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Geomorphological Constrains and the Occupation of Slopes Prone to Rockfall Risk in Mowo and Mokong Communities of the Mandara Mountains-Far North – Cameroon

Etame Sone Diabe[1*], Jules Balna[1], Saïdou Bogno Daniel[2] and
Nnoko Maxwell Haggat Enongene[3]
[1]Department of Geography, University of Maroua and University Institute of International Development, Mokolo, Cameroon
[2]Department of Meteorology, Climatology and Hydrology,
University of Maroua, Cameroon
[3]Physics Department, University of Maroua, Cameroon

ABSTRACT

Nowadays, rockfall is a major concern as a natural lithospheric hazard. Since the return of migrants from major metropolis that began in the 1990s, pressure has increased on land hence; steep slopes have become new settlement and agricultural areas. This paper examines the geomorphological constrains and the occupation of slopes pruned to rockfall risk in the Mowo and Mokong localities of the Mandara mountains-Far North Cameroon. Using interviews, focus group discussions in both study sites, rockfall simulation on the slopes to determine Run-Out and Impact Distance of falling blocks and determining the vulnerability of the sample sites, as well as spatial analysis through remote sensing, results show that: the trajectory and travel distance of falling rock blocks depend on major parameters like velocity, kinetic energy, slope angle, position of rocks, weathering process, and rock mass. Also, more that 90% of the settlements and farmlands as well as electricity transmission lines and roads are found on along the trajectory of falling blocks. Also, more than 50% of the houses are constructed beyond the indicators of maximum run-out distance of falling rock blocks making them more vulnerable to this hazard. The impact intensity (Force) varies from 241,195.50 N to 754,055.46 **N** from very gentle slopes to steep slopes respectively and will crush everything on its way. Furthermore, more than 98.5% of the population under study do not see rockfall as a risk but as the manifestation of anger of their "gods" who protect them, solve their problems and who they worship, respect and pay allegiance to. Territorial planning policies should incorporate the respect of a maximum run out distance limit for construction on rockfall risks slopes to reduce their vulnerability to this hazard.

Key words: Natural hazard, Rockfall risk, Pressure on land, Mowo/Mokong of the Mandara Mountains, Far north Cameroon

INTRODUCTION

There is no slope on which physical and human processes operate on, that remains 100% stable. Mass movement hazards have been affecting humanity worldwide. The magnitude and frequency varies from one place to another. One of the processes involved in this mass movement is rockfall which is the rapid type. This hazard is defined as the potential for a rockfall event to detrimentally affect society (Briones-Bitar *et al.,* 2020; Cruden, 1996; Žabota & Kobal, 2020); it is quantified by the volume of rock involved and by the probability of the event (Abele, 1994). The hazards of rockfall are grater in areas with intense seismic activities especially where earthquakes are the principal triggering factors (Marinos & Tsiambaos, 2002). It is one of the most frequent and damaging types of mass movement

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[*] Corresponding Author

(Rosser & Massey, 2022). Slope dynamics associated with hazards have several causes (Corominas *et al.,* 2017); this movement covers a particular distance for the highest effect to be registered (Legros, 2002; Fell, 1994; Matsuoka & Sakai, 1999). The role of geomorphology in preventing natural hazards in developing countries have been studied by Yang *et al.* (2017); Ritchie (1963), while others worked on landslide zonation and mapping in mountainous areas (Dorren, 2003; Selby, 1982; Žabota & Kobal, 2020).

In the tropical Sahel region with clear-cut characteristics different from those of the temperate and cold regions of the world, rockfall analysis has been given little attention meanwhile it constitutes a potential risk factor to be considered. In Cameroon, most attention has been given on landslide in the western highlands of the country which constitute a wet zone. Little has been done in the drier part of Cameroon concerning mass movement. This has been a visible type that is the center of focus in this research and which is affecting lives and property of the population. The case of the Mandara Mountains (MM) of the Far-North Region of Cameroon is an example. This slope –changing process has been creating tension as well as damages on both human lives and property which the population attributes to being “the manifestation of the anger of their gods on them”. The notion of rockfall risk is viewed by the Mandara Mountain people as spiritual manifestation. This is because they consider the rock blocks as their gods and carryout incantations and sacrifices to these spirits.

The Mandara Mountains are a mountainous region remarkable for its rich cultural and spiritual diversity. They are considered a religious territory (Alawadi, 2017). The stones found there have always been considered sacred objects since the work of the first ethnologists led by Marcel Griaule during the Sahara-Cameroon ethnographic mission (de Lauwe, 1937). Among the Mofu, the rock stone is a living being, which surrounds men, an emanation of the mountain, and therefore a place of force whose physical contact ensures contact with the Spirit (Morin, 1996). His anger is feared, to cut into him to trace a path is to hurt him, to offend him. In this region, stones occupy a central place in the spirituality and traditions of the populations of the Mandara Mountains in Cameroon (Vincent, 1971).

There is continuity between the social environment and the natural environment, which is revealed in a rather cohesive and communicative interaction (Descola, 2011). Their use in rituals, places of worship and agricultural practices testifies to the importance given to these natural elements in local culture. To better understand the relationship between man and nature, we must draw on African cosmologies (Sarr, 2017; Mbembé, 2023).

Mountains have a particular importance in the spirituality of the Mofu. For this community, mountains are seen as sacred places where ancestral spirits reside and religious rituals are conducted. They believe that mountains are points of connection with the spiritual world and play a key role in transmitting spiritual traditions and teachings. Many religious rites and ceremonies take place on the mountains, symbolizing closeness to deities and ancestors. These people also attach great importance to protecting the environment of the mountains, considering them to be sacred places to be preserved. The mountains are therefore not only spiritual spaces, but also essential elements of the cultural and religious identity of the Mofu. These places therefore occupy a central place in their spirituality as sacred places of connection with the divine, ritual practice and preservation of ancestral traditions.

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Rock blocks detachment from the steep slopes with destination on human settlement and installations at the foot of the mountains is frequent and has been on an increase for the past two decades. The mountains have steep slopes with near- about-detaching-rock blocks of granito-gneissic complex as most rocks on the Cameroon trend (Gazel *et al.,* 1956; Kagou Dongmo *et al.,* 2005; Zangmo *et al.,* 2009). The frame of this article is to show the geomorphologic constrains in the two localities, evaluate the vulnerability of the population to rockfall risk in tropical dry areas leaning on geologic characteristics of rocks found on the Mandara mountains, determine the processes operating on the slopes and their prominent effects given the proximity of the inhabitants to this danger and sensitize on a change in their mind-set towards believing science to reduce risks linked to traditional believes considering their own area example.

