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Contribution of Deformation Measurements on the Southern Flank of Nyiragongo Volcano by Inclinometry and Gps in the Monitoring and Predictionof Volcanic Eruptions

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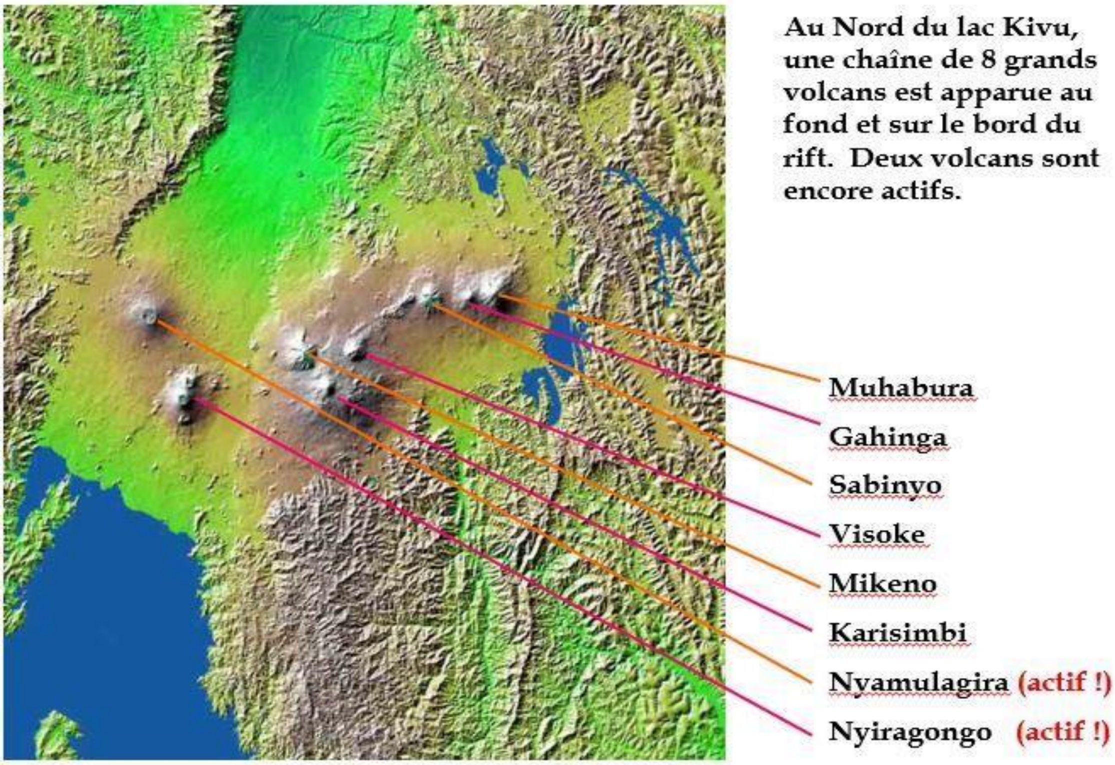
INTRODUCTION

Volcanic eruptions are a major risk especially the plans: regional, national and international (biotic and abiotic factors) during its passage. Although generally predictable, this phenomenonis nonetheless particularly dangerous and destructive.

One of the most impressive features of the western branch of the East African Rift is the volcaniccomplex located north of Lake Kivu. This volcanic complex consists of eight major volcanoes distributed in an east-west direction perpendicular to the rift axis: Muhabura, Gahiga, Sabinyo, Visoke, Karisimbi, Mikeno, Nyamulagira and Nyiragongo.

With the exception of a short-lived lava expulsion on the northern flank of the Visoke River, recent eruptions in the Virunga region have been confined to Nyiragongo and Nyamulagira volcanoes (Hamaguchi and Zana, 1993) (Brousse et al., 1979) (Kasahara et al., 1992)These twovolcanoes are well known for their lava lake eruptions and their Hawaiian-type flows. Some authors suggest that they are representative of hotspot volcanism in the African tectonic plate (Hamaguchi and Zana 1993).



