

Discovery of pyroclastic surge deposits in Bamenda volcano (Bambili, West-Cameroon, Cameroon volcanic Line): importance in chronostratigraphy of the massif

ABSTRACT

Field studies in Bambili locality (NE of Bamenda city) have recently permitted us to discover above the welded massive lapilli tuff (mIT), the remnant blocks (up to 6.5 x 11 m) of pyroclastic surge deposits characterized by well sorted and distinctly stratified layers with thickness ranging between 8 to 35 cm showing a graded bedding. In addition to ashy matrix, the different layers of the deposits are made up of lithic fragments of various natures, represented by devitrified fiammes, vitrophyres, trachytes, rhyolites, granites and ignimbrites. The mineralogy of these surge deposits is quasi identical to those of welded mIT; they are made up of alkali feldspar (sanidine), quartz, plagioclase, clinopyroxene, biotite and Fe-Ti oxides. The discovery of the pyroclastic surge deposits of Bambili, emitted from Mt Oku vent permit to reconsider the chronostratigraphy of the Bamenda volcano. In fact, after the trachytic lava flow, the pyroclastic flow deposits have then permitted the formation of the welded ignimbrites represented by dark gray and whitish units; pulsating hydrostatic and magma pressures have subsequently produced alternating hydromagmatic pyroclastic surges, which have afterward cover the massif followed by basaltic flows.

Keywords: surge deposits, welded ignimbrites, Bamenda volcano, West-Cameroon

1. INTRODUCTION

THE INTRAPLATE CAMEROON VOLCANIC LINE (CVL) FORMS ONE OF THE MAJOR LINEAMENT OF THE AFRICAN CONTINENT (FIG. 1). IT CAN BE COMPARED TO THE EAST AFRICAN RIFT SYSTEM, WHICH IS CURRENTLY DEFINED BY AN ALMOST SW-NE GEOLOGICAL LINEAMENT (MEAN VALUE: N30°E). IT IS MADE UP OF A CONTINENTAL PART AND AN OCEANIC PART, MAKING IT A UNIQUE FEATURE IN AFRICA AND EVEN IN THE WORLD [1]. THE CONTINENTAL PART INCLUDES BOTH PLUTONIC COMPLEXES AND VOLCANIC MASSIFS. THE OCEANIC PART IS ENTIRELY VOLCANIC AND CONSISTS OF FOUR WELL-STUDIED ISLANDS (BIOKO, PRINCIPE, SÃO TOMÉ, AND ANNOBON) AND TWO LARGE SEAMOUNTS [2].

RECENT WORK [3] REPORTED THE EXISTENCE OF IGNIMBRITIC DEPOSITS ONLY IN THE CONTINENTAL PART OF CVL; THESE ROCKS ARE FOUND MAINLY IN THE CENTRAL AREA OF CVL WHERE THE IGNIMBRITES OF MOUNTS BAMBOUTO AND BAMENDA ARE LOCATED AND FORM THE MOST IMPORTANT DEPOSITS WITH RESPECTIVELY 13.5 AND 6.3 KM³. WITH THE ALTERATION AND POOR CONDITION OF THESE ROCKS OUTCROPS, THE ESTIMATED VOLUMES WOULD BE SIGNIFICANTLY HIGHER. OUTCROPS OF SMALLER SIZES (<1 KM³) WERE IDENTIFIED IN OKU [4, 5], NKOOGAM [6] AND NGANHA [7] VOLCANOES. STUDIES IN THESE MASSIFS SO FAR HAVE SHOWN THAT THESE IGNIMBRITES ARE ONLY DEPOSITS OF PYROCLASTIC FLOWS WITH NO INTERNAL STRATIFICATION.

