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The nature and chronostratigraphy of Quaternary pyroclastic accumulations from Lake Barombi Mbo (West-Cameroon)

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ABSTRACT

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The K/Ar dating of a limburgitic flow indicates that the Barombi Mbo maar was active a million years ago. The morphology of the maar and the unusual high K_2O/Na_2O ratio of the limburgite suggest either that this age is too old or that this flow is not the last activity of the maar. Twenty three meters of sediments were cored from the bottom (core BM6) of the 110-m-deep lake which currently fills the maar. They are composed of clayey and sideritic laminae with interstratified ash layers in the lower half of the core. These ashes, composed of slightly vesiculated sideromelane with olivine and labradorite phenocrysts, have been dated between 21,000 and 11,000 yr. B.P. They show no alteration and correspond to aerial fallout of alkaline (sodic) basaltic affinity, which is common in the area, but are distinct from the mafic magmas which generated the maar. The origin of the tilting and uplifting of a 1.5-m sedimentary column in the lower part of the core remains controversial. Holocene-age pyroclastites are rare and consist of a mixture of granulitic xenocrysts and typically transitional tachylite similar to volcanics from the northeast (Manengouba). Magnetite microspherules occurring in Holocene layers have no volcanic equivalent. They could be related to biogenic or pedogenetic processes induced by more humid climatic conditions.

Introduction

The Cameroon line is a major structural feature of Central Africa. This still active volcano-tectonic ridge contains numerous lakes of volcanic origin, the largest of which is Barombi Mbo. The lake (4° 39′ 45′′ N and 9° 24′ 15″ E) is situated near the town of Kumba, approximately 60 km northeast of Mount Cameroon and 30 km southeast of Roumpi Mounts. Within the framework of research on Quaternary paleo-environments of the African tropical rain forest, a series of cores was extracted from the Barombi Mbo lacustrine sediments (Maley et al., 1990). Radiocarbon dating downcore on the total (mineral+organic) carbon fraction of the sediments combined with paleomagnetic curves provide a tightly constrained chronological scale for the layers of ash which the sediments contain.

Like Lake Monoun and Lake Nyos, situated about 200 km to the northeast, Lake Barombi Mbo occupies a maar, a crater resulting from phreatomagmatic explosions. The tragic consequences of the recent CO_2 outburst at Lake Monoun (August 1984) and Lake Nyos (August 1986) (Sigurdsson et al., 1987; Tazieff,

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1989; Sigvaldason, 1989; Barberi et al., 1989) underscore the importance of further analysis of lacustrine sediments and of the recent volcanic activity of this region.

Geological framework

The southern part of the "Cameroon line" consists of the Oku, Bamboutos, Roumpi, Manengouba, and Mount Cameroon volcanic massifs, which stretch along a zone of NE–SW-oriented fractures. The line extends into the ocean along the same trend with the volcanic islands of Bioko (formerly Fernando Po), Principe, Sao Tome and Annobon, as well as numerous seamounts (Fig.1) (Gèze, 1943; Cornacchia and Dars, 1983; Fitton and Dunlop, 1985). The absence of systematic age variation along this ridge is at variance with the hypothesis of its formation resulting from hotspot activity, following the Morgan model (Cornen and Maury, 1980; Morgan, 1981; Fitton and Dunlop, 1985). Indeed, Mount Cameroon remains active whereas a recent northeastward shift of explosive activity is reported in this paper.

We owe to Gèze (1943) the definition of three successive volcanic series in the continental domain: a basaltic "lower black series" of Tertiary age; a trachy-phonolitic "medium white series", probably of Neogene age; and a basaltic "upper black series" of Quaternary to very recent age.

The study region to the northeast of Mount Cameroon is composed of basalts of the upper black series which blanket the granito-gneissic substratum (Fig. 1) (Dumort, 1968). Barombi Mbo lake fills the easternmost recent crater of a succession of three coalescing maars, the oldest one being in the west. These structures belong to the upper black series. The 8 km^2 and flat bottom second crater forms part of the catchment area of Barombi Mbo lake. Owing to the amount of granito-gneissic pebbles in the streams of this second crater, it seems likely that the crystalline basement is directly below the surface (Maley et al.,1990).

The lake, whose surface has an altitude of 301 m, has an approximate diameter of 2 km, and a maximum depth of 110 m. It is drained by a steep-sided outlet stream situated to the southeast (Fig.2).

The walls of the youngest crater rise about 100 m above the lake level, they are entirely volcanic and show two similar series of basaltic tuff lapilli separated by a palaeosol. The upper series contains peridotite nodules and has tree moulds at its base (Gouhier et al., 1974). Fragments of peridotite nodules and gneissic xenoliths are widespread. The low-angle, stratification of the tuffs, which is either sub-horizontal or dips 10–15° towards the lake (Gèze, 1943), characterizes this structure as a tuff-ring (Lorenz, 1973). Finally, on the northeast shore, a much younger (Gèze, 1943) and short prismatic lava flow cropping out of the bottom of the internal wall has spread toward the maar center: its distal part is submerged beneath the lake's waters (Fig. 3).

Sampling conditions and research methods

The coring operations were conducted from a catamaran-type floating platform, 6×6 m in size, which was anchored in the middle of the lake. The piston corer used was made by D.A. Livingstone and operated by himself and his staff (G. Kling, C. Stager, J. Maley, P. Nduni and A. Zogning). The corer was composed of a series of 3-m-long steel shafts, 56 mm in interior diameter, which was manipulated with the help of a derrick and a winch. This study concentrates on the longest of the cores: BM6, 23.5 m long, extracted in the center of the lake, under 110 m water depth (Figs. 2 and 3). The BM6 core consists entirely of laminated sediments, the thickness of each lamina being more often less than a centimeter. Each sampled section was of the order of 10 cm. Complementary samples of particular laminae or parts of lamina were studied in more detail. Sedimentological and palynological studies are pre-

