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Multi-hazard risk mapping and assessment on an active volcano: the GRINP project at Mount Cameroon

Pierre Thierry · Laurent Stieltjes · Emmanuel Kouokam · Pierre Nguéya · Paul M. Salley

Abstract To help improve the safety of its population faced with natural disasters, the Cameroon Government, with the support of the French Government, initiated a programme of geological risk analysis and mapping on Mount Cameroon. This active volcano is subject to a variety of hazards: volcanic eruptions, slope instability and earthquakes. Approximately 450,000 people live or work around this volcano, in an area which includes one of Cameroon's main economic resources. An original methodology was used for obtaining the information to reply to questions raised by the authorities. It involves several stages: identifying the different geological hazard components, defining each phenomenon's threat matrix by crossing intensity and frequency indices, mapping the hazards, listing and mapping the exposed elements, analysing their respective values in economic, functional and strategic terms, establishing typologies for the different element-at-risk groups and assessing their vulnerability to the various physical pressures produced by the hazard phenomena, and establishing risk maps for each of the major element-at-risk groups (population, infrastructures, vegetation, atmosphere). At the end of the study we were able (a) to identify the main critical points within the area, and (b) provide quantified orders of magnitude concerning the dimensions of the risk by producing a plausible eruption scenario. The results allowed us to put forward a number of recommendations to the Cameroon Government concerning risk prevention and management. The adopted approach corresponds to a first level of response to the authorities. Later developments should make it possible to refine the quality of the methodology.

Keywords Mount Cameroon · Multi-hazard geological risk mapping · Vulnerability assessment · Landslides · Volcanic risk · Earthquakes

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1 Introduction

1.1 Mount Cameroon

Mount Cameroon is a major volcano located in Cameroon, at the edge of the Gulf of Guinea (Atlantic Ocean) and about 60 km west of the town of Douala. It extends between latitudes 3°57′ and 4°27′ N and longitudes 8°58′ and 9°24′ E (Fig. 1) and dominates the towns of Buea and Limbe, among others.

Including the Fako cone, this active volcano rises to 4,095 m altitude. Elliptical in shape and oriented roughly northeast/southwest (N030–N050), its long axis is around 50 km and its short axis 35 km.

Mount Cameroon is probably a volcanic horst fed mainly by fissures, most with a NE-SW orientation. It is composed of alkali basalt (undersaturated), which varies relatively little between picrite, basanite, hawaiite and mugearite, accumulating as large flows and cinder cones aligned along the gaping fissures controlling the eruptive dynamism. Analyses show no difference in either the evolution of the chemistry with age or the series. The lavas rest on Miocene and Pliocene sedimentary successions making up the piedmonts (Dumort 1968; Hedberg 1968; Nni 1984; Déruelle et al. 1987; Zogning 1988; Nkoumbou et al. 1995; Cruz Mermy et al. 2006).

Mount Cameroon has given rise to several catastrophic events over the past few years: eruptions in 1999 and 2000 that led to villages being evacuated (Déruelle et al. 2000; Suh et al. 2003), many earthquakes (Ambeh and Fairhead 1991; Ateba and Ntepe 1997; Ubangoh et al. 1997) including the destructive 1999 earthquake at Buea, landslides and mudflows that killed 24 people at Limbe in 2001 (Ayonghe et al. 2004) and four people at Buea in 2006.

Fig. 1 Location of Mount Cameroon

These types of phenomena threaten, to various degrees, around 450,000 people and some of Cameroon's main infrastructure, including the Sonara oil refinery, the Limbe power station, and industrial and semi-industrial plantations (banana, hevea-rubber, tea or palm oil, cacao).

1.2 The GRINP project

Despite various scientific studies, the Cameroonian authorities have no clear idea of the level of risks associated with the volcano. It was in order to respond to this need that a project entitled "Mount Cameroon Surveillance" was set up within the Mines and Geology Directorate of the former Ministry of Mines, Water and Energy. The main purpose of the project was to (a) delimit eruptive-product impact zones along the Cameroon line, and more particularly in the Mount Cameroon area and (b) assess, through geotechnical, geomorphological and geological study, the terrain behaviour in order to anticipate possible damage levels. The project is financed entirely by the Cameroon Government and an initial field programme was carried out in 2000/2001 (Kouokam 2001).

The GRINP (Gestion des Risques Naturels et Protection Civile—*Natural Risk Management and Civil Protection*) project falls within this perspective. Its objective was to reply to a certain number of questions raised by the authorities and the population, such as:

– When and how might natural hazardous phenomena (volcanic eruptions, landslides, earthquakes) occur?
– Where might these phenomena occur and what would be their nature?
– Who is threatened by their effects, and when does one run a risk?
– What is the magnitude of damage likely to occur?
– How can one protect against their effects and prepare for a crisis?

The main objective of the project was thus a "risk inventory" in terms of the different hazardous geological phenomena likely to occur in the Mount Cameroon area (volcanic eruptions, earthquakes and landslides) in order to (a) allow preparations to be made for the volcano's next eruptive crises and (b) establish the elements for a programmed risk management (before, during and after the catastrophic events) by drawing up material and technical, social and economic, and administrative and financial prevention measures.

The measures are reflected in the regional planning and development decisions as regards infrastructures, networks, housing and human and economic activities.

In order to provide pertinent information to the authorities, it was necessary to assess:

– The threat (hazard), for which the main characteristics are the frequency (F) or probability of occurrence of the different geological phenomena, the intensity (I) or destructive power of the said phenomena and the extension (E) expressing what percent of the threatened surface is possibly affected;
– The potential damage on the elements at risk (human, economic, strategic, etc.). For this aspect an inventory and localization of the exposed elements (population, buildings, vegetation, etc.) were followed by an assessment of the expected damage levels (vulnerability) from the threatening phenomena.

Combining the two risk components (hazard and element-at-risk) through a Geographic Information System (GIS) enabled us to produce several risk zoning maps related to the geological phenomena around Mount Cameroon and corresponding to the major

element-at-risk categories. The precision adopted for this mapping is compatible with a scale of 1:200,000.

The project took place over 2 years and was carried out by a Franco-Cameroonian team (Thierry et al. 2006).

1.3 Procedural framework of the study

Although many studies have been concerned with the analysis of volcanic hazards on active volcanoes, this is not the case where integrated risk assessment is concerned (Pareschi et al. 2000). An original methodology, adapted from work carried out in the France, West Indies (Stieltjes 1997; Stieltjes and Mirgon 1998; Stieltjes et al. 2001), was therefore developed and implemented on Mount Cameroon. It hinges around five major phases that lead to a risk analysis and a prevention policy, which follow one another as follows:

– *Characterization of the physical environment* (geological and tectonic setting, geomorphology, known natural phenomena, past events) used as a basis for assessing and then zoning the geological hazard levels;
– *Hazard assessment and zoning* leading to an evaluation of the threat level of the entire site in terms of both occurrence probability and expected intensity. This assessment must look at two different objectives: (a) identification of the most dangerous areas in terms of an overall hazard that simultaneously integrate the different phenomena and (b) identification of the physical impacts of each hazardous phenomenon so as to determine potential damage;
– *Characterization of the exposed elements* (systematic analysis of the regional system) leading to an identification of the main elements at risk in the region (resources) and an assessment of their value and prioritization;
– *Vulnerability analysis of the elements at risk* so as to assess their resistance to the impacts of the different anticipated physical effects. From this, it is possible to assess the damage and determine the weak points in the regional system;
– *Risk analysis* in terms of hazard plus value and vulnerability of the elements at risk. It measures the human, social, economic and environmental impact of predictable disasters that can then be specified in terms of the different exposed milieus (population and infrastructures, natural and agricultural environment, atmosphere).

These five phases provide the basic methods for the region's preventive spatial planning and the search of socially acceptable preventive solutions. To be effective, these solutions must then be integrated into a regional management and development plan (land use plan).

These phases are discussed in detail in the following sections.

