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GEOSTATISTICAL PREDICTION OF FUTURE VOLCANIC ERUPTION AND RISK ASSESSMENT FOR THE MOUNT CAMEROON VOLCANO

P.N. LAPI, A. E.OFOMA, J.O. AMOBI, S. A. NGAH AND O. I.CHIAGHANAM

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ABSTRACT

This study presents a statistical analysis forecasting a possible future volcanic eruption in Mount Cameroon. The study is primarily undertaken to assess the risk, determine the frequency of the successive eruptions and from this, forecast a possible future eruption of the Mount Cameroon volcano. This will assist in future planning and possibly put in place hazard mitigation strategies that will forestall the loss of lives and property.

Results show that the series of Mount Cameroon eruptions are random and independent of time. Also, it is predicted within the limits of any reasonable doubt that the interval for the next major eruption that will emit lava with a volume of about 10million m^3 is probably in the year 2022. This extrapolation is in line with the May 28, 2000 eruption barely fourteen months after the March – April 1999 eruption. However, the timing may be earlier or later and the volume may be more or less since the predicted values are approximations.

INTRODUCTION

Some of the dangers posed by volcanic eruptions are actually the loss of life, property and/or environmental losses such as loss of farmland and biodiversity. The extent of lava flow over arable land inhibits farming activity over several years. The turn over time of lava flows on the slopes of Mount Cameroon is estimated to be at least 300 to 600years (Nouhou et al., 2001), suggesting that it will require a long time before entire vegetation is reconstituted after a lava flow.

Mount Cameroon is located on the coast of West Africa, southwest of Cameroon, along the coastal belt of the Gulf of Guinea (Fig. 1). It lies between Latitudes $3^0 57'$ – $4^0 27'$N and Longitudes $8^0 58'$ – $9^0 24'$E, and marks the highest mountain in Central and West Africa, rising up to 4,095m above sea level. Mount Cameroon is part of a chain of volcanic mountains that starts from about 100km southwest of Cameroon (Fig. 2) at the Island of Pagalu, Sao Tome, Principe,

to Bioko, through Kupe, Manengouba, Bambouto, Oku and Nkogam to the Adamawa highlands and ends with the Kapsiki Plateau (Ngonge, 1988; Njonfang et. al., 1992). Mount Cameroon rises abruptly from the coast above sea level to reach the summit about 20km hinterland. The main Plateau is about 50km long and 35km wide and covering an area of about 1800km^2 trending SW – NE (Ngonge, 1988).

Certain authors like Dèruelle (1982), Dèruelle et al (1987), Fitton et al (1983), Nkoumbou et al (1995) have carried out the risk assessment associated with volcanic eruptions in Mount Cameroon. However, published works on possible future eruptions in Mount Cameroon are few and remain the exclusive preserve of the Government or the Company that carried out the study. This present study will therefore, attempt to predict a probable time for future eruption of the Mount Cameroon volcano.

The main thrusts of this study are to assess the risks that will be associated with an eventual volcanic eruption of Mount Cameroon, determine the frequency of the successive stages of eruption so as to establish a possible trend of the events that will assist in the prediction of a probable time for future eruption of Mount Cameroon.

P.N. Lapi, Department of Geology, University of Nigeria, Nsukka
A. E. Ofoma, Department of Geology, University of Nigeria, Nsukka
J.O. Amobi, Institute of Geosciences and Space Technology, Rivers State University of Science and Technology, Port Harcourt. Rivers State, Nigeria
S. A. Ngah, Institute of Geosciences and Space Technology, Rivers State University of Science and Technology, Port Harcourt. Rivers State, Nigeria
O. I. Chiaghanam, Department of Geology, Anambra State University, Uli, Anambra State, Nigeria