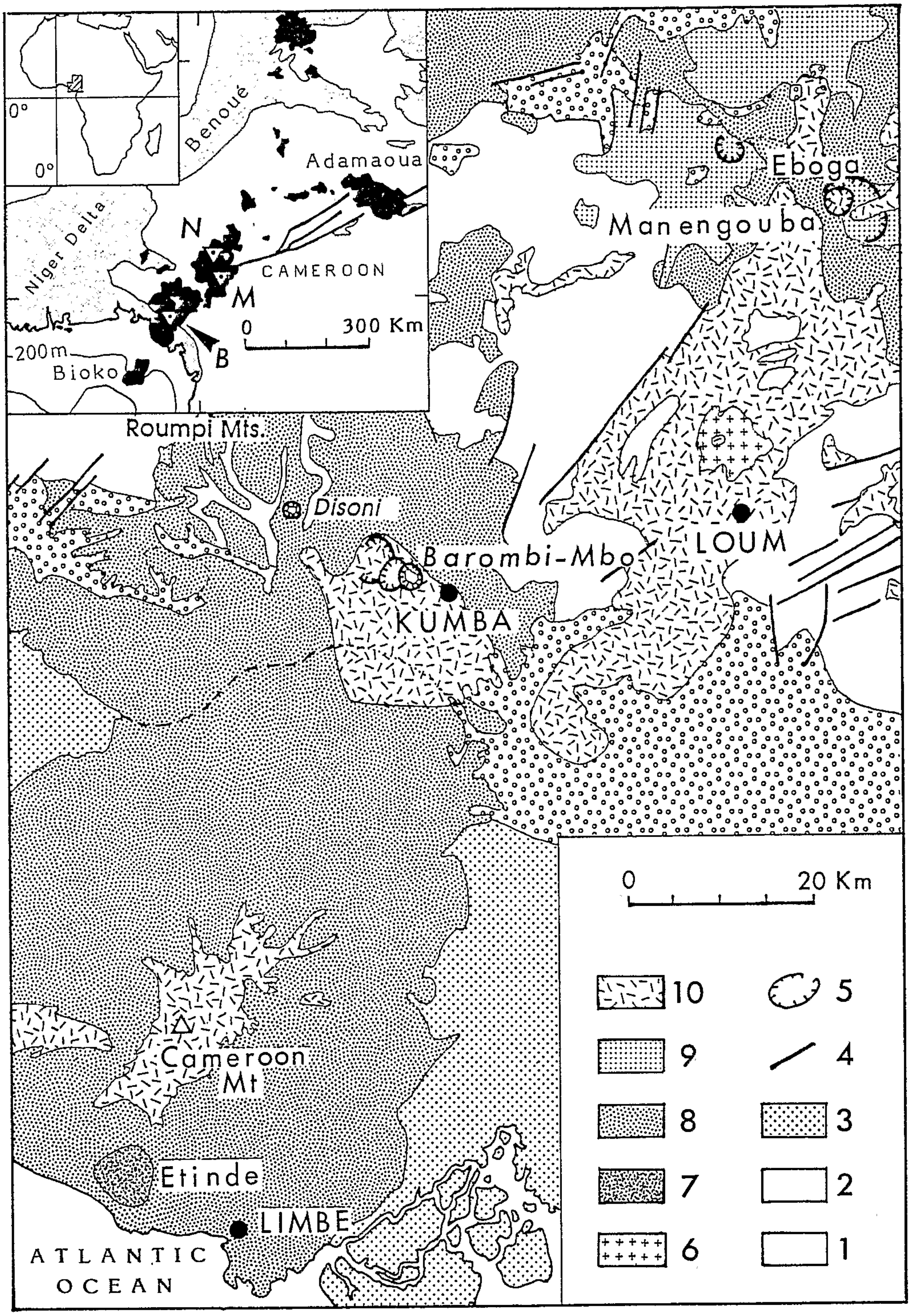

Fig. 1. Geological map, simplified from part of the 1:500,000 map of Dumort (1968.) *1*=crystalline basement; *2*=Cretaceous sediments; *3*=Cenozoic sediments; *4*=fault; *5*=maar and caldeira; *6*=Tertiary syenite of Mont Koupé; *7*=foidic lavas from Etinde; *8*=basalts of the "Lower Black Series"; *9*=trachytes; *10*=recent basalts of the "Upper Black Series". Inset: Position of the Cameroon line in Africa (top left). In black, volcanic ridge (Miocene to the Present), from West Cameroon to Adamaoua; stippled: Benoué trench and Niger delta. Pointed triangles situate the approximate positions of lakes Nyos (*N*), Monoun (*M*), and Barombi Mbo (*B*).

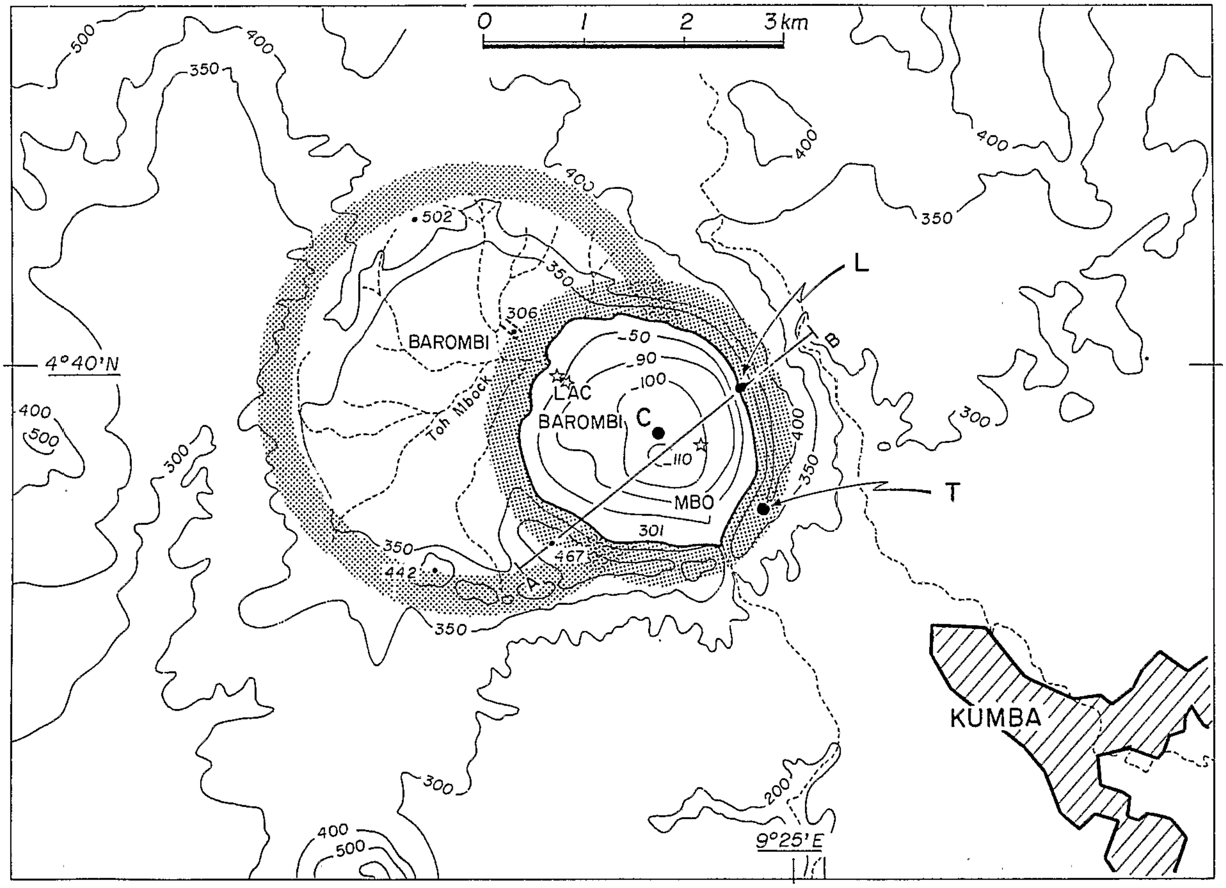

Fig. 2. Schematic map of Lake Barombi Mbo area, adapted from 1:50,000 map (sheet Douala-Buea 3b/NB 32-IV-3b; I.G.N., Paris). Elevation in meters. Stippled: ring zones of the two most recent craters. Hachured: Kumba city area. C=location of the core BM6; L=flow of limburgite; T=sampling location of the maar tephra. Stars=situation of other cores. Line AB refers to the cross section of Figure 3.

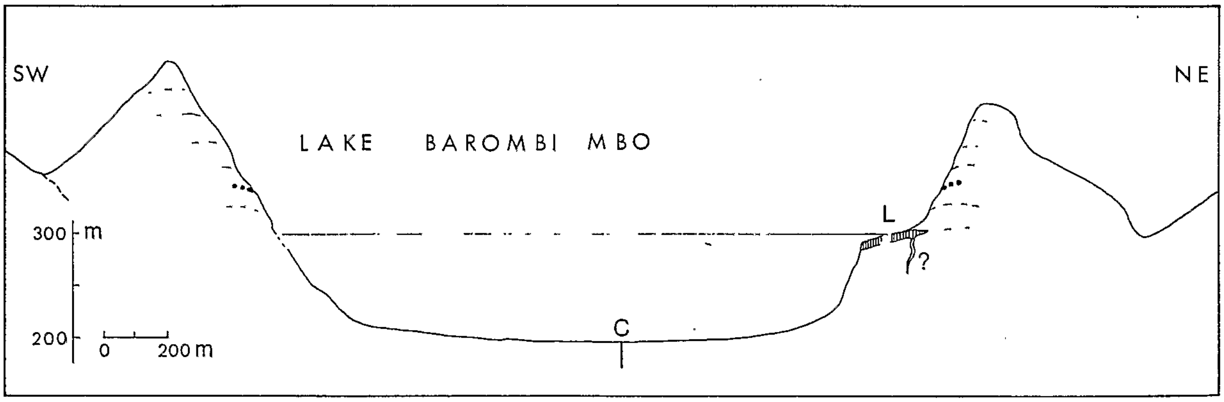

Fig. 3. Cross section along line AB of Figure 2 showing the limburgitic flow (L), the approximative situation of core BM 6 (C) and its length, the dip of the maar tephra and of the palaesol (dots). Cross section of the lake is after the sismic records of Kelts et al. (1986). Height and distances in meters.

sented elsewhere (Maley et Brénac, 1987; Maley, 1989; Maley et al., 1990; Giresse et al., 1991).

