The geological control and triggering mechanisms of landslides of 20th July 2003 within the Bamboutos Caldera, Cameroon

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ABSTRACT

On July 20th 2003, a spontaneous swarm of more than 120 landslides occurred within the Bambouto caldera killing 23 people, 700 livestock, and displacing more than 1000 people. There was no evidence of seismic activity which activated the event. Field studies of landslide scars indicated their link to steep slopes of incising river valleys with recent deforestation. New findings indicate 70% of the scars located in weathered rhyolitic rocks within the caldera, while the peripheral parts were less affected by these hazards. Interpretations of grain size analysis of clay samples collected above and below slide surfaces confirmed higher susceptibility of the upper unit above the sliding surfaces to sliding with the lower unit being more stable. Statistical analysis of rainfall data collected from 1991 to 2003 and daily rainfall during the month of July 2003 highlight rainfall as the immediate trigger of the landslides. Under the influence of excessive pore water pressure and high slope angles of 30^0 to 80^0, slope failure from perched aquifers formed above the sliding surfaces, causing the landslides. These findings have provided useful information on the geological control and the role of precipitation in the triggering of the landslides. This is essential for addressing future mitigative measures that could be adopted to protect the inhabitants living with this caldera.

Key words: Bamboutos caldera, Magha, landslides, rhyolites, heavy rainfall, perched aquifer.

RÉSUMÉ

Une masse de plus de 120 glissements de terrain s'est produise le 23 juillet 2003 dedans la caldeira Bambouto, tuant 23 personnes, 700 bétail, et déplaçant plus de 1000 personnes. Il n'y avait aucune preuve évidente d'une activité séismique ayant causer cet incident. Les enquêtes sur place relatives aux cicatrices des glissements de terrain montrent qu'elles sont liées aux pentes raides des fentes des vallées à déforestation récente qui descendent vers la rivière. De nouvelles recherches indiquent que plus de 70% des cicatrices se trouvent dans des rochers rhyoliques érodes dedans la caldeira, alors que les parties extérieures sont moins affectées. Les interprétations des analyses de particules d'argile prélevées en haut et en bas des surfaces glissantes confirment une haute susceptibilité du niveau supérieur aux surfaces glissantes alors que le niveau inférieur est plus stable. L'analyse statistique des données de pluviosité collectionnées de 1991 à 2003 et tous les jours pendant le mois de juillet 2003, soulignent la pluviosité comme élément immédiat de cause des glissements de terrain. Sous l'influence de l'absorption excessive de la pression d'eau d'une haute inclinaison d'angle de 30° à 80°, il y a eu par conséquence, une chute de pentes emmenant des aquifères perchées situé au dessus de ces surfaces glissantes, causant ainsi les glissements de terrain. Ces recherches ont donné des informations utiles sur le contrôle géologique et le rôle de la précipitation dans l'amorcement de ce désastre. Tout ceci est essentiel pour le redressement des mesures atténuantes futures qui pourront être adoptées pour protéger les habitants vivant dedans la caldeira.

Mot clés: Caldeira Bambouto, Magha, glissement de terrain, rhyolites, haute pluviosité, aquifères perchées.

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INTRODUCTION

Landslides are common disasters within the Bambouto caldera during the past two decades following extensive deforestation and farming activities which have rendered the region barren of its original rich vegetation. The region was originally rich in lowland evergreen forest (0-800 m), sub-montane forest (800-1600 m), and sub-alpine grassland (2000-3000 m) (Thomas et al (1992) and Tchouto (1995)) but has been drastically destroyed for the establishment of farms. On July 20th 2003, more than 120 landsides occurred within this caldera killing 23 people, 700 livestock, and displacing more than 1000 people (Elites report 2003). Farmlands, houses, bridges, pipe-borne water and roads were destroyed. This extent of damage to lives and property was unprecedented although historical data is indicative of sporadic occurrences of landslides in the region.

The caldera is located in the south western part of Cameroon between latitudes 5°38` and 5°43` N and longitudes 9°58` and 10°06` E (Fig 1) on the Bambouto Highlands within the Cameroon Volcanic Line (Fitton, 1987; Deruelle et al., 1991 and Nono et al., 2004). It has an approximate surface area of 100km², with a length of about 16km in an east-west direction, and a north-south width of between 5km in the west, to 7km in the east (Dumort, 1968). Landslide occurrences along this Line have been linked to meteorological and seismic events as the most common triggering mechanisms, with the topography, rock types, degree of weathering, and human intervention on slopes as secondary causative factors (Lambi, 1991; Ayonghe et al., 1999, 2002, 2004). However, attempts to link the distribution of landslides scars to specific soils and/or rock types as well as the systematic investigations of the detailed geology of the caldera, the soil types and their mineralogy, the physical properties of the regolith, the mechanism, and the role of precipitation in triggering these landslides have never been carried out.

The aim of this paper is therefore to investigate the scale and extent of the landslides, identify the lithologies and soil types affected most, determine the controlling factors which triggered these

