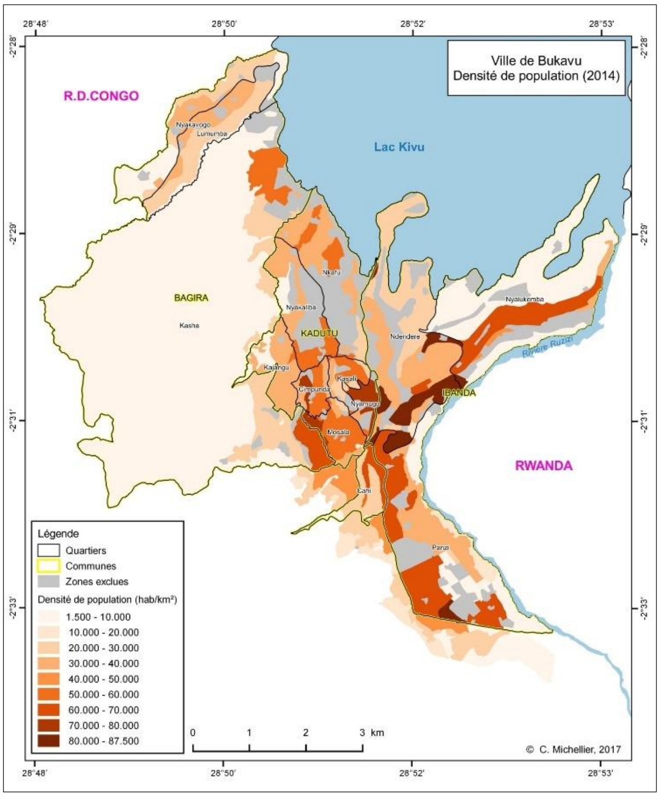
| **Communes** | Population estimates (GeoRisCA, 2015) | Official numbers (Administration, 2015) | Official numbers (Prov. Min. Health, 2015) |
|---|---|---|---|
| **Goma** | 192.815 (± 46.517) | 298.418 | 250.997 |
| **Karisimbi** | 487.120 (± 51.248) | 579.905 | 471.569 |
| *Nyiragongo* | *95.871 (± 17.519)* | | |
| **GOMA** | **775.806 (± 115.284)** | **878.323** | **722.566** |

The particularity of Goma is the high calculated uncertainty, compared to the numbers drawn from our study. Several hypotheses can be advanced to explain it. First, if the total number of inhabitants shows a difference of 100,000 people between the two cities, the area of Goma exceeds 60km² (while Bukavu covers about 44km²). However, we maintained the same sample size in the municipalities of this city (40 plots per commune). The overall number of plots could therefore be increased during the next survey. In addition, Goma has semi-rural districts where surveys have been difficult to implement, due to the absence of visible urban linearity (river, gullies, etc.) on the satellite image for the delimitation of the plots. Increasing the number of islets in these semi-rural areas would also be an added value for the quality of the survey results. This recommendation could be extended to other areas of the city, and also to Bukavu, up to the extent that the financial means to carry out a larger investigation permit.

After obtaining these global population estimates, the following step was to localize the population at the scale of the districts and, within these districts, at the scale of the morphological zones. **POPULATION DENSITY MAPS** were derived from these calculations (Figure 29).

**Bukavu** is a very densely populated city, with maximum population density reaching in some places more than 85,000 inh./km². The old city which was initially occupied by

Europeans corresponds to the districts of Nyalukemba and part of Ndendere. Today, these districts are still those where the administrative buildings are in function and where the richer people are living, along the lake. The hills on which the city has developed from the 1940's, with the installation of the "*Centre Extra Coutumier*" (C.E.C.) of Kadutu (i.e. centers only for black people) corresponds today to the areas where the buildings density is the highest. Another C.E.C. has developed at Bagira, to the North of the city center. It remains a dense area, separated from the old districts by Kasha, a rural district of Bukavu. In this area, houses are not constructed close to each other. The newly developing area is to the south, corresponding to the Panzi district. It is nowadays a secondary city center of Bukavu. New buildings are constructed nearly every day. The building density is not yet as high as in Kadutu commune, but it could become so.



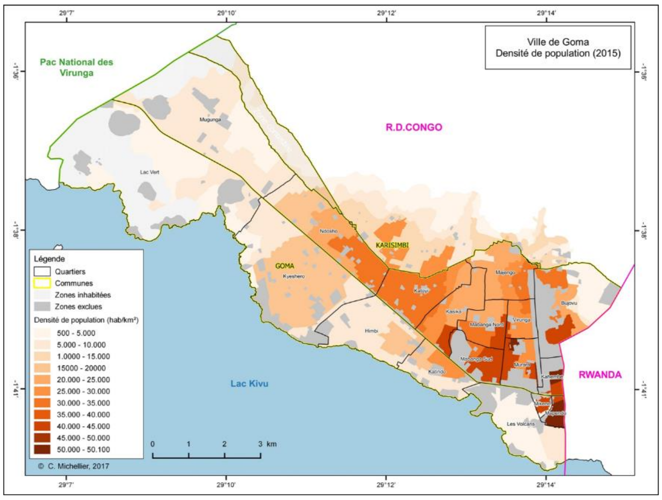




*Figure 29. Population density maps of (A) Bukavu and (B) Goma.*

The city center of **Goma** (markets, administrative buildings) is quite limited and concentrated mainly in the eastern part of the city. Other commercial areas are developed along the main roads. The richest districts of the city are found along the shore of lake Kivu. To the west, in the districts of Lac Vert and Mugunga, the buildings density is lower, but the demographic pressure seems to be high and could imply a strong development of this area in the coming years. Finally, the city might not continue

to expend strongly to the north, as there is another administrative entity, the Nyiragongo territory, which remains so far quite rural, and the VNP boundary, which constitutes a major constraint.
In her thesis, Michellier (2017) provides a detailed analysis of the population distribution within the two studied cities.

Finally, **THE SOCIO-ECONOMIC DATABASES HAVE PROVIDED VARIOUS TYPES OF DATA.** If this data is essential to the vulnerability analysis, it also constitutes a baseline database on the population of Bukavu and Goma. Such a demographic study of Bukavu (e.g. population estimations, population densities, and demographic and economic statistics) was previously conducted in 1978 (Fransen et al., 1978), but never in Goma (Figure 30; for more details on the demographic outputs of the demographic survey, cf. Michellier (2017).

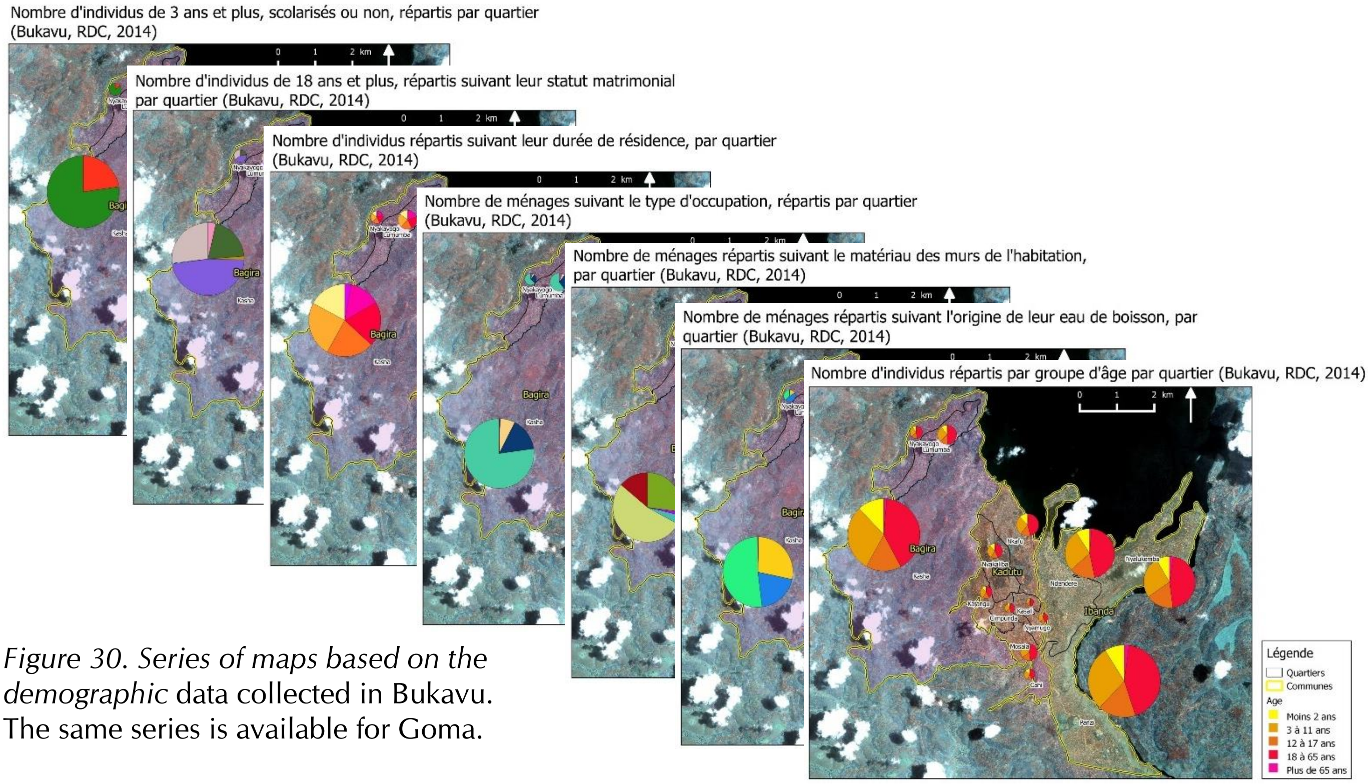



*Figure 30. Series of maps based on the demographic* data collected in Bukavu. The same series is available for Goma.

### 2.6.5. Vulnerability assessment based on the collected data

**METHODS** (Michellier et al., *in prep.*; contribution from F. Barette)

Although only sparse data was available at the beginning of the project, the vulnerability assessment could finally be based on a wide socio-economic database, comprising data at the individual and at the household level. Therefore, methodologies based on quantitative statistical analyses were explored and the Social Vulnerability Index developed by Cutter et al. (2003) was chosen. A social vulnerability index (SoVI) is characterising the social vulnerability of people living in the predefined morphological zones. The socio-economic characteristics of these MZ were investigated, based on the socio-economic data collected at the level of the household and individual, and then used as input for the assessment of the social vulnerability (Figure 31).

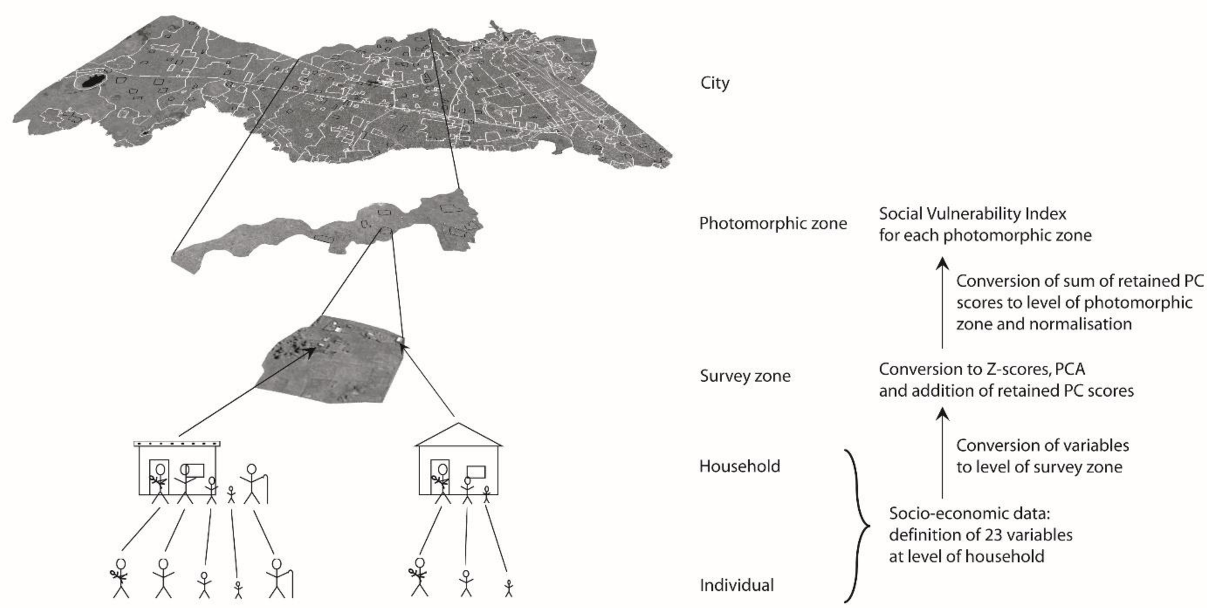



*Figure 31. Illustration of the methodology and the different levels considered in the assessment of the social vulnerability in Goma.*

From this dataset, 23 variables related to concepts of vulnerability were defined at the level of the households (Table VIII). These variables were converted to the level of the sampled plots as:

$$V_i = \sum_{h=1}^{H} \left( \frac{I_m}{I_i} V_m \right)$$

where $\boldsymbol{V_i}$ is the value of a given variable at the level of the plot, $\boldsymbol{H}$ is the number of surveyed households in the plot, $\boldsymbol{I_m}$ is the number of individuals living in the household $\boldsymbol{m}$, $\boldsymbol{I_i}$ is the total number of individuals living in the plot and $\boldsymbol{V_m}$ is the value of the given variable at the level of the household.