Petrology and dating of the maar

Maars are structures usually difficult to date. In this case, the lava flow can help to constrain the period of the supposed last volcanic activity of the Barombi Mbo.

This lava is dark, slightly vesicular and composed of olivine Fo_{82} phenocrysts, the rims of which are sometimes iddingsitized, and of homogeneous, non-oxidized titanomagnetite in a matrix of clinopyroxene microcrysts and abundant brownish glass, without feldspar (Tables 1 and 2). The few vesicles present are edged with a fine rim of devitrified groundmass. Finally, rare quartz xenocrysts edged with reaction rims are present.

Two samples were analyzed and dated. Minor alteration observed on the first is confirmed both by the loss on ignition of the chemical analysis and by the near-saturation in normative silica that is inconsistent with modal mineralogical composition. This minor altera-

TABLE 1

Whole-rock chemical analyses and norm of samples from the limburgite lava flow (1 and 2), of ashes from the Loum volcano (3) and ash layers from the BM6 core (4–8). The negative references correspond to levels on the core. [Mg] = Mg/(Mg + Fe_{total} + Mn) in atomic proportions (CRPG analyses, Nancy).

Ref	1	2	3	4	5	6	7	8
	limburgite		ashes					
	MBO.1	MBO.3	ScLoum	−12.8	−12.9	−15.4	−15.8	−17.25
SiO_2	41.63	40.31	48.71	47.10	46.50	44.30	44.50	45.10
TiO_2	3.45	3.65	2.81	3.13	3.15	3.19	3.16	3.57
Al_2O_3	12.41	13.17	15.38	16.80	16.93	15.15	14.61	16.30
Fe_2O_3	14.65	14.86	12.93	12.50	12.50	13.00	13.10	13.50
MnO	0.23	0.20	0.15	0.25	0.21	0.16	0.17	0.38
MgO	9.06	9.25	6.40	5.54	5.21	8.28	8.72	5.81
CaO	10.27	11.17	8.33	7.91	7.27	9.74	9.88	8.14
Na_2O	1.54	1.51	2.91	4.90	4.50	3.40	3.30	3.90
K_2O	1.61	1.87	0.85	1.50	1.50	1.10	1.10	1.30
P_2O_5	0.97	1.10	0.44	0.62	0.63	0.61	0.58	0.49
L.O.I.	4.35	2.51	0.82					
Total	100.17	99.60	99.73	100.25	98.40	98.93	99.12	98.49
Qz								
Or	10.04	11.50	5.13	8.92	9.09	6.64	6.62	7.88
Ab	12.94	4.30	25.14	25.37	28.67	17.22	16.85	24.29
An	23.42	24.61	26.96	19.56	22.14	23.31	22.23	23.74
Ne	0.44	4.87		8.87	5.63	6.58	6.28	5.18
Wo	10.15	11.00	5.26	6.80	4.62	9.33	10.12	6.15
En	6.03	6.59	2.87	3.62	2.41	5.64	6.18	3.25
Fs	3.61	3.83	2.20	2.97	2.08	3.19	3.38	2.72
En			12.09					
Fs			9.26					
Fo	12.46	12.19	0.92	7.20	7.64	10.80	11.18	8.13
Fa	8.21	7.80	0.78	6.50	7.27	6.74	6.74	7.49
Mgt	3.36	3.37	2.87	2.74	2.79	2.89	2.90	3.01
Ilm	6.91	7.22	5.45	5.99	6.14	6.19	6.12	6.96
Ap	2.43	2.72	1.07	1.48	1.53	1.48	1.40	1.19
D.I.	23.41	20.68	30.27.	43.16	43.39	30.43	29.76	37.35
[Mg]	54.86	55.08	49.42	46.43	44.99	55.68	56.75	45.48

TABLE 2

Selection of microprobe analyses of mineral (Camebax, 15 kV, 10–12 nA,). 1 and 2=olivine from the ashes at level −17.25 m; 3: olivine from the Loum ashes; 4, 5, 6=phenocrysts from the Barombi Mbo limburgite lava flow (sample no. 3), 4=olivine, 5=micropyroxene, 6=titanomagnetite; 7=roughly rolled titanomagnetite sampled in the outlet beach sand, 8=magnetite microsphere. Structural formulae calculated on the basis of 4 oxygens: olivine, 6 oxygens: pyroxene, 32 oxygens and 24 cations; magnetites. Al* corresponds to Al(IV) for no. 5 and to total aluminium for the others; Ca, Mg, Fe+Mn: atomic proportion; X'usp: ulvöspinel content calculated according to Stormer (1983)

Ref	1 Olivine	2	3	4	5 Pyroxene	6 Magnetite	7	8
	−17.25	−17.25	ScLoum	MBO.3	MBO.3	MBO.3	MBO.P	−4.05
SiO_2	39.59	39.69	38.80	40.42	42.48	0.07	0.05	0.56
TiO_2	0.0	0.07	0.0	0.01	4.91	17.14	9.41	0.07
Al_2O_3	0.0	0.03	0.10	0.05	9.67	7.35	6.71	0.11
Cr_2O_3	0.12	0.0	0.08	0.21	0.02	0.22	0.03	0.05
FeO	17.23	18.75	22.95	16.77	8.22	64.06	76.96	91.59
MnO	0.15	0.26	0.21	0.32	0.13	0.66	0.62	0.55
MgO	42.99	42.31	39.33	44.54	10.82	7.35	2.47	0.0
CaO	0.27	0.25	0.22	0.21	23.36	0.08	0.0	0.0
Na_2O	0.03	0.01	0.06	0.02	0.73	0.0	0.03	0.02
K_2O	0.04	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	100.42	101.37	101.75	102.34	100.34	96.93	96.28	92.95
Si	1.001	1.000	0.994	0.999	1.610	0.019	0.014	0.174
Al(IV)					0.390			
Al*	0.0	0.001	0.003	0.002	0.042	2.391	2.268	0.040
Ti	0.0	0.001	0.0	0.0	0.140	3.557	2.029	0.016
Cr	0.003	0.0	0.002	0.0	0.001	0.048	0.007	0.012
Fe^{3+}						6.409	9.654	15.582
Fe^{2+}	0.364	0.395	0.492	0.347	0.261	8.375	8.804	8.021
Mn	0.003	0.006	0.005	0.007	0.004	0.154	0.151	0.144
Mg	1.619	1.589	1.502	1.641	0.611	3.023	1.056	0.0
Ca	0.007	0.007	0.006	0.006	0.949	0.024	0.0	0.0
Na	0.002	0.0	0.003	0.001	0.054	0.0	0.017	0.012
K	0.001	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	3.000	2.999	3.007	3.003	4.062	24.000	24.000	24.001
Fo	81.51	79.86	75.16	82.28			0.314	0.002
X'usp								
Ca					51.99	0.526		
Mg					33.50			
Fe+Mn					14.52			

tion casts some doubt on the ages of 1.15 and 1.09 Ma obtained on this sample.

With 40.31% silica, 9.25% MgO, high levels of TiO_2 (3.65%) and P_2O_5 (1.1%), 5% normative nepheline and a lower L.O.I., the second sample is clearly a mafic alkaline lava, the mineralogical features of which correspond to a *limburgite* (Fig. 4). Microprobe analyses indicate that potassium is uniquely concentrated in the homogeneous and abundant glass of the groundmass, which does not appear, under the microscope, to have undergone any major alteration. The very marked potassic nature, indicated by the high K_2O/Na_2O ratios of the bulk analysis (1.0–1.2) and of the glass (i.e. 2.0) (Table 1, no. 2; Table 3, no. 7) (Fig. 5) is distinct from that normally recorded ($K_2O/Na_2O=0.5$) for basic lava of the region (Gouhier et al., 1974).

