GORISK

The combined use of Ground-Based and Remote Sensing techniques as a tool for volcanic risk and health impact assessment for the Goma region (North Kivu, Democratic Republic of Congo)

FINAL REPORT

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Coordination :
Royal Museum for Central Africa (RMCA)

Project partners :
- National Museum of Natural History of Luxembourg (NMNH)
- University of Luxembourg (Uni.lu)
- Second University of Naples (UniNap)

Local end-users :
- Goma Volcano Observatory (GVO)
- Volcanic Risk Mitigation Program (UNOPS)
- Centre scientifique et médical de l'ULB pour ses activités de coopération (CEMUBAC)

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1. INTRODUCTION

Launched in January 2007 in the frame of the STEREOII program, GORISK is a multidisciplinary project oriented towards the implementation and improvement of ground-based and spaceborne tools for volcanic risk and health impact assessment in the Goma region (North Kivu, DRC). This area (potentially 1 million people) is threatened by two highly active volcanoes, the Nyiragongo and the Nyamulagira. The Nyiragongo eruption in January 2002 had an important and long-term economical, socio-political and humanitarian impact on the region. Though the Nyamulagira eruptions are not a major direct threat for populations, it erupts every two years and represents a real concern for the environment.

The GORISK project involves four European partners, the Royal Museum for Central Africa (RMCA, coordinator), the National Museum for Natural History of Luxembourg (NMNH), the University of Luxembourg (Uni.lu) and the Second University of Naples (UniNap) and three local end-users, the Goma Volcano Observatory (GVO), the Risk Management Unit of UNOPS (RMU, also named Unité de Gestion des Risques (UGR) in French) and the Belgian NGO CEMUBAC.

The main objectives of this initiative are to provide these three interconnected end-users working in the Nyiragongo – Nyamulagira volcanic context with appropriate products and services to assess the volcanic hazards and to mitigate the related risks. It follows three parallel axes: strengthening of the local capacity with new products and services, transversal pluri-disciplinary approach and capacity building including implication and training of the end users. GORISK is acting upstream of the division between direct and indirect volcanic risks. The direct risks are essentially related to short-term volcanic crisis and erupted material, whereas indirect risk deals with mid- to long-term effects on the environment or/and the population.

2. PROJECT OVERVIEW

This two-years project has started at the beginning of 2007. Below is an overview on the overall sequence of the project.

2.1. GENERAL DESCRIPTION

GORISK is composed of the following main activities:

- **Satellite based observations:**
    - InSAR deformation measurements
    - Optical data for map updates
    - Optical data for volcanic plume monitoring (outsourced)
- **Ground based observations:**
    - Ground deformations measurements
    - Gas and water monitoring
    - Health data collection
- **Data integration**
- **Outputs production:**
    - Deformation maps and InSAR by-products
    - Continuous tilt measurement
    - Geochemistry dispersion maps
    - GIS platform
    - Updated map of Goma
- **Capacity building**

One of the major inputs to the project is the systematic SAR acquisition that relies on ESA Category 1 projects (CAT-1 3224, CAT-1 3690). The routine acquisition was negotiated with ESA prior to the project start-up. On the equipment side, the NRF-Lux has provided the project with 3 tiltmeters, 4 data acquisition and transmission system for tilt stations and 2 permanent CO_2-Rn gas monitoring stations. The equipment was installed at an early stage of the project, in March and June 2007. The first GPS geodetic stations of a network of 7 that have been provided as an external support by NMNH were also installed during that period.

The CEMUBAC partner has collected water in the province but it has been complicated by the difficult security situation and the permanent war context in part of the province (e.g. Masisi and Walikale). Health data have been analysed by the same partner.

2.1.1. Main facts:

March – June 2007:

- First field campaigns.

July 2007:

- The GVO announces that its own funding has reached its end on 30th June 2007.

- Change of coordinator at RMCA while the former moved to Goma for the management of a two years EU project and hence providing valuable local assistance

February 2008:
- GORISK obtains the authorization to use part of its functioning budget to compensate for that unscheduled situation (GORISK contract was clear, negligence at the head of CRSN-GVO)

April 2008:
- Mid-term steering committee in Goma
- Plane crash in Goma (more than 70 victims after official numbers) with 1 RMCA and 1 NMNH staffs aboard. Both escaped safely.

July 2008
- NMNH partner obtained additional funding from Ministry of Foreign Affairs of Luxemburg to support specific activities of GORISK, the payment of prime to involved staff at GVO, the update of the seismic data server at GVO. However political manoeuvrings prevented the signature of the contract before the end of the same year.

October 2008:
- Strong recrudescence of the insecurity; the situation remained highly unstable for several months.
- Dismounting of gas measurement stations in Bulengo, Rusayo, and Munigi
- The field campaign is postponed

March 2009:

- First extension of the project until September 2009. No budget modification.

June 2009:
- Jacques Durieux passed away. He was project the manager for the UNOPS Risk Mitigation Unit and end user of the GORISK.

July 2009:
- Upon requirement of the Minister, a deep re-structuration of the GVO and the CRSN is initiated; new director general is nominated at GVO. GVO was thereafter detached from CRSN.

September 2009:
- Second steering committee is held at RMCA (Belgium). A second extension of the project is approved at the unanimity and fixed the end to December 2009. No budget modification.

December 2009:
- A last one month extension of the project fixed the end of the project to January 31st 2010

January 2010:

- The eruption of the Nyamulagira started on January 2nd 2010
- Lake Kivu Workshop 13-15 January 2010 in Gisenyi. Meeting with stakeholders and the scientists involved in the region.

March 2010:

- Change of coordinator at RMCA. The former coordinator came back from Goma and took over the management of GORISK.

2.2. IMPLEMENTATION DIFFICULTIES

2.2.1. General considerations

The project was designed to tackle specific problems linked to the monitoring of these poorly monitored and studied volcanoes located in an area where nothing is obvious and straightforward.

Indeed, for years, for various and complex reasons, the Democratic Republic of Congo has suffered from a constant degradation of its economy. In the East of the country, the politic instability and the war lead to drastic consequences for the population which is often forced to flee their land. The insecurity, the precarious situation of the public services that often suffer from irregularly paid salaries, the absence of an efficient education system, etc. are responsible for a survival-type economy strongly dependent from the international aid.

In this context the achievement of the public services tasks is often compromised or very difficult, and it is especially the case for the research institutes like the CRSN to which the GVO belonged until July 2009. They often rely on external support through isolated projects, rarely by a global approach with a long-term vision. Knowing that, it is fairly easy to understand that the project had to face a variety of problems responsible for delays and incompletion of some tasks.

This section provides the reader with a global overview on the general context and presents types of obstacles encountered by the team and their impacts on the project. The list is by far not exhaustive.

Though the project has been often threatened and its achievement endangered, the experience has demonstrated that the huge energy spent into tedious management struggles was worthy (e.g. the follow-up of the 2010 Nyamulagira eruption). One could consider that listing problems is devoid of interest; however, in order to understand the value of the work and the results obtained, it is important to have an idea about the overall context. The most serious problems and solutions are going to be presented in respective result sections (Section 3).

Though most difficulties were due to large scale and unbearable causes, it is worth noting that in desperate situations, individuals or groups can act for their own interest at the expense of the community. This project has suffered from recurrent adverse situations where individual interest was in balance with the interest of the community that is exposed to very high volcanic risk. That aspect must be kept in mind while reading this report.

2.2.2. Management related problems

GORISK managed to obtain the authorization from BELSPO for using part of the functioning cost to secure the payment of primes to sentinels in charge of the security of ground based stations. Unfortunately, during that period of negotiation, we were forced to require the dismantling of the equipment that cannot remain unattended in the field. This has also resulted in an important gap in the measurements.

On the other side, on the logistic front, the list of small but sometime critical problems that occurred is long. It ranges from external sources like the theft of the main electric wire outside the GVO compound (> 4 times during the duration of the project), to internal sources like the misuse of telecommunication system by individual(s) for personal purpose, or impossibility to replace vital network parts like ageing batteries etc.

Although such problems are in most cases falling under the management responsibility of the GVO user, GORISK had to solve them - mainly remotely - to secure the achievement of the tasks. It is also important to note that the situation improved dramatically since the restructuration in July 2009. If difficulties may persist from financial or structural reasons, acts of sabotage and malice have ceased.

2.2.3. Political and security context

The political situation and related security concerns have also had an impact on the overall sequence of the project. In October 2008, the field campaign had to be postponed for 6 months following the degradation of the political situation and the recrudescence of the fights between armed groups near and within Goma. From that period until May 2010, the access to the volcano was also impossible: various armed factions are illegally exploiting the forest for charcoal. Consequently, no direct visual observations of the Nyiragongo’s crater lake activity were performed during 1 year and a half. The state and level of the rapidly rising lava lake (50-80m / year) remained totally unsupervised. The field access was during the main part of the project limited to Goma and vicinities, and from time to time to the West and the North-East of the city.

2.2.4. GVO structure context

At the time when the GORISK project started, the GVO was still a department under the authority of the Centre de Recherches en Sciences Naturelles (CRSN) located in Lwiro, South-Kivu.

In July 2009, the Ministry decided to modify the GVO structure, to split the CRSN and place the GVO as an independent structure lying under his direct authority and headed by a new General Director. As a consequence, a significant improvement of the GVO management was observed as well as an encouraging improved follow up of the on-going activities.

2.3. EXTERNAL SUPPORT (MFA, NMNH GPS, …)

Mid 2008, NMNH partner managed to obtain additional funding from the Luxemburg Ministry of Foreign Affairs (MFA - Cooperation Department) to support the monitoring of the volcanoes in the Virunga Province. This emergency fund was dedicated to avoid the otherwise inevitable interruption of the GORISK monitoring activities of the threatening volcanoes and hence allow the further development of complimentary activities in the framework of the GORISK project. However, that assistance was very difficult to materialize because of administrative.

It was finally entrusted to the Risk Management Unit (RMU/UGR)-UNOPS, the only available and certified organization to administrate it locally. Nevertheless, the heavily complicated administrative UN regulations drastically delayed the onsite budget availability.

In addition to that, NMNH has also provided support with the implementation of the GPS network that provides an important and complimentary add-on to GORISK.

2.4. STEERING COMMITEE

In April 2008, the first meeting of the steering committee was held in Goma, allowing its members to appreciate and to evaluate the progress of the project and the field working conditions. The report of the steering committee pointed out many positive points as the installation of the ground-based networks, the InSAR ground deformation monitoring, the inventory and mapping of *mazuku*, training of local staff, installation of GCP for geocoding the Ikonos image, etc. Regarding the *in-situ* data, the steering committee stressed that all efforts made for installing the observational stations are only valuable if data collection, data continuity, and timely sharing amongst the partners is guaranteed. In addition to the difficult regional security context encountered during the 1st year of the project, the steering Committee raised 6 main problems, mainly related to the local partner GVO, which seriously jeopardized the objectives of the project. These problems concerned the Internet connection, the mobile connection, the payment of sentinels, the power supply, the sharing of seismic data and the sharing of data between the different departments of GVO. The Belgian Science Policy asked to find solutions to these problems and made of it a condition to the continuation of the project.

On the 2nd of September 2009 (hence after the drastic structural changes at GVO), the steering committee and the GORISK partners again met in Tervuren (Belgium) to present and to assess the results of the GORISK project. The committee was unanimous in its praise of the progress made since the first meeting of the Steering Committee and the results obtained, especially given the adverse local field conditions. Nevertheless, the committee, aiming at strengthening the output and the legacy of the project, made a number of recommendations.

2.5. PROJECT EXTENSIONS

The Belgium Scientific Policy (BELSPO) agreed a first extension of the project; the end of the project was therefore postponed to September 2009. This request was based on the statement that even if the beginning of the project was a success, two elements did have some influence on the project, causing delays in the acquisition and integration of data. The first element was the unstable political and security situation in this region, making fieldwork (water and gas sampling and measurements, maintenance of monitoring stations) difficult, not to say sometimes and in some places impossible. The second element was the structural and financial problems encountered by GVO, as explained previously.

A second extension of the project was obtained until the end of December 2009. An ultimate extension of one month was agreed to get the opportunity to participate in an international meeting in Gisenyi (Rwanda) organized by US National Science Foundation, ("Tropical Rift Lake Systems: Integrated Volcanologic, Tectonic, and Biogeochemical, and Geohazard Assessment of Lake Kivu"). The operational end of the project was then decided and fixed on the 31st of January 2010.

2.6. PROJECT VALIDATION

On the 2nd of January 2010, the Nyamulagira erupted and a GORISK team[1] arrived on site on January 10th to assist the Goma Volcano Observatory (GVO) in collecting and processing field data and observations. Results and observations obtained during that mission are going to be developed further in this report but one can already mention that that eruption has been considered as an opportunity to successfully validate the outputs of the project.

3. RESULTS

3.1. INTRODUCTION

By sake of clearness, the presentation of the results is organized by main disciplines rather by work packages. Each of them is then detailed by subdisciplines:

Ground deformations		**Geochemistry**			**GIS**		**Health**		**Training**	**Validation**
InSAR	*Ground Based*	*Ground based fixed*	*Ground based mobile*	*Plume monitoring*	*GVO DB*	*Map update*	*Water sampling*	*Indicators / eruptions*		

[1] Team composition: Dr N. d'Oreye[1]; Dr. F. Kervyn[2]; Benoît Smets[2]; C. Wauthier, PhD student[2]; Pr D.Tedesco[3]
[1] National Museum of Natural History, Luxembourg (NMNH), [2] Royal Museum for Central Africa, Belgium (MRAC), [3] 2nd University of Naples, Italy (UniNAP)

3.2. GROUND DEFORMATIONS

Among remote sensing techniques that can be applied to the monitoring of the volcanic activity in the Virunga, SAR is playing a very important role, as it is not depending on field accessibility, adverse weather conditions or frequent cloud screen. Although the land use —that is characterized here by forests and dense vegetation surfaces— is not ideal for an optimum application of SAR interferometry (InSAR) the technique was found (under specific conditions, i.e. systematic satellite programming schedule) to provide highly valuable information in terms of geodynamical processes.

Where the phase coherence is preserved, the data are continuous in space but are strongly dependent of the re-visiting cycle of the satellite sensors, the orbital constraints, the acquisition plans, etc. For these reasons, InSAR cannot be considered as a real time monitoring system.

This has motivated the deployment of ground-based systems dedicated to monitor the ground deformation at stations installed in strategic locations. These are providing measurements continuous in time when the ground conditions (e.g. security) allow so. Tiltmeters have been installed as part of the GORISK project, whereas an external Nmnh sponsoring has provided a geodetic GPS network as an add-on.

3.2.1. InSAR deformation monitoring

InSAR is based on the combination of successive radar images of an area, acquired from a similar orbital position and looking geometries. On the one hand, technical constraints are concerning the successive close orbital positions that must also be determined with a very high accuracy. On the other hand, the surface specification for the phase of the radar signal to be preserved between the acquisitions imposes bare or poorly vegetated surfaces. Other limitations are linked to the atmosphere that can cause phase delay that could lead to misinterpretations.

In most cases, the cross combination of data acquired at different dates can help in discriminating the respective phase delay contributions and hence isolate the signal associated to the tracked geological process.

At the exception of specific images obtained in the framework of collaborations with other teams, all the SAR data were obtained through ESA CAT-1 projects support.

The acquisition strategy was defined in order to maximize the frequency even though the orbital cycle is limited to 35 days. Acquiring independent InSAR datasets at a few days intervals makes sense in the study of sudden events.

3.2.1.1. Semi-automated systematic data processing and Webtool (WP 1100 & 1300)

All possible ENVISAT ASAR data are systematically programmed and ordered for a given set of Modes, Tracks and Swaths over the studied area thanks to the grant of CAT-1 ESA research projects. A routine acquisition scheme has been setup and had yield to rapidly growing amount of SAR data at a rate of 6 new scenes every 35 days.

3.2.1.1.1. *Data processing:*

After data availability notification by ESA, an automated script downloads and archives the corresponding files. A set of optimized parameters is predefined for automated processing: crop size, multilook factor, Digital Elevation Model (DEM), maximum spatial baseline, file naming and locator, etc… Based on these parameters, a single command line will either allow for computing a single interferogram or all the possible combinations of a given scene, with each compatible scene in the database. The launch procedure is kept manual in order to 1) avoid too many simultaneous launches on a given computer and 2) for the operator to choose between a few options such as the type of precise orbit(s) to use, to modify the default list of masters or slaves scenes to combine with the given image, to choose to unwrap the final residual phase.

This (semi-)automated procedure is based on the DORIS InSAR open source software (TU Delft), Mathematica© routines, and shell scripts running on Mac OS X environment.

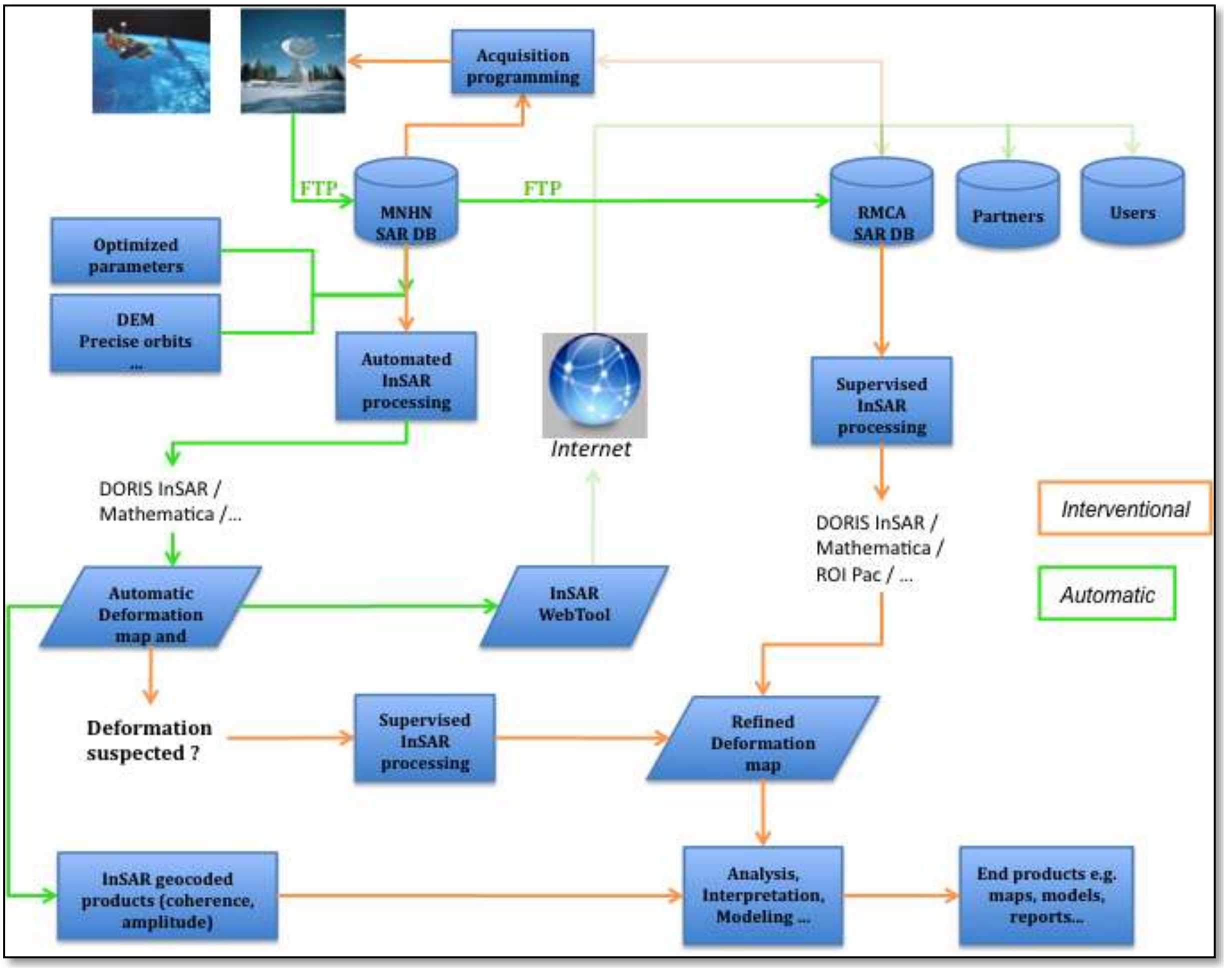

Figure 1 : ***Flow chart illustrating the processing chain of SAR data processing, from the ordering to the deformation maps and beyond (modelling, etc.)***

3.2.1.1.2. *The webtool:*

More than being a tool for quickly and efficiently looking through the thousands of InSAR products, the web tool also helps to easily discriminate artefacts from deformations, to detect seasonal variations or continuous slow phenomena, and to detect timing errors or frame shifts.

Automated scripts collect the results of all the pairs processed for each given Mode, Track and Swath. The Sun-Raster figures in radar geometry are converted to JPG and renamed with relevant information such as volcano name, the Master and Slave orbit numbers and their dates, the perpendicular and temporal baselines and the altitude of ambiguity. Filtered phase interferograms, filtered phase interferograms wrapped on the amplitude and coherence maps are then converted to JPEG and made available in sorted tables on internet.

When logged in using the appropriate password, the user chooses a target (i.e. a volcano) and a Mode/Track/Swath in the column to the left and the type of product to display (coherence phase or phase wrapped on amplitude).

A first triangular table pops up (Figure 2) filled with small yellow-green icons. These icons refer to computed interferograms. The column and line headers are respectively the Master and Slave characteristics (date and orbit number). Empty cells mean that no interferogram could be computed for that given pair. The table allows the user to view on a single page which products are available vs. time.

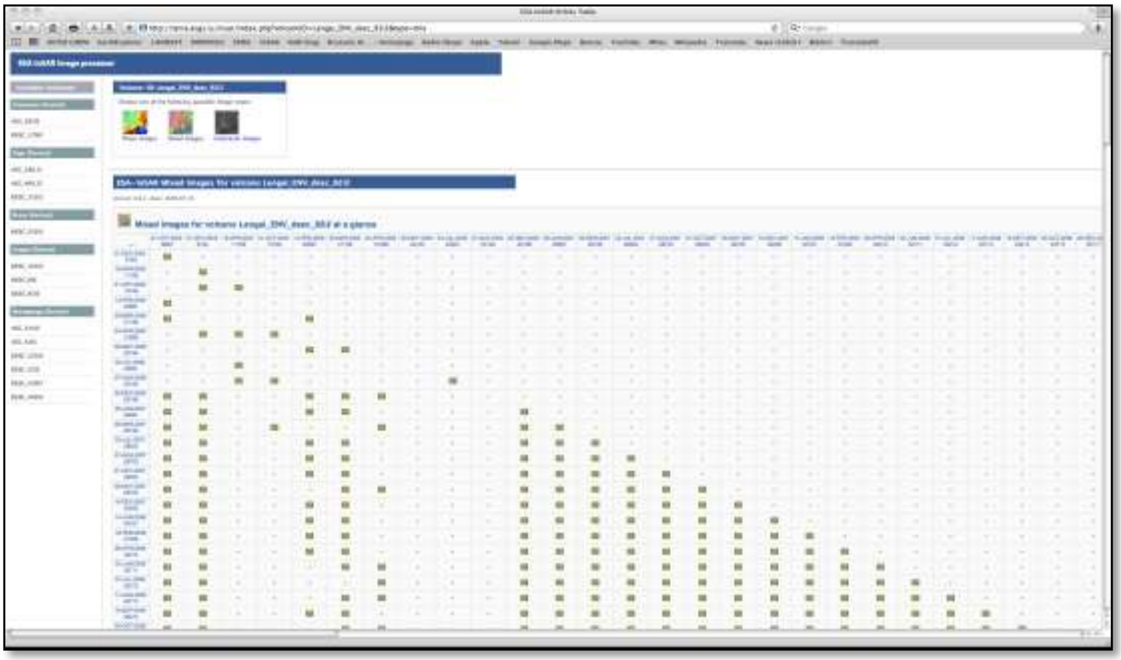

Figure 2: Web tool for InSAR product visualization. The operator selects a target (i.e. a volcano) in the column to the left and a Mode/Track/Swath. Three kinds of product to display are offered in the small upper window: the coherence maps, the phase interferograms, or the phase wrapped on the amplitude. The table displays all the interferometric pairs computed in the database.

When the operator moves the mouse pointer over one of these yellow cells, a low-resolution preview of the interferometric products pops up. A second table similar to the first one is also displayed. It shows low-resolution thumbnails instead of yellow icons. The table is obviously much larger but offers a global view and the possibility to compare many products at a glance (Figure 3).

On Figure 3, one can appreciate the potentiality of the tool: the two interferograms shown in the upper blue frame are enlargements of only the Nyiragongo crater area. These are extracted from the two interferograms at the right of the blue-framed interferograms in the table. Similarly the two interferograms shown in the red frame to the right of the figure are similar zooms extracted from the two interferograms at the top of the red-framed interferograms in the table. The amplitude of the signal (about 1,5 colour cycle in the present case) is about the same on every affected interferogram (see blue and red frames) whatever the altitude of ambiguity is. This rules out possible DEM related errors. The unframed zoom is the enlargement of the same crater area, taken from the interferogram just below the contact point between the blue and red frames in the table. None of the independent interferograms spanning the affected image show similar signal (see unframed interferograms), demonstrating in one glance that the observed signal that could have been misinterpreted as deformation is actually an atmospheric artefact.

3.2.1.1.3. ***Conclusions for the semi-automated processing and WebTools:***

The automated bulk processing and the web interface have proven to be a simple, quick and efficient tool for the management of the large InSAR database. It also helps to easily discriminate artefacts from deformations, to detect seasonal variations or continuous slow phenomena, or to detect timing errors or frame shift.

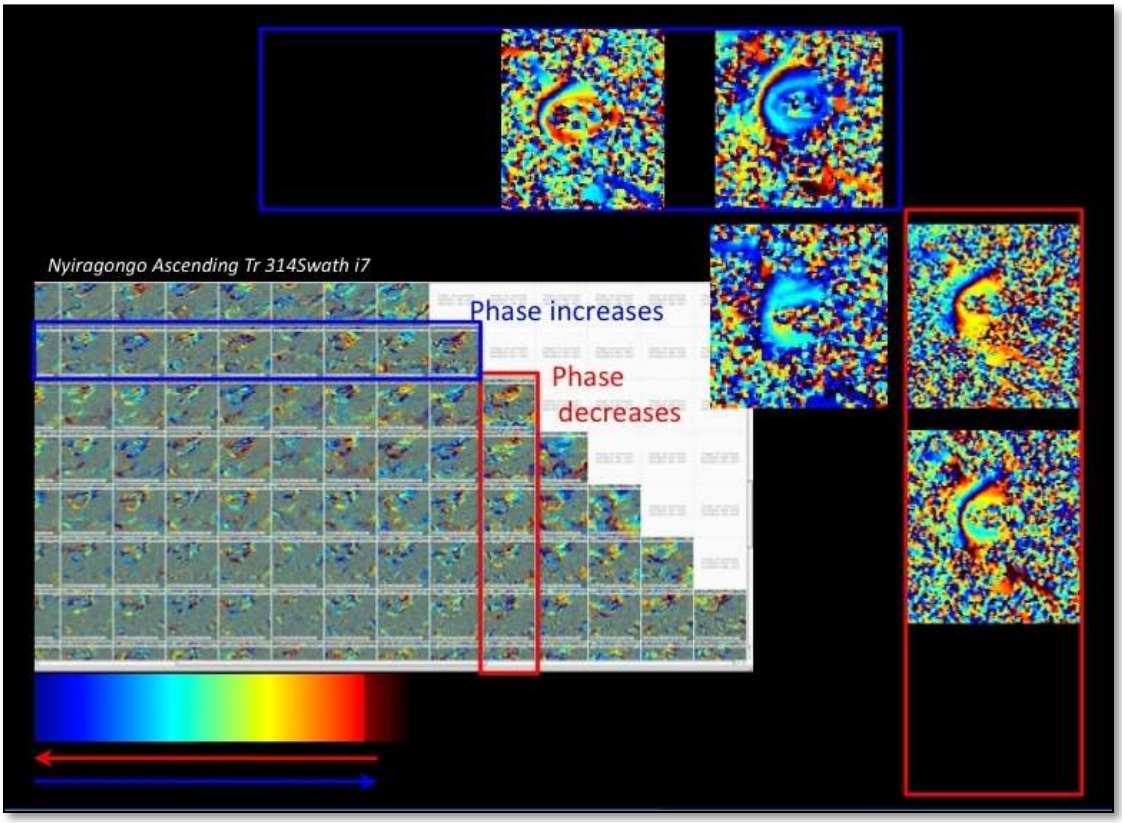

Figure 3: Table on white background: extract of web tool showing phase interferograms of the Nyiragongo area, DR Congo (Nyiragongo Ascending Track 314 Swath i7). Interferograms framed in Blue and Red show an atmospheric artefact affecting the Nyiragongo volcano (too small to be seen in the table – see enlargements to the right instead). The sign of

phase delay observed on the crater area is reverted when the affected image is used as a Slave (line framed in Blue; phase increases) or a Master (column framed in red; phase decreases).

Thanks to the pre-defined parameters and the automated procedure, the tools are also useful for fast response in case of a crisis. Usually each new scene can be combined with the previous most recent compatible image from the database to produce the last interferogram within less than 30 minutes.
The procedure was set up and upgraded step-by-step during the project and tailored for our needs and the hardware in use, based on our configurations.
The WebTools is a powerful tool for those dealing with mass processing; its access is limited to granted users and requires a login and a password[2].
A more detailed technical description of the processing and the InSAR WebTool is provided in d'Oreye and Celli (2010).

3.2.1.2. Archives processing (WP 1300)

The processing of the available SAR archives was performed at the early stage of the project and was essentially dedicated to the study of the eruption of the Nyiragongo in January 2002.

During 2007, the NMNH processed the hundreds of satellite SAR archives and images acquired for the needs of the project. More than 3500 interferograms were computed out of that 10-years long database.

3.2.1.3. Refined processing of specific pairs and deformation source modelling

As already mentioned above, the semi-automated processing of the fast growing dataset sometime requires refined processing of pairs where ground deformation signal is suspected. It is indeed essential that every interferogram be carefully analysed in order to potentially detect precursors of an eruptive crisis; although no such pre-eruptive deformations has ever been observed during the period of the project. More attention is paid when external signals are recorded (e.g. seismicity) or during eruptions when a rapid assessment of the situation is required by the local authorities.

For major events such like the 2002 eruption, fine tuned processing is iteratively performed and the deformation maps are utilized for the deformation source modelling and interpretation.
The events that have required detailed processing are:

- the eruption of Nyiragongo (2002),
- the eruptions of Nyamulagira (2002, 2006 & 2010),
- the Bukavu earthquake (2008).

[2] Interested user can contact Dr Nicolas d'Oreye at NMNH by Email : ndo@ecgs.lu .

3.2.1.3.1. *Nyiragongo 2002 (Wauthier et al., in prep. & Wauthier et al., 2010)*

Displacements associated to the 17 January 2002 eruptive event were captured by radar data from the ERS-2 satellite[3] and the RADARSAT-1[4] satellite. The acquisition time of the various interferograms indicate that all the observed ground deformation took place between January 14 and February 13 (Wauthier et al., 2010).

The interferograms presented below (Figure 4) show complex ground displacements, with several overlapping fringes patterns, probably associated to a combination of sources of magmatic and/or tectonic origin.
The main signals are observed in area A, B, C & D. The signal observed in A corresponds to the compaction of Nyamulagira lava flow piles. In B & C, the asymmetric fringe patterns are related to the injection of the dike that fed the 2002 eruption. In the Goma area (D), a subsidence of about 15cm in the LOS can be observed.

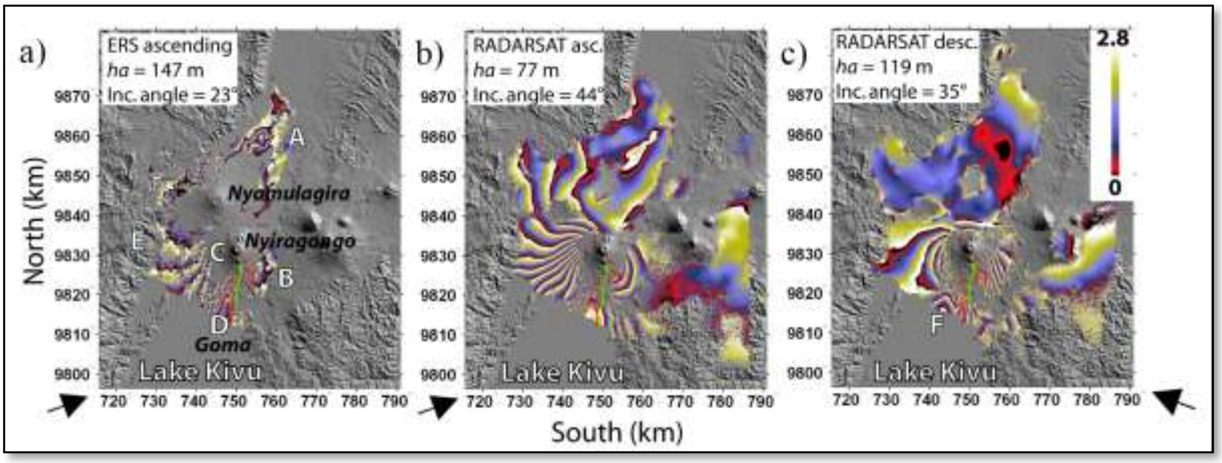

Figure 4: The 3 interferograms considered in this study (from left to right): ERS-2: 6 September 00 – 3 July 02; RADARSAT-1, ST6 mode: 31 December 01 – 17 February 02; RADARSAT-1, ST4 mode: 21 December 01 – 03 March 02. One color circle represents a 2.8cm satellite-ground range change with positive fringe (red-blue-yellow) corresponding to positive range. Black arrows show Line Of Sight (LOS) vector direction. The 2002 lava flow are shown in red and eruptive fissures are drawn in green. See the text for the interpretations of signals referred as A, B, C, D, E and F.

Modelling studies have been undertaken in order to determine the sources of the observed displacements. The numerical method used to model the InSAR displacements is a 3D Mixed Boundary Element Method (MBEM), which takes into account realistic topographies as well as any number and geometry of faults and pressure sources. This method is combined with a near neighbourhood inversion algorithm (NA) to determine the most likely sources parameters. The medium is assumed linearly elastic, homogeneous and isotropic. In order to find the models that best explain the observed data, a misfit function is defined, which quantifies the discrepancy between observed and modelled displacement.

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[3] ERS-2 data are provided in the frame of ESA Cat-1 project nr 3224 and AO ALO3690

[4] RADARSAT-1 data are provided by Canadian Space Agency and Alaska Satellite Facility

Preliminary inversion with ERS data only have shown that part of the InSAR data, close to the known eruptive fissure, can be explained with a dike connected to the fissure (Wauthier et al., 2010)

The three data sets available for the eruption are conjointly inverted. InSAR data that are assumed not to be generated by the dike are masked out. The best-fit model (Figure 5) obtained corresponds to a sub-vertical dike, extending down to a few km. Both the quasi-vertical dike dip and the small overpressure (0.23MPa) are consistent with the extensional rifting context.

Finally, thanks to additional modelling of various InSAR data sets and to the experience acquired on the field, it was possible to provide the first plausible explanation and models of the unprecedented broad volcano-tectonic deformation associated to the last and devastating Nyiragongo eruption (Wauthier et al. 2010). These new models (Wauthier et al. in prep) offer the first explanation matching the geodetic data as well as the visual and geochemical observations and provide a plausible explanation for an 8-years old enigma.

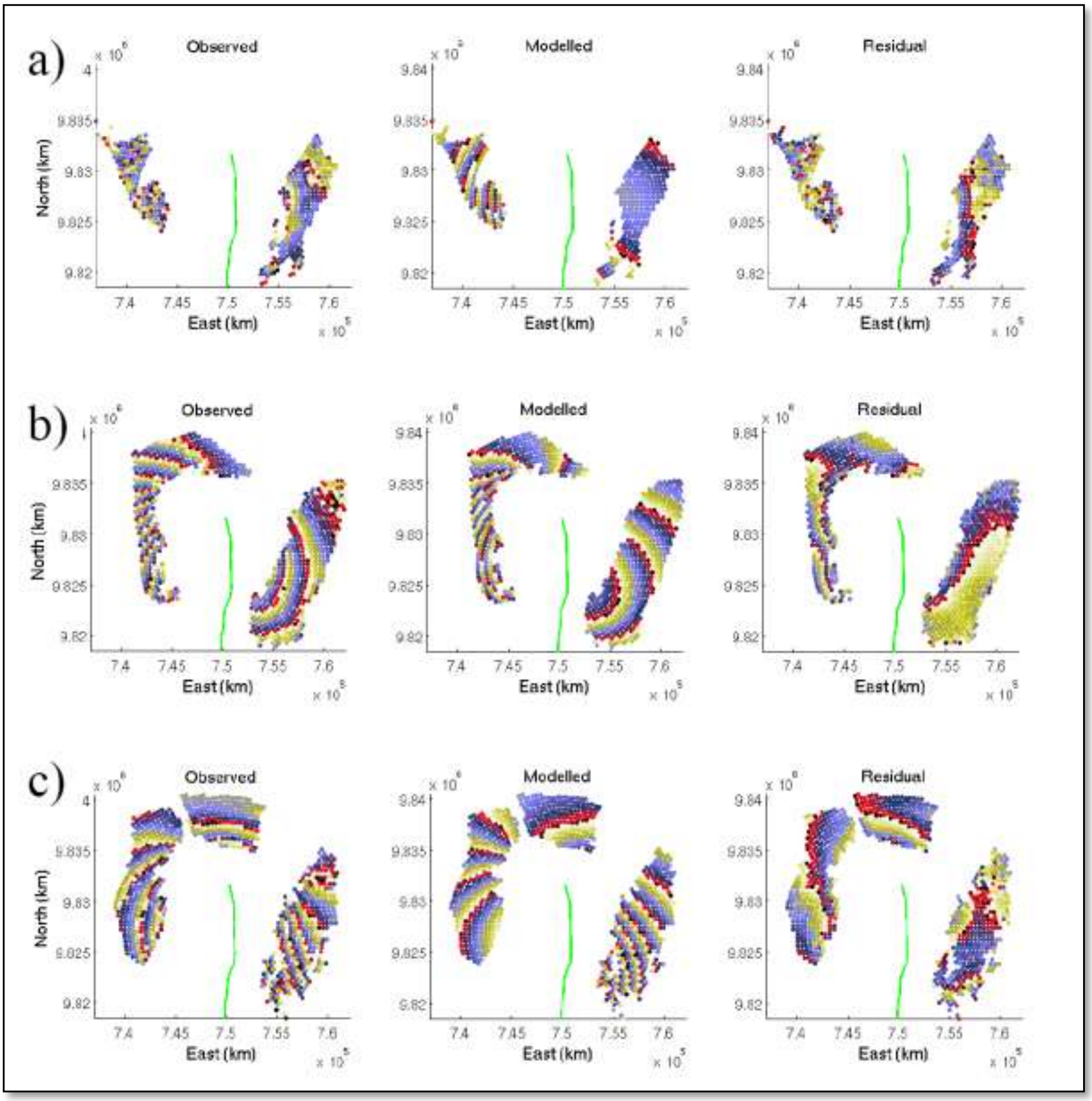


Figure 5 : ***Observed (left) – modelled (center) – residuals (right) interferograms at subsampled data points obtained from a simultaneous inversion of the three SAR geometries considering a single dike. The dike is connected to the ground surface at the location of the eruptive fissure represented in green. (After Wauthier et al., 2009).***

These new models involve the presence of a second source of magmatic or tectonic origin below lake Kivu and the Goma area, which has large implications in terms of risk assessment for the whole region. They indicate that the opening of eruptive fissures or fault movements on the lake floor cannot be ruled out in the future and demonstrate the urgent need of additional in-depth studies as Lake Kivu contains high concentrations of dissolved carbon dioxide and methane. That lethal gas could be released with major water disturbances and have drastic consequences for the two million people living in the area. Unlike Lake Nyos in Cameroon that killed 1700 people in 1986 in a few minutes within a distance as far as 10km from lakeshores, gas concentration in the Lake Kivu is hopefully far from saturation.

However, a large magma intrusion into the deep layers of the lake could cause a mixing event and force its overturn.

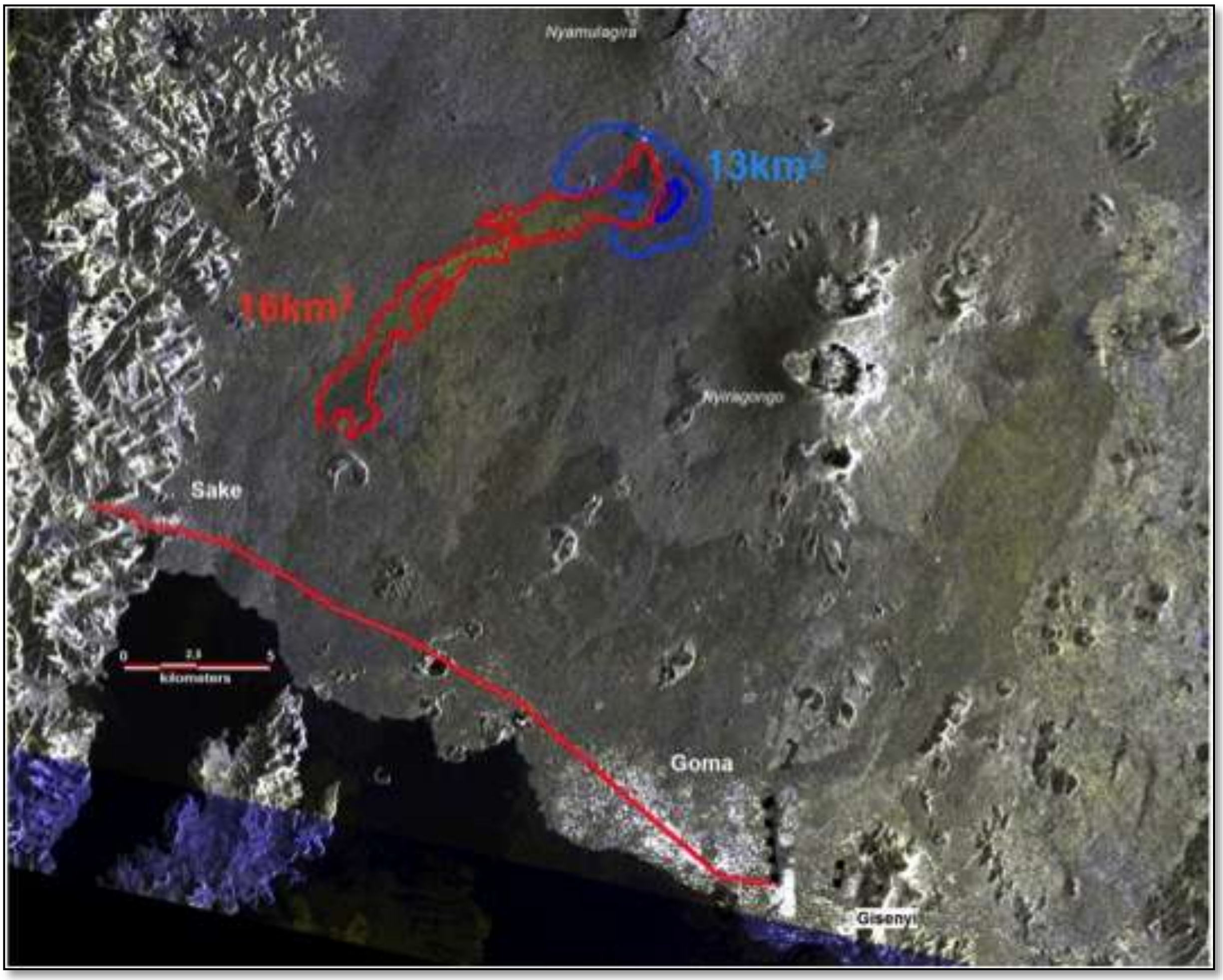


Figure 6: November 2006 lava flow (red) and cinders (blue) extent from ENVISAT intensity image difference.

The systematic monitoring of the East African Rift using InSAR carried out since a few years [d'Oreye et al., 2008; Poland, 2006] is of course of great help; but InSAR has limitations (e.g. water bodies) and it is therefore imperative that the local seismic, and other ground-based networks be also improved.

3.2.1.3.2. *Nyamulagira 2006 (Cayol et al., 2009 a & b, Cayol et al., in prep.)*

In November 2006, an eruption took place on the South Eastern Flank of Nyamulagira from a fissure located halfway between Nyamulagira and Nyiragongo. A lava flow was reported extending southward toward the inhabited areas of Lake Kivu and the main supply road for Goma. At that time, strong fights between armed groups and FARDC in the area forbidden any fieldwork to assess the progression of the flow. Moreover, adverse meteorological conditions combined to intense smoke produced by the burning forest lead to very poor visibility. During several days no assessment of the lava flow speed and direction was possible. An emergency acquisition of ENVISAT data was obtained from ESA and few hours later, an estimation of localization of the eruptive center and the lava flow extent were provided based on intensity images (Figure 6).

The flow was moving in the direction of the vicinity of Sake and the main road —a highly strategic axis on the economic, security, and humanitarian point of view—. But the eruption stopped after few days and the flow remained at about 6 kilometer from the road.

This eruption was covered by interferograms from three different view angles, two from descending orbits and one from an ascending orbit (Figure 6). The interferogram from the ascending orbit has the most favourable spatial and temporal baselines and shows a signal over a 200 km² area East, North and South of the presumed eruptive fissure. The interferograms from descending orbits show displacements over 25 km² area North and East of the fissures (Figure 7)

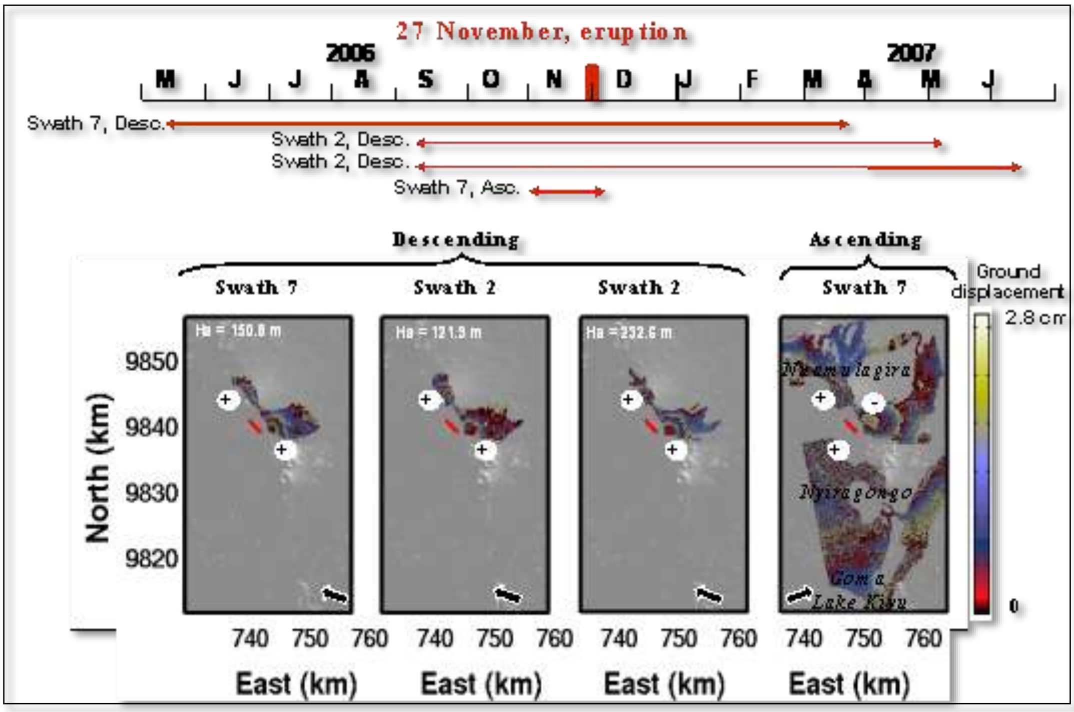


Figure 7: ENVISAT data covering the Nyamulagira eruption

The interferograms were analysed using a method that combines a 3D numerical modelling for elastic medium with a near neighbourhood inversion algorithm. Preliminary results show that two sources are needed to explain the measured displacements. One of the sources corresponds to a dike located between Nyamulagira and Nyiragongo, which is aligned with the axis linking the two volcanoes. For the other source, the best-fit model is obtained when combining a dike and a spherical magma chamber (Figure 8).

