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Remnants Blocks of Pyroclastic Surge Deposits in Bambili, Cameroon Volcanic Line: New Insights into the Lithostratigraphy of Mount Bamenda

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

Field studies in Bambili locality (NE of Bamenda city, West-Cameroon), situated in the central part of Cameroon Volcanic Line, have recently permitted us to identifier above the welded massive lapilli tuff (mlT), remnant blocks (up to 6.5 x 11 m) of pyroclastic surge deposits. The latter are characterized by well-sorted and distinctly stratified layers with thicknesses ranging from 8 to 35 cm and showing graded bedding. The layers are matrix-supported and heterolithic, with the lithic

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fragments consisting of devitrified fiammes, vitrophyres, trachytic and rhyolitic cognates, granites and ignimbrites. The mineralogy of these surge deposits is quasi identical to that of the welded mlT which consists of alkali feldspar (sanidine), quartz, plagioclase, clinopyroxene, biotite and Fe-Ti oxides. The presence of these remnants blocks of pyroclastic surge deposits in the Bambili locality, emitted probably from Mt Oku vent, permit to reconsider the chronostratigraphy of the Bamenda Highlands. In fact, after a trachytic lava flow, a pyroclastic flow deposits allowed the formation of the welded ignimbrites represented by dark grey and whitish units; pulsating hydrostatic and magma pressures have subsequently produced alternating phreatomagmatic pyroclastic surges, which have afterward covered 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 lineaments of the African continent (Fig. 1) [1]. It can be compared to the East African rift system, which is currently defined by an almost SW-NE geological lineament (mean value: N30ºE). 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 (67 to 10.8 Ma) and volcanic massifs (51.8 Ma to Present) ([1] and references therein). 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 in the continental part of the CVL. These deposits were found mainly in the central area of the CVL, especially within the Mount Bambouto and the Mount Bamenda, with estimated volumes of 13.5 and 6.3 km^3, respectively [3]. Considering both alteration and poor condition of these outcrops, their actual volumes could be significantly higher than the estimated ones. Outcrops of smaller sizes (<1 km^3) were identified in Oku [4,5], Nkogam [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 [3].

Pyroclastic density currents are inhomogeneous mixtures of volcanic particles and gas that flow according to their density relative to the surrounding fluid (generally the atmosphere) and due to Earth's gravity [8,9]. They move at high speeds (100 to 300 m/s [10]) on the earth surface, mainly controlled by gravity [11,12,13,14], and frequently implying a turbulent regime [11,15,16,17]. Deposits of pyroclastic density currents are generally categorized according to lithology and sedimentary structure, as ignimbrites, block-and-ash flow deposits and pyroclastic surge deposits [8]. Pyroclastic surge deposits come from turbulent flows, less concentrated or diluted, in which the ashy and gaseous fraction predominates. They generally consist of successive parallel and stratified beds and occasional cross-stratification [8]. The beds are relatively low thickness, well sorted, with or without fine ashy matrix. Recently, pyroclastic flows deposits characterized by welded and non-welded ignimbrites with massive lapilli tuff (mlT) facies and massive lithic-rich breccias (mlBr) facies were described in the Mount Bamenda [3]. In this work, we highlight the existence of pyroclastic surges deposits in the volcanic sequence of the area. These surges deposits are found in remnants of pyroclastic blocks at Bambili locality, situated in the NE of Bamenda town. They are investigated here in detail in order to understand their origin, and to bring insight into the eruptive history of the Oku vocano and thus to give their importance in the chronostratigraphy of the Bamenda volcanic field.

2. GEOLOGICAL SETTING

The Mount Bamenda (600 km^2) constitutes in volumetric importance the fourth largest volcano of the CVL after Mount Cameroon, Mount Manengouba and Mount Bambouto. It constitutes 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 [18,19,20]. The Bamenda volcano, on top of which exists the lake Bambili, lies between longitudes 10º00'E and 10º30'E and latitudes 05º45'N and 06º10'N and culminates at 2621 m asl.

The Mount Bamenda is characterised by the presence of two calderas: calderas of Santa-Mbu

(6 x 4 km width) and Lefo (4 x 3 km width) (Fig. 2). They are small sized compared to neighbouring Bambouto caldera and open respectively to the west and southeast [21]. Their floors, located at elevation of 550 m and 400 m respectively, are mainly composed of trachytic domes, which are also abundant on the external slopes of the volcano. In addition to Bambili Lake, many other craters, created probably by phreatomagmatic explosions and occupied by lakes are present in the area. Case examples are, Lake Awing and Lake Oku.