The variables at the level of the survey zone were subsequently converted to z-scores and used as input in a Principal Component Analysis (PCA; Jolliffe, 1986) based on the SPSS software. A varimax rotation was applied to enhance the interpretation of the component matrix and principal components (PCs) with an eigenvalue larger than one were retained for the construction of the social vulnerability index. For each survey zone, the scores of the retained PC were added together as:

$$W = \sum_{k=1}^{K} a_j W_j$$

with ***K*** the number of retained PCs (eigenvalue > 1), $\boldsymbol{a_j}$ a positive or negative sign depending on the interpretation of the PC with respect to the vulnerability, ***Wj*** the score of the PC ***j*** in the plot and ***W*** the sum of the PCs retained for each plot.

The sums of the PC scores were converted to the level of the morphological zones as:

$$W_Z = \sum_{i=1}^{I} \left( \frac{J_i}{P_i} W_i \right)$$

where ***I*** is the number of plots in a morphological zone, ***Ji*** is the number of inhabitants living in a plot, ***Pi*** is the total number of people living in the plots of the morphological zone, ***Wi*** is the sum of the retained PC scores for each plot, and ***Wz*** the sum of the retained PC scores in a morphological zone.

Finally, this result was normalised to a 0 – 1 scale to define the social vulnerability index for each morphological zone.

*Table VIII. Variables defined in the vulnerability study.*

| ***Variable*** | ***Abbreviation*** | ***Description*** |
|---|---|---|
| Number of individuals living in the household | NUMIND | |
| Average age of the individuals living in the household | AVGAGE | |
| Proportion of dependent individuals living in the household | PROPDEP | Proportion of individuals living in the household that may be dependent on another individual. An individual is considered as dependent if its age is smaller than 16 years or larger than 65 years. |
| Maximum residence time in the city of Goma of an individual living in the household | MAXRESTIME | Maximum residence time (in years) in the city of Goma of an individual living in the household |
| Proportion of individuals living in the household and with an age above three that have been or are currently going to school. | PROPSCH | |
| Basic education followed by an individual in the household | BASEDUC | Boolean variable identifying if at least one individual living in the household acquired a basic education level (*i.e.* at least secondary school) |
| Maximum number of languages spoken by an individual living in the household | MAXLAN | |
| Proportion of individuals living in the household that declared to be economically active (*i.e.* being part of the active population) | PROPACT | |
| Household monthly income per person | INCOMEP | Household monthly income per person (*i.e.* total monthly household income divided by the number of individuals living in the household). |
| Household with less than two independent people | <2INDEP | Boolean variable identifying if less than two independent people (*i.e.* age between 16 and 65) are living in the household. This variable identifies single-parents households or households consisted only of dependent individuals. |
| Proportion of woman living in the household | PROPWOMAN | |

| | | |
|---|---|---|
| Threat of hazard | THRHAZARD | Boolean variable identifying if the household was threatened by a hazard in the past. |
| Experience of hazard | EXPHAZARD | Boolean variable identifying if the household experienced a hazard in the past. |
| House with an economically costly wall material | WALL | Boolean variable identifying houses with an economically costly wall material (*i.e.* bricks, stones, concrete or cement). |
| House with an economically costly roof material | ROOF | Boolean variable identifying houses with an economically costly roof material (*i.e.* roof tiles, asbestos cement, galvanised metal sheet or concrete). |
| House with an economically costly floor material | FLOOR | Boolean variable identifying houses with an economically costly floor material (*i.e.* floor tiles, stones, concrete or cement). |
| Household possessing at least one radio | RADIO | |
| Household possessing at least one mobile phone | MOBPHONE | |
| Household possessing at least one multimedia device (*i.e.* television, computer of DVD-player) | MULTIMEDIA | |
| Household possessing at least one bicycle | BICYCLE | |
| Household possessing at least one moto | MOTO | |
| Household possessing at least one car | CAR | |
| House area | HOUSEAREA | |

## RESULTS

The results of the PCA, including the explained (cumulative) variance, interpretation, sign and component matrix are provided in
Table IX and Table X for Bukavu and Goma respectively. Variables linked to education and economic levels of the households are the main categories highlighted by the PCAs. Other elements, such as the structure of the household, and the residence time were also included in the Social Vulnerability Index calculation. The SoVI derived from the PCA gives a picture of the long-term impact a potential hazard could have on the population. Areas in dark orange are those where the population would have more difficulties facing and recovering from a disaster.

*Table IX. Results and interpretation of the PCA for Bukavu.*

| | **Var. (%)** | **Cum. Var. (%)** | **Eig.** | **Main interpretation** | **Representative variables and loadings** | **Sign** |
|---|---|---|---|---|---|---|
| PC 1 | **30,0** | **30,0** | **6,6** | **Economic factors and household resources and structure** | **HOUSEAREA (0,87)**<br>**CAR (0,87)**<br>**BICYCLE (0,76)**<br>**INCOMEP (0,75)**<br>**WALL (0,74)**<br>**PROPDEP (-0,62)** | **-** |
| PC 2 | **9,9** | **39,9** | **2,2** | **Education and economic factors** | **BASEDUC (0,76)**<br>**FLOOR (0,68)**<br>**PROPSCH (0,64)**<br>**MULTIMEDIA (0,62)** | **-** |
| PC 3 | **9,1** | **49,0** | **2,0** | **Communication and residence time** | **MOBILE (0,78)**<br>**MAXRESTIME (-0,78)** | **+** |

| | | | | | | |
|---|---|---|---|---|---|---|
| PC 4 | **7,0** | **56,0** | **1,5** | **Risk perception and past disasters experience** | **THRHAZARD (0,93)**<br>**EXPHAZARD (0,93)** | **-** |
| PC 5 | **6,4** | **62,3** | **1,4** | **Resources and household structure** | **PROPACT (0,70)**<br>**<2INDEP (0,61)**<br>**NUMIND (-0,78)** | **-** |
| PC 6 | **5,6** | **68,0** | **1,2** | **Household structure** | **PROPWOMAN (0,75)** | **-** |

The spatial variability of the **SoVI in Bukavu** (Figure 32) highlights the low social vulnerability of Nyalukemba and Ndendere, both of which border the lake. These districts are home to the wealthier population of the city: it is a population that has the economic ability to cope with an event, with a level of monthly income among the highest, many goods, spacious plots, and benefit from infrastructural facilities, such as access to water and electricity. In addition, these neighborhoods are those that include the most educated individuals (i.e. one of the highest grade levels). The Nkafu neighborhood also has several areas with low population vulnerability, but the evidence for low vulnerability in this industrial area is difficult to pinpoint. The population living in the southern part of the Panzi district is also weakly vulnerable. This is the area bordering the Panzi hospital: while overall the Panzi population has lower monthly incomes than the lakeside neighborhoods, this area may be favored by the presence of the hospital, which provides work for a large number of people living in its perimeter. Another part of low social vulnerability is visible in the district of Kasali. This area is made up of the last vestiges of the *centre extra-coutumier*, where habitatations made of sustainable materials have persisted until today. This type of habitations has the effect of reducing the social vulnerability of the population, despite a lower standard of living and access to education more restricted than in the Ndendere and Nyalukemba districts. The district of Mosala also has several areas still built with brick houses of the *centre extra-coutumier*. Their level of social vulnerability stands out as relatively low, compared to other close spaces. The low level of social vulnerability of the area of Kasha district, which is in contact with Mosala and corresponds to the Funu landslide zone, is however surprising. Although we are here in one of the poorest areas of the city, the fact that this population is aware of the risk incurred and has already experienced the impact of catastrophic geological phenomena, could contribute to reduce its social vulnerability - in the sense that if the population has already been confronted to an event, it is considered less vulnerable because of its understanding of the risks involved. Indeed, having the feeling to be threatened by an earthquake or a landslide, or having already experienced disaster in the past plays also a significant role in the level of vulnerability of the population, in the sense that the more people know about the potential risk, the less they are vulnerable.

Much of the Nyamugo district has a high level of social vulnerability. This is even stronger for a fringe of Mosala and Cimpunda districts. Here we find the footprint of the *cité nouvelle*, built spontaneously alongside the old *centre extra coutumier*. The main characteristics have remained a low economic level of the resident population, which is materialized by a habitations described as anarchic (very tight, very small, and built with mediocre quality materials).

The population living in the territory of Kabare, beyond the administrative limits of the city, has a marked semi-rural character, which translates directly into a relatively strong social vulnerability. This trend is also visible in the semi-rural area of Kasha. The population lives in more rudimentary conditions than in the rest of the city. It lives mainly from agriculture, which generates little income, and has rarely material goods such as cars, bicycles, multimedia devices. Finally, houses are often made of wood, with a tin roof. To this is added a lower scholorisation level than in the rest of the city and an education level that does not often exceed primary school, and rarely the secondary school. As a result of this way of life, the social vulnerability of this area stands out as the highest. A similar level is found along the Ruzizi river. This unstable area with steep slopes remains cheap for a population that cannot afford to live elsewhere.

*Table X. Results and interpretation of the PCA for Goma.*

| | Var. (%) | Cum. Var. (%) | Eig. | Main interpretation | Representative variables and loadings | Sign |
|---|---|---|---|---|---|---|
| PC 1 | **32,3** | **32,3** | **7,1** | **Economic factors and household resources** | **INCOMEP (0,84)<br>WALL (0,83)<br>HOUSEAREA (0,79)<br>CAR (0,74)<br>MULTIMEDIA (0,72)<br>BICYCLE (0,64)<br>FLOOR (0,61)** | **-** |
| PC 2 | **10,7** | **43,0** | **2,4** | **Education and communication** | **MOBILE (0,81)<br>BASEDUC (0,80)<br>PROPSCH (0,80)<br>RADIO (0,62)** | **-** |
| PC 3 | **10,5** | **53,6** | **2,3** | **Household resources and structure** | **NUMIND (0,75)<br>PROPACT (-0,87)** | **+** |
| PC 4 | **6,3** | **59,9** | **1,4** | **Risk perception and past disasters experience** | **EXPHAZARD (0,81)<br>THRHAZARD (0,75)** | **-** |
| PC 5 | **5,8** | **65.7** | **1,3** | **Household structure** | **<2INDEP (0,69)<br>PROPWOMAN (0,65)** | **+** |
| PC 6 | **4,6** | **70.3** | **1,0** | **Economic factors** | **MOTO (0,78)** | **-** |

In **Goma,** the **SoVI** (Figure 32) presents a gradient from the city center to the borders of the city. It is distributed along a growing gradient from South-East to North-Northwest, ranging from residential neighborhoods to semi-rural and newly-built neighborhoods in the city. The population living in Les Volcans district has economic and educational characteristics that give it a very low level of social vulnerability. This district corresponds to the old European quarter of the colonial city; it is made up of large plots, with spacious dwellings, equipped with water and electricity, and whose occupants possess a great material wealth. This district 'Les Volcans' is however cut in two parts by an area of greatest vulnerability, which corresponds to the area that had been impacted by the lava flows of the 2002 volcanic eruption. Housing construction materials and / or the economic level of households that have resettled in this devastated part of the city do not have quite the same characteristics as the older parts.

At the extreme opposite, the social vulnerability map highlights three poles of high social vulnerability. These areas, although scattered at the ends of the city, have similar characteristics. These are semi-rural areas, whose population - as well as in a large part of the Kasha district of Bukavu - has maintained an agriculture-based lifestyle, with some houses in wood, and low monthly incomes rarely in cash, and if any a very small amount (less than US $ 100 per month). These areas of high vulnerability, located far from the area impacted by the 2002 lava flows, are inhabited by a population not only recently installed, but also not having undergone the last eruption and therefore less aware of this threat.

Much of the Mugunga district, as well as the Northern area beyond the administrative boundaries of Goma City, in Nyiragongo territory, also experience a high level of social vulnerability. What particularly characterizes these areas is their recent development, mainly due to an influx of rural people in search of a safer place than the countryside. This population is poor (low monthly incomes, few material goods) and has a low level of education, making it particularly vulnerable. Moreover, the affected population of the 2002 eruption had largely resettled in Mugunga district. The authorities had parceled out a part of this district to accommodate the families who lived in the ESCO camp and who had lost everything. Since the disaster, it is possible that these households have remained at an economic level still very low.

Apart from these extremes, the rest of the city has a medium level of social vulnerability, which is difficult to characterize as such values may depend on different parameters. For example, the districts of Mapendo and Kahembe include the poorest populations of the city. However, their level of social vulnerability is low; this may be because of a proportion of people who have completed a relatively high level of education, because of a high perception of the geological hazards threat or because of a high proportion of women. Another example: the Kyeshero district is the one that brings back the greatest number of people having lived a geological hazard; this population may have been disturbed in its activities by the *mazuku* (*i.e.* local areas where $CO_2$ is accumulated up to lethal level; Smets et al., 2010a). It is in this district that the largest number of threats related to a geological disaster is reported. Associated with a difficult household economic situation and a low level of education, western Kyeshero stands out as a very vulnerable area.