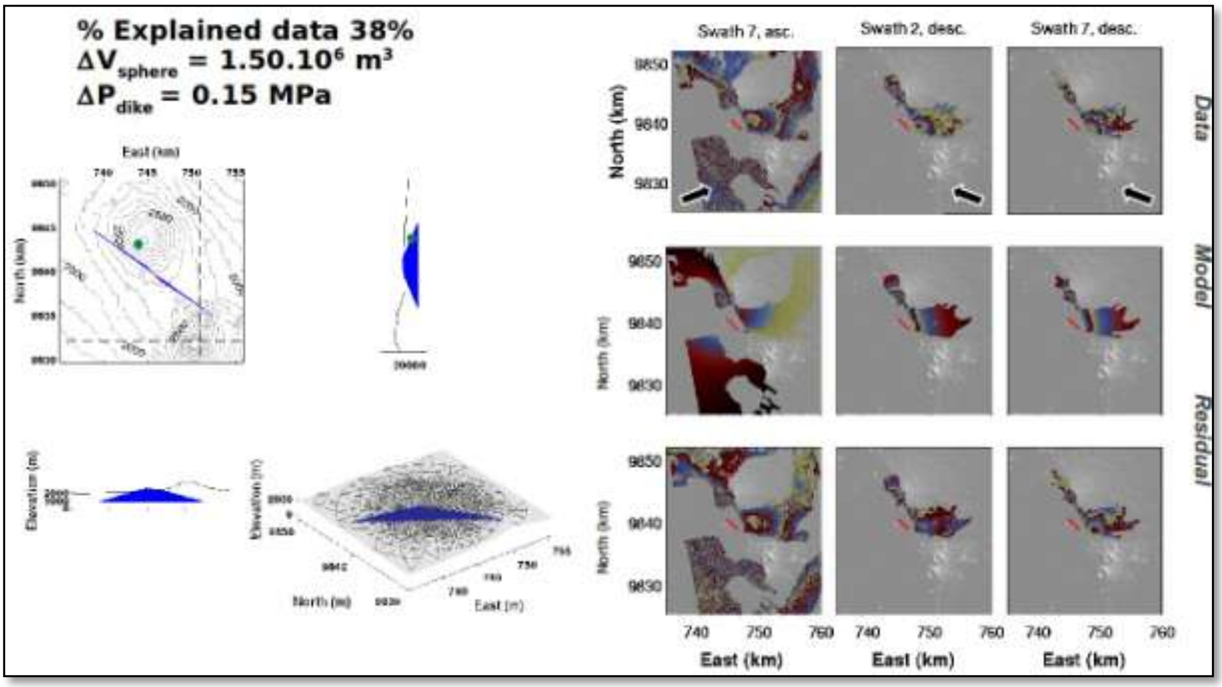


Figure 8: ***The best-fit model is obtained with a combination of a dyke trending along the Nyamulagira – Nyiragongo axis, and a spherical magma chamber (green spot on the left figure).***

3.2.1.3.1. *Bukavu 2008 (d'Oreye et al., in press)*

On February 3rd 2008 07:34:12 UT (09:34 local time), a Mw 5.9 Earthquake struck the cities of Bukavu and Cyangugu along the border between South Kivu in Democratic Republic of Congo and the Rusizi District in the West Province of Rwanda. The event was followed by many felt aftershocks among which four events with magnitude decreasing from 5 to 4.1 on the same day. Seven more events with magnitude above 3.7 occurred throughout the rest of the month.

This earthquake is of particular interest due to its shallow depth and proximity to active volcanoes and Lake Kivu, which contains high concentrations of dissolved carbon dioxide and methane. The possible similarity with dyking events recognized in other parts of East African Rift (EAR) suggested the potential association of the earthquake with a magmatic intrusion, emphasizing the necessity of accurate source parameter determination.

Regrettably no seismic network was operating that day. Fortunately, satellite Radar interferometry efficiently complemented the teleseismic waveforms studies to accurately infer the source parameters of this moderate earthquake (Mw<6).

An ENVISAT InSAR interferogram was computed with baselines conditions favourable enough to overcome the vegetation-induced decorrelation. The interferogram shows a single deformation pattern with a peak-to-trough line-of-sight deformation of about 10 cm (3 fringes) (Figure 10). Independently, a pair of ALOS PALSAR L-band images allowed performing an other interferogram (Figure 9A) which shows a consistent deformation pattern. The logic of pair comparison and the fact that the deformation is smooth and mapped by two independent sensors at different dates allow us to rule out atmospheric artefacts.

Fault plane geometry was modelled using a rectangular dislocation with uniform slip embedded in a homogeneous, isotropic and elastic half-space (Okada, 1985). The deformation map was inverted using an unconstrained direct search nonlinear optimization algorithm, based on the simplex free-derivative method (Nelder and Mead, 1965). Both ALOS and ENVISAT data set were inverted separately (***Figure 9***) as well as in a joint inversion (***Table 1***).

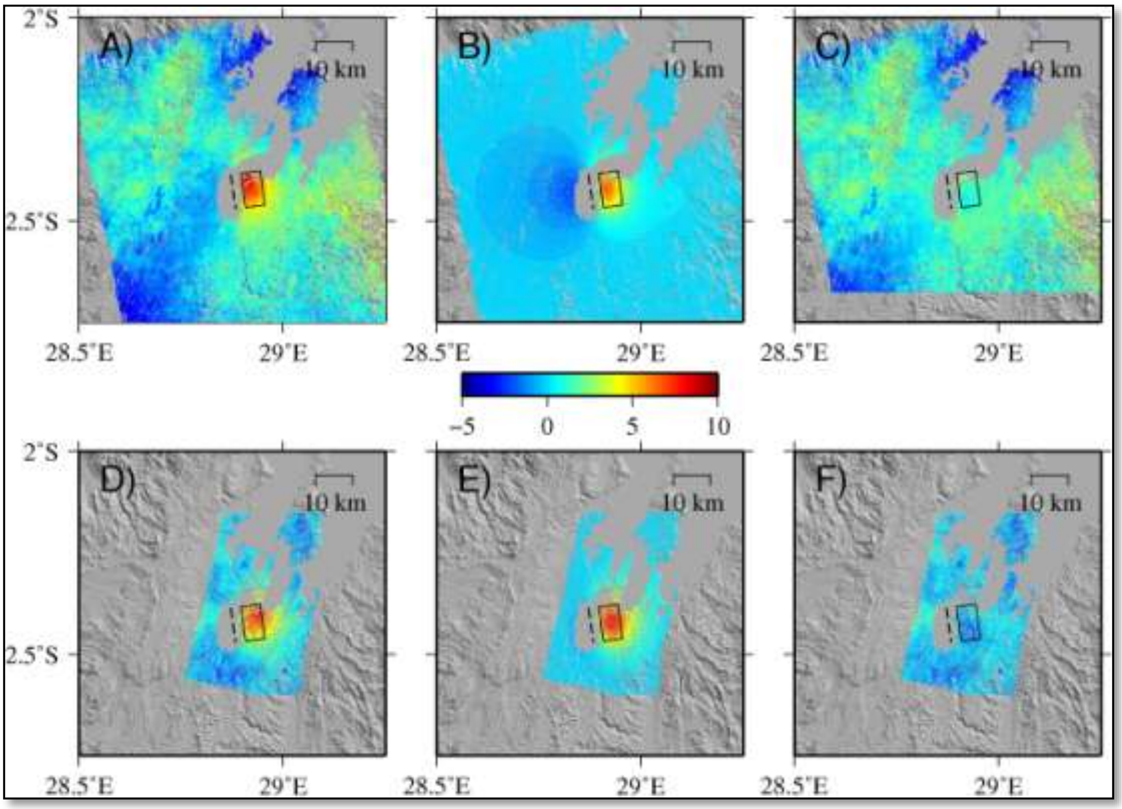


Figure 9: ***InSAR co-seismic deformation associated to the 2008 mb 5.9 Bukavu earthquake. (A) Unwrapped ALOS interferogram (Ascending orbit): deformation expressed in cm, in satellite line of sight (LOS). (B) Best-fit model (C) Residuals. (D) Unwrapped ENVISAT interferograms (descending orbit): deformation expressed in cm in LOS (E) Best fit model (F) Residuals. Deformation is positive away from the satellite***

The source parameters derived from the best-fit inversion confirm the quasi NS strike angle derived from seismicity (Figure 10). InSAR could successfully infer accurate depth and location. The focal mechanism, strike and depth (Table 1) are consistent with local tectonics. The geodetic moment magnitude estimated from InSAR (Mw 5.9) is similar to the moment magnitude estimates from the teleseismic study suggesting that the observed deformation pattern is probably almost entirely co-seismic and related to a brittle rupture with almost no aseismic slip. It also confirms the shallow depth of the source (8.9 km + 0.3 km).

In the mature eastern branch of the EAR, magmatism is known to play a major role in lowering the seismicity during rift opening. Magma-assisted opening seems also to prevent the occurrence of large magnitude earthquakes in active volcanic provinces of the western branch of the EAR such as in the 12Myr old Virunga Volcanic Province. The mode of extension in the younger, yet extinct, South Kivu Volcanic Province is however poorly understood. Our results provide insights into the style of rifting occurring in that part of the EAR and hence will aid future studies on seismic risk.

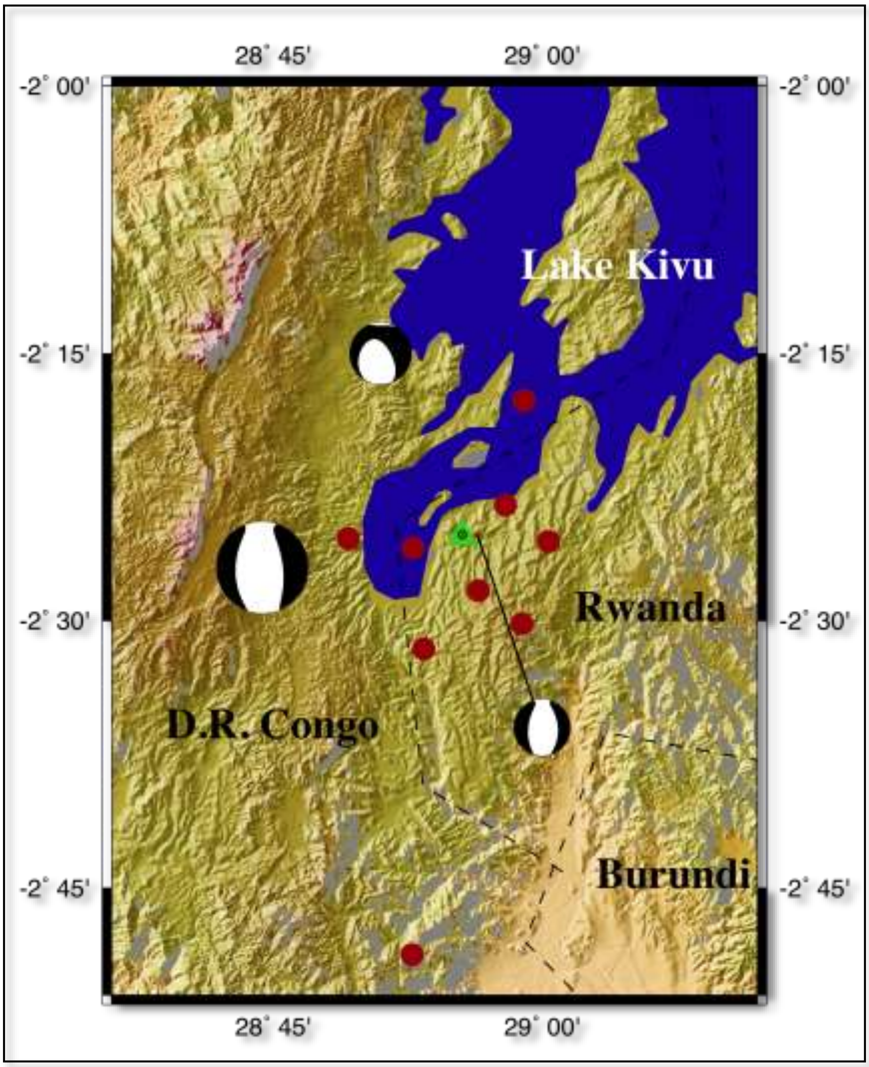


Figure 10: ***Focal mechanisms from the teleseismic data (this study) for the main shock (2008/02/03 7:34:13), and for two aftershocks (northern is 2008/02/14 2:07:47, southern is 2008/02/03 10:56:10). Red dots show the National Earthquake Information Center's***

locations for earthquakes within a month of the main shock. The green triangle shows the location of the rupture fault obtained from the geodetic inversion. (From d'Oreye et al., in press)

Inversion data set	Depths (km)	Dip (Deg)	Strike (Deg)	Rake (Deg)	Latitude (Deg)	Longitude (Deg)	Moment (10^{17} Nm)
ENVISAT	9.3 ± 0.6	46.6 ± 2.5	351.5 ± 10.0	-91.5 ± 14.3	28.9425 ± 0.0009	-2.4060 ± 0.0036	9.61 ± 0.10
ALOS	9.8 ± 0.3	63.0 ± 0.5	352.3 ± 0.5	-92.5 ± 15.7	28.9196 ± 0.0006	-2.4216 ± 0.0004	11.64 ± 0.02
Joint ENVISAT+ALOS	8.9 ± 0.3	58.6 ± 0.8	352.4 ± 1.6	-105.2 ± 16.6	28.9260 ± 0.0006	-2.4219 ± 0.0020	9.79 ± 0.004
Broadband+CMT	7.8 ± 2.0	51.5	350.1	-100.6	28.74 ± 0.01	-2.45 ± 0.01	9.43 ± 0.06

Table 1 : Best fit models computed from InSAR and teleseismic modelling and inversions (After d'Oreye et al., in press)

3.2.1.4. Nyamulagira 2010

On January 2nd 2010, the Nyamulagira volcano started a new eruption. That event has been considered by the GORISK partners as an opportunity to test the improved input provided to the involved end users.
The complete sequence and description of the eruption is presented and detailed in the section 3.9 Validation including the ground deformations aspects.

3.2.1.5. Velocity deformation maps

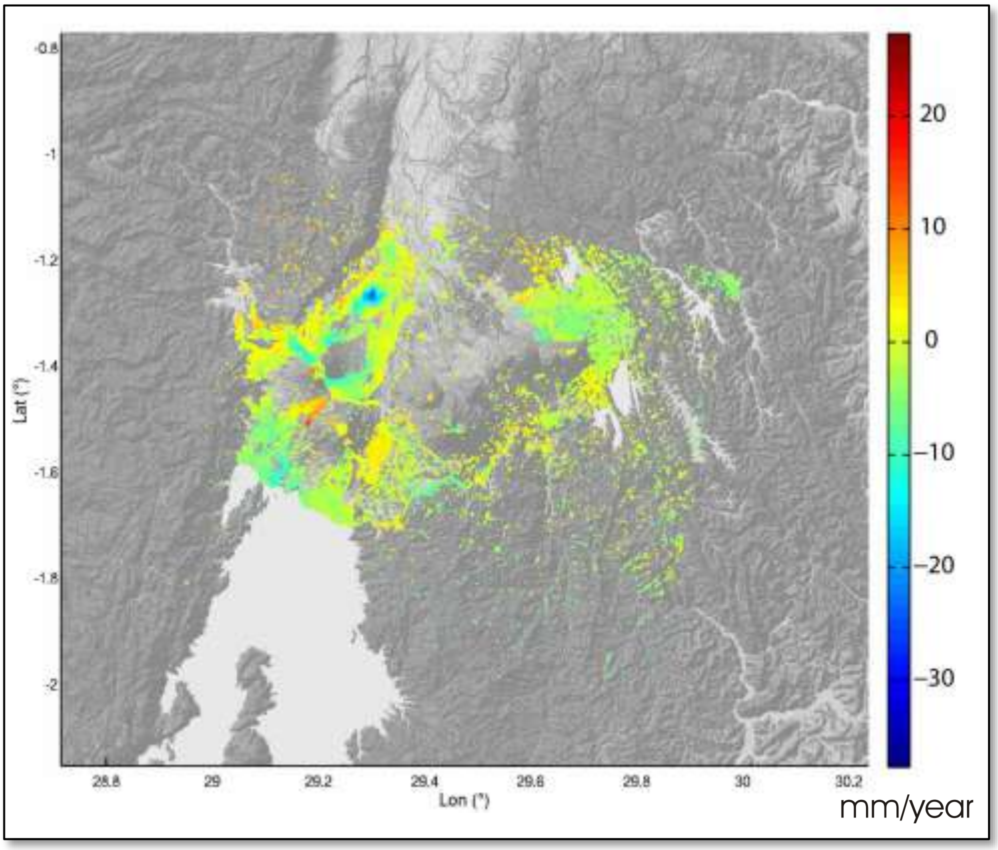
Thanks to the large amount of SAR data acquired over the last 5 years, multi-temporal InSAR methods were applied in the Virunga Volcanic Province. Two methods were used and compared: the small baseline (SBAS) method developed at IREA (Sansosti et al., 2010) and the "StaMPS" method that combines a small baseline and persistent scatterer (PS) approach (Hooper, 2008).
The resulting mean deformation velocity map and displacement time series were produced and discussed. Both techniques show similar results: lava compaction of the Nyamulagira old lava flows out- and inside the crater as well as some co-eruptive deformations. Many coherent pixels were also detected outside the rift valley although no significant displacements could be identified away from the escarpments (Figure 11).

3.2.1.6. Problems encountered and their (potential) solutions

The main problem that has affected the ground deformation monitoring during the project is the failure of ARTEMIS.
In November 2006, the satellite ARTEMIS had a failure and was no longer able to transmit the data from ENVISAT to the ESA receiving ground station. Though ENVISAT is equipped with a data recording system, the acquisition of some of our richest modes was no longer possible due to conflicts with other data user with

higher priority along the same orbit. This was the case for example for the ascending orbit, track 228, swath i2 (36 scenes).

Solution: Other modes were defined and a new database was setup



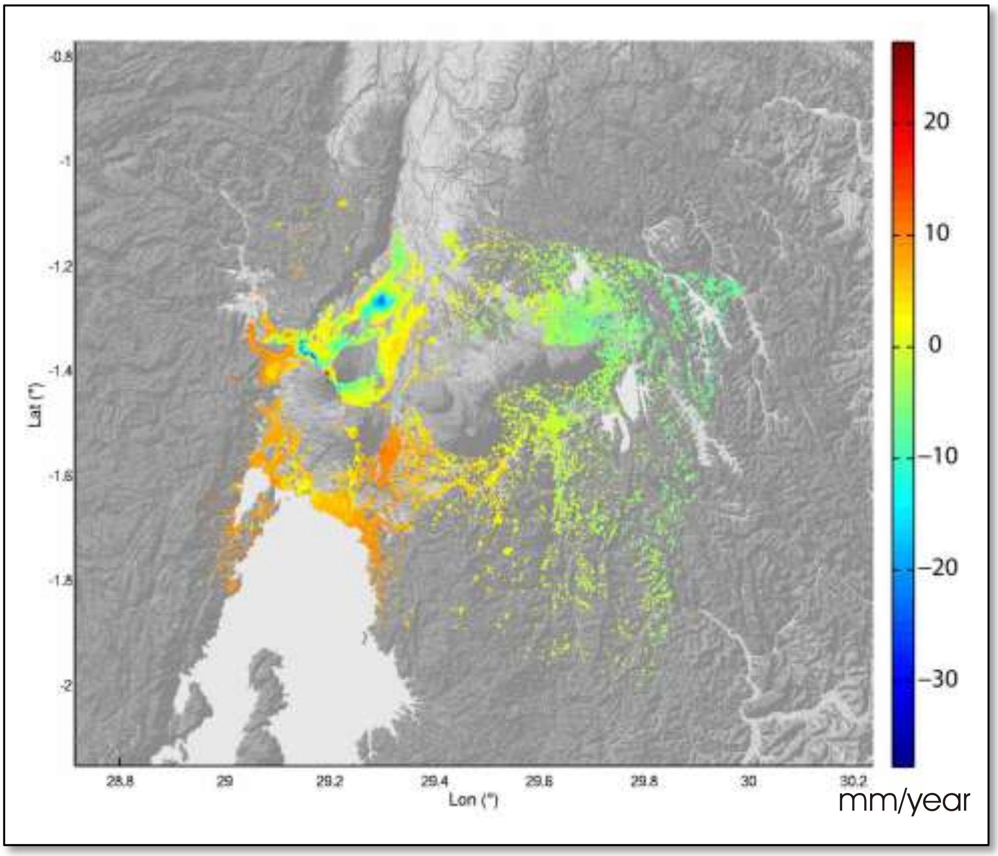


Figure 11: Mean Line of Sight (LOS) velocity maps obtained with the STAMPS (up) and IREA (bottom) methods.

3.2.2. Ground-based deformation monitoring

As it has been mentioned earlier, the limitations and advantages of the monitoring of ground deformations by remote sensing techniques are balanced by ground-based systems. More precisely, ground-based instruments such like tiltmeters or geodetic GPS are recording data continuously in time at a selectable time rate. The data however are discrete in space which contrasts with the wide areas covered by satellite data acquired at fixed dates and time.
As part of the project, a network of tiltmeters was deployed whereas parallel initiative leads to the necessary support for the deployment of a geodetic GPS network[5].

3.2.2.1. Tiltmetry

To replace the previous network abandoned in 2004 when the previous foreign partners decided not to pursue their collaboration with GVO, five continuous tiltmeters monitoring stations were installed during the first field campaign in 2007.
The site locations were selected upon criteria based on geophysical relevance, accessibility, and security concerns. A trade off has to be found and the stations were installed in areas were intriguing deformation signals were observed on the interferograms of the 2002 Nyiragongo eruption. Because of the requirements of such equipment (constant T°, stable bedrock conditions…), the building of dedicated hut with vault was sometimes necessary, whereas in other places, natural caves (e.g. lava tunnels) were arranged to host the equipment.

Because of the field accessibility restriction, the five sites are all installed on the southern slope of the Nyiragongo resp. in:

- Ngangi: tilt exclusive, lava tunnel
- Munigi: tilt exclusive, hut with vault
- Bulengo: co-located with seismic station, hut –no vault -. Replacement of pre-existing tilt equipment.
- Rusayo: co-located with seismic station, hut –no vault -. Replacement of pre-existing tilt equipment.
- Kibati: co-located with seismic station, ICCN[6] ranger's hut, shallow vault on the back of the hut.

Another station was also installed in Kibumba, co-located with the seismic station, but it has been vandalized and the decision was taken not to replace it (***Figure 12***).

[5] Seven geodetic GPS station obtained from Museum of Natural History of Luxemburg from mid 2008
[6] ICCN : Institut Congolais pour la Conservation de la Nature

3.2.2.1.1. ***Station setup and tiltmeters installation***

TECHNICAL DESCRIPTION: (site constraints and requirements…, difficulties …)

As mentioned above, the tiltmeters must be installed following specific requirements.

The first main technical constraint is a stable basement. Given the high sensitivity of the instruments, it must be installed on a representative surface of the object whose tilt has to be monitored. Typically, an *in situ* non-weathered and non-fractured rocky surface is the ideal site provided it is not located close to noise sources (e.g. passing trucks…). Other important constraints are related to the temperature, the moisture, as it may affect the signal too.

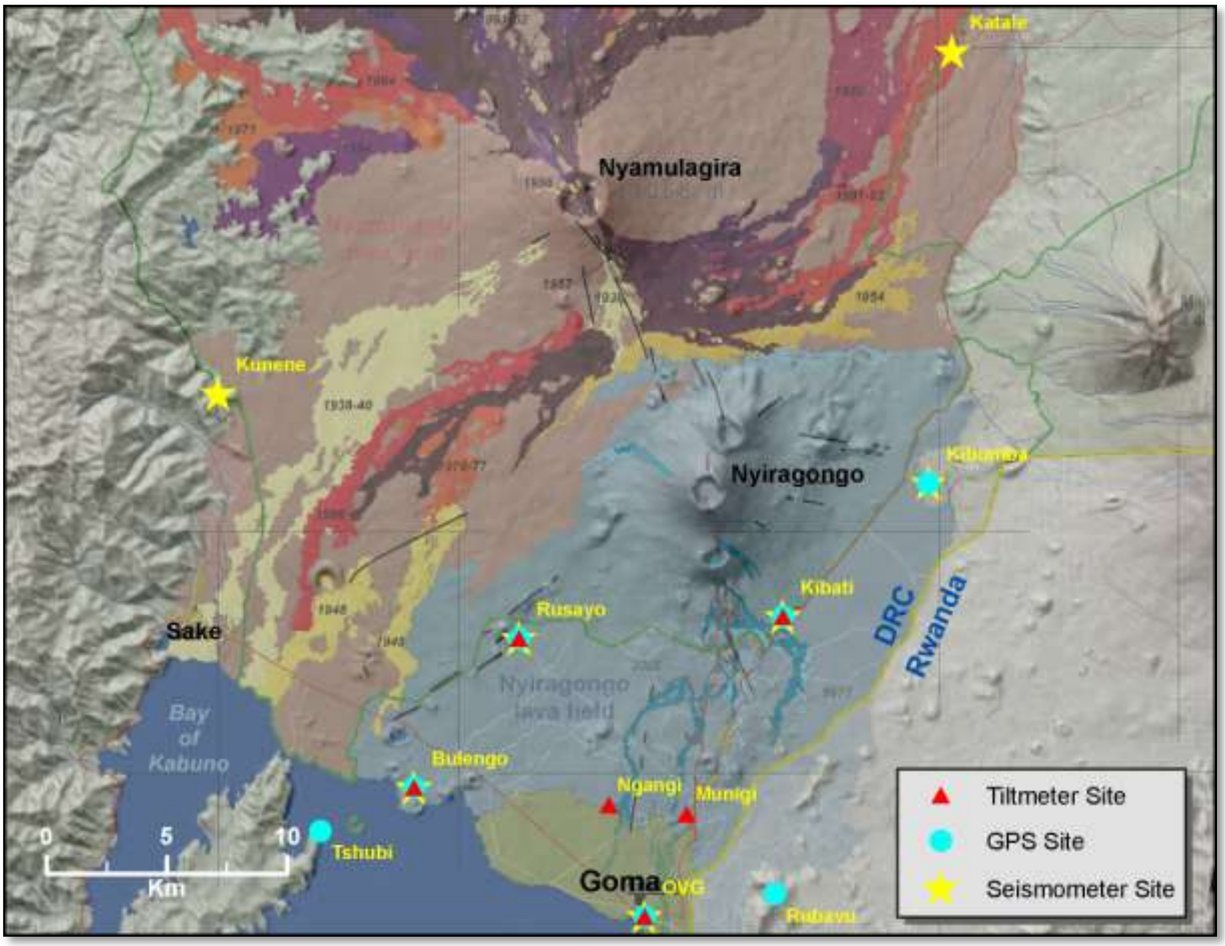


Figure 12 : ***Localization of tiltmeters and GPS installed in the frame of the GORISK project and of seismometers installed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV, Italy) after the 2002 eruption and maintained by the Goma Volcano Observatory. (Background: Volcanological map after Smets et al., 2010).***

In volcanic areas, lava tunnels are generally good sites where many of these conditions are met (Figure 13). But lava tunnels are formed under very specific conditions of lava rheology and terrains slopes and are not always available.

To find a stable site on basement rock is not easy neither: volcanic areas are generally covered by thick cinder and/or fertile soils. For that reasons, some sites require digging operation.

The instrument are coupled to the ground by resting on 3 stainless steel bars sealed with low-shrink epoxy in the bedrock or resting on 3 small iron pads sealed on a concrete pillar anchored into the bedrock. The bars or pads are arranged along E-W and N-S directions and their top is carved with holes and gouges in order to provide a unique installation position. This ensures reinstallation with exactly the same azimuths if temporary dismantling is required.

Finally, an effort is made to protect as much as possible the ensemble of temperature variations (e.g. polystyrene box).

Figure 13: Different site configurations and preparation for tilt equipment installation. In areas like Munigi where no hard bedrock is present, a vault has been excavated (g – see next

page) and the instrument has been installed in the grounding (i – see next page), covered by an iron slab secured with a padlock. A wooden hut with an iron roof is built on top to secure the site (a) and store the solar panels for the night. Lava tunnels (b) are usually preferred because of constant temperature and humidity conditions. This is the case in Ngangi where two walls are forming a room inside a lava tunnel with an iron door to secure the equipment. A hut is built on top to secure the access and the solar panels (d). Whenever possible, co-location of the equipment with existing infrastructure is preferred to reduce the costs and logistic. Picture (c) is shows the station of Rusayo where the tiltmeter is installed on the seismic station concrete block (h) or outside in a dedicated pit (i) such as in Kibati. Power supply is a major concern and solar panels are daily put outside (e) in the morning and inside after sunset by the sentinel. (f) displays the acquisition system setup in the Rusayo station.

As evidenced here, such type of site represents a significant investment of time and energy. Another important aspect to be taken into account is the time during which the instrument is expected to remain. Tilt measurements are meaningful if they are recorded during a sufficiently long period —typically months or years— in order to identify the seasonal effects or the meteorological influences...

For all those reasons special care was dedicated to the site selection and station design and building.

3.2.2.1.2. *Equipment and configuration*

The network consists of 4 analog and one digital biaxial Applied Geomechanics tiltmeters of the "AGI 700" serie. Their resolution is better than 0.1 microradian.

Among these five stations, three were acquired by GORISK while two analog ones were coming from former GVO projects supported by Japan and Italy. These last two stations were however not operating since many years as they were dismounted after technical problems and support interruption. They were refurbished in the frame of the GORISK project.

GORISK provided new acquisition and data transmission system via cellular phone for the four analog tiltmeters now installed in Ngangi, Munigi, Rusayo and Bulengo stations.

The digital tiltmeter was not initially planned in the budget but we could afford it while the manufacturer offered us significant discount on the analog models. We chose a digital model in order to use a GPS receiver we had as datalogger. The station was first installed in Kibati using one of the Nmnh's Leica GRX1200 GPS receivers as acquisition system. However, that GPS receiver model was expensive. After its destruction by lightning the whole GPS network was re-equipped with cheaper equipment (model GMX 902) allowing also setting up more stations. Unfortunately these new receivers do not provide on-site data storage capacity and the digital tiltmeter was not reinstalled. Finally, the whole GPS station of Kibati was looted in November 2008.

Its reinstallation is however still possible providing that specific software is written and some hardware are adapted, which could be done in the future if the budget allows it.

3.2.2.1.3. ***Recording rate***

The data acquisition system for the analog tiltmeters is based on CR100 dataloggers by Campell Scientific. The system is able to record up to 8 differential or 16 single-ended analog input. Data are digitized using a 13 bits A/D converter and multiplexed to be transmitted by cellular phone. The system has an internal memory large enough to store several months of data in case of transmission failure. Data are sampled at one minute though the system allows higher sampling rate.

3.2.2.1.4. ***Transmission***

The data transmission system relies on the mobile cellular phone network. The data could either be called anytime by the operator, or transmitted automatically every night from the stations to the server at GVO.

Such a phone transmission was first stopped when the SIM card was stolen from the modem placed in a locked room at GVO. That SIM card was then used as a public phone and the thief left an unpaid bill of more than 3.000 USD that the GVO could not pay. Phone links were then blocked by the provider and data had to be downloaded manually at the occasion of irregular visits of GVO staff in the stations. In the mean time, the phone company changed ownership and the "voice-data" mode was no longer supported. We tried another telephone company, which, despite what they announced, didn't support that mode neither. So far, data are still downloaded on site using a laptop computer. Currently, investigations are made to upgrade the system using GPRS mode to resume the automated data transfer from stations to GVO.

3.2.2.1.5. ***Archiving and processing procedures***

Data are archived on a dedicated computer, which is connected to a ftp server connected to the Internet. Data are archived locally on DVDs as well as automatically sent during the night to Luxembourg were they can be made available to any other authorized partner.

3.2.2.1.6. ***Tilt measurements and interpretation***

The tilt measurements continuity is affected by the political context and the field security. Dismounting for security concern has caused the main data gap (see Table below). In other circumstances, smaller gaps in data recording occurred because of technical problems like the theft of power supply (batteries, cables and/or solar panels), difficulties encountered in the GVO management (e.g. unavailability of the car for maintenance, unpaid salaries, etc.).

Note: in some cases data might be marked as "acquired" in the Table here below though they can be partly or totally useless e.g. when one of the instrument's components drifted out of range, or when the power supply was too low (due to ageing batteries) leading to unreliable data.

Start Date	Stop Date	Nr of recordings days	Cumulated Gap Durations (days)	Reason of gaps
BULENGO STATION				
Mar. 29 2007	Aug. 30 2007	147	7	Diverse
Aug. 30 2007	Mar. 13 2008	0	196	Dismantled for security reason
March 13 2008	Feb. 4 2010	648	45	Diverse
RUSAYO STATION				
Jul. 19 2007	Nov. 8 2008	448	30	Diverse
Nov. 8 2008	Feb. 24 2009	0	108	Dismantled for security reason
Feb. 24 2009	Mar. 19 2010	328	60	Diverse
NGANGI STATION				
Mar. 28 2007	Oct. 11 2007	197	0	OK
Oct. 11 2007	Mar. 11 2008	0	152	Dismantled for security reason
Mar. 11 2008	Mar. 17 2010	722	14	Diverse
MUNIGI STATION				
Mar. 29 2007	Oct. 11 2007	196	0	OK
Oct. 11 2007	Mar. 13 2008	0	154	Dismantled for security reason

Mar. 13 2008	May 5 2009	386	32	Diverse
May 5 2009	Jun. 19 2009	0	45	
Jun. 19 2009	Mar. 17 2010	269	2	Diverse

- Long-term measurements:

Unfortunately, because of the numerous gaps, the long-term interpretation is not possible. Many gaps are indeed immediately preceded or followed by drifts due to manual drift corrections and/or new zero position after reinstallation and/or power supply stabilization. Data from both sides of these gaps can hence not be linked. However, for the sake of the figures, artificial offset were applied. These steps added manually may however dramatically change the significance of the plots (***Figure 14***). They are hence only to be considered for quality evaluation purpose.

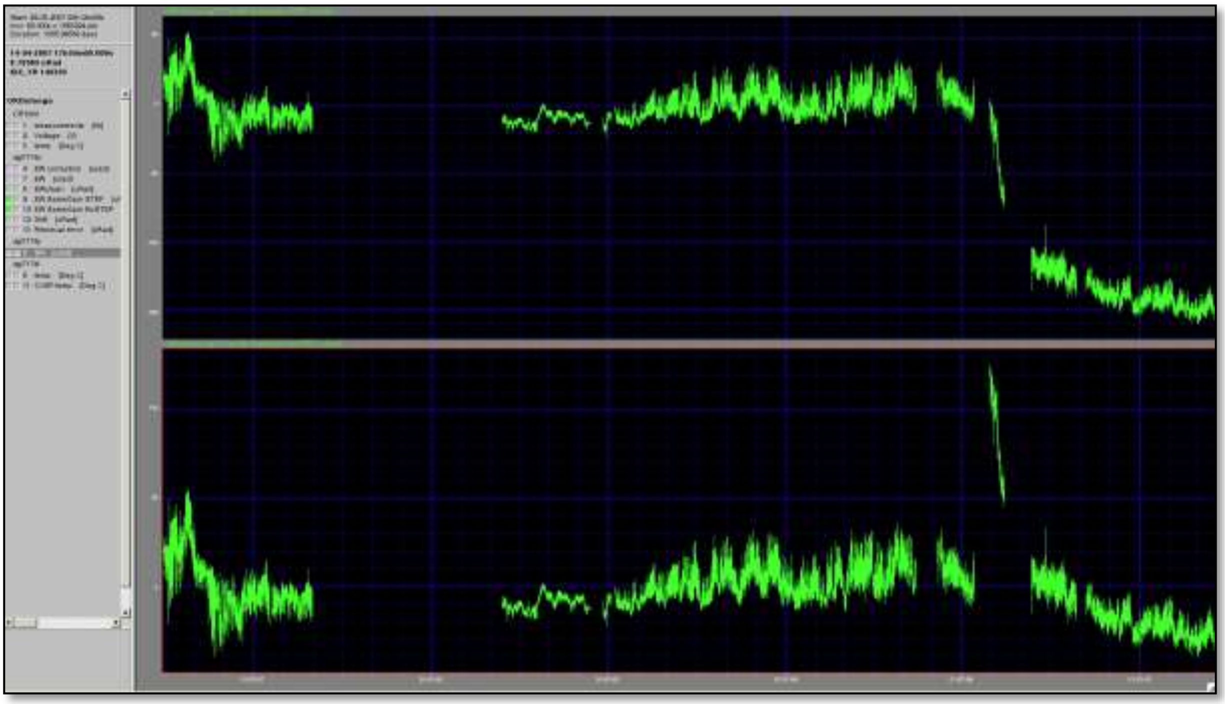


Figure 14: EW tilt at Bulengo station from 2007 to 2010: example of two equally plausible scenario: manual offsets were added before and after long gaps due to dying power supply. We have no reason to favour one or the other scenario or even other ones.

The figures here after show the whole database for NS and EW Temperature and Power Supply respectively (***Figure 15***, ***Figure 16***, ***Figure 17***, ***Figure 18***).

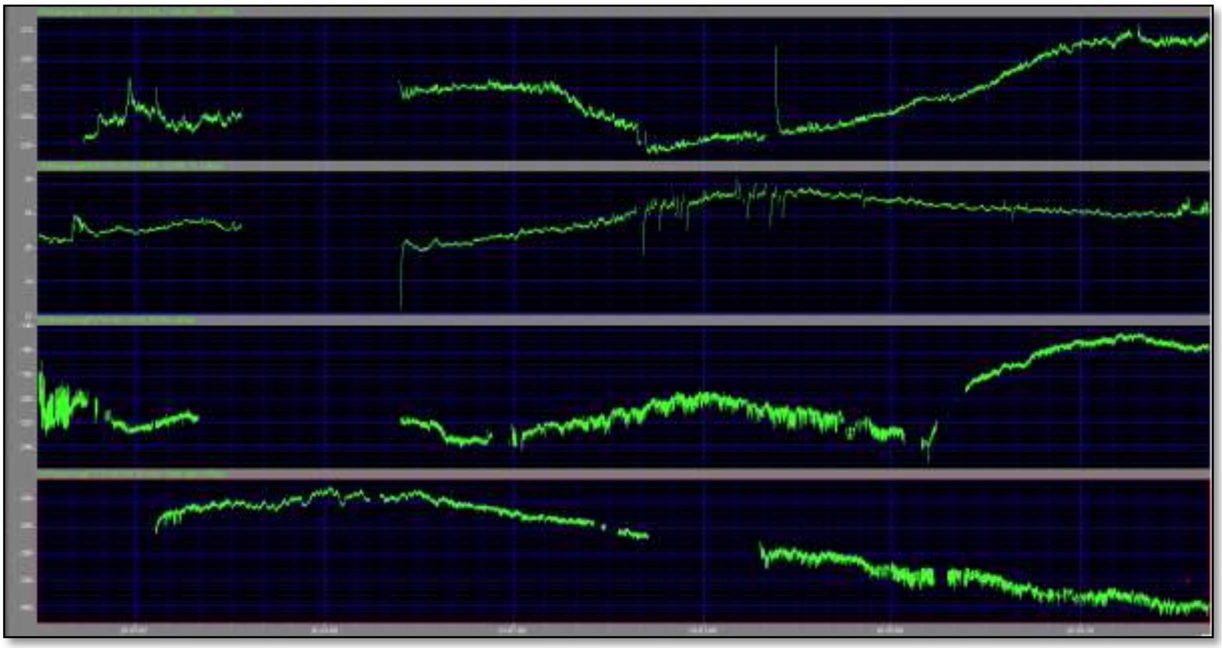


Figure 15: From top to bottom: NS tilt measured at Ngangi, Munigi, Bulengo and Rusayo (from installation in 2007 up to February 2010). Vertical axis spans respectively 12, 8, 120 and 270 microradians. Attention, manual offsets have been applied to data after gaps for the sake of clarity. This however may introduce significant errors on the long- and short-term interpretation. The plot is for visual assessment of the data quality only.

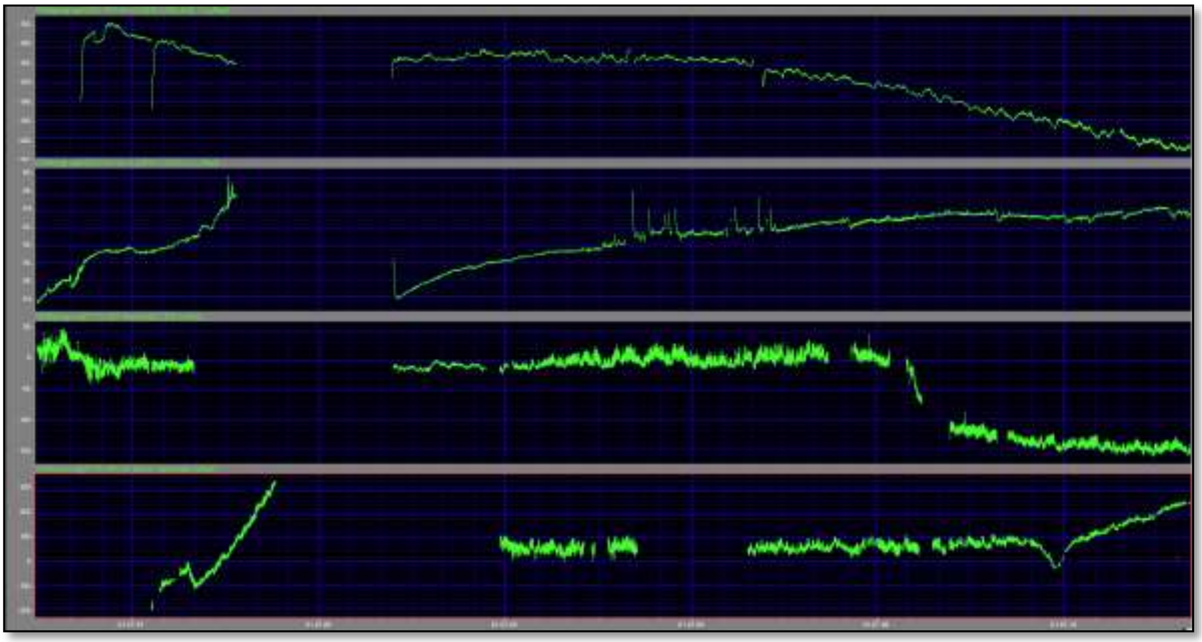


Figure 16: From top to bottom: EW tilt measured at Ngangi, Munigi, Bulengo and Rusayo (from installation in 2007 up to February 2010). Vertical scale spans respectively 15, 17, 240 and 600 microradians. Attention, manual offsets have been applied to data after gaps for the sake of clarity. This however may introduce significant errors on the long- and short-term interpretation. The plot is for visual assessment of the data quality only.

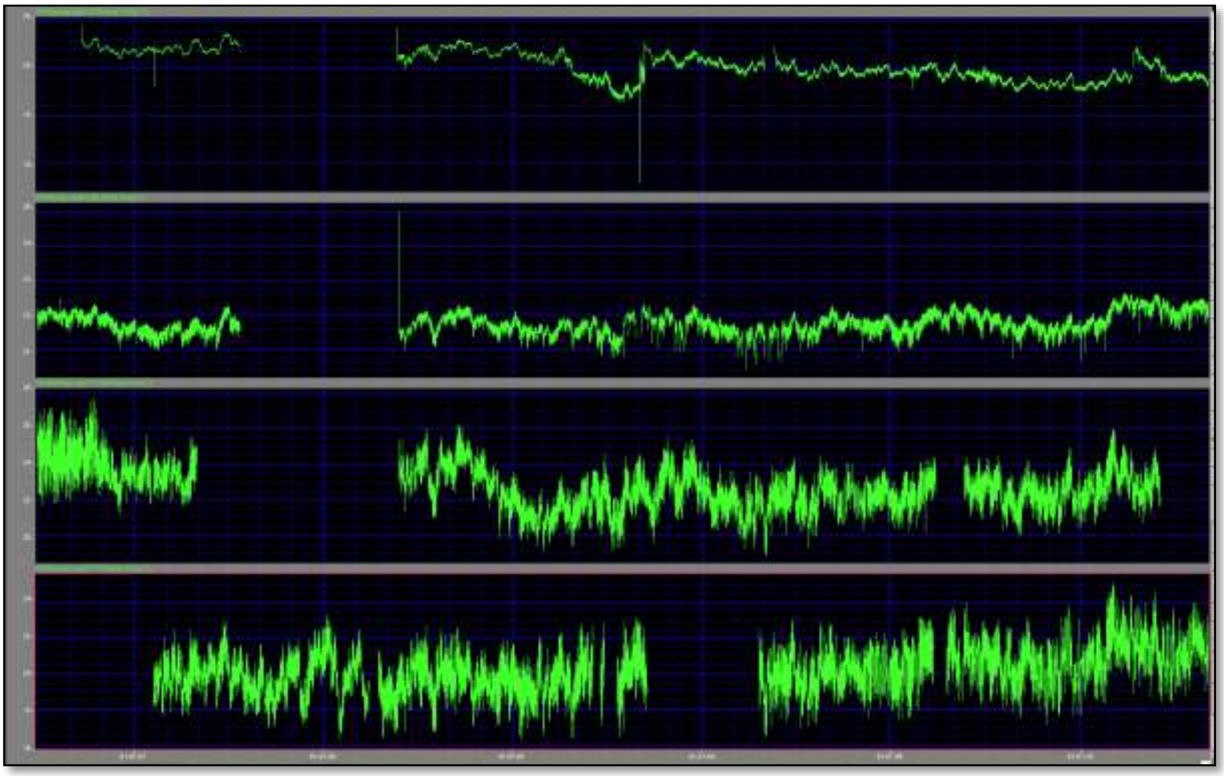


Figure 17: From top to bottom: Temperature of the tiltmeter measured at Ngangi, Munigi, Bulengo and Rusayo (from installation in 2007 up to February 2010). Vertical scale ranges respectively 7-25, 20-25, 19-28 and 16-25 degrees.