Am 22. Mai 2021 ereignete sich nach einer fast 19-jährigen Beruhigung eine weitere reißende Eruption des Nyiragongo. Der Vulkan

hatte jedoch schon lange vorher starke Signale ausgesandt,insbesondere durch seinen intrakrateralen Ausbruch am 29. Februar 2016. Die Eruption ereignetesich in einer überschwänglichen Phase, wobei die Güsse in drei Richtungen ausfielen, die sich durch die Brüche geöffnet hatten: Nordostflanke (Kaneza-Achse), Nordwestflanke (Rusayo-Achse) und Nord-Südflanke (Munigi-Achse). Sie verursachte materielle und menschliche Schädenin den Randgebieten der Stadt, wobei die Gebäude und verschiedene Infrastrukturen viel stärker betroffen waren. Die Schäden waren jedoch geringer als beim Ausbruch von 2002.

Die starke seismische Aktivität nach dem Ausbruch hat einige alte Brüche reaktiviert und neue Brüche an der Südflanke geschaffen, die sich bis in die Stadt Goma erstreckten. Sie waren vor allem in den Vierteln Majengo, Katoyi, Mabanga, Vulkane und Bujovu zu sehen. Die intensive seismische und tektonische Aktivität in und um Goma hat zu einer Erkundungskampagne geführt,um die neuen offenen Brüche und die alten Brüche zu identifizieren, die nach dem Ausbruch vom

Mai 2021 reaktiviert wurden. Es sei darauf hingewiesen, dass die Reaktivierung der Verwerfungen auch im Becken des Kivu-Sees nach größeren tektonischen Ereignissen wiederholtbeobachtet wurde (Munyololo et al., 1999; Ciraba et al., 2012).