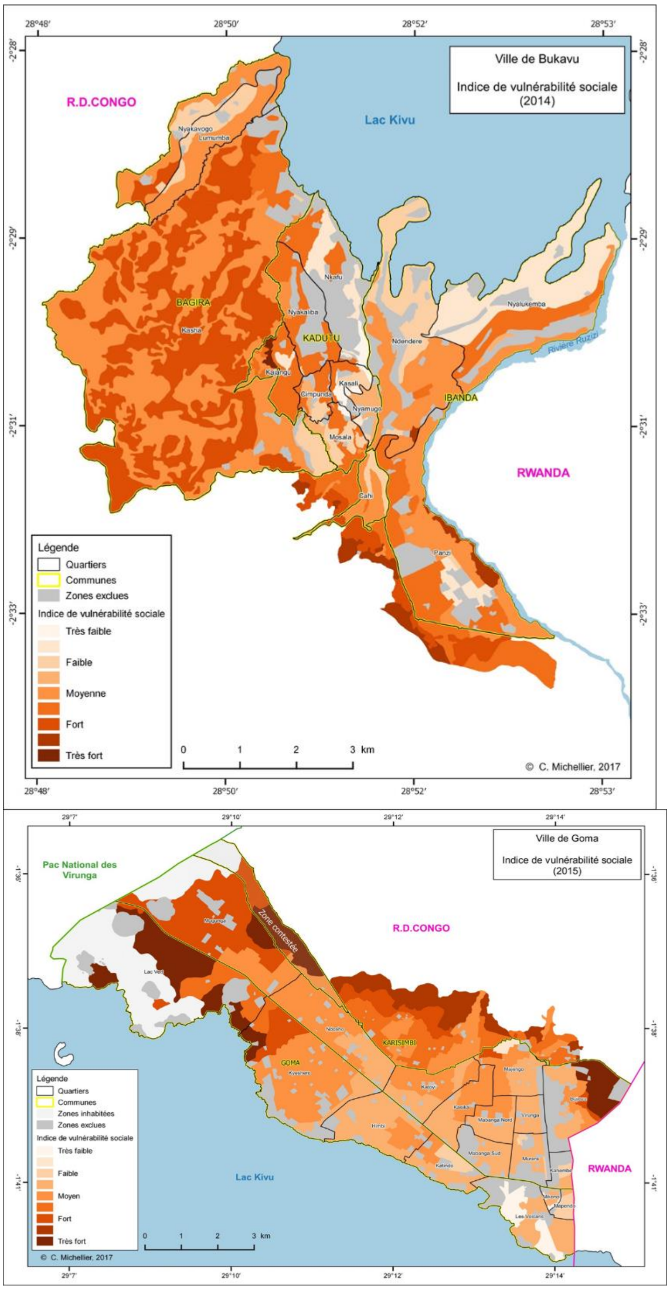



*Figure 32. Social vulnerability maps of Bukavu and Goma.*

The final step of the vulnerability analysis was to **AUTOMATE THE DATA PROCESSING** – from the Excel database to the creation of the corresponding maps – to allow the researchers to repeat the statistical and vulnerability analyses over time and in different places. To reach this additional objective, an IT tool was developed: after coding in "R" the commands which allow the data processing, a QGIS plug-in was developed as a user-friendly interface. By uploading the appropriate Excel files merging all the data from the survey, collected at the individual and the household levels, as well as the required shapefiles, the results of the statistical analyses are produced in few minutes at the scales of the communes, districts, and morphological zones, and become available in map format.

Combining the level of vulnerability of the population with its exposure and the probability of occurrence of hazards leads to determine the level of risk of the different districts of the studied cities: the risk of landslides in Bukavu and the risk of lava flows in Goma.

## 2.7. Which level of georisk in the cities of Bukavu and Goma?

### 2.7.1. Inventory of existing management institution (Burundi, RDC, Rwanda) and needs for risk management improvement

**METHODS**

Representatives of various governmental institutions, which could be affected by georisks or involved in their prevention and management, have been met. It has enabled us to establish their roles and their actions in the field, their interactions with other institutions and define what GeoRisCA could bring them.

As early as in June 2012, we started collecting information and data to complete the tasks 5420 Inventory of existing management institution (Burundi, DRC, Rwanda) and 5430 Needs for risk management improvement. This assessment was completed meeting representatives of institutions in charge of disasters management and risk prevention. We carried out these tasks in Bujumbura, Kigali, Bukavu and partly in Goma. Indeed, in Goma, the security situation prevented us from completing these tasks but we are keeping abreast of the evolution of the political situation and will schedule field work as soon as the security returns to normal.

In parallel to the state of the art conducted in the WP 4000 Vulnerability mapping analysis, the task 5210 Regional risk mapping and modelling and 5310 State of the art of local risk mapping and modeling were initiated. Some scientific papers have already been earmarked to be used for the drawing up of the risk assessment methodology.

**RESULTS** (Michellier et al., 2016)

These tasks were completed in Bujumbura, Kigali, Bukavu and partly in Goma.

**Bujumbura**

The Civil Protection (Direction Générale de la Protection Civile) is in charge of the disasters prevention and management policy. It is a direction of the Police Nationale du Burundi. The staff remains so far poorly qualified in the field of natural disaster prevention and management. It coordinates the national platform for prevention risk and disaster management boarded with representatives of several State institutions and NGOs.

Lacking the necessary means to achieve its duty, the Civil Protection is turning to external financial support. For example, the United Nations Development Program (UNDP) supports it, particularly for prevention/awareness actions. The unit is

encountering difficulties visiting the field, checking risk prone areas and intervening in case of emergency after a disaster.
Besides, there is also a small intervention of the Ministry of the Environment in the field of disaster prevention and in environmental impact assessment. Every new infrastructure (either public or private) should in principle be submitted to an assessment before the construction starts. However, the legislation is inadequate and not often respected.
There seems to be a will to integrate the concepts of risk in several sectors, such as land-use management and development (cadaster, planning), environment conservation... But on the ground, the standards, where they exist, are not met and there is no sanction policy for failure to comply with them.

**Bukavu**

A risk management department was created following the 2008 earthquake. When GeoRisCA started in June 2012 (first field campaign), it was still at an embryonic stage: it had no defined mission, no staff, nor structure; the process was almost still at the project stage. During the September 2012 field visit and workshop, the GeoRisCA team insisted on the necessity for Bukavu city and the South Kivu province to have an operational institution in disaster prevention and management. Assisted by the NGO Oxfam Novib and OCHA, a Civil Protection office depending from the Province Government was officially created in Dec. 2012. In March 2013, this office started defining its first contingency plan for Bukavu City (and later for the South Kivu province) with the help of multi sectorial international and national institutions to response and act altogether if a disaster occurs. The Provincial Government does not financially support the Civil Protection which still relies on external support (*e.g.* Oxfam Novib and OCHA). The creation of such a structure represents however a positive advance towards risk management It should become a credible coordinated counterpart for e.g. national and international aid agencies like OCHA in an emergency situation.
OCHA has indeed the mandate to coordinate the humanitarian actions during crisis, including the natural disasters; it coordinates the various NGOs on the field. OCHA also conducts regular prevention campaigns in the whole province.
The national Red Cross has a wide network of volunteers (who have followed a training adapted to crisis situations) distributed in the province (more than 13.000 people), and 3.000 located in Bukavu. Volunteers are coordinated by a provincial disaster response team that is mandated to assess needs and to organise distributions (food, material goods). The community is trained in first aid, so that rescuers can work with communities when they are facing emergency situation. Relationships with the Provincial Government are preferred, but this latter does not provide any financial support. The Red Cross hopes that it will change through collaboration with Civil

Protection. The Government was asked to have an emergency fund to provide the appropriate response in disaster-affected areas without delay. The lobbying in this sense continues.

**Goma**

Civil Protection of North Kivu is the official institution in charge of disasters prevention and management in Goma and the whole province. This service was created after the 2002 Nyiragongo eruption. It depends from the Provincial Government and has therefore limited intervention capacity. Civil Protection works with the GVO and National Red Cross. It also collaborates with UNOPS that is achieving a disasters prevention and management project focused on the volcanic risk.

The Civil Protection essentially focuses on community awareness and prevention programs (on the radio, in schools, through the avenue chief), the GVO has is in charge of the volcanic activity monitoring and early warning. The EU-UNOPS project provides some support to GVO and contributes to prevention campaigns. The project will end at the end of 2013. Through these joint actions, the main objective is that the community appropriates the risks, learns to live with it and develop its own resilience mechanisms.

There is a contingency plan for Goma city with regards to the volcanic risk. But it is not based on rigorous scientific parameters, the risk level of each district has not been assessed, neither has their number of inhabitants, nor preferred evacuation routes in case of volcanic eruption. However, in case of a volcanic disaster, the mechanism foresees that GVO, in charge of continuous monitoring of the volcano, sends warning to the authorities and Civil Protection responds in collaboration with aid through the OCHA coordination.

**Rwanda**

MIDIMAR is the Ministry in charge of the management and prevention of disasters (and refugees) in Rwanda. Historically, a risk management unit was already established in 2003, first integrated into the Ministry of Planning and then in the Office of the Prime Minister in charge of civil protection. The Ministry was finally created in April 2010 to address the problem of natural disasters independently. At that time, it coordinated the Disaster Management National Task Force; but although this latter was providing a real support in the field of disasters response allowing the coordination of NGO’s actions, it collapsed in 2010.

Aside from this, the disaster prevention and management policy is still under development.

Currently, the Ministry conducts actions in the field of hazards prevention (not focused on geohazards). The Research Department also undertakes studies for disasters

mitigation, by investigating the field with local authorities or heads of households, using GPS and remote sensing to locate events. In case of a disaster, MIDIMAR, which has no focal points in the field, works in close collaboration with the National Red Cross.
The interventions of the National Red Cross are both at the time of the crisis and in terms of prevention activities, in collaboration with MIDIMAR and sometimes with the support of the UNHCR. Catastrophic event are often reported by the volunteers within the community. The information is then relayed to the district level that transfers it to the national level and to MIDIMAR. Interventions are shared between the Red Cross and MIDIMAR, *i.e.* the two institutions are not in the field at the same time to avoid creating confusion among beneficiaries. The Red Cross also has a program of "Vulnerability Capacity Assessment", developed through household's surveys and focus group meetings with the authorities. This approach does not seem to be coordinated with the research program of MIDIMAR. This could be an improvement of the disasters prevention and management policy in Rwanda.

### 2.7.2. Local urban risk maps: how to integrate hazard and vulnerability factors identified in the urban sites into a GIS?

Risk prevention is a priority for reducing the impact of disasters. Achieving this objective requires a detailed knowledge of the distribution of potentially at-risk population - in our study, characterized by the population density - as well as the evaluation of its vulnerability. Other elements exposed (or assets) that the population could be the subject of such a study, or could be included in the overall vulnerability assessment. At the origin of this research project, we had considered including road, water and electricity networks in our risk assessment. But due to the difficulty of collecting data, it was not possible to integrate them in the final results.
In addition, the risk assessment also requires a detailed knowledge of the hazards that threaten populations, the infrastructures and all the exposed elements. To define the risk level of a population therefore corresponds to combine these three aspects - hazards, exposed elements and vulnerability - according to the following equation:

$$\text{Risk} = \text{Hazard} \times \text{Assets} \times \text{Vulnerability}$$

In other words, risk assessment requires the combination of hazard assessment, exposure distribution and vulnerability, which is a complex task in a context of low availability and reliability of data, such as cities of Bukavu and Goma (Michellier et al., 2016).

## METHODS

The objective of the GeoRisCA project was to develop useful decision-making tools for disaster risk reduction. We have chosen to develop risk maps based on an easy-to-reproduce methodology. In this type of risk assessment, GIS has become an indispensable tool for integrating information and spatial analysis (Alcorn et al., 2013, Castellanos Abella and Van Westen, 2007, Dao and Peduzzi, 2004; Leone 2004, Lirer and Vitelli 1998).

The results of the hazard assessment presented above have led to the development of susceptibility map for landslides for Bukavu and a lava flow invasion probability map for Goma. As explained in section 2.3 and 2.4, both documents are based on a large amount of field information and statistical analysis. They represent the hazard component of the risk equation on which our study is based.

Assets and vulnerability are based on the maps based on our field survey data. Indeed, to carry out the risk assessment of landslides in Bukavu and lava flows in Goma, we used the population density map of the two cities. We associated them with the Operational Vulnerability Index also evaluated from the socio-economic survey data. We chose to use the Operational Vulnerability Index rather than the Social Vulnerability Index, as the selection of the variables used is anchored in (1) our in-depth knowledge of the urban environments studied, (2) the quality of the data available to us, as well as (3) the opinion of the Congolese experts.

Risk assessment is based on the interaction between the probability of a hazard occurring, the density of the population and its vulnerability. These last two components are evaluated at the morphological zone level. The risk map thus combines these three layers of information (Figure 33 and Figure 34). Solely the areas of the map where the three layers of information are available present a level of risk to landslides or lava flows. Specifically, after rasterizing each of the three maps, we have multiplied the three pixel layers together, in accordance with our risk equation, to obtain a new map whose value of each pixel corresponds to the level of risk of landslides or lava flows. The same methodology was applied for the development of risk maps for both cities.