Petrographic and geochemical studies showed that the Mt Bamenda lavas consist of basanites, basalts, hawaiites, mugearites, benmoreites, trachytes, rhyolites and ignimbrites [22]. Those ignimbrite overlays the granite and gneiss basement rocks and are covered by laterised basaltic flow. The felsic lavas are most abundant than intermediate types (mugearites and benmoreites). The radiometric dating of this active volcano gives ages ranging from 0 Ma to 17.4 Ma for the basaltic lavas, and from 18.98 Ma to 27.40 Ma for the felsic lavas [22]. As in the case of neighbouring Mt Bambouto, it can be assumed that the ignimbrites of the Bamenda volcano belong to Miocene formations because the succession of deposits is similar for the two volcanoes with Precambrian basement rocks (granite in the majority) at the base of each stratigraphic section [3].

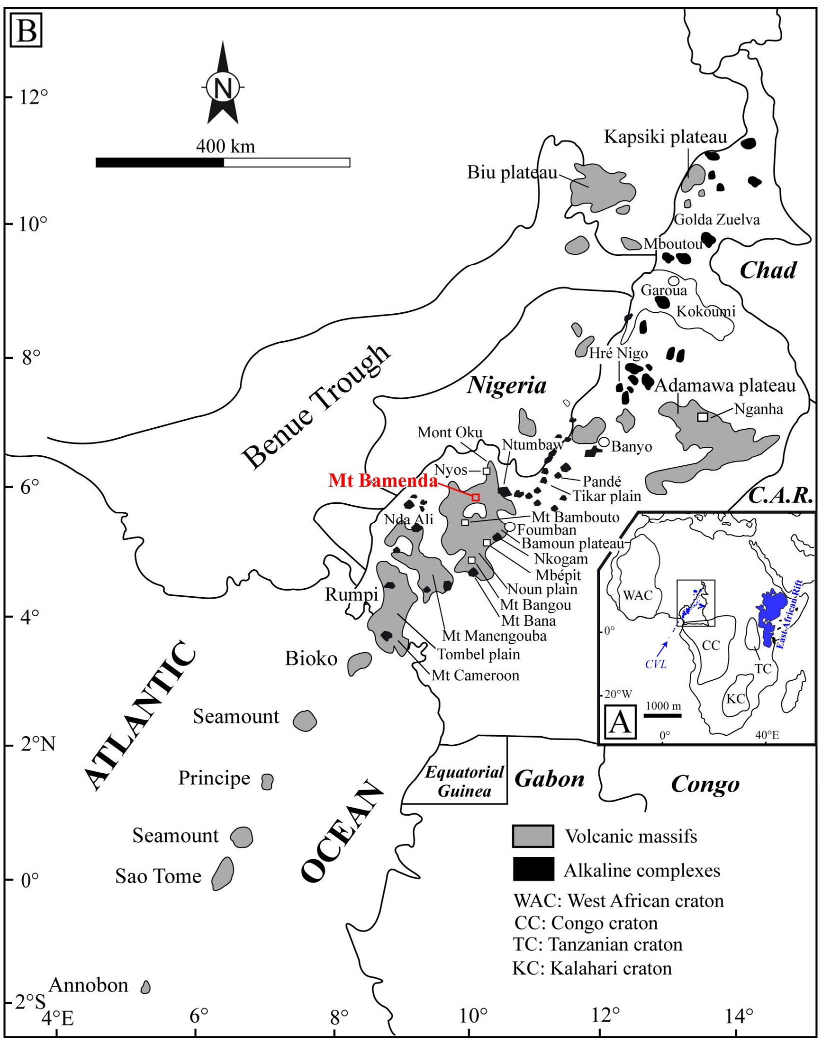

Fig. 1. Map of Cameroon showing: A) Location map of the Cameroon Volcanic Line (CVL) in Africa, and B) the distribution of the CVL magmatism. Locations of seamounts are after Burke [2]. C.A.R.: Central African Republic