The dates obtained from the second sample

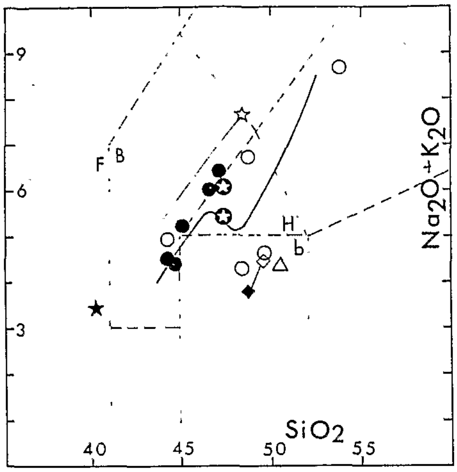

Fig. 4. Alkali/silica diagram for the volcanics of Barombi Mbo maar. Filled symbols = whole rock; open symbols = glass analyses. Tie lines join both analyses. Star = limburgite flow; ringed star = pyroclasts of the tuff-ring; circles = Pleistocene ashes of the lacustrine deposits; triangle = Holocene ashes; diamond = ashes from volcano near Loum. The coarse line separates Mount Cameroon and Mounts Roumpi volcanics (left side) from Manengouba lavas (right side) (adapted from Dunlop, 1983, and Nkoumbou, 1990). Dashed lines according to IUGS classification (Le Bas et al., 1986); *F* = foidite; *B* = basanite; *H* = hawaiite; *b* = basalt.

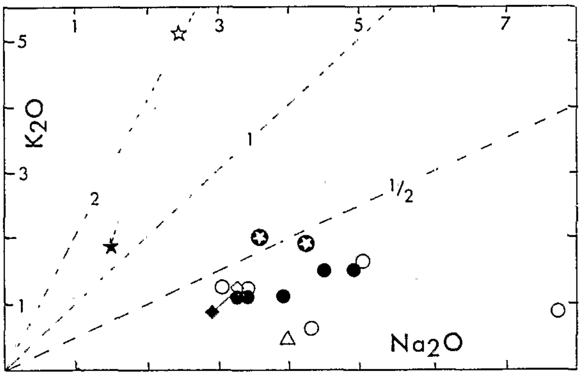

Fig. 5. Distribution of whole rocks and glasses in a K_2O/Na_2O diagram. Same symbols as in Fig. 3. The K_2O/Na_2O ratios of 2, 1 and 1/2 are indicated by dashed lines.

are quite similar to those of the first (Table 4). Both samples have potassium content of the same order (1.61 and 1.87 %K_2O), but, owing to their similar low radiogenic argon content, they are of equivalent low quality. Despite this fact, the coherence of the 4 measurements plotted on an isochron diagram with $^{40}Ar/^{36}Ar = f(^{40}K/^{36}Ar)$, is obvious (Fig. 6). It shows a straight correlation whose slope allows the calculation of this lava's isochron age. With the ordinate at the origin close to the reference value 295.5, the isochron age obtained is similar to the conventional age calculations: 1.05 ± 0.07 Ma, which strongly supports the first results. This extrusive volcanic activity of the maar would thus be not much older than the Quaternary.

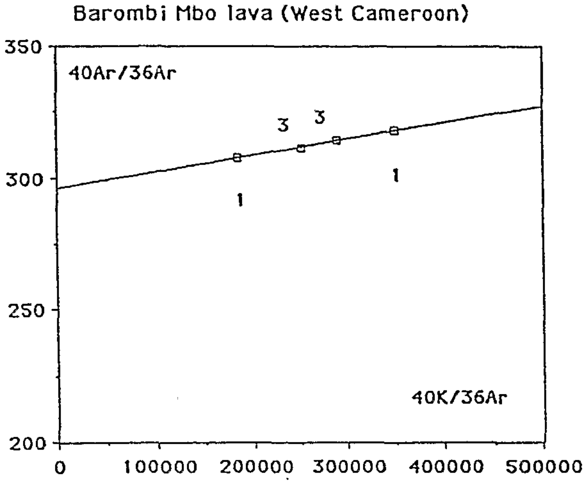

Fig. 6. $^{40}Ar/^{36}Ar$ versus $^{40}K/^{36}Ar$ isochron diagram of the samples 1 and 3 from the Barombi Mbo limburgite flow.

The tephra sampled from the east of the maar, near the top of the tuff-ring, show a very heterogeneous mixture of juvenile lapilli and substratum fragments. The more numerous fragments are identical to those taken in the brook (Toh Mbock) in the second crater to the west (Fig. 2) and consist of biotite-rich sillimanite gneiss, with occasional staurolite and garnet. The abundant plagioclase ranges from albite to oligoclase. The Barombi Mbo substratum is thus inferred to belong to the sillimanite zone of the "pelitic complex of the West" (Dumort, 1968). According to the few K/Ar datings (567 and 576 Ma) performed on this

TABLE 3

Micropobe analyses of plagioclases and glasses from the tephra and the lava flow. 1 and 2 = plagioclases from the ashes in BM6 core, level −17.25, 3 = plagioclases from the Loum volcano ashes; 4 to 8 glasses; 4 = glass from the ashes in BM6 core, level −17.25; 5 = idem, level −3.45; 6 = glass from the Loum volcano ashes; 7 = glass from the Barombi Mbo limburgite lava flow; 8 = lapilli from the Barombi Mbo tuff ring. K, Na, Ca by atomic proportions.

Ref	1 feldspar	2	3	4 glass	5	6	7	8
	−17.25	−17.25	ScLoum	−17.25	−3.45	ScLoum	MBO.3	MBO.T
SiO_2	52.10	51.84	54.70	48.34	50.50	49.57	48.45	47.26
TiO_2	0.59	0.10	0.05	3.70	2.66	3.72	1.19	3.94
Al_2O_3	27.22	29.57	28.57	14.52	14.80	14.53	22.50	14.51
Cr_2O_3	0.06	0.01	0.09	0.12	0.07	0.09	0.0	0.0
FeO	1.62	0.75	0.61	12.35	12.29	12.33	5.71	11.46
MnO	0.15	0.0	0.0	0.14	0.16	0.08	0.12	0.25
MgO	0.38	0.17	0.09	4.72	5.75	4.94	1.79	4.24
CaO	11.89	13.59	11.66	10.55	7.92	8.90	4.03	8.77
Na_2O	4.25	3.73	4.76	3.03	3.92	3.23	2.49	3.53
K_2O	0.40	0.20	0.24	1.26	0.43	1.23	5.07	1.95
Total	98.66	99.96	100.77	98.73	98.50	98.62	91.35	95.91
K	2.36	1.16	1.38	8.53	3.31	9.04	41.44	13.27
Na	38.36	32.80	41.89	31.30	45.69	36.03	30.90	36.54
Ca	59.28	66.04	56.73	60.17	51.00	54.94	27.66	50.18

TABLE 4

K-Ar dating of the Barombi Mbo limburgite lava flow. Analytical results obtained with a mass spectrometer A.E.I. MS 20, by isotopic dilution with argon 38 tracer. Tracer calibration with biotite USGS LP-6 Bio (sample 11-II-C4). The potassium decay constants used are those recommended by Steiger and Jäger (1977) and the conventional age errors are calculated with the formula of Cox and Dalrymple (1967)

Sample (ref.)	Weight (g)	K_2O (%)	$^{40}Ar^*/^{40}Ar^t$ (%)	$^{40}K/^{36}Ar$	$^{40}Ar/^{36}Ar$	conv. Age (Ma)	σ (Ma)
MBO.1	0.8090	1.61	4.0	182749	307.8	1.2	0.4
	0.8175	1.61	7.0	348026	317.7	1.1	0.2
MBO.3	1.0820	1.87	6.0	287966	314.4	1.0	0.3
	0.9550	1.87	5.0	249813	311.1	1.1	0.4

complex 40 km northwestward (Nkoumbou, 1990), it has a Pan-African age. Most of the lapilli have spherical shape and consist, for the most part, of vesiculated glass which has been palagonitized to various degrees. Vesicles are spherical sometimes ovoid and very rarely coalesce. When the lapilli are relatively unmodified, some rare olivine (Fo$_{82}$), plagioclase (An$_{61}$Or$_{1.4}$) and titanomagnetite crystals can be observed. Some non- palagonitized lapilli are wholly crystallized with dominant labradorite. Rare examples contain clinopyroxene and amphibole microcrysts. Finally, lapilli include frequently olivine, orthopyroxene, spinel or biotite xenocrysts. They result respectively from the break-up of peridotite nodules and of the gneissic basement.