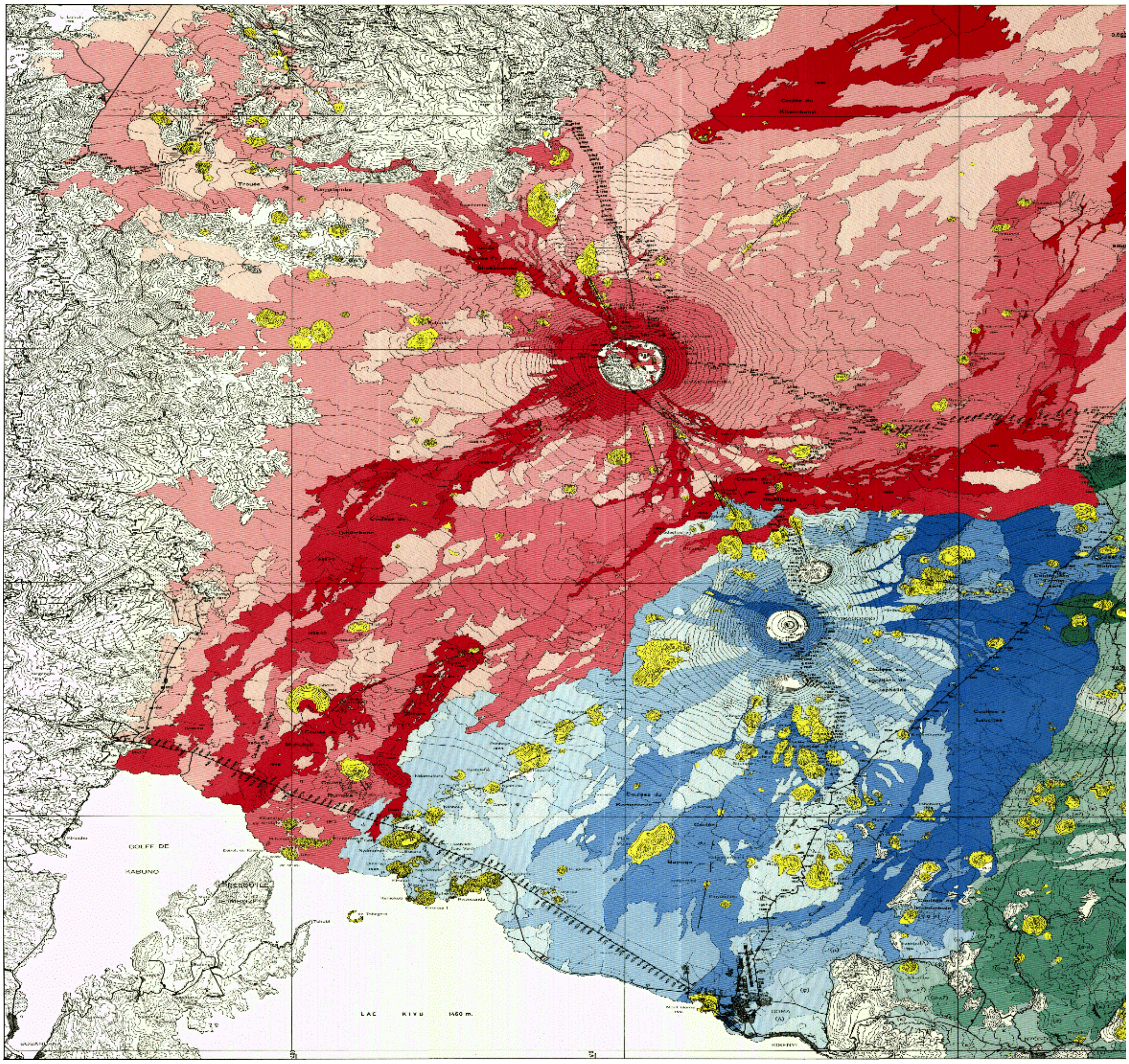
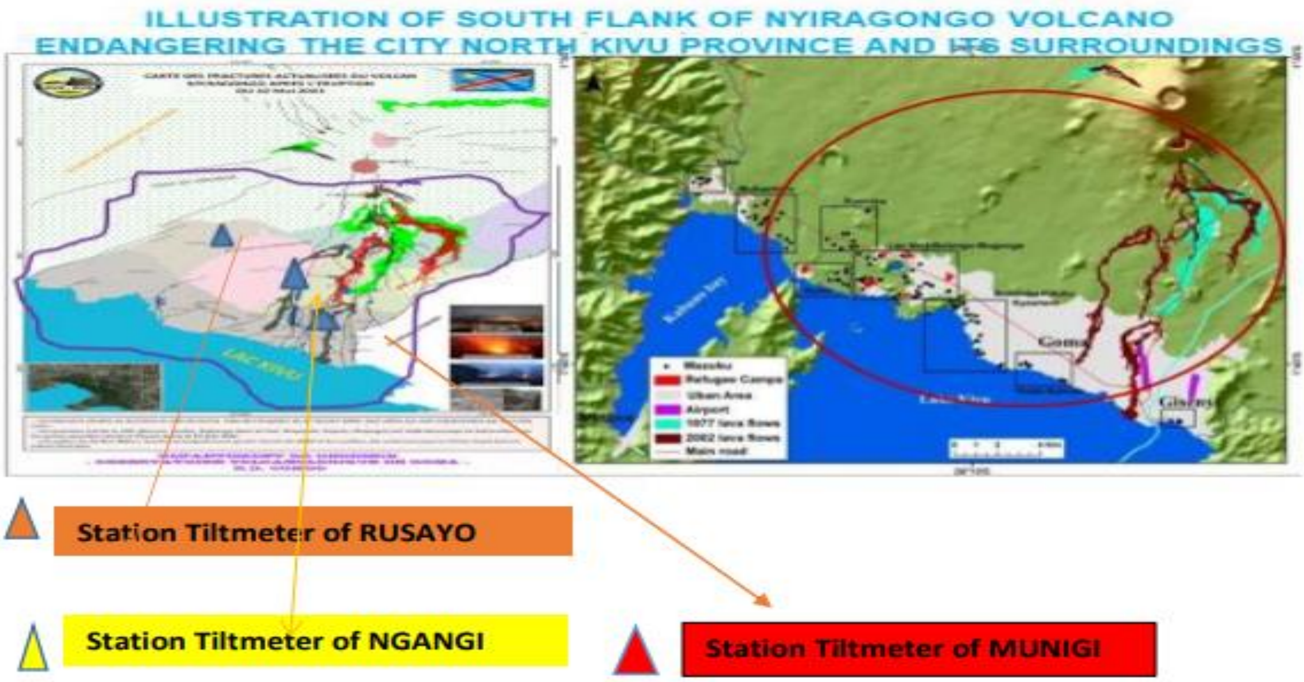


Fig. 2. Karte von Thonnard 1965

Volcanism is always the result of a rise of deep magma, but its surface manifestations may differfrom eruption to eruption.

