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VOLCANIC HAZARDS ASSESSMENT OF OLDOINYO LENGAI IN A DATA SCARCITY CONTEXT (TANZANIA)*

AVALIAÇÃO DOS RISCOS VULCÂNICOS DO OLDOINYO LENGAI NUM CONTEXTO DE ESCASSEZ DE DADOS (TANZANIA)

Tony Rey
University Paul-Valéry Montpellier 3, Department of Geography, LAGAM laboratory (France)
ORCID 0000-0003-2827-3919 tony.rey@univ-montp3.fr

Frédéric Leone
University Paul-Valéry Montpellier 3, Department of Geography, LAGAM laboratory, (France)
ORCID 0000-0003-2330-1474 frederic.leone@univ-montp3.fr

Stéphanie Defossez
University Paul-Valéry Montpellier 3, Department of Geography, LAGAM laboratory (France)
ORCID 0000-0001-7397-666X stephanie.defossez@univ-montp3.fr

Monique Gherardi
University Paul-Valéry Montpellier 3, Department of Geography, LAGAM laboratory (France)
ORCID 0000-0002-0836-4760 Monique.gherardi@univ-montp3.fr

Fleurice Parat
University Montpellier, Geosciences Montpellier (France)
ORCID 0000-0001-8827-6682 fleurice.parat@umontpellier.fr

ABSTRACT

The objective of our study is to establish an assessment of four volcanic hazards in a country threatened by the eruption of the OlDoinyo Lengai volcano. The last major eruption dates back to 2007-2008 but stronger activity in 2019 has revived the memory of volcanic threats to the Maasai and Bantu communities and human activities (agro-pastoral and tourism). The methods chosen have had to be adapted to the scarce and incomplete data. The volcanic hazards and their probability of occurrence were analysed on the basis of data available in the scientific literature and were supplemented by two field missions combining geography and hydro-geomorphology. Our study enabled us to map the hazards of ash fall, lava flows, lahars and avalanches of debris. Each hazard was spatialised by being ascribed an intensity. They are sometimes synchronous with the eruption sometimes they occur several months or years after a volcanic eruption. The results are the first step towards developing a volcanic risk management strategy, especially for the pastoral communities living around Lengai and for the growing tourist activities in this area.

Keywords: Lahars, ash, lava, Rift, Maasai.

RESUMO

O objectivo do nosso estudo é estabelecer uma avaliação de quatro processos vulcânicos num país ameaçado pela erupção do vulcão Oldoinyo Lengai. A última grande erupção data de 2007-2008, mas uma actividade mais forte em 2019 reavivou a memória das ameaças vulcânicas às comunidades Maasai e Bantu e às actividades humanas (agro-pastoril e turismo). Os métodos escolhidos exigiram uma adaptação aos dados escassos e incompletos. Os processos vulcânicos e a sua probabilidade de ocorrência foram analisados com base nos dados disponíveis na literatura científica e foram complementados por duas missões de campo combinando geografia e hidrogeomorfologia. O nosso estudo permitiu-nos mapear os riscos de queda de cinzas, fluxos de lava, lahares e avalanches de detritos. Cada processo foi espacializado com a atribuição de uma intensidade. Por vezes estão sincronizados com a erupção, mas outras vezes ocorrem vários meses ou vários anos após uma erupção vulcânica. Os resultados são o primeiro passo no desenvolvimento de uma estratégia de gestão do risco vulcânico, especialmente para as comunidades pastoris que vivem em redor de Lengai e para as actividades turísticas crescentes nesta área.

Palavras-chave: Lahares, cinzas, lava, Rift, Maasai.

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Introduction

Volcanoes are complex geological systems that can produce a wide variety of dangerous phenomena during and after eruptions. These include glowing clouds, lava flows, pyroclastic flows, debris avalanches, ballistic projections, plumes and ashfalls, as well as volcanic earthquakes, landslides, gas emissions, floods, and fires (Baxter and Horwell, 2015). In response to these volcanic threats, states are attempting to put in place disaster risk management strategies despite existing uncertainties. To manage uncertainty, it is necessary to identify hazards, their intensity and spatial extent. The recognition of the issues at stake and the characterisation of territorial vulnerabilities make it possible to produce risk maps. The difficulty therefore lies in acquiring reliable data to characterise hazards and volcanic risks. According to the available data, there are many methods for assessing and mapping volcanic hazards (Thouret *et al.*, 2000; Leone and Lesales, 2009; Connor *et al.*, 2015), such as the probabilistic method with the development of event trees (Newhall and Hoblit, 2002), and the use of digital models (Felpeto *et al.*, 2007; Favalli *et al.*, 2011; Tarakada, 2017). These methods require reliable data, acquired through the work of geologists, geomorphologists, volcanologists and geographers. Consequently, for poorly documented volcanoes, probabilistic scenarios are based on field investigations and, if possible, on modelling (Neri *et al.*, 2013).

The objective of this article is to establish a diagnosis of the volcanic risks on the territory of Lengai. In 2008, 65,000 people were affected by the impacts of the eruption of the Oldoinyo Lengai (OLD), and several thousand people left their villages for a few weeks to several months (NEMC, 2008). NGOs provided food aid to almost 36,000 people (Msami, 2007). Faced with these poorly documented and insufficiently mapped volcanic threats, we present our progress in assessing the impacts of four volcanic hazards: ash fallout, lava flows, lahars and debris avalanches. Their assessment is based on probabilistic and deterministic approaches. The combined approaches underline the difficulties in scoping volcanic hazards for a region where data are scarce. Finally, we discuss the results and challenges we have faced using these approaches.