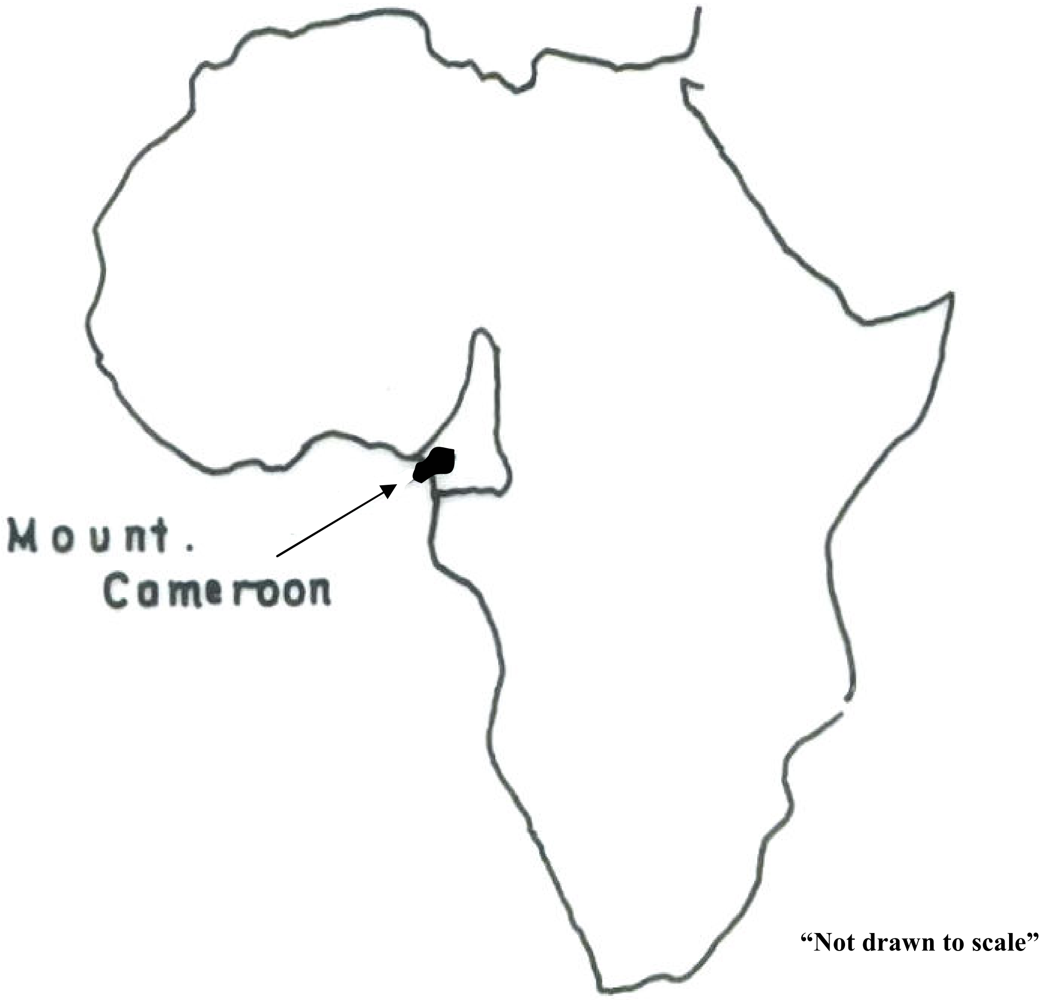
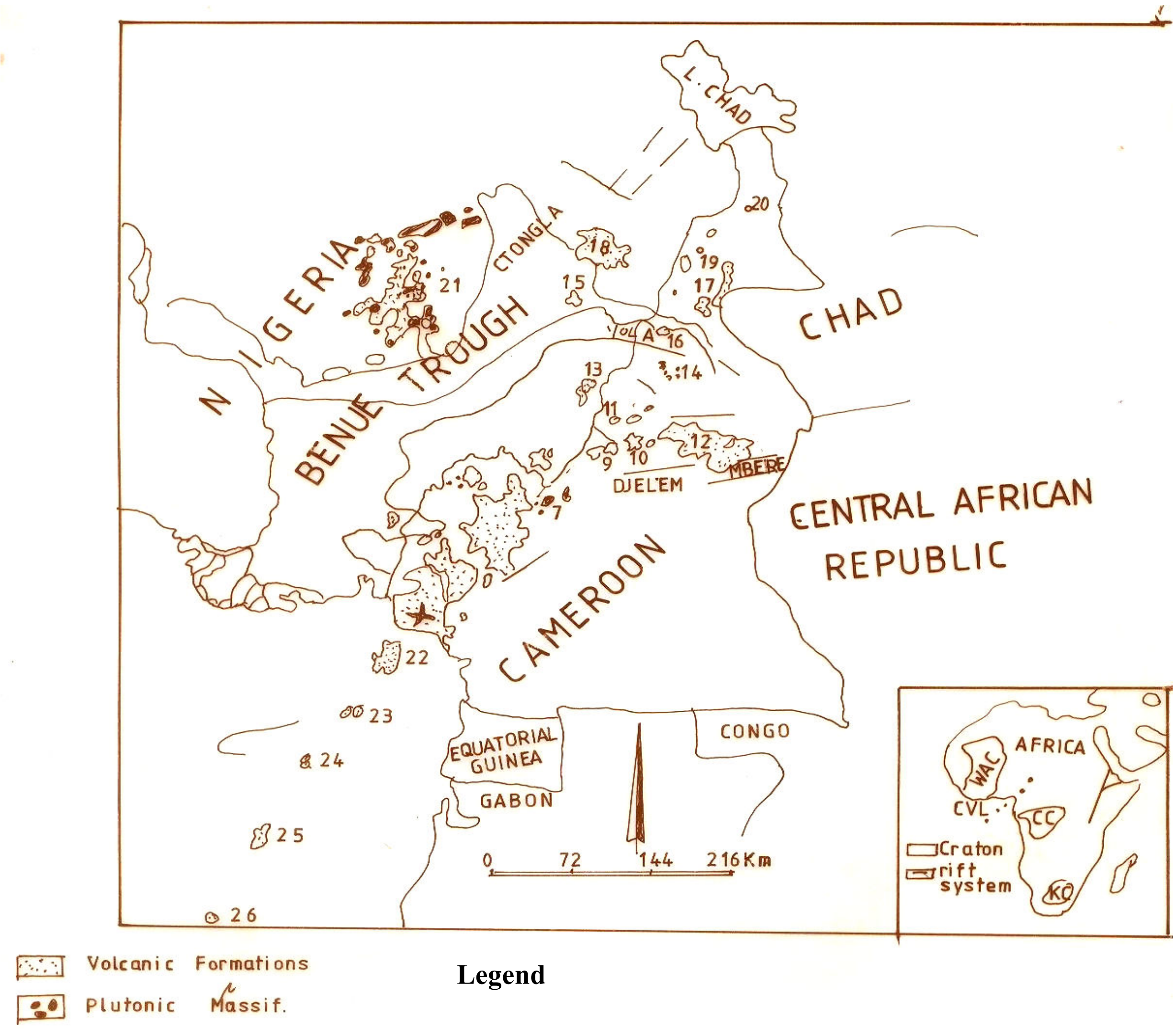


Fig. 1. Location of Mount Cameroon



Legend

1. Rumpi mountain
2. Manengouba mountain
3. Mamfe volcanism
4. Mount Bambouto and Bamileke plateau
5. Bamenda-oku mountain
6. Volcanism of the Nyos region
7. Tikar plain plutons
8. Gotel mountain
9. Tchabal mbabo
10. Tignere massif
11. Tchabai Ngandaba
12. Ngoundere plateau
13. Shebshi mountain
14. Poli massif
15. Gombe – Yola
16. Southern Garoua region
17. Mayo louti - lere
18. Damaturu plateau
19. Mandara mount
20. Syenitic massif of mora
21. Jos Plateau
22. Bioko Island
23. Subsurface volcanoe
24. Principe
25. Sao Tome
26. Pagalu

X. Mount Cameroon

Fig. 2. The Cameroon Volcanic Line (After Ngwa, 1978)

Geology/Physiography of Mount Cameroon

The origin of the Cameroon volcanic line has been proposed by many authors. Some of these authors have attributed it to a deep source hot spot magma (Ngonge, 1988; Amboh, 1989). Moreau et al., (1987) have proposed that the Cameroon volcanic line is a fracture zone related phenomenon. However, this fracture zone model does not offer any explanation as to what caused the partial melting in the mantle. According to Fitton et al.; 1983 an upwelling asthenospheric plume initially situated beneath the Benue Trough but now located beneath the Cameroon line and the Gulf of Guinea, may have given rise to the volcanic line. The general accepted origin of the Cameroon volcanic line has been that of closed spaced hot spots (Zogning, 1997).

Tectonically, the crystalline Basement of the Cameroon volcanic line lies within the mobile belt between West Africa and the Congo cratons. It comprises of the Pan African granitic rocks that have yielded Middle Proterozoic Nd model ages (Nzenti, 1998). To the north of the Cameroon volcanic line lies the Benue Trough of Nigeria which is a 1000km long depression that extends from the Niger Delta to the Chad Basin (Fitton, 1980), and to the south is the Foumban shear zone which is considered to be the continuation of the Pernambuco lineament of Brazil.

Mount Cameroon is a large volcanic horst which belongs to the Cameroon volcanic line and it is one of the largest volcanoes in Africa. It is composed of alkaline basalts and basanites interbedded with small amount of pyroclastic material (Fitton, 1987). Texturally the lavas vary from aphyritic to strongly porphyritic types. Many recent volcanic cones found on the mountain are aligned in a SW-NE direction. The oldest basalt of Mount Cameroon is assigned an age of 9Ma while the oldest lavas are estimated to be of Upper Miocene age (Fitton, 1987; Lockwood & Rubin, 1989). Comparative geochemical study of lava from the 1982 volcanic eruption with that of the 1999 eruption suggest a common parent magma for the two eruptions (Lapi, et al., 2006). Mount Cameroon is presently the only active volcano in the Cameroon volcanic line, which has erupted eight times in the last century (Ubangoh et al., 1997).