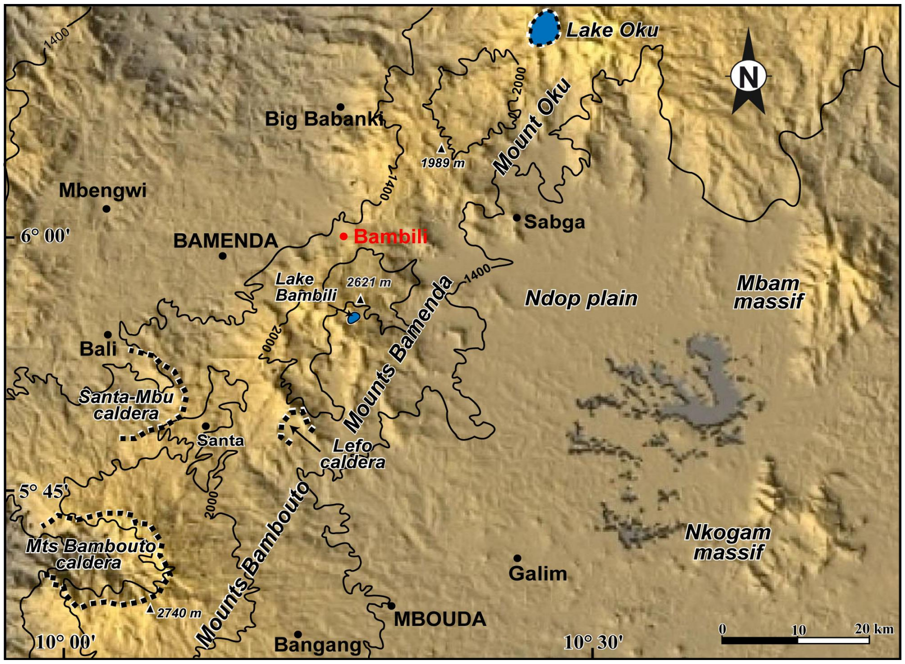

Fig. 2. Digital Elevation Model (DEM) of Mt Bamenda and surroundings

3. MATERIALS AND METHODS

Field investigations were made on remnant blocks of surge deposits of Bambili situated in Bamenda volcanic area. Stratigraphic section of Bambili ignimbrites and pyroclastic surge deposits was obtained from the field data. Only blocks in place were taken into account to establish the complete succession of pyroclastic surge deposits. In order to characterize the mineral assemblages and textures of welded ignimbrites, optical studies using transmitted and reflected-light microscope were undertaken on thin sections from representative samples.

For geochemical analysis, samples were collected from outcrops, as well as from a few detached blocks of ignimbrites. The samples consist of glassy or vitric clasts and fiamme from within the ignimbrite matrix or, more commonly, material taken from unaltered vitrophyres of the ignimbrites. Seven samples have been analysed for major elements. These samples were crushed in a steel jaw crusher and reduced to fine powder in agate mortars. Powders were analysed for major oxides by X-ray fluorescence spectrometry (XRF) with Bruker S4 PIONEER spectrometer at Mission de Promotion des Matériaux Locaux (MIPROMALO, Yaoundé) laboratory in Cameroon with analytical accuracy of 1%.

4. FACIES CHARACTERISTICS OF THE BAMBILI PYROCLASTIC REMNANTS DEPOSITS

The pyroclastic deposits of Bambili (Fig. 3 and 4) are characterized by two main volcanic facies: a massive lapilli tuff (mLT) and a massive lithic breccias (mLBr) facies. Based on these facies, the pyroclastic sequence of Bambili was subdivided into three stratigraphic units (Fig. 5b):

- A lower unit (U_1) characterized by the mlT facies; this lower part is dark grey
- A second whitish unit (U_2) also characterized by the mlT facies, and
- An upper unit (U_3) consisting of a series of alternating poorly sorted and clasts-supported mlBr beds and ashy beds (Fig. 5b).

4. 1 The Lower Unit (U_1) of the mlT Facies

- The lower unit of the mlt facies is a dark grey pyroclastic flow, which locally is being rubeficated (Figs. 4, 5 and 6a). This rubefaction is reflected by the presence of reddish areas in the deposit. The rock is dense and massive.