The intrusion of magma within the volcanic edifice can lead to variations in pressure in the chamber and the magma conduit, temperature and fluid circulation, which are manifested by surface deformations, which can be detected with the help of various sensors: Inclinometer, Laser Distance Meter, GPS Network During a magmatic intrusion, the rock fractures resulting in microsismicity (earthquakes ofmagnitude less than 2-3), followed regularly by seismometers placed around the volcanoes Managing such a catastrophe is an enormous task; for it is not confined to a particular place, nordoes it quickly disappear as soon as it appears.



The main aim of this study is to develop a system of instrument networks composed of different types of sensors: GPS, tiltometers (Tiltemeter) to better understand different deformations relatedto volcanic activities on the surface, finally to monitor them properly and predict volcanic eruptions, but also the management of an exposed entity has such risks.

The methodology for this study will focus much more on the use of deformation sensors: the inclinometer and GPS receivers for monitoring and predilection of a future eruption and will beaccompanied by the dialectical method that will help us to compare the documentation that we will exploit and the realities that we will find on the ground. It will help us to establish the relationship between concepts and materials in field research.

From these measurements, different interpretations can follow depending on the volcanic nature(e.g. magma rise) or either tectonic or even seismic nature.

1. Contribution to the study of deformations

Unlike other methods of geodetic point measurements in space (such as GPS or distance measurement), inclinometry can detect very low amplitude deformations because it basically measures a spatial derivative of the displacement at a point. Detection levels of the order of 10−9can thus be achieved, i.e. two orders of magnitude below the magnitude of land-based tidal waves. Typically, pressure variations associated with deep magma movement, as detected at the earliest point in other volcanoes, result in surface deformations of the order of 10−7 to 10−8 [Kamo & Ishihara, 1989; Linde et al., 2005]. Inclinometry is also distinguished by its ease of implementation in real time since it is a punctual measurement in space, absolute and immediate (it does not require a reference frame or data processing to provide a physical measurement). These two features make inclinometry a particularly suitable technique for real-time monitoring. This high sensitivity leads to the absoluteneed for a perfect coupling of the instrument with the ground, and the search for sites where external disturbances (thermomechanical effects and fluid circulation) will be as low as possible.

The sensitivity levels achieved by inclinometry allow better constraint of deep source models [Kamo & Ishihara, 1989; Beauducel & Cornet, 1999; Linde et al., 2005] and shallow source models [Toutain et al., 1992; Voight et al., 1998; Peltier et al., 2007], provided that a network ofsensors is well distributed over the building and/or used as a complement in an integrated modelof the strain field. Another important constraint in the interpretation of inclination measurementsis the integration of topography into models; even for deep sources, variations in surface inclination are strongly affected by the free surface effect [Beauducel & Cornet, 1999].

2. Sensor/ground coupling and perturbations

The techniques commonly used on volcanoes can be grouped into five types, the advantages anddisadvantages of which are briefly discussed (modified from [Beauducel 1998]).

(a) Surface installation: inclinometers are mounted on a massive lava flow and protected locallyby an insulating housing. The instruments are good at measuring the deformations of the building, but the sunlight on the surface causes strong temperature gradients in the rock; the
“thermal” deformations are therefore significant (up to 100 µrad/day, for example, at the Rusayostation) and difficult to correct a posteriori because they are highly non-linear and dependent on local fracturing and sunlight [Beauducel, 1992; 1998]. On the other hand, because the rock is notporous, disturbances from rain will be limited to the effects of loading and temperature changes in the rock.