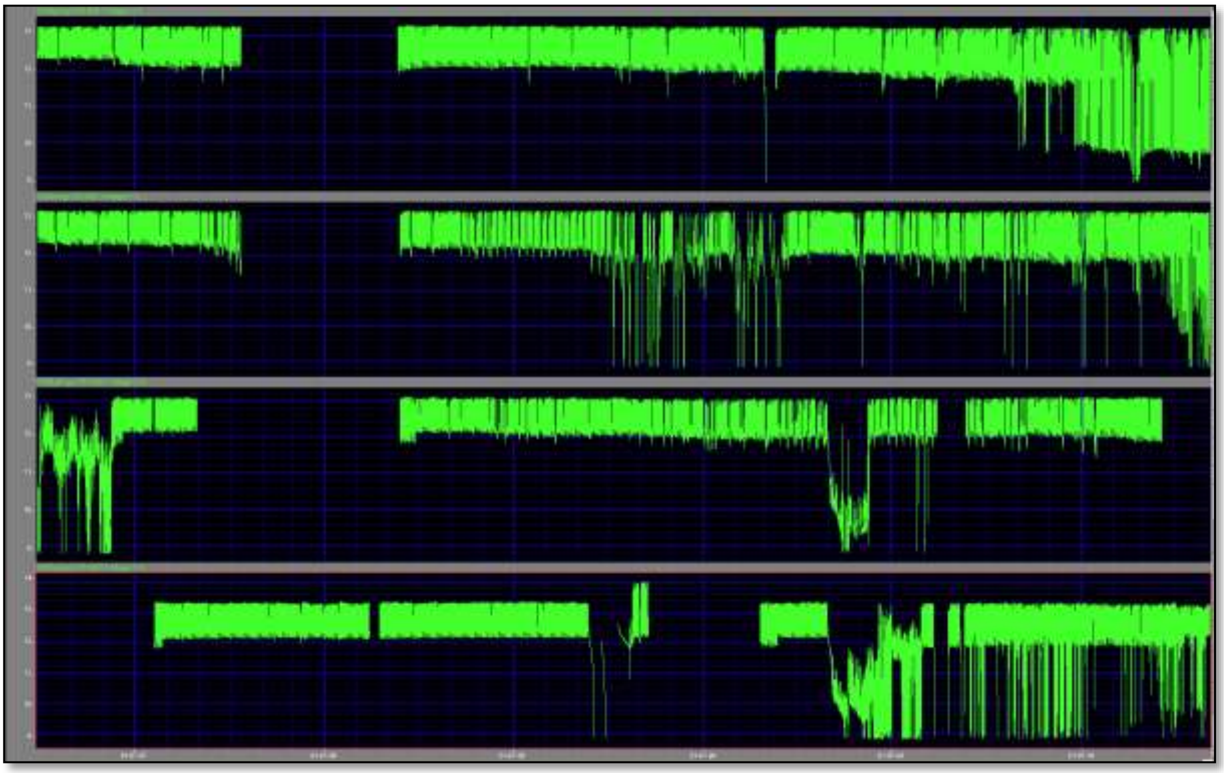


Figure 18: From top to bottom: Power supply voltage of the tilt station measured at Ngangi, Munigi, Bulengo and Rusayo (from installation in 2007 up to February 2010). Vertical scale ranges about 8-14 Volts. One can clearly see the spikes and values below 12 volts during which measurements are usually not reliable.

- Short-term measurements:

As expected, the normal daily tilt variations are visible on each component at each station. These are due for instance to thermal and air pressure direct and indirect effects, earth tides and lake tides loading effects etc…

The daily variations of the temperature and the power supply charging/discharging cycles (***Figure 19***) allow discriminating the tilt signals associated to stormy conditions from those related to insufficient power supply.

The power supply monitoring allows detecting the ageing of the batteries before the power supply actually breaks, or checking whether the solar panels are correctly exposed every morning by the sentinels.

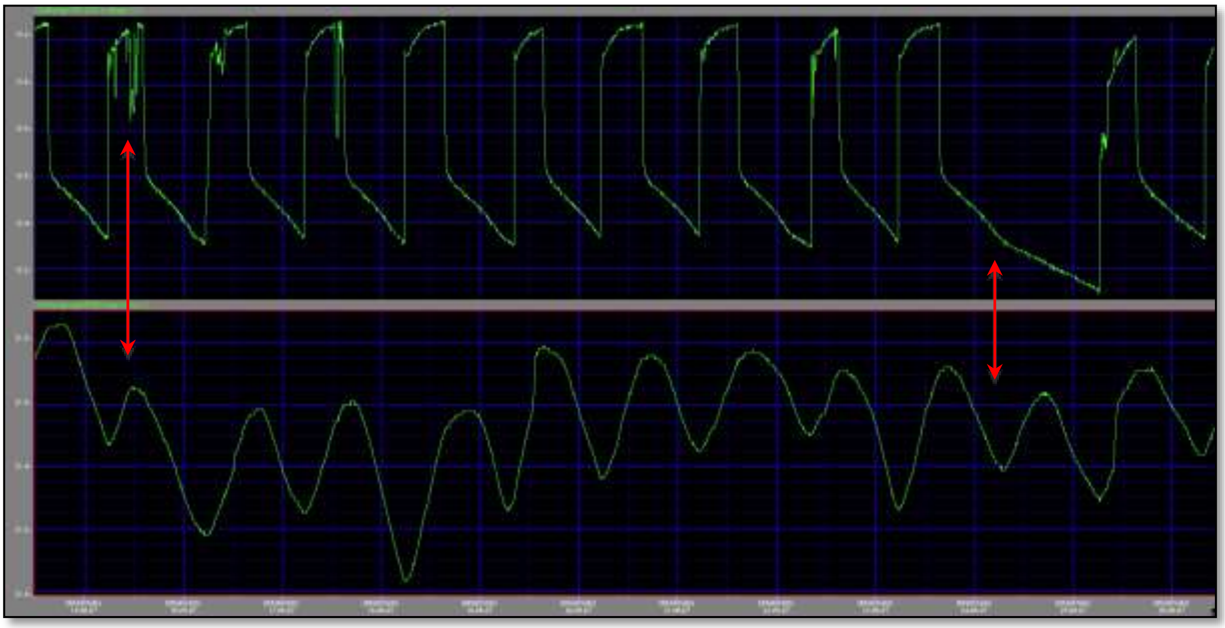


Figure 19: Example of a 12 days-long record of power supply (top) and temperature (bottom) at Munigi station. The normal charging cycle during the day increase the power supply from 13 to 13.3 Volts while during the night the voltage fell progressively from 12.6 to 12.3. Stormy conditions can be identified during the first charging cycle (red arrow to the left) and can be correlated to a drop of the average temperature of 0.3 degrees. The smaller red arrow to the right pinpoints a missing charging cycle, which is a day during which the sentinel did not exposed the solar panel.

As exampled in Figure 20, the impact of the daily tilt variations by artificially enlarging their amplitude will probably also affect most the mean value, rending impossible both the long- and short-term interpretation.

- Commitment of the GVO staff:

The GVO staff was trained for the site selection, installation and maintenance of the instruments. They are also trained to the pre-processing of the data (i.e. conversion from the raw format imposed by the datalogger to the special TSoft format which is a data processing software freely available from the Royal Observatory of Belgium: ***http://seismologie.oma.be/TSOFT/tsoft.html***).

The staff is also trained for the basics of data processing and interpretation.

Tilt signals associated to the Nyamulagira January 2010 eruption will be presented in section 3.9.

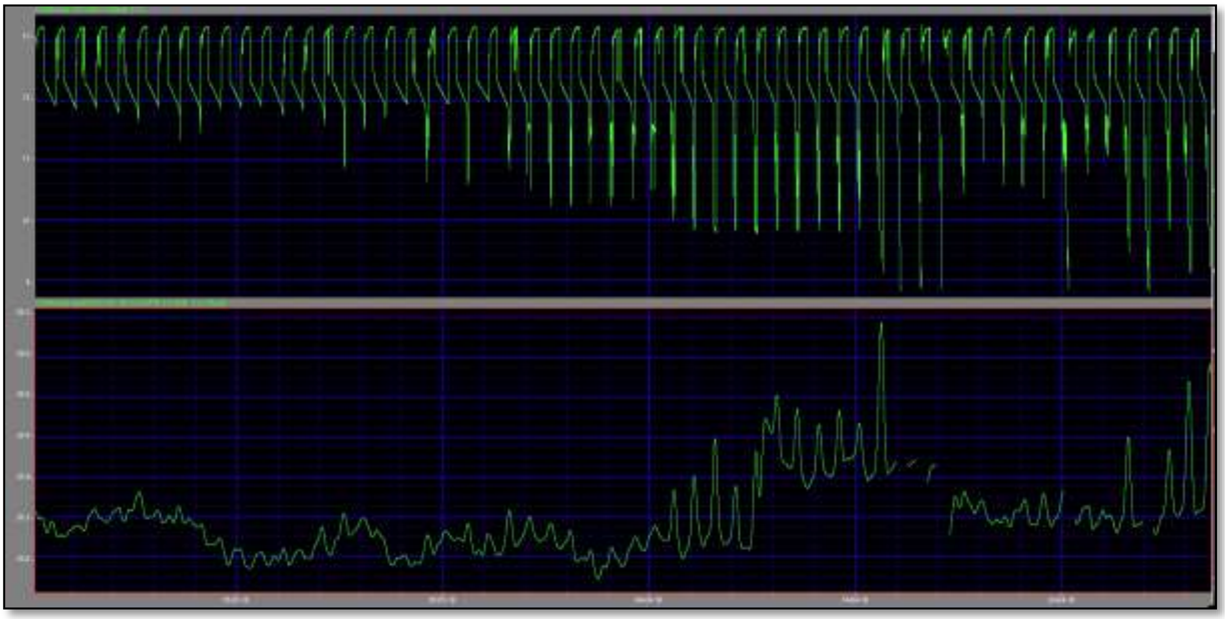


Figure 20: Example of a 57 days-long record of power supply (top) and NS tilt (bottom) at Munigi station. The normal charging cycle during the first third of the figure will progressively degrade as the battery is dying. The power supply will decrease as low as 9 volts during the night.

3.2.2.2. GPS

In addition to the GORISK tiltmeters network, NMNH sponsored the acquisition and installation of 7 permanent geodetic GPS instruments.
They have been installed resp. in (see map on Figure 12):

- Kibati: co-located with seismic station
- Kibumba: co-located with seismic station
- Rusayo: co-located with seismic station
- Bulengo: co-located with seismic station GVO
- Tshubi: new station exclusive GPS
- Mount Goma: new station exclusive GPS.
- Rubavu (Rwanda): new station exclusive GPS.

The GPS monuments have been built as much as possible according the IGS recommendations: typically, a concrete structure with a 2 meters high pillar build on a 1m^3 base block anchored with rebars sealed in the bedrock (Figure 21 and Figure 22). The site selection and network configuration must take into account the bedrock conditions, the localization with respect to the expected ground motions (constant rift opening, seismic and/or volcanic induced ground movements, possible slope creeping etc…), the data transmission requirements (the 800 Mhz radios used requires line of sight installations, Figure 24), the security etc. Proper grounding and lightning strike protection was mandatory.

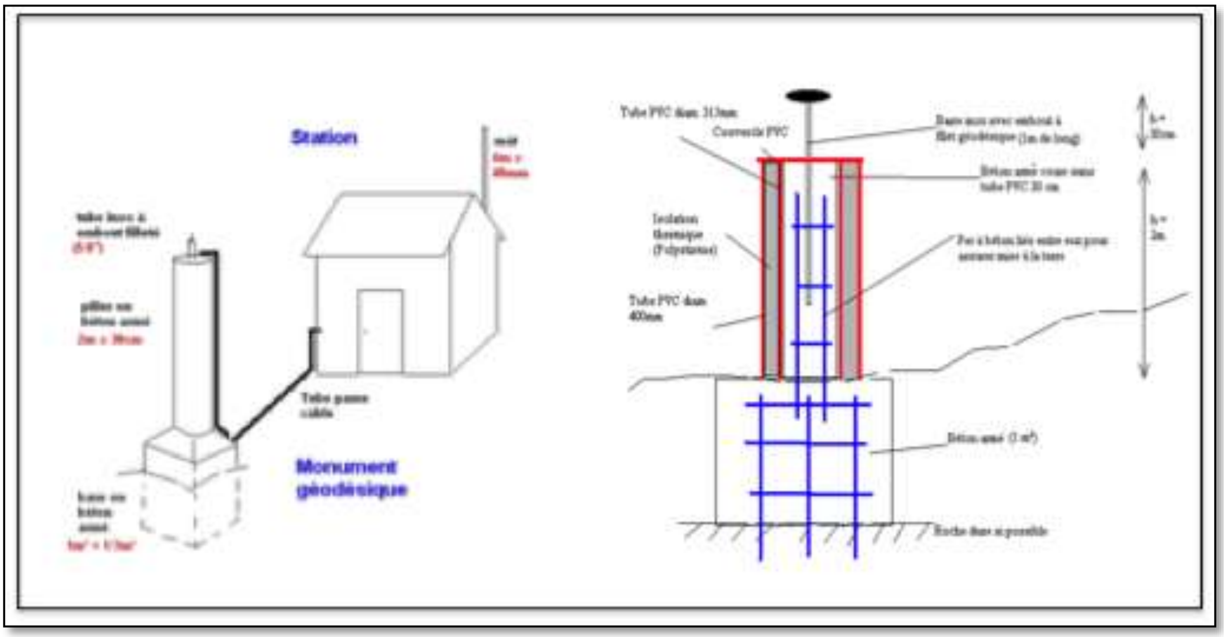


Figure 21: GPS site norms and methodology adopted for the setup of the GPS network. The monument building and installation procedure follows as much as possible the recommendation of IGS.

The site selection is usually based on the following steps:

- Selection of the area of interest based on geological criteria
- Radio visibility check on DEM
- Site investigation in the field and GPS visibility check (mask)
- Administrative concerns (negotiations with the land owner, military zone, etc.)

Figure 22: Anchoring the monument to the base rock at Rusayo station (left) and building of the concrete base (right).

Figure 23: Illustration of GPS monuments build for the Goma volcanoes network. GPS Monument in Tshubi (left) and Rubavu (right)

Figure 24: Setup of the communication system in Rusayo (left) and Kibati (right).

Figure 25: Servers at GVO: master radios are visible on the high table to the left of the computers used for data acquisition and ftp servers. UPS and the power rectifier/inverter are below the table.

3.2.2.2.1. *Equipment and configuration*

GPS receivers are Leica GMX 902 GG and AX1202 Antennas able to track GPS and GLONASS satellites. Signals are radioed in real time to GVO (Figure 25) using Intuicom 800 MHz radios either in a direct link or via radio repeaters. The network is divided in two branches, which collects data from the station located to the North or to the West of GVO.

The two masters radios are connected to a Macintosh "MacMini" computer via an USB-to-multi-serial converter (Figure 26). Macintosh computers were chosen because their operating system is Linux based and are much stable, more flexible for configuration, automation and scripting, and are less vulnerable to viruses. Viruses are a real concern for all the computers in GVO and spread very quickly through the Internet but also via USB keys or home made burned DVD's.

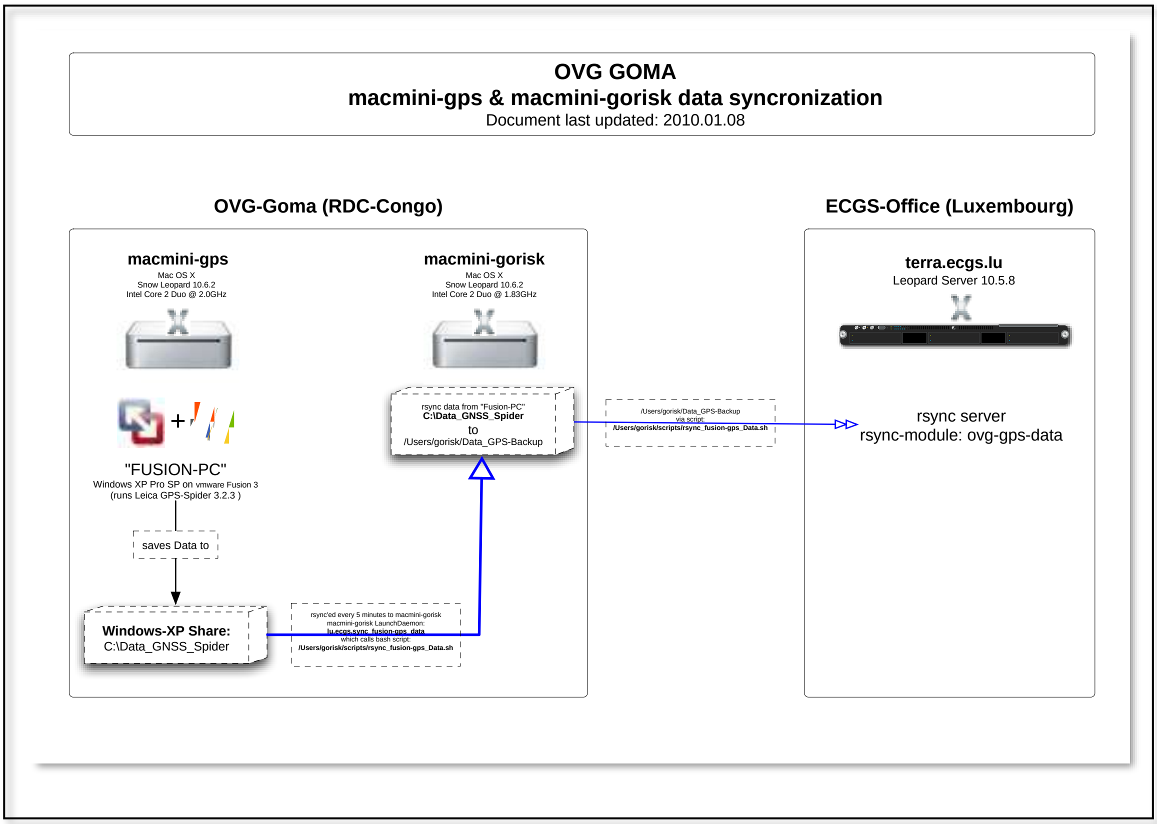
However, the Leica Spider software dedicated for the GPS network management and the data archiving is only developed for Windows. For that reason a Windows XP Pro session is running in a Fusion Virtual Machine© hosted in the MacMini.

A software called NavLink© allows attributing an internal port number to each radio of the network. These ports are wired to Spider, which could hence record the data in real time. Spider also computes the variations of the baselines between each station in real time. It archives theses values in dedicated files and broadcasts them to more internal ports. A software called GNSSQC can be used to monitor and plot these baselines in real time.

A second MacMini computer is used as an archiving and data-sharing server. It is connected to the MacMini hosting Spider through a protected local network and connected to the Internet through an independent network.

A large set of automated procedures archives the data on both computers, deletes obsolete files to avoid disks overflow, transmits the data by Internet to Luxembourg, checks the power supply and sends alarms by e-mail in case of failure etc…

Since there is no possibility to have a physical IP address (and dynamic DNS services are not possible because of the local provider and the satellite links), there was no possibility to manage the computers remotely. To overcome some of these limitations, a set of AppleScripts©, Automators© scripts and shell scripts were set up to be activated by specific e-mails sent to a given address. This allows us for instance to restart the MacMini at GVO from abroad, to send screenshots of the GVO server by e-mail, to get the list of running processes or to execute almost any kind of complex Unix commands lines.



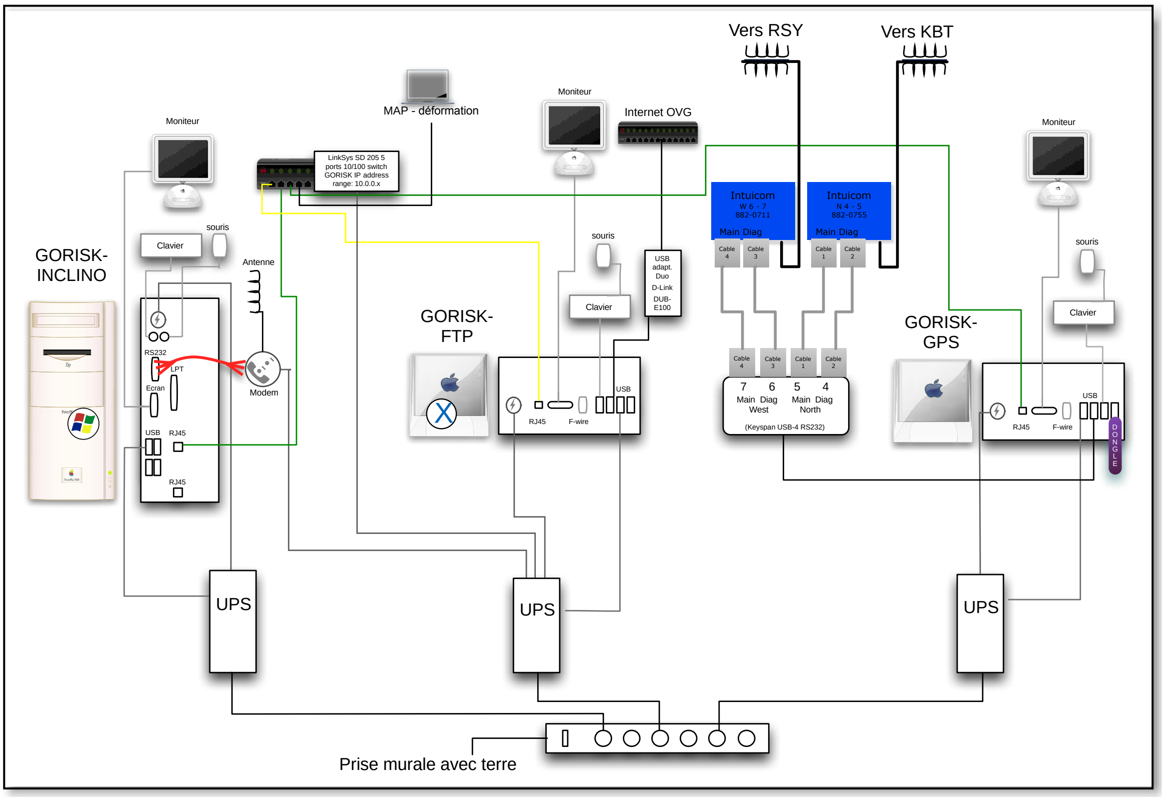


Figure 26: Concept sketch of the GPS acquisition / archiving / transmission system. The data are received from the instruments onto the "macmini-gps" which transfer data on the "macmini-gorisk". As illustrated on the below sketch, "macmini-gorisk" serves as a hub to deliver both GPS and tilt data (from "gorisk-inclino" computer) via FTP to Luxembourg (NMNH).

3.2.2.2.2. *Data transmission*

There is no data logger at the GPS stations and data must be transmitted by radio in real time to be archived directly at GVO. As a consequence any perturbation in the radio transmission or interruption of the computer at GVO means a loss of data.

3.2.2.2.3. *Archiving and processing procedures*

The transmitted data are stored on the server at the GVO and automatically sent daily at NMNH through Internet. Backups are also weekly burned on DVDs.

A preliminary estimation of the baseline vectors is visualized at GVO by the staff either in real time using GNSSQC, or thanks to baseline files converted automatically in the same TSoft format as the one used for the tilt data (Figure 27). This allows the GVO staff to process preliminary tests. The refined dedicated GPS processing is so far performed in collaboration with other partners (University of Madrid) and will be soon implemented at NMNH.

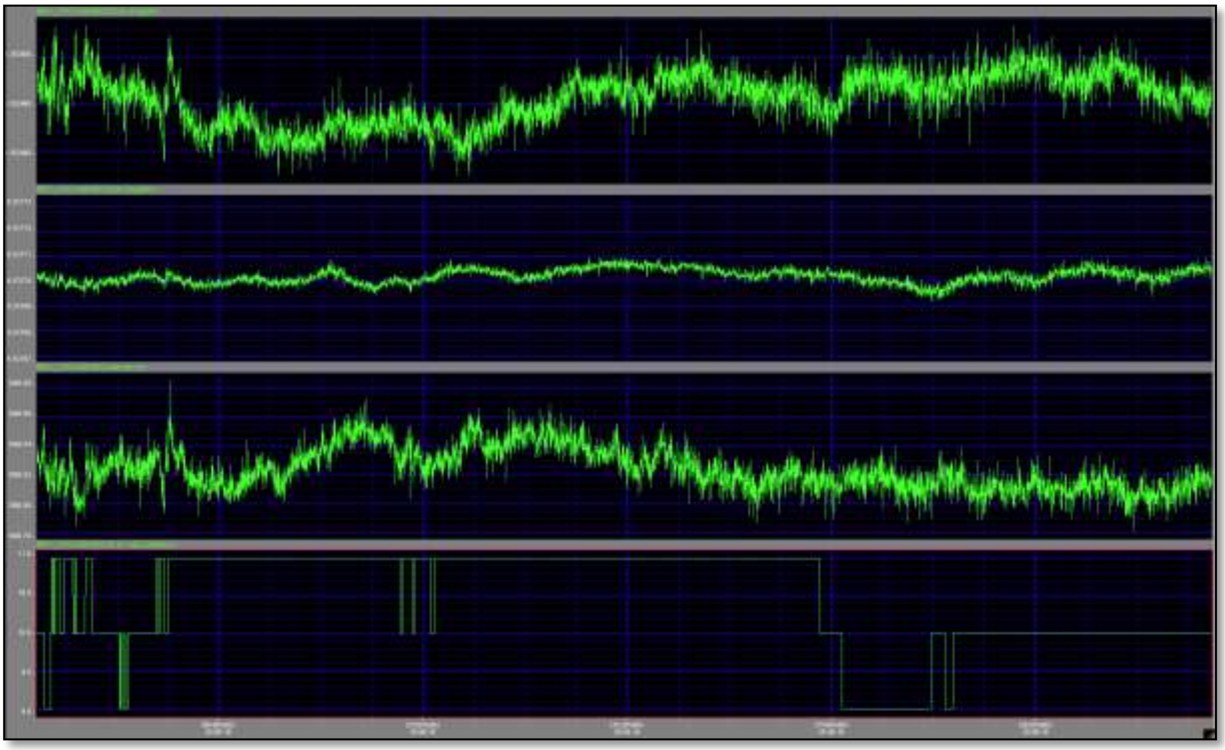


Figure 27: Example of Rubavu-GVO baseline replayed in TSoft format: From top to bottom: Latitude, Longitude, Altitude and nr of satellites. The figure spans 6 hours on September 2010. Sampling rate is 1 data/sec. Note that when reception or transmission quality decreases spikes and drifts may appear in the plots. This only affects the fast estimate of the baselines and not the refined post-processing.

3.2.2.2.4. *GPS measurements and interpretation*

The Goma GPS network was completed in September 2010 with the installation of the station in Rubavu in Rwanda. However, the other stations were usually operational since mid 2009, and the deformation signal associated to the January 2010 eruption has been observed after processing with using a distant reference IGS station located in Kigali (see section 3.9).

3.2.2.3. Synergy between GORISK ground deformation measurements and extensometry

The processing of tilt and InSAR data with regard to extensometric data collected by GVO in locations along the 2002 eruptive fracture was initially foreseen. However, no extensometric data were made available to the GORISK team. But following discussions with the staff, suggested deformation measurements were found not relevant (e.g. lower resolution) for being compared to GORISK measurements.

3.2.2.4. Problems encountered and solutions

The main problems encountered by ground based measurements of ground deformations have been caused by measurement discontinuities.
Three types of discontinuities must be reported:

3.2.2.4.1. ***Discontinuity for security reasons:***

- In November 2008, with the degradation of the political situation, the conditions in the vicinity of Goma were such that dismounting of too exposed equipment was decided. In the station of Kibati however, the GVO staff was unable to access the site in time and the equipment was looted (GPS, transmission and power supply equipment).
  The war context that prevailed for some weeks to months also implied that the staff had other priorities: protection of their family, search for survival means for an unknown duration, etc.

  Other stations were also looted during less tense - though still unsecure - periods. At these occasions however, only power supplies were usually stolen (e.g. in Kibumba, Mount Goma…).

  <u>Solution:</u>
  There is of course not much solution to tackle the problem of civil war or political instability, but it is essential that the partners remain in close and constant contact with the end user in the field in order to appreciate the situation and help in anticipating possible required actions like dismounting the equipments.
  An appropriate site selection that also takes into account the security concerns is crucial and can save from uncomfortable situations.

3.2.2.4.2. ***Discontinuity for technical reasons:***

- When GORISK brought the tiltmeters network back to life and extended it, we observed that two old tiltmeters were defectives as well as their acquisition system. These were partly repaired or replaced.
- Many discontinuities also occurred due to normal ageing of some parts that could not be replaced on time (see discontinuities for management reasons).
- Other discontinuities occurred as commonly encountered with any kind of instruments deployed on the field. For example, antenna cables were destroyed by rodents in Kibati despite the protective tubing.

- Some interruptions, or more exactly delays in operation, were caused by inappropriate hardware provided by manufacturers (such as 2.4 GHz radios used during the first GPS network deployment and unable to operate because of the sparse vegetation blocking the signal transmission)
- Some connectors were corroded because of the acid rains such as in Rusayo, and some other were discovered miss functioning when taken out of the box at the time of the installation.
- Interruptions in GPS records were also caused by a crash of all the receivers after a modification by the Russian space agency of some frequencies of their GLONASS satellites. This required upgrading the firmware of each GPS receivers.
- Interruptions of GPS data were also caused by computers crashes when the power ran out at GVO for longer time than what UPS can hold. This caused direct loss of data, but also caused a more critical failure after some time while these improper shutdowns do not allow Windows to close and clean the many temporary files its creates resulting in an overflow of the disk that could not easily be repaired since the files are invisibles.

  Solution:
  Intervention of the GORISK partners was often necessary to help solving such problems. External expertise remains necessary to help in the diagnostic and to provide the assistance e.g. for re-configuration of the equipment.

- Problem associated with lightning:
  The region records one of the highest rates of lightning strike per km^2 per year. In Kibati for instance, lightning had destroyed a GPS receiver and its transmission system, whereas at GVO it was responsible for the destruction of two servers, one radio and one USB-to-4 serials converter. Another GPS receiver was also damaged for an unknown reason during tests performed at GVO prior a reinstallation.

  Solution:
  The damaged equipment had been replaced or repaired and lightning protections were reinforced. However, the static discharge of a lightning can indirectly affects electronic devices by induction and no reasonable solution exists.

- Problem associated with inappropriate actions:
  Some data were lost after an incorrect memory card swap (the card was not properly replaced in its slot after a manual download of the gas measurement stations in "Le Chalet" unfortunately just before the January 2010 eruption), or a cable plugged in the wrong connector (as for the GPS Rusayo station after January 2010), or a cable unplugged for an unidentified reason (as for Bulengo in November 2010).

  Solution:
  The training is repeated (and improved) at each mission of the European partners in Goma. Users manuals and checklists are

constantly updated and improved. However, it will never be possible to foreseen all possible situations that could be encountered and the overall network quality will always relies on the rigorousness of the operators and the ability of the local staff.

3.2.2.4.3. ***Discontinuities for management reasons:***

Occasional dismantlings dictated by the insecurity were necessary. This had drastic consequences on the project. However, the good will of the staff directly involved as well as the absence of any other support to the volcano monitoring dictated us to find solutions to these problems. Few examples are:

- The theft of a SIM card exclusively dedicated to data transfer lead to unpaid bills of more than 3.000USD and subsequent service interruption by the provider.

  Solution:

  After a first reimbursement by one of the partners the service was partially reactivated but after further complications as explained in section 3.2.2.1.4 here above, we were forced to suspend the GSM transmission and organize manual downloads at each station. The GSM transmission however can be resumed at any time upon decision of the GVO management and providing – if the telephone provider do not support the "voice-data" mode – a possible change of modem.

- Management failures also concerned unpaid bills and due salaries to sentinel in charge of the station security with the consequences that the security was no longer guaranteed (before July 2009).
- There were also recurrent problems with the power supply at GVO. While power cut-off are very common problems in Goma, the time before switching on the generator often exceeded the capacity of the batteries with the consequence a general reboot of the computers and related complications.

  Solution:

  Financial agreement between GVO and RMU/UGR allowed GVO paying the phone and Internet bills and also buying the fuel for the generator. Training and raising the staff awareness to the need of a faster reaction in case of power cut-off were achieved.
- The financial difficulties of the GVO are sometime such that staff salaries but also bills are not paid in due time, preventing for instance actions as simple as the replacement of batteries before their failure. For the Internet service, service interruptions were responsible for gap in data transmission to NMNH and interruption in communication with the staff. The frequent unavailability of the GVO vehicles has often limited the staff to access the station for regular and basic maintenance.

  Solution:

  At the beginning of 2008, an internal transfer (2500€) within the GORISK budget was made and secured the continuation of the activities. Since the end of 2008, an external support was obtained from the Ministry of Foreign Affairs of Luxemburg to help the functioning of GORISK in priority areas (see section 2.3).

Following the institutional changes that occurred upon ministry decisions, the situation turned much better and the new management is now drastically improved. From July 2009 and onwards, the problems were discussed with the head of GVO and solutions were found together.

3.3. GEOCHEMISTRY

3.3.1. Introduction

In GORISK, three main aspects of geochemistry have been addressed:

Geochemistry		
Ground based fixed	*Ground based mobile*	*Plume monitoring*

The « mobile » measurements are corresponding to the *in situ* measurements of gas (mazuku, see further), and analysis performed on water samples collected in the field.

The mobile measurements were initially dedicated to the monitoring of volcanic fallouts. But the preliminary test performed with passive filters within the plume on the crater rim by the UniNap partner (University or Naples II) were deceiving and have conducted to the conclusion that no valuable information could be obtained trough that channel.

It is for that reason that the focus has been set firstly on the study by the RMCA of the mazuku or depressions where CO_2 accumulates at very high concentration and that represent a significant risk for the population; and secondly, the sampling of water in areas generally covered by the plume. The sampling was performed by the CEMUBAC partner also interested in the water quality.

Remote sensing contribution to the monitoring of the volcanic plume dispersion has also been achieved trough external collaboration with VISOR – NSF project.

3.3.2. Ground based “mobile” geochemical measurements

3.3.2.1. Study of the Mazuku

Mazuku means evil wind in Swahili and corresponds to lowland (depressions) where carbon dioxide is released and, being heavier than the air, accumulates at high -often lethal- concentration (10% of CO_2 in the air can be considered as the deadly threshold for a short time exposure). Mazuku are abundant in Goma and surrounding areas and are currently the most important natural risk in terms of human loss for the area. There is an urgent need for more systematic mapping, study, and monitoring of mazuku. An appropriate risk management also needs to be implemented (Smets et al., 2010a). In the framework of a Master Thesis in Natural Hazards Management at University of Liège (Belgium) and the GORISK project (Smets, 2007; van Overbeke et al., 2010), mazuku were studied systematically for the first time. All known mazuku along the Lake Kivu shoreline were mapped using

GPS. The morphology of each mazuku was described in detail and three campaigns of systematic gas measurement were performed. This first approach allowed us to distinguish some preferential areas where gas escapes from the ground and accumulates by gravity in the depressions. A preliminary risk assessment was also proposed, as a basis for first mitigation actions.

3.3.2.1.1. *Identification of mazuku*

Despite a wide variety in shape (round, elongated …) and area (from 10m² to 1ha in the surveyed area), typical features characterize the mazuku:

- Some plant species prefer high CO_2 concentration and natural CO_2 springs often lead to a distinct vegetation zonation. The presence of papyrus, light green grass, and sometimes kaki moss is typical. However, where gas concentration is too high, vegetation cannot develop; in such locations, only bare and weathered rock is observed.
- Weathered lava surfaces where gas accumulates is also a typical features.
- The presence of dead animals (insects, mammals, birds,…) is a reliable indicator for the mazuku.
- High CO_2 concentrations cause a warm feeling near the ground surface that is related to a reaction of the skin.

The depressions where gas is accumulating are often located at the foot of lava flows and are created for instance by the collapse of cavities roofs, by joint fractures, etc. It is not clear whether the gas flux is higher beneath or around the mazuku but it is likely that CO_2 follows preferential ways like faults, fissures, permeability variations and contacts between lava layers to reach the surface. Being heavier than air it accumulates in those depressions.

3.3.2.1.2. *Mapping of mazuku*

The systematic mapping of Mazuku has been undertaken in order to study their regional distribution and their potential link with volcanic and/or tectonic structures as well as with groundwater systems (Figure 28). The strong concentration of mazuku near the lakeshore suggests a potential link with the aquifer. Etiope (1997) advocate that such a continuous flux of CO_2 requires the presence of a buffer zone where the gas accumulates before it released upon saturation. The occurrence of mazuku North of Sake and North of Nyamulagira volcano might also be explained by the possible presence of an aquifer.

The systematic mapping is also important for land use planning as well as for risk management.

Geomorphological study was also performed on the IKONOS image acquired in the frame of the project. It allowed the detection of mazuku in the Bulengo area that have been confirmed by field observations (Figure 29). This detection based on the combination of visible and near infrared channels evidenced zoned vegetation and lava weathering. However, the technique has some limitations: small mazuku are difficult to detect whereas black patches that characterize the weathered rock surfaces is not unambiguous. A field validation remains necessary.

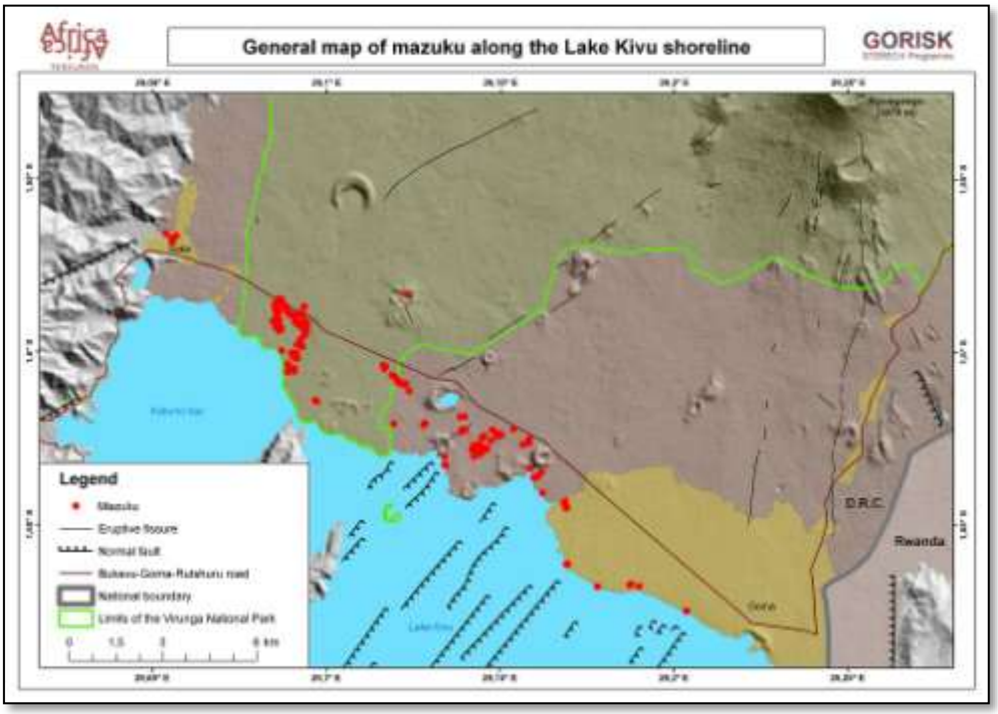


Figure 28: Location of mazuku along the northern border of Lake Kivu and schematic structural context. The volcanic fractures are derived from Thonnard et al. (1965) and field data of the Royal Museum for Central Africa. Sinuous and straight escarpments are based on Pouclet (1977), Ebinger (1989) and Wauthier et al. (2008). The shaded relief in the background is derived from the SRTM DEM.

Figure 29: Detection of mazuku in the Bulengo area using an Ikonos image. This image allowed detecting new mazuku, which were confirmed by fieldworks. However, this technique has some limitations. Small mazuku are difficult to detect and black patches can correspond to crops or private properties without vegetation. Left: several patches without vegetation correspond to large mazuku localized along the limit between two lava flows in the Virunga National Park (1 km N of Lake Kivu shoreline). Right: Bulengo (W of Goma). Red dots are the location of known mazuku. This image shows how it is

difficult to detect – especially small-size – mazuku in urban areas where land use is more complex.

3.3.2.1.3. *Hypothesis of formation & origin of the gas*

Mazuku were found to correspond to a convergence between two phenomena: 1/ the link between a CO_2 source and a network of fractures allowing the gas to reach the surface, and 2/ a depression where denser CO_2-rich gas can gravitationally accumulate.

According to Vaselli et al. (2002, 2003) and Tedesco et al. (2007), gas isotopic signatures (C and He ratios) in mazuku indicate a deep magmatic origin. Based on helium isotope ratios, all gas emissions are indeed unambiguously related to a deep-mantle source, with a R/Ra (Helium ratio) of about 8. The results obtained after analysis of recently collected gas samples are consistent with previous studies (Table 2). Those samples were collected along the strip area between Goma and Sake (Figure 30). For a detailed interpretation of those results, see Tedesco et al. (2010).

	R/R_a	$(R/R_{air})_c$	$d^{13}C$	$^{40}Ar/^{36}Ar$	He/Ne	^{4}He	^{36}Ar	CO_2	$^{40}Ar^*/^{4}He$	$CO_2/^3He$ (x 10^9)
Eastern and central zones of the Rift										
Bikumbo	6,64	7,46	nd	296	8,4	19		695,000		4
Bulengo Seminaire	7,22	8,27	-5,77	296	6,95	8		658,600		8,2
Bulengo Summit	5,79	7,12	nd	296	9,56	20		645,400		4
Chalet	4,22	6,45	-6,61	296	2,7	9		400,000		7,6
Esco	5,56	6,59	-6,55	296	5,45					
Himbi	5,81	6,51	-5,33	296	7,87	6		445,100		9,2
Kabutembo	6,47	6,64	-6,39	296	33,34	11		424,000		4,3
Kanyabihondo 1	5,49	6,81	-5,31	296	4,4	14		483,430		4,5
Kanyabihondo 2	5,55	7,48	nd	296	3,4	13		496,000		4,9
Kanyabishoho	6,04	7,3	-5,76	296	5,01	11		608,000		6,6
Katwa	6,28	7,66	-5,66	296	4,8	12		470,100		4,5
Koshokero	6,64	7,44	nd	296	6,5	14		532,000		4,1
Nzulu	6,89	7,38	-6,76	296	12,94	22		606,700		2,9
Rumoka crater	5,78	7,42	-6,34	296	3,9	9		463,200		6,4
Ruwasimvani	6,16	8,35	-5,29	296	3,4	20		590,230		3,4
Western zone of the Rift										
Sake Birere	6,38	6,93	-10,5	296	10,66	31		645,900		2,3
Sake Ecole	6,81	7,65	-11,7	295	7,9	21		637,100		3,2
Sake Gisimba	6,64	7,72	-10,2	295	6,2	32		590,110		2
Sake Spring	6,52	7,25	-11,6	295	8,6	28		402,000		1,6
Kabuno Bay (-140 m)	5,54	5,54	-10,3	350	550	11	0,122	964,300	0,61	11,4

Table 2: Isotopic values and gas concentrations of samples from surveyed mazuku. CO_2, ^{36}Ar and ^{4}He concentrations are in units of µmol/mol; nd = not detected. Table from Tedesco et al. (2010)

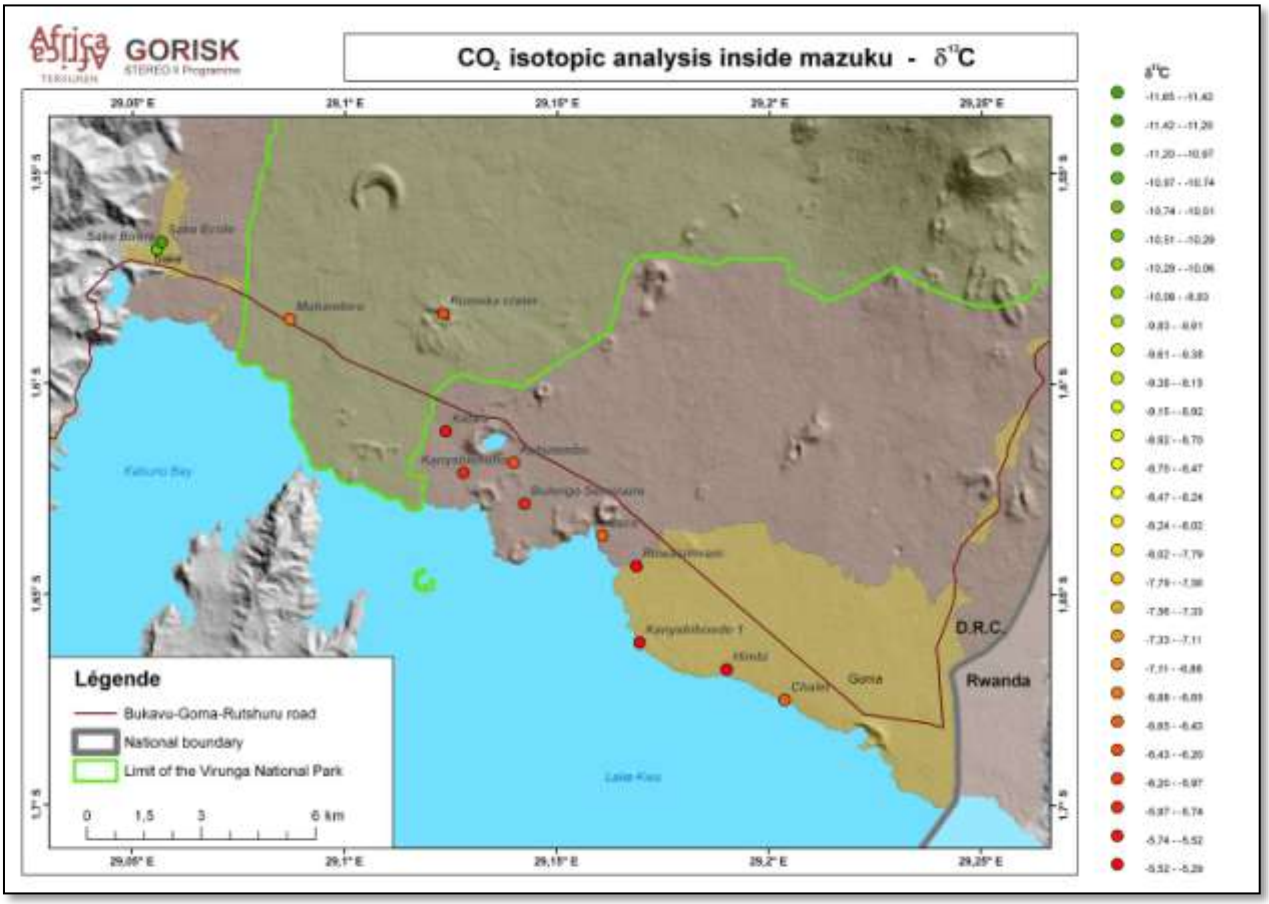


Figure 30: Map of mazuku sampled for gas analysis. The colour of each location depends on the $\delta^{13}C$ value of the corresponding mazuku.