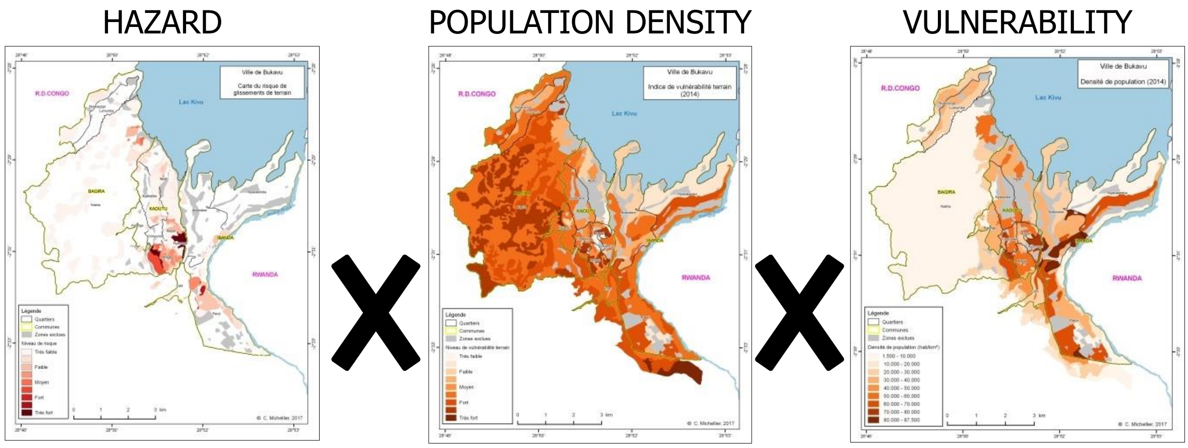



*Figure 33. Schematic presentation of the integration of data related to issues, vulnerability and hazards in order to obtain the risk map for Bukavu (© C. Michellier)*

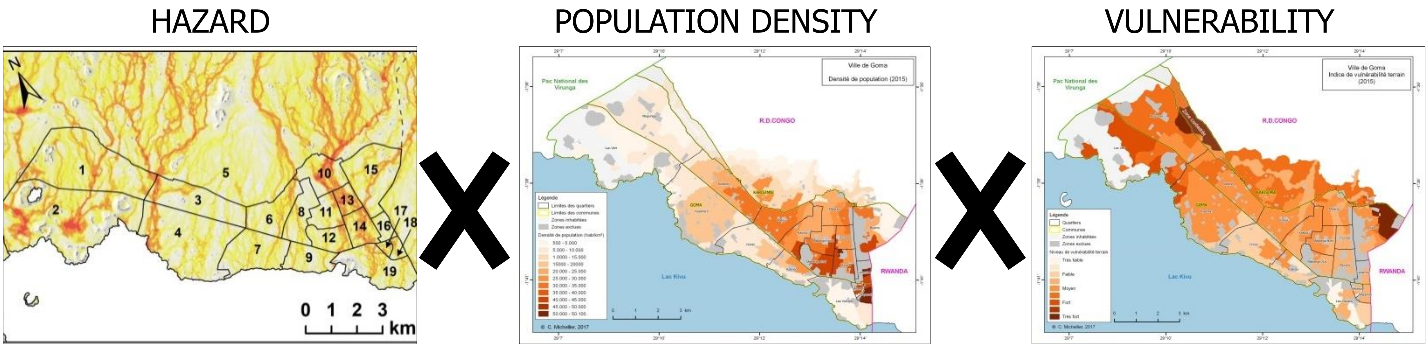



*Figure 34. Schematic presentation of the integration of data related to issues, vulnerability and hazards in order to obtain the risk map for Goma (© C. Michellier)*

## RESULTS

**The Bukavu landslide risk map** (Figure 35) highlights the city center - the districts of Nyamugo, Mosala and Kasali - as being the most at risk. It is worth mentioning that these are also among the oldest populated neighbourhoods. This area has a high population density, a high level of vulnerability due to the low economic level of households, and the presence of slow and regular movements of land which contribute to the deterioration of housing, thus endangering the population. This landslide has preoccupied the city authorities since the 1970s (Bureau of Urban Planning Studies, 1978) despite them not taking any measures to protect the local population.

In addition to the Funu zone marked by a steady and slow movement (Baligamire et al., 2017), the Wesha River Valley, west of *La Botte*, also stands out as a high-risk landslide area (Kulimushi Matabaro et al., 2017). The physical processes are more sudden and fast than that observed at Funu, and disasters are regularly reported in this area of Bukavu. Taking into account infrastructures, such as the road network, the water and electricity distribution network, in the risk assessment would probably bring out the same zones: our field visits have often led us to note that infrastructures were damaged in these districts.

Finally, further South, in the Panzi district, areas of steep slopes regularly experiencing landslides have also been identified; yet, in the absence of alternatives, the population is still massively-settled in these high-risk areas.

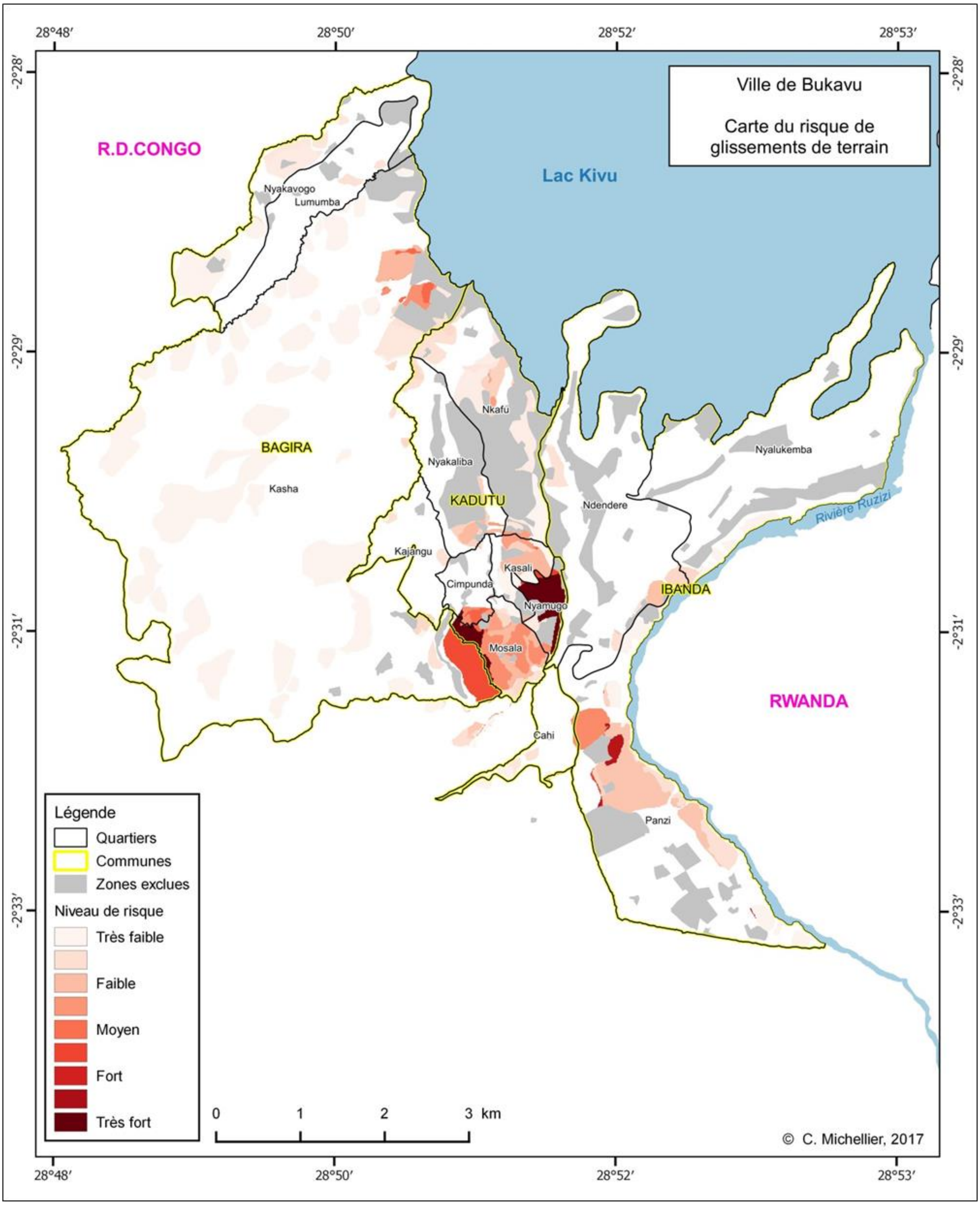



*Figure 35. Landslide risk map for Bukavu City.*

The **lava flow risk map for the city of Goma** (Figure 36) shows the spatial distribution of the level of risk regarding the invasion of a lava flow. This map incorporates a set of eruption scenarii and, therefore, does not exclude areas at low risk from being impacted by the next eruption. The lava flow risk map is particularly influenced by the spatial

distribution of the lava flow hazard. In Goma, the areas with high population density have been shown to be poorly vulnerable (cf. sections 2.5.4. and 2.5.5.). These two layers of information (*i.e.* vulnerability and population density) tend to leave the map of hazards take over.
The lava flow risk map mainly highlights three areas: one that had already been affected by the lava flow of the 2002 eruption that had crossed the city to reach the lake and two areas to the west, in Kyeshero and Ndosho districts on one hand, and Mugunga and Lac Vert on the other hand. These districts correspond to the new extension of Goma.

In recent years, *Le Cinquantenaire*, located in the center of the Mugunga district (grey area on the map) has undergone significant development (construction of a school and a church, installation of administrative structures, project of a new sports stadium, etc.). Following the 2002 volcanic eruption, this area was designated by the Authorities as the new administrative center – and, in the long run, the new economic center - of the city of Goma. Although the population has not yet invested heavily in this area, the provincial government seems to maintain its plans to relocate the main administrative offices there. However, on the lava flow risk map, *Le Cinquantenaire* appears to be affected by the highest level of risk, just like the city center of Goma. The impact on this still peripheral area would certainly be less significant for the social and economic life of Goma than a new destruction of the city center. Indeed, an eruption affecting Mugunga would result in the displacement of a small number of people, because population density is still low in this district. On the other hand, these people have been identified in our vulnerability assessment as particularly vulnerable; they are therefore economically and socially fragile, which would imply that they should face great difficulties in facing a crisis on a medium and long term perspective.
The impact of a new eruption on downtown Goma could only be more catastrophic than that of 2002, because of the densification of the population and activities over the past 15 years. The very high level of risk assessed for the districts of Majengo, Virunga and Murara emphasizes the need to strengthen prevention programs, to disseminate more information to the population, to consider the relocation of community infrastructures and define the evacuation routes by taking into account their very high level of risk, as well as those located further west.

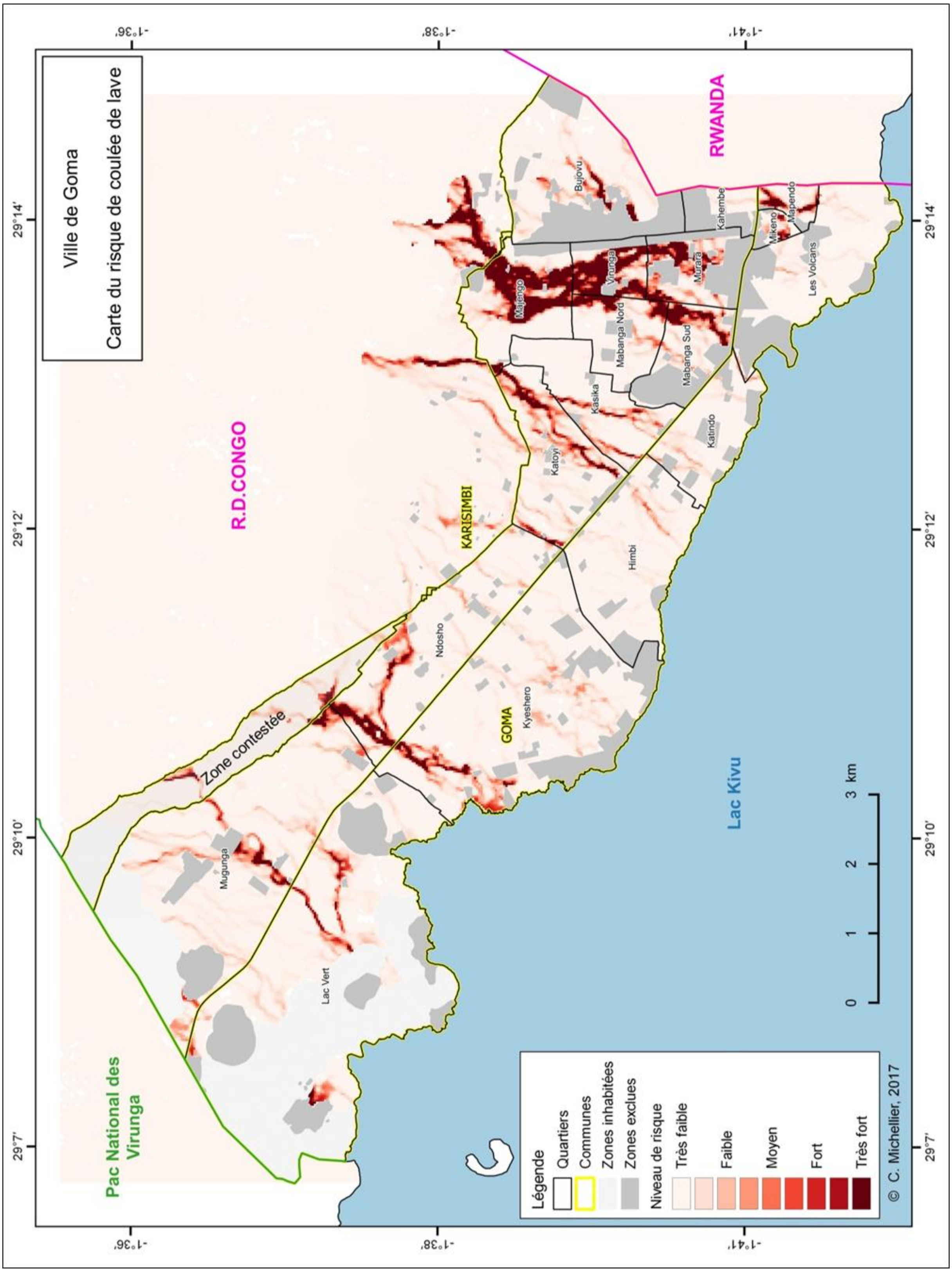



*Figure 36. Lava flow risk map for Goma city and surroundings.*

From our study of the exposed elements and their vulnerability to geological hazards in the cities of Bukavu and Goma, combined with the results of the hazards evaluation, we have **developed specific risk maps for the two cities**. These documents are not only a scientific breakthrough, but they are also operational documents.