2 Characterization of the physical environment

It must be emphasized that the risk approach uses scientific knowledge that is based largely on the 1:100,000- and 1:50,000-scale geological maps compiled during the project (Cruz Mermy et al. 2006).

The studies have made it possible to characterize the hazardous geological phenomena that occur on Mount Cameroon and which can be broken down into three major categories of events: volcanic eruptions, slope instabilities and earthquakes. Not only can these events

interfere with one another, but they can also take various forms. Consequently, we have taken nine different phenomena into consideration as geological hazard components:

- *Six volcanic phenomena* linked to the eruptions (lava flows, aerial fallout, gas, lahars, medium- and large-amplitude ground movements, tidal waves),
- *Two slope instability phenomena* (landslides and block falls),
- *One tectonic phenomenon* (earthquakes).

As an example, we can take the study of the "lava-flow" component of the volcanic eruption hazard.

2.1 Characterization of the "lava-flow" component

The basalt lava flows pour out from fissures opening up in the volcanic edifice as a result of swelling or tectonic extension. These effusive emissions are composed of a basaltic alkaline magma that generally shows little differentiation and gives facies ranging from porphyritic lava (matrix enclosing large millimetre- to centimetre-size crystals) to aphyritic, composition ranging from picrite (basalt with abundant porphyritic olivines—up to 30%) up to basalt (thus a relatively fluid magma), and even up to a hawaiite composition (possibly mugearite). Intermediate facies represent only a very small volume (a few percent of all the basalt emitted).

The flows can be divided into:

- *Very fluid flows* that flow and advance rapidly (upstream speeds of up to 60 km/h, becoming slower downstream). The resultant flows are generally long (up to 10–15 km) and may reach the piedmont: either the sea or the plain (lying at an altitude of around 400 m). The width of the flows varies according to the slope and the viscosity, but can be as much as 500–800 m.
- *Fluid to slightly fluid flows* that flow and advance fairly rapidly (several km/h) near their point of emission, then slow down (several hundred m/h) as they cool and become more viscous. These flows may ramify into several arms as the more fluid part of the lava (protected from cooling by the thick mantle of scoria and blocked by the thick massive viscous front) escapes laterally to form a new lava tongue. The rate of advance at the flow front becomes very slow: a few metres per hour to a few metres per day. The resultant flows are generally shorter (up to 5–7 km long) and wider (up to 1 km) than the 'very fluid' flows, and their advance can halt even on a very steep slope (30°) if the front is no longer fed.

Lava flows cause the total destruction of all surface objects in their path, either through combustion, melting or spontaneous ignition, or through overlap or burial, or through a combination of processes. The intensity of this component will always be maximal.

Earlier authors describe 13 historical eruptions, the oldest of which dates from 1815 (Zogning 1988). These historical flows (13 in 200 years) correspond to an average return frequency of the order of 15 years. The eruption centres are located at the summit of the volcano or in the upper parts of the slope, and generally correspond to one or more juxtaposed craters or to fissures, and sometimes to a combination of the two. From these historical eruptions, the flows are approximately equally distributed between the two types described above (the more and the less fluid). Thus, time return is two times longer (30 years) for the longest, very fluid lava flows extending 10 km from the point of emission.

Field observations combined with aerial-photo and satellite-image analysis have also revealed the presence of 388 recent, but undated, eruption centres. Relative ages for these centres can be established from the freshness of the morphology and the level of weathering; six C^{14} determinations for these events give ages between 600 and 6,000 years BP (Bulourde 2001; Cruz Mermy et al. 2006). In addition, 49 volcanic cones associated with older events have also been identified.

3 Hazard zoning

3.1 Principle

The ultimate objective is to produce a single map synthesizing the threat level to be taken into account so as to aid and orient the authorities' decisions. For example, how does one rank the threat between two areas is likely to be affected by:

– Either a medium-intensity earthquake with a 100-year return period, which will affect the entire sector approximately equally;
– Or a lava flow of maximal intensity, but with a thousand year return period, which will affect a necessarily limited area of the same sector.

To be able to reply to such a question implies, in the first place, qualifying and then quantifying or weighting the three characteristics of each hazardous natural phenomenon over a given reference period; i.e.

– *The probability of occurrence (frequency)* which is the estimated return period between two events in a given sector;
– *The intensity*, which is the physical impact on the exposed elements and environments. The potential intensity should be expressed on a scale that is consistent between all the phenomena. In hazard zoning, it is assessed in terms of damage vis-à-vis a single type of exposed element, such as a common building. Note, however, that a global approach cannot be used for assessing the anticipated damage to the other element-at-risk because of their diversity. The intensity must be expressed individually and directly in terms of physical impacts, such as the weight of ash on roofs or the impact of blocks;
– *The possible extension*, or extensive character, of the hazardous phenomena. The whole of a sector may be affected, as for example in the case of an earthquake, or the phenomenon may be limited spatially within the zone, as with a landslide on a slope.

One must then combine the values of these different parameters to determine a maximal threat index to identify the most hazardous zones. The adopted approach involves various stages:

– Defining the typology of the hazardous phenomena to be taken into account;
– Determining a pertinent reference period for assessing the frequencies;
– Identifying reference events representative of the expected phenomena;
– Establishing quantified reference scales for the frequency, intensity and extensive character;
– Establishing, for each of the considered hazardous phenomena, a combined frequency/intensity matrix, and mapping a threat index corresponding to the maximum locally obtained value. Note that the extensive character is considered as constant for a given phenomenon. This assumption is compliant with the working scale of this study;

– Crossing the different hazard maps to obtain an overall map showing the maximal threat index for each point.

3.2 Definition of the frequency, intensity and extension scales

The adopted reference period was fixed at 10,000 years BP, which roughly corresponds to the Holocene. From this, a frequency scale was established on the basis of the available datings of the different events and on the known phases of the volcano's activity. The scale is given in Table 1.

A frequency index (Q_f) was then calculated by taking the inverse of the longest return period retained for each frequency class. However, since the results of a risk analysis must be interpreted by non-scientists, the Q_f index is multiplied by 100 so as to give values (Q_F) that can be intuitively understood.

At the same time, a consistent intensity scale was established between each of the nine identified phenomena. Table 2 gives this scale with the different expertise rules retained for volcanic phenomena (Stieltjes 1997). As noted earlier, the intensity of volcanic phenomena is expressed here in terms of the damage to the built-up environment and not in terms of the eruption magnitude. It is thus a "relative intensity" (effects on the human environment) and not an "absolute intensity" of the eruption. To illustrate the notion, one can say that if there was a house at such and such a point, it would be subjected to this much amount of damage.

The given numerical equivalent (cf. Table 3) corresponds to the degree of maximum damage retained for the exposed reference element (here the global settlement). As with the frequency, the numerical equivalent is multiplied by 100 to make things clearer for the non-scientists.