MATERIAL AND METHOD

Study Area

The MM is a volcanic range that extends to about 193km along the northern portion of the Cameroon Nigeria border from the Benue River in the south to Mora in the north. The mountains culminate to about 1492m above sea level. It is part of the Cameroon trend which begins from the Bioko Island through Mt. Cameroon to Mora. It is one of the high population density areas (>100 inhabitants/km^2) in Cameroon with >400.000 people and >30 ethnic groups (Gaimatakwan, 2016; MacEachern, 2011, 2012). According to David and Robertson (2012: 171), the MM people constitute the Mada, Mouktele, Mofu, Mafa, Kapsiki, Podoko and Moura‘h. Our attention in this paper is on Mowo and Mokong (the Mafas and the Mofus) who inhabit the slopes and the foot of these mountains with local religion (**Figure 1**). They believe in spirits living in rock blocks and they consider them as gods who protect them, solves their problems and to whom they perform sacrifices, owe allegiance, respect and have high recognition for. These localities have a population of about 8500 people as well as several visitors.

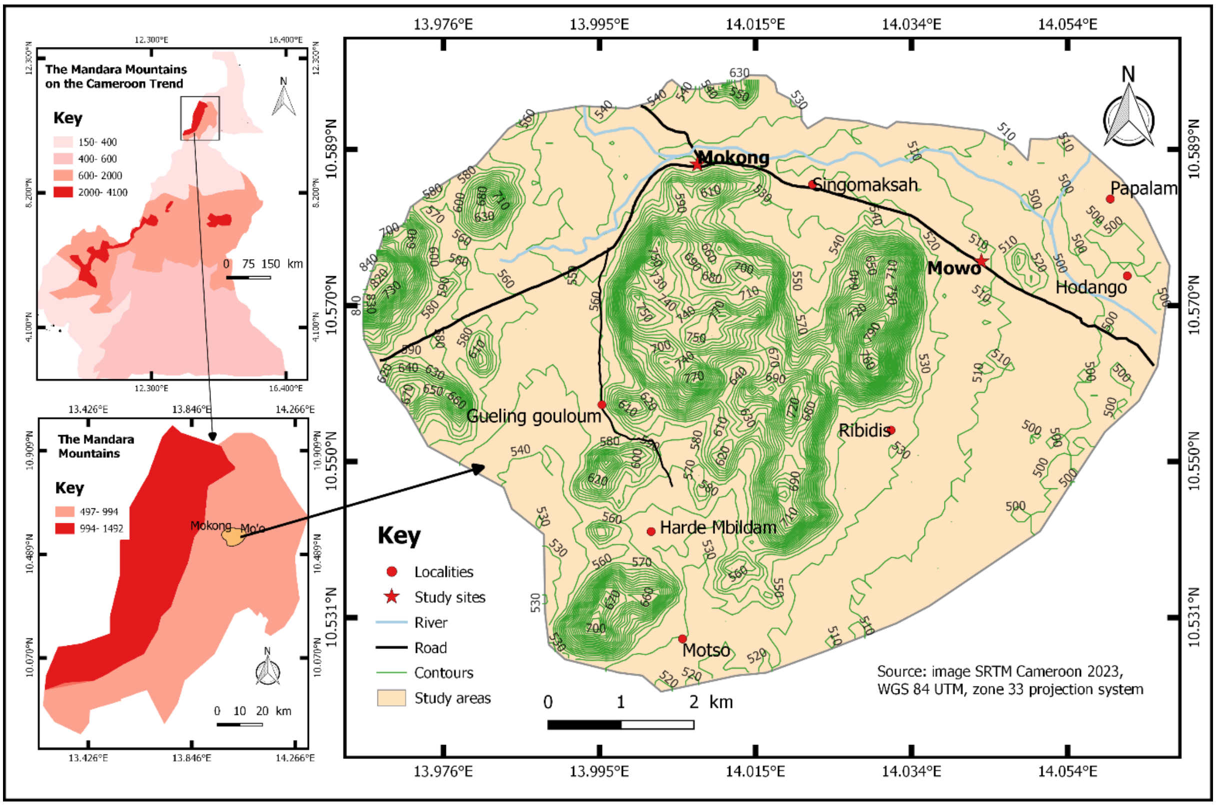


Figure 1: Study areas

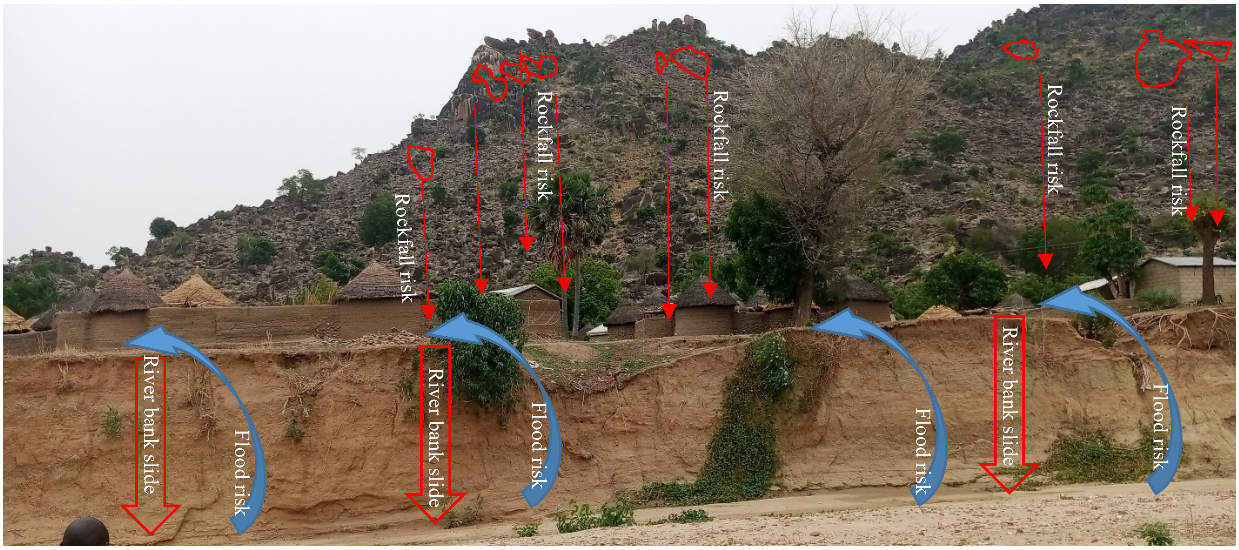
Data Collection and Analysis

To determine the level of slope material stability and the frequency of rockfall against the increasing population and their installations on these slopes, a series of field experiments were carried out at different slope angles and sites with different parameters. Interviews were effected on the population in the two localities and the persons interviewed were 40 years plus. This was to be able to suggest measures that will limit the occurrence of such hazards after coming out with susceptibility map to rate slopes as per the frequency of rockfall.