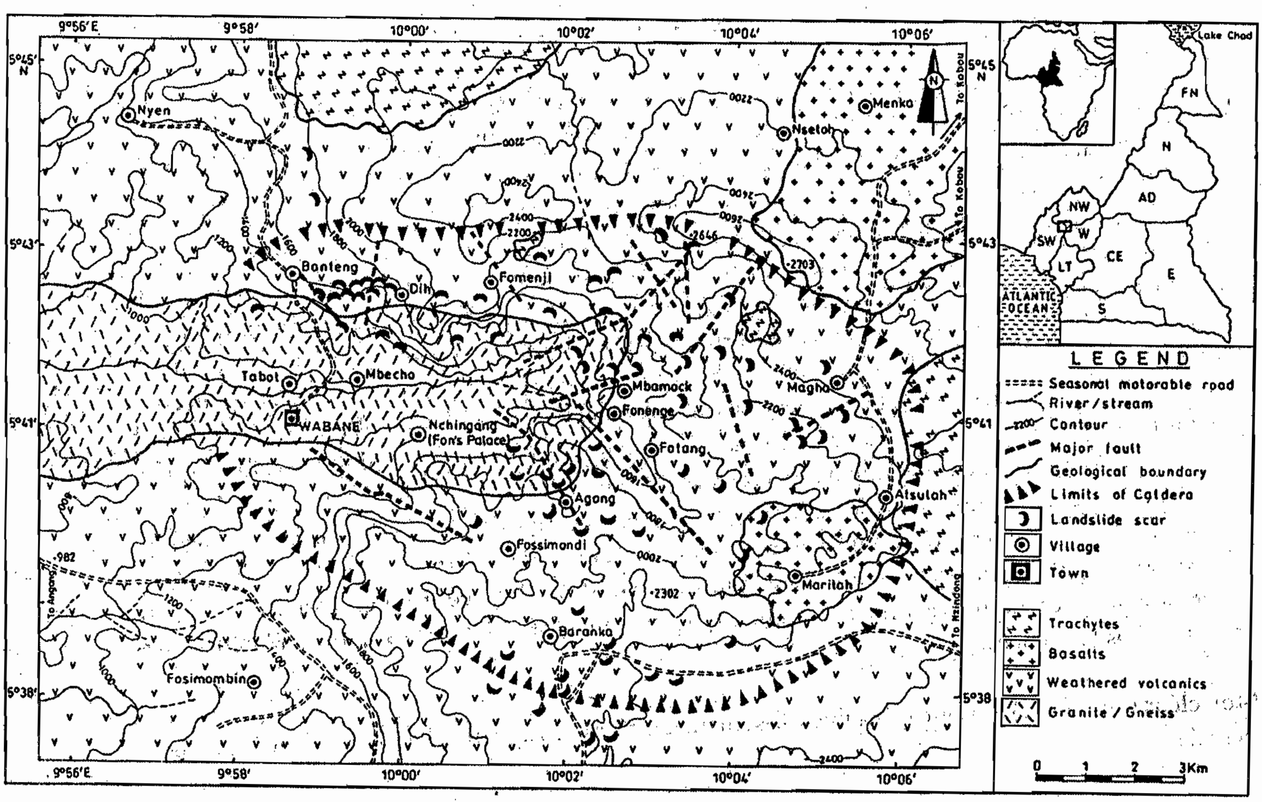


Fig. 1: The location and geological setting of the Bambouto caldera

disasters, and attempt to establish a link between the distribution of landslides scars and the rocks and soil types within the caldera. The specific objectives are to assess the susceptibility of the soils above, on, and below landslide surfaces, based on grain size analysis using standard procedures and mineralogical compositions of clays. The roles of human interference and of meteorological conditions in triggering these disasters are also investigated.

METHODOLOGY

The methods of investigation were carried out in two phases, the field phase and the laboratory phase.

a) Fieldwork/Field Observation.

A field research programme was initiated shortly after the event and five (5) months later during the dry season, during which a geological mapping of the region was prepared to indicate the rock and soil types as well as the structural setting of the caldera. A total of 76 accessible recent and ancient landslide scars were mapped and superimposed on a geological map developed during the field mapping. Surface areas and approximate volumes of regolith were computed. The lithological configurations of scars, slide types, and hydro-geological features associated with them were assessed in an attempt to identify and classify the different types of landslides. Soil samples were collected from landslide scars at Banteng, Fotang and Magha for grain size analysis. At each chosen landslide location, samples were collected above the sliding surface, on the sliding surface itself, below the sliding surface, and from the regolith. Samples 1,2 and 3 are from the landslide scar and the x samples from the transported regolith.

The entire caldera was divided into five regions namely: Magha, Lower Bamumbu, M'mock Leteh, M'moucknglh and M'mockmbie (Apang, Awut), and Lewoh based on size, location and accessibility. Information on the level of destruction by the landslides was obtained from field visits, traditional authorities such as quarter heads, important personalities in the communities, the general public and from a report written by the elites of the region. The field investigation was carried out in an attempt to unveil the evolution and most likely causes of the landslides. The information obtained included the number of deaths and those injured, the total number of families and persons displaced, number of houses, schools, farms, bridges, roads and culverts destroyed as well as the livestock killed by the landslide event (Elites Report, 2003). These aspects were considered for the establishment of the level of damage in each region as well as the total damage for the entire caldera with respect to specific types of mass wasting events.

Rainfall data obtained from the nearest meteorological station at the Santa Tea Plantation, located 7km north of Magha, for a period of 10 years and during the month of the disaster were provided by the Meteorological Centre of the Cameroon Development Corporation, Tiko. These were analysed with the aim of identifying quantity thresholds and durations which might have been responsible partially or directly in triggering the landslides.

The Shuzui (2000) classification scheme of landslides was modified and used to determine the different types of slides in the entire region (Table 1). This involved the utilisation of the history of landslides, their frequency, and the extent of movement as well as the properties of the slip surfaces in order to classify the different landslides. Thirty (30) landslide scars were selected for the analysis, ten (10) each from Banteng, Magha and Fotang. This was followed by measurements of the length, and width of each scar, as well as the height of the scarp in order to determine the volumes generated by the various scars using the formula:

$$V = \frac{1}{6}\pi(HxWxL)$$

Where:

V	=	Volume
π	=	Pie (3.143)
H	=	Height
W	=	Width
L	=	Length

Table I: Classification of landslides based on the Shuzi (2000) Scheme

Property of slip surface	Mineral composition of slip surface		History of landslide Mov't		
	Content of clays	Content of silicate minerals	Continuity of Mov't		Displacement
			Number of Mov't	Frequency of Mov't	
Striation type	+	●	2 times	—	20 m
Brecciated type	○	■	4 times	Once in ten yrs	30 m
Mylonite type	Δ	Δ	About 40 times	Once in every yr	>45 m
Clay type	■	○	Over 100 times	10 times/yr	>50 m
	●	+	Over 100 times	2 times/yr	>70 m

+ : extremely small amount (1-10%); ○ : small amount (11- 35%); Δ : average (31-65%); ■ : large amount (66-90%); ● : extremely large amount (>90%)

Soil samples were collected from the various locations for identification and classification by considering, colour, texture, extent of laterisation, nature of the slopes, the pH and the type of material, and finally the possible name of the soil. Locations were registered using a Cobra 500 GPS. This was to ensure the establishment of a proper distribution pattern and a construction of a soil map of the caldera.

b) Laboratory Analysis

Grain size analysis was carried out using 25g per sample measured from the original homogenous sample, into pre-cleaned Teflon sample bottles. About 2.5 ml of the suspension agent 2% solution of Na_2CO_3 was added to the samples. All the bottles were placed on a shaker for two days to ensure complete separation of the particles. The particle size intervals used were 1/16 mm and above for the sand; 1/16 - 1/136 mm for the coarse silt; 1/136- 1/256 mm for the fine silt, and sizes less than 1/256 mm for the clays.