In order to be able to take into account, the spatial extension of the phenomena within a given area, we used two extension index (i_{ext}) values, as follows:

– $i_{ext} = 0.5$ for phenomena that only affect a limited part of the considered area. For example, the anticipated return period for the lava flows on the southwestern side of the massif is of type F_3 (every 100–500 years). But this probable lava flow, several kilometres long by several 100 m wide, will only cover part (albeit possibly a

Table 1 Frequency scale

Frequency class	Qualification of the event frequency	Return period for the type of activity or phenomenon (order of magnitude) (years)	Quantification of the phenomenon frequency (Q_f)	Index used for the threat matrices ($Q_F = 100 \times Q_f$)
F_0	Very low to negligible	5,000–10,000	10^{-4}	0.01
F_1	Very low	1,000–5,000	2×10^{-4}	0.02
F_2	Low	500–1,000	10^{-3}	0.1
F_3	Moderate	100–500	2×10^{-3}	0.2
F_4	High	50–100	10^{-2}	1
F_5	Very high	10–50	2×10^{-2}	2
F_6	Quasi-permanent	1–10	10^{-1}	10

Table 2 General volcanic-hazard intensity scale for an effusive volcano (adapted from Stieltjes 1997)

Intensity class qualification	Damage level (exposed reference element: overall development)	Triggered volcanic phenomena (applied expertise rules)	Types of damage (examples)
I_0 Very low	≤5% damage	Ash fallout <1 cm	No danger for the population; temporary difficulties,
		Diffuse gas, acid rain	
		Tsunami wave (<0.5 m)	No great damage for agriculture (other than plants close to the ground),
			Slight local corrosion of materials and vegetation
I_1 Low	5–10% damage	Ash deposits, pumice, lapilli (thickness 1–20 cm)	Little real direct danger for the population: major difficulties
		Gas, not very dense acid rain	
		Tsunami wave (0.5–2 m)	Possibly notable damage for agriculture, cattle, etc.
			Corrosion, abrasion of vegetation, mechanical equipment, industrial equipment and installations, etc.;
I_2 Moderate	10–50% damage	Ash deposits (20 cm to 1 m)	Population: difficulties in breathing, vision
		Fallout of Pelé's hair	
		Gas, dense acid rain	Significant damage to buildings, networks
		Tsunami wave (2–4 m)	Major damage to cattle, agriculture, water points, etc.
I_3 High	50–80% damage	Heat effect near a flow	Damage or partial destruction of buildings, infrastructures
		Thick deposes of ash, lapilli, scoria (1–1.5 m)	Great danger for the population
		Lahar (mud flow) <1 m	
		Tsunami wave (4–8 m)	
I_4 Very high	≥80% damage	Lava flow	High risk of serious injury or death for the population, cattle, fauna present in the area
		Ash or scoria fallout (deposits ≥1.5 m), ejected blocks	
		Lahar (mud flow) ≥1 m	Total destruction of vegetation, buildings and infrastructures
		Tsunami wave (≥8 m)	

Table 3 Volcanic-phenomenon intensity levels used for the Mount Cameroon hazard assessment and zoning

Intensity class	Qualification of the hazard intensity	Degree of damage (reference: global settlement)	Numerical equivalent (E_I)
I_0	Very low to negligible	<5% damage	5
I_1	Low	5–10% damage	10
I_2	Moderate	10–50% damage	50
I_3	High	50–80% damage	80
I_4	Very high	≥80% damage	100

significant part) of the considered area. This limited spatial extension in fact diminishes the probability of occurrence at any point in the area, and thus the threat index;
- $i_{ext} = 1$ for extensive phenomena of the earthquake or ash-fallout type which affect an entire sector simultaneously.

At this stage of the Mount Cameroon risk analysis, we kept the binary dimension of the parameter for lack of anything better, considering the working scale. This point should be improved in future studies.

3.3 Constructing a threat matrix and hazard classes

On the basis of the three components (frequency, intensity, extension) it is possible to construct a threat matrix, which is the product of the vector Q_F, the transpose of vector E_I, and the scalar i_{ext}. The elements of this matrix are termed threat indices and are noted i_m (cf. Fig. 2).

The threat indices are used in the hazard zoning maps to characterize each area exposed to hazardous geological phenomena. Different $(Q_F \times E_I)$ doublets are possible for the same phenomenon over a same area. For example, low intensity phenomena are likely to recur at a high frequency, whereas a very high intensity phenomena will be less frequent. Insofar as these phenomena are not independent of one another (two events of different intensities cannot occur at the same time in the same place), it is preferable to keep the maximal index obtained per area rather than the sum of the different possibilities.

The hazard is then qualified through correspondence with value classes, the threat indices being distributed according to five main classes, and is classified from "negligible" to "very high".

In order to facilitate the interpretation of such a hazard map by local authorities, who are often scarcely familiar with the concept of natural risks, it was considered judicious to associate the hazard class with an overall recommendation level. Thus:

- *Negligible hazard* (for threat indices i_m of less than 1): no recommendation for normal permanent human settlements;
- *Low hazard* ($i_m = 1$–10): no specific recommendation, but a certain vigilance is required, in particular for the exposed elements of great or primordial importance;
- *Moderate hazard* ($i_m = 10$–50): permanent human settlement is possible, but specific precautions are recommended, depending on the phenomena involved;
- *High hazard* ($i_m = 50$–100): permanent human settlement is inadvisable, unless major precautions are taken;
- *Very high hazard* ($i_m \geq 100$): permanent human settlement should be avoided.

$$I_m = i_{ext} \cdot Q_F \times {}^t E_I = i_{ext} \cdot \begin{pmatrix} F_0 \\ F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \end{pmatrix} \times {}^t \begin{pmatrix} I_0 \\ I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} = i_{ext} \cdot \begin{bmatrix} 0.01 \\ 0.02 \\ 0.1 \\ 0.2 \\ 1 \\ 2 \\ 10 \end{bmatrix} \begin{bmatrix} 5 & 10 & 50 & 80 & 100 \\ 0.05 & 0.1 & 0.5 & 0.8 & 1 \\ 0.1 & 0.2 & 1 & 1.6 & 2 \\ 0.5 & 1 & 5 & 8 & 10 \\ 1 & 2 & 10 & 16 & 20 \\ 5 & 10 & 50 & 80 & 100 \\ 10 & 20 & 100 & 160 & 200 \\ 50 & 100 & 500 & 800 & 1000 \end{bmatrix}$$

Fig. 2 Construction of a threat matrix for an extensive phenomenon

3.3.1 Hazard zoning

In order to compile the nine hazard zoning maps, i.e. one for each studied phenomenon, we established the characteristics of the reference events: i.e. the intensities, dimensions, locations and geological contexts. We then determined the number of occurrences of these reference events in different areas, using earlier descriptions and by searching for indications of old events in the field.

For the lava hazards in particular, the relative ages were tied into different datings taken from the literature or carried out as part the project.

This work made it possible to draw up a zoning map of the eruption frequencies (Fig. 3) which gives the probability of a renewed eruption on the basis of past events.

From the eruption frequencies map, it was possible to establish a hazard zoning map for the different phenomena involved, taking the principal parameters as the extension of the reference phenomena, their intensity and their frequency (return period) in the area. For the lavas, the intensity is always considered as maximum.

The weighted matrix profile for the lavas thus varies from $I_4 \times F_0$ to $I_4 \times F_5$ (cf. Table 4) depending on the threat area under consideration. Insofar as the lavas will occupy only a limited part from the area in which, an eruption will occur, the extension index (i_{ext}) is taken as 0.5. The *threat indices* used in the different areas *thus vary from* 0.5 *to* 100 (which represents a weighing factor of 1–200 between the area with the lowest threat and that with the highest threat from lava flows).

For the lava flows on Mount Cameroon, the hazard is thus liable to have four values (high, moderate, low and negligible). The hazard can be mapped on the basis of ground morphology and average flow length (cf. Fig. 4).
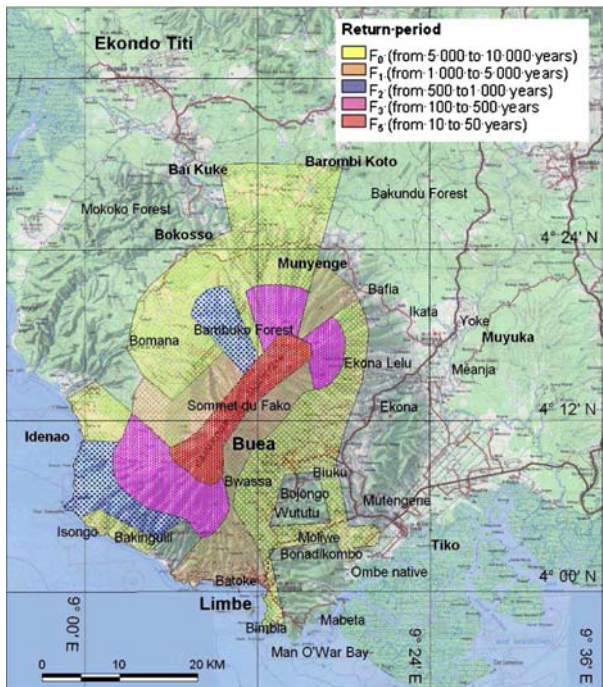
**Fig. 3** Mapping eruption frequencies on Mount Cameroon

Table 4 Threat matrix for the areas exposed to lava flows on Mount Cameroon (matrix shading is in accordance with legend of Fig. 4)

	I_0	I_1	I_2	I_3	I_4
F_0					0.5
F_1					1
F_2					5
F_3					10
F_4					50
F_5					100
F_6					

The other components of the volcanic hazard (aerial fallout, lahars, etc.) were treated in a similar way, enabling the construction of six volcanic hazard zoning maps.