3.3.2.1.4. *Preliminary hazard assessment – risk mitigation*

Hazard assessment and risk mitigation of mazuku are very important tasks given the population growth recorded in the area.

The mazuku are apparently stable in space and in time (over timescales of our measurements, description in archive, witnesses, etc.). However, the danger arises also from the fast variations in CO_2 concentration with meteorological parameters like wind, rain, and atmospheric pressure; it can catch anyone wandering inside the depression aware or not aware of the danger.

Important movements of IDP's (Internally Displaces Populations) - not aware about the mazuku hazards - and the rapidly increasing demographic growth and anarchic urban developments in the region are also greatly increasing vulnerability and risk. Two vulnerability surveys carried out in the Bulengo area (area where refugee camps were settled) by a Congolese NGO revealed the alarming news that at least 37 people were killed by mazuku in 2007 (Buhendwa, 2007). Informative and preventive campaigns were already carried out and signposts installed at main known mazuku sites but several additional efforts could be performed taking into account for example the recently settled populations and the newly urbanized areas. Preventive and curative low-cost solutions have already been suggested by Smets

(2007), as for example the basic modifications proposed for wood houses built on mazuku (Figure 31).

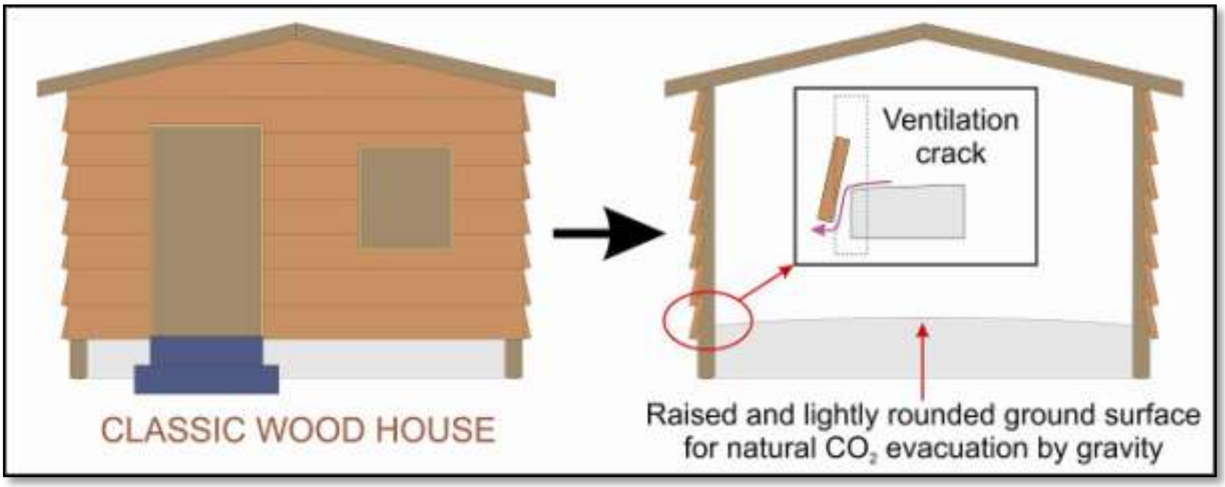


Figure 31: Example of a basic modification for wood houses built on mazuku. As CO_2 is heavier than air, a raised, if possible non-porous, and bulging ground with ventilation openings along the walls would drastically reduce the risk of lethal concentration inside the house (from Smets et al., in press).

Additional work is required to improve the quantitative hazard assessment. Hazards maps, deeper studies of the possible link between mazuku and volcano-tectonic activity, quantitative analysis of gas concentration variations with meteorological parameters, etc. are the priorities. These investigations have started under GORISK but a more appropriate framework is required to cover the whole aspects of such an investigation. The accessibility is another concern though much can be performed from relatively secured sites.

3.3.2.2. Water sampling and analyses

In collaboration with the CEMUBAC, a water sampling strategy has been setup by the UniNap partner to study both areas that are generally covered by the volcanic plume, and areas where the volcanic plume is rare (Figure 32).

It is indeed suggested that the volcanic plume can affect the water quality either by the contamination of surface water by the deposition of particles, or more directly by the contamination of meteoric water.

The task was very complicated because the average plume spreads West of Nyiragongo, over areas where intense tensions and fights were continuous all over the period of the project. Nevertheless, because the CEMUBAC is involved in the support to primary health care in that area, several sampling campaigns were possible. The recurrent sampling at different seasons at specific sites was not achievable.

3.3.2.2.1. *Results and interpretation*

All samples have been analysed at the Second University of Napoli, Department of Environmental Sciences (UniNap). The preliminary results are showing for most samples high Fluorine content, well above the WHO threshold (Figure 33). This (very) high amount of F in water may have serious consequences on human health and on the environment (plant growth delay).

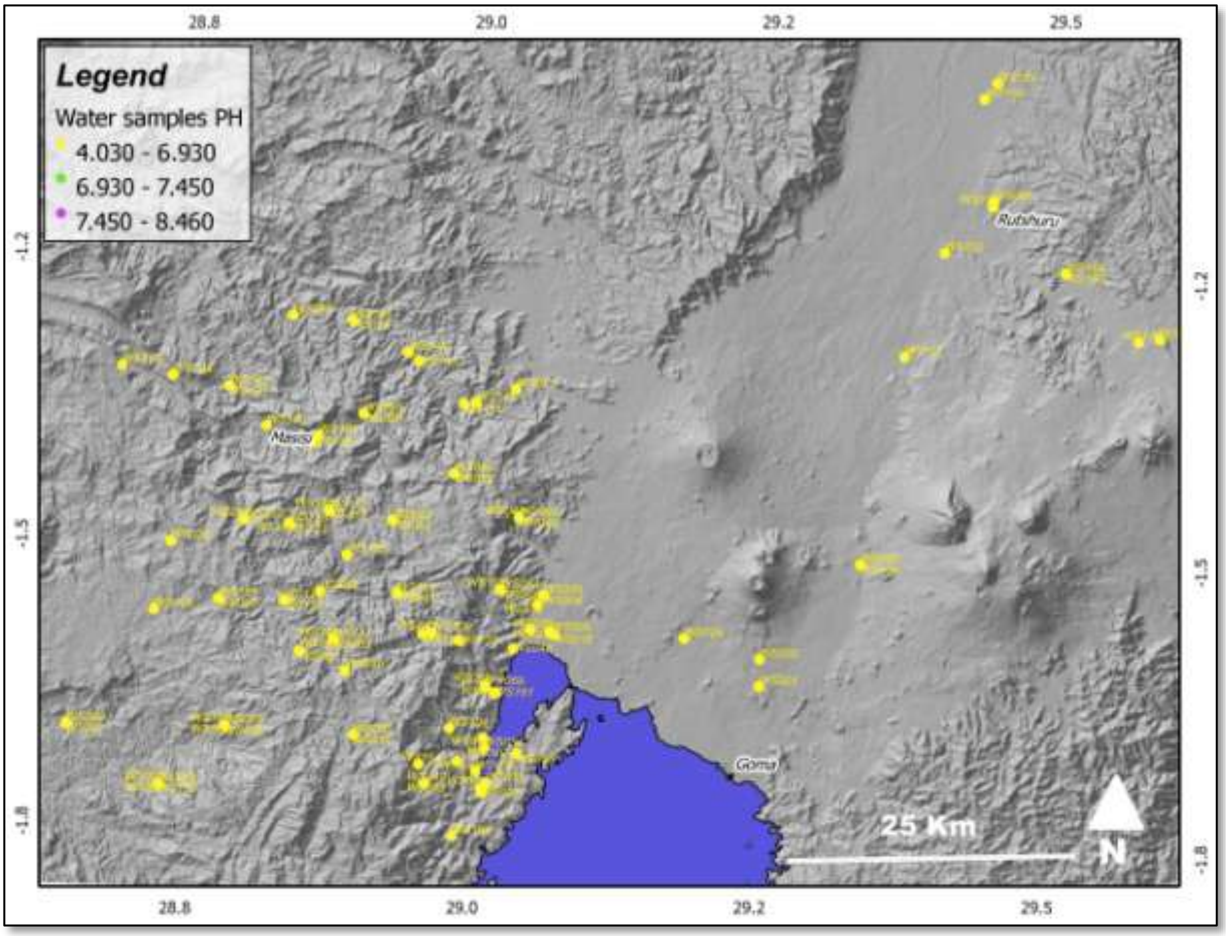


Figure 32: Distribution map of the water samples collected in the framework of the project by partners.

Excess in fluorine in drinking water is accompanied by a characteristic sequence of changes in teeth, bone and peri-articular tissues. These changes lead to a variable degree of locomotors disability, ranging from simple mechanical back pain to severe, crippling, combined locomotors and neurological impairment (McGill, 1995). In its severe form, dental fluorosis is characterized by black and brown stains, as well as cracking and pitting of the teeth. Although no quantitative data are available yet, dental fluorosis is common in the region of Sake (west of Goma) and represents of public health concern.

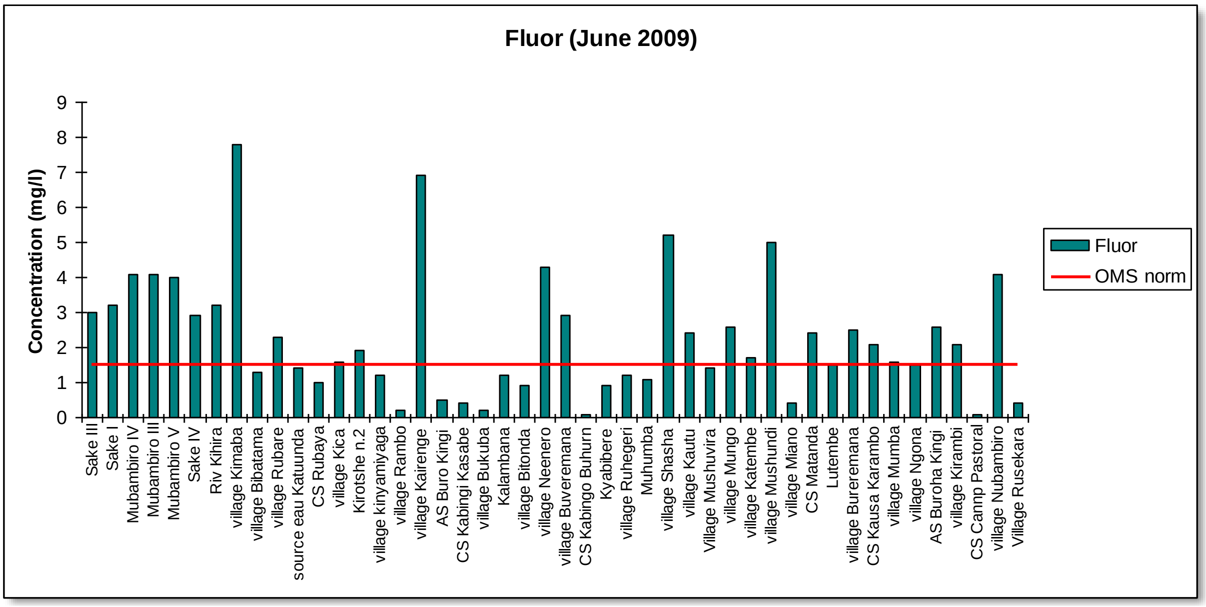


Figure 33: Concentrations of F for some of the surveyed sampling sites. The red line displays the WHO norms of drinkability.

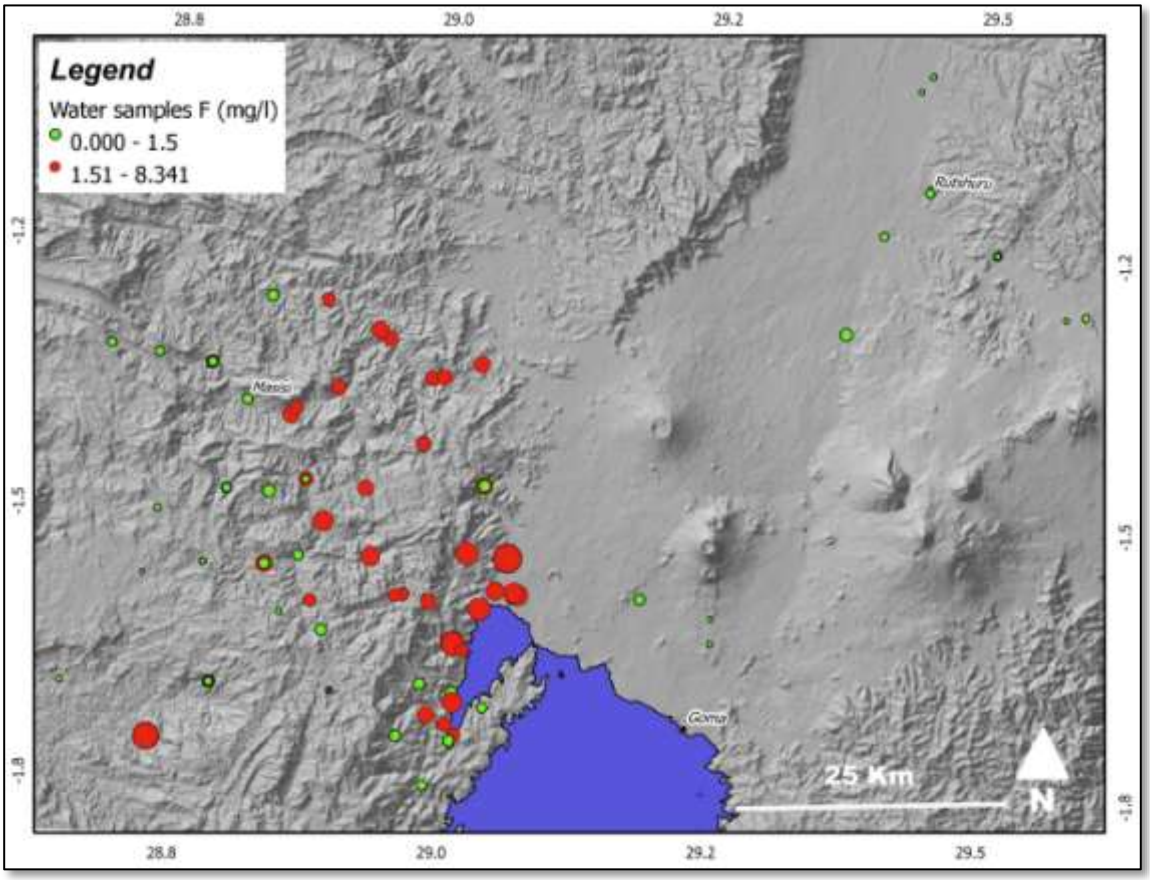


Figure 34: Distribution of the water sample with Fluorine content classified in green, below WHO threshold and red, above threshold. The symbol size depicts the F content.

Other elements are observed in abnormal quantities as exampled in the map of the Figure 35 where Chloride dispersion is displayed. Other chemical property like the PH is also studied with regards to the plume dispersion (Figure 36).

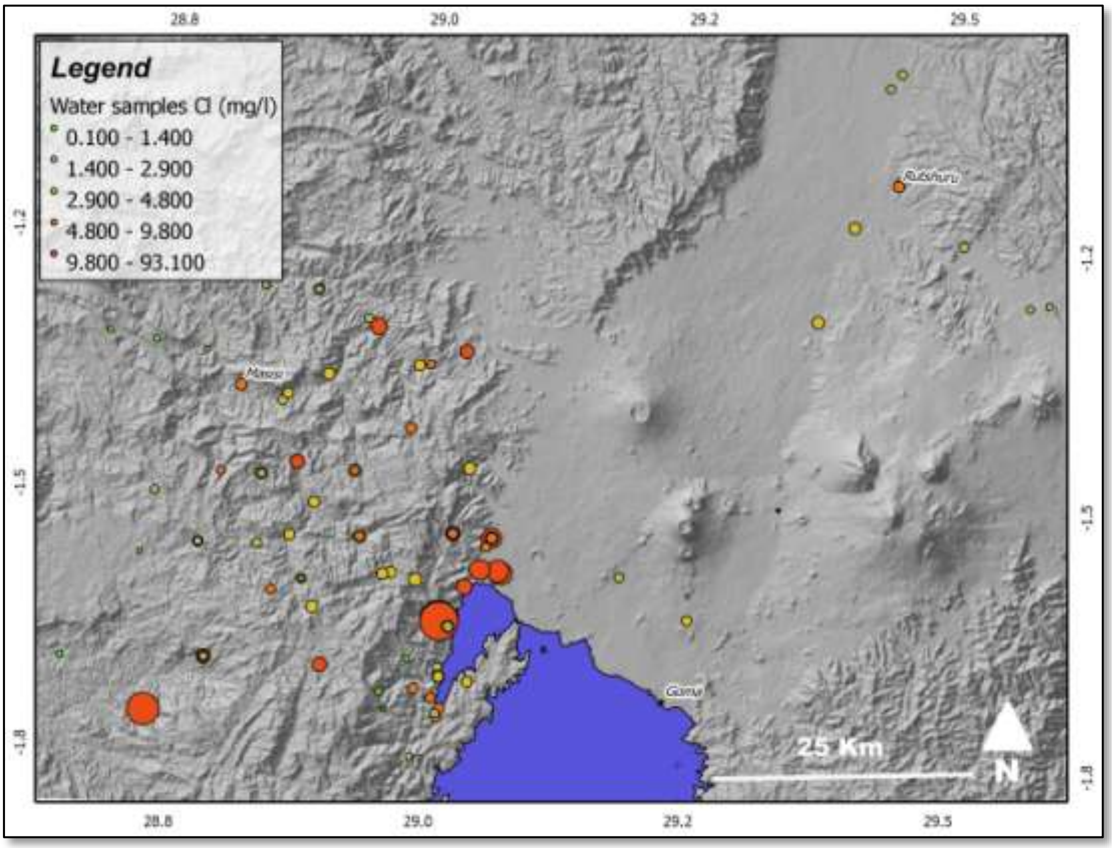


Figure 35: Dispersion map for the Chloride in water samples.

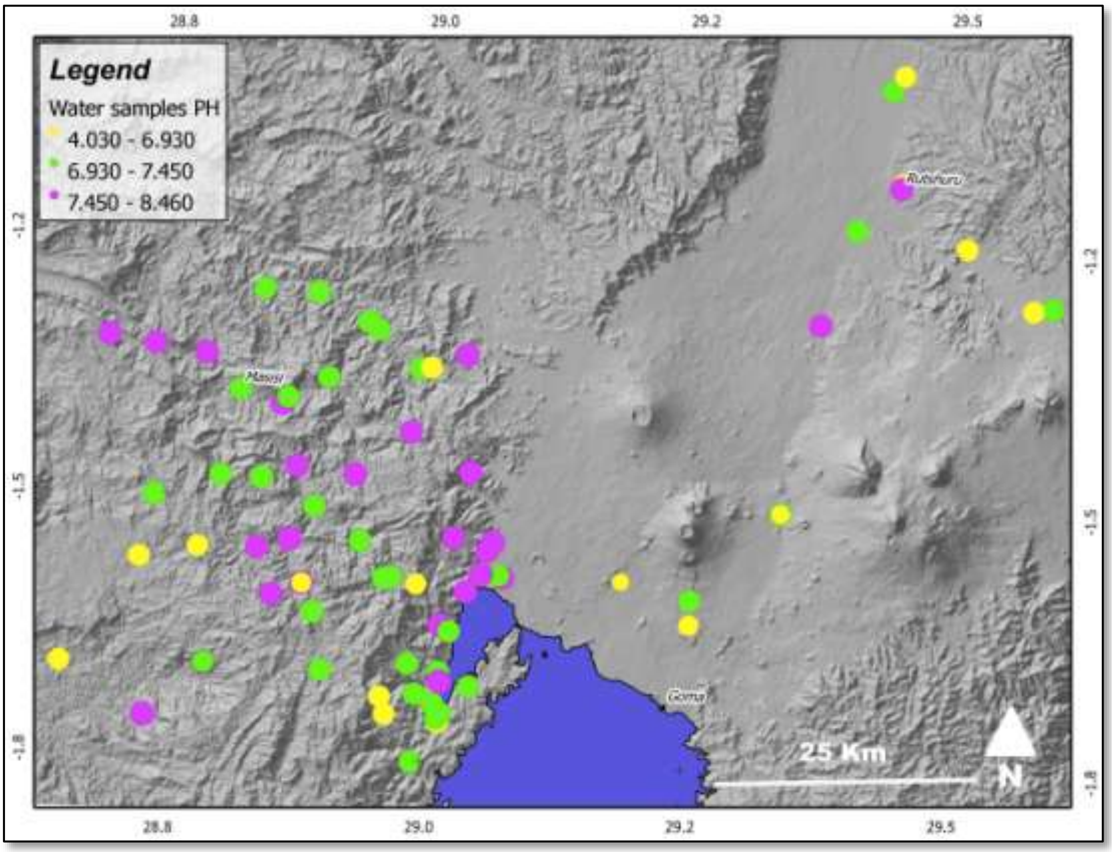


Figure 36: Map showing the PH distribution among the water samples collected in the field.

3.3.2.3. Problems encountered in the achievement of the task

As for the other tasks, security has been a serious concern. Another problem was the location of the sampling sites because the use of a GPS was not always possible as it may endanger the team in the field where armed groups consider such device as suspicious.

Solution:

The sampling was organized according to the situation.

When no GPS location is available, the samples are located according to the most reliable and available geographic database

3.3.3. Ground based fixed geochemical observations

3.3.3.1. CO_2-Rn measurements in soil air and in the atmosphere

Radon, a radioactive decay product of the element uranium, is an important terrestrial gas whose presence and concentration can be easily measured. As inert gas, radon is far more affected by physical than by chemical processes that affect other geogenic gases. Increased concentrations of radon are often found in soils above highly fractured rock associated with geologic fault systems and active volcanoes. Changes in the chemical composition of ascending gases are known for long time to be linked with seismic activities, gas migration along faults and fractures and active tectonic processes. Gas anomalies can be explained by a relative increase in permeability and modified flow/migration paths.

Three continuously operating gas (CO_2 and radon) monitoring stations were deployed in June 2007 at Bulengo, Munigi and Rusayo (Figure 37). Because that type of measurements was completely new for the region of Goma, there were *a priori* no ideal sites. The choice for these three locations was dictated by security concerns, as the devices could be co-located with other equipment in those supervised places. For insecurity reasons these stations had to be given up in 2008. In 2008 a new station based on more sensitive detectors was installed in a mazuku situated in a secure location.

From the general point of view, the passive degassing of the volcano is supposed to be geographically homogeneously distributed. It is expected that gases reach the surface easily via fractured zones of the crust that are not precisely known in the area. Carbon dioxide and radon were measured in the subsoil, presently in a mazuku vent. CO_2 levels are also recorded in the atmosphere. In a first approach it was aimed to gather knowledge on CO_2 content underground and above the ground and the dynamics of CO_2 and radon exhalation. Radon is associated in the study as radon often gives complementary information on the geophysical, geological and geochemical environment. Normally the production sites of both gases are different. For the study area, CO_2 may have a routing over long distances, even going down to the mantle. On the other hand, radon due to his small lifetime ($T = 3.8$ days) is produced close to the measuring point. To be carried over long distances radon needs carrier gases, air or CO_2, the possible distances between the radon originating point and the measuring point depend on the velocity of the carrier gases. CO_2 and radon are often correlated.

The correlation between the geochemical variations and the ground deformations will be part of the end user validations.

3.3.3.1.1. ***Station setup and instrument installation***

Radon and CO_2 are measured continuously, at a rate of one measurement every 30 minutes. In Rusayo and Bulengo, CO_2 and radon were measured simultaneously in the subsurface soil-air close to the stations at a depth of 0.6 m together with CO_2 in the air 1.5 m above ground. In Munigi CO_2 and radon were measured in the void place under the observation room of the geophysical station. Radon concentrations were highest in Munigi (mean 3 kBq/m^3), lower in the soil gas in Rusayo and Bulengo (mean 1 kBq/m^3). Compared to subsoil radon usually measured elsewhere, these levels were very low, evidencing low radium content of the surrounding rocks or lava.

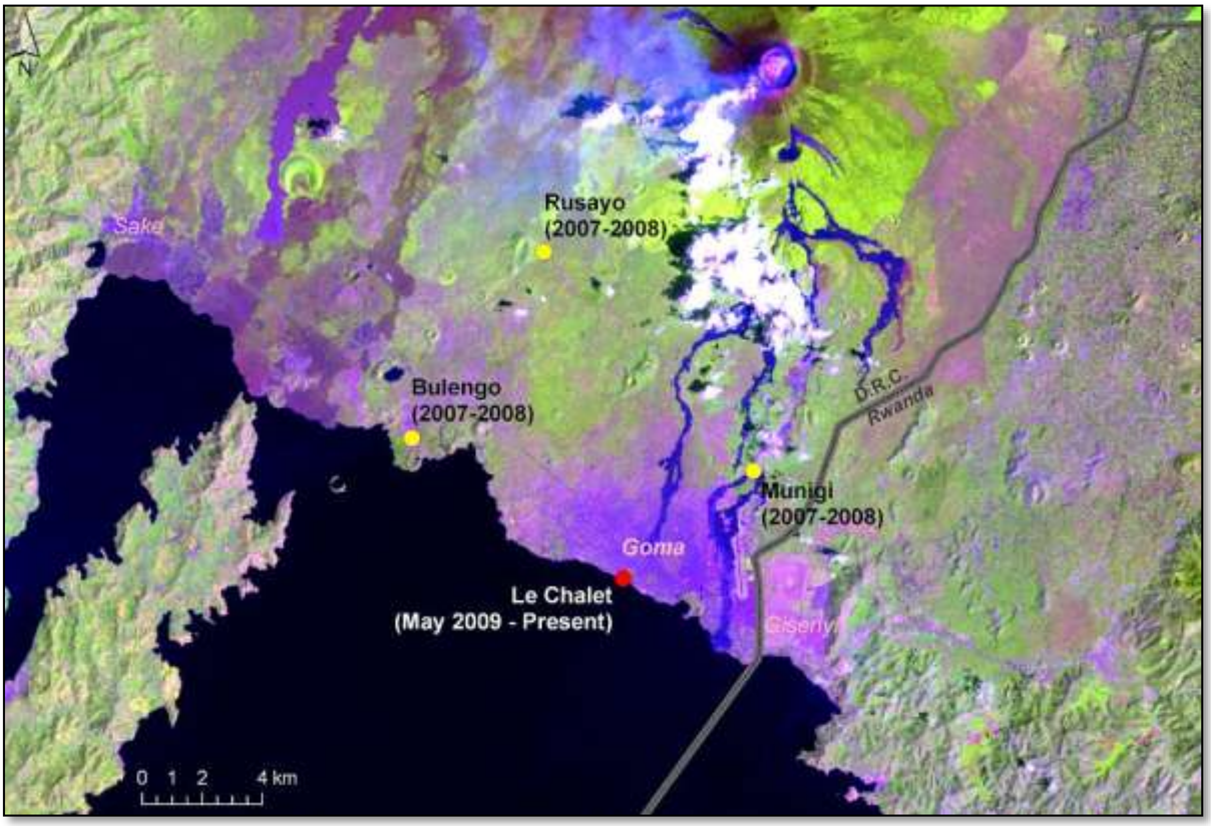


Figure 37: former and current location of ground-based instruments for CO_2-Rn measurements

Figure 38 gives an example of continuous measurements in Rusayo. CO_2 and Rn were collected in silicon tubing in 60 cm depth close to the station, before being pumped regularly into the measuring unit. Radon and CO_2 experienced important variations but they are poorly correlated. Mean CO_2 levels in the ground were from 2 to 5 %; in the outside air these levels were very low. Unfortunately it was not possible to have information on atmospheric parameters like temperature and atmospheric pressure. For this reason in January 2010, a Davis weather station was installed. We expected a better correlation with radon measurements and when, for security reasons, all the tree stations had to be dismounted in 2008, it was decided to look for more appropriate locations. For different technical reasons the dismounted stations could not be used any more. It was decided to install one station in a secure place and more promising site. The choice finally was a permanent new station setup in "Le Chalet" hotel, in the Katindo area (Goma West) (Figure 39). By moving into an inhabited area where high CO_2 flux is observed, we added an important aspect to the general volcanological studies. Indeed, the detailed study of the outgassing dynamics and its implications for the people living or even staying close to a mazuku provides crucial informations for urban planning and public health management.

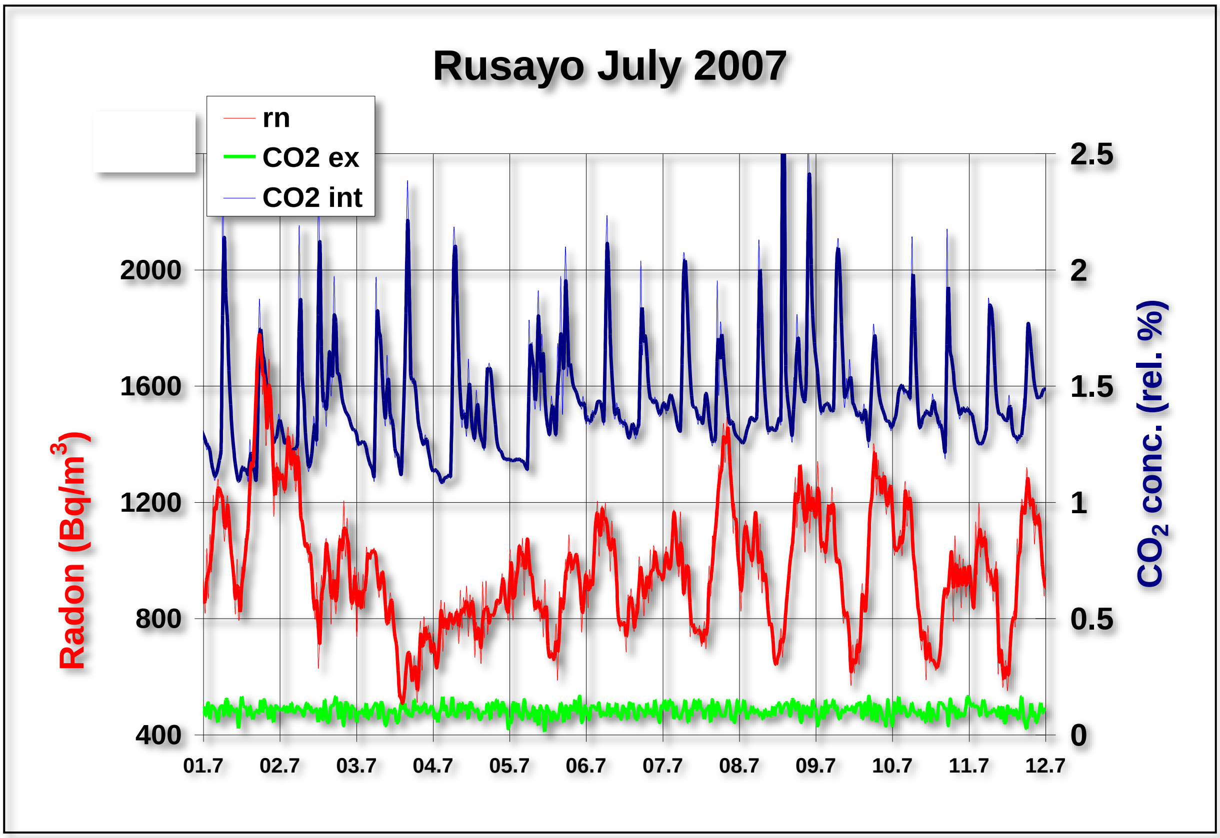


Figure 38: Example of radon and CO2 concentrations in the subsoil, at a depth of 60 cm

At the mazuku site, a gas probing tube is inserted into the soil (depth of ~ 30 cm) and is connected to a pump that sucks the gas out into the measuring unit where the radon monitor and a CO_2 monitor (range up to 100%) are connected in series. Through a tube, placed some 2 m above ground, ambient air is drained to a second CO_2 monitor (range up to 20 %).

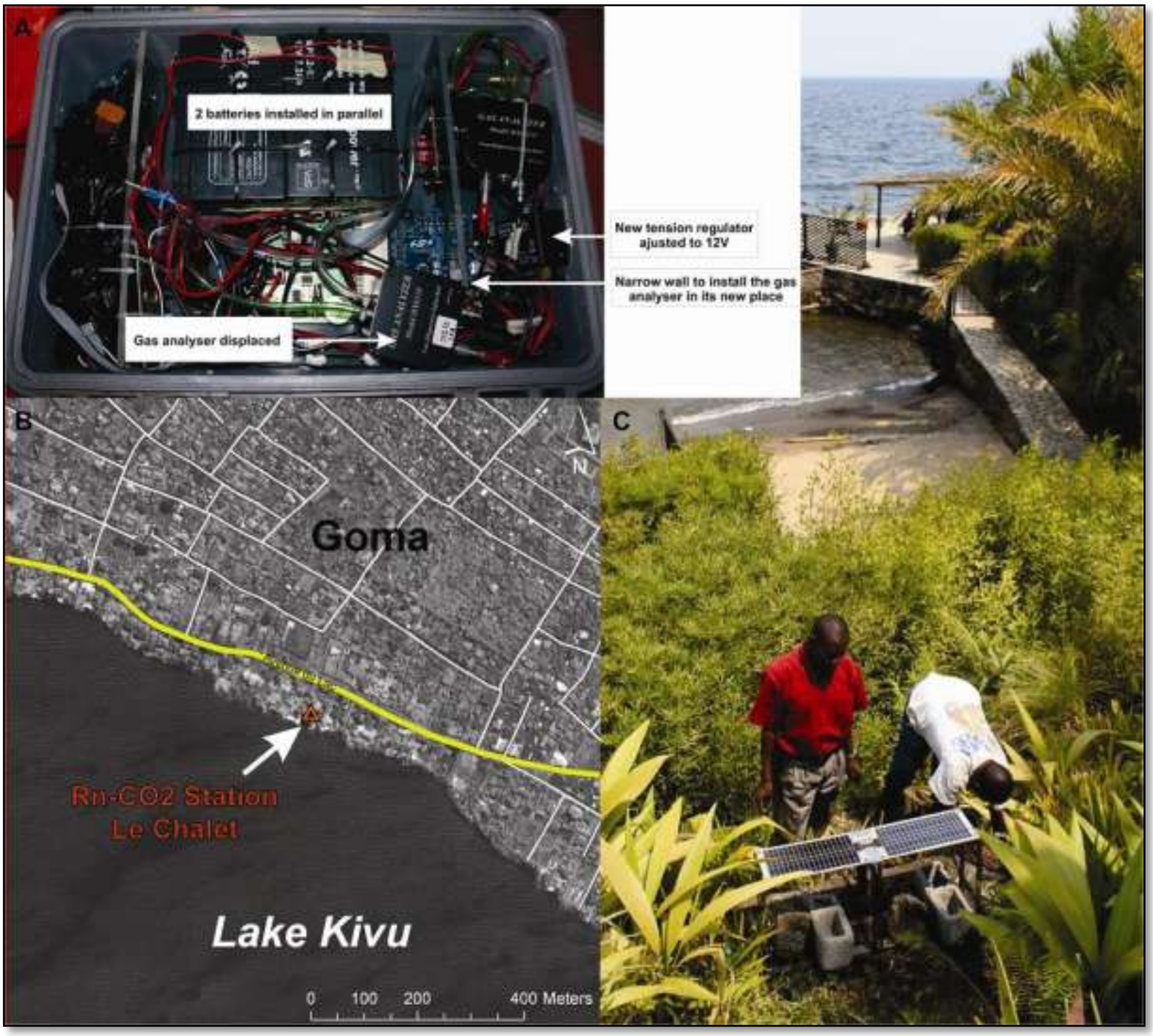


Figure 39: installation of the CO_2-Rn continuous measuring station in "Le Chalet", Goma. A = major changes inside the instrument during the August 2009 maintenance. B = Location of the station "Le Chalet". C = Solar panel installation.

The team in charge of these measurements sends the data regularly to the partner at University of Luxemburg. Data were processed in Luxembourg and the results (concentrations per unit of air volume) sent back to GVO. In the future the data will be processed at GVO and in Luxembourg; the results and their interpretation will be discussed. It is planned to install a second station on a mazuku in a site to be defined.

The power supply is given by solar panels, connected to a lead battery working as buffer.

3.3.3.1.2. *Measurements on a mazuku*

The records on the mazuku site show besides CO_2 and Rn levels, the voltage of the lead buffer battery and the temperature inside the Pelicase box. These parameters are interesting, as in the lack of weather station data, they give information on sun irradiance and on luminosity. The battery is charged whenever the solar panel is irradiated creating a higher measured voltage.

A first result is that radon concentrations and CO_2 levels are much higher than those measured in the three former stations.

The analysis of the datasets suggests a great influence of meteorological parameters on CO_2-Rn levels (Figure 40). The Chalet site is located on the lakeshore and is therefore exposed to the wind that has a strong impact on open-air measurements. Especially sudden gusts may cause sudden depressions of the levels, as outgassing air is replaced by fresh air. The measuring unit is equipped with a 'Lukas' scintillation cell for radon measurements and two modular gas analyzers for CO_2, those detectors are based on infrared absorption. The data from the CO_2 and radon probes are stored on a memory card that is regularly downloaded and the data archived at GVO.

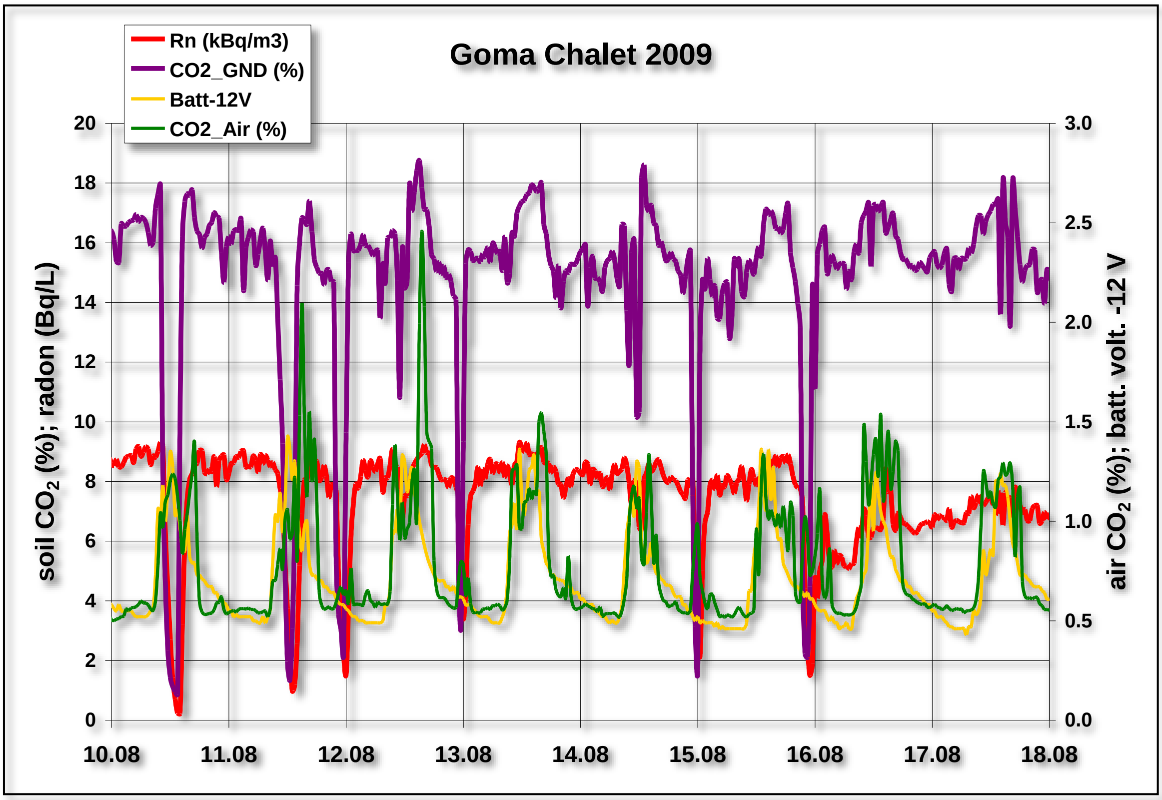


Figure 40: Display of the recorded parameters at the 'Chalet' mazuku for the period of August 10th – 18th, 2009.

Most of the time, exhaling radon and CO_2 are in phase (Figure 41). The sudden lows especially happen at the same time and are of similar relative importance. Highest values for radon and CO_2 are recorded around midday, whereas lowest mean values are rather stable at night though sometimes interrupted by sudden gusts that depress the levels(Figure 43). Mean levels of both gases varied slightly over the measured period. For radon a continuous decrease was observed up mid October 2009 (Figure 42). The eruption of the Nyamulagira in January 2010 could possibly be linked to these variations; unfortunately, there is a gap in data acquisition after November 23th 2009 (due to an incorrect a memory card replacement) and it was therefore not possible to analyse Rn and CO_2 variations close to the eruption and during the event.

CO_2 measured in the outside air did not experience these sudden lows as ground-based levels. Stable during nighttime, the levels increased regularly during daytime. It is interesting to notice that there is a strong link between solar irradiation and CO_2 levels; CO_2 in the air was highest during sunshine periods. As CO_2 was measured close to vegetation, part of these variations could be explained.

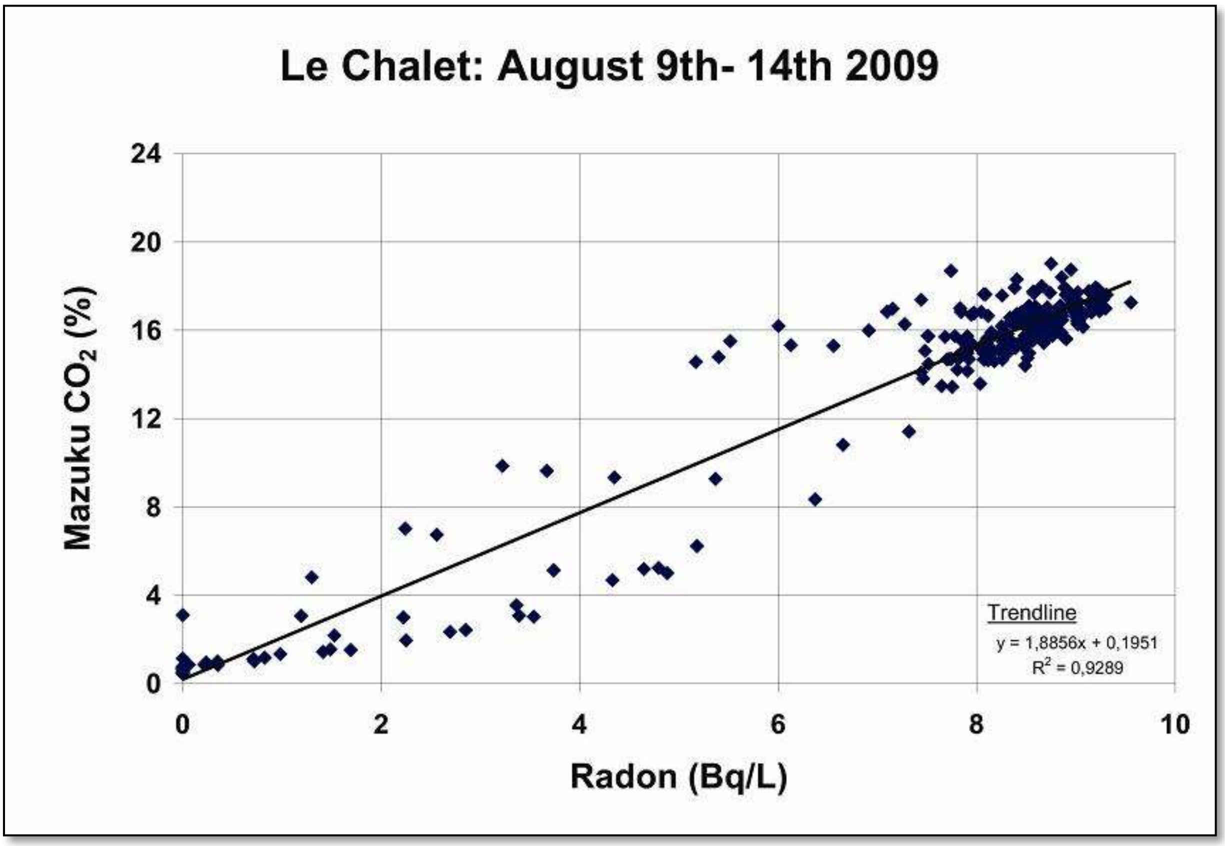


Figure 41: Graph displaying the good correlation between Radon and CO2.

Our observations showed that parameters like wind, atmospheric pressure or rainfalls may strongly influence gas concentrations. To quantify that influence, a weather station has been installed near the CO_2-Rn station in January 2010. Furthermore a special care in the choice of the sucking point appeared to be essential for good quality measurements. These aspects have been addressed during the October 2010 field campaign during which the first weather data have been downloaded and structural modification to improve the gas measurement have been achieved. As a result, the decrease in daily variations was observed.