Based on these maps, what are the measures that the Civil Protection could take? How important are these new decision tools to the Civil Protections for helping with prevention and risk management?

# 3. POLICY SUPPORT

The origin of the GeoRisCA project is based on the need to develop not only a methodological approach to assess the risk in a region where this concept has not yet been implemented, but also to develop decision support tools for the institutions in charge of risk management and prevention. The studied region is regularly affected by disasters, and the civil protections of North and South Kivu have recently developed their contingency plan, which are aiming at improving the management of crisis. In both provinces, these documents mainly refer to past disasters, but do not address the issue of risk assessment through better scientific knowledge of the hazard and an estimate of the vulnerability of the population and the infrastructures likely to be damaged. The scientific content of these documents is therefore extremely limited.

Beside the products that were delivered as output results of the project (vulnerability map, population map, risk maps, hazard maps ...), recommendations have been formulated and discussed during the restitution workshop organized in December 2016 in Bukavu, Goma, and Kigali.

The recommendations are distributed in different categories; some are general and do not concern a specific site and are addressed to all —authorities and scientists—, others are specific to each city, and target a specific institution.

## 3.1. General recommendations

### 3.1.1. Improving communication between all stakeholders

Improving dialogue between authorities, scientists and civil society is essential. It is crucial that everyone knows the scope and limits of their responsibilities.

Scientists play a decisive role since they must not only share their knowledge with the next generation of researchers, but also transmit useful, relevant and above all reliable information to the authorities in a clear language and at the right time. In all circumstances, they must take care to nuance and bring all the necessary reserve to avoid the serious consequences of false alarms, and panic reactions.

For their part, the authorities must ensure that they are able to understand the scientists' information and, if necessary, associate experts within their teams who can assist them in this task.

### 3.1.2. Improving awareness and prevention

On the basis of the knowledge and experience acquired, awareness and prevention programmes must be reinforced towards target groups (schools, workplaces, community) so that the population is as well informed as possible and knows how to behave in the event of an alert or crisis.

### 3.1.3. Taking into account the results of the risk and vulnerability assessment

GeoRisCA results should be integrated and considered in contingency and evacuation plans. Risk maps, population and vulnerability distribution maps are important decision support tools. Based on sampling, they are certainly not a panacea but provide the most accurate data available to date.

This also applies to urban planning. The development of new quarters and the construction of public or private infrastructure should take into account the risk maps provided by GeoRisCA.

### 3.1.4. Repeat and maintain vulnerability assessment

Managing risk involves knowing the vulnerability of the population and infrastructure. This imposes:

- to know as well as possible the size of the population and its spatial distribution as well as its level of vulnerability.
  - ⇨ A census should be conducted and maintained using a computerized civil registration system.
  - ⇨ Renewal of surveys to update and collect socio-economic data such as those conducted by GeoRisCA should be considered;
- to continue and refine the vulnerability assessment in its dynamic character (see 3.1.5);
- To carry out a cadastre of sensitive infrastructures (public places, administrative buildings, schools, places of worship, etc.).

### 3.1.5. Continue to develop research activities

The GeoRisCA project has made it possible to tackle concepts hitherto unknown in the region and to develop methodologies adapted to the context. However, these concepts and methodologies need to be refined and improved to take into account aspects that could not be taken into account. For example, the evolution of vulnerability as a function of time: the distribution of vulnerability varies according to the time of day, according to population movements, its concentration in certain activity zones, etc.

The study of hazards must also be continued, which implies, for example, the search for structural means to ensure the maintenance of measurement instrument networks, or means enabling scientists to continue their work.
Special attention should be given:

a) strengthening the scientific capacity of institutions in charge of monitoring. This requires protecting and strengthening partnerships with institutions that have the necessary expertise and capacity to implement in this specific context.
b) the maintenance and development of measuring instrument networks.
An efficient and operational network exists today, developed within the framework of GeoRisCA and the RESIST projects. However, no measures have yet been taken to guarantee the maintenance of this network (replacement, repair, deployment of new instruments).

Other actions should also be considered in the future such as the extension of the seismic network towards the South of the Lake Kivu Basin and Tanganyika where seismic hazard is more important. This extension would make possible the refinement of seismic hazard estimation.
Further geological mapping of the area through field work, aerial and satellite observations would also be desirable. While the latter are longer-term objectives, they are essential and require the development of strategies to enable their implementation.

## 3.2. Specific recommendations for the city of Bukavu

The **Bukavu** landslide risk map developed in GeoRisCA highlights areas in the city where the population is subject to the greatest threats. Due to the type of localized landslide hazard, and slow processes that affect certain areas of the city, the impact of a disaster remains limited. The population is often aware of this risk, but has no opportunity to settle in other areas of the city. Displacement of the entire neighbourhoods has been planned since the 1970s, but the demographic pressure is too strong and such action requires a solid dedicated political will. Bukavu is not the priority of the South Kivu's Civil Protection regarding landslides risk. Actions are concentrating on the region bordering Lake Kivu to the North, where landslides are often sudden and devastating.
The integration of the landslide risk map into the future contingency plans of the city of Bukavu could help develop prevention programs, for example in schools or community centers such as markets, to raise awareness among the population regarding the dangers of residing in these risk areas. In terms of spatial planning, the existence of a landslide

risk map can also guide the development of the city towards safer areas. However, it must be ensured that this map is not diverted from its primary purpose of risk prevention, nor used to endorse arbitrary spatial planning policies.

From the discussions held between the various stakeholders, the main raised concern is about the prevention and remediation measures that can be taken to mitigate the negative impact of landslides and earthquakes.
Whereas GeoRisCA is the first project aiming at studying landslides at the scale of the Kivu region, mapping landslides sites and compiling the earthquake catalogue to assess the seismic risk were two of the main achieved tasks. They are the prerequisites to further detailed work at specific sites. From the results obtained from that study, the following comments and recommendations have been formulated:

- Based on the seismic risk assessment achieved during GeoRisCA, a dedicated study of the seismic micro-zoning at the urban and periurban levels is recommended. It would provide a finer estimation of the spatial distribution of the seismic response and amplification in case of earthquakes.
  Based on that detailed seismic study, building standards and rules, taking the seismic risk into account, could be formulated.
- It is not always easy to identify a landslide and even less (the) process in action. It is therefore important to be very careful about the interpretations that are requiring field observations, satellite and aerial image analysis, etc.).
- The process is often complex and requires expertise that needs to be developed locally. Mitigation actions cannot be generalized and are always the result of cases by cases analysis.
- In many cases, landslides are natural and no preventive measures can be taken. The best approach consists in the identification and understanding of the factors responsible for landslide occurrence (susceptibility and hazard maps) and to take them into account in the land-use management.
- In General, when a zone can be identified as prone to landslides, generic measures can be considered like:
  - Water accumulation and concentration of flows must be avoided. Effective drainage of water outside areas of instability often contributes to reduce the risk.
  - Overload (heavy construction, landfill), particularly at the level of the head of the landslide and sensitive slopes should also be avoided.
  - Removing material at the foot of unstable/sensitive slopes increases the risk of instability.

  - In general, trees have a positive effect on the stability of the slopes essentially because they prevent the surface erosion and promote water absorption.
- Where infrastructure is already damaged, there is no quick fix. In some cases, the problem can never be solved; at best it can be attenuated. The only approach relies on a case-by-case study, taking into account the stakes in place (economic, ethical, political, environmental, etc). A dedicated expertise is always necessary.

## 3.3. Specific recommendations for Goma

In **Goma**, the risk situation associated to the volcanic hazard requires the highest attention.

### 3.3.1. Improving prevention and raising awareness

Based on the risk map established in GeoRisCA, prevention and awareness measures should be strengthened through media campaigns, posters or paintings, exhibitions, cultural events, lectures, school....

Serious game like the game Hazagora that is dedicated to inform, educate, and raise the awareness of the participants also offer nice possibilities (Mossoux et al., 2016a). The Civil Protection of North Kivu has been very interested in Hazagora - developed partly in the framework of GeoRisCA - which seeks to highlight the mechanisms of resilience that a community can develop to cope with various hazards; and it is planned to use this game for outreach in Goma high schools. The education and awareness of the population should lead to better preparation for future volcanic crises. More specifically, the population should know (i) the eruptive mechanisms of the Nyiragongo volcano, (ii) the monitoring activities in place and their limits, (iii) the consequences that could result from lava flows, (iv) to which zone(s) of Goma they should be directed in case of an alert, (v) which means of communication should be used during a volcanic crisis, (vi) how will they be informed of the evacuation, and when.

### 3.3.2. Adapting the contingency and evacuation plans

Existing contingency and evacuation plans should be adapted. Indeed, to date, they have considered only one lava flow scenario, the one that is closest to the 2002 eruption (*i.e.* a fissure opening on the southern flank of Nyiragongo volcano with one or more branches of lava flow destroying the eastern part of the city of Goma). Currently, the contingency plan mentions that, in case of crisis, the population - *a priori* the entire population of Goma - will have to be evacuated to a distance of between 3 and 43 km, towards Sake and Rwanda.

However, some evacuation sites are located in areas characterized by a very high susceptibility to lava flooding. In addition, a massive evacuation of the population could lead to other severe problems that would not be easy to manage (for example, infectious diseases, malnutrition and violence). The complete evacuation of a city of nearly 800,000 inhabitants should be considered in the form of different phases, depending on the gravity of the situation and its evolution, and not necessarily entirely.

### 3.3.3. Taking the lava flow risk into account for urban planning and development

Finally, the risk assessment of lava flows is a necessary tool for planning the future development of the city. Chirico et al. (2009) have shown that barriers could be used to divert major lava flow paths and protect part of the city of Goma. One of their proposals, however, is highly questionable since it consists of diverting the main lava flow paths in an area between Goma and Gisenyi, and may not help to ease relationships between the DRC and Rwanda. Finally, the development of the city given the risk of lava flows should be considered as a long-term perspective where predictive tools are used for planning. First, the construction of new houses and buildings should be avoided in high-risk areas. Critical infrastructures, such as schools and hospitals, should be moved from these risky areas. Scientific research should be provided more support to develop an effective warning system for an upcoming eruption. A realistic evacuation plan should be put in place taking into account the risk maps associated to the considered as most probable eruptive scenarios. The evacuation plan should focus on the high-risk areas identified in GeoRisCA, and the population should not travel more than a few hundred meters to a few kilometers.

### 3.3.4. Pursuing researches on the volcanic hazards

Researches on the volcanic hazards should be pursued and supported. The scientific researches on Nyiragongo and Nyamulagira are very young compared to some other active volcanoes in the world. Some dataset are only a few years old. The vision that we have on the behavior of these volcanoes is therefore very limited and the interpretation of the recorded data as eruption precursors highly challenging.

### 3.3.5. Specific recommendations for the Goma Volcano Observatory:

Scientific recommendations:

- Continue the development and maintenance of monitoring systems (deformation, seismic, geochemical, meteorology...) and ensure homogeneous coverage of the volcanic zone as far as possible.
  - If possible, ensure redundancy of the measuring stations (pair of nearby stations).
  - To avoid at all costs the interruptions in the continuous recordings (seismic, GPS, thermal...) ➔ foresee the material necessary for the fast replacement in the event of breakdown, and to ensure the regular recharging of the units for the transmission of the data in real time...
  - Maintain the transmission and continuous recording of data to servers, in particular, ensure the quality of the power (stable and uninterrupted) supplying the servers, the quality of Internet transmission etc....
  - Make at least two regular backups of the data and store them in separate locations.
  - Continue characterization and dating of past eruptions, including lava flows in the Bulengo area, Mount Goma and the entire phreatomagmatic cones. Take advantage of any excavation work in and around Goma to inventory and characterize the extent and type of pyroclastic deposits (including collection of ash and paleosol samples).
  - To establish correlations between tephra-chronological analyses in Lake Kivu with studies of sub-aerial volcanic deposits, including in the central and eastern Virunga zone. ➔ constrain the periods of return of the various types of eruptions.
  - Develop a physical hazard model related to phreato-magmatic eruptions once sufficient field constraints are available.
  - Support the development of a real-time monitoring system for the Nyiragongo lava lake to complete the existing monitoring network. Maintain a photographic database of volcanoes and their craters: images taken from similar points of view and archived with the necessary information (author, date, conditions, specific observations...)
  - Take into account the new scientific results to develop a series of realistic and diversified eruptive scenarios. For each scenario, numerical simulations of the intensity and spatial distribution of the hazard process could be produced in order to constrain the magnitude and extent of the impacts on the different elements exposed.

- Continue the development of databases (monitoring, GIS, geochemistry) and set up a data management system to make these data available to local and international researchers and to evaluate the quality of the data in order to deepen their interpretation.
- Record visual observations, unusual facts, field reports etc. in a database for later comparison with data analyses to assist in their interpretation. This can also be done in the form of an observation bulletin published at regular intervals.

Recommendations scheduling:

- Take into account the phreato-magmatic hazard, its spatial distribution and its impact characteristics in the contingency plan.
- Take into account the lava flow susceptibility map for the identification of evacuation zones and routes.
- Take into account the spatial distribution of hazards (lava, mazuku, phreatomagmatic) for long-term urban development (especially in Bulengo area) and evacuation plans.
- Continue regular activities to raise public awareness of volcanic processes and risks to promote good responses in times of crisis, based on the contingency plan. Specifically for areas affected by mazuku, regular information is needed for new inhabitants and to prevent new construction in areas with high $CO_2$ concentrations.
- In the contingency plan, the role and responsibilities in terms of decisions of the different institutions involved in crisis management must be clearly identified. Establish a communication plan towards the population to ensure clear and direct communication during a crisis.
- Ensure that the population and its expectations regarding hazards are listened to and responded to in an appropriate manner.