Study area

Ol Doinyo Lengai (OLD), "mountain of god" is venerated by the Maasai. For this ethnic community, the volcano represents the home of their god Ngai. Living near the OLD is not without its dangers and constraints but they are accepted. It's a territory made of assets and opportunities and a territory marked by a strong identity and cultural traditions (myths and rytuals).

Context

OLD is a stratovolcano in the vast East African Rift Plain, located in northern Tanzania, 16 km south of Lake Natron (fig. 1). Peaking at 2952 m, the OLD rises 2000 m above the Gregory Rift Valley Plain (photo 1).

Fig. 1 - The Oldoinyo Lengai area (Data source: SRTM30, Natural Earth, Google Earth; conception: T. Candela, 2021).

Fig. 1 - *A área Oldoinyo Lengai (Fonte dos dados*: SRTM30, Natural Earth, Google Earth; concepção: T. Candela, 2021).

Photo 1 - Lengai plain occupied by traditional settlements and the "mountain of god", January 2020 (Photography by T. Rey)

Fot. 1 - *A planície de Lengai ocupada por povoados tradicionais e a "montanha de deus",* Janeiro 2020 (Fotografia de T. Rey)

The OLD is highly studied for its petrological characteristics (Lee *et al.*, 2016; Weinstein *et al.*, 2017; Mattsson *et al.*, 2018) because it's the only active volcano to emit natrocarbonatite lava (Bell *et al.*, 1998; Dawson, 1998; Zaitsev and Keller, 2006; Kervyn *et al.*, 2008a). The eruptive activity of OLD is characterised by effusive eruptive phases of natrocarbonatite lava and explosive phases of nephelinite, known to have occurred in 1917, 1940-1941 and 1966-1967 and the most recent in 2007-2008 (Dawson *et al.*, 1995 and 1998; Keller *et al.*, 2010).

The understanding of eruptive activity in volcanic history has been reviewed by several international and Tanzanian scientific teams (Pyle *et al.*, 1995; Keller, 2002; Keller and Klaudius, 2003). Seismicity is also the subject of particular attention with important instrumentation installed around the volcano (Albaric *et al.*, 2010; Stamp *et al.*, 2016; Weinstein *et al.*, 2017). Seismic activity is currently monitored in real time by Ardhi University in Tanzania and the Institute of Geoscience and Mineral Resources in South Korea and is the subject of further studies on its "plumbing" and seismic-volcanic links with the Gelai.

The last major eruption took place in September 2007 and lasted until April 2008 (photo 2 and 3). It has been the topic of several publications (Mitchell and Dawson, 2007; Keller *et al.*, 2010; Kervyn *et al.*, 2010; Mattsson and Reusser, 2010) and many different mechanisms have been proposed to explain the activity associated with explosive episodes (Vaughan *et al.*, 2008; Kervyn *et al.*, 2008b). This eruption is the most well documented in terms of eruptive dynamics (Kervyn *et al.*, 2008a) impacts of ash fallout on vegetation and resilience (De Schutter *et al.*, 2015), the characteristics of ash deposition (Mitchell and Dawson, 2017, Bosshard-Stadline *et al.*, 2017), the influence of the release of fluorine contained in the 2008 lavas and ashes and its toxicity to water. The 2007-2008 eruption provides recent data on the impacts of volcanic hazards. However the Lengai space has also been the subject of other older volcanic phenomena, such as gravity movements (Kervyn *et al.*, 2008b) and pyroclastic flows. These geological and hydro-geomorphological legacies have been grouped together in the geological map of Lengai (Sherrod *et al.*, 2013) and have helped us to assess volcanic hazards.

Photo 2 - The Oldoinyo Lengai during an eruption (Photography by G. Seielstad, taken on 02-04-2008).

Fot. 2 *- O Oldoinyo Lengai em erupção (Fotografia de G. Seielstad, tirada a 02-04-2008).*

Landscapes of Oldoinyo Lengai

The East African Rift Valley delimits the eastern part of this area, which we divide into two large areas: the Oldoinyo Lengai and the plain (including Lake Natron):

- The volcano culminates at 2962 metres. It is characterised by increasingly steep slope profiles as it approaches the crater (fig. 2);

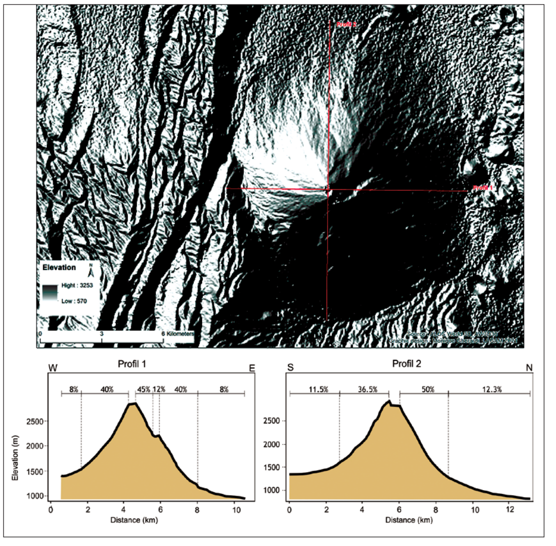

Fig. 2 - Characteristics of the slopes of the Lengai Volcano. The OLD is one of the most difficult volcanoes to climb because of its steep slopes and the high risk of boulder falls (conception: T. Rey, 2021).

Fig. 2 *- Características das encostas do vulcão Lengai. OLD é um dos vulcões mais difíceis de escalar devido às suas encostas íngremes e ao elevado risco de queda de rochas (*concepção: T. Rey, 2021).

- Erosion processes are very active on the steep slopes of the volcano where we can observe very deeply incised talwegs in the volcanic rock. During the rains, the talwegs evacuate the pyroclastic materials towards the plain. The geomorphological processes are particularly active as the deposits of the alluvial

Photo 3 - Channel in lava flow deposits from the 2007-2008 eruption worn by water, situation in February 2018 (Photography by T. Rey).