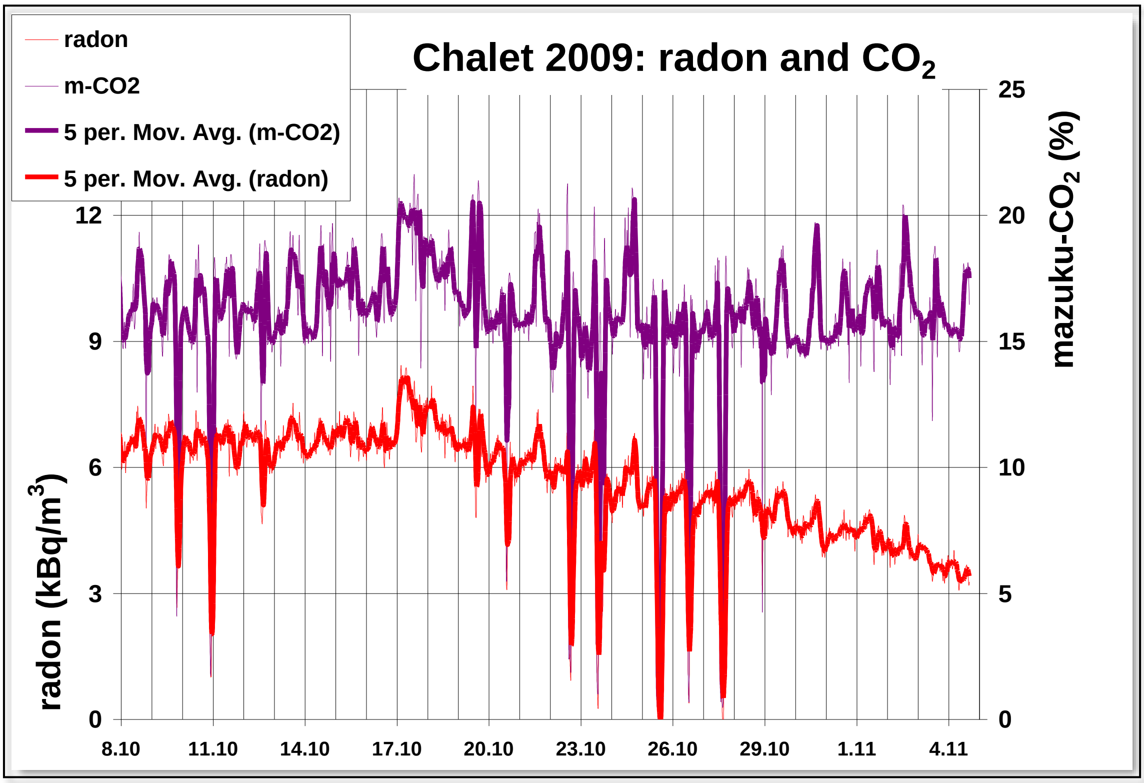


Figure 42: From October 19th 2009, Rn concentration decreases constantly. This Rn variation could suggest a linkage to the January 2010 eruption of Nyamulagira.

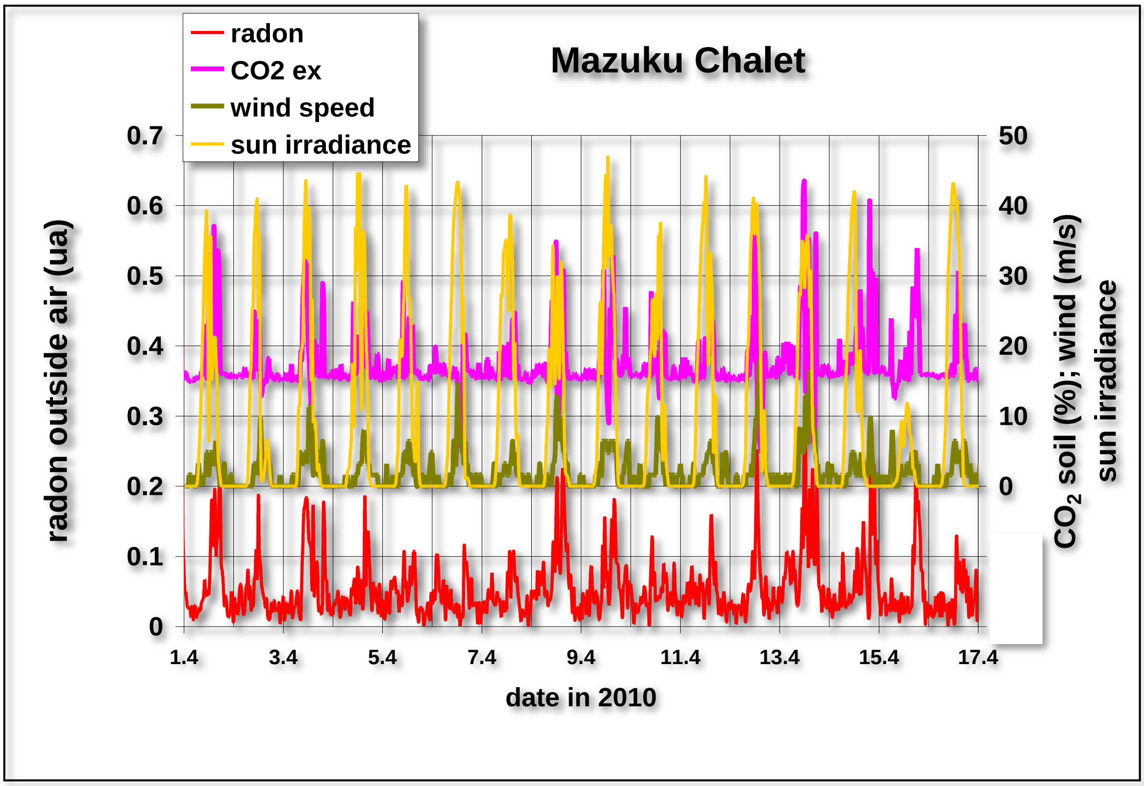


Figure 43: Graph showing the influence of the meteorological parameters on gas CO_2 and Rn concentrations measured in the air (Rn) and in the subsurface (CO_2)

3.3.3.2. CO_2-Rn in ground water

As originally proposed in the project description, the monitoring of Radon within ground water was foreseen. However, one of the characteristics of the area is the rare occurrence of surface water —springs or rivers. The only observed springs are located in the western part of the rift, in the area of Sake (see Figure 37) where intermittent springs have been described in relation with earthquakes and eruptions. However, the accessibility and security of that area were not guaranteed and did not allow the installation of a permanent measurement station.

3.3.3.3. Problems encountered and their (potential) solutions

The major problems encountered during the implementation of the ground based fixed geochemical monitoring were:

- the political situation and the security in the area that prevented the deployment of measurement stations at better locations (e.g. important mazuku and water springs)
- the adaptation phase was much too long for different reasons: inexperienced staff required intervention of the partner that had to be postponed (2008 security crisis).

Solutions:

Uni.lu will maintain its commitment in the future and pursue the measurements at "Le Chalet". Improvements will be performed with additional weather parameters that will be taken into account and ameliorate the data interpretation.

If the situation allows, additional stations will be deployed: a new generation of CO_2 sensors developed at Uni.lu, with less energy consumption, to be installed at two locations where security of the devices is guaranteed.
A data transmission system would also improve the data integration at GVO.

3.3.4. Ground based- and remote sensing monitoring of the volcanic plume

The monitoring of the volcanic plume falls under the topics of the EU-NOVAC and of the US NSF-VISOR projects that are focused on ground-based and spaceborne monitoring of the plume respectively. GORISK has established a discussion with those two groups in order to integrate pre-interpreted data provided by these 2 projects.

3.3.4.1. NOVAC

The NOVAC project (www.novac-project.eu) has been funded by European Union under the FP6 programme, with the aim to establish a global network of stations for the quantitative measurement of volcanic gas emissions. The network concerns 15 volcanoes around the world including the Nyiragongo. The instrumentation is based on a Scanning Dual-beam mini-DOAS, developed within the EU-project DORSIVA and representing a major breakthrough in volcanic gas monitoring.

Scanning mini-DOAS NOVAC instruments have been installed in 2007 (Figure 44). The already existing instrument at Rusayo was upgraded and at the same time 2 additional instruments were installed at Kunene and Sake. A repeater station for the data link from Sake was installed at Mbuzi. This repeater station will later also be equipped with a scanning DOAS instrument. The stations at Rusayo, Kunene and later Mbuzi all use a novel scanning geometry, conical scanning. With this geometry larger deviations in wind direction can be covered with each instrument and the "dilution"- effect due to atmospheric scattering is reduced. By combining data from 2 locations, viewing the gas plume from 2 sides, the concentration distribution in a vertical cross-section of the plume may be derived using tomographic techniques.

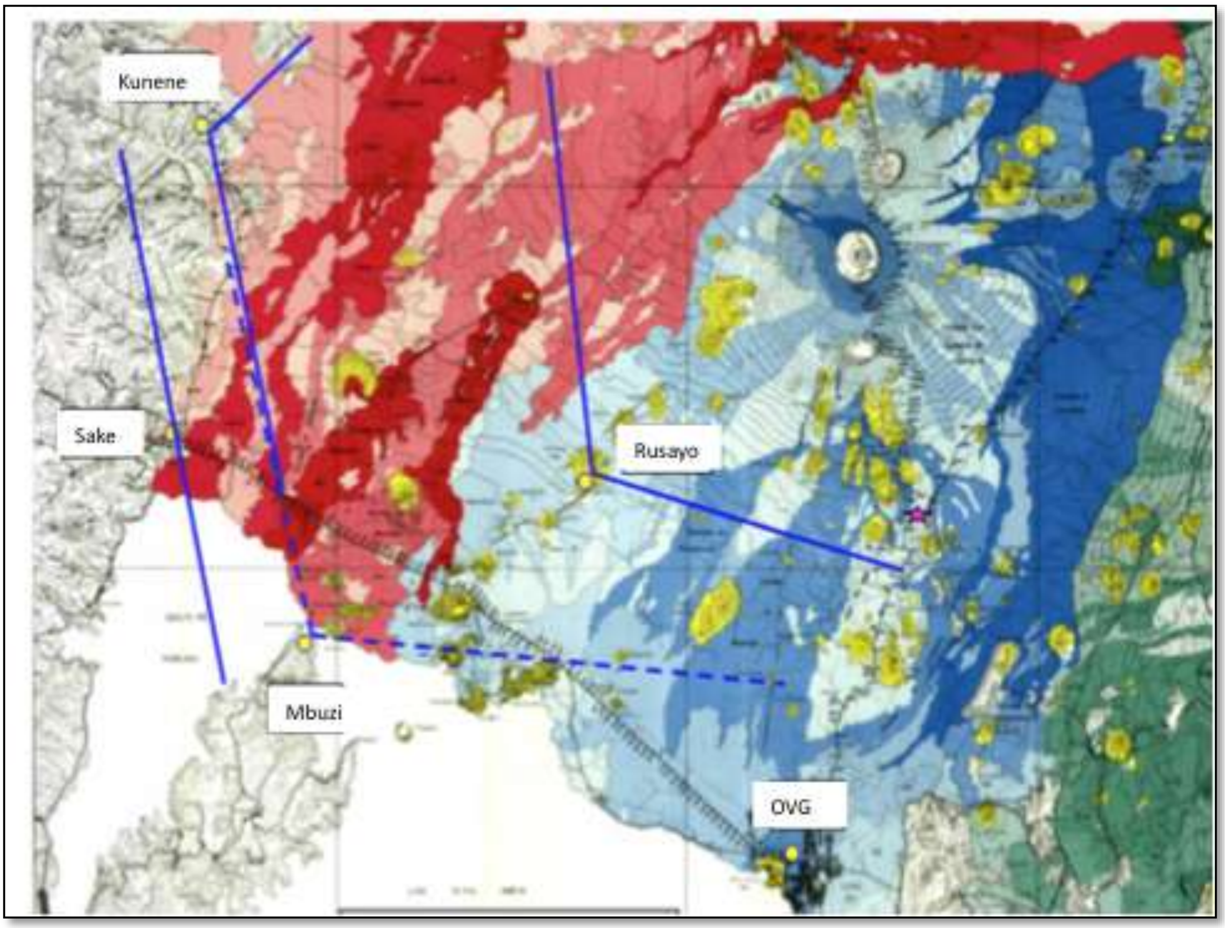


Figure 44: Map showing the installations of NOVAC instruments at Kunene, Sake and Rusayo. Mbuzi is a repeater site that will later be equipped with a NOVAC instrument.

3.3.4.1.1. *NOVAC preliminary results*

The following results and figures are extracted from the NOVAC report (Galle & Yalire, 2007, Internal NOVAC report)

A total of 79742 scans have been obtained from the stations during the period March 2004 – February 2010. From these scans, 47571 (59.6%) present actual observations of the plume that can be used for estimate the gas flux (Figure 45).

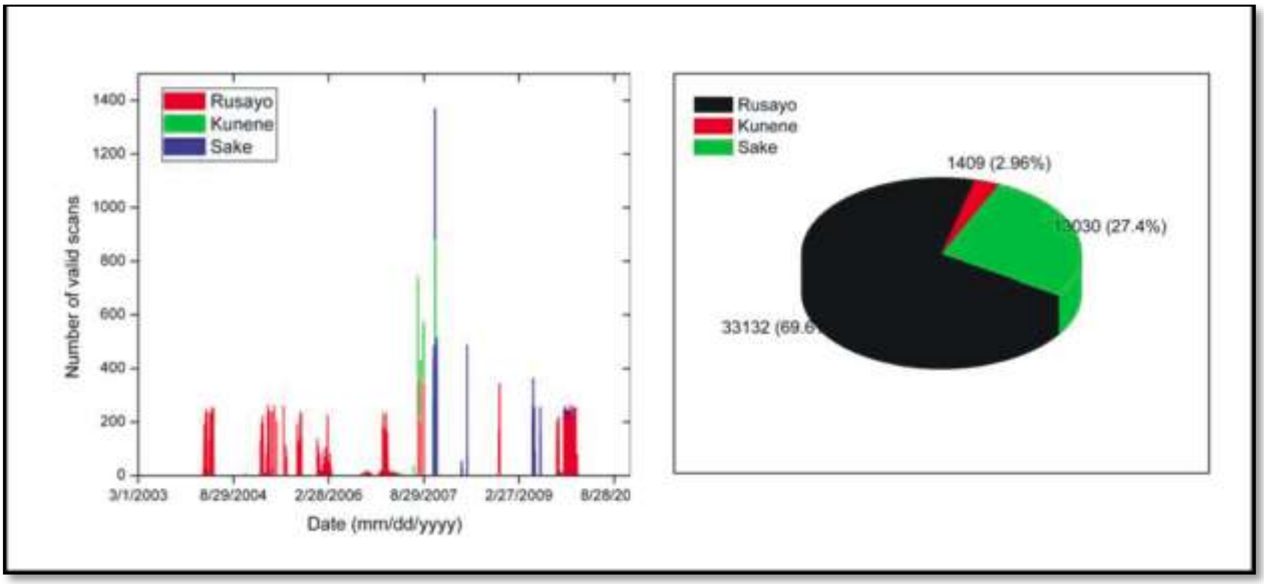


Figure 45: Number of valid scans (scans that gives a flux measurement value) recorded from 3 scanning systems at Nyiragongo volcano (Courtesy of B. Galle)

As a by-product of these plume scans, the plume direction can also be determined by using measurements from one or two stations. Figure 46 depicts the statistical distribution of plume direction for the entire study period. It's interesting to note the fairly stable wind transport direction at Nyiragongo (266 ±12deg).

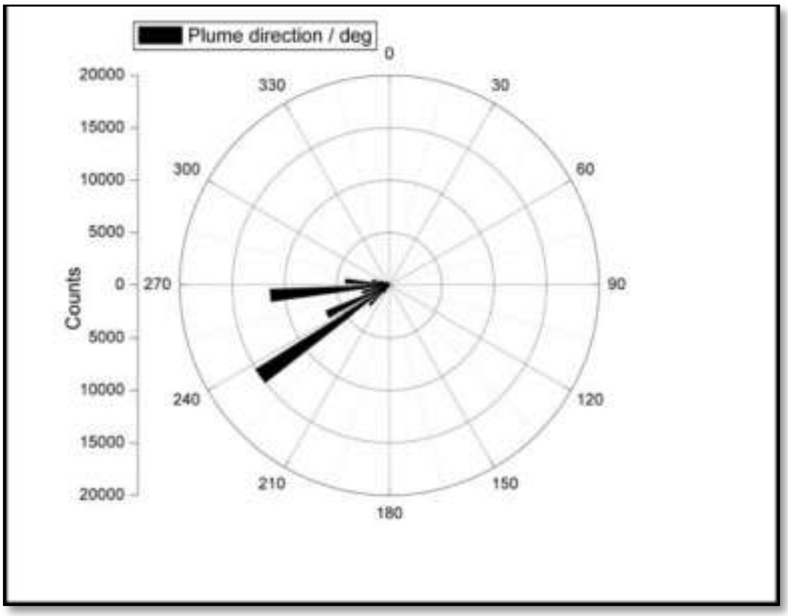


Figure 46: statistical distribution of the plume direction observed by the scanning network

The plume height has also been calculated (Figure 47) from triangulation of simultaneous measurements from two stations or assumed to be equal to the crater plume when such calculation could not be performed (this is a reasonable approximation given the predominantly passive character of the emissions of Nyiragongo volcano during the period of interest).

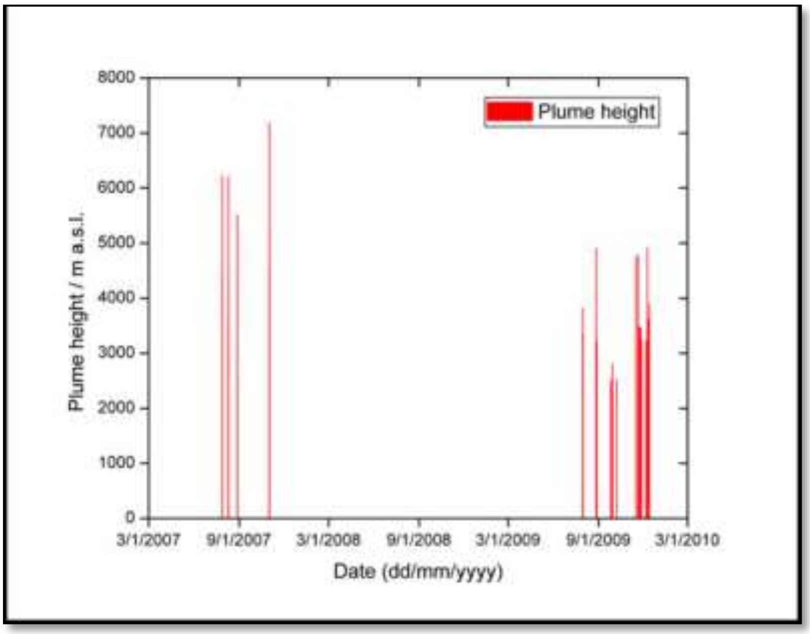


Figure 47: plume height calculated from triangulation of simultaneous scanning observations

In total, 406 daily values of SO2 emission rates were calculated and the average daily flux of SO2 obtained from our measurements is 16.41kg s^{-1} (1418 tons/day) with a standard deviation of 6.08kg s^{-1} (525 tons/day).

3.3.4.1.2. *Problems encountered*

NOVAC encountered some problems with the DOAS during the period covered by the GORISK project, mainly linked to insecurity. One DOAS was destroyed and two instruments were brought back – temporarily - to the observatory to prevent them from vandalism. This had caused some critical delay in the analysis and transmission of the data to GORISK.

3.3.4.2. VISOR

Both Nyamulagira and Nyiragongo are prodigious sulphur emitters, the former during its frequent effusive eruptions and the latter via persistent degassing since 2002. ViSOR project[7] has the aim to investigate the origins and dynamics of SO_2 emissions from Nyamulagira and Nyiragongo.

GORISK integrates the VISOR data that are based on the Ozone Monitoring Instrument (OMI) satellite sensor into the GIS platform in order to create SO2 dispersion maps.

OMI was launched on the EOS-Aura satellite in July 2004 and superseded Earth Probe (EP) TOMS in 2006. OMI is a hyperspectral UV-Visible spectrometer with 8-fold better ground resolution (13x24 km at nadir) and an order of magnitude higher sensitivity to SO2 than TOMS. Hence, OMI can detect passive volcanic degassing in addition to the eruptive emissions measured in the past by TOMS. OMI can also

[7] Virunga Volcanic SO_2 Emission Research project
http://userpages.umbc.edu/~scarn/virunga/index.htm

measure anthropogenic SO2 emissions. SO2 is currently being measured over the entire earth using the Ozone Monitoring Instrument (OMI).

Measurement units

The gas is measured in Dobson Units (DU), the number of molecules in a square centimetre of the atmosphere. Should all of the sulphur dioxide in a column of the atmosphere be compressed into a flat layer at standard temperature and pressure, one Dobson Unit would be 0.01 millimeters thick and would contain 0.0285 grams of SO2 per square meter. For SO2, the typical background level concentration (i.e. away from emissions related to pollution and volcanic eruptions) is much less than 1 DU. Emissions related to pollution and small volcanic eruptions are of the order of 1 DU or a few DU. Strong and explosive eruptions may lead to concentrations well above 10 DU, even as high as 100 DU. (e.g. see http://www.oma.be/BIRA-IASB/Molecules/SO2archive/info/?kind=dobson).

The main purpose of including SO2 data in GORISK was motivated by the impact of volcanic activity on population health. The integration of daily SO2 dispersion vector maps as a layer of the GIS platform was initially foreseen. After discussion with VISOR colleagues about the setup of an automated shape file extraction routine, other option was decided based on the use of an alert threshold over which such maps should be produced. The main reason for that decision is the constant decrease in SO2 emission since 2005.

3.3.4.2.1. ***Problems encountered***

The VISOR data were not regularly provided as it was initially discussed with the partner. The partner is strongly involved and committed in other project and was following the GORISK activity on best effort basis. As a consequence, the automated production of SO2 dispersion vector files was not implemented by the partner and the GIS integration was therefore limited to those made available.

The impact on the project essentially concerned the assessment of the impact on public health (e.g. the spatial relation health impact – plume dispersion). However, the experience (and the NOVAC wind distribution computation) suggests that one can consider the plume in a sub-permanent direction W to the Nyiragongo crater as displayed in the (Figure 48).

3.4. HEALTH STUDY

3.4.1. Introduction

Since late 2002, satellite remote-sensing data have shown Nyiragongo to be a significant and persistent point source of SO2 to the free troposphere (Sawyer at al, 2008; Carn, 2002/2003). Nyamulagira, with its 40 confirmed eruptive events from 1865 to 2005, contributes also significantly to the global terrestrial sulphur flux and may be considered as one of the largest volcanic source of sulphur to the atmosphere for the past few decades (Bluth & Carn, 2008).

Gas emissions may occur in association with eruptions, but are also common between the eruptions at many volcanoes and geothermal areas where they may be vented from the main crater, from fumaroles fields, or diffusely through the soil. Volatiles emitted include CO and CO2, SO2, HCl, HF, H2S and radon. The potential effects of acid gases are bronchoconstriction, aggravation of respiratory disease and eye and skin irritation. CO2 and H2S can cause asphyxiation and Rn can cause lunge cancer after long exposure (Hansell et al., 2006).

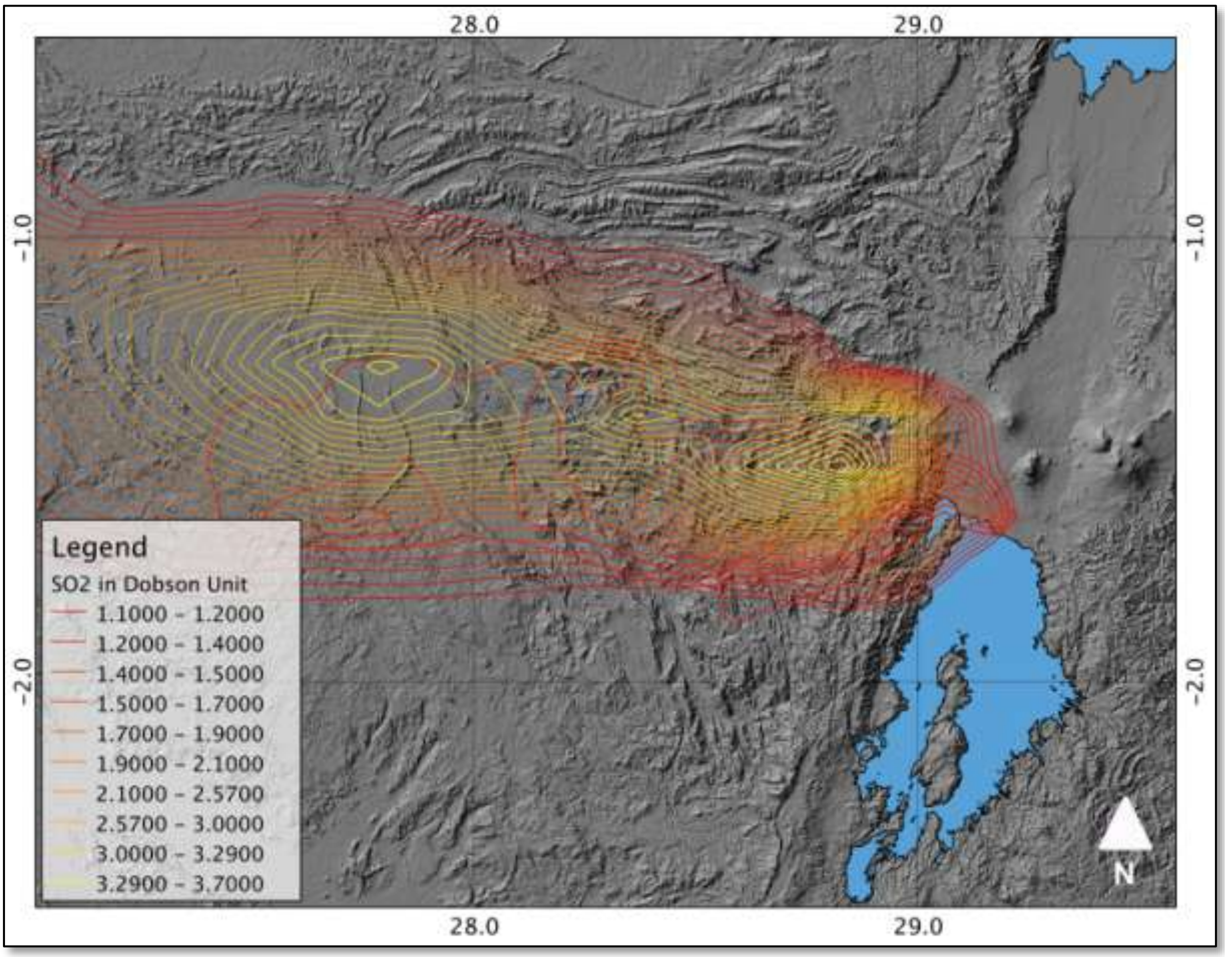


Figure 48: Schematic map displaying the SO_2 plume dispersion for the period 2004 – 2008. The shapes are those for DU > 1 and were extracted from trimester averages of the given period. No filtering has been defined and the data are including the Nyamulagira 2006 eruption. This figure is based on raw data and is for illustration purpose only.

According to the USGS-Volcano Hazards Program (http://volcanoes.usgs.gov/hazards/gas/index.php), the volcanic gases that pose the greatest potential hazard to people, animals, agriculture and property are sulphur dioxide, carbon dioxide and hydrogen fluoride. The effects of SO2 on people and the environment vary widely depending on (1) the amount of gas a volcano emits into the atmosphere; (2) whether the gas is injected into the troposphere or stratosphere; (3) the regional or global wind and weather pattern that disperses the gas.

Sulphur dioxide (SO_2) is a colourless gas with a pungent odour that irritates skin and the tissues and mucous membranes of the eyes, nose and throat. Sulphur dioxide chiefly affects the upper respiratory tract and bronchi.

The health effects of volcanic gases have been reviewed by Hansell & Oppenheimer (2004) and after this systematic review, the few studies relating to health hazards of volcanic gases indicate that SO_2 and acid aerosols from eruptions and degassing events were associated with respiratory morbidity and mortality but not childhood asthma prevalence or lung function decrements. They reported also that epidemiological studies are lacking for several volcanoes producing large quantities of gases in proximity to populated areas, such as Mount Etna on Sicily, Popocatépetl near Mexico City, Miyakejima in Japan, Nyiragongo in Democratic Republic of Congo and Masaya in Nicaragua.

One objective of the GORISK project is to fill the gap between the volcanic risks and the public health sector and to provide a first estimation of the problem extent.

3.4.2. Methodology

In DRC, international cooperation programs are supporting the Ministry of Health by implementing the *Système d'Information Sanitaire* (SIS) that includes a health database where both structural and sanitarian data are recorded.
The implementation in the field requires the contribution of local actors, typically the personnel of the Ministry of Health (de-centralized teams), and the partners of the Health sector like international agencies or NGO's (e.g. CEMUBAC). The data are gathered in health centers scattered all over the province in both plume-prone and plume-free areas (Figure 48).

The methodology is based on the selection within the dataset of data concerning air or water related diseases: breath disease, eye and skin infections and diarrhoea. The data are recorded for 2 age categories: < 5years and ≥ 5 years, and they have been normalized and expressed in number of case/10000 inhabitants. They are provided per trimester and per health center.

3.4.3. Datasets

A first dataset with data from 2000 to 2006 has been provided at the end of 2007. A second data set including data from 2007 and 2008 has been provided in August 2009. The short notice has limited the interpretation capacity.

3.4.4. Epidemiological study

The inspection of the health data allows highlighting a relative increase of given pathologies during certain periods. The study of the possible relationship with the volcanic activity (mainly SO_2 degassing) was performed partly based on the use of SO_2 dispersion maps from ViSOR. Notice that we encountered some problems for the integration of health data in the GIS because of inaccurate or absence of geographic coordinates for numerous health structures where data are collected. Another problem is related to variations in the toponymy of the localities where those health centers are. That major problem is known in DRC and attempts are made to progressively acquire unambiguous GPS locations.

As an example, the OMI satellite has recorded high concentrations of SO2 during the fourth trimester of 2004. Figure 49 displays the SO2 dispersion curves and the breath diseases distribution for the same period. It appears that only a few number of health centers are showing a significant increase in breathe disease in areas where the SO2 concentration is the highest (> to EU norms). No significant increase in skin, eye and diarrhoea can be pointed out though.

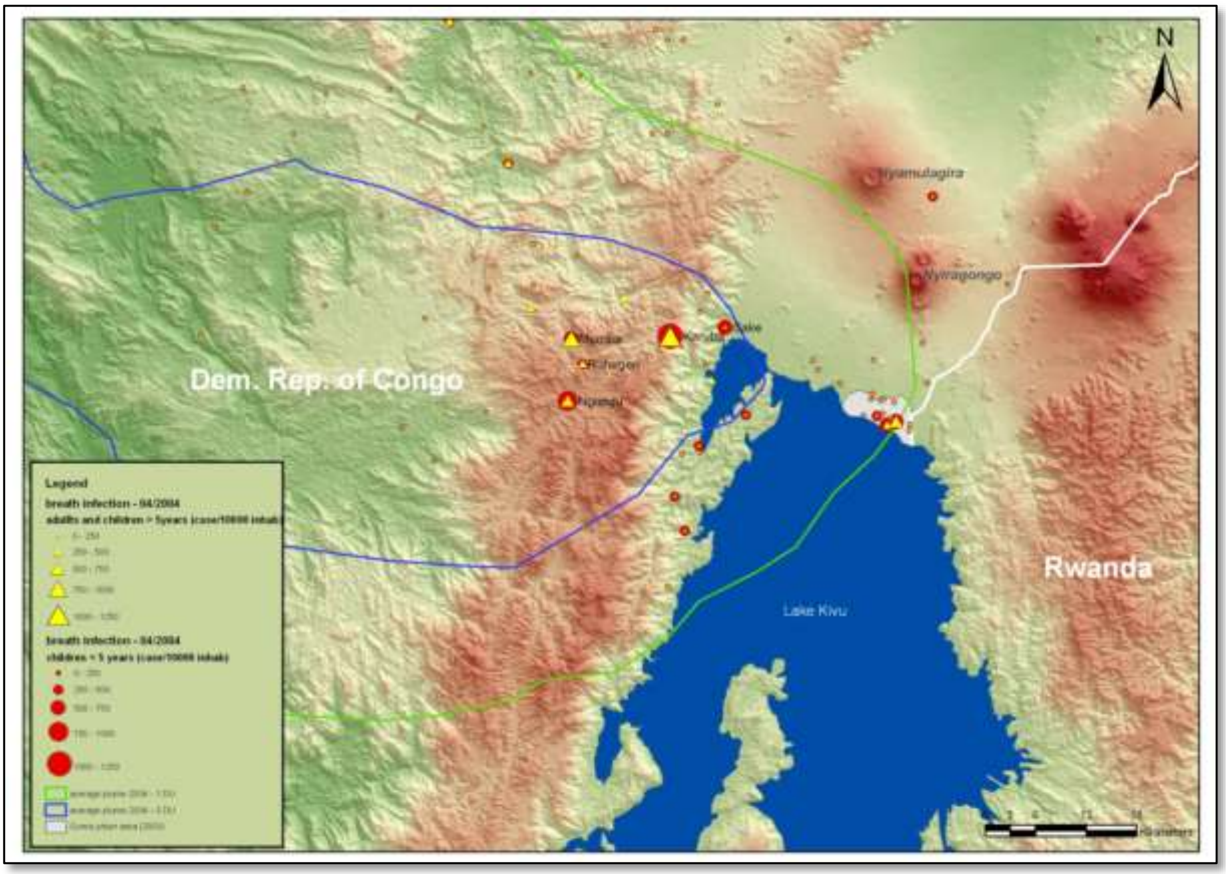


Figure 49: SO2 dispersion curves and breath disease distribution during the 4th trimester 2004

3.4.5. Discussion:

The apparent correlation between high SO2 and breath diseases requires however more investigations because that observation is not clear for all health structures.
The assessment of the effects of SO2 on the environment and health requires the estimation of actual SO2 concentrations (in terms of parts per million or ppm, for example) and the approximated vertical SO2 distribution. One also need to consider how much SO2 actually reaches ground level where it directly affects health, and how much is involved in acid precipitation; the local meteorological conditions are controlling the vertical distribution of the SO2 plume. The topography is likely an important factor and areas located downwind and at higher altitude (e.g. on the flanks of the main rift valley) could be more exposed. In summary, health and environment impacts depend on the thickness and the altitude of the SO2 plume (Carn, personal communication). The difficulties encountered by the NOVAC project

with the DOAS in the Goma area (3.3.4.1) lead to a delay in the transmission of data such as plume height, plume direction, SO2 fluxes that would have been useful to better constrain the actual SO2 amount affecting the plume-prone area.

From the biostatistical point of view, a study has been undertaken with the department of Biostatistic of the faculty of medicine (Université libre de Bruxelles). This study is still underway but the first results confirm the difficulty to highlight a "direct" relationship between volcanic activity and the human health and the results are evidencing that other parameters must be taken into consideration even if they are difficult to constrain. Some of the most obvious are mentioned below.

3.4.5.1. Sanitary conditions

The sanitary conditions are in direct link with the poverty and concerns for instance the access to health cares, or water. It also involves the level of education, or the condition of the health centers —building and equipments— (damages caused by a lack of maintenance, degradation by looting…). The sanitary conditions are in direct relation with the overall political situation, the accessibility of the area (access of supply and aid), or the condition of the road infrastructure…

The political and security situations are also responsible for massive Internally Displaced Populations (IDP's) that are more vulnerable.

3.4.5.2. Site effects

By site effects, we consider the parameters related to the environment, such as the natural or anthropic influence on the parameters. For instance the urban pollution that prevails in densely populated areas like the city of Goma where the dense traffic, the poor quality of the fuel and the vehicles, combined to the heavy dusty conditions of the dry season, are likely contributing against population health.

The topography, the vegetation, the specific local meteorological conditions (wind, rain…) will also influence the dispersion and the circulation of the SO_2 in the air and water.

3.4.5.3. Data quality

For the purpose of this study, the CEMUBAC has collected the raw data that are consigned at each health structure and that are likely the more reliable and accurate. The experience suggests however that a better option would have been to begin with a global overview based on data compiled at the province level, and go for the details based on that preliminary approach.

It has also been evidenced that attention must be paid to the political and security context as important population movements are strongly affecting the statistics based on hypothesis of constant population and the evolution with time of the investigated parameters.

One cannot rule out the presence of inaccuracies or erroneous data at the source. This can be explained by the potential link and/or influence of the data on funding support, primes, etc.

3.5. DATA INTEGRATION

So far, most of the results obtained in isolated initiatives aiming at improving either the monitoring or the risk assessment of the Nyiragongo-Nyamulagira volcanoes are usually not systematically analysed in a global way. There is no doubt however that the parameters individually studied are the elements of a highly complex system that are mutually interacting and influencing each other's.
For a global approach, the most efficient option relies on GIS, which requires that the data be structured in such a way that they can be merged and integrated into a single spatial reference system.

In the frame of the GORISK project, the GIS includes the data collected by the GVO, those collected in the frame of the project, and any other relevant data gathered from various origin.
The data are of various types:

- RASTERS
  - InSAR (deformation maps and by products)
  - Ikonos
  - Aster
  - Archive imagery (Landsat)
  - …

- VECTORS
  - Lava flows
  - SO2 maps
  - Goma urban area map
  - Interpretation of raster data

- TABLES
  - Tilt
  - GPS
  - Gas analyses
  - Water analyses
  - Health data
  - Other GVO data (seismic, geochemical, etc.)

As far as the data collected by the project activities are concerned, their structure is defined accordingly without further major difficulties. For the data collected by the GVO, the major problem encountered is the lack of a clear data policy needed for sharing and valorising the information. That critical question has been at the centre of the discussion during the project and remains under the responsibility of the GVO.

Despite its public mission, the GVO encountered difficulties in setting up an internal data sharing policy between its different departments, and externally, with its partners. The setup of a GIS has therefore suffered from that situation and has been delayed.

The recent changes that took place in the GVO structure and managing staff have been accompanied by a marked will of constructive collaboration allowing starting the initialization of the GIS activity.
An audit has been performed at the end of the project aiming at listing the type of data collected by each department, and discussing the structure of each source data.
As a result, we proposed a standardized data structure to GVO; the proposed canvas can be applied to the archived data as well as to the new acquisition.

The key-aspect of the proposed methodology relies on coding of every significant measurement site and on its geographic location.
The observations performed by the GVO and their partners are generally associated to given location where occasional, recurrent, regular, or continuous measurements are made. Each site has been attributed a site code in order to avoid misspelling or even duplication of the name when several site are located close to each other in a same location for example (see and Figure 50).

3.5.1. GORISK products:

3.5.1.1. InSAR data layer

As part of the InSAR processing chain that has been setup at NMNH, the geocoding of slant range InSAR products (amplitude image, deformation maps, coherence maps,…) has been implemented and includes the export in the ENVI image format.
The geocoding being performed on the SRTM topographic model, its accuracy is propagated to the resulting products; in particular, the horizontal accuracy is approximately 20 meters.
The analysis of individual deformation maps is possible as well as time series of coherence maps, or delineation of lava flows based on combinations of amplitude and coherence data.

3.5.1.2. Tilt data layer

Tilt data are recorded at 4 permanent sites and are essentially characterized by the high sampling rate of data recorded (1 minute). Data are processed using the dedicated time series software TSOFT[8] that allows in-depth analysis, filtering, etc. The processed output file can be used afterwards to provide data more easily handled in a GIS: one tilt data per day/hour/… for example to detect possible regional deformation on the long term or during crisis. This however requires uninterrupted time series.

By default, the tilt data provided to the GIS is taken systematically at one-day interval and at a given time of the day so that the daily variations minimized.
Symbology is adapted to best reflect the tilt signal that has been converted in such way that X and Y tilt components are translated into polar coordinates (tilt angle and direction).

[8] TSOFT : http://seismologie.oma.be/TSOFT/tsoft.html

3.5.1.3. GPS data layer

The GPS data are reflecting the relative motion of stations compared to a reference station installed in a "stable" location. Data measurements are expressed in ΔX, ΔY, and ΔZ. So far, the GPS data have been recorded, but detailed processing has been restricted to selected periods of abnormal volcanic/tectonic activity (for instance the eruption of Nyamulagira in January 2010, see section 3.9.1.1.2).

3.5.1.4. CO_2 – Rn data layer

Valuable CO_2 and radon data measurements are available since the installation of the new sensor in « Le Chalet » site in August 2009. The measurements are corresponding to CO_2 and Radon concentration in the air. Again, a daily cycle is observed and the data provided to the GIS is at a rate of one data per day at a given time.

3.5.1.5. "Mobile" geochemical measurements

For the geochemical parameters like gas in mazuku or water samples that have been measured occasionally in various locations, the data are stored in fixed tables where elements concentrations are provided at a given location and date. These data do not reflect the variation with time of those parameters. However, they provide valuable information that can be analysed in the light of other information layers.

3.5.1.6. VISOR SO_2 data layer

The SO_2 dispersion maps provided by VISOR are in vector « shp file » format. They are directly ingested by the GIS and display the curve of iso-concentration in SO_2 in DU (Dobson Units). The plan was to feed the GIS with weekly or monthly data. But the circumstances forced us to consider these data on a request basis.

3.5.1.7. NOVAC SO_2 data layer

The SO_2 data measurements collected on the ground by the DOAS are corresponding to SO_2 flux in tons/day. The measurements are made vertically along a scanning line. The spatial representation of such data is complicated by the fact that it depends on the plume occurrence along the scanning line. The option has been taken to represent the data at the station itself notwithstanding the 3D variability of their geographic representation.

3.5.2. Non GORISK data layers

The non-GORISK data layers are essentially those corresponding to the data routinely collected by the GVO and the health data provided by the CEMUBAC partner.

3.5.2.1. GVO – seismic data layer

The seismic data recorded at GVO are coming from a network of 7 stations deployed around the two volcanoes (Figure 50). The seismic data are upon the highest importance because of the relation between the volcanic activity and the seismicity. The seismic data are stored on the GVO server.
The seismic GIS layer essentially consist in :

- X, Y, Z (depth) coordinates of the epicenter,
- the magnitude,
- the number of stations used in locating the epicenter,
- the error on location,
- the date
- the time (hhmmss)
- the type of earthquake (long period / high frequency)

The exact location, the magnitude, the type, and the time of the seismic event are the most important parameters. The spatial distribution with time helps in interpreting the source mechanisms but can also be studied by taking other layers into account ; for instance to evaluate the possible correlation between seismicity and ground deformations or with geochemical parameters.

3.5.2.2. GVO – ground deformations department

In addition to the tilt and GPS measurements, the ground deformation department of the GVO is also in charge of extensometric measurements made on 2002 eruptive fractures where temperature is also measured.
These measurements are made as regularly as possible at specific locations along the fracture.
Refer to Table 3 for the complete list of parameters measured by the ground deformation department.

3.5.2.3. GVO – department of geochemistry

The geochemistry department is responsible for the geochemical measurements performed in the frame of the GORISK project (see section 0). It has also in charge the VISOR data interpretations and the measurements made in the frame of the NOVAC project. Beside of these actions lead within collaborative supports, that department has the responsibility of monitoring geochemical parameters such like CO_2 and CH_4 fluxes in Mazukus and along the eruptive fracture of 2002. They are also collecting water samples and mobile DOAS measurements.
Refer Table 3 to for the complete list of parameters measured by the geochemistry department.

3.5.2.4. GVO measurement sites

In the frame of the project, a discussion started about the GIS platform deployment aiming at improving the GVO data management, analysis, and interpretation. In other words, the GIS segment is the key-link between the GVO scientist and partners, and the stakeholders (authorities, agencies, NGO's, etc). Due to internal problems, GVO remains in a position where data sharing is limited.

GORISK has therefore focused its commitment in that domain to the definition of a base —a standardized data structure— that would facilitate the data integration. A list of all the data collected has been setup and a homogenous structure has been proposed.

The methodology takes into account the fact that the monitoring of the volcanic activity is based not only on routine measurements achieved at specific sites or stations but also on measurements made in locations selected upon relevance in a given situation.

GD / T°	GD / Extenso	GD / Meteo	GD / Tilt	GD / GPS
Site	Site	Site	Site	Site
Date	T°C air sur site	Date	Charge batterie	Date
T°moy	T°C fracture immédiate ThCouple/Hg	Heure	Température extérieure	Heure
	CO2 % volume dans fract.	T°	Température instrument	Ligne de base
	Vent N=nul Fa=faible M=moyen F=fort	%Humid.	Tilt in direction X	DX
	Météo S=soleil P=pluie Nu=nuage	Force Vent	Tilt in direction Y	DY
	Moyenne mesures corrigées thermique mm	Direction Vent	Tilt direction (azimut)	DZ
	Ecart type mesures corrigées thermique mm	Précipit .	Tilt angle (rad)	
	Erreur max répétabilité plus écart type mm	UV		
	Ecartement cumulé différence mesure moy - mesure init mm	PA		

Géoch / CO2	Géoch / SO2	Géoch / Eau	Géoch / CO2-Rn	Géoch / SO2-DOAS
Site	Site	Site	Site	Site
Date	Date	Date	Date	Downloaded
%CO2	flux	Lieu de récolte	Heure	Pre-evaluated
PA (pression atm.)		Date d'analyse	%CO2	Archived
		App. Utilisé	%Rn	Post evaluated
		pH		Flux
		Conduct.		Comment
		Tempér.		
		F-(Fluorimètre)		
		F-(Spectro) ppm		
		SO4-- ppm		
		NO3- ppm		
		Cl- ppm		
		OBSERVATIONS		

Sismologie
Date
Heure
Type
Latitude
Longitude
Profondeur
Magnitude
Nbre stations
Err. Loc
Err. Prof

Table 3: Lists of parameters measured by the various GVO departments

As far as the routine measurements at stations are concerned, all the GVO measurement sites have been listed and attributed a code. The coding is essential for instance to avoid misspelling problems or the use of a same name for different sites within a given area. As an example, the Ground Deformation Dept. is using the name Munigi for the tilt station but also for the extensometric measurement site. Both are located in the same village but are few hundred meters away of each other. Site codes are unambiguous and avoid problems that would lead to confusion in the database. The site table contains the site codes, the site names, the geographic coordinates and the department/parameter involved (**Error! Reference source not found.**). The syntax of the code is simple and has been defined arbitrary. GORISK proposed the methodology to the GVO who can of course adapt the structure and the coding according to their own constraints.