## 3.4. Contingency and evacuation plans

With the end of the GeoRisCA project, we have engaged a more intense dialogue with the North and South Kivu authorities and with the Civil Protections in particular; to discuss the possible integration of risk maps into contingency and evacuation plans. J.M Bwishe, technical secretary of the South Kivu Civil Protection, seems very enthusiastic about the benefit of the landslide risk map for the upcoming development of the Bukavu City Contingency Plan. Following the official submission of this document, he therefore proposed to include it in the official disaster risk reduction documents. Contacts are continuing in this direction. With the Civil Protection of North Kivu, after a week of intense discussions about the follow-up of the lava flow risk assessment documents in Goma, we came up with a protocol for integrating GeoRisCA results into the contingency plan and their consideration for the review of the evacuation plan. Beyond these commitments made with the Civil Protection of North and South Kivu regarding the risk maps developed within the GeoRisCA project, we can conclude, more generally, that this assessment of vulnerability and risk in this region opens the door to new research opportunities, while strengthening the link with local institutions - scientific and decision-making.

## 3.5. Concluding remarks:

Assessing the risk associated to natural hazards in the region of Goma and Bukavu is far from being limited to a scientific exercise. GeoRisCA has significantly contributed to install a high level of interactions between scientists and the authorities. One of the key-factors is the fact that for the first time, the society and the natural sciences have been put together.

This is not the fact from GeoRisCa only, it does correspond to the global evolution and a raising awareness to natural risk and disasters in general.

In 2015, a regional platform was established in the region with the support of UNDP and gathering all the stakeholders concerned by natural hazards. Representatives from the authorities, the Civil Protection, researchers from universities and research centers, NGO's have been invited as member of that platform in order to share experience, ideas, and discuss about priority actions to be developed.

Despite the fact that the platform operation seems highly dependent of the external support, it is an interesting approach that deserves further exploration.

# 4. DISSEMINATION AND VALORISATION

From the start of the project, we have worked on its visibility and paid attention to warrant a wide dissemination of information within the scientific community involved in risk research both at the international and local levels.

**The GeoRisCA website**

In June 2012, the first valorisation step was the creation of a project logo and the launch of GeoRisCA website (http://georisca.africamuseum.be). It benefited from a large number of visits, and traffic increased significantly after the field campaign organised in September 2012. In total, between June 2012 and May 2013, we recorded 185.462 hits from 4,789 different visitors. In 2014, we reached more than 333,500 hits from 4,474 visitors and 221,670 hits from 7,781 visitors in 2015. In 2016, the website received less visits (60,338 hits), but by a larger number of people (6,631 visitors).

Throughout the project, the website was regularly updated with the results of the project. For instance, we regularly uploaded published scientific papers and conferences abstracts, as well as general information and pictures, to enhance result dissemination and project information distribution. We created a mailing list created which was upgraded after each field campaign and subscribers were kept regularly informed of the project progress.

In order to enhance the visibility of our last field mission, we created a blog dedicated to the 10-days results presentation in Central Africa (https://africamuseum.science.blog/). A short film was produced to explain the benefits of GeoRisCA to scientists, local authorities and the institutions involved in disasters management and risk prevention; it will soon be available on *YouTube*.

**Local experts workshops to the launch of the GeoRisCA project**

In September 2012, a joint field campaign of all GeoRisCA teams was organised. The aim was to introduce GeoRisCA to the largest relevant audience possible in Burundi, DRC, and Rwanda. Workshops were organised in Bujumbura, Bukavu, Goma and Kigali. The organisation of these workshops was based on the stakeholders identification performed during the previous field mission, in June - July 2012. The audience of the September workshops was made of scientists involved in research and education, representatives of public institutions, local and international NGOs, and cooperation agencies. More than 175 persons attended.

The objectives of the workshop were multiple:

- Meeting with different scientists and local stakeholders;

- Presentation of the methodologies that would be applied for each theme by the GeoRisCA experts and discussions with the local scientists;
- Identifying synergies with similar or complementary on-going actions;
- Identifying data/tools already available and accessible;
- Opening a dialogue on the outputs of the project according to the needs of the potential end-users in terms of tools for the prevention and management of geohazards.

A lot of questions were asked during these workshops, and many contacts were established with local scientists, national authorities and international institutions from the three countries (Burundi, DRC, Rwanda). The development of such a network has facilitated the implementation of the project, allowed to call upon willingness to be part of this research and create synergies between existing programs.

Regular contacts with the local authorities and the Civil Protection from the three countries were organised throughout the project. It was a real success in DRCongo (Bukavu and Goma). Unfortunately, it was possible no longer to work with Burundi from mid-2015 due to political unrest. In respect of Rwanda, after several months and despite numerous attempts, the collaboration with the Ministry of Disaster and Refugees Affairs from Rwanda failed. In spite of the signature of a Memorandum of Understanding in June 2014 and the exchange of methodological propositions to work together on the vulnerability assessment, MIDIMAR never responded with any data and stopped communicating from January 2015. Communication resumed only in August 2015, just a month before the launch of their National Natural Risk Atlas.

**Scientific papers and international conferences**

The results of the project were valorised step-by-step through the publication of scientific papers published in peer-reviewed journals, and regular presentations at international conferences. Several high level scientific papers have already been published in major journals, and others are still in preparation. Most of these are open-access or available on the GeoRisCA website or on demand (see *Part 5. Publications*).

From the start of the project, contributions were also presented at international conferences, including the International Congress Livelihood 2013 (Ethiopia, 2013), the Active volcanism and Continental Rifting (Rwanda, 2013), the Annual International Conference 2014 of the Royal Geographical Society (UK, 2014), the 5th Geobia (Greece, 2014), the Colloquium of African Geology (Tanzania, 2014), the International Association of Geomorphologists Regional Conference (Russia, 2015), the International conference “Résilience aux catastrophes naturelles d’origine anthropique en République démocratique du Congo” (DR Congo, 2015), the 35th International Geological Congress (South Africa, 2016), the “Young Researchers’ Overseas Day” (Belgium, 2014 to 2016), the conferences "Cities on Volcanoes" (Mexico, 2012; Indonesia, 2014; Chile, 2016), the European Geosciences Union General Assembly (Austria, 2012 to 2016), the American Geophysical Union (San Francisco, 2012 to 2016). This has reinforced the visibility of GeoRisCA at the international level. This effort was maintained until the end of the project and beyond.

**HAZAGORA: will you survive the next disaster?**

In the framework of GeoRisCA, Sophie Mossoux, PhD student from VUB supervised by Matthieu Kervyn has developed an educational board game called HAZAGORA. The game was developed for students, civil society and other stakeholders with the aim to improve the knowledge of players on different hazards and illustrate the usefulness of various risk reduction strategies. In the game, players impersonate a character living on an island. Each year, they receive a salary used to meet their basic needs and to develop their community. Huts, houses and roads can be built but as the island is randomly threatened by geological hazards (earthquake, tsunami, lava flow and volcanic ash fall), players can also invest in protection measures. In this context, players virtually experience the impact of hazards and they are directly confronted with the implications of decisions taken during the game. Moreover, players come to realise that what they live in the game reflects situations in real life and that prevention measures are important to take both at a personal and at a community level.

In the framework of GeoRisCA, HAZAGORA was presented in January 2015 in Bukavu to a group of Congolese students (most of them geologists and geographers) and in April 2015 in Goma to the researchers from the Goma Volcano Observatory, *i.e.* people directly involved and possibly threatened by hazards presented in HAZAGORA. It was an opportunity to evaluate their knowledge of such types of events and the strategies to develop to respond to a catastrophic event. After playing HAZAGORA, players had a better understanding of the hazards. They can easily relate their experience in the game to situations that might happen in real life and realise that prevention and mitigation measures are important both at a personal and at a community level. The educational impact of the game was evaluated by a survey and published in a scientific paper (Mossoux et al. 2016). S. Mossoux received an award for Science communication from the Flemish Academy of Sciences for this game. The game is now available to various actors for continuing awareness-building activities.

**AVCoR-2013 workshop**

Besides the GeoRisCA project, a second Active Volcanism and Continental rifting (AVCoR-2013) workshop was held in November 2013 (12-14) in Rubavu District, in the Western Province of Rwanda. It was co-organised by Royal Museum for Central Africa

(RMCA, Belgium), the National Museum of Natural History (NMNH, Luxembourg), the Rwanda Energy and Water Sanitation Authority (EWSA), and the Delegation of the European Union in Rwanda, which also sponsored the event. This meeting was attended by 132 participants from Africa, Europe, and the United States. In total, 5 scientific sessions shared 50 oral presentations, 8 keynotes lectures, and 42 posters. During this conference, GeoRisCA was presented through 14 oral interventions and 11 posters. The conference had a significant regional impact, in particular because of the presence of the main institutions involved in natural risks management, which participated actively in the discussions.

The meeting fully met the expected two-fold objectives that were:

- Reviewing the current scientific knowledge about active volcanism and continental rifting in the Kivu region by 1) gathering East African Rift (EAR) experts from various disciplines and 2) discussing the modern modeling approaches and observational techniques, such as remote sensing, radar interferometry, GPS, geochemistry.
- Bridging the gap between the scientific research community and the institutions concerned by geohazards (government, civil protections, NGO's, donors…) and therefore foster the dialog between these two worlds.

As a general recommendation, making continued progress in understanding of rift mechanisms relies on an appropriate balance of three non-dissociable aspects: 1/ the main scientific questions which need to be more deeply studied, 2/ knowledge management which combines the scientists and the authorities, and 3/ capacity building for the scientists of the region.

At the AVCoR-2013 conference, GeoRisCA first results were presented and discussed. This conference was a rare opportunity for such a scientific and institutional audience to meet and exchange about top priority scientific questions on active tectonic and volcanism interactions, associating geohazards, societal and institutional related concerns like awareness, prevention, management, and mitigation. Participant's feedback was unanimously positive and a request for organizing further AVCoR meetings was clearly formulated. A special issue of the Journal of African Earth Sciences (peer reviewed) presenting the main contributions to the workshop was published in 2017.

**RGL-GeoRisk: a capacity building program**

Between February and April 2014, a group of 25 Congolese researchers have been trained by RMCA scientists in hazards and risk assessment in the framework the RGL-GeoRisk program (financed by the Belgian Cooperation). Over the third year of the GeoRisCA project, 13 of these scientists were involved in individual studies conducted under the supervision of RMCA researchers involved in GeoRisCA. At the beginning of

May 2015, they presented the results of their research, some of which constitute direct inputs for GeoRisCA.
Between September 2015 and April 2016, five trainees came in Europe for a 3-month fellowship at RMCA to pursue with their research project under the supervision of RMCA researchers. A special issue of the GeoEcoTrop Journal (peer reviewed) presenting the main researches of these RGL-GeoRisk students was published in 2017.

**Restitution of the GeoRisCA results: final worshops**

Finally, a team of 7 scientists involved in the GeoRisCA project organised the presentation of the final results in Bukavu, Goma and Kigali, at the beginning of December 2016. The format of this restitution week was threefold:

- *A general presentation of the final results*, including an overview of the methodologies developed, the techniques used and the analyses performed according to the type of data available. Like for the meetings organized at the beginning of the project, these presentations were addressed to a large audience composed of scientists involved in research and education, representatives of public institutions, local and international NGOs, cooperation agencies and journalists.
- In Bukavu and Goma, specific scientific workshops addressed to scientists and representatives of local institutions involved in disaster prevention and risk management, urban planning and environment conservation. During these 3-hour workshops, detailed explanations regarding methodologies and results were provided. Ample time during these sessions was also dedicated to open questions;
- A final working session organised in both Bukavu and Goma. This was addressed to scientists only (mainly our partners during the project) in order to transfer the methodologies and the tools developed within GeoRisCA to them, in order to ensure in-house expertise. For instance, the VUB team trained the researchers from the Goma Volcano Observatory in the use of the Q-LavHA modeling tool and the ULB team trained them with the automatic statistical analyses tool, which allows to compile population data following large household field surveys.

**Focus on Goma risk perception**

The book "Précarités et bien-être à Goma" presenting the results of the in-depth risk perception study was (and will be) presented through conference presentations, book reviews in African studies journals and Internet forums. The author, Théodore Trefon, will actively promote this book towards journals like Africa, African Affairs, Afrique contemporaine, Anthropos, Canadian Journal of African Studies, Choice, Civilisations, Development in Practice, Foreign Affairs, International Journal of African Historical

Studies, Leeds African Studies Bulletin, ROAPE, etc. The book, co-written in French with Noel Kabuyaya, is currently being translated in English.
In addition, Théodore Trefon will promote the book through the Congo Masquerade blog (http://congomasquerade.blogspot.be/).

# 5. PUBLICATIONS

## 5.1. International Peer-Reviewed Publications (mentioning GeoRisCA)

### 5.1.1. Risk perception (2 peer-reviewed publications)

Trefon, T., Kabuyaya N. (2016) Précarité et Bien Etre à Goma (RDC): Récits de vie dans une ville de tous les dangers, Tervuren/Paris: Les Cahiers de l'Institut Africain / L'Harmattan. 200 pages. French version.

Trefon, T., Kabuyaya N. (In preparation) Goma: Stories of strength and sorrow from eastern Congo, London: Zed Books (English version).

### 5.1.2. Seismic hazard (3 peer-reviewed publications)

Delvaux, D., Mulumba, J.-L., Sebagenzi, M.N.S., Fiama Bondo, S., Kervyn, F., Havenith, H.-B. (2016). Seismic hazard assessment of the Kivu rift segment based on a new sismo-tectonic zonation model (Western Branch, East African Rift system). Journal of African Earth Sciences. *In press*. Available online: 22-OCT-2016, doi: 10.1016/j.jafrearsci.2016.10.004.