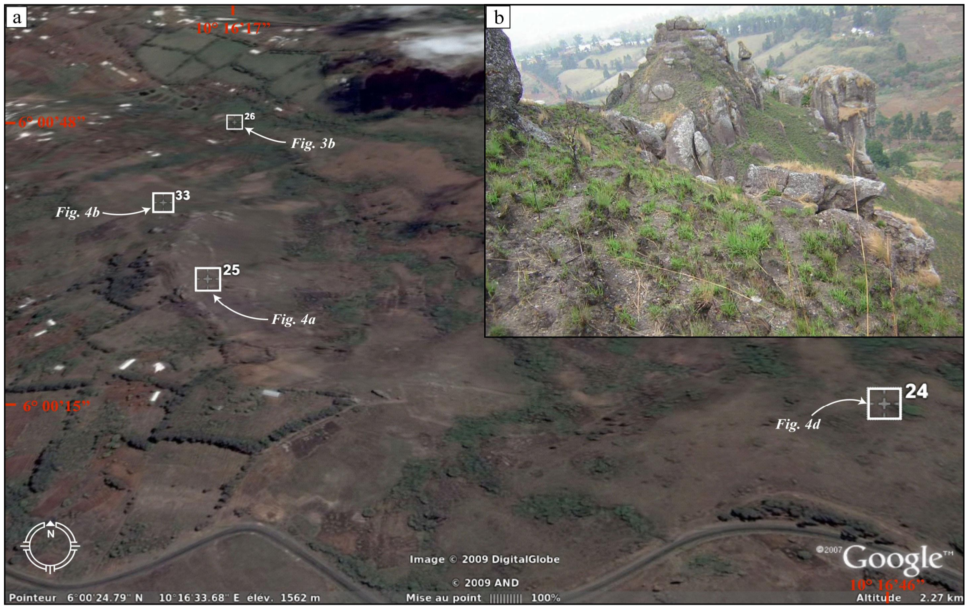

Fig. 3. a) Google map of Bambili town showing the ignimbrite outcrops; b) Landscape with ignimbritic remnants of whitish unit of welded mlT lithofacies

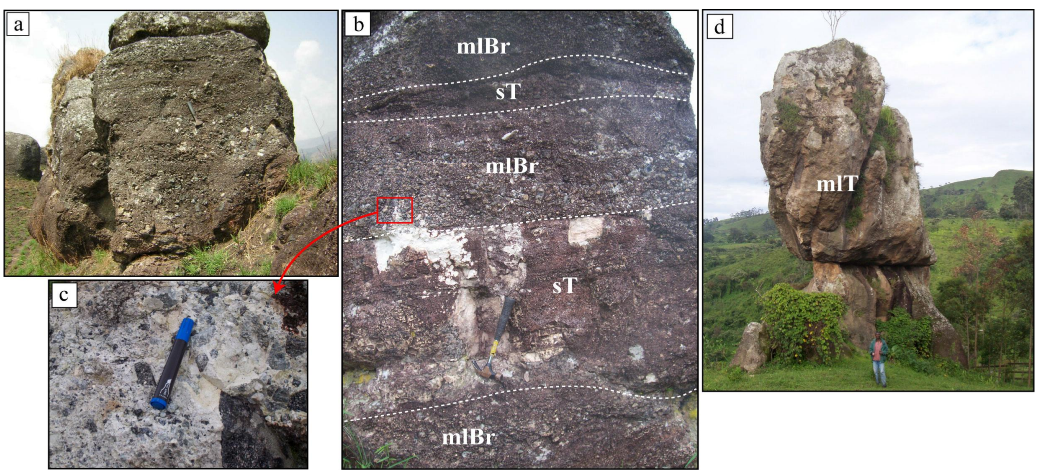

Fig. 4. a) and b) Remnant blocks of pyroclastic surge deposits of Bambili; c) Fine-poor matrix of mlBr; d) Remnant block of whitish unit of welded mlT. mlBr: massive lithic breccia; mlT: massive lithic tuff; sT: stratified tuff/ash

The volcanic clasts population includes about 5% of aphyric and porphyritic rhyolitic fragments (with dimensions not exceeding 0.5 x 0.3 cm, and many black and white aphyric fiammes, which are wispy, lenticular and distorted. These aphyric fiammes are up to 1.2 x 0.2 cm in sizes and represent about 30 to 35% of the facies, giving to the deposit an eutaxitic texture. We interpret them to be flattened juvenile pumice lapilli.

In thin sections, this eutaxitic texture is well characterised by preferentially oriented or imbricated devitrified fiammes suggesting that transport direction of pyroclastic current was roughly directed toward azimuth 235 (Fig. 6b). The chemistry of these fiammes showed that they are ryholitic in composition, with SiO_2: 73.65 – 76.44% and Na_2O + K_2O: 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 millimetre. The ignimbrite underwent hot welding compaction, as indicated by the subhorizontal compaction foliation defined by the fiamme, the deformation of fiamme around the margins of lithic clasts (Fig. 6h), the plastic deformation of cuspate matrix shards and the presence of spherulitic and micropoikilitic textures (Fig. 6i) within the fiamme, resulting from high-temperature crystallization of a glassy precursor [23,24,25]. Quartz and alkali feldspar (sanidine) are abundant; plagioclase, clinopyroxene, biotite and Fe-Ti oxides (ilmenorutile; Fig. 6c) are less represented.