					DEPARTMENTS		
Site	Site_Code	Longitude	Latitude	Altitude	Defo	Geoch	Sismo
Bugarura	OVG001	29,24558	-1,62787	1675	T°		
Bugarura 1	OVG002	29,24558	-1,62787	1675	T°	CO2	
Bugarura 2	OVG003	29,24572	-1,62608	1680	T°	CO2	
Bugarura 3	OVG004	29,23895	-1,62892	1660	T°	CO2	
Bulengo	OVG005	29,14050	-1,63292		Tilt / GPS		Sismo
Cabanes	OVG006	29,25167	-1,52303	3179	T°		
Chalet	OVG007	29,20372	-1,67519			CO2 / Rn	
Kanyaruchinia	OVG008					H2O	
Katale	OVG009	29,34180	-1,35745				Sismo
Kibati	OVG010	29,27840	-1,56890		Tilt / GPS		Sismo
Kibati 2	OVG011					H2O	
Kibumba	OVG012	29,33290	-1,51890		Tilt / GPS		Sismo
Kibumba 2	OVG013					H2O	
Kunene	OVG014	29,06720	-1,48552				Sismo
Luboga	OVG015	29.1170	-1.2650				Sismo
Monigi 3	OVG016	29,14740	-1,38151	1621		H2O	
Mubambiro	OVG017					H2O	
Mugara	OVG018	29,24378	-1,61402	1472	T°,Extenso		
Mugunga	OVG019	29,13000	-1,60871	1518		H2O	
Muja	OVG020					H2O	
Munigi 1	OVG021	29,24588	-1,63744	1621	T°	CO2	
Munigi 2	OVG022	29,24260	-1,64276	1621	Tilt		
Ngangi	OVG023	29,21330	-1,63937		Tilt		
Nyiragongo	OVG024	29,25135	-1,52802	3411	T°		
OVG	OVG025	29,22670	-1,68120		Meteo / GPS	H2O	Sismo
Rubavu	OVG026	29,27547	-1,67257	1910	GPS		
Rusayo	OVG027	29,17980	-1,57711		Tilt / GPS	DOAS	Sismo
Rusayo 2	OVG028	29,17980	-1,57711			H2O	
Sake	OVG029	29,05570	-1,56710			DOAS	

Sake-Kimoka	OVG030					H2O	
Shaheru	OVG031	29,25385	-1,54003	2760	T°;Extenso		
Tshubi	OVG032	29,10536	-1,64894		GPS		
Bulengo 1	OVG033	29,14242	-1, 63039				
Bulengo 2	OVG034	29,14378	-1,62975		/Tilt/ GPS		Sismo
Bulengo 3	OVG035	29,14369	-1,62725				
Himbi 1	OVG036	29,19008	-1,66800			CO2	
Himbi 2	OVG037	29,19077	-1,66747			CO2	
Himbi 3	OVG038	29,19008	-1,66800			CO2	
Munigi	OVG039	29,14740	-1,38151	1621		CO2	
Kihira	OVG040	29,04701	-1,57128	1481		H2O	
Kimoka	OVG041						
Kunene 1	OVG042						
Kunene 2	OVG043						
Mubira	OVG045						
Mushaki	OVG046						
Rubavu / Burinda	OVG047						
Rubavu / Rugerero	OVG048						
Kisheke 1	OVG049	29,01452	-1,71147	1479		H2O	
Kisheke 2	OVG050						
Kobe 1	OVG051						
Kobe 2	OVG052						
Tingi	OVG053	29,04727	-1,56247	1498			
Lemera1	OVG054				Extenso		
Lemera 2	OVG055	29.24884	-1.60131		Extenso		
Kaneza 1	OVG056				Extenso		
Kaneza 2	OVG057				Extenso		
Mudjoga 1	OVG057	29.25876	-1.58287		EDM		
Mudjoga 2	OVG058	29.25956	-1.58535		Extenso		
Bitunguru	OVG059				Extenso		
Hop. Gisenyi	OVG060	29.25381	-1.67014		Extenso		
Kinyambasha	OVG061	29.28333	-1.56707	2006	EDM		
Mutaho	OVG062	29.23555	-1.57710	1997	EDM		
Kinyunzu	OVG063	29.22393	-1.61363	1662	EDM		
Rusayo	OVG064	29.18163	-1.57465		Extenso		
Rubavu	OVG065	29.27526	-1.67516	1936	EDM		
Bushwaga	OVG066	29.25991	-1.62644	1859	EDM		
Buhumba	OVG067	29.27035	-1.62966	1960	EDM		
Muja	OVG068	29.21085	-1.61200	1805	EDM		
Mt Goma	OVG069	29.22430	-1. 68138	1594	EDM		
Nyira Som1	OVG070	29.24664	-1.52713	3436	Extenso		
Nyira Som2	OVG071	29.24980	-1.52902	3335	Extenso		
Kingi /Ruhuhuma	OVG072	29.06935	-1.48833	1855		H2O	

Table 4: Table with the most significant measurement sites monitored by GVO and its partners. Not all the GPS coordinates are available because some site have been in use in the past and abandoned. The three involved departments are "Deformation", "Geochemistry", and "Seismology". It is possible that a department has in charge the monitoring of parameters that would logically fall under a more appropriate department, but this has to be considered in the light of previous projects history and "person to person" type of collaboration.

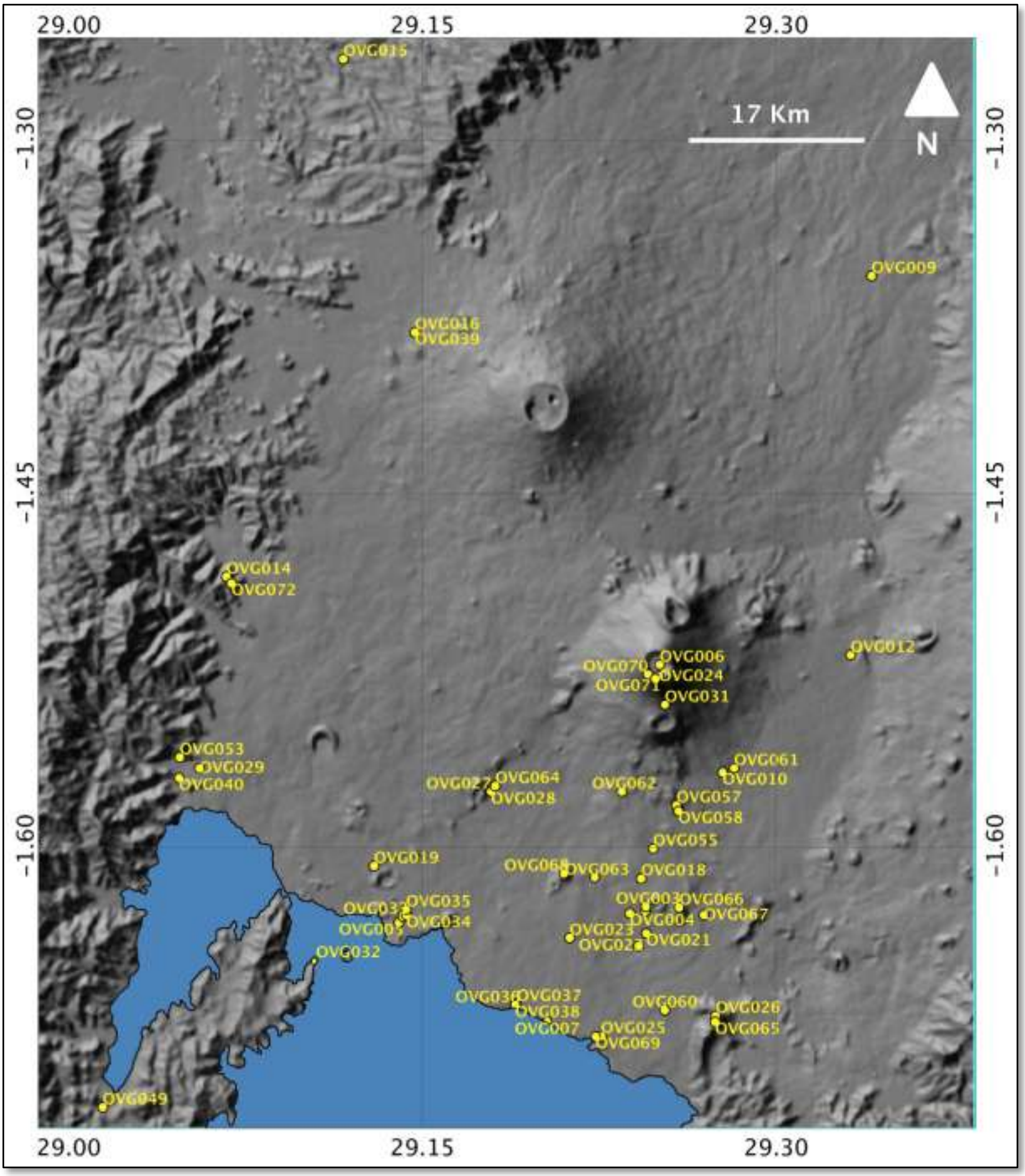


Figure 50: Map of GVO measurement sites. Not all the sites are displayed as some GPS coordinates are reported missing. This is generally the case for abandoned sites i.e. sites where measurements have been occasional.

3.5.2.5. Health data layer

Health data are provided by the CEMUBAC under the tabular format. Each health structure is listed with corresponding indicators. The geographic positioning of the structure either relies on GPS coordinates acquired during the sampling, or on approximate location obtained from variable origins.

As an example, a portion of the table corresponding to respiratory infections is provided below; the data are given in number/trimester (for ex.: irad12000 corresponds to the number of records during the 1st trimester of year 2000).
The records are referenced to the health area and correspond to the data collected at Health Centre of Reference within each area.

Aire	LAT	LONG	irad1 2000	irad2 2000	irad3 2000	irad4 2000	irad1 2001	irad2 2001	irad3 2001	irad4 2001	irad1 2002	irad2 2002
CBCA BAMBU/ZS BIRAMBIZO	-1,11417	29,2228	17	0	26	0	0	76	150	119	42	54
kibirizi	-0,914844	29,200470	0	61	0	0	116	72	141	288	105	179
tongo	-1,38333	26,1333	0	0	0	0	0	0	0	0	0	0
singa	-1,081382	29,116093	61	0	0	0	8	0	8	59	3	0
Butare	-1,141250	29,254583	0	0	0	0	0	0	21	0	116	65
katsiru	-1,121912	29,104007	0	0	0	0	0	0	0	0	186	299
nyanzale	-1,012337	29,102958	0	0	0	0	0	0	0	0	33	19
rusekera	-1,270389	29,195813	0	0	0	0	0	0	0	0	74	198
kishishe	-1,041786	29,209540	0	0	0	0	0	0	0	0	35	9
Kibingo	-0,950012	29,191247	0	48	0	0	17	0	0	13	48	45
bulindi	-0,783333	29,1167	0	13	0	13	0	0	0	76	64	115
birundule	-0,819111	29,106300	0	0	0	0	0	0	0	0	0	0
ngoholo	-1,166667	29,116667	0	0	0	0	0	0	0	0	0	0
kabati	-0,983333	29,0667	0	0	0	0	0	0	0	0	12	0
faraja	-1,083306	29,231270	0	26	0	0	11	34	62	85	116	155
CBCE bambo	-1,11417	29,2228	0	0	0	0	0	0	0	0	102	105

3.6. MAP UPDATE

Until recently, the map for the urban area of Goma did virtually not exist. There is an archive map created in colonial time when Goma was still a very small locality but it strongly contrasts with the size of the current city that grew of about 2.000% in a third of a Century, i.e. evolved from <50.000 inhabitants in 1977 (year of the first historical eruption of Nyiragongo) to about 400.000 in 2002 (year of the second eruption) to about nearly one million inhabitants nowadays.
In 2008, the SODERU NGO has produced a new map based on QuickBird imagery and local GPS surveys. That work was achieved in the frame of the EU-funded CIG project (Centre d'Information Géographique). But with the important demographic movements related to unstable political situation and war, a rapid growth of the urban area is observed. The map of Goma was updated in the frame of GORISK to provide the RMU/UGR end-user with an appropriate support to their crisis management. Planned uses are ranging from emergency evacuation planning (e.g. in case of eruption) to urban planning (cadaster, water & power supplies, etc.). The map is based on very high spatial resolution (1m) IKONOS imagery.
The acquisition of stereo precision IKONOS images was scheduled for the beginning of the project but remained unsuccessful because of the constant atmospheric screen during the whole project duration. As an alternative, archived non-stereo IKONOS images dated from June and July 2008 were used.

3.6.1. Image acquisition and orthorectification

The orthorectification was based on the SRTM-1 DEM and the georeferencing has been performed using 41 Differential GPS ground control points (GCP). The following figure (Figure 51) summarizes the orthorectification processing of the IKONOS image. The estimated accuracy of the final product is 0.5 to 2 pixels in higher relief areas; that corresponds to an accuracy of 0.5 to 2 meters.

3.6.2. Map update

3.6.2.1. The urban map of Goma

The updating process was essentially focused on the road network that has been digitized and classified by categories based on their importance, their surface type or their quality (Table 5). The product is provided to the RMU/UGR end user who can add its own thematic layers related to risk management.

Name_1	Name_2	Type	Surface	Quality
e.g. Rue Goma-Sake	e.g. RN2	- National road - Regional road - Main road - Secondary road - Footpath	- Asphalt - Soil - Gravel	Good (allow a fluid driving) Moderate (damaged road) Bad (poorly suitable for vehicles)

Table 5 : Main attributes (in English) of roads mapped using the IKONOS image.

Two thematic maps have been produced: 1) a map with roads sorted by type and 2) a map with roads sorted by quality (Figure 52 and Figure 53).

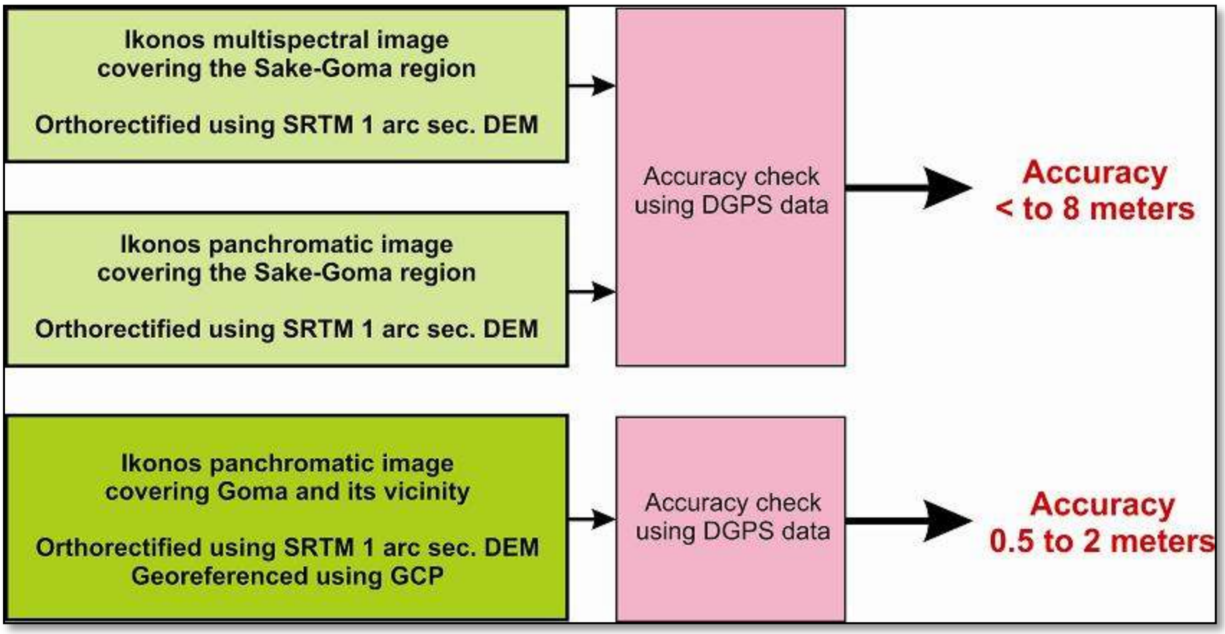


Figure 51: Orthorectification processing of IKONOS images and level of accuracy.

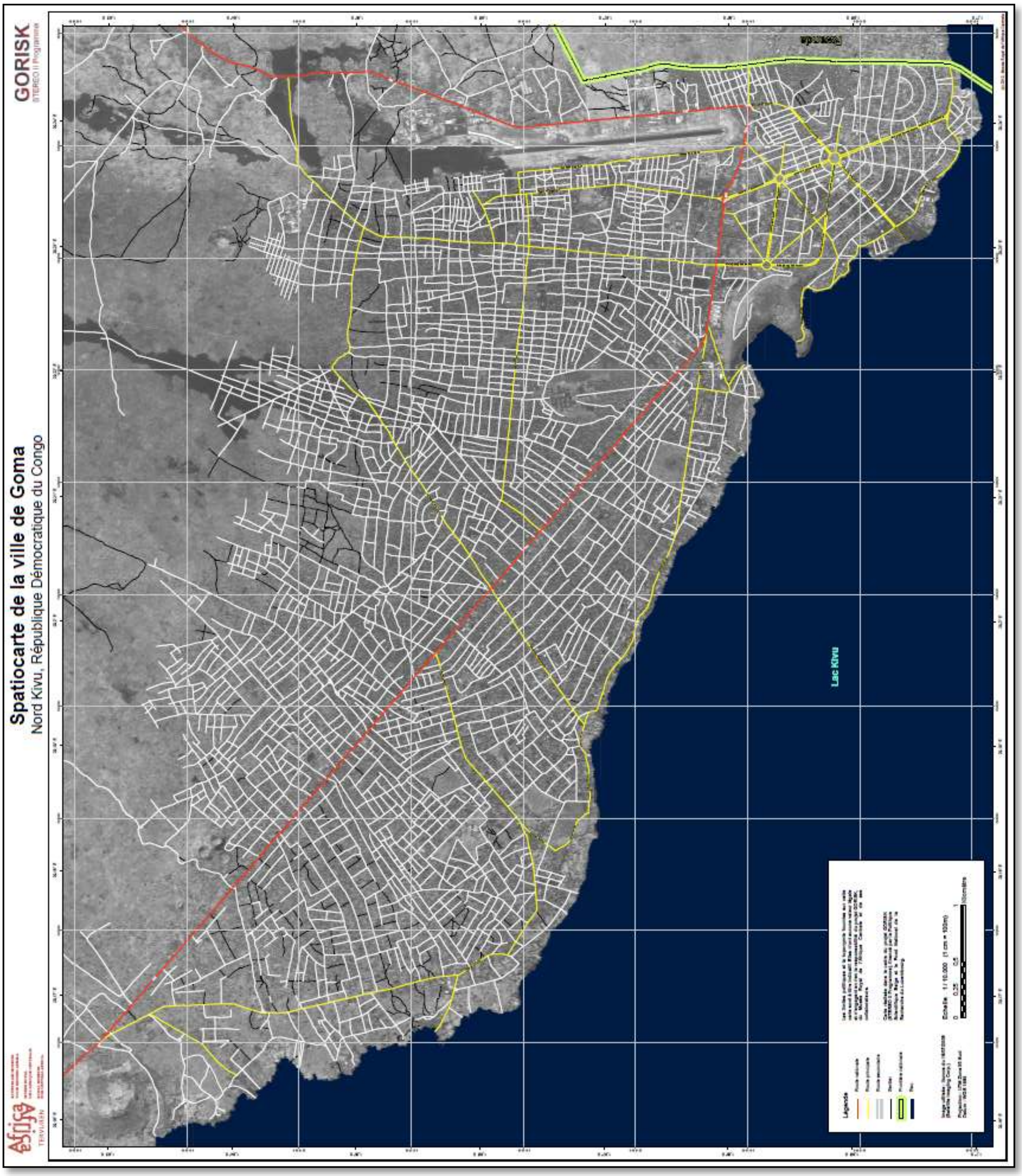


Figure 52 : Map of Goma with roads classified by type. Red lines are national roads, yellow lines are main roads, white lines are secondary roads and black lines are footpaths.

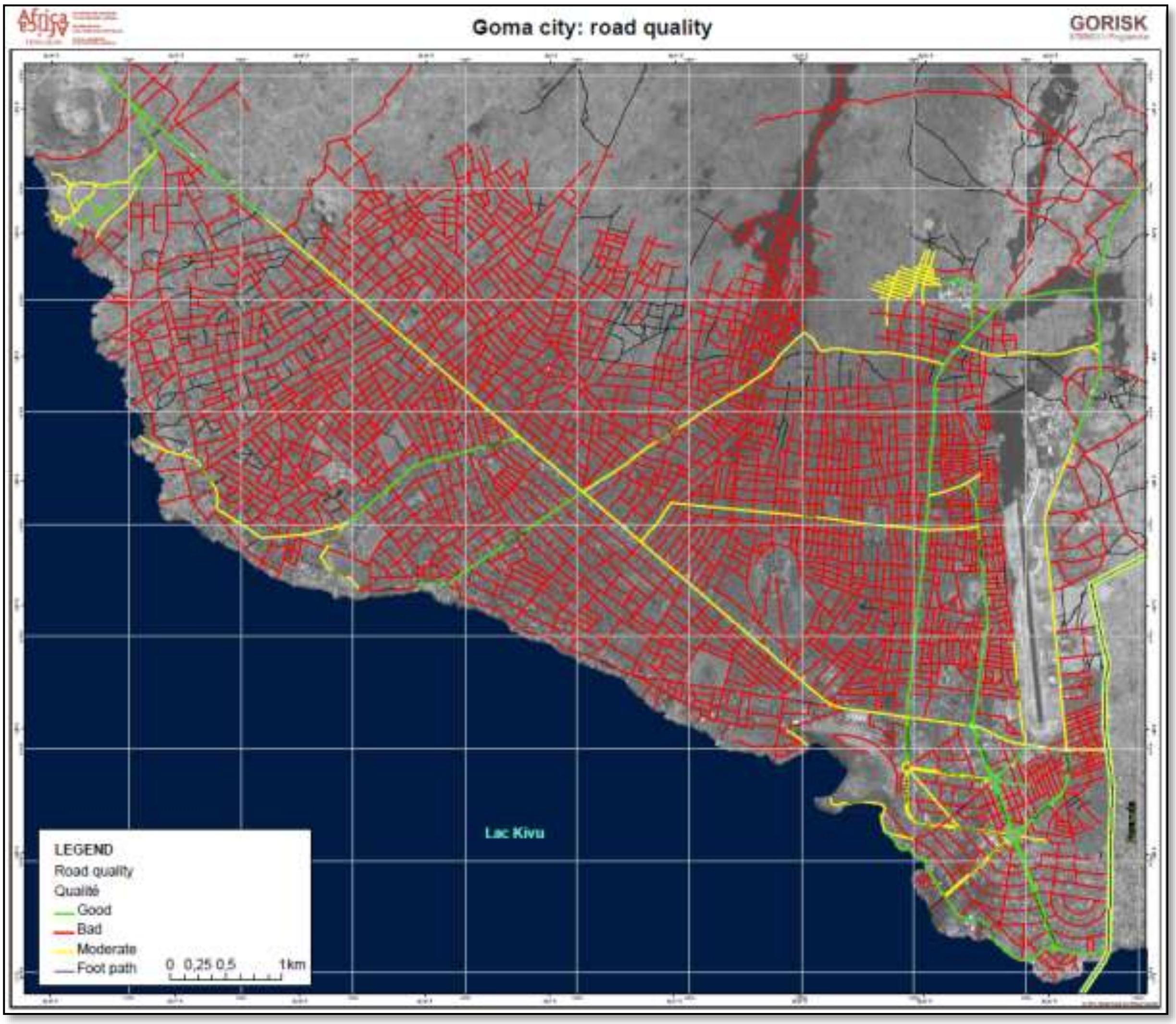


Figure 53: Map of Goma with roads classified by quality. Green lines are good roads, yellow lines are roads with a moderate quality, red lines are damaged and difficult to practice roads, black lines are footpaths.

3.6.2.2. The volcanological map of Nyamulagira

The only existing volcanological map was produced in the 1960’s by Thonnard et al. (1965). This map was realized by interpreting three independent sets of aerial photographs. The mosaic was assembled with the help of 9 triangulated points and theodolite field measurements. Comparison of the digitized and geocoded map with recent GPS measurements in the field revealed local distortions in the map, which induce planimetric errors locally reaching more than 2 kilometres. Contour lines on the 1965 map only give a general idea of the relief as they lack elevation values. In addition, the Nyamulagira erupted 19 times since the production of the 1965 map, which makes the latter totally out-dated.

An updated map with recent lava flows was essential for scientific purposes, but it is also paramount for hazard assessment, environmental and urban management.

Nyamulagira lava flows from 1938 to 2010 were mapped (Figure 54) using optical images (Landsat, ASTER, ALI) as well as amplitude and coherence images derived from radar imagery (ENVISAT-ASAR, ERS, JERS). Integrated in a GIS database with additional data (*e.g.* eruptive fissures, topography, land use, etc.), it provides a flexible and easy-to-update map.

Such an interactive map was of a great help during the management of Nyamulagira eruption in January 2010. Moreover, lava flow lengths, surfaces and volumes were estimated for the last 26 eruptions and contributed to the unravelling of the recent historical eruptive activity at Nyamulagira and to lava flow hazard maps. Combined to lava flow simulations it also provides some insights about possible future eruptions impacts.

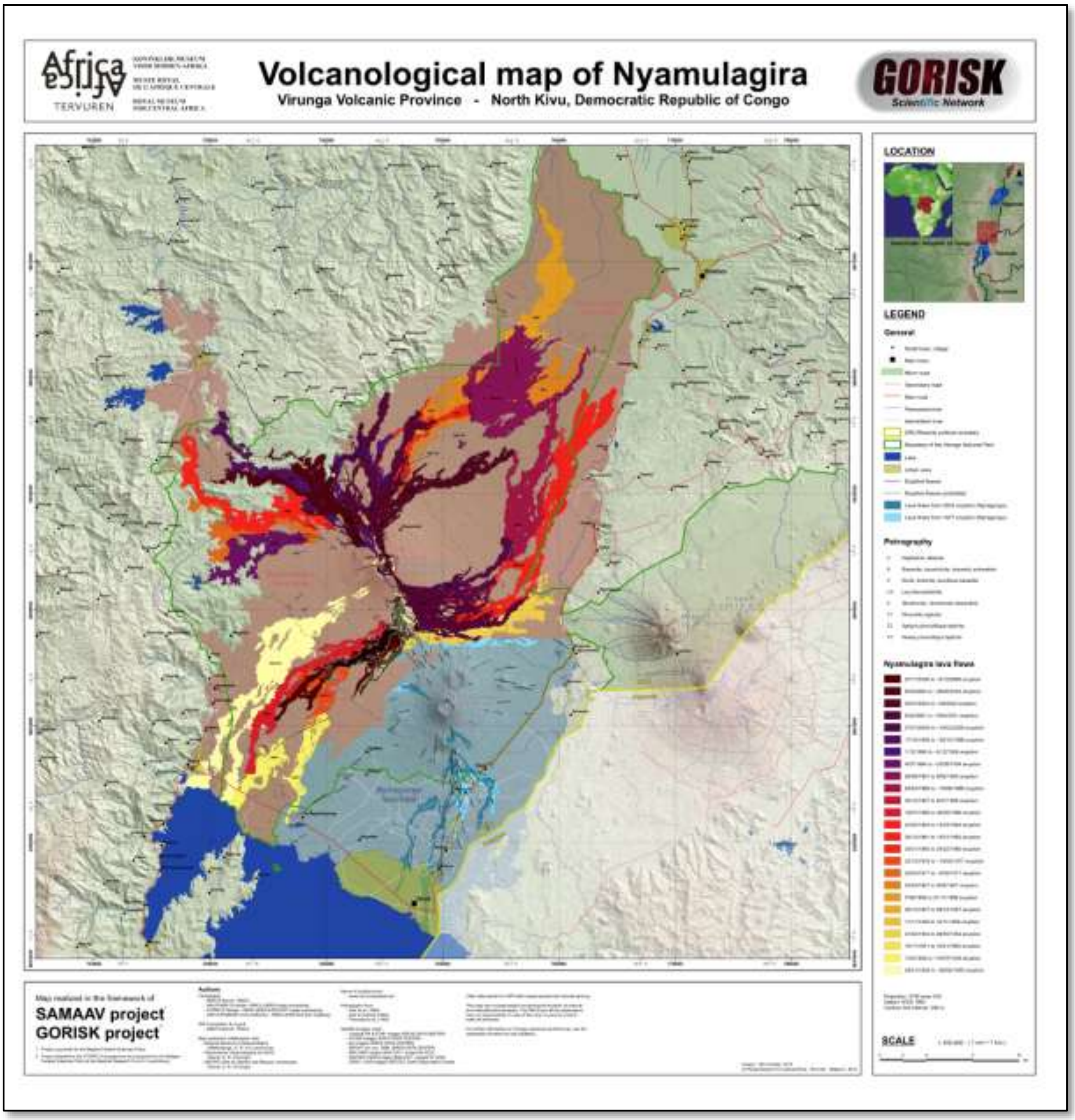


Figure 54: Volcanological map of Nyamulagira: lava flows from 1938 to 2010 were mapped using optical images (Landsat, ASTER, ALI) as well as amplitude and coherence images derived from radar imagery. Lava flows of 1977 and 2002 Nyiragongo eruptions are also visible in light and dark blue respectively.

3.7. GORISK EXTRAS AND OPENINGS

Aside from the initial objectives of the GORISK project, the remotely sensed data helped contributing to other volcanic hazards and environmental issues that were not initially foreseen for being studied.

On the one hand, from the environmental point of view, the data acquired in the frame of the project contributed assessing and even quantifying the deforestation due to lava flows (Smets et al., 2010b). This could be extended to further assessment of anthropogenic deforestation (illegal charcoal production and logging in the Virunga national park, crop field pressure etc.).

On the other hand, from the volcanic related hazards point of view, the project evidenced that mudflows are poorly documented notwithstanding their attested threat. This was recently illustrated to the East of Nyiragongo and Nyamulagira where other Virunga volcanoes are highly affected by erosion. Their main edifices are cut by deep gullies of dense temporary hydrographical networks, which are activated only during heavy rain, triggering torrential events (Jost, 1987). Those torrents, during exceptional rain and in the presence of large amount of unconsolidated alterites and pyroclasts, develop in devastating mudflows as it occurred several times during the last hundred years.

On 16 May 2010, such a mudflow surging form the Karisimbi volcano destroyed 232 houses in the village of Kibiriga (DR Congo), killing about 50 people and devastating 7 hectares of crops (Figure 55). Damages also occurred on the Rwandese flank of the volcano. This event is however the first lethal one ever reported, portraying the dramatic increased risk due to the exponential demographic and urban growth associated to the deforestation and subsequent soil erosion.

This event reveals the need for a global natural hazard assessment and management in the region.

3.8. TRAINING (WP 5000).

To ensure the sustainability of the methodology and to secure the appropriated use of the provided equipment, the involved GVO staff was offered a two levels training.

3.8.1. Training provided onsite

During each the 15 field missions, the staff involved was given training in all covered domains ranging from site selection based on specific criteria, to site monument building, equipment setup, data acquisition, data processing, and general maintenance of the whole chain.

The training was handled during those activities but dedicated sessions were concluded during every mission as well as a plenary session for the whole staff in order to inform the GVO about what was achieved (Figure 56). Some training sessions have been video recorded in order to leave the staff the opportunity to share their knowledge with other staff members or to re-display the movie on demand when the situation requires so.

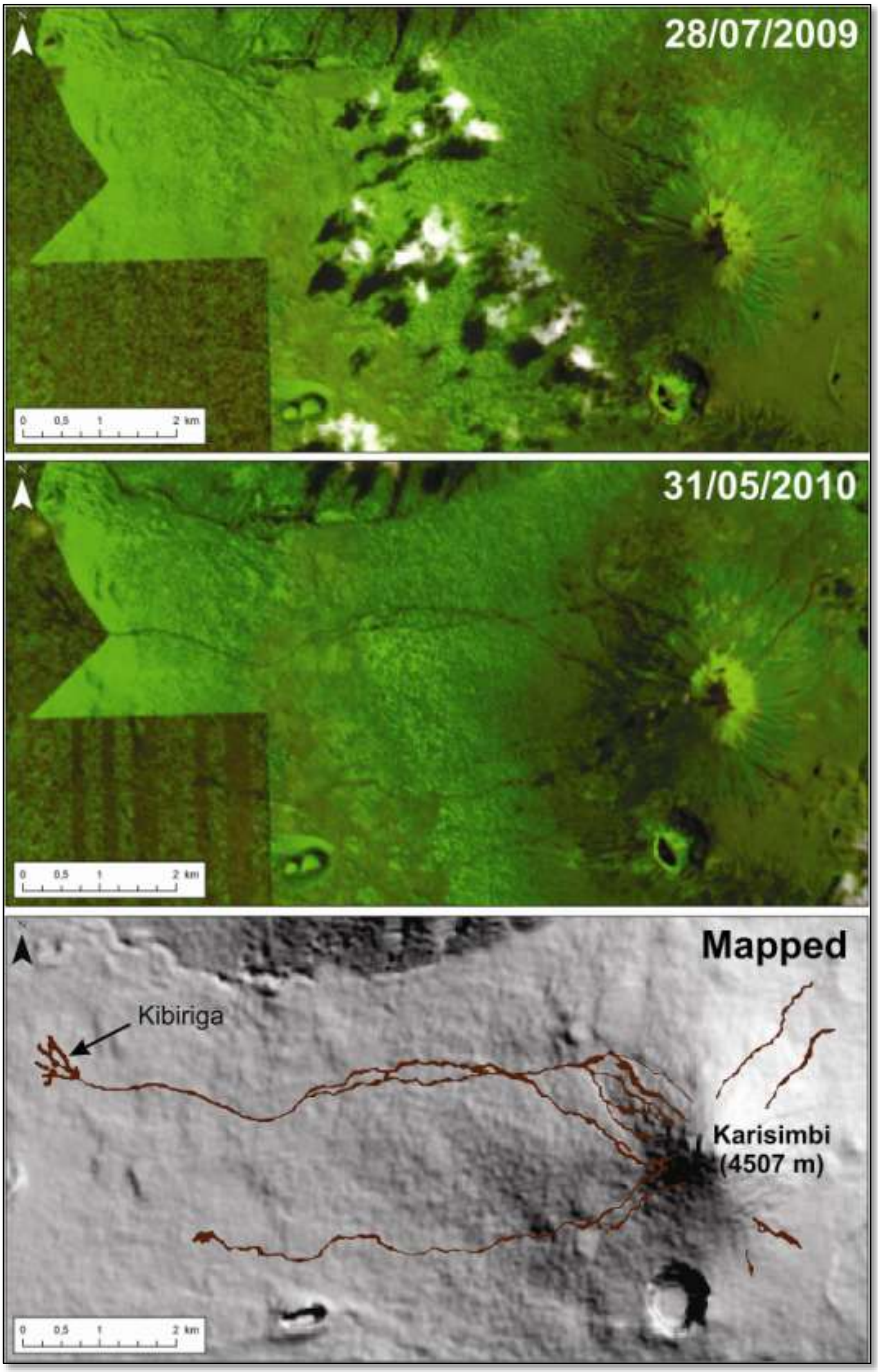


Figure 55: ALI multispectral images from the NASA EO-1 satellite acquired in July 2009 (up) and May 2010 (middle) allowed detecting and mapping likely mudflows (bottom). The two largest mudflows mapped Western of Karisimbi are linked to the 16 May 2010 tragic event.

Specifically written manuals illustrated with screenshots and figures, software and hardware's manuals, blue prints, network detailed descriptions and check lists were also provided at each mission.

Trainings covered the fields of tilt, GPS, GIS, InSAR basics, and geochemistry. Partners from RMCA, NMNH, Uni.lu, and UniNap have all contributed to the local training

Moreover, training is also given trough the important permanent remote assistance provided during the whole duration of the project to solve specific problems (either by e-mail or by phone).

Figure 56: Training seminars at GVO office and during work in the stations.

3.8.2. Training provided outside

Training was also provided outside DRC, in Belgium at RMCA and University of Luxemburg. In 2007, a first session of 4 months at RMCA was focused on the use of GIS and was provided to one GVO staff member (Montfort Bagalwa) and one RMU/UGR staff member (Innocent Badryio). A second session of 2 months at RMCA was dedicated to remote sensing and provided to the same GVO staff member in 2009.

In 2008, Mathieu Yalire was hosted during few weeks at the University of Luxemburg and taught on the use of the CO2 measurement stations.

In addition to dedicated training session, a delegation of 4 (3 GVO, 1 RMU/UGR) has been invited to attend the AVCOR meeting organized in Luxemburg in November 2007. In August 2009, one GVO staff member attended the "*Advanced workshop on evaluating, monitoring, and communicating volcanic and seismic hazards in East Africa. Trieste Italy August 20-24 2009.*"

3.9. VALIDATION BY END-USERS

The eruption of Mount Nyamulagira, one of the most active volcanoes in Africa, has started to erupt on 2nd of January at 2:17am (local time, UTC+2).

It is the first eruption since the beginning of the project and it constitutes a good exercise for a potential eruption of the close neighbour Nyiragongo that is the major concern for the city of Goma. The GORISK team arrived on site on January 10th to assist the Goma Volcano Observatory (GVO) in collecting and processing field data and observations (see Internet site of the RMCA-NMNH Volcano-Tectonic Team[9]). Nyamulagira flows are indeed usually not a direct threat for the population and the infrastructure except when it develops southwards as it was the case. In that situation, monitoring the flow size and speed is crucial to inform the authorities for appropriate decisions.

It is the first time that an eruption in the Virunga is monitored simultaneously and in real time with so many different disciplines: seismology, InSAR, tiltmetry, GPS and visual observations, optical remote sensing (IR/visible). The daily surveys were possible with the gratefully assistance of the MONUC who assists the team with helicopter overflights. This was indeed the only possibility to assess the evolution of the situation and the progression of the flows with repeated GPS waypoints measurements while the field remains hardly accessible due to local insecurity.

3.9.1. Description of the eruption

The eruption started both in the main crater — a 2 x 2,3 km caldera — and along a fracture on the southeastern flank of the volcano. The eruption started without significant precursor but for one hour and a half of increased seismicity. This contrasts with the previous eruption of November 2006 that was preceded by one

[9] http://terra.ecgs.lu/rnvt/

day and a half of seismic precursors. The eruptive activity corresponds to lava fountains and lava flows, gas and ash plume ***Figure 57***).

Figure 57: lava fountains, SE flank of Nyamulagira (top) and active lava channel (bottom) (Photos by B. Smets)

During the first days, a small lava lake with lava fountains appeared in the pit crater located in the northeastern part of the caldera whereas lava flows were spreading in the south and southwestern part of the caldera.
Outside the caldera, on the southeastern flank of Nyamulagira, a wall of lava fountains erupted from a 600 meters-long fissure and lava flowed south, following two main paths (***Figure 58***).

After few days, a 150 m high spatter cone developed on the flank fissure where the eruptive activity concentrated.

The observations made during the January 27th overflight indicated that no lava fountain or lava flows were longer observed. Only fumarolic activity has been seen in the eruptive vent suggesting that the eruption has reached its end. Those visual observations are also confirmed by a steep drop of the seismic activity recorded on January 27th at 11 A.M. UTC (1 P.M. local time).

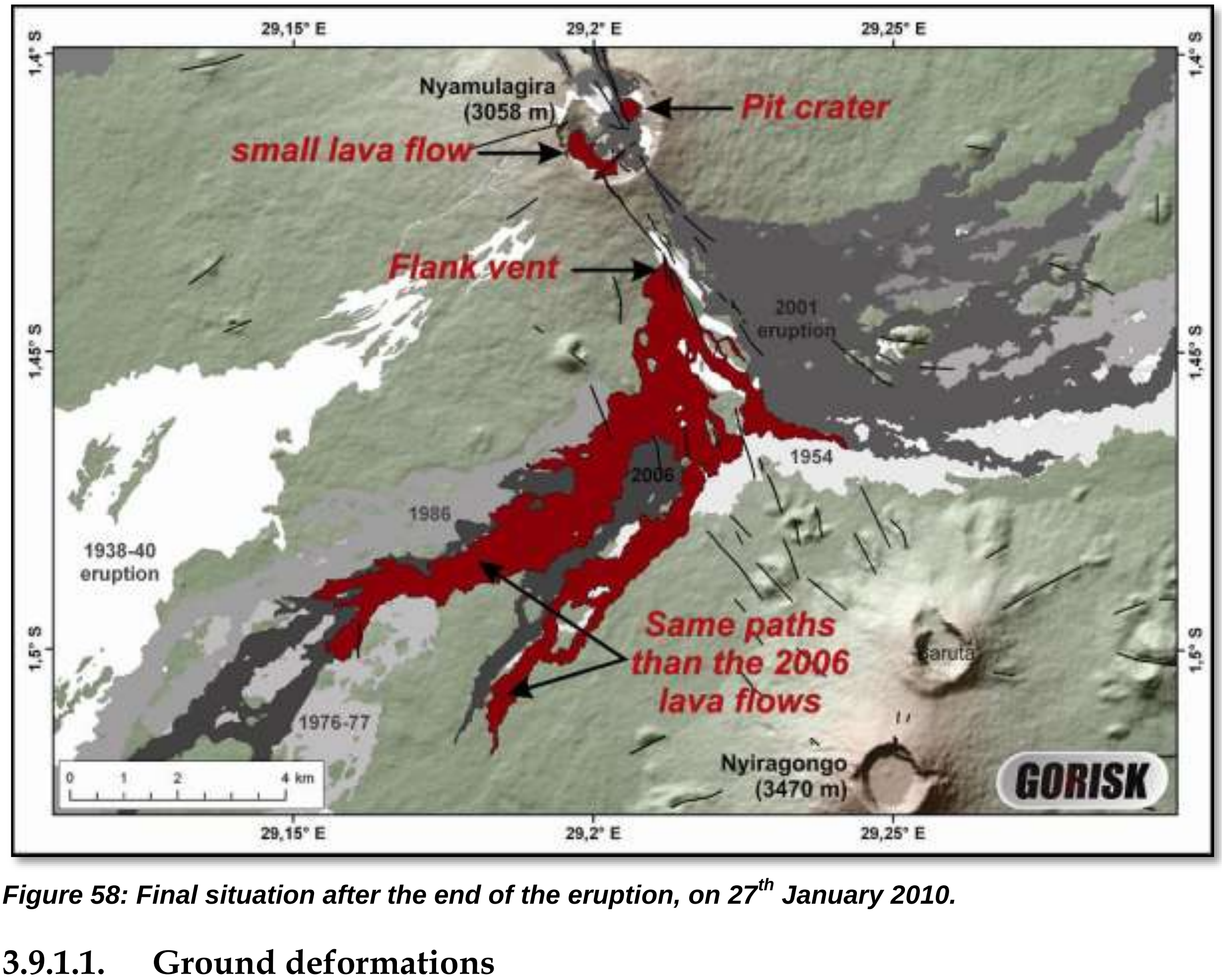


Figure 58: Final situation after the end of the eruption, on 27th January 2010.

3.9.1.1. Ground deformations

At the early stages of the eruption, the authorities and humanitarian community feared that both Nyamulagira and Nyiragongo could be involved. In particular persistent rumours were circulating in the city about possible imminent eruption of the Nyiragongo, creating confusion and fear among the population.

An emergency procedure was started with ESA to ensure that other user on the same orbit would not jeopardize the next ENVISAT acquisition. The first image was acquired on January 8th and less than half an hour after ESA notified its availability on the FTP site, the interferogram was computed. The deformation map directly confirmed that only the Nyamulagira was involved in the eruption. The scientific feedback was provided locally to the community during a meeting held at the OCHA office in Goma and further information from successive images acquired and processed during the next weeks were provided to the local authorities during the daily meetings that were held at GVO.

3.9.1.1.1. ***ENVISAT-ASAR acquisition***

The first image (Descending Track 450) has been acquired on the 8th of January at 7h39 am (UT). The availability notification by ESA has been received the 8th of January at 5h28 pm (LT) and less than half an hour later the first results (deformation, coherence and amplitude images) were obtained. Fifteen minutes more were necessary to obtain the geocoded maps products (ENVI format).

Following images have been received within a little bit longer period of time:

- Image of 11 January 7h44am (UT) (Descending Track 493) has been received the 12 January at 2h16pm (LT) and processed in the evening. As the NMNH partner was in Goma at that time and due to the slow local Internet connection, the data have been processed remotely from Goma on the computers in Luxembourg. Doing so, only the results need to be transferred.
- Image of 14 January 7h50 am (UT) (Descending Track 35), has been received the 19 January at 11h02 am (LT) and processed in the evening (as for the former, on the computers in Luxembourg, managed from Goma)
- Image of 14 January 8h23 pm (UT) (Ascending Track 42) has been received the 27 January at 1h30 am (LT) and processed in Luxembourg during the afternoon.
- Images of 27 January 7h40 am (UT) (Descending Track 221) and of 2 February 8h26 pm (UT) (Ascending Track 314) have been received respectively the 29 January at 6h43 pm (LT) and the 5 February at 00h12pm (LT) and processed immediately.

Results and interpretations

As important and valuable information, InSAR data evidenced a lava flow inside the caldera during the onset of the eruption. The flow was detected thanks to the loss of coherence observed between the image of 8th January 2010 comparatively to the pre-eruption 7th December scene (***Figure 59***).

The loss of coherence observed in the image of 8th January 2010 (***Figure 60***) also allowed detecting part of the flow as it partly covered the coherent 2006 fresh lava flow. Indeed, the eruption took place in the forest where phase coherence is not preserved and the lava flow not detected by InSAR except in areas of pre-existing coherence.

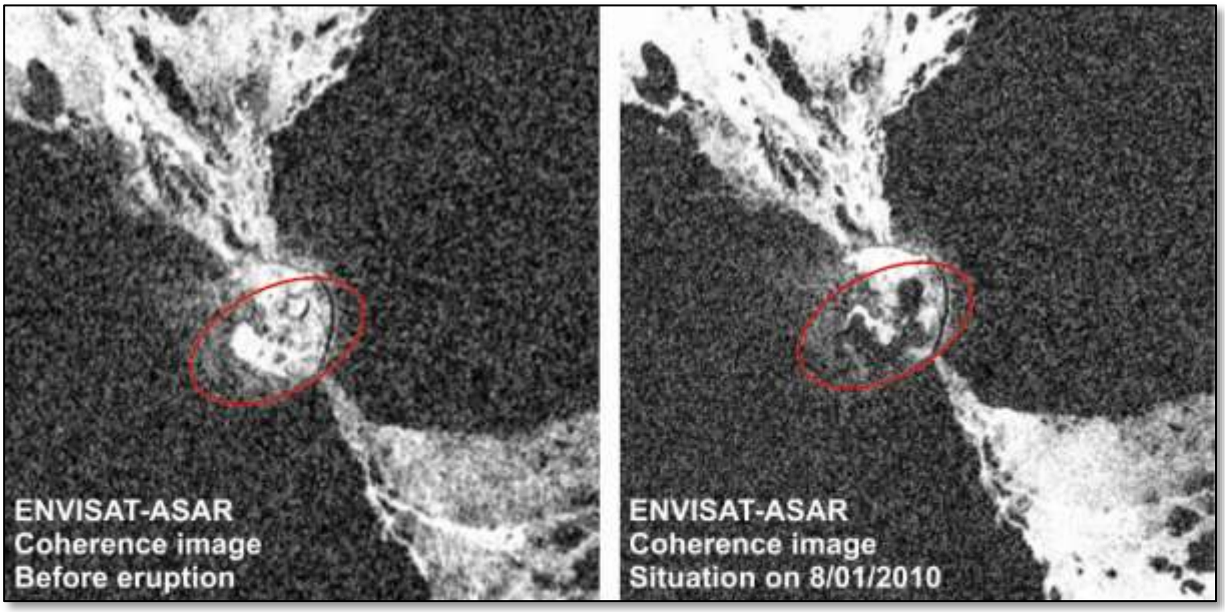


Figure 59: Coherence images from 7th December 2009 (left) and 8th January 2010 (right). ENVISAT-ASAR imagery acquired in the framework of the ESA CAT-1 project nr 3224). Red circle shows the decorrelation associated to the lava flow inside the caldera.