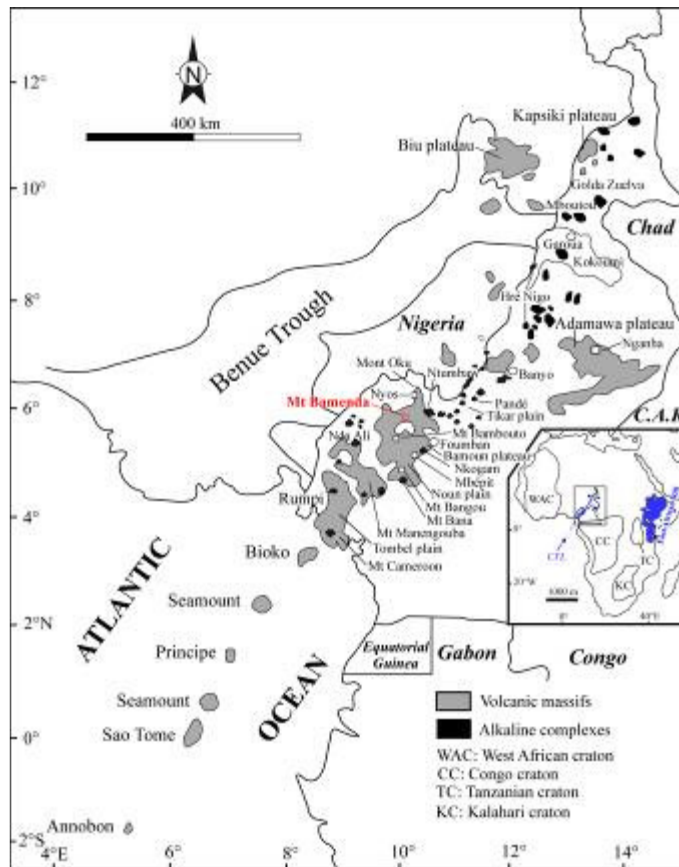


Fig. 1. Map of Cameroon showing the distribution of the Cameroon Volcanic Line (CVL) magmatism. Locations of seamounts are after Burke [2]. C.A.R.: Central African Republic. Inset: location map of CVL in Africa.

Deposits of pyroclastic density currents have generally categorized according to lithology and sedimentary structure, as ignimbrites, block-and-ash flow deposits and pyroclastic surge deposits [8]. Until now, only welded and non-welded ignimbrites with their massive lapilli tuff (mlT) and massive lithic breccias (mlBr) facies have been described in the Mount Bamenda [3]. These ignimbrites represent the deposits of pyroclastic flows. In this work, we highlight the existence of pyroclastic surge in the Bamenda volcano, at Bambili locality, situated in the NE of Bamenda town. These surge deposits are investigated here in detail in order to understand their mode of deposition and give their importance in the chronostratigraphy of the Bamenda volcano.

2. GEOLOGICAL SETTING

Mount Bamenda (600 km²) constitute in volumetric importance the fourth largest volcano of the CVL after Mt Cameroon, Manengouba and Bambouto. They constitute with the Bambouto mountains to the SW and the Oku massif to the NE (Fig. 2), the three central volcanoes belonging to the volcanic centres of the Western Cameroon Highlands. Their basement consists of Pan-African granitoids [9, 10, 11]. Bamenda volcano lies between longitudes 10°00'E and 10°30'E and latitudes 05°45'N and 06°10'N and culminates at 2621 masl at lake Bambili borders.

The Mount Bamenda is characterized by the presence of two calderas: calderas of Santa-Mbu (6 x 4 km) and Lefo (4 x 3 km) (Fig. 2). They are small sizes and open respectively to the west and south-east [12]. Their floor located respectively at elevation of 550 m and 400 m is mainly composed of trachytic domes, which are also abundant on the external slopes of the massif. Many craters caused by explosive volcanism, are occupied by lakes generated by phreatomagmatism like Bambili Lake, Lake Awing and Lake Oku.



Fig. 2. Digital Elevation Model (DEM) of Mt Bamenda and surroundings.

