

Remnants blocks of pyroclastic surge deposits in Bambili, Cameroon volcanic Line: New insights into the lithostratigraphy of Mount Bamenda

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 discover 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 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: 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 (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 only 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 13.5 and 6.3 km³, respectively [3]. Considering both alteration and poor condition of these outcrops, the actual volumes could be significantly higher than the estimated ones. Outcrops of smaller sizes (<1 km³) 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].

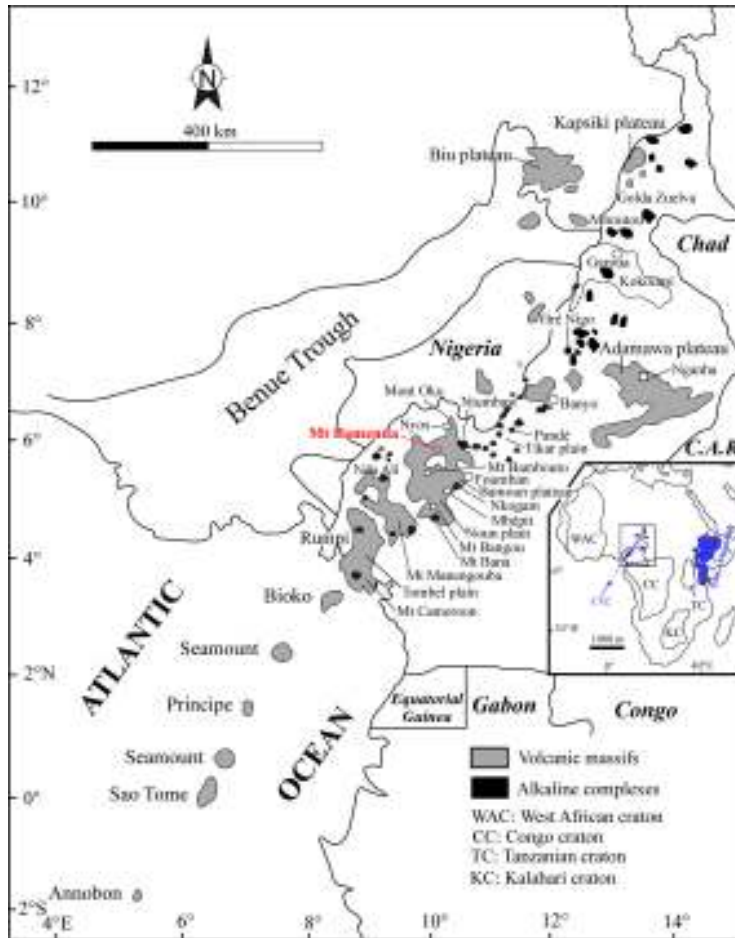


Fig. 1. Map of Cameroon showing the distribution of the Cameroon Volcanic Line (CVL) magmatism. Locations of seamounts are after Burke [2]. C.A.R.: Central African Republic. Inset: location map of CVL in Africa.

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. Until now, only the deposits of pyroclastic flows represented by 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]. In this work, we highlight the existence of pyroclastic surge 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, bring insight into the eruptive history of the Oku volcano, and thus to give their importance in the chronostratigraphy of the Bamenda volcanic field.

2. GEOLOGICAL SETTING

The Mount Bamenda (600 km²) 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 centers 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 10°00'E and 10°30'E and latitudes 05°45'N and 06°10'N and culminates at 2621 m asl.

The Mount Bamenda is characterized 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 neighboring 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. 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 show that the Mt Bamenda lavas consist of basanites, basalts, hawaiites, mugearites, benmoreites, trachytes, rhyolites and ignimbrites [22]. These ignimbrite overlays the granite and gneiss basement rocks 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 17.4 Ma

to present for the basaltic lavas, and from 18.98 Ma to 27.40 Ma for the felsic lavas [22]. As in the case of neighboring 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].