The step-like morphology of an ovoid shaped Mount Cameroon (Horst) comprises; the lower flanks at the base and three superimposed plateau above each, separated from each other by escarpments. They are the hut II Plateau, hut III Plateau and the summit Plateau (Zogning, 1997). Mount Cameroon forms a watershed for some rivers and streams. It has a drainage pattern with main Rivers like River *Mame*, *Limbe* River, *Ndongo* River with a deep gorge, *Bimbia* River, *Yoke* River and River *Mongo* all taking their source from the top central relief of Mount Cameroon and flowing or radiating in different directions (Fig. 3). The surrounding lowlands of Mount Cameroon comprise diverse mosaic of soil types including ferralitic clays formed by the weathering of igneous rocks, ash deposits, deposits of outwashed material from conglomerates of water-worn rocks and flat poorly drained plains of recent alluvium that is sandy or silty in composition (Ngonge, 1988). The vegetation on Mount Cameroon is based on two main approaches; the phytogeographic approach is related to broad vegetation zones or belts (Ngonge, 1988), while the second approach is based on local occurrence of plant communities. Annual mean rainfall decreases in a SW-NE direction of the massif to about 8,650mm at Isongo close to Debundscha (Fig. 4). Short dry season occurs between December and February. However, humidity remains high at 75% - 80% throughout the year (Ngonge, 1988). The persistent cloud cover and mist on Mount Cameroon greatly restricts the total number of sunshine hours received per year, which is 900 – 1200hrs at sea level and decreases with altitude.

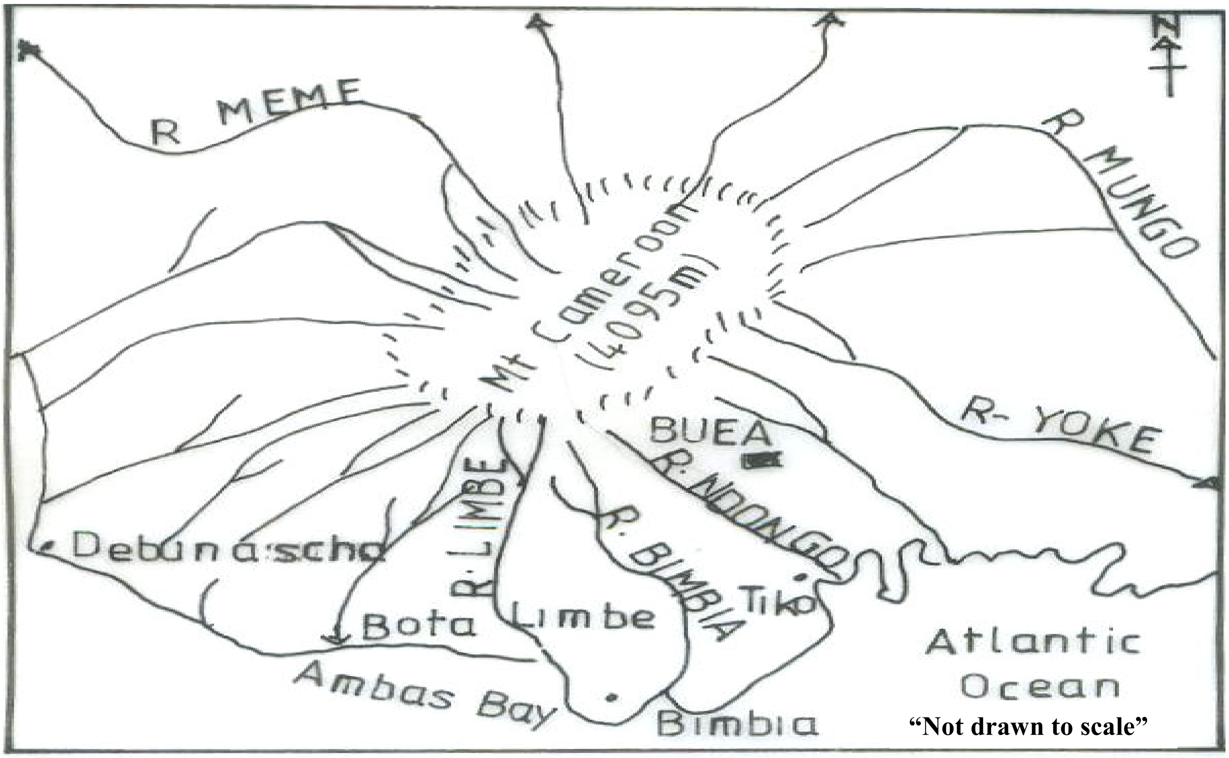


Fig 3: Mount Cameroon Radial Drainage pattern (After Ngwa, 1978)

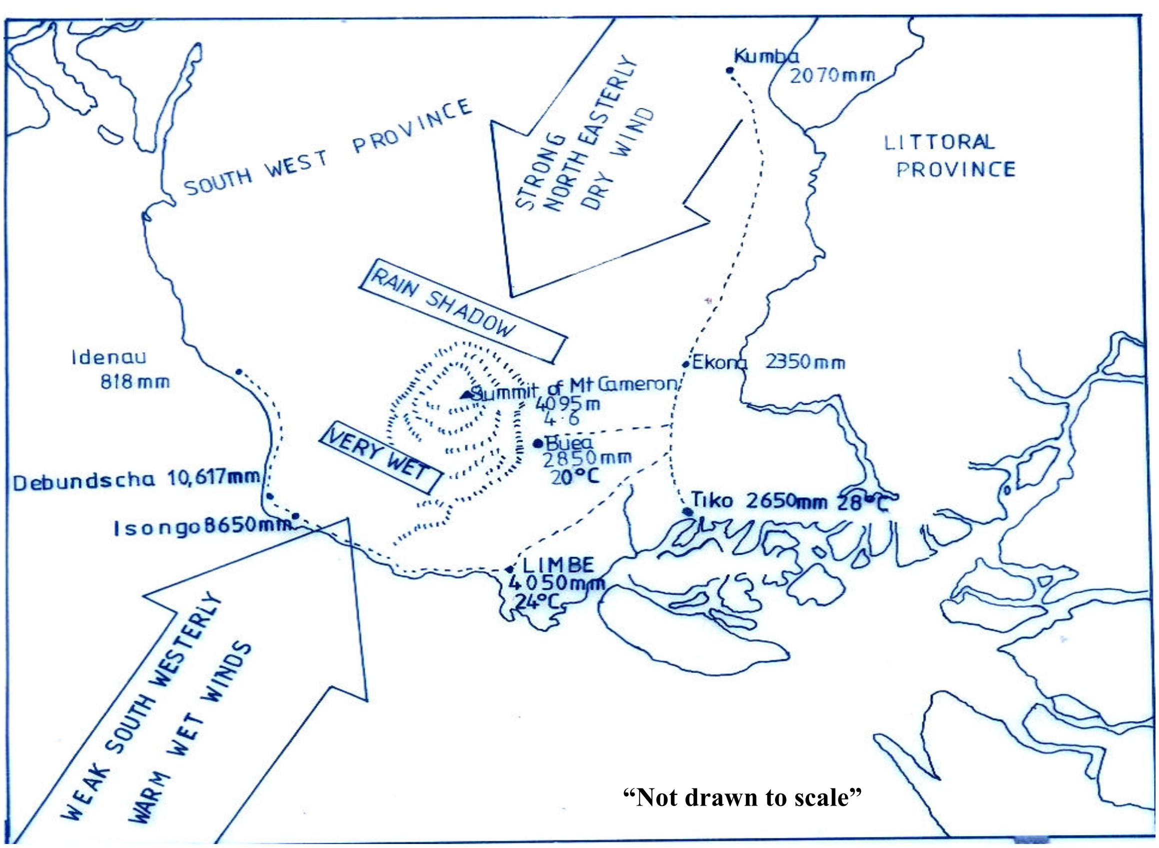


Fig. 4: Climate in the Area of Mount Cameroon (After Ngwa, 1978)