Petrographic and geochemical studies [13] show that the mts Bamenda consist of basanites, basalts, hawaiites, mugearites, benmoreites, trachytes, rhyolites and ignimbrites. These ignimbrite overlays basement rock (constituted by granite and gneiss) and are covered by laterized basalt. The felsic lavas are most abundant than intermediate types (mugearites and benmoreites). The radiometric dating of this active volcano gives ages ranging from the current to 17.4 Ma for the basaltic lavas and from 18.98 Ma to 27.40 Ma for the felsic lavas. As in the case of neighboring Mts Bambouto, the ignimbrites of the Bamenda volcano belong to Miocene formations.

3. FIELD STUDY AND PETROGRAPHY

The ignimbrites sheets of Bamenda volcano constitute about 7.5% of the rocky outcrops of the volcano representing approximately 45 km² with a volume estimated at 6.3 km³; these deposits lie on the trachytic flows and the granito-gneissic basement and covered in places by columnar jointed basaltic flows.

The ignimbrite of Bambili (Fig. 3 and 4) consists of mIT facies in its basal part represented by a single cooling unit constituted by two flow units (dark gray unit and whitish unit), covered by multiple layers of poorly sorted and matrix-poor BrIm facies (Fig. 5). Pyroclastic surge deposits of Bambili are characterized by stratified ashy layers insert in BrIm facies. Anisotropy of magnetic susceptibility study of Bamenda volcano showed that these deposits were emitted from Oku vent (1.8 x 2.2 km) situated in mount Oku, the neighboring NE volcano [3].



Fig. 3. a) Google map of Bambili town showing the ignimbrite outcrops; **b)** Landscape with ignimbritic remnants of whitish unit of welded mIT lithofacies.

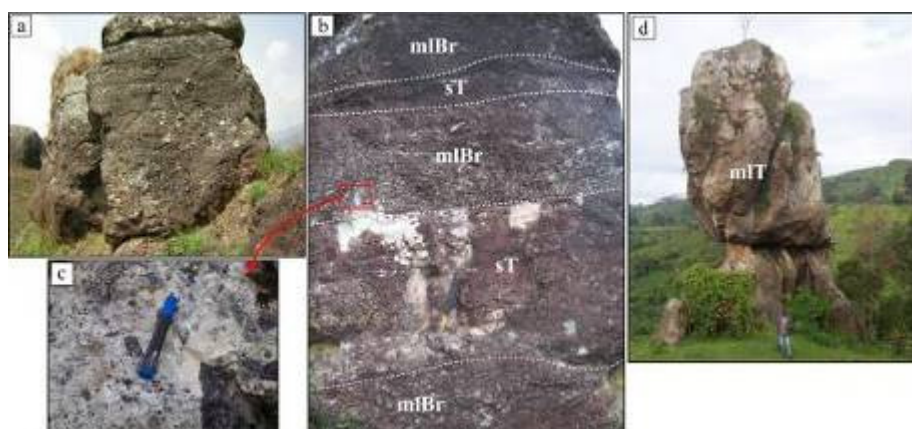


Fig. 4. Ignimbrite outcrops of Bambili. a) and b) Remnant blocks of pyroclastic surge deposits of Bambili; **c)** Fine-poor matrix of mIBr; **d)** Remnant block of whitish unit of welded mIT. mIBr: massive lithic breccia; mIT: massive lithic tuff; sT: stratified tuff/ash

3. 1 Base of the mIT facies

The base of the mIT facies is a flow unit whose color is dark gray and rubefied in places (Fig. 5 and 6a). This rubefaction is reflected by the presence of reddish areas in the deposit. The rock is dense and massive.