X-ray diffraction analysis of samples was carried at the Soil Science Laboratory at the University of Ghent, Brussels to identify the possible clay minerals produced from the weathering of the rocks in the region. The X-ray diffractometer (XRD) was equipped with a Cu tube anode, a secondary monochromatic graphite beam, a proportional xenon filled detector and a 35 position multiple sample changer. The incident beam was automatically collimated. The second beam side comprised a 0.1 mm receiving slit, a roller slit and a 1° anti-scatter slit. The tube was operated at 40kv and 30 mA, and the XRD data were collected in a theta, 2-theta geometry from 3.00' onwards, at a step of 0.020° 2-theta, and a count time of 1 second per step. XRD patterns of powdered samples were recorded without specific pre-treatment such as heating and glycol treatments.

Results from field work and observations

Eyewitness accounts of the event and field observations indicated that on Sunday 20th July 2003, between 10.00am and 1.00pm during continuous rainfall which had lasted for more than three days, inhabitants of Magha heard a loud explosion. This preceded some rumbling and ground shaking across the valleys and this was closely followed by water flowing from temporal springs which emerged from the subsurface. Fountains of water occurred in some areas, this being indicative of the unusual rise in water pressure within perched aquifers probably due to continuous rainfall for many days. Vertical movements along zones of weaknesses were observed at Dih and Magha, where joints were produced spontaneously over long distances and with widths of 50mm to 350mm.

The more than 120 landslides which occurred spontaneously, killed 23 people and produced large volumes of regolith charged with tree trunks, rock boulders, and objects (sheets of corrugated zinc, broken furniture, and other types of debris) derived from destroyed houses. The resultant sloth produced from the regolith caused floods in the streams which feed the River Meyi. The floods increased the rate of lateral erosion of the banks of the river at its lower courses, and together with the landslides destroyed, 261 houses, 52 bridges, 86 culverts, 496 farms, 385 livestock killed, 229 families displaced and 1015 persons displaced, (Table 2).

Geomorphologically, the inner part of the caldera is constituted by steep slopes found along deeply incised gullies produced by faulting. These gullies control the drainage pattern of the area for they combine to form the River Meyi which breaches the western part of the caldera and flows towards Mamfe (located about 55km south-west of the study area) where it forms the Cross River. Streams have cut through the underlying volcanic rocks to expose the basement rocks consisting mainly of syenite and a limited amount of granitic rocks, exposed by the River Meyi and its tributaries. The Tertiary volcanics, composed of rhyolites, pyroclastics, basalts, phonolites and trachytes, occupy the higher slopes and unconformably overlie the basement syenites (Fig. 1).

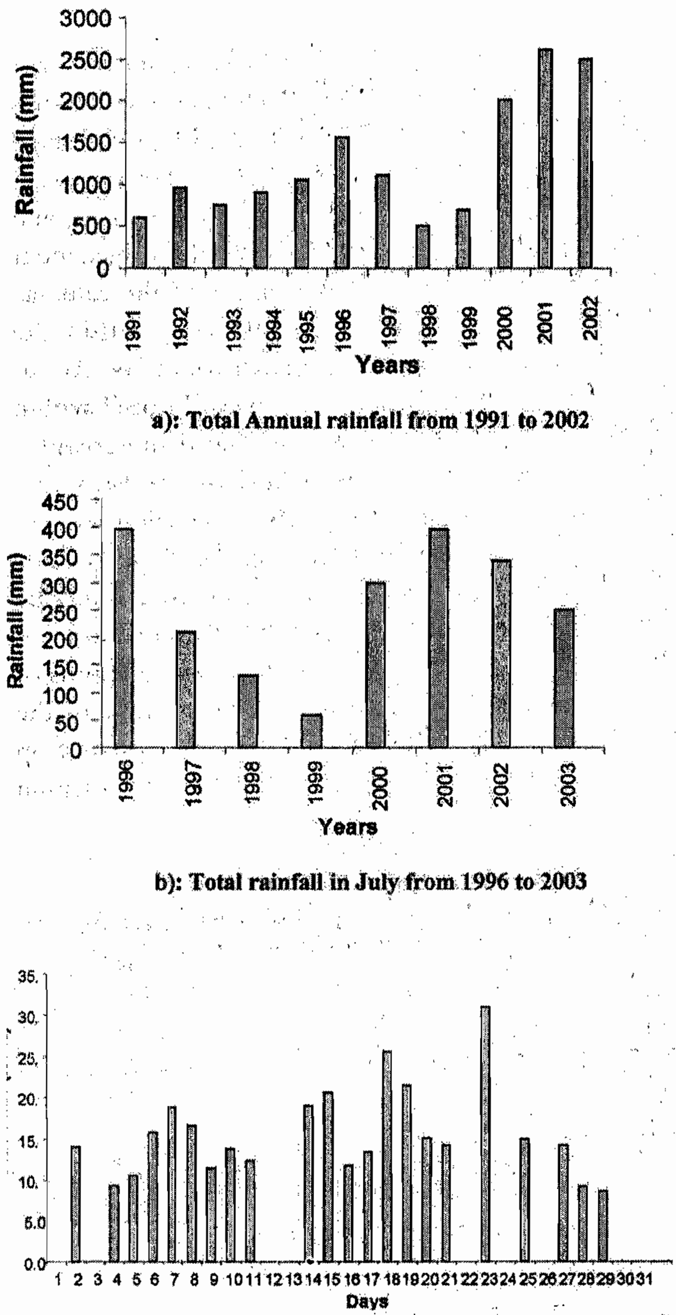
The main landslide types (Table 3) encountered within the weathered rhyolites and pyroclastics were mylonite type and brecciated types. Limited scars of striations types (rockfalls) were encountered on inaccessible, highly jointed, and steep escarpments of the crystalline basement rocks located at the lower limits of the caldera.. Some of the landslides especially within the volcanics showed rotational properties. About 70% of the landslide scars were located within weathered volcanics that produced the complex volcanic soils. Generally, most of the landslides were concentrated on steep slopes along gullies and on the ridges of the caldera. Their widths ranged from 5m to over 120m in composite landslides while the slopes of the slide surfaces ranged from 20o to 60o. The projected depths of movement, or headscarps, were generally of the order of 3m deep although greater depths of up to 7m were observed in the mylonite slides within

Table 2: Damage caused by the landslides within the caldera.