METHODOLOGY

The statistical techniques used for this study are those of Cox and Lewis (1966). They include

- Cumulative plot of the total number of eruptions (N_t) that have occurred against time (t) to show changes in the average rate of occurrence.
- Rank attributed to each eruption based on the volume of magma (m) erupted and number of eruptions with same magnitude (n). This will be used to calculate the mean recurrence interval (Tr), and evaluate the damage potential of the eruptions.
- Histogram of the number of events occurring in successive equal interval of time to determine directly the local periods of fluctuation from the average rate of occurrence.
- Empirical survivor function to test for frequency of the events in time, and the log empirical survivor function to show the degree of frequency of the eruption with time.
- Comparison of the midpoints of the eruption sequence to the centroid (ratio of sum of time from the start of the series to the i^{th} eruption to the total number of eruption (N)). This is to detect a trend in the rate of occurrence of the eruption i.e. increasing or decreasing rate of occurrence.
- Extrapolation of a plot of the cumulative volume of magma erupted with respect to time from 1909. This is to estimate the quantity of farmland, and estimated biodiversity lost so far and future expectation.

The information used as input data for the statistical analysis were sourced from existing literature, archives on Cameroon volcanic eruption on the internet, documentations from the institute *de Recherches Geoligiques et Minieres,* Ekona Cameroon (IRGM), on-line report of USAID-office of foreign disaster assistance/GCI, Inc., and individual's oral reports that were made public.

RESULTS AND DISCUSSION

The study presents a quantitative analytical approach to the risk assessment of the Mount Cameroon eruptions. So far, there is dearth of scientific write-ups with a purely quantitative approach to volcanic risk analysis. Figure (5) is a map of Cameroon showing a defined area with high risk of volcanic eruption. This area coincides with the Cameroon volcanic line (CVL). Figures 6 and 7 present the socio-economic and natural factors as well as volcanic risk zonation maps respectively, based on the unavoidable volcanic eruption experienced and lava flows on the Mount Cameroon slopes. Volcanic eruptions and lava flows are most likely to occur in the areas delimited on these maps.

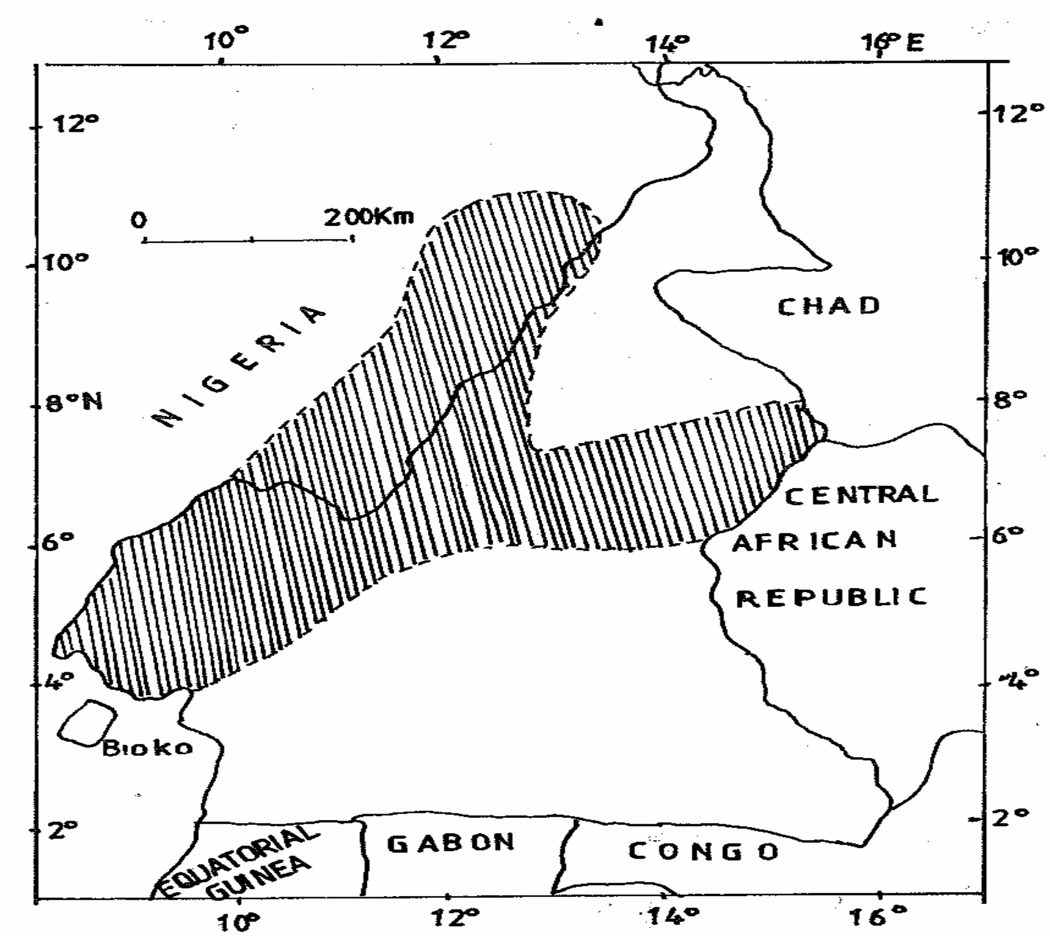


Fig. 5: Map of Cameroon showing a zone with high risk of volcanic eruption (shaded), based on records of events between 1982 and 2000. (Adapted from Deruelle et al., 1987)