The glass composition of the lapilli nearly devoid of crystals is considered to be representative of the whole rock and, thus, it can be compared to that of the limburgite whole-rock composition (Table 1, no. 2; Table 3, no.8).

The maar lapilli have higher SiO_2 (+5%), Al_2O_3 (+2%), Na_2O (+2%), lower MgO and CaO and similar K_2O contents (Fig. 5). Their $K_2O/Na_2O=0.5$ ratio appears to be consistent with that of the regional lavas. Therefore, the high K_2O/Na_2O ratio of the limburgite has to be explained.

Characteristics of the ash layers interstratified in the lacustrine deposits

Sedimentary environment

All of the 23.5-m-long BM6 core is composed of mm- to cm-thick laminae, consisting of dark brown to green clay and rich in organic material (5–10% organic carbon). Each lamina is composed of a lower micro-layer rich in quartz, feldspar, muscovite, pyroclasts, sponge spicules and woody plant fragments, and a more clayey upper micro-layer with yellow siderite crystals whose abundance determines the pigmentation of the deposit (from blue to yellow) (for more details see Maley et al., 1990; Giresse et al., 1991).

In the lower half of this core, 21 black ash layers have been counted. Between 21 and 22.5 m, the regular horizontal deposits are abruptly interrupted by a column with vertically oriented layers (Fig. 7). The laminated nature of these layers is exactly the same as above and beneath this part of the core. This laminated nature excludes a mass slide from the adjacent slopes where cores have shown very different facies: sediments from BM 9 cored under 32 m water depth are relatively coarse-grained mud with several brownish layers, those from BM 7 and BM8 (−59 m) are noticeably finer-grained, but also quite homogeneous. As shown by a series of new short cores, the limit of the extension of the deeper laminated sediments is generally near −90 m, that is to say close to the footslope.

The upper half of the core does not present distinct ash layers, volcanic elements are rare and dispersed in the sediments.

Pyroclast morphology and mineralogical composition

In the lower half of the core, black ash beds, with millimeter to centimeter thicknesses, records distinctive episodes of marked lacustrine sedimentation. The particles only rarely exceed 0.5 mm in diameter and are typically fine to coarse ash (Schmid, 1981). They comprise two types of pyroclasts:

(1) Particles of lava made up of slightly vesiculated glass, brownish in color when their thickness is less than 100 μm (sideromelane). Their shape is generally angular but numerous grains are broken droplets with bright surfaces and a clearly marked fluidal texture, rare shards have a palagonite skin. All have vesicles with thick walls, and contain few phenocrysts and no microcrysts (Fig. 8).

(2) Numerous crystals and crystal fragments of the same dimensions (0.5 mm maximum) as the lava particles occur in variable proportions. Phenocrysts and single crystals have identical composition : Fo_{80} olivines (Table 2, no. 1 and 2) and labradorite $An_{66}Or_1$ to $An_{59}Or_2$, rarely exceeding 0.2 mm (Table 3, no. 1 and 2; Fig. 9). These minerals are homogeneous, in equilibrium with the sideromelane and not altered. Pyroxene, opaque minerals and xenocrysts were not detected. The sole distinguishable difference between these ash layers, the greater or lesser abundance of the single crystals, olivine in particular, is not indicative of ashes from different origins. The absence of alteration, the homogeneous granulometry and the flat lamination indicate that the ash beds are direct volcanic fallout deposits.

Pyroclasts occur infrequently in the sandy fraction of the upper part of the core. They are composed of lava granules up to 0.5 mm maximum size and clustered or isolated crystals. The mineral fraction is composed of:

(1) olivine Fo_{82} in euhedral and unaltered crystals;

(2) plagioclases $An_{56}Or_1$ and $An_{63}Or_1$, in elongated and large crystals respectively. The

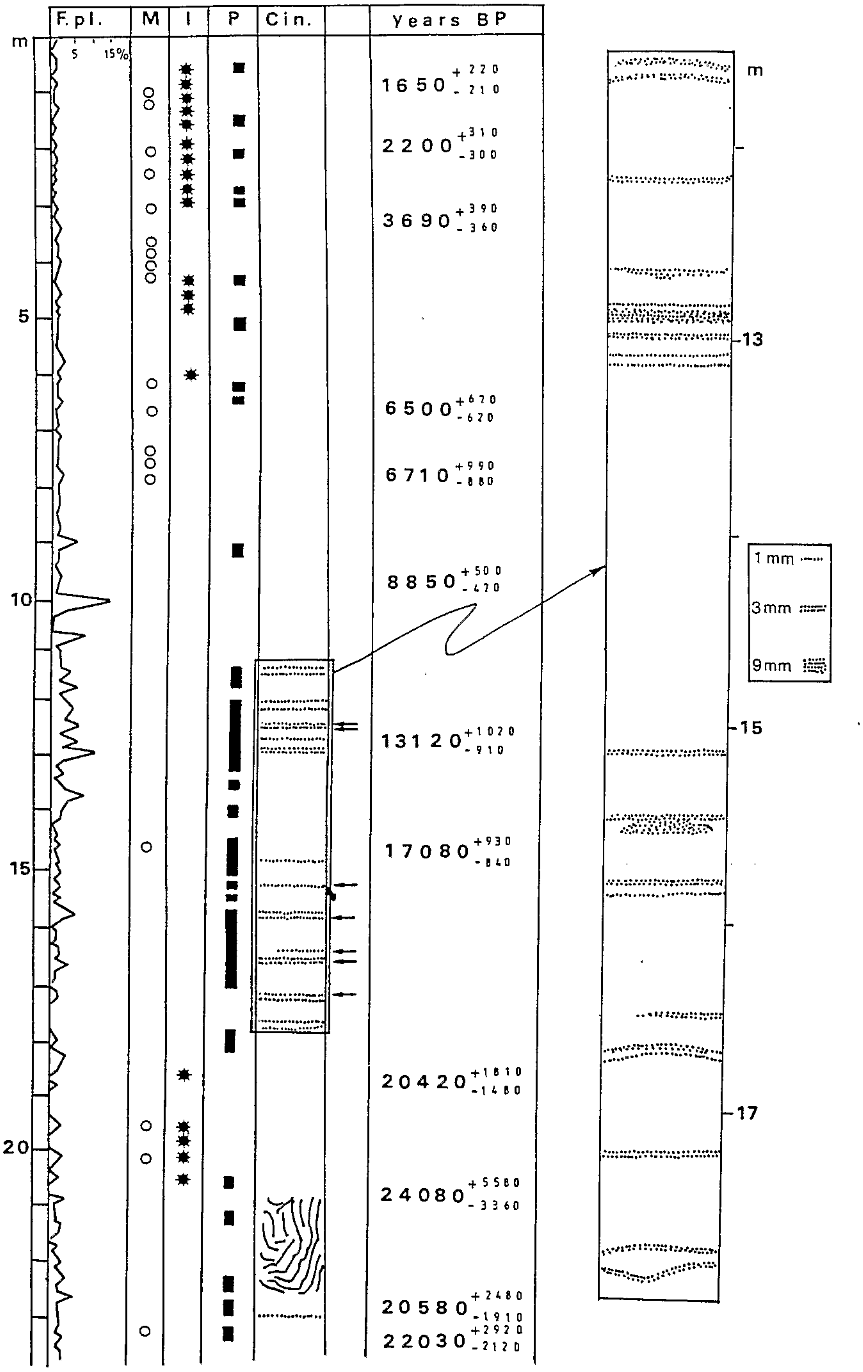

Fig. 7. Vertical distribution of plagioclases feldspars (F.pl.) (calibration by X-ray diffractometry), magnetite spheres (M), brown granules (I), vitreous pyroclasts (P) and ash layers (Cin) on scale of radiocarbon dates. Beneath 21.5 m, contorted lines indicate the laminae orientation in the tilted slab. The relative thicknesses of the observed ash layers are shown at the right of the figure.