ZONES	DEATH (persons)	INJURED (persons)	FARMS DESTROYED	LIVESTOCK KILLED	HOUSES DESTROYED	BRIDGES DESTROYED	CULVERTS DESTROYED	FAMILIES DISPLACED	PERSONS DISPLACED
Magha	20	04	125	232	108 (plus two schools destroyed)	10	25	108	352
Lower Bamumbu	02	-	162	126	121 (plus three schools partially affected)	20	36	121	566
M'mock Leteh	-	-	78	-	-	-	-	-	-
M'mock Ngih	01	-	131	27	29 (plus three schools partially destroyed)	19	18	-	97
Lewoh	-	-	-	-	03	03	07	-	-
TOTAL	**23**	**04**	**496**	**385**	**261**	**52**	**86**	**229**	**1015**

weathered pyroclastic materials. The volumes of the scars ranged from around 30m3 for the small slides to 60,000m3 for the gigantic slides.

Histogram plots of averaged annual rainfall from 1993 to 2002 indicated a pattern of two cycles of increasing rainfall with peaks in 1996 and 2001, followed by periods of decreasing rainfall (Fig. 2a). Plots of total rainfall during the month of July alone from 1994 to 2004 indicated continuous high values from 2000 to 2003 (Fig. 2b), while plots of total daily rainfall for the month of July 2003 indicated continuous rainfall from 14th to 21st July (Fig. 2c).



a): Total Annual rainfall from 1991 to 2002

b): Total rainfall in July from 1996 to 2003

c): Daily rainfall in July, 2003

Fig. 2: Rainfall Data
(a) Total annual rainfall from 1991 to 2002,
(b) Total rainfall in July from 1996 to 2003.

Three main types of soils were found in the area. These included (Fig 3) complex volcanic soils (reddish to whitish clayey soils of acid to basic reaction); young volcanic soils (dark brown stoney clayey soil, with evidence of laterisation), and the sandy clayey soils (gritty acid soil usually deep and well drained, with relief from rugged to gentle slopes). The sandy clayey soils occupy the central position of the study area, the young volcanics are located around the peripheries and the complex volcanic soils are found in between the two (Fig 3). The measured pH of these volcanic soils averaged 5.0.

Laboratory Results

The results of sieving and hydrometer analysis of samples collected at Magha, Banteng, and Fotang are presented in Table 4. The different curves produced are presented in Fig 4.The four samples (1 to 4) showed a difference in grain size distribution for the four sets of curves. Figure 5 is a plot of the silt, sand and clay fractions for the regrouped 1 and 2 above the sliding surface and the 3 below it on the Howard et al. (1988) triangle.

The XRD patterns for the FPA1 sample collected above the sliding surface indicate that this zone is rich in sanidine and quartz. The clay mineral present is mainly kaolinite constituting about 16.4%. It also has subordinate amounts of muscovite. Sample FPA2 located below sample FPA1 is dominated by quartz (~ 78.6%), with small quantities of chlorite, muscovite and kaolinite with a significant gibbsite amount of 5.8%. The total clay content here is estimated at 9.0%. The reddish brown gibbsitic slide surface material (SSM) located below FPA2 has 95.2% gibbsite, and muscovite and quartz constitute only 2.8% and 2.0%, respectively, confirming the fact that progressive leaching of silica and the alkalis lead to an increase in aluminium. The FPA3 sample located below the SSM sample is

Table 3: Mapped landslide types based on Shuzui (2000) Classification Scheme.

LOCATION	SAMPLE Number	% CLAY CONTENT	% SILICATE MINERALS	DISPLACEMENT	N° OF MOVEMENTS	FREQUENCY OF MOV'T	CLASSIFICATION
MAGHA	M1	44	56	55	abve 40 time	once/yr	Mylonite Type
	M2	32	68	45	abve 40 time	once/yr	Mylonite Type
	M3	38	62	40	abve 40 time	once/yr	Mylonite Type
	M4	40	60	52	abve 40 time	once/yr	Mylonite Type
	M5	22	78	30	4 times	once/10yrs	Brecciated Type
	M6	18	82	22	4 times	once/10yrs	Brecciated Type
	M7	48	52	60	abve 40 time	once/yr	Mylonite Type
	M8	36	64	48	abve 40 time	once/yr	Mylonite Type
	M9	38	62	44	abve 40 time	once/yr	Mylonite Type
	M10	46	54	56	abve 40 time	once/yr	Mylonite Type
BANTENG	B1	20	80	20	4 times	once/10yrs	Brecciated Type
	B2	28	72	24	4 times	once/10yrs	Brecciated Type
	B3	18	82	15	4 times	once/10yrs	Brecciated Type
	B4	10	90	18	2 times	—	Striation Type
	B5	37	63	39	abve 40 time	once/yr	Mylonite Type
	B6	36	64	40	abve 40 time	once/yr	Mylonite Type
	B7	28	72	28	4 times	once/10yrs	Brecciated Type
	B8	36	64	48	abve 40 time	once/yr	Mylonite Type
	B9	41	59	53	abve 40 time	once/yr	Mylonite Type
	B10	35	65	41	abve 40 time	once/yr	Mylonite Type
FOTANG	F1	40	60	54	abve 40 time	once/yr	Mylonite Type
	F2	48	52	70	abve 40 time	once/yr	Mylonite Type
	F3	8	92	10	2 time	—	Striation Type
	F4	44	56	48	abve 40 time	once/yr	Mylonite Type
	F5	45	55	35	abve 40 time	once/yr	Mylonite Type
	F6	14	86	24	4 times	once/10yrs	Brecciated Type
	F7	28	72	36	4 times	once/10yrs	Brecciated Type
	F8	40	60	41	abve 40 time	once/yr	Mylonite Type
	F9	35	65	38	abve 40 time	once/yr	Mylonite Type
	F10	42	58	47	abve 40 time	once/yr	Mylonite Type