4.2 The Intermediate Unit (U_2) of the mIT Facies

The second unit U_2 of the mIT facies (Fig. 5) is whitish (Figs. 4 and 6d). Juvenile rock fragments from the unit consist of highly vesiculated pumice. They are chalk-white in colour and rhyolitic (SiO_2: 74.36 – 76.11% and Na_2O + K_2O: 8.1 – 9.23%) in composition (Fig. 7). Those pumices are subrounded to ovoid and constitute about 35 to 40 vol. % of the clasts population. They vary in size from 2.2 x 1.9 cm to 0.3 x 0.2 cm. The other fraction of the clasts population comprises lithicsrare (less than 5%) trachytic lithics, about 2 vol. % lithics of black vitrophyres, 2 vol. % of xenoliths of ignimbrite (that are difficult to identify because of their advanced status of alteration. Xenoliths of granite (1%) (Fig. 6e) are also observed and are generally well preserved in this unit. The dimensions of these lithics granitic xenoliths do not exceed 0.4 x 0.2 cm.

The deposits' matrix is made up of submillimetric devitrified fiammes, small (< 1 mm) rock fragments and individual mineral fragments 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.

4.3 The Upper Unit (U_3): The mlBr Facies

The upper unit of the Bambili pyroclastic sequence consists of the mlBr facies (Figs. 5 and 8a). The unit has an overall white color and is lithic-rich, with a low consistency in volume fraction of lithics compared to the previous mIT facies on which it lies with a sharp contact. The unit U_3 is characterized by a distinct stratification (Fig. 5b) that appears in some of these remnant blocks. The stratification is characterized by alternating coarse-grained clast-supported beds of up to 35 cm thick, and fine-grained matrix-supported beds, with thicknesses not exceeding 8 cm (Fig. 4a). The fine-grained and matrix-supported beds are grey to whitish in color with low proportion of accretionary lapilli (Fig. 4b). In contrast, the coarse-grained clast-supported beds are lithic-rich, generally poorly sorted and diffusely stratified in some outcrop.

Rock fragments constituting this ignimbrite are varied in nature. The most represented are enclaves of vitrophyres (25 to 35%) with black colour (Figs. 8a and 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 vitrophyres is essentially vitreous with some crystals of quartz and feldspar (Fig. 8d). The geochemistry of these vitrophyres (Fig. 7) shows that they are rhyolitic in composition (SiO_2: 71.03 – 73.23% and Na_2O + K_2O: 7.12 – 7.88%). Enclaves of rhyolite are light grey coloured 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 contain large quartz crystals (11 x 9 cm) constituting about 5% of the rock. Enclaves of first ignimbritic phase (Figs. 8a and b) included in the second phase were found in this facies; they measure up to 18 x 16.5 cm. These enclaves of ignimbrites contain the same rock fragments than the country rocks. Matrix, whitish in colour, consists essentially of consolidated volcanic ashes in which small rocks and minerals fragments are embedded. Rock fragments constituting this unit vary in nature. The most represented (25 to 35 vol. %) are accidental lithics of vitrophyres with black color (Figs. 8a and c); some filled channels can contain up to 70 vol. % of these accidental lithic fragments. They range in size from 22 x 19 cm to 5 x 2.5 cm. These lithics are essentially prismatic with chilled margins. Under the microscope, the vitrophyre shows a glassy matrix with rare crystals of quartz and feldspar (Fig. 8d). The geochemistry of these vitrophyres shows that they are rhyolitic (SiO_2: 71.03 – 73.23% and Na_2O + K_2O: 7.12 – 7.88%) in composition (Fig. 7). Lithic fragments of rhyolite with light gray color are also observed. They represent about 5 vol. % of the clast population and their sizes range from 14 x 12 cm to 0.8 x 0.6 cm. Some fragments can reach up to 45 x 35 cm. Lithic fragments of the granitic basement rock (up to 11 x 9 cm) are rare and usually contain large quartz crystals (up to 1.8 x

1.6 mm) constituting about 5 vol. % of the rocks. Lithics of the lower ignimbritic unit (Fig. 8a, b) identified in the second unit are also found in this upper unit. They measure up to 18 x 16.5 cm and contain fragments of the country rock. The deposit' matrix is whitish in color and consists essentially of consolidated volcanic ashes in which small rocks and minerals fragments are embedded.