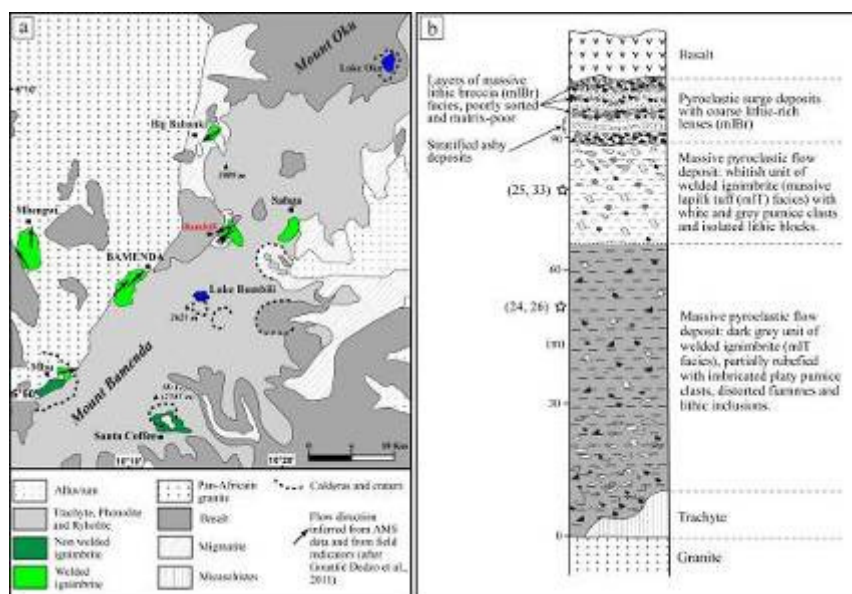


Fig. 5. a) Geological map of mounts Bamenda and surroundings. **b)** Stratigraphic section of Bambili ignimbrites; the numbers 24, 25, 26, 33 represents sampled sites for anisotropy of magnetic susceptibility (AMS) studies (after [3]).

The volcanic clast population includes both apyric and porphyritic rhyolite (whose dimensions do not exceed 0.5 x 0.3 cm and represent 5% of the facies) and many aphyric black and white fiammes (30 to 35% of the facies; up to 1.2 x 0.2 cm;) which are wispy, lenticular to much stretched and generally distorted displaying a eutaxitic texture; these fiammes are interpreted to be flattened, juvenile pumice lapilli.