RESULTS

Mowo and Mokong Geomorphologically Constrained Localities

The geographic position of Mowo and Mokong localities places the two localities between steep slopes in the south and Mayo Boula River in the north. They are located at an altitude that varies between 500m-530m above sea level. These localities cannot expand northward due to this river course with unstable banks as erosion is also frequent causing the banks to collapse hence, they prefer to move close to the steep slopes of the Mandara mountains where rockfall frequency is a threat to human lives and property (**Picture 1**).



Picture 1: Physical constrains of Mowo and Mokong localities

Spirituality and Rockfall in Mowo and Mokong Communities

The spirituality of the people of the Mandara Mountains in general, and among the Mofu in particular, is deeply linked to their natural environment. Mountains, rocks and natural phenomena such as falling rocks are seen as sacred and carry important spiritual meanings. According to local beliefs, mountains and rocks are inhabited by powerful spirits. Sudden and unexplained rockfalls are interpreted as signs of the activity of these spirits. People see them as messages, warnings or manifestations of the will of the supernatural forces that govern their world. Rituals and sacrifices are often performed at the locations where these rockfalls occur, in order to honor the spirits and maintain balance between the physical and spiritual worlds.

The Mofu of the Mandara Mountains places great importance on spirituality in their culture. For them, each element of nature is animated by a certain form of spiritual force. The falling of stones is seen as a sign of the will of the spirits or ancestors. Depending on their beliefs, a falling stone can symbolize a message, a warning or a call to action. In Mofu cosmology, stones are often associated with stability, strength and wisdom. Local legends associate rockfall from mountains with spiritual events or omens. These natural phenomena are sometimes interpreted as divine signs, reinforcing the connection between the stones and spirituality in the region. Thus, when stones fall unexpectedly, this can be interpreted as an upheaval of the natural order of things or as a disruption of spiritual harmony. Village elders are usually consulted to interpret these events and guide the community on what to do next.

Rockfall are a common natural phenomenon in this mountainous region. For the Mofu, they are often seen as signs or omens. Indeed, they first presage change. The Mofu consider that sudden and unexpected rockfall often herald future changes, whether positive or negative. This can mean the arrival of visitors, good or bad news, or even important events within the community. Then, they are messages addressed to the ancestors, since in Mofu cosmology; ancestors are seen as spiritual guides who sometimes communicate with the living through natural phenomena such as falling rocks. These can be interpreted as messages or warnings from the ancestors. It also means the presence of spirits.

Some rockfall are associated with the presence of spirits, genies or other supernatural entities that inhabit the mountain. Their manifestation can be seen as a sign of their activity or their discontent. Finally, rockfall are protective rituals, because faced with these phenomena, men have developed rituals and practices to protect themselves and reconcile the forces of nature. This may include offerings, prayers, or ceremonies aimed at appeasing the mountain spirits.

Ultimately, Rockfall have an important symbolic and spiritual dimension for the Mofu community, who interpret them as signs, messages or manifestations of the supernatural forces present in their mountainous environment. This understanding shapes their relationship with nature and their way of adapting to it. Understanding and managing these natural phenomena is an integral part of traditional cosmology and spiritual practices in this region.

This belief in the spiritual dimension of nature is fundamental for the mountain communities of the Mandara Mountains and profoundly shapes their relationship with the environment. The falling of stones thus takes on a sacred meaning beyond its simple physical dimension. It is important to understand that the relationship between spirituality and rockfall among the Mofu is deeply rooted in their history, traditions and values. It is an essential aspect of their cultural identity and their understanding of the world around them.

Characteristics and Share Strength of Rocks on the Slopes of the MM

The share strength of rocks on the MM slopes have become very weak that even wind triggers great rockfall as a result of the steep angles of the slopes, greater physical weathering (exfoliation) and tectonic cavities of 1.5m-6m long and between 0.75m to 2.94m deep. More than 95% of the potential rock blocks geared towards a fall have cavities that only need push-range of 5cm- 68cm for a rupture to occur. This brings about a non-proportionate distancing amongst the potential rock blocks destined to fall (**Picture 2)**.

Picture 2: Potential rock blocks destined to fall

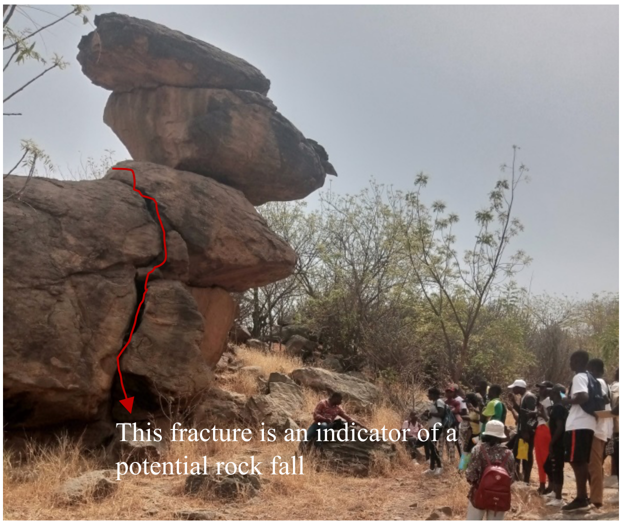
Slope angles in parts of the mountain area are gentle which makes majority of the rock blocks destined to fall to gradually move with little velocity. Other portions of the mountain slopes have been scarped such that greater shares sizes of rocks can be mobilized if all conditions are united (that will give gravity an upper hand at the detriment of the share strength of the rock blocks on the slopes). The slopes with the same characteristics were classified in categories hence, 06 categories were brought out through slopes stability scaling, where vertical and horizontal sections of the sample areas were considered to rate the slopes as having; very low risk, low risk, average risk, high risk and very high risk of rockfall.

Field observation and past history made us to understand that rockfall had existed for long but the frequency has increased as the population also increases. This is seen on the presence of several large rock blocks at the foot of the slopes and in the compounds of the inhabitants. Also, 75% of the house construction is done on the fallen rock blocks as well as those that have taken place recently (**Figure 5**) in Mowo and Mokong communities.

Physical weathering and stability of rock masses

From observation, the rocks of the MM have been weathered severely through temperature alternations leading to rock exfoliation (Picture 3). This process of rock peeling is so intense due to very high temperatures ranging between 32ºC-41ºC. This has made most rock blocks to require just a few centimeters of displacement for them to start moving downslope. With a sample measure of 50 rock blocks along the 6 main slope categories, the volume of the rocks vary from 1.2m-9.4m in diameter. More than 70% of the rocks especially on steep slopes are overhanging and the average distance separating them range between 1.5m-8.75m.

Rock fracturing has also been observed through biological weathering (as plant roots grow in the cracks of the rocks, they increase in size within the cracks causing the rocks to eventually shatter). This increases the number of rock masses free to fall on the slopes of these mountains. Friction is less on the slopes hence, most rock blocks fall freely. From field observation, potentially unstable rocks are more on steep than on gentle slopes.