As far as landslides are concerned, it was possible to identify different mechanisms:

– Major phenomena on the scale of the volcano's flanks that give rise to very thick lahar deposits on the volcano's eastern and western piedmonts. These lahars have been dated between 24,000 years BP (Zogning 1988) and 3,500 years BP (Cruz Mermy et al. 2006);
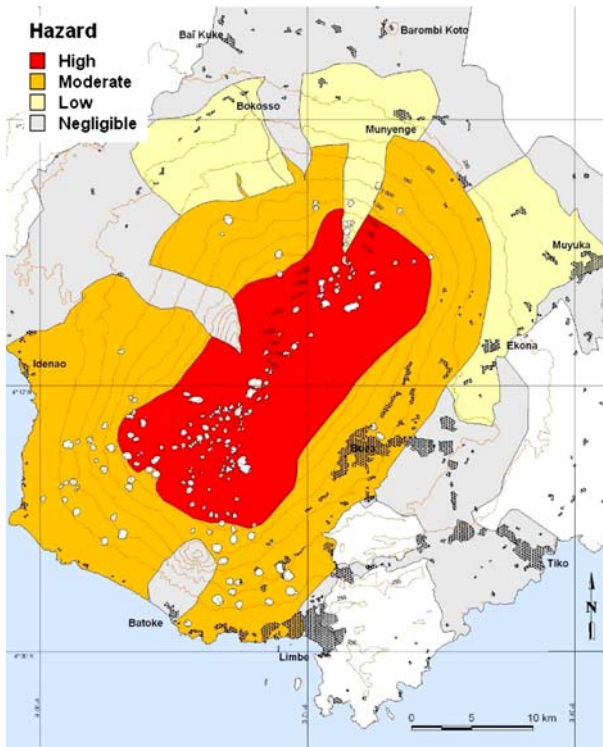
Fig. 4 Zoning the lava flow component of the volcanic hazard

– Slope instabilities, rotational slip evolving to mud flows and occurring annually on the slopes with a favourable geology (mainly clayey-silty sediments or basalt alterites);
– Block falls and cliff collapse.

Establishing intensity scales, crossed with the frequency scale, enabled the construction of threat matrices and hazard zoning maps consistent with those established for the volcanic hazard components.

In order to assess the seismic hazard, we took into consideration the effects of the local earthquakes generated at the level of the Mount Cameroon volcano; no analysis of the regional macroseismicity was made. This seismic activity is only really known for the past 100 years (historic seismicity) and has only been measured for the past 30 years (instrumental seismicity). It is currently monitored by the Geophysical and Volcanological Research unit at Ekona.

The reference earthquakes of 1909 and 1999 easily reached a low intensity level (I_1: slight damage) and approached the moderate intensity level (I_2: significant damage) in the most affected areas. The return period between these two earthquakes (90 years) led us to take into account, a frequency intermediate between 50 and 100 years. The adopted frequency index (F_4) will thus be 1.

The seismic hazard map identifies the areas located immediately above the zones of seismic swarms determined between December 1985—March 1986 and January—April 1987 (Ambeh and Fairhead 1991). This map is also based on the region's seismic map for the 1985–1992 period (Ateba and Ntepe 1997).

It should be noted that the Mount Cameroon volcanic massif is located at the intersection of major structural faults (Cruz Mermy et al. 2006) where six main trends are distinguished:

• The "Cameroon–Gabon" trend of N005–N015;
• The Cameroon Volcanic Line (CVL) trend of N025–N040;
• The Adamawa trend of N065–N070;
• A N080–N090 trend;
• The Gulf of Guinea trend of N105–N145;
• A N160–N170 trend.

Even though the seismic swarms appear, based on our current knowledge, more particularly associated with the N170 structural axis, the period of available seismic records (150 years) does not allow us to limit the Mount Cameroon microseismicity to this single structure. Moreover, given the 1:200,000 scale adopted for this study, the site effects (both lithological and topographical) could not be taken into consideration. The entire study area is thus considered as representing a moderate seismic hazard.

Superposing the nine hazard maps then enabled us, whilst retaining the locally determined maximum threat index, to draw up an overall geological hazard map for Mount Cameroon (Fig. 5).

Four large areas of very high or high hazard have been identified, which are hardly (if at all) compatible with permanent human settlement:

– The topmost part of the volcano and site of the most frequent volcanic eruptions;
– The clayey piedmonts (Limbe–Mabeta massifs, Mokoko River massif, Tamben–Misellele escarpment) where destructive landslides occur annually;
– The main thalwegs on the flanks of the massif, likely to channel mudflows down to the plain or the sea;
– The flanks and piedmont of Mount Etinde, exposed to block falls and rockslides.
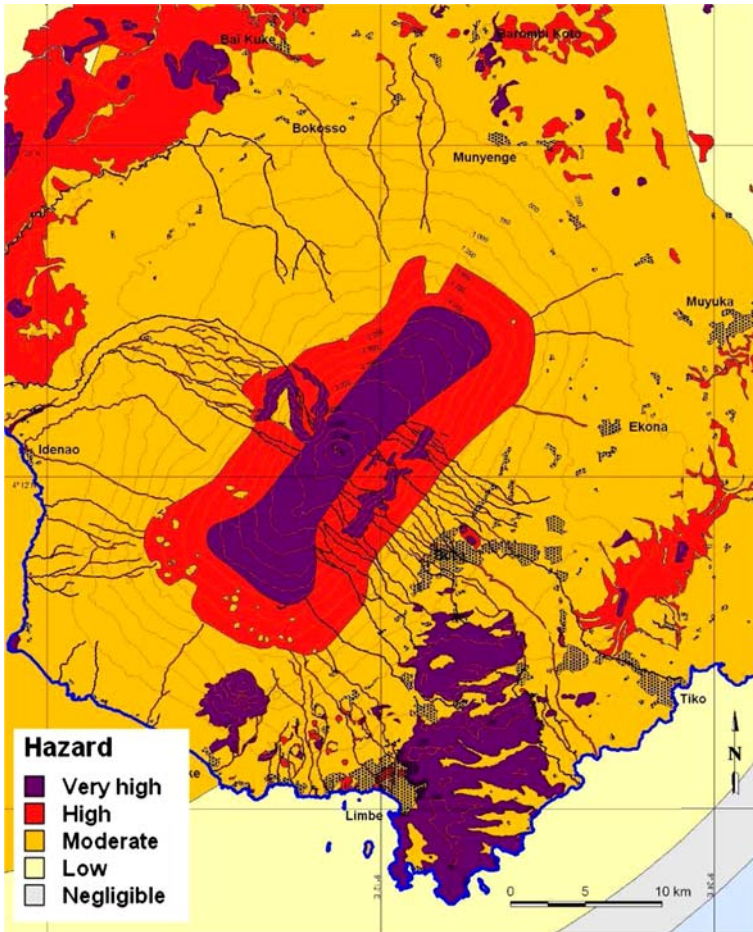
Fig. 5 Overall geological hazard zoning for Mount Cameroon

4 Characterization of the exposed elements

4.1 Inventory of the elements at risk

The information for the inventory and location of the exposed elements, followed by the analysis of the different values (human, social, monetary, economic, strategic, environmental) was obtained from the relevant Cameroonian government departments and concerned organizations, completed by an analysis of available satellite images and field surveys. The elements considered by the Cameroonian authorities as being the most important were listed and mapped:

– Population (urbanized areas and sites of periodic concentrations of people, such as schools, main centres of worship, markets, stadiums);
– Strategic buildings for crisis management (governance, army and security, health centres);

– Buildings, infrastructures and networks (housing, water-supply systems, power networks, roads and bridges, telecommunications relays);
– Natural environment and farmland (vegetation and hydrography, food crops and industrial plantations);
– Main centres of economic and financial interest (banks, factories, tourist centres).