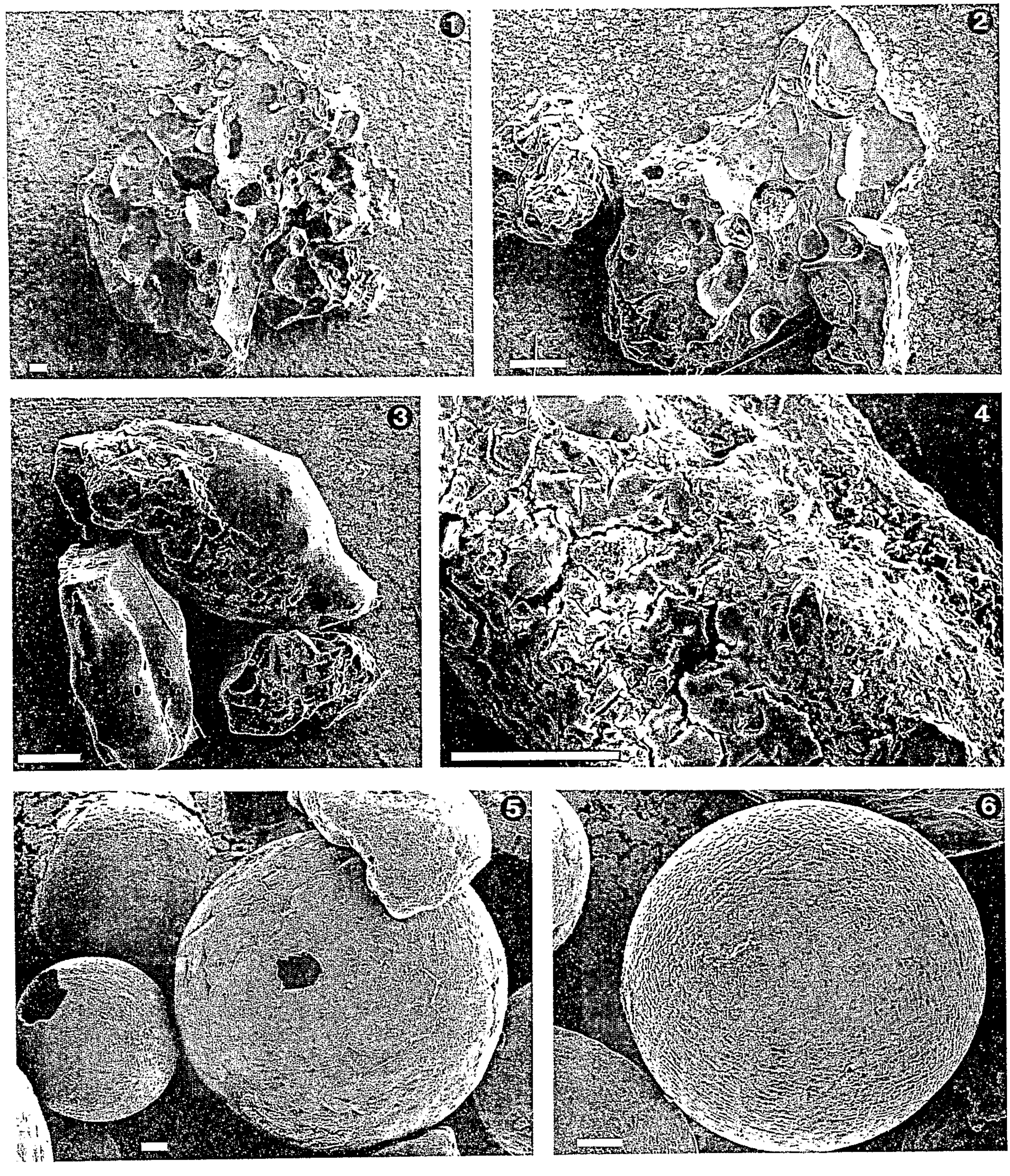

Fig. 8. SEM micrographs (secondary electrons, 15 kv acceleration-SMEB Nantes) of ashes and magnetite spheres. (1) vesiculated ash from strombolian volcano in the Loum vicinity; (2) one of the most vesiculated ash from the Pleistocene layers of the BM 6 core; (3) fluidal droplet from the same level; (4) detail of the palagonite skin of a shard in the same level; (5) and (6) magnetite sphere of the 4.05 m Holocene level showing hexagonal (5) and dentritic sutures (6). The scale bar represents 100 μm in 1, 2, 3, 4, and 10 μm in 5 and 6.

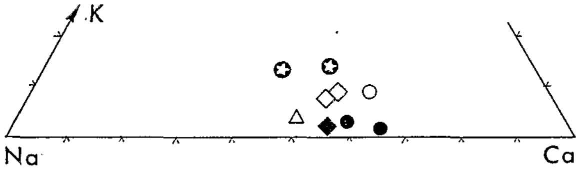

Fig. 9. Position of feldspars and glasses on a K-Na-Ca diagram (atomic proportions). Filled symbols = feldspar; open symbols = glass; ringed star = pyroclasts of the tuff-ring; circles = Pleistocene ashes of the lacustrine deposits; triangle = Holocene ashes; diamond = ashes from volcano near Loum.

latter locally have mechanical (lenticular) twins and are frequently broken;

(3) fragments of perthitic orthoclase; and

(4) clusters of large augite with schiller type inclusions and of brown hornblende and subordinate apatite. Few other clusters of actinolitic hornblende and titanomagnetite have also been observed.

The lava particles are highly vesiculated and most of them are almost entirely opaque because of the spotting by minute crystals including titanomagnetite and some Fe and Fe-Ni sulfides (tachylite). Some skeletal olivine Fo_{82} and plagioclases $An_{56}Or_1$, have been identified. These pyroclasts are interpreted to be vesiculated quench ashes also derived from direct fallout but their geochemistry and xenocrysts population clearly distinguish them from those of deeper levels.

The layers of the five meters at the top of the core exhibit orange to brown granules, and *magnetic black spherules*, which are absent or rare in the lower part of the core (Figs. 7 and 8). Though granules and spherules frequently occur in the same layers, no genetic link has been found between them. Most of these brown granules seem to result from diagenetic precipitation of kaolinite and ferruginous hydrates more or less cemented by siderite (Giresse et al., 1991). Some rare examples are clearly derived from fersialitic soil crust, whereas even others even rarer exhibiting oolithic texture, show Ni sulfide spherules up to 25 μm ($Fe_{4.1}Co_{4.0}Ni_{54.9}S_{37.0}$ wt.%).

Magnetic-black spherules, sized from 100 to 900 μm, are frequently hollow with several spherical, or one single offset, vacuoles. Their smooth and shiny external surfaces as well as the internal ones, usually show polycrystalline, sometimes dendritic, microstructure with hexagonal sutures (Fig. 8). The EDS spectra does not display any iron substitution and in particular, no detectable nickel or titanium content. A single spherule has a ferroan apatite crystal included. Microprobe analyses record low and constant manganese contents with only small amounts of silica (0–1% SiO_2) and aluminium (0.07–3.8% Al_2O_3). Calculations of stochiometric formulae do not indicate maghemitisation or hydration (Table 2, no. 8).