3. MATERIAL 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 accuracy of 1%.

4. FACIES CHARACTERISTICS OF THE BAMBILI IGNIMBRITE AND PYROCLASTIC SURGE REMNANTS

The ignimbrite and pyroclastic surge deposits 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 grey unit and whitish unit), covered by multiple layers of poorly sorted and matrix-poor mIBr facies (Fig. 5). The pyroclastic surge deposits of Bambili are characterized by stratified ashy layers insert in mIBr facies.



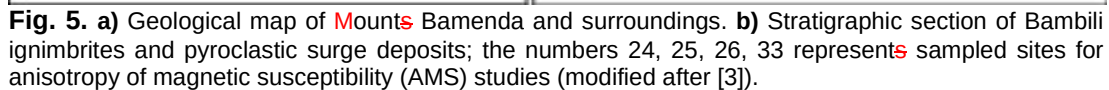
Fig. 3. a) Google map of Bambili town showing the ignimbrite outcrops; **b)** Landscape with ignimbritic remnants of whitish unit of welded mIT lithofacies.



Fig. 4. 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

4. 1 The Lower unit of the mIT facies

The Lower unit of the mIT facies is a flow unit whose color is dark grey 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.



The volcanic clast population includes both aphyric 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.

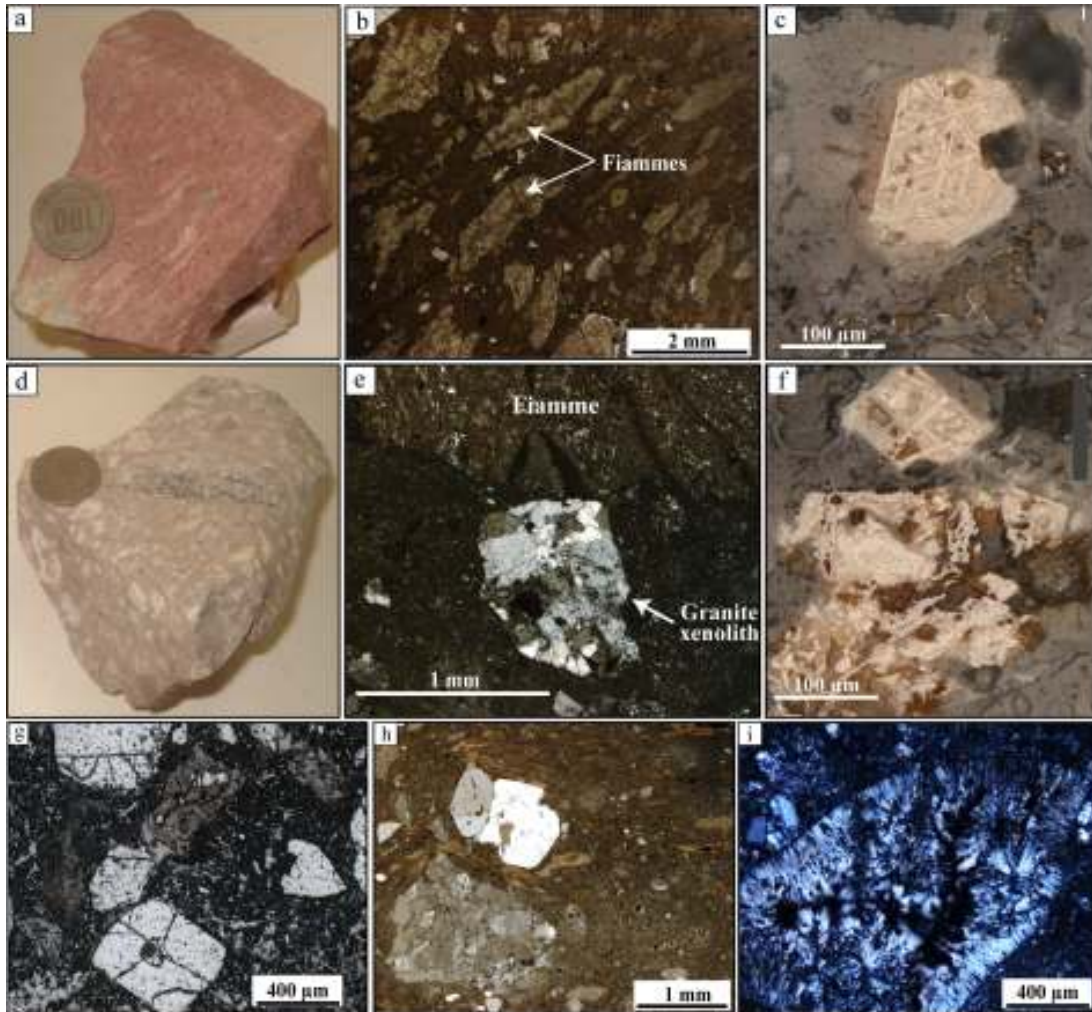


Fig. 6. **a)** Sample of rubefied dark grey unit (DGU) of mIT and **b)** the corresponding microphotograph showing the eutaxitic texture with imbricated fiammes; **c)** Crystal of titanohematite with thin exsolution lamellae of ilmenorutile in the DGU; **d)** Sample of mIT whitish unit (WU) and **e)** 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; **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 they are ryholitic 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 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 cusped 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]. The minerals such as Quartz and alkali feldspar (sanidine), are abundant; plagioclase, clinopyroxene, biotite and Fe-Ti oxides (ilmenorutile; Fig. 6c) are less represented.

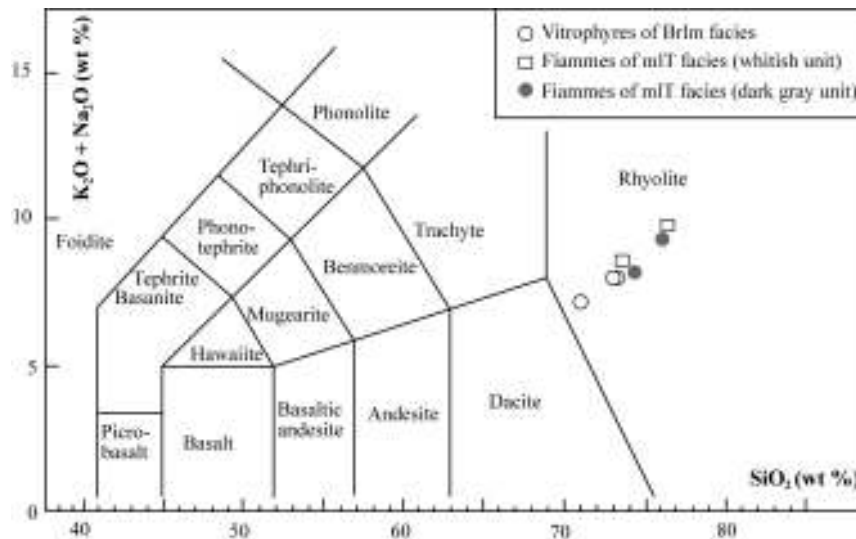


Fig. 7. TAS classification graph [26] for whole rock pumice and vitrophyres samples collected from the Bambili ignimbrites during this study.