Fot. 3 - *Os depósitos de fluxo de lava da erupção 2007-2008 escavados pela água, situação em evereiro 2018 (Fotografia de T. Rey).*

plain are mainly composed of fine, unconsolidated pyroclastic materials.–The volcanic flanks also show traces of former large-scale gravitational movements such as those observables in the north-northeast. More recently, long fractures have appeared on the western flank of the volcano. Vegetation is mainly represented by herbaceous plants which disappear towards 1750 metres above sea level;

- The plain is drained by numerous rivers that end their course in Lake Natron. Geomorphological processes are most active during the two rainy seasons: the first from March to May (called *masika*) and the second from October to December (called *vuli*). Rainfall then reaches between 40 and 400 mm per month, with occasional localized episodes of high intensity (e.g. 126.4 mm in 24 hours on 26 April 2019, Arusha Weather Station). These heavy rain cause floods and flash floods in urban area (Mikova *et al.*, 2016). The Lengai Plain is also punctuated by hills resulting from debris avalanches identified by Kervin (2008) and lava flow deposits near the southern shore of Lake Natron (Sherrod *et al.*, 2013).

The population and socio-economic activities within the Lengai area have vulnerabilities that expose them to varying intensities to volcanic threats and hydro-meteorological hazards.

Population and activities

The OLD area, which includes the districts of Ngorongoro and Longido, had a population of nearly 300,000 (National census, 2012). Rural people accounted for nearly 97% of the population in these two districts, while urban people represented less than 3%, or nearly 17,000 people. However, these figures are now obsolete in view of the rapid urban growth that is driven by demography and rural exodus (Agwanda and Amani, 2014). The population is distributed in medium-sized towns (Kitumbeine) and sometimes large villages such as Engaruka, Ngare Sero, while the unsettled Maasai live in the bomas. In addition to the permanent bomas, other sites are used during seasonal migrations (Homewood and Rodgers, 1991). Indeed, the dominant activity is extensive livestock farming, practised primarily by the Maasai and Bantu. The sustainability of pastoral activities also relies on the use of other economic resources from agricultural and tourist activities. Seasonal crops are mainly located in the plains, while the shores of Lake Natron are exploited for salt. Tourism is becoming more and more important in economic activities. More than 1,235,000 tourists visited Tanzania in 2016 (MNRT, 2017), an average annual growth of 4% since the mid-1990s (UNWTO, 2017). Tourist tours in Northern Tanzania generally start from Arusha and go to Lake Manyara, Tarangire National Park, Ngorongoro Crater and Serengeti National Park. According to the Ngorongoro Crater Area, the attractiveness of Ngorongoro has attracted more than 600,000 tourists in 2016, with an annual growth of 19%. Some tourists and scientists are venturing further north towards the Lengai volcano and Lake Natron. The growth of tourism in the OLD area is leading to an increase in lodges and at the same time to an improvement in the quality of the roads located on the major tourist routes, such as the 160 km of asphalt roads between Arusha and Ngorongoro. As for the secondary roads, which are more extensive, they are made up of roads and numerous river fords which are sometimes not accessible during the rainy season.

Methods and data

Consequences of an OLD eruption the OLD are ash fallout, lava flows, ballistic projections, gas, lahars and debris avalanches, with direct and indirect effects. All these hazards are not necessarily synchronous with the eruptive crisis. They have intrinsic characteristics, controlled by other factors such as rainfall, topography, gravity and earthquakes. They can then manifest themselves on temporalities that go beyond the eruptive crisis. We have chosen to evaluate 4 of the most frequent and intense hazards in the OLD area. The plurality of methods is justified by the scarcity of available data.

Ash fallout hazard

The analysis of ash fallout and deposit thickness were done using data from the 2008 eruption (fig. 3), geomorphological and petrographic analysis and the use of a numerical model. The maximum probabilistic scenarios were produced with the Tephra 2 model (fig. 4), which is a physical (VHASS: https://ccop-geoinfo.org/vhazard/HazardAssessment), webGIS-based, open-access, online model that simulates ash fallout dispersion and deposit thickness (Bonadonna *et al.*, 2005; Connor and Connor, 2006).

The 2007-2008 eruption represented our standard hazard. Data such as the estimated plume height of 15,000 m and the mass of the eruption around 2.10^7 m^3 (Kervyn *et al.*, 2010). The granulometric data come from ash sampling on the flanks of the OLD during our field campaign in January 2020 (photo 4).

Our granulometric analyses by sieving (4 mm - 64 microns) provided information on the maximum (phi) and minimum (phi) grain size, the median grain size (phi) and the standard deviation (phi). The meteorological parameters (wind and average speeds) were obtained from the Tanzania Meteorology Agency data. The ASTER GDEM digital terrain model at 30 m resolution provided a sufficiently fine topography for mapping ash fallout. Using Tephra 2, we generated 6 probabilistic scenarios:

Fig. 3 - Dispersion of Lengai ashes during the 2007-2008 eruption.

***Fig. 3 -** Dispersão das cinzas do Lengai durante a erupção 2007-2008.*

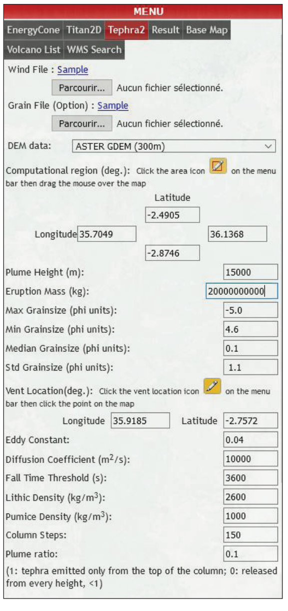

Fig. 4 - Example of the Tephra 2 interface and the data to be input in the model.