Picture 3: Rock fracturing

Rainfall factor

Climate of the sahelian type: rainfall is very scanty and varies 450 mm à 850 mm per year. It is available for only three months and during heavy down pours it facilitates the removal of soil from the deposition pockets where parts of rock blocks are buried to expose them to exfoliation processes in the 9 months dry periods. Rainfall also favour agricultural activities which increase the mutilation of the soil texture depth and structure on the slopes hence, provoking several Rockfall episodes through the creation of ridges and furrows.

Soil factor

The soils are less cohesive and coarse in grains due to the presence of sand. This permits water infiltration in the short rainy season which causes little chemical weathering in the rocks. This facilitates the breaking of the rocks during falls and spurs up other subsidiary Rockfall with several trajectories of fall and distance. It reduces slope stability by weakening the share strength if the slope and increases the rock blocks' gravitation vulnerability to fall.

Fracture orientation: east- west fracture orientation on north - south slope angle provides favourable pathways for Rockfall in the Mandara Mountains. These fracture orientations give an added advantage to the force of gravity at the detriment of the rock block share strength on the slopes. More than 80% of the rock blocks have been fractures by physical weathering stemming from the alternation of high heat during the day and cold at night. This is evidenced by the angular rock blocks fragments found at the foot of the mountains on which the local population dry their millet on. The orientation and the density of these fractures shows that the frequency of rock block detachment will be high in the near future.

Bedding thickness: though not a sedimentary basin, we can apply this term here to explain how the thickness of rock block and their position on the slope affects their fall. In the areas where rocks have been tilted at an angle of 90° (vertically) on the Mandara mountain slopes very close to the missionary buildings at Mokong and around the new construction area at Mowo, more that 70% of the rock blocks have greater thickness towards the top and less at the base. This creates favourable conditions for gravity to downplay of the resistant force of the rock blocks thereby acting as a spurring factor to favour rock block detachment.

Most of the rocks on these slopes are hard rocks such as granite and basalt. They likely maintain their shape during a Rockfall event. From the indicators in the field, 98% of the rocks have maintained their shape despite the great height from where they fell. The travel distance was also considerable or significant since these rock blocks remain intact as they fall given their hardness.

Weathering: weathering of rocks on the Mandara Mountains is predominantly physical than chemical. This is due to intense sunshine with great heat (temperatures between 35°c-41°c from February to May). Rocks peel off in the exfoliation process reducing their sizes and making them vulnerable to fall. That is rocks that need just a few centimeters to separate from where they hang are often spurred to rupture through this process.

Vegetation consideration: the scanty vegetation on these mountains has been cut to almost 95%by the population for fuel wood. This increases the risk of Rockfall since no trees mean limited barrier to falling blocks. 85% of the potential rockfall are found on non-vegetated category of slopes and 68% of the population inhabits the slopes foot of this slope category.

Slope gradient: slope gradient determines how free falling a rock block can be and the distance that the block will travel if all other factors are held constant. The more the gradient the greater will be the fall. Slopes angle range between 48°-64° which makes the rocks to remain potential risk to the foot slope population.

Human action: farming and rearing has also increased the vulnerability of rocks to fall. Cultivation of crops in the Mandara Mountains goes with ground tilling which removes the thin layer of soil that prevents the rocks from falling hence; they become less resistance on the slopes since their share strength is often reduces favoring the force of gravity.

Past rockfall events

Several rock blocks have fallen from the MM. This is evident by the presence of many of the rock blocks of different diameter ranging from $6m^3$-$8m^3$ around the settlements found at the foot of the slopes. The stone quarries (stone cracking for house construction) taking place at the foot of these slopes and on the rock blocks that have fallen many years back. Most often, the falling rock blocks provoke fire that consume farms and animals as well as destroy tress and micro fauna (environmental disaster). The events that accompanied the fallen rock blocks have been censored on (**Table 1**).

Table 1: Events of rockfall and accompanied impact

Date	Description of event	Location of event
1974	Rockfall that killed a widow and two of her children after destroying her house.	Mokong
1987	Rockfall that destroyed two millet bands through fire provoked by the descending rock blocks at Mokong.	Mokong
1987	Rockfall that killed a woman who was looking for clay to produce calashes at the foot of the slopes.	Mowo
11/02/ 1990	After returning from match pass, a rockfall killed an average number of 6 goats that were grazing at the foot of the slope.	Mowo
2007	A huge mass of rock blocked the leg of a woman who was cultivating her farm. It was a medical doctor who came to amputate her leg.	Mowo
2017	A woman was caught between two rock blocks when she went to send away baboons from her millet farm. A 58 years old man confirmed that it was his wife.	Mowo
2018	Large rock blocks blocked the main road to the farms this called for a meeting which made the road to be deviated.	Mokong
2018	Large rock blocks descended the slopes and covered the firewood that was being dried on other previously fallen rocks.	Mokong
2018	A large rock block descended the slopes and provoked many other small block falls that destroyed 2 houses and blocked the main entrance to the compound of a Mokong notable.	Mokong
2019	Large rock blocks descended the slopes and blocked the main water hole of the Mokong locality they were only obliged to dig again some 50m from the previous one and the population confirmed that the new water hole was not as clean as the previous one.	Mokong
2020	About 3 rockfall events occurred which blocked the runoff gutters making it to deviate from its original path into the farms of the peasants who suffered erosion effect and till date the areas have not been recovered for farming again. The rock blocks reduced farmland sizes through erosion and the occupation of the farmland by the large rock blocks.	Mowo and Mokong
2021 / 2022	2 cases of rockfall have been confirmed with no damages but these rock blocks have positioned other rocks blocks in critical positions that mobility is sure to continue any time soon.	Mowo and Mokong

Source: Field data 2022

As concerns Rockfall Frequency in the two localities, greater frequency of rockfall history is registered in Mekong than in Mowo.

THE TRAJECTORY OF FALLING ROCK BLOCKS, TRAVEL DISTANCE AND RISK ANALYSIS

a. ***Trajectory of falling rock blocks***

The distance of the potential falling rock blocks from the source to the foot of the slope ranges between 1.8m-278.5m above the slope foot. Rocks that frequently fall range in size from 5m^3-46m^3 corresponding to areas where slopes are very steep with greater fracture or crack intensity as wells as a separation distance between the fractured blocks ranging from 0.92m- 2.22m.