characterised by quartz and sanidine, about 46.2% and 38.5%, respectively. It contains small amounts of kaolinite and muscovite. This unit also contains a small amount of gibbsite, (1.1%), possibly due to Al retention following leaching by descending solutions along joints. The clay content is about 9.7% (Table 5). The gibbsitic band (SSM) located above the FPA3 sample indicated the zone where aluminium is retained.

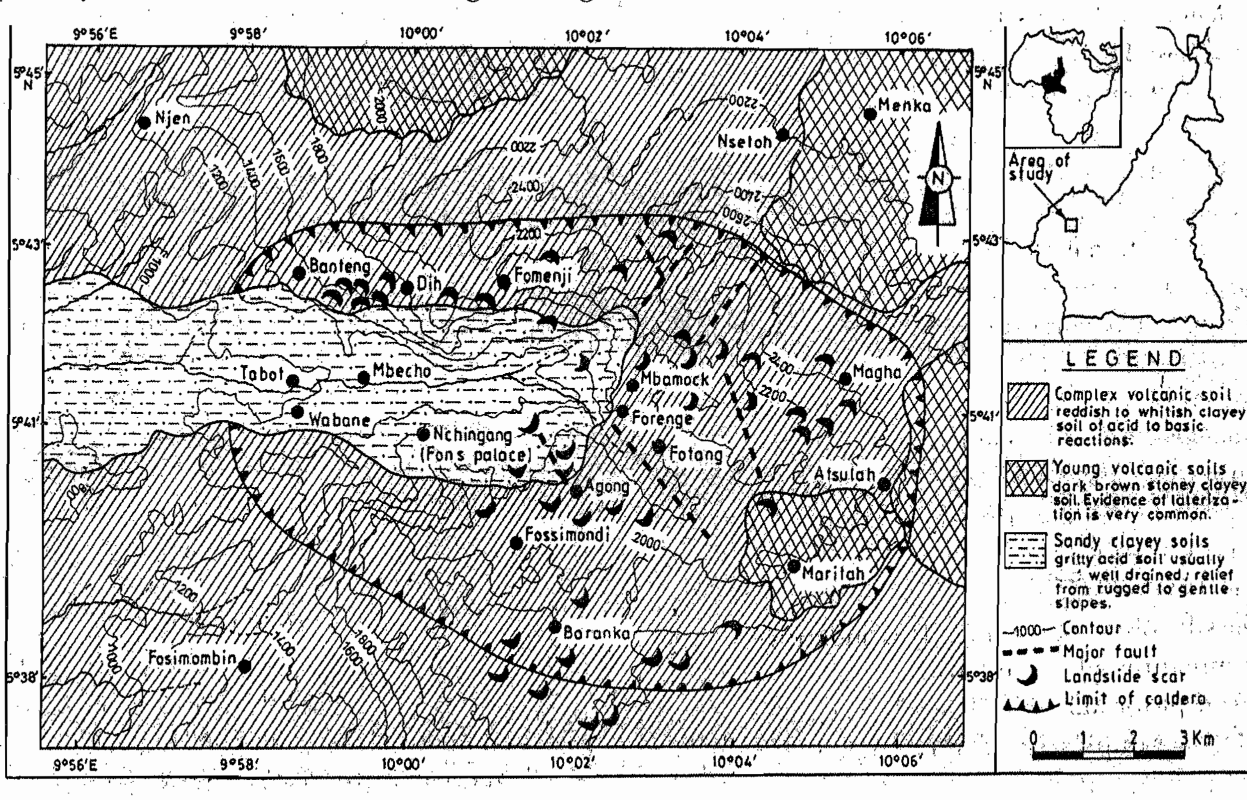


Fig. 3: Soil Map of Study Area

Table 4: Results of grain size analysis.

	GRAIN SIZE ANALYSIS												
		BPC1	BPC2	BPC3	BX	FPA1	FPA2	FPA3	FX	MPA1	MPA2	MPA3	MX
	clay	12.96	21.29	17.03	8.32	44.69	15.66	0.07	41.75	24.33	23.63	34.05	16.07
	fine silt	44.68	25.41	24.13	54.09	20.9	24.61	10.25	21.43	19.25	21.17	27.14	27.21
	coarse silt	21.45	7.32	49.71	18.78	12.07	20.75	7	16.22	20.15	20.98	8.67	19.73
	sand	20.91	44.98	9.13	18.11	22.34	38.97	82.59	21.43	43.25	31.17	27.14	35.63
CUMMULATIVE FREQ.													
	Grain size	BPC1	BPC2	BPC3	BX	FPA1	FPA2	FPA3	FX	MPA1	MPA2	MPA3	MX
clay	0.001 mm	12.96	21.29	17.03	8.32	43.69	15.66	0.07	41.75	24.33	23.63	34.05	16.07
fine silt	0.01 mm	57.64	46.7	41.16	62.41	64.59	40.27	10.32	63.18	43.58	44.8	61.19	43.28
C Silt	0.1 mm	79.09	54.02	90.87	81.19	76.65	61.02	17.32	79.4	63.73	65.78	69.86	63.01
sand	1.0 mm	100	99	100	99.3	99	99.99	99.91	100.83	97.98	96.95	97	98.64
			PROPORTION OF THE DIFFERENT FRACTIONS (Susceptibility)										
		wt	%							wt	%		
BPC1-2	clay	34.25	17					BPC3	clay	9.13	9		
	silt	98.86	50						silt	73.84	74		
	sand	65.89	33						sand	17.03	17		
	Total	199							Total	100			
								FPA3	clay	0.07	1		
FPA1-2	clay	60.35	30						silt	17.27	17		
	silt	78.33	39						sand	82.59	82		
	sand	61.31	31						Total	99.93			
	Total	199.99											
								MPA3	clay	34.05	35		
									silt	35.81	37		
MPA1-2	clay	47.96	25						sand	27.14	28		
	silt	90.55	41						Total	97			
	sand	56.42	34										
	Total	194.93											