***Fig. 4 -** Exemplo da interface Tephra 2 e dos dados a introduzir no modelo.*

Photo 4 - Sampling of volcanic ash, situation in January 2020 (Photography by T. Rey, 2020).

***Fot. 4 -** Amostragem de cinzas vulcânicas, situação em janeiro 2020 (Fotografia de T. Rey, 2020).*

a standard eruptive scenario (analogous to 2007-2008), then increased to 25% and 50%, with dominant E--S-E winds and without dominant winds.

Pyroclastic flows (lahars)

The lahar hazard was characterised using topo-morphological and sedimentary data. The overlay of the Sentinel (03 February 2019 in true colour composition, 10m resolution) and Landsat (04 June 2009 in true colour composition, 30m resolution) scenes highlights the most active flow axes between 2009 and 2019. The W-SW flank of the Lengai and a large part of the Lengai plain are concerned (fig. 5).

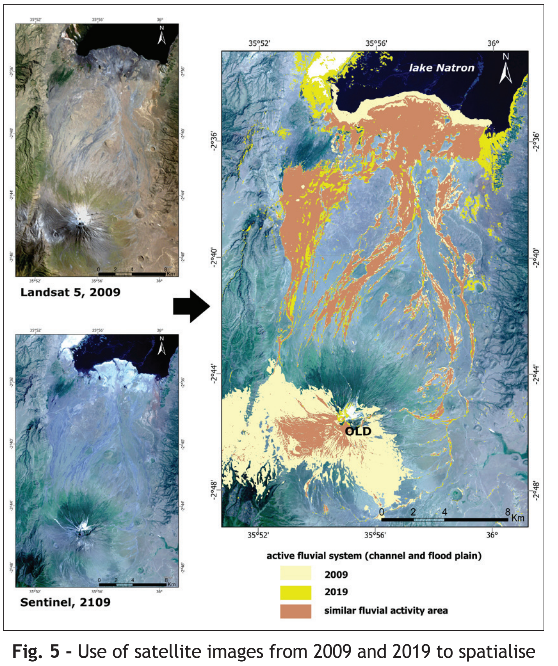

Fig. 5 - Use of satellite images from 2009 and 2019 to spatialise the most active rivers (conception: T. Rey and J-P Cherel, 2021).

***Fig. 5 -** Utilização de imagens de satélite de 2009 e 2019 para espacializar os rios mais ativos (concepção: T. Rey and J-P Cherel, 2021).*

With the Flow Order tool in ArcGis, we generated the catchment areas and hierarchised the hydrographic network according to Strahler's method. The sometimes inaccurate or incomplete data required a manual verification of the hydrographic network (fig. 6). We then extracted data on the shape, area, slope and density of drainage (Table I). In the absence of measuring instruments and video recordings of lahars (and floods) in this area, we used the Manning-Strickler formula to estimate the flows and flow velocities. This approach combines field data with mathematical calculations, is an interesting solution for extrapolating hydrological dynamics during high-energy events (Rey *et al.*, 2017). The data needed for the calculations were taken from topometric measurements made in the main talwegs during the January 2020.

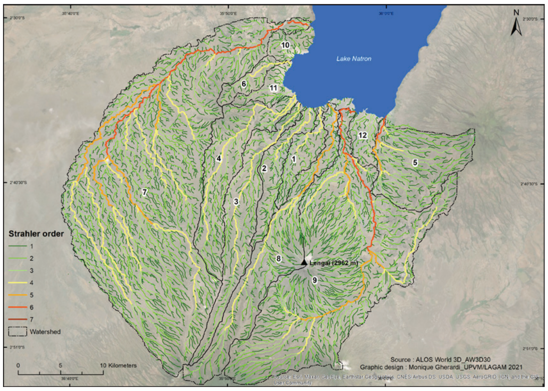

Fig. 6 - Mapping of the hydrographic network for each catchment area (Conception: M. Gherardi, 2021).

***Fig. 6** - Mapeamento da rede hidrográfica para cada bacia hidrográfica (Concepção: M. Gherardi, 2021).*

Table I - Main characteristics of the catchment areas

Tabela I - Principais características das bacias hidrográficas.

Code Basins	Area km²	Index of compacity	Drainage density	Channel slope [m/km]
1	25	1,96	2,84	12,9
2	34	2,26	2,76	50,1
3	77	2,55	2,31	60,1
4	83	2,06	2,77	41,7
5	85	1,34	2,74	51,6
6	15	1,95	2,47	68,7
7	510	1,74	2,98	32
8	109	2,55	2,64	55,1
9	328	1,95	2,93	31
10	16	1,33	2,69	42,7
11	16	1,82	2,88	94,7
12	18	1,65	2,61	7,7

Lava flows hazard

The characterisation of lava flow hazard was based on the study of 72 reports between 01/1983 and 09/2020 (https://volcano.si.edu/volcano.cfm?vn=222120) and the work of Kervyn *et al*. (2008). We built up a database on the signs of volcanic activity of the OLD: lava flows (width, length, direction), evolution of hornitos, fractures on the cone, fumaroles, ash plume (Table II). The data made it possible to qualify the preferential directions of the lava flows (fig. 7). The mapping of the lava flow hazard is also based on old flows identified by Sherrod *et al*. (2013).

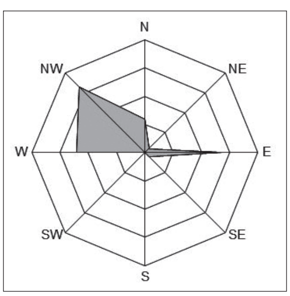

Fig. 7 - Graph representing the preferential directions of lava flows between 1983 and 2020 (conception: T. Rey, 2021).