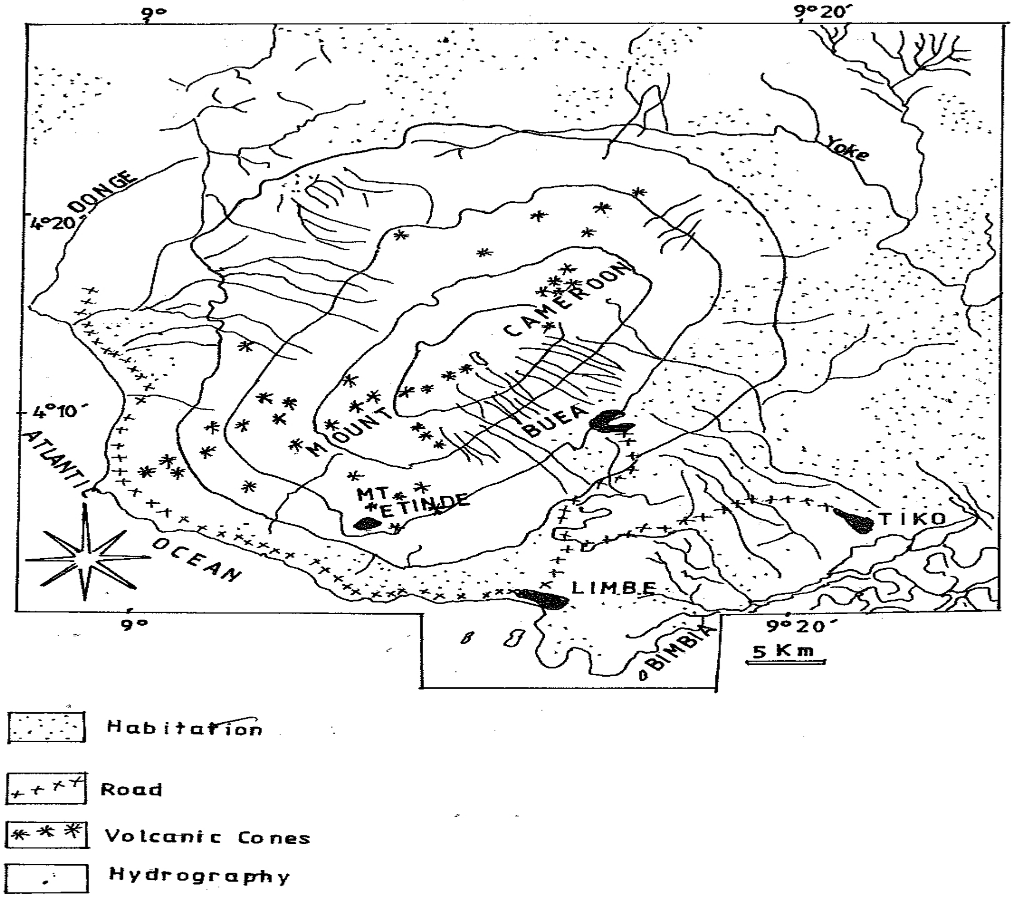


Fig. 6. Volcanic risk assessment map, Socio-Economic and natural factors of Mount Cameroon (Adapted from Geographic data Deruelle et al., 1987)

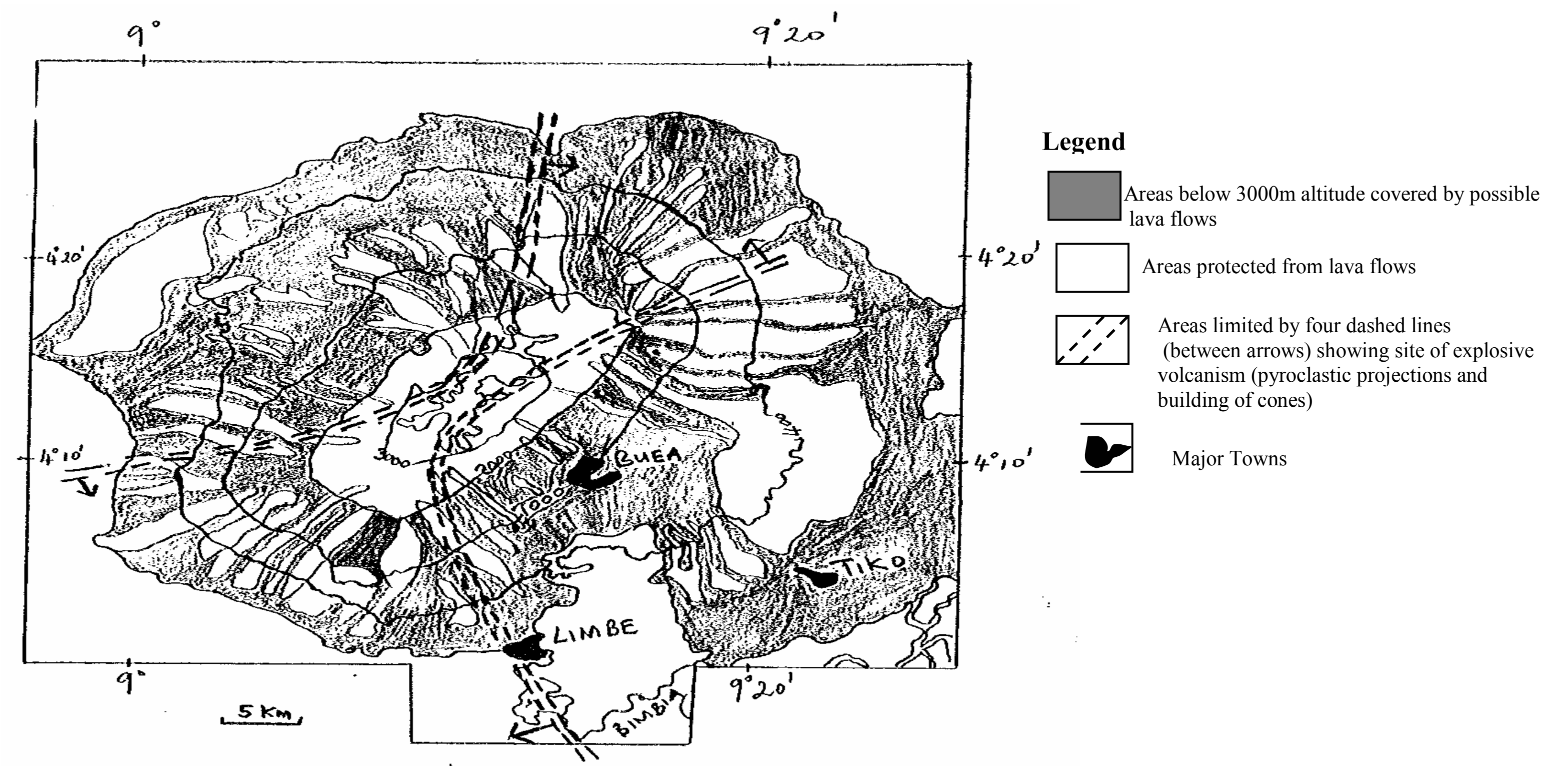


Fig. 7. Volcanic risk zonation map of Mount Cameroon (Adapted from Deruelle et al., 1987)

The statistical methods were applied to the authenticated years of recorded Mount Cameroon volcanic eruptions from 1800 to 2000 (Tab. 1). The limit of years of eruption, number of eruptions within each limit and the cumulative total number of eruptions (N_t) that occurred at or before time (t) is presented in Table 2. The cumulative plot of the total number of eruptions (N_t) that occurred at or before time (t) against time (t) is presented in Figure 8. It is aimed at evaluating the rate of occurrence of Mount Cameroon eruptions with time. This plot shows a general increase in the rate of occurrence of Mount Cameroon eruptions with time. The average rate of occurrence obtained by determining the ratio of total number of eruptions (16) to the number of time interval (10) chosen, gives approximately two (2) eruptions per interval of 20years. A histogram plot (Fig. 9) of 20years interval against number of eruptions identifies the periods of fluctuations from the average rate of occurrences. The histogram shows a significant fluctuation in rate of occurrences with time. Such fluctuation indicates a lack of trend linkage with time for the Mount Cameroon volcanic eruptions.