The path followed by falling rock blocks down slope is not fixed since they are often deviated by other previous rocks found on their way down slope. This makes it possible for a detached rock block to assume several directions before attaining slope foot. This change of trajectory is favoured by the shape of the rock block, its mass and the potential and kinetic energy it possesses, moving surface roughness and the presence of vegetation. Greater rockfall on these slopes have been on the phases of slopes where vegetation cover is less and where the bedrock crops on the surface at a distance of about 70-85m and the slope angles ranging between 48°-64°. Greater exfoliation process takes place at this height reason why the probability of Rockfall is high as well as the frequency.

b. *Travel distance of rock blocks*

The angle of the slope determines the velocity and the travel distance of the falling rock blocks. From field experiments performed on 3 slope categories, they revealed that: on a distance of 50m (measured at an altitude between 95m-145m from slope base) a rock block of 4.54m^3 travelled along the distance in 12 seconds with a velocity of 3.92m/sec. At the end point of the rock block under simulation (95m from slope base), there were two other rock blocks that were on its path. These two blocks were displaced on an average distance of 3.9m (rollout distance). This horizontal displacement distance after the impact was influenced by the height of fall, the slope angle (48°-64°) and the initial velocity (3.92m/sec) of the rock block. As for the impact distance, it was determined by: velocity, slope angle on the shape of the rock (semi-circular). As the slope angle increases, the impact distance initially increased and later reduced.

c. *Intensity of rockfall impact*

The intensity of rockfall impact is very high on steep slopes meanwhile on gentle slopes; the fall impact effect is low. The slope categories as shown on Table 2 has been portrayed on figure … to demonstrate areas of probable Rockfall and the trajectories they take to reach the run out area where the population has installed their settlement. The shape of the rock blocks influences the speed and direction of fall of the blocks. Smooth and round or circular blocks move faster than angular blocks. The circular blocks move on a straight path down slope at great velocity especially where the outcrop of the bedrock is uniformly smooth too. The angular rock blocks deviate from their trajectory and move in a haphazard manner downslope.

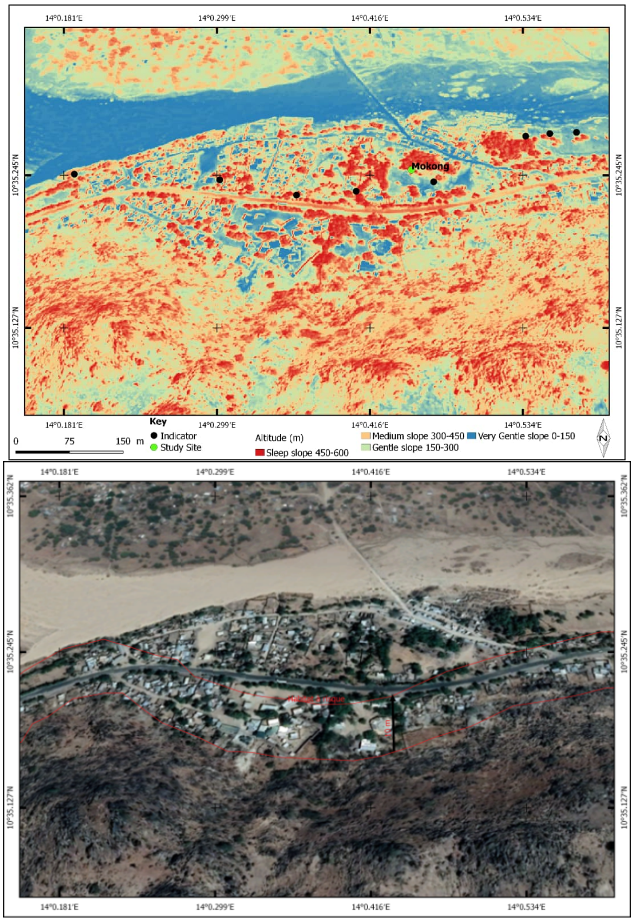


Image plate 1: High risk Rockfall area

It is important to also note that there are multiple falls orchestrated by single rocks mobilized by either wind, animals or by weathering. These blocks then fall freely under the influence of gravity. This was the case of the 2018 Rockfall event in which a large block detached at about 78m from a slope at Mokong and provoked more than 10 other blocks to the villagers who came out of their houses in the number to witness the event. This Rockfall event moved at different directions which in turn created 4 other minor block displacements. This provoked fear amongst destroyed 2 houses and blocked the main entrance to the compound of a Mokong notable. This forced many villagers to leave their houses around the slopes in question to reside with their neighbors further away from the area. But in the morning, they decided to regain their homes with the expression that "the *gods* were not happy with them".

Table 2: Slope category, rock volume and density

Slope category	**Rock volume**		**Slope angle as per area considered**	**Highest Altitude**	**Rollout distance**	**Rock type**	**Rock density (X10^{2}kg/m”)**
Very Gentle slope	4.54m^3	6.5m^3	10°-20°	95m	50m	Gneiss	2.7
Gentle slope	4.54m^3	12m^3	20°-30°	145m	150m	Granite	2.7
Medium slope	4.54m^3	15.5m^3	30°-48°	190m	300m	Basalt	3.0
Steep slope	4.54m^3	46m^3	48°-64°	278.5m	450m	Basalt	3.0

The mass of each rock is obtained from the formula: mass = density of rock x rock volume i.e. $m = \rho \text{ x v}$.

*** Measure of Rockfall speed***

To measure the velocity of Rockfall, we use the principle of work done by a solid in relation with the center of gravity and mechanical energy theory based on a Galilean referential **(Figure 2).**

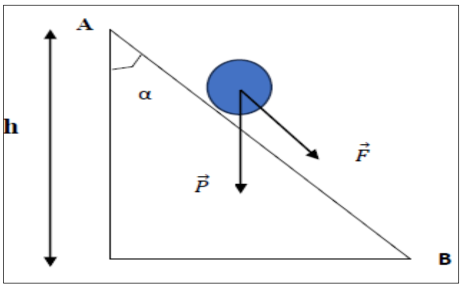


Figure 2: Work done by a solid (s)

If the center of gravity G is displaced from A to B in a straight line along the trajectory (AB), then:

-The work done by the weight is:

W_{AB}($\vec{P}$) = P*AB*cosα = mgh with h = ABcosα and P = mgh

-The work done by the force $\vec{F}$ is:

$W_{AB}(\vec{F})$ = F*AB*cos($\vec{F},\overrightarrow{AB}$) with cos($\vec{F},\overrightarrow{AB}$) the angle between the force $\vec{F}$ and the displacement AB

Note: the work done by the weight is peculiar. It is also equal to the potential energy (E_{PA}) of weight $\vec{P}$.