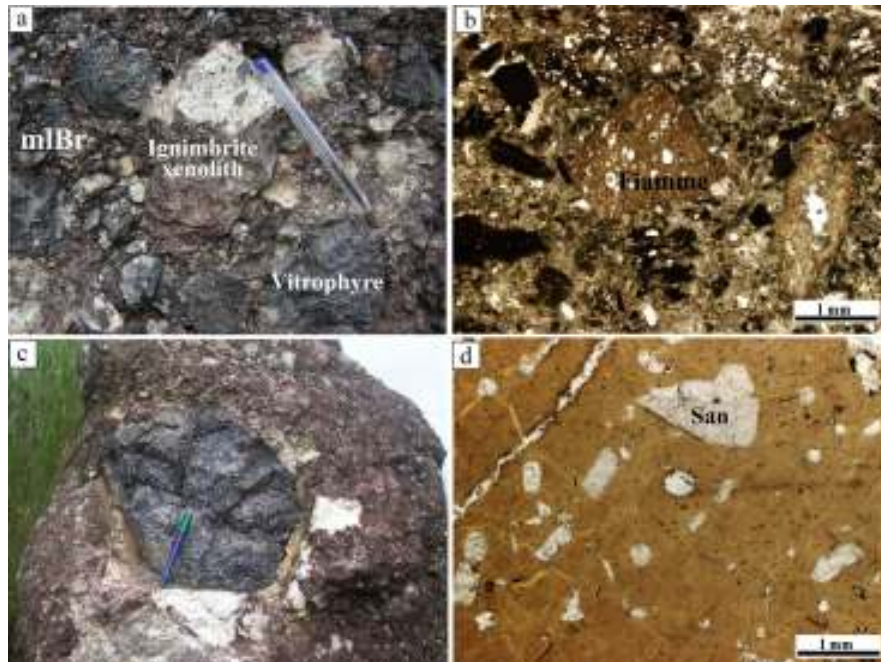
4. 2 The second unit of the mlT facies

The second unit of the mlT facies is whitish and has low density (Fig. 5 and 6d). The rock is characterized by the presence of numerous vesicular pumices, with chalk-white colour and also rhyolitic in composition (Fig. 7; SiO_2 : 74.36 – 76.11% and $Na_2O + K_2O$: 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 devitrified fiammes, small rock fragments smaller than one millimetre, 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.

4. 3 The upper unit: mlBr facies

The surface mlBr facies (Fig. 5 and 8a) is represented by an ignimbrite whose overall colour 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 mlT unit. Consistency depends on the abundance of enclaves, so areas dense of rocky enclaves are more resistant to erosion and in this way the remnant blocks are predominantly made up. Stratification is observable in some of these blocks and is characterized by alternating coarse-grained deposits of more than 35 cm thick and fine particle size deposits not exceeding 8 cm of thickness (Fig. 4a). Pyroclastic surge divisions are ash- to lapilli-sized,

207 grey to whitish in colour with low proportion of accretionary lapilli (Fig. 4b). The lithic breccia
 208 is generally poorly sorted and diffusely stratified in some outcrop^s.
 209



210
 211
 212 **Fig. 8. a)** Detail of mlBr facies and **b)** microphotograph of ignimbrite enclave **c)** Enclave of vitrophyre
 213 and **d)** the corresponding microphotograph.
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215 Rock fragments constituting this ignimbrite are varied in nature. The most represented are
 216 enclaves of vitrophyres (25 to 35%) with black colour (Fig. 8a,c); some pockets can contain
 217 up to 70% of these rock inclusion. Their dimensions range from 22 x 19 cm to 5 x 2.5 cm.
 218 These enclaves are essentially prismatic elements with chilled margins. Under microscope,
 219 the matrix of vitrophyres is essentially vitreous with some crystals of quartz and feldspar
 220 (Fig. 8d). The geochemistry of these vitrophyres (Fig. 7) shows that they are rhyolitic in
 221 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
 222 light grey coloured and represent 5% of the rock volume with sizes ranging from 14 x 12 cm
 223 to 0.8 x 0.6 cm; some elements reach up to 45 x 35 cm. The basement rock enclaves are
 224 rare and usually contain large quartz crystals (11 x 9 cm) constituting about 5% of the rock.
 225 Enclaves of first ignimbritic phase (Fig. 8a,b) included in the second phase were found in this
 226 facies; they measure up to 18 x 16.5 cm. These enclaves of ignimbrites contain the same
 227 rock fragments than the country rocks. Matrix, whitish in colour, consists essentially of
 228 consolidated volcanic ashes in which small rocks and minerals fragments are embedded.
 229