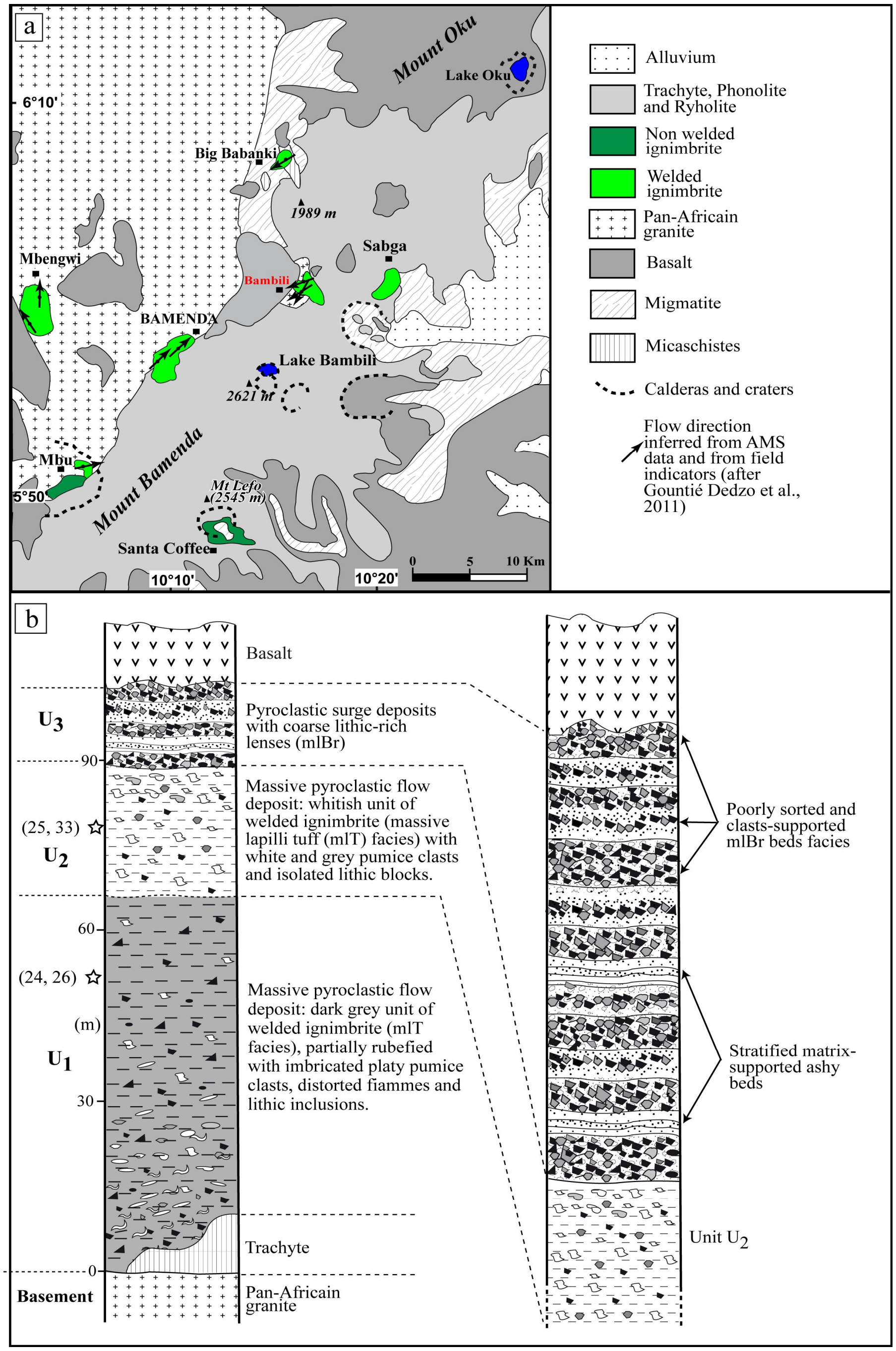

Fig. 5. a) Geological map of Mount Bamenda and surroundings. b) Stratigraphic section of Bambili ignimbrites and pyroclastic surge deposits; the numbers 24, 25, 26, 33 represent sampled sites for anisotropy of magnetic susceptibility (AMS) studies (modified after [3])