***Fig. 7** - Representação gráfica das direcções preferenciais dos fluxos de lava entre 1983 e 2020 (concepção: T. Rey, 2021).*

Table II - Characteristics of lava flows and size of crater breaches between 1983 and 2020.

Tabela II - Características dos fluxos de lava e dimensão das quebras de crateras entre 1983 e 2020.

Lava direction	Number of events	Crater opening width (m)	Frequencye (%)
NE	1	2	10
N	6	12	60
NW	17	33	150
E	14	27	90
W	12	24	23
SE	1	2	0

Debris avalanches hazard

Four debris avalanches have been identified by Keller and Klaudius (2003): the largest event (4.9 km^3) named Zebra is dated around 10,000 years BP, the most recent Cheetah (0.2 km^3) around 2700 years BP (Klaudius and Keller 2006), and between these two events there is Orix (0.1 km^3) which is undated and a fourth debris avalanche identified on the shore of Lake Natron and dated at 793 ± 63 ka (Sherrod *et al*., 2013). All of these events correspond to flank collapses of the OLD (fig. 8). The mapping of this hazard is therefore based on geomorphological legacies (Table III), the energy line method (Hungr *et al*., 2005) and recent geomorphological data acquired during the January 2020 field investigation.

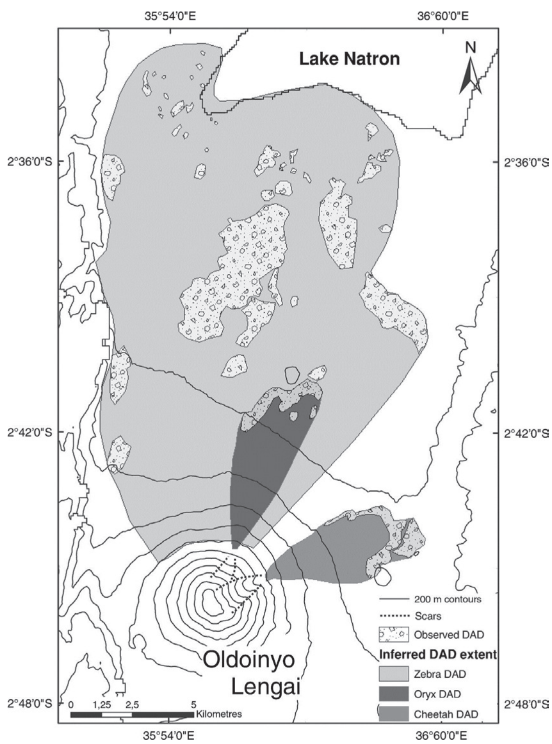

Fig. 8 - Representation of the four debris avalanches (*Source: Kervyn et al., 2008*).

***Fig. 8** - Representação das quatro avalanches de destroços (Fonte: Kervyn et al., 2008).*

Table III - Characteristics of debris avalanches.

Table III - Características das avalanches de detritos.

Name of DAD	Area (km²)	Volume (km³)	H/L*
Zebra	197,4	4,9	0,108
Oryx	12,4	0,1	0,223
Cheetah	11,5	0,2	0,229
Kerimasi	33,1	1,0	0,120

H -Height of slope;
L - Run out distance between crown and maximum landslide extension

Source: modified from Kervyn *et al.*, 2008
Fonte: adaptado de Kervyn et al., 2008.

Results

All scenarios are based on activity focused on the current Oldoinyo Lengai crater (fig. 9).

Ash fallout

The results for the "no wind scenarios" highlight two distinct situations. For the scenario equivalent to the 2006 eruption, the model shows a rather radio-concentric dispersion. The maximum thickness of the deposits is estimated at 95 and 98 cm for all the three scenarios. These data are in accordance with the observations made by Schutter *et al*. (2015) who measured ash and lapilli deposits from the 2007 eruption at around 80 cm. What allowed us to have realistic data was the integration of the granulometric parameters. Indeed, even with a significant increase in the eruption mass the scattering of ashes is relatively limited due to the coarse size of the ashes. According to the concentric model, the ash can extend more than 20 km. Engaruka and Engare Sero (more than 13,000 inhabitants) appear to be the most exposed to this hazard.

The results for the "scenarios with dominant E—S-E winds" show a dispersion of ashes towards the rift. The maximum thickness is estimated at 56 cm and 710 cm, and is limited to the sides of the volcano. In accordance with the 2007 eruption data, the coarser volcanic materials accumulate on the slopes of the volcano and the finer materials are dispersed by the winds over 30 km, depositing on the rift plateau to the west and on the villages located further north such as Engare Sero. In the 25% and 50% scenario, the ash could be deposited more than 40 and 55 km from the crater. Therefore, in a maximum probability scenario, we estimate the danger zone to be 55 km from the crater.