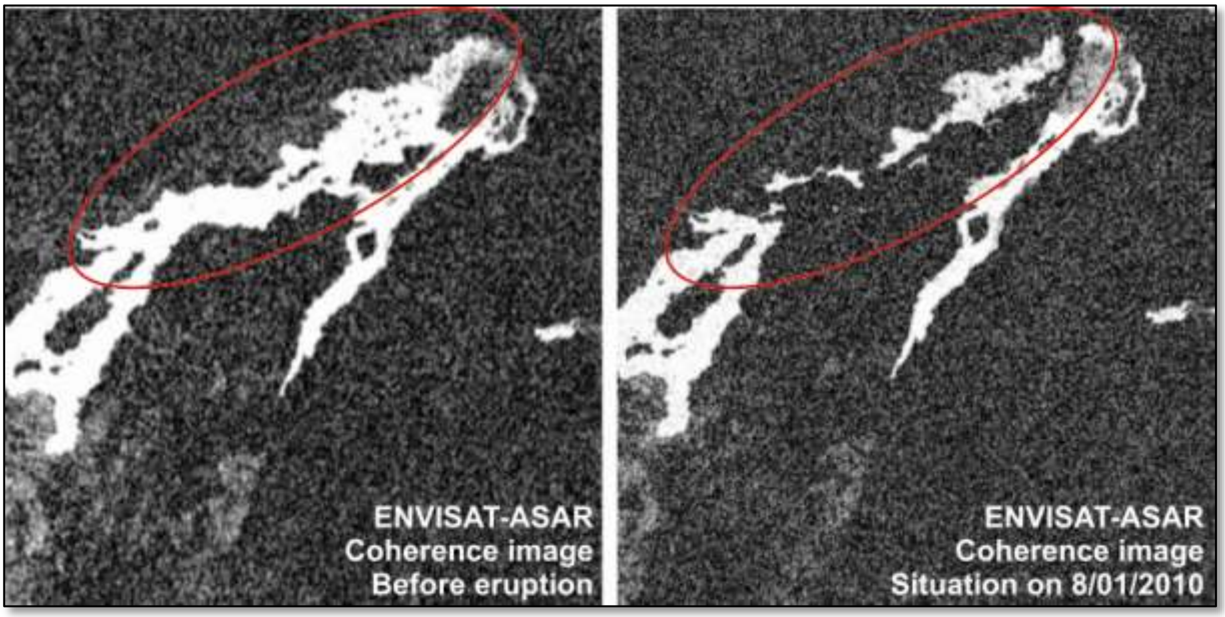


Figure 60: Coherence images from 7th December 2009 (left) and 8th January 2010 (right). ENVISAT-ASAR imagery acquired in the framework of the ESA CAT-1 project nr 3224). Red circle shows the decorrelation associated to the lava flow along the Southern flank of the volcano.

The first interferogram calculated on 8th January 2010 (Figure 61) showed the ground deformation due to the 2nd January 2010 eruption. Each fringe on the interferogram represents 2.8 cm of movement in the satellite direction.

Preliminary forward modeling shows that diking processes as well as deflation of the Nyamulagira magmatic chamber are involved to explain the InSAR displacements. Interestingly, two dikes and spherical magma source are needed to explain most of the deformation, as it was the case for the 2006 eruption.

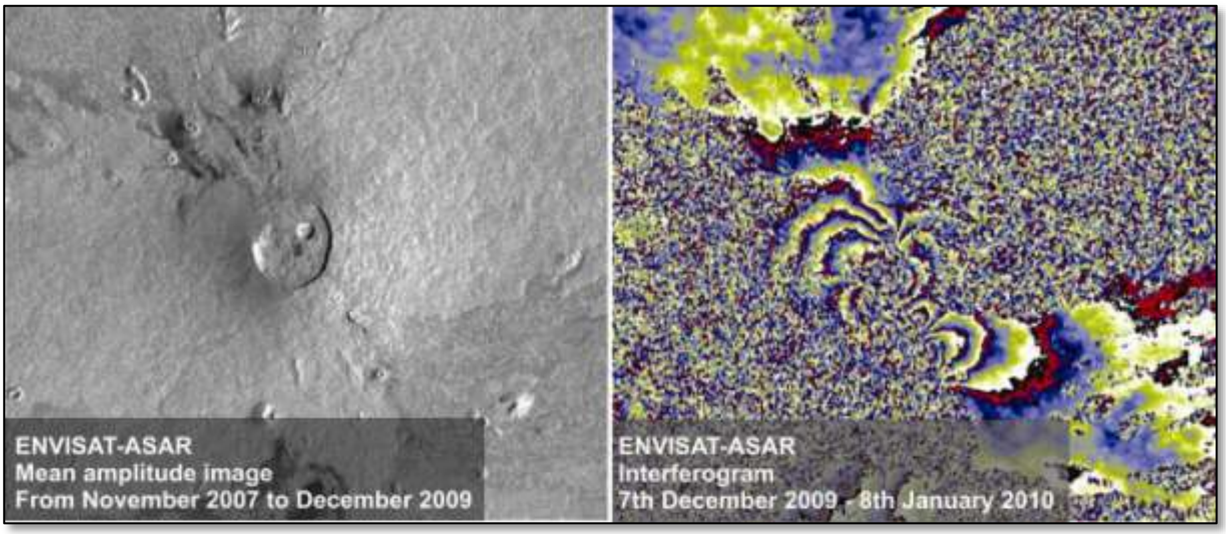


Figure 61: *Amplitude image showing the Nyamulagira (left). Phase signal associated over the same area (right): the first interferogram computed shows the ground deformation due to the 2nd January 2010 eruption. Each fringe on the interferogram represents 2.8 cm of movement in the satellite direction.*

3.9.1.1.2. *Tiltmeters and GPS stations*

The GPS network:

At the time of the eruption, 3 GPS stations were operating: GVO, RSY and RBV. The northern branch of the network experienced a transmission problem at the relay station of KBT hence affecting KBB. TSI and RBV were not operational yet.

The resolution of the real time baseline computations did not allowed to detect any significant changes above the noise level that could be associated to the eruption. However the post processing made at University of Madrid (Instituto de Astronomia y Geodesia; CSIC-UCM) with the Bernese 5.0, using jointly GPS and GLONASS observations, as well as precise ephemerides and earth orientation parameters revealed clear displacements (up to ~2cm) associated to the eruption. The closer the station, the larger are the observed signals (Figure 62, Figure 63, Figure 64).

Precise Point Positioning (PPP), daily and weekly solutions were computed spanning the four months period from October 27, 2009 to February 28, 2010. Signals were too small to be seen on the PPP solutions but were clearly seen for the 3 stations on the weekly solutions (see figures). In addition, displacements are too small to be detected clearly with the epoch-by-epoch technique, though a small jump (up to approx. 2 cm) can be detected in the coordinates of BLG, OVG and RSY for January 2, 2010, between 01:00 and 07:00 hours.

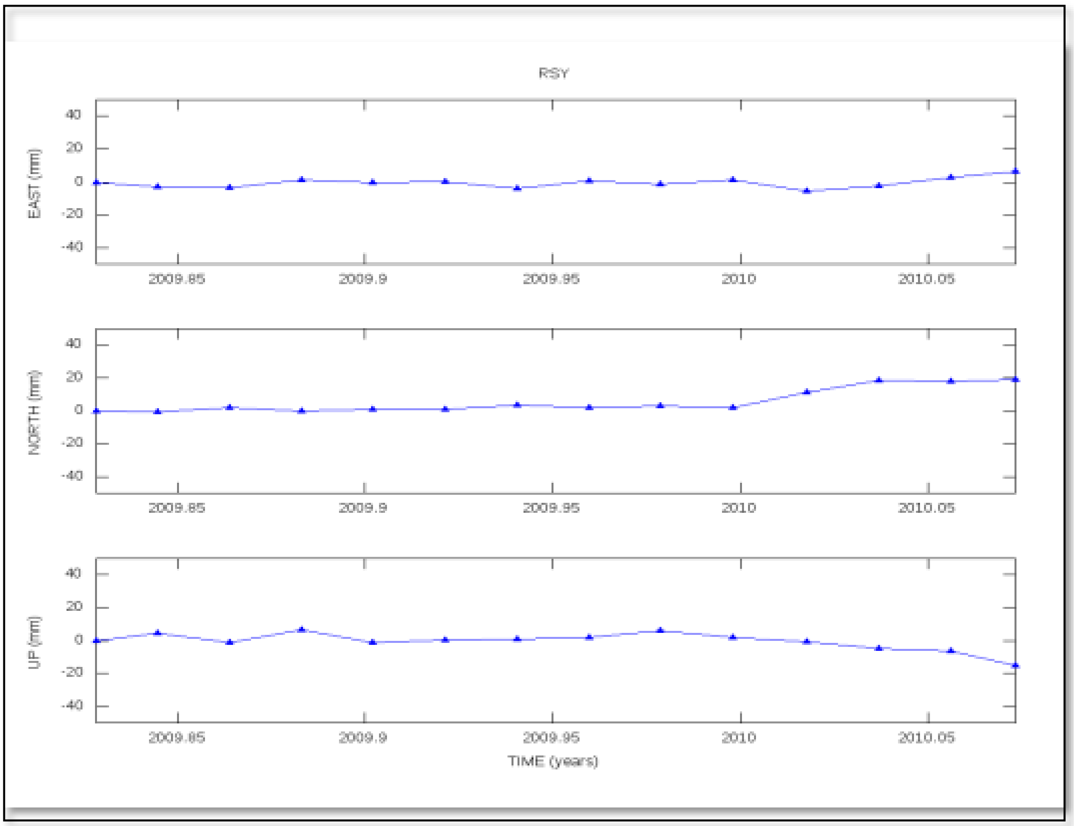


Figure 62: Weekly solutions at Rusayo station (15 km from the main eruptive center): East, North and vertical displacement (in mm).

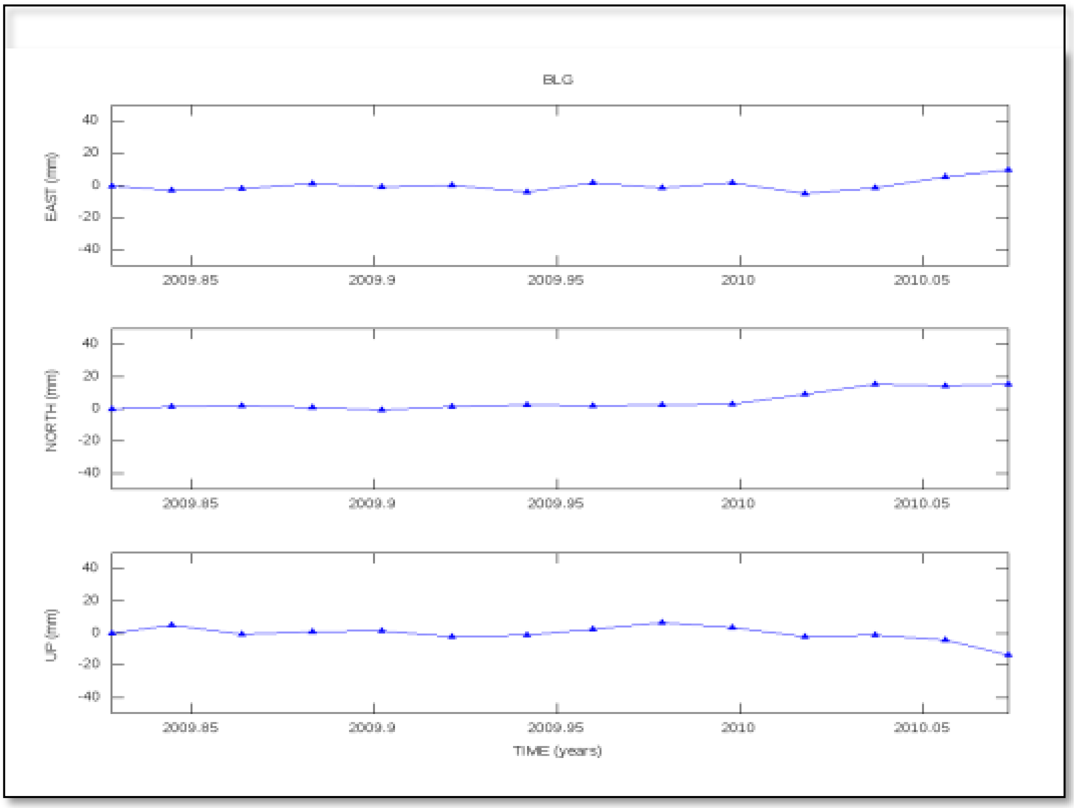


Figure 63: Weekly solutions at Bulengo station (23 km from the main eruptive center): East, North and vertical displacement (in mm).

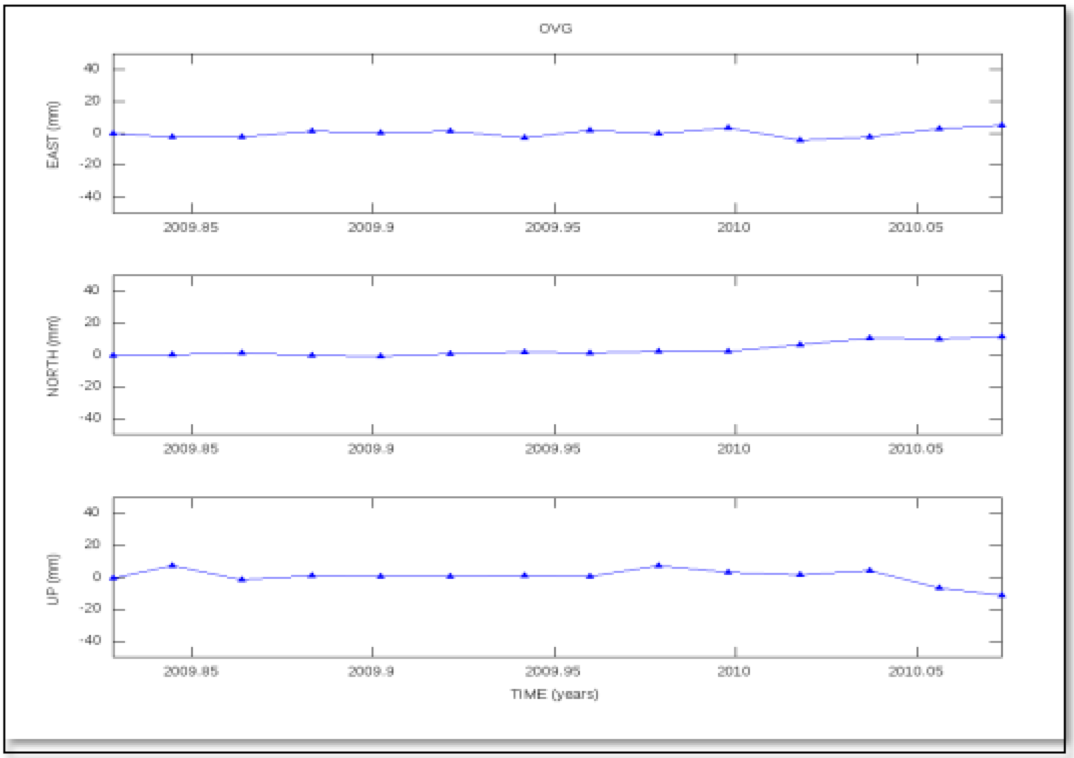


Figure 64: Weekly solutions at Mount Goma station (26 km from the main eruptive center): East, North and vertical displacement (in mm).

<u>The Tilt network:</u>

As mentioned here above, the interpretation of the tilt data is hampered by the numerous gaps and power supply failures. It will require more detailed analysis though one can already clearly observe a sharp increase of the background noise at the time of the onset, then a variation of the noise level that could be clearly correlated with the different phases of the eruption, and a sharp decrease after January 27th 2010 when the eruption stopped (***Figure 65***). Such variations and level of noise were never observed since the beginning of the records in 2007 (i.e. without occurrence of other eruption).

3.9.1.1.3. *NOVAC Results*

It is interesting to show the period between 1 and 10 January 2010 (Figure 66), given the explosive eruption of Nyamulagira that has been detected by the instruments.

3.9.1.1.4. *VISOR results*

First information about the spatial dispersion of the plume accompanying the eruption and the estimation of its SO_2 concentration - very important for the monitoring and the managing of the eruptive crisis - have been provided by the VISOR partner.

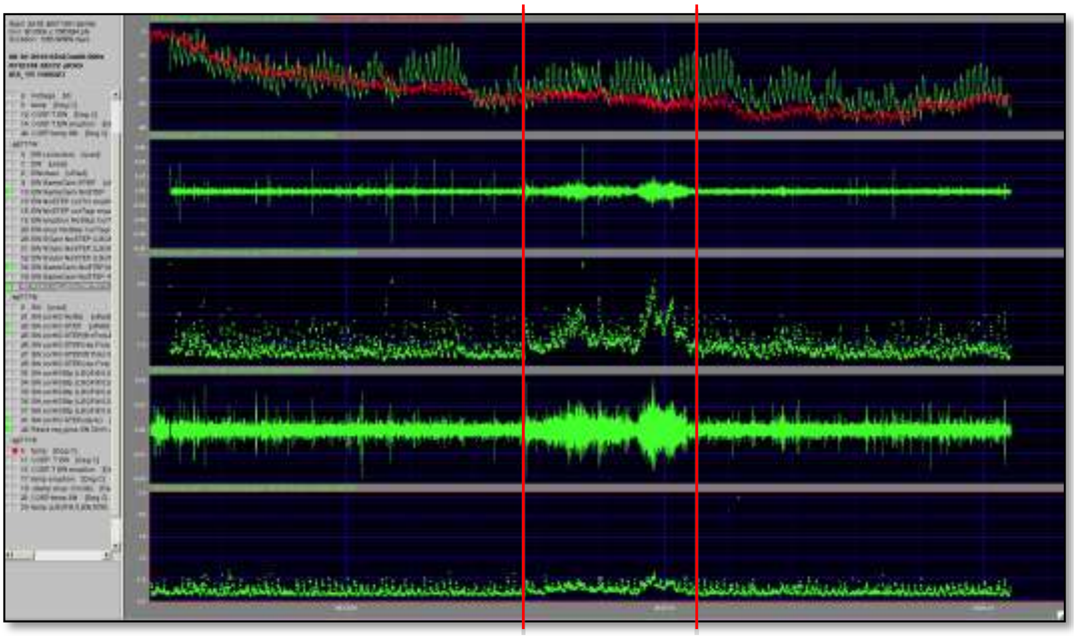


Figure 65: 140 days of records at Bulengo station. From top to bottom: EW (green) & SN (red) tilt; EW time derivative; Residuals of moving linear regression of EW tilt vs T° (3h long data sample with a 1h overlap); SN time derivative; Residuals of moving linear regression of SN tilt vs T° (3h long data sample with a 1h overlap). Sharp variations of the noise level are observed at the time of the eruption (red lines) on both components. Similar variations are observed for every tilt station.

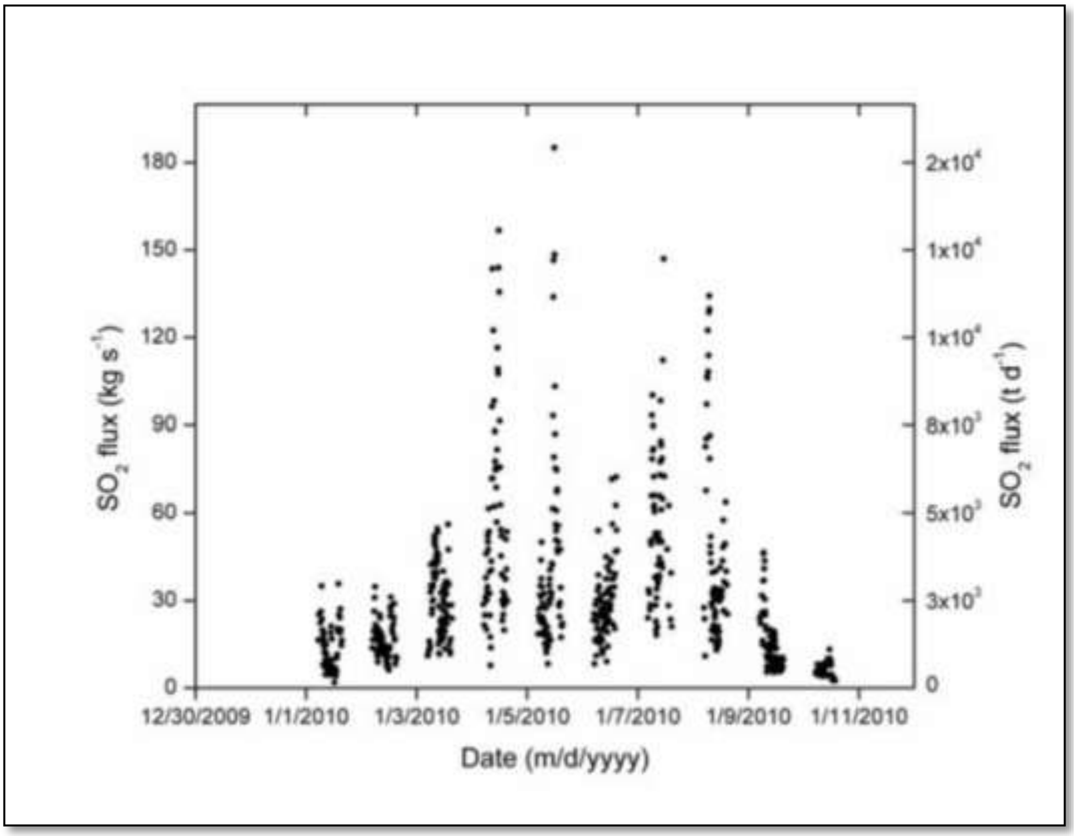


Figure 66: SO2 fluxes observed at Nyiragongo during 1-10 January 2010. The peaks may correspond to the eruption of Nyamulagira volcano on the first hours of 2 January 2010.

Unfortunately, due to a problem with the OMI satellite instrument that measures the SO2 concentrations, there were significant data gaps in the daily data that would produce artefacts in daily shapefiles. As a consequence, some averaging was needed to fill in the gaps. Figure 67 presents the SO2 dispersion and concentration averaged for the period between the 2nd and 6th of January.

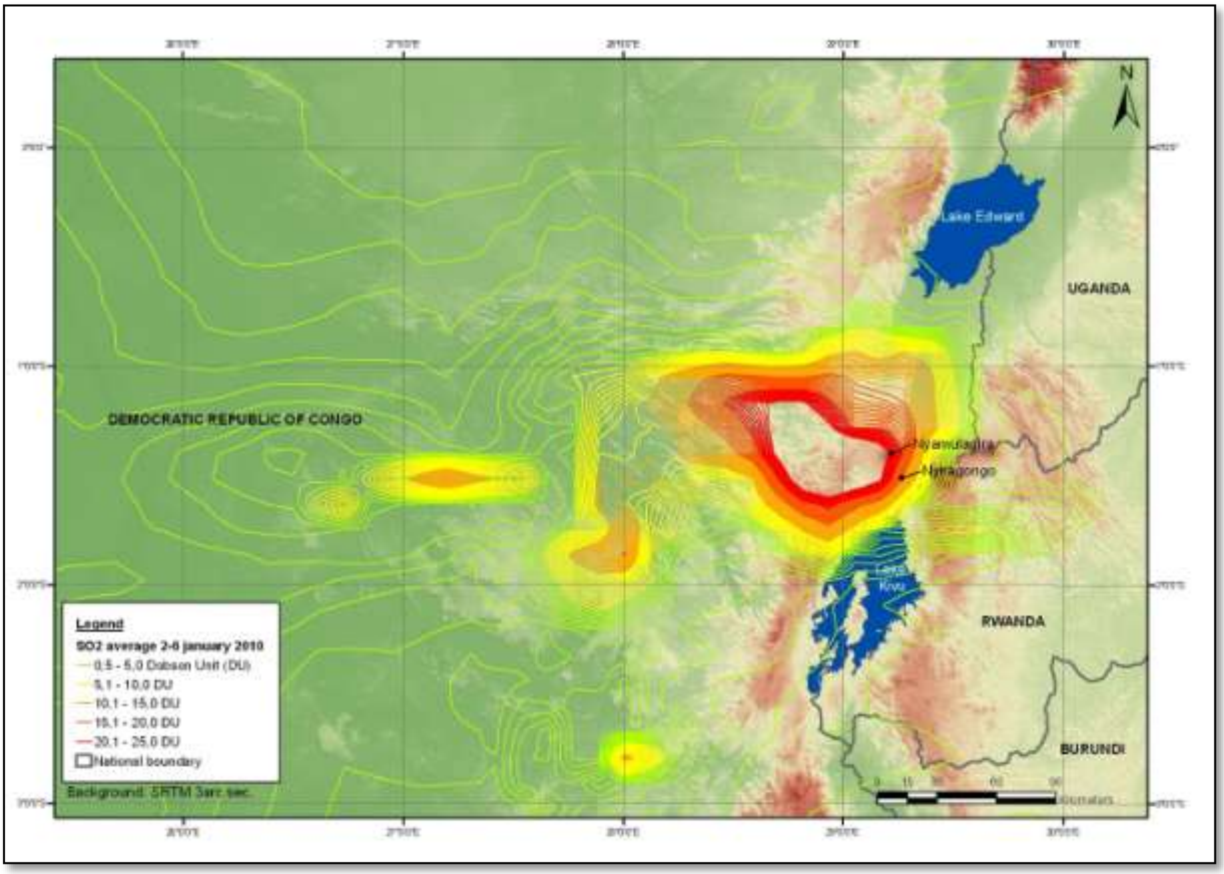


Figure 67: SO2 dispersion map for the averaged period from 2nd to 6th January 2010

The concentrations in SO2 are significantly higher than the mean observed during the last months. Such a sharp event is suspected to significantly contribute to population health impact. Hence corresponding health data should be processed separately.

3.9.1.1.5. *GORISK real-time monitoring and hazard assessment*

All information collected by the GVO and the GORISK partner from spaceborne and ground-based monitoring as well as from helicopter overflights were daily processed and interpreted in order to give a fast response to the needs of the local authorities and those of the important humanitarian community of Goma (Figure 68). Using the GORISK GIS database, quick maps were produced in order to show the evolution of the eruption (Figure 69) at the daily crisis meetings organized by the GVO. The GORISK database also allowed comparing the 2010 eruption with the previous events.

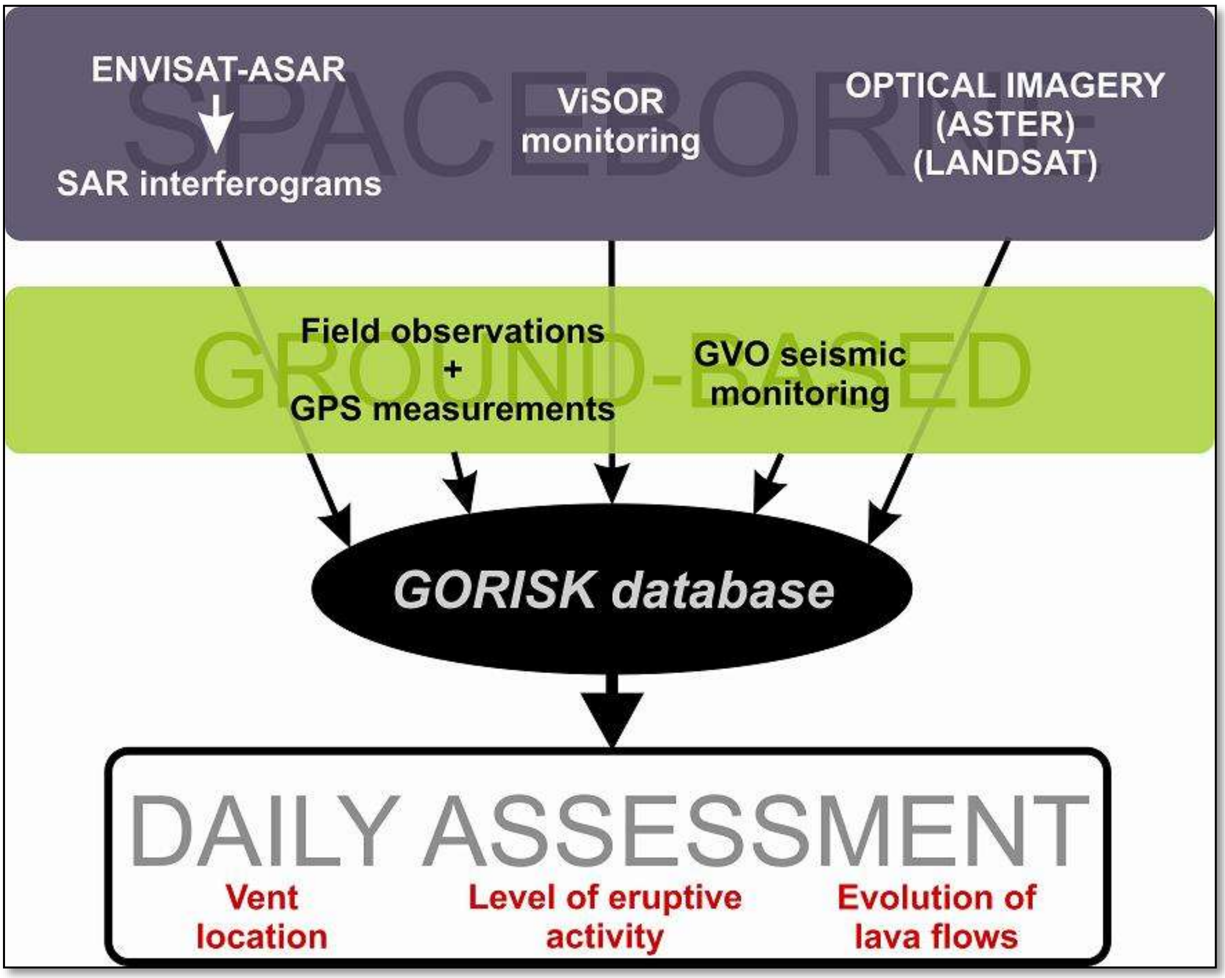


Figure 68: ***Scheme of the data processing in order to provide a daily hazard assessment during the eruption. Both spaceborne and ground-based monitoring techniques were useful to assess the level of volcanic activity.***

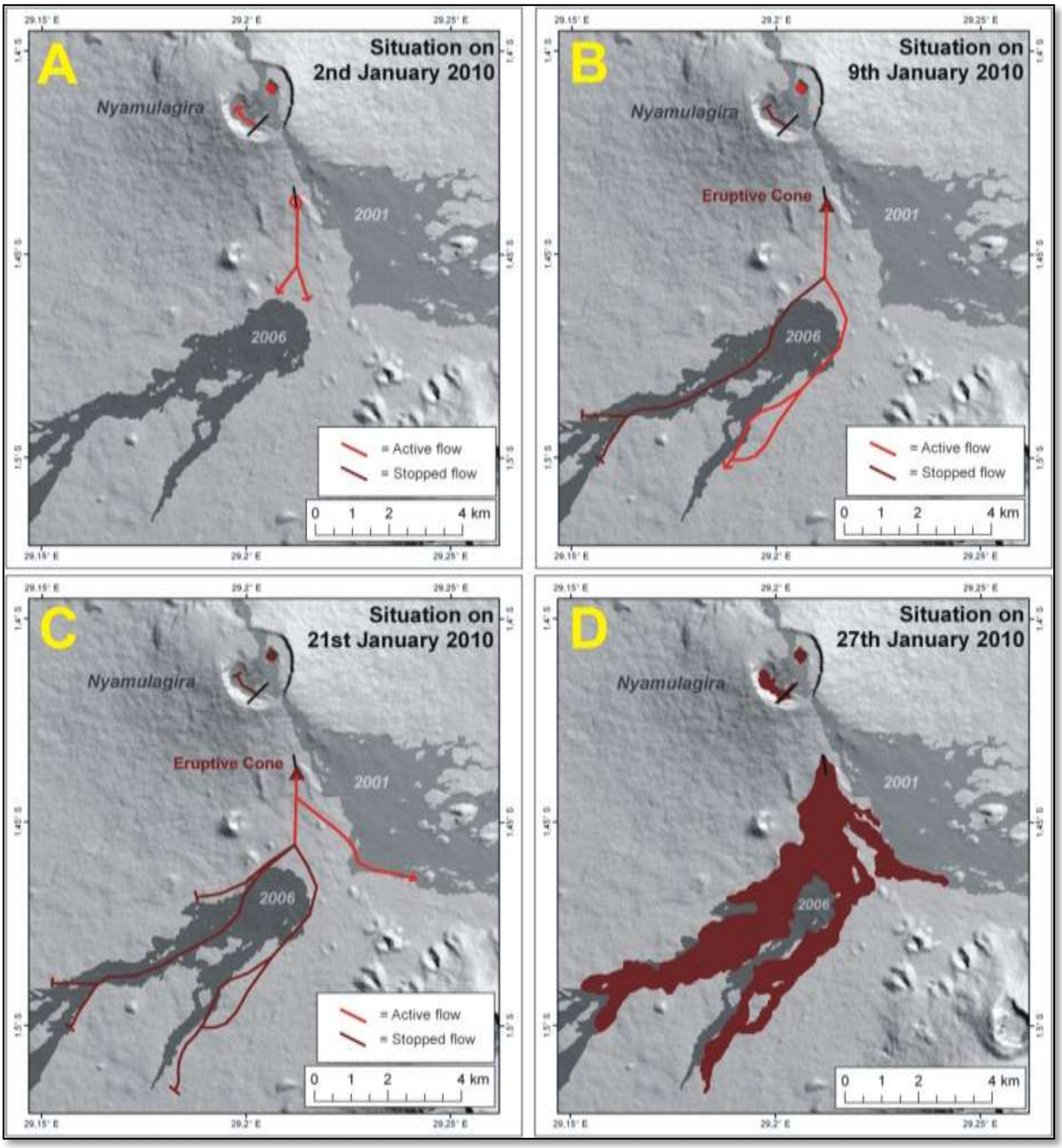


***Figure 69:** Four examples of quick maps produced in order to show the evolution of the different lava flow paths. The figure D shows the final status of the eruption mapped at the end of the eruption using ASTER thermal bands.*

3.10. DISSEMINATION (WP 11000)

Results and products were disseminated through various means:

- 4 peer reviewed papers and 3 more in prep. for international scientific journals (see 3.10.1.1).
- 2 special volumes (see 3.10.1.2)
- 3 peer reviewed proceedings (see 3.10.1.3) and one extended proceeding (see 3.10.1.4)
- More than 50 abstracts (see 3.10.1.5) presented at 20 international conferences (see 3.10.2)

- Geological map (see 3.6.2.2), updated urban maps (see 3.6.2.1) and mapping of mazuku (see 3.3.2.1.2)
- Web tools for InSAR products (see 3.2.1.1.2)
- Manuals and protocols for maintenance and data processing (see 3.8)
- Video of training session (see 3.8.1)
- Various articles in newspapers and TV show (see 3.10.3.1)
- Various websites related to the project (3.10.3.2)
- Various reportage on internet after the January 2010 eruption (3.10.3.3)
- Various working visits and meetings
- Contributions to Global Volcanism Program (see 3.10.3.3)
- Large database of pictures (eruptions, evolution of the lava lake in the Nyiragongo crater etc…) (see 3.10.3.4)
- Participation to public photo exhibition (see 3.10.3.4)
- Organisation of the AVCOR workshop, contribution to the Lake Kivu workshop. (see 3.10.3.5)
- White paper of the Lake Kivu Workshop (3.10.3.5)
- Training sessions in RDC and Europe (see 3.8)
- 3 scientific seminars (see 3.10.3.6)

3.10.1. Publications (Peer reviewed, proceedings and abstracts)

3.10.1.1. Peer reviewed publications

The January 2010 eruption of Nyamulagira (North Kivu, D.R. Congo): eruption description using multiple monitoring techniques.
Smets B., et al., In prep.

Nyamulagira 2006 eruption from InSAR.
Cayol V et al., In prep.

Nyiragongo volcano 2002 eruption constrained by multibeam InSAR data.
Wauthier C. et al., In prep.

Source parameters of the 2008 Bukavu-Cyangugu earthquake estimated from InSAR and teleseismic data.
d'Oreye N., Gonzalez P., Shuler A., Oth A., Bagalwa M., Ekström G., Kavotha D., Kervyn F., Lucas C., Lukaya F., Osodundu E., Wauthier C., Fernandez J.
Geophysical Journal International, in press.

A new map of the lava flow field of Nyamulagira (D.R. Congo) from satellite imagery.
Smets, B., Wauthier, C., d'Oreye, N.
Journal of African Earth Science, vol. 58; Iss. 5, 778-786, 2010, doi:10.1016/j.jafrearsci.2010.07.005.

Dry gas vents ("mazuku") in Goma region (North-Kivu, Democratic Republic of Congo): formation and risk assessment.
Smets, B., Tedesco, D., Kervyn, F., Kies, A., Vaselli, O., Yalire, M.M.
Journal of African Earth Sciences, vol. 58; Iss. 5, 787-798, 2010, doi:10.1016/j.jafrearsci.2010.04.008.

Gas isotopic signatures (He, C and Ar) in the Lake Kivu region (western branch of the East African rift system): Geodynamic and volcanological implications.
Tedesco, D., Tassi, F., Vaselli, O., Poreda, R.J., Darrah, T., Cuoco, E., Yalire, M.M.
Journal of Geophysical Research 115, B01205, 2010

3.10.1.2. Peer-reviewed Journal and Book Special Volumes:

Journal of African Earth Sciences, Volume 58, Issue 5, Pages 721-860 (December 2010)

Volume 29 of the "Cahier Bleus" of the European Centre for Geodynamics and Seismology, 131 pp, 2010

3.10.1.3. Peer-reviewed proceedings:

Monitoring of volcanic activity in the Goma region (N-Kivu, Democratic Republic of Congo) and mitigation of related risks by both spaceborne and ground-based techniques: experience of the GORISK project.
van Overbeke A.-C., Bagalwa M., Durieux J., Kavotha D., Kervyn F., Kies A., Lukaya F., Mitangala P., d'Oreye N., Osodundu E., Smets B., Tedesco D., Wauthier C., Yalire M.M.
Cahier du Centre Européen de Géodynamique et de Séismologie, vol.29, 89-96, 2010

Modeling of InSAR displacements related with the January 2002 eruption of Nyiragongo volcano.
Wauthier C., Cayol V., Kervyn F., d'Oreye N.
Cahier du Centre Européen de Géodynamique et de Séismologie, vol.29, 115-128, 2010

Automatic InSAR systematic processing and web based tool for efficient data mining: application to volcano monitoring in Africa.
d'Oreye N., Celli G.
Cahier du Centre Européen de Géodynamique et de Séismologie, vol.29, 23-32, 2010.
Also available in ESA Special Publications SP-677 on CD-ROM.

3.10.1.4. Extended Proceedings

Systematic InSAR Monitoring of African Active Volcanic Zones: What we have learned in three years, or a harvest beyond our expectations.
d'Oreye N., Kervyn F., Calais E., Cayol V., Fernández J., Frischknecht C., Gonzales P., Heleno S., Oyen A., Wauthier C.
Proc. Second workshop on USE of Remote Sensing Techniques for Monitoring Volcanoes and Seismogenic Areas (USEReST 2008), Naples, Italy, November 11-14, 2008, 1-4244-2547-1/08/$20.00 ©2008 IEEE, pp57-62

3.10.1.5. Conference Abstracts

2011

The 2008 seismic crisis in the southern Kivu basin (DR Congo/Rwanda).
d'Oreye N., González P.J. , Shuler A., Oth A., Bagalwa L., Ekström G., Kavotha D., Kervyn F., Lucas C., Lukaya F., Osodundu E., Wauthier C. & Fernández, J.
Abstract, 23rd Colloquium of African Geology, Johannesburg January 8-14th 2011

New insights into eruptive activity and lava flow hazard at Nyamulagira volcano, D.R.C., from a new GIS-based lava flow map.
Benoît Smets, Matthieu Kervyn, FrançoisKervyn, Nicolas d'Oreye, Christelle Wauthier
Abstract, 23rd Colloquium of African Geology, Johannesburg January 8-14th 2011

The january 2002 eruption of Nyiragongo volcano (DRC) captured by InSAR.
Wauthier, C., Cayol, V., Kervyn, F., and d'Oreye, N.
Abstract, 23rd Colloquium of African Geology, Johannesburg January 8-14th 2011

2010

(Re)location of the February 2008 Bukavu earthquake. Was it associated with magma intrusion ?
N. d'Oreye, P.J. Gonzalez, A. Shuler, L. Bagalwa, G. Ekström, D. Kavotha, F. Kervyn, C. Lucas,F. Lukaya, E. Osodundu, A. Oth, C. Wauthier, J. Fernandez
Abstract, Tropical Rift Lake Systems: Integrated Volcanologic, Tectonic, and Biogeochemical, and Geohazard Assessment of Lake Kivu, Gisenyi, Rwanda
13-15 January 2010

Continuous CO2 and Radon recording in/around mazuku.
A. Kies, Z. Tosheva, B. Smets
Abstract, Tropical Rift Lake Systems: Integrated Volcanologic, Tectonic, and Biogeochemical, and Geohazard Assessment of Lake Kivu, Gisenyi, Rwanda
13-15 January 2010

GORISK Project: a multi-disciplinary approach for the monitoring of the volcanic activity in the Goma region (N-Kivu, DRC) and the mitigation of related risks.
A-C van Overbeke, I. Badriyo, M. Bagalwa, K. Karume, D. Kavotha, F. Kervyn, A. Kies, F. Lukaya, P. Mitangala, N. d'Oreye, E. Osodundu, B. Smets, D. Tedesco, C. Wauthier , M. Yalire.
Abstract, Tropical Rift Lake Systems: Integrated Volcanologic, Tectonic, and Biogeochemical, and Geohazard Assessment of Lake Kivu, Gisenyi, Rwanda
13-15 January 2010

Lethal dry gas vents called "mazuku" North of Lake Kivu (D.R. Congo): Preferential location, gas dynamics and their implication for risk management.
B. Smets, F. Kervyn, A. Kies, D. Tedesco, O. Vaselli, M.M. Yalire
Abstract, Tropical Rift Lake Systems: Integrated Volcanologic, Tectonic, and Biogeochemical, and Geohazard Assessment of Lake Kivu, Gisenyi, Rwanda
13-15 January 2010

Lava flow hazard from Nyamulagira volcano (North Kivu, D.R. Congo).
B. Smets, M. Kervyn.
Abstract, Tropical Rift Lake Systems: Integrated Volcanologic, Tectonic, and Biogeochemical, and Geohazard Assessment of Lake Kivu, Gisenyi, Rwanda
13-15 January 2010

The January 2002 eruption of Nyiragongo volcano (DRC) captured by InSAR.
C. Wauthier, V. Cayol, N. d'Oreye, F. Kervyn.
Abstract, Tropical Rift Lake Systems: Integrated Volcanologic, Tectonic, and Biogeochemical, and Geohazard Assessment of Lake Kivu, Gisenyi, Rwanda
13-15 January 2010

InSAR displacements associated with the November 2006 and January 2010 Nyamulagira eruptions.
V. Cayol, C. Wauthier, N. d'Oreye, F. Kervyn, and the GVO Team,
Abstract, Cities on Volcanoes, Tenerife, Canary Islands, (Spain) May 31 to June 4, 2010

Description of the January 2010 Eruption of Nyamulagira (North Kivu, D.R. Congo),
Karume Katcho, Kavotha Deogratias, Kervyn François, Lukaya François, d'Oreye Nicolas, Rukeza Bagalwa, Smets Benoît, Tedesco Dario, Wauthier Christelle and the GVO team,
Abstract, Cities on Volcanoes, Tenerife, Canary Islands, (Spain) May 31 to June 4, 2010

Study of the Nyiragongo – Nyamulagira Area (Dem. Rep. of Congo) by Means of Multi-Temporal InSAR Approaches: Comparison of the Stamps (TU Delft) and SBAS (IREA) methods.
Wauthier, C., Hooper, A., Sansosti, E., Zeni, G., Pepe, A., d'Oreye, N.
Abstract, Cities on Volcanoes, Tenerife, Canary Islands, (Spain) May 31 to June 4, 2010

The Combined Use of Multispectral and Radar Satellite Images to Map the Lava Flow Field of Nyamulagira (North Kivu, D.R.C.).
Smets Benoît, Wauthier Christelle, d'Oreye Nicolas
Abstract, Cities on Volcanoes, Tenerife, Canary Islands, (Spain) May 31 to June 4, 2010

SBAS-DInSAR Investigation of the displacement field at Nyamuragira and Nyiragongo volcanoes in Congo.
G. Zeni, A. Pepe, P. Tizzani, S. Pepe, G. Solaro, N. D'Oreye, J. Fernandez, P. Gonzalez, E. Sansosti
Abstract, Cities on Volcanoes, Tenerife, Canary Islands, (Spain) May 31 to June 4, 2010

Analysis of historical eruptive activity at Nyamulagira (North Kivu, D.R.C.): implications for hazards.
B. Smets, M. Kervyn, F. Kervyn
Abstract, Cities on Volcanoes, Tenerife, Canary Islands, (Spain) May 31 to June 4, 2010

New insights into eruptive activity and lava flow hazard at Nyamulagira volcano, D.R.C., from a new GIS-based lava flow map.
Benoît Smets, Matthieu Kervyn, François Kervyn, Nicolas d'Oreye, Christelle Wauthier
Abstract, AGU 13–17 December 2010, San Francisco, California, USA

Activity of Nyiragongo and Nyamulagira Volcanoes (Dem. Rep. of Congo) Revealed Using Geological, Geophysical and InSAR data
C. Wauthier, V. Cayol, A. Hooper, F. Kervyn, P. Marinkovic, d'Oreye, M. Poland.
Abstract, AGU 13–17 December 2010, San Francisco, California, USA 2010

Temporal and spatial evolution of eruptive activity at Nyamulagira, DRC, and its implications for hazards.
B. Smets, M. Kervyn
Abstract, Europen Geophysical Union General Assembly, May 2-7, 2010
Vienna, Austria

Monitoring of volcanic activity in the Virunga Province (N-Kivu, DRC): Experience of the GORISK project and illustration with the Nyamulagira January 2010 eruption.
Kervyn F., d'Oreye N., Smets B., van Overbeke A-C, Wauthier C., Tedesco D., Kies A., Mitangala P., Badriyo I., Karume K., Kavotha D., Bagalwa M., Yalire M., Lukaya F., Osodundu E.
Abstract, Belgian Earth Observation Day 2010, May 6, 2010, Chaudfontaine, Belgium

2009

Was the February 2008 Bukavu seismic sequence associated with magma intrusion?
N. d'Oreye, P.J. Gonzalez, A. Shuler, L. Bagalwa, G. Ekstöm, J. Fernandez, D. Kavotha, F. Kervyn, C. Lucas, F. Lukaya, E. Osodundu, A. Oth, C. Wauthier.
Abstract, 95th Journée Luxembourgeoises de Géodynamiques, November 9-11, 2009, Echternach, Luxembourg

The MW 5.9 February 3rd 2008 Bukavu Earthquake.
d'Oreye N., Gonzalez P., Shuler A., Bagalwa M., Ekstöm G., Kavotha D., Kervyn F., Lukaya F., Osodundu E., Oth A.
Abstract for 2009 IEEE International Geoscience & Remote Sensing Symposium, July 13-17 2009, Cape Town, Africa

Seismic and volcanic activity in Africa monitored by InSAR.
d'Oreye N., Calais E., Cayol V., Fernández J., Frischknecht C., Gonzalez P., Heleno S., Kervyn F., Marinkovic P., Oyen A., Wauthier C.
Abstract for 2009 IEEE International Geoscience & Remote Sensing Symposium, July 13-17 2009, Cape Town, Africa

InSAR displacements associated to the November 2006 Nyamulagira eruption.
Cayol V., d'Oreye N., Kervyn F., Wauthier C. and the GVO Team
Abstract for 2009 IEEE International Geoscience & Remote Sensing Symposium, July 13-17 2009, Cape Town, Africa

L-band contribution to C-band InSAR studies of African volcanic areas.
Wauthier C., Oyen A.M., Marinkovic P.S., Cayol V., Fernandez J., Gonzalez P., Hanssen R.F., Kervyn F., d'Oreye N., Shirzaei M., Walter T.R.
Abstract for 2009 IEEE International Geoscience & Remote Sensing Symposium, July 13-17 2009, Cape Town, Africa

The January 2002 eruption of Nyiragongo volcano (DRC) captured by InSAR.
Wauthier C., Cayol V., Kervyn F., d'Oreye N.
Abstract for 2009 IEEE International Geoscience & Remote Sensing Symposium, July 13-17 2009, Cape Town, Africa

The importance of remote sensing in the monitoring of volcanic activity in the Goma region (DR of Congo): experience from the gorisk project.
van Overbeke A.-C., Smets B., Wauthier C., d'Oreye N., Tedesco D., Kies A., Mitangala P., Bagalwa M., Yalire M., Lukaya F., Kavotha D., Osodundu E., Durieux J., Kervyn F.
Abstract for 2009 IEEE International Geoscience & Remote Sensing Symposium, July 13-17 2009, Cape Town, Africa

Automatic InSAR systematic processing and web based tool for efficient data mining: application to volcano monitoring in Africa.
N. d'Oreye, and G. Celli.
Abstract, FRINGE09, ESA-ESRIN, Frascati(IT), 30 November - 04 December 2009

InSAR displacements associated to the November 2006 Nyamulagira eruption.
V. Cayol, N. d'Oreye, F. Kervyn, C. Wauthier and the GVO Team
Abstract, FRINGE09, ESA-ESRIN, Frascati(IT), 30 November - 04 December 2009

The January 2002 eruption of Nyiragongo volcano (DRC) captured by InSAR.
Christelle Wauthier, Valérie Cayol, François Kervyn and Nicolas d'Oreye
Abstract, FRINGE09, ESA-ESRIN, Frascati(IT), 30 November - 04 December 2009

Was the February 2008 Bukavu seismic sequence associated with magma intrusion ?
N. d'Oreye, P.J. Gonzalez, A. Shuler, L. Bagalwa, G. Ekstöm, D. Kavotha, F. Kervyn, F. Lukaya, E. Osodundu, A. Oth, C. Wauthier
Abstract, FRINGE09, ESA-ESRIN, Frascati(IT), 30 November - 04 December 2009

Deformation modeling from multiswaths in InSAR data at Nyiragongo and Nyamulagira volcanoes.
V. Cayol, C. Wauthier, N. d'Oreye, F. Kervyn and the GVO staff.