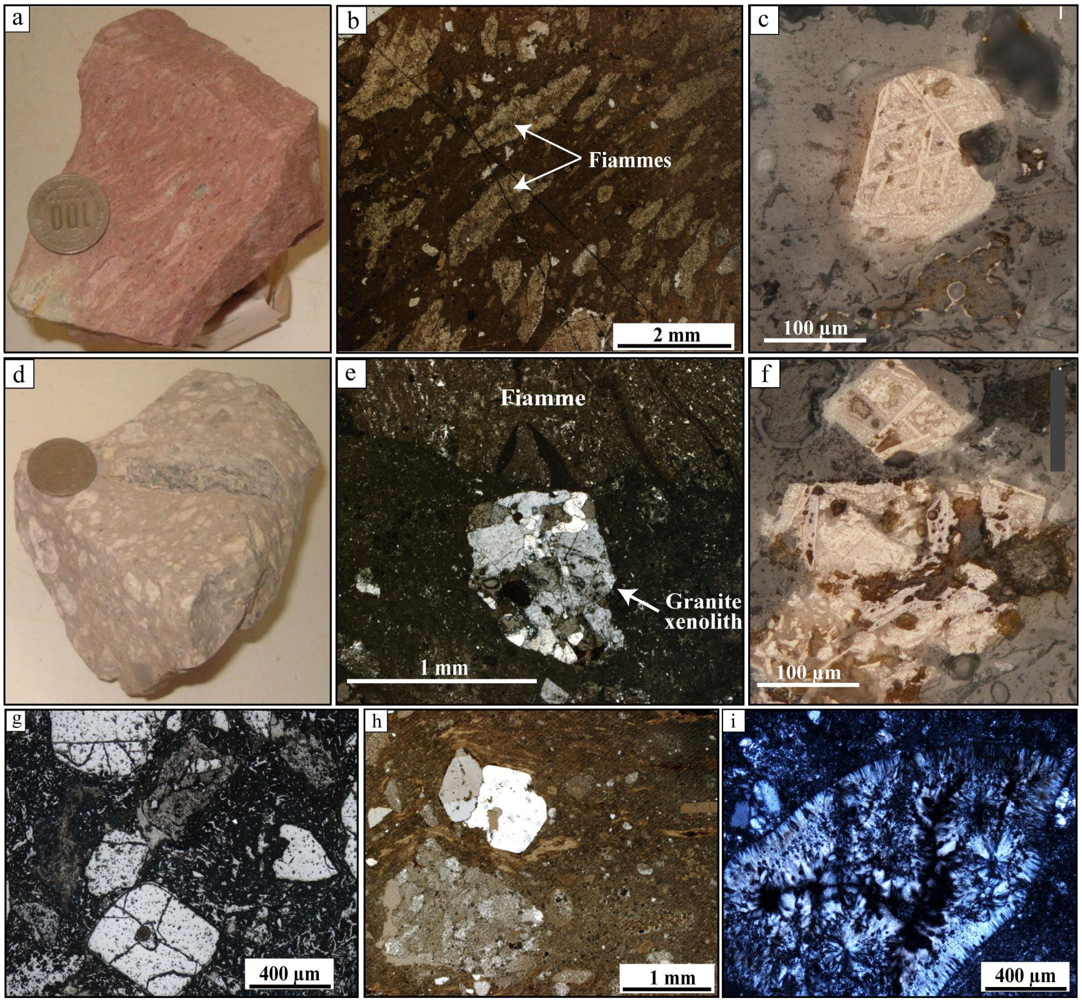

Fig. 6. a) Sample of rubefied dark grey unit (DGU) of mIT and b) the corresponding microphotograph showing the eutaxitic texture with imbricated fiammes; c) Crystal of titanohematite with thin exsolution lamellae of ilmenorutile in the DGU; d) Sample of mIT whitish unit (WU) and e) the corresponding 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 and crystals; 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

5. DISCUSSION AND CONCLUSION

The ignimbrites sheets of Bamenda volcano constitute about 7.5% of the rocky outcrops of the volcano representing approximately 45 km^2, with a volume estimated at 6.3 km^3. These deposits lie on the trachytic flows and the granito-gneissic basement and are covered in places by columnar jointed basaltic flows. The studied deposit succession shows evidence of multiple changes of eruptive regime and emplacement modes that 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, becoming weakly concentrated and rich in ashy and gaseous fraction.

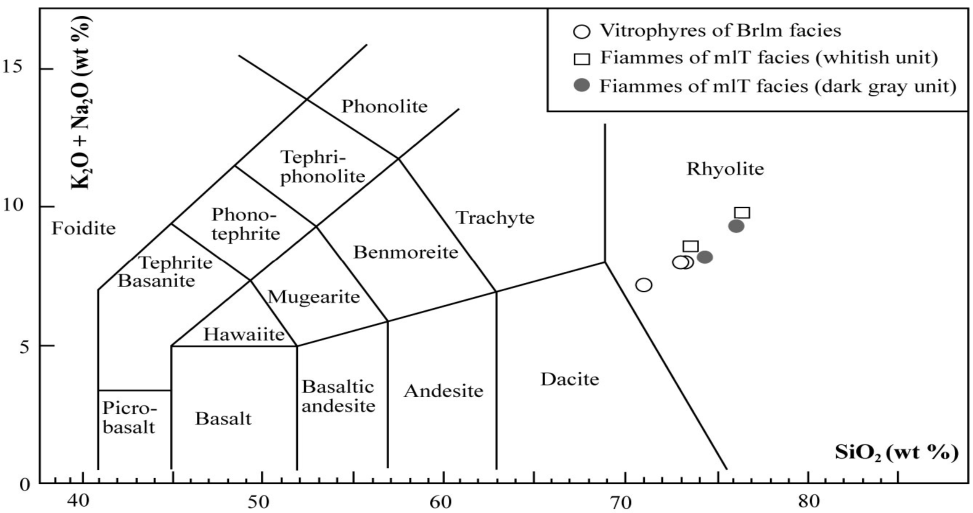

Fig. 7. TAS classification graph [26] for whole rock pumice and vitrophyres samples collected from the Bambili ignimbrites during this study