Chemical compositions

Five of the ash layers from the lower half of BM6 core were analyzed by absorption spectrometry (Table 1). All these analyses show great similarity. The total of weight oxides close to 100 are indicative of the low volatile contents of these ashes. Thus, they appear very different from the Barombi Mbo limburgite and the maar lapilli which are volatile-rich (Cl among others), as is usual for this type of lava. The high TiO_2, P_2O_5 and alkali content, the fairly high MgO (5–8%) and CaO (7 to 10%), and the moderate silica content (44–47%) of these ash layers show that they were produced by an alkaline, sodic ($K_2O/Na_2O = 0.3$) and slightly differentiated magma ($45 \leq [Mg] 56$, Ni = 75 ppm). In an AFM diagram (Fig. 10), these ash analyses show subtle iron enrichment trend, confirmed by microprobe analyses of their glass. With more than 5% normative nepheline and DI values between 30.1 (olivine-rich tephra levels) and 40.1, the norms are typical of basanitoid ($DI \leq 35$) and hawaiite ($35 \leq DI \leq 50$) magma types (Maury, 1976). Increasingly large normative nepheline contents in the glass are indicative of a trend towards greater silica under-saturation of the residual liquids.

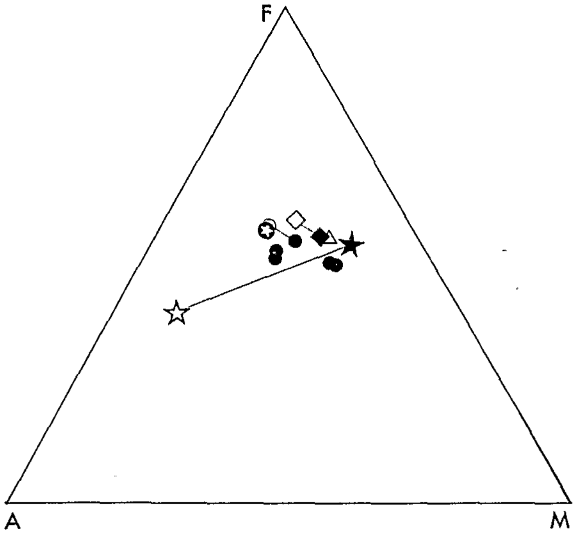

Fig. 10. Position of volcanics from Barombi Mbo maar on an AFM diagram (A: Na_2O+K_2O, F: $FeO_{total}+MnO$, M: MgO). The dashed line joins the whole rock to its glassy counterpart. Filled symbols = whole rock; open symbols = glass analyses. Star = limburgite flow; ringed star = pyroclasts of the tuff-ring; circles = Pleistocene ashes of the lacustrine deposits; triangle = Holocene ashes; diamond = ashes from volcano near Loum.

In the upper part of the core, the fresh vesiculated quench ashes, are particularly poor in potassium (0.43% K_2O) and quite rich in silica (50.5 %) (Table 3, no. 5). Their DI value of 36.2 and 14% normative hypersthene are indicative of transitional magmas clearly distinct from the more calcic, magnesian and potassic maar lapilli.

Chronostratigraphy

The 23.5 m of the BM6 core correspond approximately to sediments accumulated during the last 25,000 years. Radiocarbon dating was performed on the total carbon of the sediment (organic carbon+siderite carbon) by M. Fournier (ORSTOM, Bondy). At about −10 m a comparative dating of neighbouring levels was conducted, using the total carbon on the one hand (8480, +400, −420 yr. B.P.) and the carbon linked to organic matter on the other (after destroying the siderite) (8850, +500, −470 yr. B.P.). This demonstrates that the organic carbon results were 5% older. Since the planktonic production of the lake is very low, the main source of organic matter comes from the catchment basin feeding the lake. For this reason, the age difference is probably an expression of the average residence time of the organic material in the A2 horizons of catchment soils before erosion and subsequent accumulation in the lacustrine sediments. A bias towards older radiocarbon ages is again apparent when we compare the accumulation rate calculated using radiocarbon dates (Maley et al., 1990) to that calculated with the secular paleomagnetic variation curves (Thouveny and Williamson, 1988), it can also be attributed to this pedogenetic residence time (Giresse et al., 1991). These measurements lead us to conclude that the carbon which took part in the siderite authigenesis (10–20% of the deposit) is mainly organic in origin. If the CO_2 which contributed to the formation of the siderite had been magmatic in origin (i.e. with "dead carbon" component), the dates based on the carbon isotopes would have given aberrant ages, without stratigraphic correlation, as in the case of the carbonates sampled from the bottom waters of Lake Monoun and dated at 18,000 yr. B.P. (Sigurdsson et al., 1987).

On this chronological basis we can calculate that the rate of sedimentation is between 13 and 46 g cm^{-2} 10^{-3} years, with higher sedimentation occurring in the first half of the Holocene. The periodicity of the laminae is in the range of 15–19 years, and corresponds to the major floods of the Toh Mbock river which drains the catchment of the second crater.

If we disregard the 1.5 m of sediments uplifted between 21 and 22.5 m, the ash deposits – and their emission – took place between approximately 21,000 and 10,000 yr. B.P. and thus, taken as a whole can be ascribed as Pleistocene. No regular periodicity is apparent in these deposits which follow one another at 10 to 1000 years intervals. A greater frequency of pyroclastic deposits is however apparent between 20,000 and 17,000 yr. B.P. and between 13,000 and 11,000 yr. B.P. The semi quantitative distribution curve of plagioclase feldspar in the sediment (Fig. 7) follows the ash frequency and shows a significant decrease at Holocene levels (from 9000 yr. B.P.). It marks, with a shift of one to 2 millennia, the episodes of ash fall on the catchment. This shift suggest a flux of particulate material throughout the beginning of the Holocene, before a period of forest and soil development in the drainage basin. This period of pedogenesis favored the formation of kaolinite which is six times more abundant in the clay spectrum than during Pleistocene times. The rare pyroclast-bearing levels found in the Holocene sediments of the upper part of the core, indicate a more discrete or a distant explosive activity, insufficient for the production of very distinct ash layers.

Discussion

Age and sedimentation rate

An empiric relationship established mainly on recent European maars indicates they have a diameter/depth ratio ranging from 10 to 5 (Dr. Camus, pers. commun., 1991). The lake surface is at the mean altitude (300 m) of the area. Consequently a maximum depth of 200–400 m would be predicted based on the 2-km diameter of the Barombi Mbo maar and, deducting the present water depth, the thickness of the sediment deposit would be about 100–300 m. To reconcile this estimation with a volcanic activity aged at 1.05 Ma implies some variation in the sedimentation rate in the lake before the last 25,000 years during which it reaches an average near 1 mm/year (as in recent European maars). But, a sedimentation rate as low as the average of 0.3 mm/year for a period of 1 Ma seems unrealistically low and it would be even more critical if it is assumed that the lake was existing before the limburgite extrusion, 1.05 Ma ago. Other explanations to this discrepancy would be:

(1) The 1.05 Ma aged lava postdates the first phreatomagmatic activity of the maar sealed by the palaeosol dipping toward the lake, and this flow has not been entirely blown up during the following explosive phase.

(2) The limburgite has been contaminated during the intrusion of the lava. Indeed the maar tephra, lapilli included, carry a great amount of biotite derived from the pan-African gneissic basement. A small fraction of the remelted tephra mixed with magmas "en route" would affect Si, K contents and age, However, the fact that both maar lapilli and limburgite have similar K_2O contents rules out this hypothesis.

(3) The major change between maar lapilli and limburgite involve Na_2O, Al_2O_3, SiO_2 and CaO the ratios of which coincide with that of albite-oligoclase feldspars. Thus, a process of selective (gaseous ?) transfer would tentatively explain the sodium loss and consequently the production of K-rich limburgite from more "normal" basaltic magmas.

Origin of the ashes

Different types of magmas have been identified by Dunlop (1983) among the main volcanic massifs of southwest Cameroon. The mineralogy and the high magnesian and calcic features coupled with the high alkali contents of the limburgite and the maar lapilli, are consistent with the characters of Mount Cameroon lavas or of basaltic last sequence of the Roumpi Mounts (Nkoumbou, 1990).