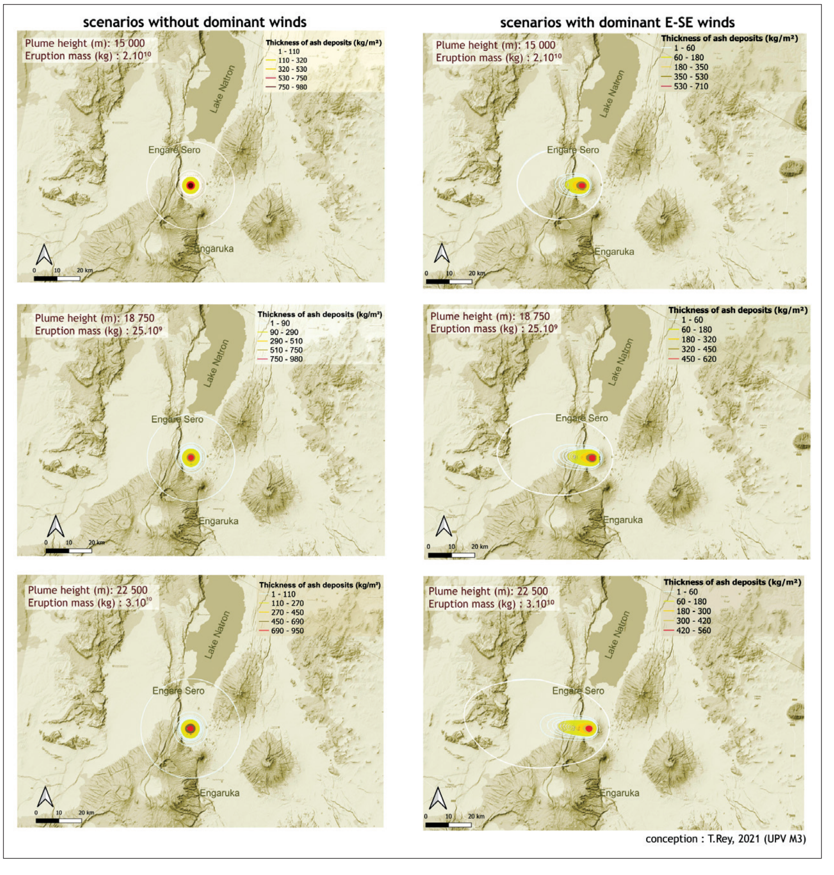

Fig. 9 - Representation of 6 likely scenarios using Tephra 2: represented are the ash dispersion and the thickness of the deposits, with easterly winds and without prevailing winds (Conception: T. Rey, 2021).

***Fig. 9 -** Representação de 6 cenários probabilísticos utilizando Tephra 2: está representada a dispersão de cinzas e a espessura dos depósitos, com ventos de leste e sem ventos dominantes* (Concepção: T. Rey, 2021).

The ashes can therefore spread up to more than 30 km (taking into account the last eruption of 2007-2008 and probably even further if we consider that ashes of the OLD making up the “Namorod Ash” formation were trapped in the Olduvai Gorge (LeRoy Hay, 1976), located 70 km from the OLD! The fact is that the diffusion of the ash depends on multiple factors such as the granulometry of the pyroclastic materials, wind direction and speed, the total volume of the eruption and the height of the plume.

The qualification of the hazard levels is in progress with the choice of critical threshold (thickness of deposit). Being in an agro-pastoral zone, it will be necessary to establish a threshold at which the ash deposits no longer allow livestock to be fed. For example, a threshold of 3-5 cm would be sufficient to kill the surface vegetation. But seeds and roots are preserved in the soil and can lead to vegetation establishment quickly after the end of the eruption (Shutter *et al.*, 2015). For buildings, we can incorporate thresholds to qualify the level of risk of roof collapse, such as a 10 cm threshold for dry ash (Blond, 1984).

Pyroclastic flows hazard (lahars)

On the slopes of the volcano and on the Lengai plain, the current hydro-geomorphological processes are clearly visible. They are the result of sedimentation and ablation processes.

Our topomorphological data from 3 rivers in the plain underline that velocities and flows can exceed 4m/s and 210 m^3/s and probably more in some talwegs that could not be measured due to lack of time. The bed load composed of relatively fine pyroclastic materials, and some large multi-decimetric blocks (photo 5). In the same talweg (photo 6) we highlights the formation of the Lengai plain. It underlines the succession of flood deposits which participate in the aggradation of the plain (here ~2 meters). The lithofacies (thickness, size, sorting) reflect the hydrological variability of rivers, with periods more intense than others.

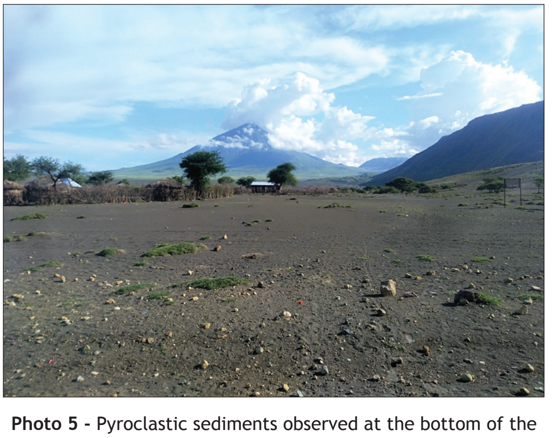

Photo 5 - Pyroclastic sediments observed at the bottom of the river, January 2020 (Photography by T. Rey, 2021).

Fot. 5 - *Pyroclastic sediments observed on the river bed, January 2020 (Fotografia de* T. Rey, 2021*).*

Photo 6 - Observation of numerous flood sequences (and lahars) involved in the aggradation of the plain, January 2020 (Photography by T. Rey, 2021).

Fot. 6 - *Observação de numerosas sequências de inundações (e lahares) que participam na agradação da planície (Fotogradia de* T. Rey, 2021*).*

A geochronological analysis of river formations should make it possible to better identify these periods marked by active hydrodynamics and their temporal recurrence.

The lahar hazard is very high on all the sides of the volcano. We have observed on the slopes of the Lengai a large quantity of mobilisable tephras (observation 2020), which due to the steep slopes (36% to 50% between 1600 and 2960 m) and the numerous talwegs are likely to be transported to the plain. In the plain, the lahar hazard is also very high in the main rivers. The lahar hazard is moderate to low in the areas adjacent to the main talwegs and in the river-lake delta (fig. 10).