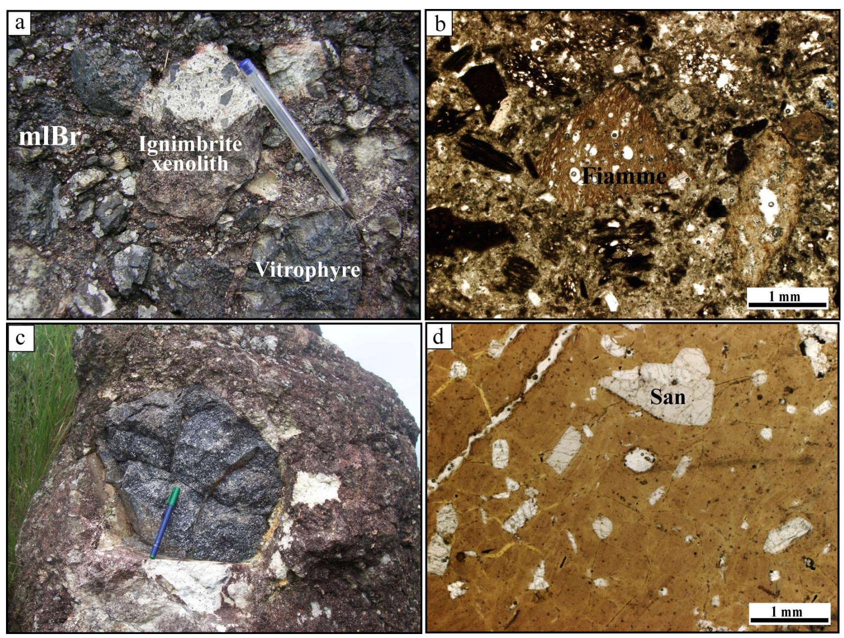

Fig. 8. a) Detail of mlBr facies and b) microphotograph of ignimbrite enclave c) Enclave of vitrophyre and d) the corresponding microphotograph

In particular, phreatomagmatic deposits may form during late eruptive stages following disruption of the top of the magma chamber (e.g., [27]). The presence of vesicular tuff layers in pyroclastic deposits along with the dominance of blocky, poorly vesicular ash particles with hydration cracks generally suggest a wet pyroclastic surges origin [28]. This also indicates a phreatomagmatic activity [28]. Anisotropy of magnetic susceptibility study of Mount Bamenda showed that these deposits were emitted from Oku vent (1.8 x 2.2 km), in which is located the lake Oku, situated in the neighbouring NE volcano [3]. The location of this lake will justify the presence of these wet surges in the late surge deposits of Bamenda volcanic field.

The mlBr unit is composed of an alternation of stratified clast-supported layers and laminated ash layers, which can be interpreted as a medialto-distal deposit produced by phreatomagmatic surges and contemporaneous fallout [29]. 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. [30,31,32,33]). However, it is difficult to confirm this depositional mechanism, especially in the absence of an extending outcrop. Nevertheless, given that a single surge layer is composed by a well-graded coarse lapilli-rich bed covered by a more fine ash bed [33,34], it is likely that our remnant blocks that present the same characteristics were deposited by a phreatomagmatic surge. In addition, these deposits are partly covered by more recent basaltic lava flow. According to [33,34], a single surge layer is composed by a well-graded coarse lapilli-rich bed covered by a more fine ash bed.

In the last phase of the eruption, magma would have encountered a groundwater body to generate a large phreatomagmatic explosion, which likely produced a huge amount of ash and lithic fragments. This explosion resulted in the formation of the phreatomagmatic pyroclastic surges characterizing U_3. The vitrophyres abundantly found in this surge deposits unit would have derived from juvenile lava that cooled rapidly in the contact of water, and then sprayed out 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 phreatomagmatic fragmentation [35,36,37,38,39]. Depending on the extent of water-magma interaction, fallout layers made of couplets of ash and lapilli can form surge deposits. They can be formed through 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. [16,33,40,41]. Therefore, phreatomagmatic deposits show remarkable variability in grain-size from layer-to-layer and within layers.

In conclusion, we inferred that the eruptions of Bamenda volcano were affected by interaction with water of the lake Oku, 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, followed by welded ignimbrites represented by dark grey and whitish units and pyroclastic surge deposits covered by basaltic flow.

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COMPETING INTERESTS

Authors declare that there are no competing interests.

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