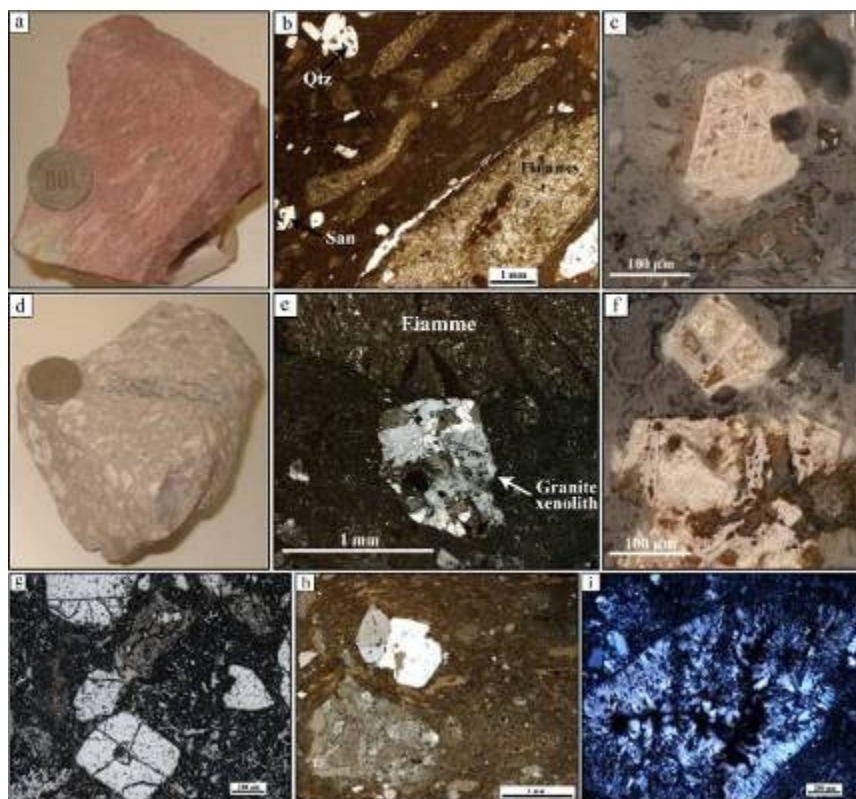


Fig. 6. **a)** Sample of rubified dark grey unit (DGU) of mIT and **b)** the corresponding microphotograph showing the eutaxitic texture with imbricated fiammes; **c)** Crystal of titanohematite with thin exsolution lamellae of ilmenorutile in the DGU; **d)** Sample of mIT whitish unit (WU) and **e)** the corresponding microphotograph showing xenolith of granite; **f)** Crystals of titanohematite with thin exsolution lamellae of ilmenorutile in the WU; **g)** Devitrified matrix of WU showing relict shards, lithic fragments and multiple alkali feldspar fragments; **h)** Basal DGU showing subhorizontal compaction foliation defined by the fiammes and deformation of fiammes around the margins of lithic clasts; **i)** Devitrification of large fiamme in DGU showing micropoikilitic texture characterized by crystallization of microlites (mainly cristobalite and alkali feldspar) along the boundaries of the glass shards or within glassy masses.

In thin sections, this eutaxitic texture is well characterized by preferentially oriented or imbricated devitrified fiammes showing that transport direction of pyroclastic current was roughly directed toward azimuth 235 (Fig. 6b). The chemistry of these fiammes shows that there are rhyolitic in composition (SiO_2 : 73.65 - 76.44% and $\text{Na}_2\text{O} + \text{K}_2\text{O}$: 8.5 - 9.75%) (Fig. 7). The matrix is devitrified and comprises various proportions of relict shards (Fig. 6g) and lithic fragments (mainly trachytic) with a diameter inferior to the millimeter. The ignimbrite underwent hot welding compaction, as indicated by the subhorizontal compaction foliation defined by the fiamme, deformation of fiamme around the margins of lithic clasts (Fig. 6h), plastic deformation of cusped matrix shards and the presence of spherulitic and micropoikilitic textures (Fig. 6i) within the fiamme (resulting from high-temperature crystallisation of a glassy precursor; [14, 15, 16]. The minerals such as quartz and alkali feldspar (sanidine), are abundant; plagioclase, clinopyroxene, biotite and Fe-Ti oxides (ilmenorutile; Fig. 6c) are less represented.

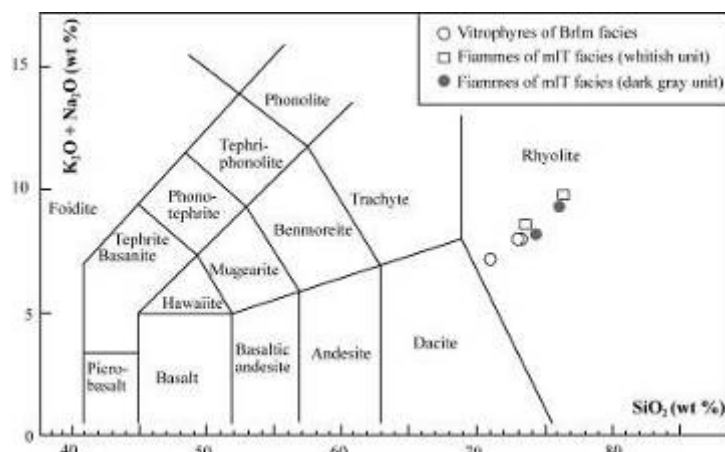


Fig. 7. TAS classification graph [33] for whole rock pumice and vitrophyres samples collected from the Bambili ignimbrites during this study.