*** Theory of mechanical energy***

"In a Galilean referential, the variation of the mechanical energy of a system is equal to the sum of work done on the system by external forces i.e. $\Delta E_{mec} = \sum W_{AB}\left(\vec{F}\right)$"

In our case we have:

$$\Delta E_{mec} = \sum W_{AB}\left(\vec{F}\right) \Leftrightarrow E_{mA} - E_{mB} = W_{AB}(\vec{F}) \qquad (0.1)$$

$$W_{AB}\left(\vec{F}\right) = E_{cA} + E_{pA} - E_{cB} + E_{pB} \qquad (0.2)$$

With $E_{cA} = \frac{1}{2}mv_A^2$, $\mathrm{E}_{pA} = mgh$, $\mathrm{E}_{cB} = \frac{1}{2}mv_B^2$, $\mathrm{E}_{pB} = 0$ and $W_{AB}(\vec{F})$ = F*AB*cos($\vec{F},\overrightarrow{AB}$)

$$\therefore \frac{1}{2}mv_A^2 + mgh - \frac{1}{2}mv_B^2 = F * \mathrm{AB} \qquad (0.3)$$

with cos($\vec{F},\overrightarrow{AB}$) = 1, since ($\vec{F},\overrightarrow{AB}$) is a null angle (i.e. angle between $\vec{F}$ and $\overrightarrow{AB}$ is zero)

From equation (1.1), making F the subject of the formula gives:

$$F = \frac{\frac{1}{2}mv_A^2 + mgh - \frac{1}{2}mv_B^2}{AB} \qquad (0.4)$$

If v_A, the initial speed of the Rockfall is the same as the final speed (neglecting air resistance and frictional forces due large rock masses), then the force on the rock is given by:

$$F = \frac{mgh}{AB} \qquad (0.5)$$

Note: E_{CA} = kinetic energy at point A
E_{CB} = kinetic energy at point B
E_{PA} = potential energy at point A
E_{PB} = potential energy at point B
W_{AB} = work done by the force $\vec{F}$

Now, consider the equation of motion:

$$s(t) = s_0 + v_0.t + a_0.\frac{t^2}{2} \tag{0.6}$$

Where v_0 = initial velocity, a_0 = initial acceleration (it is constant along the path).

The distanced covered by the Rock falling from a height h before reaching point B (the house) is:

$$s_0 = \frac{h}{\cos\alpha} \tag{0.7}$$

Where α is the steepness of the slope as indicated on the figure above. Point B corresponds to s = 0.

The acceleration depends on the steepness and its magnitude is given by $g.\cos\alpha$. Assuming $v_0 = 0$, the equation of motion reduces to:

$$s_0 = \frac{h}{\cos\alpha} - g.\cos\alpha.\frac{t^2}{2} \tag{0.8}$$

The negative sign is because we start at a distance s_0 and want to go down to s = 0, so the acceleration is negatively directed. The time t_1 required to reach point B, i.e. at s = 0 is:

$$s(t) = 0 \Rightarrow t_1 = \sqrt{\frac{2h}{g.\cos^2\alpha}} \tag{0.9}$$

The velocity after the said time is:

$$s'(t_1) = g.\cos\alpha.t_1 = g.\cos\alpha.\sqrt{\frac{2h}{g.\cos^2\alpha}} = \sqrt{2gh} \tag{0.10}$$

Note:

$s'(t_1) = \frac{ds(t_1)}{dt_1}$ And the acceleration on a steeper slope is greater than less steep slope and acts on the body not along as it does on the less steep slope consequently, no matter the number of Rock falling at the time, end up with the same speed.

So, rock speed is given by:

$$v = \sqrt{2gh} \tag{0.11}$$

With g = acceleration due to gravity, h = rock altitude.

For gneiss rock, the density is 2.7 x 10^3 kg m^{-3}. This is summarized in **Table 3.**

Table 3: Rockfall impact intensity

Slope category	Rock volume		Slope angle as per area considered	Highest Altitude	Rollout distance	Rock speed $\left(v=\sqrt{2gh}\right)$	Rock mass $\left(m=\rho \text{ x v}\right)$	Impact intensity (F) $\left(F=\frac{mgh}{AB}\right)$
Very Gentle slope	4.54m^3	6.5m^3	10°-20°	95m	50m	43.17 m s^{-1}	17550 kg	**327,114.45 N**
Gentle slope	4.54m^3	12m^3	20°-30°	145m	150m	53.34 m s^{-1}	32400 kg	**307,249.20 N**
Medium slope	4.54m^3	15.5m^3	30°-48°	190m	300m	61.06 m s^{-1}	41850 kg	**241,195.50 N**
Steep slope	4.54m^3	46m^3	48°-64°	278.5 m	450m	73.92 m s^{-1}	124200 kg	**754,055.46 N**

It is noticed that, this impact force will increase with altitude (h) and mass of the rock but decreases with rollout distance. In our study areas (Mokong and Mowo), the impact intensity (Force) varies from 241,195.50 N to 754,055.46 **N** from very gentle slopes to steep slope respectively. This force can conveniently destroy all the type of houses constructed on the foot of these mountains. The characteristics of the houses are as follows; mud houses 56%, cement blocks without iron bars 35% and mud bricks mixed built with cement mortar 09%. The fragility of these buildings makes them very vulnerable to any force this make the destruction intensity to be highest.

d. Run out area and characteristics

The run out distance of falling rock blocks in the Mokong and Wowo communities short and it constitutes the preferred area for construction. Electricity lines and more than 30% of the new constructions of these two localities are found on this run out distance. Picture plate 1 portrays the run out distance of the rock blocks that have fallen before and that are still to fall. The frequency of Rockfall in this area is very high and from field inquires an average of 2 blocks fall per year.

Picture plate 1: Run out distance and type of buildings at risk

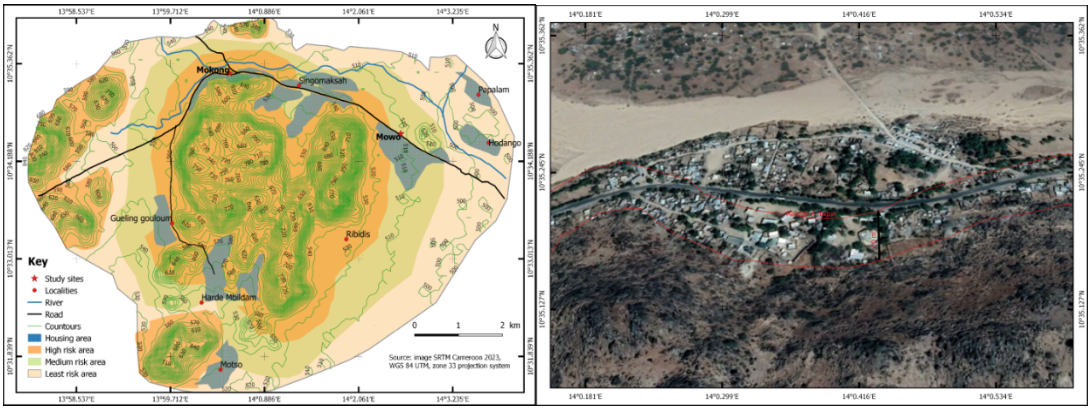
Picture a and b on Plate 1 shows the run out distance of falling rock blocks and type of buildings mostly found on the run out distance

Risk indicators of Rockfall and determination of places of high risk

**Rockfall Risk evaluation*

The Mokong/Mowo risk evaluation can be made by considering the following parameters; slope angle, rock release altitude, slope roughness to check friction of moving rocks, slope height, the vegetation found on the section of the slope, distance separating potential rock block, past history of Rockfall and the direction of the previous falls, the share strength of the rocks on the slope (rock block resistance), rock volume or mass (m^3), rainfall intensity, wind speed, slope infiltration rate and drainage, rock block alignment and number, animal and human influence. These parameters can be grouped into 6 sub classifications namely: slope geometry, the geology and rock block characteristics, spurring factor, drainage conditions, fauna and flora character and the effects and factors related to past history of Rockfall.