Ganza Bamulezi, G., Mavonga Tuluka, G., Delvaux, D. *In press*. Analyse sismotectonique de quelques failles actives de la partie occidentale du rift du Kivu en République démocratique du Congo (RDC). Geo-Eco-Trop.

Smets, B., Delvaux, D., Ross, K.A., Poppe, S., Kervyn, M., d'Oreye, N., Kervyn, F. (2016). The role of inherited crustal structures and magmatism in the development of rift segments: Insights from the Kivu basin, western branch of the East African Rift. Tectonophysics 683, 62-76. DOI:10.1016/j.tecto.2016.06.022.

### 5.1.3. Volcanic hazards (16 peer-reviewed publications)

Barette, F., Poppe, S., Smets, B., Benbakkar, M., Kervyn, M. (2016). Spatial variation of volcanic rock geochemistry in the Virunga Volcanic Province: Statistical analysis of an integrated database. *Journal of African Earth Sciences, in press,* http://doi.org/10.1016/j.jafrearsci.2016.09.018.

Geirsson, H., d'Oreye, N., Mashagiro, N., Syauswa, M., Celli, G., Kadufu, B., Smets, B., Kervyn, F.. *In press*. Volcano-tectonic deformation in the Kivu Region, Central Africa: Results from six years of continuous GNSS observations of the Kivu Geodetic Network (KivuGNet). *Journal of African Earth Sciences*. DOI: 10.1016/j.jafrearsci.2016.12.013.

Ji, K.H., Stamps, S.D., Geirsson, H., Mashagiro, N., Syauswa, M., Kafudu, B., Subira, J., d'Oreye, N. (2016). Deep magma accumulation at Nyamulagira volcano in 2011 detected by GNSS observations. *Journal of African Earth Sciences, in press, available online 7 June 2016*, ISSN 1464-343X,ttp://dx.doi.org/10.1016/j.jafrearsci.2016.06.006.

Li, L., Canters, F., Solana, C., Ma, W., Chen, L., Kervyn, M. (2015). Discriminating lava flows of different age within Nyamuragira's volcanic field using spectral mixture analysis. *International Journal of Applied Earth Observation and Geoinformation, 40*, 1-10.

Mossoux, S., Saey, M., Bartolini, S., Poppe, S., Canters, F., Kervyn De Meerendre, M. (2016). Q-LAVHA: A flexible GIS plugin to simulate lava flows. *Computers & Geosciences, 97*, 98-109.

Poppe, S., Smets, B., Fontijn, K., Rukeza, M.B., De Marie Fikiri Migabo, A., Milungu, A.K., Namogo, D.B., Kervyn, F., Kervyn, M. (2016) Holocene phreatomagmatic eruptions alongside the densely populated northern shoreline of Lake Kivu, East-African Rift: timing and hazard implications. *Bulletin of Volcanology*. 78-82.

Samsonov, S., d'Oreye, N., Smets, B. (2013). Natural and anthropogenic ground deformation monitored using high spatio-temporal resolution MSBAS time series method. Proc. MultiTemp 2013 Workshop: 7th International Workshop on the Analysis of Multi-Temporal Remote Sensing Images: "Our Dynamic Environment," 1–3.

Smets, B., d'Oreye, N., Kervyn, M.,Kervyn, F. Eruptive activity of Nyiragongo volcano: the true figures. *To be submitted in Bulletin of Volcanology*.

Smets, B., d'Oreye, N., Kervyn, M., Kervyn, F. Gas piston activity of the Nyiragongo lava lake: First insights from a Stereographic Time-Lapse Camera system, *Journal of African Earth Sciences, in press, Available online 21 April 2016*, http://dx.doi.org/10.1016/j.jafrearsci.2016.04.010.

Smets, B., Delvaux, D., Ross, K.A., Poppe, S., Kervyn, M., d'Oreye, N., Kervyn, F. (2016). The role of inherited crustal structures and magmatism in the development of rift segments: Insights from the Kivu basin, western branch of the East African Rift. *Tectonophysics, 683*, 62-76. doi: 10.1016/j.tecto.2016.06.022

Smets, B., d'Oreye, N., Kervyn, F., Kervyn, M., Albino, F., Arellano, S. R., et al. (2014a). Detailed multidisciplinary monitoring reveals pre- and co-eruptive signals at Nyamulagira volcano (North Kivu, Democratic Republic of Congo). *Bulletin of Volcanology*, *76*(1), 787. http://doi.org/10.1007/s00445-013-0787-1

Smets, B., d'Oreye, N., Kervyn, F. (2014b). Toward Another Lava Lake in the Virunga Volcanic Field? *EOS Transactions American Geophysical Union 95 (42)*, 377–378 – DOI: 10.1002/2014EO420001 (Peer-reviewed press article).

Smets, B., Kervyn, M., d'Oreye, N., Kervyn F. (2015). Spatio-temporal dynamics of eruptions in a youthful extensional setting: insights from Nyamulagira volcano (D.R. Congo), in the western branch of the East African Rift. *Earth Science Reviews, 150*, 305-328.

Ross, K.A., Smets, B., De Batist, M., Hilbe, M., Schmid, M., Anselmetti, F.S. (2014). Lake-level rise in the late Pleistocene and active subaquatic volcanism since the Holocene in Lake Kivu, East African Rift. *Geomorphology, 221*, 274–285.

Syavulisembo, A, Havenith, H.-B., Smets, B., d'Oreye, N., Marti, J. (2015) Preliminary assessment for the use of VORIS as a tool for rapid lava flow simulation at Goma Volcano Observatory, DR Congo, Nat. Hazards Earth Syst. Sci., 15, 2391–2400.

Wauthier, C., Smets, B., Keir, D. (2015). Diking-induced moderate-magnitude earthquakes on a youthful rift border fault: The 2002 Nyiragongo-Kalehe sequence, D.R. Congo. *Geochemistry, Geophysics, Geosystems, 16*, 4280-4291.

### 5.1.4. Mass movement hazard (12 peer-reviewed publications)

Dewitte, O., Draida, S., Maki-Mateso, J.-C., Jacobs, L., Delvaux, D., Thiery, W., Hamenyimana, J.-B., Kulimushi Matabaro, S., Machiels, O., Michellier, C., Monsieurs, E., Mugaruka Bibentyo, T., Nahimana, L., Ndayisenga, A., Ngenzebuhor, P.-C., Nkurunziza, P., Ntenge, A.J., Trefois, P., Kervyn, F., Havenith, H.-B.. *In preparation*. Landslide susceptibility in the North-Tanganyika – Lake Kivu Rift zones. *Geomorphology*.

Dewitte, O., Mugaruka Bibentyo, T., Kulimushi Matabaro, S., Balegamire, C., Basimike, J., Albino, F., Delvaux, D., Havenith, H.-B., Jacobs, L., Kalikone Buzera, C., Michellier, C., Monsieurs, E., Mugisho Birhenjira, E., Nshokano, J.-R., Nzolang, C., Trefois, P., Kervyn, F.. *To be submitted*. Landslide hazard in Bukavu (DR Congo): a geomorphological assessment in a data-poor context. *Natural Hazards*.

Draidia, S., Ntenge, A., Nahimana, L., Ndayisenga, A., Nkurunziza, P., Dewitte, O., Fagel, N., Havenith, H.-B.. *In preparation*. The role of rock and soil weathering on landslide dynamics – Case studies from Rwanda and Burundi. *Engineering Geology*.

Jacobs, L., Dewitte, O., Poesen, J., Delvaux, D., Thiery, W., Kervyn, M., 2016. The Rwenzori Mountians, a landslide-prone region? *Landslides* 13, 519–536.

Kulimushi Matabaro, S., Mugaruka Bibentyo, T., Muhindo Sahani, W., Michellier, C., Dewitte, O., *In press*. Landslides and elements at risk in the Wesha watershed (Bukavu, DR Congo). *Geo-Eco-Trop*.

Maes, J., Kervyn, M., de Hontheim, A., Dewitte, O., Jacobs, L., Mertens, K., Vanmaercke, M., Vranken, L., Poesen, J. (2017). Landslide risk reduction strategies: A review of practices and challenges for the tropics. *Progress in Physical Geography*. , 1-31. doi: 10.1177/0309133316689344.

Maki Mateso, J.-C., Dewitte, O, (2014). Towards an inventory of landslides and the elements at risk on the Rift flanks West of Lake Kivu (DRC). *Geo-Eco-Trop* 38, 137-154.

Monsieurs, E., Jacobs, L., Michellier, C., Maki Mateso, J.-C., Basimike, J., Ganza Bamulezi, G., Kulimushi Matabaro, S., Mugaruka Bibentyo, T., Nahimana, L., Ndayisenga, A., Nkurunziza, P., Kervyn, F., Thierry, W., Demoulin, A., Kervyn M., Dewitte, O.. *To be submitted*. Landslide inventory for hazard assessment in data-poor context: a regional-scale approach in Central Africa. *Landslides*

Monsieurs, E., Kirschbaum, D.B., Thiery, W., van Lipzig, N., Kervyn, M., Demoulin, A., Jacobs, L., Kervyn, F., Dewitte, O., *In press*. Constraints on Landslide-Climate Research Imposed by the Reality of Fieldwork in Central Africa. 3rd North American Symposium on Landslides.

Mugaruka Bibentyo, T., Kulimushi Matabaro, S., Muhindo Sahani, W., Dewitte, O.. *In press*. Anatomy of Nyakavogo landslide (Bukavu, DR Congo): interplay between natural and anthropogenic factors. *Geo-Eco-Trop*.

Nibigira, L., Draidia, S., Havenith, H.-B. (2015). GIS-based landslide susceptibility mapping in the Great Lakes region of Africa, Case study of Bujumbura Burundi. [IAEG XII Congress ,15-19 September 2014, Torino/ Italia]. Article published by Springer International Publishing in: "*Engineering Geology for Society and Territory*" - Volume 2 , 2015, pp 985-988.

Nobile, A., Dille, A., Monsieurs, E., Dewitte, O., d'Oreye, N., Kervyn, F.. *In preparation*. Multi-temporal InSAR monitoring of landslides in a tropical urban environment: focus on Bukavu (DR Congo). *Remote Sensing*.

### 5.1.5. Vulnerability and risk assessment (9 peer-reviewed publications)

Balegamire, C., Michellier, C., Muhigwa, J.-B., Delvaux, D., Dewitte, O.. *Submitted*. Vulnerability of buildings exposed to landslides: a spatio-temporal assessment in Bukavu (DR Congo). Geo-Eco-Trop.

Assani Ciza, D., Karume, K., Kervyn, K., Michellier, C.. *Submitted*. La vulnérabilité des réseaux de distribution de l'eau et de l'électricité dans la ville de Goma, face aux coulées de lave du volcan Nyiragongo (RD Congo). Geo-Eco-Trop.

Michellier, C., Pigeon, P., Kervyn, F., Wolff, E. (2016). Contextualizing vulnerability assessment: a support to geo-risk management in central Africa. Natural hazards, 82: 27-42.

Michellier, C., Barette, F., Kervyn, M., Wolff, E., Kervyn, F.. (a) *In preparation*. Assessing social vulnerability in a context of scarcity of available and reliable data: the cases of Bukavu and Goma, DR Congo.

Michellier, C., Kervyn, F., Katoto, P., Nemery, B., Dramaix, M.. *To be submitted*. Health impact of SO2 emissions from the Nyiragongo and Nyamulagira volcanoes (DR Congo). Analysis of routine health data between 2000 and 2010. *Journal of Environmental Health*.

Michellier, C., Kulimushi Matabaro, S., Kadekere, I., Kervyn, F., Wolff, E.. (b) *In preparation*. Estimation de la population à Bukavu: revue des différentes méthodologies. Espaces Populations Sociétés.

Mossoux, S., Delcamp, A., Poppe, S., Michellier, C., Canters, F., Kervyn, M. (2016). Hazagora: will you survive the next disaster? – A serious game to raise awareness about geohazards and disaster risk reduction. *Natural Hazard and Earth System Science, 16*, 135-147.

Shimoni, M., Lopez, J.F., Forget, Y., Wolff, E., Michellier, C., Grippa, T., Linard C., Gilbert M. (2015). An urban expansion model for African cities using fused multi temporal optical and SAR data. Geoscience and Remote Sensing Symposium (IGARSS), 1159-1162.

Syavulisembo, A.M., Michellier, C., Kervyn, F. (In preparation) Nyiragongo volcano: temporal evolution of the potential impacts of 2002-like lava flows on Goma city (Democratic Republic of the Congo). *Journal of African Earth Sciences*.

## 5.2. Student theses and reports (2 PhD thesis, 5 M. Sc. thesis, 5 B. Sc. papers, 10 reports)

Feltz, A. (2013). Calibration d'un modèle thermorhéologique et probabilistique de coulées de lave appliqué au volcan Nyamulagira, R.D.C. (English title : Calibration of a thermorheological and probabilistic model of lava flows applied to Nyamulagira volcano, D.R.C.). *M.Sc. thesis, Université Catholique de Louvain*.

Hamenyimana, J.B. (2014). Inventorying landslide processes in the Bujumbura area (Burundi). 12-week traineeship, *Royal Museum for Central Africa* (supported by the Belgian Directorate-General for Development Cooperation).

Maki Mateso, J.C. (2014) Landslide processes in the Lwiro Area (DR Congo) and the elements at risk – a regional approach. *Master complémentaire en Gestion des Risques Naturels, Université de Liège*..