Interpretation and discussions

New evidence from the field indicated that the Precambrian basement is unconformably overlain by an alternation of volcanic fall and flow. In this case the centre of the caldera is occupied by Precambrian rocks despite the fact that previous work suggested the presence of ignimbrites at the centre of the caldera (Nono et al. 2004). The relationship between the Precambrian rocks and the volcanics, as well as the alternation of volcanic flows and falls, suggest a perfect setting for the occurrence of landslides, because permeability differences are created during rainfall. This resulted in the formation of geological boundaries. According to Ayalew (2000), such a geological boundary marks a sharp change in engineering properties and is therefore significant for slope stability analysis and classification.

The grain size distribution (Fig. 4) is indicative of predominantly silty sand for most of the samples (except for M3 which is sandy clay). The three sets of samples (F- for Fotang; B-for Banteng and M-for Magha) clearly portray differences in grain size distribution curves.The samples from the regolith at Magha (Mx) and Banteng (Bx) indicated lower clay fractions while samples from Fotang (Fx) tend to show a higher value. In accordance with the Unified Classification Scheme, the former are classified as silty sand (SS) while the later is a sandy clay (SC). During transportation of the regolith most of the fine particles are lost due to sorting .Therefore the regolith is generally poor in the fine fraction. The samples above the sliding surfaces are relatively richer in the clay fractions and poorer in the coarse fractions. This justifies the fact that weathering is more intensive within these zones and progresses gradually towards the interior; resulting in the physical and chemical breakdown of the various particles.

Howard et al., (1988) and Telerico et al., (2004), carried out similar studies of soils from landslides and used the results to establish the range of soil grain sizes that are most susceptible to sliding and established that soils containing large amounts of clay or gravel are less susceptible, since their components have a stabilising influence on the soil mass. The plot of results of grain size analysis on the grain size triangle (Fig.5) indicates a high susceptibility to sliding of the samples above the sliding surface while the samples collected below this sliding surface plot outside the failure zone. Samples below the sliding surface had a predominance of one grain size fraction that tends to stabilise the unit. The upper materials showed a relatively even distribution and this facilitated movement of the materials downslope. Talerico et al 2004 described the same behaviour within glacial soils in New Jersey.

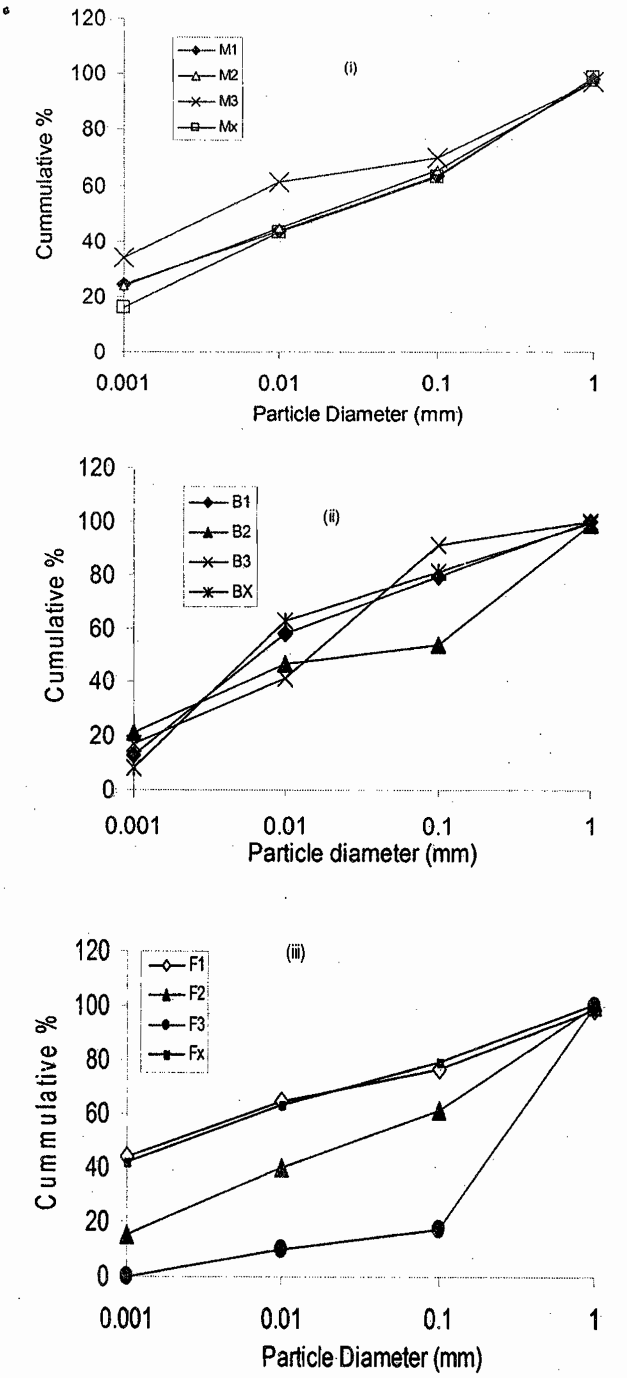


Fig. 4: Plots of results of grain size distribution at Magha (M), Banteng (B), and Fotang (F)

Table 5: Results of grain size analysis.