3. 2 Second unit of mIT facies

The second unit of mIT facies is whitish and has low density (Fig. 5 and 6d). The rock is characterized by the presence of numerous vesicular pumice, with chalk-white color and also rhyolitic in composition (Fig. 7; SiO_2 : 74.36 - 76.11% and $\text{Na}_2\text{O} + \text{K}_2\text{O}$: 8.1 - 9.23%). Pumice shapes are subrounded to ovoid and they constitute about 35 to 40% of the volume of the rock; their dimensions vary from 2.2 x 1.9 cm to 0.3 x 0.2 cm. Trachytic enclaves are rare (less than 5%); enclaves of black vitrophyres represent less than 2% of the rock; xenoliths of ignimbrite (2%) are difficult to identify because of their advanced status of alteration. Xenoliths of granite (1%) (Fig. 6e) are generally well preserved in this unit. The dimensions of these enclaves do not exceed 0.4 x 0.2 cm. The matrix is made up of submillimetric devitrify fiammes, small rock fragments smaller than one millimeter and minerals such as: sanidine, plagioclase, biotite and Fe-Ti oxides (ilmenorutile; Fig. 6f). Subvertical elutriation pipes (0.5 to 0.7 cm in diameter) are present in the surface regions of the outcrop.

3. 2 Surface BrIm facies

The surface BrIm facies (Fig. 5 and 8a) is represented by an ignimbrite whose overall color is white with a low consistency (Fig.4a-d) compared to the previous facies. This lithic-rich ignimbrite generated by the second eruption episode has a sharp contact with precedent mIT unit. Consistency depends on the abundance of enclaves, so areas of high rocky enclaves are more resistant to erosion and that's why the remnant blocks are predominantly made up. Stratification is observable in some of these blocks and is characterized by alternating coarse-grained deposit of more than 35 cm thick and fine particle size deposit not exceeding 8 cm of thickness (Fig. 4a). Pyroclastic surge divisions are ash- to lapilli-sized, grey to whitish in colour with low proportion of accretionary lapilli (Fig. 4b). The lithic breccia is generally poorly sorted and diffusely stratified in some outcrop.

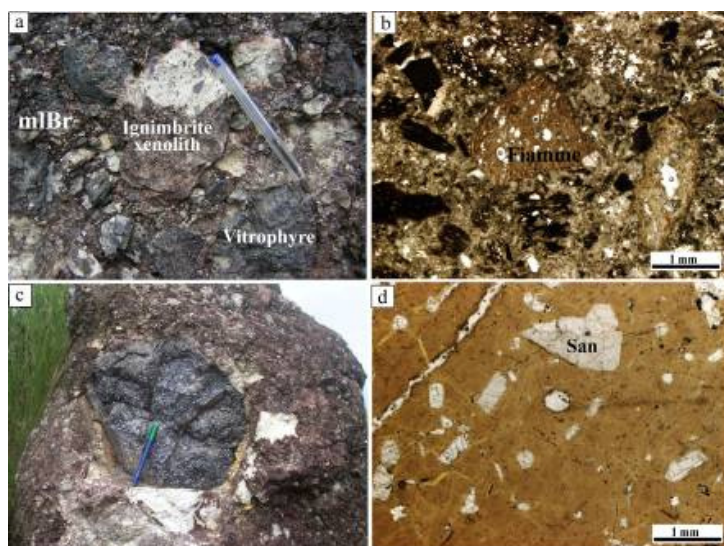


Fig. 8. a) Detail of mlBr facies and b) microphotograph of ignimbrite enclave c) Enclave of vitrophyre and d) the corresponding microphotograph.