230 5. DISCUSSION AND CONCLUSION

231
 232 The ignimbrites sheets of Bamenda volcano constitute about 7.5% of the rocky outcrops of
 233 the volcano representing approximately 45 km², with a volume estimated at 6.3 km³. These
 234 deposits lie on the trachytic flows and the granito-gneissic basement and are covered in
 235 places by columnar jointed basaltic flows. The studied deposit succession shows evidence
 236 of multiple changes of eruptive regime and emplacement modes that likely occurred during a
 237 single eruptive event. The stratified character of the deposits observed at Bambili can be
 238 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.

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 surge deposits, along with the dominance of blocky, poorly vesicular ash particles with hydration cracks, indicates a genesis as wet pyroclastic surges of phreatomagmatic origin [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 ~~mount Oku~~, the neighboring NE volcano Oku [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 medial-to-distal deposits 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] and [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 has encountered water and thus generated a large explosion that has suspended the huge amount of ash and lithic fragments. Pulsating hydrostatic and magma pressures produced phreatomagmatic pyroclastic surges. The vitrophyres abundantly found in these surge 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 phreatomagmatic fragmentation [35, 36, 37, 38, 39]. Depending on the extent of water-magma interaction, surge 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. [16, 33, 40, 41]). As a consequence, hydromagmatic 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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289 **COMPETING INTERESTS**

290

291 Authors declare that there are no competing interests.

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293 **AUTHORS' CONTRIBUTIONS**

294

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

297

298 **REFERENCES**

299

- 300 1. Déruelle B, Ngounouno I, Demaiffe D. The "Cameroon Hot line" (CHL): a unique
301 example of active alkaline intraplate structure in both oceanic and continental
302 lithospheres. *Compte Rendus Géoscience*. 2007;339:589-600.
- 303 2. Burke K. Origin of the Cameroon Line of volcano-capped swells. *Journal of Geology*.
304 2001;109:349-362.
- 305 3. Gountié Dedzo M, Nédélec A, Nono A, Njanko T, Font E, Kamgang P, Njonfang E.
306 Launeau P. Magnetic fabrics of the Miocene ignimbrites from West-Cameroon:
307 implications for pyroclastic flow source and sedimentation. *Journal of Volcanology and*
308 *Geothermal Research*. 2011;203:113-132.
- 309 4. Dunlop HM. Strontium isotope geochemistry and potassium-argon studies on volcanic
310 rocks from the Cameroon Line, West Africa. PhD Thesis, University of Edinburg,
311 Edinburg; 1983.
- 312 5. Lissom J. Etude pétrologique des laves alcalines du massif d'Oku: un ensemble
313 volcanique de la "Ligne du Cameroun". Thèse Université Pierre et Marie Curie, (Paris
314 VI) ; 1991. French.
- 315 6. Kamgang P. Contribution à l'étude géochimique et pétrologique du massif de Nkogam
316 (pays Bamoun, Ouest-Cameroun). Thèse Doctorat 3^e cycle, Université de Yaoundé;
317 1986. French.
- 318 7. Nono A, Déruelle B, Demaiffe D, Kambou R. Tchabal Nganha volcano in Adamawa
319 (Cameroon): petrology of a continental alkaline lava series. *Journal of Volcanology and*
320 *Geothermal Research*. 1994;60:147-178.
- 321 8. Branney MJ, Kokelaar P. Pyroclastic density currents and the sedimentation of
322 ignimbrites. *Geological Society of London Memoirs*. 2002;27.
- 323 9. Valentine GA, Fisher RV. Pyroclastic surges and blasts. In: Sigurdsson H (Ed.)
324 *Encyclopedia of Volcanoes*, Academic Press. 2000;571–580.
- 325 10. Wilson CJN, Houghton BF. Pyroclast transport and deposition. In: Sigurdsson H (Ed.)
326 *Encyclopedia of Volcanoes*, Academic Press, 2000;545–554.
- 327 11. Carey S. Transport and deposition of tephra by pyroclastic flows and surges.
328 *Sedimentation in volcanic Settings*. Society of Economic Paleontology and Mineralogy
329 Special Publication. 1991;45:39–57.
- 330 12. Druitt TH. Pyroclastic density currents. In: Gilbert JS, Sparks RSJ (Ed) *The physics of*
331 *explosive volcanic eruptions*. Geological Society of London Special Publication.
332 1998;145:145–182.
- 333 13. Belousov A, Voight B, Belousova M, Petukhin A. Pyroclastic surges and flows from the
334 8–10 May 1997 explosive eruption of Bezymianny volcano, Kamchatka, Russia. *Bulletin*
335 *of Volcanology*. 2002;64, 455–471.
- 336 14. Burgisser A, Bergantz GW. Reconciling pyroclastic flow and surge: the multiphase
337 physics of pyroclastic density currents. *Earth Planetary Science Letters*. 2002;202:405–
338 418.
- 339 15. Fisher RV. Transport and deposition of a pyroclastic surge across an area of high relief:
340 the 18 May 1980 eruption of Mount St. Helens, Washington. *Geological Society of*
341 *America Bulletin*. 1990;92:938–954.