FPA1		Counts	Percentages (%)
	Sanidine	4076	44.7
	Quartz	3008	33.0
	Kaolinite	1499	16.4
	Muscovite	538	5.9
FPA2	Quartz	2683	79.6
	Muscovite	205	6.1
	Gibbsite	195	5.8
	Chlorite	180	5.3
	Kaolinite	106	3.2
FPA3	Quartz	3398	46.2
	Sanidine	2829	38.5
	kaolinite	632	8.6
	Muscovite	413	5.6
	Gibbsite	77	1.1
SSM	Gibbsite	2944	95.2
	Muscovite	86	2.8
	Quartz	62	2.0
MPA1	Sanidine	1376	53.7
	Orthoclase	398	15.5
	Quartz	237	9.2
	Gibbsite	180	7.0
	Kaolinite	149	5.8
	Montmorillo nite	56	2.2
	Geothite	27	1.1
MPA2	Sanidine	1728	72.6
	Muscovite	349	14.7
	Montmorillo nite	161	9.2
	Kaolinite	83	3.5
MPA3	Sanidine	961	56.8
	Muscovite	345	20.4
	Analcite	144	8.6
	Kaolinite	137	8.1
	Gibbsite	92	5.4
	Quartz	12	0.7

The implication of clays in slope stability in this region is indicated by the mineralogy of the slide surface materials (SSM) that are exceptionally rich in gibbsite (95.2%). This is the first time that the presence of gibbsitic bands have been reported on landslide scars along the Cameroon Volcanic Line (CVL) The unit above the sliding surface (FPA1) and the bottom set (FPA3) are rich in sanidine feldspar which is considered as the source material for gibbsite. Strikingly the slide surface material (SSM) and the unit close to it, have very little sanidine feldspar. This indicates that the feldspars and some muscovite were intensively weathered, and that other elements were leached out and this favoured the concentration of Al_2O_3. The presence of moisture accelerated the weathering of sanidine around these joints to produce the gibbsitic bands. Kaolinite which also represents an intermediate stage in the formation of gibbsite is found in all the units (FPA1, FPA2, FPA3), and it is most abundant in the upper unit (FPA1). This supports the fact that intensive weathering and leaching occurred at the units above the gibbsitic bands.

Parry and Frank (2000) while working on weathered volcanics and granitic rocks in Hong Kong confirmed that kaolinite formed from the weathering of feldspar and mica, was found concentrated within sinuous veins and constituted the main factor causing slope failure. The fine-grained nature and the intensive concentration of Al_2O_3 increased the ability of the SSM unit to absorb a high percentage of water. The limited permeability of the slide surface in this work is confirmed by the limited amount (1.1%) of gibbsite found within the FPA3 lower unit. This implies that only a limited amount of solution capable of causing weathering and leaching, circulated within these lower zones. This phenomenon results in the charging of the gibbsitic layer and due to low permeability, the upper unit (FPA1) is also subsequently recharged heavily during prolonged rainfall. Parry and Frank (2000) stated that this often resulted in the formation of clays that lower the strength of rocks, resulting in slope destasbilisation. Therefore increase in weight above the gibbsitic layer (probably from rainfall) will reduced the strength

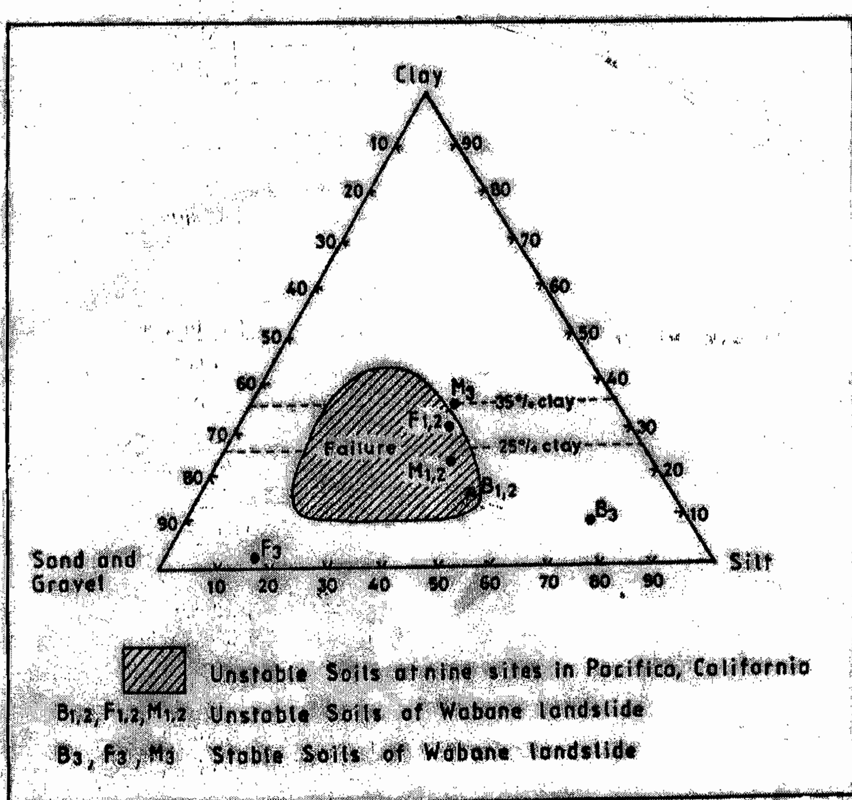


Fig. 5: Plots of results of grain size analysis of six samples on the Grain Size

of rocks and coupled with the angle of inclination that generally averages about 35°, can easily support slope failure.

The MPA samples do not show the development of the gibbsitic bands although a very small amount of gibbsite could be detected in the samples, as seen in MPA1 and MPA2. The presence of montmorillonite distinguished these samples from the rest. The clay minerals are gibbsite, kaolinite and montmorillonite and the non-clay minerals are sanidine, orthoclase, quartz, muscovite, goethite and analcite. Worthy of note is the fact that lithologically the facies within such regions are a complex mixture of rhyolitic tephras, basic pyroclastics, and very thin basic flow which are often reduced to thin slabs.

Earlier works in the region (Tchoua, 1973; Youmen, 1994; and Nono et al., 2004) recognised the diversity in the lithologic facies. The MPA1 and MPA2 are shown to exhibit completely different properties from the MPA3 unit as they contain clay contents of 15.0% and 12.7% respectively. The presence of montmorillonite in them signifies that they can absorb much water, shrink and swell to a reasonable extent and this can destabilise the overlying regolith. It also represents a unit that can reduce permeability, resulting in the recharge of the overlying unit leading to slope destabilisation.