Rock elements constituting this ignimbrite are varied in nature. The most represented are enclaves of vitrophyres (25 to 35%) with black color (Fig. 8a,c); some pockets can contain up to 70% of these rock inclusion. Their dimensions range from 22 x 19 cm to 5 x 2.5 cm. These enclaves are essentially prismatic elements with chilled margins. Under microscope, the matrix of vitrophyre is essentially vitreous with some crystals of quartz and feldspar (Fig. 8d). The geochemistry of these vitrophyres (Fig. 7) show that they have rhyolitic in composition (SiO_2 : 71.03 - 73.23% and $\text{Na}_2\text{O} + \text{K}_2\text{O}$: 7.12 - 7.88%). Enclaves of rhyolite are light gray colored and represent 5% of the rock volume with sizes ranging from 14 x 12 cm to 0.8 x 0.6 cm; some elements reach up to 45 x 35 cm. The basement rock enclaves are rare and usually represented by large quartz crystals (11 x 9 cm) constituting about 5% of the rock. Enclaves of first ignimbritic phase (Fig. 8a,b) included in the second phase were found in this facies, it measures 18 x 16.5 cm. These enclaves of ignimbrites contain the same rock elements than the country rock. Matrix, whitish in color, consists essentially of consolidated volcanic ashes in which are embedded small rocks and minerals fragments.

4. DISCUSSION AND CONCLUSION

The studied deposit succession shows evidence of multiple changes of eruptive regime and emplacement modes which likely occurred during a single eruptive event. The stratified character of the deposits observed at Bambili can be attributed to a spatial and temporal variation of the nature of pyroclastic current, which would have been transformed into pyroclastic surge with a current, became weakly concentrated and rich in ashy and gaseous fraction.

In particular, hydromagmatic deposits may form during late eruptive stages following disruption of the top of the magma chamber (e.g., [17]). The presence of vesicular tuff layers, along with dominance of blocky, poorly vesicular ash particles with hydration cracks, indicates an origin as wet pyroclastic surges of hydromagmatic origin [18].

The BrIm deposits are composed of an alternation of stratified clast-supported layers and laminated ash layers, interpreted as a medial-to-distal deposit produced by hydromagmatic surges and contemporaneous fallout [19]. On other volcanoes, similar deposits were

interpreted as fallout deposits or as pyroclastic surge and co-surge fallout deposits, due to the contemporaneous presence of characteristics normally pertaining to both fallout and surge deposits (e.g. [20, 21, 22, 23]. It is difficult to discriminate between the two depositional mechanisms, especially in the absence of a large number of outcrops. In our case, only remnant blocks reflect the presence of pyroclastic surge deposits; in addition, these deposits are partly covered by more recent basaltic lava flow. Nevertheless, a single couplet constituted by both coarse and fine-grained layers is interpreted as deposited from a single surge [23, 24] and this lithofacies is interpreted as inferred to be a medial-to-distal deposit from hydromagmatic surges and concurrent simultaneous fallouts.

The large crater of Mount Oku in which is located the lake Oku, who is suspected to be the center of emission of these ignimbrites [3] will justify the presence of accretionary lapilli in the late surge deposits of this volcano.

In the last phase of the eruption, magma has encountered water and thus generated a large explosion which was suspended the huge amount of ash and lithic fragments. Pulsating hydrostatic and magma pressure produced alternating hydromagmatic pyroclastic surges. The vitrophyres abundantly found in these deposits would be the lava cooled rapidly by water, and then sprayed by the explosion. The complex dynamics of water-magma interaction defines the nature of explosive activity, characterized by variable energy outputs and different degrees of magmatic or hydromagmatic fragmentation [25, 26, 27, 28, 29]. Depending on the extent of water-magma interaction, deposits can be formed by fallout layers made of couplets of ash and lapilli, by the alternation of fallout layers and surge deposits, or by the simultaneous concurrent deposition from both processes, leading to the formation of highly complex deposits made of numerous (from few tens to over thousands) of thin tephra beds (e.g. [23, 30, 31, 32]. As a consequence, hydromagmatic deposits show remarkable variability in grain-size from layer-to-layer and within layers. Definitely, we inferred that the eruptions of Bamenda volcano were affected by interaction with lake water, generating phreatomagmatic pyroclastic flows and surges. The new chronological succession of geological formations of Bambili can be considered as follows: trachytic flow at the base, follow by welded ignimbrites represented by dark gray and whitish units and pyroclastic surges deposits covered by basaltic flow.

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