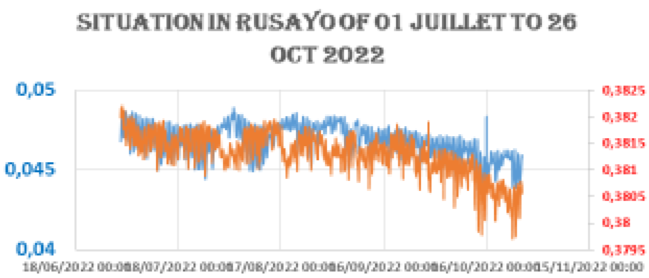
(b) Installation of wells in deposits: the inclinometer is buried a few metres deep at the bottomof a well dug in a layer of deposits. The temperature variations are then extremely small (at a depth of one metre, diurnal variations are already practically zero), but the temperature gradientsremain present in this non-conductive medium, generating thermo-mechanical deformations nevertheless important. In addition, the measurement is strongly disturbed by rainfall and groundwater movement in this porous medium; the latter effects are strongly non-linear and practically impossible to correct [Wolfe et al., 1981; Evans & Wyatt, 1984].
c) Installation in natural cavity: the use of caves, lava tunnels or deep fractures greatly reducesthermal effects and weather disturbances. These are generally excellent sites, but cavity effects are predominant and depend entirely on the three-dimensional shape of the cavity [Harrison 1976; Pinettes 1997]. Strain modelling based on these signals will then be more complex (as for strain measurements) because the precise geometry of the site, which is usually unknown, wouldhave to be introduced into the model.

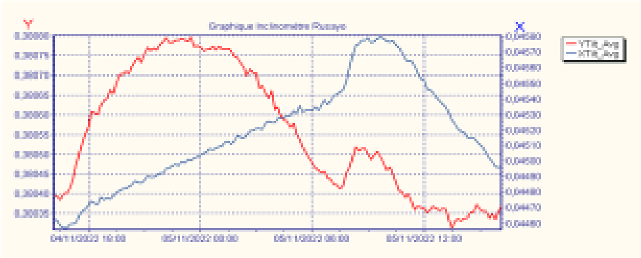
(d) Drilling or tunneling installation in massive rock: inclinometers are installed deep into a massive lava flow. This system offers a perfect coupling with the rock and is free of all types of noise [Yoshikawa, 1962; Eto, 1965; 1966; Kamo & Ishihara, 1989], but the cost of its construction is prohibitive, unless you take advantage of a pre-existing tunnel. As this geometryis generally simple and known, cavity effects are attenuated, and can be taken into account moreeasily in a numerical model.

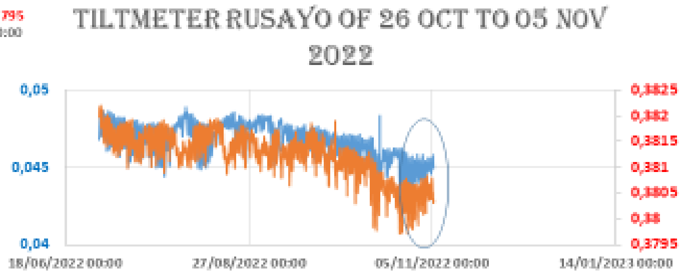
(e) “Merapi” type installation: inclinometers are placed on a massive lava flow, but this iscovered by a thin layer of deposits (a few metres) which forms a natural insulation over a large area around the instruments. As a result, the temperature gradients are low, and neither sunlight nor water circulation has a significant effect on the measurements [Beauducel & Cornet, 1999]. The effects of rainfall are limited, as for type (a), to the effects of loading on the lava flow and toa lesser extent to changes in temperature.
In this study, we will look for sites corresponding to the characteristics of tunneling facilities in massive rock and natural cavity. The search for sites results from a delicate compromise between the quality of the site, accessibility (especially for the drill), and the radio link (few or no relays).

TREATMENTS/RESULTS
The data processing here of our Tiltmeter network is done with the RTMC free software, which leads us to make the representation

of the graphs with Excel due to the lack of the RTMC Pro (RealTime Monitoring Control) software.