Yuki et al. (2006) while working on sandstones and mudstones in the Boso Peninsular, Japan, concluded that the variation in saturated hydraulic conductivity was a pointer to the occurrence of landslides. They discovered that the hydraulic discontinuity in a profile at a depth of about 0.6 m corresponded to the potential failure plane which was the top of the mudstone. Therefore the clay units greatly reduced the percolation of water, creating the possibility of the occurrence of landslides.

In terms of the soil types presented in Fig 3, the complex volcanic soils constitute about 65 %, of the study area, the young volcanic soils about 20 %, and the sandy clayey soils about 15 %. This region falls within the tropics and satisfy the conditions for both physical and chemical weathering. The pH value of 5.0 greatly support the intensive weathering experienced. Mvondo Ze (1991) and FAO/UNDP (1977, 1989) while working on Mount Cameroon which forms part of the series of peaks of the Cameroon Volcanic Line, concluded that the pH ranged between 4 - 6.5. This confirms the fact that the region has suffered from intensive weathering. The greater proportion of the complex volcanic soils with little or no stones and with the red colouration, supports long and intensive weathering. This has been confirmed by the large amount of clay minerals particularly gibbsitic clays within soils.

The caldera is made up of v-shaped valleys, formed within the predominantly weaker lithologies of the volcanic rocks which are highly prone to weathering, erosion and transportation. Such processes appear to be quite rapid and the rugged topography has had little time to adjust, thereby leaving over-steepened hillside slopes, some of them nearly vertical in inclination. Griffiths et al., (2002) described similar incised canyons and v-shaped valleys (in Spain) developed in stronger geological strata beneath, with weaker lithologies above. They further pointed out that the latter is usually in a state of marginal stability. The occurrence of different types of landslides in such terrains is accordingly a reflection of the varied geology, the associated weathering of the rocks, and the steep topography.

The location of over 70% of the landslide scars within the complex volcanic soils is considered to be the consequent to the plastic flow of the resultant clays produced by the weathering of these rocks. Some of the landslide scars were situated on old scars. According to Santaloia et al., (2001), the reactivation of ancient landslides may follow slow progressive plastic straining, with either the formation of new slip surfaces, or the slipping of the soil mass along a pre-existing slip surface. Such slope failures are controlled basically by factors such as the geology and resultant soil types, the topography, and the pore water pressure resulting from prolonged and/or intense rainfall which acts as the main triggering mechanism.

The rainfall data indicate a long period of scarce rainfall from 1991 to 1999 with a high inter-annual variability in 1996. Such a long period of dryness must have resulted in changes in the physical properties of the weathered materials, particularly the development of contraction joints. This was proceeded by a period of heavy rainfall from 2000 to 2002 (Fig. 2a), causing high infiltration within the weathered materials overlying the thick iron oxide concretion beds, that are failure surfaces.

Histogram plots of monthly total rainfall in the month of July indicated a drop from 1996 to 1999 and high values from 2000 to 2003 (Fig. 2b). The weathered volcanics were probably over saturated during the later years, resulting in differences in competence of the rock materials. According to Polemio et al., (2000), such heavy rainfall over a long period leads to a high rate of infiltration within steep slopes thereby triggering landslides.

Plots of daily rainfall in July 2003 (Fig. 2c) indicated continuous rainfall which for barely a week preceding the event, produced 135mm of rainfall as compared to the weekly average of 58mm (3,000mm annually) in this area (Olivry, 1986). According to Polloni et al., (1996), such antecedent rainfall controls the soil moisture and is critical in initiating debris flow on slopes of 30° to 40°. Furthermore, Ng and Shi (1998) found that such rainfall intensity and the original position of the initial groundwater level, affect the stability of slopes. They further suggested that a slope could remain stable even under excessive rainfall if the initial groundwater level is low and that the factor of safety would only decrease if the duration of rainfall is increased. Santaloia et al., (2001) described similar movements of clayey solids activated by high seasonal rainfall. Transient perched groundwater tables formed under such conditions produced the springs observed at Magha prior to, and after the event.

Yue and Lee (2002) and Ayonghe et al., (2004) reported similar impervious bottom layers in thick sandstones in south west China and in volcanic cones in Limbe, Cameroon respectively. Griffiths et al., (2004) equally reported similar slope failures in Papua New Guinea where permeable limestone overlaid a thick stratum of impermeable clay. Rainfall infiltration in these cases led to the formation of perched groundwater tables, which, in the cases of Limbe and the present study area, was evidenced by water seeping out of bedding interfaces as springs for several days after landslide events.

CONCLUSIONS

The study has been used to unveil the causes and the underlying mechanisms involved in triggering the landslides within the Bambouto caldera. A new geological setting of the region as well as a soil map of the area have been established based on detailed fieldwork. Precambrian syenites and limited granitic rocks occupy the south western breached section of the caldera. The mapped distribution of the landslide scars indicated over 70% located within weathered rhyolites which produced the complex volcanic soils. This is indicative of the susceptibility of these rocks to sliding when saturated by intense and prolonged rainfall. The sliding was further facilitated by the existence of impermeable dipping slide surfaces with gibbsitic bands covering the surfaces. Analysis of grain size distribution of weathered materials above and beneath slide surfaces revealed different properties, with the upper units being more susceptible to sliding while the units below the sliding surfaces are more stable. This justifies the frequent movement of the upper units over the more stable lower units experienced within the study area..

Statistical analyses of rainfall data were indicative of the fact that intense rainfall for three days coming after four days of slight rainfall was the principal factor that triggered the swarm of landslides. Highly permeable pyroclastic materials overlying the impermeable surfaces became charged with groundwater to produce perched aquifers. The bedding planes then reduced the shear strength of these saturated rocks leading to the landslides. However, other factors such as extensive deforestation, man-made cut slopes for roads, farming and for other structures, equally enhanced the slope failures especially where the impermeable bedding planes were well established.

Effective future mitigation strategies against these disasters will include the development of an engineering geological and geomorphologic model of the region which will facilitate the identification of areas prone to potential landslides as well as avoiding settlements and development projects within the areas with weathered rhyolitic clays where most of the landslide scars were mapped, and which have been delineated as high landslide risk zones.

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