In the lacustrine sediments from the lower part of the core, ash layers, mainly composed of weakly vesicular sideromelane, would be indicative of ashes produced by hydroclastic eruptions. The absence of any xenocrysts, the very weak palagonitization as well as the fluidal shape of some droplets would imply brief and intense phreatomagmatic episodes at low depth and likely in previous volcanic structures (Lorenz and Zimanowski, 1984; Heiken and Wohletz, 1985). The alkali/silica ratios of the ash layers are similar to those of the Mount Cameroon lavas but the latter are distinctly more calcic for comparable magnesium contents and they are pyroxene-bearing (Dunlop, 1983; Deruelle et al., 1987). The last series of lavas from Roumpi Mounts also contain pyroxene phenocrysts, but their whole-rock compositions are much closer. Unfortunately, no information about tephra of this sequence is available. The ashes sampled on a small recent strombolian volcano situated near Loum, 25 km to the east, and the lacustrine pyroclastic deposits also reveal similar features (Table 1, no. 3; Table 2) (Figs. 5 and 8). Although ashes of Loum volcano appear to be more vesicular, olivine phenocrysts are slightly more ferriferous (Fo_{75}) and plagioclases as well as the glass are slightly more sodic. Both these Loum tephra and the ashes from the Barombi Mbo lacustrine deposits show similar indication of low volatile contents: whole-rock analyses have low L.O.I. and glasses analysed by microprobe present a total of weight oxides close to 100. However, for similar silica content, and besides few glass analyses, the ashes from the lacustrine deposit show higher alkali contents than the tephra of Loum volcano which belong to the Manengouba volcanics (Fig. 4). The ashes of the lake deposits have features intermediate between typical Mount Cameroon and Manengouba lavas. They are probably aerial ejecta related to phreatomagmatic episodes of the neighbouring strombolian volcanoes or even to other maar like that occupied by the lake Disoni, 15 km northwestward, and belonging to the Mounts Roumpi sector (Gèze, 1943).

In the upper part of the core, the transitional nature of the ashes appears similar to the Manengouba lavas (Dunlop, 1983). These ashes, and the xenocrysts occuring with them, have not been observed in the ejecta of Mount Cameroon (Deruelle et al., 1987) or in those of the nearest volcanoes. Moreover, the association of mechanically twinned labradorite, perthitic orthoclase, schillerized clinopyroxene and brown hornblende is typical of catazonal crustal levels which are not represented in the close surroundings. The nearest catazonal formation is partly overlain by the Manengouba massif where the caldera of Eboga, about 65 km northeast of Barombi Mbo, was still active until very recently and is known to have produced gabbro enclosures (Dunlop, 1983). Therefore this association would represent either ejecta of small strombolian eruptions of the nearby volcanoes of Manengouba massif (i.e. those of Loum area), where the distribution of deep crust xenocrysts has yet to be identified, or they are from the most recent volcanoes of Eboga.

Origin of the magnetic spherules

Magnetic spherules have been described in several environments, usually characterized by their reducing conditions and often by their high iron and carbon contents i.e. deep sea sediments (Jedwab, 1970 ; Freeman, 1986), limestone or biodegraded oil (McCabe et al., 1987; Mc Whinnie et al., 1990). Magnetic spherules have also been observed by one of us (P.G.) in the very recent deposits of lakes Bambuluwe, Doube and Wum and infrequently in the soils of the top of the tuff-ring or in the beach sand of the Barombi Mbo lake. Though industrial pollution cannot be strictly excluded in these cases, such a pollution is improbable in the core since spherules occur in layers aged up to 6500 yr. B.P. A volcanic origin for the spherules is ruled out since, as can be seen in the literature and in Table 2 (analyses 6, 7 and 8) volcanic magnetite is always titanium-bearing or, in volcanic sublimates, shows Ni and Cr substitutions (Toutain et al., 1985). These magnetite spherules are often related to micrometeorites more or less modified by melting during atmospheric entry (Jedwab, 1970; Brownlee et al., 1984). But the request of successive falls of similar extraterrestrial dust in the area seems questionable. The great resemblance of magnetite spherules with fire or industrial products (Heiken and Wohletz, 1985) suggest that they could be produced by the reduction of goethite from ferruginous soils during savanna or forest fire (Schwertmann, 1988). Since no charcoal particles have been detected in the sediments layers bearing magnetite spherules, this hypothesis has to be ruled out. On another hand a biogenic origin is often ascribed to similar spherules in several carbon-bearing sediments (McCabe et al., 1987; McWhinnie et al., 1990). Indeed, but at a different scale, ultrafine-grained magnetite is known to be produced both in biogenic under anaerobic conditions (magnetotatic bacteria in particular, generates crystals with hexahedroid morphology), and chemical ways during pedogenic processes involving carbon rich soils (Lovley et al., 1987; Bazylinski et al., 1988; Maher and Taylor, 1988; Stolz et al., 1990; Fassbinder et al., 1990). Such an hypothesis of authigenic origin is attractive but the link between ultrafine grained magnetite and spherules has yet to be proved.

Conclusions

The 23.5 m of sediments cored from the center of the Barombi Mbo crater lake represent only a fraction of the total accumulation of lacustrine deposits likely to reach up to 300 m. The activity of this lake as a catchment collector is probably younger than a million years. This age is that of a small limburgitic flow which was supposed to be the last volcanic activity of the maar. This limburgite and the maar lapilli have affinities, with Mount Roumpi lavas. Compared to the maar lapilli, the unusually high K_2O/Na_2O ratio of the limburgite is tentatively related to a secondary and selective loss of sodium.

The plagioclase feldspar content of the lacustrine sediments correlates with the ash layers interstratified in these deposits.

From 21,000 to 11,000 yr. B.P., the accumulation of unaltered glassy particles, particularly in the lower micro-layers of the laminae, records at least 21 episodes of pyroclastic fallouts from basanitoid or hawaiite (sodic) magmas. These magmas lacking iron oxide fractionation have features intermediate between the lavas typical of Mount Cameroon and Manengouba. They probably came from nearby volcanoes belonging to the Roumpi sector.

About 21,000 yr. B.P., a 1.5-m slab of the lacustrine deposits was vertically tilted. A slided block is unlikely an explanation of this tilting since the basic character and the grain sizes of the disturbed sediments match the sediment facies in basinal areas and are distinct from those of the slopes and the deltaïc zone of the Toh Mbock outlet. The preservation of laminated slabs implies that transport distances were limited, and did not destroy the primary bedding. An earthquake creep due to nearby volcanic activity could be a causal mechanism but no important slumpings of non-laminated sediments from the slopes of the lake have been found in the cores studied. Another explanation for this disturbed section would consist of a more or less localized violent gas burst. At the light of recent tragedies nearby Lakes Nyos and Monoun (Sigvaldason, 1989), where the mechanism of CO_2 release remains controversial, such a tilting would support the hypothesis of a sudden expulsion of gas trapped in the volcanic pipe breccia below (Barberi et al., 1989; Tazieff, 1989).

From 11,000 years to the present, ash beds are no more formed but sediments contain dispersed highly vesiculated ashes with transitional character. Their scarcity is indicative of a more discrete or more remote volcanic activity. The presence of augite, amphibole and labradorite xenocrysts. suggest an origin situated in the Manengouba sector, 40–60 km ENE of Barombi Mbo. Extraterrestrial or volcanic origin for the magnetite spherules of these levels is improbable, they are likely derived from authigenic magnetite produced in situ or by pedogenic processes. The latter could be related to the increase in humidity, and consequently in weathering, soil development and sedimentation rate recorded since the beginning of Holocene times.

Significant volcanic activity took place along the part of the Cameroon Line close to the Barombi Mbo maar between 21,000 and 11,000 years ago. During the Holocene, this activity decreased or shifted northeastward: probably in Manengouba area and, 200 km further, at Nyos, a 400-yr-old maar (Lockwood and Rubin, 1989). The recent activity of Mount Cameroon (in the southwest) is not recorded in the sediments of Barombi Mbo lake.

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