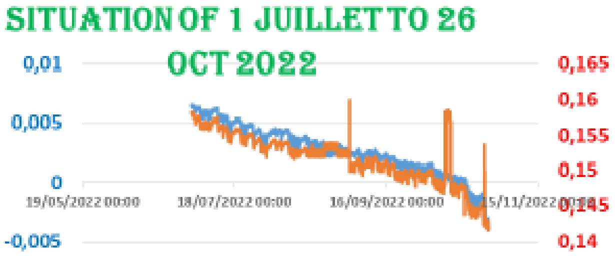


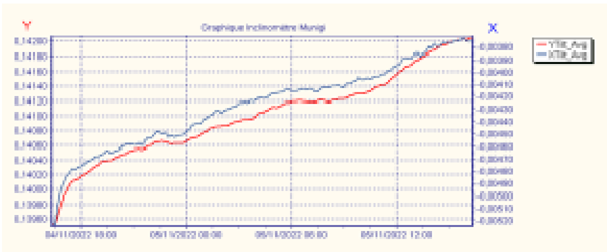


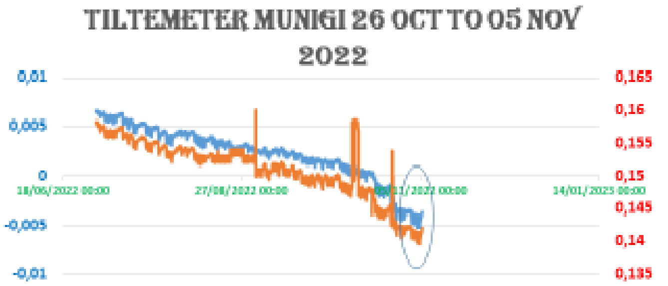


During this period from 08 to 26/10/2022, despite the many fluctuations, there was a small inflation on the X-Axis of the order of 0.000 38167 degrees (6.661 398 156 0868 Microradian [µrad]) to the east of the Y-Axis where there was a small deflation of 0.0002285 degrees (3.988 077 340 807 Microradian [µrad] to the north.

Despite the multiple fluctuations, there was a small inflation on the X-axis of the order of 0.000 74183 degrees (12.947 375 990 07 Microradian [µrad]) to the east of the Y-axis where there was a deflation of 0.0001923 degrees or 3.356 268 151 585 1 Microradian [µrad] to the north.