All the collected information was entered into a computerized database.

The land occupation was mapped mainly from satellite images: Landsat TM of December 1986 and December 2000 (30 m ground resolution), Aster of 1 January 2003 and 25 April 2004 (15 m ground resolution). The various boundaries (urbanized areas, plantations) were systematically surveyed by GPS as part of the project. Outstanding buildings and infrastructures, as well as the road system, were also systematically plotted by GPS. Paper plans of the network layouts were provided by the relevant management departments.

4.2 Assessment of the elements at risk

In order to be able to (a) assess the cumulated economic value, and (b) analyse the vulnerability, we mapped the urban density and the building distribution according to two main types: "light" buildings made out of wood, and "standard" buildings made out of breeze-blocks and concrete. This mapping, based on a statistical count, also allowed us to inventory the multi-storey buildings. More than 9,700 houses were characterized, which represents about 15% of the building inventory.

The various values of the elements at risk were assessed at two levels:

– Qualitatively: the different elements at risk were classified in terms of their economic importance (local, regional, national, international) and in relation to their crisis management value (low, significant, high, paramount) so as to give a prioritization according to different crisis-related periods (i.e. crisis-free or normal, pre-crisis, crisis and post-crisis or recovery). The classification was established in close consultation with the local and national authorities and highlights the critical elements of the system that absolutely must be safeguarded;
– Quantitatively: number of inhabitants per locality; evaluation of the unit costs of the various infrastructures, agricultural production, etc. This involved assessing economic and human orders of magnitude of the potential damage. It involved, for example, determining the costs per m^2 of construction (Table 5), per kilometre of paved road, per telephone relay, etc.

Table 5 Average construction costs in the Mount Cameroon region (updated in 2006)	Type of construction	Cost per m^2 of housing (Fcfa) (1,000 Fcfa = €1.53)
	Wooden or clay-brick cabin without foundations	15,000–25,000
	Wooden or clay-brick cabin on a masonry foundation	35,000–50,000
	Mixed construction building (breeze-blocks and wood or sheet metal)	65,000
	"Standard" house of breeze-blocks and reinforced concrete (R0–R1–R2–R3)	120,000 per storey

Assessing the value of the different element-at-risk was based on information obtained from the various services and organizations responsible for the social system.

4.3 Characterizing an element-at-risk class: example of the health function

The Provincial Delegation of the Ministry of Public Health listed 61 health centres for the Fako Department (which corresponds roughly to the study area). These were all localized with a GPS, and 55 were found to be located within the study zone.

Out of the 55 health centres within the study zone:

– Three are provincial hospitals (PH),
– Eleven are private or public district hospitals (DH),
– Three are district medical centres (DMC)
– Thirty eight are health centres, either simple (HC) or integrated (IHC).

4.3.1 Economic assessment

The Ministry of Public Health assesses the average construction and equipment costs for the health centres as:

• 40 million Fcfa for an unequipped integrated health centre, to which one must add:

  – drilled well and water tower = 11.5 million Fcfa
  – biomedical equipment = 15.0 million Fcfa
  – accommodation = 25.0 million Fcfa
  giving a total of 91.5 million Fcfa

• 250 million Fcfa for a district medical centre
• 850 million Fcfa for a district hospital
• 1,750 million Fcfa for a provincial hospital

It is thus possible to assess the total capital budget (updated to 2006) for the health function within the study area at about 19 billion Fcfa or 29 million Euros.

4.3.2 Prioritization

Table 6 shows the levels of importance assigned to each category of health centre for the four designated crisis-related periods (crisis-free or normal, pre-crisis, crisis and post-crisis

Table 6 Levels of importance according to the health centres for the four crisis periods

	Crisis-free/normal	Pre-crisis	Crisis management	Post-crisis/recovery
Provincial hospital	H	H	P	H
District hospital	S	S	H	H
District medical centre	S	S	H	H
Integrated health centre	S	S	H	H
Health centre	L	L	S	S

P, paramount; H, high; S, significant; L, low

or recovery). These are always high (H) for the provincial hospitals insofar as they represent the medical benchmark for the sector and rise to paramount (P) during the crisis because these establishments are equipped for severe cases. The district hospitals, district medical centres and integrated health centres are considered as representing the same levels of importance: significant (S) in normal and pre-crisis periods, high (H) during the crisis and post-crisis recovery periods. The health centres, often with little equipment, have only a low level of importance (L) in normal periods, but take on a significant level (S) during the crisis and post-crisis recovery periods because they are likely to play a support role.

5 Vulnerability analysis of the elements at risk

5.1 Principles of the vulnerability analysis

The vulnerability expresses the level of damage suffered by an element or group of elements as a result of the happening of a natural phenomenon of given intensity and magnitude. The vulnerability can be considered in physical, social, environmental and/or economic terms.

It is assessed by the damage coefficient (D), expressed in relative terms as "no damage", "some damage", "major damage", "total loss" or by a numerical scale from 0 (no damage) to 1 (total destruction).

For the purpose of the vulnerability analysis in the Mount Cameroon region, the large bodies of elements exposed to the different hazardous natural phenomena can be grouped into three major categories:

– *Population* the vulnerability is assessed from the physical standpoint (dead, wounded, affected) and also takes into account psychological aspects;
– *Infrastructures* more particularly buildings, road infrastructures, engineered constructions (bridges), telecommunication infrastructures (masts and telephone relays);
– *Natural environment* vegetation and crops (subsistence farming and industrial plantations), plus fauna and hydrography.

Assessing the vulnerability of each environment with respect to each phenomenon for a given intensity requires several stages of analysis:

– In the first place, an agreement has to be reached so as to signify the damage coefficient D (between 0 and 1) for each type of element at risk. One cannot use the same definition to characterize damage to buildings and damage to vegetation;
– Then, for geological phenomena such as ash fallout or earthquakes, which do not cause a binary vulnerability, one must define a scale of intensity based on the physical aspects of the phenomena. In addition to the general intensity scales used for assessing the hazard, it is necessary to "detail" the intensity via the different physical effects (blast, corrosion, impact energy, etc.) or aggressions that affect the elements at risk. Insofar as the element-at-risk classes will give very different responses to various aggressions, this aspect is used for analysing and quantifying the vulnerability. Thus, when we speak of physical intensity, this is based on the variation of the physical characteristics of the different effects at a given place;

– Finally, one has to list all the exposed elements, establish a typology for these element-at-risk and assess their vulnerability with regards to a given phenomenon by establishing a correlation between the damage scale and the physical intensity scale.

The principle of the adopted methodology is outlined in the diagram of Fig. 6.

In order to define the typologies (step 1 of Fig. 6), given the high homogeneity of the elements at risk in the Mount Cameroon area, only the buildings and industrial plantations were subdivided into different types. Seven categories of building are distinguished: makeshift houses carabot huts (B1), wooden huts (B2), clay-brick huts (B3), mixed-structure houses, breeze-blocks and wood (B4), houses on piles (B5), permanent modern houses and buildings, breeze-blocks and concrete (B6), sheet metal constructions (B7). Most of the buildings are wooden huts and breeze-block/concrete constructions. These have two types of roof: the R1 roof, which is poor quality sheet metal with a shallow slope or a broad span—this type of roof is generally found on the carabot and the wooden huts, the clay–brick houses, the permanent buildings and the industrial sheet-metal buildings; and the R2 roof, which is of medium-quality sheet metal with a steep slope—this type of roof, which is in the minority, is generally found on the pile-supported and the mixed-structure (wood and breeze-block) houses.