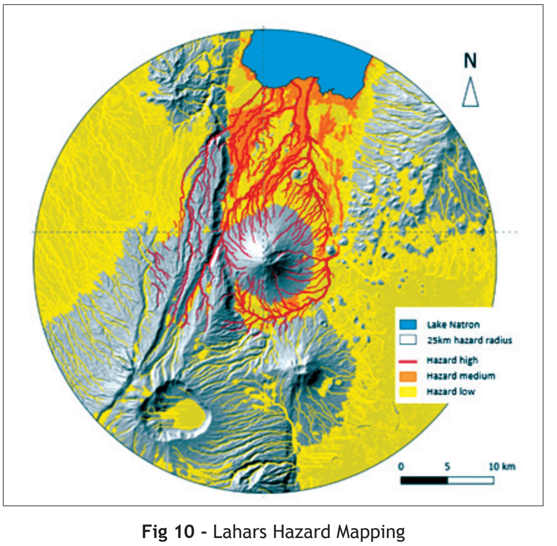

Fig 10 - Lahars Hazard Mapping (conception: F. Leone).

Fig 10 - *Mapeamento da severidade dos processos de Lahars* (concepção: F. Leone).

We continue the analysis of lahars using the LaharZ model (Iverson *et al.*, 1998) and our 6 diffusion and ash thickness scenarios (Tephra2 scenarios). The comparison of models and field data will make it possible to improve the spatial representation of this hazard.

Lava flows hazard

Our approach has made it possible to qualify two levels of hazard, a high and a moderate hazard. This distinction is based on the one hand, on the lava flows mapped by Sherrod *et al*. (2013) and, on the other hand, it is based on the analysis of the recurrence of flows between 1980 and 2020.

2/3 of the volcano's surface is in a high hazard zone, 1/3 in a moderate hazard zone. This situation can be explained above all by the location of the breaches at the rim of the crater and the evolution of the fractures on the flanks. The low hazard zone is delimited at the foot of the volcano (fig. 11).

Deep talwegs and steep slopes play a major role in channelling lava flows. By example, the last large lava flow from the volcano flowed in a deep channel on a W-NW axis for more than 3 km and three smaller flows located to the north (length: 70 m), to the NW (length: 150 m), to the east (length: 90) from the crater.

Debris avalanche hazard

Four debris avalanches have been identified in the OLD area. Three debris avalanches were triggered on the northern flank. The deposits of the most energetic phenomenon were observed nearly 20 km from the present crater (Keller and Klaudius, 2003). The fourth debris avalanche was triggered on the eastern flank and propagated towards the E-N-E.

According to Kervyn (2008), the collapses occurred mainly at right angles to a dyke which would have generated underlying instability and fragility. The configuration of the internal faults or the geometry of the internal structures may have controlled the orientation of the collapses. In addition, we can also point out that the slopes of the northern flank are more unstable and subject to gravitational movements due to the very steep slopes and the less resistant and more unconsolidated pyroclastic materials (Nepheline) compared to those of the southern flank (Phonolite). The delimitation of the low hazard zone is based on the characteristics of the *Karimasi* and *Zebra* debris avalanches (extension and energy), the moderate hazard zone on the *Oryx* debris avalanche (fig. 12). Concerning the high hazard, we have chosen to represent it following our recent geomorphological observations. Indeed, the western flank presents numerous zones of instability with long and wide fractures in the proximity of the crater (photo 7). We have established a "high hazard" zoning for this probable debris avalanches, which is based on energy analogous to the *Orix* and *Cheetah* debris avalanches.

The debris avalanche scenarios do not take into account possible tsunamis on Lake Natron that could be generated by the instability of the northern flank of the OLD, nor do they take into account the possibility of the river being blocked by a debris avalanche from a gravitational movement on the western flank, a situation that would have already occurred during the Cheetah event from the E-NE flank to the Kerimasi and Gelai volcanoes (Klaudius and Keller 2006).

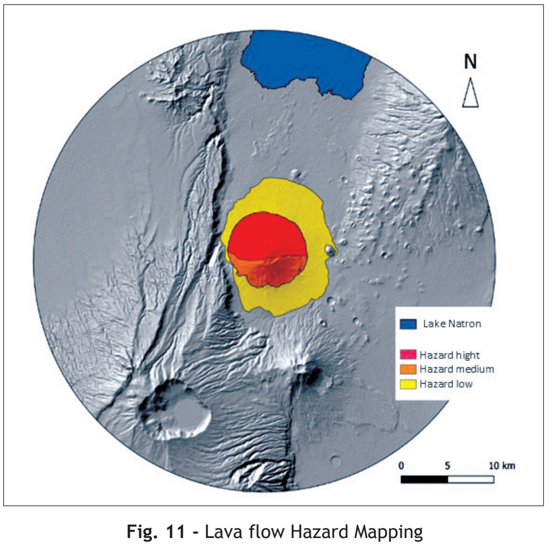

Fig. 11 - Lava flow Hazard Mapping (conception: F. Leone).

Fig. 11 - *Mapeamento da severidade do fluxo de lava* (concepção: F. Leone).

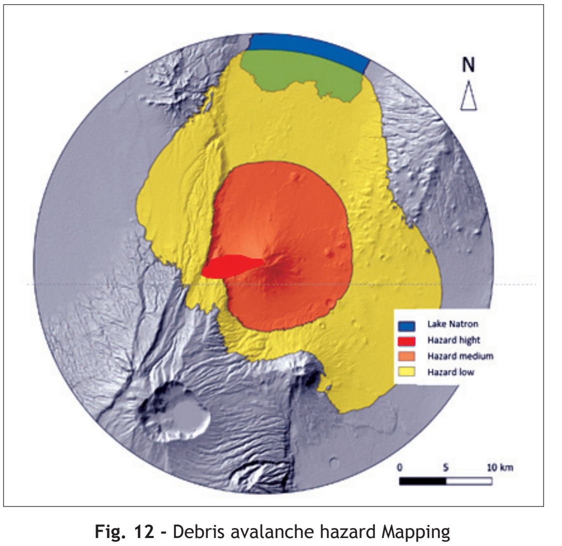

Fig. 12 - Debris avalanche hazard Mapping (conception: F. Leone and T. Rey, 2021).