Abstract, Advanced Workshop on Evaluating, Monitoring and Communicating Volcanic and Seismic Hazards in East Africa, Trieste, Italy, August 17-28, 2009

The Goma volcanic observatory around Nyiragongo and Nyamulagira volcanoes.
M. Bagalwa et al.
Abstract, Advanced Workshop on Evaluating, Monitoring and Communicating Volcanic and Seismic Hazards in East Africa, Trieste, Italy, August 17-28, 2009

2008

Three years of systematic ground deformation monitoring of active African volcanoes performed at the National Museum of Natural History of Luxembourg.
d'Oreye N., Kervyn F., Calais E., Cayol V., Fernández J., Frischknecht C., Gonzalez P., Heleno S., Oyen A. and Wauthier C. (2008)
Abstr. Luxembourg Earth Observation Day - Remote sensing applications in hydrology, November 19th 2008, Bourglinster, Luxembourg

InSAR displacements associated to the November 2006 Nyamuragira eruption.
Cayol V., N., d'Oreye N., Kervyn F. and the GVO Team
Abstr. IAVCEI 2008 general assembly, 18-22 August 2008,Reykjavik, Iceland.

Modeling of InSAR displacements related with the January 2002 eruption of Nyiragongo volcano (DRC).
Wauthier C., Cayol V., d'Oreye N., F. Kervyn F.
Abstr. IAVCEI 2008 general assembly, 18-22 August 2008,Reykjavik, Iceland.

GORISK – The combined use of Ground-based and Remote Sensing techniques as a tool for volcanic risk and health impact assessment for the Goma region (N-Kivu, Democratic Republic of Congo).
A.-C. van Overbeke et al.
Abstract, Belgian Earth Observation Day 2008, February 12, 2008, Namur, Belgium

2007

Ground deformations associated to the Nyiragongo 2002 and the Nyamulagira 2006 eruptions (DR Congo) revealed by InSAR.
d'Oreye N., Kervyn F., Cayol V., Wauthier C. and the SAMAAV team
Abstract, 24th Gen. Assembly of the Int. Union of Geod. And Geophys., July 2007, Perugia, Italy

InSAR study and monitoring of the Nyiragongo – Nyamuragira volcanoes, Democratic Republic of Congo.
d'Oreye N., Kervyn F., Fernández J. and the SAMAAV team
Abstract, ESA ENVISAT Symposium, 22-28 April 2007, Montreux (Switzerland)

The November 2006 Nyamulagira eruption revealed by InSAR.
d'Oreye N., Cayol V., Kervyn F. and the GVO team
Abstracts of the 26th ECGS Workshop on "Active Volcanism and Continental Rifting", Luxembourg, 19-21 November 2007

Modeling of InSAR displacements related with the January 2002 eruption of Nyiragongo volcano (DRC).
Wauthier C., Cayol V., Kervyn F. and d'Oreye N.

Abstracts of the 26th ECGS Workshop on "Active Volcanism and Continental Rifting", Luxembourg, 19-21 November 2007

Towards the progressive setup of a GIS platform integrating major monitored volcanic parameters of the GORISK project, Nyiragongo (DR Congo).
Kervyn F., d'Oreye N., van Overbeke A.-C.
Abstracts of the 26th ECGS Workshop on "Active Volcanism and Continental Rifting", Luxembourg, 19-21 November 2007

Recent seismic activity at volcano Nyamulagira, western Rift Valley of Africa.
Lukaya F.N., Kavotha D., Mavonga T., d'Oreye N., Kervyn F., Durieux J., Bizimana R., Wafula M.
Abstracts of the 26th ECGS Workshop on "Active Volcanism and Continental Rifting", Luxembourg, 19-21 November 2007

Petrochemical Geodynamics of Nyiragongo and Nyamuragira Volcanoes in the Western Rift of the East African Rift System (EARS).
A.R. Basu, A.P. Santo, R. Chakrabarti, O. Vaselli, D. Tedesco
Abstracts of the 26th ECGS Workshop on "Active Volcanism and Continental Rifting", Luxembourg, 19-21 November 2007

Radon and CO_2 measurements around Nyiragongo.
Antoine Kies, Harald Hofmann, Zornitza Tosheva
Abstracts of the 26th ECGS Workshop on "Active Volcanism and Continental Rifting", Luxembourg, 19-21 November 2007

Nyiragongo – A Unique Global Bromine and Sulphur Emission In to The Free Troposphere.
N. Bobrowski N., G.B. Giuffrida, D. Tedesco, M. Yalire
Abstracts of the 26th ECGS Workshop on "Active Volcanism and Continental Rifting", Luxembourg, 19-21 November 2007

The "mazukus" in South of Nyiragongo and Nyamulagira (DRC): hypothesis of formation and first risk assessment.
B. Smets, F. Kervyn, D. Tedesco, O. Vaselli, M.M. Yalire
Abstracts of the 26th ECGS Workshop on "Active Volcanism and Continental Rifting", Luxembourg, 19-21 November 2007

Active and Passive Margins of the Western African Rift: Helium and Carbon Isotopic Signatures in the Lake Kivu Region (D.R.C.).
D. Tedesco, R.J. Poreda, F. Tassi, O. Vaselli, M. Yalire
Abstracts of the 26th ECGS Workshop on "Active Volcanism and Continental Rifting", Luxembourg, 19-21 November 2007

The January 2002 Volcano-Tectonic Eruption of Nyiragongo volcano, Democratic Republic of Congo.
D. Tedesco, O.Vaselli, P. Papale, S.A. Carn, M. Voltaggio,G.M. Sawyer, J. Durieux, M. Kasereka, F. Tassi.
Abstracts of the 26th ECGS Workshop on "Active Volcanism and Continental Rifting", Luxembourg, 19-21 November 2007

Environmental impact of the Nyiragongo volcanic plume after the 2002 eruption.
O. Vaselli, F. Tassi, D. Tedesco, E. Cuoco, B. Nisi, M.Y. Mapendano
Abstracts of the 26th ECGS Workshop on "Active Volcanism and Continental Rifting", Luxembourg, 19-21 November 2007

Modelling of InSAR displacements related with the January 2002 eruption of Nyiragongo volcano (DRC).
Wauthier C., Cayol V., d'Oreye N., Kervyn F.
Proc. of 4th ESA Fringe 2007 workshop, ESA-ESRIN, Frascati, Italy, 26-30 November 2007.

InSAR displacements associated to the November 2006 eruption of Nyamulagira.

Cayol V., d'Oreye N., Kervyn F. and team GVO
Proc. of 4th ESA Fringe 2007 workshop, ESA-ESRIN, Frascati, Italy, 26-30 November 2007

Ground deformations associated to the Nyiragongo 2002 and the Nyamulagira 2006 eruptions (DRC) revealed by radar Interferometry.
Kervyn F., d'Oreye N., Durieux J., Kies A., Lukaya F., Mitangala P., Tedesco D.
Proc. of Workshop on Natural and Human-induced Hazards and Disasters in Africa / Conference on the East African Rift System (EARS-07). 21-25 JULY 2007, Kampala, Uganda.

Monitoring the ground deformations of Nyiragongo – Nyamuragira volcanoes and assessing the impact on health and on the environment. The GORISK project.
Kervyn F., d'Oreye N., Durieux J., Kies A., Lukaya F., Mitangala P., Tedesco D.
Proc. of Workshop on Natural and Human-induced Hazards and Disasters in Africa / Conference on the East African Rift System (EARS-07). 21-25 JULY 2007, Kampala, Uganda.

3.10.2. Meeting and congress

2011 (planned):

January 8-14th 2011: 23rd Colloquium of African Geology,
Johannesburg, South Africa
3 contributions planned

2010 (planned):

13–17 December 2010,
American Geophysical Union, Fall Meeting, San Francisco, California, USA
2 contributions planned

2010:

13-15 January 2010 : Tropical Rift Lake Systems: Integrated Volcanologic, Tectonic, and Biogeochemical, and Geohazard Assessment of Lake Kivu,
Gisenyi, Rwanda
6 contributions (and the chairing of the session dedicated to tectonic)

May 31 – June 4, 2010 : 6th Cities on volcanoes, International Conference
Puerto de la Cruz, Tenerife, Canary Islands, Spain
6 contributions

May 2-7, 2010 : Europen Geophysical Union General Assembly 2010
Vienna, Austria
1 contribution

May 6, 2010 : Belgian Earth Observation Day 2010
Chaudfontaine, Belgium
1 contribution

2009:

November 30 – December 4, 2009 : ESA Fringe 2009 Workshop
ESA-ESRIN, Frascati, Italy
4 contributions
August 17-28, 2009 : Advanced Workshop on Evaluating, Monitoring and Communicating Volcanic and Seismic Hazards in East Africa
Trieste, Italy
2 contributions

June 13-17, 2009 : IEEE International Geoscience & Remote Sensing Symposium
Cape Town, South Africa
6 contributions (including 2 invited keynote lectures)

November 9-11, 2009 : 95th Journée Luxembourgeoises de Géodynamiques
Echternach, Luxembourg
1 contribution

2008:

November 19, 2008 : Luxembourg Earth Observation Day
Bourglinster, Luxembourg
1 contribution

November 11-14, 2008 : 2nd Workshop on USE of Remote Sensing Techniques for Monitoring Volcanoes and Seismogenic Areas (USEReST)
Naples, Italy
1 contribution (invited keynote lecture)

August 18-22, 2008 : IAVCEI General Assembly 2008
Reykjavik, Iceland
2 contributions

February 12, 2008 : Belgian Earth Observation Day 2008
Namur, Belgium
1 contribution

2007:

November 26-30, 2007 : ESA Fringe 2007 Workshop
ESA-ESRIN, Frascati, Italy
2 contributions

November 19-21, 2007 : AVCoR07 Workshop "Active Volcanism and Continental Rifting with a special focus on the Virunga (North Kivu, DRC)"
Luxembourg, Luxembourg
11 contributions *(Meeting organized by NMNH & RMCA)*

July 21-25, 2007 : Workshop on Natural and Human-induced Hazards and Disasters in Africa / Conference on the East African Rift System (EARS-07)
Kampala, Uganda
2 contributions

24th IUGG General Assembly

July 2-13, 2007
Perugia, Italy
1 contribution

April 23-27, 2007 : ESA ENVISAT Symposium
Montreux, Switzerland
2 contributions

3.10.3. Others

3.10.3.1. Contributions to newspapers, brochures and TV show

Newspapers and brochures

Contribution to "FOCUS, on Research & Innovation in Luxembourg" n°3/2010: « The thrill of pure science », pp 44-45
Contribution to "dossier carrières: les métiers des sciences ", CEDIES 2008, pp 54-55
Contribution to "supplément Recherche du Lëtzebuerger Land", October 17, 2008: « Eruption du volcan Nyamulagira : Une équipe luxembourgeoise de scientifiques surveille des volcans africains »
Contribution to "Firwat net Fuerscher ?", ProScience 2008, p28 & 32
Contribution "Science Connection , December 2010" (in press)

TV Shows

Participation to the "Dok Show", RTL, May 4, 2008.

3.10.3.2. Websites

http://www.ecgs.lu/gorisk
http://terra.ecgs.lu/rnvt/gorisk-project/ECGS /eruption
http://www.africamuseum.be/research/projects/prj_detail?prjid=427
http://www.fnr.lu/en/Grants-Activities/Research-Programmes/Projects/The-Combined-Use-of-Ground-Based-and-Remote-Sensing-Techniques-as-a-Tool-for-Volcanic-Risk-and-Health-Impact-Assessment-for-the-Goma-Region-North-Kivu,-Democratic-Republic-of-Congo,-Africa-GORISK
http://eo.belspo.be/Directory/ProjectDetail.aspx?projID=831

3.10.3.3. Web reports

http://www.esa.int/esaCP/SEM6UYKOP4G_index_1.html
http://www.esa.int/esaEO/SEM3UUKOP4G_index_2.html
http://x-journals.com/2010/congo-receives-help-from-space-after-volcano-eruption/

Contribution to Smithsonian Global Volcanism Program :
http://www.volcano.si.edu/reports/bulletin/contents.cfm?display=complete

3.10.3.4. Pictures database

A very large picture databank is constantly growing, fed by various sources (scientific partners, informal exchanges with visitors and tourists…). Such a collection represents a highly valuable source of information when for instance, the follow up of the lava lake level and evolution of the morphology inside the crater of the Nyiragongo crater is concerned.

Moreover a public exhibition has been organized at « Royal Photo Club de Huy » by P. Luc, J. Degée and B. Smets, 9-11 April 2010, Huy, Belgium)

3.10.3.5. Workshop organization

Workshop motivated and organized by the GORISK partners:

> "*ACTIVE VOLCANISM AND CONTINENTAL RIFTING, WITH A SPECIAL FOCUS ON THE VIRUNGA (NORTH KIVU, DRC)*", Luxembourg, November 2007.

The workshop has been attended by 80 participants from 19 countries, including 15 participants from 6 African countries.

Other relevant workshop:

> « *WORKSHOP ON TROPICAL RIFT LAKE SYSTEMS: INTEGRATED VOLCANOLOGIC, TECTONIC, AND BIOGEOCHEMICAL, AND GEOHAZARD ASSESSMENT OF LAKE KIVU* ». Gisenyi, Rwanda, January 13- 15, 2010.

That workshop has been organised by both US-NSF and Rwanda authorities. The primary aim of the workshop was to bring together for presentations and discussions a set of scientists working in all of the pertinent disciplines: tectonics and volcanology, physical and biological limnology, evolutionary biology, spatial science, as well as hydrocarbon exploration and extraction engineers. These 58 scientists and engineers came from six North American and European countries, and five African countries. Each had direct experience working in the Lake Kivu area, other anoxic lake or active volcanic systems within the East African Rift, or brought expertise directly applicable to the Lake Kivu system.

White paper of the Kivu workshop:

The discussions summarized the state of scientific knowledge in the Lake Kivu system and set the stage for breakout sessions that defined a consensus set of questions for collaborative and multi-disciplinary research programs that would address the research priorities in the context of regional capacity building and development. The white paper is available at the following address: http://dirs.cis.rit.edu/node/270

3.10.3.6. Scientific seminars

Technical University of Delft (NL), "Hell… How to overcome the difficulties in monitoring African volcanoes", d'Oreye N., December 2009

Technical University of Delft (NL), "Study and monitoring of an active African volcanic area by InSAR", Ch. Wauthier. September 2009

GFZ, Potsdam, Germany, "Radar Interferometry (InSAR) captured the January 2002 eruption of Nyiragongo volcano (DRC)", February 2009.

4. CONCLUSION

Launched in January 2007 in the frame of the STEREOII program, the GORISK multidisciplinary project was oriented towards the implementation and improvement of ground-based and spaceborne tools for volcanic risk and health impact assessment in the Goma region (DR Congo). It involved 4 European partners (RMCA, NMNH, Uni.Lu and UniNap) and 3 local end-users (GVO, UGR/RMU-UNOPS and CEMUBAC).

The main objectives were to provide these interconnected end-users working in the Nyiragongo – Nyamulagira volcanic context with appropriate **products and services** to assess the volcanic hazards and to mitigate the related risks: the direct risks (essentially related to short-term volcanic crisis and erupted material) and indirect risk (mid- to long-term effects on the environment or/and the population).

Though the project has been often threatened and its achievement endangered by looting, sabotage, plane crash, insecurity, collapse of the local structures, war, field inaccessibility…, the experience has demonstrated that the huge energy spent into tedious management struggles was worthy.

In particular, the last eruption of the Nyamulagira in January 2010 allowed demonstrating the efficiency of the new tools and methods we developed. That eruption was indeed the first one ever monitored in the Virunga simultaneously and in real time with so many different disciplines: seismology, satellite radar interferometry (InSAR), tiltmetry, GPS, thermal, geochemical and visual observations. In addition, it provided the local actors and scientists with the opportunity to evaluate the preparedness for managing the next crisis for the inevitable eruption of the close neighbour Nyiragongo that is the major concern for the city of Goma.

<u>What was achieved: the GORISK deliverables</u>

The consortium successfully provided the end-users with appropriate
<u>Products (and equipment)</u>: up-to-date permanent tilt-, GPS- and gas monitoring networks, weather station, GIS architecture and databases, urban and geological maps, satellite radar interferometry, geochemical investigation tools, a weather station etc.
<u>and services</u> : training in networks setup, maintenance and data processing methods, follow up of the ground deformation monitoring by satellite radar interferometry, follow up of the geochemical and thermal remote sensing, study of recent volcanic and tectonic activity etc.).

The involved end-users have a full access to the instruments and/or corresponding databases: data from the ground-based monitoring networks are recorded, stored and archived by GVO in Congo and a copy is automatically transferred to Europe; water or gas samples are sent to Europe for analyses or processing and results are sent back to the involved end-users. Only the large amount of remotely sensed data and products (>20 TerraBytes) are not systematically transferred to Congo because of the limited Internet bandwidth and local storage capacity. Instead, these data are routinely processed in Luxembourg and Belgium and only the significant results and outputs are transferred to the corresponding end-users.

More specifically, GORISK has fully met its commitments:

All the deliverables have been made available including

- The **study of the Nyiragongo 2002 eruption**. Thanks to the experience acquired on the field and to the SAR archives from various sensors, it was possible to provide the first plausible explanation and models of the unprecedented broad volcano-tectonic deformation associated to the last and devastating Nyiragongo eruption (Wauthier et al. 2010). These new models (Wauthier et al. in prep) offer the first explanation matching also the visual and geochemical observations and provide a plausible explanation for an 8-years old enigma.
- The **water sampling** by CEMUBAC (despite the difficult security situation and the permanent war context in part of the province) and **health data analyzed** by the same partner (correlation with water and air analyses). Remote sensing contribution to the monitoring of the volcanic plume dispersion has also been achieved trough external collaboration with VISOR – NSF project.
- Various **training sessions** at the occasion of the 15 field missions of the European partners **in Goma and** during 2-4 months-long sessions **abroad** (in RMCA and Uni.lu).
- More than 50 contributions in 20 international **conferences**, 7 **peer-reviewed papers** so far and more in prep. and two **special volumes** (Journal of African Earth Science vol. 58, Iss. 5, pp 721-860, 2010; Blue Book of the European Centre for Geodynamics and Seismology vol. 29, 131 pp, 2010).

  But the project also brought more:
- The development and setup of a **systematic and semi-automated ground deformation monitoring system by satellite radar interferometry** (InSAR). The dense database ordered by the GORISK partners to ESA which programmed accordingly the satellite, allowed the detection of ground deformation signals in vegetated areas that were not detectable in the past due to the sparse SAR acquisition and the resulting large temporal and spatial baselines. It also allowed PSI/SBAS time series analysis that provided the highest resolution deformation and velocity maps. In particular, it allowed the **study of the 2006 and 2010 eruptions of the Nyamulagira and the 2008 Bukavu earthquake (Cayol et al. in prep; Smets et al. in prep; d'Oreye et al. accepted)**.
- The development of a **web-based tool** for the management of the thousands of interferometric products (deformation maps, decorrelation maps, etc.) for data mining and data sharing. It also allows to quickly discriminating deformation from atmospheric artefacts or orbital phase residuals (d'Oreye and Celli, 2010).
- The setup of an **automated archive and ftp servers**. Because it was impossible to log in the computers in Congo from abroad and manage the computers remotely, we developed a large set of automated scripts and procedures for archiving, pre-processing, and transmitting the data through Internet, verifying the power and UPS status etc. We also developed procedures for having the computers to execute various scripts activated by coded e-mails. This for instance allows receiving by e-mail a screenshot of the monitors in Congo, to reboot the server or to execute any given Unix command line and send the results back in Luxembourg.

- The production of an **updated volcanological map of the Nyamulagira** (mapping of the 26 last eruptions since the last map produced in the 60th and integrated in a GIS database with complementary datasets) (Smets et al, 2010) and **urban map of Goma** (an update of map from the colonial time when Goma virtually did not existed was required e.g. by the RMU/UGR end-user for the crisis contingency plan for that rapidly growing city).
- The **first systematic study of the "mazuku"** (depressions where CO_2 accumulates at very high concentration and causing many fatalities each year - currently the most important natural risk in terms of human loss for the area) and their preliminary mapping (Smets et al., 2010).
- The creation of a **pluridisciplinary** and hence more **global approach** to the benefit of end users. End users that have sometime found a framework to address and tackle major institutional and structural concerns.
- Also concerning regional issues, the project has promoted the initiation of an international collaboration between DR Congo (Goma Volcano Observatory) and Rwanda (Rwanda Geology and Mine Authority) for operating the GPS network and for geodetic surveys.
- Dissemination of the information through various articles in newspapers, websites (e.g. about the January 2010 eruption: http://www.esa.int/esaEO/SEM3UUKOP4G_index_0.html), TV show and scientific contribution to the Global Volcanism Program (e.g. http://www.volcano.si.edu/world/volcano.cfm?vnum=0203-02=&volpage=var#bgvn_3508)

The project also allowed shedding light on some broader and more **fundamental questions related to plate tectonic** and contributed to advance the knowledge of the continental rifting processes in general and the East African Rift in particular (see for instance the unravelling of the 2002 eruption and the study of the 2008 Bukavu earthquake that contribute to the understanding of the opening of those portions of the EAR).

Motivated by GORISK partners, the first « Active Volcanism & COntinental Rifting (AVCOR) with special focus on the Virunga (Nord Kivu, DRC) » meeting[10] organized in Luxembourg in November 2007 also initiated a much broader initiative of a working group composed of Occidental and African scientists. That working group - also named AVCOR after the meeting - aims at developing training, research and monitoring in Africa.

The collaborative spirit that has and still prevails also served the discussions of scientific questions or research orientation, priorities, and policies to be developed at the local, regional, and continental scale. These aspects have been discussed during the AVCOR meeting, but also at the Lake Kivu international meeting held in Gisenyi (Rwanda) in January 2010 which issued with a white paper on the setup of an integrated research framework.

[10] 80 participants from 19 countries attended the workshop, including 15 participants from 6 African countries who (co-)authored >25% of the contributions. The workshop was organized by the GORISK partners.

Finally, the fallouts of GORISK stirred more projects introduced among others to European, German and Canadian space agencies to carry on the study of the Virunga and other parts of the EAR.

PERSPECTIVES AND RECOMMENDATIONS

Maintain and capitalize the benefits

Although most of the objectives of the project were completed (and sometimes exceeded), **significant needs - mainly in terms of resources and training - are still required for a robust, reliable and autonomous monitoring of these volcanoes by local staff and at the international standards level**. **In addition, the real time monitoring network for a robust early warning system is not yet fully operational at the international standards level (e.g. the seismic monitoring must urgently be rebuilt) and we are still missing fundamental knowledge about the structure and rheology of the area.**

With that respect, **additional efforts are undeniably strongly required** to sustain and develop what was recently set up; the threat on Goma remains indeed very high. The volcanoes are and will remains very active for decades or centuries and more eruptions will occur – there is no doubts about that. The 2002 eruption suggested that there could even be some **volcanic activity within the city** itself, threatening potentially one million inhabitants (the population of Goma rose of 2.000% in a third of a century, growing from <50.000 inhabitants in 1977 (year of the first historical eruption of the Nyiragongo) to <300.000 in 2002 (year of the second eruption) to ~1 million nowadays). A worse scenario would also involve the Lake Kivu and raise the related risk of a **massive lethal gas outburst** that would concern the 2 million people living in the Kivu Basin.

Best effort-based long-term commitment

Beyond the deadline of the project, aware of those needs and of the increasing risk, the scientific partners of GORISK organized themselves in a ***network*** named GORISK after the project. That **GORISK *network*** aims at consolidating the experience gained during the original project and at exploring new opportunities to improve the understanding of eruptive processes and to improve the risk management. Furthermore, the GORISK scientific partners continue their support, though only on the scientific and technical level. For instance, scientists from NMNH and from Uni.lu spent 2 weeks respectively in September-October and in October-November 2010 for carrying on the networks maintenance and development as well as improving the training of local staff. The study of the January 2010 eruption of the Nyamulagira is still under way and will be the topic of a collaborative paper to be submitted soon. The follow up of the maintenance and data processing is still under normal way and daily contacts are maintained by e-mail among the partners and end-users.

So far that **GORISK *network*** operates based on the sole good will and with the restricted own budgetary resources from the partner's institutions. Such a situation does not guaranty the sustainability of the efforts. Therefore the partners continue looking at the opportunities that may arise to reinforce the monitoring capacities and developing the international collaborations with GVO.

Furthermore, a Memorandum of Understanding (MoU) between GVO and European scientists is in preparation to establish the future of the collaboration and the scientific and technical support the scientific partners could ensure (in the limit of our available budget and time and according to the priorities established by our authorities). That MoU will also be a tool for all the partners for additional fund raising and may serve as a springboard for new projects. It is obvious that the volcanoes will last for much longer than the duration of projects and it is as much obvious that Nyamulagira and Nyiragongo will be erupting again (it is only a matter of "When and where" rather than "If" an eruption will occur). The experience acquired in the frame of the present efforts has to be reinforced and made sustainable. All the partners are aware of it and will try – in the limits of their possibilities – to look for as many opportunities as possible to carry on the support to GVO and RMU/UGR.

Sensitize and mobilize driving forces

Beyond these short- to medium-term actions, there is also a strong need for a long-term strategy aiming at developing a robust, reliable and autonomous monitoring of these volcanoes by local staff and at the international standards level. This is most probably a multi decennial task, far beyond the scope of common scientific and research projects.

Foremost it is a policy – with its budgetary implications – that could only be decided by the local national authorities. In such a process, scientists can at the most provide expertise and advices, something they must develop from these short- to medium-term projects.

In that perspective, there is no doubt that the experience gained with GORISK would definitely be an asset for future discussions on policies or institutional development in that sector - or in the natural hazards assessment sector more generally - at the local/regional/national levels (with a strong commitment of the responsible authorities), but also in agreement with International programs such as **GMES&Africa** for example to which GORISK contribution is upon the highest value.

Joint efforts

The present BELSPO/FNR support to the GORISK project was highly beneficial. However the unprecedented results that were achieved in Goma despite the difficulties would not have been possible without the implication of other entities: the Luxembourg Ministry of Foreign Affairs, UNOPS, ECGS, not mentioning the implication of NMNH and RMCA. It was worth the energy and tenacity we had to put in. The outcomes of these sustained efforts exceeded our expectations, leading to scientific results not limited to the volcano monitoring or impact assessment. All that - the initiated network of collaborations, the data acquired and those to come, and the already achieved results - will be the fuel for more researches by our teams and for young researchers and PhD's over the next years provided that reasonable support can be obtained from various sources committed in sustainable development and scientific cooperation.

5. ANNEXES

5.1. LIST OF DELIVERABLES AND PRODUCTS

- Georeferenced InSAR deformation maps:
    - ✓ ~3000 Wrapped & unwrapped interferograms covering the Nyiragongo - Nyamulagira – northern Lake Kivu shoreline area. (see 3.2.1 & 3.2.1.1.2)

- Georeferenced InSAR coherence maps:
    - ✓ ~3000 Coherence maps (see 3.2.1 & 3.2.1.1.2).

- Instruments:
    - ✓ 4 Tiltmeters (see 3.2.2.1)
    - ✓ 7 permanent GPS receivers (not from GORISK) (see 3.2.2.2)
    - ✓ Gas measurements (see 3.3.3):
        - ✓ 1 continuous CO2 – Rn monitoring station installed
        - ✓ 2 stations currently at Uni.lu to be upgraded
    - ✓ One weather station (see 3.3.3.1.1)

- Tilt deformation data layer:
    - ✓ Continuously recorded tilt data: it aliments the deformation database and contributes to data the interpretation (see 3.2.2.1.6).

- Geochemistry dispersion map:
    - ✓ Recurrent and scattered geochemical analysis of seeping gas, aerosol, and water samples contribute to establish distribution maps (see 3.5.1.6 & 3.5.1.7) and a dispersion model (implemented externally by VISOR and NOVAC partners).

- Epidemiological data:
    - ✓ The epidemiological enquiry (see 3.4.3) results are ingested as one of the GIS layers (see 3.5.2.5)

- Creation of an archive database:
    - ✓ Thousands of InSAR products covering 1997 – 2010
    - ✓ Continuous tilt records since March 2007 (continuing) with 3% of interruptions (apart from the dismantling for security reasons).
    - ✓ Continuous GPS records
    - ✓ SO2 dispersion maps (trimestral from Sept. 2004 to Dec. 2008, monthly from Sept. 2004 to May 2007). After 2008, available only on demand.
    - ✓ Health data: epidemiological data for four diseases from 2000 to 2008.
    - ✓ Water analyses
    - ✓ CO2 measurements

- ✓ Ikonos image from 2008

- Maps:
  - ✓ Updated map of the city of Goma: Goma and surrounds have been covered at a scale suitable for the use of the risk management (1:25.000 or 1:10.000). High resolution colour satellite image, main infrastructure vector layers. (see 3.6.2.1)
  - ✓ Map of mazuku (See 3.3.2.1.2)
  - ✓ Volcanological map of Nyamulagira (See 3.6.2.2)

- Recommendation to health sector:
  - ✓ Improvement of the health information system must be recommended according to the results of the epidemiological studies. The CEMUBAC end user is currently analysing the data in the framework of a Ph.D. thesis performed at the ULB - Public Health School.

- Reports:
  - ✓ See previous list of reports, papers and meeting contributions

5.2. LIST OF MISSIONS

2006

- September – October
  - NMNH, RMCA
  - Project preparation, station prospection

2007

- March – April, 2007
  - NMNH - RMCA
  - Kick-off meeting of GORISK project
  - Station building (Munigi, Ngangi), monument building (Mount Goma, Kibati) & Instruments installation (Tilt in Munigi, Ngangi, Rusayo and Bulengo)
  - Study of mazuku (geomorphological study and hazard assessment)

- June
  - Uni.lu - UniNap
  - Collecting water samples from chosen profiles in the southern side of Lake Kivu
  - Collection of gas samples and gas condensates from the inner part of Nyiragongo volcano
  - Collection around the volcano of gases from selected mazuku, for chemical and isotopic (He and C) analysis
  - Installation and testing of the

- July
  - NMNH - RMCA
  - Resolution of communication problems between tilt stations and GVO
  - Setup data server at GVO and transmission to Luxembourg
  - Participation in the conferences “Natural and human induced geohazard” and “international Conference on the East African Rift System EARS 2007” (Kampala, Uganda)

- September – October
  - NMNH – UniNap
  - Collections of water and gas from mazuku and ground waters fro chemical and isotopic analysis
  - Tilt network maintenance
  - Monument building (Kibumba, Rusayo, Bulengo) and set up GPS network (Kibati, GVO) with 2.4 GHz radio transmissions.

2008

- February – March
  - RMCA – UniNap
  - Gas Sampling & mazuku mapping
  - Construction of Ground Control Points previous to Ikonos image acquisition
  - Installation of CO2-Rn station in "Le Chalet"

- April
  - NMNH - RMCA
  - Steering committee meeting
  - Shortened because of plane crash accident

- June
  - NMNH
  - Tilt network and data server maintenance
  - Test 800MHz radios for GPS data transmission

2009

- March
  - NMNH
  - Special meeting in Kinshasa

- April – May
  - NMNH – RMCA
  - Collection of GCP points for the orthorectification of the Ikonos image
  - Installation of a new CO2-Rn measurement station in "Le Chalet"
  - Tilt and GPS networks and data server maintenance
  - Update radios 800MHz for GPS data transmission (GVO, KBT, KBB, RSY, BLG).

- August
  - RMCA
  - Collection of GCP points for the orthorectification of the Ikonos image
  - Station CO2-Rn "Le Chalet": Improvement of power supply (one additional battery, new power regulator)

- September-October
  - NMNH
  - Repair computers and change material damaged by lightning
  - Tilt and GPS networks and data server maintenance
  - Monument building (Tshubi)
  - Repair Kibati GPS station

2010

- January
    - NMNH, RMCA, UniNap
    - Monitoring of the Nyamulagira eruption
    - Monitoring of Nyiragongo (gas measurements)
    - GIS platform
    - GPS installation (Tshubi)
    - Tilt and GPS networks and data server maintenance
    - Cartography of the Ngangi fracture
    - Monument building (Rubavu)
    - Installation of a meteorological station in "Le Chalet", Goma
    - Improvement of the GPS network
    - Visibility of the project (Internet site creation)

- September-October
    - NMNH
    - Tilt and GPS networks and data server maintenance
    - GPS installation (Rubavu)

- October-November
    - Uni.Lu
    - Geochemical ground based instruments maintenance
    - training

5.3. LIST OF WORKPACKAGES

Work-package	Description	Institution	Equivalent M/M
WP 1000	**INSAR GROUND DEFORMATION MONITORING**	**Coordinator: RMCA (C)**	
WP1100	Setup of a semi-automated systematic data processing. Semi-automated processing will be refined using optimized default parameters and scripts. The method has been tested and validated within the SAMAAV project.	NMNH (P2)	(0.5)
WP1200	Archives processing. Most of the available archives have already been processed in the frame of the SAMAAV project; some additional processing may be required for specific periods/events. They will follow the semi-automated method.	NMNH (P2)	(0.5)
WP1300	New acquisition and processing. New ENVISAT acquisitions are to be programmed and ordered. They will essentially match the ESA Background Mission planning. They will follow the semi-automated method.	NMNH (P2)	(1.5)
WP1400	Detailed processing of specific pairs. The systematic and semi-automated method is suitable for the detection of deformation signal. Additional detail processing is required for specific pairs where deformation is observed; fine tuning of the parameters is needed for the interpretation.	RMCA (C)	7 + (6)
WP1500	Deformation source modelling. Though the deformation information is a valuable for the monitoring of the activity, the source modelling would allow a better understanding of the mechanisms involved.	NMNH (P2), RMCA (C), external expert in modelling	(1)
WP 2000	**GROUND-BASED DEFORMATION MONITORING**	**Coordinator: NMNH (P2)**	
WP 2100	Processing of tilt and extensometric archived data. Existing tiltmeters have recorded data for a limited period of	NMNH (P2)	(0.5)

	time; these data need to be (re)processed. Archived extensometric data will also be analysed in relation with the corresponding InSAR data.		
WP 2200	Reinstallation and upgrade of 2 existing tilt stations. This will involve repair, implementation of data transmission, GPS time synchronization. Installation takes into account the InSAR coherence maps.	NMNH (P2)	(0.5)
WP 2300	Acquisition and calibration of new tilt stations. Preliminary qualification and calibration of these 2 new stations in Underground Lab for Geodynamics of Walferdange (GDL).	NMNH (P2)	(0.5)
WP 2400	Tilt stations installation. Field mission(s) for selection of about 8 sites for possible tiltmeters installation, monument building, and installation of the 4 tiltmeters (the two renovated and the 2 new ones) in 4 of the sites. The site selection will depends on the localization with respected to possible/expected volcanic deformations (taking into account the coherence map from InSAR archives analysis) and practical criteria: underground galleries availability, properties of the bedrock, cellular phone network availability, security, possibility to install power and antennas etc…	NMNH (P2)	(1.5)
WP 2500	Data processing and interpretation. To be performed in relation with remotely sensed information.	NMNH (P2) GVO (P5)	(1.5) (1.5)
WP 3000	**GROUND BASED GAZ MONITORING**	**Coordinator: Uni.lu (P3)**	
WP 3100	CO2 and Radon exhalation measurements. Study of the relationship between the circulating fluids and active tectonic structures	Uni.lu (P3), GVO (P5)	(2.5) (3)
WP 3200	CO2 and Radon in subsoil air and in the atmosphere close to the surface. The gas monitoring is able to give information regarding the built up of local deformation and volcanic activity in its earlier stages.	Uni.lu (P3), GVO (P5)	(2.5) (3)
WP 3300	CO2 and Radon in underground water. Measurement of these gas in	Uni.lu (P3), GVO (P5)	(2.5) (3)

	underground waters e.g. hot and cold springs		
WP 4000	**VOLCANIC FALLOUTS GROUND MEASUREMENTS**	**Coordinator: UniNap (P4)**	
WP 4100	General Mapping of the area and decision on the kind of network and size that should be used. This point, the most important will be decided, together with all partners.	UniNap (P4) = all partners	2
WP 4200	Training to sample collection with GVO researchers and/or students	UniNap (P4) , GVO (P5)	(0.5) (0.5)
WP 4300	Short Course related to the different techniques, collection and analysis, of gases and particulate from plume and rain waters. Part of the course will be devoted to well known “case histories” on similar volcanoes (e.g. Hawaii). Data interpretation.	UniNap (P4) , GVO (P5)	(0.5) (0.5)
WP 4400	Map construction and model simulation	UniNap (P4)	2 + (1)
WP 4500	Analysis will be done at DSA (Caserta) for both water main composition (ion chromatography) and metals and minor or trace components (ICP-MS).	UniNap (P4)	(2)
WP 4600	Data discussed with the different partners will be given to “end users” with suggestions and advices.	UniNap (P4) + all partners	
WP 4700	Creation of a specific and dedicated data set and iso-elements maps that will help to constrain areas with acid species anomalies.	UniNap (P4)	2
WP 5000	**TRAINING**	**Coordinator: RMCA (C)**	
WP 5100	Ground-based techniques (tilt, diffusive samplers, gas). Training will take place for the installation, maintenance, and acquisition of ground based measurements.	NMNH (P2) UniNap (P4) Uni.lu (P3)	(1) (0.5) (0.5)
WP 5200	Remote sensing (InSAR, GIS). Training will take place for the interpretation of InSAR deformation products. It will also involve basics of image manipulation and GIS.	RMCA (C) NMNH (P2)	1 (0.5)
WP 5300	Local sharing and spreading of information. The results are going to be uploaded and stored by each partner on an FTP site which will be made available	RMCA (C) NMNH (P2) Uni.lu (P3)	1 (1) (0.5)

	to users.	UniNap (P4)	(0.5)
WP 6000	**GIS DATABASE**	**Coordinator: RMCA (C)**	
WP 6100	GIS integration of InSAR products. Georeferenced InSAR products (coherence and deformation maps, DEM). and interpretation in coordination with ground-based measurements. This step is required by the end users for further interpretations.	RMCA (C)	2 + (1)
WP 6200	GIS integration of tilt measurements. Tilt measurements are provided for specific locations.	RMCA (C)	1
WP 6300	GIS integration of gas measurements. Gas measurements are provided for specific locations.	RMCA (C)	1
WP 6400	GIS integration of plume measurements. Volcanic plume measurements are produced from NOVAC and VISOR projects as 2-D products to be Georeferenced and integrated into GORISK data.	RMCA (C)	2 + (2)
WP 6500	GIS integration of health archived data. Health data are available for the last 10 years which is the best database for DRC.	RMCA (C)	1
WP 6600	GIS integration of new health data. New health data are recorded systematically and regularly by health centers and centralized by regions.	RMCA (C)	1
WP 7000	**VOLCANIC PLUME DATA INTEGRATION**	**Coordinator: RMCA (C)**	
WP 7100	Acquisition of pre-interpreted DOAS data. DOAS data will be obtained from the NOVAC project through the Chalmers University. These measurements provide accurate information on SO2 concentration in the volcanic plume.	RMCA (C)	1
WP 7200	Acquisition of daily SO2 maps. Daily SO2 maps produced from various space borne sensors will be obtained from the VISOR project through the University of Maryland. They provide an estimation of the SO2 concentration in the volcanic plume and the spatial distribution of the plume.	RMCA (C)	1

WP 7300	Interpretation of remote sensing SO2 data. The SO2 plume data will be integrated to ground based measurements for interpretation and correlation studies.	UniNap (P4) Uni.lu (P3)	1 + (1) (0.5)
WP 8000	**MAP UPDATE**	**Coordinator:** **RMCA (C)**	
WP 8100	Acquisition of a new high resolution image of the Goma area. A high resolution image will be acquired from IKONOS or QUICKBIRD for updating the existing maps. Ground control points (GCP) will be acquired in the field using a bi-frequency GPS for image rectification.	RMCA (C)	1 + (1)
WP 8200	High resolution image rectification. Image rectification is required for further integration in the GIS.	RMCA (C)	0.5
WP 8300	Vectorization. The most relevant vectors will be digitized from the high resolution image for the use of risk assessment.	RMCA (C)	0.5
WP 9000	**PROVISION OF HEALTH DATA**	**Coordinator:** **CEMUBAC** (P7)	
WP 9100	Acquisition of archived health data. Archived health data are available for the last 10 years. Their study (pathologies, spatial distribution) may reveal interesting features.	CEMUBAC (P7)	(0.5)
WP 9200	Acquisition of new health data; Systematic health data are recorded in health centers and centralized by regions. As for the archived, their study (pathologies, spatial distribution) may reveal interesting features to be compared to geochemical measurements.	CEMUBAC (P7)	(0.5)
WP 10000	**VALIDATION**	**Coordinator:** **UNOPS (P6) and RMCA (C)**	
WP 10100	Validation InSAR and tilt data. Validation will be achieved by using ancillary data: seismicity, field observations, field knowledge.	GVO (P5)	(9.5)
WP 10200	Validation of gas measurements suitability. The suitability of gas	GVO (P5) CEMUBAC (P7)	(1) (0.5)

	measurements for health purposes need to be assessed for possible adaptation.		
WP 10300	Validation of updated maps. Updated maps will be validated in the field using individual GPS control.	UNOPS (P6) GVO (P5)	(4) (8)
WP 10400	Relevance of the information provided. The relevance in terms of format of the information provided will be validated.	GVO (P5) UNOPS (P6) CEMUBAC (P7)	(4) (4) (0.5)
WP 10500	Validation of the GIS platform	GVO (P5) UNOPS (P6) CEMUBAC (P7)	(8) (4) (0.5)
WP 11000	**REPORT AND DISSEMINATION**	**Coordinator:** **RMCA (C)**	
WP 11100	Mid term report	All partners	
WP 11200	End term report	All partners	
WP 11300	Presentation at meeting and congresses	All partners	
WP 12000	**COORDINATION**	**Coordinator:** **RMCA (C)**	3

5.4. LIST OF ABBREVIATIONS

AVCOR: Active Volcanism and Continental Rifting
BELSPO: Belgian Science Policy
CEMUBAC: Centre scientifique et médical de l'ULB pour ses activités de coopération
CRSN : Centre de Recherche Scientifique National (D.R.C.)
CSIC-UCM: Consejo Superior de Investigaciones Científicas – Universidad Complutense de Madrid (Spain)
DEM: Digital Elevation Model
DRC: Democratic Republic of Congo
EAR: East African Rift
EARS : East African Rift System
ESA: European Space Agency
EU: European Union
FARDC: Forces Armées de la République Démocratique du Congo
FTP: File Transfer Protocol
GCP: Ground Control Point
GIS : Geographic Information System
GPS: Global Positioning System
GVO: Goma Volcanological (or Volcano?) Observatory
ICCN: Institut Congolais pour la Conservation de la Nature
IGS: International GNSS Service
INGV: Istituto Nazionale di Geofisica e Vulcanologia (Italia)
InSAR: Interferometric Synthetic Aperture Radar
LOS: Line Of Sight
MFA: Ministry of Foreign Affairs (Luxembourg)
MONUC: Mission de l'Organisation des Nations Unies au Congo
NGO: Non-Governmental Organization
NMNH: National Museum of Natural History of Luxembourg
NOVAC: Network for Observation of Volcanic and Atmospheric Change
OMI: Ozone Monitoring Instrument
Uni.Lu: University of Luxembourg
UniNap: Second University of Naples
RMCA: Royal Museum for Central Africa
RMU/UGR: Risk Management Unit / Unité de Gestion des Risques
PPP : Precise Point Positionning
SAR : Synthetic Aperture Radar
TU Delft: Delft University of Technology (Netherlands)
UN: United Nations
UNOPS: United Nations Office for Project Services
US: United States (of America)
USGS: U.S. Geological Survey
ViSOR: Virunga SO_2 Emissions Research
WHO: World Health Organization

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