- 342 16. Dellino P, La Volpe L. Structures and grain size distribution in surge deposits as a tool
343 for modelling the dynamics of dilute pyroclastic density currents at La Fossa di Vulcano.
344 *Journal of Volcanology and Geothermal Research*. 2000;96:57-78.
- 345 17. Valentine GA, Fisher RV. Pyroclastic surges and blasts. In: Sigurdsson H (Ed.)
346 *Encyclopedia of Volcanoes*, Academic Press. 2000;571–580.
- 347 18. Toteu SF, Van Schmus WR, Penaye J, Michard A. New U–Pb and Sm–Nd data from
348 north Cameroon and its bearing on the pre-Pan African history of central Africa.
349 *Precambrian Research*. 2001;108:45-73.
- 350 19. Nzolang C, Kagami H, Nzenti P, Hotz F. Geochemistry and preliminary Sr-Nd isotopic
351 data on the Neoproterozoic granitoids from the Bantoum Area, West Cameroon:
352 evidence for a derivation from a Paleoproterozoic to Archean crust. *Polar Geoscience*.
353 2003;16:196-226.
- 354 20. Nzolang C. Crustal evolution of the Precambrian basement in west Cameroon:
355 inference from geochemistry, Sr–Nd and experimental investigation of some granitoids
356 and metamorphic rocks. Ph.D. thesis, Graduate School of Science and Technology,
357 Niigata University, Japan; 2005.
- 358 21. Gountié Dedzo M, Njonfang E, Kamgang P, Nono A, Zangmo Tefogoum G, Kagou
359 Dongmo A, Nkouathio DG. Dynamic and evolution of the Mounts Bambouto and
360 Bamenda calderas by study of ignimbritic deposits (West-Cameroon, Cameroon Line).
361 *Syllabus Review, Science Series*. 2012;3:11-23.
- 362 22. Kamgang P, Njonfang E, Nono A, Gountié Dedzo M, Tchoua FM. Petrogenesis of a
363 silicic magma system: Geochemical evidence from Bamenda Mountains, NW
364 Cameroon, Cameroon Volcanic Line. *Journal of African Earth Sciences*. 2010;58:285-
365 304.
- 366 23. Lofgren G. Experimentally produced devitrification textures in natural rhyolite glass.
367 *Geological Society of America Bulletin*, 1971a;82:553-560.
- 368 24. Lofgren G. Spherulitic textures in glassy and crystalline rocks. *Journal of Geophysical*
369 *Research*. 1971b;76:5635-5648.
- 370 25. Lofgren G. An experimental study of plagioclase crystal morphology: isothermal
371 crystallization. *American Journal of Science*. 1974;274:243-273.
- 372 26. Le Bas M, Le Maitre R, Streckeisen A, Zanettin B. A chemical classification of volcanic
373 rocks based on the total alkali-silica diagram. *Journal of Petrology*. 1986;27:745-750.
- 374 27. Sigurdsson H, Carey S, Cornell W, Pescatore T. The eruption of Vesuvius in A.D. 79,
375 *National Geographic Research*. 1985;1:332-387.
- 376 28. Palladino DM, Simeì S. Eruptive dynamics and caldera collapse during the Onano
377 eruption, Vulcini, Italy. *Bulletin of Volcanology*. 2005;167:423-440.
- 378 29. Zanon V, Pacheco J, Pimentel A. Growth and evolution of an emergent tuff cone:
379 Considerations from structural geology, geomorphology and facies analysis of São
380 Roque volcano, São Miguel (Azores). *Journal of Volcanology and Geothermal*
381 *Research* 2009;180:277-291.
- 382 30. Wohletz KH, Sheridan MF. A model of pyroclastic surge. *Geological Society of*
383 *American Special Paper*. 1979;180:177-194.
- 384 31. Fisher RV, Schmincke HU. *Pyroclastic rocks*. Springer-Verlag, New York. 1984.
- 385 32. Cole PD, Guest JE, Duncan AM, Pacheco JM. Capelinhos 1957–1958, Faial, Azores:
386 deposits formed by an emergent surtseyan eruption. *Bulletin of Volcanology*.
387 2001;63:204-220.
- 388 33. Dellino P, Isaia R, La Volpe L, Orsi G. Interaction between particles transported by
389 fallout and surge in the deposits of the Agnano–Monte Spina eruption (Campi Flegrei,
390 Southern Italy). *Journal of Volcanology and Geothermal Research*. 2004;133:193-210.
- 391 34. Sohn YK, Chough SK. Depositional processes of the Suwolbong tuff ring, Cheju Island
392 (Korea). *Sedimentology*. 1989;36:837-855.
- 393 35. Wohletz KH, Sheridan MF. Hydrovolcanic eruptions: II. Evolution of basaltic tuff rings
394 and tuff cones. *American Journal of Science*. 1983;283:385-413.