The empirical survivor factor was carried out to estimate the probability that an eruption has not occurred before a given time interval. However, before this is done the authenticated years of eruption, interval between eruptions in years, length of eruption intervals in years, percentage survivor (i.e. the proportion of time intervals greater than the length of time intervals in years) and the logarithmic percentage survivor is estimated (Tab. 3). The empirical survivor factor is therefore, obtained by plotting the percentage survivor (ordinate) against the length of time intervals in years (abscissa) (Fig. 10). The general principle is that if the eruptions occur randomly in time, the survivor factor will be exponential in form. This plot clearly shows that the survivor factor for the Mount Cameroon volcano is exponential in form and therefore, suggests that the eruptions occur randomly with time. Also the plot of logarithmic percentage survivor against length of time interval in years (Fig. 11) shows a remarkable departure from the empirical survivor factor, with the points on the plot almost representing a mirror image on an imaginary line indicating a high degree of randomness for the Mount Cameroon eruptions. This further emphasizes the lack of consistency in the Mount Cameroon eruptions. Based on the above it may be understood that the series of Mount Cameroon eruption events are

Table 1: Authenticated years of eruptions of Mount Cameroon volcano for the period 1800 – 2000

1800	1845	1909	1959
1815	1865	1922	1982
1835	1866	1925	1999
1838	1868	1954	2000

Table 2. Year of eruptions (yrs), Number of eruptions between years and Cumulative total number of eruptions of Mount Cameron

Year of eruption (yrs)	Number of eruptions between years	Cumulative total number of eruptions
1800	2	2
1820	2	4
1840	1	5
1860	3	8
1880	0	8
1900	1	9
1920	2	11
1940	2	13
1960	0	13
1980	3	16
2000		

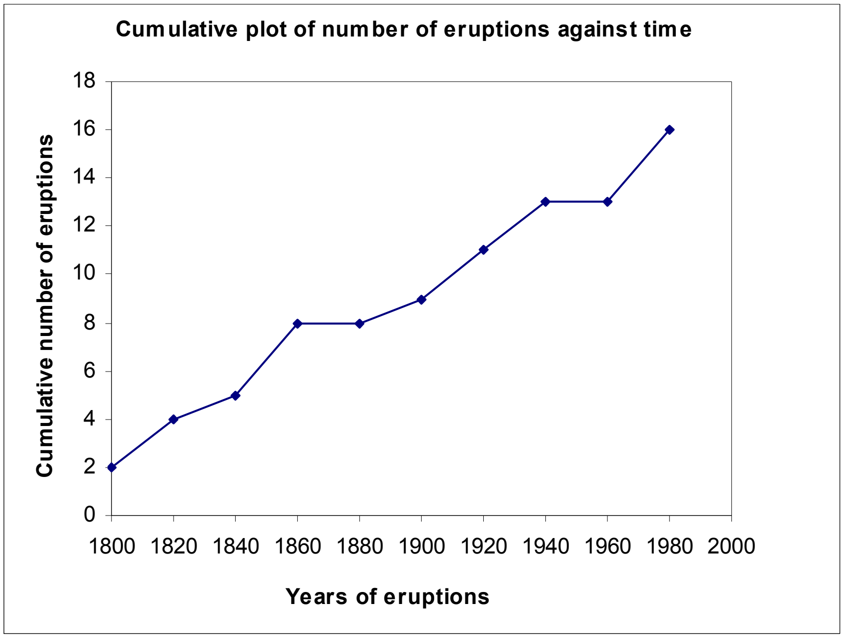


Fig. 8. Cumulative plot of number of eruptions against time

1	1800	2
2	1820	2
3	1840	1
4	1860	3
5	1880	0
6	1900	1
7	1920	2
8	1940	2
9	1960	0
10	1980	3
11	2000	

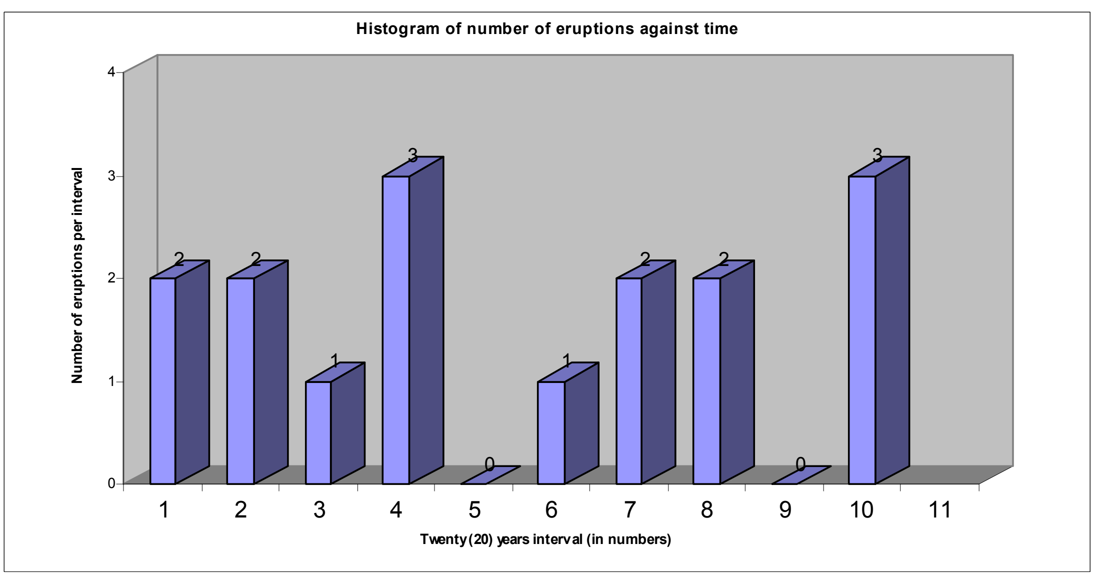


Fig. 9. Histogram of the number of eruptions against time (values on the x-axis represent number of years; see Table above)

Table 3: Authenticated years of eruption, interval between eruption, length of time interval in years, percentage survivor and log percentage survivor

Authenticated years of eruption	Interval between eruption	Length of time interval in years	Percentage Survivor (%)	Log Percentage Survivor
1800	15	1 x 2	86	1.93
1815	20	2	80	1.9
1835	3	3 x 2	66	1.82
1838	7	5	60	1.78
1845	20	7	53	1.72
1865	1	13	46	1.66
1866	2	15	40	1.6
1868	31	17	33	1.52
1909	13	20 x 2	20	1.3
1922	3	23	13	1.1
1925	29	29	6	0.78
1954	5	31	0	0
1959	23			
1982	17			
1999	1			
2000				