The different types of industrial plantation in the area are for bananas, palm oil, hevea-rubber, tea and firewood (for drying the tea).

Physical characterization of the types (step 2) was done partly from field observations, especially at the different building sites (cf. Fig. 7), and partly from questioning local builders. A photo atlas was compiled of the different types of element at risk.

The damage scales (step 3) were taken mainly from the literature (Léone 1995 and Stieltjes et al. 2001). For example, the damage scale (coefficient D) for the buildings can be defined by treating the two main components separately, i.e. the vertical structures and the roofs (Tables 7 and 8).

As far as agricultural production is concerned, one can distinguish the following plant categories: creeping and small plants (V1); yams, cocoyam and manioc–cassava (V2: tuber plants); tea plants and banana trees (V3: herbaceous plants); maize (V4: cereals); coffee trees and cacao trees (V5: small trees); hevea-rubber and oil palms (V6: trees).
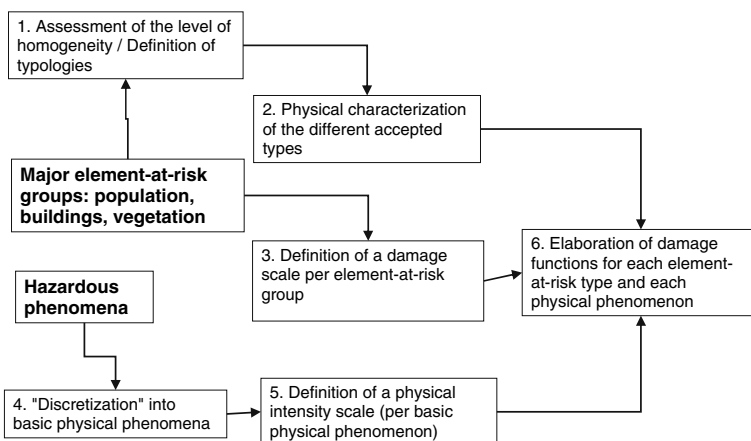

Fig. 6 Diagram of the vulnerability assessment principle used for the GRINP project

Fig. 7 Construction of
a breeze-block/concrete house

Table 7 Definition of the damage coefficient for analysing the vulnerability of a building's vertical structure (adapted from Stieltjes et al. 2001)

Damage level	Percent damage (%)	Coefficient D
Structures intact	0	0
Very little damage	<5	0.05
Limited damage	5–10	0.10
Major damage (repairs possible)	10–50	0.50
Structures almost destroyed (repairs difficult)	50–80	0.80
Structures completely destroyed	>80	1

Table 8 Definition of the damage coefficient for analysing the vulnerability of a building's roof (adapted from Stieltjes et al. 2001)

Damage level	Percent damage (%)	Coefficient D
Roof intact	0	0
Small holes or bumps/Slight sagging	10	0.10
Large holes/Partial collapse	50	0.50
Total collapse	100	1

Steps 4 and 5 aim to define the destructive power of the phenomena through different physical actions. Our work also drew on the results of earlier studies (Blong 1984; Léone 1995; Cronin et al. 1998; Pomonis et al. 1999; Searl et al. 2002; Spence et al. 2004, 2005a, b).

As an example, consider the intensity scale adopted for ash fallout (Table 9). One has to consider the impact of the ash on roofs (failure at around 20 cm of ash deposit), and also on plantations (negative effects as of a few millimetres of ash deposit) as shown in Tables 10 and 11.

The ash depths are taken for dry ash with an average density of about 1.

At this stage of the study, the vulnerability analysis for each element-at-risk class is done through matrices of the intensities of the different physical effects against the expected damage based on the average characteristics. The vulnerability analysis is aimed mainly at a support for the authorities' deliberations and enables recommendations

Table 9 Physical intensity scale for ash accumulation

Physical intensity	Depth of accumulation (in mm)
I	1
II	5
III	10
IV	20
V	50
VI	100
VII	200
VIII	400
IX	800
X	1,200

Table 10 Damage coefficients for roofs relative to the intensity of ash accumulation

Ash accumulation	Roof	
	T1	T2
I	0	0
II	0	0
III	0	0
IV	0	0
V	0	0
VI	0.1	0
VII	0.5	0.1
VIII	1	0.5
IX	1	1
X	1	1

to be made in terms of constructive measures and the establishment of land use regulations.

6 Risk analysis and main results

6.1 Principles of the risk analysis

Geographic crossing of the hazard and the element-at-risk maps enable one, in the first instance, to identify element-at-risk zones exposed to the different phenomena. It also makes it possible to assess or quantify the number of elements present in each threatened zone, and well as the corresponding element-at-risk values. This, for example, is the case where the population, the kilometres of road and the water supply systems, the strategic buildings, etc., are concerned.

A distinction was made between three major groups of element-at-risk—population, infrastructures and vegetation—which react differently to the natural phenomena. For example, earth tremors that can be very harmful to houses, have no effect on plantations. It was thus necessary to differentiate the pertinent hazards for each of the major element-at-risk groups.

Table 11 Damage coefficients for agriculture relative to the intensity of ash accumulation

Ash accumulation	V1	V2	V3	V4	V5	V6
I	0	0	0	0	0	0
II	0.1	0	0	0	0	0
III	0.5	0.1	0.1	0.1	0	0
IV	0.8	0.8	0.5	0.1	0.1	0.1
V	1	1	0.8	0.5	0.1	0.1
VI	1	1	1	0.8	0.1	0.1
VII	1	1	1	1	0.5	0.5
VIII	1	1	1	1	0.8	0.8
IX	1	1	1	1	1	0.8
X	1	1	1	1	1	0.8

Deeming that the element-at-risk of paramount importance warrant specific distinction, we compiled five risk zoning maps:

- Risk zoning for the population;
- Risk zoning for the elements at risk of paramount importance for crisis management or of international importance (from the standpoint of their economic interest);
- Risk zoning for buildings, infrastructures and networks (housing, drinking water supplies, centres of economic interest, etc.);
- Risk zoning for agriculture (industrial plantations, subsistence farming);
- Risk zoning for the natural environment (vegetation and hydrography).

To illustrate the approach and determine a few orders of magnitude, we computed a *volcanic eruption scenario*. It reproduced, on the north of the Fako cone (summit of Mount Cameroon), an eruption of the type that occurred in 1922; i.e. eruption dynamics identical in terms of material quantities and characteristics as those of the 1922 eruption, but in a different area. This eruption scenario enabled us to assess the damage (for example, buildings destroyed, number of people to be evacuated, farming losses), providing results that enable the Cameroonian authorities to (a) better delimit the dimensions of the potential problems and (b) improve their preparations in the event of new crises.

6.2 Analysis of the volcanic risk

All the flanks of the volcano are directly exposed to two direct threats:

- *The arrival of a lava flow* The frequency and distribution of lava flows around the volcano over the past two centuries does not allow us to consider that a significant part of the volcano's slopes (including the town of Buea) is sheltered from such an event. The occurrence of a lava flow raises the question of population displacement and reception. Such an evacuation could be difficult, especially on the northern and western sides of the volcano because of the poor state of the roads;
- *Ash fallout* The explosive character of the eruptions in the recent (historical and pre-historical) past caused the ejection of a very large amount of ash into the atmosphere. The occurrence of such an event must be systematically and carefully taken into

consideration. It is important for buildings to adapt such an eventuality: for example, steeply sloping roofs (>45°) and reinforced frames for individual houses. The dominant winds being east-northeasterly, the industrial and agricultural sites located to the west-southwest of the volcano should take this phenomenon into account in order to minimize any damage.