- 395 36. Houghton BF, Hackett WR. Strombolian and phreatomagmatic deposits of Ohakune
396 craters, Ruapehu, New Zealand: a complex interaction between external water and
397 rising basaltic magma. *Journal of Volcanology and Geothermal Research*. 1984;21:207-
398 231.
- 399 37. Kokelaar P. Magma–water interactions in subaqueous and emergent basaltic
400 volcanism. *Bulletin of Volcanology*. 1986;48:275-289.
- 401 38. White JDL, Houghton B. Surtseyan and related phreatomagmatic eruptions. In:
402 Sigurdsson, H., Houghton, B.F., McNutt, S.R., Rymer, H., Stix, J. (Eds.), *Encyclopedia*
403 *of Volcanoes*, Academic Press, San Diego. 2000;495-511.
- 404 39. Mastin LG, Christiansen RL, Thornber C, Lowenstern J, Beeson M. What makes
405 hydromagmatic eruptions violent? Some insights from the Keanakākoī Ash, Kīlauea
406 Volcano, Hawaii. *Journal of Volcanology and Geothermal Research*. 2004;137:15-31.
- 407 40. Chough SK, Sohn YK. Depositional mechanics and sequences 705 of base surges,
408 Songaksan tuff ring, Cheju Island, Korea. *Sedimentology*. 1990;37:1115-1135.
- 409 41. Dellino P, Isaia R, La Volpe L, Orsi G. Statistical analysis of textural data from complex
410 pyroclastic sequences: implications for fragmentation processes of the Agnano–Monte
411 Spina tephra (4.1 ka), Campi Flegrei, southern Italy. *Bulletin of Volcanology*.
412 2001;63:443-461.
- 413