Slopes of these two localities were classified according to these parameters and most of the parameters varied from one slope to the other. Such variability could be seen on the volume and number of rock blocks, the distance separating them, the vegetation density and human influence of the slopes. This made us to classify the slopes under very low, low, moderate, high and very high risk slopes depending on the vulnerability of the population and their establishments in the two localities (Figure and image plate 1).



Source: image SRTM Cameroon 2023, WGS 84 UTM, zone 33 projection system

Figure and image plate 1: Rockfall vulnerability indicators

DISCUSSION

The understanding of Rockfall risk and the geological makeup of the Mandara Mountains (MM) owes its base in the mastery of the history of the Cameroon Trend (CT). The MM is one of the great continental volcanoes of the Cameroon trend consisting of Mount Cameroon, mount Bamboutos, the Bamenda highlands, mount Oku through the Tchabals, Alantika to the study area. The Cameroon trend is a trans-tensional passive rift, showing an alternation of volcanic horsts (from which rocks fall) and grabens as shown by Moreau *et al.* (1987); Meyers *et al.* (1988); Déruelle *et al.* (2007). Tectonic extension caused lithospheric thinning, asthenosphere upwelling and the formation of a magmatic hot line, trending N30°E. The continental sector of the Cameroon trend can be divided into a southern part, which extends from the coast to the southern edge of the Adamawa Plateau, and a northern part, from Adamawa Plateau and the Mandara Mountains which constitutes our study area has also been demonstrated by Kagou Dongmo *et al.* (2001).

Both parts of the Cameroon trend are under laid by Pan African basement rocks consisting mainly of schists and gneisses intruded by granites and diorites as evidenced in the work of Déruelle *et al.* (1991 and 2000); Kagou Dongmo *et al.* (2001); Nkouathio *et al.* (2002); Suh *et al.* (2003); Itiga *et al.* (2004); and Kagou Dongmo *et al.* (2010) as the main rocks that fall from the Mandara Mountain slopes. Volcanic rocks that comprise the main risk object in the Cameroon trend on which the Mandara Mountains that constitute our zones of study; Mowo and Mokong) is found range in composition from basalts to trachytes and rhyolitic has been examined by Wotchoko *et al.* (2005).

The evolution of the MM is due to successive extrusions. This succession is traced from 1.55 to 0Myr on an uplifted granito-gneiss basement of about 1100m of altitude above sea level. These mountains extend about 193km along the Cameroun Nigeria borders from River Benue (South) to Mora (North). An important volcanic activity took place along the trend from the Eocene to recent times making it a volcano-tectonic apparatus above the uplifted granite basement (Déruelle *et al*., 1991). It is cross-cut by N 30° to 50°E and N 140°E faults (Déruelle *et al*., 1991, 2000; Kagou Dongmo *et al*., 2001; Nkouathio *et al*., 2002; Suh *et al*., 2003; Itiga *et al*., 2004; Wotchoko *et al*., 2005; Kagou Dongmo *et al*., 2010) and has a diameter of about 200km. These tectonic characteristics portray great influence on the nature of and height from where the rocks fall as revealed in this research.

The MM are pluto-tectonic related geomorphological isolated units such as Mount Marouare, Nzokok, Loulou, Mindif, etc with steep scarps on certain phases (around the town of Maroua). The MM are polygenic volcanic complex characterized by fissural volcanic activity giving rise to more than 120 strombolian cones, with some initiated by phreato-magmatic explosive events which hold rocks today that threaten the lives of the people found in these two localities.

The same causes produce the same effects and as a result, the history of the Cameroon trend is similar. Hence, generalizing the results of Fitton & Dunlop (1985) we conclude that, the recent ages of the MM: 0,40 Myrs±0,04 Myr for the basanite, 0,94±0,06 and 0,48±0,29 Myr for the basalts. Also, Kagou Dongmo *et al.* (2010) mentioned the existence of geological contradictions between commonly accepted history of the volcanic activity of the Cameroon Trend and their findings based on K/Ar and 40 Ar/39 methods suggest a new time frame which varies between 0,24 Myr to 0,05 Myr as revealed by Lee (1994). These rocks weather today greatly to provide room for the detached blocks to fall as shown in this research.

These findings led to a complete revision of the conventional history of the Cameroon trend. To this effect, petrological and magmatic features are documented from mineral and chemical analyses. The analysis revealed that the volcanic rocks belong to the alkaline sodic series, evolving from basanite to trachyte as shown by Youmen *et al.* (2005) and Kagou Dongmo *et al*. (2010). Given that all these mountains are found on the Cameroon Trend and formed by same orogenesis, the Mandara Mountains have the same characteristics and portrays protruding rocks destined to fall as shown in this work.

CONCLUSION

This article examined the geomorphological constrains and the occupation of slopes pruned to rockfall risk in the Mowo and Mokong communities of the Mandara mountains-Far North Cameroon. It displayed that the Mowo and Mokong localities are faced with a dilemma of two great risks: that of rockfall and of flood to which they are vulnerable. They are obliged to construct close to *Mayo* (river) Tsanaga or on the travel distance of falling rock blocks. Occupying rockfall pruned slopes of the Mandara Mountains according to the population constitute just an aspect of normality and the notion of risk is not in their vocabulary as they belief that when a rock block falls, then the "gods" of the mountains are angry and they must do a sacrifice to appease them. More than 80% of the population of these two localities is vulnerable to rockfall and flood risks from *Mayo* Tsanaga. This is seen on the density of the population found around the run-out distance of potential falling rock blocks. Measures to be implemented include the following:

- Sensitizing the population on natural hazards which will spur a complete turnaround on their local belief about these phenomena is key to their security;
- Building a boulder wall around the indicators of maximum rolling distance is also a way out;

- Vegetating the foot slopes with resistance plant species like *Anogiensus* and *tamarindus indica*;
- Construction of houses should not go beyond the indicators on maximum runout distance of falling rock blocks;
- The banks of *Mayo* Tsanaga should be fortifies with rock armors to reduce the risk of floods.

REFERENCES

Abele, G. (1994). Large rockslides: their causes and movement on internal sliding planes. *Mt. Res. Dev., 14,* 315-320.

Alawadi, Z. (2017). La montagne comme territoire religieux chez les peuples du Sahel. L'exemple des Zoulgo de Tokombéré (Extrême-Nord Cameroun) ? *Annales de l'Université de Moundou, Série A, Faculté des Lettres, Arts et Sciences Humaine, 3*(1), 163-184.