Fig. 12 - *Mapeamento do risco de avalanche de detritos (concepção: F. Leone and T. Rey, 2021).*

Photo 7 - Fractures along the western flank of the Ol Doinyo Lengai. Observations January 2020 (Photography by T. Rey)

***Fot. 7 -** Fracturas ao longo do flanco ocidental do Ol Doinyo Lengai. Observações em janeiro de 2020 (Fotografia de T. Rey).*

Discussion

The results underline the volcanic threats that affect the populations in this area. The methods chosen alternate between field data, historical and bibliographical data, and modelling. These choices have been oriented to compensate for the insufficiency or absence of data. The results thus have limitations, but these cannot hide the singularity and originality of the results. These have made it possible to produce the first maps of volcanic hazards in the OLD space.

The scarcity of data is a problem encountered by other researchers in many territories, hence the need to adapt methods (Maharani *et al.*, 2016; Selva *et al.*, 2019). The combination of probabilistic and deterministic approaches makes sense and appears to be an interesting and accessible solution for states with insufficient human and logistical resources. The mapping of volcanic threats is essential for the prevention, protection and evacuation of people at risk. It is part of the volcanic risk dimension, where strategies make it possible to reduce the impact of future disasters, particularly for economically vulnerable and fragile communities.

A second point that needs to be emphasised is the temporality of the threats. The 4 volcanic hazards analysed in this article are not all synchronous with the eruptive crisis and can occur over very different temporalities.

Lahars can occur during the eruptive crisis or later after the eruption (De Belizal *et al.*, 2013), with a recurrence of lahars over several years such as Pinatubo (Crittendden and Rodolfo, 2002) or Merapi (Bignami *et al.*, 2013; Jenkins *et al.*, 2013; Wibowo *et al.*, 2015). In the OLD area, in each rainy season, (i.e. during the months of May, October, November and December, lahars can be triggered. On the sides of the volcano, the ash and lava deposits are easily moved, while the thin lava can also be mobilised after mechanical fragmentation. The plain is mainly characterised by the transport and deposition of fine materials (gravel and sand). The deposits are the result of erosion processes on the sides of the volcano and in the reworking of the alluvial sediments by incision of the beds and banks. However, in the absence of information on the flows, absence of videos and testimonies, we cannot be more precise in the kinematics of the flows.

The probability of debris avalanches is more reduced: four known phenomena in almost 800,000 years. Their triggering is due to internal factors (earthquakes) and exogenous factors (rainfall, slope and crater instability) that are difficult to measure (Meunier *et al.*, 2008; Miyabuchi *et al.*, 2015). Nevertheless, certain wide and deep fractures that can be observed on the steepest slopes of the volcano (above 40°) can help us to map areas marked by active instability. It is also known that the lava covering the unconsolidated pyroclastics favours instability of the flanks.

The fall of ashes and lava flow have a temporality that follows the eruption. However, the impacts of ash fallout can occur over longer periods of time, extend beyond the Lengai area and rapidly cause a series of local and regional damages: damage to housing, ash-covered roads reducing or blocking access, diversion of air traffic and reduction in tourist flows, respiratory difficulties for humans and animals, ingestion of ash by livestock, burnt crops, and depending on the composition of the ash (Ph, acidity, minerals), sometimes lasting pollution of the soil and fresh water (Witham *et al.*, 2005 ; Horwell and Baxter, 2006). For example, the last eruptive crisis required the displacement of 5,000 and 7,000 people. In Engare Sero and Engaruka-Ngwesuku, people were displaced for more than 10 months (NEMC, 2008). NGOs and the Red Cross provided food aid to nearly 36,000 people (Msami, 2007). In Lesele, ashes prevented families from returning to their bomass, which was abandoned (Courtesy of J. Keller and J. Klaudius in https://volcano.si.edu). In addition, fluorine concentrations posed a threat to the water supply for livestock and local people (De Schutter *et al*., 2015; Bosshard-Stadline *et al*., 2017). Livestock keepers then had to move their livestock to find healthy pastures and unpolluted water. For thicker ash coverage, the formation of a new soil layer is required to establish new plants, leading to a much longer recovery period. Humans are also exposed to fluoride, and over the years they report diseases such as rachitis.

Conclusion

Although the volcanic hazards in Lengai are real, the scientific literature on their quantification is scarce and relatively poor, even in the presence of a relatively rich literature on the geology of space. ~~.~~This situation did not provide a solid basis for the quantification of risks in the future. To fill this gap and prepare the ground for future quantification of volcanic risk, we proposed scenarios for four volcanic hazards. The scenarios were developed using a deterministic and probabilistic approach. These approaches need to be developed further, for example through the acquisition of a high-resolution DTM to better define the kinematics of lava flows and lahars, and to establish a geochronological framework for the sequences of lahars and debris avalanches that have been identified but not dated. In order to establish multi-risk maps, we continue our assessment of socio-economic issues and their vulnerability to volcanic threats. An analysis of the accessibility and vulnerability of road networks is also conducted in the framework of evacuation scenarios (during the rainy and dry seasons). An analysis of the perception of the Maasai communities living around the volcano is also underway in order to identify the complex relationships that exist between the Lengai God's abode volcano and the Maasai. In the end, we will be able to propose volcanic risk management strategies adapted to the local context.

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