Some sectors of the volcano are partly exposed to three indirect threats:

– *Lahar flows in certain thalwegs*, principally on the southeastern and northwestern flanks of the volcano. Lahars (mudflows deriving from the accumulation of ash following a volcanic eruption) concentrate mainly in the thalwegs and their vicinity, and are extremely devastating. In many cases, land use immediately next to these thalwegs should be strictly controlled. Certain activities could be tolerable, but any permanent settlement should be avoided.
– *Large-scale landslides associated with the volcanic activity* correspond to partial collapse of the volcano's side. Such events have occurred in the recent geological past (return period of 500–5,000 years), in particular on the southeastern and northwestern flanks of the volcano.
– *Tidal waves (tsunamis)* of volcanic origin are likely to inundate *the low-lying coastal areas*, in particular the towns of Limbe and Tiko. These are generally related to either lahars or large-scale landslides reaching the sea; in the former case, wave heights can reach several metres. The main risk-reduction measure here is an awareness campaign calling for the public and tourist operators to be extremely vigilant about such a phenomenon.

6.3 Analysis of the landslide risk

The piedmont areas as well as the steepest slopes of Mount Cameroon are directly exposed to three types of threat:

– *Slow or rapid landslides* can occur each year in certain dominantly clayey geological formations (basalt alterites and old volcanic cones, Tertiary sedimentary formations) which are extremely susceptible to this type of phenomenon.
Such landslides have caused almost 30 deaths over the last decade (Limbe, Buea). Our assessment at the 1:200,000 scale used for the study leads us to estimate the number of people living in such areas at around 12,000. A more detailed study should be carried out at plot scale ($\sim$ 1:5,000) so as to more accurately delimit the areas at maximum risk and strictly forbid any human occupation of these zones.
– *Block falls* of all dimensions up to cliff collapse are likely to occur on the steeper slopes of the mountain. As a general rule these happen away from the inhabited and cultivated areas. However, minor block falls and collapses (a few 10s of m^3) are likely to occur, particularly from the road embankments. It is because of our work scale, that such small areas were not taken into account in our study.
– *The formation of natural dams* by mass slides is likely to generate abrupt, highly destructive events such as the sudden emptying of ponded water (breaching of the dam). The utmost attention should be paid by the authorities in the event of such dams being formed.

6.4 Analysis of the seismic risk

Based on present knowledge, we consider that Mount Cameroon and its piedmont zones are exposed to moderate seismicity (magnitudes 4–5) that could cause damage to locally important buildings (fissures, structural changes if not ruin) owing to its potentially shallow focus (depth of the order of 10 km). Such damage corresponds to an intensity of VI–VII (EMS98 scale).

Breeze-block/concrete constructions, which represent approximately half the buildings within the study area, are particularly vulnerable to such earthquakes. It is therefore essential to encourage owners and builders to construct one- to two-storey houses using earthquake-resistant designs. In addition, the construction of several storey buildings in the most threatened zones (Buea, Mutengene, Tiko) should be strictly controlled through the application of earthquake-resistant construction rules.

According to enquiries among the population, it would appear that the 1999 earthquake contributed to diminishing, if not drying up, many of the springs at the altitude of Buea, which has resulted in drinking-water supply problems. This flow reduction would have been equally perceptible on the west flank of the massif.

Other than the problem of supplying the population with water, the question remains of what happens to the water that "no longer discharges, or discharges elsewhere". A hydrogeological survey of the massif could provide a better understanding of the situation.

6.5 Assessment of the geological risks at Mount Cameroon

Mount Cameroon is not one of the most hazardous volcanoes in the world. However, like all active volcanoes, it is a source of significant threats for man, his institutions and his activities, and for nature.

Four major zones of *high and very high hazard levels* have been identified that are hardly, if at all, compatible with permanent human settlement:

- The uppermost part of the volcano, site of the most frequent volcanic eruptions;
- The flanks and piedmont of Mount Etinde, exposed to block falls and rockslides;
- The clayey piedmonts (Limbe–Mabeta massifs, Mokoko River massif, Tamben–Misellele escarpment) where devastating landslides occur every year;
- The main thalwegs on the flanks of the massif, likely to channel mudflows to the plain or the sea.

Only the last two areas present a real risk associated with the presence of human settlements. These risks must be treated in priority by the Cameroonian authorities.

Most of the other sectors of the study area are located in zones of moderate hazard, associated with the possible arrival of lava flows, of significant thicknesses of ash fallout, and of a moderate seismicity.

At the end of our study, risk maps were drawn up for each of the major element-at-risk categories (cf. Fig. 8). A few *orders of magnitude* warrant being pointed out from the risk assessment:

– *Risks to humans*

- 12,000 people live in areas with a very high hazard level (where the installation of permanent human settlement should be avoided), principally at Limbe and, to a
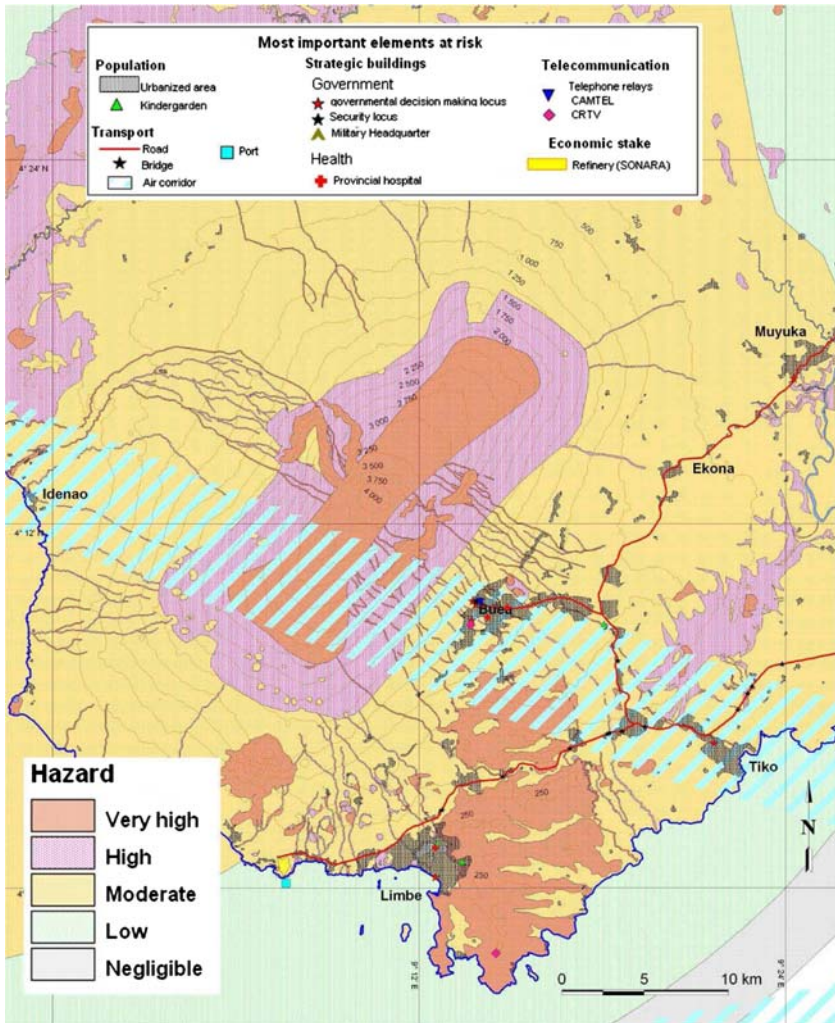
Fig. 8 Risk map showing the most important elements at risk (human, strategic, economic)

lesser extent, at Buea. They are threatened by landslides and mudflows in the thalwegs;

- 20,000 people live in high hazard areas (old volcanic cones, thalwegs, clayey slopes);
- 450,000 people live under a moderate threat (lava flows, ash fallout and seismicity);
- A kindergarten, nine primary schools and two secondary schools are located in very high hazard areas, whilst four primary schools and two secondary schools are in high hazard areas. The main threats for all these establishments are rapid landslides and mudflows.