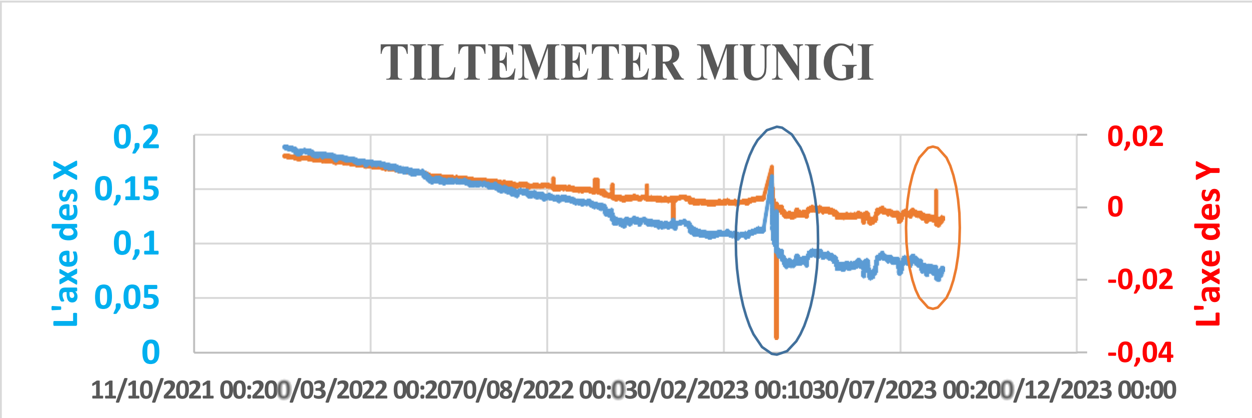




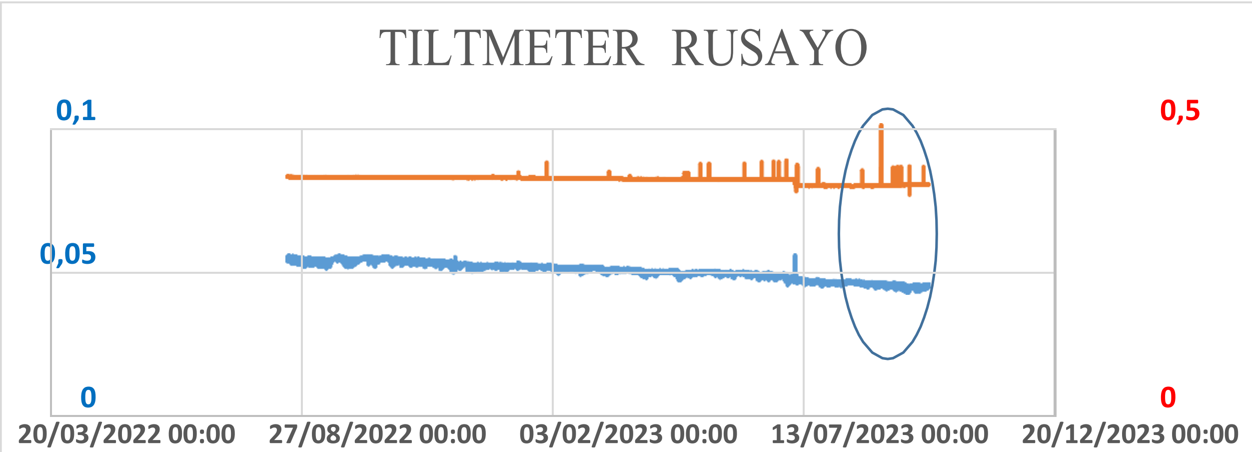


From 08 to 26/10/2022, we recorded an Inflation on 09 to 11 of 0.008999 degrees (157.062 179 386 97 Microradian [µrad]) and of 0.0116086 degrees or 202.608 291 547 01 Microradian [µrad] on 24, but despite these anomalies a Sinking (deflation) oriented towards the South – West of the station was observed on both Axis (Y and X) or 0.0052195 degrees (91.097 460 30 844 Microradian [µrad]) to the South and -0.00403083 Degree (-70.351 255 088 163 Microradian [µrad]) on the x-axis (west).

During this period, we recorded a small Inflation of 0.0004005 degrees (6.990 043 654 237 3 Microradian [µrad]) oriented to the south-west direction of the station and -0.001145 degrees (-0.199 840 199 353 35 Microradian [µrad]) on the x-axis (west).



During this period from 13 to 20 August 2023, despite the multiple fluctuations and the Inflation observed on the Y axis on 14/08/ at 3h30; Both axes recorded slight inflation from last week, of
20.449 [µrad] (X) direction EW and 7.429 [µrad] (Y) direction (NS).



Despite the multiple fluctuations and the high inflation anomaly observed on 08 August 2023 at 8:10 am on the Y axis, both axes recorded a slight inflation, of 31.942 492 371 225 [µrad] on the X axis compared to last week, which was 15.004 071 980 62 [µrad] and 85.957 465 660 721 [µrad]instead of 52.550 118 448 297 [µrad] on the Y axis, a difference of 407 [µrad] on the Y axis north-south and 16.938420390605 [µrad] on the X axis i.e. in the east-west direction.

CONCLUSION

Since November 2021, the date of the installation of these strain sensors on the southern flank of the Nyiragongo volcano, including in Ngangi, Munigi and Rusayo; the Zone has experienced several anomalies of denunciation and inflation, which has turned into sawtooths and the most observed anomalies are located almost at the same time of intense activity in the crater of the Nyiragongo volcano. The curve has a tendency to deflate after the eruption of May 2021 and with peaks that are cyclical following the perihelion period during which the earth is close to the sun. Thus, the activity of thelava lake is due not only to the activity in the magma chamber deep inside the volcano, but also tothe attraction of the moon and sun on the lava in the volcano's crater.
Thus, Tiltimetric measurement continues on the southern flank of Nyiragongo Volcano and in thefractures; is one of the elements of volcano monitoring.

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