Mommaerts, J. (2014). Thermal analysis and derivation of lava discharge rates of recent volcanic eruptions at Nyamuragira using MODIS imagery. *M.Sc. thesis, Vrije Universiteit Brussel*.

Ngenzebuhoro, P.C. (2014). Inventorying landslide processes in the Bujumbura area (Burundi). 12-week traineeship, *Royal Museum for Central Africa* (supported by the Belgian Directorate-General for Development Cooperation).

Syavulisembo, A.M. (2013). Evaluation des risques liés aux coulées des laves du Nyiragongo. Cas de la fracture principale de Munigi (République Démocratique du Congo). *M.Sc. thesis, Master complémentaire en Gestion des Risques Naturels. Université de Liège*.

Barette, F. (2015). Constraining volcanic hazard in the Virunga Volcanic Province, East Africa: spatial analysis of the geochemistry and pyroclastic cone morphometry. *B.Sc. in Geography, Vrije Universiteit Brussel*.

De Raedt, C. (2015). Bukavu: Analyses démographiques et estimation de la population. 12-week traineeship, *Royal Museum for Central Africa*.

Maki Mateso, J.C. (2015). Landslide distribution in the Rift flanks west of Lake Kivu (DRC). 12-week traineeship, *Royal Museum for Central Africa* (supported by the Belgian Directorate-General for Development Cooperation).

Syavulisembo, A.M. (2015). Analyse de la vulnérabilité spatiale de Goma (RDC) face au risque volcanique. 12-week traineeship, *Royal Museum for Central Africa* (supported by the Belgian Directorate-General for Development Cooperation).

Peeters, A. (2015). Calibration of Q-LavHA on Karthala and Nyamulagira Volcano. *B.Sc. paper, Vrije Universiteit Brussel*.

Plaetinck, L. (2015). Spatial analysis of Mazuku. *B.Sc. paper, Vrije Universiteit Brussel*.

Balegamire, C. (2016). Open-access data for assessing vulnerability to geohazards in Central Africa. *M.Sc. thesis, Master complémentaire en Gestion des Risques Naturels, Université de Liège*..

Barette, F. (2016) Analyse statistique des données des enquêtes démographiques de Bukavu et Goma en vue de l'évaluation de la vulnérabilité de la population. 12-week traineeship, *Royal Museum for Central Africa*.

Bourdon, H. (2016). Development of morphometric tools in QGIS for landslide characterisation. MSc., Université de Liège. 12-week traineeship, *Royal Museum for Central Africa*.

De Meester, J. (2016). Satellite-based precipitation products for the determination of landslide-triggering rainfall conditions. *BSc. in Geography and Geomatics, Ghent University*.

Dhabaria, N. (2016) Condition and process-based landslide susceptibility analysis applied to the Lak Kivu and Northern Lake Tanganyika area, Central Africa. MSc., in India. 8-week traineeship, *Université de Liège*.

Hage, F. (2016). Automated processing from data survey and plugin realization. 12-week traineeship, *Royal Museum for Central Africa*.

Michellier, C. (2017) Contribuer à la prevention des risques d'origine géologique: l'évaluation de la vulnérabilité des populations dans un context de rareté de données. Les cas de Goma et Bukavu (RDCongo). *Ph.D. Thesis, Université Libre de Bruxelles/Vrije Universiteit Brussel.*

Mugaruka Bibentyo, T. (2016). Spatio-temporal inventory of landslides in the city of Bukavu. 12-week traineeship, *Royal Museum for Central Africa* (supported by the Belgian Directorate-General for Development Cooperation)

Parent, M. (2016). Application of a probabilistic approach to geohazard modelling: Lava flow hazard assessment for Ngazídja, Comoros. *B.Sc. paper, Vrije Universiteit Brussel*.

Smets, B. (2016). Dynamics of volcanic activity in a youthful extensional setting studied by means of remote sensing and ground-based monitoring techniques: Nyiragongo and Nyamulagira volcanoes (North Kivu, D.R. Congo). *Ph.D. Thesis, Vrije Universiteit Brussel.*

## 5.3. Contribution to international conferences (chronological order)

### 5.3.1. Seismic hazard (19 contributions)

Delvaux, D., Kervyn, F., Mulumba, J.-L. (2013). Active tectonics in the western branch of the East African Rift System. *24rd Colloquium of African Geology, Addis Ababa, Ethiopia*. January 8-14, 2013.

Delvaux, D., Kervyn, F., Mulumba, J.-L., Kipata, M.L., Sebagenzi, M.N., Mavonga, G.T., Macheyeki, A.S., Temu, E.B. (2013). Sismotectonics in the western branch of the East

African Rift System. *EGU General Assembly 2013, Vienna, Austria*. Geophysical Research Abstracts, 15, EGU2013-2307.

Delvaux, D., Smets, B. (2013). Neotectonic framework of the Kivu rift region within its Central African context. *97èmes Journées Luxembourgeoises de Géodynamique, ECGS/NMNH, Luxembourg*. October 2-4, 2013.

Delvaux, D., Smets, B. (2013). Neotectonic setting of the Kivu rift region: Mesoproterozoic to recent evolution. *2nd meeting on Active volcanism and Continental rifting with special focus on the Kivu rift zone (AVCoR 2013), Gisenyi, Rwanda*. November 12-15, 2013.

Delcamp, A., Macheyeki, M., Kwelwa, S., Delvaux, D., Poppe, S., Kervyn, M. (2013). Volcano instabilities and debris avalanche hazard in the East African Rift. *2nd meeting on Active volcanism and Continental rifting with special focus on the Kivu rift zone (AVCoR 2013), Gisenyi, Rwanda*. November 12-15, 2013.

Mavonga Tukula, G., Delvaux, D., Tedesco, D., Durrheim, R. (2014). The Bunia (DRC-Uganda) Earthquake sequence of 2-3 July 2013 and its implication to seismic hazard assessment in the Lake Albert region. *AfricaArray Workshop, University of the Witwatersrand, Johannesburg, South Africa*. January 20-21, 2014.

Delvaux, D. (2014). Neotectonic setting and sismotectonics of the of the Kivu rift region. *AfricaArray Workshop, University of the Witwatersrand, Johannesburg, South Africa*. January 20-21, 2014.

Saria, E., Calais, E., Stamps, S., Delvaux, D., Hartnady, C. (2014). Refined kinematic model of EAR. *AfricaArray Workshop, University of the Witwatersrand, Johannesburg, South Africa*. January 20-21, 2014.

Delvaux, D., Midzi, V., El Gabry, M. (2014). Focal mechanism compilation for updating the African Stress Map. *Workshop IGCP 601 and Seismotectonic map of Africa, University of the Witwatersrand, Johannesburg, South Africa*. January 25, 2014.

Delvaux, D., Midzi,V., Andreoli, M., El Gabry, M. (2014). Focal mechanism compilation for updating the African stress map. *EGU General Assembly 2014, Vienna, Austria*. Geophysical Research Abstracts, 16, EGU2014-9253.

Delvaux, D., Fernandez, M., Dewaele, S. (2014). Geological and tectonic evolution of the Mesoproterozoic Karagwe-Ankole belt around the Kivu rift region in Central Africa: Data integration from the DRC. *CAG25 Dar es Salaam, Tanzania*. August 14-16, 2014.

Delvaux, D., Macheyeki, A.S., Saria, E., Stamps, S.D., Calais, E., Hartnady, C. (2014). Neotectonic faults and stress field of the Late Cenozoic East African Rift System around the Tanzanian Craton. *CAG25 Dar es Salaam, Tanzania*. August 14-16, 2014.

Delvaux, D., Smets, B. (2014). Two-stage evolution of the Kivu rift segment in Central Africa. *CAG25 Dar es Salaam, Tanzania*. August 14-16, 2014.

Delvaux, D., Havenith, H.-B., Kervyn, F., D'Oreye, N. , Smets, B. (2015). New seismic hazard map for the Kivu rift region. *10th Annual AfricaArray Workshop, Johannesburg, South Africa*. January 18-26, 2015.

Delvaux, D., Macheyeki, A.S., Fernandes, R.-M., Ayele, A., Meghraoui, M. (2015). Neotectonic faults and stress field in the East African Rift System around the Tanzanian Craton – A contribution to the seismotectonic map of Africa. *EGU General Assembly 2015, Vienna, Austria*. Geophysical Research Abstracts, 17, EGU2015-6338.

Delvaux, D., Smets, B. (2015). Initiation and development of the Kivu rift segment in Central Africa by reactivating un-favorably oriented structural weaknesses. *EGU General Assembly 2015, Vienna, Austria*. Geophysical Research Abstracts, 17, EGU2015-6390.

Havenith, H.-B., Delvaux, D. (2015). Seismic hazard assessment of the Kivu rift segment based on a new sismo-tectonic zonation model (Western Branch of the East African Rift system). *EGU General Assembly 2015, Vienna, Austria*. Geophysical Research Abstracts, 17, EGU2015-6082.

Meghraoui, M. and the IGCP-601 Working Group * Team (2015). The Seismotectonic Map of Africa. *EGU General Assembly 2015, Vienna, Austria*. Geophysical Research Abstracts, 17, EGU2015-5133.

Delvaux, D., Macheyeki, A.S., Kipata, M.L., Ganza, G.B. (2016). Paleostress in Central Africa reveals the Late Paleozoic-recent evolution of Central Gondwana. *35th International Geological Congress, Cape Town, South Africa*. 27 August-4 September, 2016.

### 5.3.2. Volcanic hazard (78 contributions)

d'Oreye, N., Albino, F., Cayol, V., Gonzalez, P., Kervyn, F., Samsonov, S., Smets, B., Wauthier, C., Bagalwa, L.M., Mashagiro, N., Muhindo, A., Syauswa, M. (2012) Volcano monitoring in the Virunga Volcanic Province, DR Congo. *GeoPRISMS East African Rift System (EARS), Morristown NJ, USA*. October 25-27, 2012.

d'Oreye, N., Kervyn, F., Smets, B. (2012) Achieving scientific projects in Central Africa: some shared experience. *GeoPRISMS East African Rift System (EARS), Morristown NJ, USA*. October 25-27, 2012.

Smets, B., Samsonov, S., d'Oreye, N. (2012) Ground Deformation Associated With Post-Mining Activity at the French-German Border Revealed by Multidimensional Time Series Analysis of SAR Data Acquired in Various Orbital Geometries. *AGU Fall Meeting 2012, San Francisco, California, USA*. December 3-7, 2012.

Albino, F., Smets, B., Kervyn, F., d'Oreye, N. (2012) A study of geomorphological features and volcanic deformation in the Virunga Volcanic Province (Central Africa) from Tandem-X interferometry. *AGU Fall Meeting 2012, San Francisco, California, USA*. December 3-7, 2012.

d'Oreye, N., Samsonov, S., Smets, B. (2012) Multidimensional Time Series Analysis Of Ground Deformation From Multiple InSAR Data Sets Applied To Virunga Volcanic Province. *AGU Fall Meeting 2012, San Francisco, California, USA*. December 3-7, 2012.

Albino, F., Kervyn, F., d'Oreye, N., Smets, B. (2012) Monitoring Nyamulagira and Nyiragongo volcanoes (R.D. Congo) using Tandem-X interferometry. *7th Cities on Volcanoes, Colima, Mexico*. November 2012.

Smets B., d'Oreye N., Kervyn F., Kervyn M., Ross K.A. (2013) Rift structure in the Kivu basin and recent evolution of Lake Kivu, western branch of the East African Rift. *24th Colloquium of African Geology, Addis Ababa, Ethiopia*. January 8-14, 2013.

Smets, B. (2013) Measuring volcanoes in 3D: The crucial role of Digital elevation modelling to study active African volcanoes. *30ème réunion annuelle des collaborateurs scientifiques du Musée National d'Histoire Naturelle, Luxembourg*. March 16, 2013.

Albino, F., Kervyn, F. (2013) *High resolution DEM from Tandem-X interferometry: an accurate tool to characterize volcanic activity. EGU General Assembly 2013, Vienna, Austria*. April 2013.

Kervyn, F, d'Oreye, N., Havenith, H.B., Kervyn, M., Michellier, C., Trefon, T. and Wolff, E. (2013) Geo-risk in Central Africa: integrating multihazards and vulnerability to support risk management. *EGU General Assembly 2013, Vienna, Austria*. April 2013.

Poppe, S., Smets, B., Albino, F., Kervyn, F., Kervyn, M. (2013) A new volcano-structural map of the Virunga Volcanic Province, D.R.Congo and Rwanda. In Geophysical Research Abstracts. (Vol. 15). *EGU General Assembly 2013, Vienna, Austria*. April 2013.

d'Oreye, N., Arjona, A., Samsonov, S., Smets, B., Kervyn, F. (2013) Can InSAR contribute to volcano early warning systems? *IAVCEI General Assembly 2013, Kagoshima, Japan*. July 19-24, 2013.

Smets B., Albino F., d'Oreye N., Kervyn F., Poppe S., Kervyn M. (2013) The crucial role of digital elevation modeling to study Nyiragongo and Nyamulagira volcanoes (North Kivu, Democratic Republic of Congo). *IAVCEI General Assembly 2013, Kagoshima, Japan*. July 19-24, 2013

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# 6. ACKNOWLEDGMENTS

The GeoRisCA project had the ambitious objective of assessing the risk associated with the major natural hazards to which the Kivu region is exposed. To achieve this, it has been necessary to combine various scientific disciplines from the natural and human sciences a challenging exercise in itself, as there is generally a compartmentalization between these fields of research. However, thanks to the openness of the various partners and institutions that contributed to the success of the project, the objectives were largely achieved, and often exceeded for the joint benefits of the science and of the populations leaving in the studied region.

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