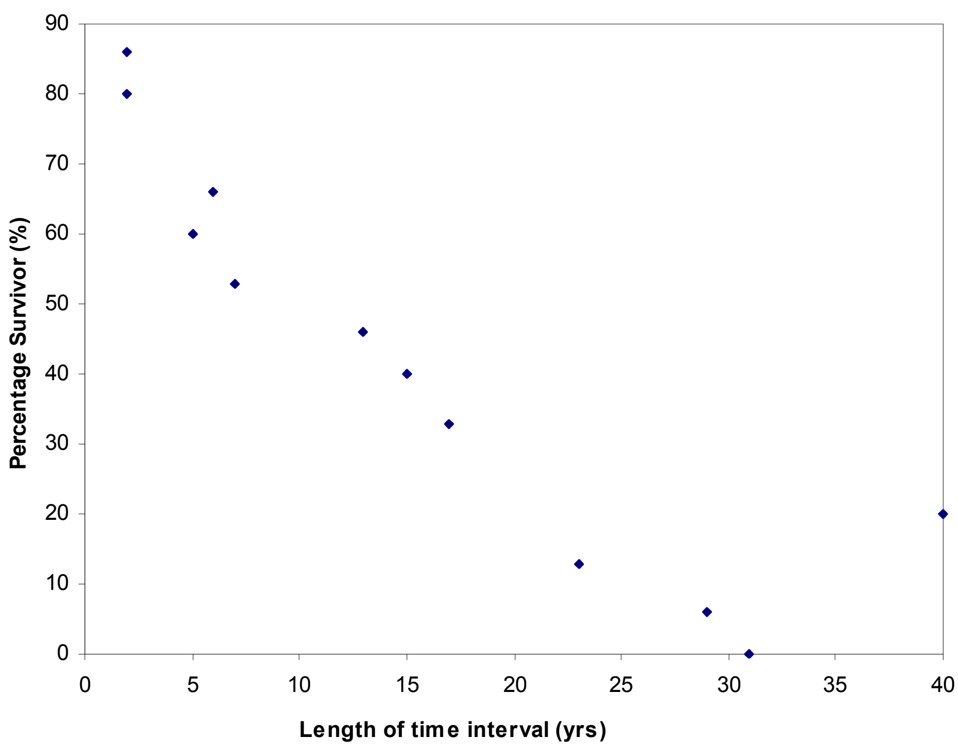


Fig. 10: Empirical survivor factor for Mount Cameroon Volcano

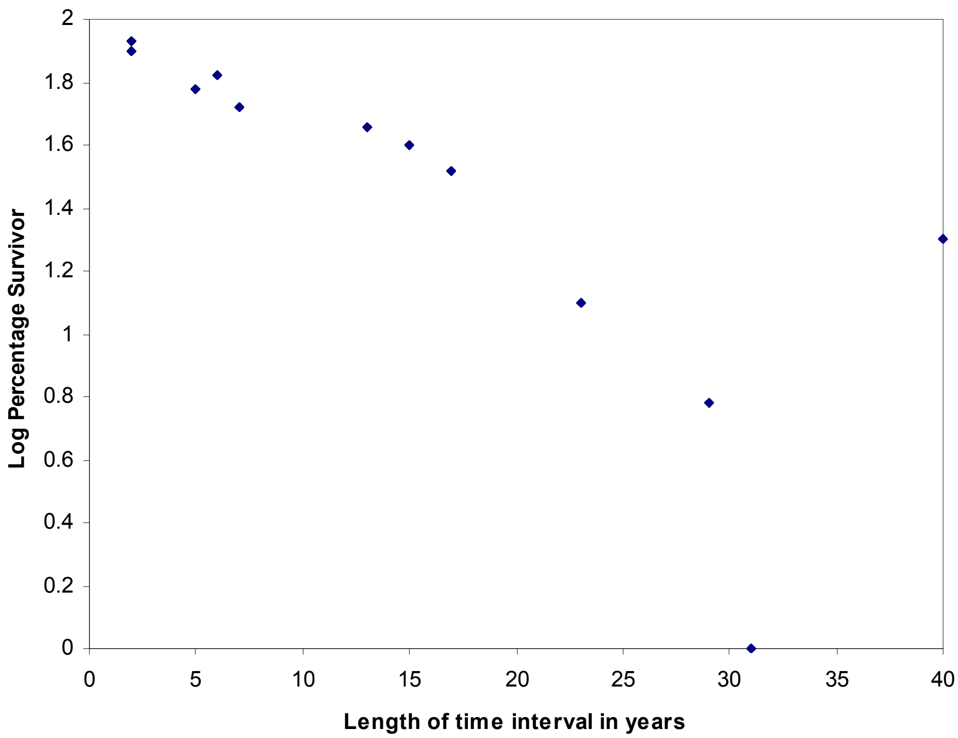


Fig. 11: Log empirical Survivor factor for Mount Cameroon Volcano

indefinitely random and independent of one another i.e. there is no relationship between an eruption that occurred at one time and that which occurred at any other later time.

Table 4 presents information on some lava flows from the 1909 to 1999 eruptions. The total volume of lava erupted is approximately estimated by assuming a uniform average value of 3m for their respective thicknesses. The timing and volume of the 1982 eruption in conjunction with data from previous eruptions of Mount Cameroon are consistent with the volcano having achieved an equilibrium or steady state with a mean rate of discharge of $0.02 \pm 0.01 m^3 s^1$ (Fitton et al., 1983). Assuming that this behavior will reoccur in future i.e. extrapolation of the mean time interval between eruptions, we can therefore, predict with confidence the interval of time to the next high risk period where a major eruption will occur emitting lava of a volume of about 10 million m^3. The parameters used for this estimation as presented in Table 5 is shown below:

- The authenticated years of eruption from 1909 to 1999
- Time interval between eruptions (X_i)
- Estimated volume of lava emitted in millions of m^3 (Y_i)
- Mean deviation $X = X_i - \ddot{X}$
- $\hat{Y} = a + bx$ gives the fitted line after selecting the least square value for ‘a’ and ‘b’ using equations

$a = 1/n\sum Y = \bar{y}$ ---- ---- ---- ---- ---- ---- Equation 1

$a = \bar{y}$ ---- ---- ---- ---- ---- ---- ---- Equation 2

$b = \sum XY / \sum X^2$ ---- ---- ---- ---- ---- ---- Equation 3

The 95% confidence interval for the next high risk period for a major eruption that will emit lava with a 10million m^3 volume is determined using the equation

$\mu_o = \hat{U}_o = \hat{Y}_o \pm t_{0.025} \times S \sqrt{1/n + X^2_o / \sum X^2}$ ---- ---- ---- Equation 4

Where:

μ_o = population mean

$\hat{U}_o$ = estimated population mean

$\hat{Y}_o$ = estimated or regressed line

$t_{0.025}$ = t-distribution two-tailed at 5% significance level, read from standard table as shown in table 6

S = standard deviation

n = number of observations (6)

The above equation source is Wonnacott et. al., (1977)

Using equation (4) above, we have

Table 4. Approximate values of some lava flows from the 1909 – 1999 eruptions

Year of eruption	Average length of lava flow (km)	Average width of lava flow (m)	Surface area (ha)	Uniform average thickness (m)	Estimated volume in million of m^3
1909	8km	39.4	315	3	10
1922	9km	1570	1377	3	41
1959	8km	460	368	3	11
1982	7km	47.6	333.3	3	10
1999	9km	760	684	3	21