– *Risks to strategic buildings for crisis management*

- Ten buildings that are strategic for crisis management lie within or close to areas of very high hazard. They are mainly located in the town of Buea. Around 106 other

buildings of strategic importance lie within an area of moderate (101) or low (5) hazard.

- Six telephone relays (i.e. the CRTV relays near Bimbia and the three "Elf" relays on the volcano) are located in very high hazard areas. Four telephone relays are in high hazard areas. In addition, 30 radio–TV centres or telephone relays are located in areas of moderate or low hazard.

– *Risks to buildings and infrastructures*

- Out of the 50,000 buildings in the study zone, 1,800 houses are in those of very high hazard and 1,600 in areas of high hazard; which are threatened by landslides. All the houses are under the threat of a moderate seismic hazard. Most of them are single-storey buildings, about 5% being two stories buildings and around 1% having three or more stories. Out of all these 50,000 houses, approximately half, built using breeze-block/concrete techniques, are highly vulnerable to earthquakes. With a damage level for such buildings ranging from 10% to 50% in the event of a destructive earthquake in the same area but slightly stronger than that of 1999, there could be between 1,000 and 5,000 houses severely damaged. One can consider that in such an eventuality, in addition to the dead and wounded, some 25,000 people would be homeless;
- Of the 550 km of main roads, paved or otherwise, 19 km (of which 9 km paved) are in areas of very high hazard and 17 km (4 km paved) are in areas of high hazard. They mainly represent thalweg crossings, corresponding to 29 bridges;
- For the drinking-water-supply and electricity networks, 9 km of drinking-water pipes out of the 170 km installed, and 2.5 km of high voltage line (HV 90 kV) and 5.7 km of medium voltage line (MV 30 kV) are threatened by a very high hazard (out of a total of 100 km MV and 90 km HV line, respectively);
- The Sonara refinery and the Limbe power station are in an area of moderate geological hazard. The threat is associated with earthquakes and lava flows, the other hazards being considered as low or negligible.

– *Risks to farm production*

- As far as subsistence farming is concerned, 3,000 ha are in areas of very high hazard (mainly the Limbe–Mabeta massif) and 5,000 ha in areas of high hazard (Tamben–Misellele slopes). In addition, about 250 km^2 are under threat of a moderate hazard (ash fallout) and 650 km^2 have only a low hazard threat. Two-thirds of the food production (including cacao production), therefore, are only slightly concerned by natural risks.
- The conclusions are equally contrasted for the industrial plantations, with 1,700 and 2,200 ha of plantations situated respectively in very-high and high hazard areas, whilst 7,800 ha are under the threat of only a moderate hazard (ash fallout); these are located mainly on the Atlantic coast (oil palms) and in the Tole sector (tea). In addition, 360 km^2 of industrial plantations are located in areas of low or negligible hazard, representing approximately three-quarters of the industrially farmed area.

– *Risks to the natural environment and the hydrography*

- The dense forest (80 km^2) is threatened by landslides on the Limbe–Mabeta massif, an area of very high hazard. Some 380 km^2 of forest, dense or degraded, are located in areas of high hazard and around 500 km^2 in areas of moderate hazard on the flanks of the volcano and in the Mokoko River sector,. About 400 and 200 km^2, i.e.

less than half the natural environment, are located respectively in areas of low or negligible hazard.

- Most of the permanent hydrographic network is in a low-hazard (308 km) or moderate-hazard (36 km) area. Nevertheless, 12 m are in steep areas and could be affected by landslides and mudflows.

7 Conclusions and recommendations

7.1 Recommendations put forward to the Cameroonian authorities

It was already possible, at the end of the study, to advance a few preliminary recommendations to the Cameroonian authorities. These hinge around five main topics:

7.1.1 Population awareness and information

A plan of action for public and local-authority awareness, information and preparation should be designed and launched. It is the initial reactions (those of the first few minutes) that largely limit the consequences of an event. Appropriate reactions of the local population are likely to considerably limit the damage. In addition, a grasp of the risk problem by the population will facilitate acceptance of the measures, possibly restrictive, decreed by the public authorities. Such an information and awareness action can only be conceived for the long term.

A first boost was given to this action in the context of the project with the production of a CD-ROM (with integrated "browser"), an awareness meeting in Buea, and the publication of an information triptyque for the general public.

7.1.2 Regulation maps

Regulation maps should be considered at two levels:

- Establishing a land-use plan at massif scale that integrates the threats associated with the natural risks. Such a plan must be based on a local dynamics of public responsibility.
- Defining strict regulations for urbanization based on 1:5,000-scale mapping, with priority for the Limbe, Buea and Baï Kuke areas. More particularly, the regulations should clearly identify the areas in which building is forbidden or conditional.

7.1.3 Reduction of population and infrastructure vulnerability

This action is complementary to the preceding one. It is an approach aimed at promoting, among both general public and the professionals, construction methods adapted to the threats, constructions adapted to slopes, implementation of earthquake-resistant techniques, roof strengthening, etc. The action could take various forms such as incentives, professional training, regulations, etc.

This point is particularly crucial for the earthquake-resistant design of large development schemes.

7.1.4 Preparation for crisis management

This action should take several forms:

– Drawing up Specialized Contingency Plans (SCP) in order to prepare the responsible services and optimize their efficiency during the initial critical hours of the disaster. The SCP could be based on different crisis scenarios developed with the GIS that was set up at the Ministry of Industry, Mines and Technological Development (MINIMIDT) under the GRINP project;
– Improving and making safe the transport infrastructures around Mount Cameroon, both for evacuating the population and for bringing in relief. Priority efforts should concern the characteristics of the main Muyuka–Munyenge–Bokosso and Bokosso–Bomana– Idenao roads. It is also necessary to inspect and make safe the thalweg crossings for national highways N3 and N8, as well as survey the steep embankments and rock slopes with a view to clearing any threatening blocks.
– Carrying out a systematic check of the locations (vis-à-vis different threats) and construction features of the strategic buildings identified in the context of the SCP. Depending on the results of this survey, it may be necessary to possibly reinforce their structure or to consider moving to another location.
– Reinforcing telecommunication capacities (for the telephony and broadcasting of instructions) under difficult atmospheric conditions (ash clouds).

7.1.5 Knowledge and monitoring of the volcano

Establishing warning thresholds in preparation for a crisis implies effective monitoring of the volcano's activity. It is desirable that the volcano surveillance devices be improved in order to anticipate eruptive crises. The efficiency of the Geophysical and Volcanological Research unit (IRGM) at Ekona is thus crucial for preventing risks and should be reinforced.

Other techniques, in particular, satellite techniques (radar interferometry, thermal imagery) could also be usefully considered for monitoring the volcano.

Finally, it is essential to continue "basic" scientific, geological, geophysical, geomorphological, hydrological studies of the Mount Cameroon massif in order to improve understanding of the geological mechanisms and so provide better bases for decisions by the authorities.

7.2 Conclusions

The methodology, along with the obtained results, has been offered both to the Cameroonian authorities and to the local populations living on the slopes and piedmonts of Mount Cameroon. As far as the authorities are concerned, it would appear that their interest bears more particularly on three points:

– Identification of the critical zones in terms of danger, essentially linked to the problems of slope instability and mudflows;
– The possibility of apprehending the overall risk level associated with the volcano, both in terms both of event recurrence and of potential impacts;

– The possibility of "bringing home", through a scenario, the consequences of a perfectly plausible eruption based on the features of the 1922 eruption localized in a different sector. The orders of magnitude of the number of people to be evacuated, the damage to farm production, road cuts etc., would enable the local authorities to rapidly analyse the dimensions of the problem.

The study has also revealed a certain number of weaknesses in our knowledge, particularly concerning the vulnerability of the different elements exposed in relation to the expected physical phenomena.

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