Briones-Bitar, J., Carrión-Mero, P., Montalván-Burbano, N., & Morante-Carballo, F. (2020). Rockfall research: A bibliometric analysis and future trends. *Geosciences*, *10*(10), 403.

Corominas, J., Mavrouli, O., & Ruiz-Carulla, R. (2017). Rockfall occurrence and fragmentation. In *Advancing Culture of Living with Landslides: Volume 1 ISDR-ICL Sendai Partnerships 2015-2025* (pp. 75-97). Springer International Publishing.

de Lauwe, P. H. (1937). Pierres et poteries sacrées du Mandara, Cameroun Nord (Mission Sahara-Cameroun). *Journal des Africanistes*, *7*(1), 53-68.

Déruelle, B., Bardintzeff, J.M., Cheminée, J.L., Ngounouno, I., Lissom, J., Nkoumbou, C., Étamé, J., Hell, J.V., Tanyiléké, G., N'ni, J., Ateba, B., Ntepe, N., Nono, A., Wandji, P., Fosso, J., & Nkouathio, D.G. (2000). Eruptions simultanées de basalte alcalin et de hawaiite au mont Cameroun (28 mars–17 avril 1999). *Comptes Rendus Académie Sciences Paris, Sciences de la terre et des planètes*, *331*, 525-531.

Déruelle, B., Moreau, C., Nkoumbou, C., Kambou, R., Lissom, J., Njongfang, E., Ghogomu, R.T., & Nono, A. (1991). The Cameroon Line: a review. In: Kampunzu, A.B., Lubala, R.T. (Eds.), *Magmatism in Extensional Structural Settings* (pp. 274–327). The Phanerozoic African Plate. Springer, Berlin.

Descola, P. (2011). *L'écologie des autres. L'anthropologie et la question de la nature*. Versailles: Éditions Quae.

Dorren, L.K.A. (2003). A review of rockfall mechanics and modelling approaches. *Prog. Phys. Geogr., 27*, 69-87.

Fell, R. (1994). Landslide risk assessment and acceptable risk. *Can. Geotech. J., 31*, 261-272.

Fitton, J.G. & Dunlop, H.M. (1985). The Cameroon line, West Africa, and its bearing on the origin of oceanic and continental alkali basalt. *Earth Planet. Sci. Lett., 72*, 23–38.

Itiga, Z., Chakam Tagheu, P.J., Wotchoko, P., Wandji, P., Bardintzeff, J.-M., & Bellon, H., (2004). La ligne du Cameroun: Volcanologie et géochronologie de trois régions (mont Manengouba, plaine du Noun et Tchabal Gangdaba). *Géochronique, 91*, 13–16.

Kagou Dongmo, A., Nkouathio, D., Pouclet, A., Bardintzeff, J. M., Wandji, P., Nono, A., & Guillou, H. (2010). The discovery of late Quaternary basalt on Mount Bambouto: Implications for recent widespread volcanic activity in the southern Cameroon Line. *Journal of African Earth Sciences*, *57*(1-2), 96-108.

Kagou Dongmo, A., Wandji, P., Tchoua, F., Nkouathio, D., Tchouankoue. J. P. & Kuepouo, G. (2001). Les inondations dans les basin versants de Santchou (Ouest Cameroun): impact sur l'environnement et la population locale. Gsaf 12: Geo-environmental catastrophes in Africa. *J. Geoscience Soc. Cameroun*, *1*(1A), 57-58.

Lee, D. C. (1994). *A chemical isotopic and geochronological study of the Cameroon Line, west Africa.* PhD thesis, University of Michigan 179 p.

Legros, F. (2002). The mobility of long-runout landslides. *Eng. Geol., 63*, 301-331.

Matsuoka, N., & Sakai, H. (1999). Rockfall activity from an alpine cliff during thawing periods. *Geomorphology*, *28*(3-4), 309-328.

Mbembé A. (2023). *La communauté terrestre.* Éditions La Découverte, 206 p.

Meyers, J.B., Rosendahl, B.R., Harrison, C.G.A., & Ding, Z.-D. (1998). Deep-imaging seismic and gravity results from the offshore Cameroon Volcanic Line, and speculation of African hotlines. *Tectonophysics, 284*, 31–63.

Morin, S. (1996). *Le haut et le bas. Signatures sociales, paysages et évolution des milieux dans les montagnes d'Afrique centrale (Cameroun et Tchad).* Talence : Centre de recherche sur les espaces tropicaux. pp. 1-156. (Pays enclavés)

Nkouathio, D.G., Ménard, J.-J., Wandji, P., & Bardintzeff, J.-M. (2002). The Tombel Graben (West Cameroon): a recent monogenetic volcanic field of the Cameroon Line. *J. Afr. Earth Sci., 35*, 285–300.

Ritchie, A.M. (1963). Evaluation of rockfall and its control on Highway. *Res. Rec., 17,* 13-28.

Rosser, N., & Massey, C. (2022). Rockfall hazard and risk. In *Landslide Hazards, Risks, and Disasters* (pp. 581-622). Elsevier. https//doi.org/10.1016/B978-0-12-818464-6.00013-5

Sarr, F. (2017). *Habiter le monde : essai de politique relationnelle*. Montréal (Québec) : Mémoire d'encrier, coll. Cadastres, 59 p.

Selby, M.J. (1982). *Hillslope material and processes.* Oxford, UK: Oxford University Press.

Suh, C.E., Sparks, R.S.J., Fitton, J.G., Ayonghe, S.N., Annen, C., Nana, R., & Luckman, A. (2003). The 1999 and 2000 eruptions of Mount Cameroon: eruption behaviour and petrochemistry of lava. *Bull. Volcanol., 65*, 267–281.

Vincent, J. F. (1971). Divination et possession chez les Mofu, montagnards du Nord-Cameroun. *Journal des Africanistes*, *41*(1), 71-132.

Wotchoko, P., Wandji, P., Bardintzeff, J.-M., & Bellon, H. (2005). Données pétrologiques et géochronologiques nouvelles sur le volcanisme alcalin néogène à récent de la rive ouest du Noun (plaine du Noun, Ligne du Cameroun). *Rev. Bulgarian Geol. Soc., 66*, 97–105.

Yang, P., Shang, Y. Li. Y. Wang, H., & Li, K. (2017). Analysis of potential rockfalls on a highway at high slopes in cold-arid areas (Northwest Xinjiang, China). *Sustainability, 19*, 414.

Youmen, D., Schmincke, H.-U., Lissom, J., & Etame, J., (2005). Données géochronologiques: mise en évidence des différentes phases volcaniques au Miocène dans les monts Bambouto (Ligne du Cameroun). *Sci. Technol. Dev., 11*, 49–57.

Žabota, B., & Kobal, M. (2020). A new methodology for mapping past rockfall events: From mobile crowdsourcing to rockfall simulation validation. *ISPRS International Journal of Geo-Information*, *9*(9), 514.