(Adapted from Zogning 1999)

Table 5: Authenticated years of eruption (yrs), Time interval between eruption (yrs) X, Estimated volume of lava emitted in million of m^3 Y, Cumulative estimated volume of lava emitted in million of m^3 and mean deviation

Authenticated years of eruption (yrs)	Time interval between eruption (yrs) X	Estimated volume of lava emitted in million of m^3 Y	Cumulative estimated volume of lava emitted in million of m^3	$X = X - \ddot{X}$	XY	X^2	$\hat{Y} = a + bx$	$Y - \hat{Y}$	$(Y - \hat{Y})^2$	Cumulative $\hat{Y}$ in million of m^3
1909	0	10	10	0 – 18 = - 18	-180	324	21.92	- 11.92	142.1	21.92
1922	13	41	51	13 – 18 = -5	-205	25	19.45	21.55	464.4	41.37
1959	37	11	63	37 – 18 = 19	209	361	14.89	-3.85	14.8	56.26
1982	23	10	72	23 – 18 = 5	50	25	17.55	-7.55	57	73.81
1999	17	21	93	17 – 18 = -1	-21	1	18.69	2.3	5.25	92.5
*2017	18	10	103	18 – 18 = 0	0	0	17.2	-7.2	51.84	109.7
	$\sum X = 108$	$\sum Y = 103$		$\sum X = 0$	$\sum XY = -147$	$\sum X^2 = 736$			$\sum(Y - \hat{Y})^2 = 735.35$	

$1/n\sum X = \ddot{X}$
$\ddot{X} = 108/6$
$\ddot{X} = 18$

$1/n \sum Y = \bar{y}$
$\bar{y} = 103/6$
$\bar{y} = a$
$a = 17.2$

$b = \sum XY/\sum X^2$
$b = -147/736$
$b = -0.19$

$S^2 = 1/n\text{-}2 \sum(Y - \hat{Y})^2$
$S^2 = 1/6 - 2 = 735.35$
$S^2 = 735.35/4 = 183.8$
$S^2 = \sqrt{183.8}$
$S^2 = 13.5$

Table 6. t-distribution values (source Wonnacott et al., 1977)

Pr/d.f.	0.25	0.10	0.05	0.025	0.010	0.005	0.0025	0.0010	0.0005
1	1.000	3.078	6.314	12.706	31.821	63.637	127.32	318.31	636.62
2	0.816	1.886	2.920	4.303	6.965	9.925	14.089	22.326	31.598
3	0.765	1.638	2.353	3.182	4.541	5.841	7.453	10.213	12.924
4	0.741	1.533	2.132	2.776	3.747	4.604	5.598	7.173	8.618
5	0.727	1.476	2.015	2.571	3.365	4.032	4.773	5.893	6.869
6	0.718	1.440	1.943	2.447	3.143	3.707	4.317	5.208	5.959
7	0.711	1.415	1.895	2.365	2.998	3.499	4.020	4.785	5.408
8	0.706	1.397	1.860	2.306	2.896	3.355	3.833	4.501	5.041
9	0.703	1.383	1.833	2.262	2.821	3.250	3.690	4.297	4.781
10	0.700	1.372	1.812	2.228	2.764	3.169	3.581	4.144	4.537
11	0.697	1.363	1.796	2.201	2.718	3.106	3.497	4.025	4.43
12	0.695	1.356	1.782	2.179	2.681	3.055	3.428	3.930	4.318
13	0.694	1.350	1.771	2.160	2.650	3.012	3.372	3.852	4.221
14	0.692	1.345	1.761	2.145	2.624	2.977	3.326	3.787	4.140
15	0.691	1.341	1.753	2.131	2.602	2.947	3.286	3.733	4.073
16	0.690	1.337	1.746	2.120	2.583	2.921	3.252	3.686	4.015
17	0.689	1.333	1.740	2.110	2.567	2.898	3.222	3.646	3.965
18	0.688	1.330	1.734	2.101	2.552	2.878	3.197	3.610	3.922
19	0.688	1.328	1.729	2.093	2.539	2.861	3.174	3.579	3.883
20	0.687	1.325	1.725	2.086	2.528	2.845	3.153	3.552	3.850
21	0.686	1.323	1.721	2.080	2.518	2.831	3.135	3.257	3.189
22	0.686	1.321	1.717	2.074	2.508	2.819	3.119	3.505	3.792
23	0.685	1.319	1.714	2.069	2.500	2.807	3.104	3.485	3.767
24	0.685	1.318	1.711	2.064	2.492	2.797	3.091	3.467	3.75
25	0.684	1.316	1.708	2.060	2.485	2.787	3.078	3.450	3.725
26	0.684	1.315	1.706	2.056	2.479	2.779	3.067	3.435	3.707
27	0.684	1.314	1.703	2.052	2.473	2.771	3.057	3.421	3.690
28	0.683	1.313	1.701	2.048	2.467	2.763	3.038	3.408	3.674
29	0.683	1.311	1.699	2.045	2.462	2.756	3.038	3.396	3.659
30	0.683	1.310	1.697	2.042	2.457	2.750	3.030	3.385	3.646
40	0.681	1.303	1.684	2021	2.423	2.704	2.971	3.307	3.551
60	0.679	1.296	1.671	2.000	2.390	2.660	2.915	3.232	3.460
120	0.677	1.289	1.658	1.980	2.358	2.617	2.860	3.160	3.373
∞	0.674	1.282	1.645	1.960	2.326	2.576	2.807	3.090	3.291

Pr = Cumulative probability or significance level
d.f. = degree of freedom

$= \hat{Y}_o \pm t_{0.025} \times S \sqrt{1/n + X^2_o/\sum X^2}$
$= 17.2 \pm 2.776 \text{ X } 13.5 \sqrt{1/6 + 0^2/736}$
$= 17.2 \pm 6.246$

The predicted confidence interval is given by the years 2000 and 2022. This extrapolation falls in line with the recent eruption of May 28, 2000 barely fourteen months after the March – April 1999 eruption. Although, it may be earlier or later in time and the lava volume may be more or less since extrapolation values are considered to be approximate values.

SUMMARY AND CONCLUSION

In most seismically active zones of the world where volcanic eruption predictions are not made, the devastation from these naturally occurring phenomenon are sometimes quite enormous. The damages to property run into millions of dollars and loss to human lives are in hundreds of thousand.

This study has attempted to predict the time the next volcanic eruption may occur in Mount Cameroon using geostatistical approach. The results of the study show a general increase in the rate of occurrence and a lack of trend linkage with time for the Mount Cameroon eruptions. The predicted confidence interval for the next volcanic eruption in Mount Cameroon is 2022. This eruption, however, might come earlier or later and the lava volume that will be emitted might be more or less since the predicted values are approximations. The important lesson the relevant authorities in both Cameroon and Nigeria should learn from this study is that countries must put in place mitigation strategies that will obviate the loss to human lives and properties should in case this natural disaster occurs.

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